The potential of VLBA to make a contribution to the study of star formation

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DFG Deutsche Forschungsgemeinschaft

- Accurate ages are crucial to understand the birth and evolution of stars
- Ages of PMS are inferred from the position of low-mass stars along evolutionary tracks
- A distance error of 20% produces an error in luminosity of 40% which translates into an age error of 70% *(Hartmann 2001)*

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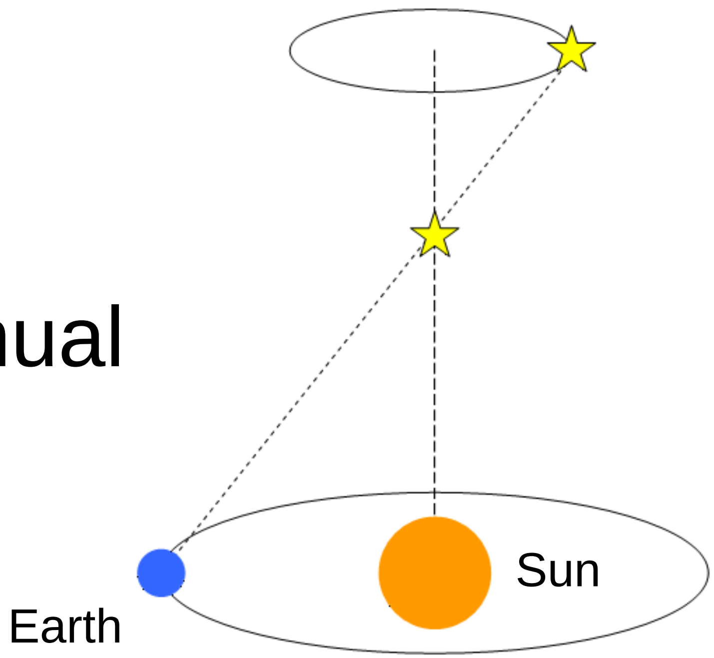
- The only direct method to measure the distance to stars is the trigonometric parallax

- Apparent change in the position of the source due to the annual rotation of the Earth

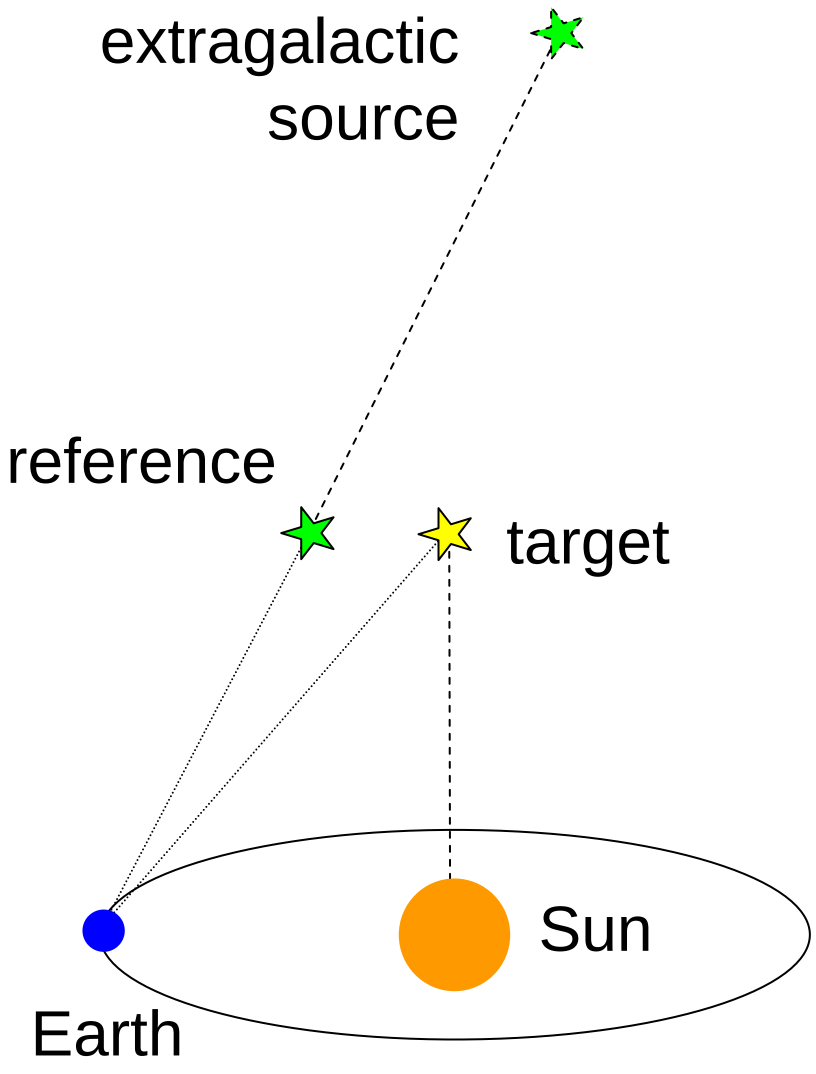


- Most of the parallax measurements to date are based on optical or near-infrared observations
- YSO tend to be surrounded by nebulosities
- They are usually optically rather faint
- Distance to low-mass stars is rarely known better than 20 to 30%
- Accurate distances to YSO are crucial to improving our understanding of the origin and evolution of solar-mass stars

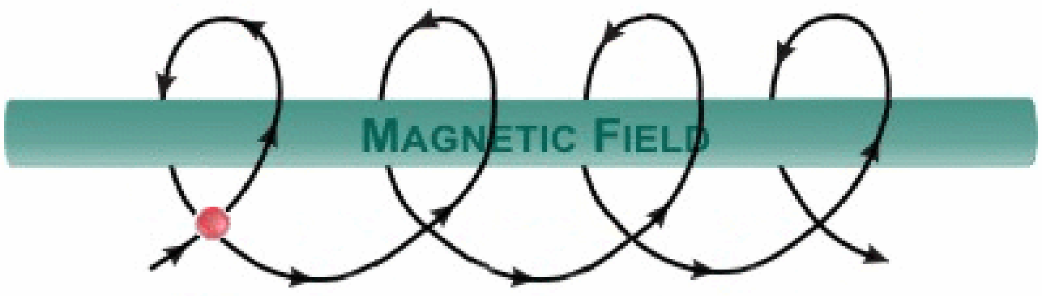
The VLBA

Owens Valley
California
Brewster
Washington
North Liberty
Iowa
Hancock
New Hampshire
Mauna Kea
Hawaii
St. Croix
Virgin Islands
Kitt Peak
Arizona
Los Alamos
New Mexico
Fort Davis
Texas
Pie Town
New Mexico

- The target can be phase referenced to an extragalactic source
- We know its position with 0.5 mas accuracy
- But needs non-thermal sources



- (CTT & WTT) or (Class II & Class III)
- Magnetic, compact and bright sources
- Non-thermal emission coming from stellar magnetospheres
- Gyrosyncrotron: acceleration due to particle gyration from mildly relativistic particles ($\gamma \leq 2$ or 3)



B ~ 1 kG

E ~ 1 MeV

(www.nrao.edu)

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- Angular resolution:
  $\delta \sim \lambda$ / D ~ 3.6 cm / 8000 km
  ~ 0.9 mas
- Precision:
  0.5 δ / SNR ~ 50 μas
  (without systematic errors)

Maximum VLBA baseline lengths in km

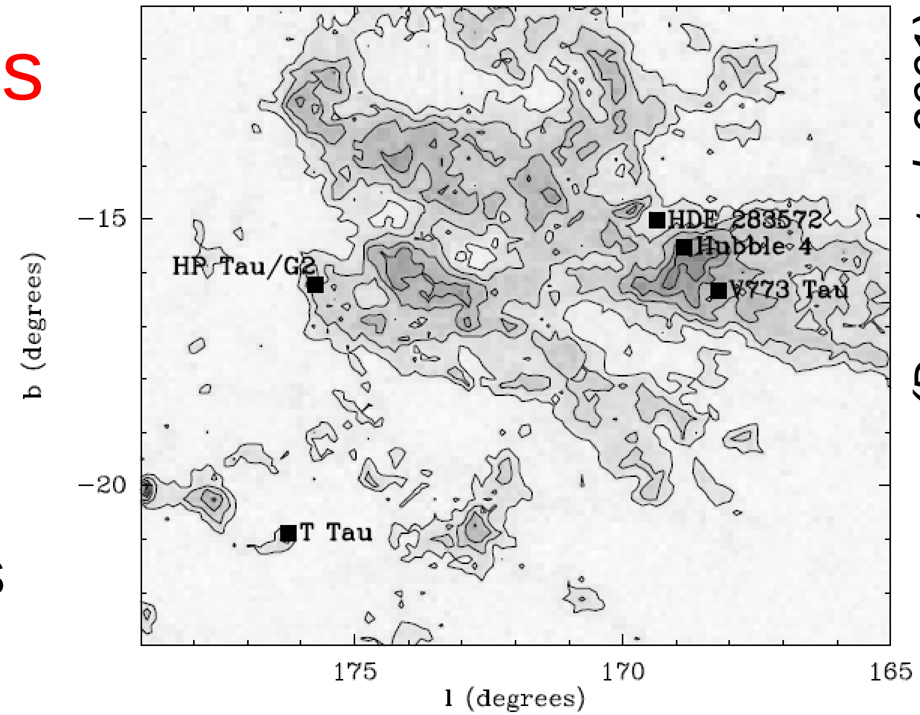
	SC	HN	NL	FD	LA	PT	KP	OV	BR	MK
SC	...	2853	3645	4143	4458	4579	4839	5460	5767	8611
HN	2853	...	1611	3105	3006	3226	3623	3885	3657	7502
NL	3645	1611	...	1654	1432	1663	2075	2328	2300	6156
FD	4143	3105	1654	...	608	564	744	1508	2345	5134
LA	4458	3006	1432	608	...	236	652	1088	1757	4970
PT	4579	3226	1663	564	236	...	417	973	1806	4795
KP	4839	3623	2075	744	652	417	...	845	1913	4466
OV	5460	3885	2328	1508	1088	973	845	...	1214	4015
BR	5767	3657	2300	2345	1757	1806	1913	1214	...	4398
MK	8611	7502	6156	5134	4970	4795	4466	4015	4398	...

(www.vlba.nrao.edu)

- Only sensitive to compact emission structures with high surface brightness
- Effectively filter out the extended thermal halo of the PMS
- Provide images of non-thermal source alone

- Much of what we know about the formation of the Sun has been derived from the observation and modeling of a few nearby low-mass star-forming regions

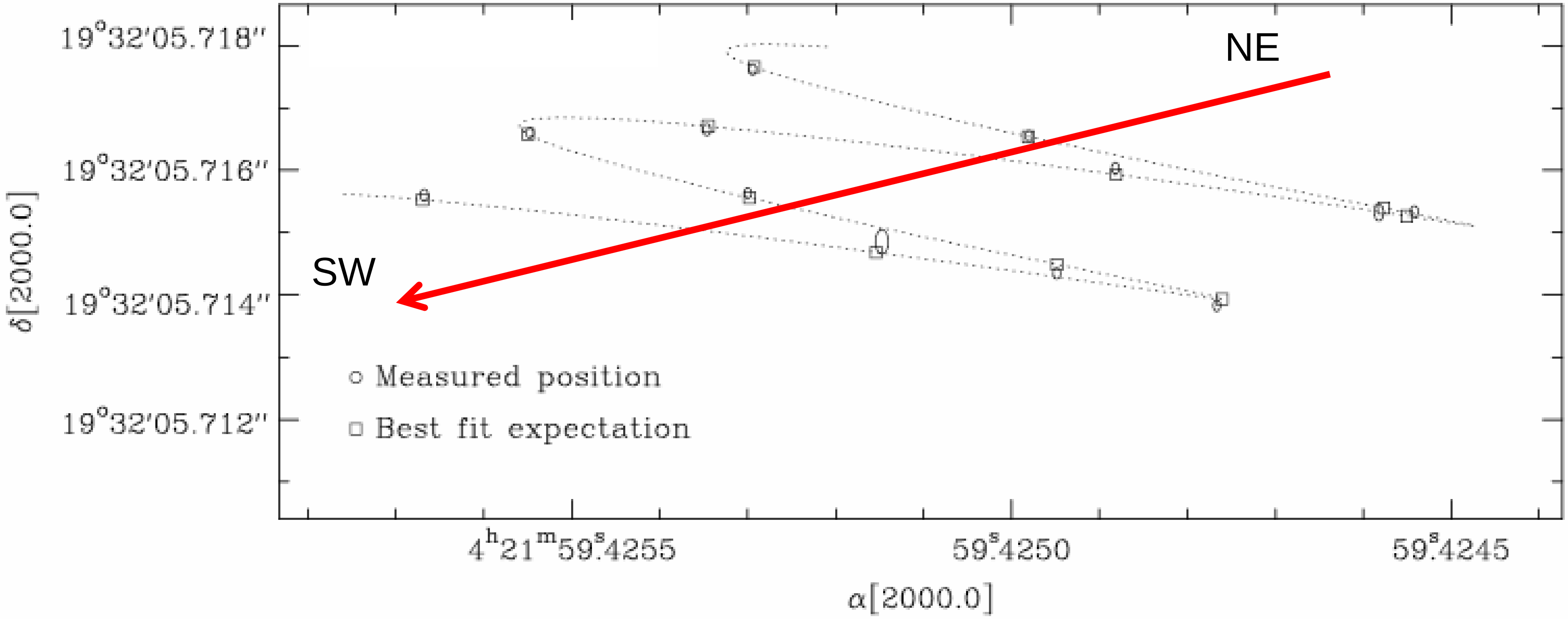
- 5 PMS stars in Taurus
- continuum mode
- 8.42 GHz (3.6 cm)
- observed every 3 months



(Dame et al. 2001)

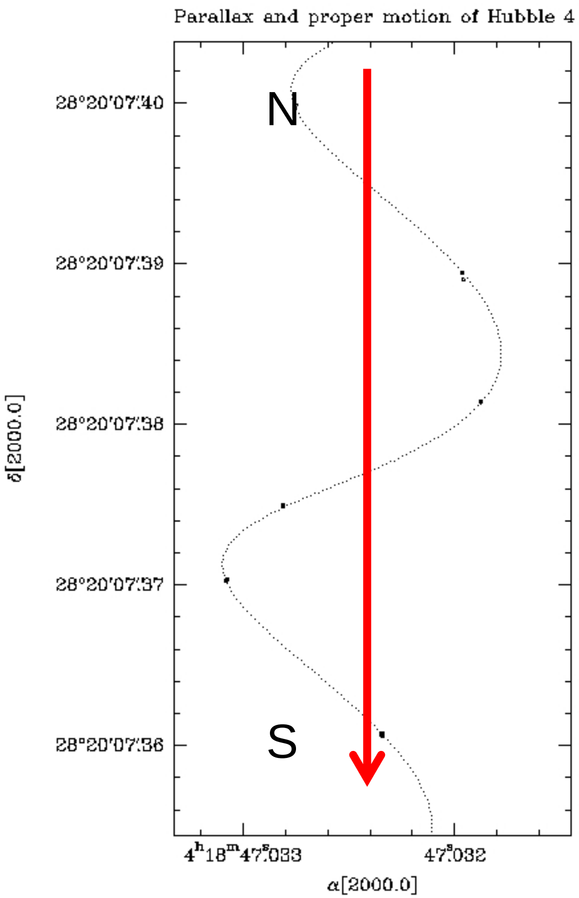
Distances to 5 stars in Taurus

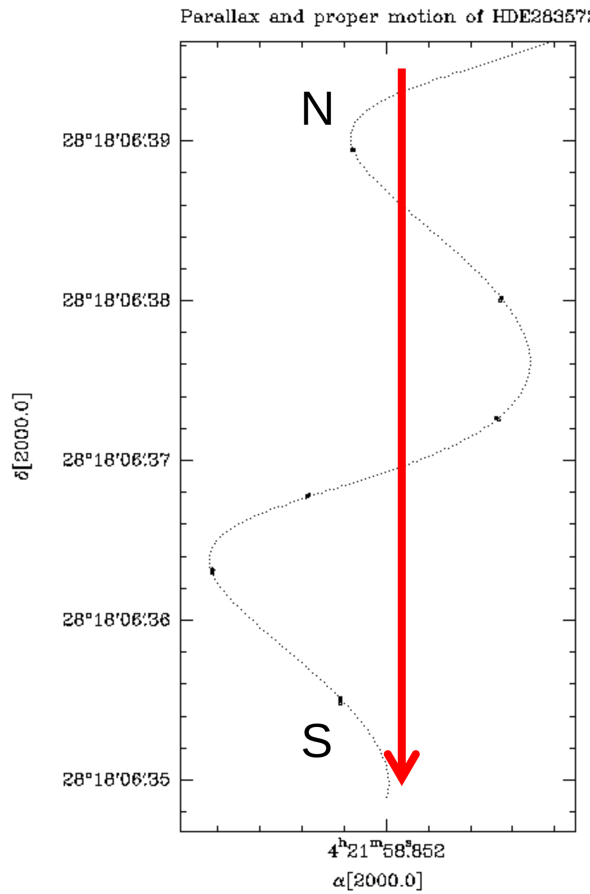
(Loinard et al. 2005, 2007)



d = 146.7 ± 0.6 pc

0.4% error



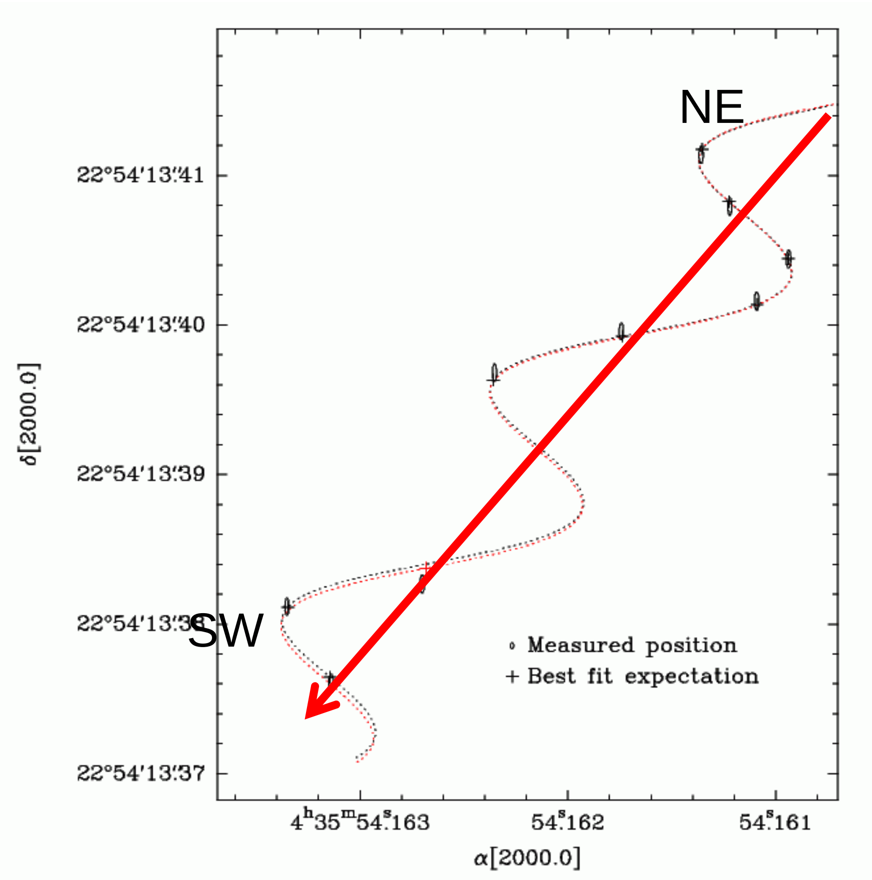


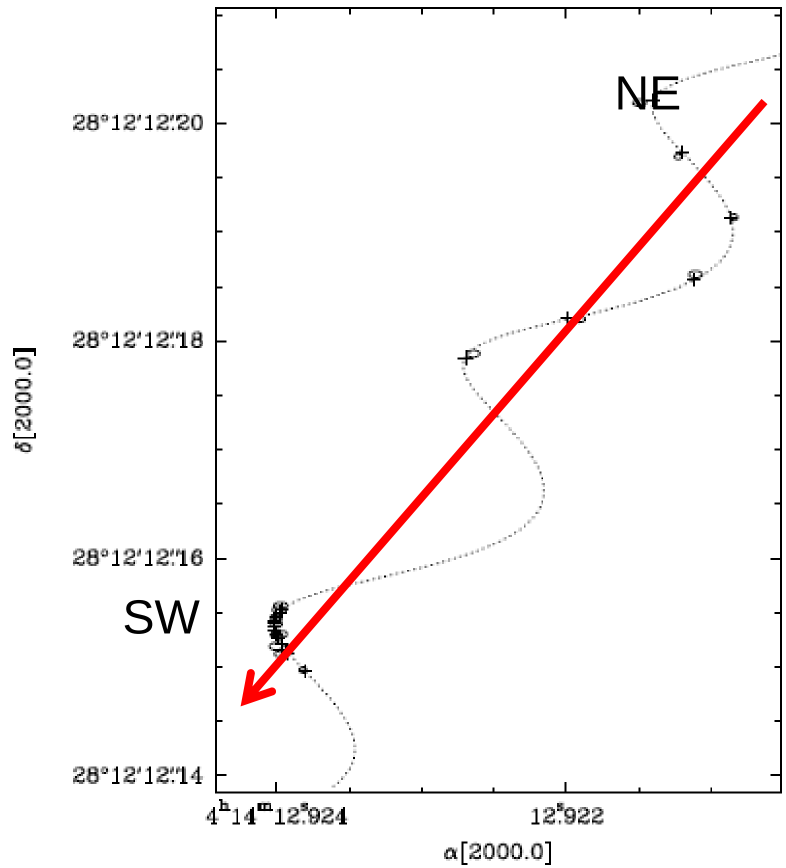
d = 132.8 ± 0.5 pc

0.4% error

d = 128.5 ± 0.6 pc

0.5% error

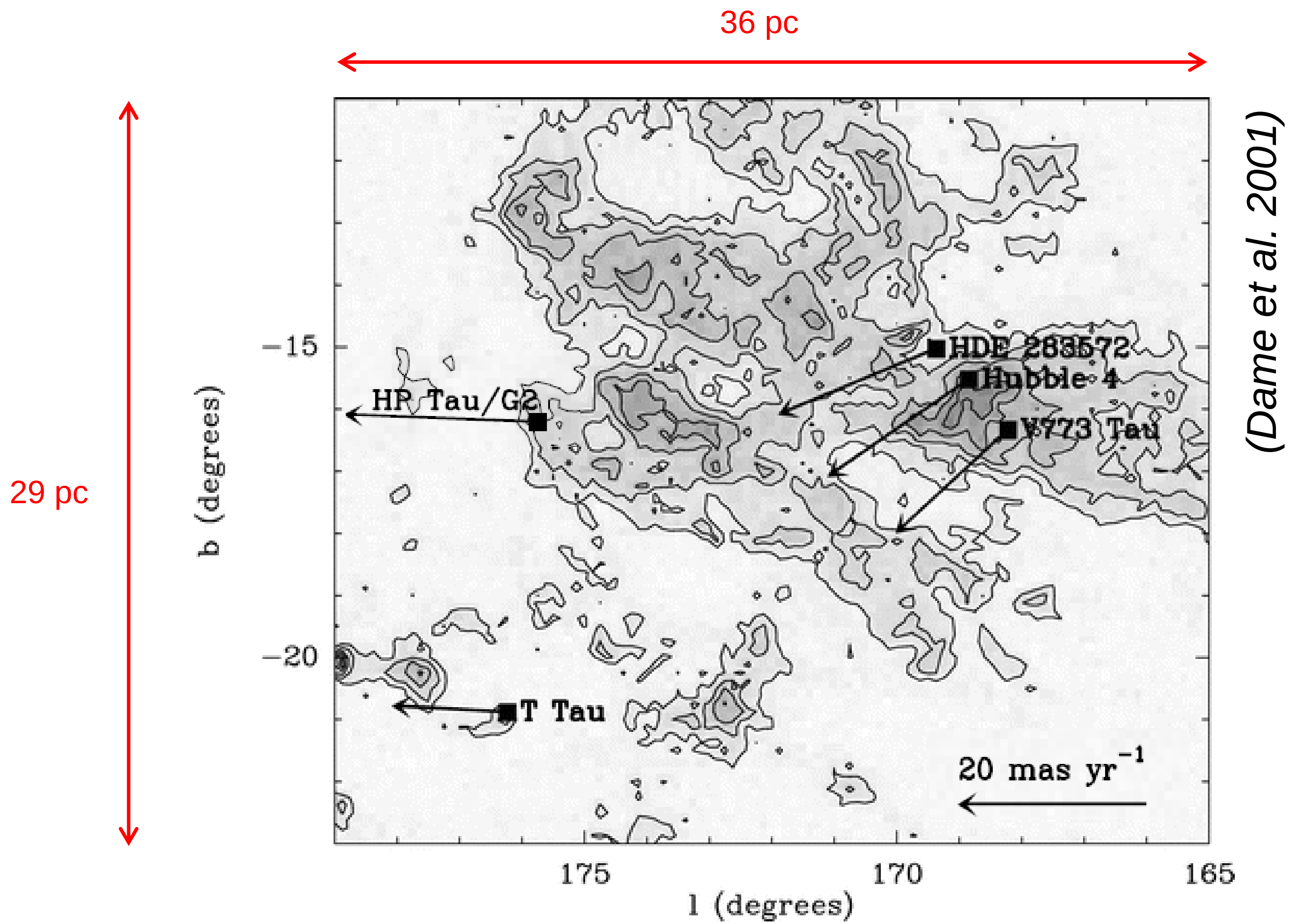




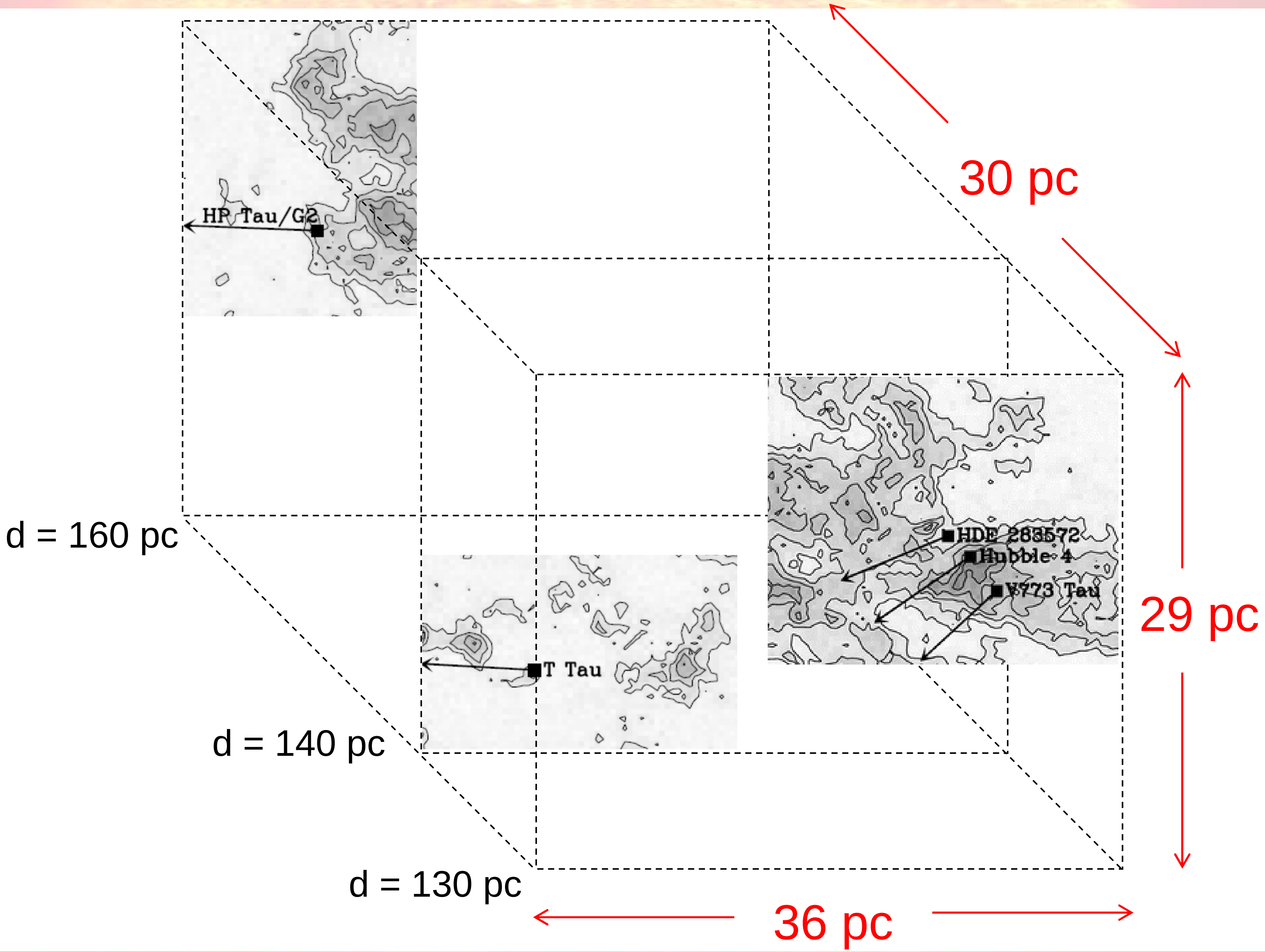
d = 161.2 ± 0.9 pc
0.6% error

d = 130.2 ± 2 pc
1.5% error

(Torres et al. 2009)

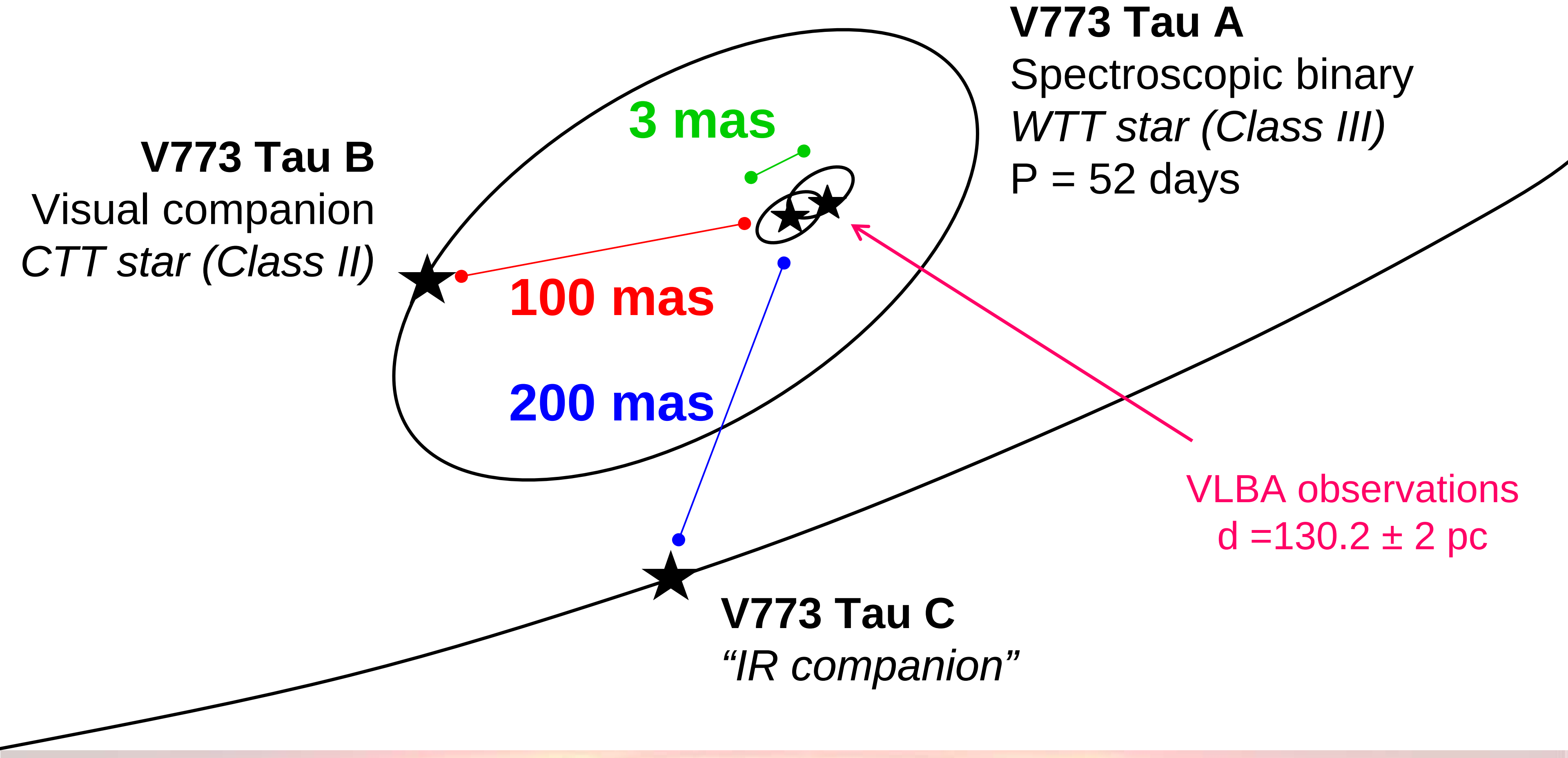


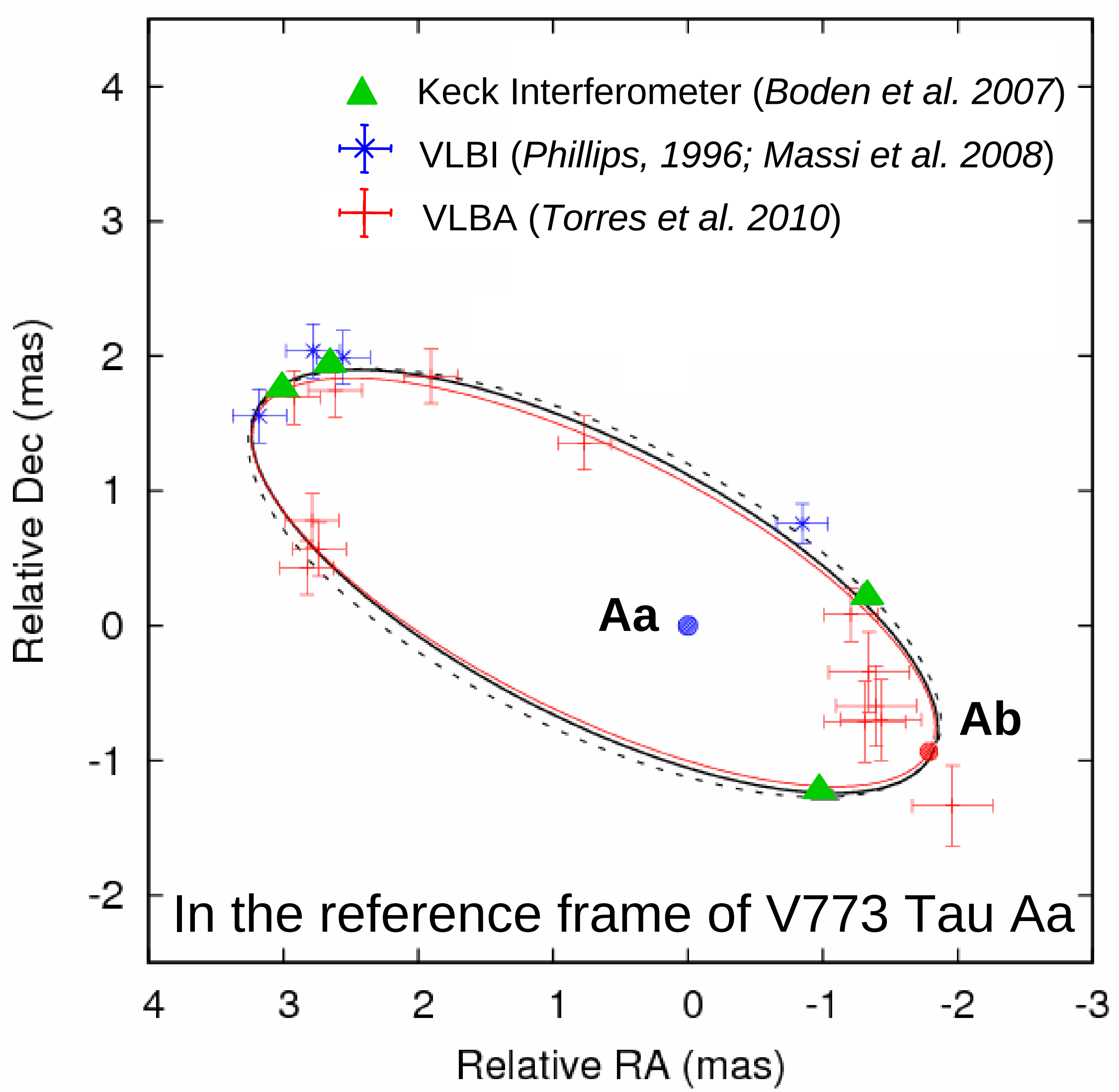
d ~ 139 pc


30 pc
HP Tau/G2
d = 160 pc
HDE 283572
Hubble 4
V773 Tau
29 pc
T Tau
d = 140 pc
d = 130 pc
36 pc

Theoretical evolutionary tracks

- Multiple system that display a variety of evolutionary states




Keck Interferometer (*Boden et al. 2007*)
VLBI (*Phillips, 1996; Massi et al. 2008*)
VLBA (*Torres et al. 2010*)
Aa
Ab
In the reference frame of V773 Tau Aa
Relative Dec (mas)
Relative RA (mas)
4
3
2
1
0
-1
-2
-3

- Spectrum ➔ Temperature
- Photometry IR ➔ magnitude
- VLBA ➔ d = 130.2 ± 2 pc

  } Luminosity
- Position in the HR Diagram ➔ Ages

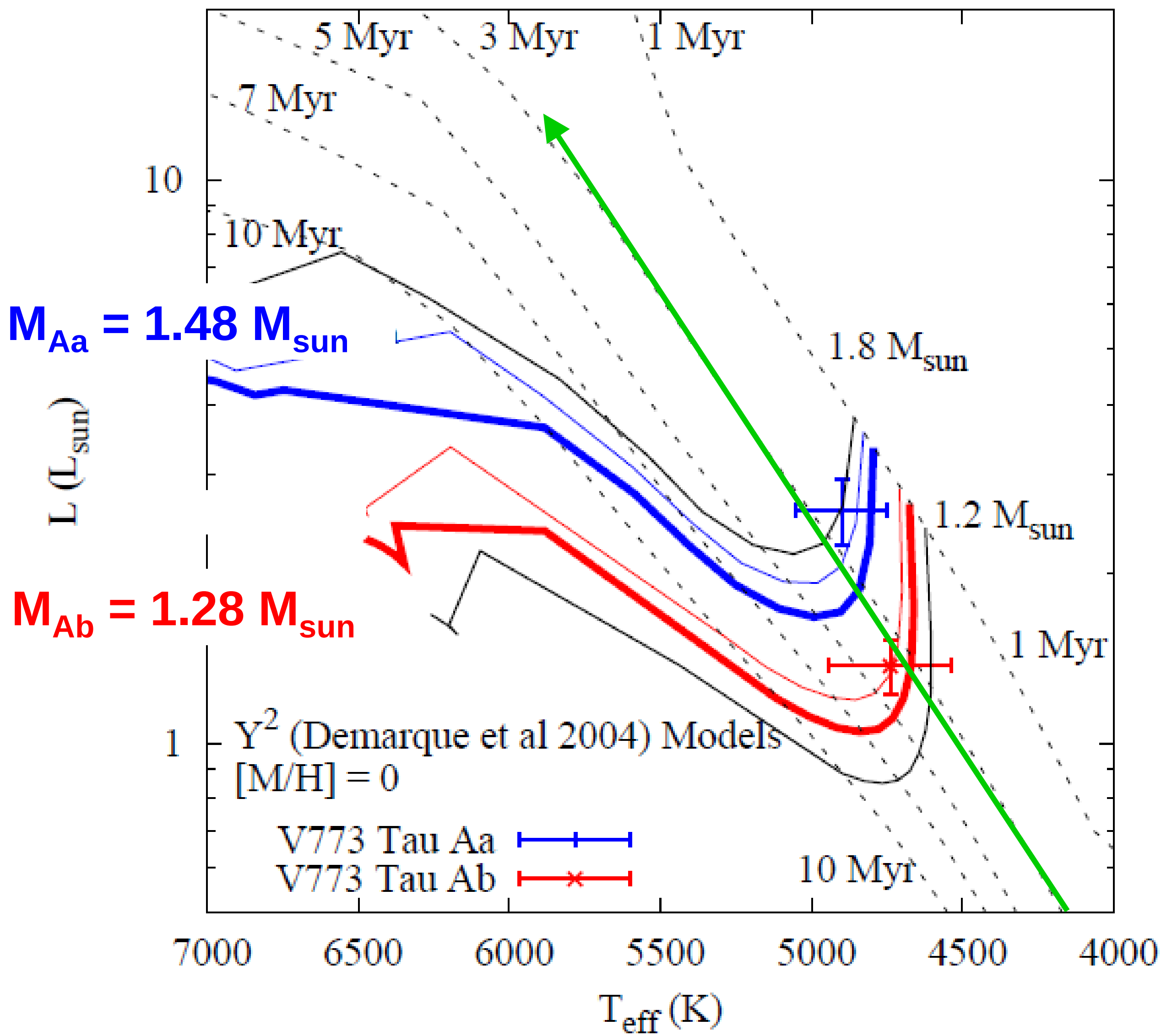
- RV + Keck + VLBI

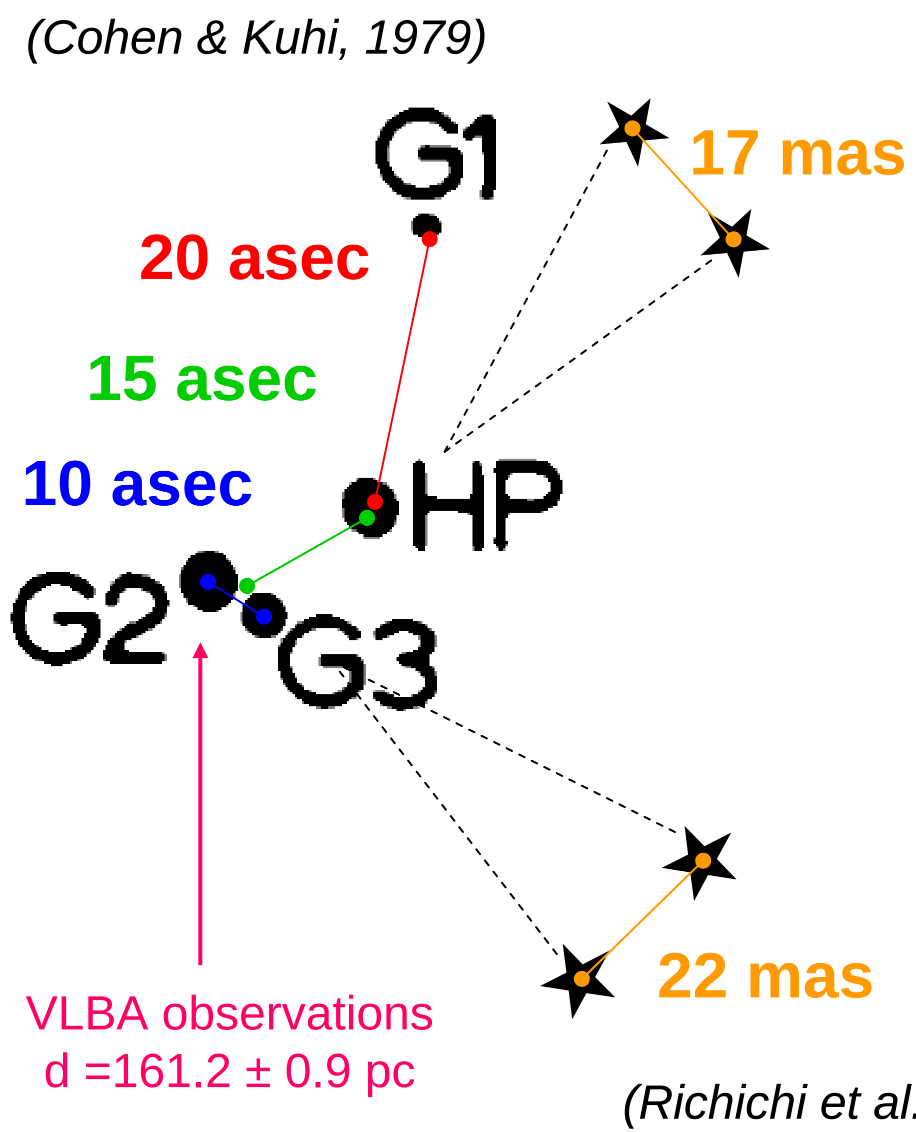
➔ $M_{Aa} = 1.48 \pm 0.12\ M_{sun}$

$M_{Ab} = 1.28 \pm 0.07\ M_{sun}$

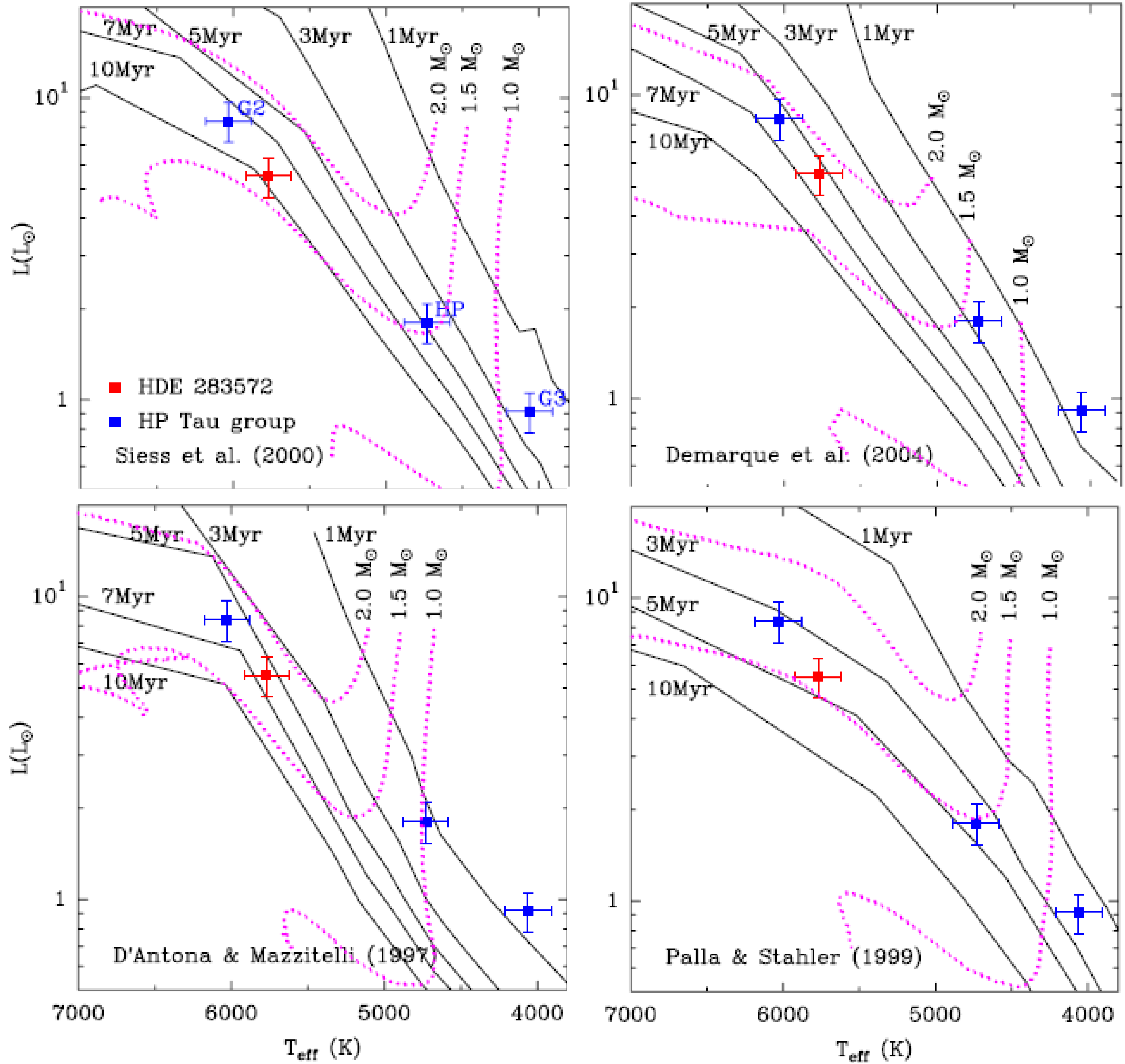
➔ Evolution of the system

(Torres et al. 2010)

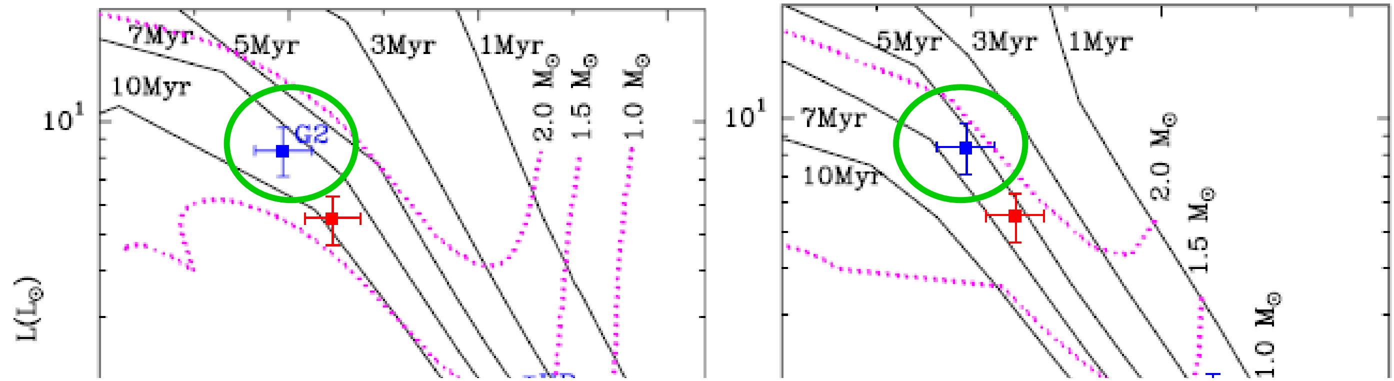




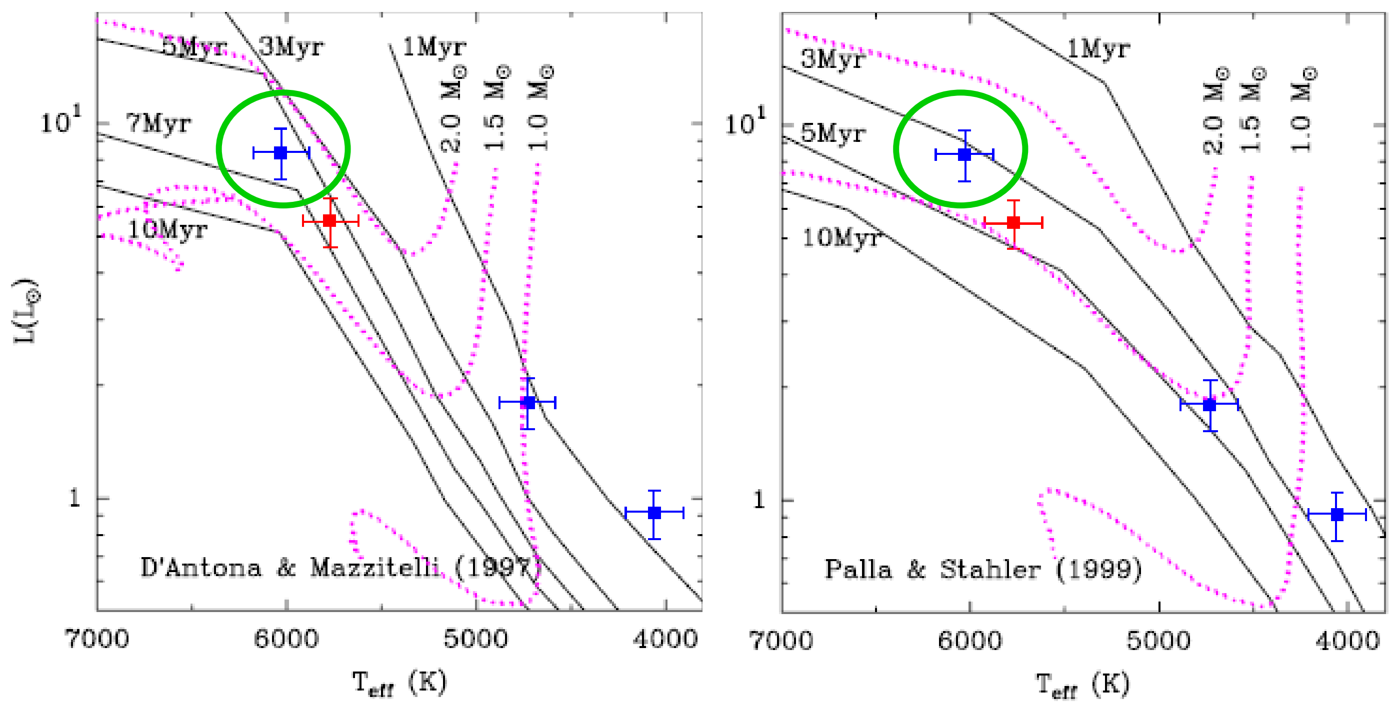
- HPTau is surrounded by a small group of young stars
- G2–G3 system appears to be a hierarchical triple system
- Members of this group are very likely to be:
  - physically associated
  - at the same distance

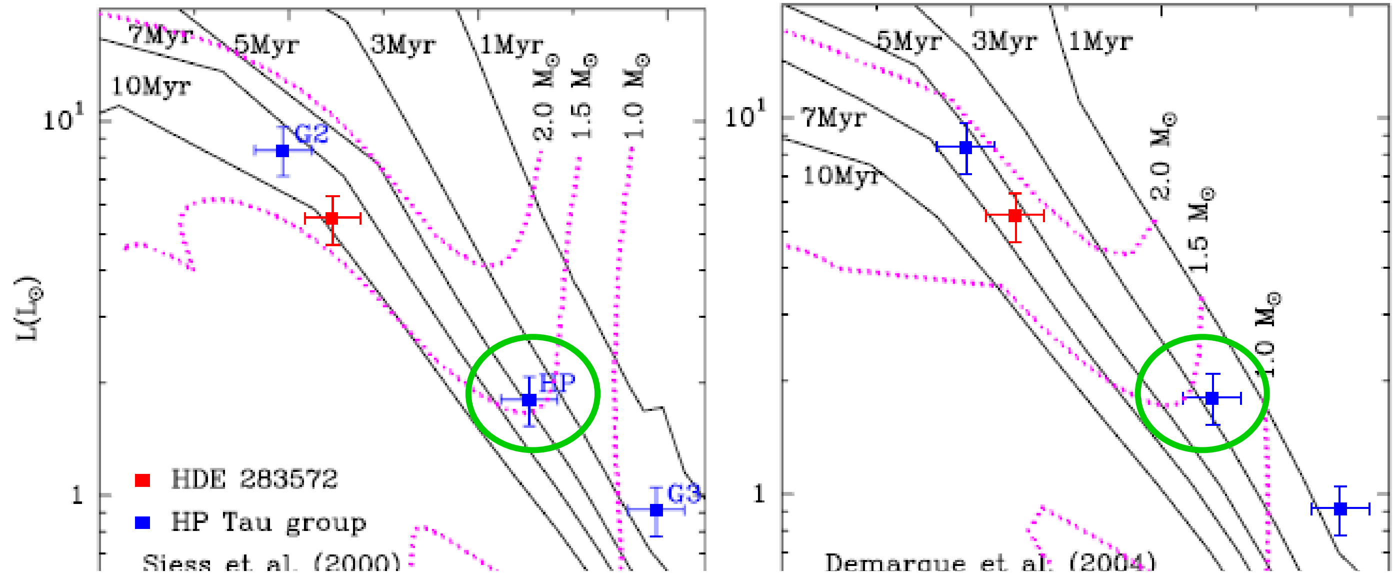


7Myr
5Myr
3Myr
1Myr
10Myr
2.0 M⊙
1.5 M⊙
1.0 M⊙
G2
HP
G3
HDE 283572
HP Tau group
Siess et al. (2000)
Demarque et al. (2004)
D'Antona & Mazzitelli (1997)
Palla & Stahler (1999)
L(L⊙)
Teff (K)
7000
6000
5000
4000
10^1
1



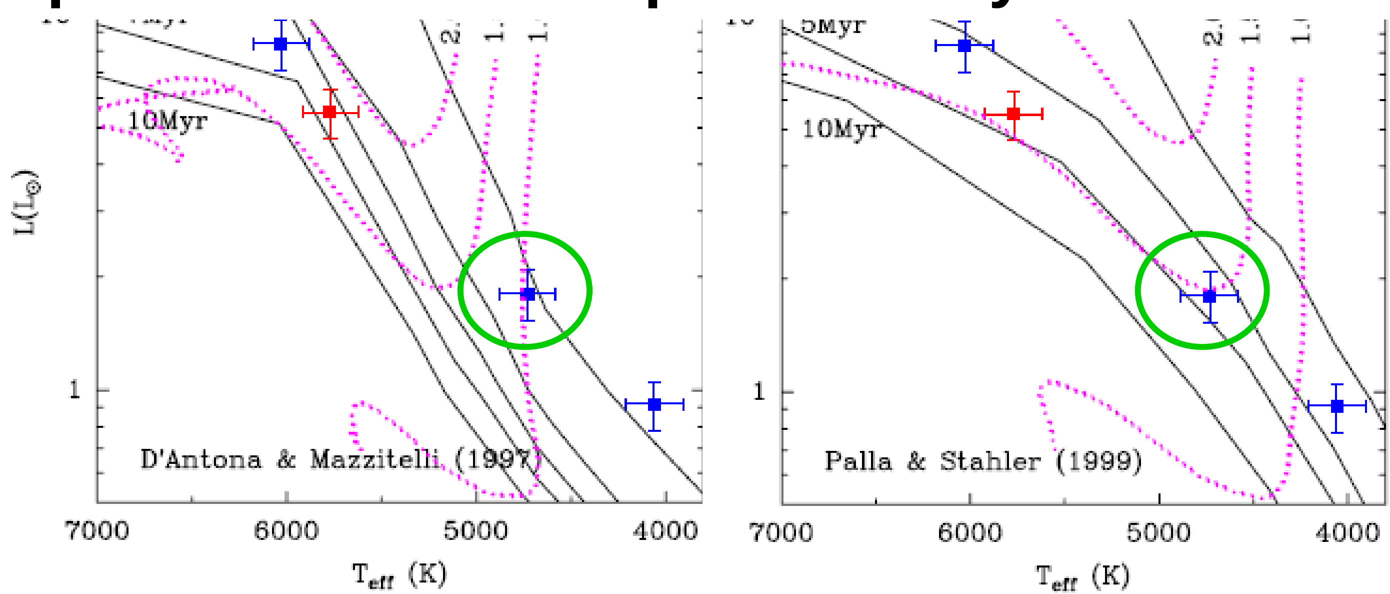
HPTau/G2 ➔ masses between 1.7 and 1.9 M_{sun}
different models predict masses consistent with each other at the 10%

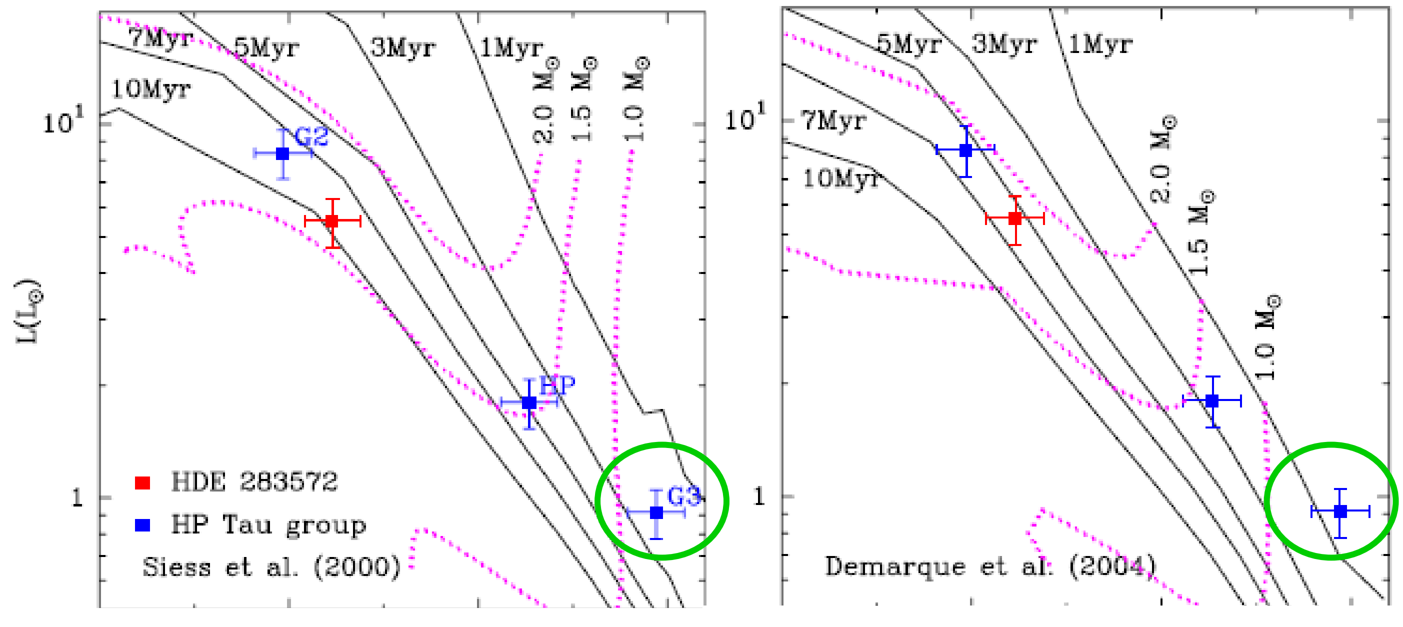




HPTau ➔ masses between 1 and 1.5 M_{sun}

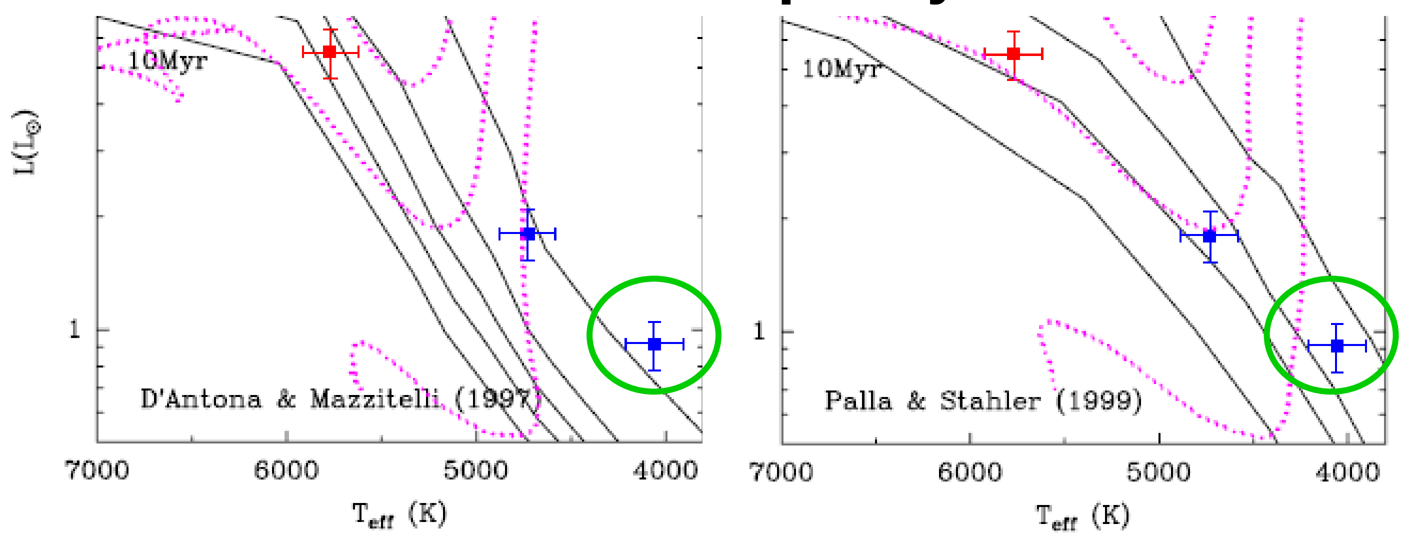
35% spread in the values predicted by different models





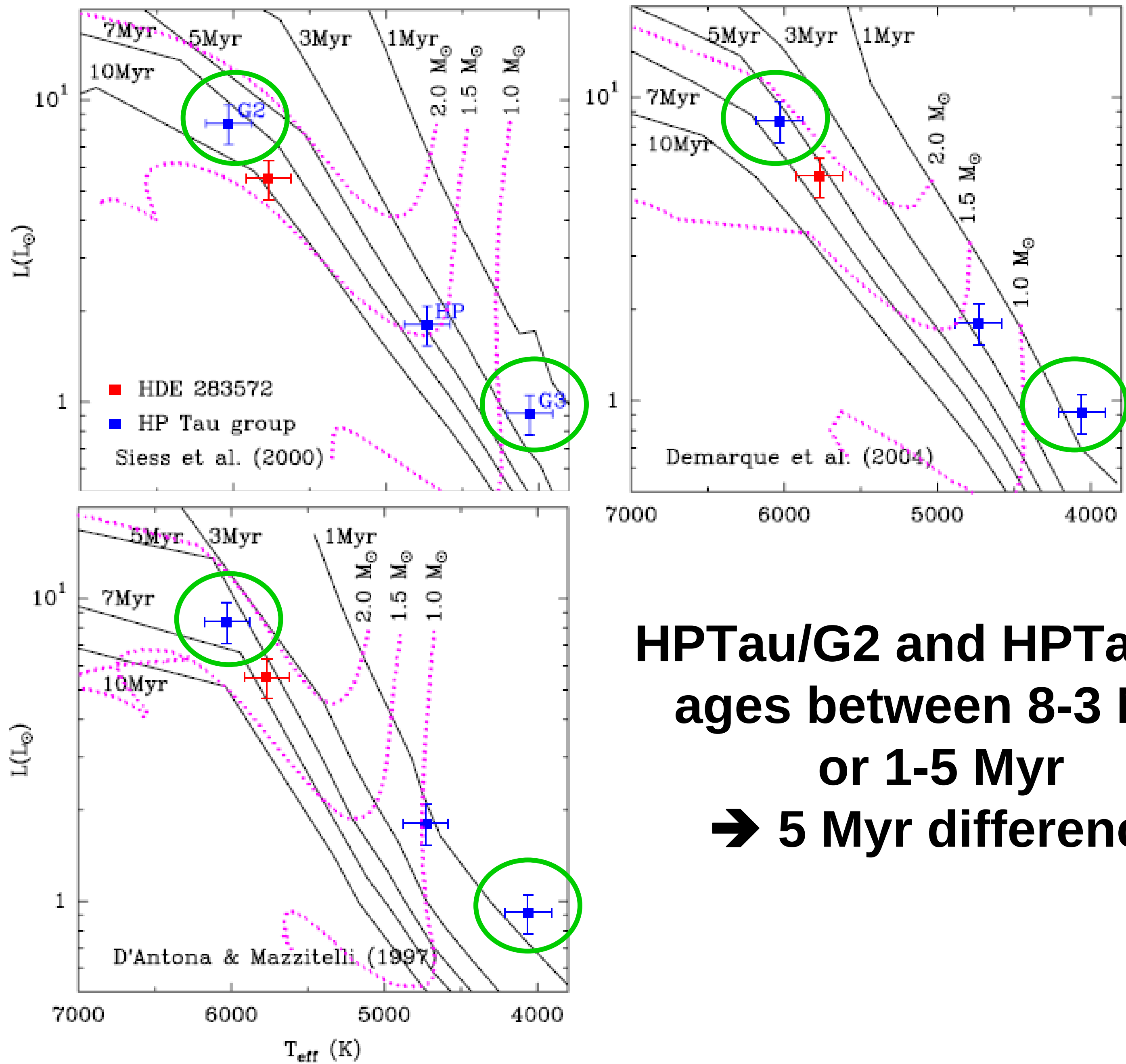
HPTau/G3 ➔ masses between 0.5 and 0.8 M_{sun}

40% discrepancy



- PMS evolutionary models tend to become more discrepant at lower mass
  (Hillenbrand et al. 2008)
- Without dynamical masses, it is impossible to asses which of the models used provides the best answer

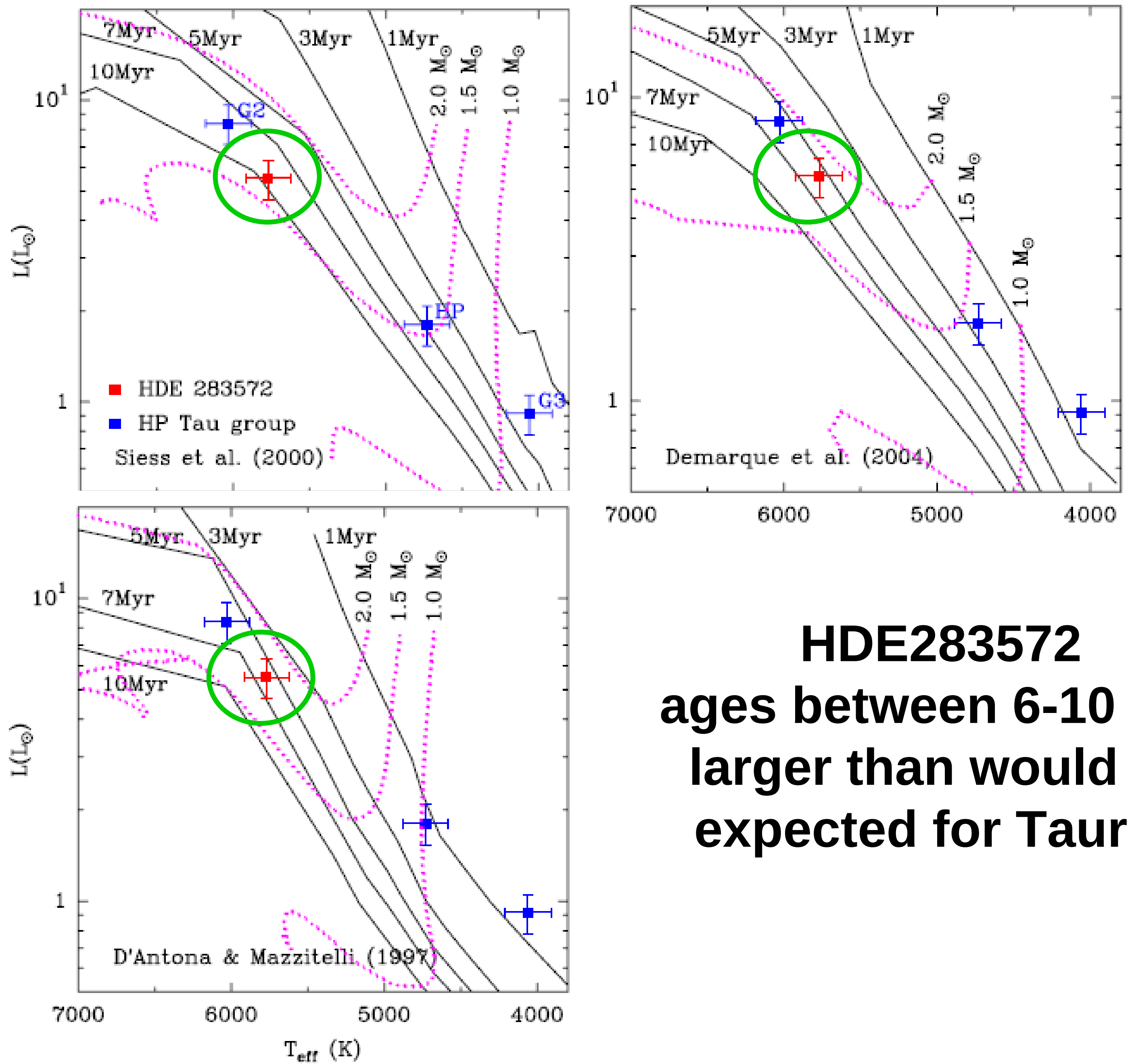
- Members of HPTau group are likely to be physically associated, they are expected to be nearly coeval
- Particularly true for HPTau/G2 and HPTau/G3 that are believed to form a system



HPTau/G2 and HPTau/G3 ages between 8-3 Myr or 1-5 Myr

➔ 5 Myr difference

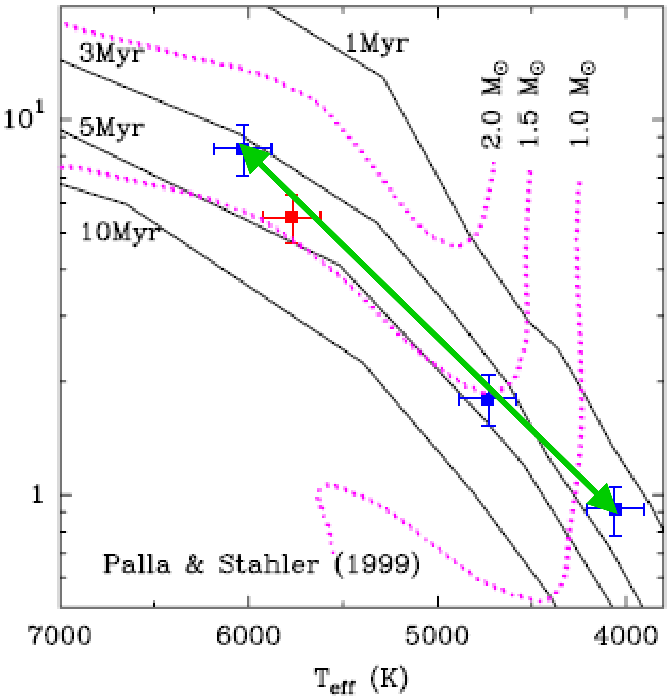
- In principle those differences could be real
- The vast majority of low-mass stars in Taurus (spectral types M and K) have ages smaller than 3 Myr *(Briceño et al. 2002)*
- Existing models could significantly over-predict the age of the relatively massive stars ($M \geq 1.5\ M_{sun}$) *(Hillenbrand et al. 2008)*



HDE283572
ages between 6-10 Myr larger than would be expected for Taurus

- The only one model that predicts similar ages for the 3 members in HPTau group is that for Palla & Staller (errors fall on the 3 Myr isochrone)
- Consistent with the ages of lower mass stars in Taurus

(Briceño et al. 2002)



- We have increased the accuracy of stellar distances by orders of magnitude
  - Errors of less than 1% to stars in Taurus
  - Distances no longer main source of error when calculating physical parameters
- Now we can talk about structure of the star-formation complexes
- We can use proper motions to find birth places

- Observations of the structure of the stars at higher resolution allow direct and accurate orbit determination for young close binaries
  - Dynamical masses
  - Constrain PMS evolutionary models

- ... and also
  - High rate of very tight binaries in our sample
  - Flaring events
  - Variation in the structure of the active magnetosphere