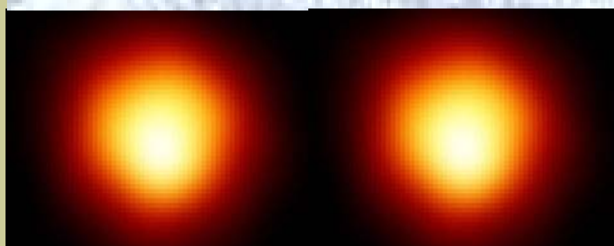
Double Star Interferometry 102:

Advanced Techniques: Dual Star Astrometry



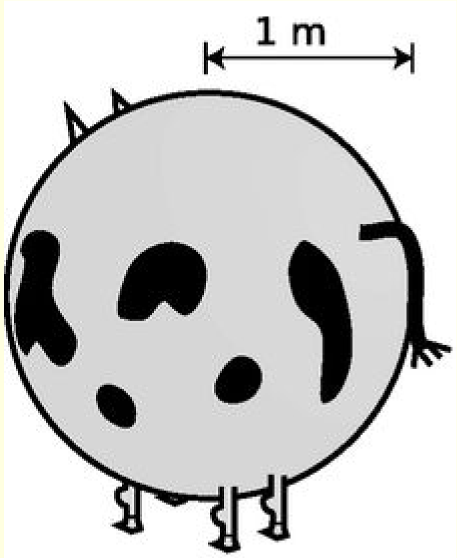
or, Why Buy One Ridiculously Complicated Interferometer When You Can Buy Two at Twice the Price?

Dr. Gerard van Belle
Lowell Observatory
February 10, 2013

Caveat Emptor

- A number of *assumptions* will be made herein
- A number of *simplifications* will be made herein
- And I'll probably make a few outright errors, which I will attempt to cover up with an aura of smug self-confidence

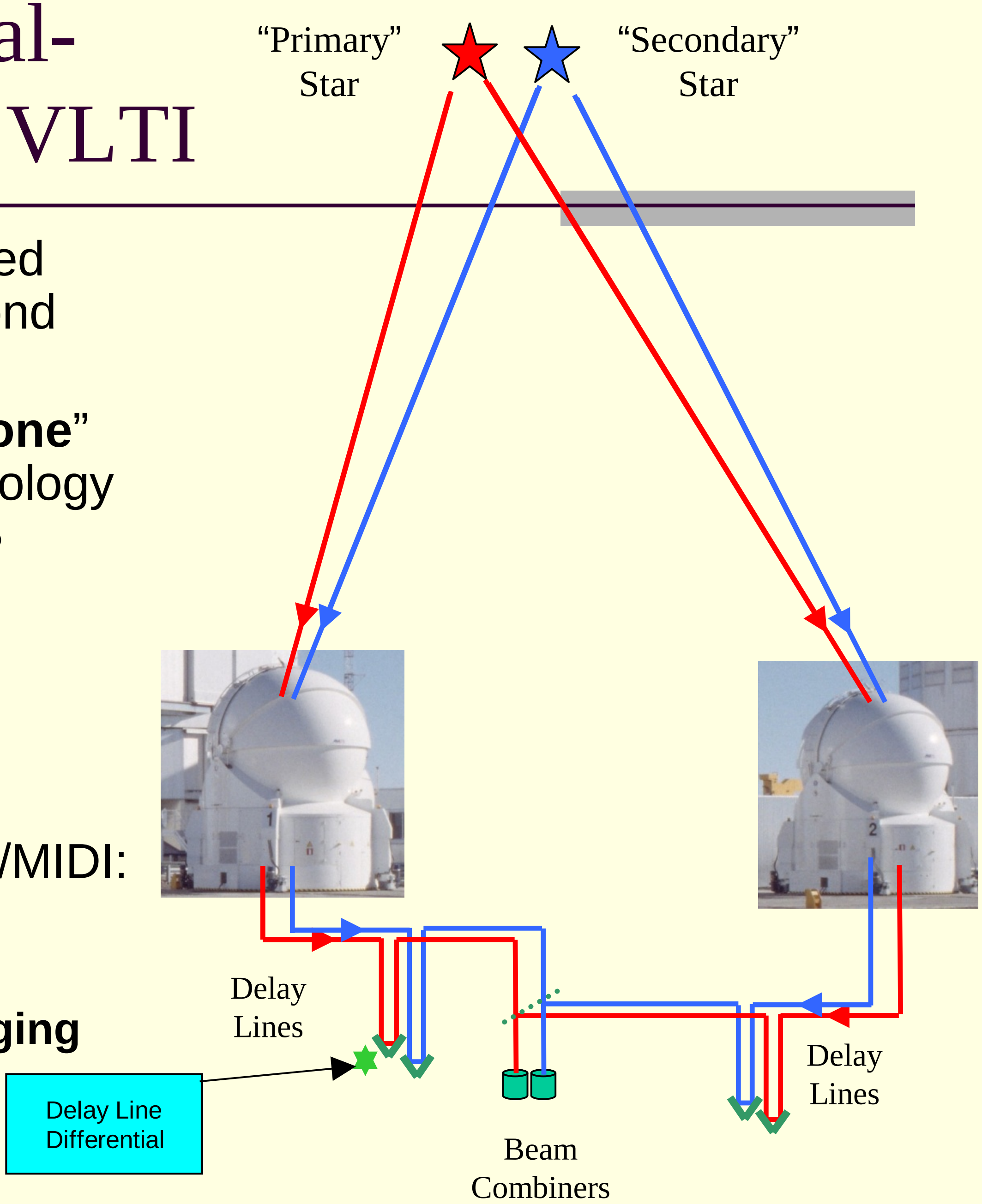
Example Astronomer Simplification:



Cows are, to zeroth order, spherical in shape.

PRIMA: The Dual-Feed Facility for VLTI

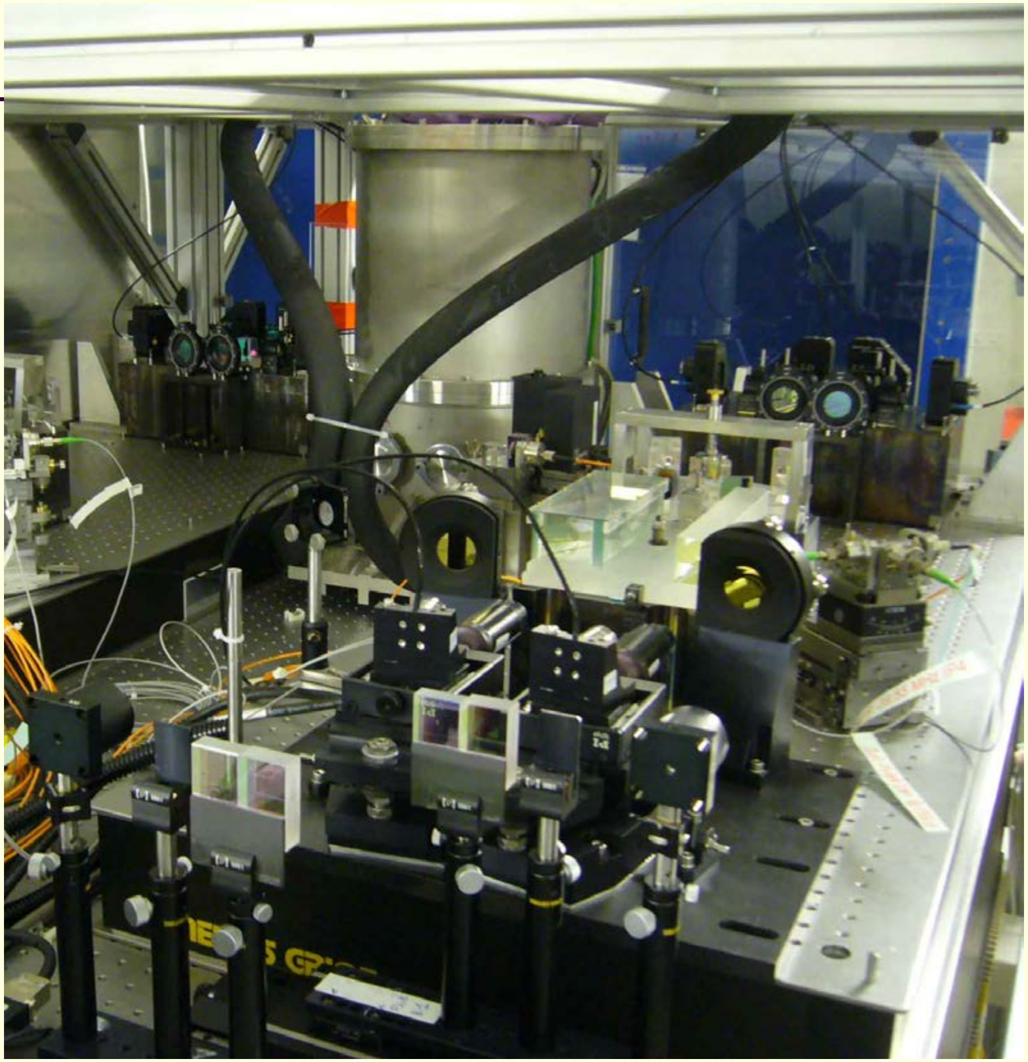
- PRIMA = Phase Referenced Imaging and Microarcsecond Astrometry
- “**Two interferometers in one**” tied together by laser metrology
- An instrument or a facility?
  - A bit of both
- Enables 3 new modes:
  - Stand-alone instrument: **Astrometry**
  - Facility feeding AMBER/MIDI:
    - **Faint star science** (like single-aperture NGS)
    - **Phase-referenced imaging**



What VLTI-PRIMA looks like in practice

Motivations for PRIMA

- Astrometry: Extrasolar planet detection
  - Initially at 70-100µas level
  - Ultimate performance: ~30µas level
  - No sin i ambiguity in masses
- Increased sensitivity for VLTI
  - Akin to 'Natural guide star' AO
  - Increase in coherence time from ~2ms to ~1000ms



How does PRIMA do this?

PRIMA Architecture

- Auxiliary Telescopes (ATs)
  - Collects starlight
- Star Separators (STSs)
  - Picks out two sources in a 120” FOV
  - Tip-tilt field stabilization (STRAP)
  - Metrology endpoint
- Main Delay Lines
  - Provide optical path delay to both starlight beams
- Differential Delay Lines (DDLs)
  - Provide optical path delay to individual starlight beams
- Fringe Sensor Units (FSUs)
  - Twin fringe trackers for starlight
- PRIMA Metrology (PRIMET)
  - Ties two starlight beam paths together
- Infrared Image Stabilizer (IRIS)
  - Tracks residual tip-tilt errors in lab
- MARCEL
  - Calibration source

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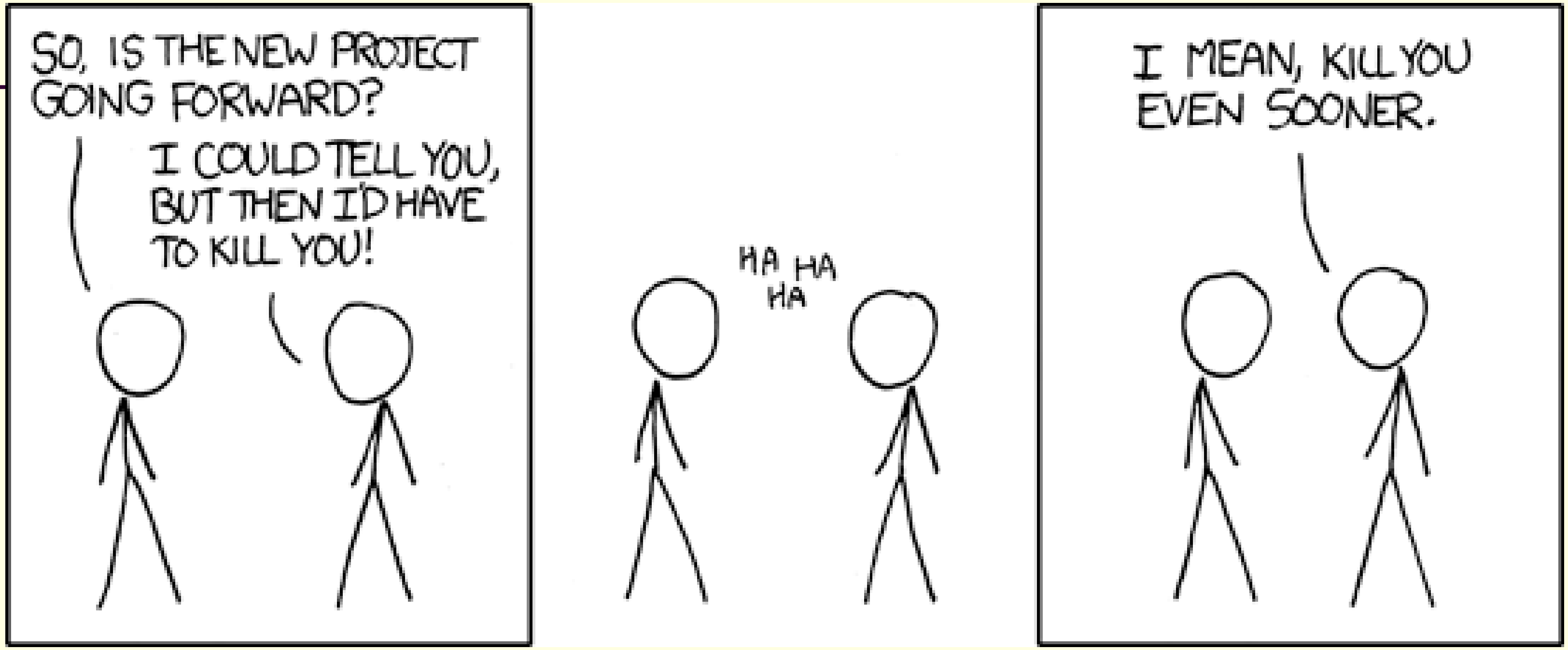
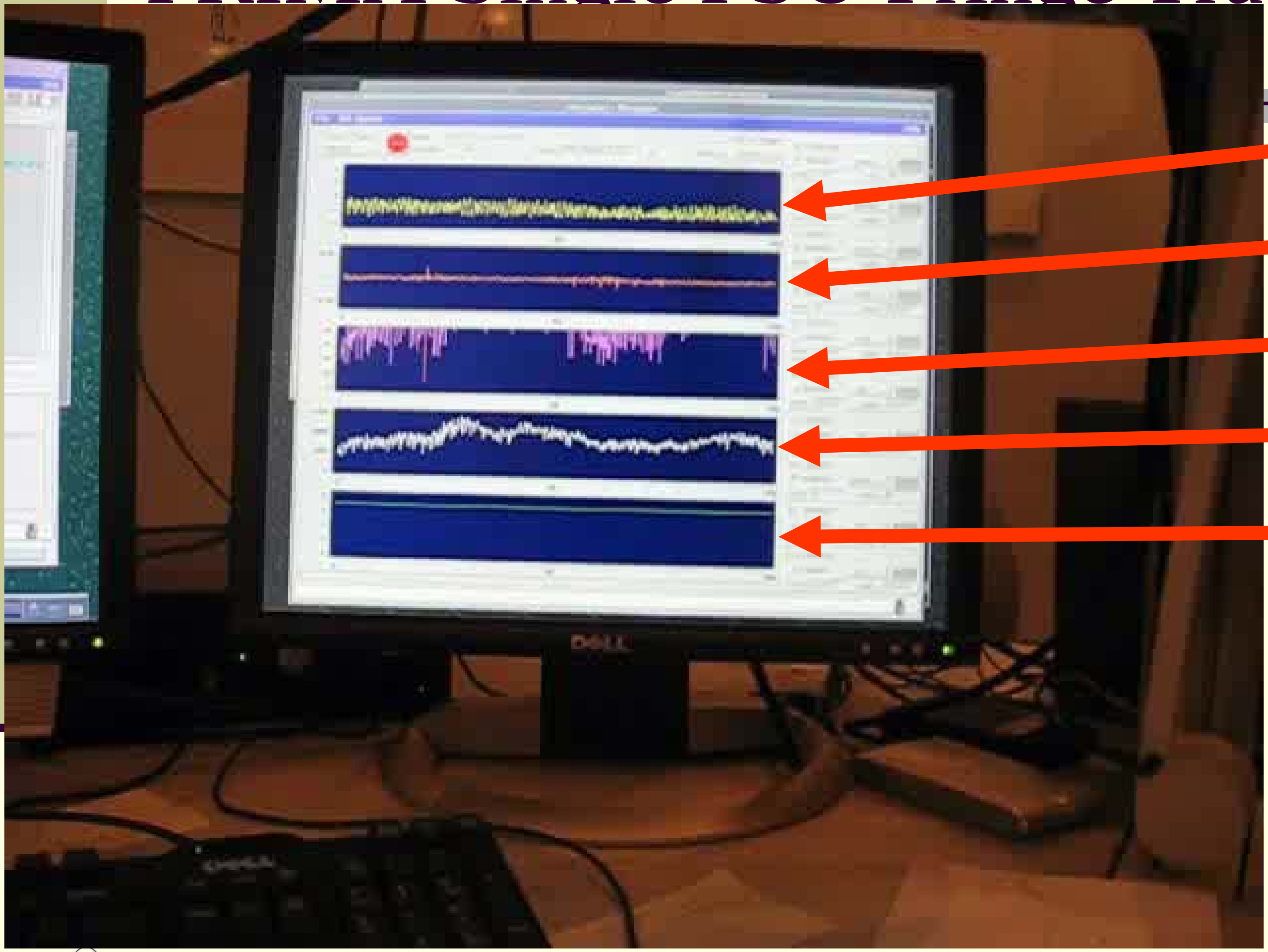
PRIMA Commissioning



www.xkcd.com

- All this technology sounds *very complicated*
- When's it going to be ready?
  - See cartoon above
- Let's take a look at *how* it's been going

Initial Steps (early 2009): PRIMA Single FSU Fringe Tracking



Phase delay

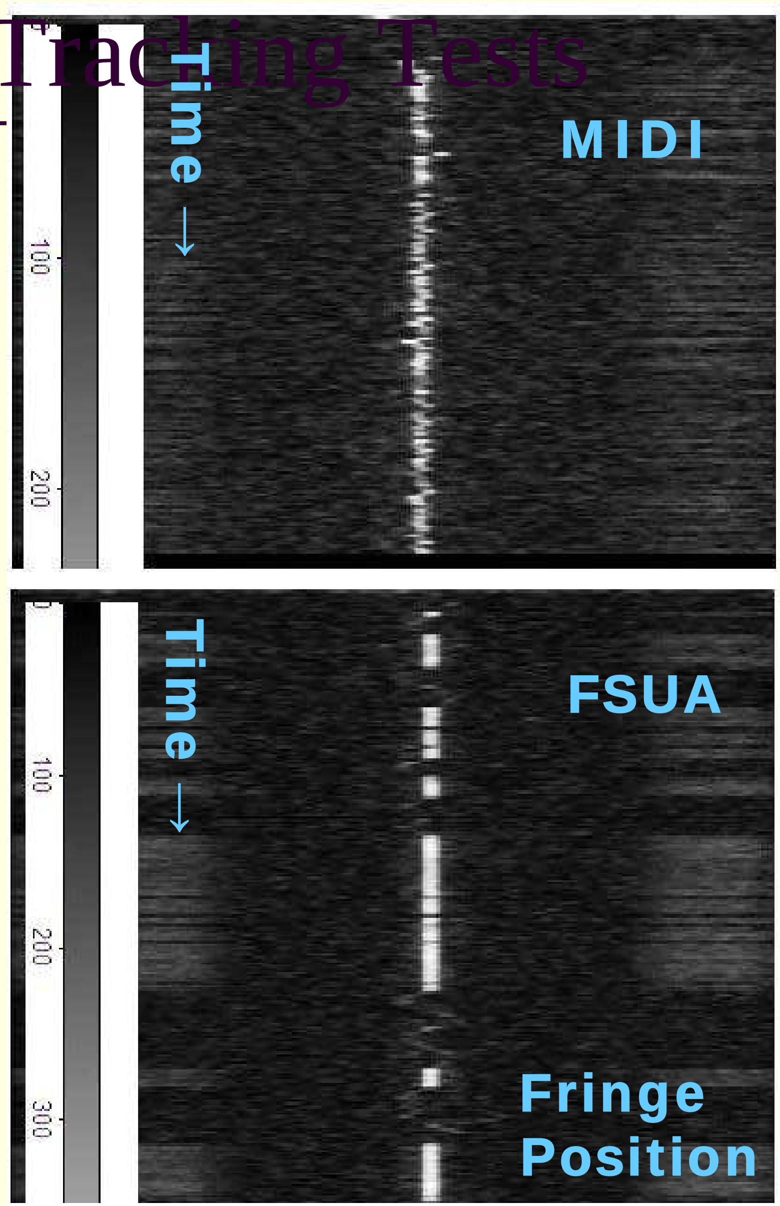
Group delay

SNR

Flux

Lock status

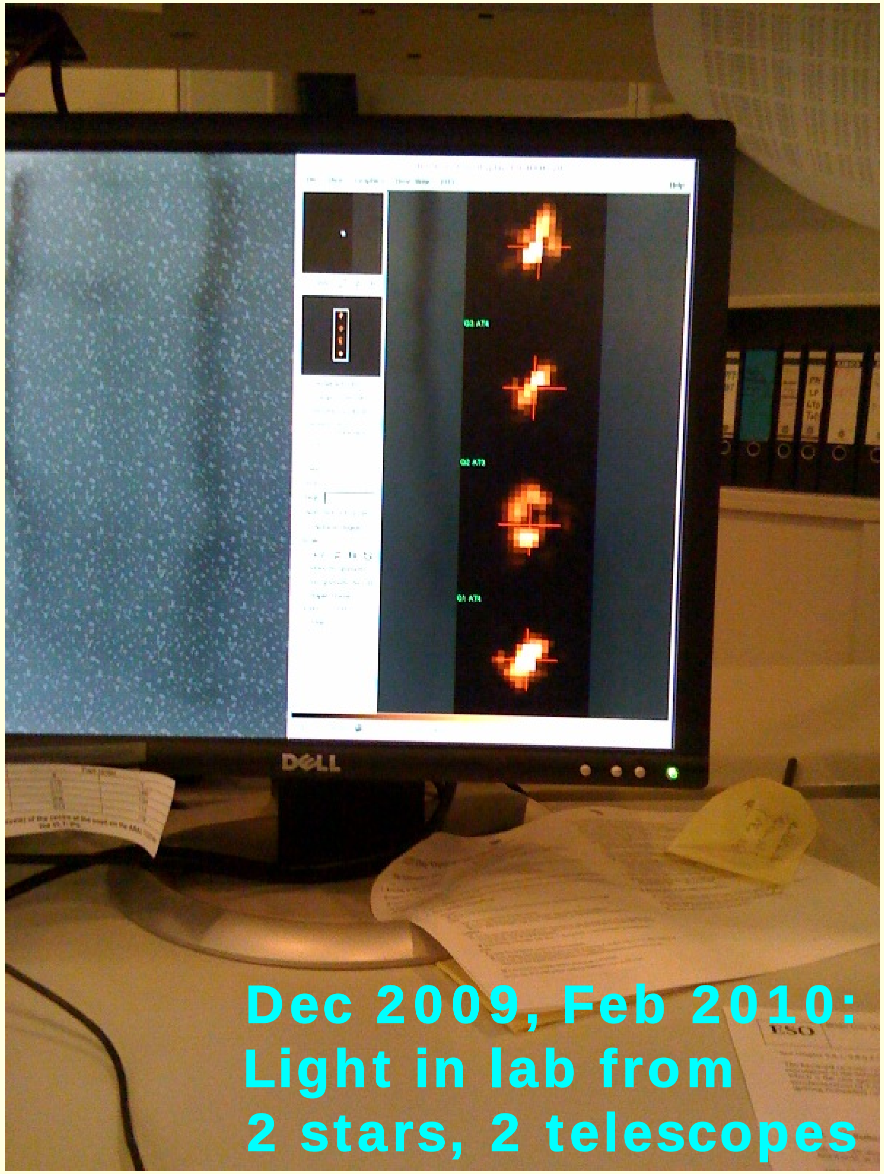
FSUA+MIDI On-Axis Fringe Tracking Tests



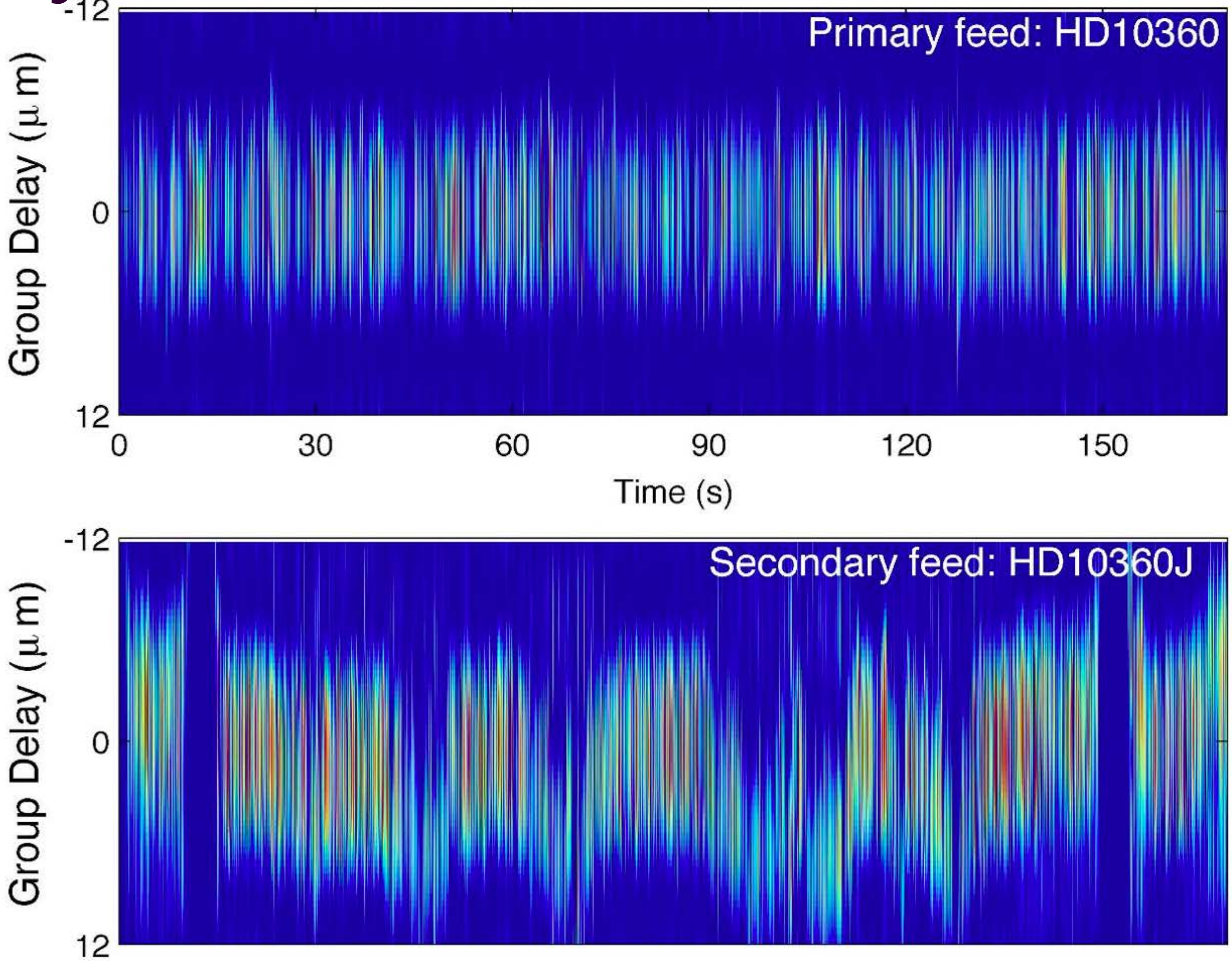
- **Engineering test** of PRIMA+MIDI
  - MIDI can provide fringe tracking (FTK) for itself
  - Same function can also be provided by PRIMA
  - Tests carried out in July, Sept 2009; Jan 2011 commissioning runs
  - **Caveat emptor: Currently a non-standard mode**
- Promising results
  - FTK errors (group delay residuals) are an order of magnitude less with PRIMA FTK
  - Also, fringes detected for targets too faint for MIDI FTK (F_{12}≈0.5Jy)
    - Well below the AT limit of 20Jy
  - Calibration unclear, though, due to open photometry questions – work in progress on that front
- Future work
  - OPC assigned time from GTO to test on a science target in risk-sharing mode

PRIMA Commissioning in late 2009, early 2010: Establishing Dual Beam Functionality

- PRIMA's unique strength will be through simultaneous interferometry of 2 stars at once
- Four starlight beams (2×2 stars) stabilized in tip-tilt for the 1st time in VLTI lab in Paranal in Dec 2009
  - Further testing took place in Feb 2010
  - Dual-star astrometry then follows with 2×FTK+metrology
- Development of this functionality into a fully operational capability was the major goal of P85 commissioning work
  - Sub-system punchlist items remain, along with system integration challenges

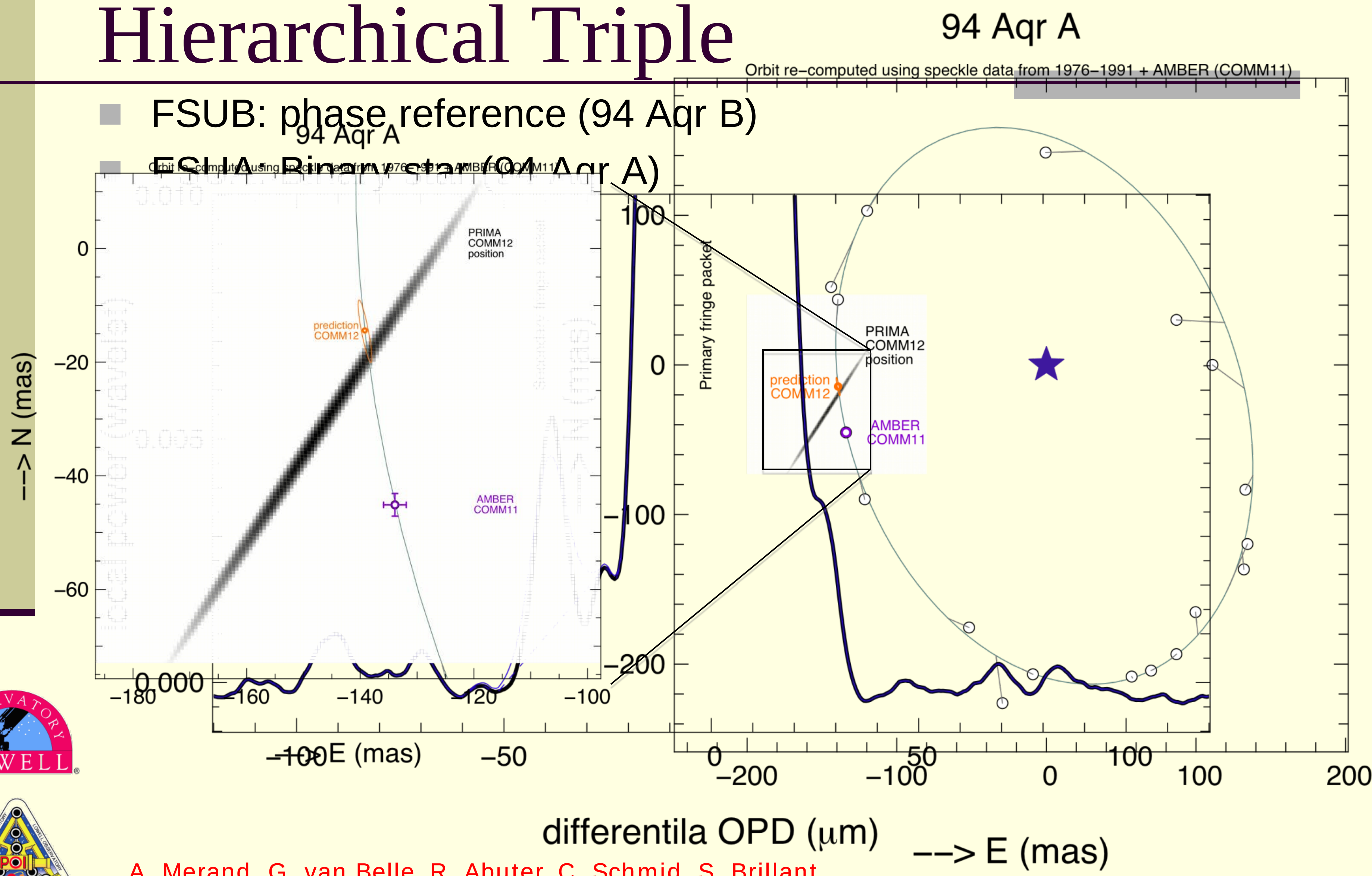


July 2010: Dual-Feed FTK



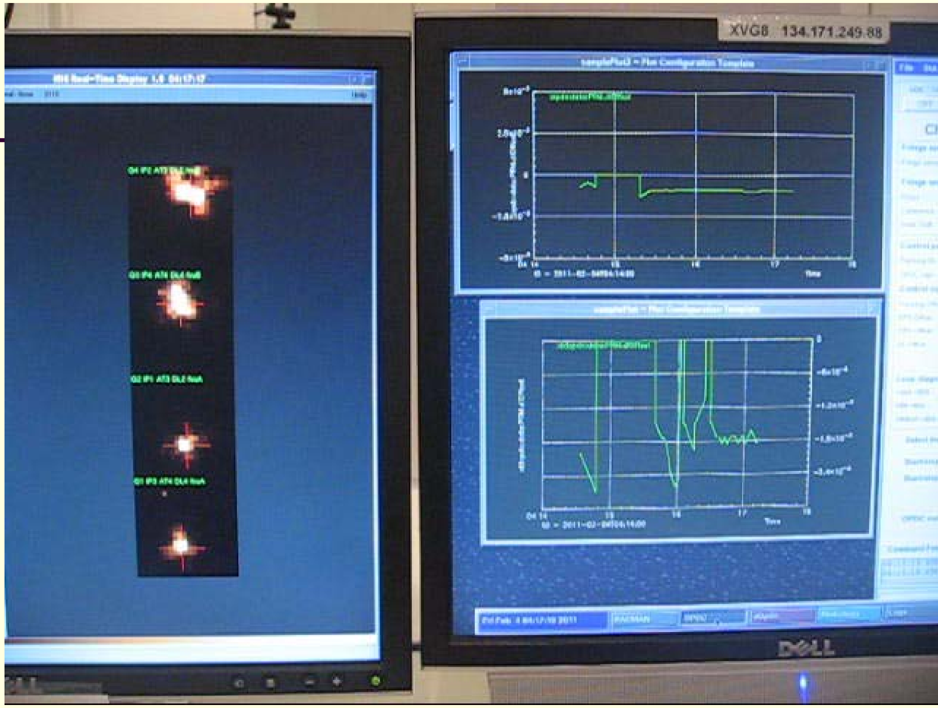
Early ‘Science’ Result: Hierarchical Triple

- FSUB: phase reference (94 Aqr B)
- FSUA: Binary star (94 Aqr A)



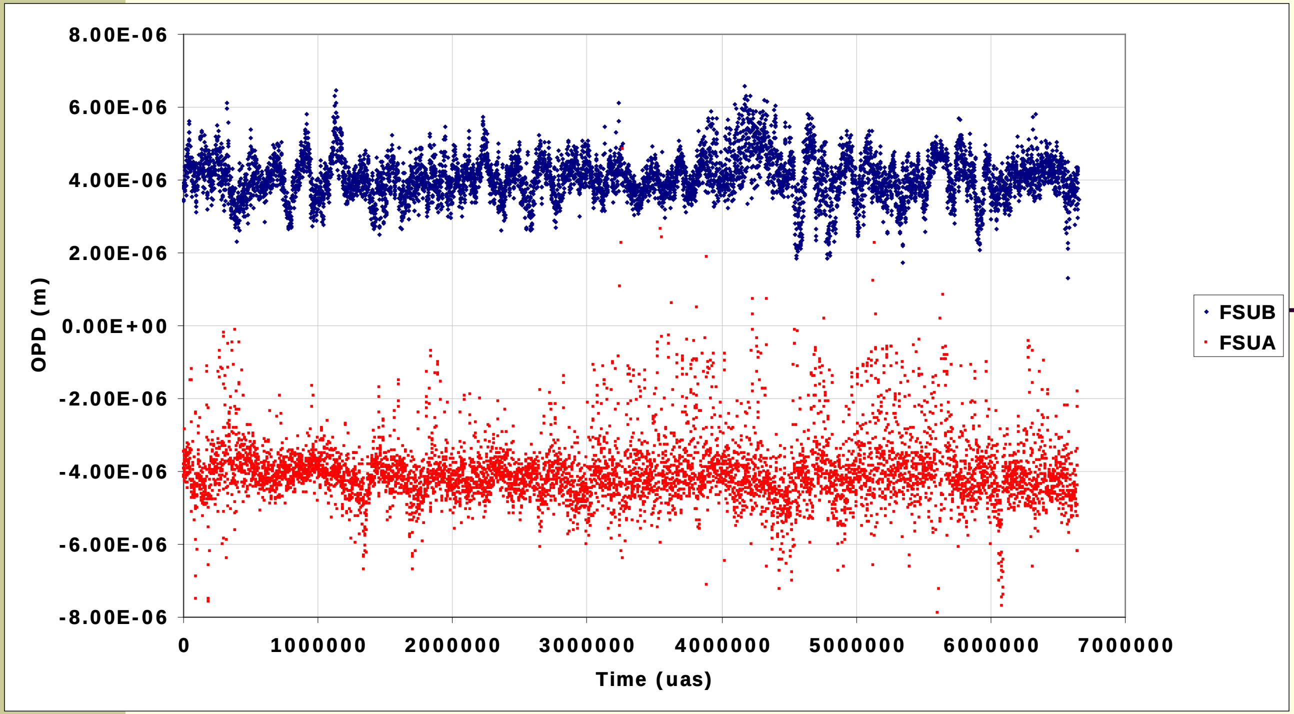
A. Merand, G. van Belle, R. Abuter, C. Schmid, S. Brillant

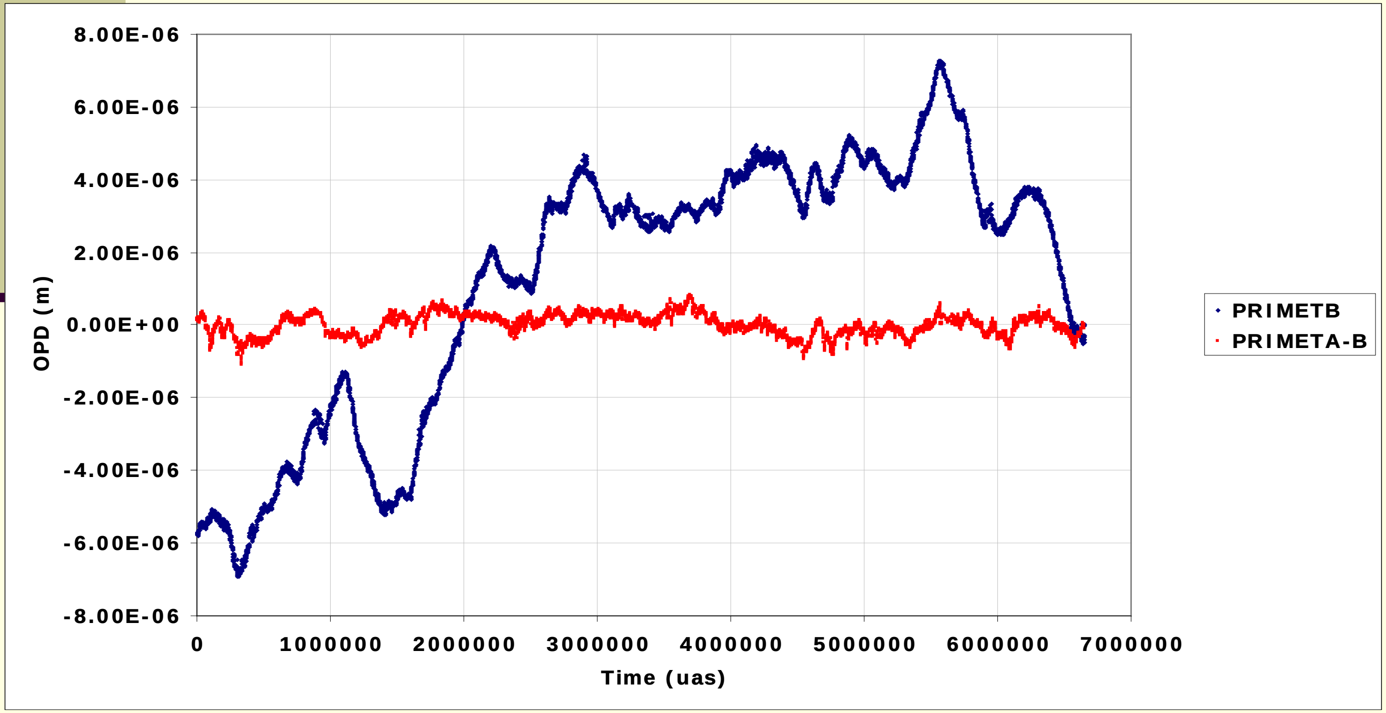
Late 2010: Dual Feed FTK with PRIMET Active



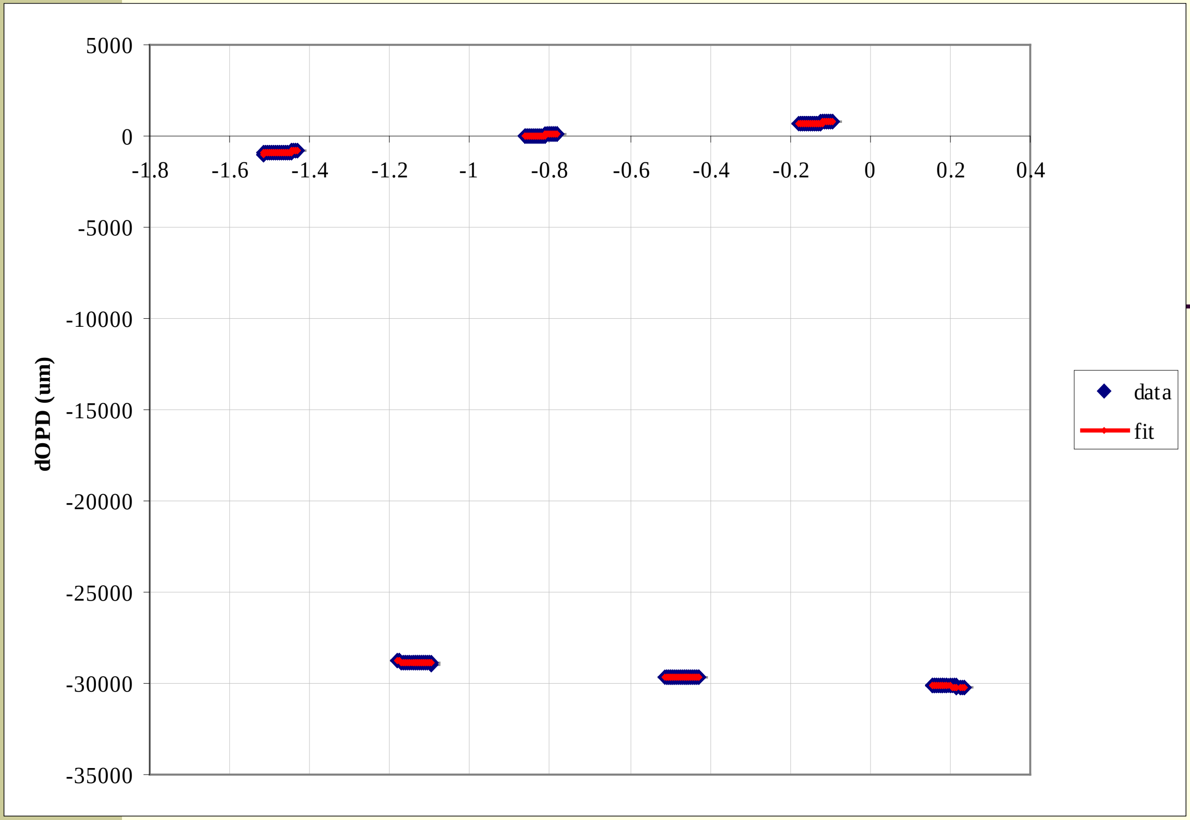
- PRIMET and dual FSU fringe tracking successful in Nov 2010
- Led to fully operational astrometric observing in Jan 2011
  - PRIMET+FSUA(1)+FSUB(2) —swap→ PRIMET+FSUA(2)+FSUB(1)
  - No loss of PRIMET tracking during swap

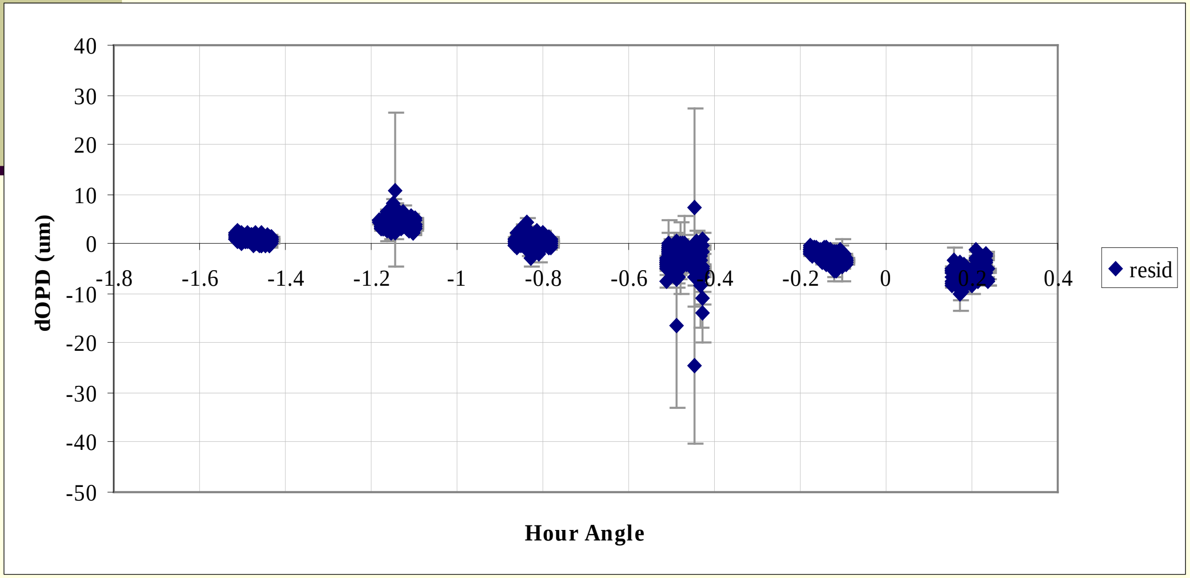
Full Dual PRIMA Operations





- Dual simultaneous FTK and metrology
- Top: FSUB and A
  - Tracking separate stars
- Bottom: PRIMETB and A-B
  - B shows effect of tracking out atmosphere (sidereal motion tracking not displayed - 2cm over 6s!)
  - A-B shows instrumental ΔOPD, residual atmosphere



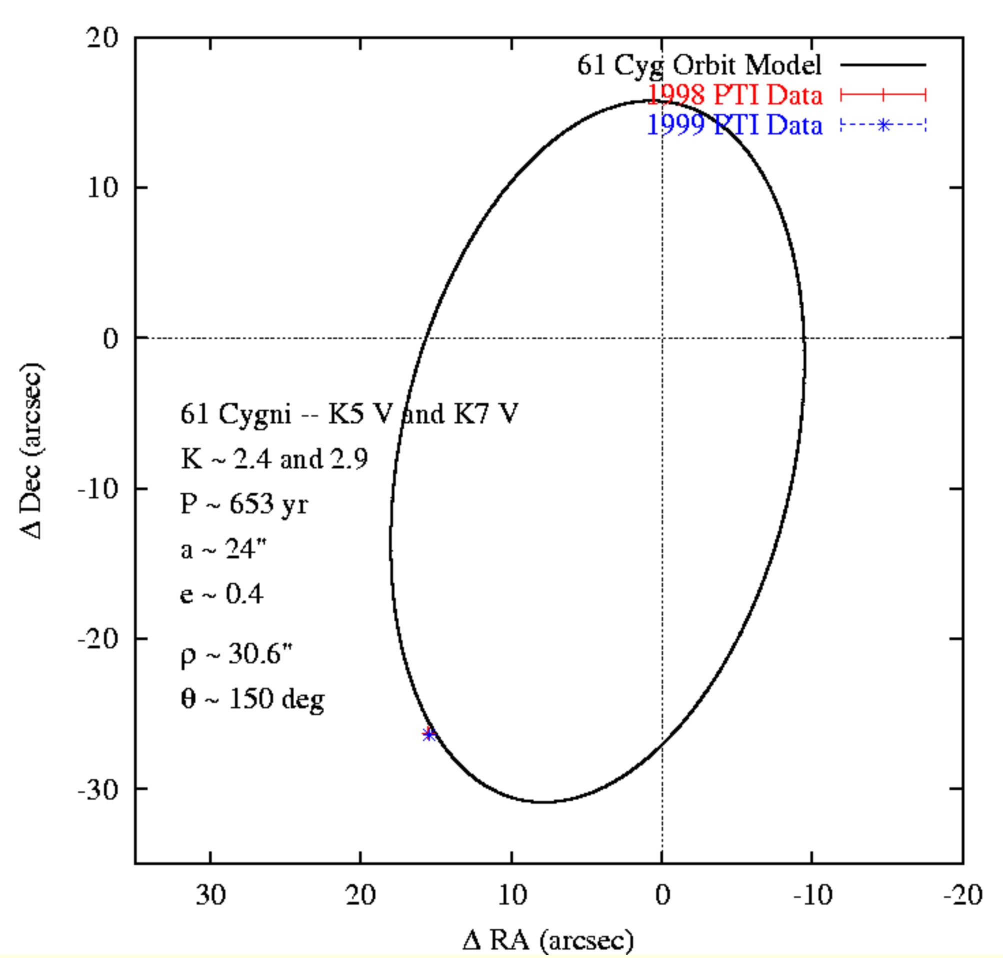


PRIMA Astrometry

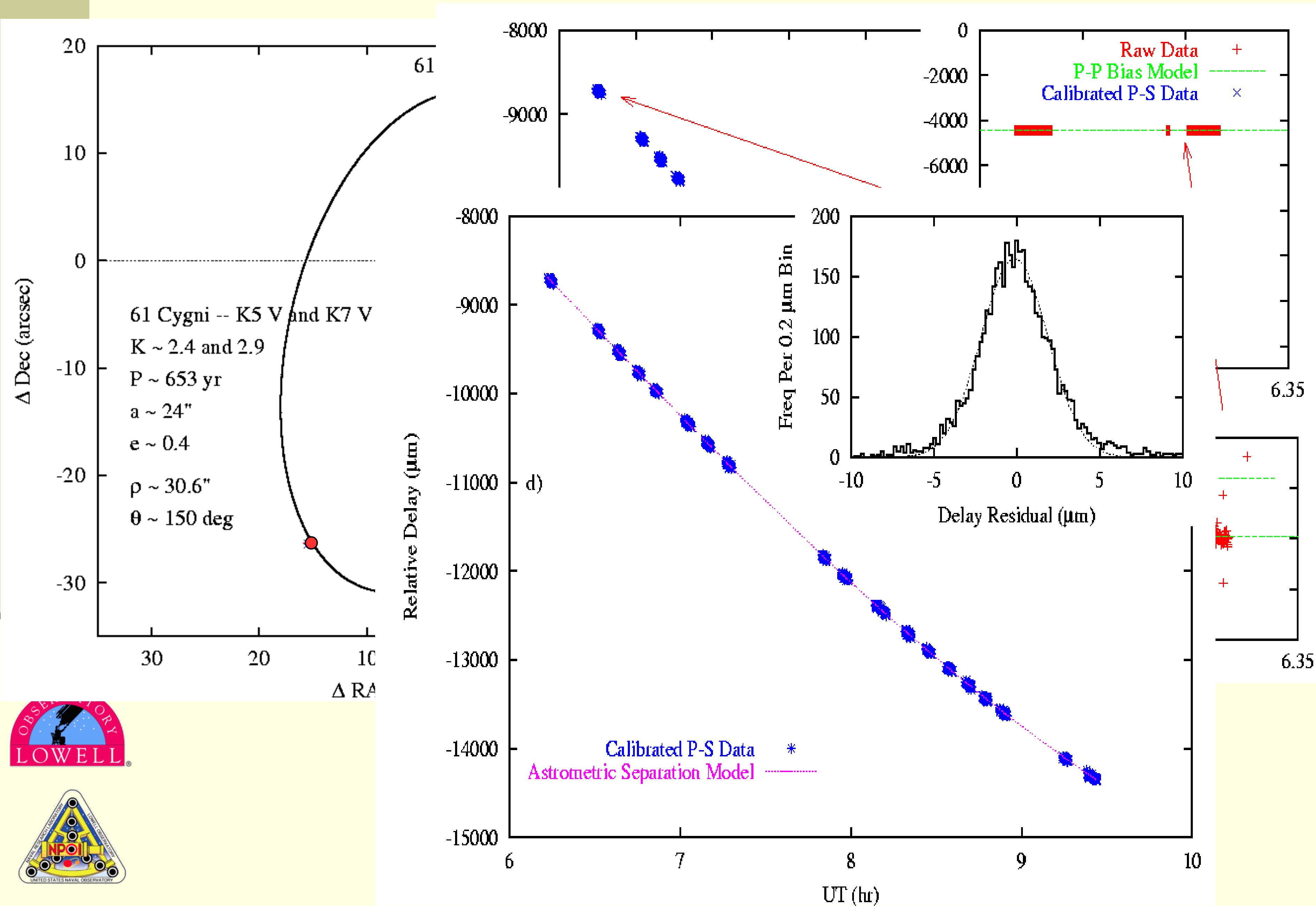
- First results
- Twin traces show metrology signal before/after PS-SS and SS-PS swap
- Lower plot shows residuals of *simple* astrometric fit
- Night-to-night repeatability of 75mas
  - Not bad, except goal is >75µas
  - Does not include fringe error signal, other known error terms
  - Clearly some systematics at ±10µm level not accounted for yet
  - Need to be at <1µm for ~ 75µas astrometry

Astrometry Mode Example: PTI Dual-Star Observations of 61 Cygni

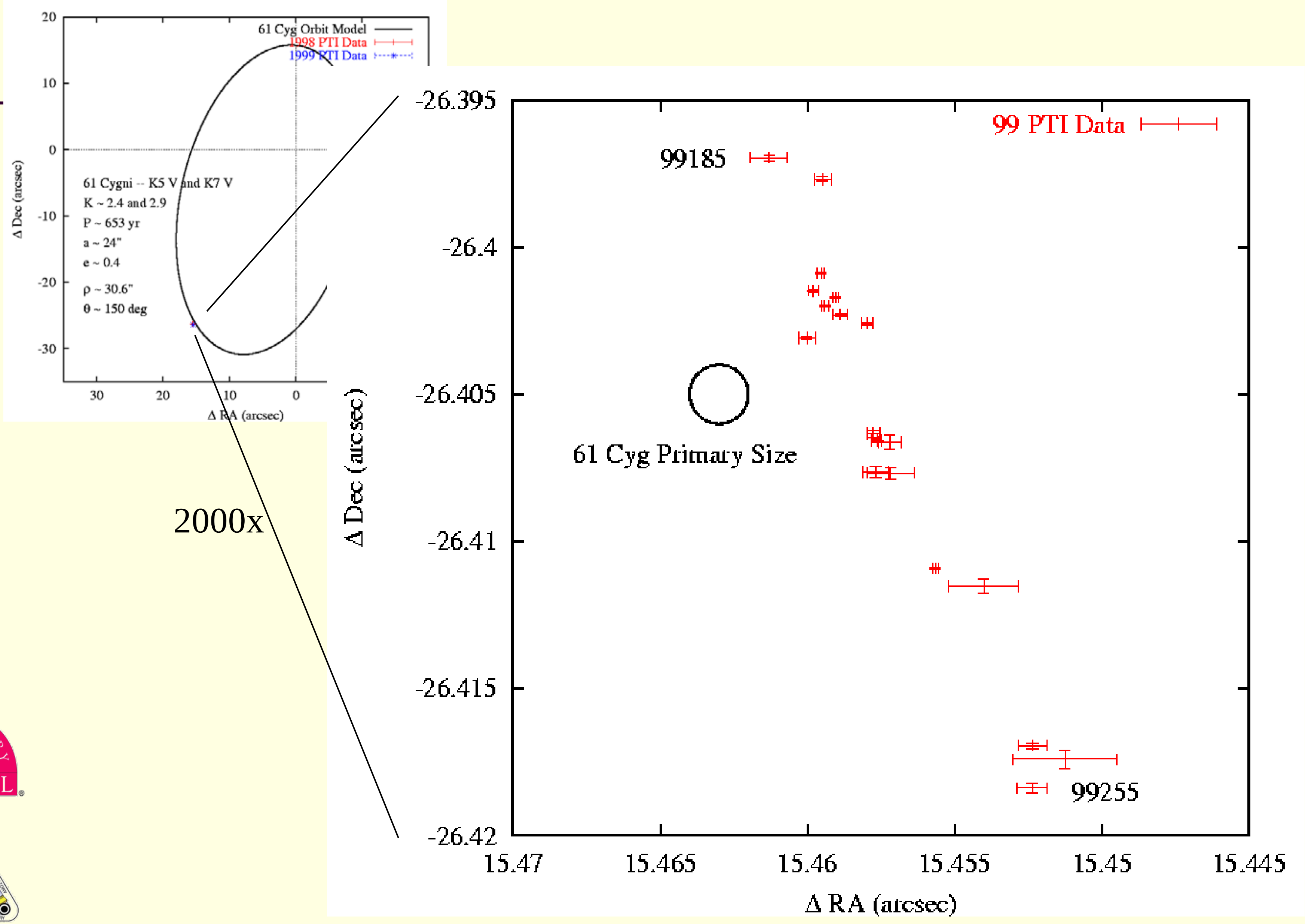
- Palomar Testbed Interferometer (PTI)
  - NASA-JPL dual-beam testbed
  - K-band, 109m baseline
  - Operated 1997-2009
  - *Very* limited sensitivity
- 61 Cygni
  - Nearby K-dwarf Visual Binary (*K*~2.5)
  - ~30” separation
  - ~ 650 yr period eccentric orbit
  - ‘God’s gift to dual-star testing’ (if you live in the N hemisphere, δ=+38°)
- We have it on Good Authority (Geoff Marcy) that there is *nothing* going on in this system WRT planets



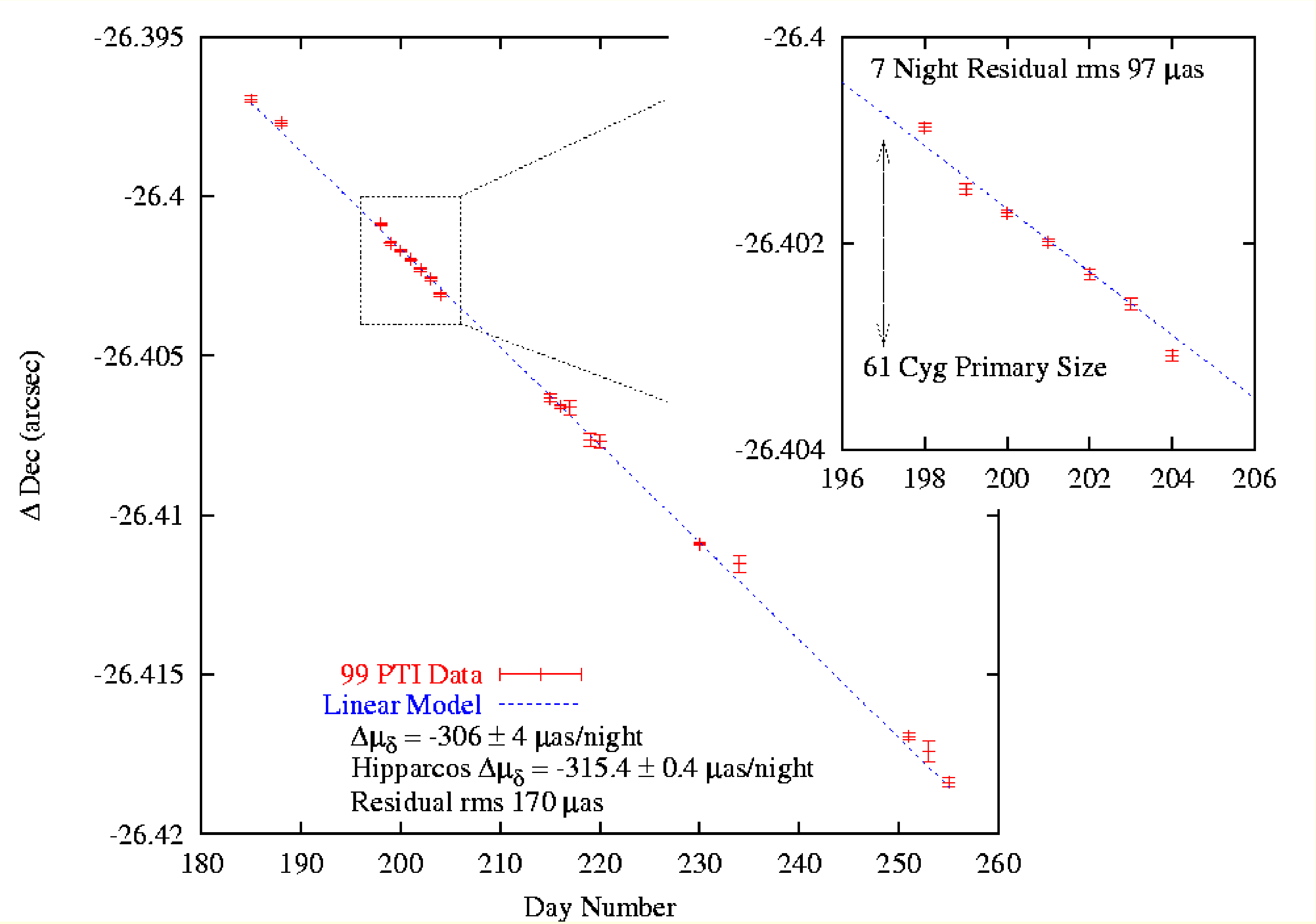
PTI Astrometry 61 Cygni I.



PTI Astrometry on 61 Cygni II.



61 Cyg 1999 Declination-Only Data



Experimental Verification

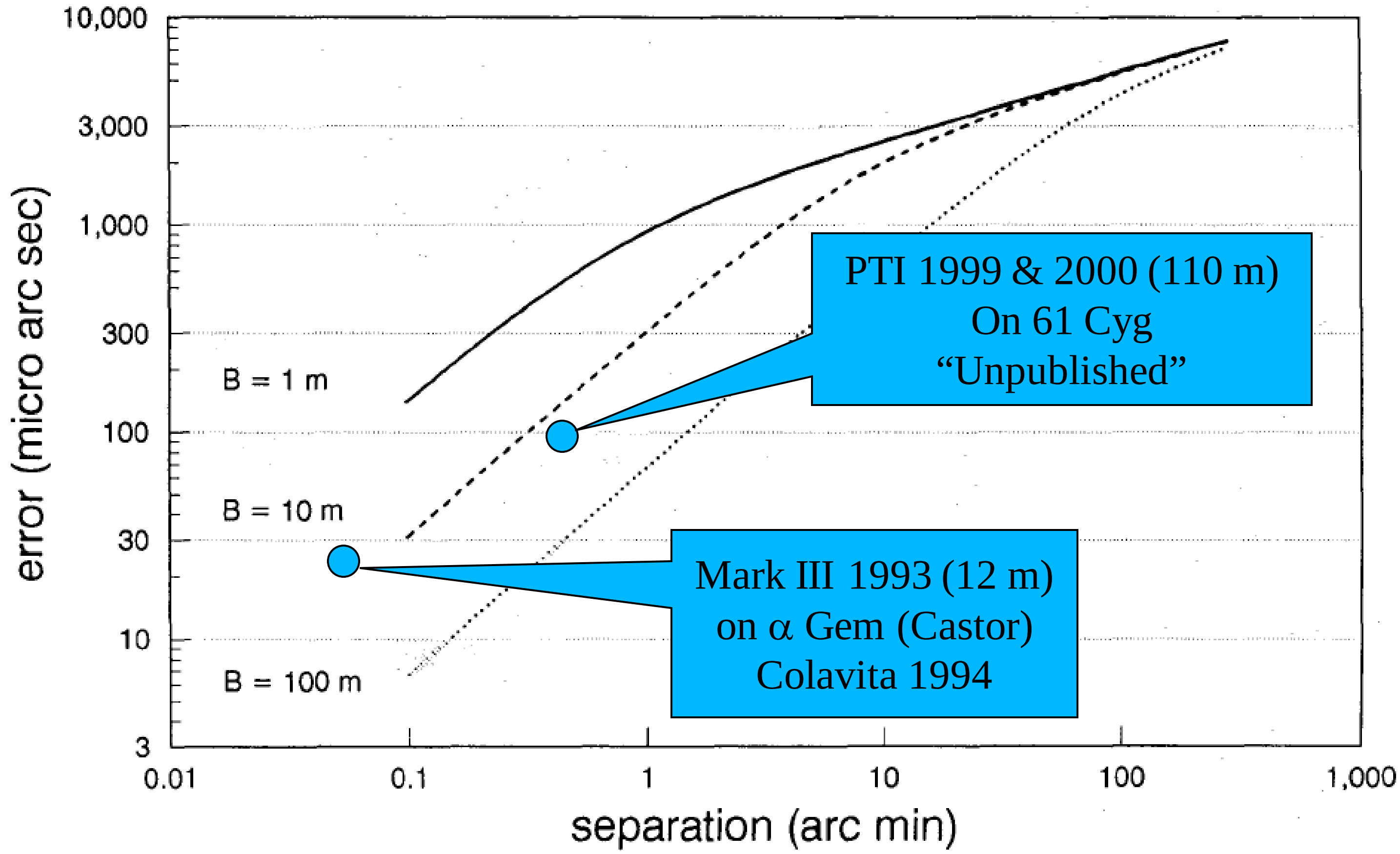


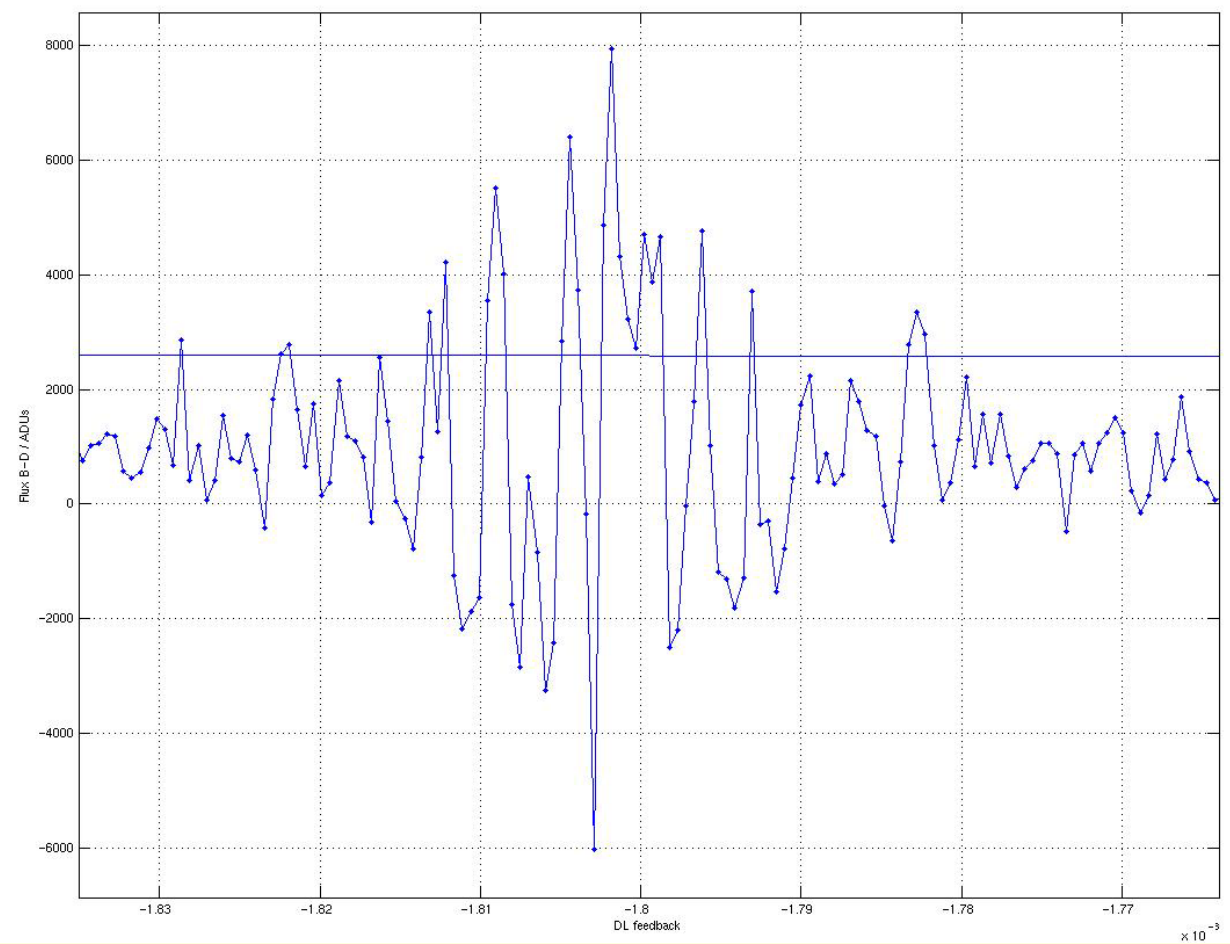
Fig. 2. Narrow- and very-narrow-angle astrometric error for several baseline lengths using measured Mauna Kea turbulence profiles and an integration time of 1 h

From Shao & Colavita 1992

Still to come: UT PRIMA Observing
Bring on the big glass

Additional Applications

PRIMA Co-Phasing Demonstration

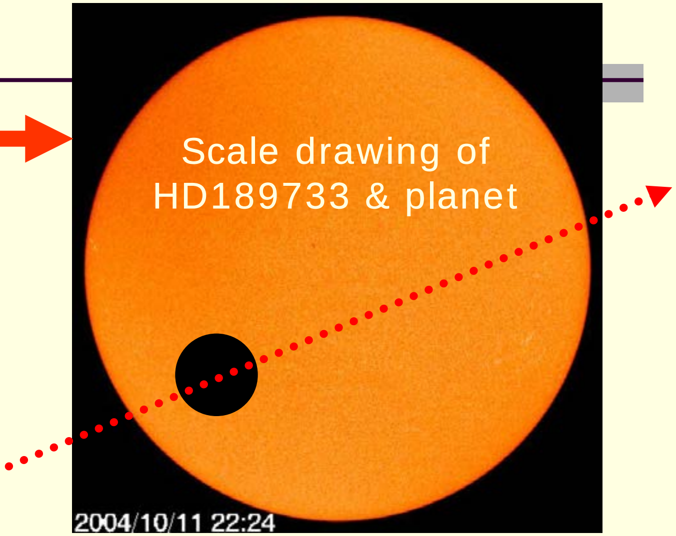


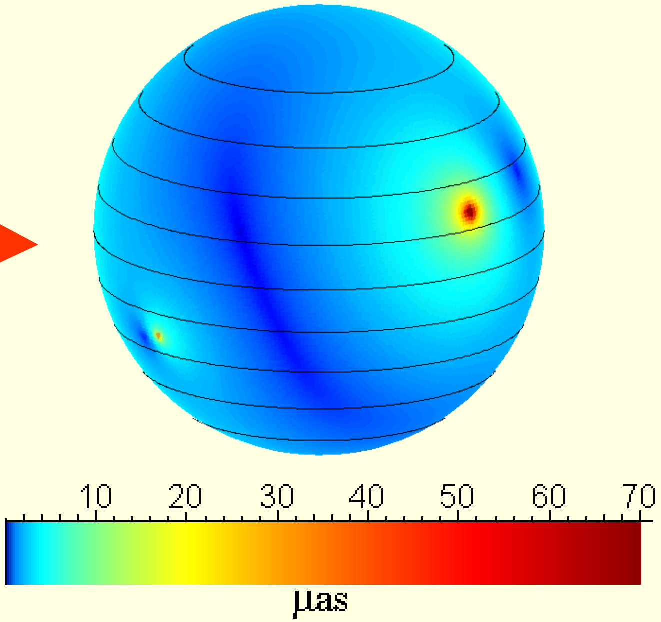
SAO221759 (m_K=7.1) stabilized by HD87640 (m_K=4.8, 6.6” distant)
WX: 0.87” / 10ms
2011.02.05 VLTI PRIMA
Plot produced with immediate post-processing

- Use of PS star to stabilize system for SE ‘staring’
  - Effectively, NGS AO for interferometry
  - PS ran at 1kHz
  - SS fringe tracking was slowed to 500Hz, 250Hz, …
- Final result: 1Hz scanning
  - Each data point on the left is one full second long
  - Factor of 1000× in integration time corresponds to 7.5 magnitudes(!)
- Compelling demo of dual-star capability

Novel Ideas for PRIMA Observing: Planet Transits, GR Effects

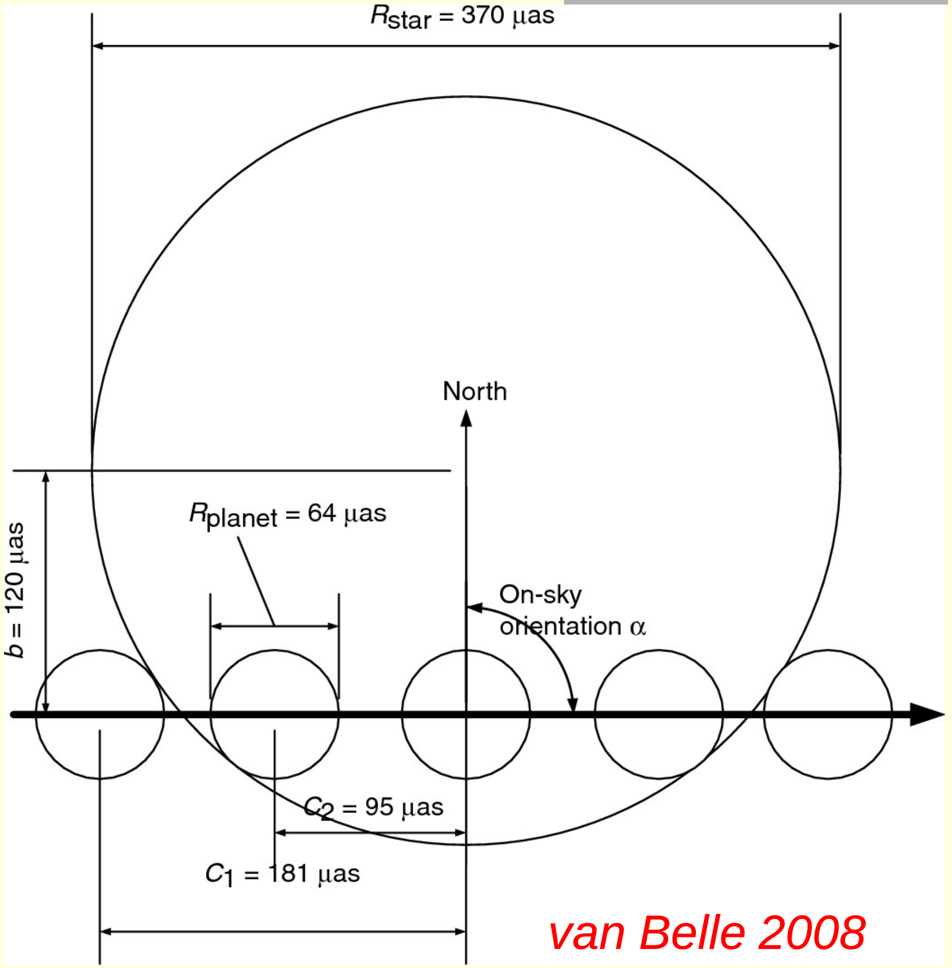
- Planet transit host stars
  - Transit event induces a photocenter shift on the star
  - Effectively a perfectly black 'starspot'
- Example case: HD189733
  - 0.376±0.031 mas (CHARA, Baines & van Belle et al. 2007)
  - Transiting planet diameter of ~60μas
  - Ratio of the areas indicates a shift of ~5uas on star centroid
    - This may be difficult
- Direct detection of GR effects
  - Measure astrometric shifts due to nearby passage of Jupiter, other large solar system bodies
- Weighing solar system objects
  - Precision astrometry of orbits



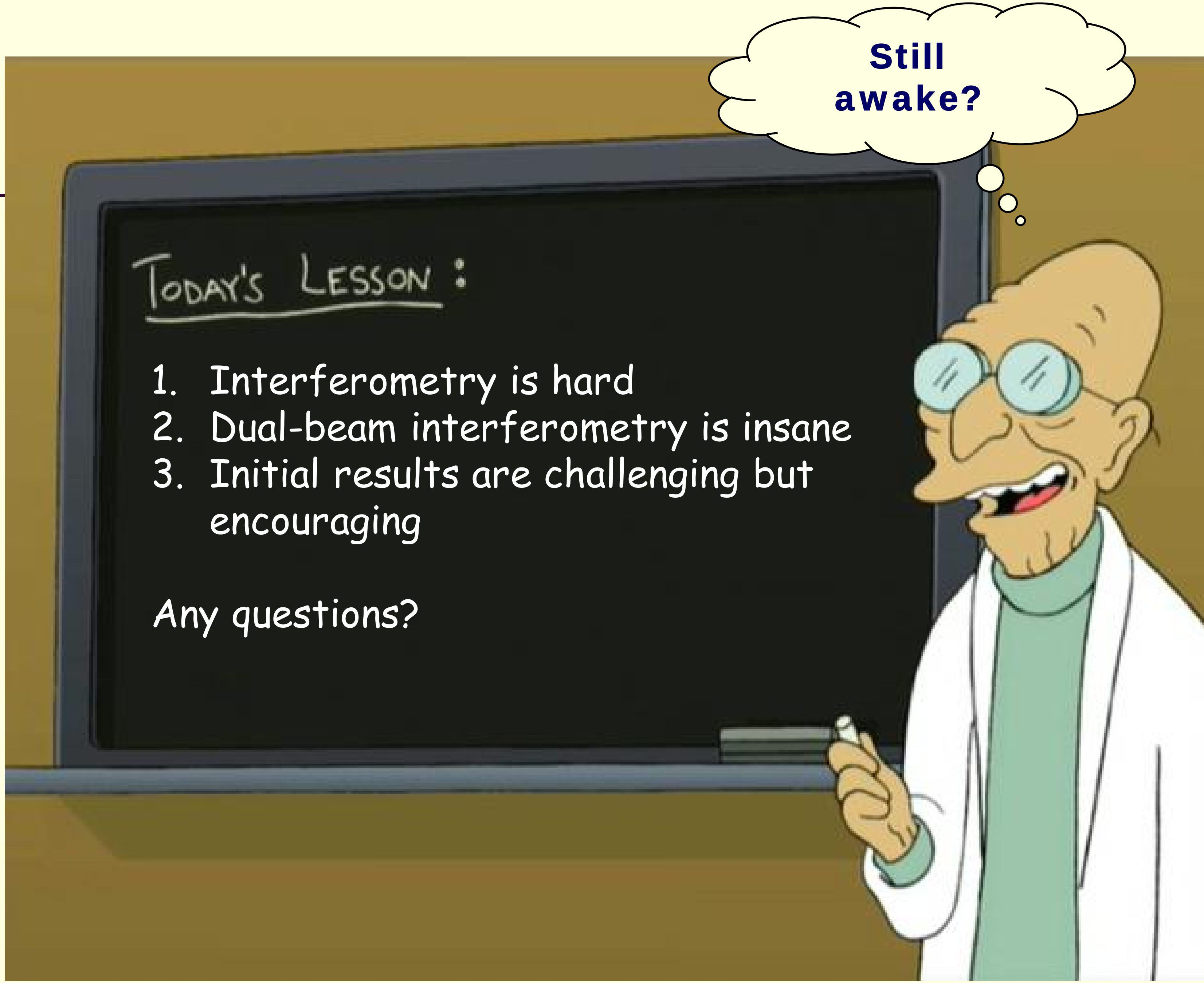


Characterization of Exoplanets: Direct Observations of Transits

- CHARA, NOI can observe exoplanet transits
- Planet's shadow is 'perfect' star spot
- λ-specific observations → atmospheric composition
- Extreme challenge: ΔCP~0.1-0.01°



van Belle 2008


Still awake?
Today's Lesson:
1. Interferometry is hard
2. Dual-beam interferometry is insane
3. Initial results are challenging but encouraging
Any questions?