National Aeronautics and
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# How to calibrate interferometric data


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# Outline

- Calibration basics
- System visibility
  - What is it
  - How is it measured
  - How does it vary
- Calibrators
  - Finding calibrators
  - Calibrator sizes
- Example of data calibration
- Errors
  - Measurement vs. systematic
  - How to determine
- Summary

- Thanks to A. Boden for providing some plots

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# Where does calibration fit in?

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Take your data

Remove detection bias and calculate visibilities (previous talk)

Remove instrument effects (this talk)

What does your data say? (next talk)

# Data calibration

- Inputs
  - Averaged visibility data with detection biases removed
  - Identification of target and calibrator sources
  - Calibrator sizes with uncertainties
- Outputs
  - Averaged target visibilities and uncertainties with ALL instrument effects removed
    - i.e. from here you can do astrophysics

- Notes
  - Only visibility amplitude data calibration considered, see previous talks for the additional calculations needed for closure phase and imaging data
  - I will use visibility squared here, as that is currently the most commonly used visibility product
  - In numerical examples, I assume B=100m, $\lambda$=2 microns

# Calibration: the basics

1. Identify the appropriate calibrators for your targets
2. Model the calibrator visibilities
3. Calculate the system visibility and uncertainty as appropriate for your instrument
4. Correct your measured target visibilities for the system visibility

To help motivate the goals of #1 and #2, we'll start with #3



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# System visibility

- Measure the visibility on a source of known size (i.e. a calibrator) to determine the system visibility, then correct your target data
  - System visibility = the response of the instrument to a point source $V_{sys}$
    - Also called visibility transfer function or interferometric efficiency
  - If your calibrator is a point source

    $V^2_{sys} = V^2_{cal}$
  - If your calibrator is NOT a point source,

$$V_{sys}^2 = \frac{V_{cal}^2}{V_{\mathrm{mod}}^2}$$

  - Then

$$V_{cal}^2 = \frac{V_{meas}^2}{V_{sys}^2}$$

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# What causes system visibility < 1

- Atmosphere
  - Seeing
  - Coherence time
- Mismatches in beams
  - Intensity
  - Polarization



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# Approaches to system visibility calculation

- Interpolation in time
  - Either linear or higher order (e.g. spline) fitting
  - Assumptions: Changes in system visibility are dependant only on time

- Averaged value accounting for temporal and angular spacings
  - Need to appropriately weight contributions from different calibrators

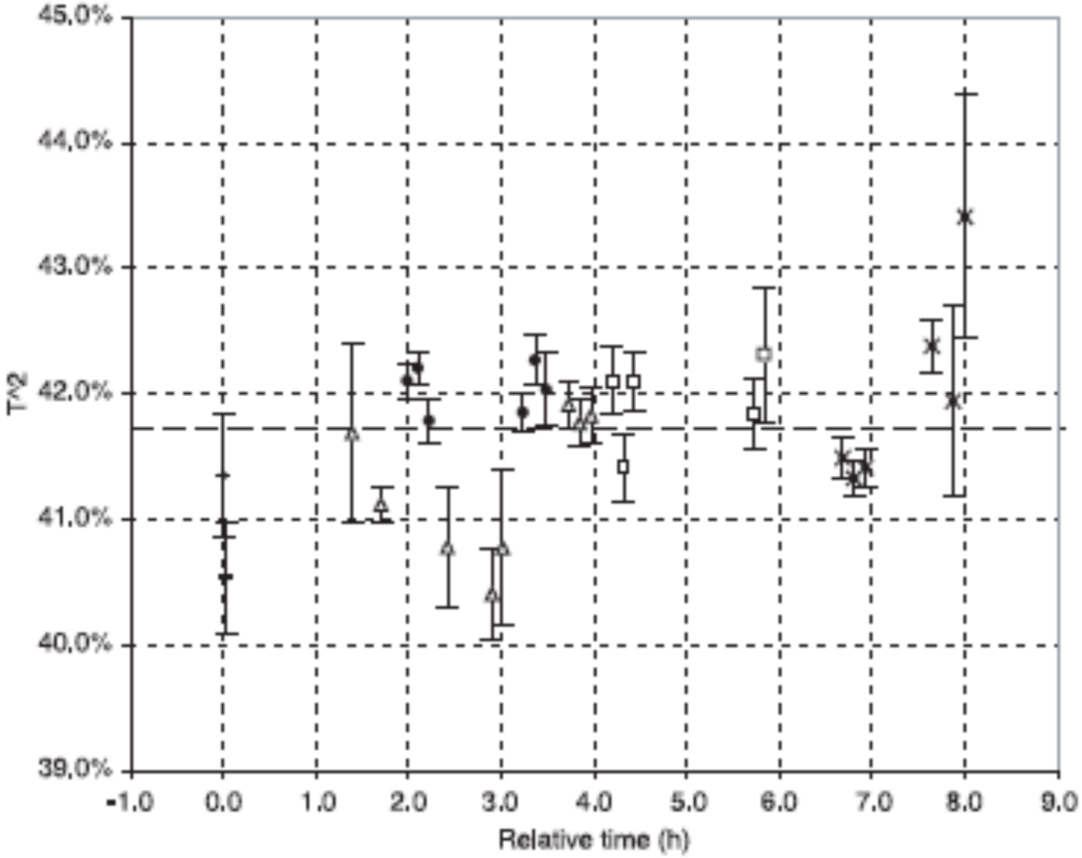
- Global instrument model
  - Generally used for instruments with high stability over the observing period

# Which approach depends on your instrument

- How does $V^2_{sys}$ vary?
  - Time
  - Elevation, azimuth
  - Source spectra

# Variability: Example 1

Good stability, linear drift with time over a night




VLTI/VINCI: Kervella et al (2004, A&A, 425, 1161)

$T^2 = 41.75\%$
$\sigma = 0.64\%$

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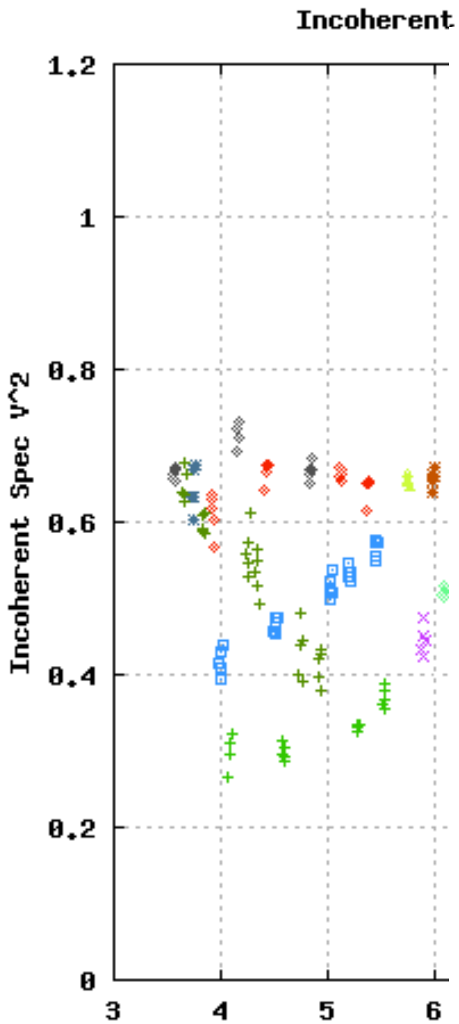
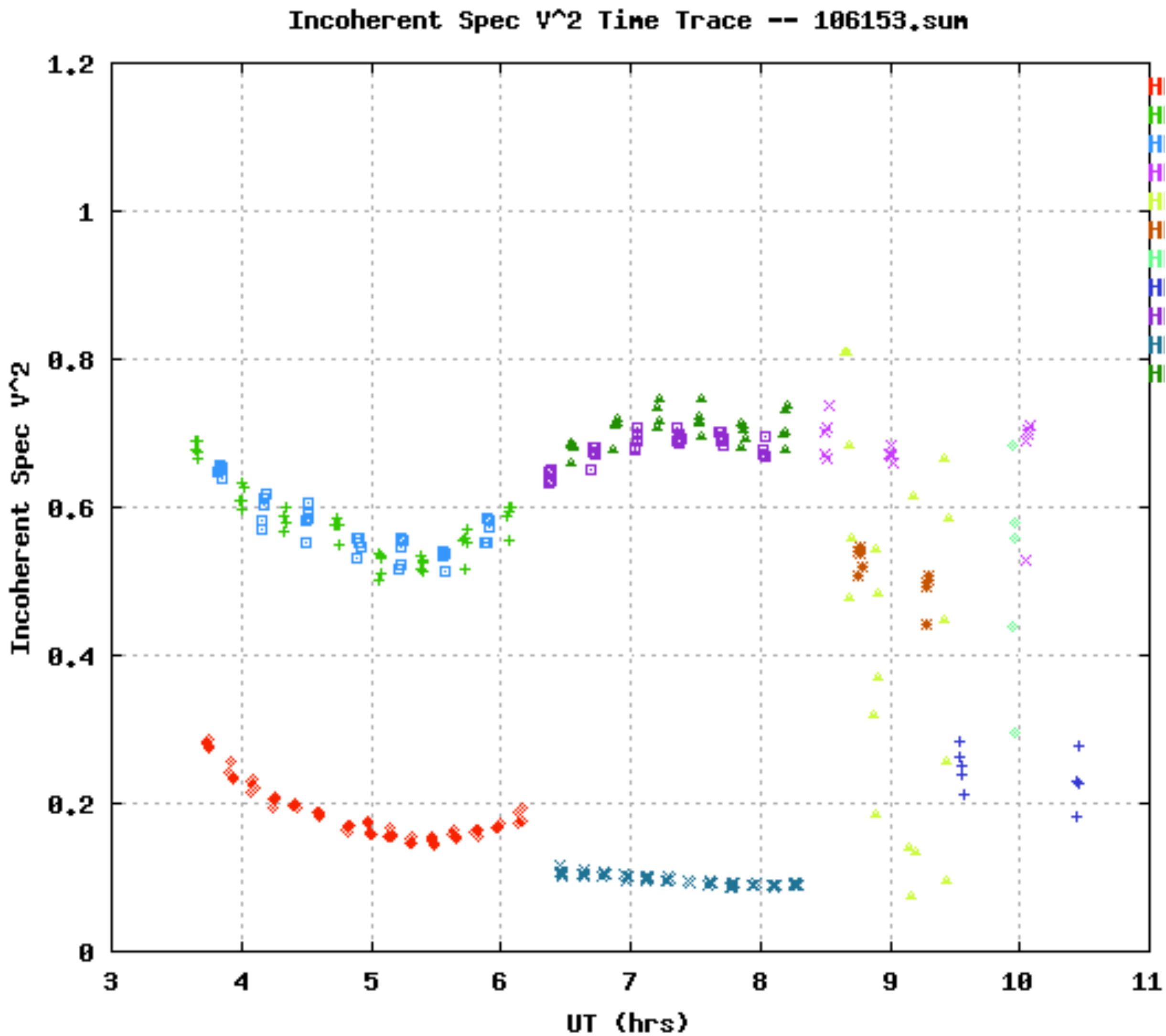
# Variability: Example 2

Sometimes the instrument performance varies greatly night to night

PTI data from 2006

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# Step 1: Find calibrators

- If you are planning new observations, you will need to select calibrators for your target
- Properties to consider
  - Angular distance from target
  - Brightness relative to target (perhaps at multiple bands)
  - Angular size
  - Variability/multiplicity (or hopefully, lack thereof)
- If using data taken already, the same principles should be considered when choosing from the available calibrator sources

# What makes a good calibrator?

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- Bright enough at observation wavelength to measure the system visibility with sufficient signal-to-noise
  - What is sufficient? - depends on what else is limiting your calibration
  - But should be close to your target brightness if the system visibility is at all dependant on brightness (or better yet, bracket your target with calibrators of different brightnesses)
- Close to your source on the sky
- Known size
  - At fainter magnitudes, it is generally possible to find (nearly) unresolved calibrators, but at brighter magnitudes, you will probably have to settle for a resolved calibrator

Generally when choosing calibrators, you will have to trade these properties against each other as there is usually no perfect match out there…

# Calibrator sizes: Why smaller is better

- Calibrator size uncertainty goes directly into system visibility uncertainty
- Uniform disk

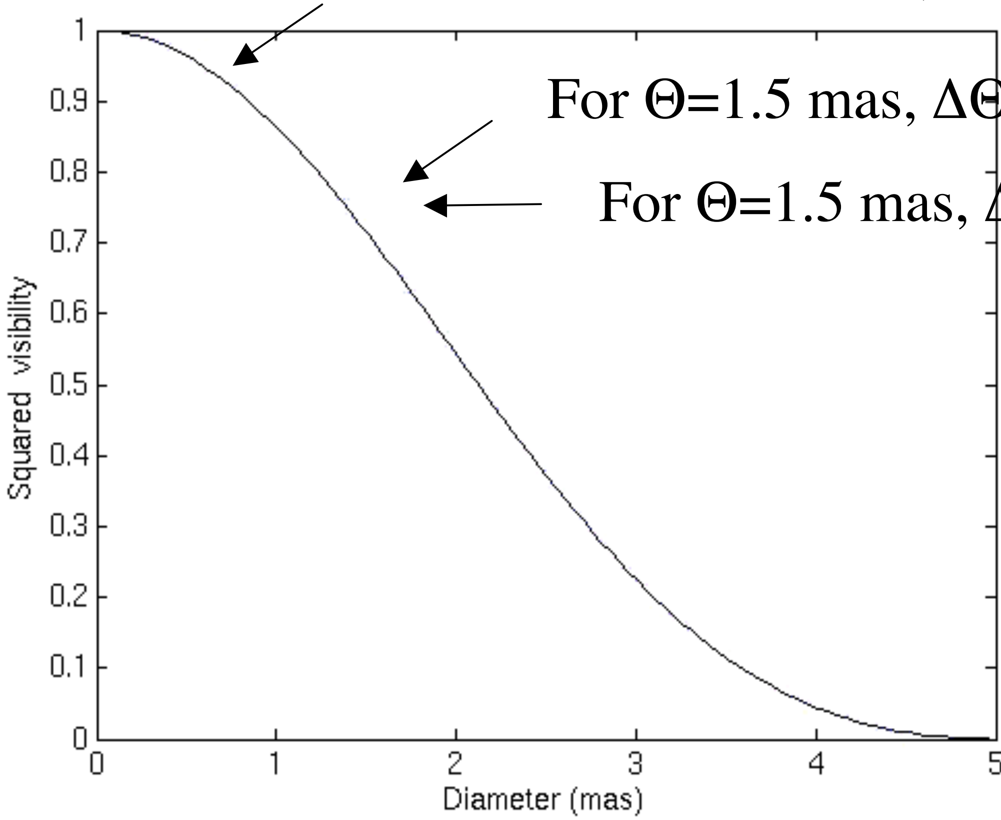
$$V^2 = \left( \frac{2J_1(\pi\Theta B/\lambda)}{\pi\Theta B/\lambda} \right)^2$$

$J_1$ Bessel function
B Baseline
$\Theta$ Angular diameter

For $\Theta$=0.5 mas, $\Delta\Theta$ = (0.025) 5% $\Rightarrow$ $\Delta V^2$=0.4%

For $\Theta$=1.5 mas, $\Delta\Theta$ = (0.075) 5% $\Rightarrow$ $\Delta V^2$=3.6%

For $\Theta$=1.5 mas, $\Delta\Theta$ = (0.025) 1.7% $\Rightarrow$ $\Delta V^2$=1.2%



# Calibrator selection methods

- More in observation planning talk
- General approaches
  1. Use list of known “good” calibrators
     - e.g. CHARM catalog (Richichi et al 2005, A&A, 431, 773)
     - But “good” depends on your situation, baseline etc.
     - May not be possible to find nearby calibrator in some parts of the sky
     - Currently these catalogs do not contain sources as faint as the sensitivity limits for the large aperture interferometers (KI,VLTI)
     - There also exist lists of theoretically derived angular sizes, but you need to beware of absolute calibrations

# Calibrator selection method cont.

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2. Choose a new calibrator from a general stellar catalog
- Hipparocs is a logical choice given the astrometric information
- Always a danger of running into a binary system, so generally best to use 2 or 3 calibrators if they haven't been previously observed with interferometry

**getCal results:**

```
### GUI catalog from getCal-2.6.2 ###
# Resolving target DG Tau via SIMBAD
## No HIP resolution for DG Tau -- using search coord 04 27 04.70 +26 06 16.2 D
DG_Tau 04 27 04.70 +26 06 16.2 D  PM?  PM?  V? K? B-V? Sp? xxx xxx trg
HDC26737 04 14 30.420 +22 27 06.713  0.103 -0.034 7.0 6.0  0.42 F5V     4.6 0.23+/-0.1  cal DG_Tau
HDC26736 04 14 32.315 +23 34 29.801  0.132 -0.048 8.1 6.6  0.66 G3V     3.8 0.20+/-0.0  cal DG_Tau
HDC284253 04 16 33.478 +21 54 26.890  0.114 -0.038 9.1 7.2  0.81 K0V     4.8 0.16+/-0.0  cal DG_Tau
HDC27732 04 23 22.330 +21 22 44.743  0.107 -0.039 8.8 7.0  0.76 G9V     4.8 0.17+/-0.0  cal DG_Tau
HDC27741 04 23 43.944 +28 11 10.663  0.064 -0.127 8.3 6.9  0.64 G0V     2.2 0.15+/-0.1  cal DG_Tau
# HIP 20533 (HD 27778) has his multiple component flag set to C
#  the C designation indicates solutions were found for individual components
#    1 components:
#    A component -- V= 6.400
# HIP 20533 (HD 27778) has his astrometric source flag set to P
#  with solution quality listed as D
HDC27778 04 23 59.762 +24 18 03.570  0.005 -0.013 6.3 6.9  0.17 B3V     1.9 0.16+/-0.1  cal DG_Tau
HDC27808 04 24 14.575 +21 44 10.477  0.128 -0.047 7.1 5.8  0.52 F8V     4.4 0.26+/-0.0  cal DG_Tau
HDC28033 04 26 18.500 +21 28 13.564  0.114 -0.036 7.4 6.0  0.56 F8V     4.6 0.24+/-0.0  cal DG_Tau
# HIP 20789 (HD 28149) has his variability flag set (1)
#  with 0.009 mag scatter in  65 observations
HDC28149 04 27 17.447 +22 59 46.812 -0.000 -0.013 5.5 5.8 -0.10 B7V     3.1 0.23+/-0.0  cal DG_Tau
HDC283668 04 27 52.933 +24 26 41.238  0.412  0.114 9.4 7.0  0.89 K3V     1.7 0.19+/-0.0  cal DG_Tau
HDC283697 04 29 43.069 +27 16 37.353  0.007 -0.047 8.7 7.3  0.49 G0V     1.3 0.14+/-0.0  cal DG_Tau
HDC29050 04 35 17.230 +23 02 42.608 -0.015 -0.068 8.9 6.8  0.77 K1V     3.6 0.19+/-0.0  cal DG_Tau
# HIP 21619 (HD 29364) has his multiple component flag set to C
#  the C designation indicates solutions were found for individual components
#    2 components:
#    B component -- V= 7.322
#    A component -- V= 7.442 at sep 4.212 arcsec/PA  11 deg
HDC29364 04 38 29.515 +26 56 21.349  0.048 -0.066 6.6 5.7  0.34 F2V:    2.7 0.24+/-0.1  cal DG_Tau
HDC29459 04 39 23.148 +25 13 05.787  0.019 -0.012 6.2 5.8  0.18 A5Vn    2.9 0.20+/-0.1  cal DG_Tau
HDC284574 04 40 05.843 +23 18 16.371  0.081 -0.038 9.4 7.4  0.81 K0V     4.1 0.14+/-0.0  cal DG_Tau
HDC29646 04 41 19.761 +28 36 53.978  0.043 -0.030 5.7 5.7  0.02 A2V     4.0 0.25+/-0.1  cal DG_Tau
```

# Calibrator selection packages

- getCal (http://msc.caltech.edu/software/getCal)
  - Searches Hipparocs catalog
    - Selects on magnitudes (visible and infrared), angular size estimate and angular separation
  - Retrieves photometry from SIMBAD and 2MASS
  - Includes photometric fitting to estimate angular size
- searchCal - part of ASPRO (http://www.mariotti.fr/aspro_page.htm)
  - Searches on-line CDS catalogs (including All-sky Compiled Catalog with 2.5 million stars, Kharchenko 2001 and interferometry/high resolution specific catalogs: Borde, Merand, Richichi)
    - Selects on magnitudes (visible and infrared) and angular separation
  - Calculates angular diameter with a surface-brightness, color index relation
  - Calculates calibrator visibility for user-specified wavelength and baseline

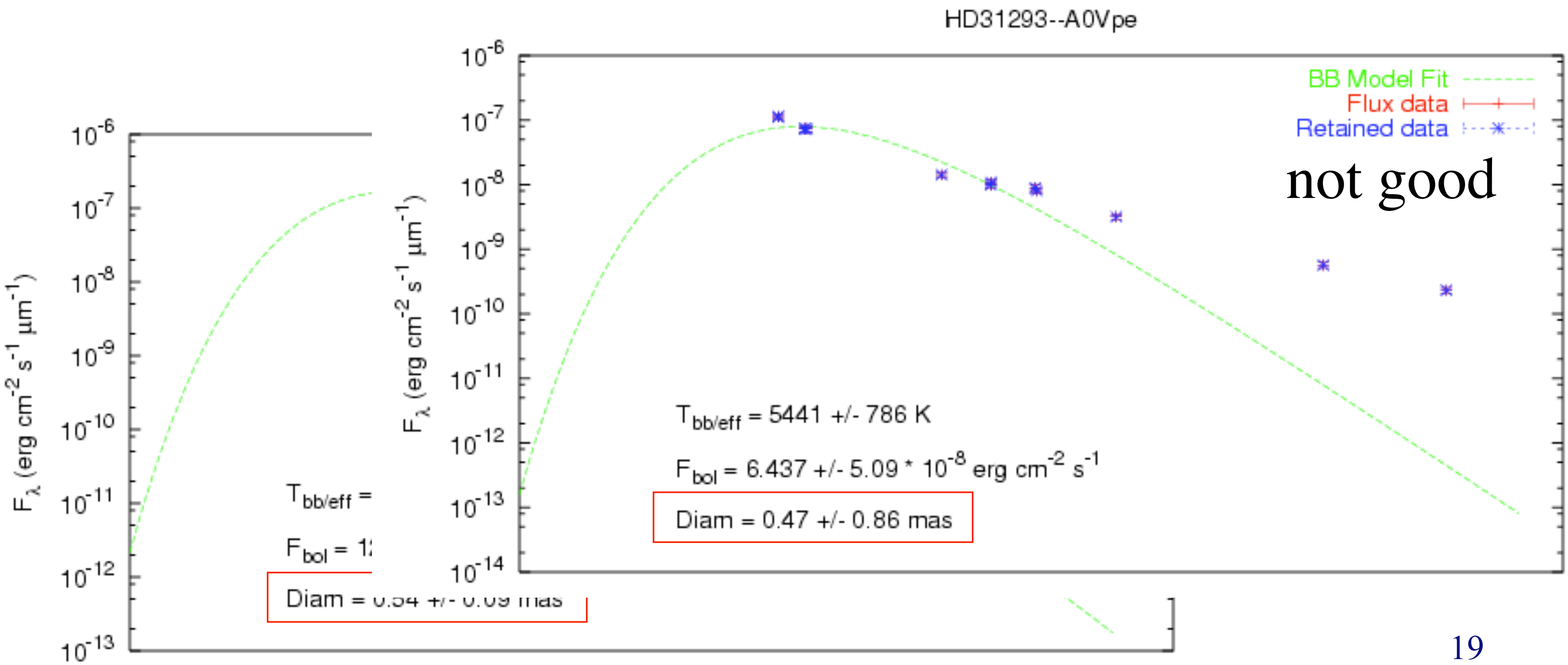
# Estimating angular sizes

- Methods
  - Previous observations (if they exist)
  - Photometric fitting
    - Blackbody
    - Stellar spectrum (synethetic or synthesized from observations)
    - But beware of absolute flux calibrations
- Generally assume calibrator is a uniform disk, but if calibrator is an early spectral type and you are working near the first visibility null, limb darkening may need to be considered
- Also need to estimate uncertainty as that feeds directly into the system visibility uncertainty

$$\sigma_{V_{sys}^2} \propto \left| \frac{\partial V_{cal}^2}{\partial \Theta} \right| \sigma_\theta$$

# Simple fitting examples

- Blackbody fits sufficient for some spectral types and moderate accuracy fits
- Even simple photometry checks can reveal problem sources



# Calibration software

- Several packages exist which do these steps for you
  - Most are written for and adjusted to specific instruments and their issues
- Examples
  - VLTI: pipelines for MIDI and AMBER (ESO, JMMC, NEVEC, FRINGE groups: links within http://www.eso.org/projects/vlti/instru/)
  - PTI/KI: V2calib package (MSC: http://msc.caltech.edu/software/V2calib)
  - Many other examples exist for other interferometers
    - If you have data from a specific interferometer you can try to adapt one of the above packages, ask if anyone has working code already, or write it yourself

# Data calibration example: HD123999

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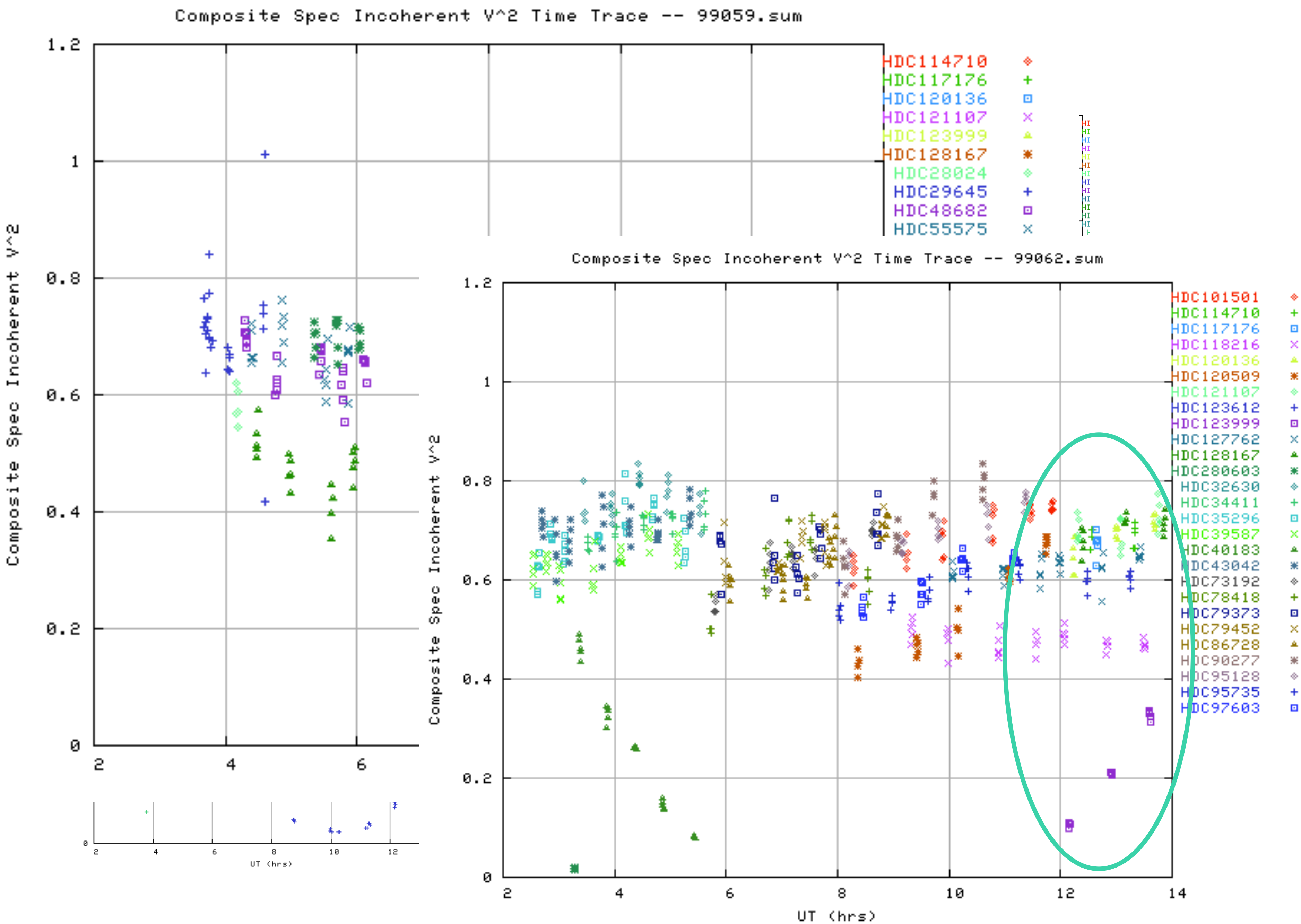
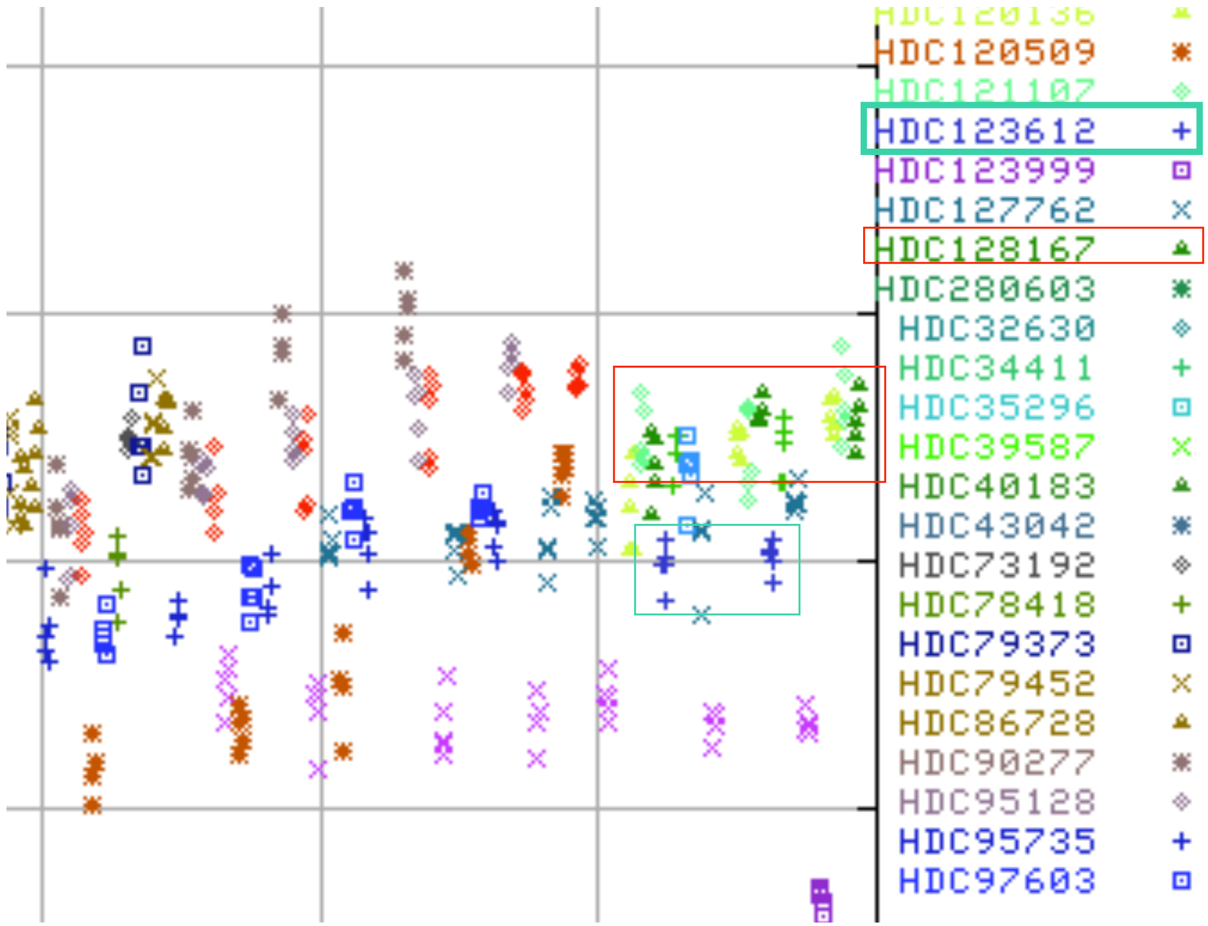


# Calibration sources

- Using getCal and SIMBAD/2MASS photometry, fit blackbodies
- HD 128167    0.84±0.06 mas
- HD 121107
- HD 123162

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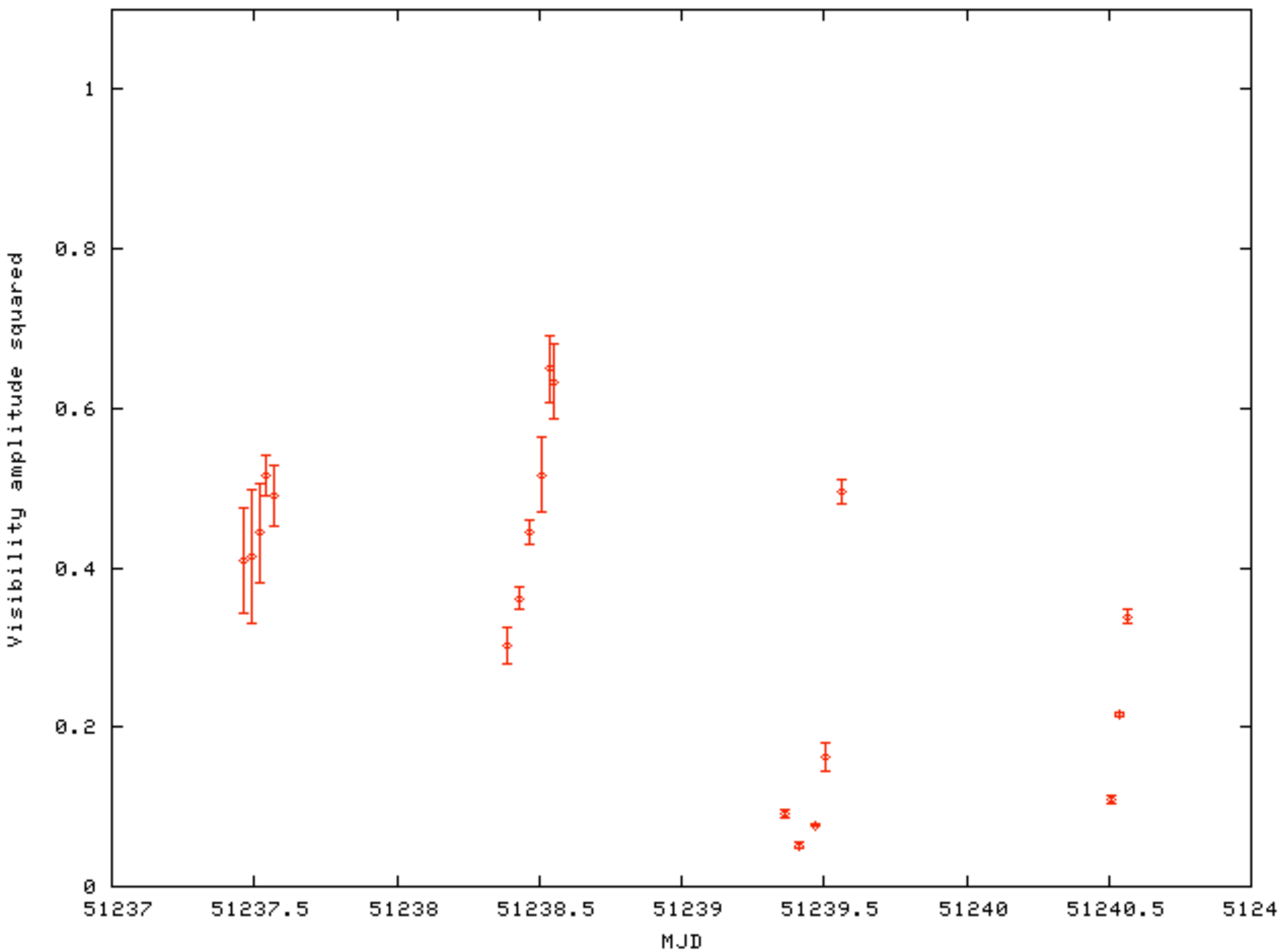
# Averaged, uncalibrated visibilities



# Run calibration package

- V2calib with PTI defaults
  - 5 25-second averaged visibilities for each source (target and calibrators) are combined to produce average and scatter
  - Calibrator sizes used to derive expected calibrator visibilities (Note that one calibrator is significantly resolved)
  - System visibility estimates for each source data point calculated as a weighted (by time and angular proximity) averaged of nearby calibrator points

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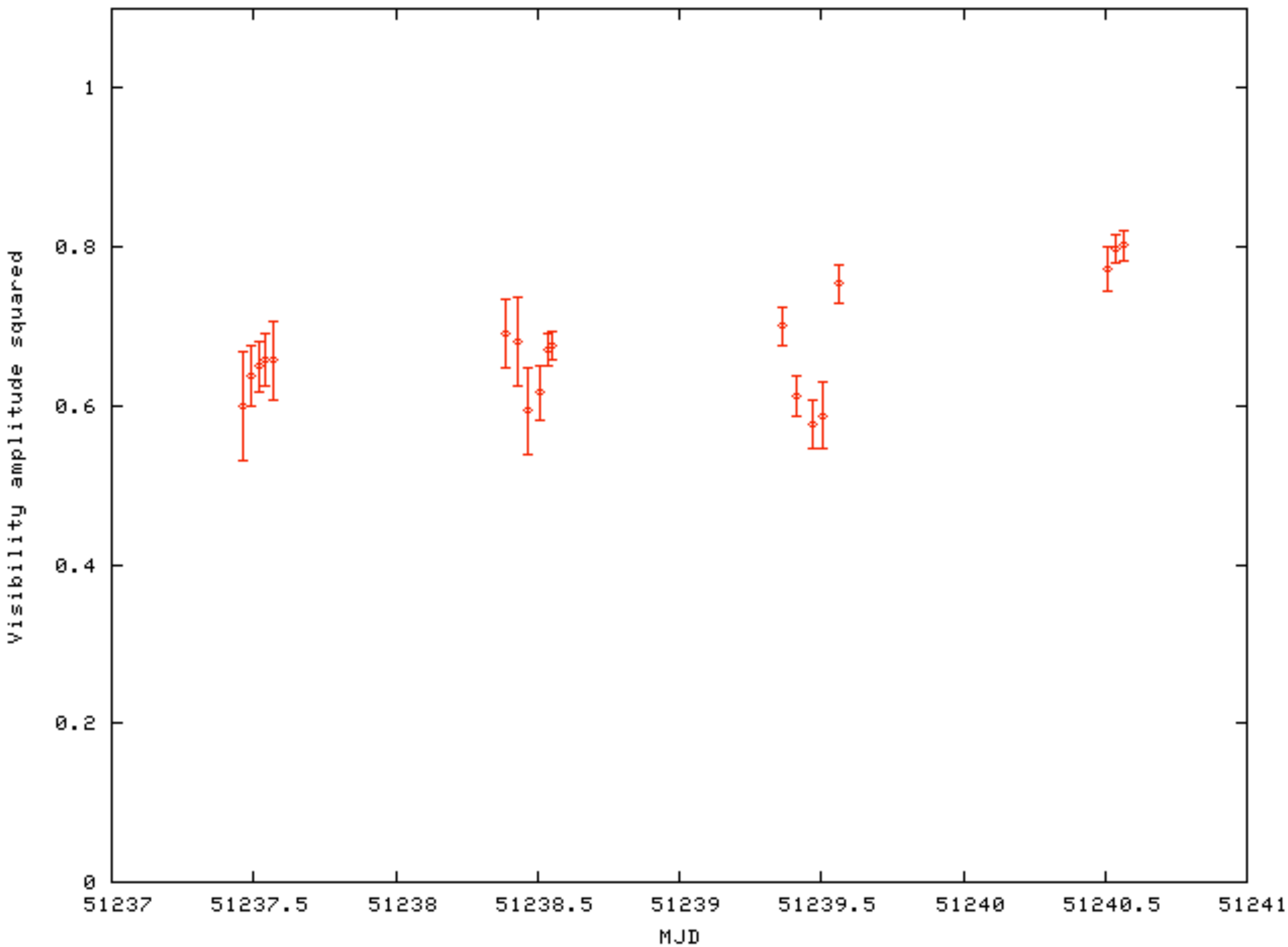
# System visibility

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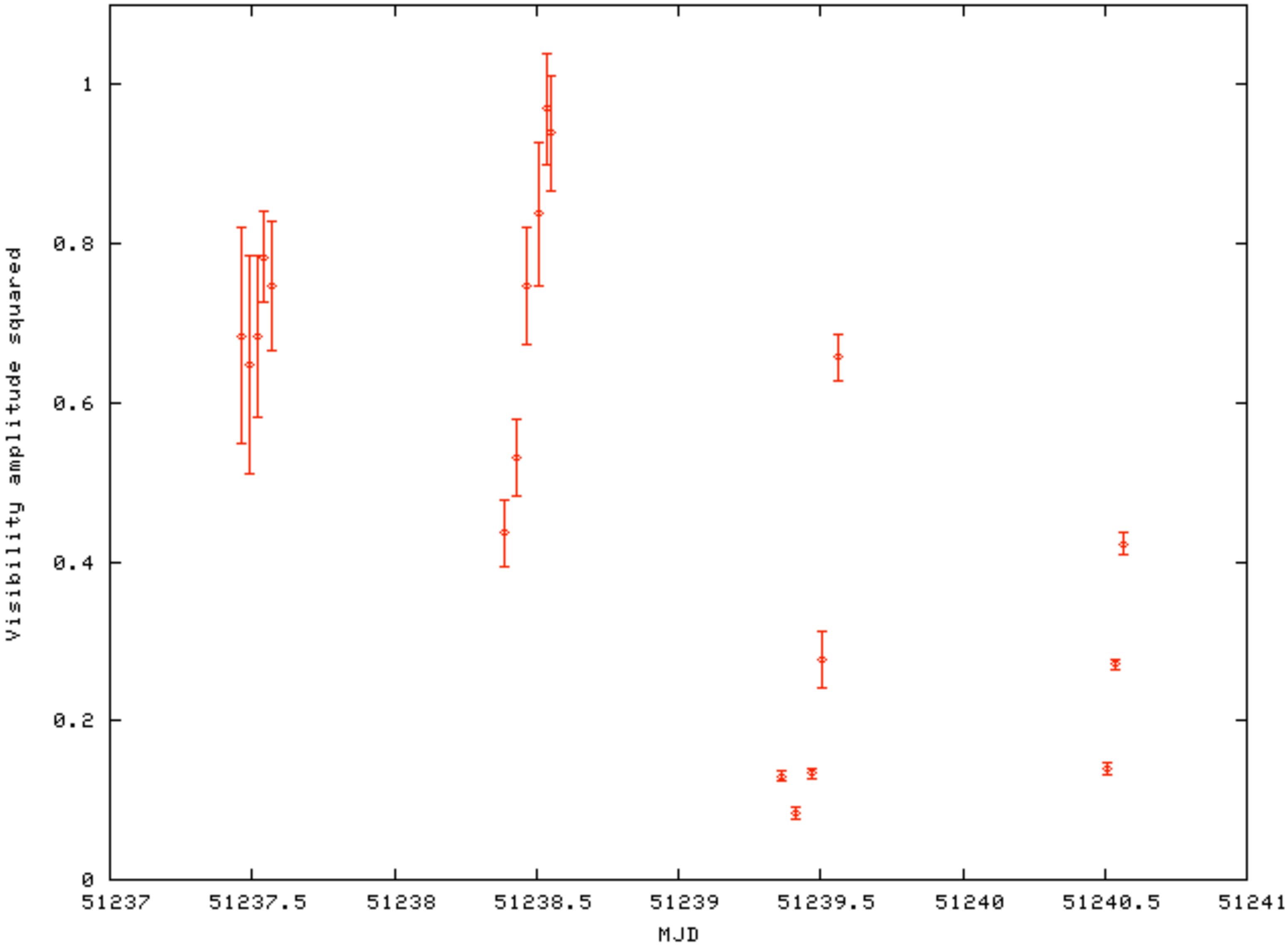
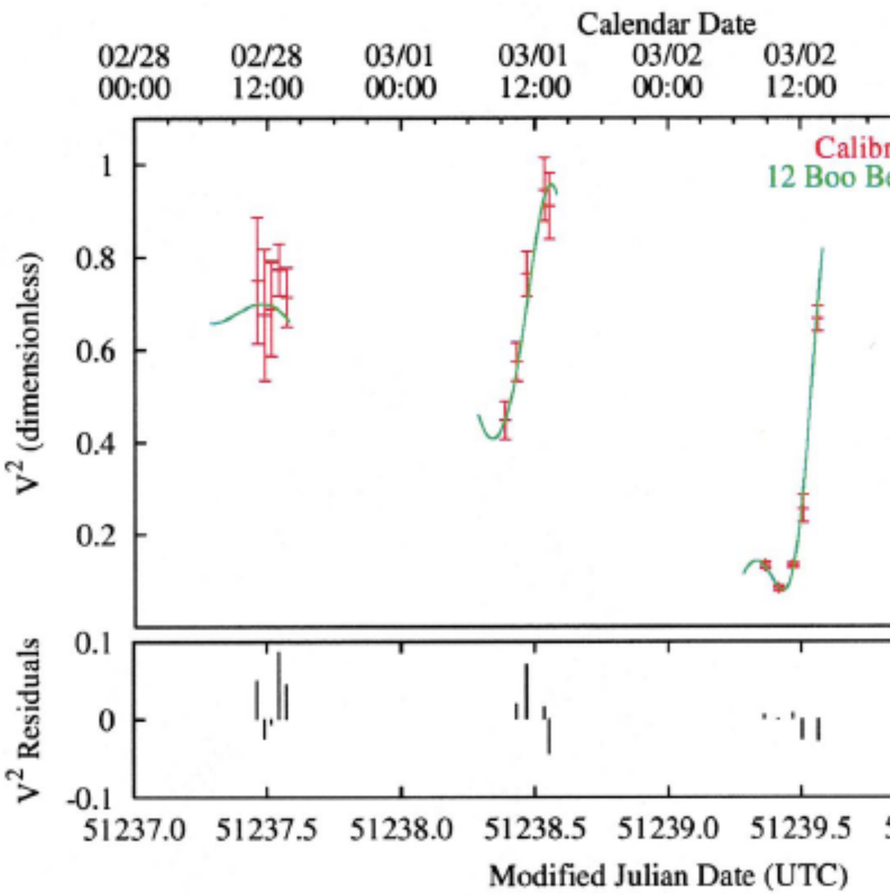
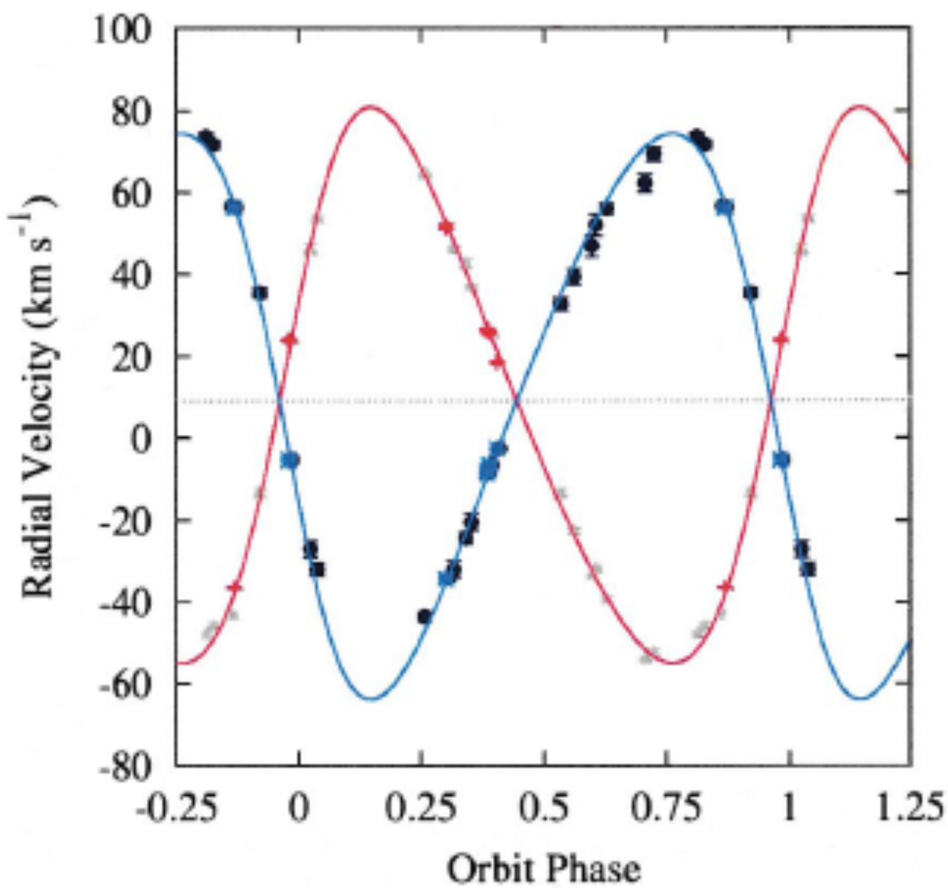
# Calibrated visibility



# Data and model (Boden et al, 2000, ApJ, 536, 880)

- HD 123999 is a double-line spectroscopic binary
- Fit PTI and radial velocity data to derive physical orbit and therefore get accurate masses, etc.

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# Uncertainties (or why should anyone believe your result?)

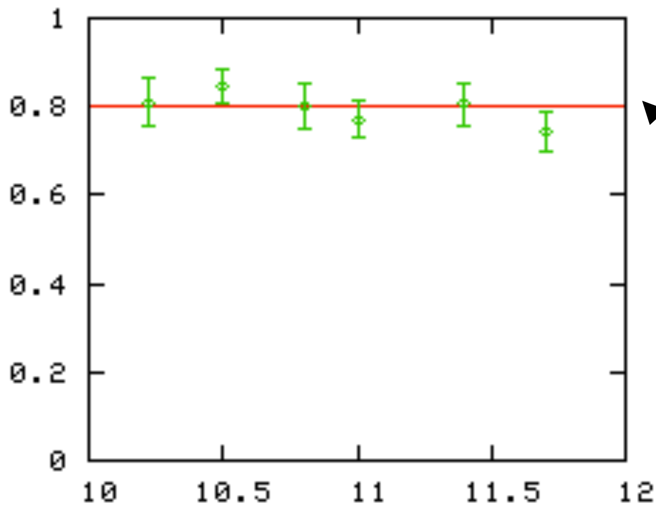


- Precision vs. accuracy
- How to determine your errors
  - Measurement (random)
  - Systematic
    - Ex. Bad calibrator size

# Precision vs. accuracy

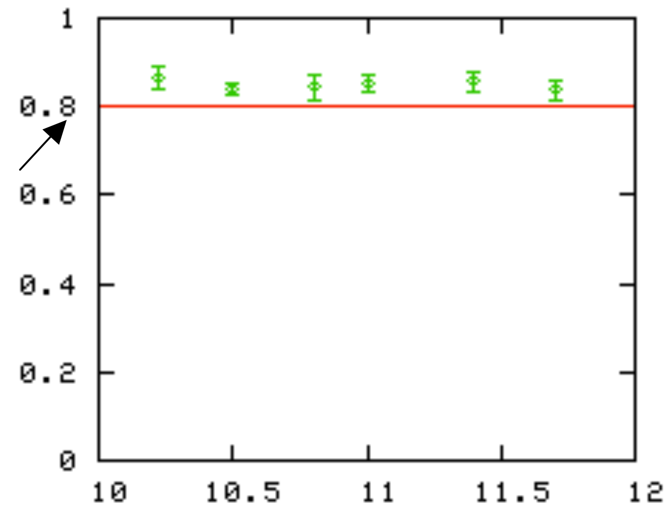
- Precision = Repeatability
  - How closely do the individual measurements of the same quantity match each other
  - Measurement error
- Accuracy = Absolute correctness
  - How closely do the measurements match the “true” value
  - Systematic error

Accurate but not precise




“true” value

Precise but not accurate

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# Measurement errors

- Depending on your data pipeline, these may be determined as part of the data reduction or the data calibration stage
  - PTI/KI:  Scatter of several 5 to 25 second averaged data points on target
    - See Colavita (1999, PASP, 111, 111)
  - VLTI/VINCI: Statistical analysis of weighted sample of individual fringe measurements to determine σ
    - See Kervella et al (2004, A&A, 425, 1161)

# Calibration errors

- Possible sources
  - Measurement uncertainties from data on calibrator
  - Uncertainty in calibrator size
- Can have a systematic component and if so, will NOT get smaller with more observations

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# How to determine systematic errors

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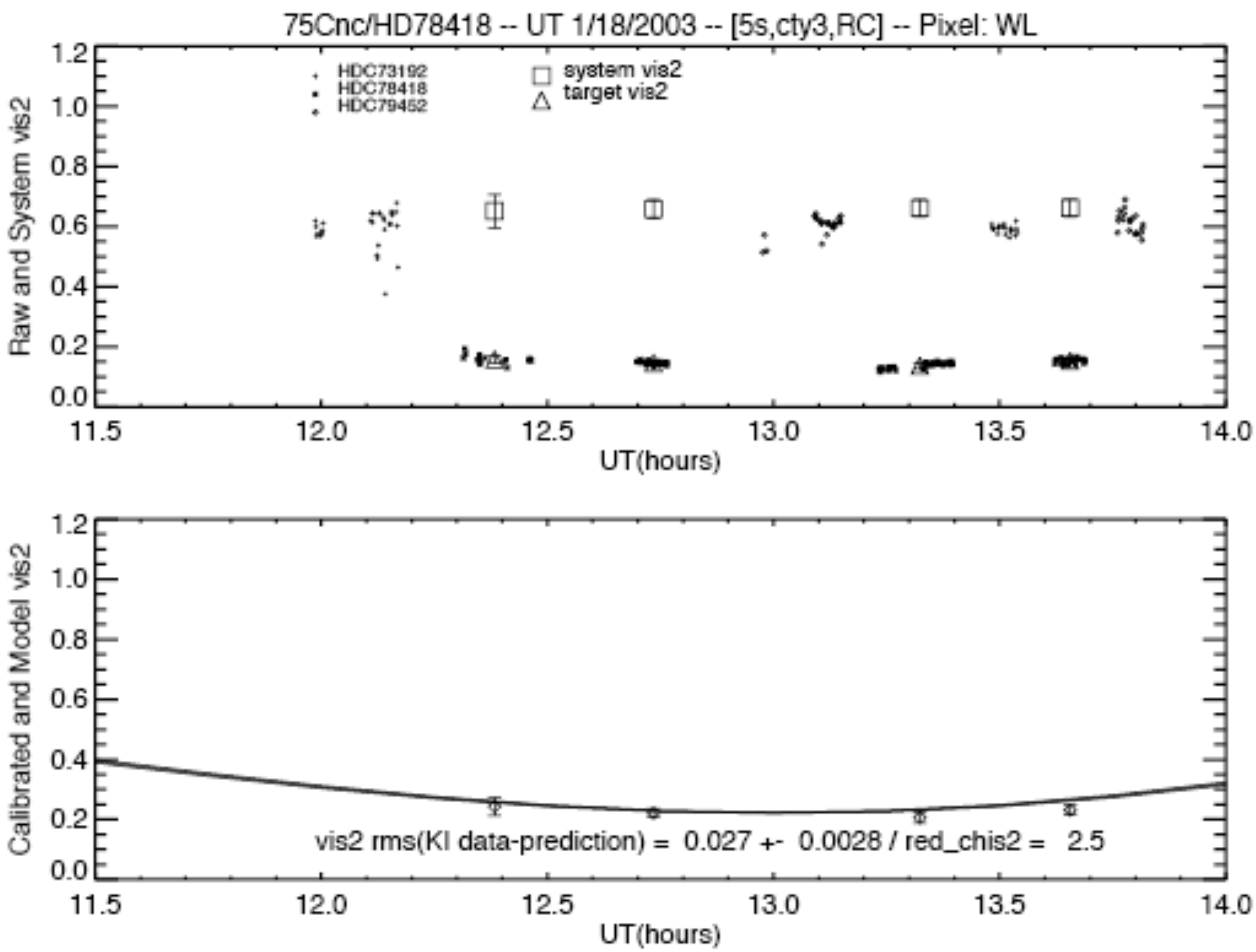
- Measure something you (think you) know
  - Calibrate calibrators against each other
    - Confirm that the system visibility varies in such a way that your calibration scheme adequately corrects the data
  - Include a control target which you expect to have a null result
    - Null result depends on your experiment and could mean unresolved (and therefore basically a calibrator, but NOT used in determining the system visibility)
  - Include a control target which you know visibility of from previous observations or other prior knowledge
    - Example: resolved star if measuring diameters, binary star with known orbit

# Systematic error determination example

- Using binary source with a known orbit to measure the performance of KI




This data and other binary data were also used to establish the recommended parameter settings for KI data calibration

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# Sources of bias: Example 1 - Incorrect calibrator size

- Take the case where you have data from two different length baselines
  - On the shorter baseline, the calibrators are (nearly) unresolved and the system visibility has (nearly) no bias
  - On the longer baseline, the calibrators are resolved and the size used is too LARGE
    - Therefore your calibrator visibility model will be too SMALL and you will OVERESTIMATE the system visibility
    - The targets calibrated visibilities on the longer baseline are UNDERESTIMATED
- Lesson: If at all possible, pick calibrators suitable for all baselines in the experiment

# Sources of bias: Example 2
# Data editing

- The target source is heavily resolved on the longest baselines
- After the reduction phase, some target data points have visibilities < 0 due to measurement and detector calibration uncertainties
  - Although this is unphysical, if you delete just these points as "bad", you will OVERESTIMATE the true target visibility and UNDERESTIMATE the true measurement uncertainty
- Minimize bias by editing data on criteria other than the visibility amplitude
  - SNR estimators
  - Phase noise (jitter)
  - Intensity balance or scatter

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# Issues for very high accuracies (< 0.1%)



- Finite spectral bandwidth
- Group delay dispersion (or longitudinal chromatic dispersion)
- Finite scan length
- Differential piston
- See Perrin and Ridgway (2005, ApJ, 626, 1138) for more details

# Give it a try yourself

- Get some data
  - Lots of public data now available
  - PTI - https://mscweb.ipac.caltech.edu/mscdat-pti
  - KI - https://mscweb.ipac.caltech.edu/mscdat-ki
  - VLTI/VINCI - http://www.eso.org/projects/vlti/instru/vinci/vinci_data_sets.html
  - VLTI/MIDI - http://archive.eso.org
- Get an existing program or try it on your own
- See what changing the parameters (calibrator size and uncertainty, system visibility uncertainty etc) does to the calibrated visibility amplitude and uncertainty

# Summary

- Main issues for good calibration
  - Understand your instrument
  - Understand your calibrators
  - Plan the experiment to measure errors at the level necessary for the desired astrophysics
    - May mean a much higher overhead on calibration and control sources