Binaries as seen by Optical Long Baseline Interferometry

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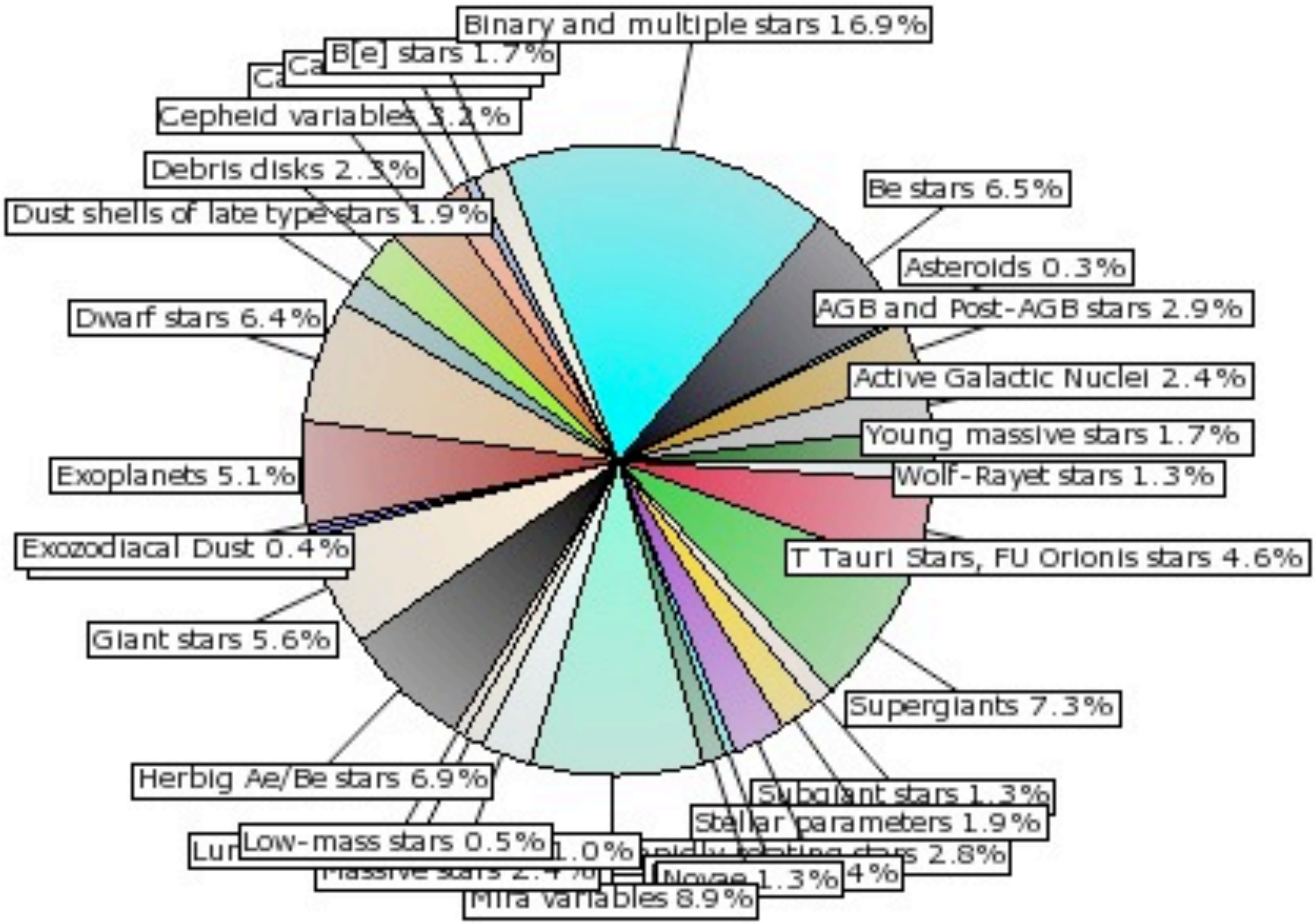
IPAG - Grenoble
PI of the PIONIER instrument

Remember: binaries are the workhorse of OLBIN

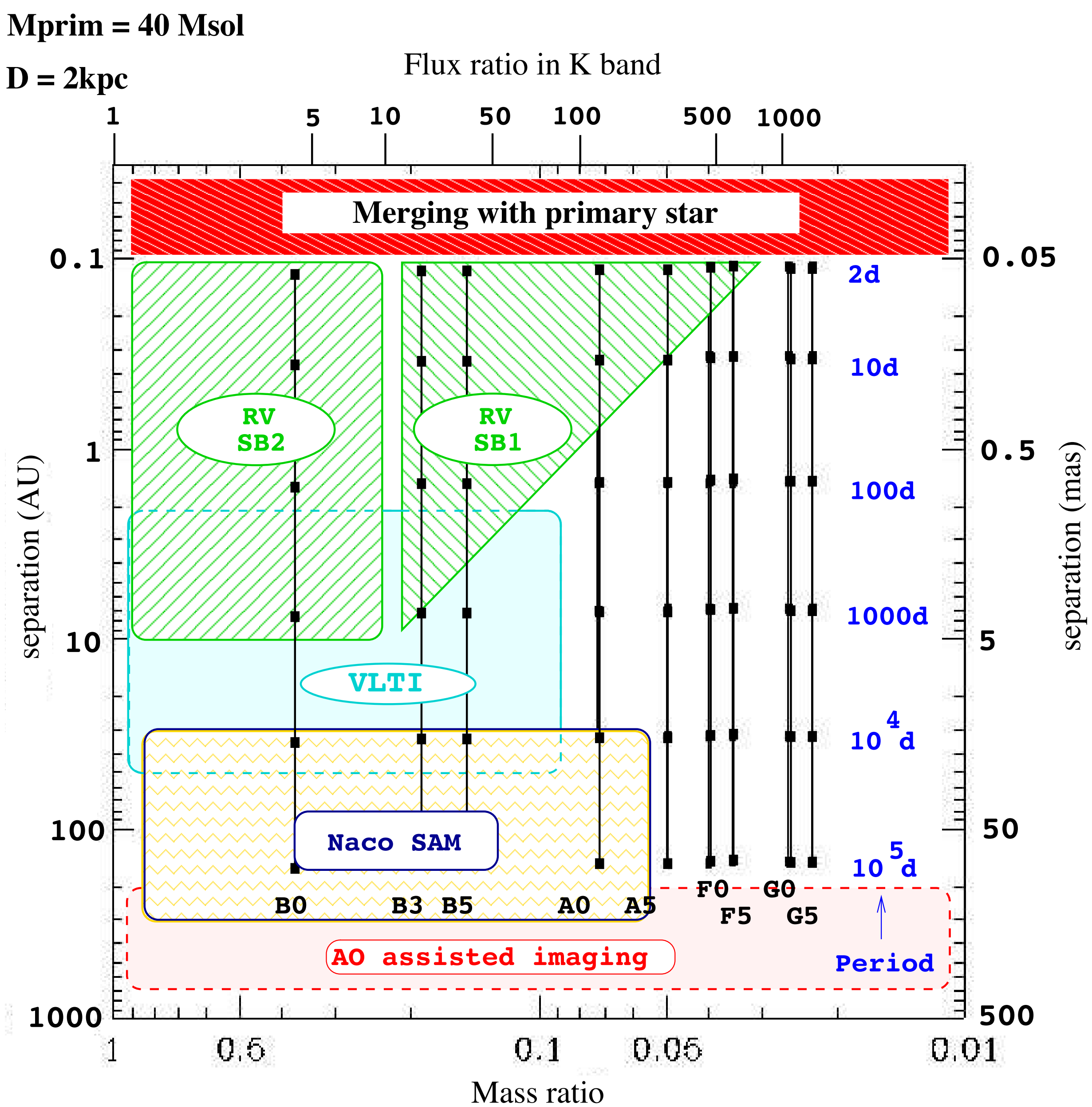


plot made with http://apps.jmmc.fr/bibdb/

Astrophysical topics covered by “binary”

- **Multiplicity (complement RV + AO)**
  - Massive stars, young stars, active stars
  - Faint companions, low mass stars and planets
- **Dynamical masses (SB2 + astrometry)**
  - All stars (massive, low mass, young, old, MS...)
- **Shaping of environment**
  - Evolved stars: shaping of PN and disk
  - Young stars: shaping of proto-planetary disk
  - Be stars: relation with the disk (generation, distortion, dissipation...)
- **Interacting binaries**
  - Evolved stars: mass transfer
  - Massive stars: wind-wind collision, X-ray emitters

Multiplicity: large surveys



Survey of massive stars at high angular resolution

I. PIONIER/VLTI observations of hundred O-stars⋆

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in preparation

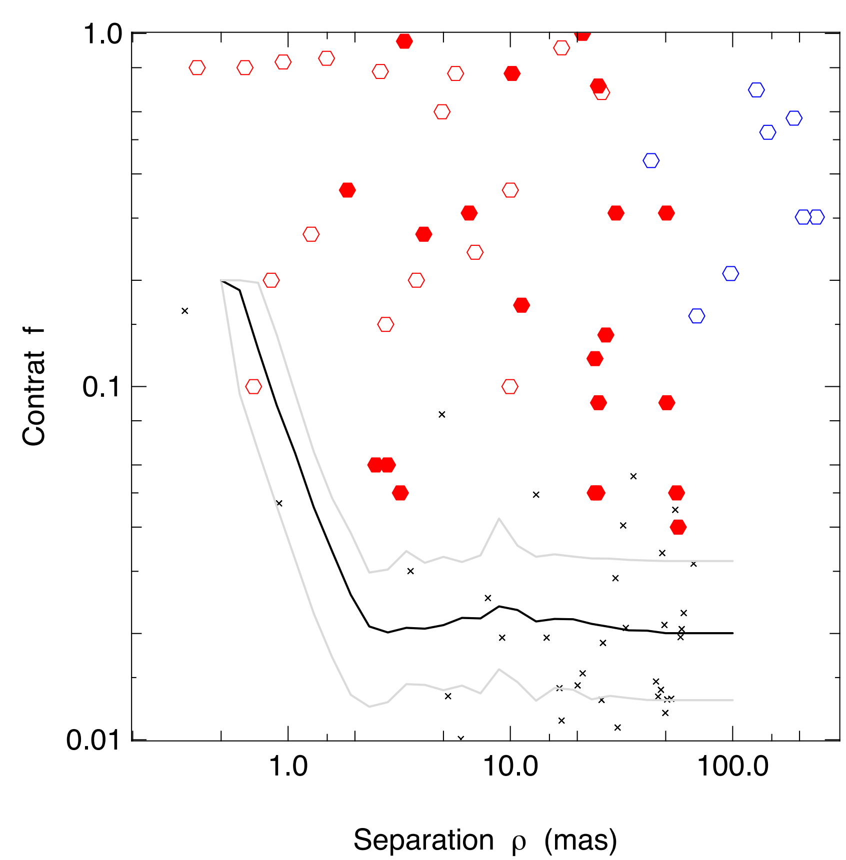
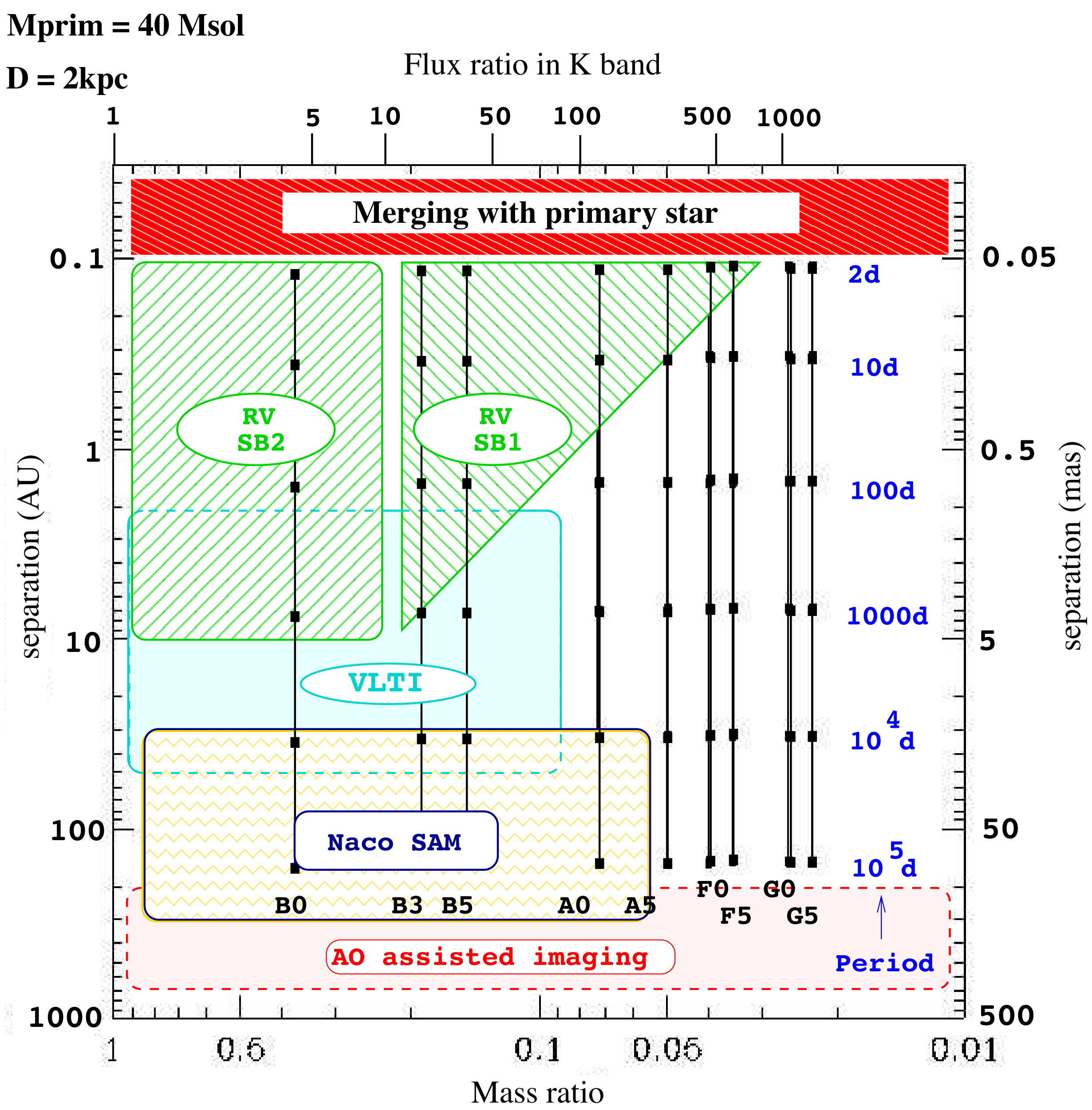


Fig. 4. Plot of separation (ρ) in milli-arcsecond vs. flux ratio (f) for pairs observed. The filled red symbols represent the pairs discovered in this survey. The open red symbols are objects for which we probably spatially resolved for the first time a known SB pair. The open blue symbols are the pairs already resolved by Mason et al. (2009) with single-dish observation. The solid lines indicate the median sensitivity of our survey and its typical variation between the objects.

Multiplicity and faint companion



Deep near-infrared interferometric search for low-mass companions around β Pictoris*

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ABSTRACT

Aims. We search for low-mass companions in the innermost region (<300 mas, i.e., 6 AU) of the β Pic planetary system.
Methods. We obtained interferometric closure phase measurements in the K-band with the VLTI/AMBER instrument used in its medium spectral resolution mode. Fringe stabilization was provided by the FINITO fringe tracker.
Results. In a search region of between 2 and 60 mas in radius, our observations exclude at 3σ significance the presence of companions with K-band contrasts greater than 5×10^{-3} for 90% of the possible positions in the search zone (i.e., 90% completeness). The median 1σ error bar in the contrast of potential companions within our search region is 1.2×10^{-3}. The best fit to our data set using a binary model is found for a faint companion located at about 14.4 mas from β Pic, which has a contrast of $1.8 \times 10^{-3} \pm 1.1 \times 10^{-3}$ (a result consistent with the absence of companions). For angular separations larger than 60 mas, both time smearing and field-of-view limitations reduce the sensitivity.
Conclusions. We can exclude the presence of brown dwarfs with masses higher than 29 M_{Jup} (resp. 47 M_{Jup}) at a 50% (resp. 90%) completeness level within the first few AUs around β Pic. Interferometric closure phases offer a promising way to directly image low-mass companions in the close environment of nearby young stars.

Key words. stars: individual: β Pic – planets and satellites: detection – techniques: interferometric – planetary systems

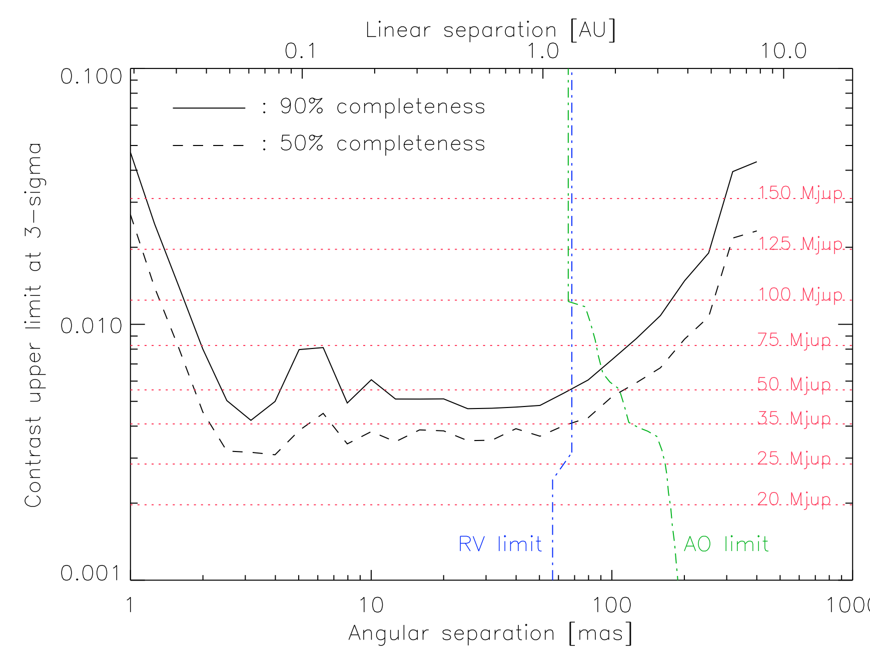
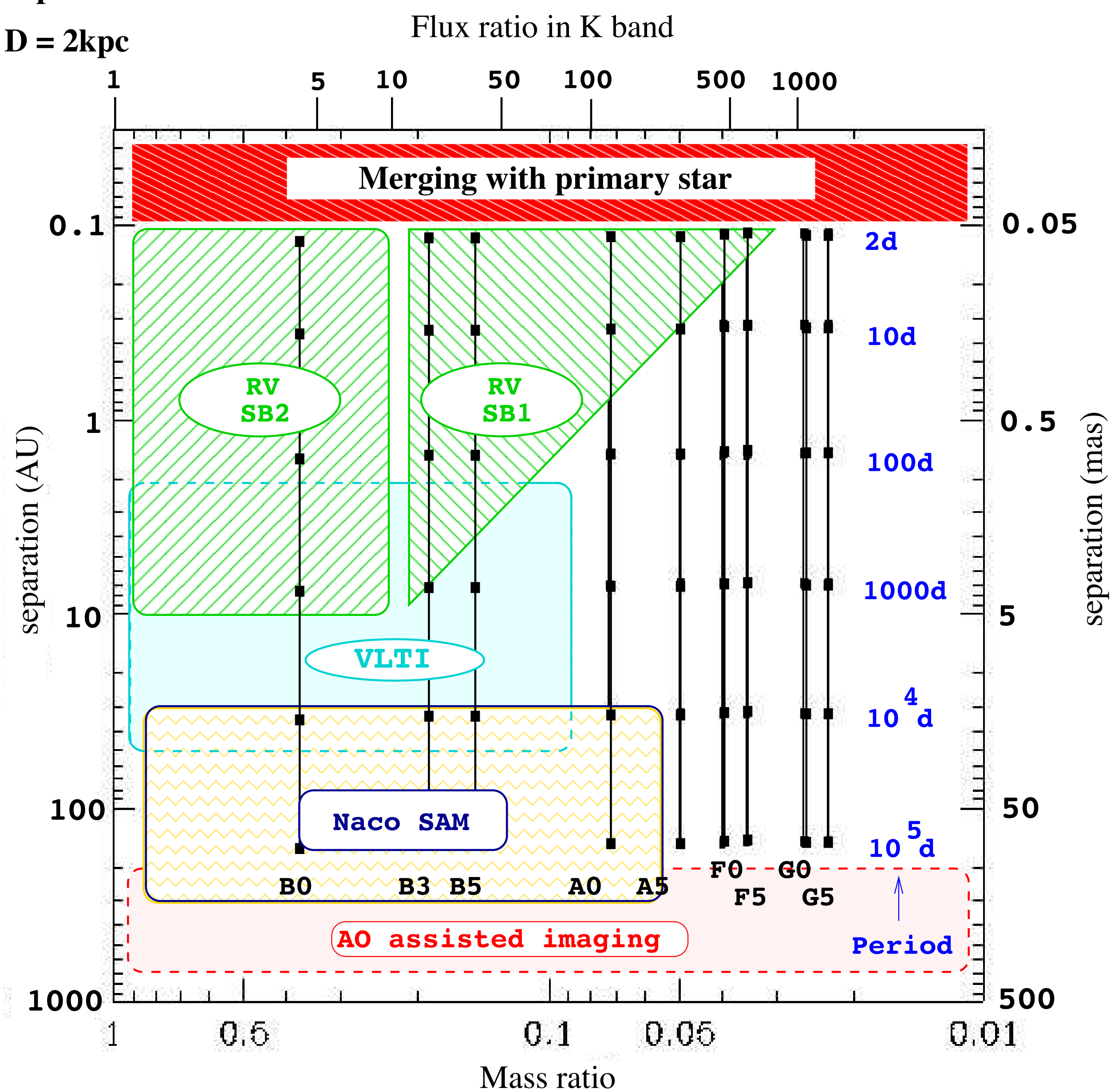


Fig. 4. Sensitivity curves showing the 3σ upper limit to the contrast of off-axis companions as a function of the angular separation for 50% and 90% completeness, computed across annular fields-of-view with 10% relative width. Equivalent masses were computed using the COND model of Baraffe et al. (2003), for an age of 12 Myr. The companion dis-

Measuring stellar masses and distance

Mprim = 40 Msol

D = 2kpc



Astronomy & Astrophysics manuscript no. zetaori
June 4, 2013

Dynamical mass of the O-type supergiant in Zeta Orionis A*

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ABSTRACT

Aims. A close companion of ζ Orionis A was found in 2000 with the Navy Precision Optical Interferometer (NPOI), and shown to be a physical companion. Because the primary is a supergiant of type O, for which dynamical mass measurements are very rare, the companion was observed with NPOI over the full 7-year orbit. Our aim was to determine the dynamical mass of a supergiant that, due to the physical separation of more than 10 AU between the components, cannot have undergone mass exchange with the companion.
Methods. The interferometric observations allow measuring the relative positions of the binary components and their relative brightness. The data collected over the full orbital period allows all seven orbital elements to be determined. In addition to the interferometric observations, we have analyzed archival spectra obtained at the Calar Alto, Haute Provence, Cerro Armazones, and La Silla observatories, as well as new spectra obtained at the VLT on Cerro Paranal. In the high-resolution spectra we identified a few lines that can be associated exclusively to one or the other component for the measurement of the radial velocities of both. The combination of astrometry and spectroscopy then yields the stellar masses and the distance to the binary star.
Results. The resulting masses for components Aa of $14.0 \pm 2.2\ M_\odot$ and Ab of $7.4 \pm 1.1\ M_\odot$ are low compared to theoretical expectations, with a distance of 294 ± 21 pc which is smaller than a photometric distance estimate of 387 ± 54 pc based on the spectral type B0III of the B component. If the latter (because it is also consistent with the distance to the Orion OB1 association) is adopted, the mass of the secondary component Ab of $14 \pm 3\ M_\odot$ would agree with classifying a star of type B0.5IV. It is fainter than the primary by about 2.2 ± 0.1 magnitudes in the visual. The primary mass is then determined to be $33 \pm 10\ M_\odot$. The possible reasons for the distance discrepancy are most likely related to physical effects, such as small systematic errors in the radial velocities due to stellar winds.

Key words. techniques: interferometric - binaries: spectroscopic - stars: supergiants - stars: fundamental paramaters - stars: individual: Zeta Orionis A

From observations to stellar masses

V2, t3Phi

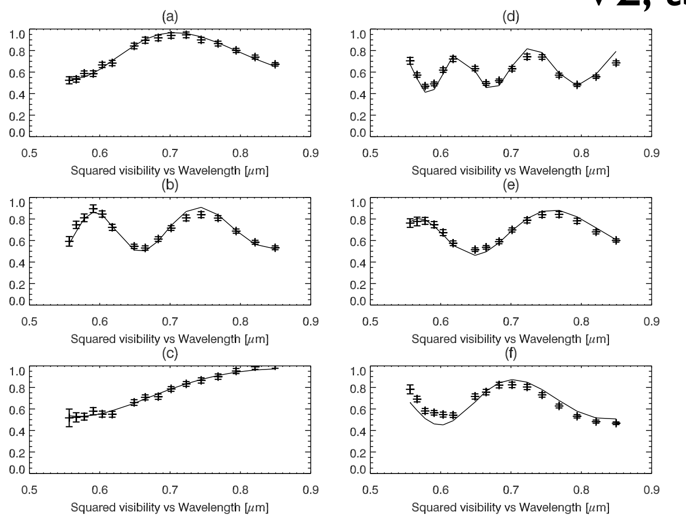

Fig. 1. Calibrated (squared) visibility amplitudes plotted versus wavelength for 2002 Dec 20 on the E-E2(a), E2-W(b), E2-N(c), E-W(d), E-N(e), and N-W(f) baselines at 7:45 UT. The solid line shows the model prediction for a fit with component separation $\rho = 24.6$ mas and PA $\theta = 87.7°$. The amplitude of the quasi-sinusoidal amplitude variation is fit with a magnitude difference $\Delta m = 2.2$.

Relative position on sky

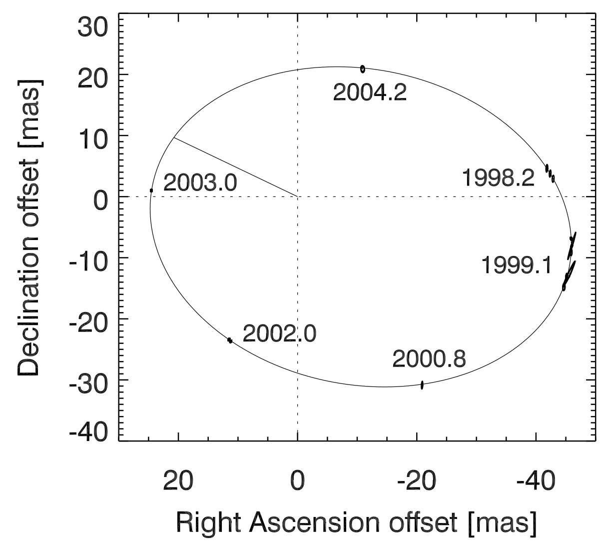

Fig. 4. Orbit of ζ Orionis Ab around Aa (center). The line indicates the secondary Ab at periastron. A few selected epochs are marked.

True masses and distance

Table 3. Orbital elements and system parameters

Orbital period	2687.3 ± 7.0 d
Periastron epoch	JD 2452734.2 ± 9.0
Periastron long.	24.2 ± 1.2°
Eccentricity	0.338 ± 0.004
Ascending node	83.8 ± 0.8°
Inclination	139.3 ± 0.6°
Semi-major axis	35.9 ± 0.2 mas
Systemic velocity	28.3 ± 0.5 km/s
Orbital parallax	3.4 ± 0.2 mas
Visual magnitude difference	2.2 ± 0.1
M_{Aa}	14.0 ± 2.2 $M_\odot$
M_{Ab}	7.4 ± 1.1 $M_\odot$
K_1 (derived)	10.1 km/s
K_2 (derived)	19.6 km/s

Spectra

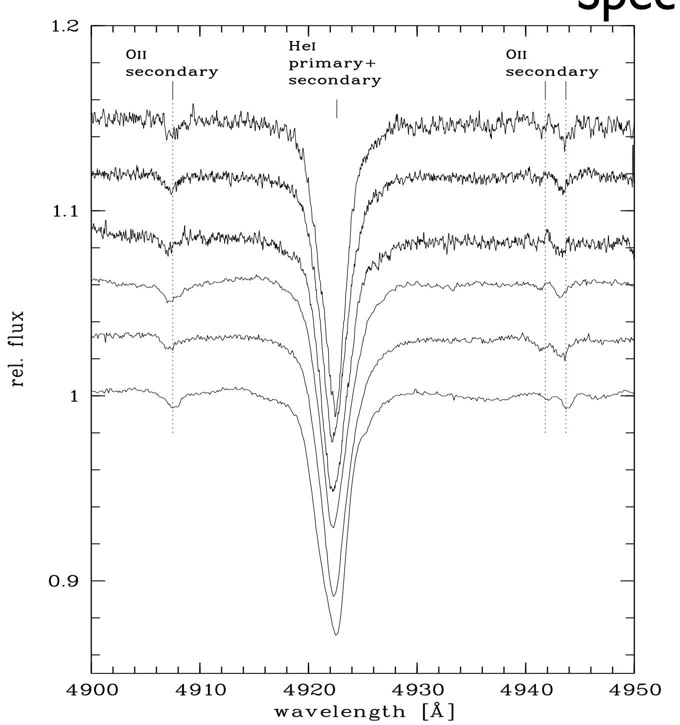

Fig. 3. The SB2 composite spectrum of ζ Ori Aa+Ab. The panel shows the weak O II 4943 lines from the secondary and the composite He I 4922 line. The three HEROS and three FEROS spec-

Radial velocities

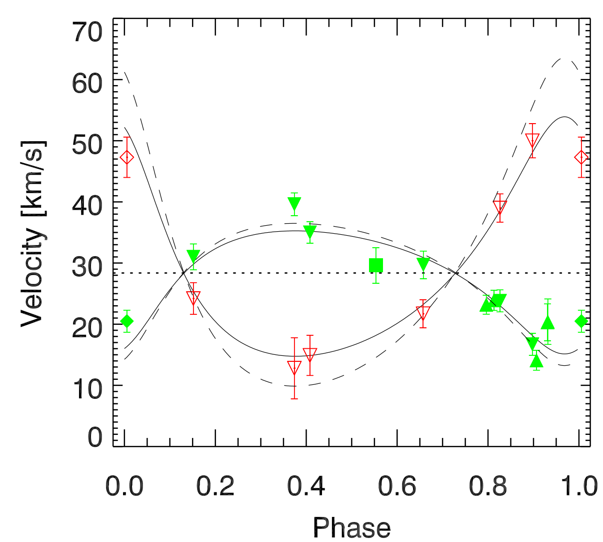

Fig. 5. The measured RVs of both components. The green (filled) symbols denote the primary (He II 4542), the red (open) symbols the secondary (O II 4943). Triangles pointing down denote FEROS/HEROS measurements, triangles pointing up denote BESO. Squares denote ELODIE, and the diamond is for UVES. The dashed lines are for the model based on the photometric distance (see discussion; the derived velocity semi-amplitudes are $K_1 = 11.6$ km/s and $K_2 = 26.8$ km/s).

Interacting binaries

FIRST RESOLVED IMAGES OF THE ECLIPSING AND INTERACTING BINARY β LYRAE

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ABSTRACT

We present the first resolved images of the eclipsing binary β Lyrae, obtained with the CHARA Array interferometer and the MIRC combiner in the *H* band. The images clearly show the mass donor and the thick disk surrounding the mass gainer at all six epochs of observation. The donor is brighter and generally appears elongated in the images, the first direct detection of photospheric tidal distortion due to Roche lobe filling. We also confirm expectations that the disk component is more elongated than the donor and is relatively fainter at this wavelength. Image analysis and model fitting for each epoch were used for calculating the first astrometric orbital solution for β Lyrae, yielding precise values for the orbital inclination and position angle. The derived semimajor axis also allows us to estimate the distance of β Lyrae; however, systematic differences between the models and the images limit the accuracy of our distance estimate to about 15%. To address these issues, we will need a more physical, self-consistent model to account for all epochs as well as the multiwavelength information from the eclipsing light curves.

Subject headings: binaries: eclipsing — infrared: stars — stars: fundamental parameters — stars: individual (β Lyrae) — techniques: interferometric

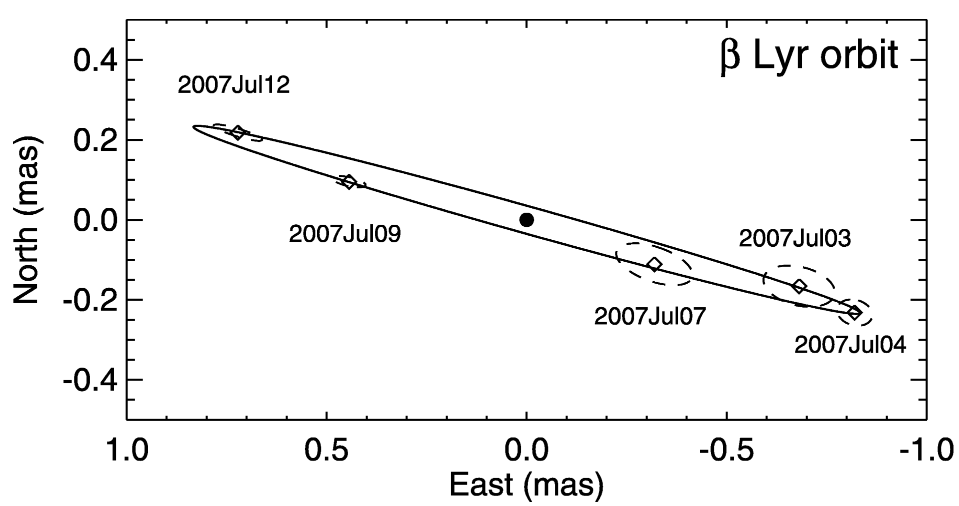
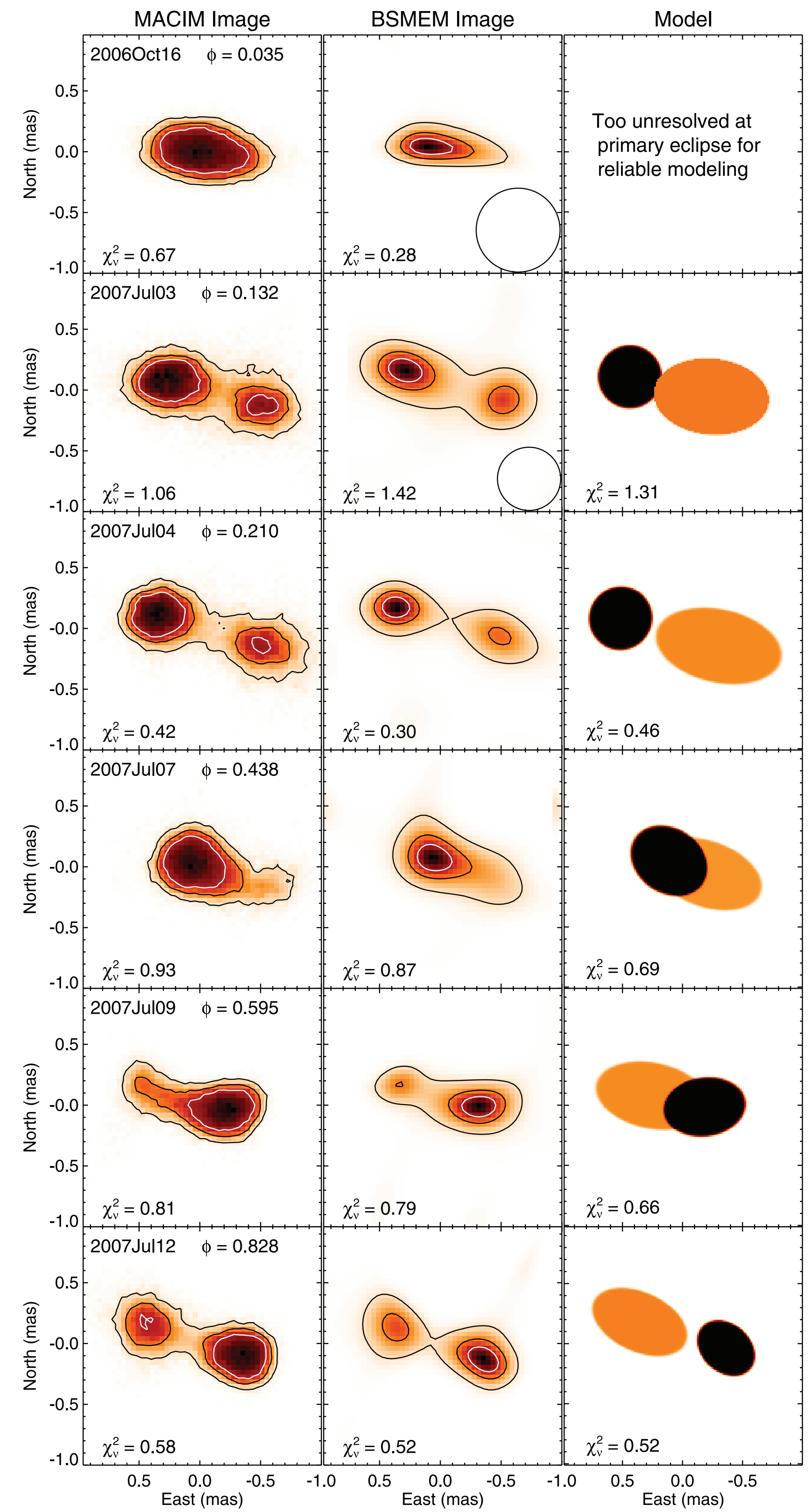


Fig. 3.—The best-fit relative orbit of β Lyr (*solid line*). The donor is indicated as a filled dot in the center. Positions of each epoch are shown by the open dots, surrounded by their error ellipses in dashed lines. The upper part of the orbit is located toward the observer.



Interacting binaries

An incisive look at the symbiotic star SS Leporis

Milli-arcsecond imaging with PIONIER/VLTI★,★★

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ABSTRACT

Context. Determining the mass transfer in a close binary system is of prime importance for understanding its evolution. SS Leporis, a symbiotic star showing the Algol paradox and presenting clear evidence of ongoing mass transfer, in which the donor has been thought to fill its Roche lobe, is a target particularly suited to this kind of study.

Aims. Since previous spectroscopic and interferometric observations have not been able to fully constrain the system morphology and characteristics, we go one step further to determine its orbital parameters, for which we need new interferometric observations directly probing the inner parts of the system with a much higher number of spatial frequencies.

Methods. We use data obtained at eight different epochs with the VLTI instruments AMBER and PIONIER in the *H* and *K* bands. We performed aperture synthesis imaging to obtain the first model-independent view of this system. We then modelled it as a binary (whose giant is spatially resolved) that is surrounded by a circumbinary disc.

Results. Combining these interferometric measurements with previous radial velocities, we fully constrain the orbit of the system. We then determine the mass of each star and significantly revise the mass ratio. The M giant also appears to be almost twice smaller than previously thought. Additionally, the low spectral resolution of the data allows the flux of both stars and of the dusty disc to be determined along the *H* and *K* bands, and thereby extracting their temperatures.

Conclusions. We find that the M giant actually does not *stricto sensus* fill its Roche lobe. The mass transfer is more likely to occur through the accretion of an important part of the giant wind. We finally rise the possibility for an enhanced mass loss from the giant, and we show that an accretion disc should have formed around the A star.

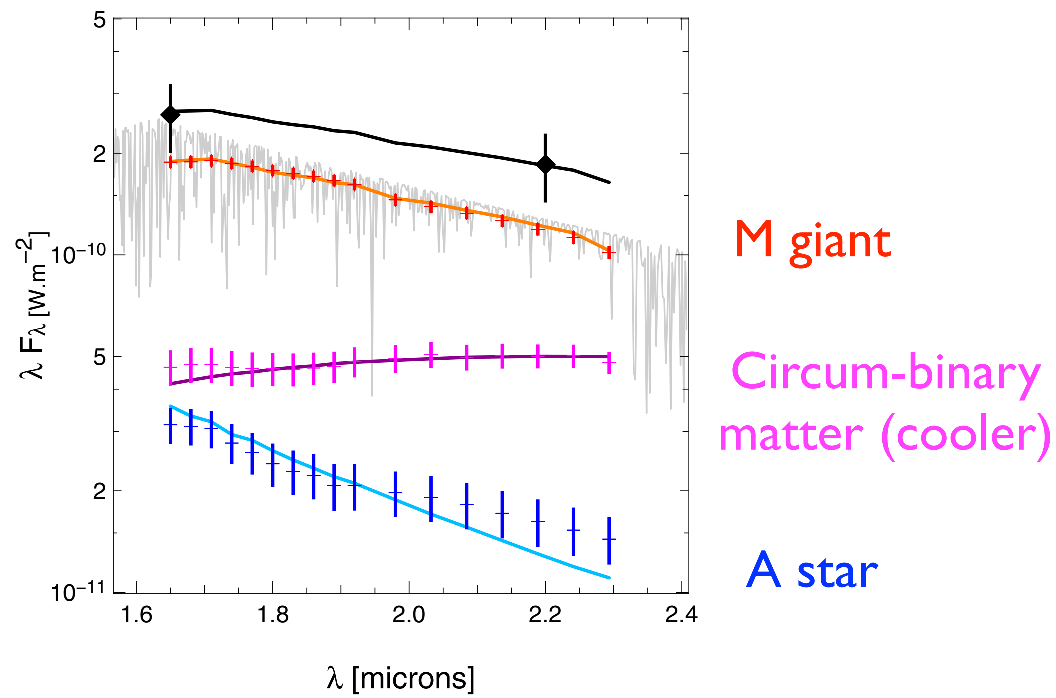


Fig. 4. Flux of the M giant (red), the A star (blue), and the envelope (magenta). The grey curve is the M star MARCS spectrum. In black is the sum of the three components adjusted to the 2MASS magnitudes in the *H*- and *K*-bands. The dots are the data plus the error bars, and the solid lines are the models for each of the components.

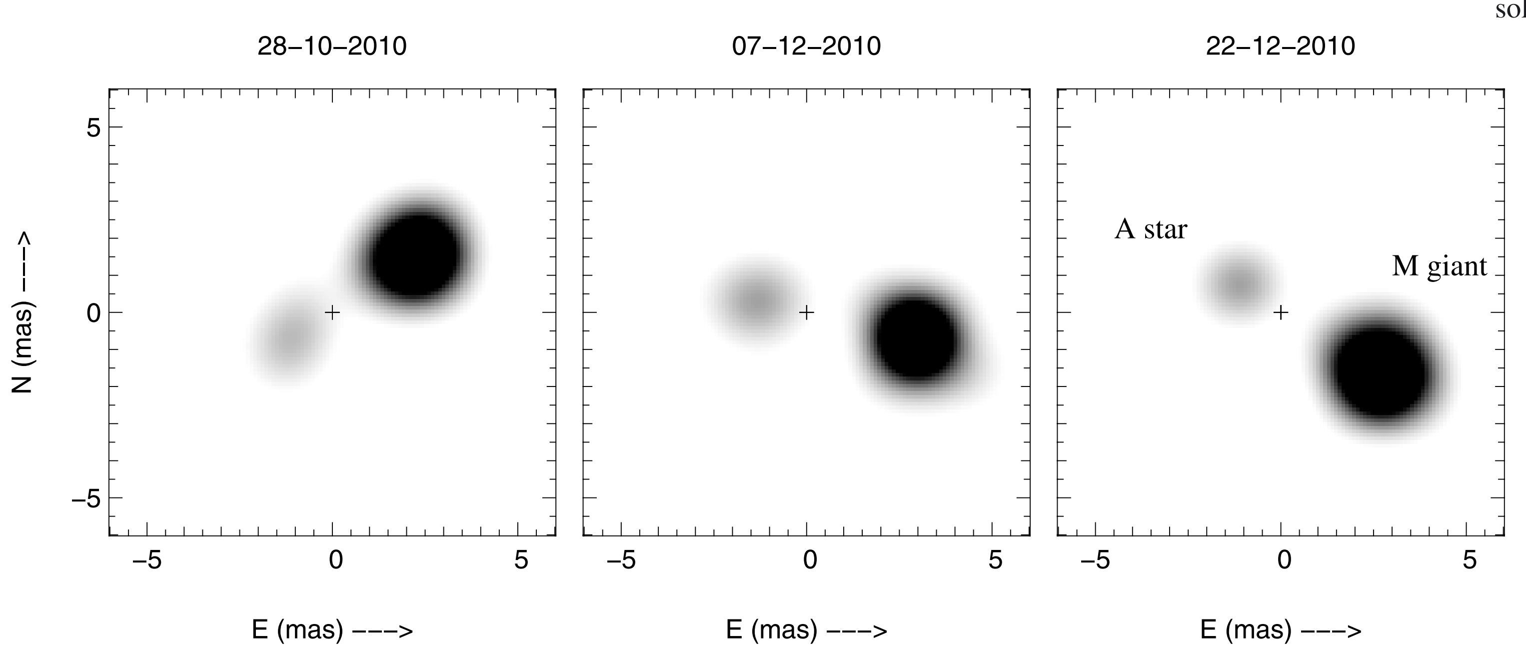


Fig. 2. Model-independent image reconstruction of SS Lep obtained during the PIONIER runs P1, P2, and P4. The resolved M giant and the A star are clearly identified. The images are centered on the center of mass (central cross) as determined from Sect. 5.2. The distortion of the giant in the image is most certainly due to an asymmetric PSF rather than to a definite tidal effect. Three faint artefacts are visible on the periphery of the image.

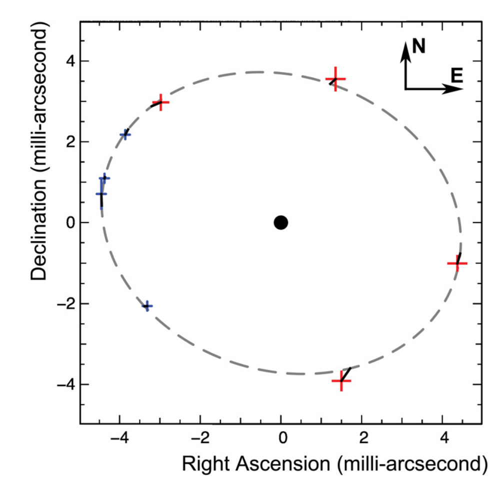


Fig. 3. SS Lep best orbit (dashed line) obtained by combining previous radial velocities (Welty & Wade 1995) with our astrometric measurements. The central dot indicates the A star. AMBER and PIONIER points are respectively presented by the red and blue crosses representing the 3-σ error bars. The corresponding points on the best orbit are indicated by the short segments originating in each point.

Formulation of a binary in visibility

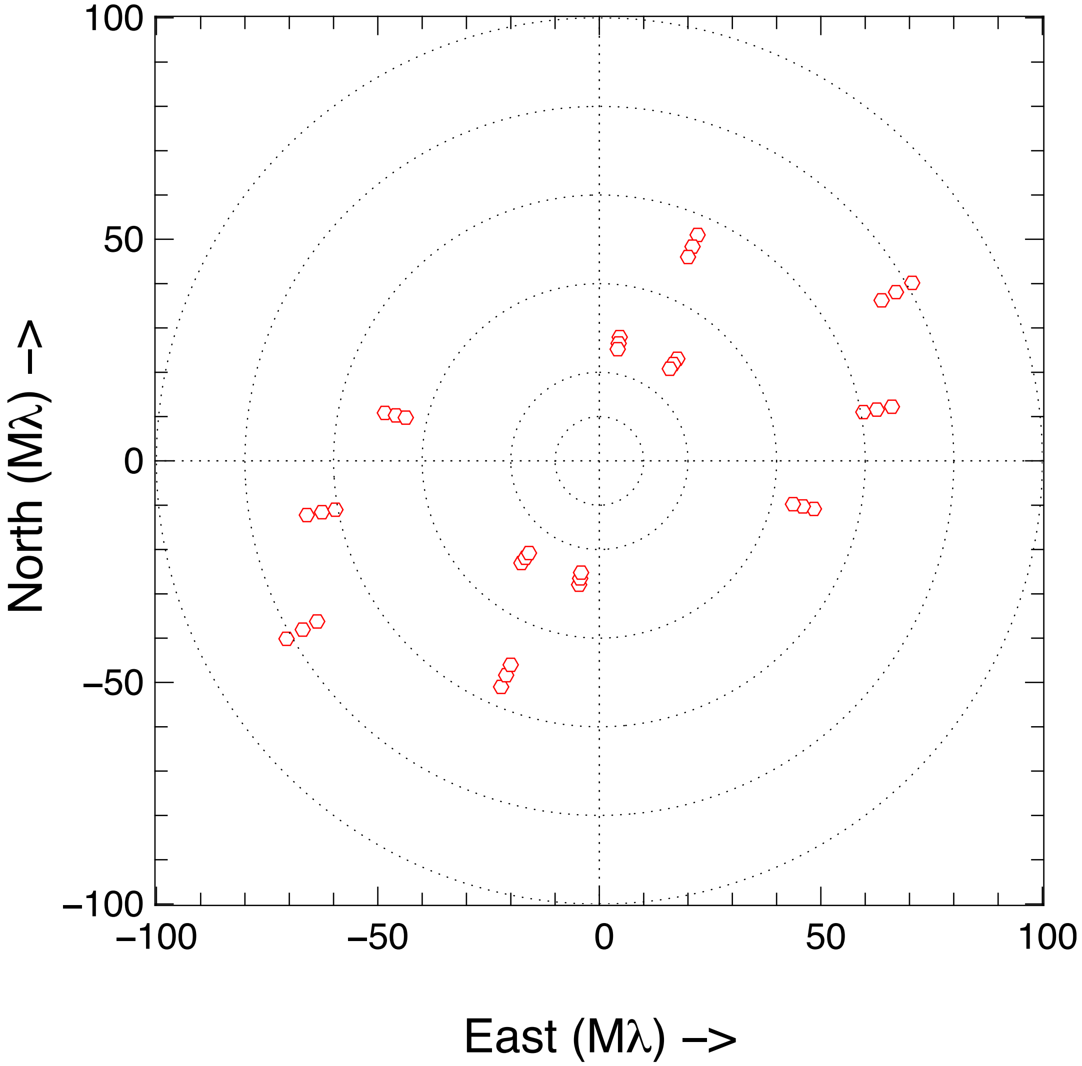
In the plane of the sky:

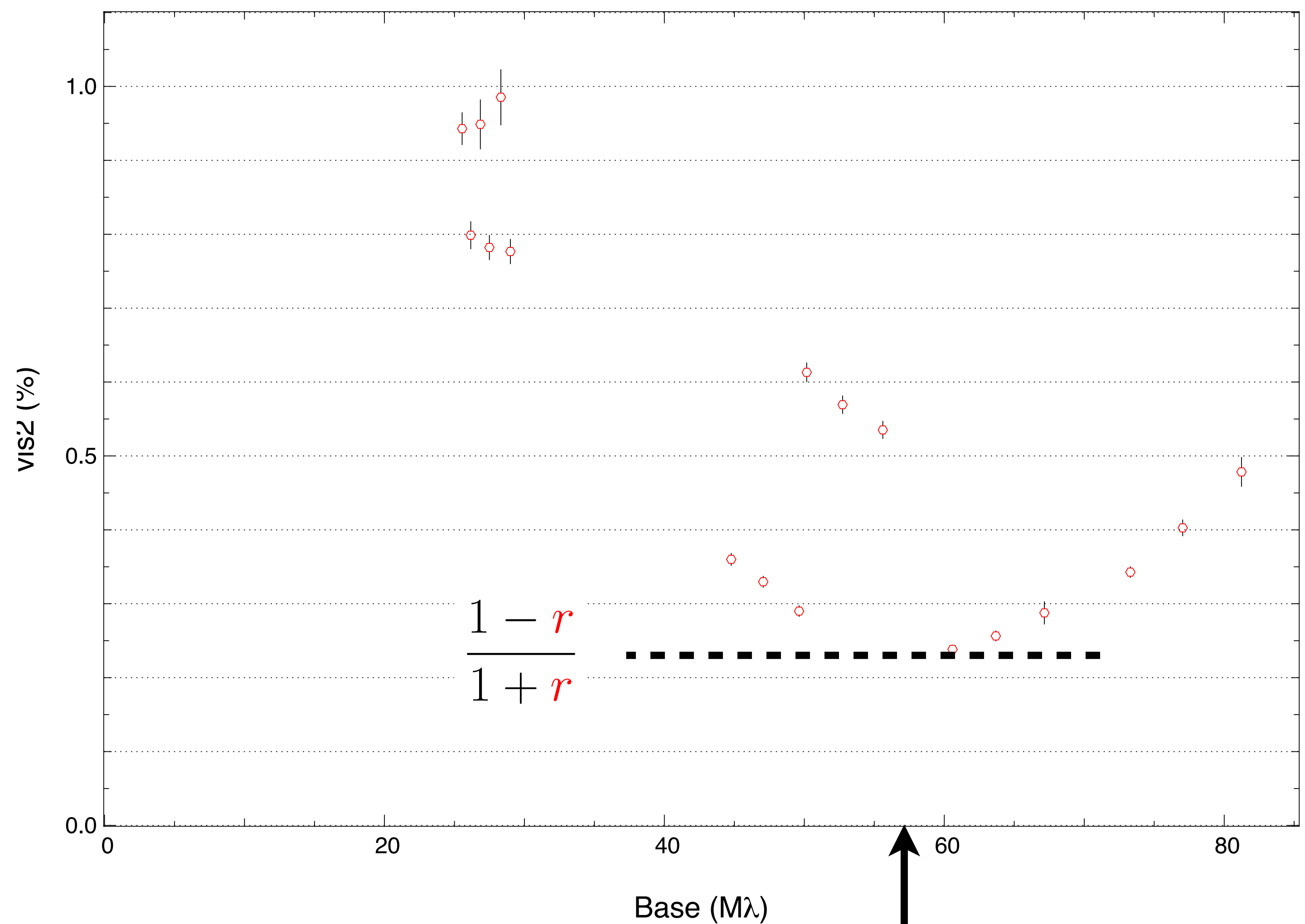
$$I = \delta(\vec{x}) \ + \ r\,\delta(\vec{x} - \vec{\rho})$$

Visibility = Fourier Transform:

$$V = \frac{1 + r\,e^{-2i\pi\frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

HD 151003

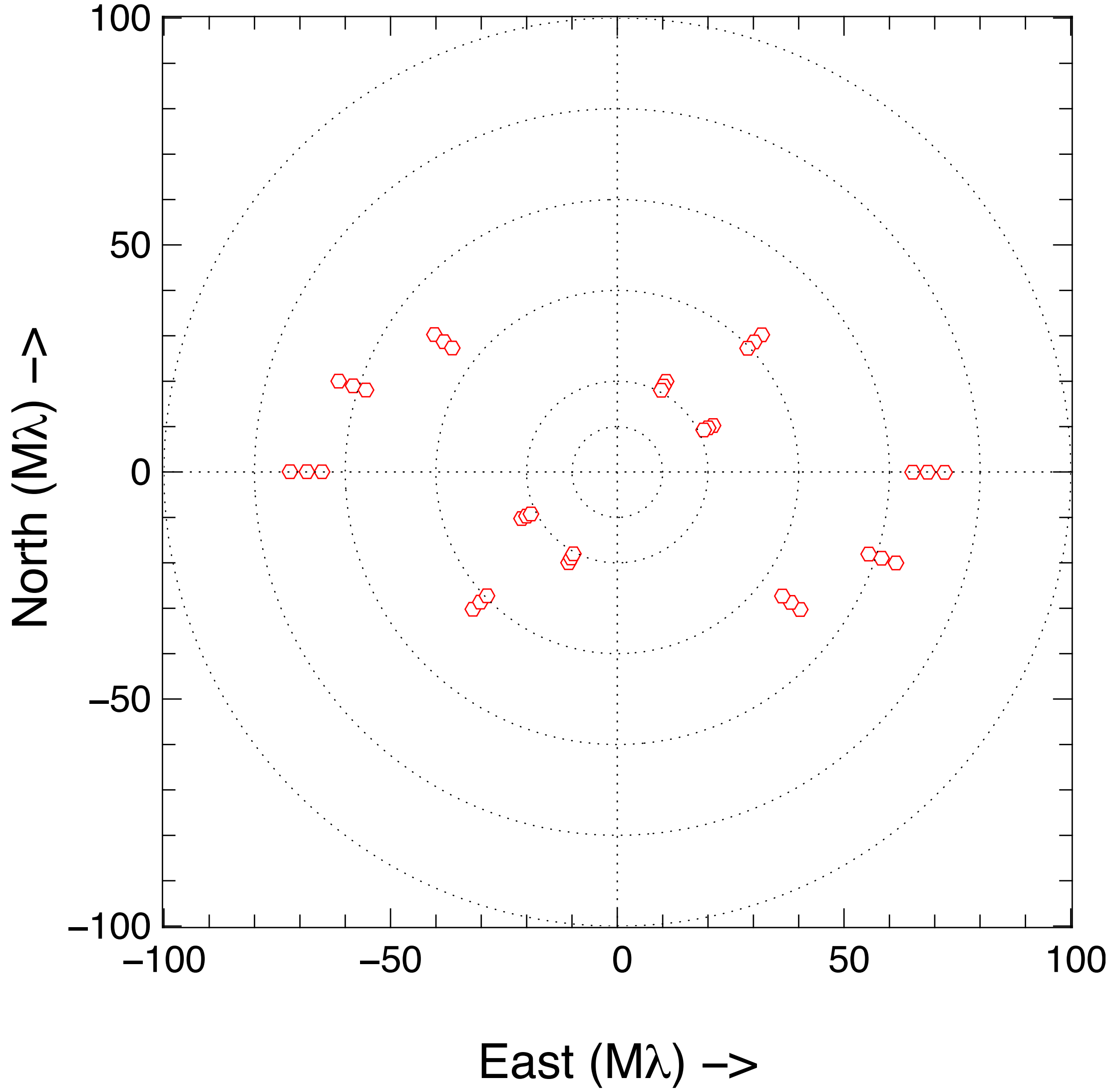


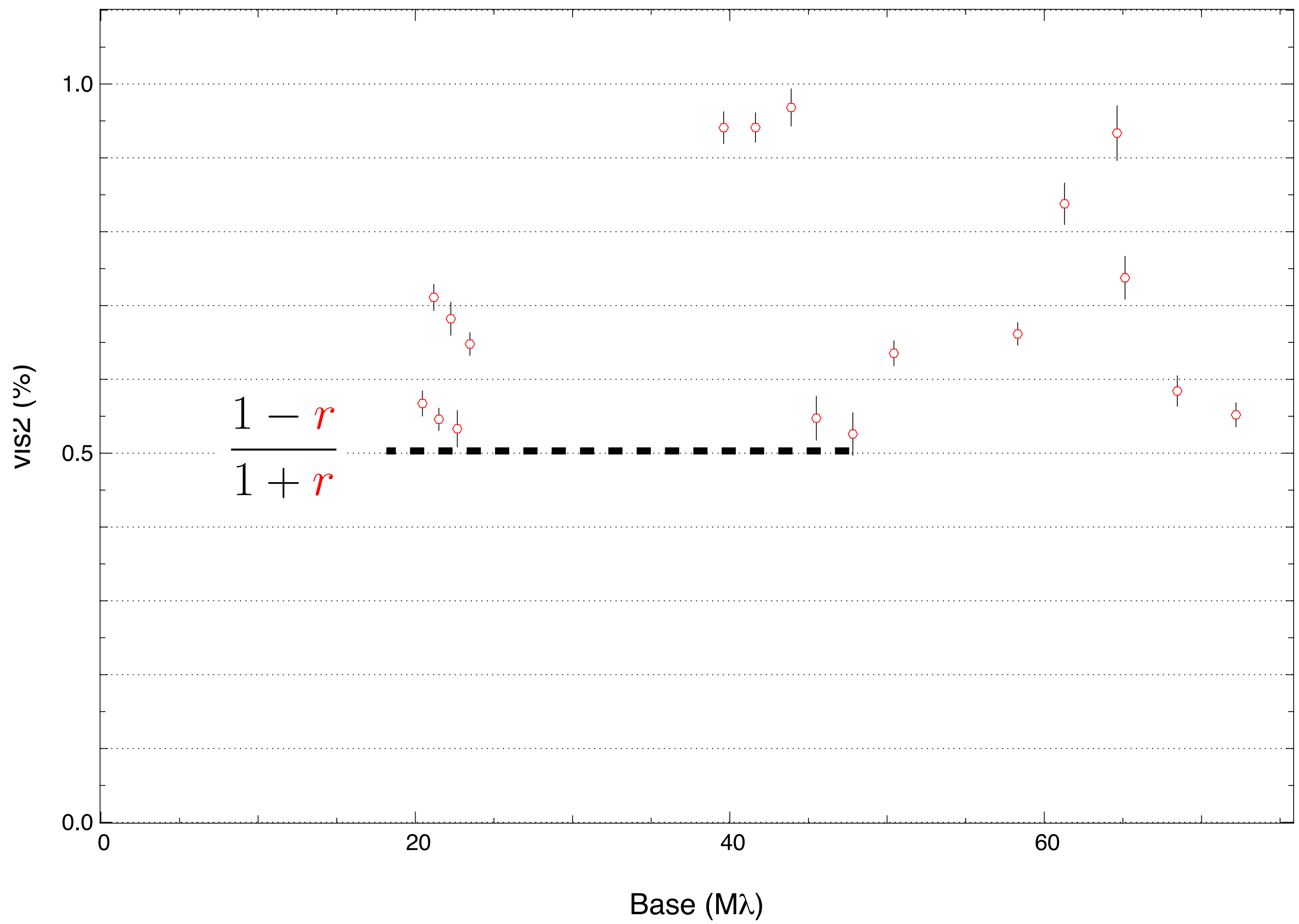


$$\frac{\vec{B}}{\lambda}\vec{\rho} = 0.5$$

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

HD 97253





$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1+r}$$

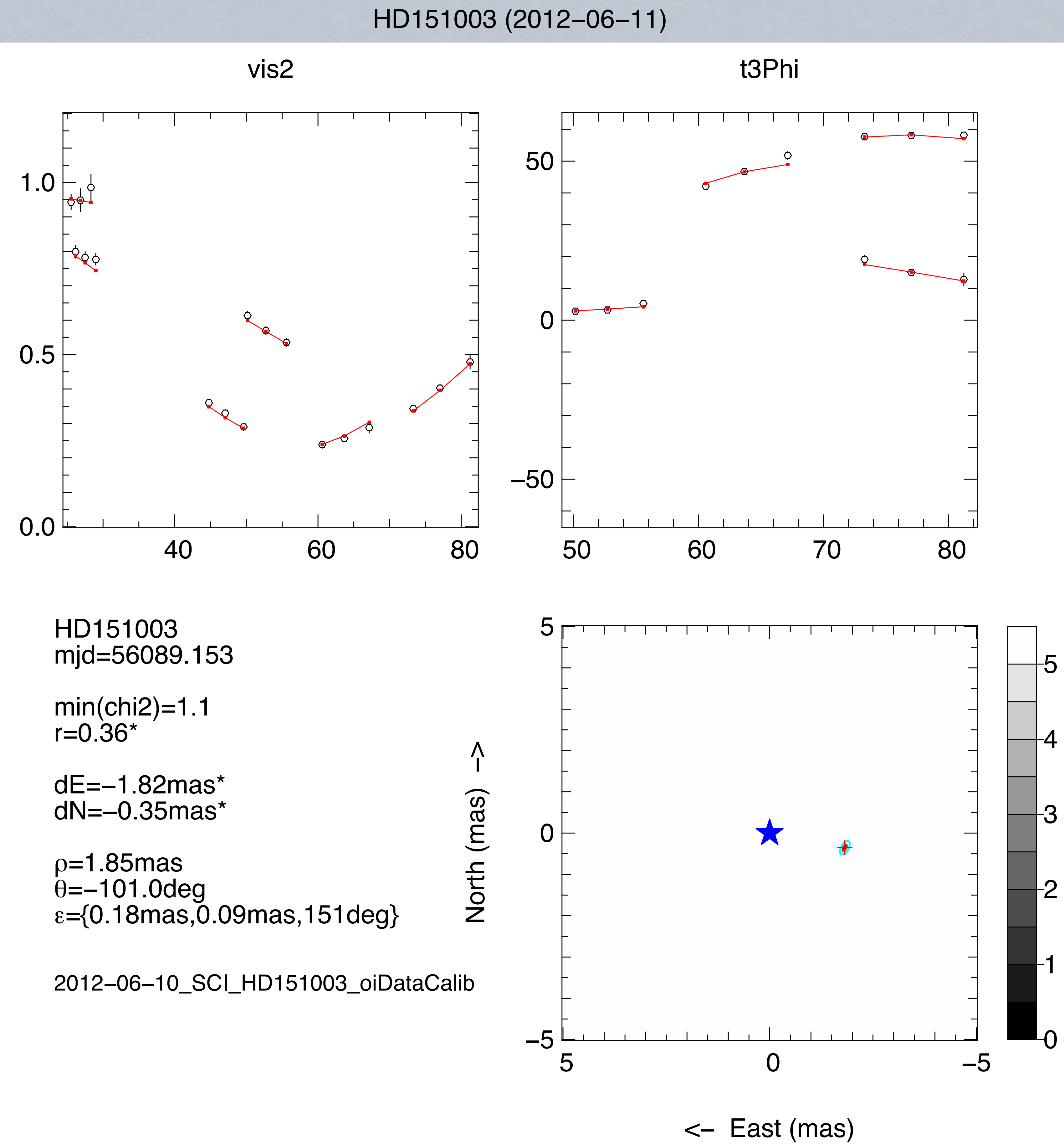
Some important aspect of the observation

- Achievable spatial resolution
- Achievable dynamic
- Unambiguous field-of-view
- Smearing and outer-working-angle

Spatial resolution: (1) easy

$$V = \frac{1 + {\color{red}r}\, e^{-2i\pi \frac{\vec{B}}{\lambda}{\color{red}\vec{\rho}}}}{1 + {\color{red}r}}$$

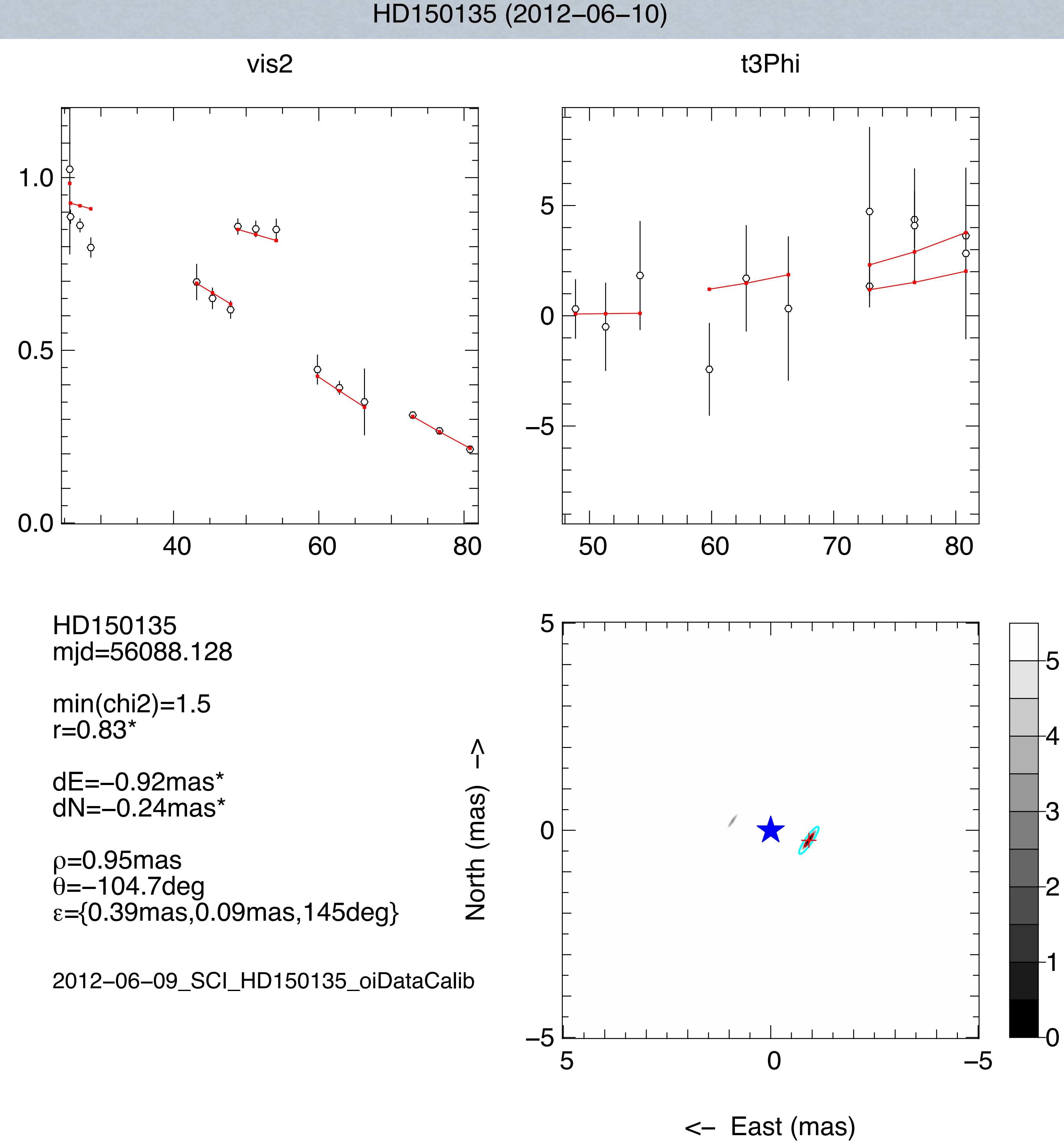
$$\frac{\vec{B}_{max}}{\lambda}{\color{red}\vec{\rho}} > 0.5$$



Spatial resolution: (2) getting closer

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

$$\frac{\vec{B}_{max}}{\lambda}\vec{\rho} \approx 0.5$$

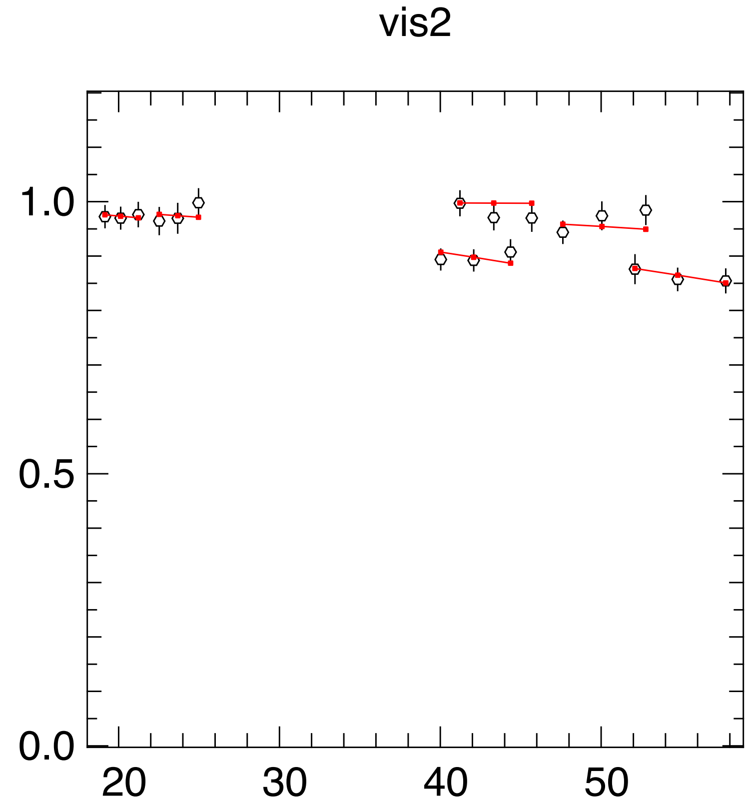


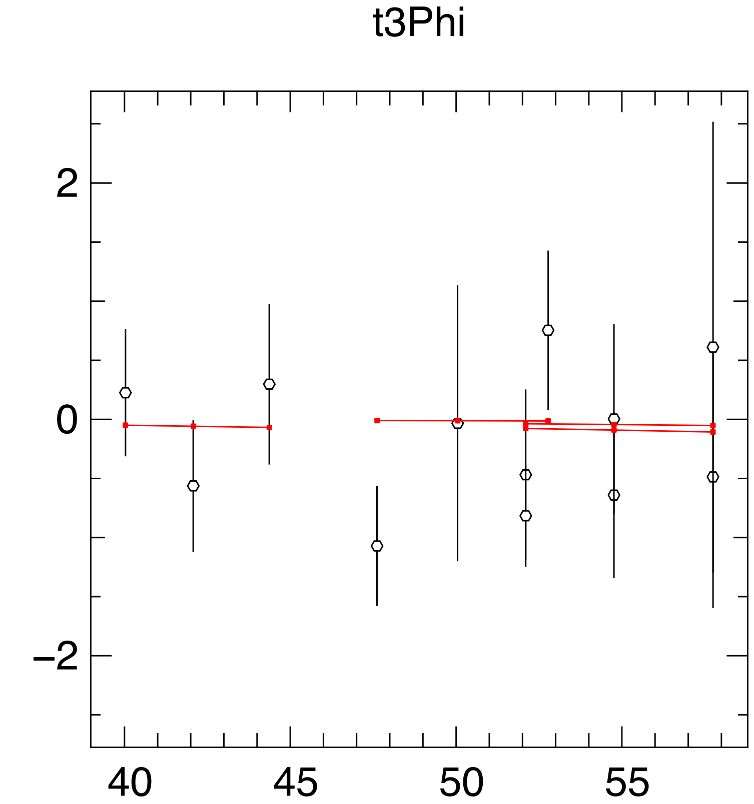
Spatial resolution: (3) too compact

HD75759 (2012−06−10)

$$V = \frac{1 + \color{red}{r}\, e^{-2i\pi \frac{\vec{B}}{\lambda}\color{red}{\vec{\rho}}}}{1 + \color{red}{r}}$$

$$\frac{\vec{B}_{max}}{\lambda}\color{red}{\vec{\rho}} << 0.5$$





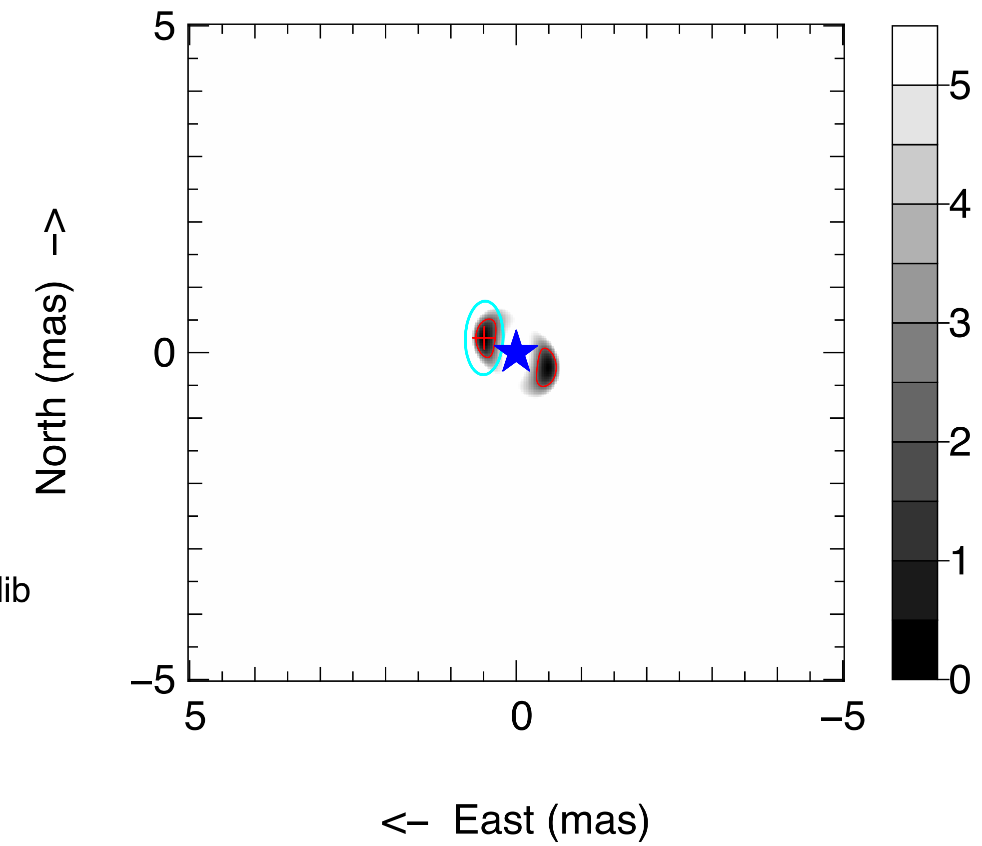
HD75759
mjd=56088.985

min(chi2)=0.7
r=0.80 (fixed)

dE=0.49mas*
dN=0.23mas*

ρ=0.54mas
θ=65.3deg
ε={0.56mas,0.29mas,178deg}

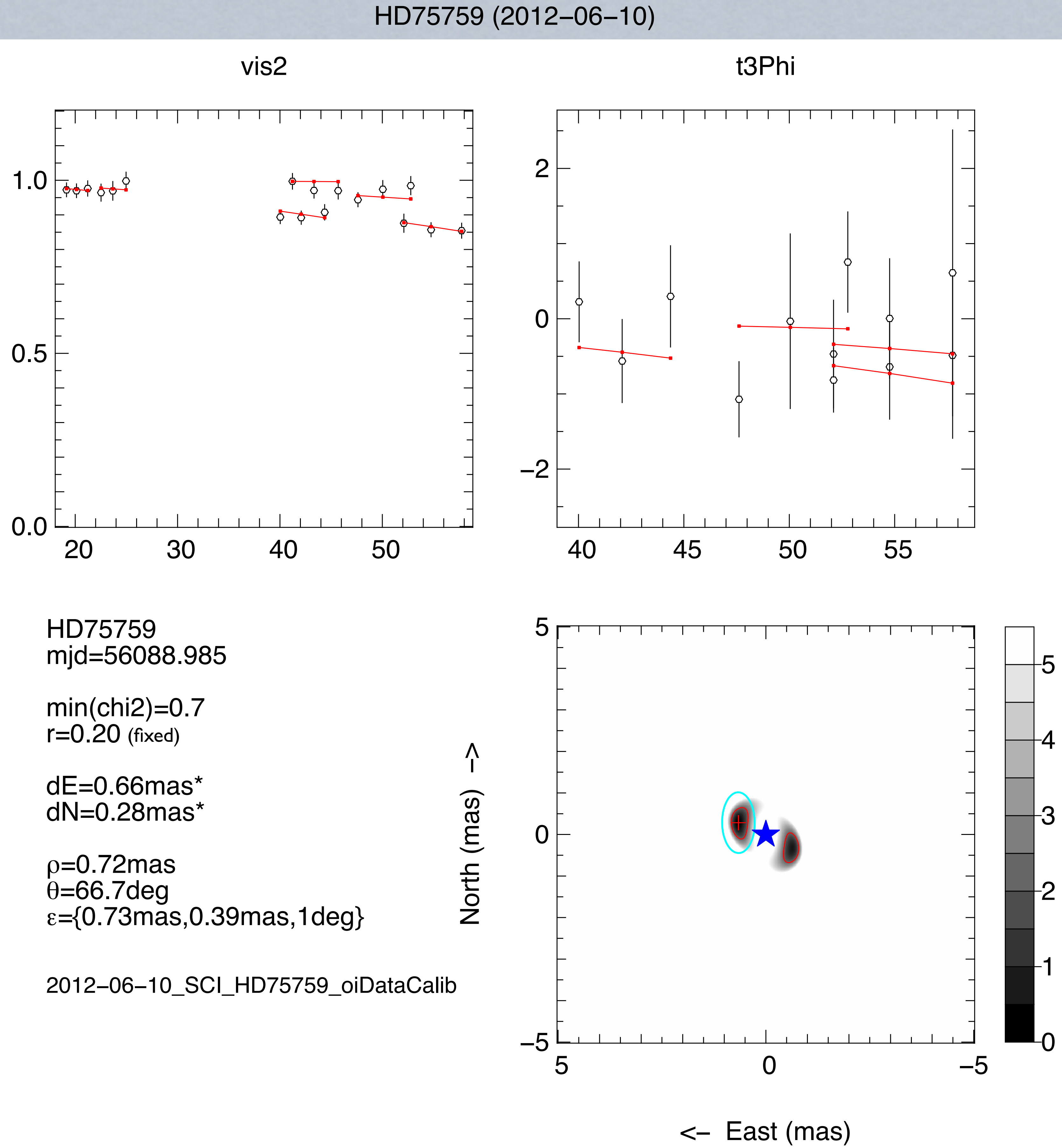
2012−06−10_SCI_HD75759_oiDataCalib



Spatial resolution: (3) too compact

$$V = \frac{1 + {\color{red}r}\, e^{-2i\pi \frac{\vec{B}}{\lambda}{\color{red}\vec{\rho}}}}{1 + {\color{red}r}}$$

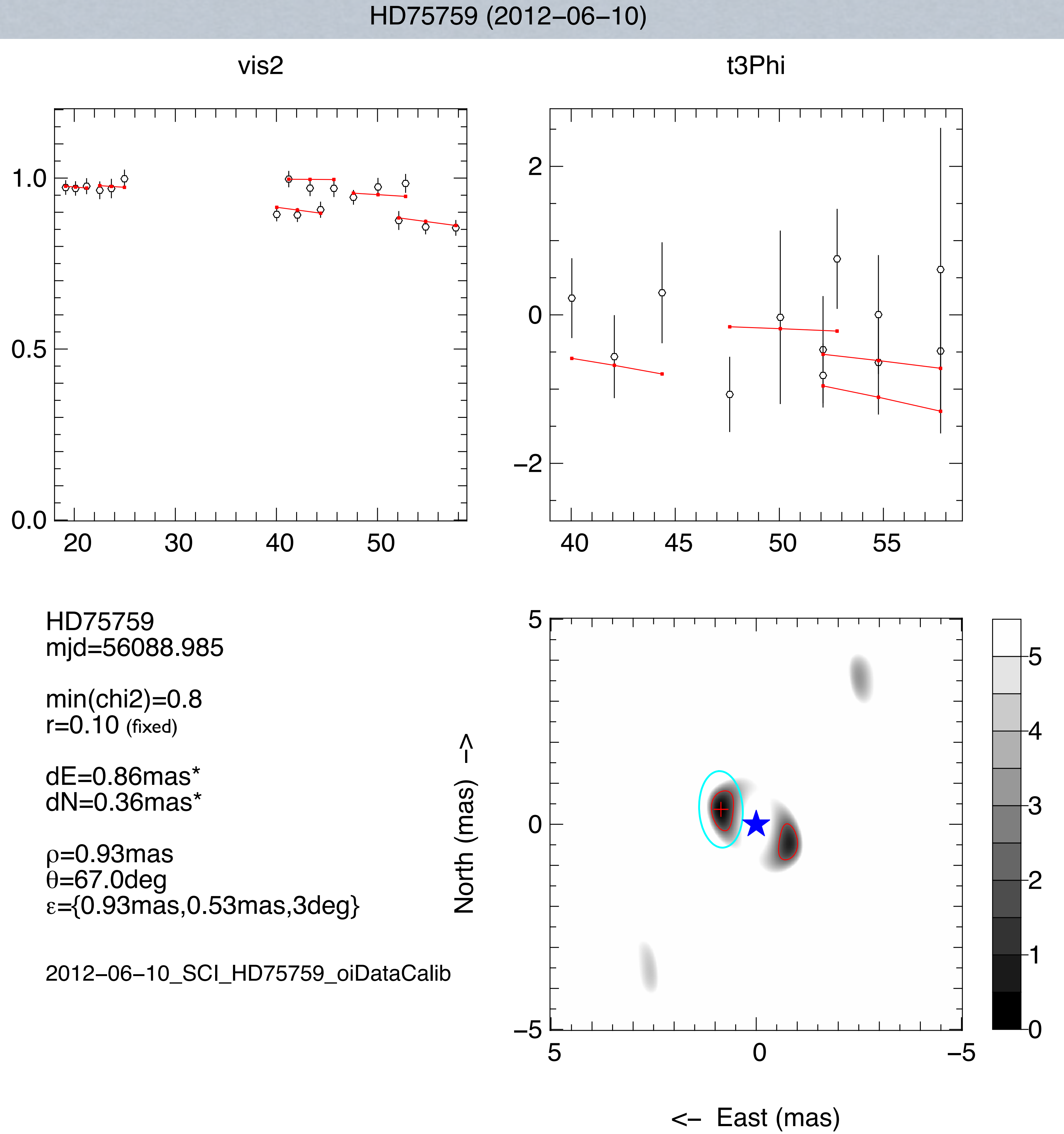
$$\frac{\vec{B}_{max}}{\lambda}{\color{red}\vec{\rho}} << 0.5$$



Spatial resolution: (3) too compact

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

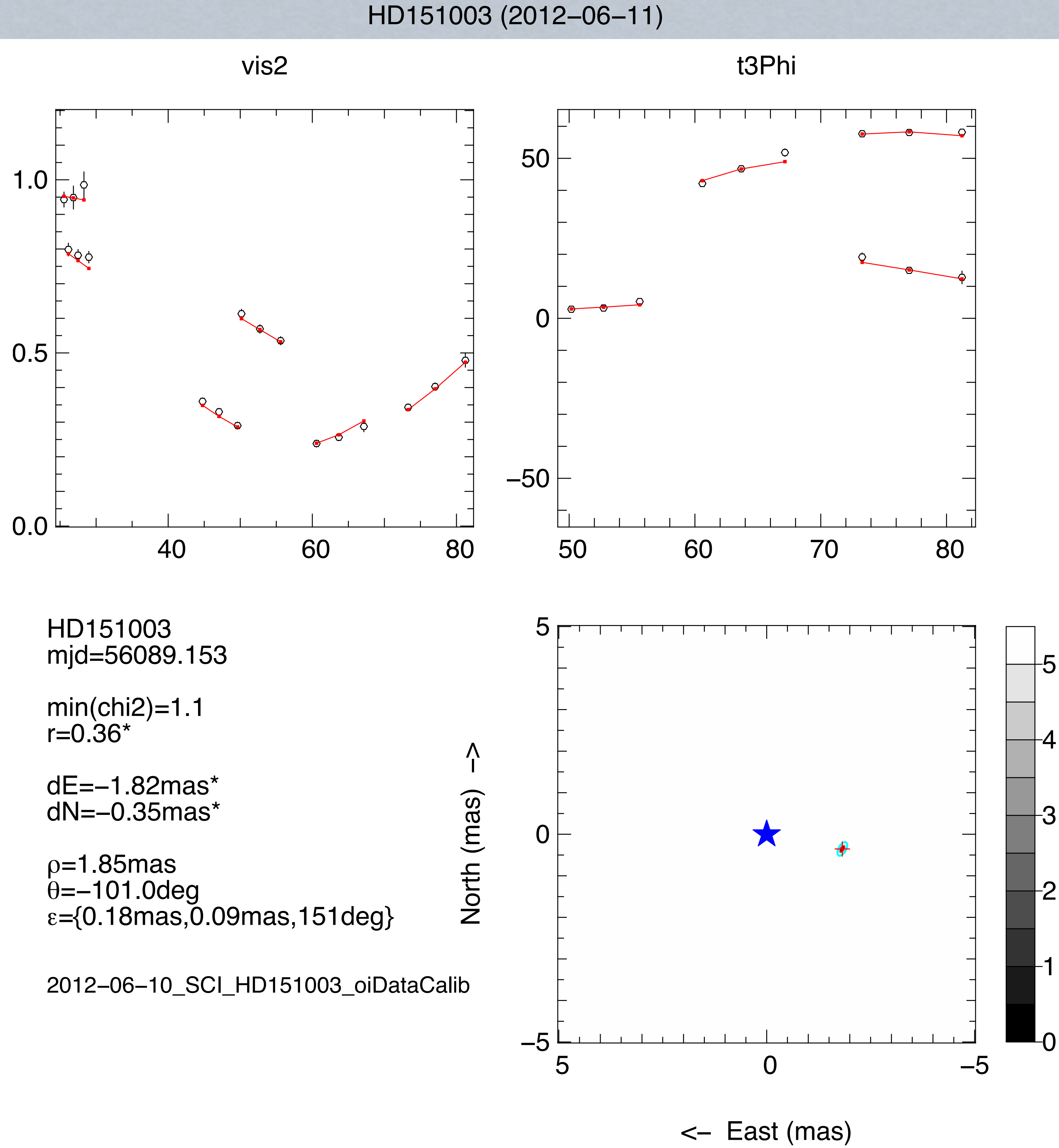
$$\frac{\vec{B}_{max}}{\lambda}\vec{\rho} << 0.5$$



Spatial resolution: (4) back to resolved

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

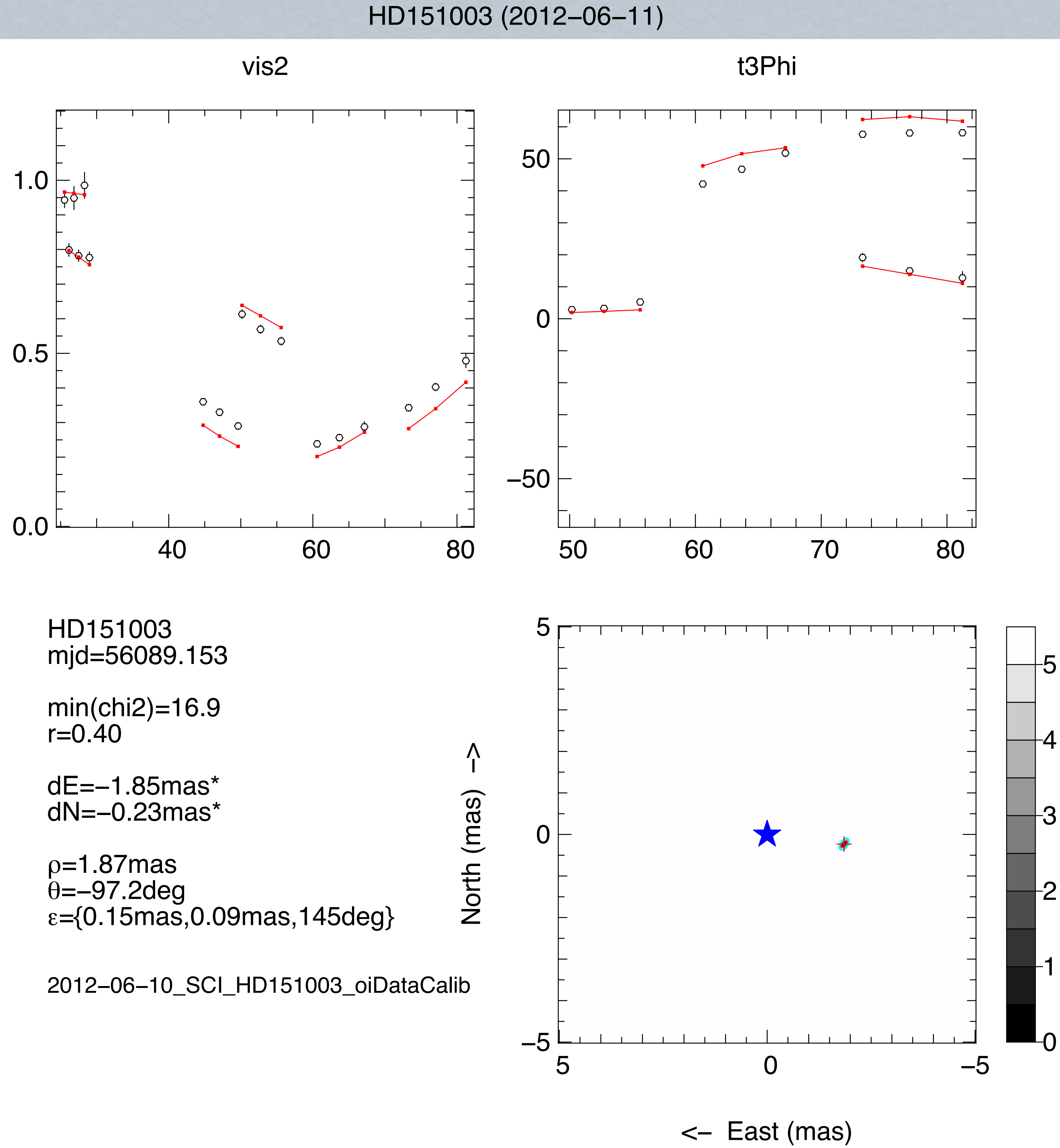
$$\frac{\vec{B}_{max}}{\lambda}\vec{\rho} > 0.5$$



Spatial resolution: (4) back to resolved

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

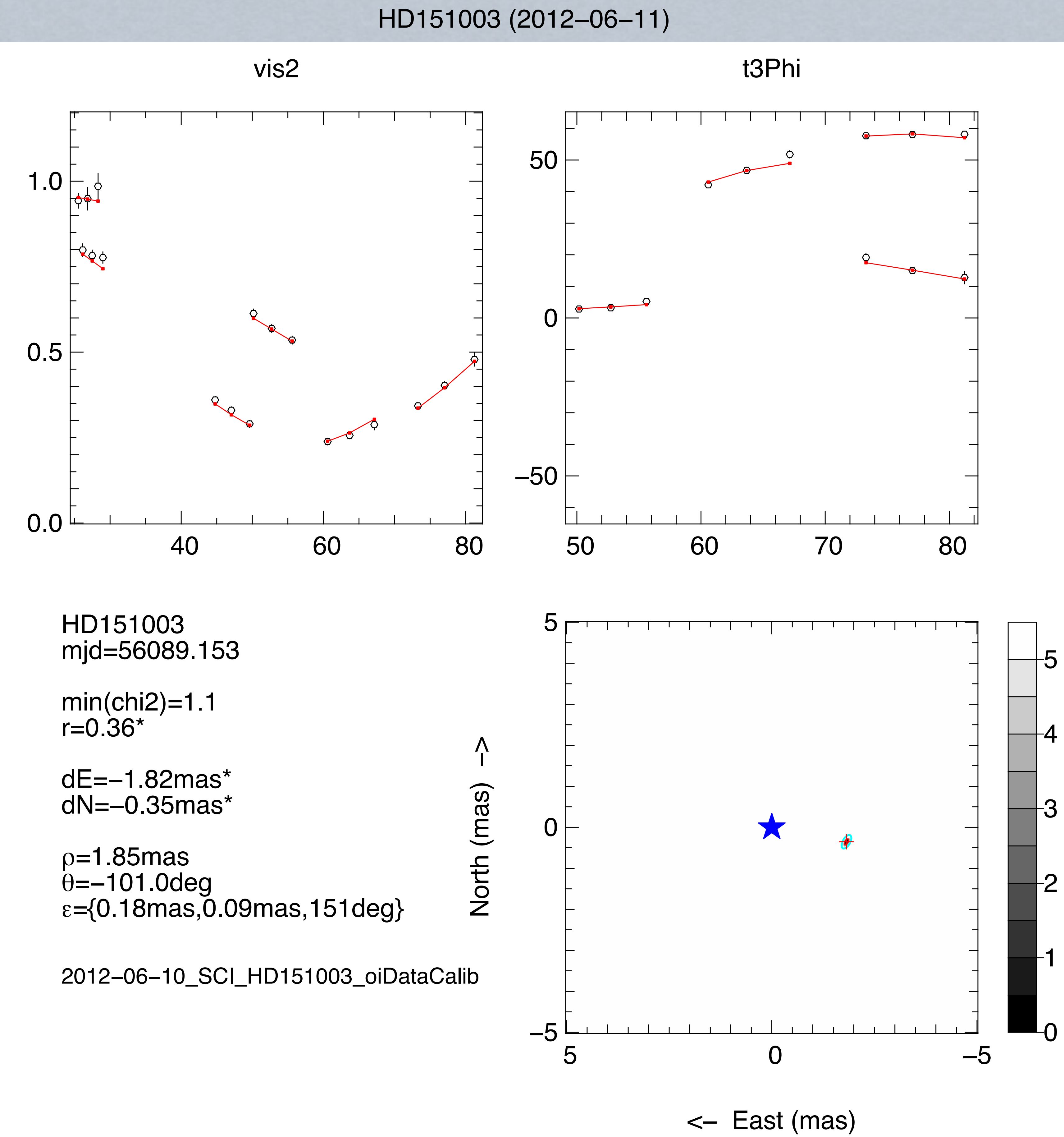
$$\frac{\vec{B}_{max}}{\lambda}\vec{\rho} > 0.5$$



Achievable dynamic: (1) a 30% contrast detection

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

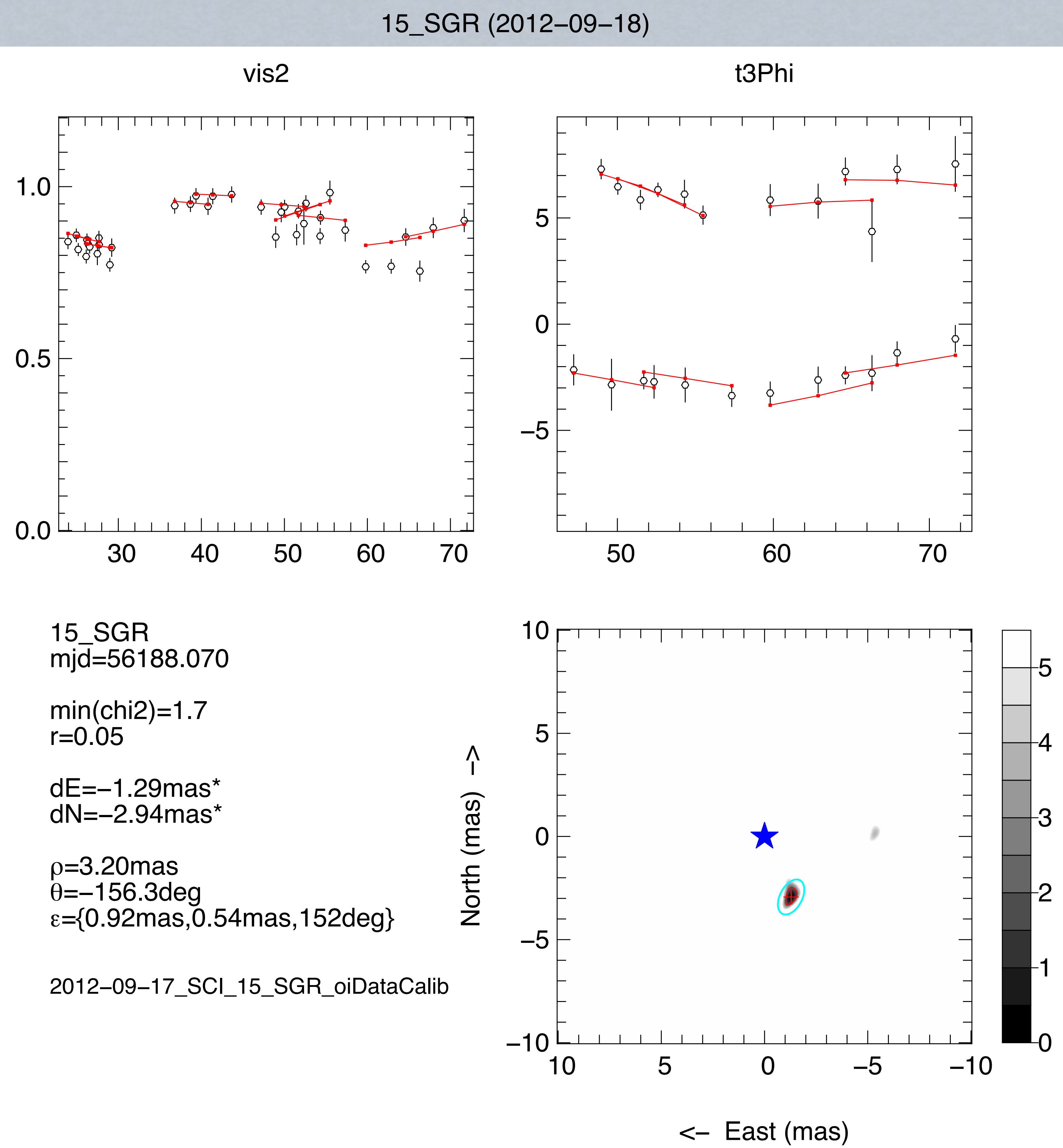
$$\frac{1 - r}{1 + r} > \sigma_V$$



Achievable dynamic: (1) a 5% contrast detection

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

$$\frac{1 - r}{1 + r} > \sigma_V$$



Achievable dynamic: (2) a 5% contrast non-detection

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1+r}$$

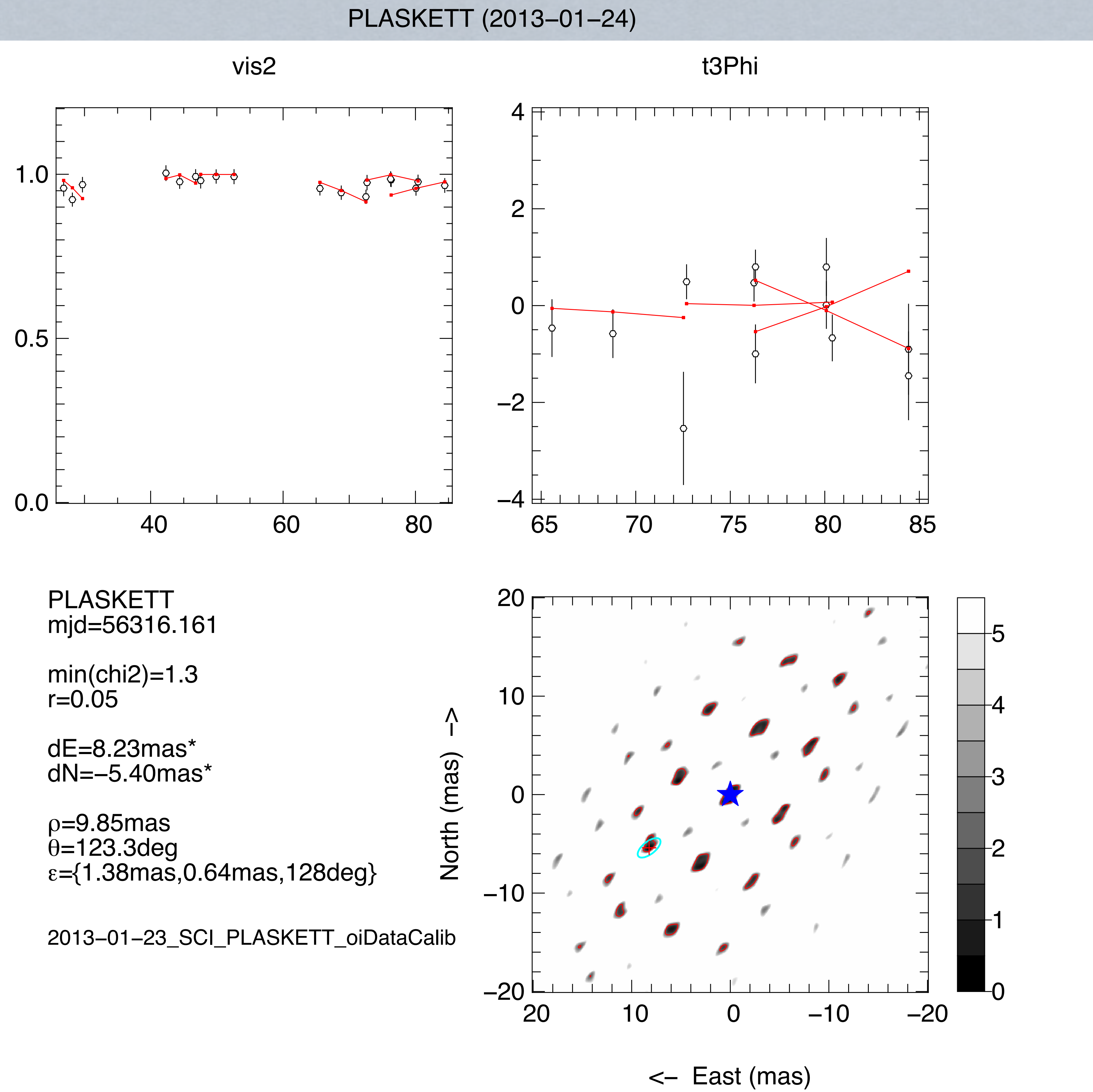
If you want to have <u>good chance</u> to detect r, you need a precision:

$$\frac{1-r}{1+r} > \sigma_V$$

If you have this precision, you <u>cannot fully discard</u> a binary of ratio r => “blind spots”.

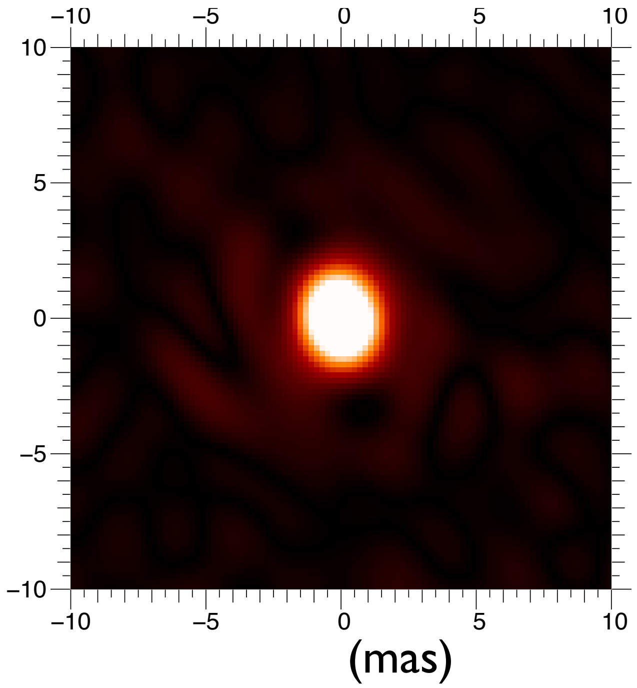
If you have plenty of baselines => no more “blind spots”, the achievable dynamics r is given by:

$$\frac{1-r}{1+r} \approx \sigma_V$$

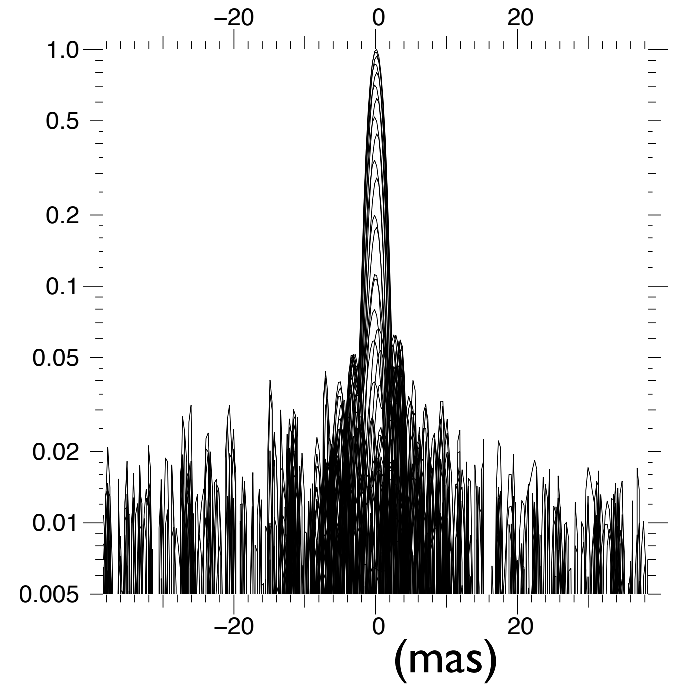


Achievable dynamic: (3) eta Carinae

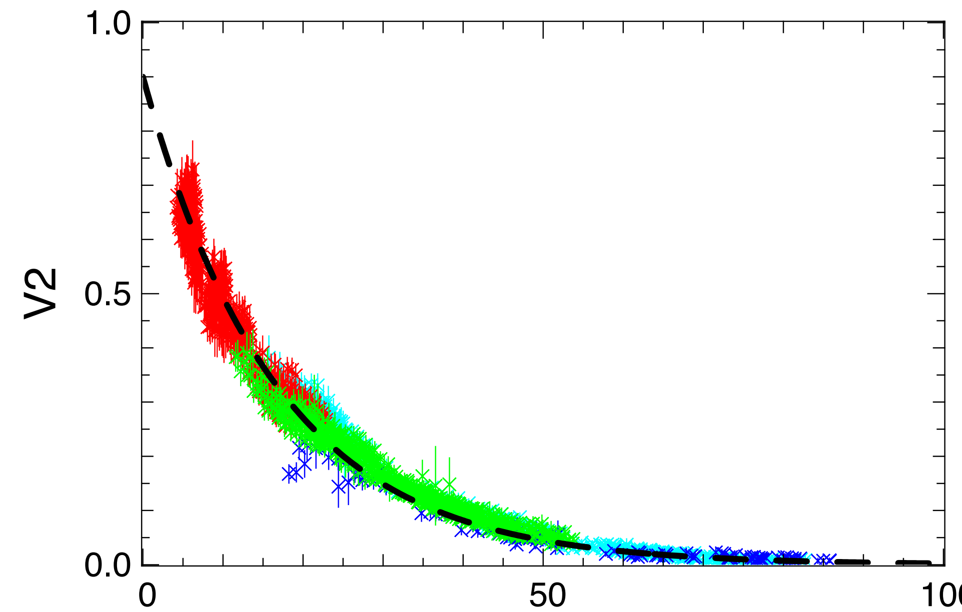
Image reconstruction

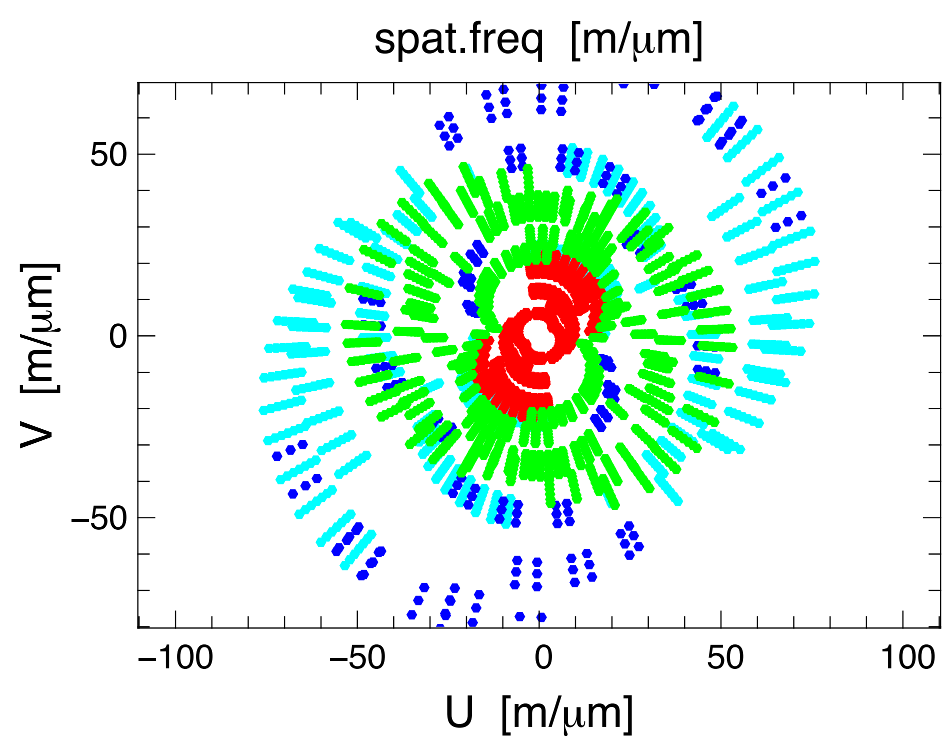


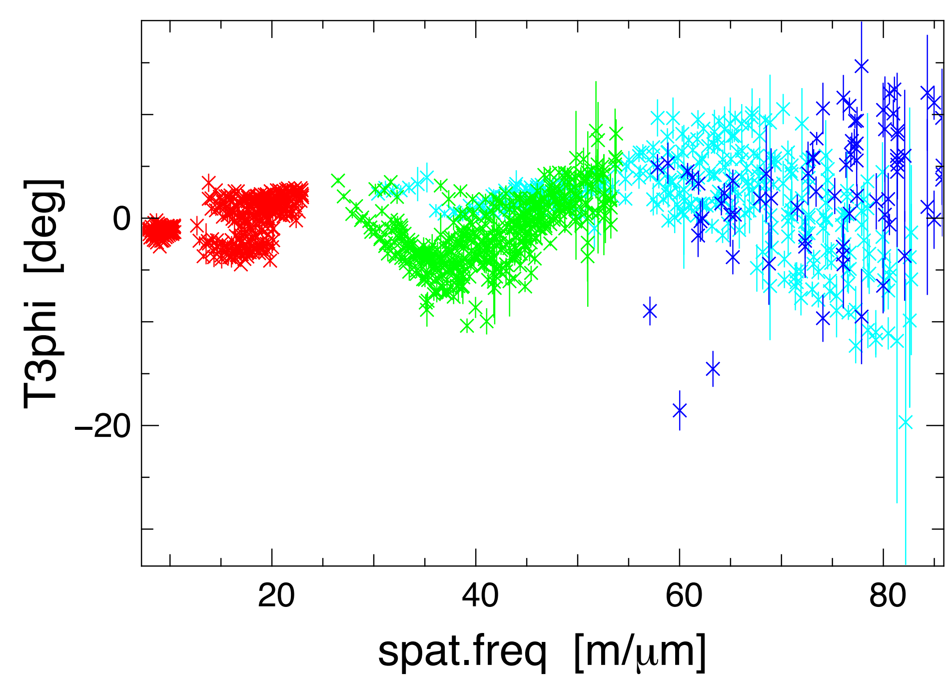
Cuts through the image



Observations





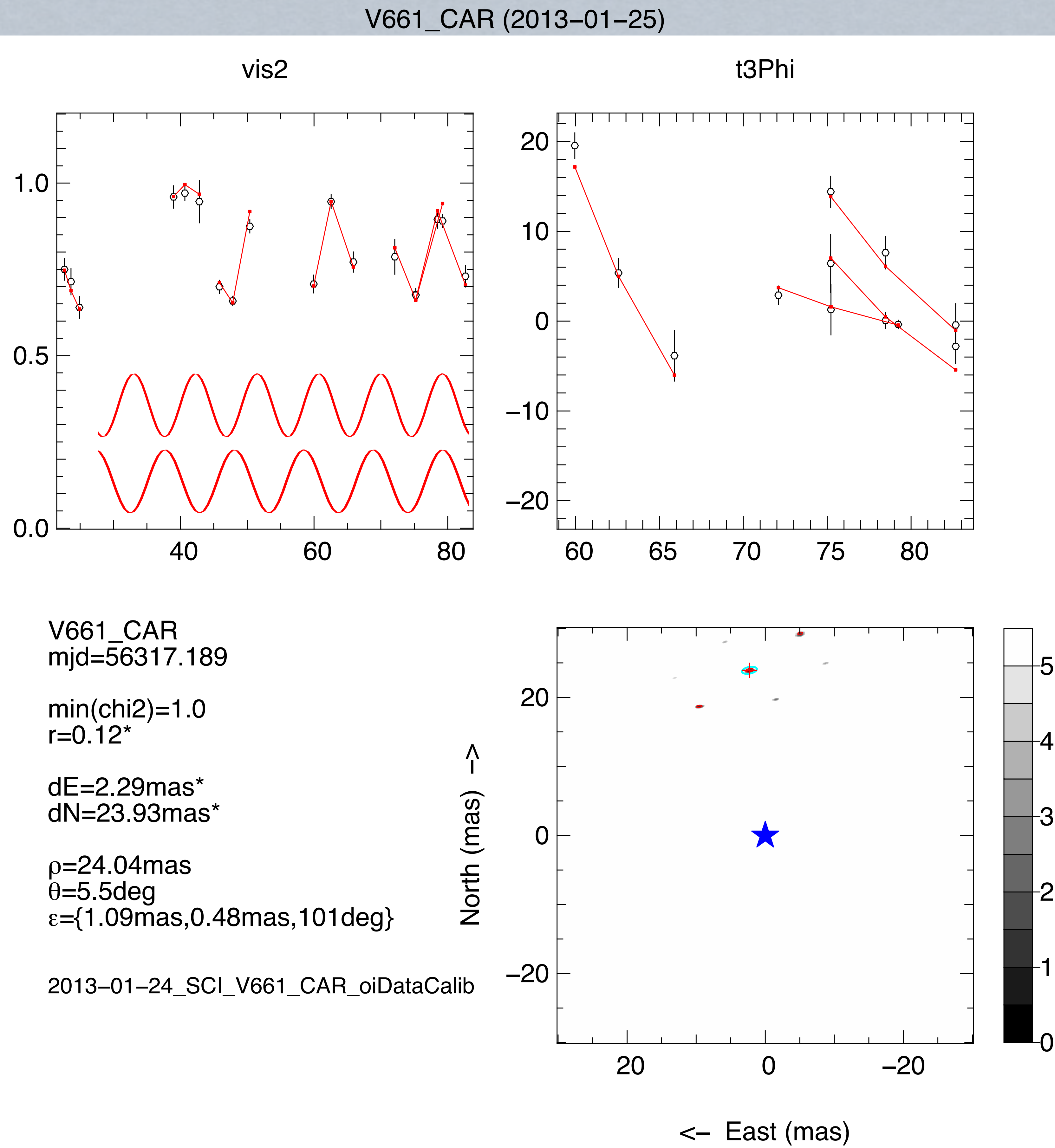


Unambiguous FOV: (1) multiple solutions

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda} \vec{\rho}}}{1 + r}$$

Did not find a clever way to quantity it :-(

Need long baseline for accurate astrometry. Need short baseline for "unicity" of the solution.



Smearing: (1) loss of V2 at high baseline

Monochromatic:

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

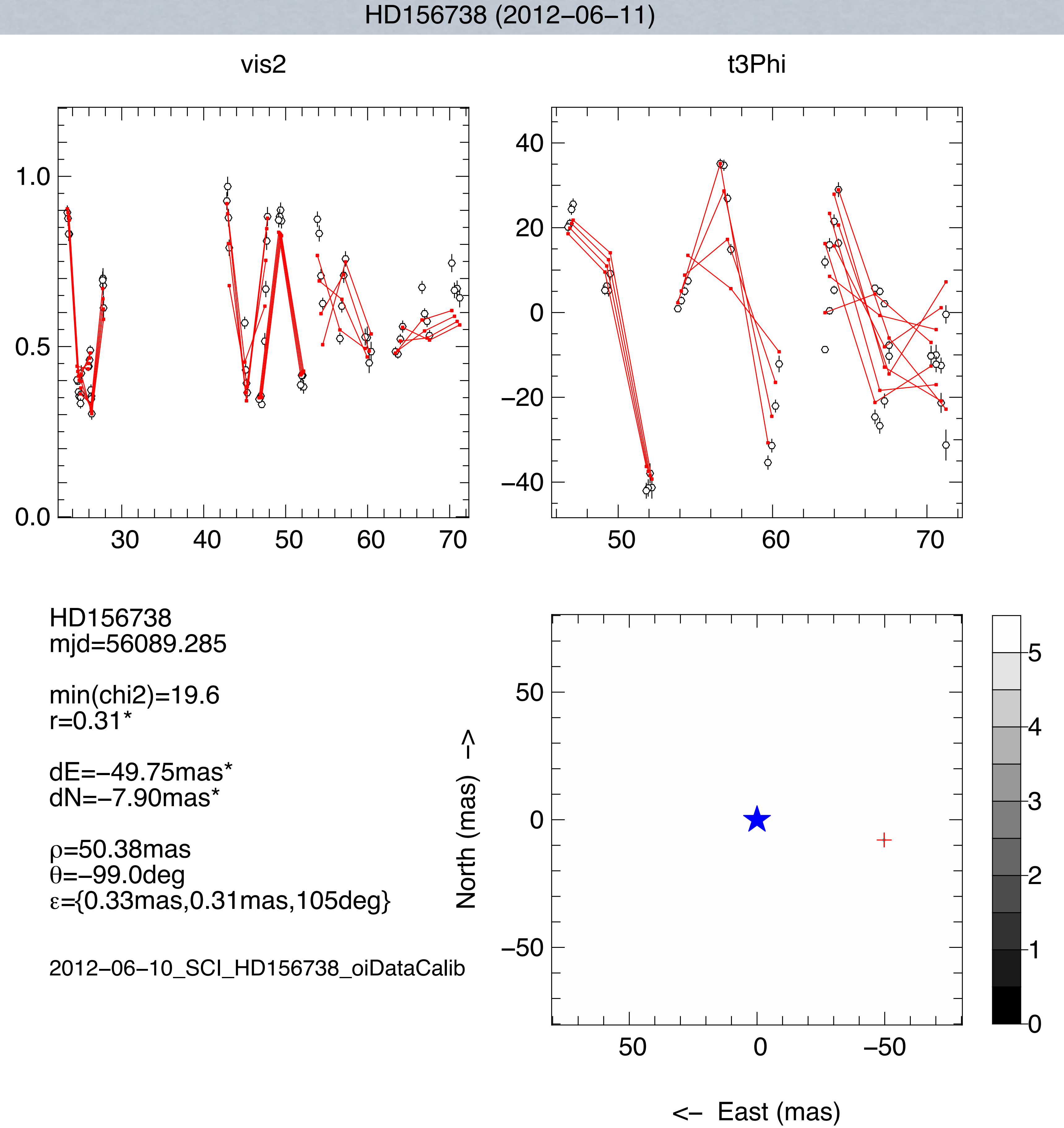
Large-band:

$$V = \int_{\lambda_0-\Delta\lambda}^{\lambda_0+\Delta\lambda} \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}\, \mathrm{d}\lambda$$

Approximate formula:

$$V \propto 1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda_0}\vec{\rho}}\, \mathrm{sinc}(\pi \frac{\vec{B}}{R.\lambda_0}\vec{\rho})$$

$$R = \frac{\lambda_0}{\Delta\lambda}$$



Smearing: (2) extreme case = flat V2

Monochromatic:

$$V = \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}$$

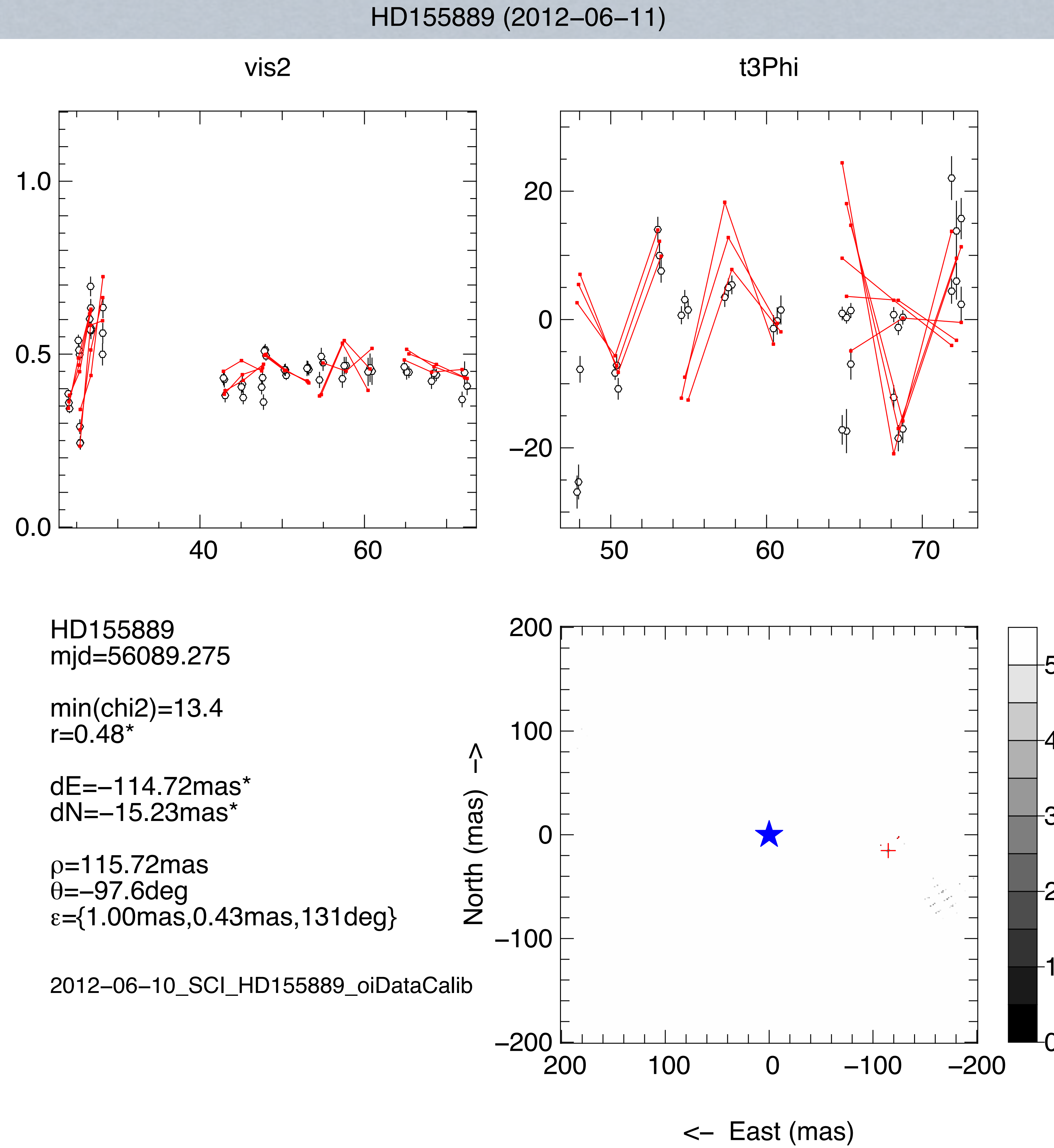
Large-band:

$$V = \int_{\lambda_0 - \Delta\lambda}^{\lambda_0 + \Delta\lambda} \frac{1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda}\vec{\rho}}}{1 + r}\, \mathrm{d}\lambda$$

Approximate formula:

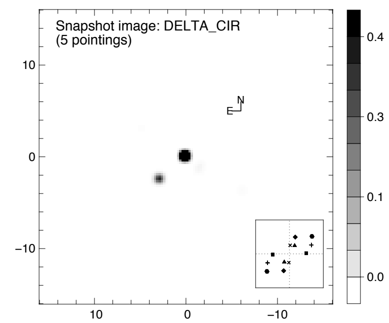
$$V \propto 1 + r\, e^{-2i\pi \frac{\vec{B}}{\lambda_0}\vec{\rho}}\, \mathrm{sinc}\left(\pi \frac{\vec{B}}{R.\lambda_0}\vec{\rho}\right)$$

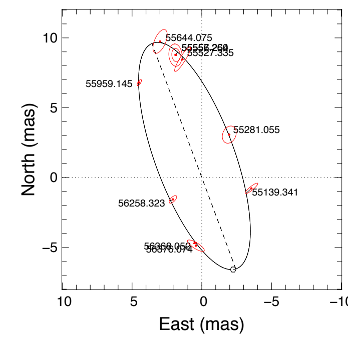
$$R = \frac{\lambda_0}{\Delta\lambda}$$

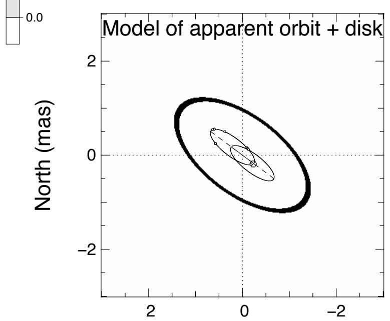


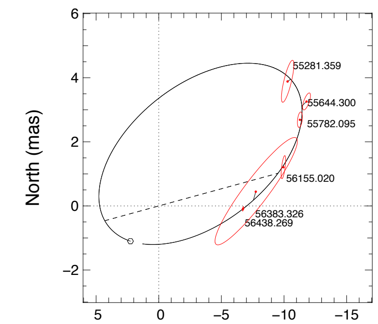
Some concluding words... what you should remember

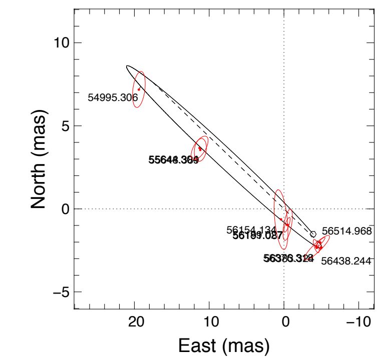
It does work:











Some programs could be nice “backup fillers”:

- Very simple signal, easy to check for self-consistency = robust to calibration = good for bad conditions
- Short pointing are useful (at least with 3+ telescopes)
- But easy programs generally need long baselines

But several aspects of observational interferometry should not be overlooked...

- **Use existing tools.**
- **Read papers to know how to do things**
- **Collaborate with people.**


4
Wish you all "nice fringes"...