The study of young stellar clusters with Gaia and VLBI astrometry

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XIX IAG Advanced School on Astrophysics: radioastronomy

FAPESP

FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

Young stellar clusters

- ❑ building blocks of the Galaxy throughout time and space

- ❑ young stellar clusters are important to
  - ❍ explain star and planet formation
  - ❍ connect models to observations

- ❑ star formation models depend on accurate observational constraints (e.g. **masses** and **ages**)

What we need …

… is to measure accurate distances.

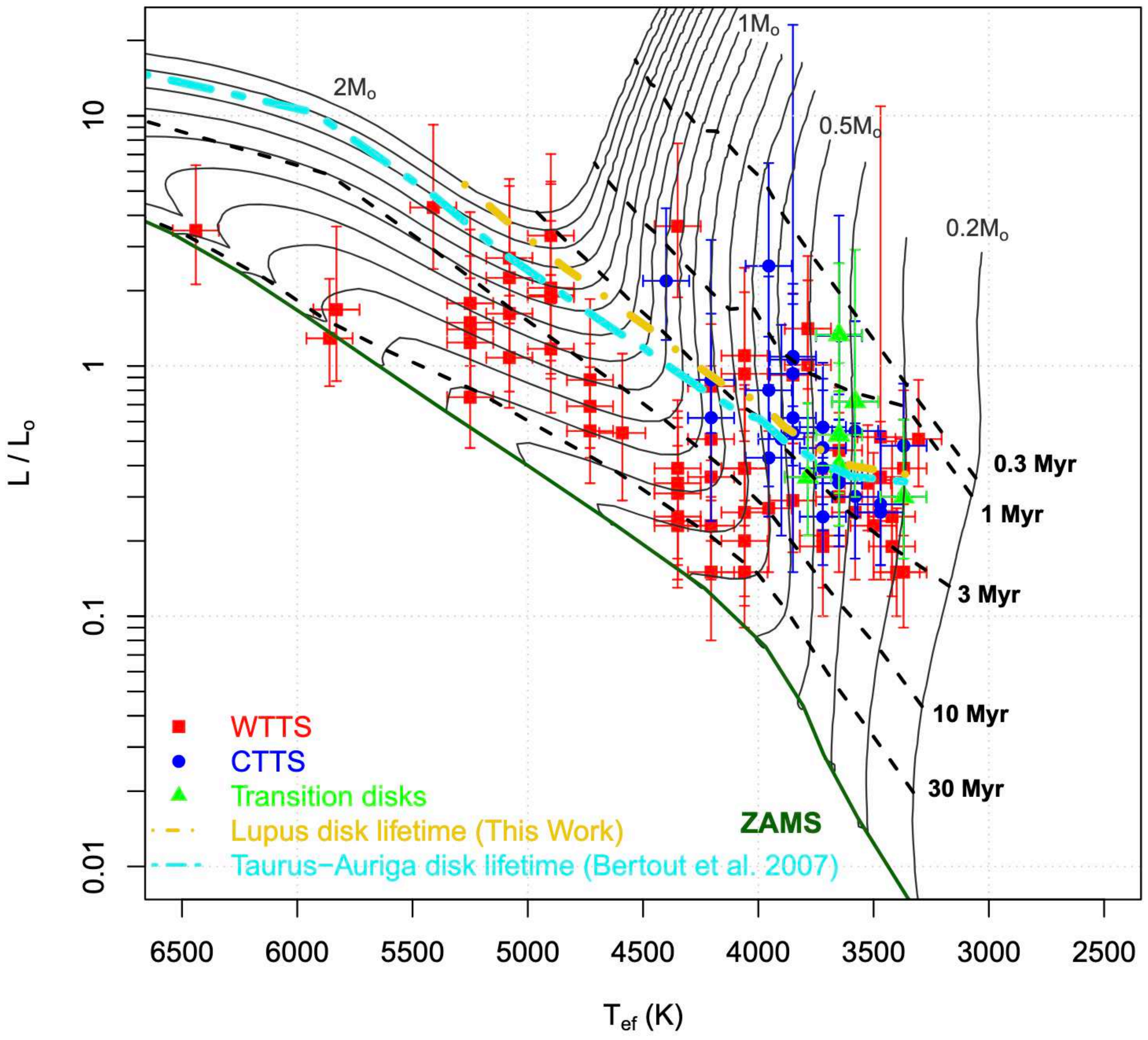
- ❑ Uncertainties on distances were **~25%** (past)

- ❑ Source of error for astrophysical parameters:
  - ❍ **25% error on the physical size**
  - ❍ **50% error on luminosities**
  - ❍ **>50% error on masses and ages** from models.

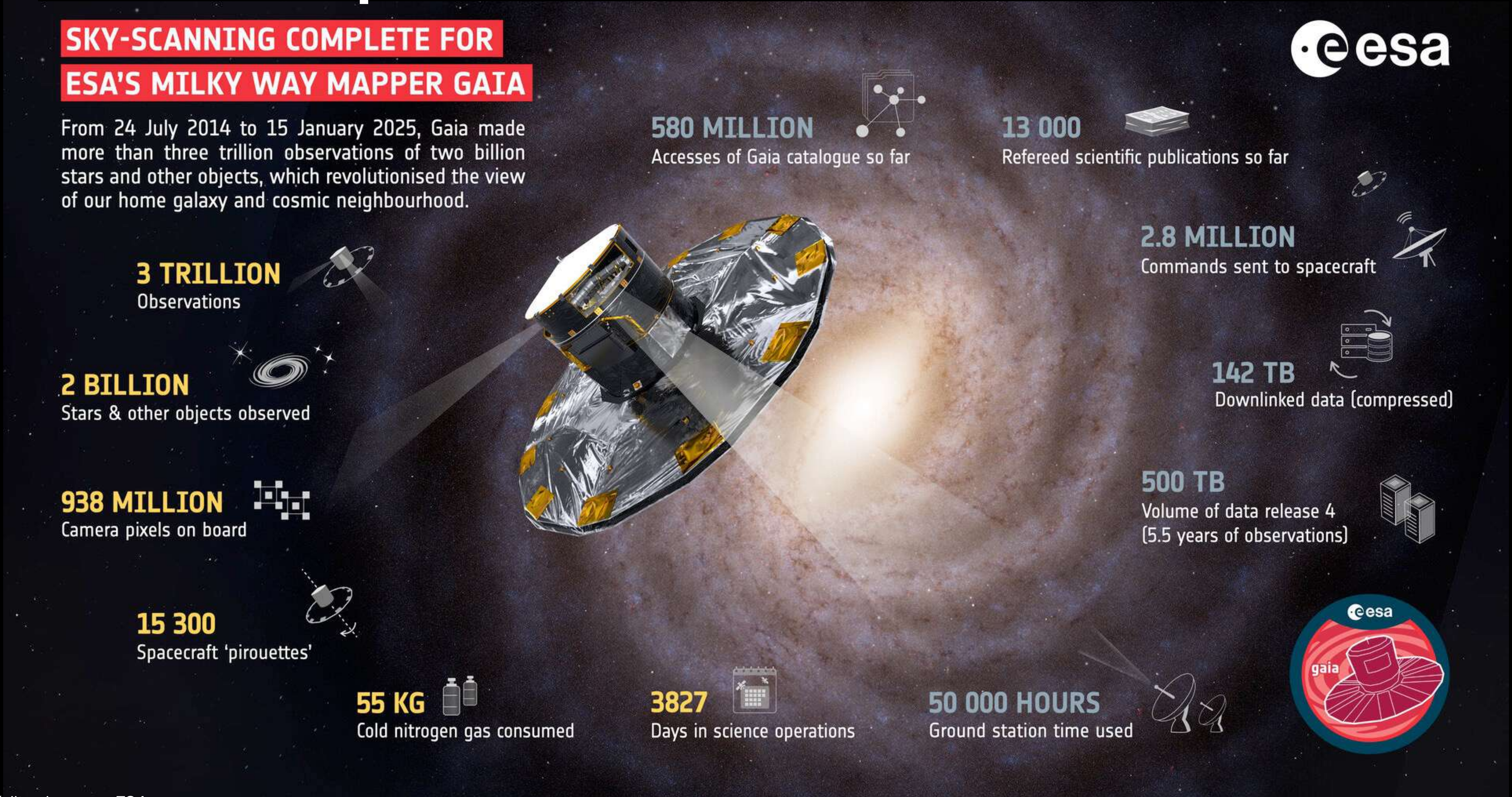
- ❑ **Structure** and **dynamics** of star-forming regions: important constraints on star formation processes and local history of star formation.

Lupus star forming region

(Galli et al. 2013)



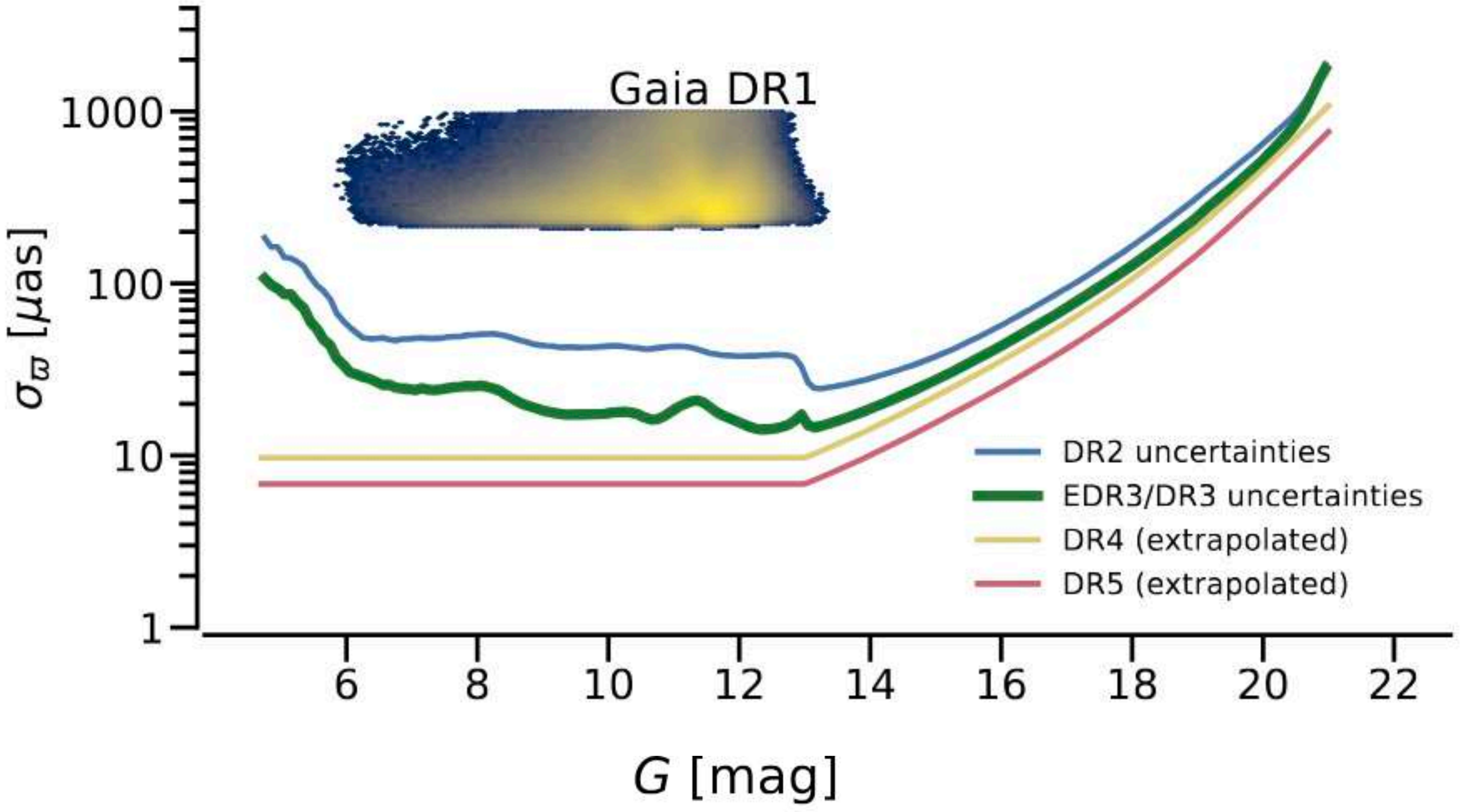
The Gaia space mission



Créditos imagem: ESA

Astrometric precison of the Gaia satellite

Parallax



Proper Motion

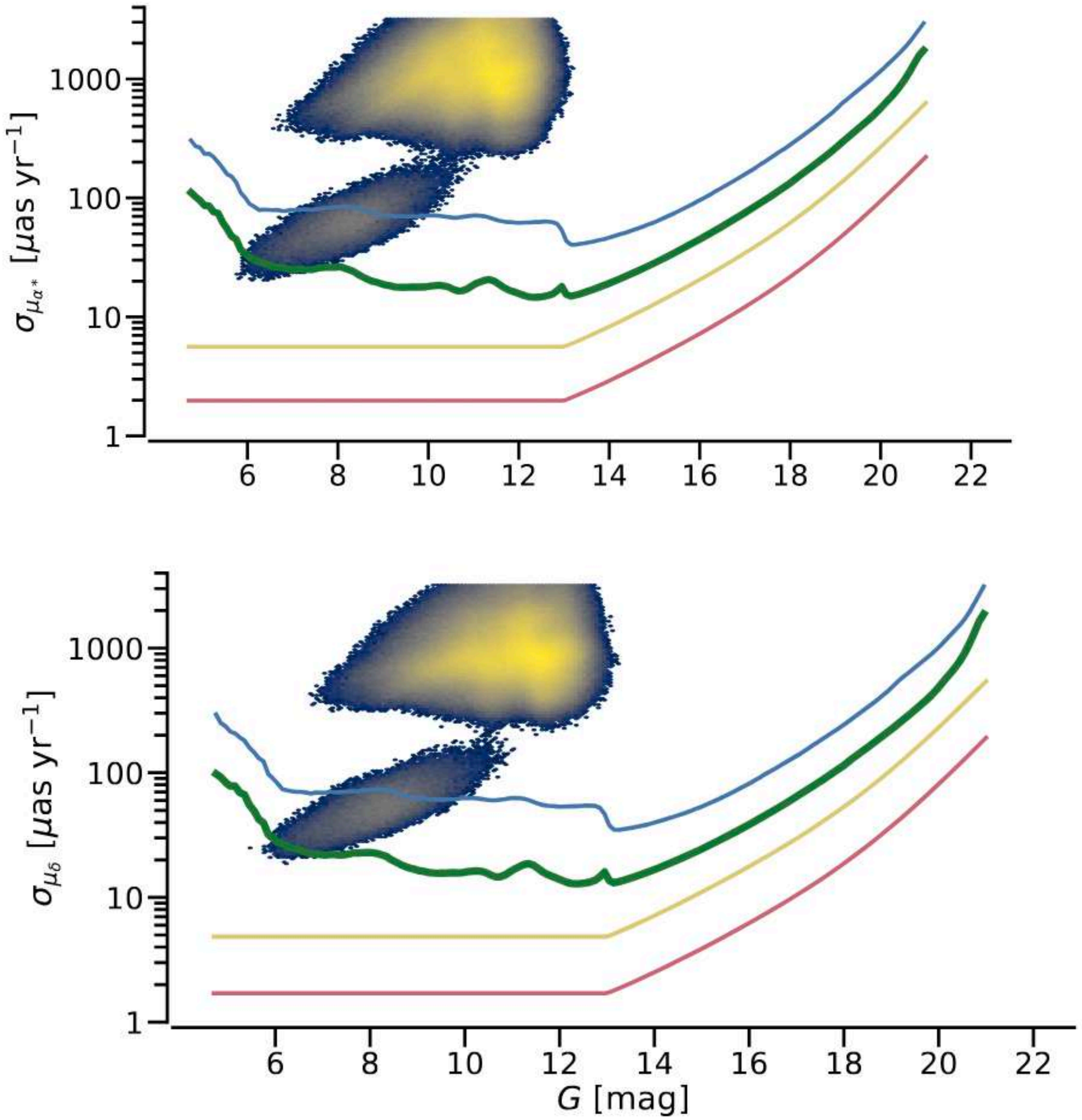


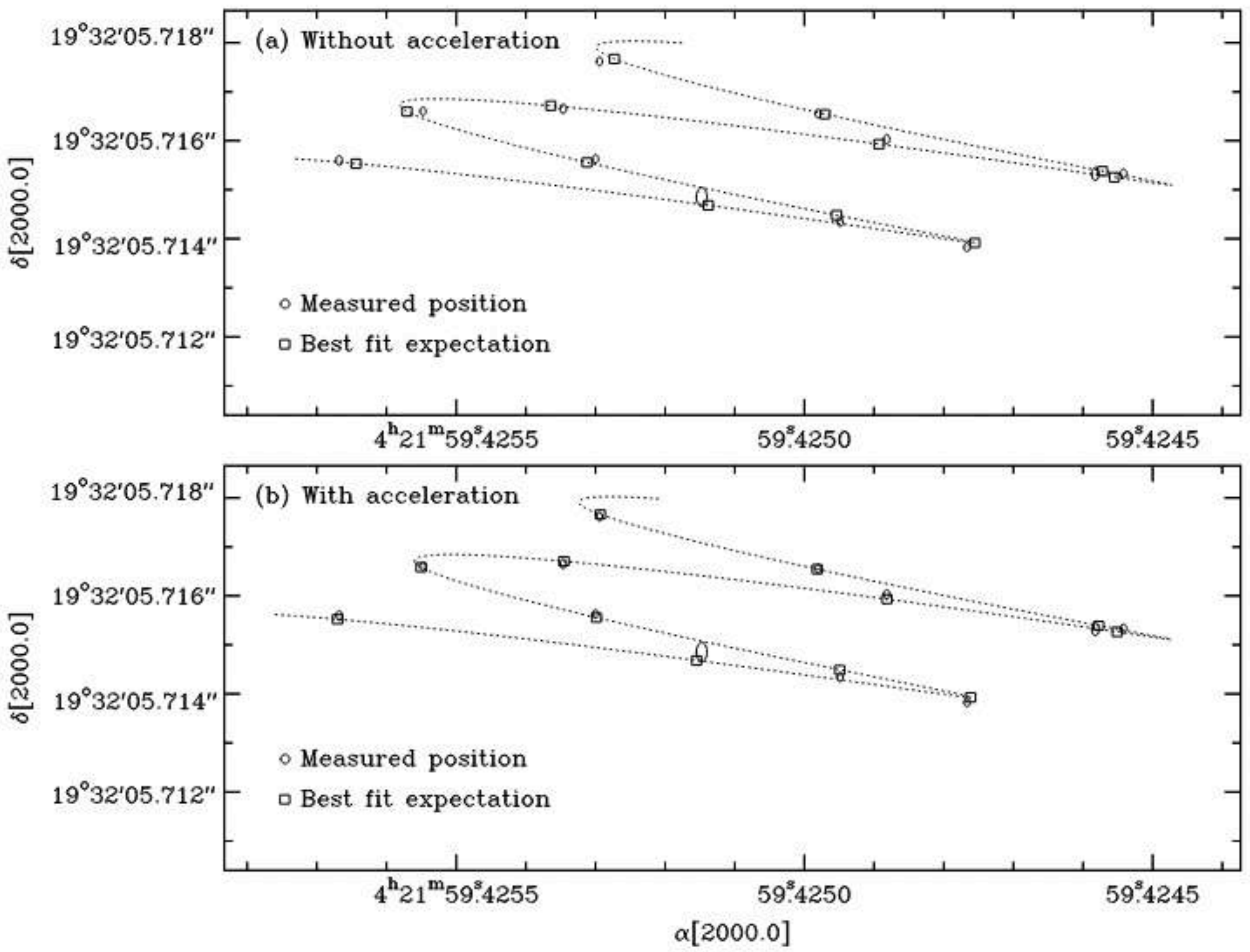
Image credits: Gaia Collaboration et al. (2022)

Mirco-arcsecond astrometry before Gaia

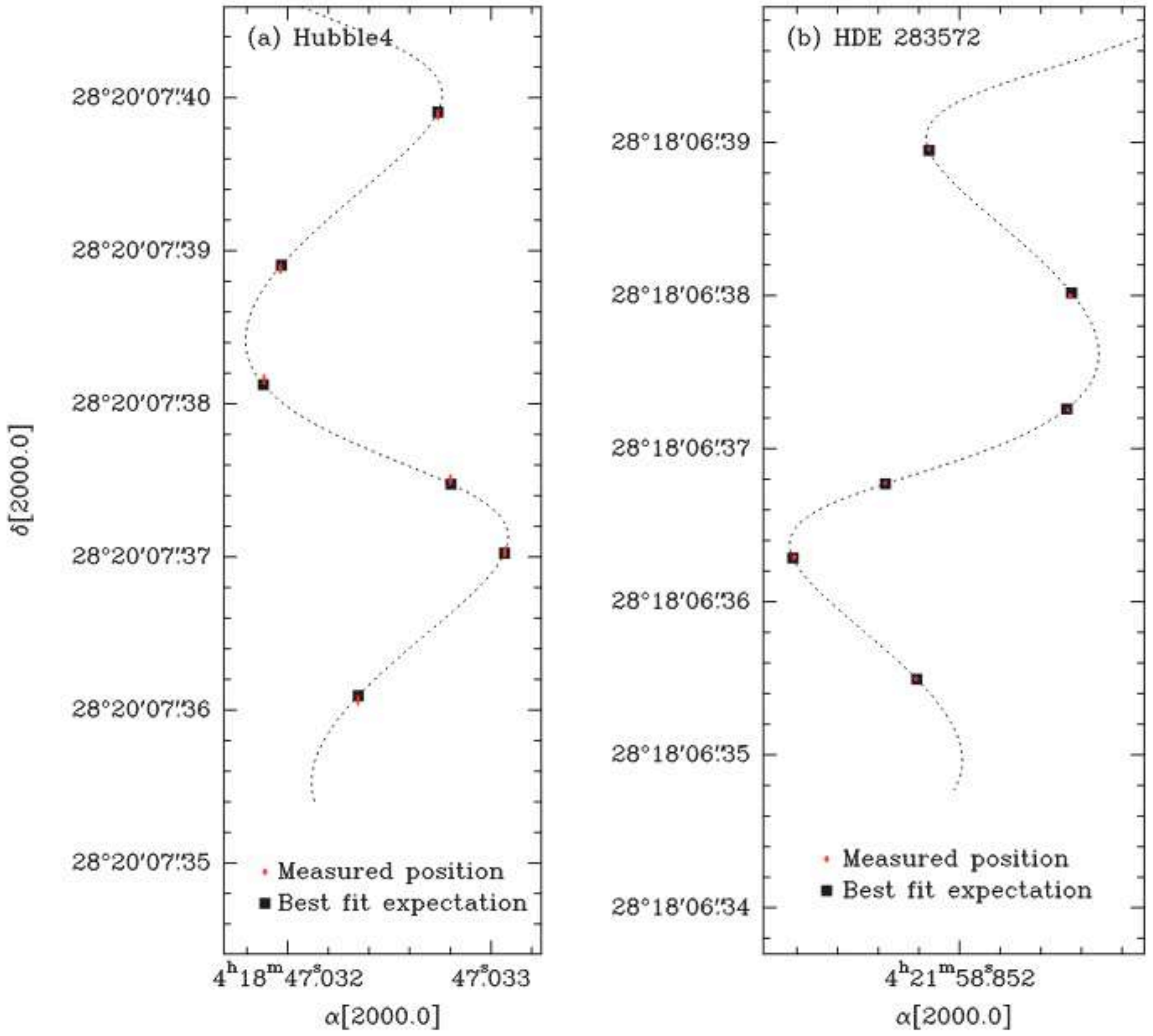
❑ Distance of 148 ± 5 pc V773Tau (**Lestrade et al. 1999**).

T Tau Sb

($d = 147 \pm 0.6$ pc, **Loinard et al. 2007**)

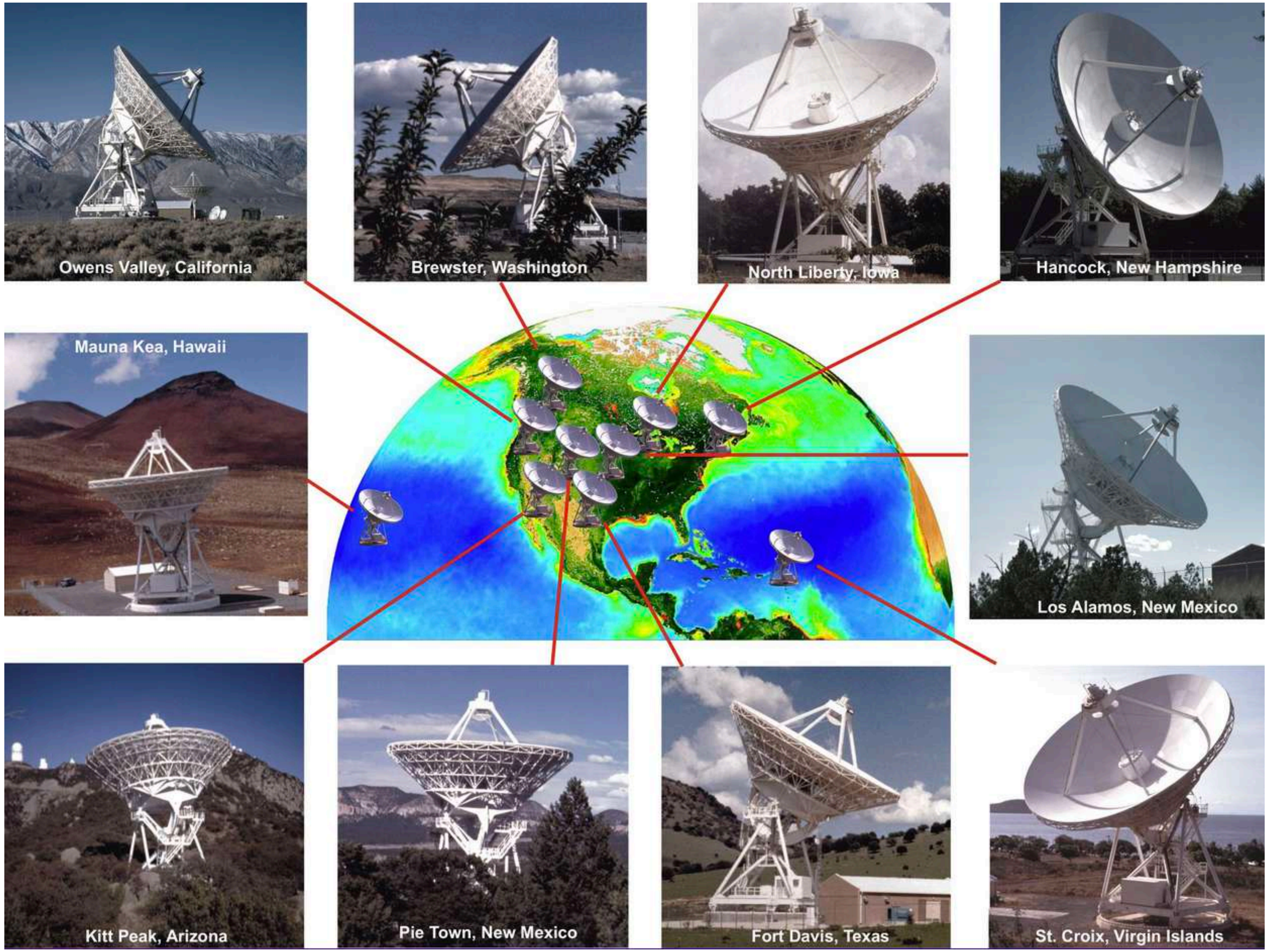


Hubble 4 ($d = 132.8 \pm 0.5$ pc) **HDE 283572** ($d = 128.5 \pm 0.6$ pc)



Torres et al. (2007)

The Very Long Baseline Array (VLBA)



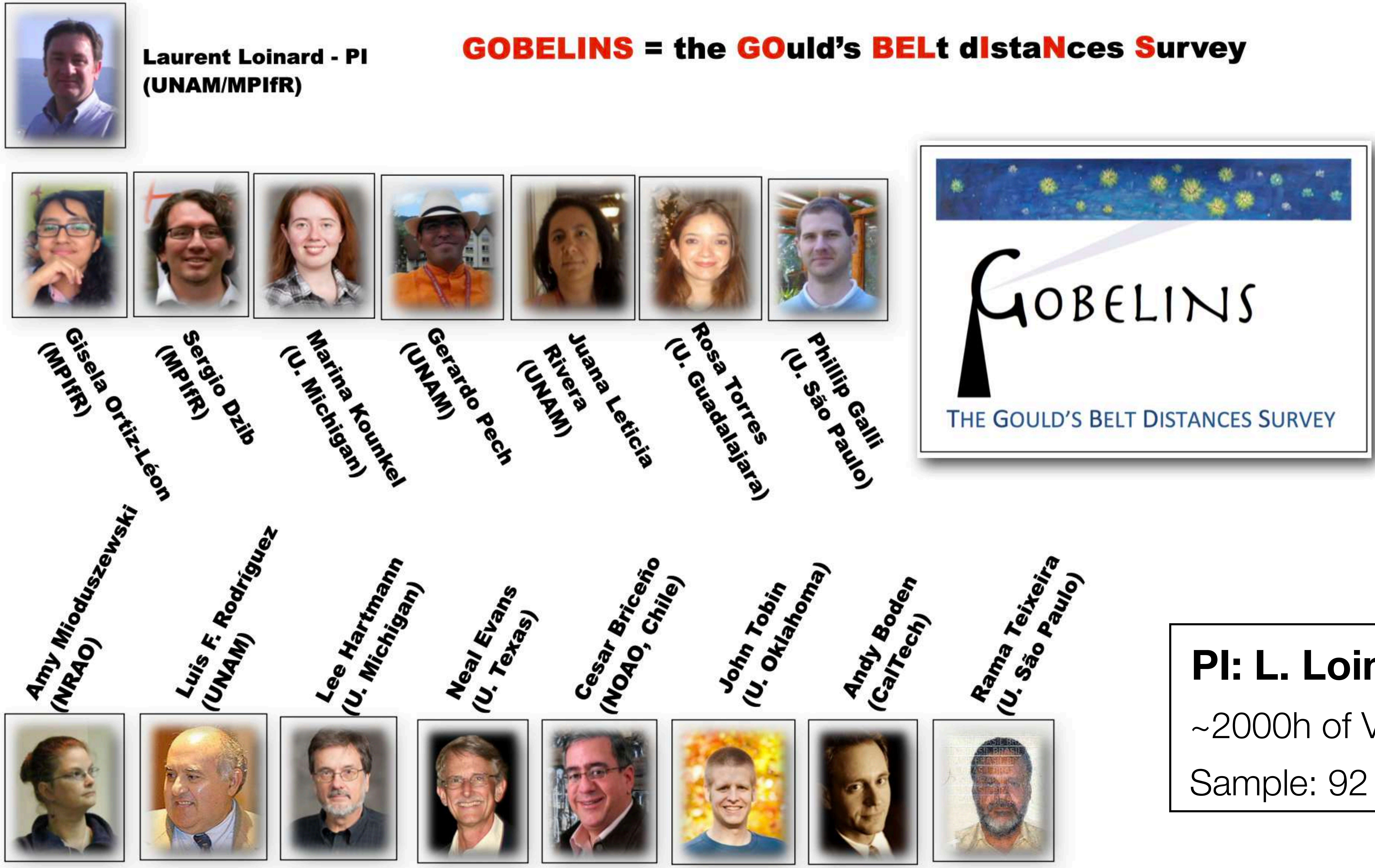
VLBA array:

- 10 radio telescopes (USA)
- baseline from MK to SC: 8600km
- operates from 3mm to 90cm

VLBA images (at 4cm):

- angular **resolution**: ~1 mas
- astrometric **precision**: $20 - 50\,\mu as$
- astrometry is relative to **quasars**

The Gould's Belt Distances Survey (GOBELINS)

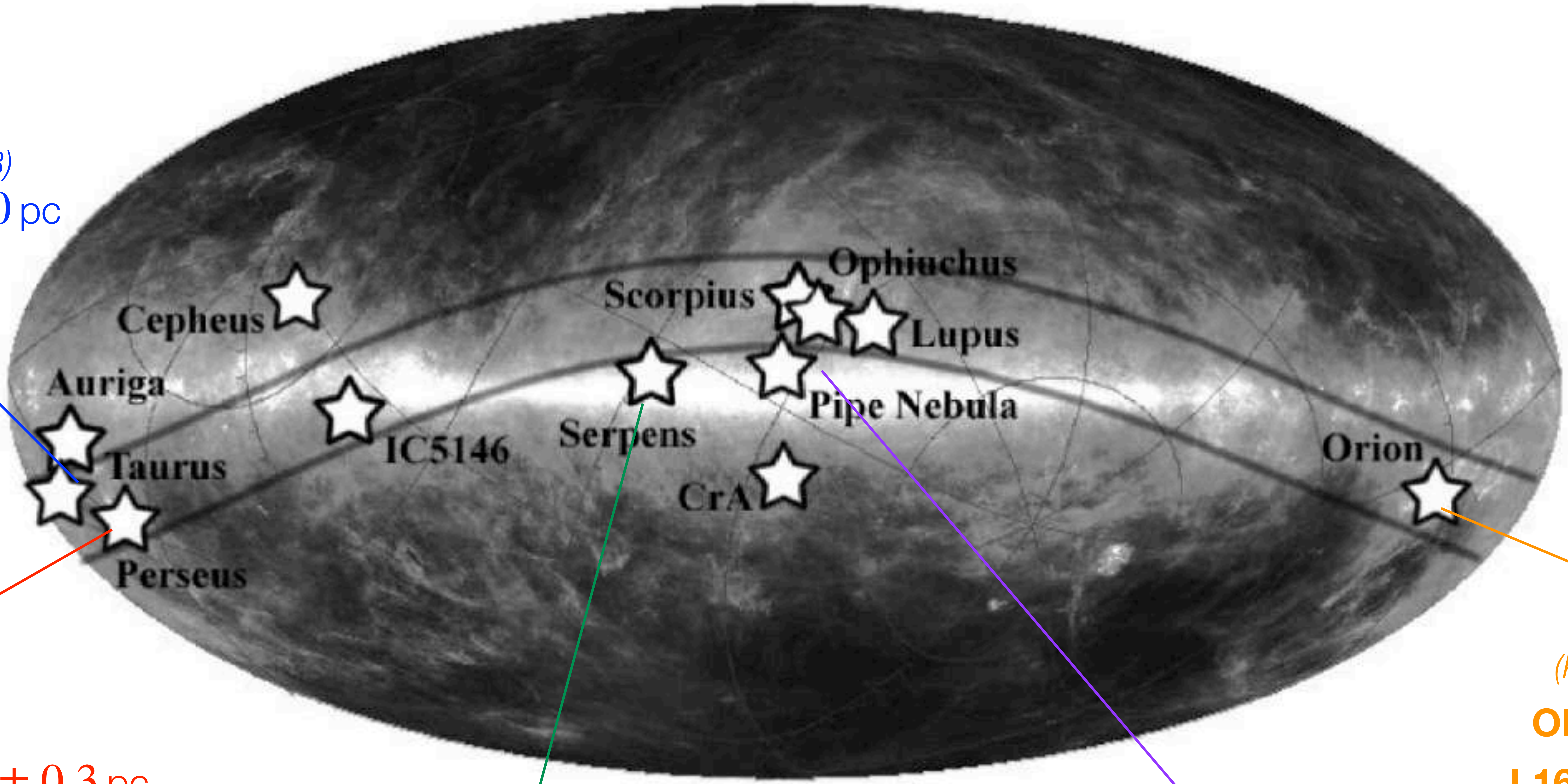


PI: L. Loinard

~2000h of VLBA time

Sample: 92 YSOs

The Gould's Belt Distances Survey (GOBELINS)



Perseus

(Ortiz-Léon et al. 2018)

IC348: $d = 321 \pm 10$ pc

Taurus

(Galli et al. 2018)

L1495: $d = 129.5 \pm 0.3$ pc

B216: $d = 158.1 \pm 1.2$ pc

L1551: $d = 147.3 \pm 0.5$ pc

L1536: $d = 162.7 \pm 0.8$ pc

Serpens

(Ortiz-Léon et al. 2017b)

Main/W40: $d = 436.0 \pm 9.2$ pc

Ophiuchus

(Ortiz-Léon et al. 2017a)

L1688: $d = 137.3 \pm 1.2$ pc

L1689: $d = 147.3 \pm 3.4$ pc

Orion

(Kounkel et al. 2017)

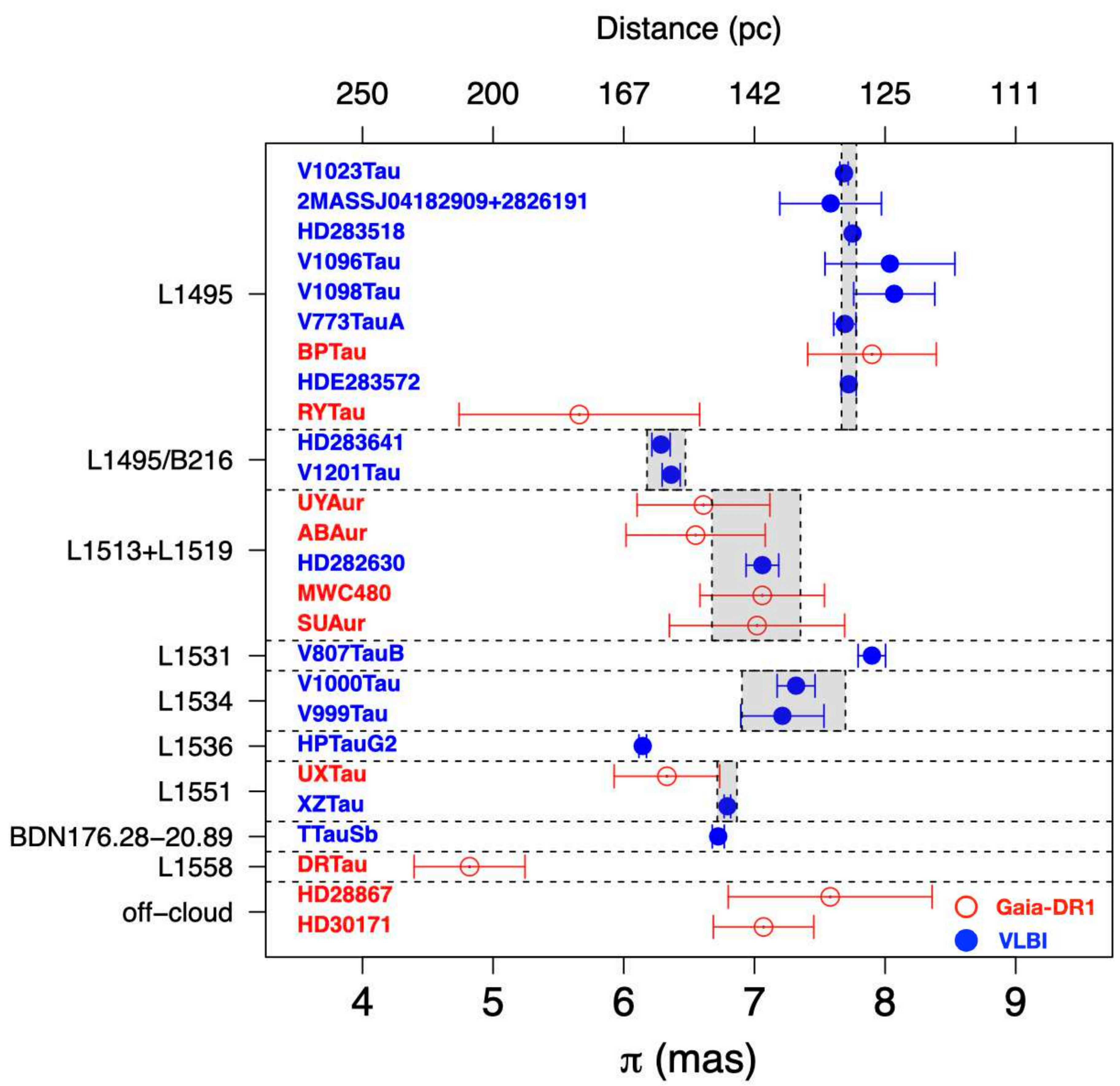
ONC: $d = 388 \pm 5$ pc

L1641: $d = 428 \pm 10$ pc

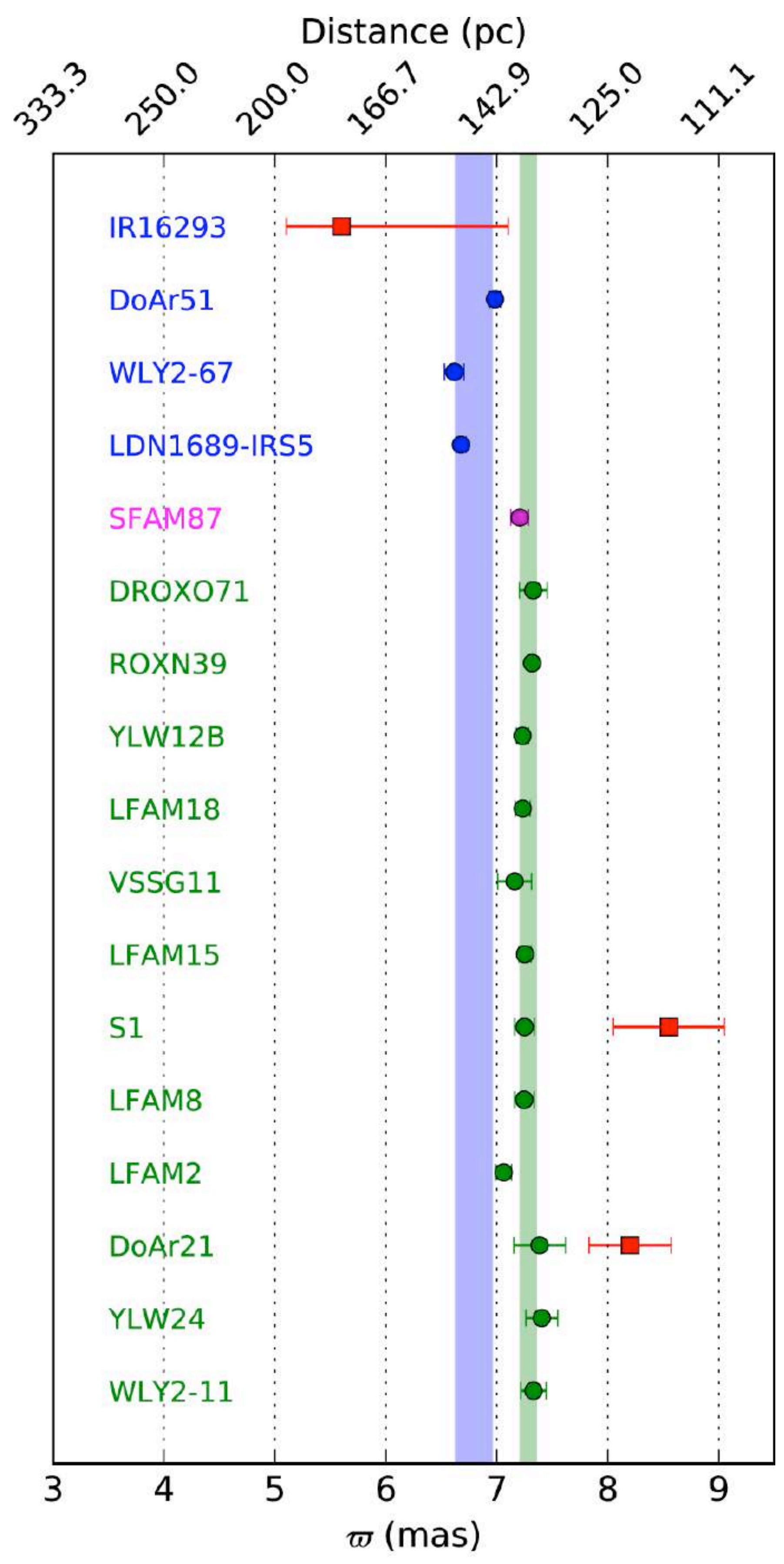
NGC 2068: $d = 388 \pm 10$ pc

The Gould's Belt Distances Survey (GOBELINS)

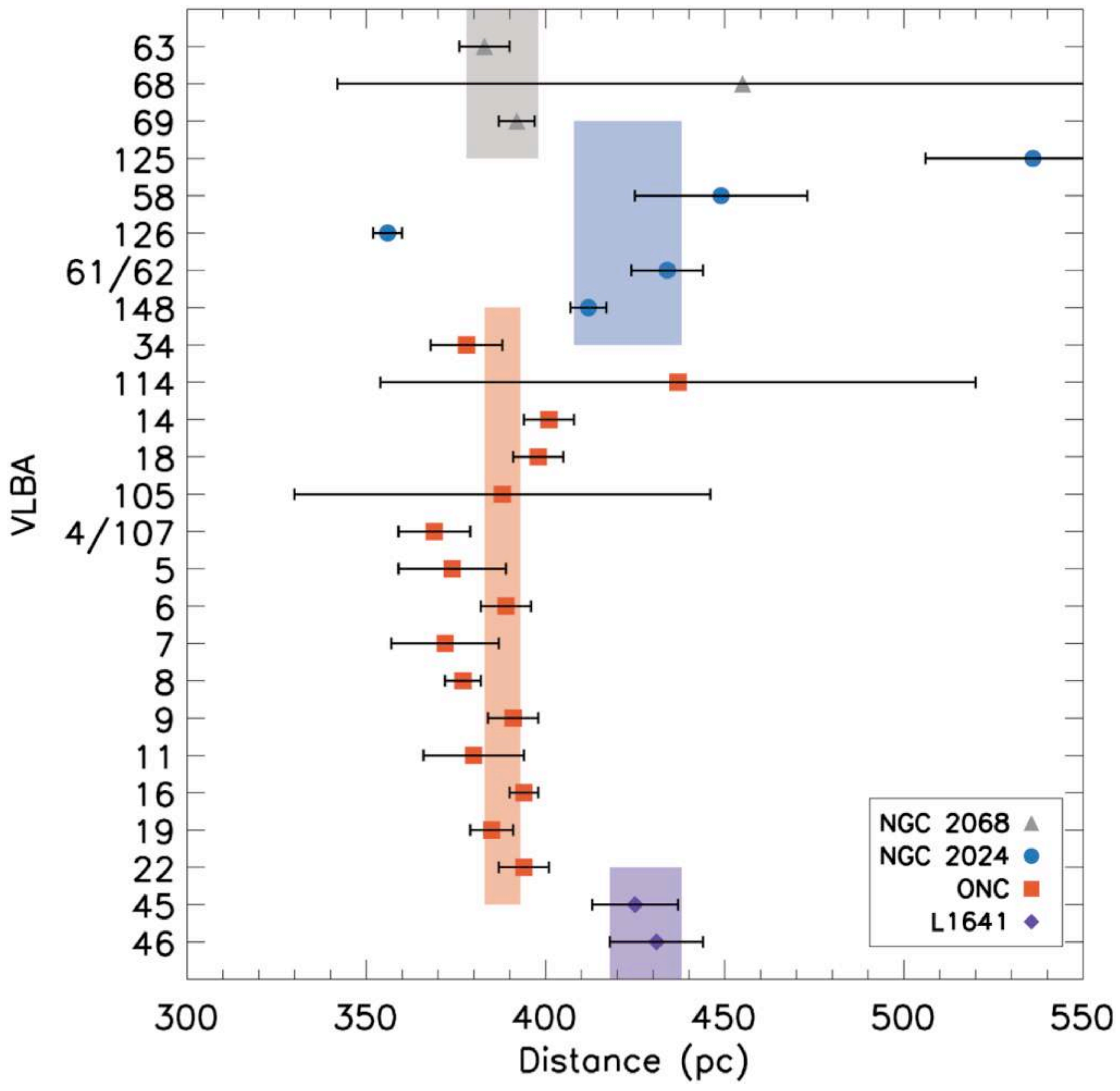
Taurus
(Galli et al. 2018)



Ophiuchus
(Ortiz-Léon et al. 2017)



Orion
(Kounkel et al. 2017)

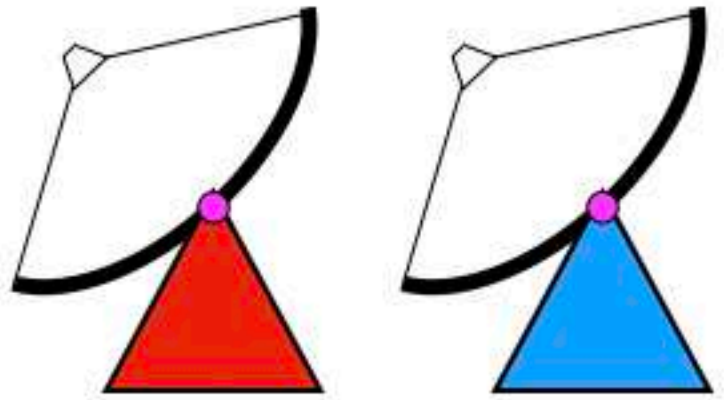


Important depth effects!

State-of-the-art astrometry

Gaia

- ❑ space astronomy
- ❑ optical domain
- ❑ all-sky survey
- ❑ affected by high extinction
- ❑ micro-arcsecond astrometry



VLBI

- ❑ ground-based astronomy
- ❑ radio domain
- ❑ target-oriented survey
- ❑ affected by target variability
- ❑ micro-arcsecond astrometry

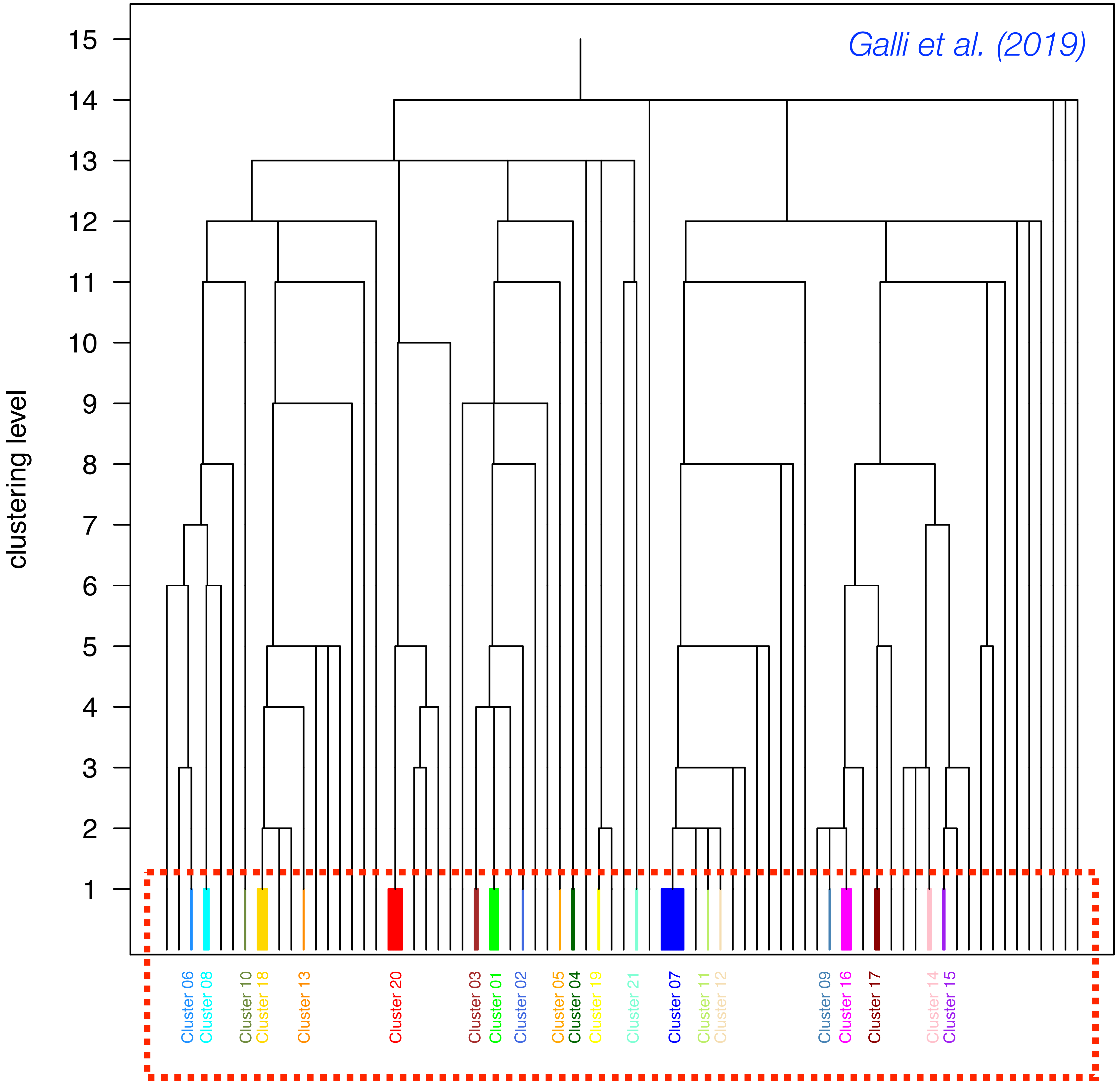
The two projects complement each other!

The Taurus star-forming region revealed by Gaia and VLBI

- ❑ **Sample:** 415 stars
- ❑ **Data:** Gaia and VLBI astrometry
- ❑ **Methods:** hiearchical clustering

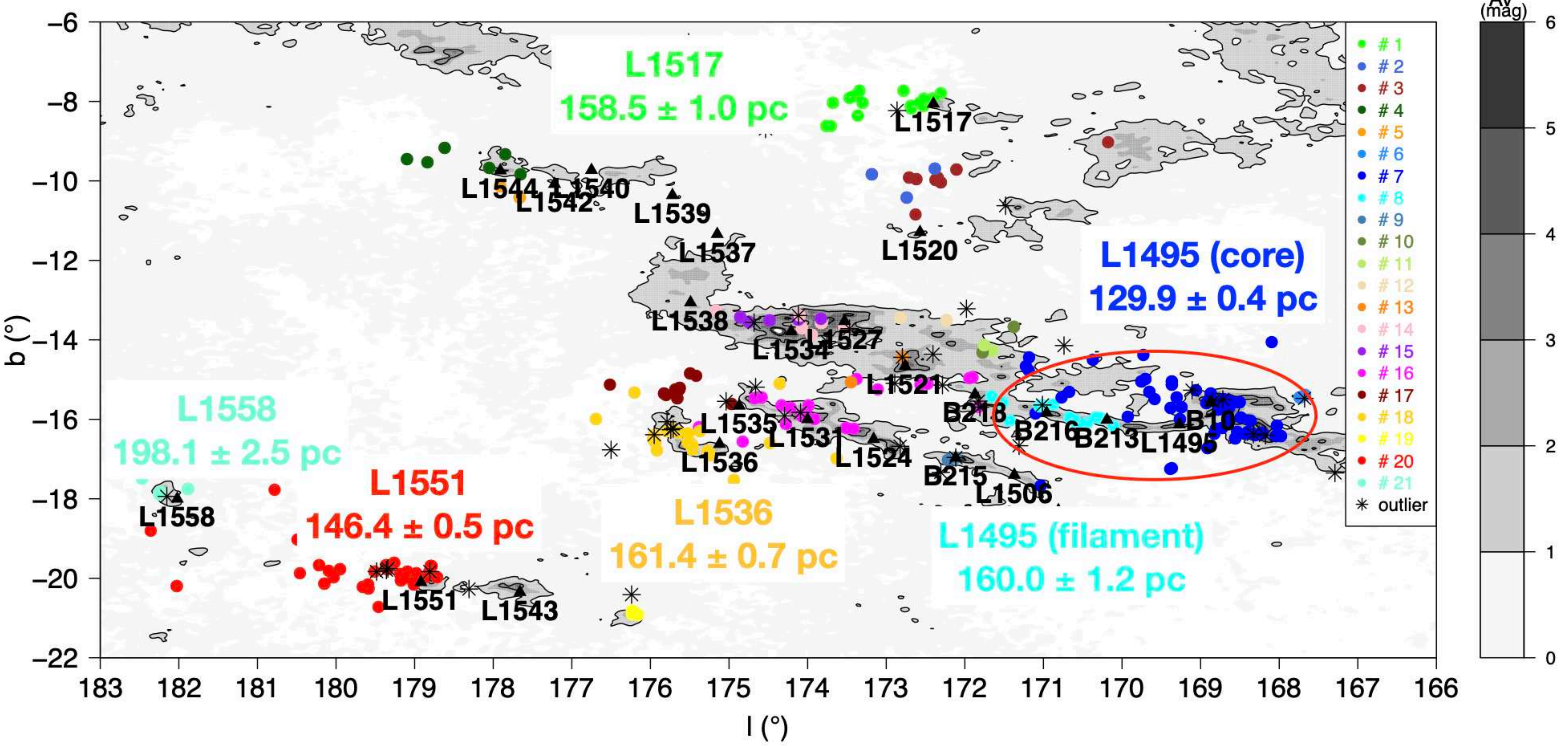
HMAC *(Li et al. 2007)*
Hierarchical **M**ode **A**ssociation **C**lustering

21 subgroups in Taurus



The Taurus star-forming region revealed by Gaia and VLBI

The Taurus subgroups are located at different distance and move with different velocities!



What can we learn about the local history of star formation?

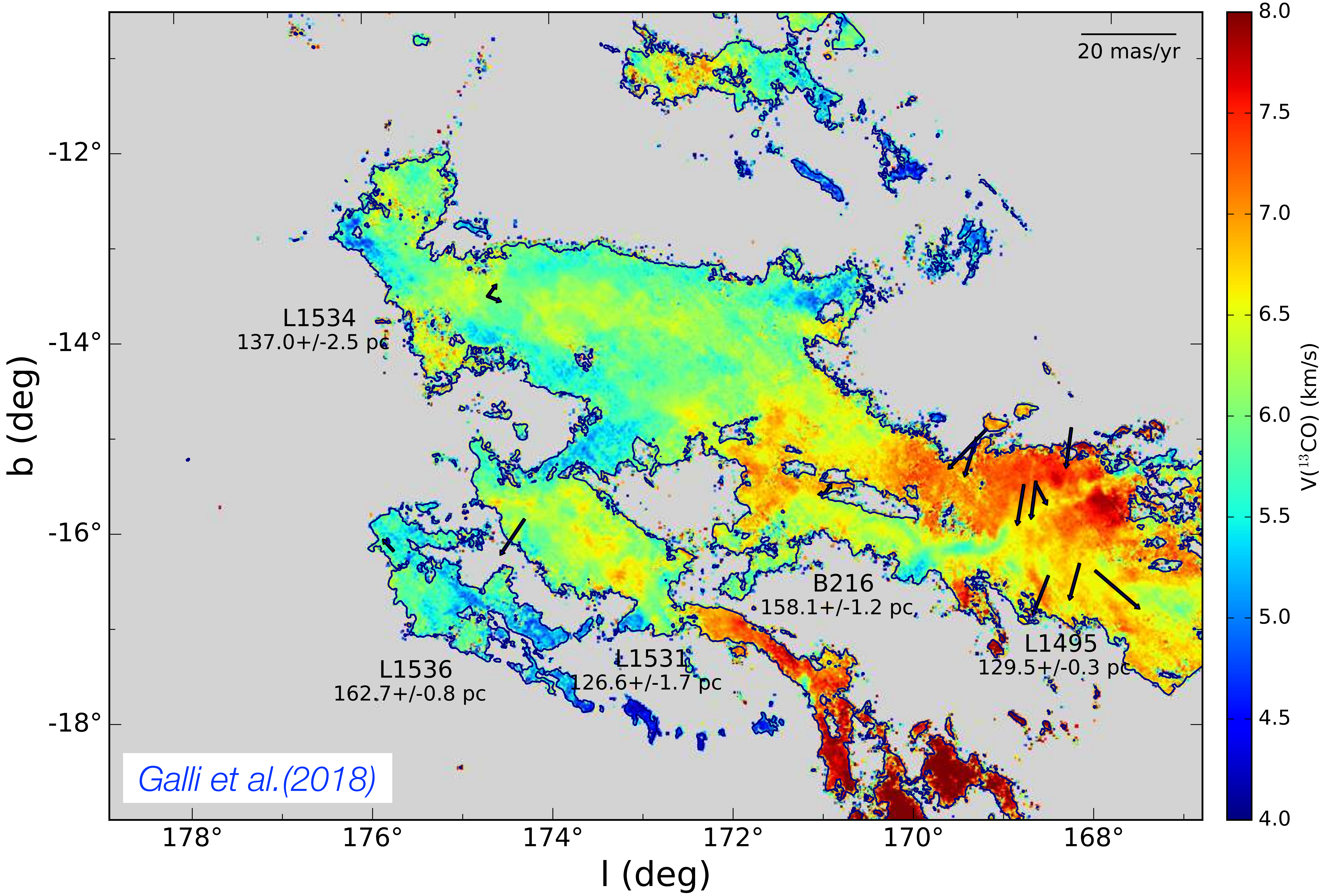
- ❑ **Taurus: multiple populations**, important depth effects and internal motions.

- ❑ Median **inter-cloud distance of ~25pc:** crossing time of **several Myr** to explain the present-day spatial distribution of stars.

❑ **<u>Example:</u> L1495 (core)** vs. **L1544**.
Relative distance of 50.9 ± 2.1pc and relative bulk motion of 2.4±0.4 km/s.
Crossing time ~21 Myr (>> age of Taurus stars ~5 Myr).

Scenario: Taurus is the result of multiple (in-situ) star-formation episodes spread over different locations of the complex.

Kinematics of the molecular gas in Taurus



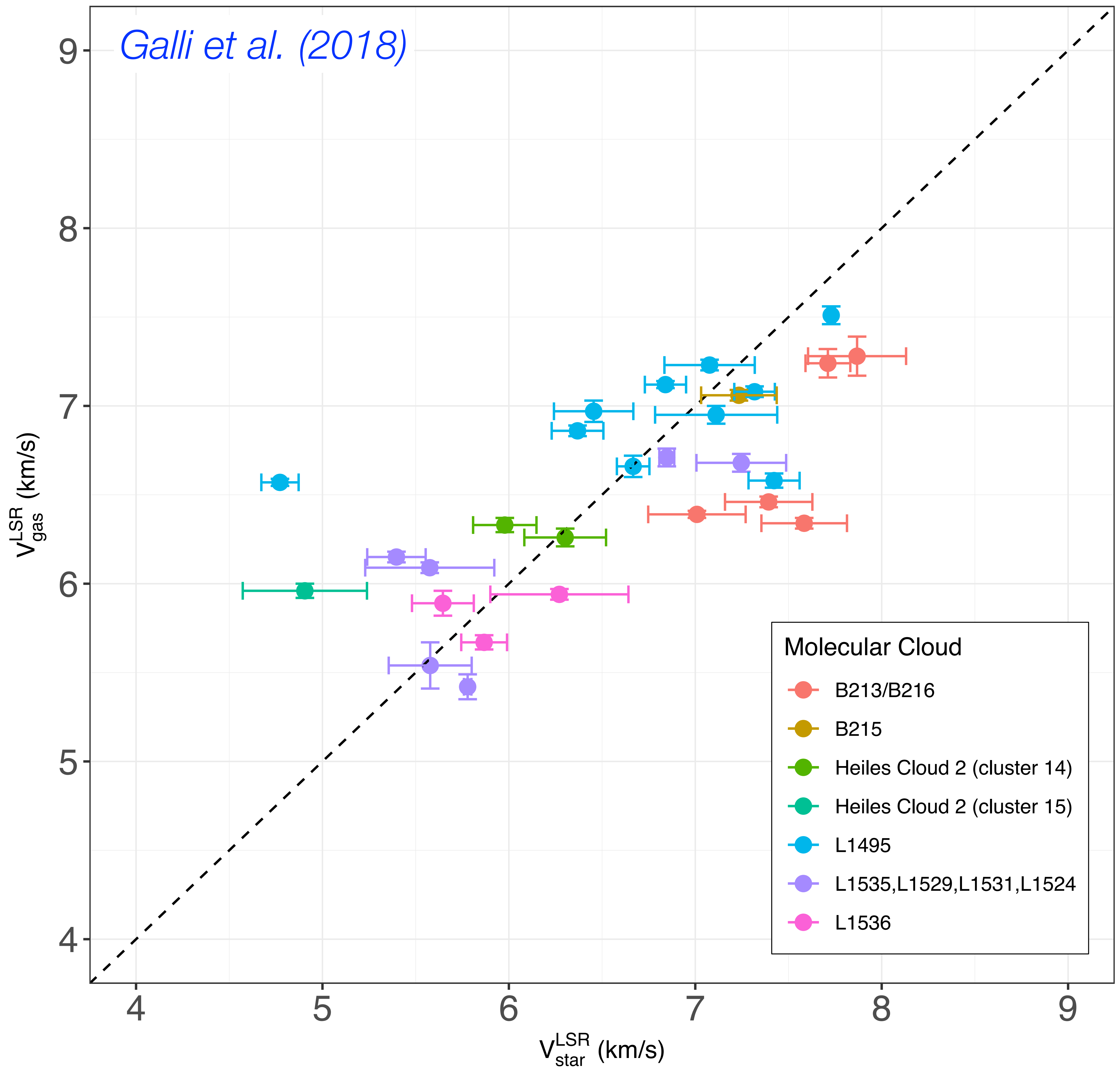
Method:

❑ FCRAO data of ^{12}CO and ^{13}CO molecular gas *(Goldsmith et al. 2008)*

❑ spectra of the gas at the position of the stars in our sample.

❑ radial velocity of the molecular gas in Taurus

Kinematics of the molecular gas in Taurus



We compare the radial velocity of the gas at the position of the stars with the radial velocity of the stars:

Galli et al. (2018):

$$\Delta v = 0.04 \pm 0.12 \text{ km/s}$$
$$\text{r.m.s} = 0.63 \text{ km/s}$$

Hartman et al. (1986):

$$\Delta v = 0.2 \pm 0.4 \text{ km/s}$$
$$\text{r.m.s} = 1.73 \text{ km/s}$$

The stars and gas are tightly coupled!

Astrometry fitting

Case I: single stars

$$\alpha(t) = \alpha_0 + \mu_\alpha t + \pi f_\alpha(t)$$
$$\delta(t) = \delta_0 + \mu_\delta t + \pi f_\delta(t)$$

5-PARAMETER ASTROMETRIC SOLUTION

Case II: binary (multiple) systems

$$\alpha(t) = \alpha_0 + \mu_\alpha t + \pi f_\alpha(t) + a_1 Q_\alpha(t)$$
$$\delta(t) = \delta_0 + \mu_\delta t + \pi f_\delta(t) + a_1 Q_\delta(t)$$

- one component is detected:

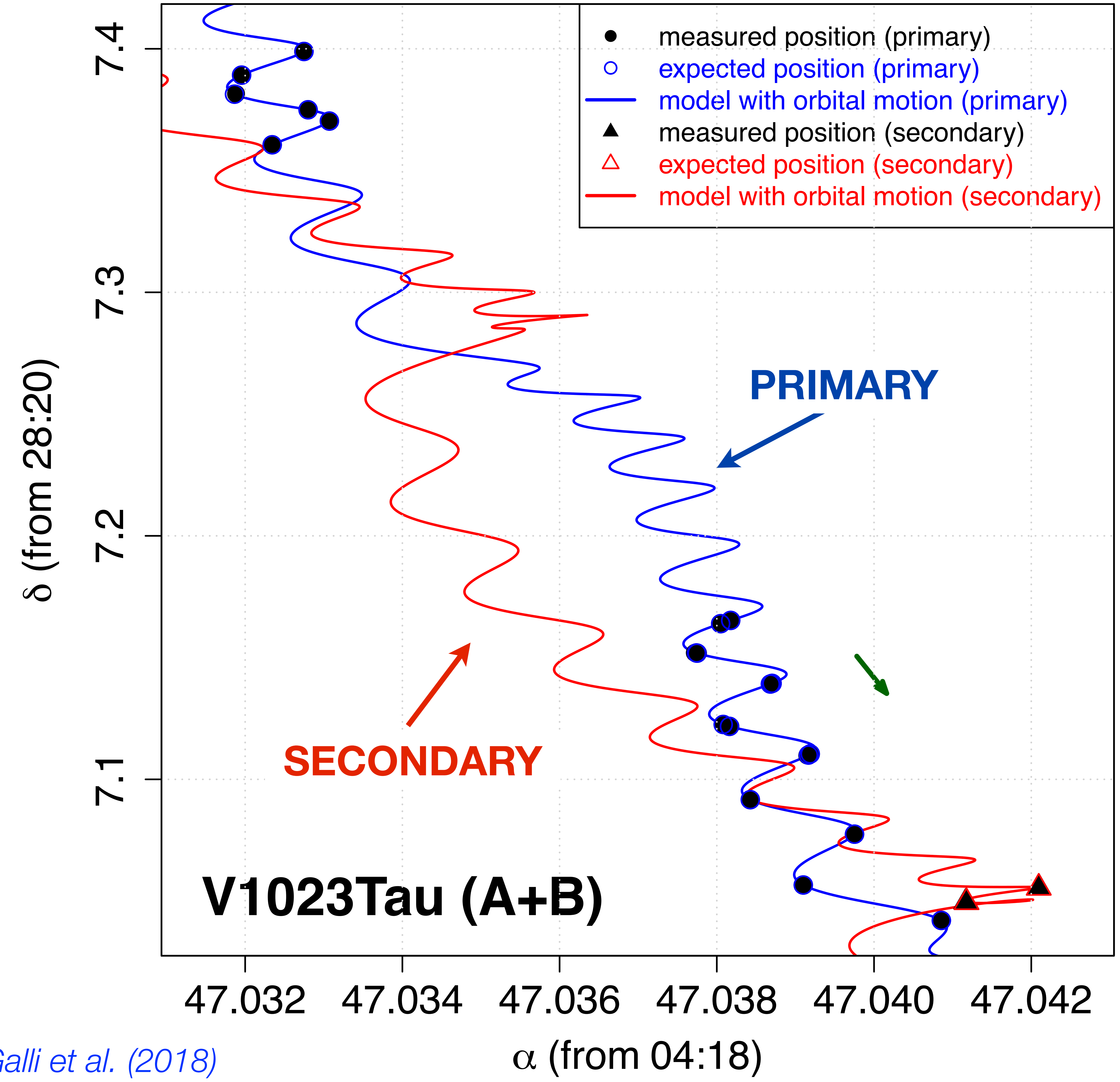
  12-PARAMETER SOLUTION (ASTROMETRY + ORBIT)

- two components are detected:

  13-PARAMETER SOLUTION (ASTROMETRY + ORBIT + MASS RATIO)

DYNAMICAL MASS!

Example: V1023 Tau



Galli et al. (2018)

Galli et al. (2018):

$$\mu_\alpha \cos\delta = 8.371 \pm 0.020 \text{ mas/yr}$$
$$\mu_\delta = -25.490 \pm 0.020 \text{ mas/yr}$$
$$\pi = 7.686 \pm 0.032 \text{ mas}$$

$$M_A = 1.234 \pm 0.023\, M_\odot$$
$$M_B = 0.730 \pm 0.020\, M_\odot$$

13 years of VLBA data!

Gaia-DR3:

$$\mu_\alpha \cos\delta = 8.707 \pm 0.112 \text{ mas/yr}$$
$$\mu_\delta = -25.483 \pm 0.083 \text{ mas/yr}$$
$$\pi = 7.850 \pm 0.097 \text{ mas}$$

The DYNAMO-VLBA project

- ❑ **Aim:** determine dynamical masses of YSOs to test evolutionary models (PI: Dzib)

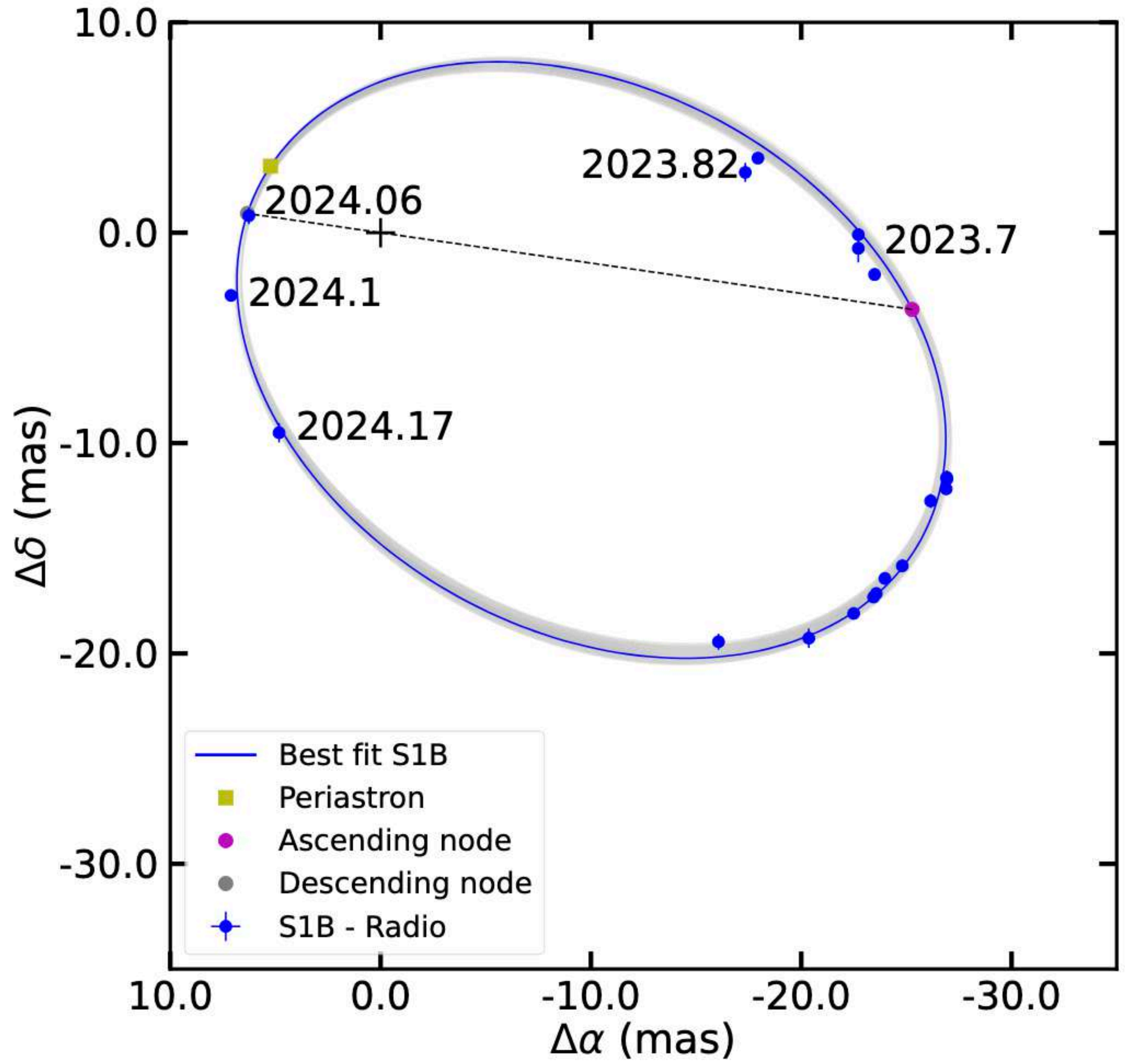
- ❑ **Methods:** multi-epoch astrometry with VLBA observations.

Oph-S1 system

$$M_A = 4.115 \pm 0.039\,\mathrm{M}_\odot$$
$$M_B = 0.814 \pm 0.006\,\mathrm{M}_\odot$$

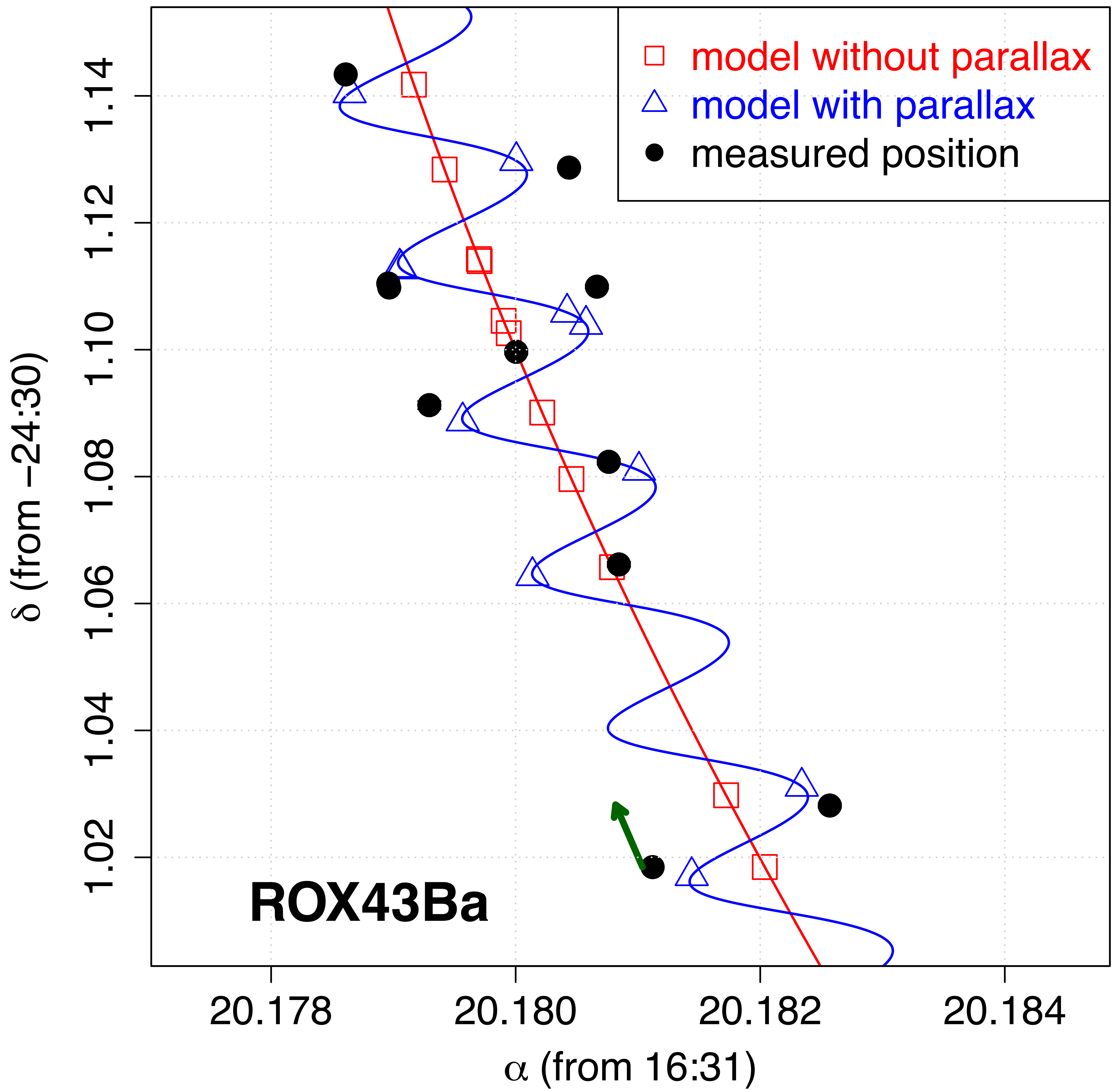
Example: Oph-S1 binary system

(Ordóñez-Toro et al. 2024; 2025)



Searching for brown dwarf companions with VLBI astrometry

- ❑ **Aim:** detect brown dwarf companions around young stars with astrometry (PI: Galli).
- ❑ **Methods:** measure the reflex motion of the "unseen" companion on the primary.
- ❑ **Targets:** YSOs with preliminary astrometric solutions with evidence of hosting substellar companions.
- ❑ **Pilot study:** three targets (V410 Tau, HII 1136 and ROXs 47B).



Conclusions

❑ **Gaia and VLBI** observations provide state-of-the-art astrometry and complement each other.

❑ The very precise **parallaxes and proper motion** measured by the two projects deliver important information on the **structure and kinematics** of stellar clusters.

↪ **investigate the local history of star formation in stellar clusters**

❑ The **dynamical masses** inferred from microarcsecond astrometry will allow us to test evolutionary models used in many star formation studies.