The space distribution of nearby star-forming regions

(and a few other nice things radio-interferometry can do for you)

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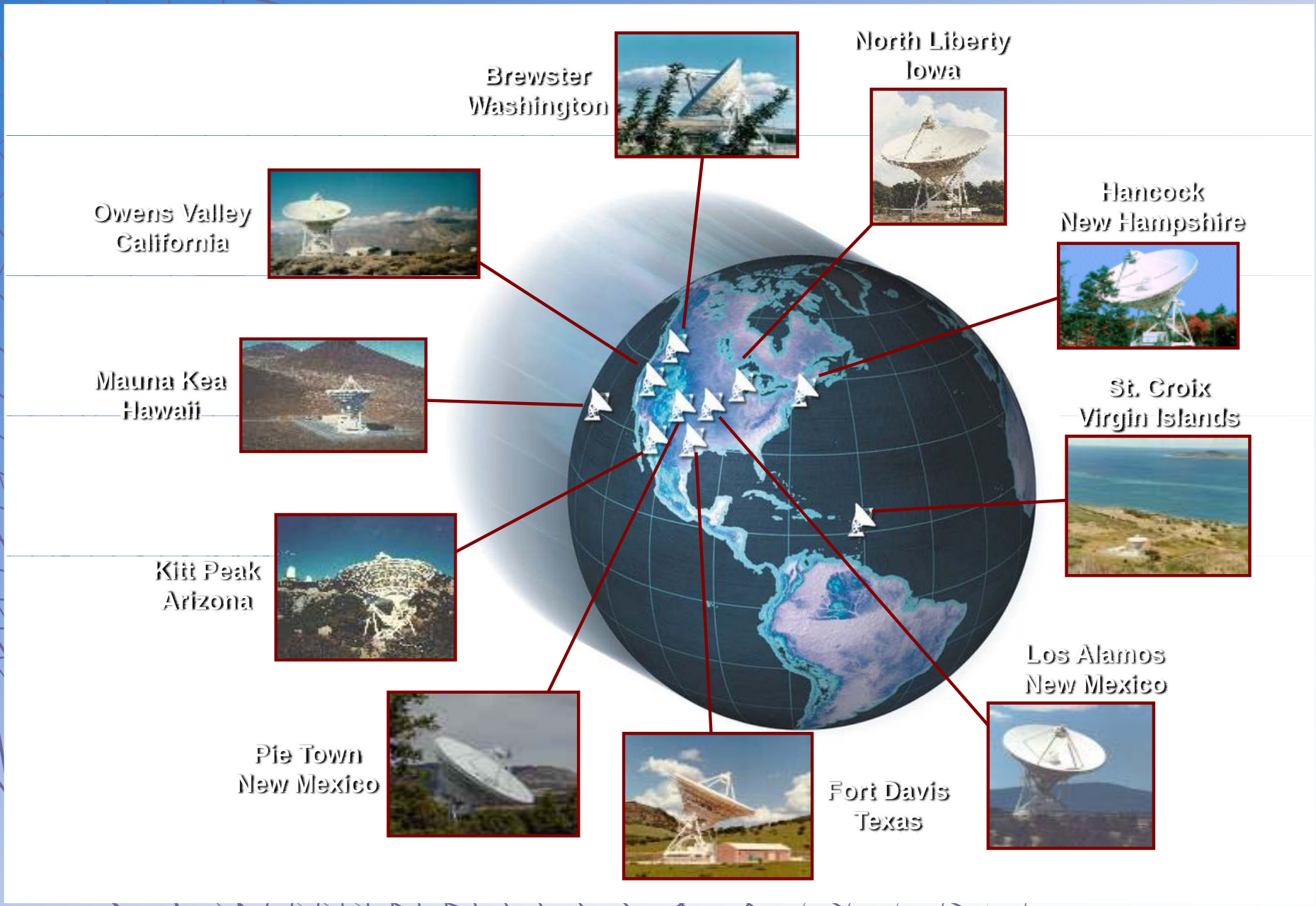
Rationale

- *The birth and pre-main sequence evolution of stars is significantly less well understood than the main sequence evolution.*
- *Accurate observational data are needed to constrain the models.*
- *Errors of 25% on the distance imply:*
  - *25% errors on sizes (e.g. of protoplanetary disks)*
  - *50% errors on luminosities*
  - *100% errors on masses from Kepler's law*
- *Distance errors dominate the error budget.*

Most of the available observational constraints come from just a few nearby star-forming regions (Taurus, Ophiuchus, etc.)

The Very Long Baseline Array (VLBA)



All observations presented here are phased-referenced and at 3.6 cm

Absolute astrometry

VLBA (at 3.6 cm):

- *Angular resolution: 1 milli-arcsecond (mas)*
- *Absolute astrometry precision: 0.05 mas*
- *Phase calibration (and, therefore, astrometry) is relative to quasars*

⟹ **Perfect instrument for astrometry**

Possible origins of motion for astronomical sources:

- *Trigonometric parallax ($\pi = 1/d$)*
- *Proper motion*
  - *of large scale origin (Galactic rotation, cluster dynamics, etc..)*
  - *of small-scale origin (e.g. orbital motions in multiple systems)*

What the VLBA can do for you…

d(pc)	1	2	5	10	20	50	100	200	500	1,000	2,000	5,000	10,000
π(mas)	1000	500	200	100	50	20	10	5	2	1	0.5	0.2	0.1
μ (mas yr^{-1})	2000	1000	400	200	100	40	20	10	4	2	1	0.4	0.2

(Proper motions calculated for v = 10 km/s)

Recall: the absolute astrometry precision of the VLBA is better 0.05 mas

What's the catch?…

With the VLBA, one pretends to have a 8000 km diameter telescope…

But all one has are 10 antennas, each 25 meters in diameter diameter…

Filling factor of that 8000 km dish: $2.5\ 10^{-10}$

The sensitivity is NOT that of an 8000 km telescope…

→ *We first need to indentify sufficiently bright sources*

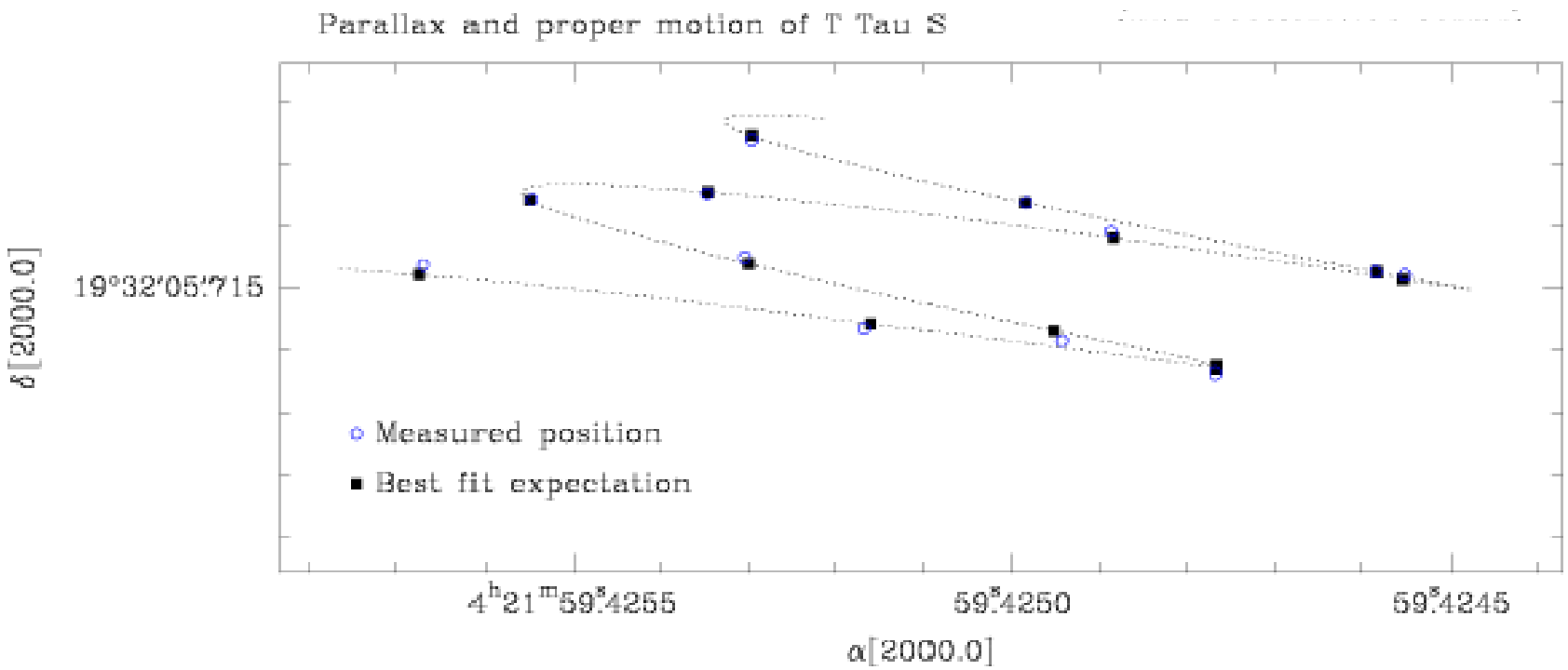
Fortunately, they exist in star-forming regions

Goal of the project:

Measure the distance to several young stars in nearby star-forming regions to obtain an accurate estimate of the distances to those star-forming sites.

Up until now, two regions have been studied: Taurus and Ophiuchus

1. T Tauri

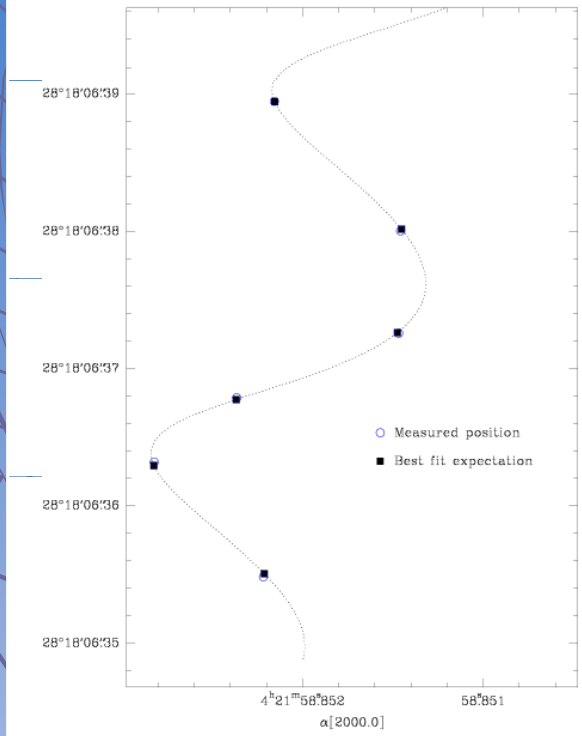


Loinard et al. 2007

d = 147.6 +/- 0.6 pc -- 0.5% precision…

Other sources in Taurus

Hubble 4



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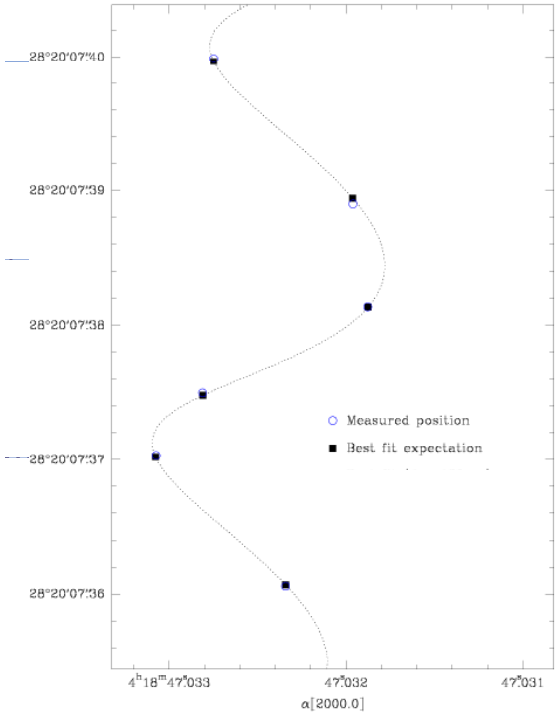
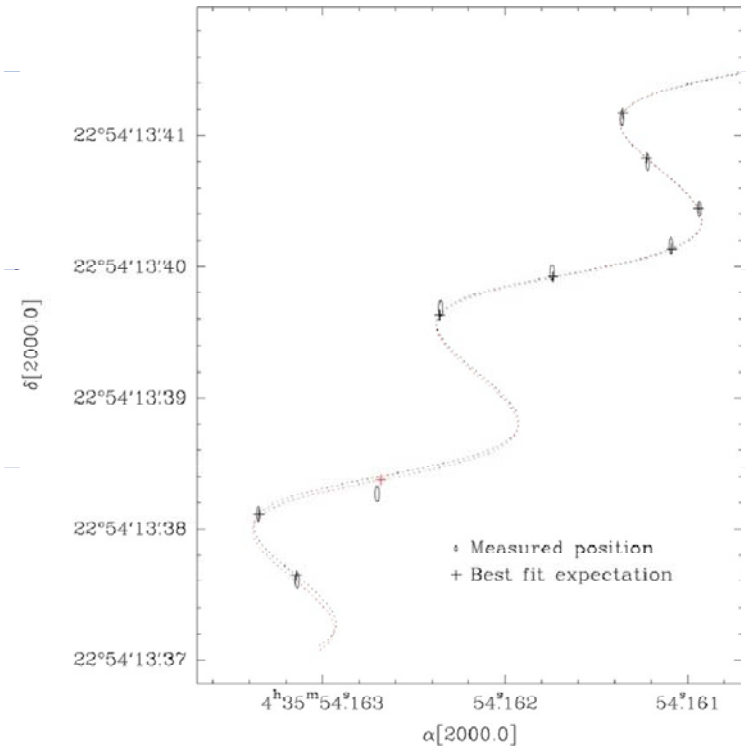


HP Tau



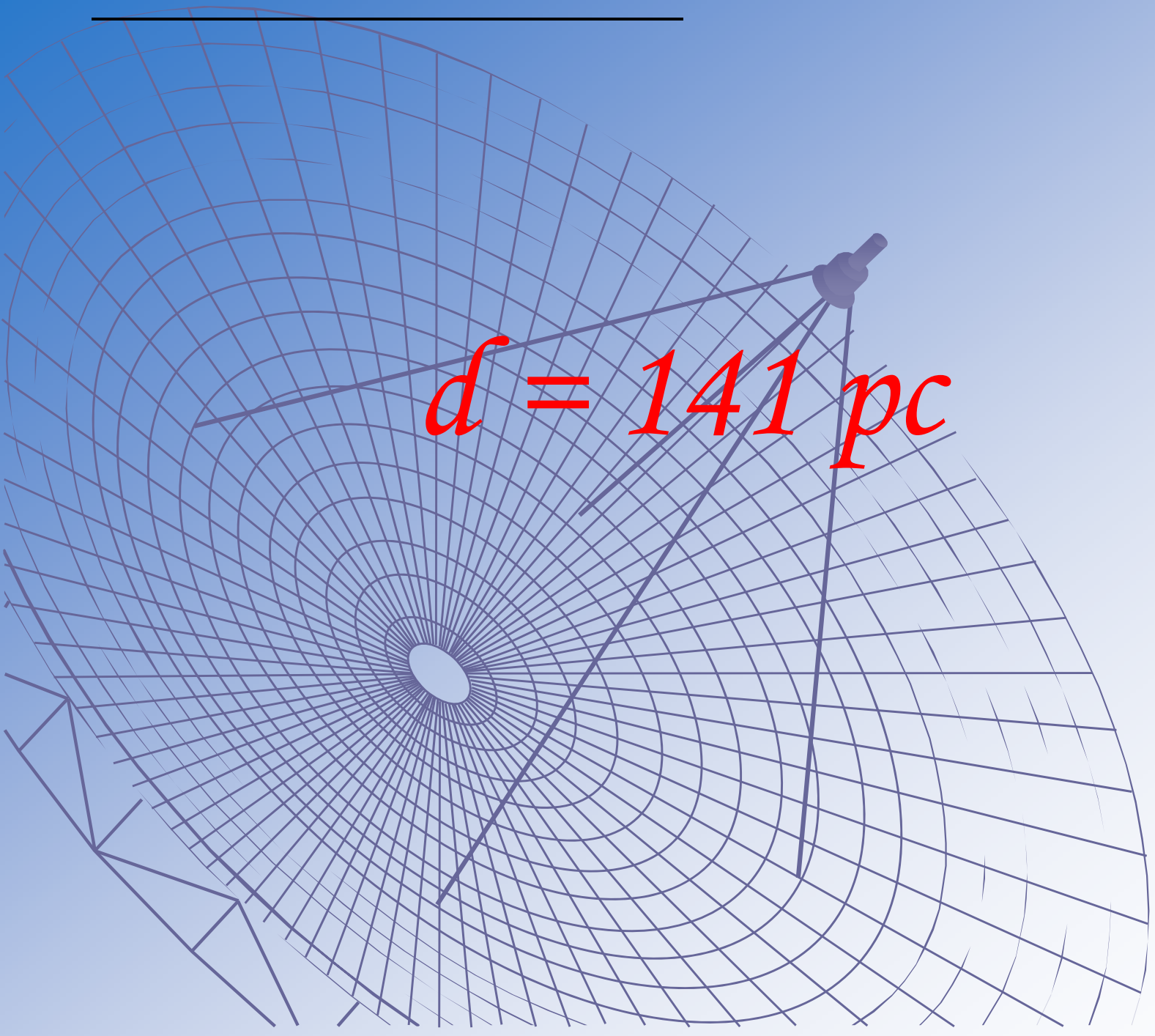
d = 128.5 +/- 0.6 pc

d = 130.8+/- 0.5 pc

d = 161.2 +/- 0.9 pc

Torres et al. 2007, 2008

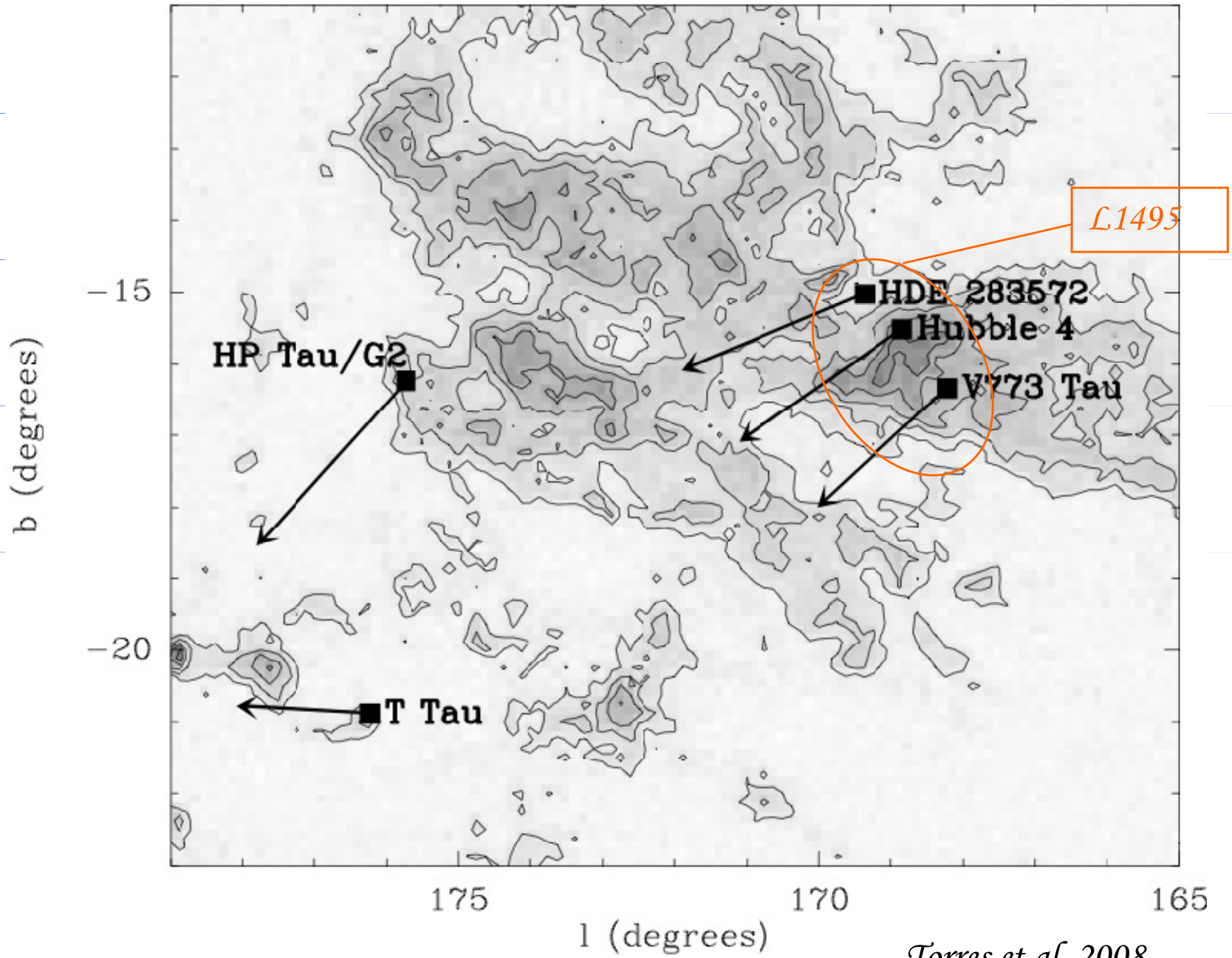
Taurus mean distance…



$$d = 141\ pc$$

Taurus (more intersting…)

3D Structure



Torres et al. 2008

ρ-ophiuchus

- *Debate: is it at 120 pc (as claimed recently) or at 160 pc (as traditionally thought)??*

Knude & Hog 1999

in correcting for the background of the superposed reflection nebula. For $R = A_V/E_{B-V}$ the value 4.5 was preferred as a result of an polarization study. CrA is particularly interesting for the evolution of the YSOs since it has the largest fraction of Class 0 objects among the 5 nearest star forming regions, Chen et al (1997). As evident from Fig. 10 the data rather suggest a distance of 170 pc, so the 130 pc distance seems to be excluded. Compared to the Chamaeleon and Lupus regions CrA is different by the absence of a well defined lower reddening level beyond the clouds. This change means that the $\log_{10}$ of a YSO bolometric luminosity should be increased with ~0.25 (or with – 0.63 mag). This may be an important change since CrA defines the cool end point of the YSO evolution.

4.4. The ρ Ophiuchus star forming region

As the last example we estimate the distance to the onset of larger reddenings for the ρ Oph direction, the result is shown in Fig. 11. The E_{B-V} – distance distribution shows the maximum excess to be homogeneously increasing out to 120 pc where the abrupt rise as expected from a homogeneous molecular cloud takes place. Beyond 150 pc there is a lower envelope at 0.20 mag, most pronounced for LC V but also for LC III. The presence of a constant lower reddening envelope indicates that 150 pc could be an upper limit for the cloud distance. Considering the frayed appearance of the ρ Ophiuchus region the few points below the lower envelope need not be a problem. Several stars in front of the 120 pc have E_{B-V} exceeding 0.1 mag.

The distance to the star forming regions in Ophiuchus has been assumed to ~160 pc, Chen et al (1995) as based on multi color photometry of heavily absorbed stars in the ρ Oph core, Chini (1981). A_V ranges from 4.3 to 11.7 for the three stars actually used. Chini proposed that the reddening is abnormal for $E_{B-V} > 1.2$, and the larger value R = 4.2 has been used in the distance determination instead of the canonical 3.1. According to Fig. 11 we do not measure such a large reddening value, the maximum is about 0.5 mag.

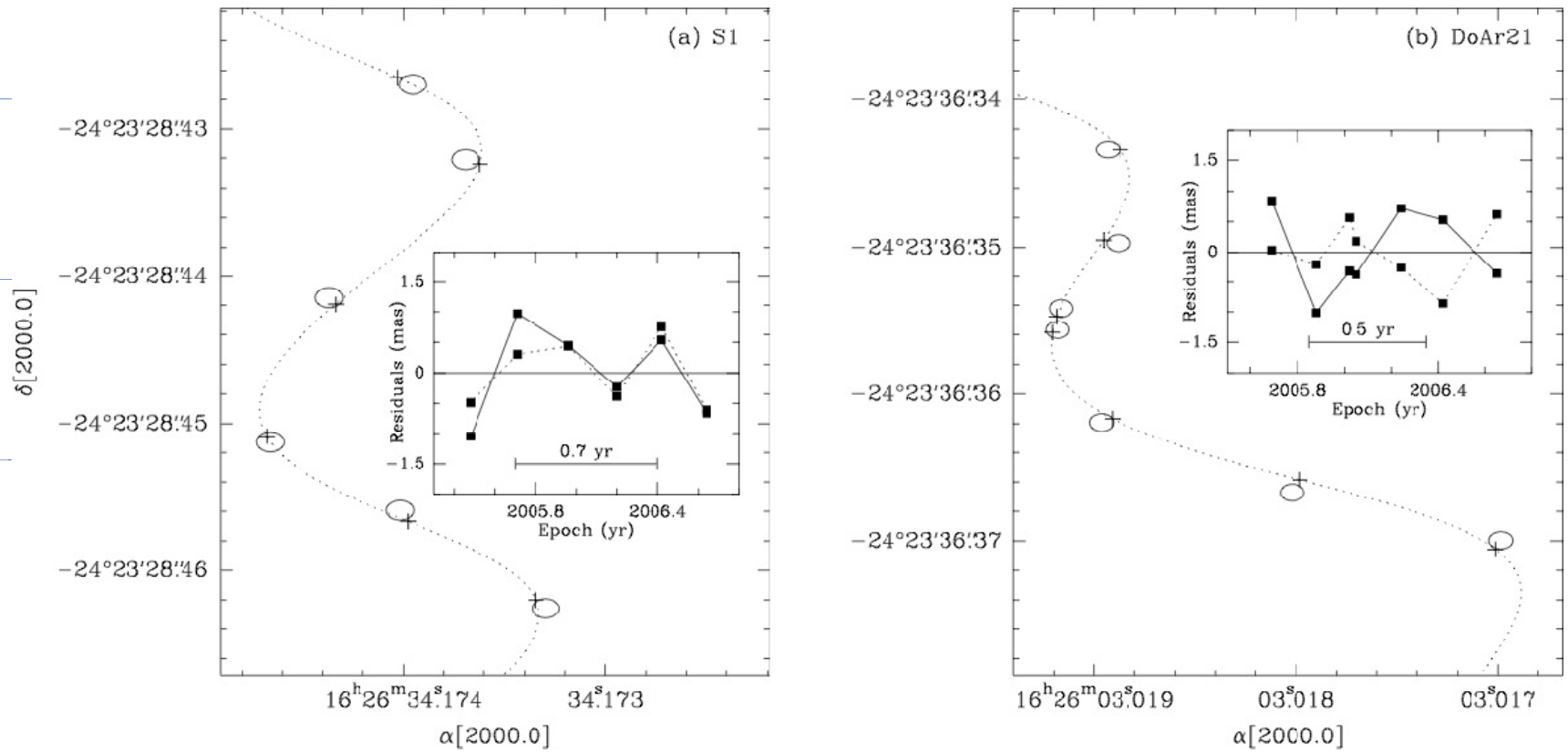
It might be questioned whether the upturn noticed in Fig. 11 at about 120 pc and the lower reddening limit of 0.2 noted from about 150 pc, at least for most of the LC V stars, relate to the same star forming features as the ρ Oph core proposed to be at 160 pc. Is the 120 pc rather connected to the off core region in Ophiuchus? Nearly all YSOs in the off core regions have visual absorptions as in the range indicated by Fig. 11, according to Table 3 of Chen et al (1997). But is it realistic that the star formation takes places over a distance range of ~40 pc? B stars from the Upper Scorpius subgroup are included in the region displayed in Fig. 11. These rather young stars are at the same distance as the subgroup, 145±2 pc (de Bruijne et al 1997), about the mean of the core and off core distance estimates.

5. Effects of the changed distances to Lupus, Corona Australis and parts of ρ Ophiuchus

As discussed above we suggest new distances for the Lupus and Corona Australis star forming regions. Lupus is moved from 140 to 100 pc and Corona Australis from 130 to 170 pc, the off core YSOs of the ρ Ophiuchus region may be as close as 120 pc. The Chamaeleon is left at 150 pc as indicated by previous photometric data. One might consider these alterations as marginal

ρ-ophiuchus

- *Debate: is it at 120 pc (as claimed recently) or at 160 pc (as traditionally thought)??*
- *So far, two stars observed (S1 and DoAr21) - more to come…*

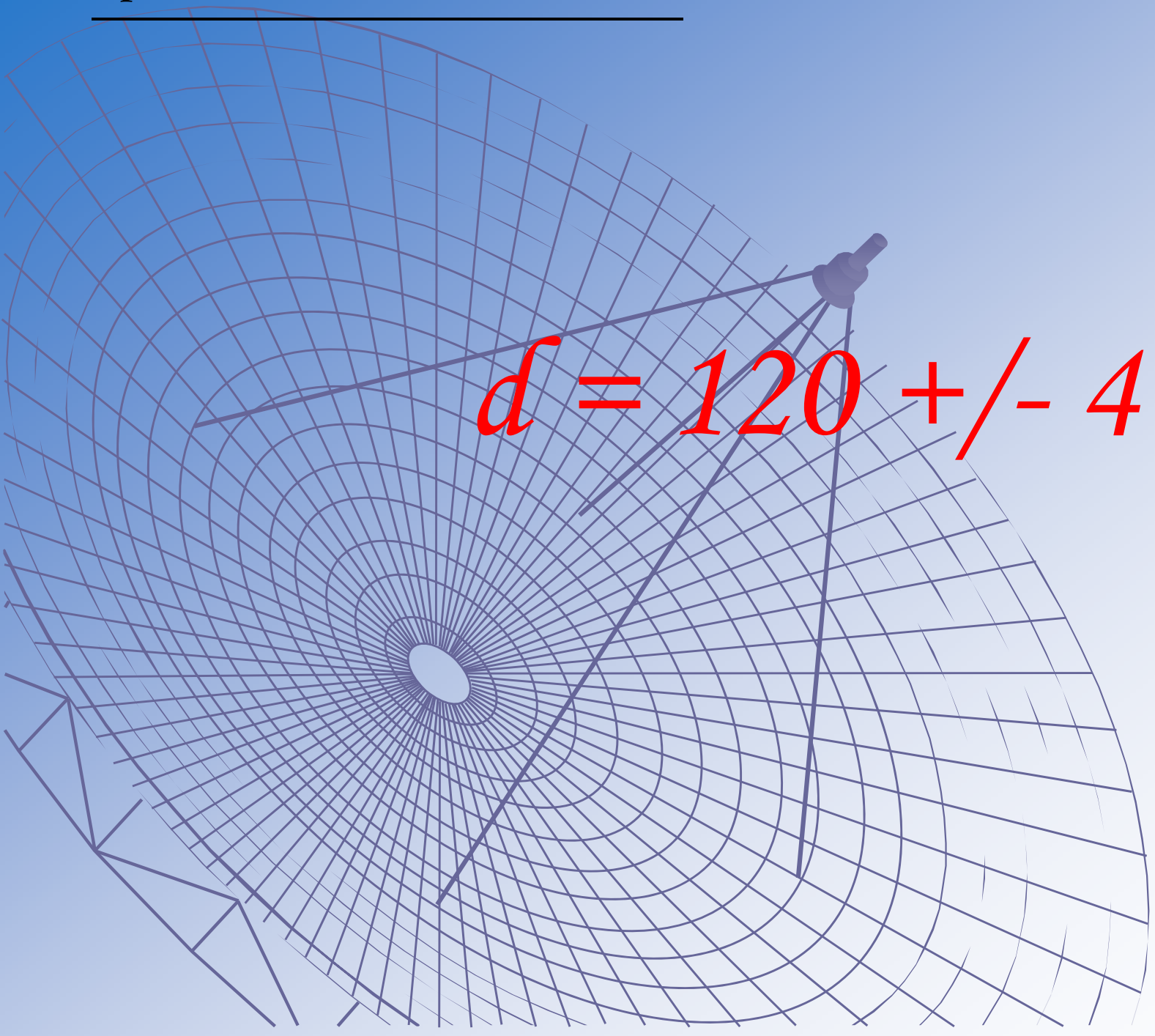


$d = 121.89\ ^{+5.83}_{-5.32}$ pc

$d = 116.90\ ^{+7.20}_{-6.41}$ pc

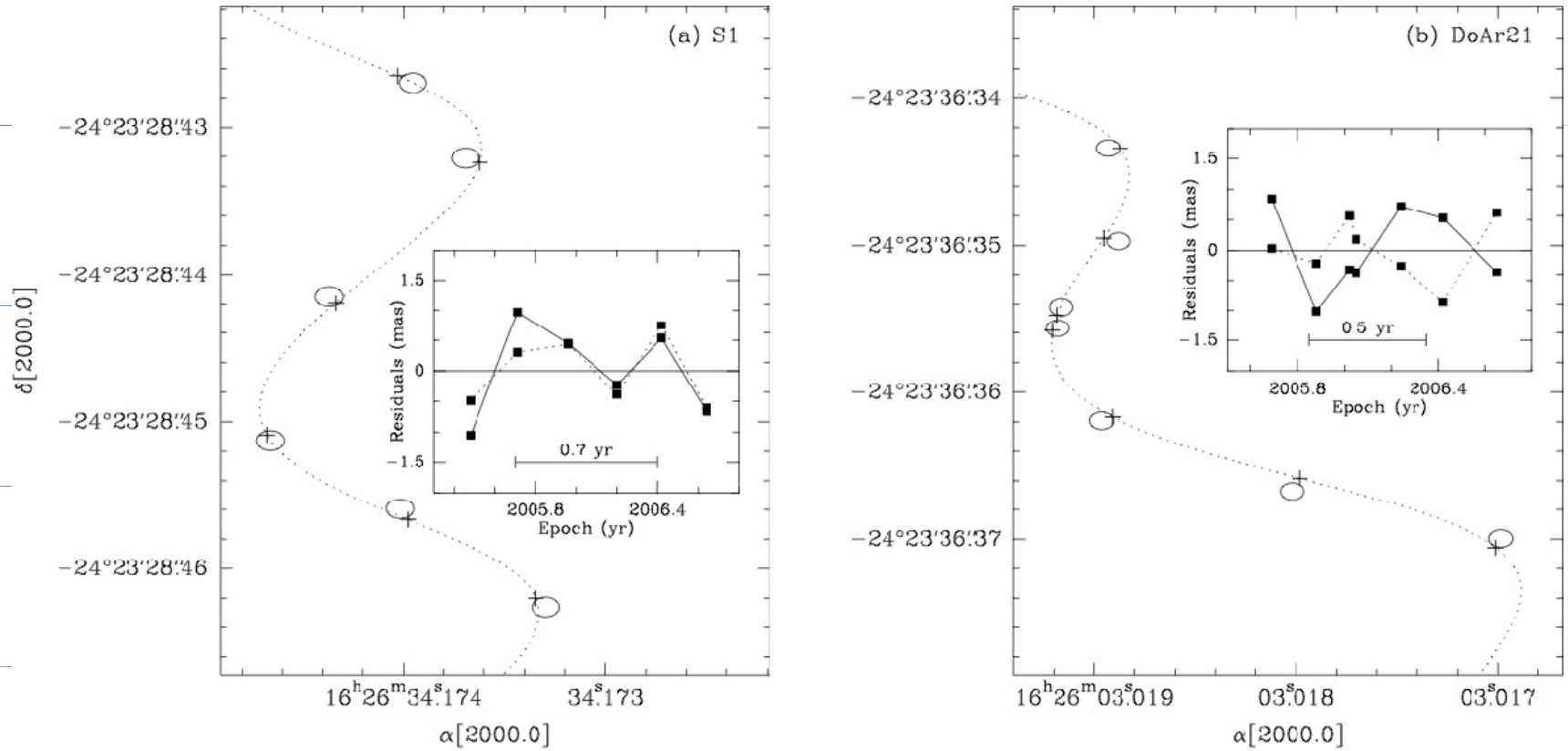
Loinard et al. 2008

Ophiuchus mean distance…



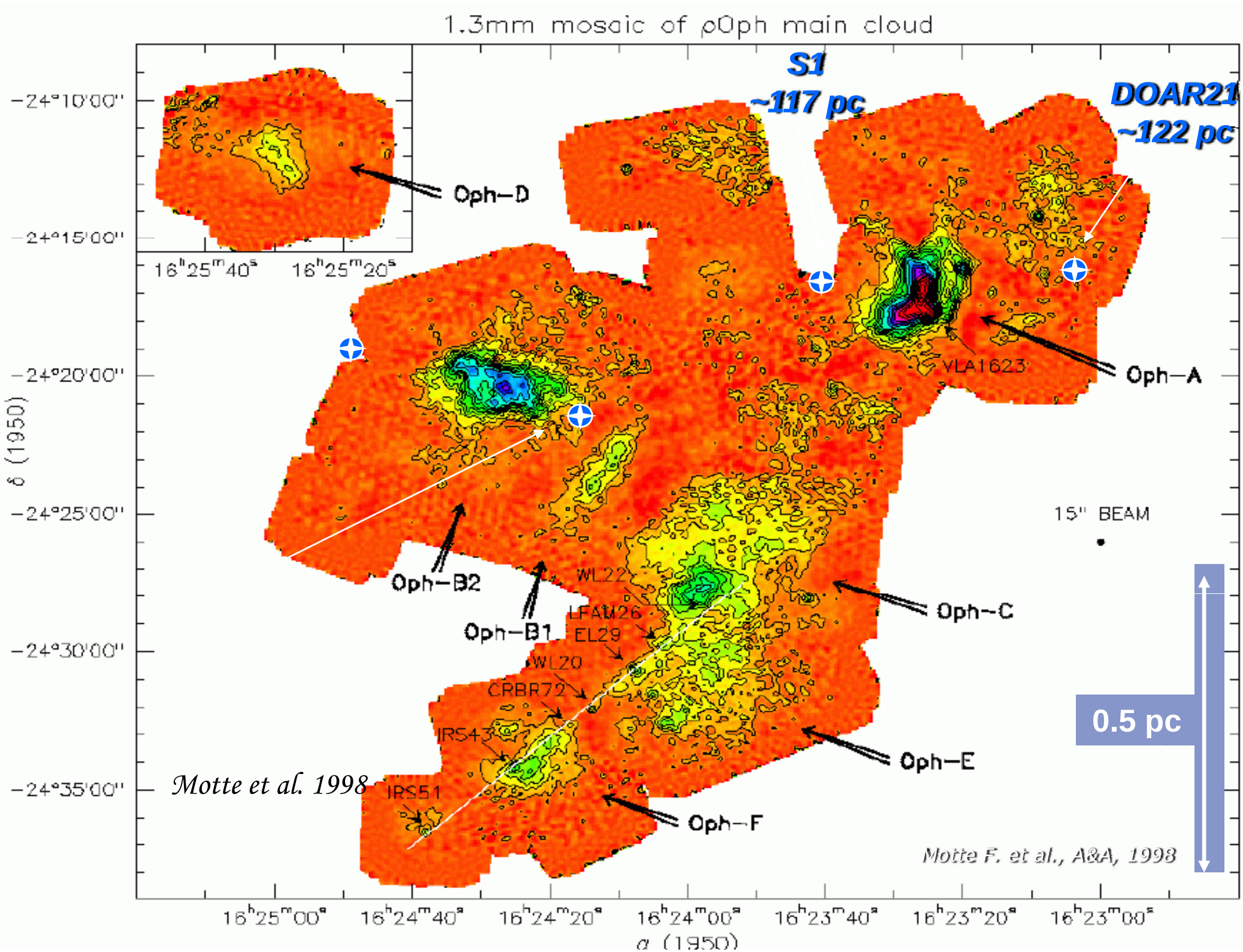
$d = 120 +/- 4\ pc$

Ophiuchus: residuals



Dominated by the unmodelled orbital motions

Loinard et al. 2008


1.3mm mosaic of ρOph main cloud
S1
~117 pc
DOAR21
~122 pc
Oph−D
Oph−A
VLA1623
Oph−B2
Oph−B1
Oph−C
Oph−E
Oph−F
WL22
LFAM26
EL29
WL20
CRBR72
IRS43
IRS51
15" BEAM
0.5 pc
Motte et al. 1998
Motte F. et al., A&A, 1998
−24°10'00"
−24°15'00"
−24°20'00"
−24°25'00"
−24°30'00"
−24°35'00"
δ (1950)
16h25m40s
16h25m20s
16h25m00s
16h24m40s
16h24m20s
16h24m00s
16h23m40s
16h23m20s
16h23m00s
α (1950)

Astronomy & Astrophysics manuscript no. Menten˙etal
February 1, 2008

The distance to the Orion Nebula

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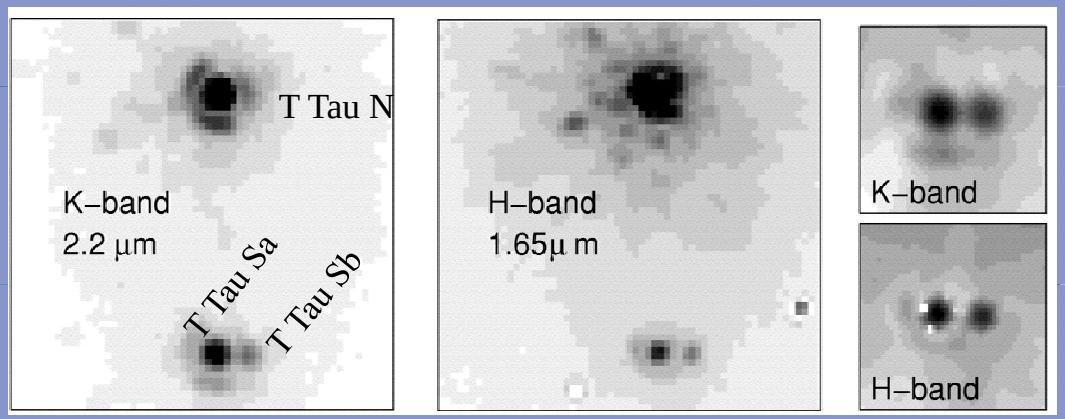
Received; accepted

ABSTRACT

We have used the Very Long Baseline Array to measure the trigonometric parallax of several member stars of the Orion Nebula Cluster showing non-thermal radio emission. We have determined the distance to the cluster to be 414 ± 7 pc. Our distance determination allows for an improved calibration of luminosities and ages of young stars. We have also measured the proper motions of four cluster stars which, when accurate radial velocities are measured, will put strong constraints on the origin of the cluster.

Key words. Stars: pre-main sequence, Radio continuum: stars

Back to T Tauri : a triple system

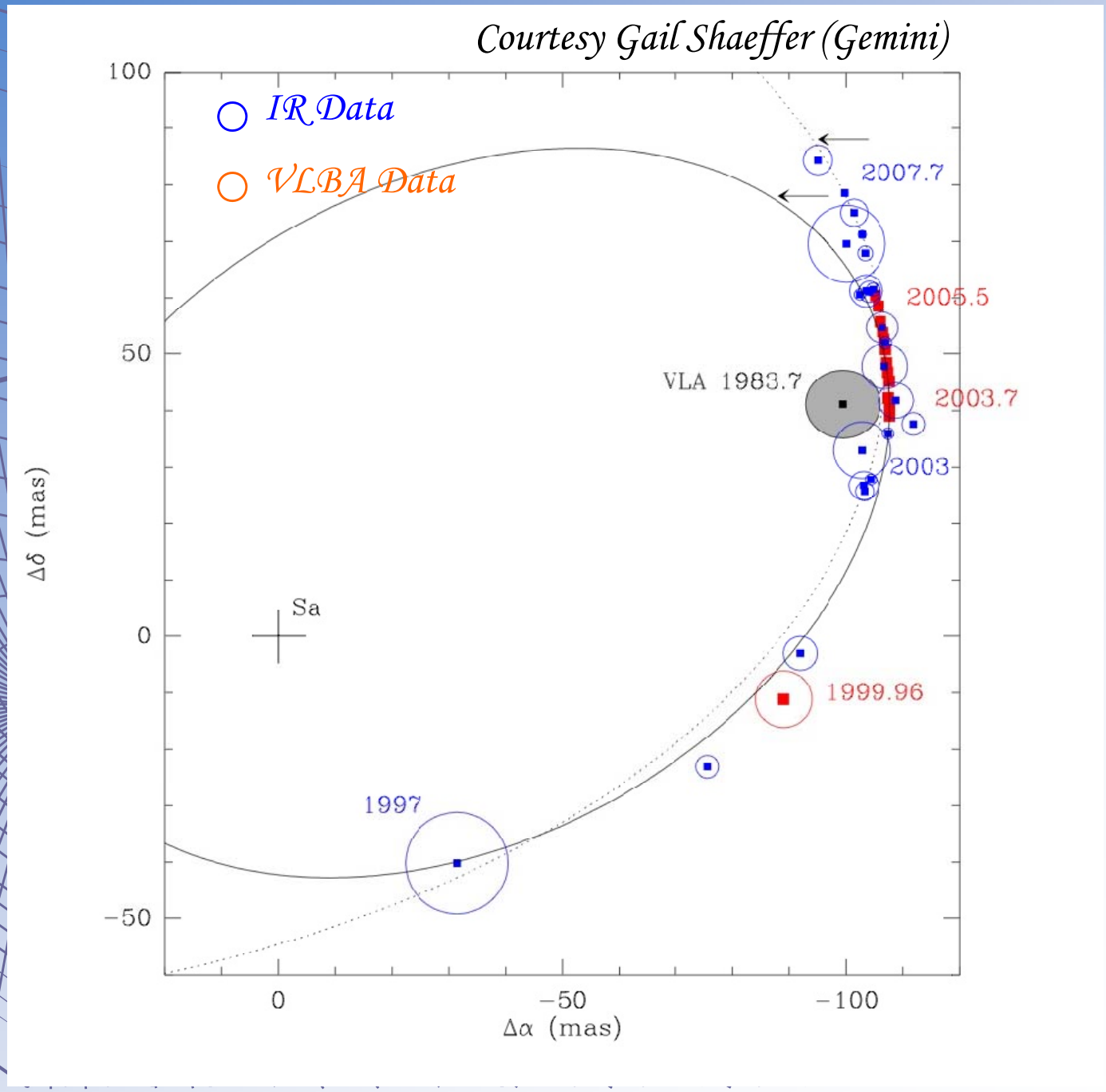


Duchene et al. 2002

The bright compact radio source detected at the VLBA is T Tau Sb.

What about orbital motions?

Orbital motions in the Sa/Sb system



Did anything happened to this orbit?

THE ASTROPHYSICAL JOURNAL, 587:L47–L50, 2003 April 10

EJECTION OF A LOW-MASS STAR IN A YOUNG STELLAR SYSTEM IN TAURUS

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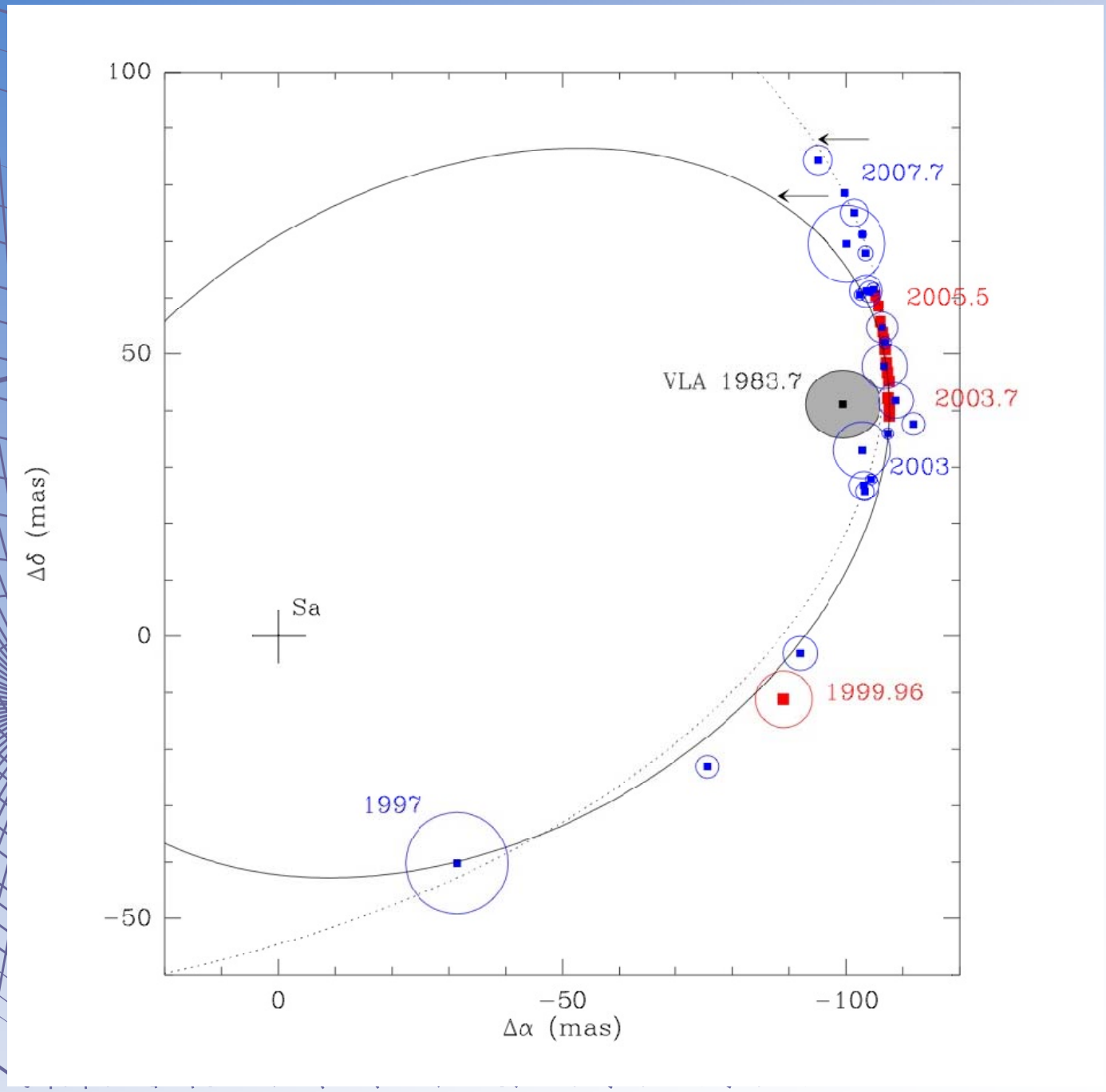
Received 2003 January 5; accepted 2003 March 6; published 2003 March 14

ABSTRACT

We present the analysis of high angular resolution Very Large Array radio observations, made at 11 epochs over the last 20 years, of the multiple system T Tauri. One of the sources (Sb) in the system has moved at moderate speed (5–10 km s^{-1}) on an apparently elliptical orbit during the first 15 yr of observations, but after a close (<2 AU) encounter with the source Sa, it appears to have accelerated westward to about 20 km s^{-1} in the last few years. Such a dramatic orbital change most probably indicates that Sb has just suffered an ejection—which would be the first such event ever detected. Whether Sb will ultimately stay on a highly elliptical bound orbit or whether it will leave the system altogether will be known with about 5 more years of observations.

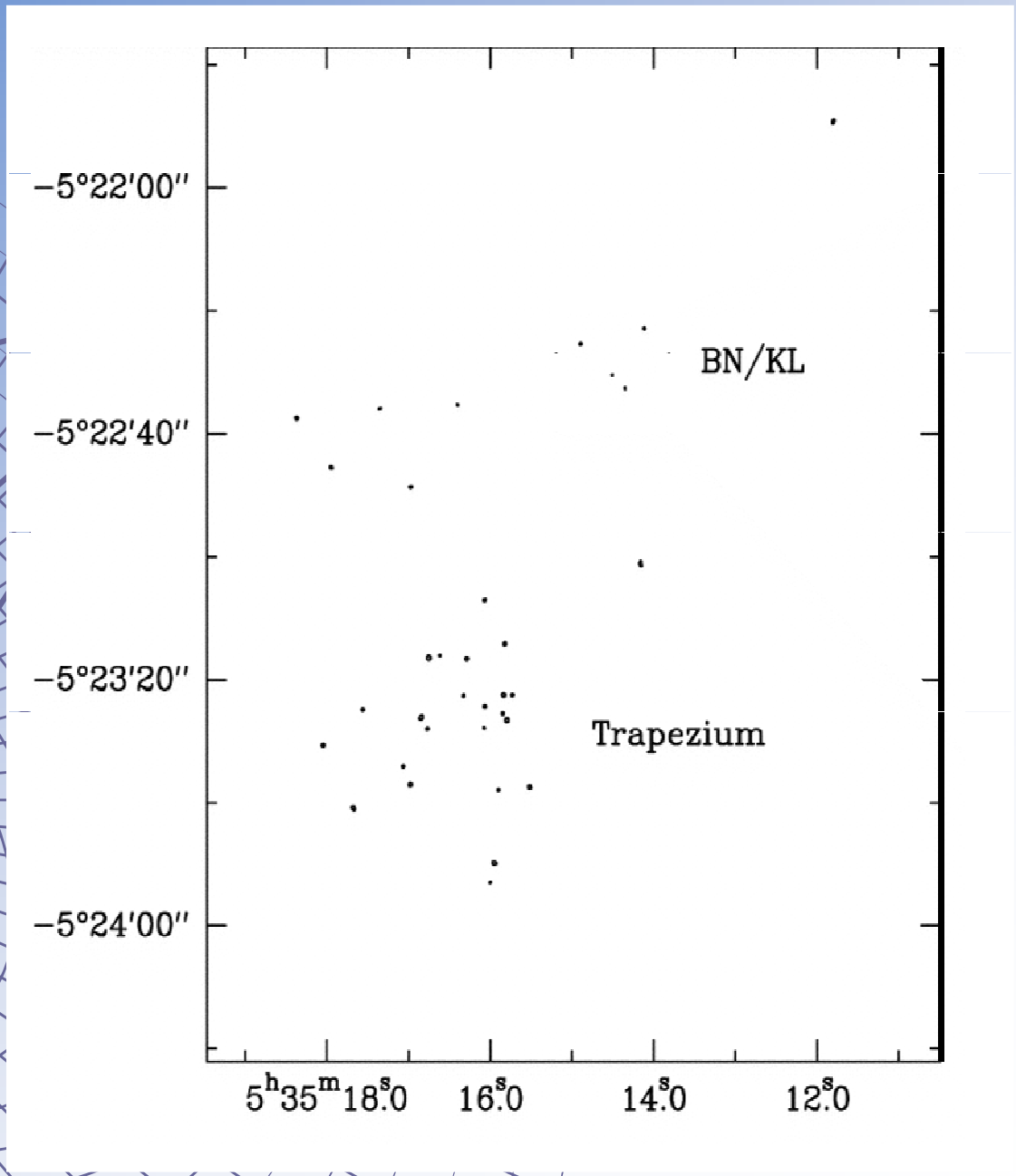
Subject headings: astrometry — binaries: general — stars: formation — stars: individual (T Tauri) — stars: pre–main-sequence

Orbital motions in the Sa/Sb system



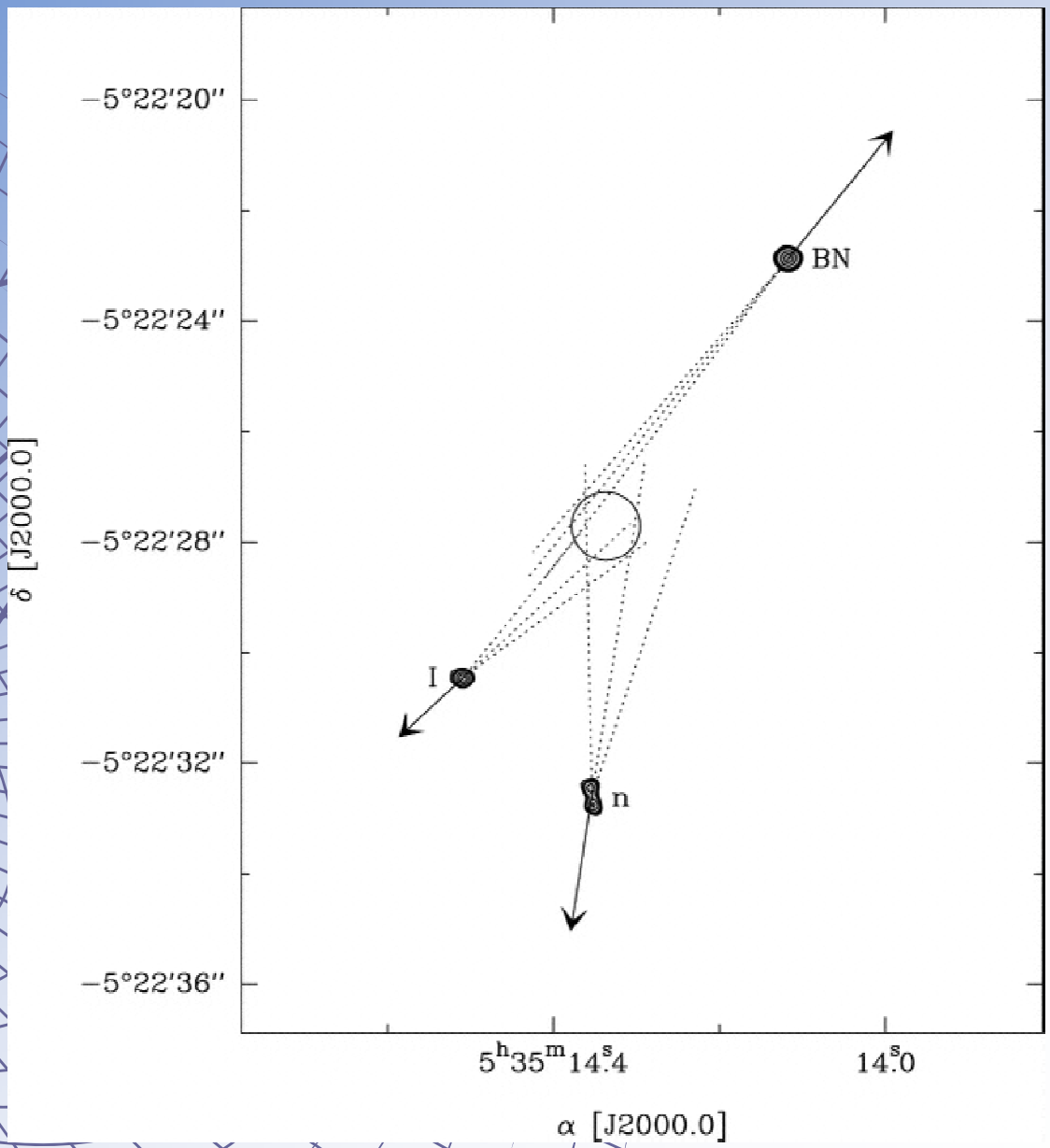
Orion at the VLA…

See Luis Rodriguez' talk



Gomez et al. 2005, 2007

Motion of the sources in the BN/KL region…



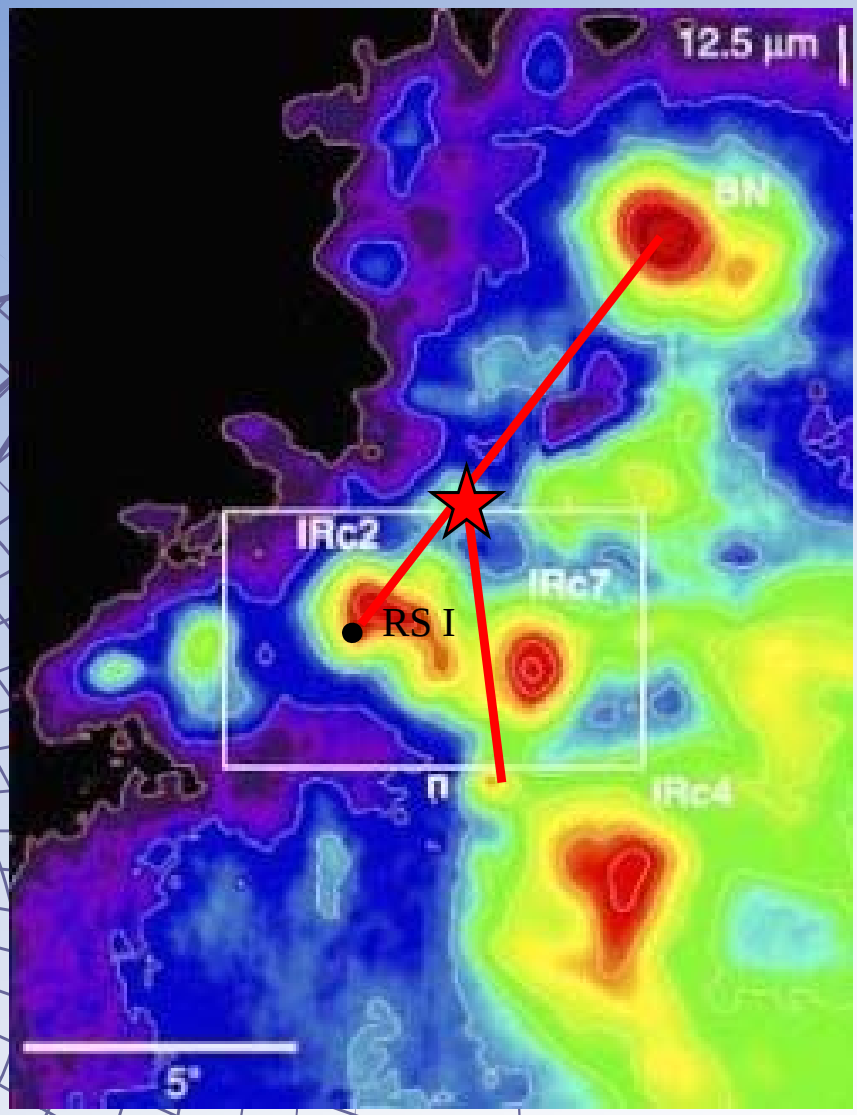
Gomez et al. 2005, 2007

Going back in time

All three sources were (at least in projection) very near each other 500 yrs ago…

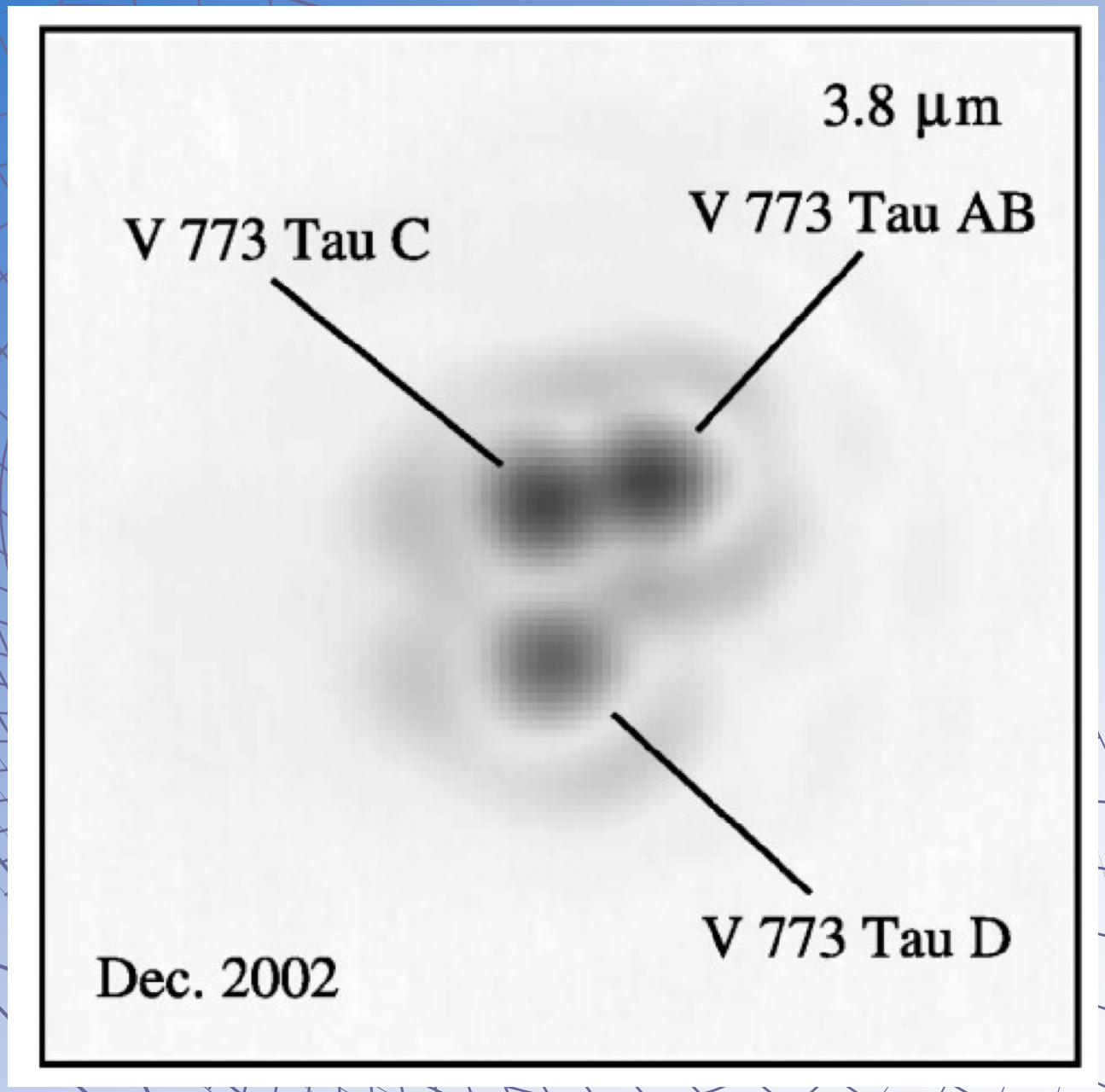
But 500 yrs is just about the age of the KL outflow (John Bally, private communication)…

And the locus of the position where the sources were very near the "origin" of the flow…



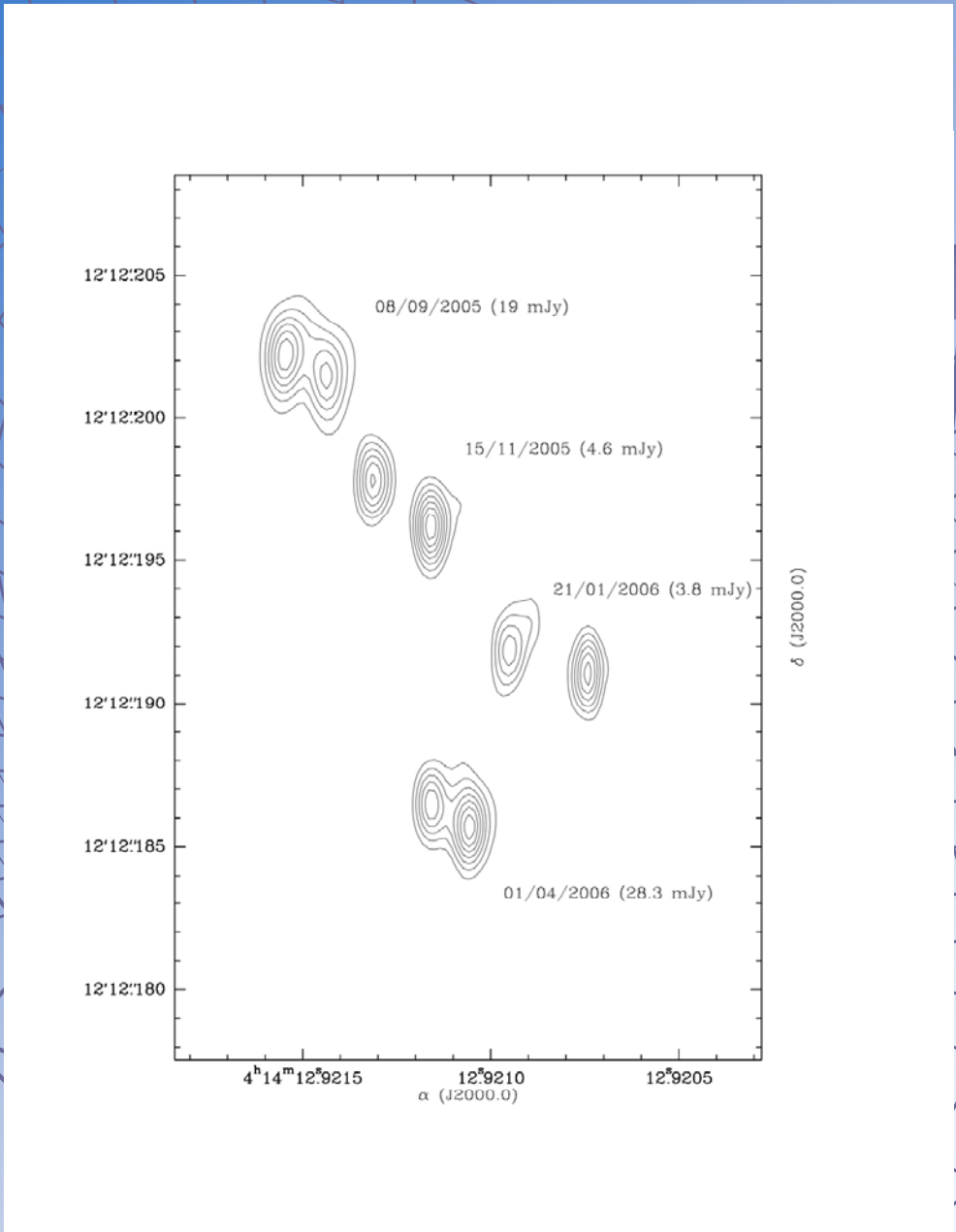
Gezari et al. (2000)

Orbital motions: V773 Tau



Duchene et al. 2003

Source V773Tau (a spectroscopic binary in a quadruple system)



First four VLBA observations

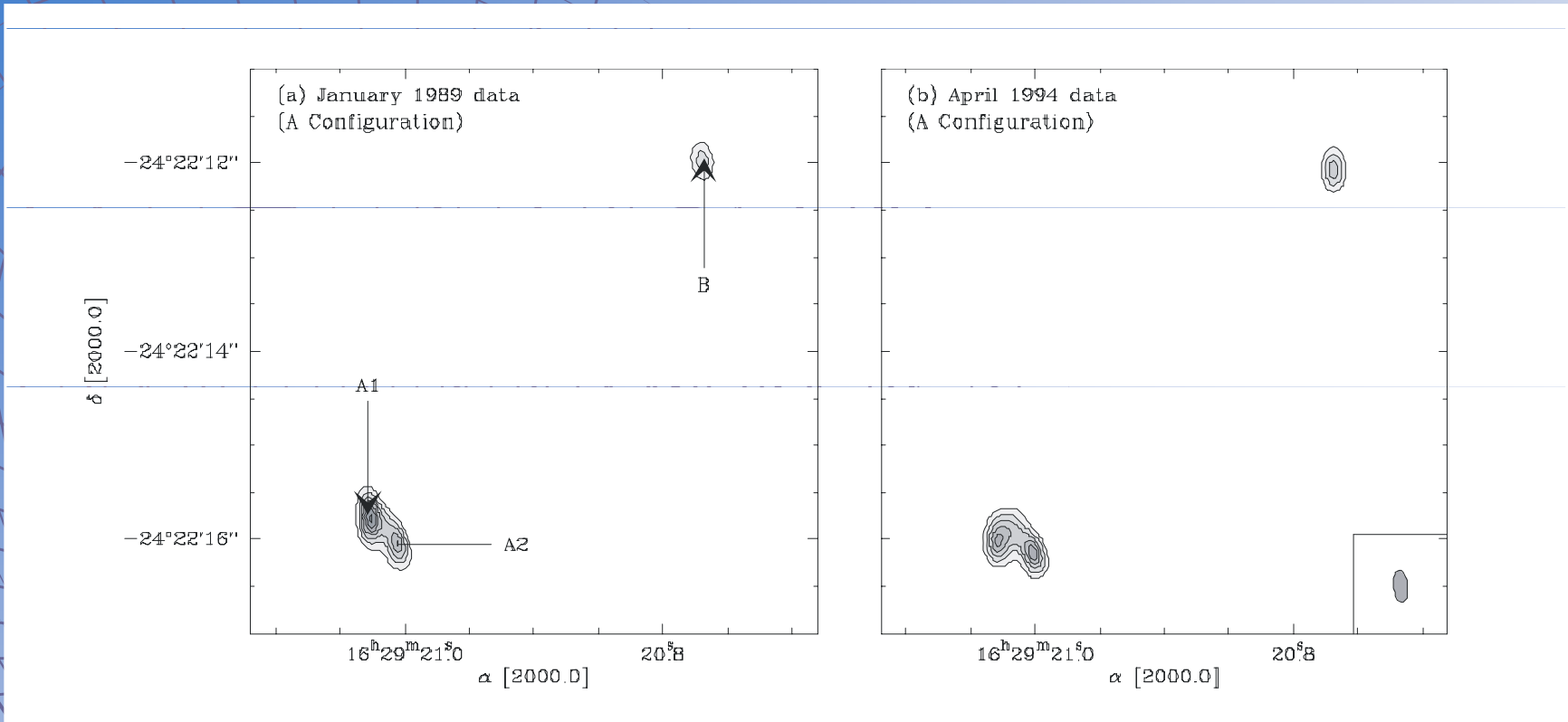
(we now have 18)

Very accurate mass determinations of ALL the members of that system

See Rosy Torres' talk…

The youngest system studied so far

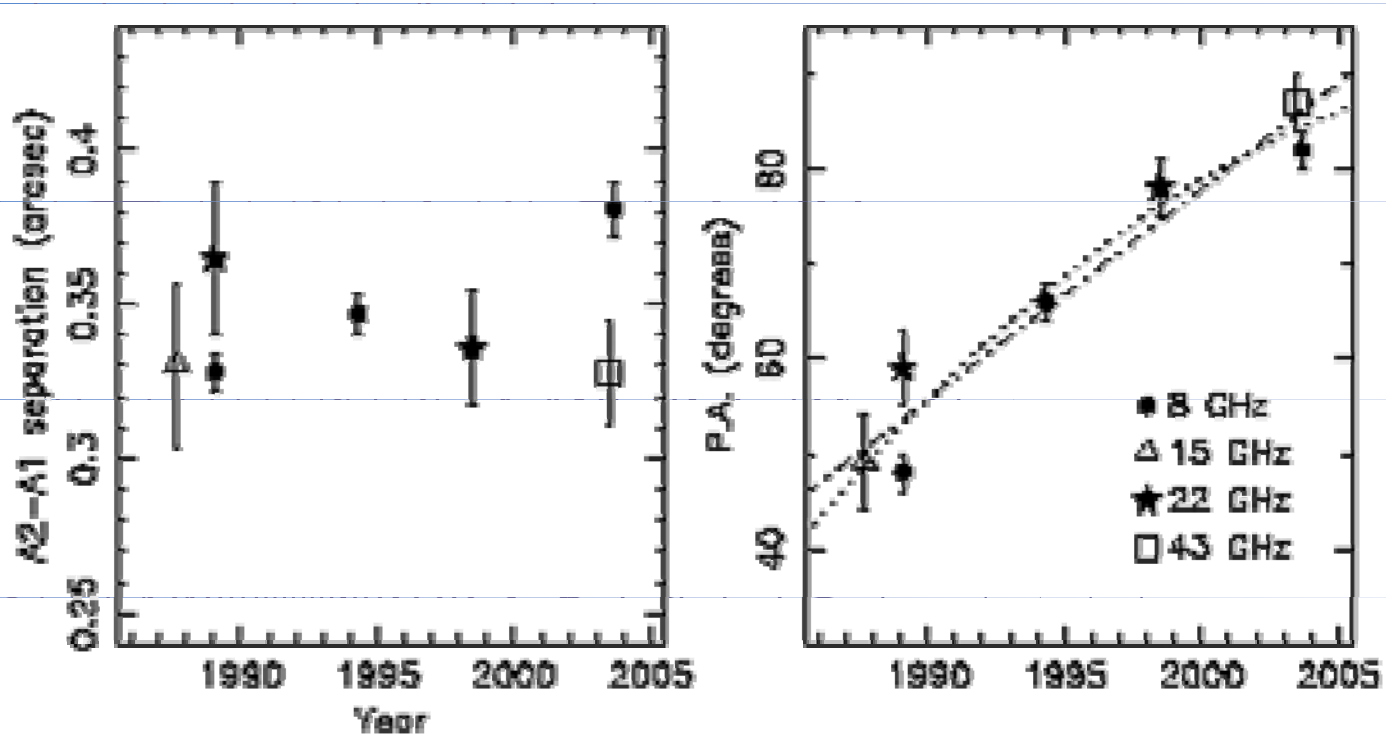
IRAS16293-2422



Loinard 2002

The youngest system studied so far

IRAS16293-2422



Chandler et al. 2005

Conclusions

- *The VLBA can measure the distance to nearby star-forming regions to very good precision.*
- *Taurus is, on average, at about 141 pc (but with significant depth).*
- *Ophiuchus is at both 120 pc.*
- *The VLBA can also trace very accurately the orbital motion in multiple systems..*
- *What happened to the orbit of T Tau Sa/Sb?*
- *What's going on in Orion?*
- *More to come…*