CONSTRAINING THE EVOLUTIONARY MODELS
Dynamical masses of the brown dwarf binary:
ε Indi Ba, Bb

Cátia Cardoso (U. Exeter) & Mark McCaughrean (U. Exeter /ESA)

Robert R. King	U. Exeter
Laird M. Close	Steward Observatory
Ralf – Dieter Scholz	AIP
Wolfgang Brandner	MPIA
Rainer Lenzen	MPIA
Nicolas Lodieu	IAC
Hans Zinnecker	AIP
Rainer Köhler	ZAH
Quinn Konopacky	UCLA
Frédéric Pont	U. Exeter

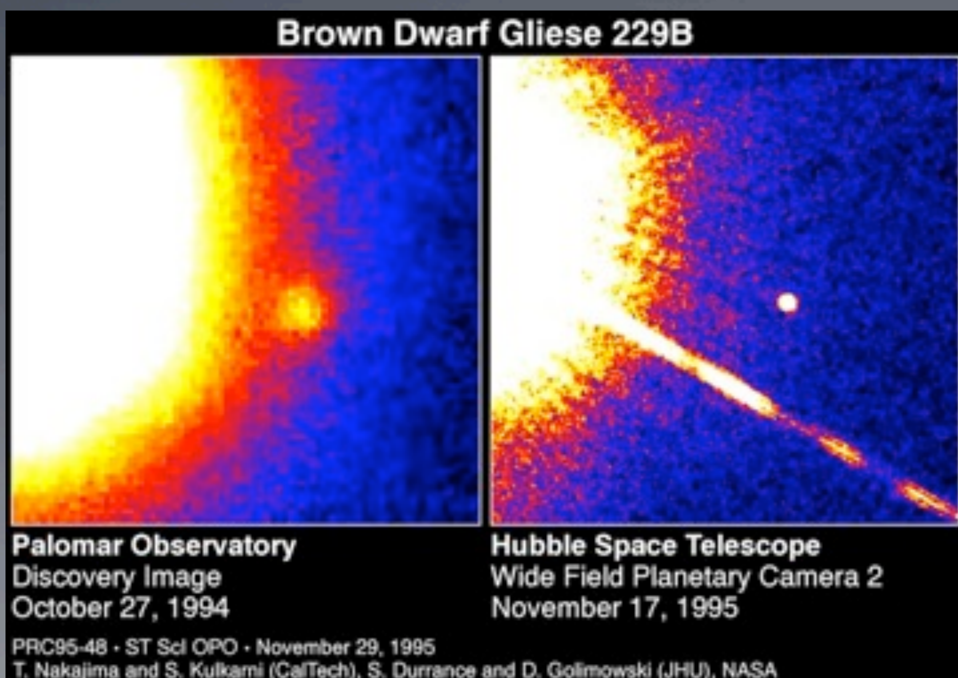
UNIVERSITY OF EXETER

constellation

Brown Dwarfs

Theorized by Kumar in 1963 and Hayashi & Nakano also in 1963.

Observed in 1995 by Rebolo et al. and Nakajima et al. also 1995.



Gliese 229B

$M \sim 40\ M_{Jup}$

T7

$d \sim 5.77$ pc

Parent star: M1

Nakajima et al. also 1995

Dynamical masses of brown dwarfs binaries

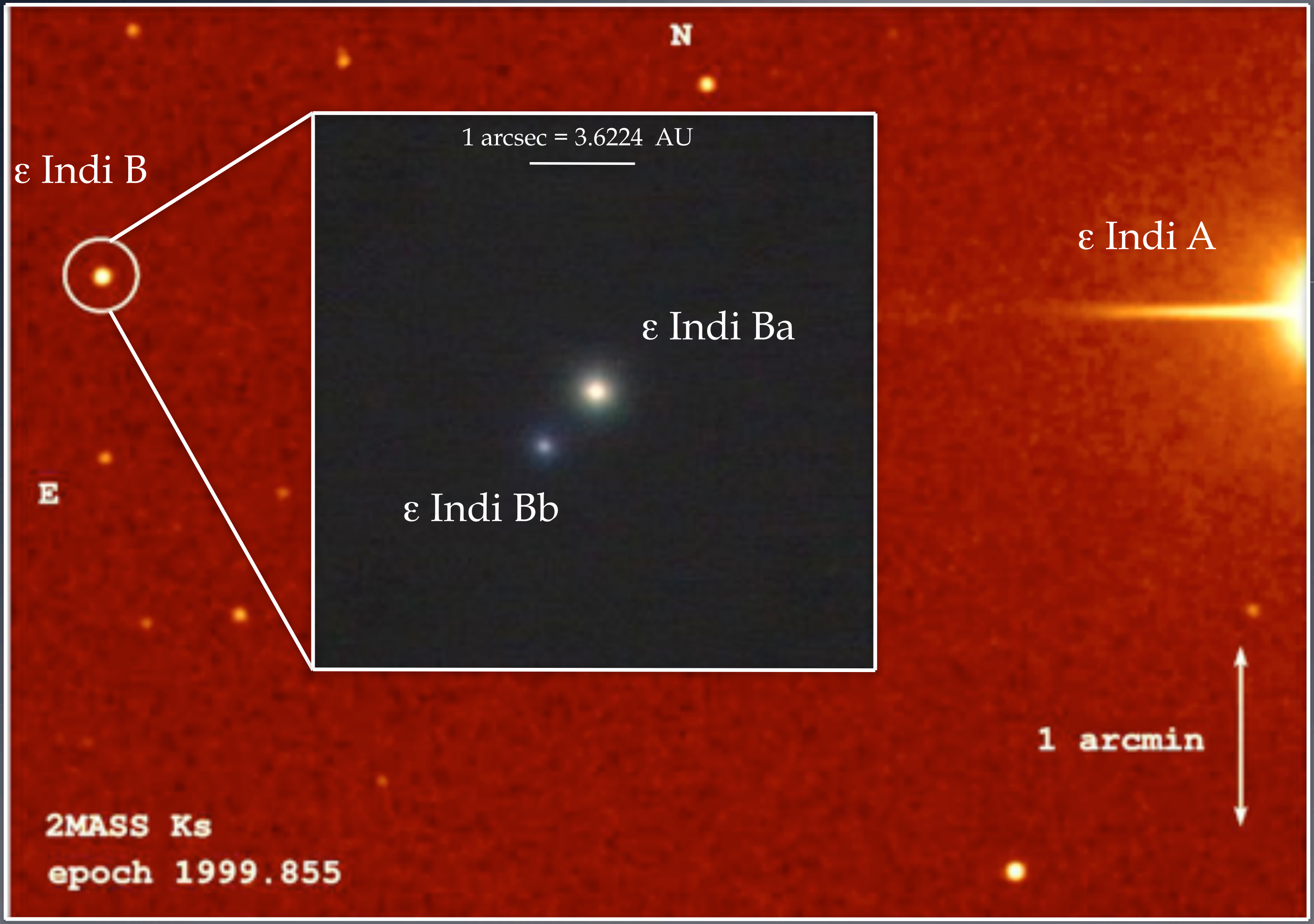
- Binary systems are very important because they allow us to determine dynamical masses in a model independent way for objects with the same age, distance and metallicity.

- Ambiguity temperature/luminosity vs age/mass

- Calibrate evolutionary models, inner structure and atmospheric models

Dynamical masses of brown dwarfs binaries

Zapatero Osorio et al. 2004	Gl 569b AB	M8.5 & M9
Bouy et al. 2004	2MASS J0746425+2000321	L0 & L1.5
Liu et al. 2008	2MASS J1534 2952AB	T5.0 & T5.5
Dupuy et al. 2008, 2009, 2010	DM for several BD systems	See talk from T. Dupuy next
Konopacky et al. 2010	DM for 15 systems, 10 new ones	



Background: Scholz et al. A&A (Letters 2003)

Inset: ESO VLT NACO adaptive optics J, H, K composite McCaughrean et al. A&A (2004)

ε Indi A: K4.5V star

ε Indi B discovered by Scholz et al. (2003)

Resolved as a binary by McCaughrean et al. (2004) & Volk et al. (IAU circular 8188)

ε Indi Ba, Bb

- Proper motion ~ 4.7 arcsec/year [2]
- Closest known brown dwarfs to Earth, at 3.6224 ± 0.0037pc [1]
- Projected separation 1500AU from ε Indi A [2]
- T1 and T6 [3]
- Age ~ 0.8 – 2.0 Gyrs from indirect age indicators [4]

[1] Van Leeuwen (2007); [2] Scholz et al. (2003); [3] McCaughrean et al. (2004); [4] Lachaume et al. (1999)

Benchmark Object

- Orbits a K4.5V star:
  - Very well constrained distance
  - Well constrained metallicity
  - Reasonably constrained age
- Closest brown dwarf binary to Earth:
  - Very bright objects
    - AO system
    - Absolute motion of barycentre against a network of background stars
  - Short period ~ 15 years
  - Well resolved

- Smith et al. 2003
  - R = 50000, near - IR spectroscopy
  - v sin i = 28 ± 3 Km/s

predicted maximum differential radial velocity ~ 5 km/s

- Audard et al. 2005
  - Radio (ATCA) & X-Ray (Chandra) imaging
  - Null detections: consistent with ultracool BDs

- Roelling et al. 2004 & Mainzer et al. 2007
  - Combined spectrum of ε Indi B with IRS on Spitzer

- Sterzik et al. 2005
  - Mid-IR photometry from VLT/VISIR

- Kasper et al. 2009
  - Low resolution near-IR spectroscopy

- King et al. 2010: "ε Indi Ba, Bb: a detailed study"

VRIzJHK$_S$LM$_{NB}$ Photometry

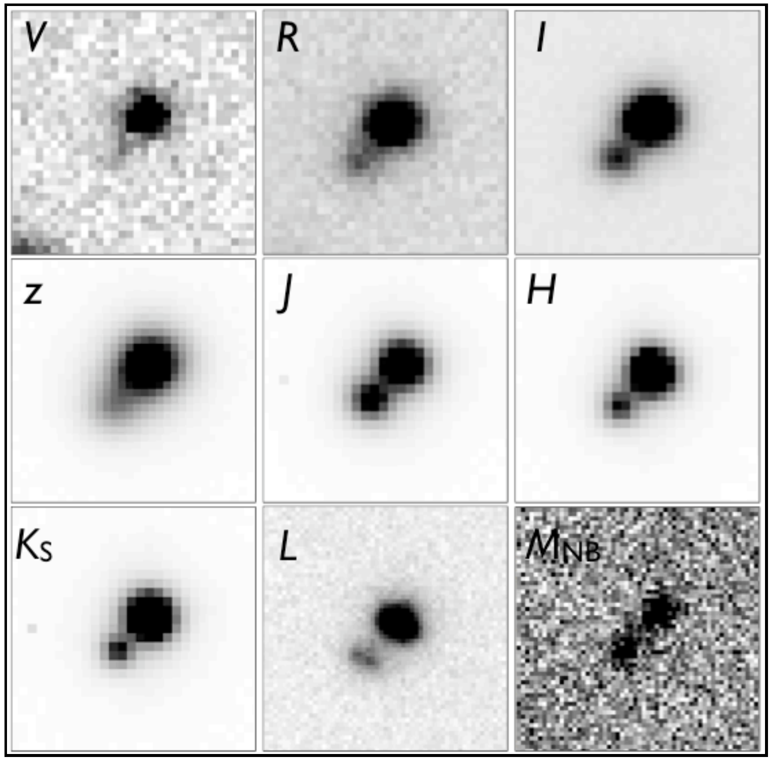
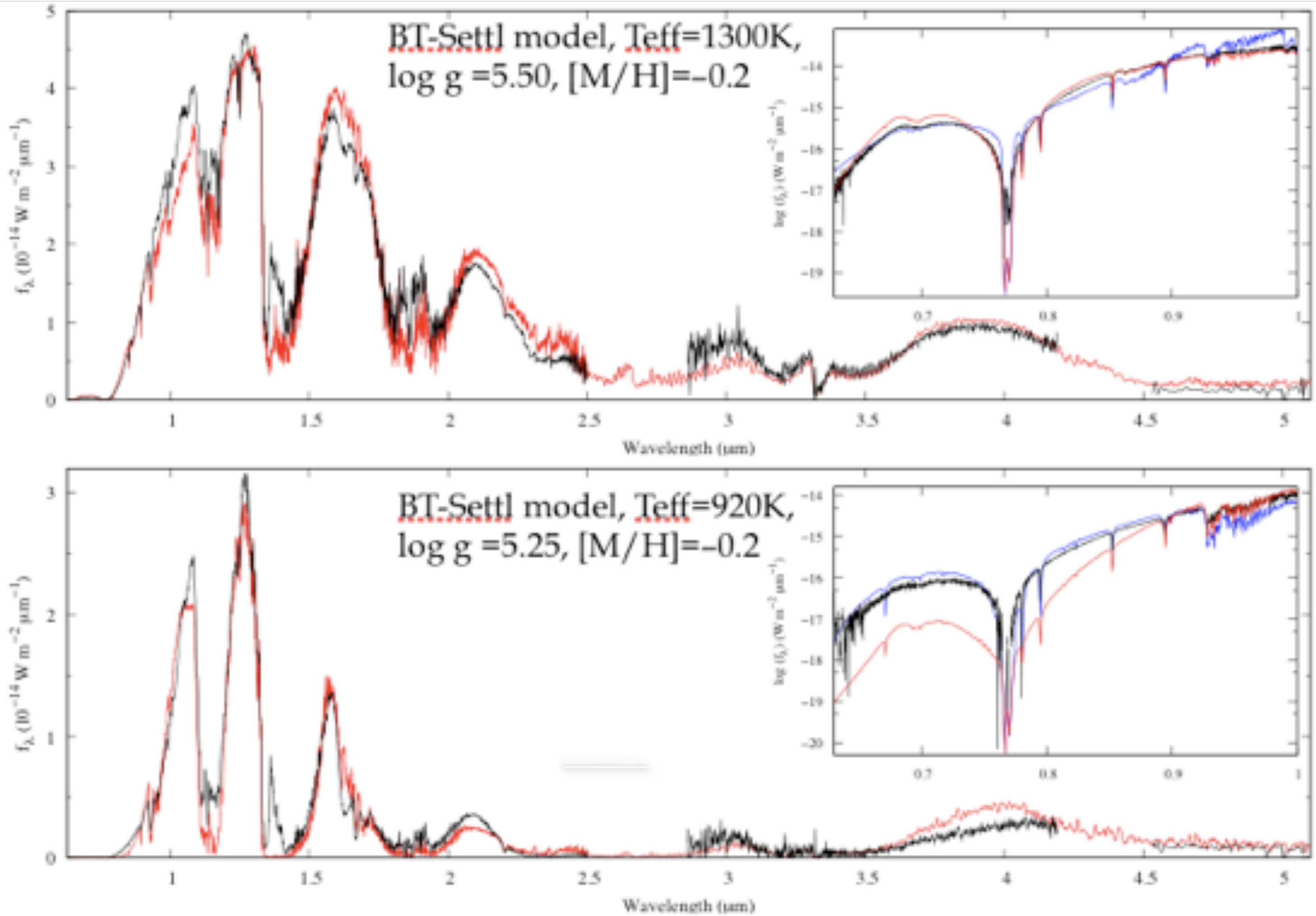


Fig. 1. From left to right and top to bottom, FORS2 $VRIz$ and ISAAC JHK_SLM_{NB} images of ε Indi Ba, Bb. Each image is a $4'' \times 4''$ sub-section of the full image. North is up, East left. The object to the south-east of the V-band image is a faint galaxy not seen in the other pass-bands. The L-band profiles are seen to be slightly elliptical. The V and M_{NB}-band images are the stacked images of all observations in those pass-bands.

King et al. 2010

Spectroscopy: optical - thermal IR

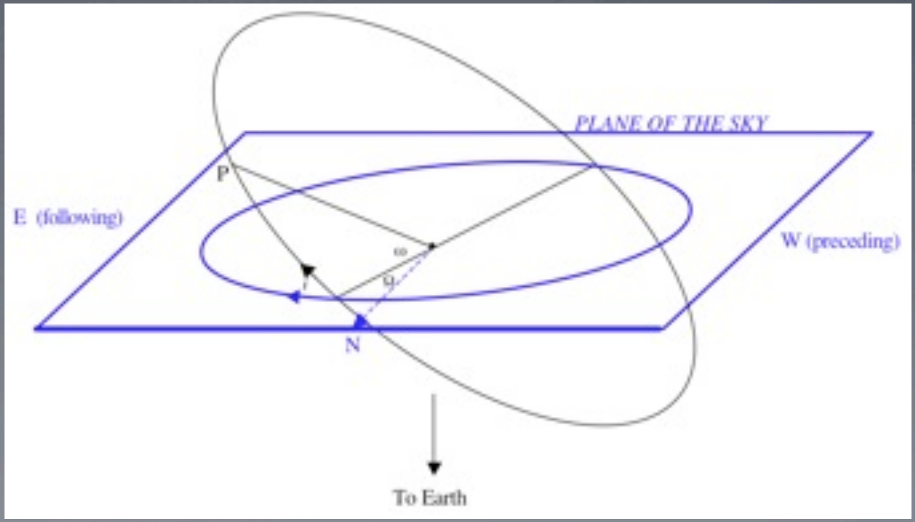


King et al. 2010

Relative Astrometry

- Kepler's 3rd Law
  - Period
  - Semi-major axis

$$m_1 + m_2 = (4\pi^2 a^3)/(GP^2)$$

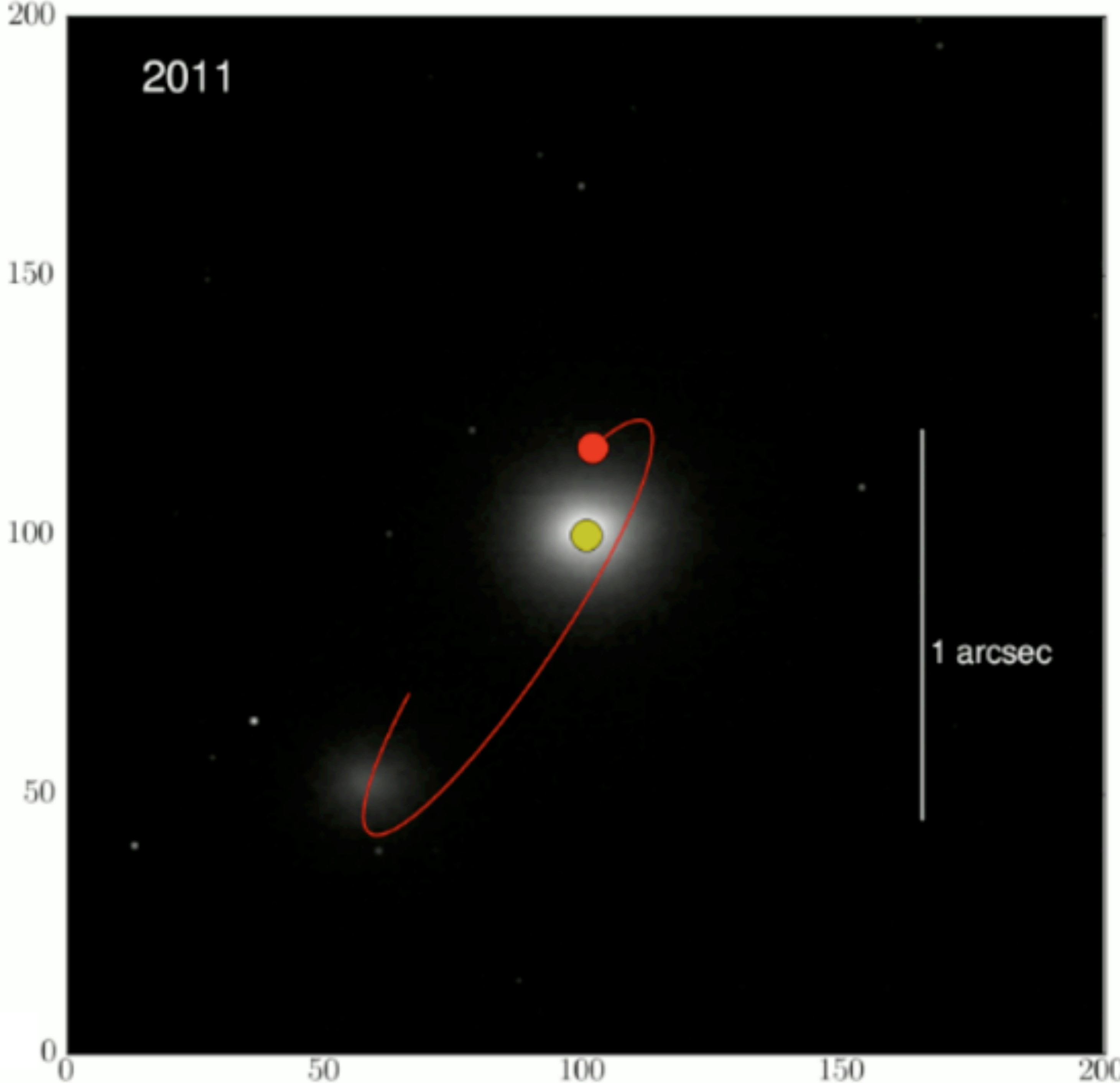


Credit image: www.astro.uvic.ca/~tatum/celmechs/celm17.pdf

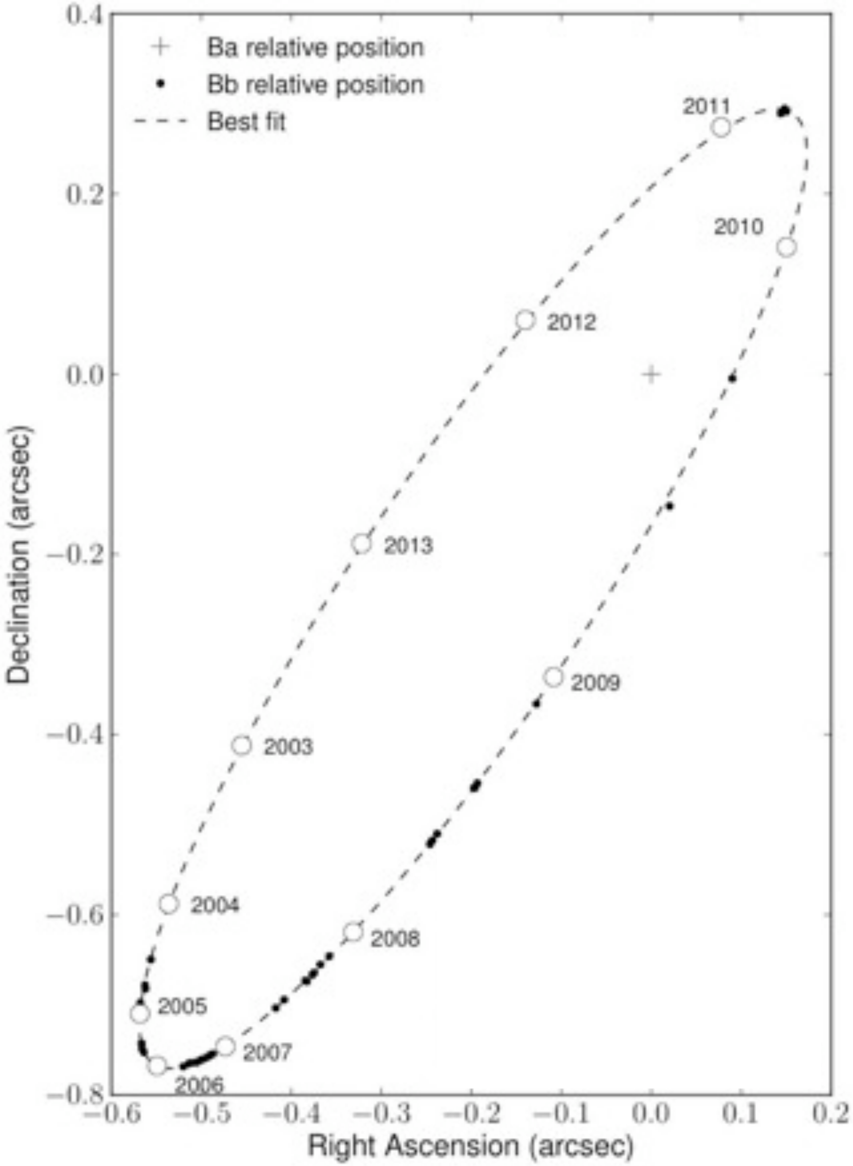
Relative Astrometry

- ESO VLT NACO adaptive optics data in J, H, K_s bands
- Total 34 epochs between May 2004 and September 2010
- More than half orbit covered

ESO VLT NACO adaptive optics J, H & K_s composite image. McCaughrean et al., A&A (2004)

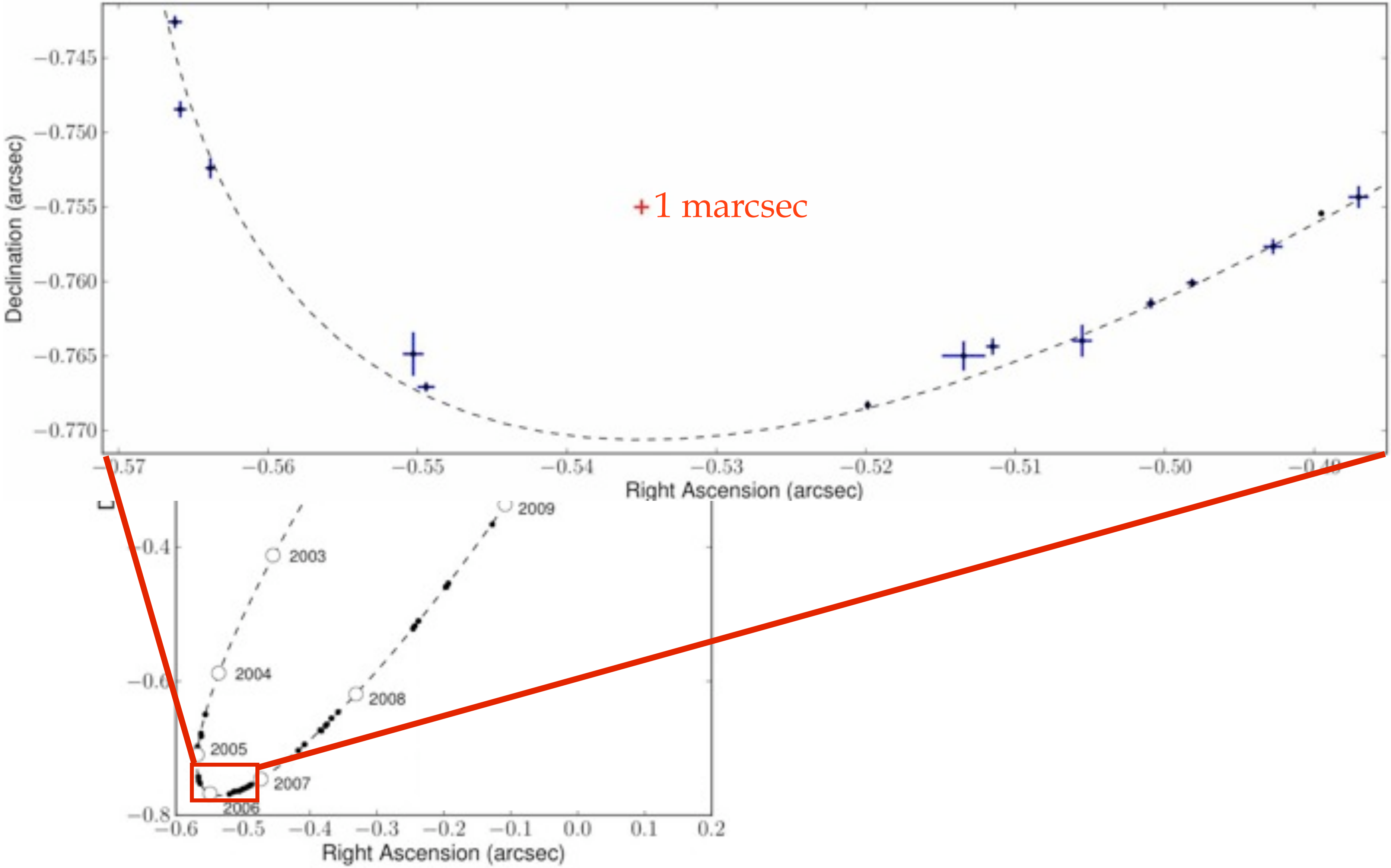

2011
1 arcsec
200
150
100
50
0
0
50
100
150
200

Relative Astrometry



Period: 10.93 years
Date of periastron: 2010.15
e: 0.541
i: -77.1 °
a: 0.6677″
System mass: 120.9± 0.3 M_{Jup}

Relative Astrometry



Results

System mass = 120.9 ± 0.3 M_{Jup}

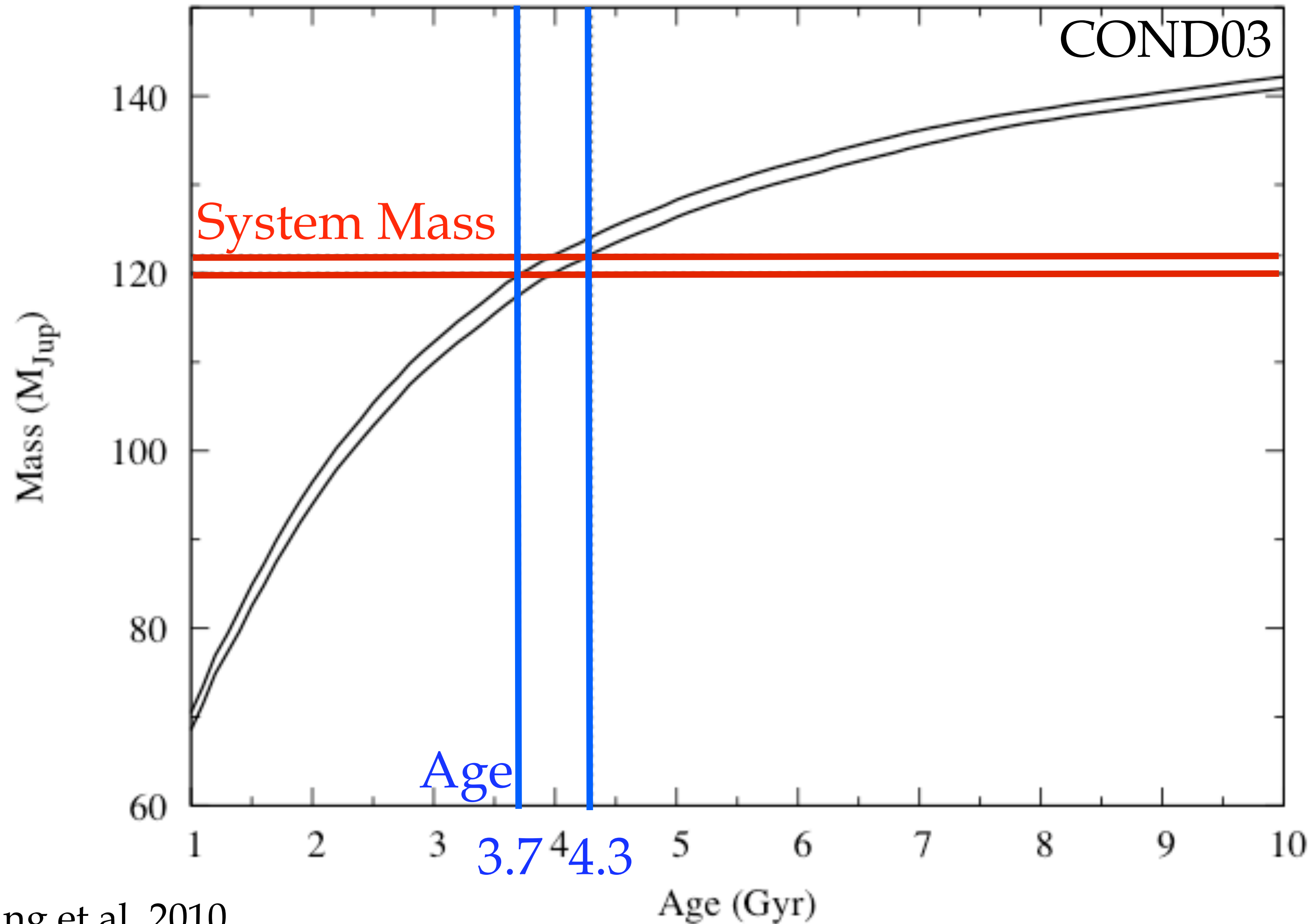
Stochastic error: ± 0.2%

Systematic errors: ± 0.2% NACO pixel scale [1]

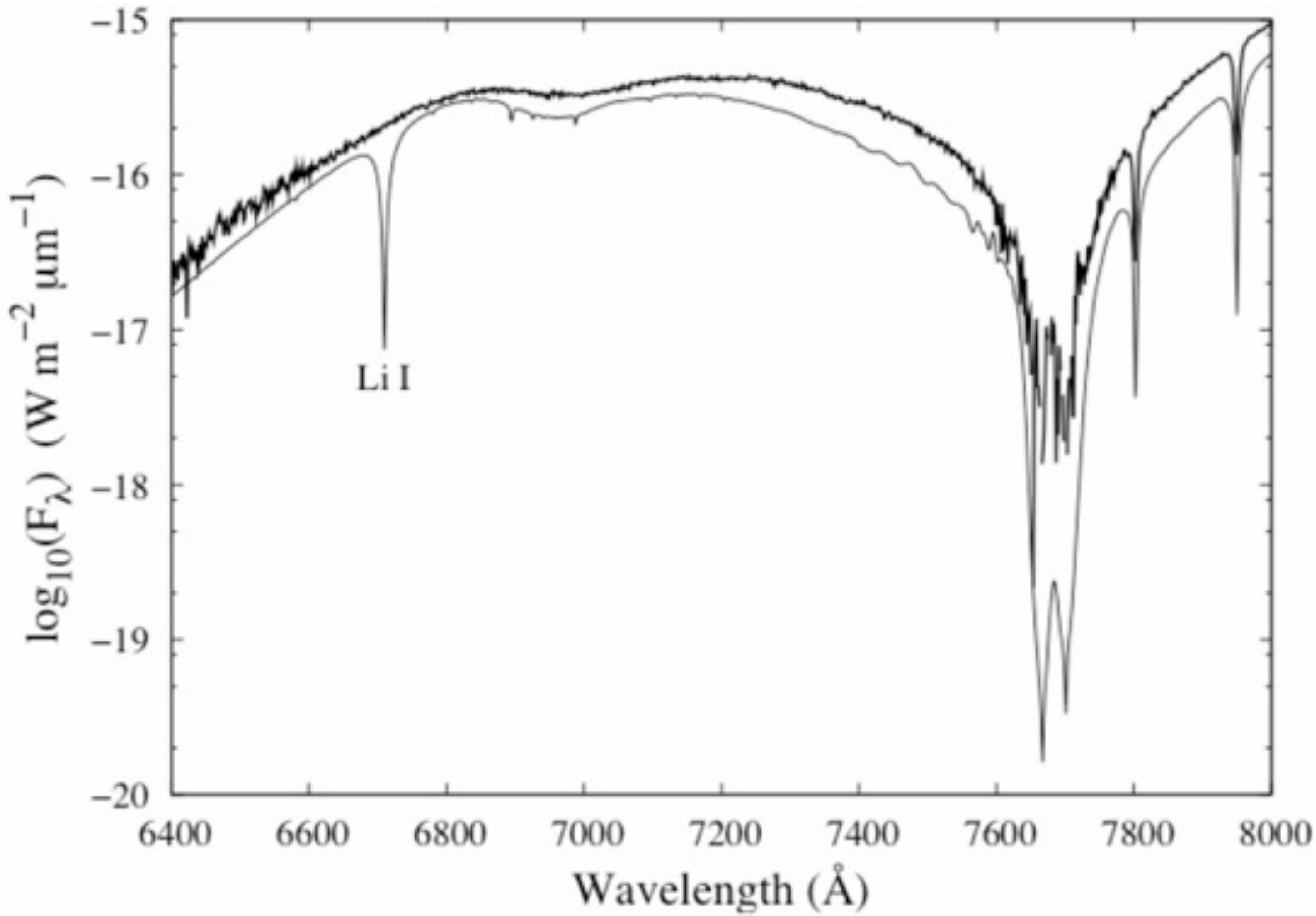
± 0.1% ε Indi A distance [2]

± 0.2% line of sight separation to ε Indi A [3]

[1] Trippe et al. 2008; [2] van Leeuwen 2007; [3] Leinert et al.1993

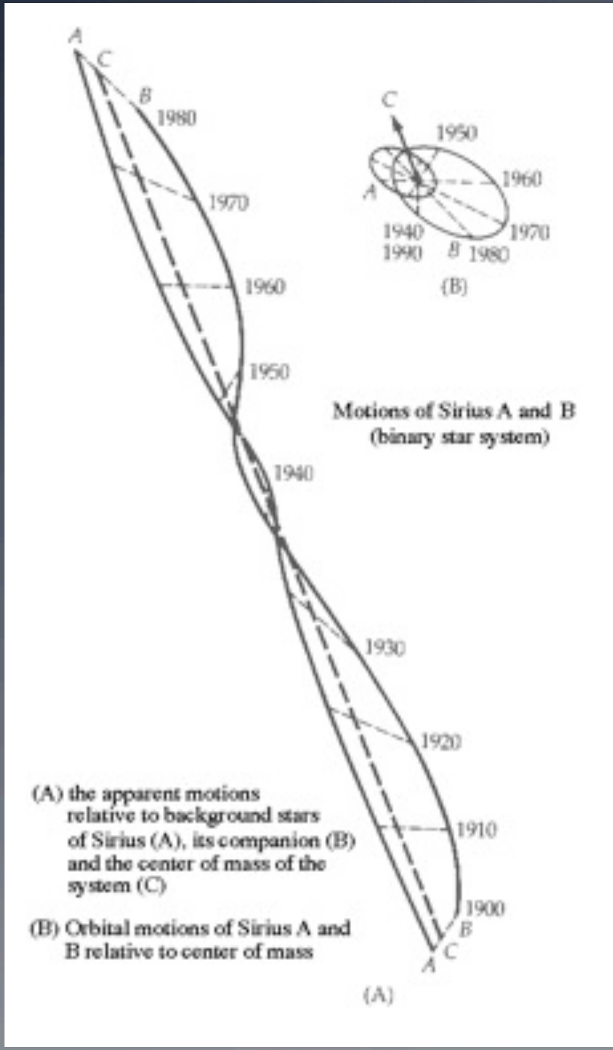


King et al. 2010,
Baraffe et al. 2003



FORS2 R~1000 optical spectrum of ε Indi Ba (upper line) and the BT-Settl (Allard et al. 2003) atmospheric model fit (lower line) (King et al. 2010). The lack of Li absorption at 6708˚A indicates a mass in excess of ~ 0.06 M⊙ (Burke et al. 2004): given the observed luminosity, this suggests an age > 3 Gyr using the Baraffe et al. (2003) evolutionary models.

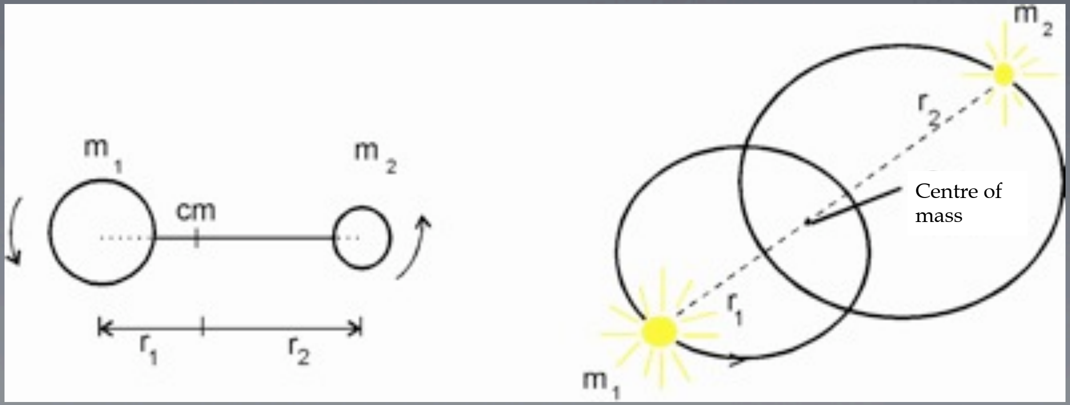
Absolute Astrometry



Credit image: Zeilik & Smith

- Definition of centre of mass: $m_1 r_1 = m_2 r_2$
- To have the individual masses:

$$m_1 / m_2 = (r_2 \sin i) / (r_1 \sin i)$$



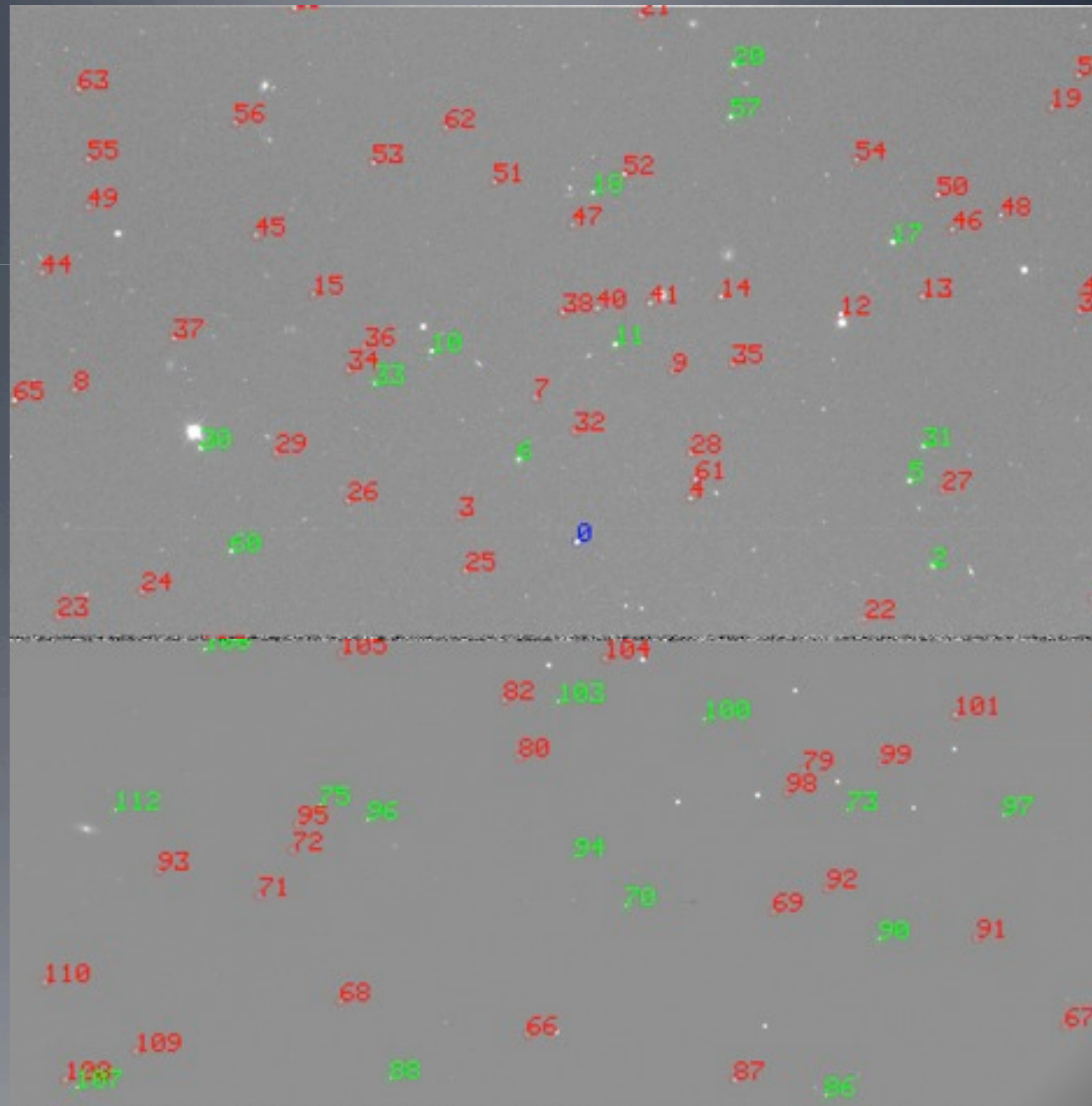
Credit image: www.astro.iag.usp.br/~jane/aga215/aula08/cap8.htm

Absolute Astrometry

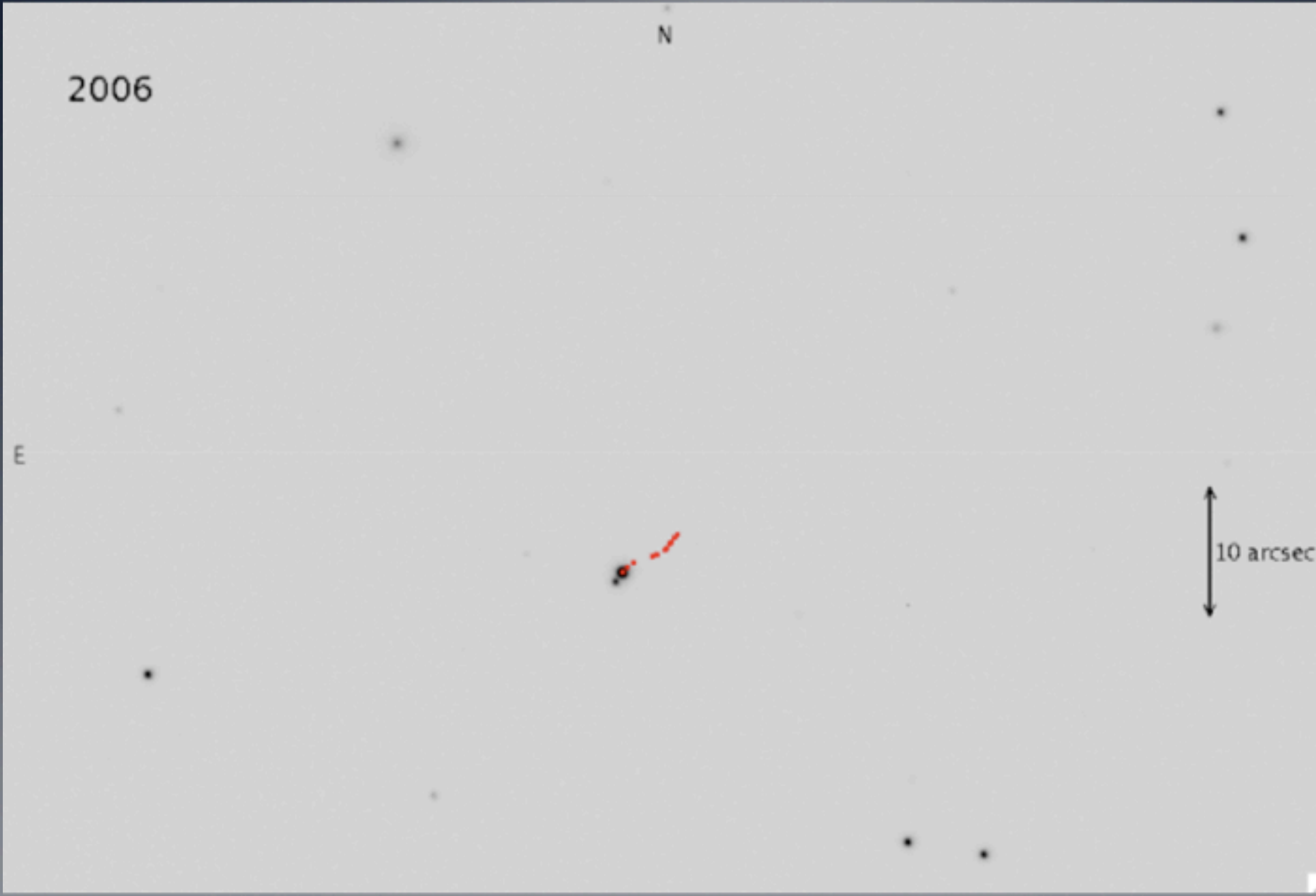
- ESO VLT FORS2 data in I – band
- Total of 43 epochs between May 2005 and September 2009
- FORS2 field of view: 8.6 x 8.6 arcmin

FORS2 field of view,
May 2005

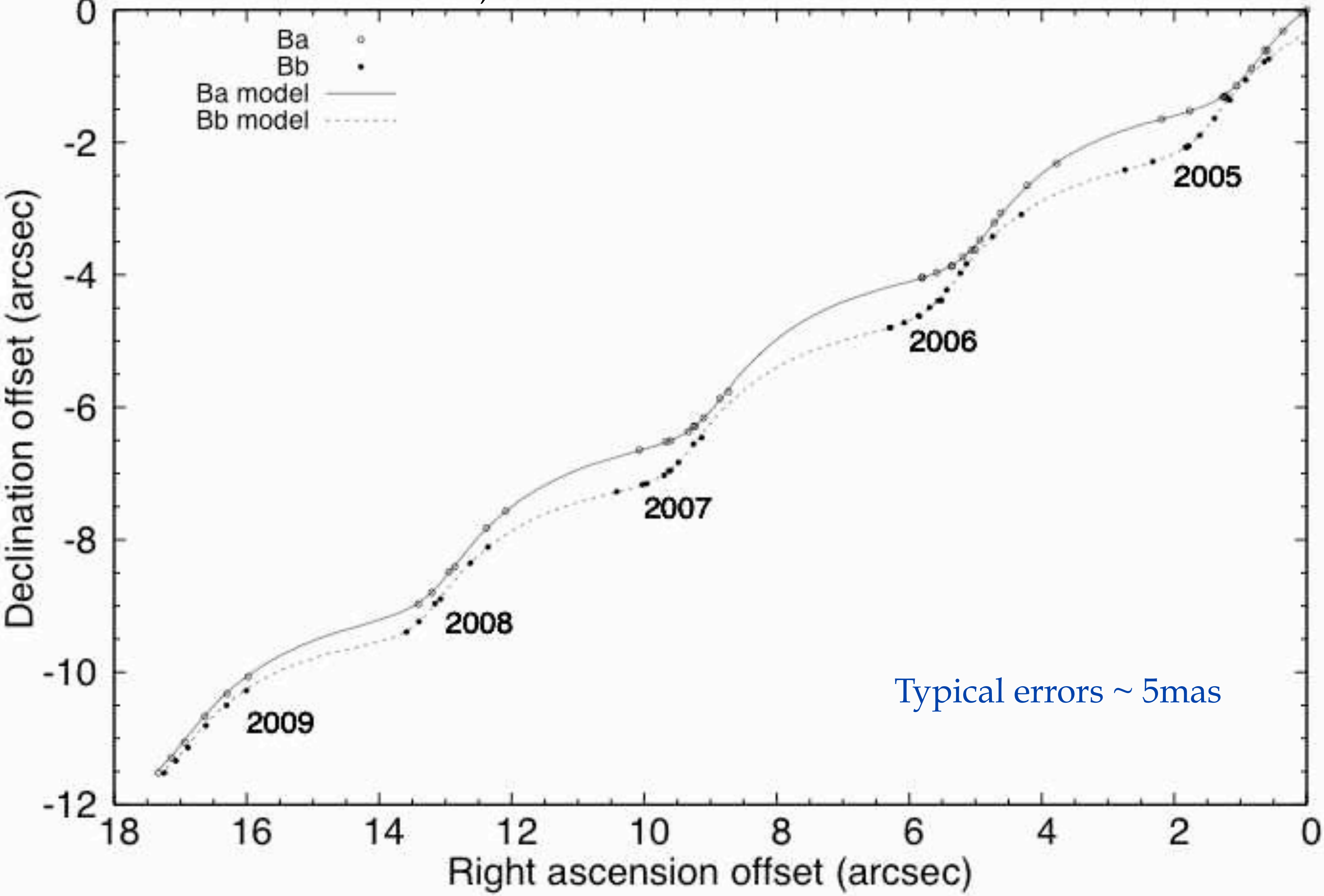
- ε Indi B in blue
- 2MASS stars (green)
  - 16 CCD1 (max)
  - 24 CCD2 (max)
- Background stars (red + green)
  - 65 CCD1
  - 47 CCD2



VLT FORS2, 8.6x8.6 arcmin FOV, 0.126 arcsec/pix, I band, 20 sec, 0.32 arcsec FWHM


2006
N
E
10 arcsec

ε Indi Ba, Bb absolute movement 2005 - 2009



Typical errors ~ 5mas

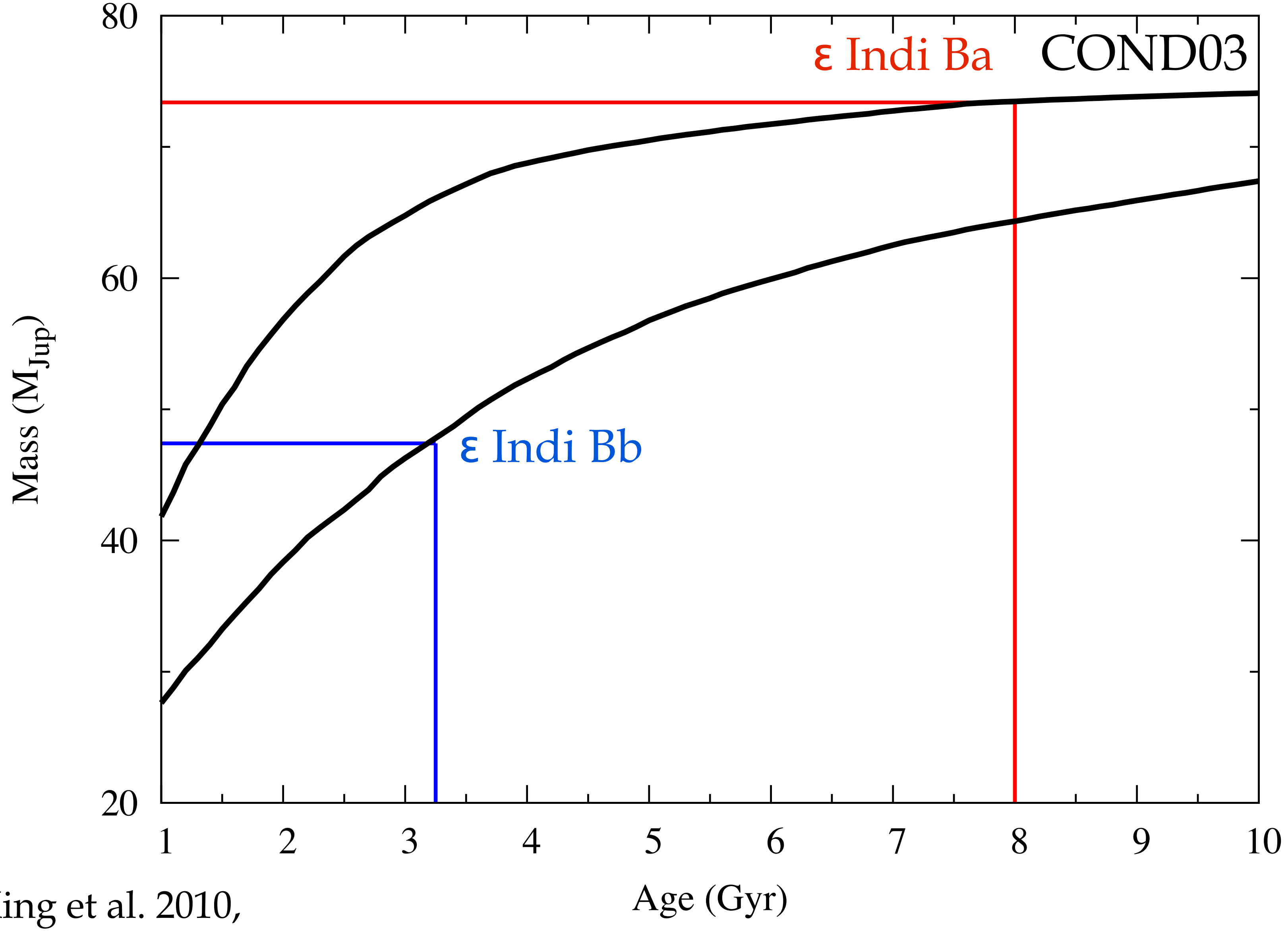
Results

$M_{Ba} / M_{system} = 0.61 \pm 0.02$

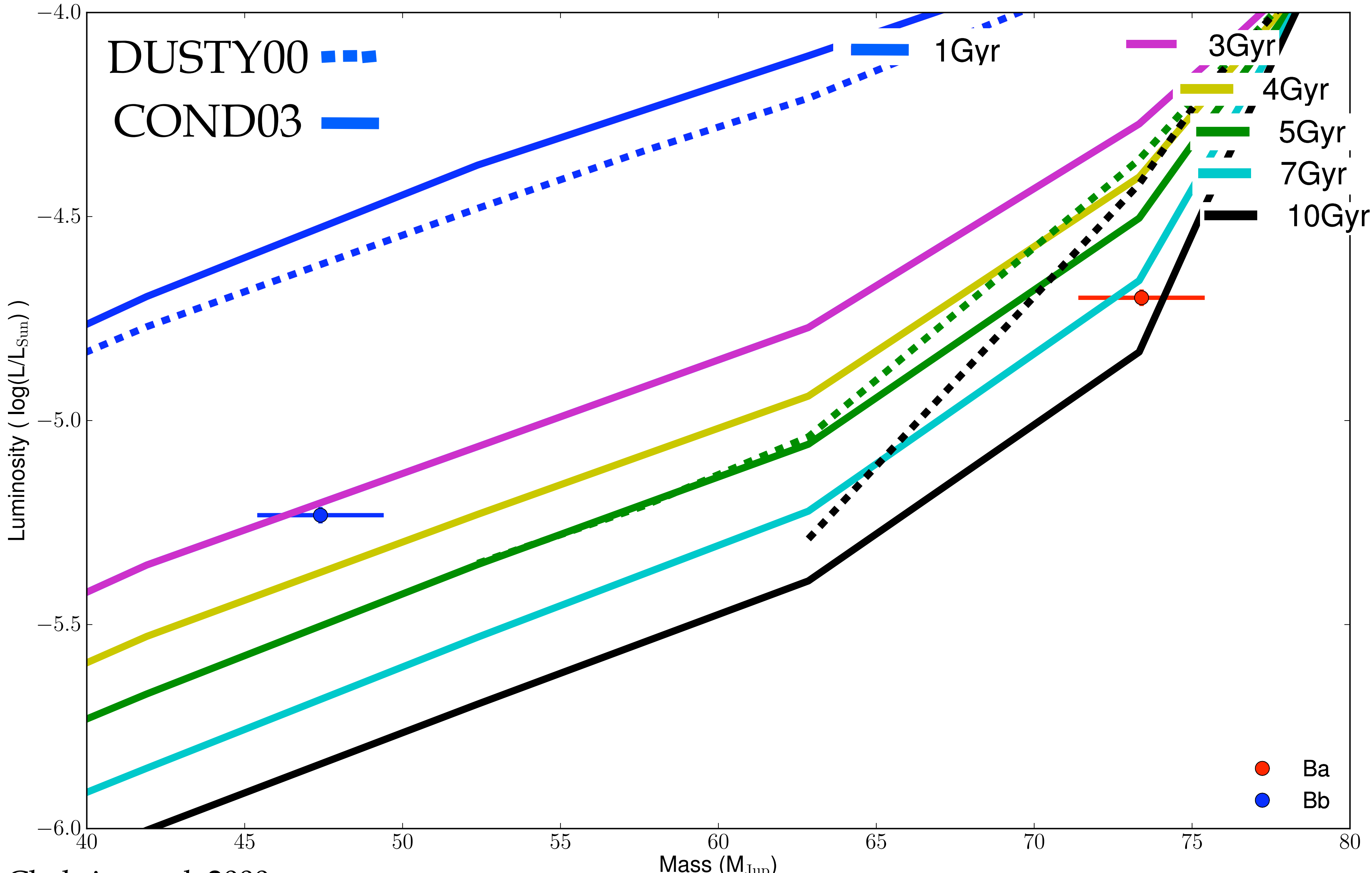
$M(\varepsilon \text{ Indi Ba}) = 73.7 \pm 2.4\ M_{Jup}$

$M(\varepsilon \text{ Indi Bb}) = 47.1 \pm 2.4\ M_{Jup}$

Model independent → Constrain evolutionary models & atmospheric models of T dwarfs



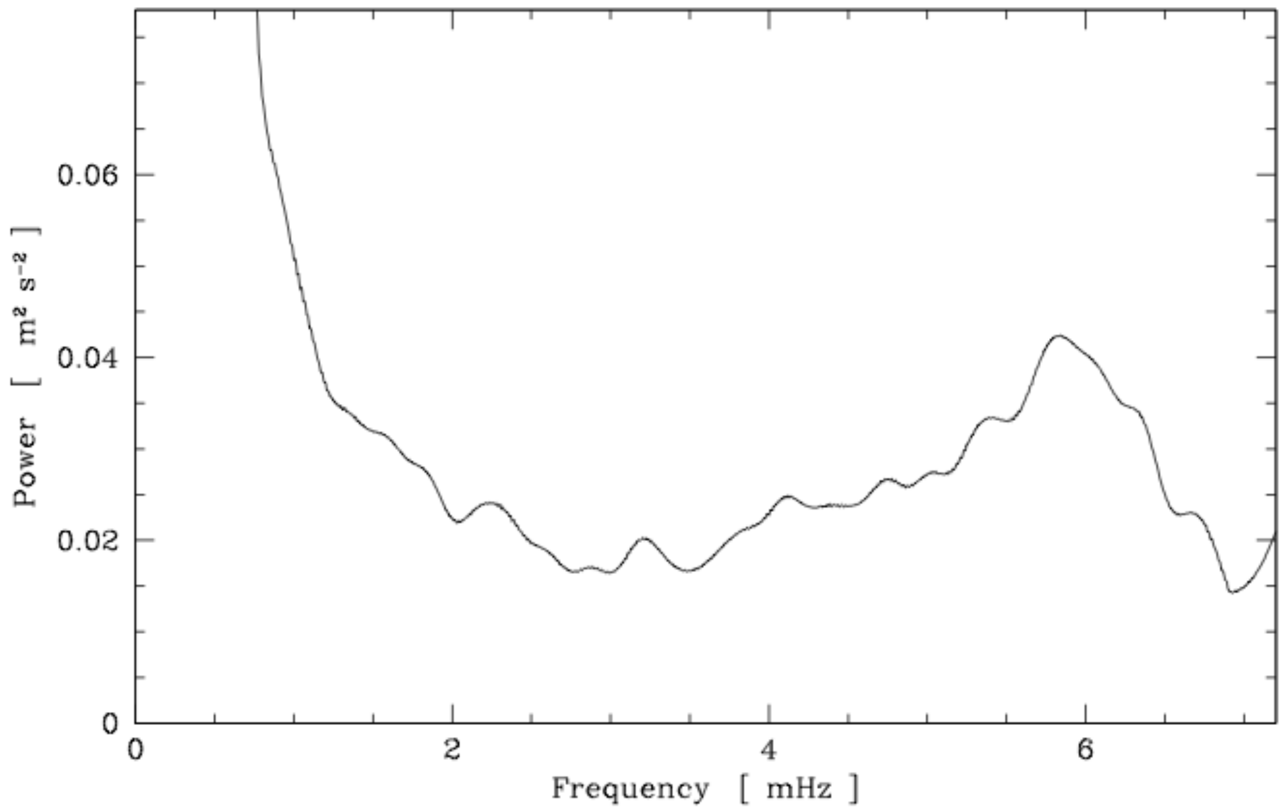
King et al. 2010,
Baraffe et al. 2003



Chabrier et al. 2000,
Baraffe et al. 2003

Future Work

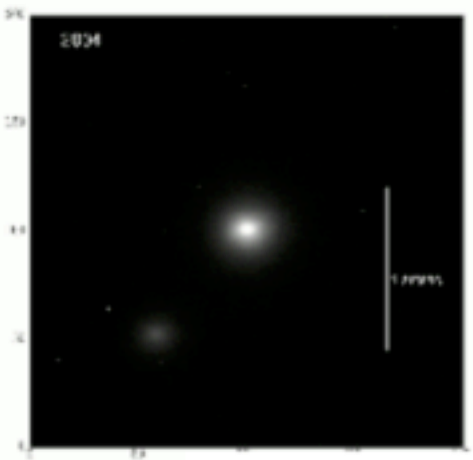
Asteroseismology study of ε Indi A for better constraint on age.

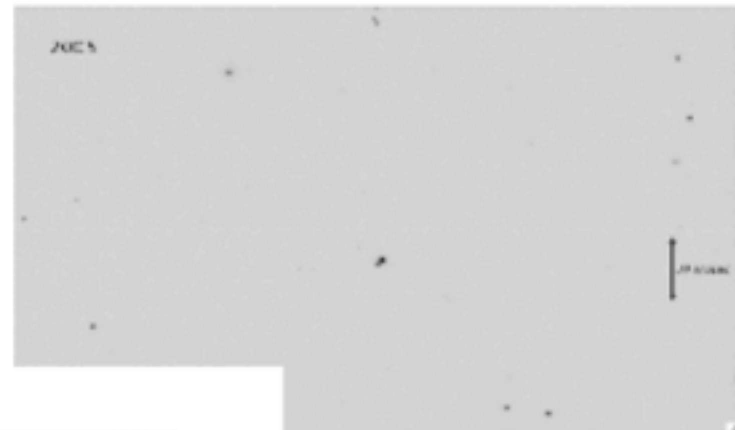


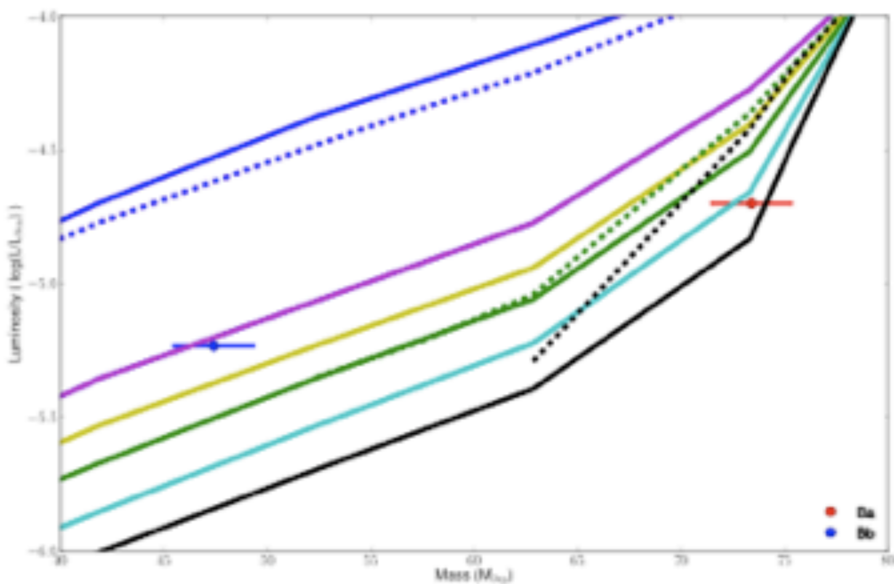
System mass = 120.9 ± 1.0 M_{Jup}

M (ε Indi Ba) = 73.7 ± 2.4 M_{Jup}

M (ε Indi Bb) = 47.1 ± 2.4 M_{Jup}







constellation

MRTN-CT-2006-035890

UNIVERSITY OF EXETER