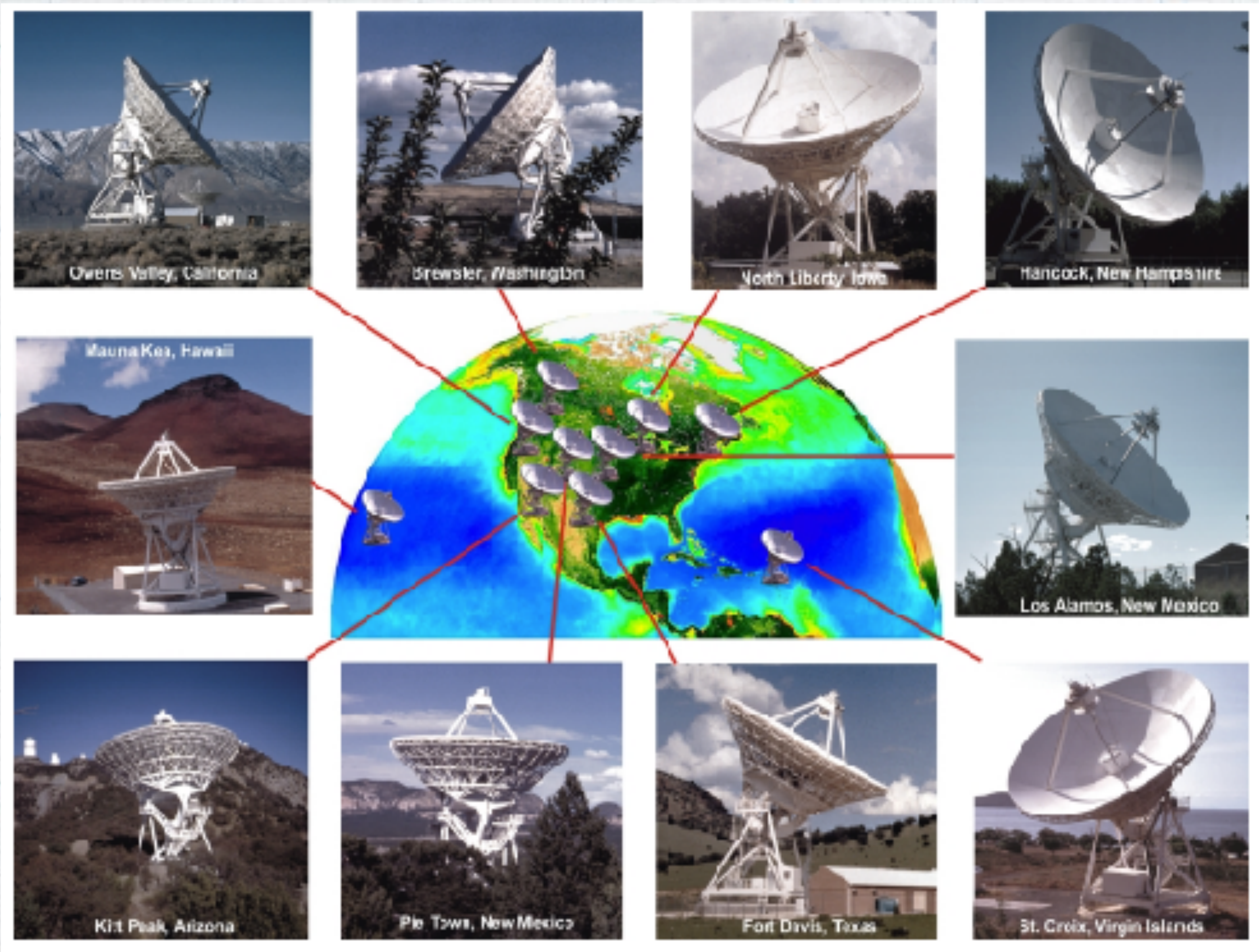
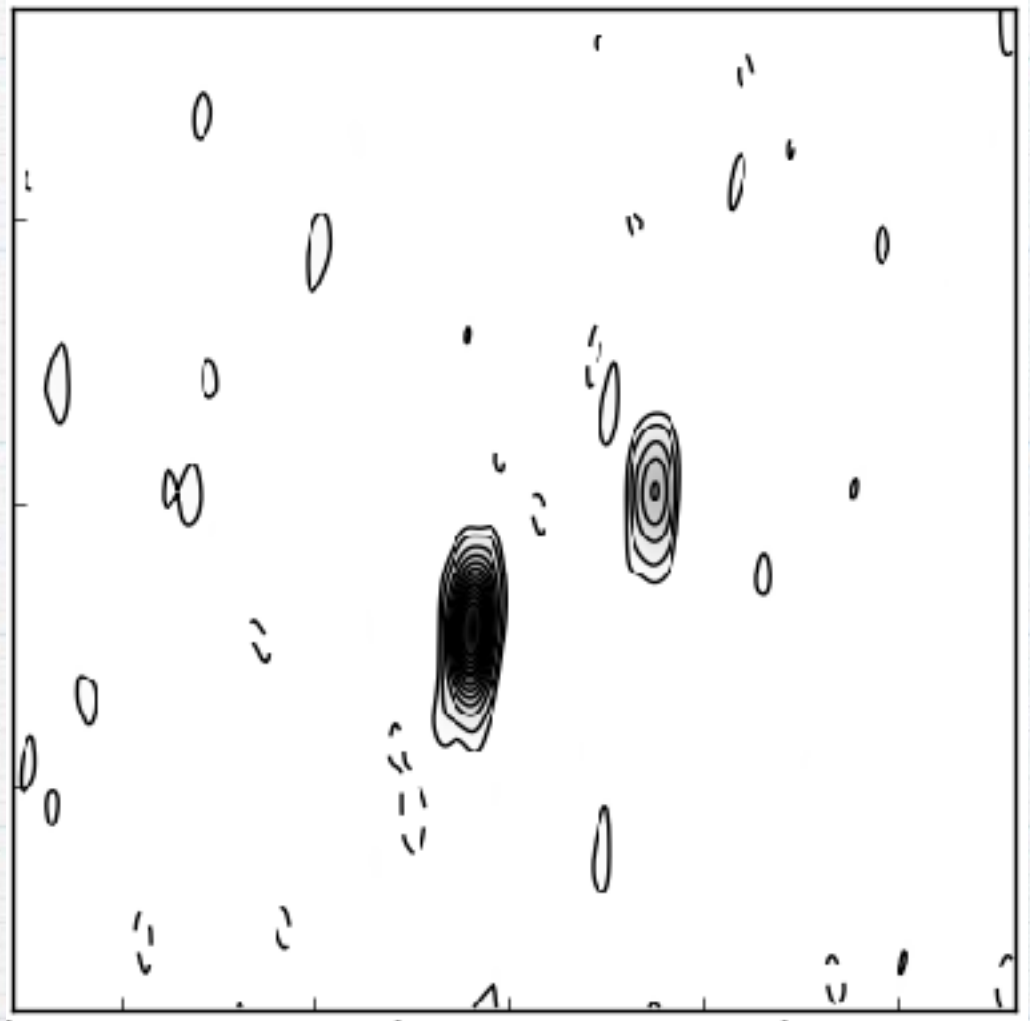
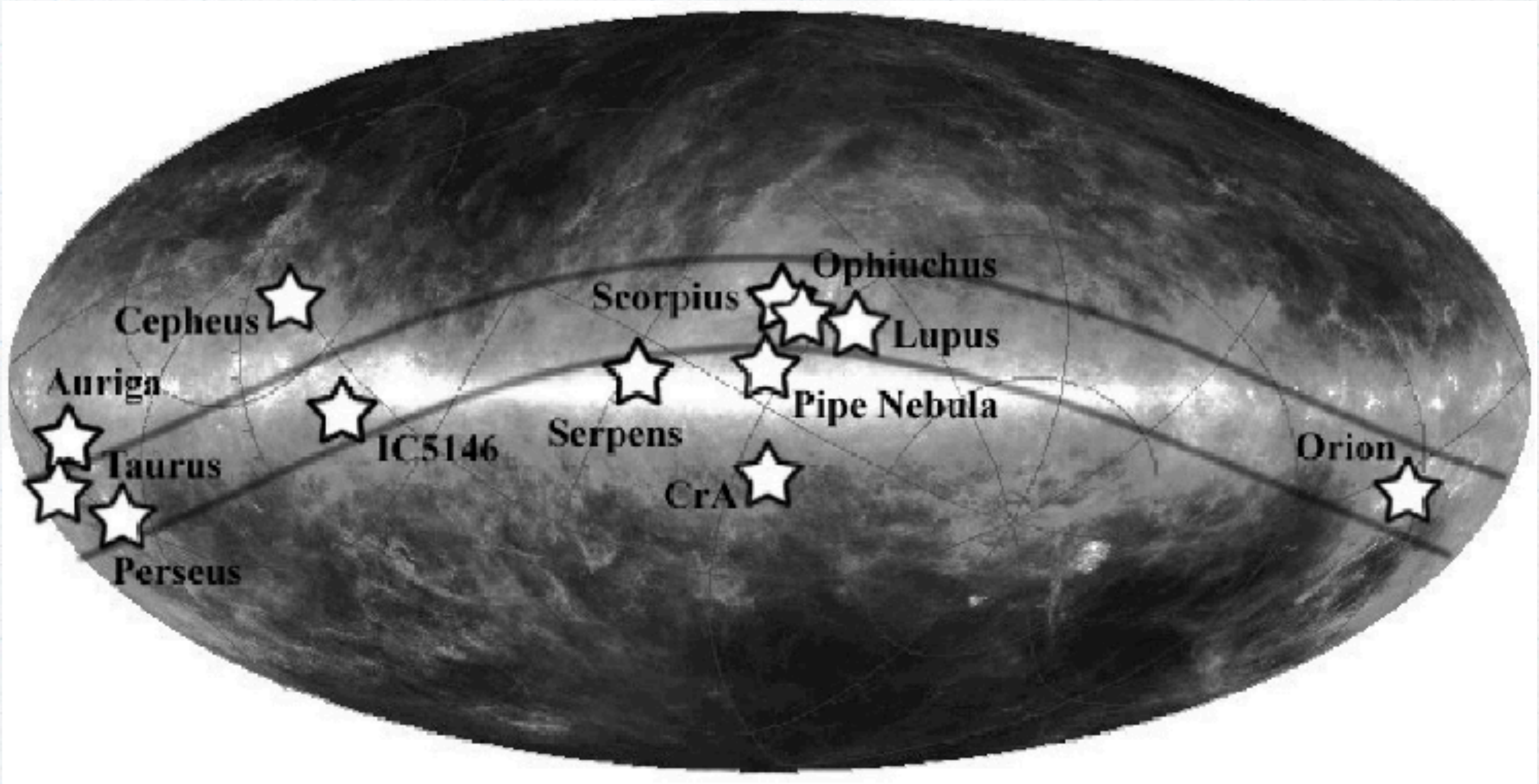
VLBI astrometry of YSOs in nearby star-forming regions







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Regional VLBI Workshop, Mexico City, 25 February - 1 March, 2019

Outline of the talk

* Motivation
* The GOBELINS project
* Comparison with Gaia
* Other astrometric works
* Future prospects

VLBI astrometry in star-forming regions

* Astrometry means
  * Accurate stellar positions
  * Parallaxes → distances
  * Proper motions → transverse velocities
  * +radial velocities → 3D spatial velocities

* Use this information to derive 3-D structure of molecular clouds
* Identify multiple components within molecular clouds
* Study the kinematics of molecular clouds

Motivation - (low-mass) star formation

* Protostar evolves from deeply embedded (optically invisible) phase (Class 0) to optically visible T-Tauri star (Class II & III).

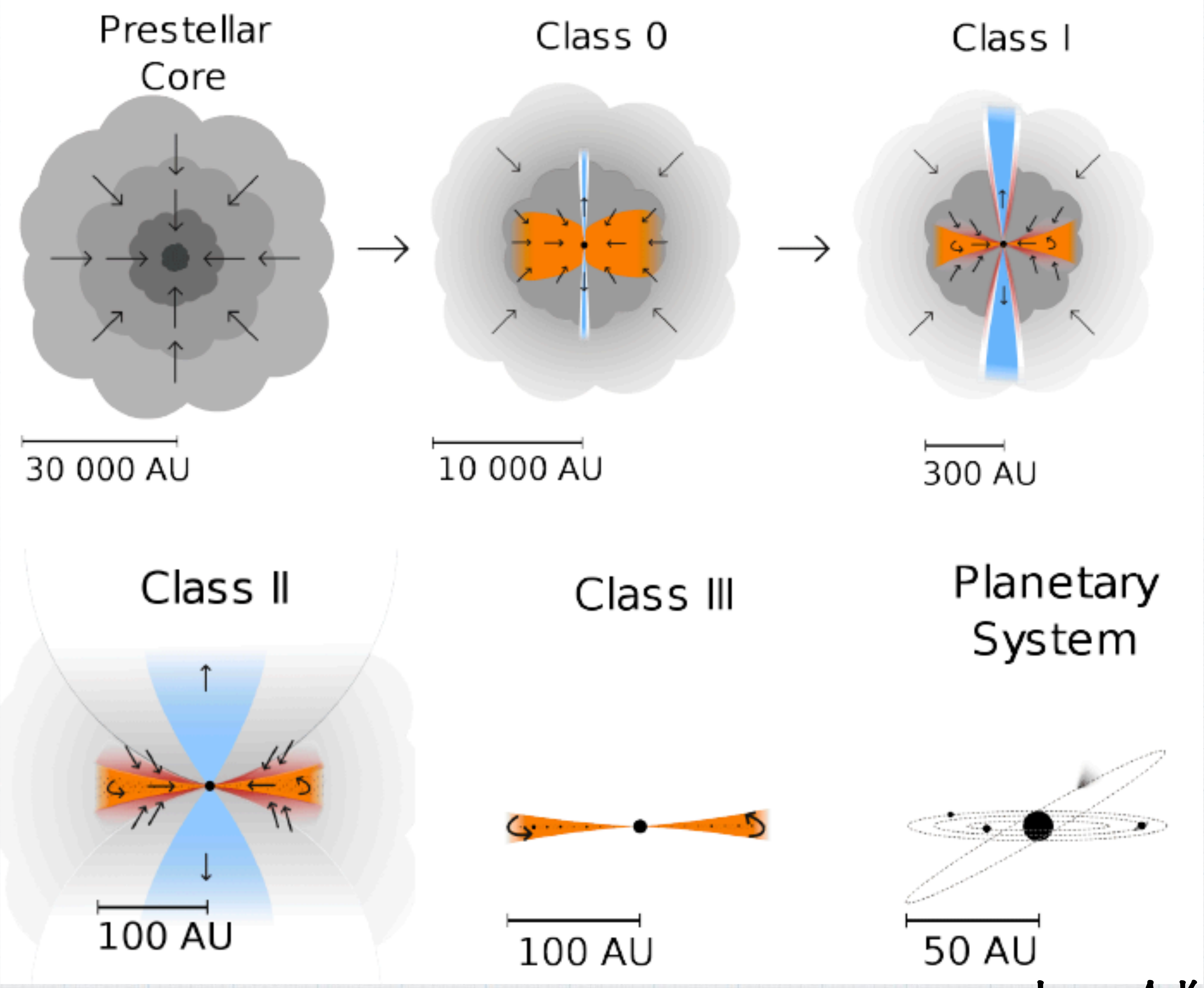
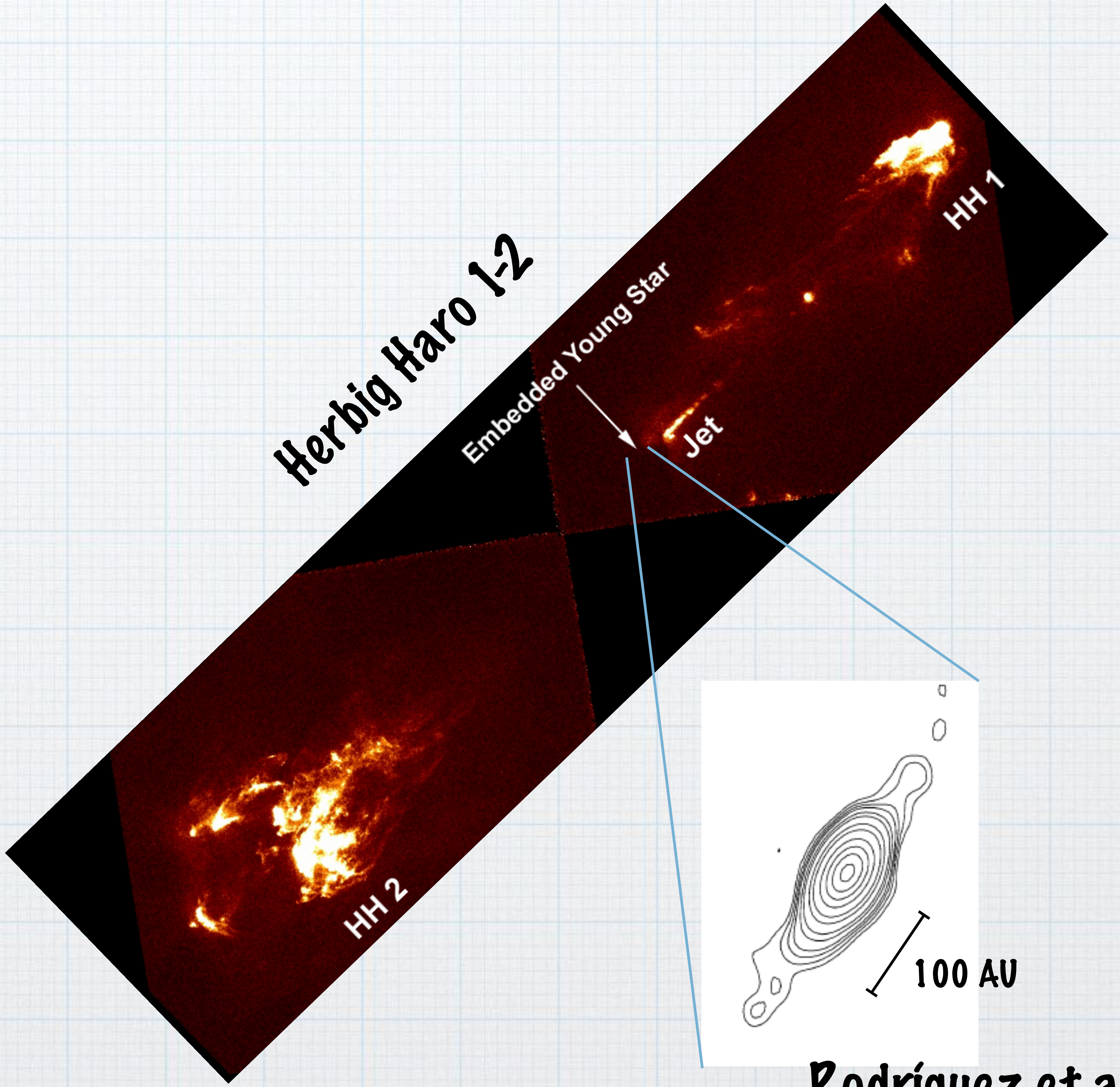


Image: A. Karska

Radio emission from (low-mass) young stars

* Free-free (thermal) jets from low-mass young stellar objects.
* Ionization by photons arising from the shock of the - mostly - neutral stellar wind against the surrounding high-density gas.

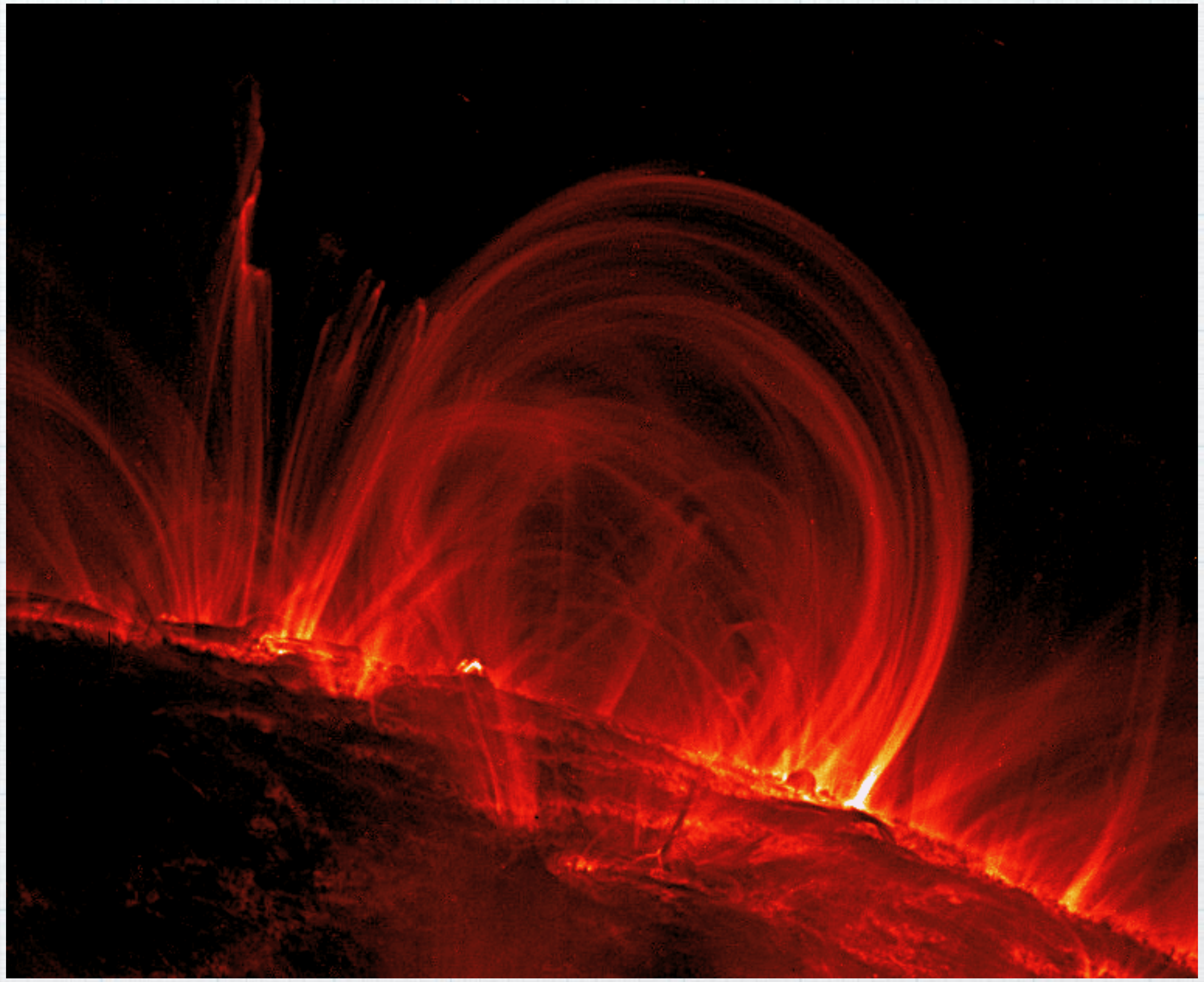


Rodríguez et al (2000)

Radio emission from (low-mass) young stars

* Non-thermal radio emission

* Low-mass stars (10^5-10^7 yr) with magnetic activity are usually sources of compact, non-thermal (gyrosynchrotron) radio continuum emission.



Radio emission from (low-mass) young stars

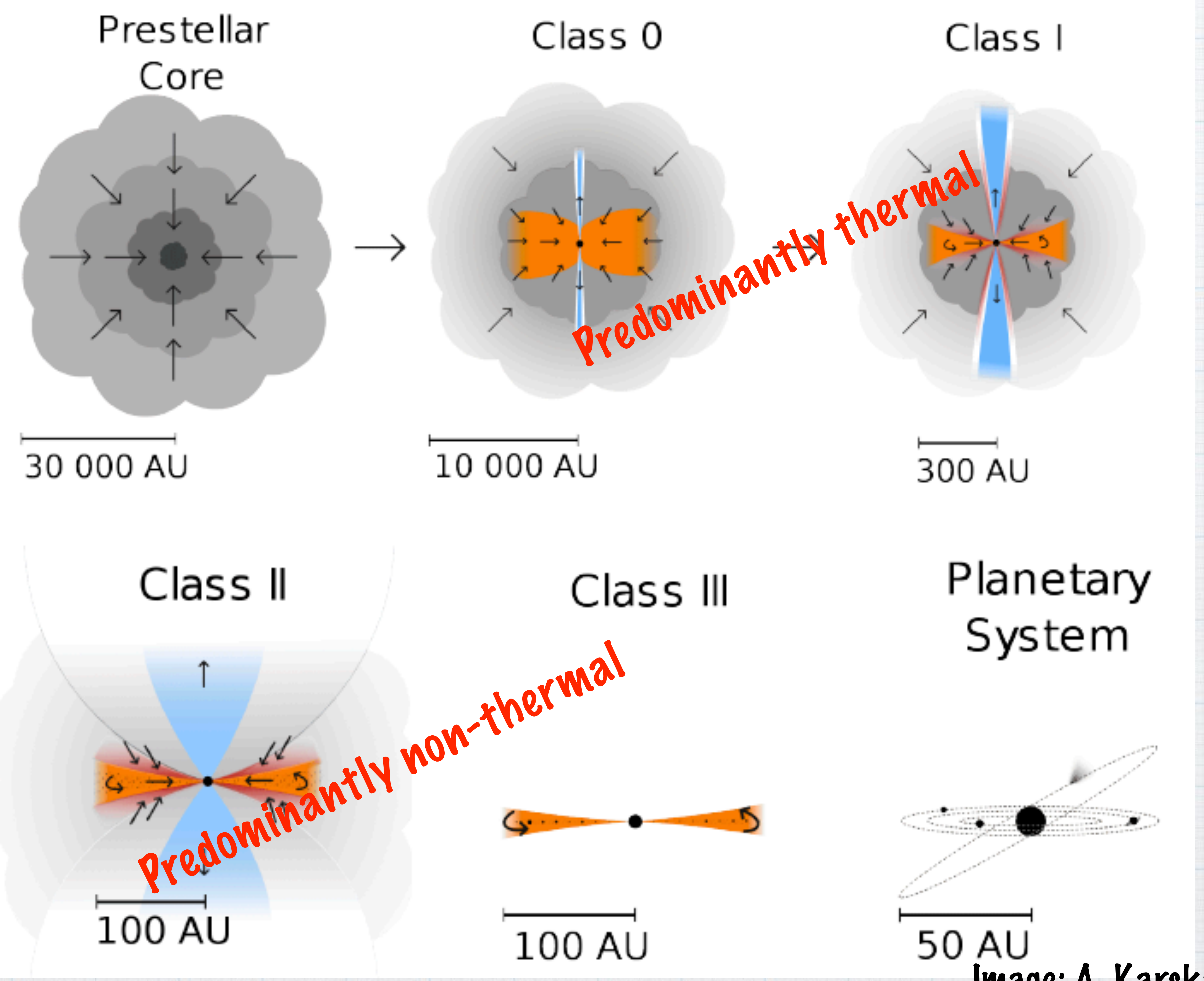


Image: A. Karska

Radio emission from (low-mass) young stars

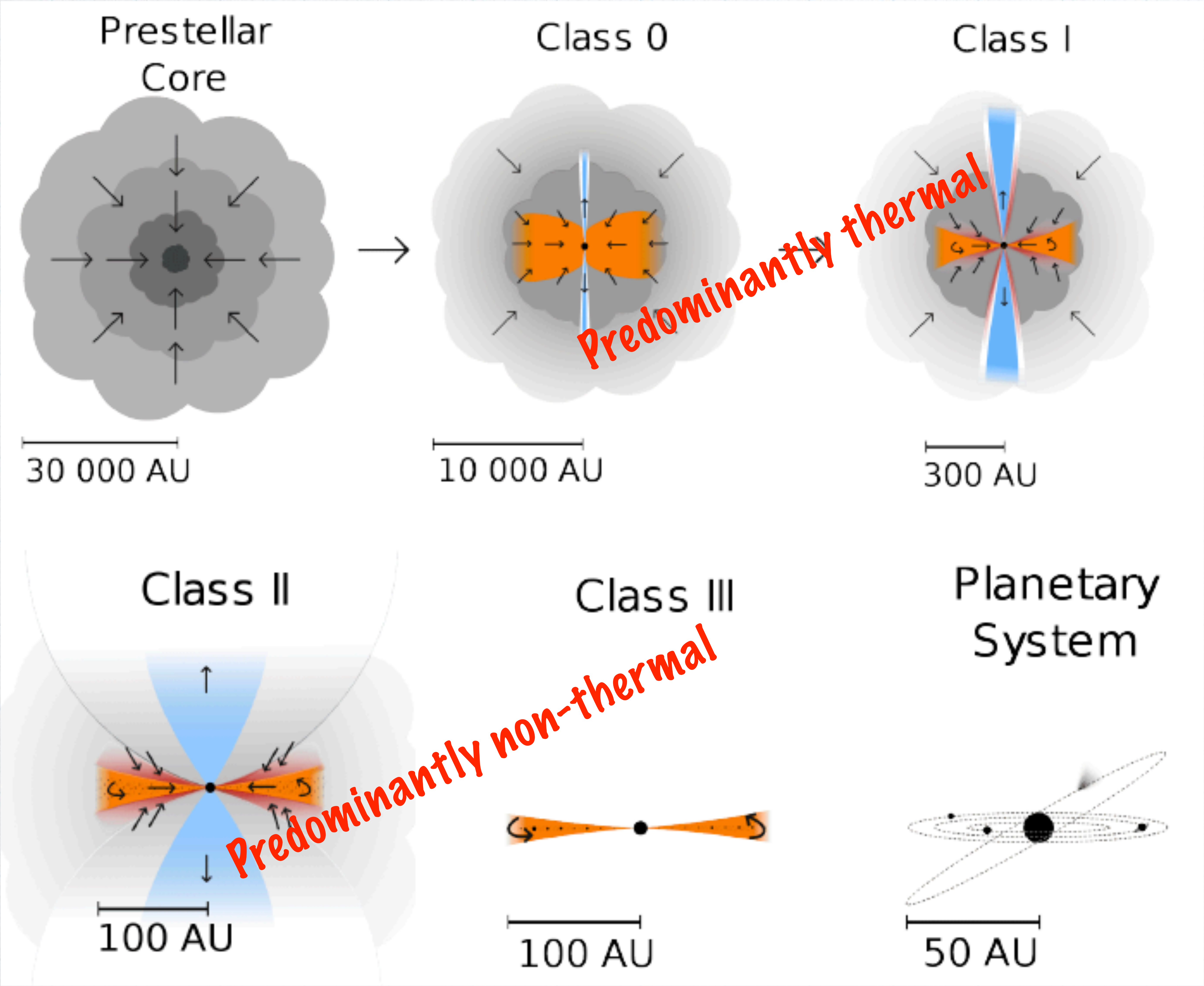
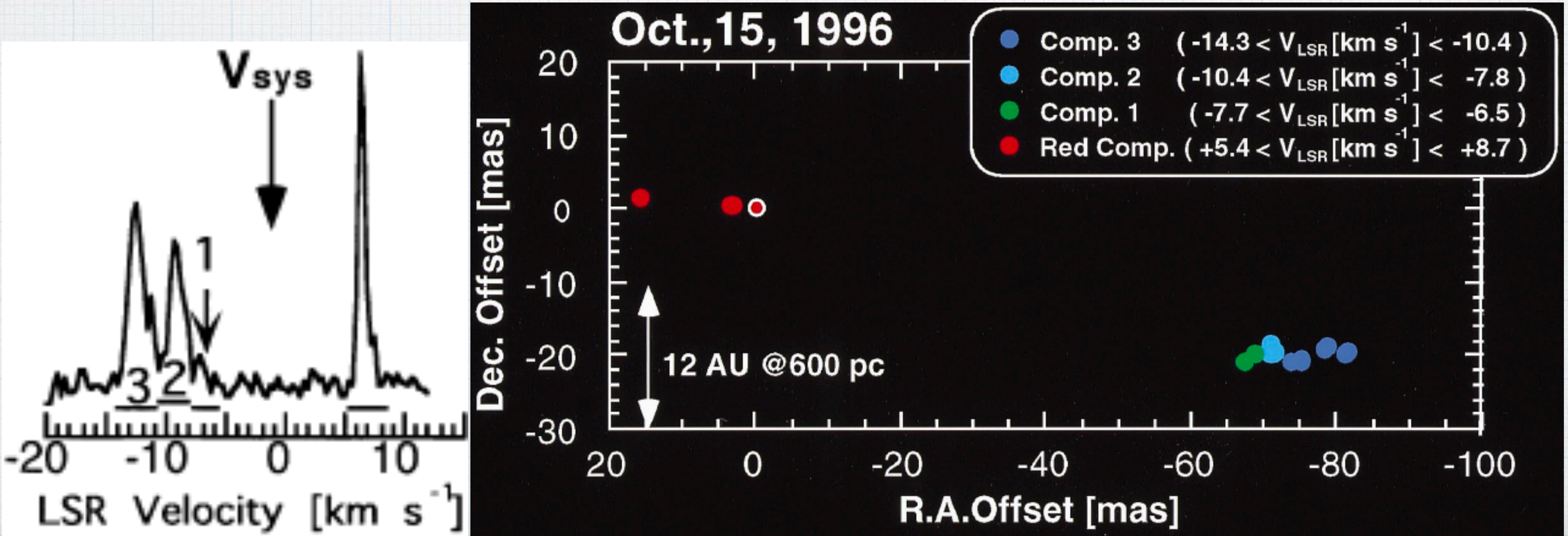


Image: A. Karska

* A few Class I protostars with non-thermal radio emission are known, e.g.:
  * YLW15 (SED properties consistent with a Class I YSO).

Radio emission from (low-mass) young stars

* Maser lines, non-thermal emission
  * Methanol (CH_3OH, at 6.7 and 12.2 GHz) masers are excited by radiative pumping in the dusty environment around massive YSOs.
  * Water (H_2O, at 22 GHz) masers trace the shocked gas in jets and outflows in low- and high mass protostars.

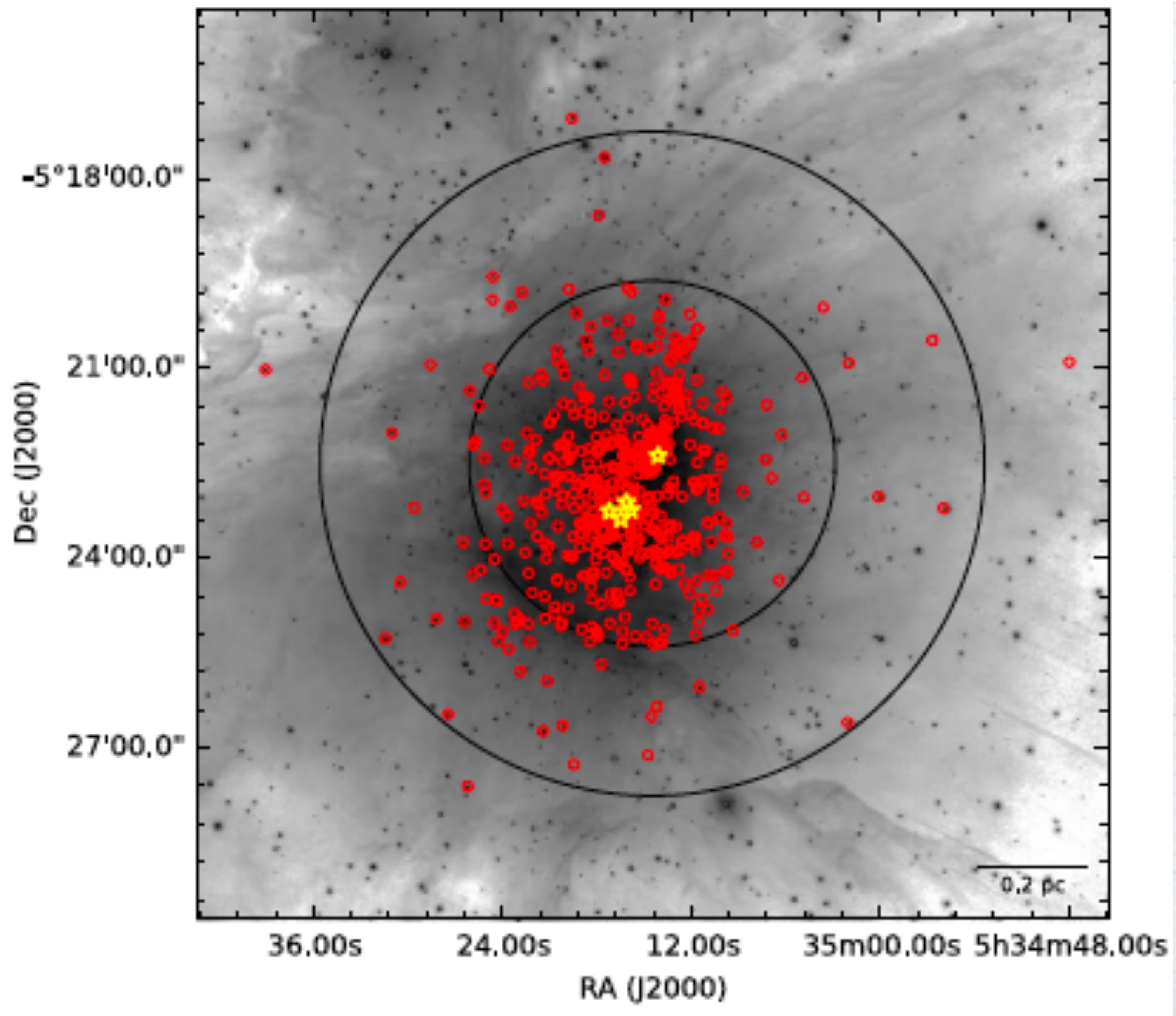


Furuya et al (1999)

Radio emission from (low-mass) young stars

- VLA widely used to characterize (and, very importantly, to locate) radio emission from YSOs, e.g.
  - Bieging et al (1984), 80 μJy/beam
  - Dzib et al (2013, 2015), 20 μJy/beam
  - Kern et al (2016), 10 μJy/beam
  - Forbrich et al (2016), 3 μJy/beam

- VLA major upgrade: increase in sensitivity



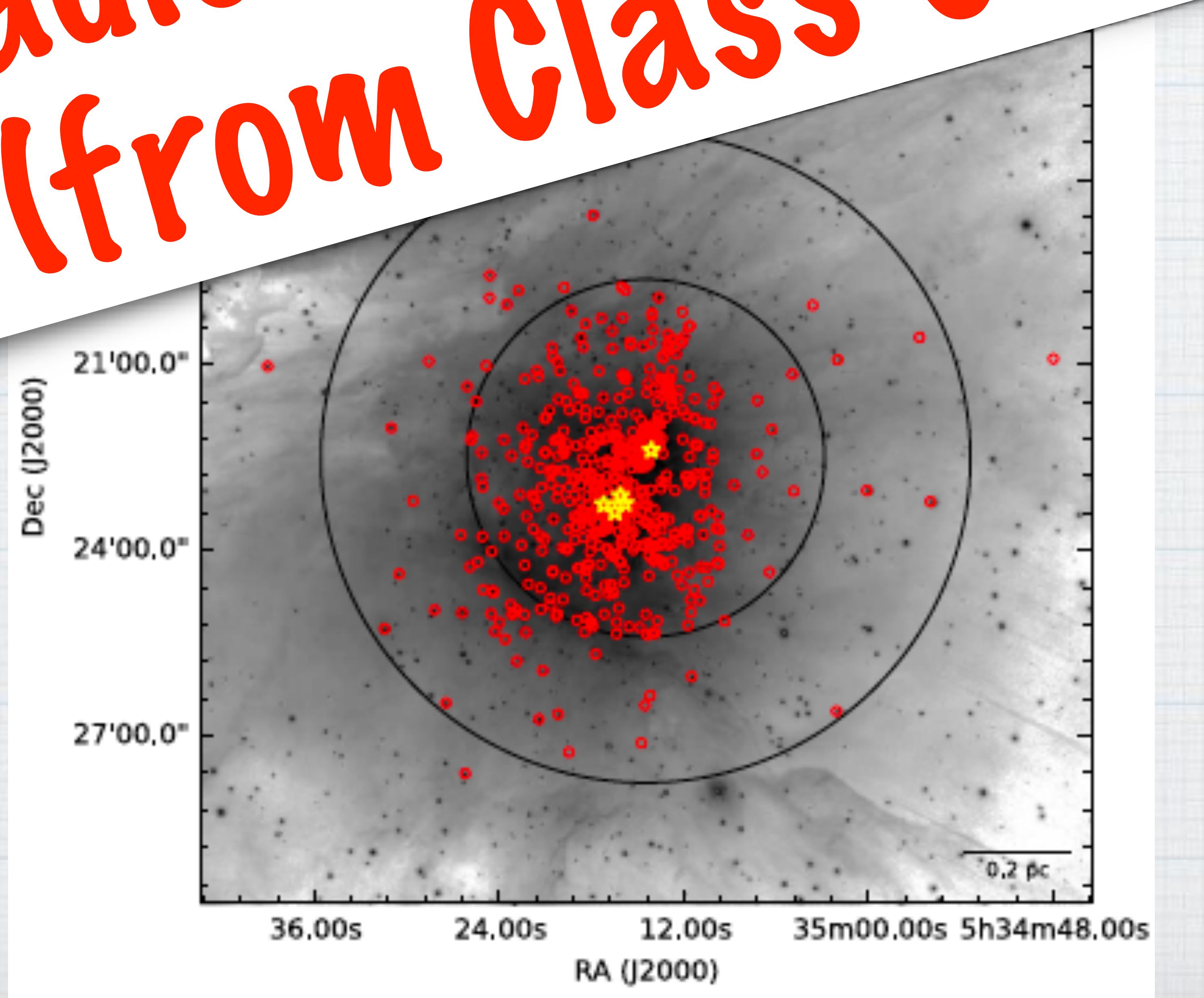
- Measurement of radio proper motions have been also obtained (e.g. Dzib et al 2017, ONC at 5 GHz).

Radio emission from (low-mass) young stars

* VLA widely used to characterize (and, very importantly, to locate) radio emission from YSOs, e.g.
  * Bieging et al (1984), 80 μJy...
  * Dzib et al (201...
  * K...
  * ...μJy/beam

Radio emission is common in young (from Class 0 to Class III) stars

* VLA ... upgr... increas... in sensitivity



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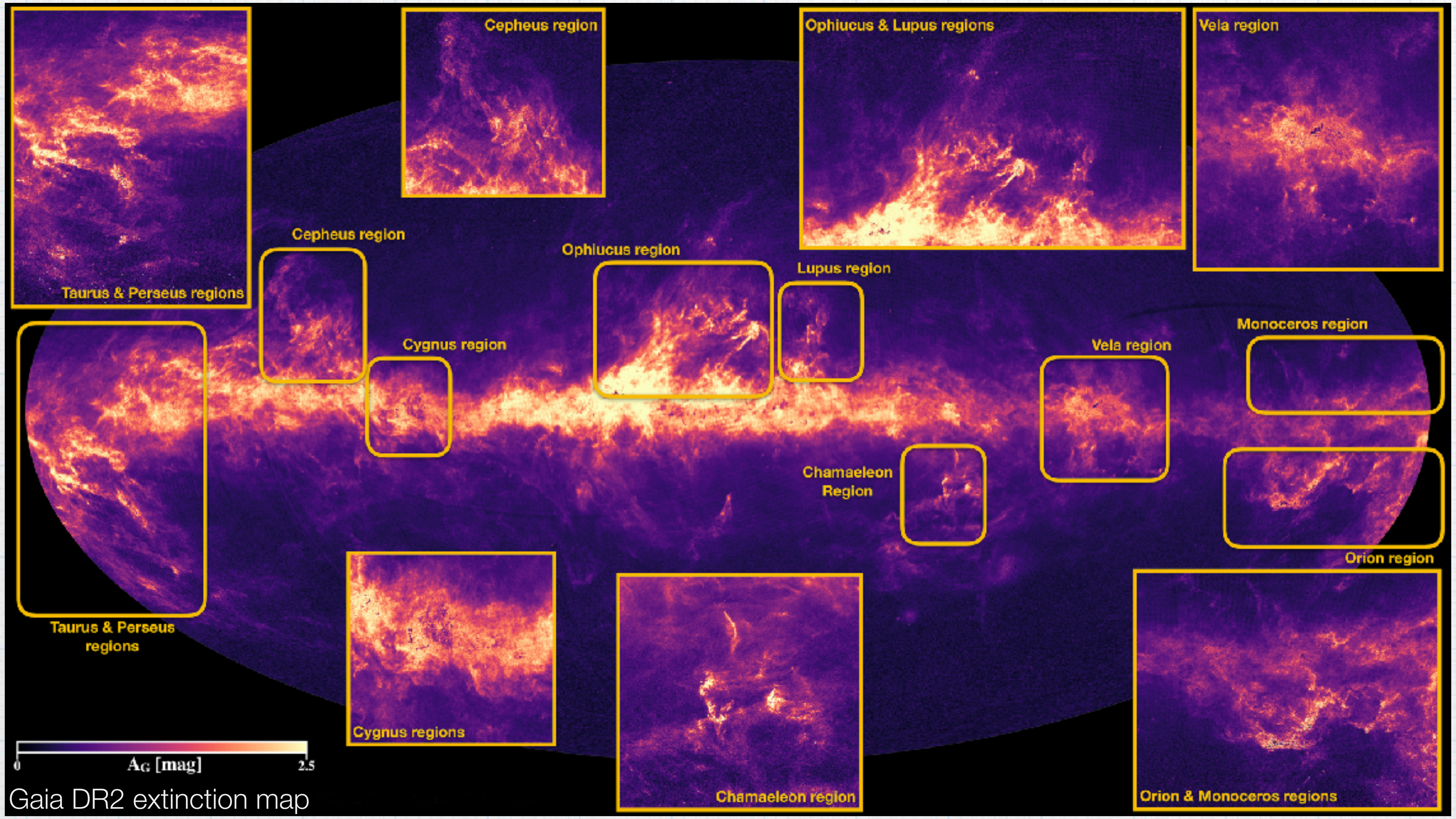
VLBI sensitivity

* VLBI sources must have non-thermal radio emission
* Brightness temperature sensitivity

$$T_b = 10^6 \left(\frac{S}{40\mu\mathrm{Jy}}\right) \left(\frac{B_{\mathrm{max}}}{8612\ \mathrm{km}}\right)^2 \mathrm{K}$$

* VLBI is sensitive only to compact, non-thermal radiation:
  * magnetic stars, masers → commonly found in SFRs.

VLBI astrometry in star-forming regions



- Observations of molecular clouds are fundamental to improve our understanding of protostellar evolution.
- Derivation of physical parameters requires knowledge of the source distance.

VLBI astrometry

- Angular resolution:

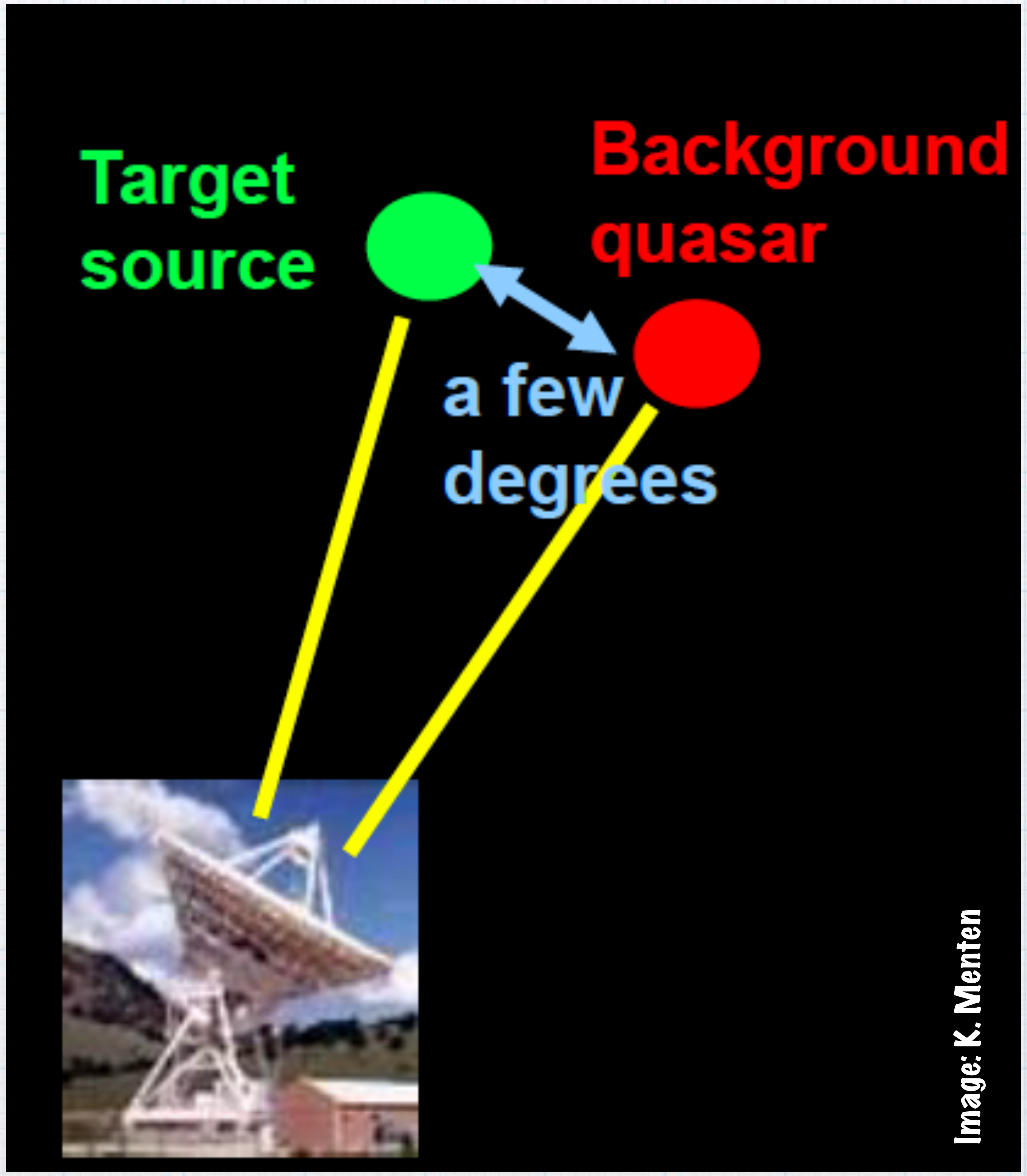
λ (cm)	5	3	1	0.7	0.3	0.1
θ_{res} (mas)	1.2	0.72	0.24	0.17	0.07	0.02

- Absolute astrometric precision: $\frac{1}{2}\frac{\theta_{\rm res}}{\rm SNR} \lesssim 50\ \mu{\rm as}$

- Systematic errors contribution > 200 μas (continuum, low-elevation targets).
  - Main contribution by unmodeled atmospheric delays
  - Possible contribution from unmodeled motions from unseen companion.

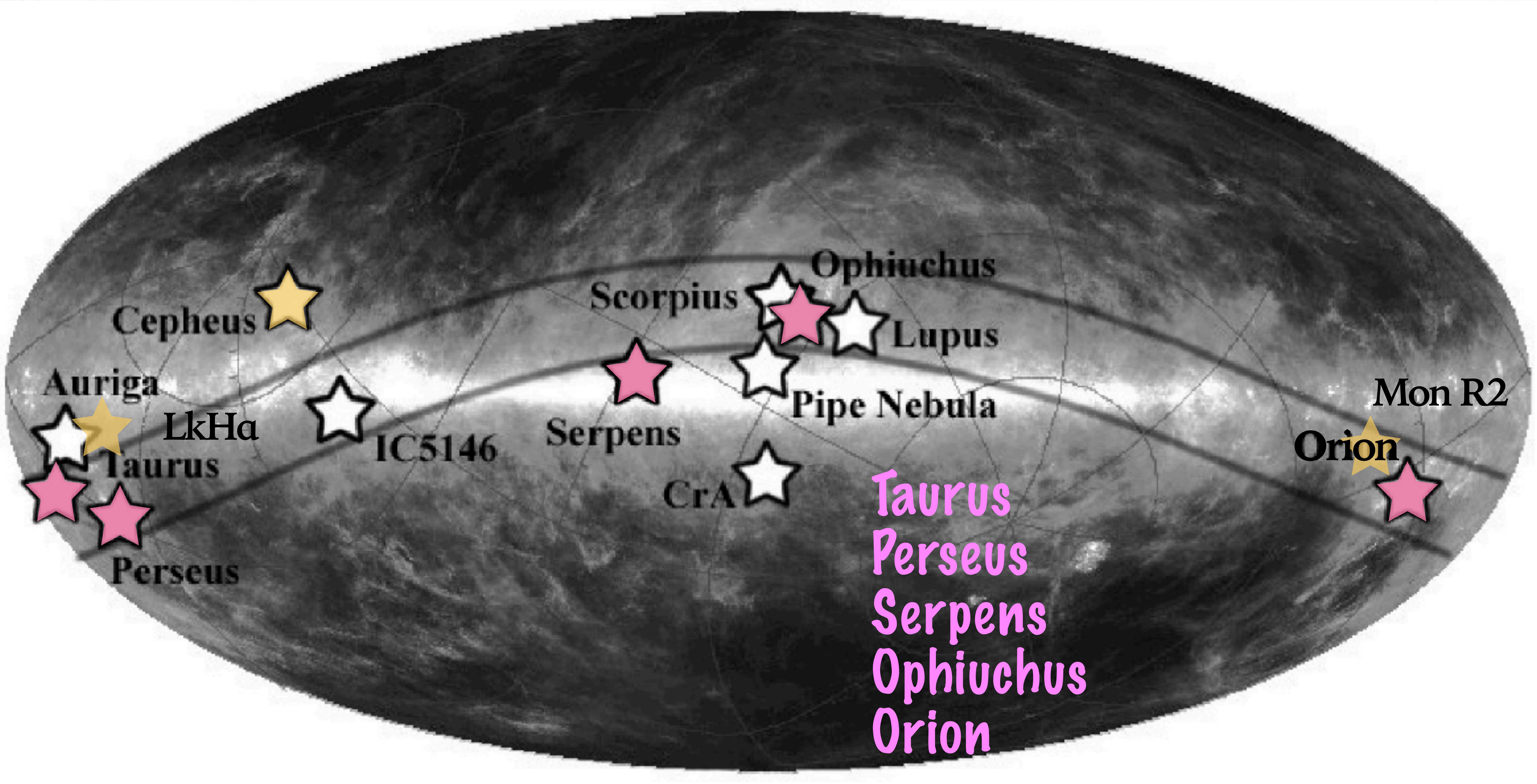
VLBI astrometry

* Phase referencing
    * Rapid switch between target and quasar.
    * Cycle time 3~5 min



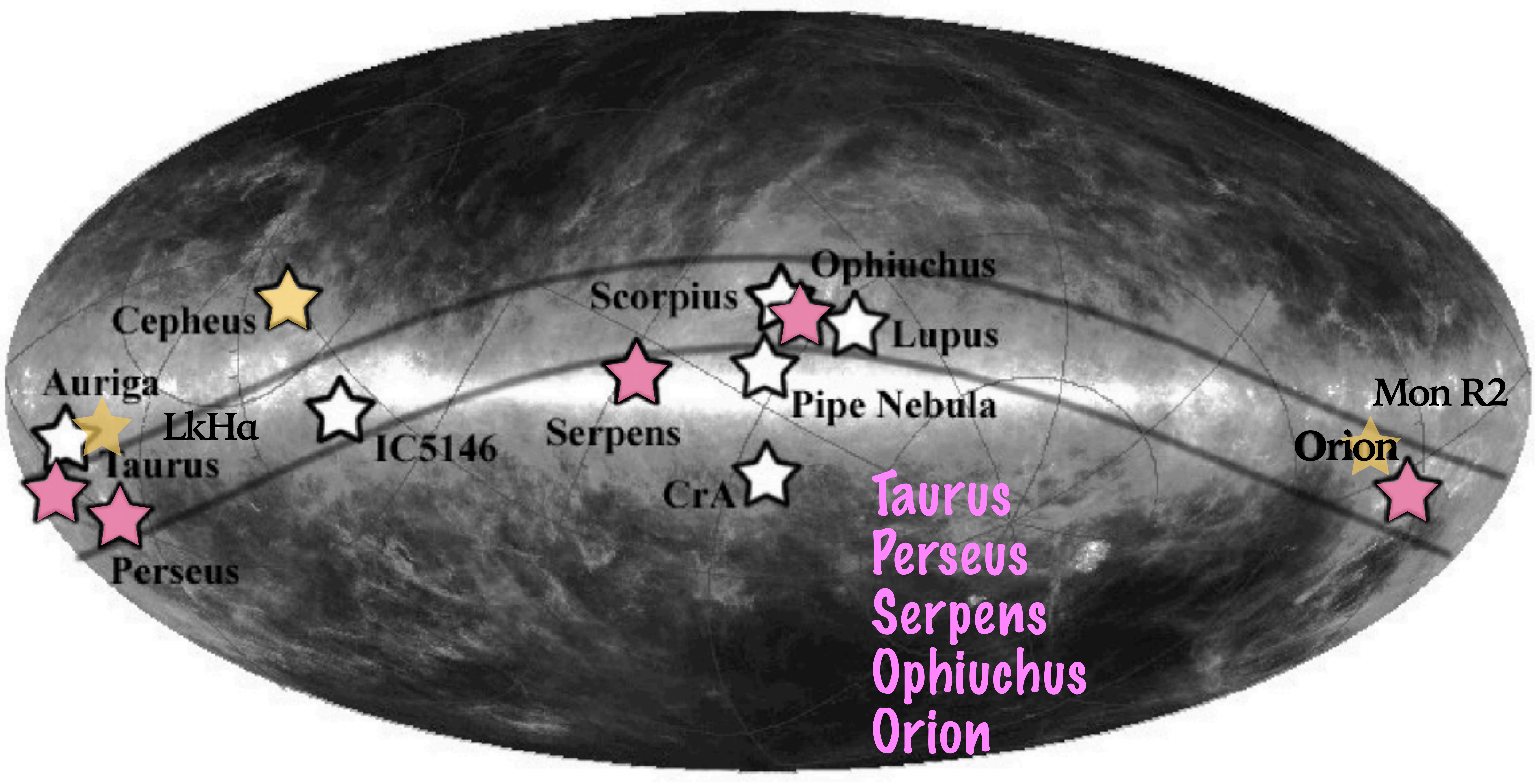
* Allows imaging of weak sources
* Positions are tied to an extragalactic reference frame

GOBELINS - A VLBA astrometric survey of (embedded) young stars



Adapted from Ward-Thompson et al. (2007)

GOBELINS - The GOuld's BELt dIstaNces Survey

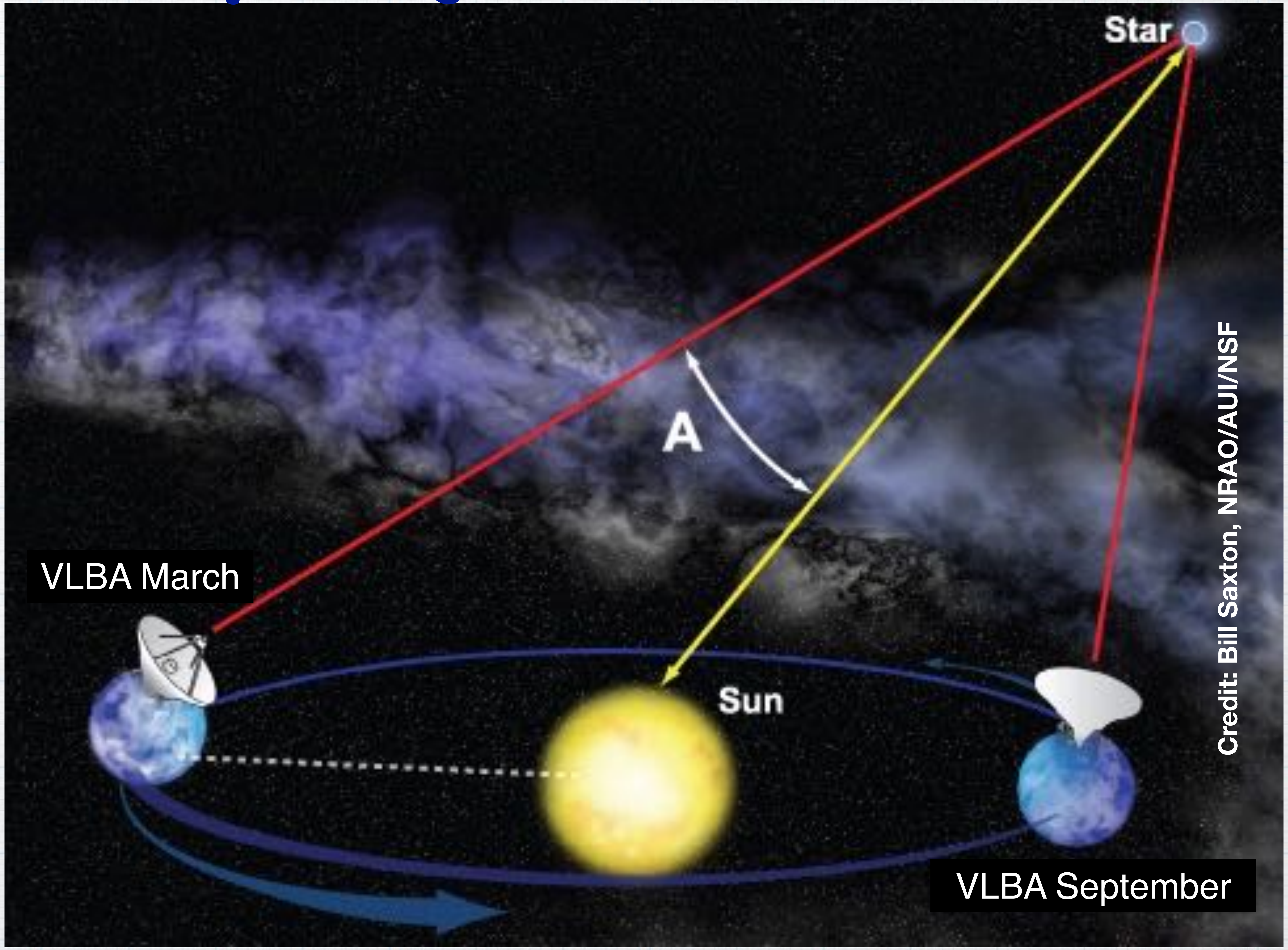


Adapted from Ward-Thompson et al. (2007)

GOBELINS - A VLBA astrometric survey of (embedded) young stars

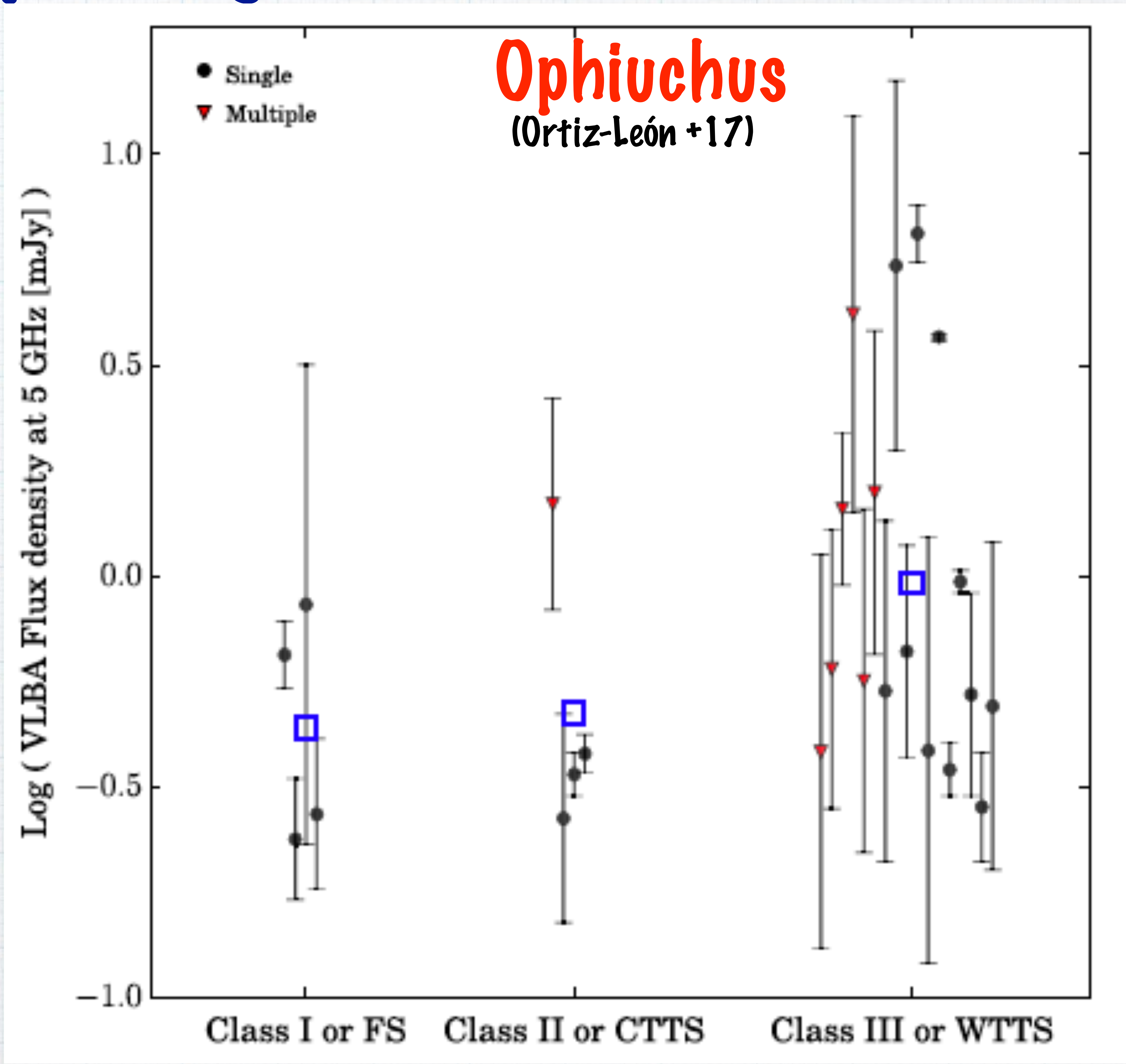
* Number of targets:

  ~270 YSOs
* 2200 hours of telescope time for period 2012-2018
* 2 epochs/yr

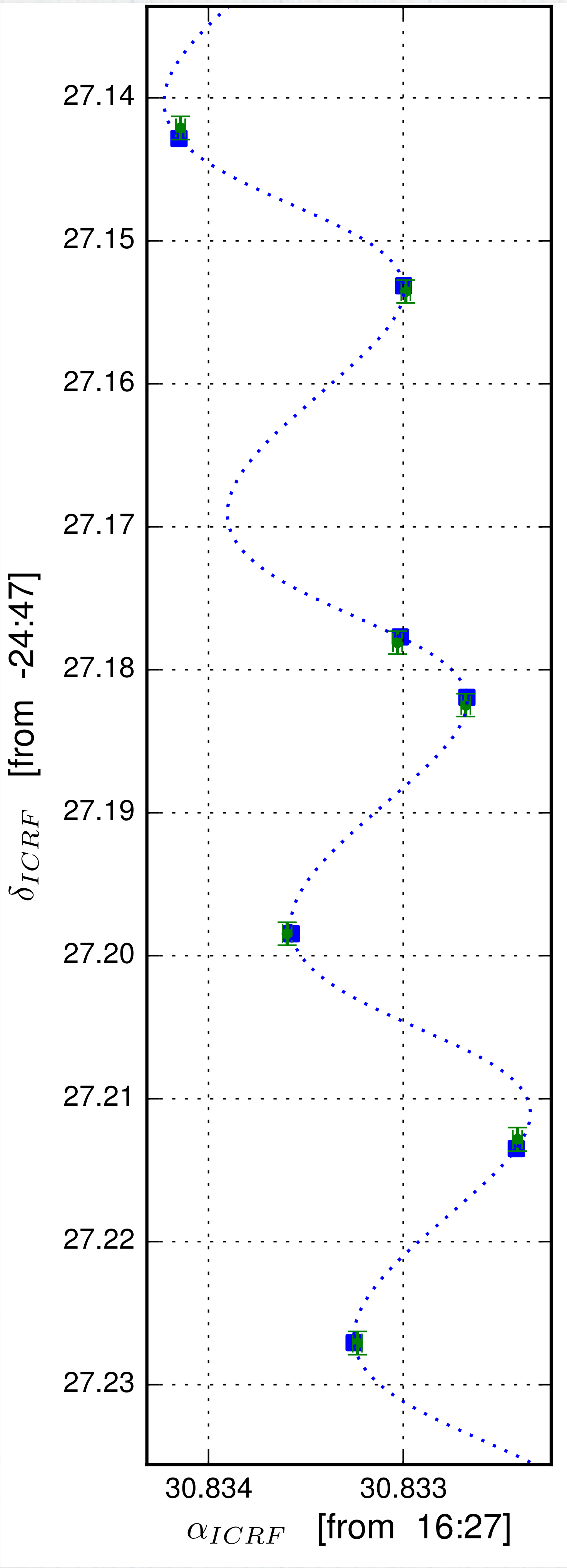


GOBELINS - A VLBA astrometric survey of (embedded) young stars

* VLBA detections
  * From Class I to Class III objects
  * Emission shows high flux variations
  * Brightness temperature consistent with non-thermal radiation (>10^6 K)

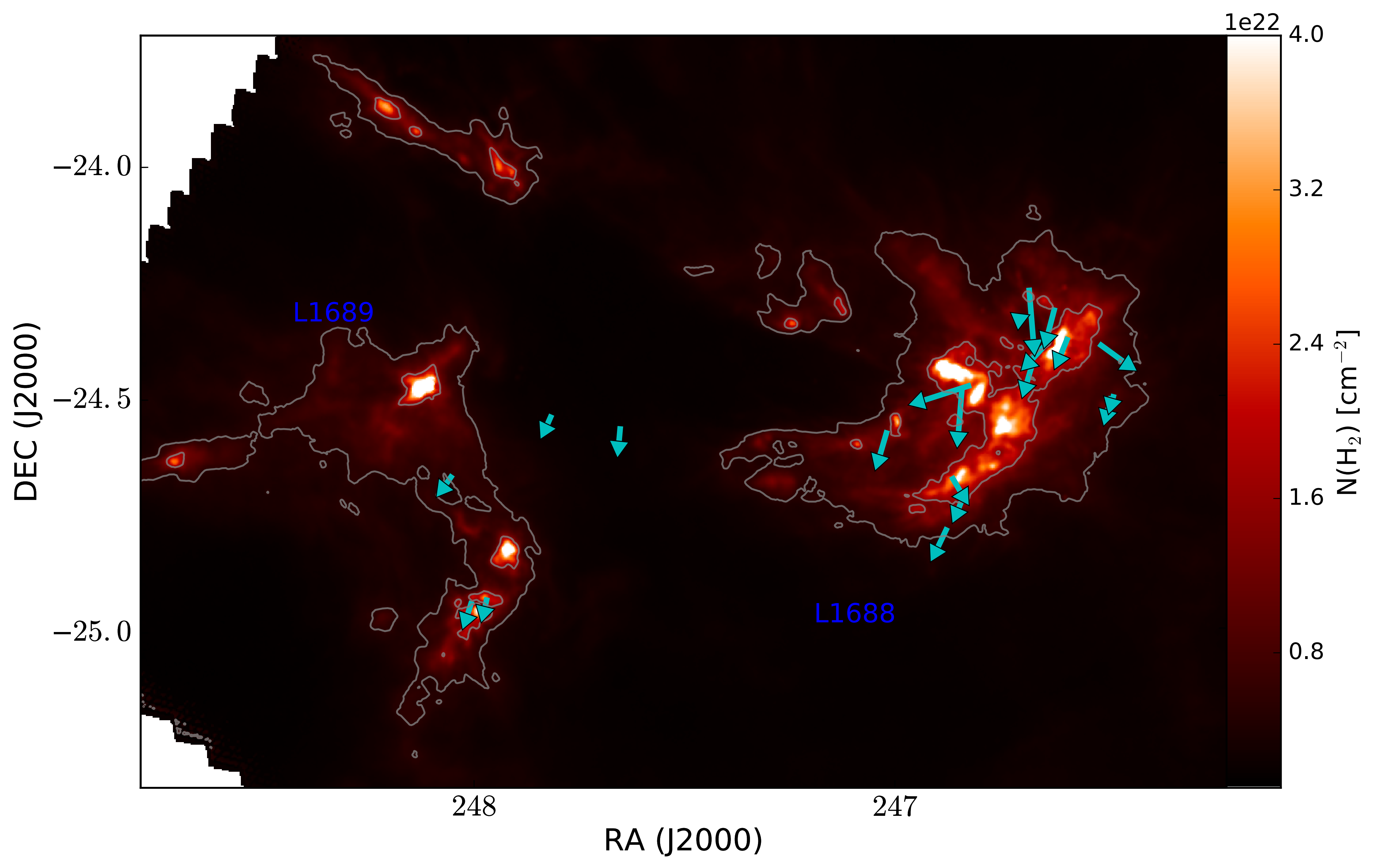


GOBELINS main results - Astrometry



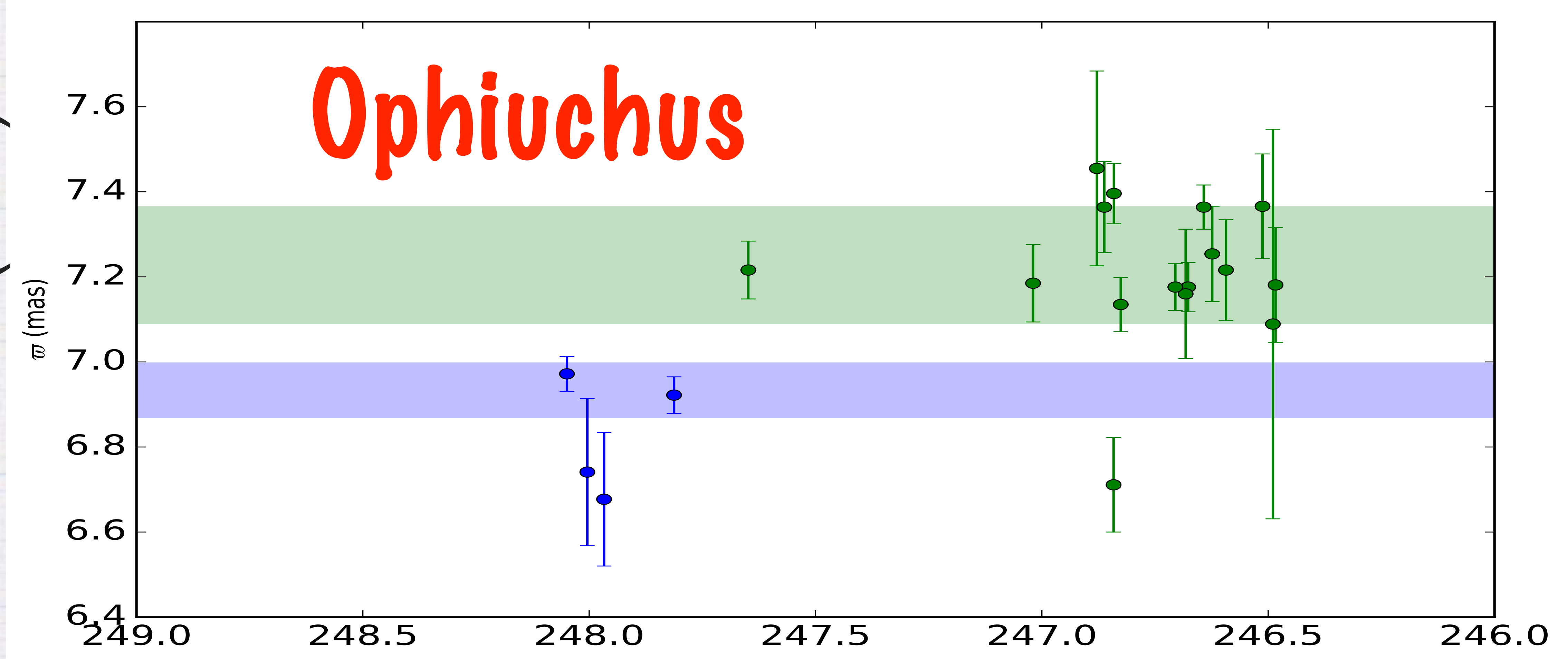
Ortiz-León +17

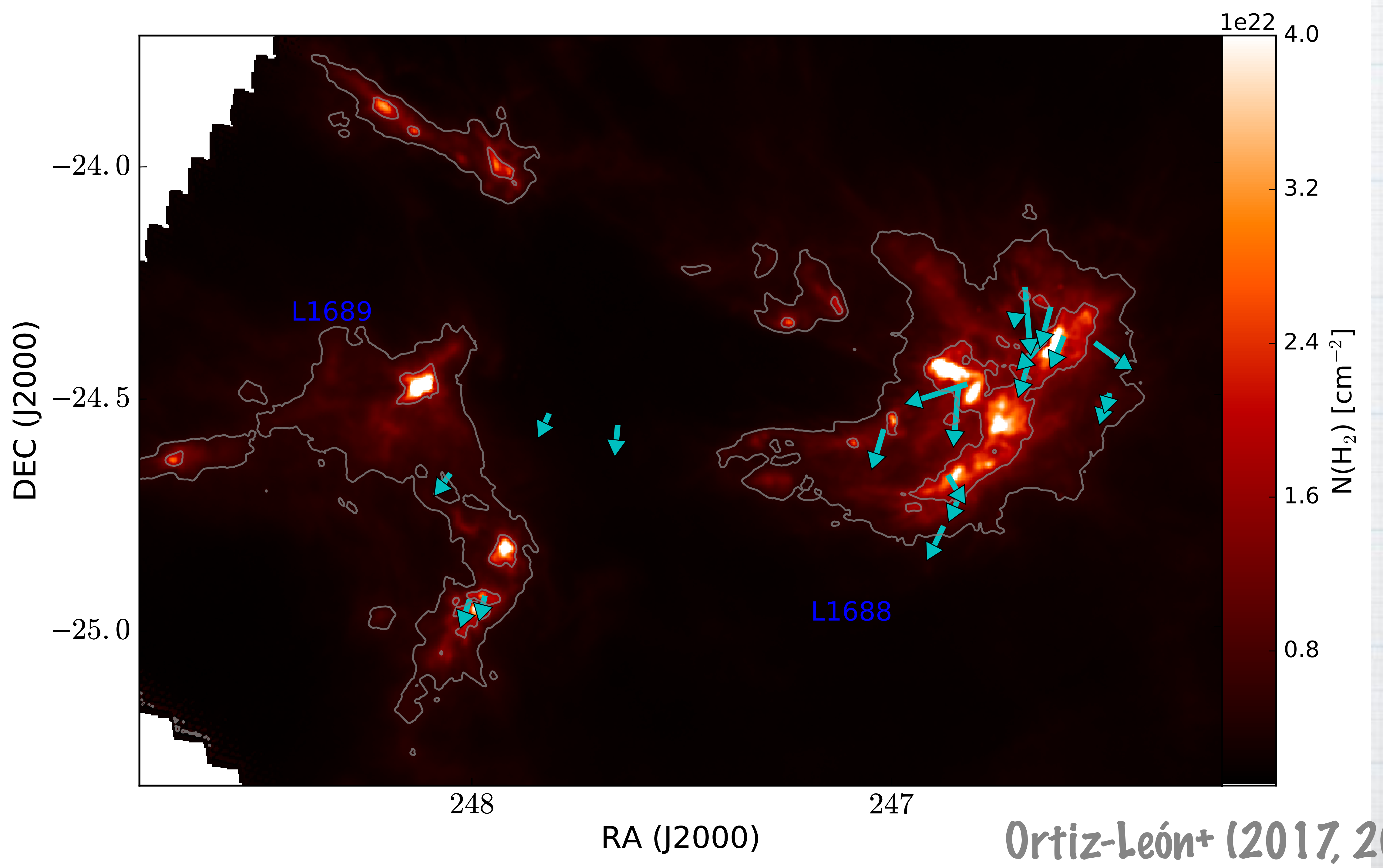
- Single stars:
  - 5 free parameters.
  - Errors on parallax range from 0.2 to 3%.
  - Systematics are the main source of error.



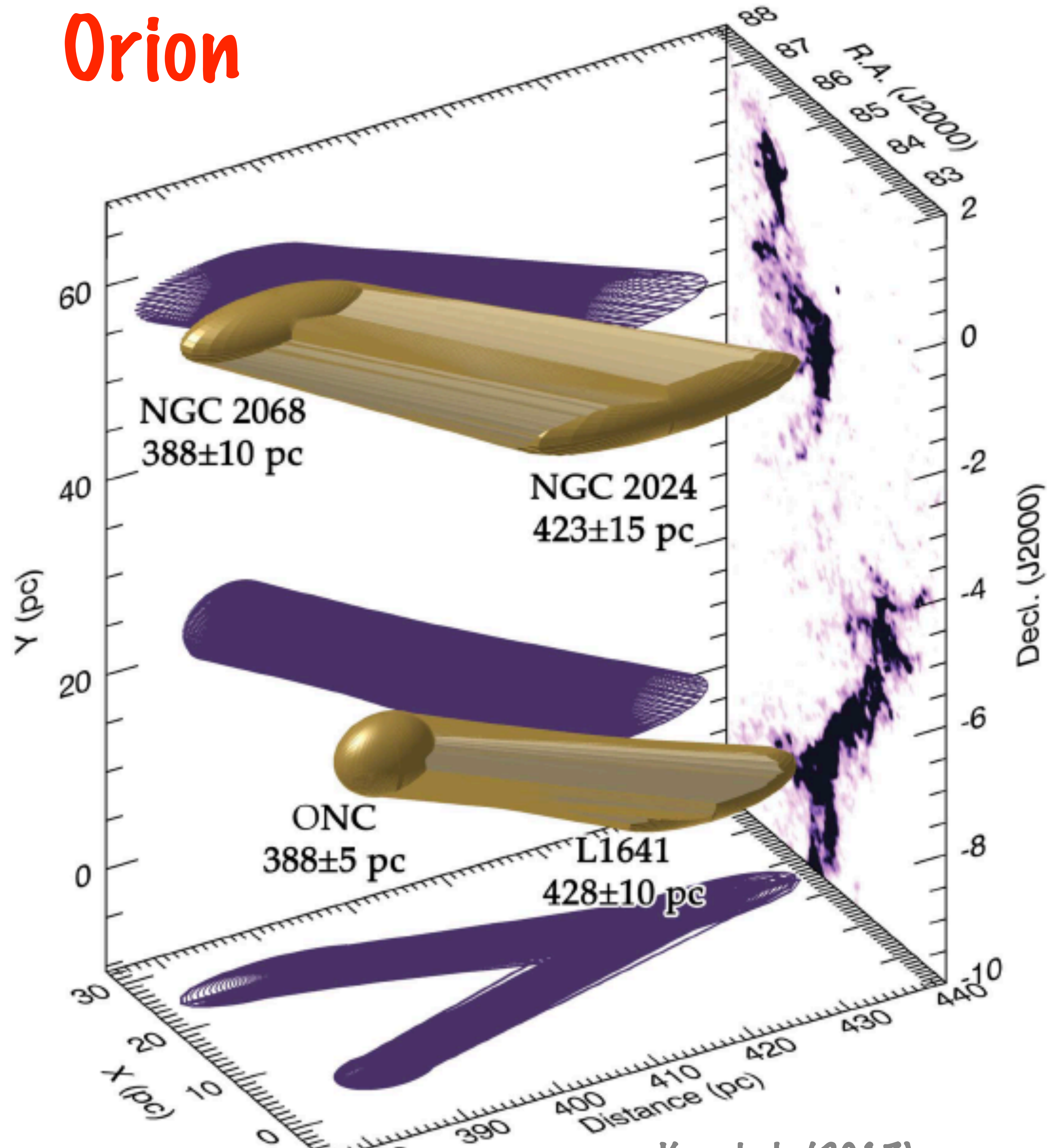
- Errors on proper motions are typically better than 0.2 mas/yr.
  - At 140 pc this translates to ~0.1 km/s.

GOBELINS main results - Distances





Ortiz-León+ (2017, 2018)



Kounkel+ (2017)

GOBELINS main results - Distances

Based on almost 100 stars with non-thermal radio emission observed

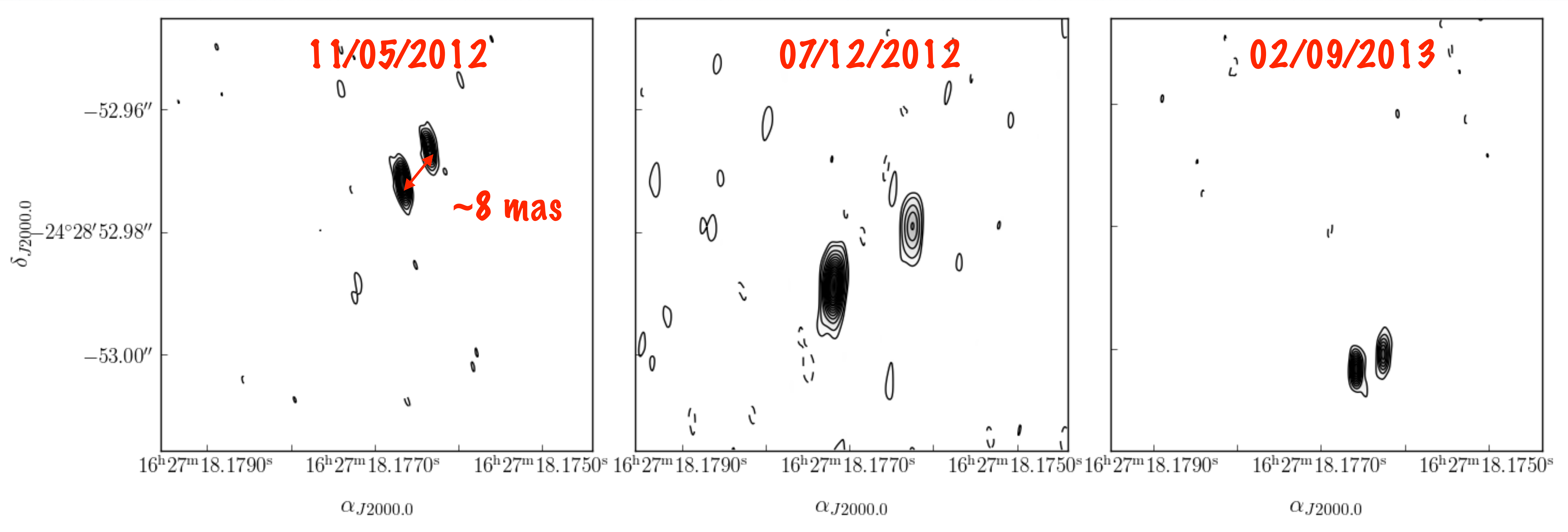
Region	Cluster	Distance
Ophichus	L1688	138 ± 3 pc
	L1699	144 ± 1 pc
Serpens	Serpens Main	436 ± 9 pc
	W40	436 ± 9 pc
Orion	Trapezium	383 ± 3 pc
	ONC	388 ± 5 pc
	L1641	428 ± 10 pc
	NGC 2024	~ 420 pc
	Sigma Ori	~ 300 pc
	NGC 2068	388 ± 10 pc

Region	Cluster	Distance
Taurus	L1495	129.5 ± 0.3 pc
	L1495/B216	158.1 ± 1.2 pc
	L1513+1519	142.6 ± 2.3 pc
	L1531	126.6 ± 1.7 pc
	L1534	138.6 ± 2.1 pc
	L1536	162.7 ± 0.8 pc
	L1551	147.3 ± 0.5 pc
	BDN176.28-20.89	148.7 ± 0.9 pc
Perseus	IC348	321 ± 10 pc

+ Cepheus, Monoceros, LKHα
Dzib et al. (2011, 2016, 2018)

References: Torres et al. (2007, 2009), Dzib et al. (2010), Ortiz-León et al. (2017ab), Kounkel et al. (2017), Galli et al. (2018), Ortiz-León et al. (2018)

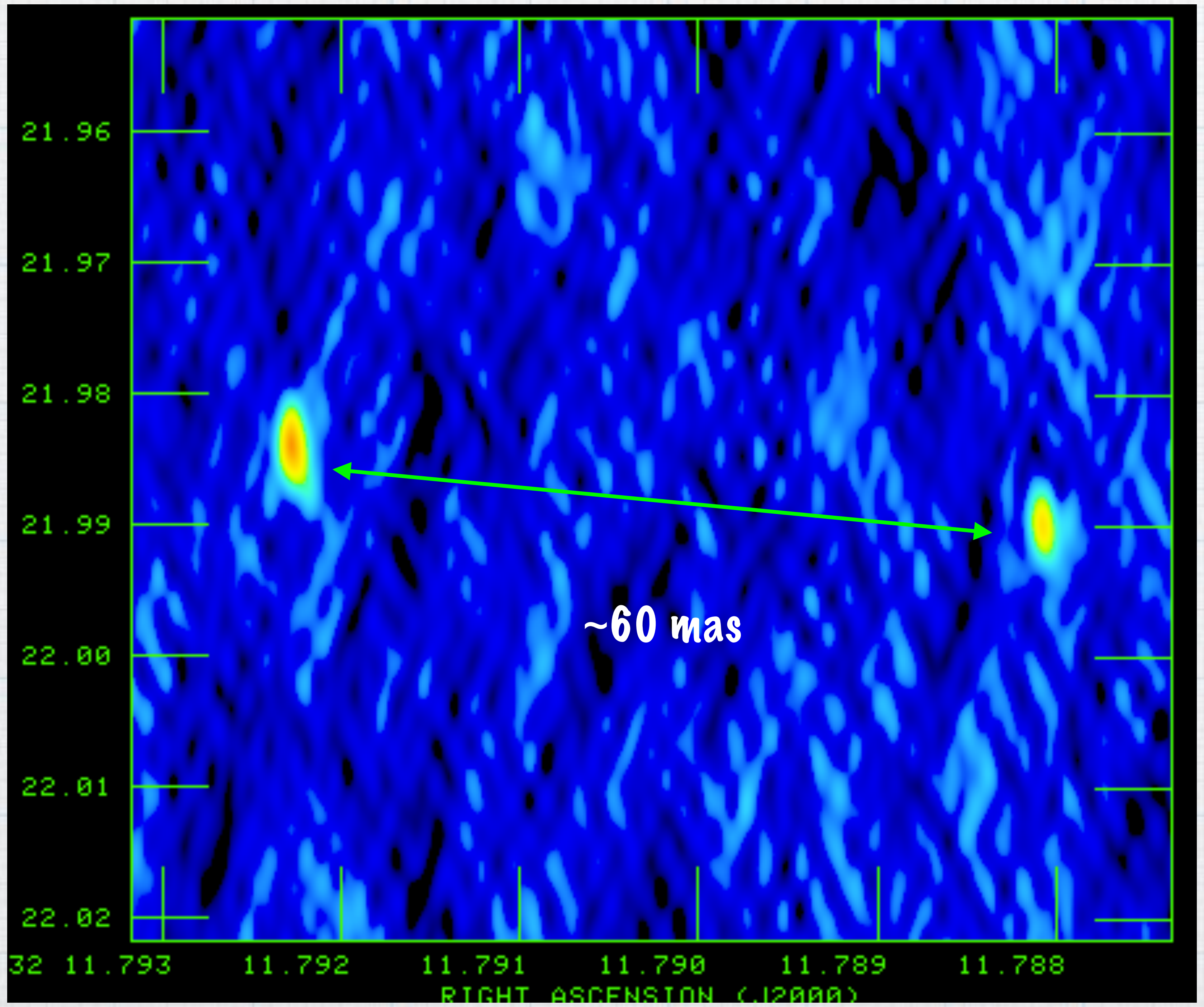
GOBELINS main results - astrometric binaries

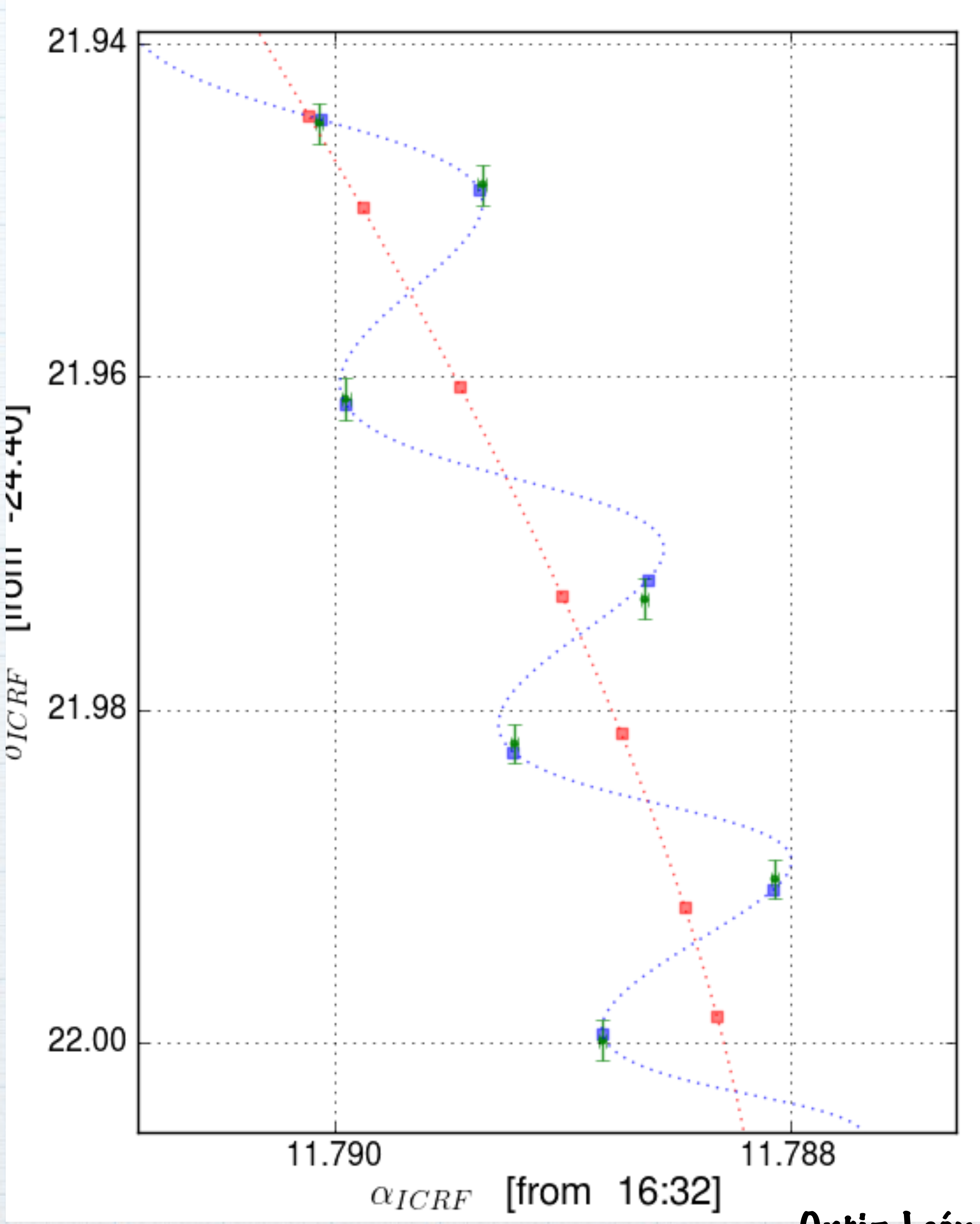


* Excess of radio-bright binaries with separations below 10 au.

GOBELINS main results - astrometric binaries

* Long-period binaries:
  * Proper motion + parallax + acceleration terms.

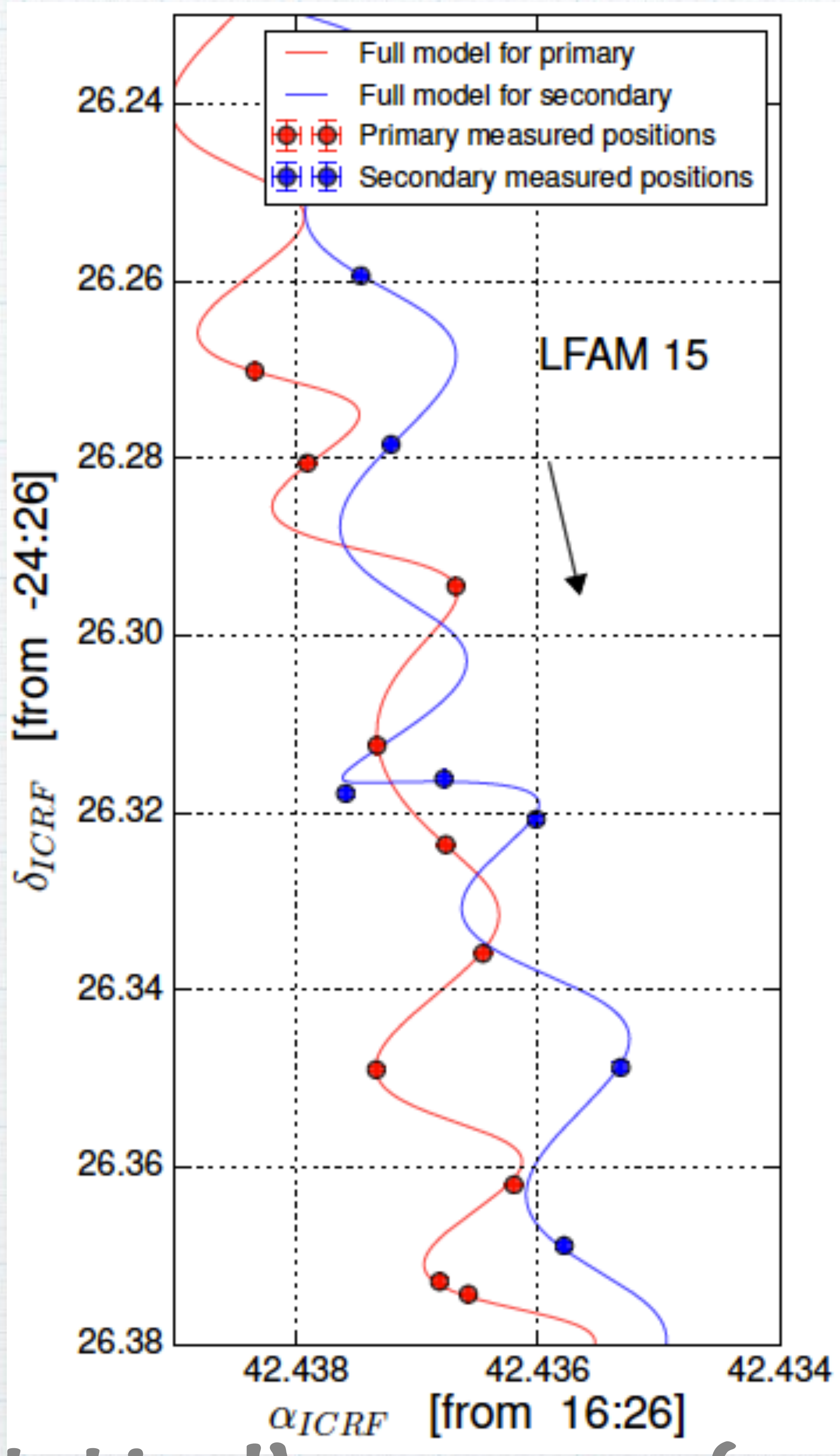


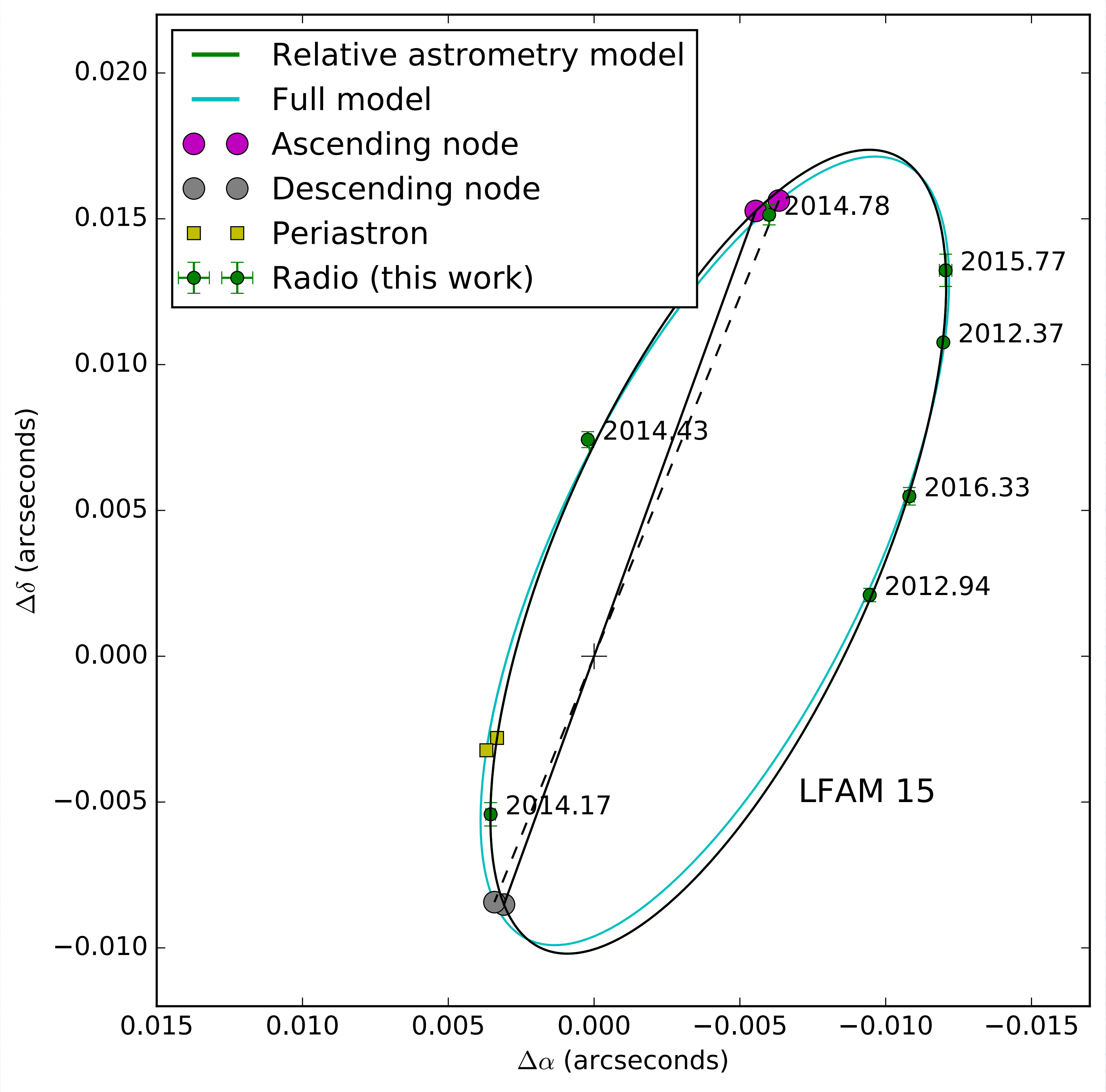


Ortiz-León et al. (2017)

GOBELINS main results - astrometric binaries

* Short-period binaries
  * Fit 5 astrometric parameters + 7 orbital parameters.





Ortiz-León et al. (2017)

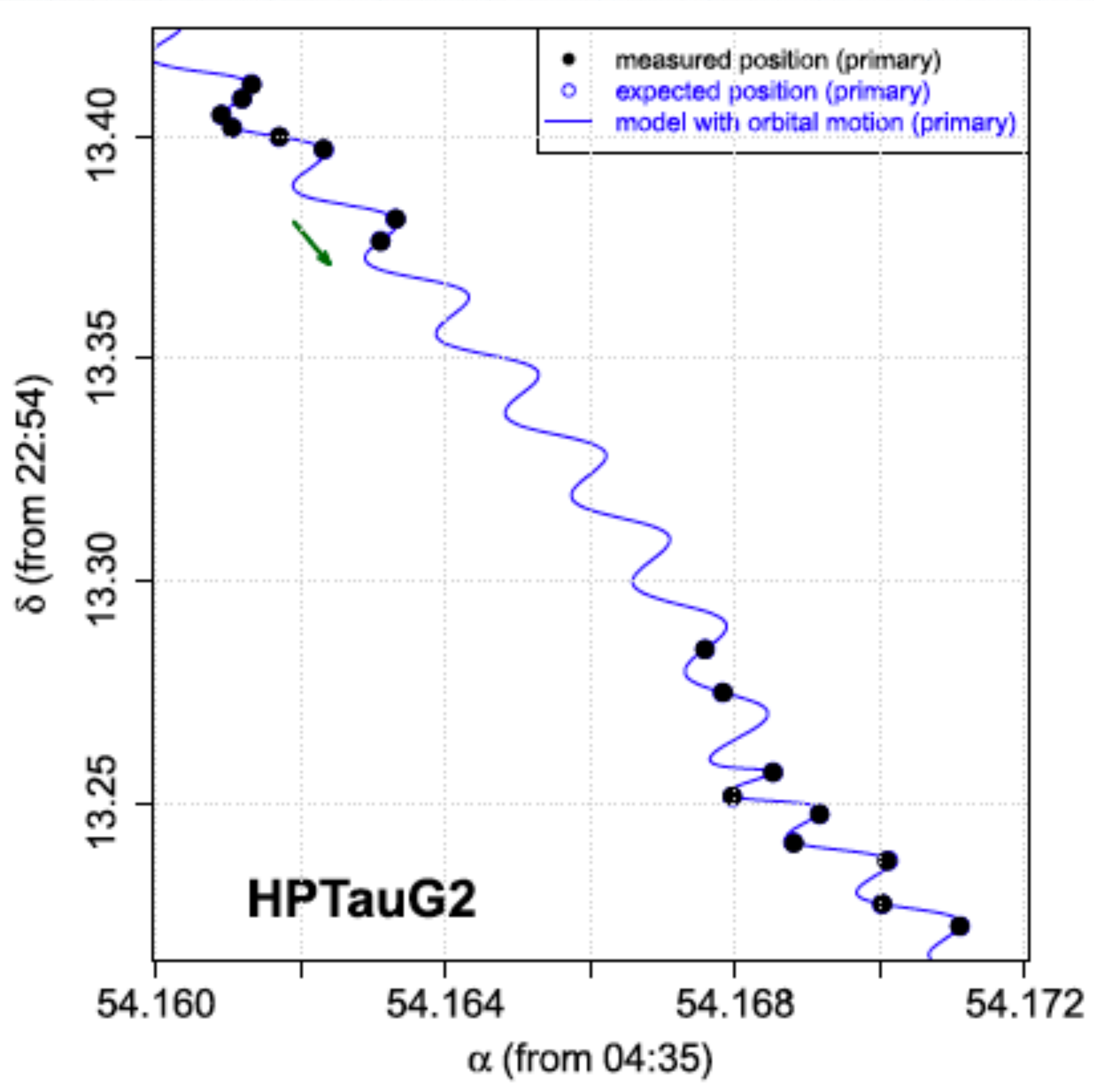
* **Dynamical** (individual) **masses** of very tight binary systems, with an accuracy of up to 2-5%.

GOBELINS main results - astrometric binaries

Name	a (au)	P (yr)	M_1 (Msun)	M_2 (Msun)
LFAM15	2.31 ± 0.02	3.598 ±0.005	0.506 ± 0.002	0450 ± 0.010
YLW12Bab	1.74 ± 0.01	1.424 ± 0.001	1.244 ± 0.007	1.362 ± 0.017
SFAM87	4.98 ± 0.03	7.673 ± 0.005	1.076 ± 0.020	1.024 ± 0.027
DOAR51	4.71 ± 0.07	8.071 ± 0.030	0.815 ± 0.004	0.788 ± 0.034
ROXN39	6.9 ± 0.1	11.77 ± 0.008	1.63 ± 0.01	0.96 ± 0.05
S1	2.65 ± 0.03	1.736 ± 0.002	5.2 ± 3.6	1.0 ± 0.7
EC95	12.4 ± 0.1	21.36 ± 0.05	1.97 ± 0.05	2.21 ± 0.10
GFM65	3.5 ± 1.0	5.5 ± 1.4	0.6 ± 1.5	0.7 ± 1.0

* Confirmed binaries
  * Ophiuchus 10
  * Serpens 2
  * Taurus 6
  * Orion 3
* Binary candidates
  * Orion 5
  * Ophiuchus 2
  * Serpens 1
  * Perseus 2

GOBELINS main results - astrometric binaries

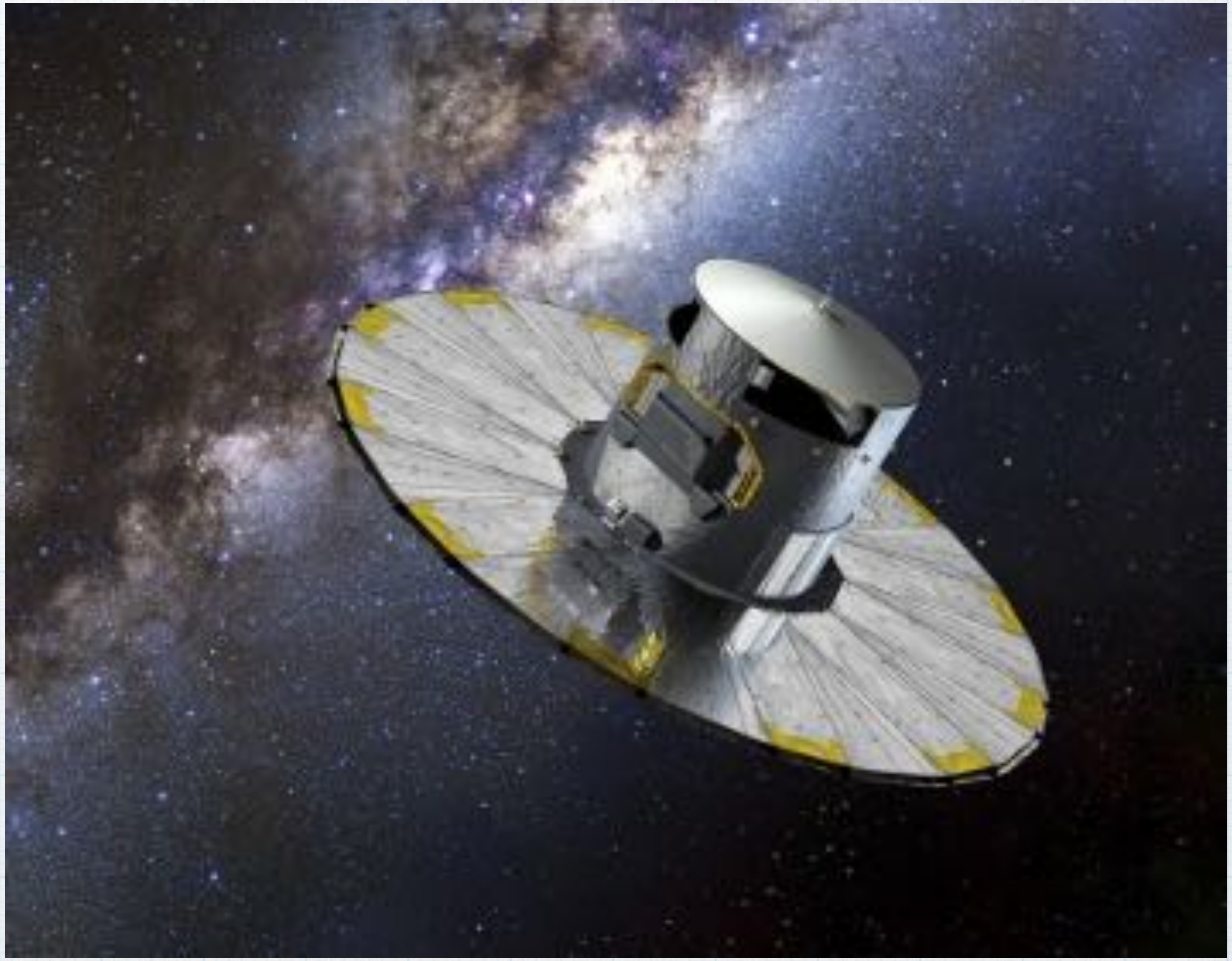


Galli+ (2018)

* Previously unknown companion detected by its astrometric signature.
* VLBI's potential to discover new hidden companions to pre-main sequence stars.

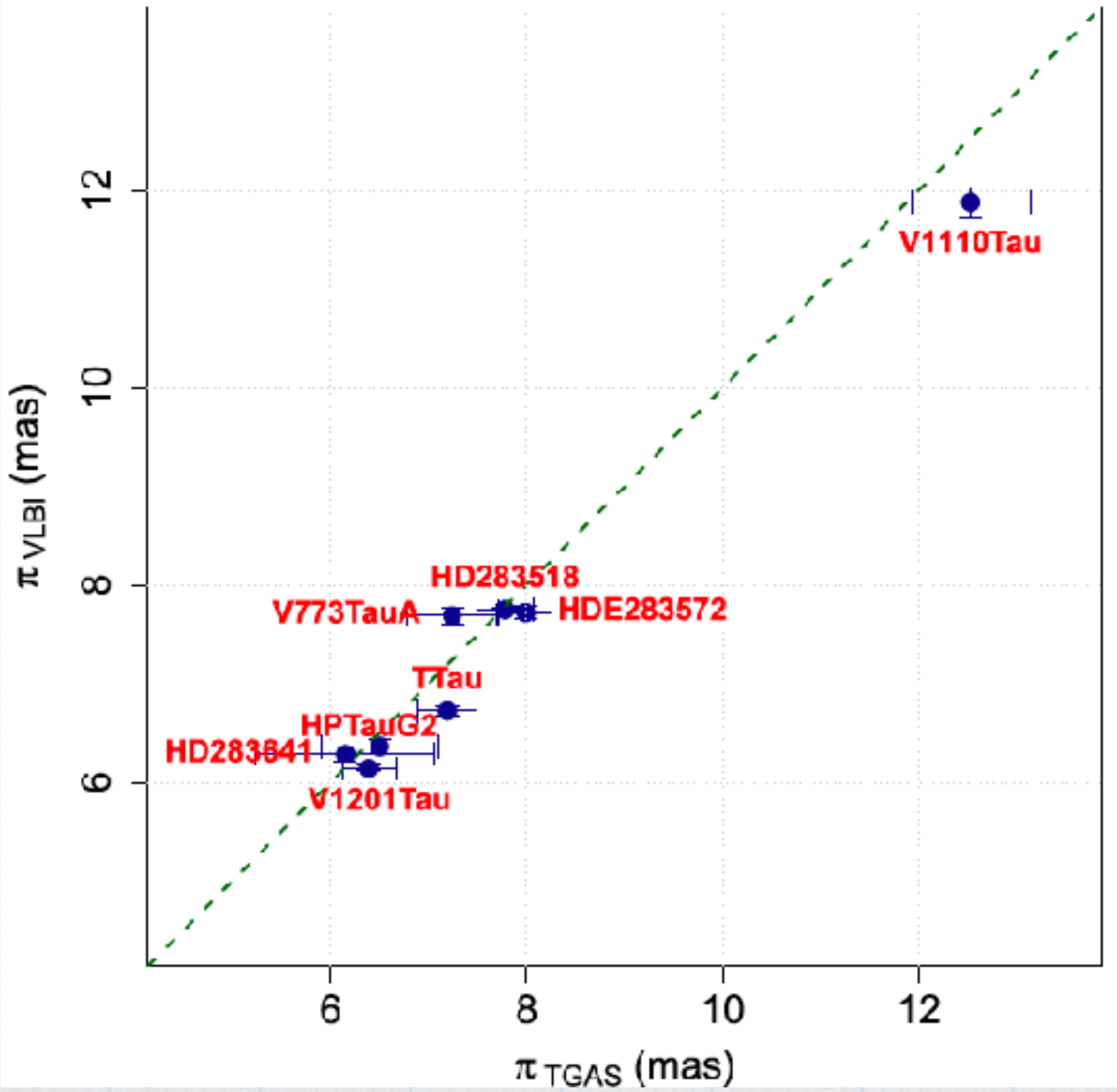
Gaia's astrometric catalogs

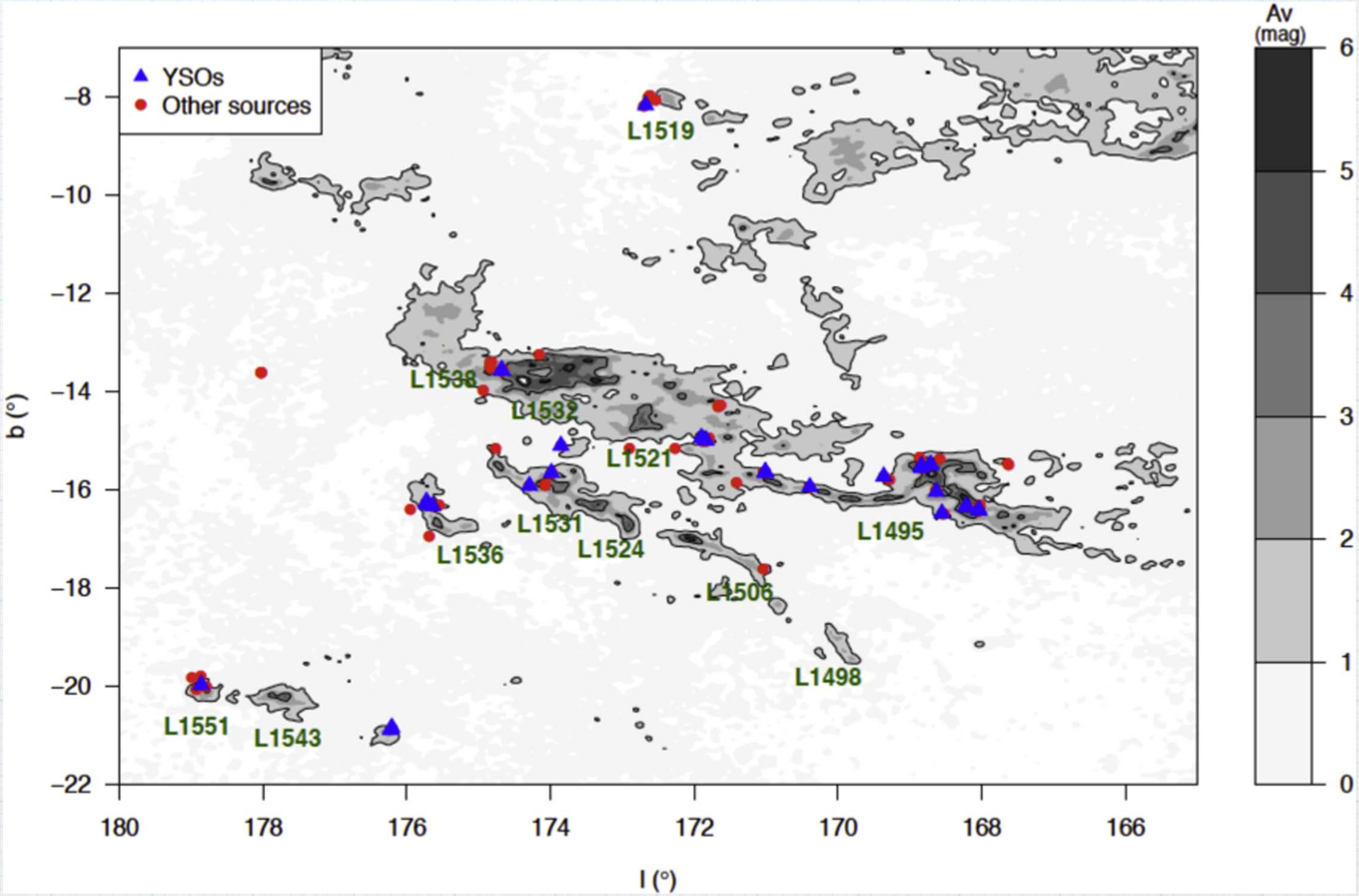
* DR1, 14 September 2016
    * 14 months of observation
    * Total number of sources: 1,142,679,769
    * Parallax and proper motions: 2,057,050 (Tycho-Gaia Astrometric Solution)
* DR2, 25 April 2018
    * 22 months of observation
    * Total number of sources: 1,692,919,135
    * Parallax and proper motions: 1,331,909,727



Taurus - VLBA + Gaia DR1

* 18 VLBA stars with astrometric solutions.
* 10 additional stars available in Gaia-DR1.
* 8 stars in common.

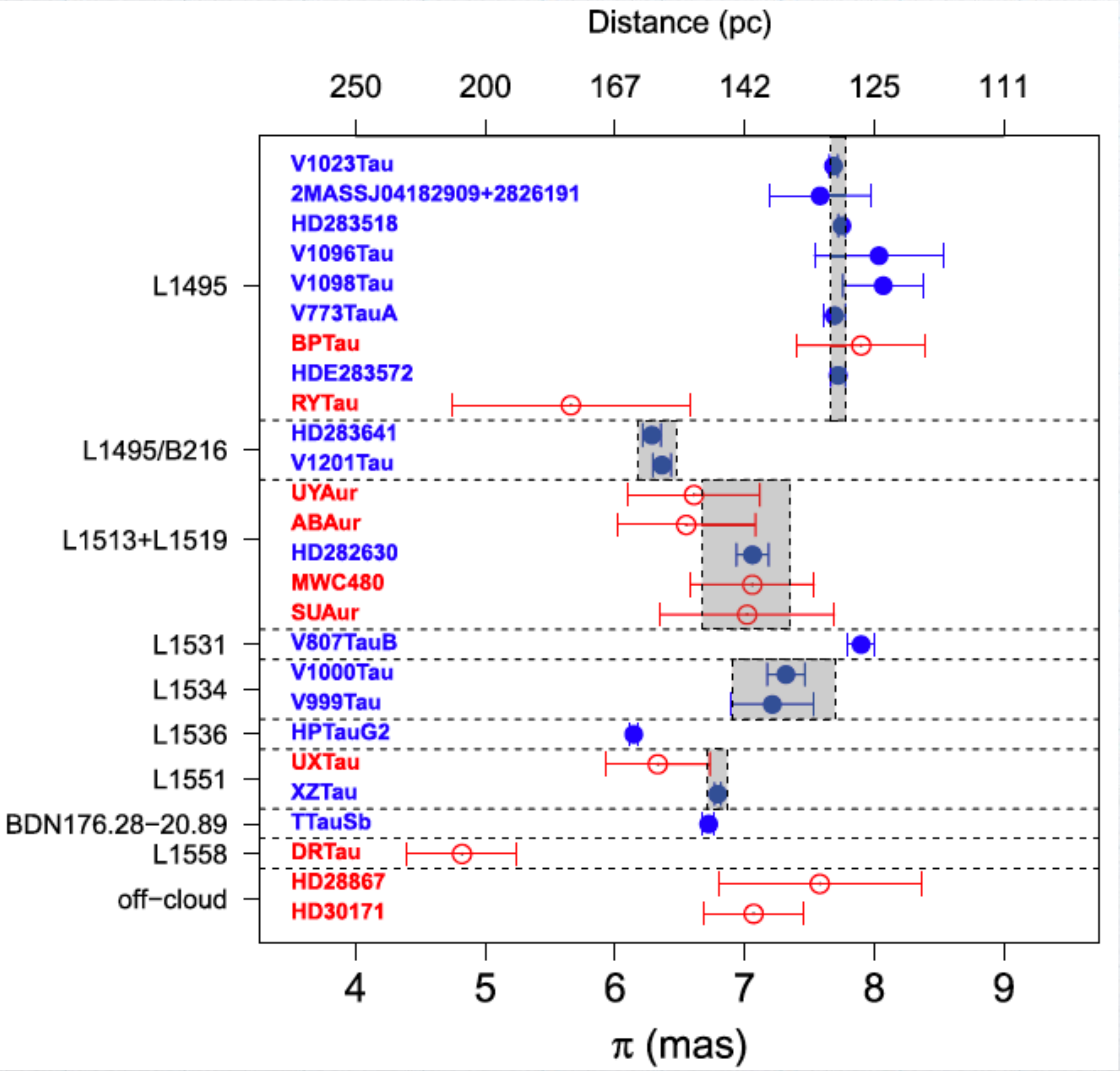


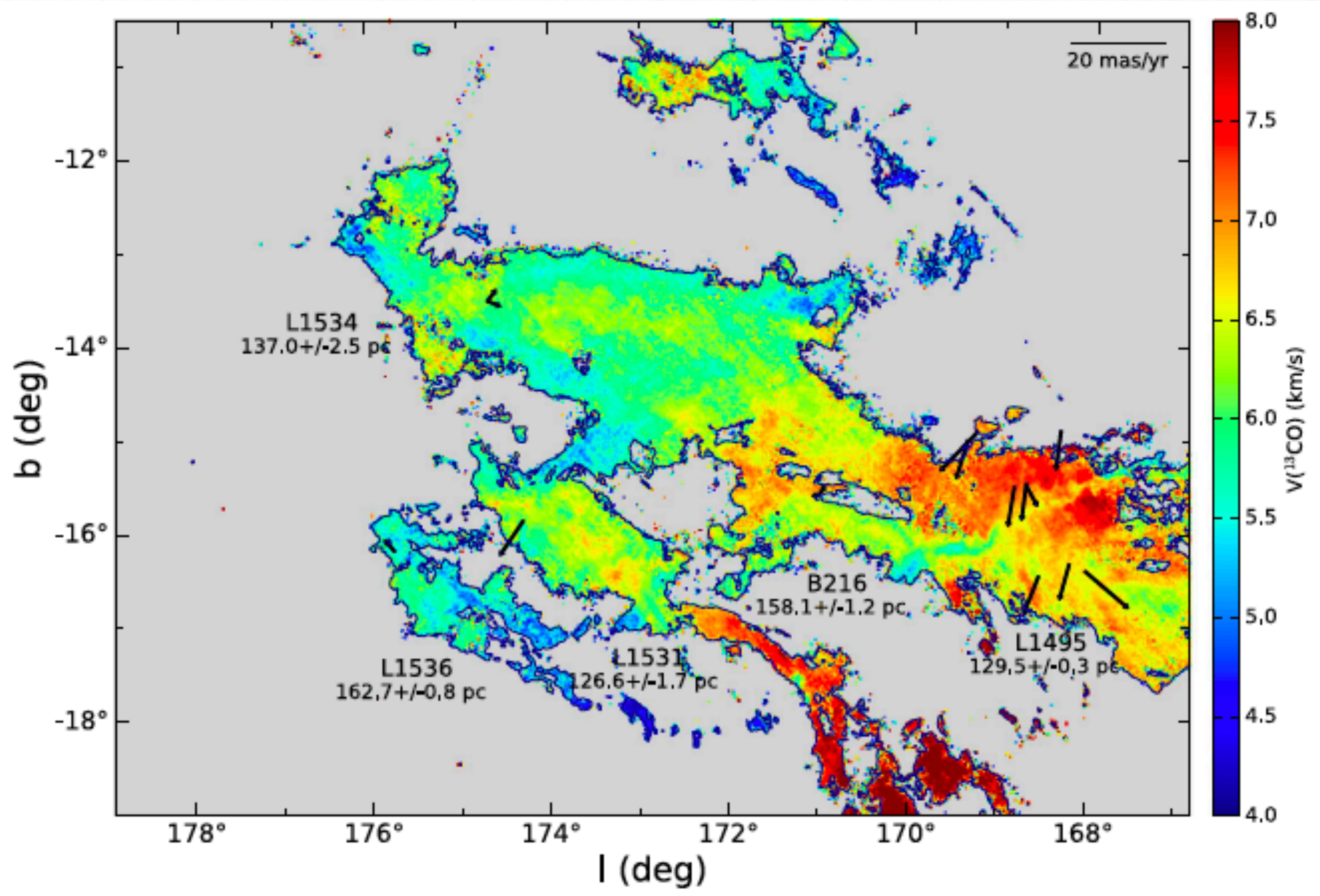


Galli+ (2018)

Taurus - VLBA + Gaia DR1

* Parallax distances reveal important depth effects within the cloud.

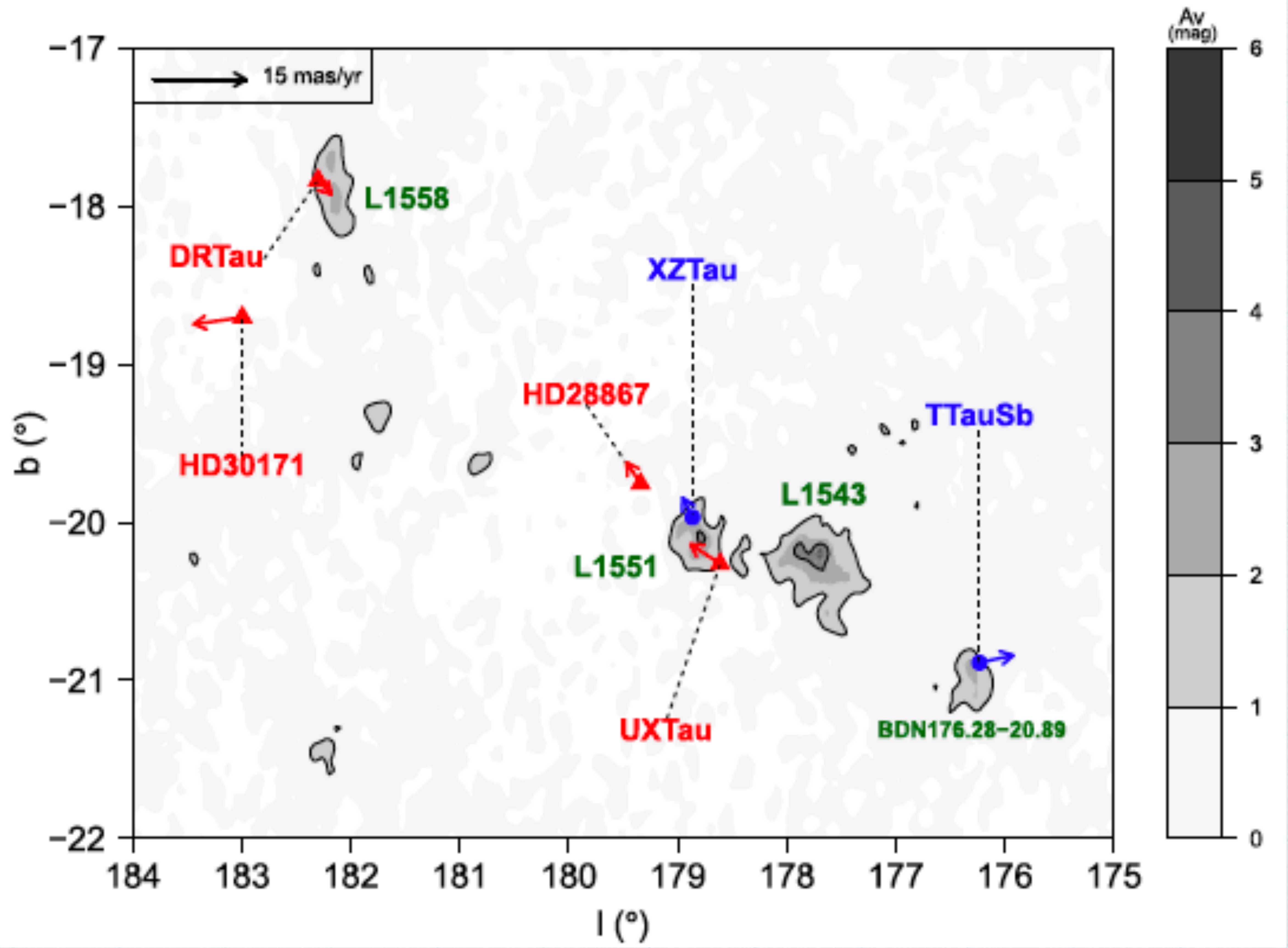


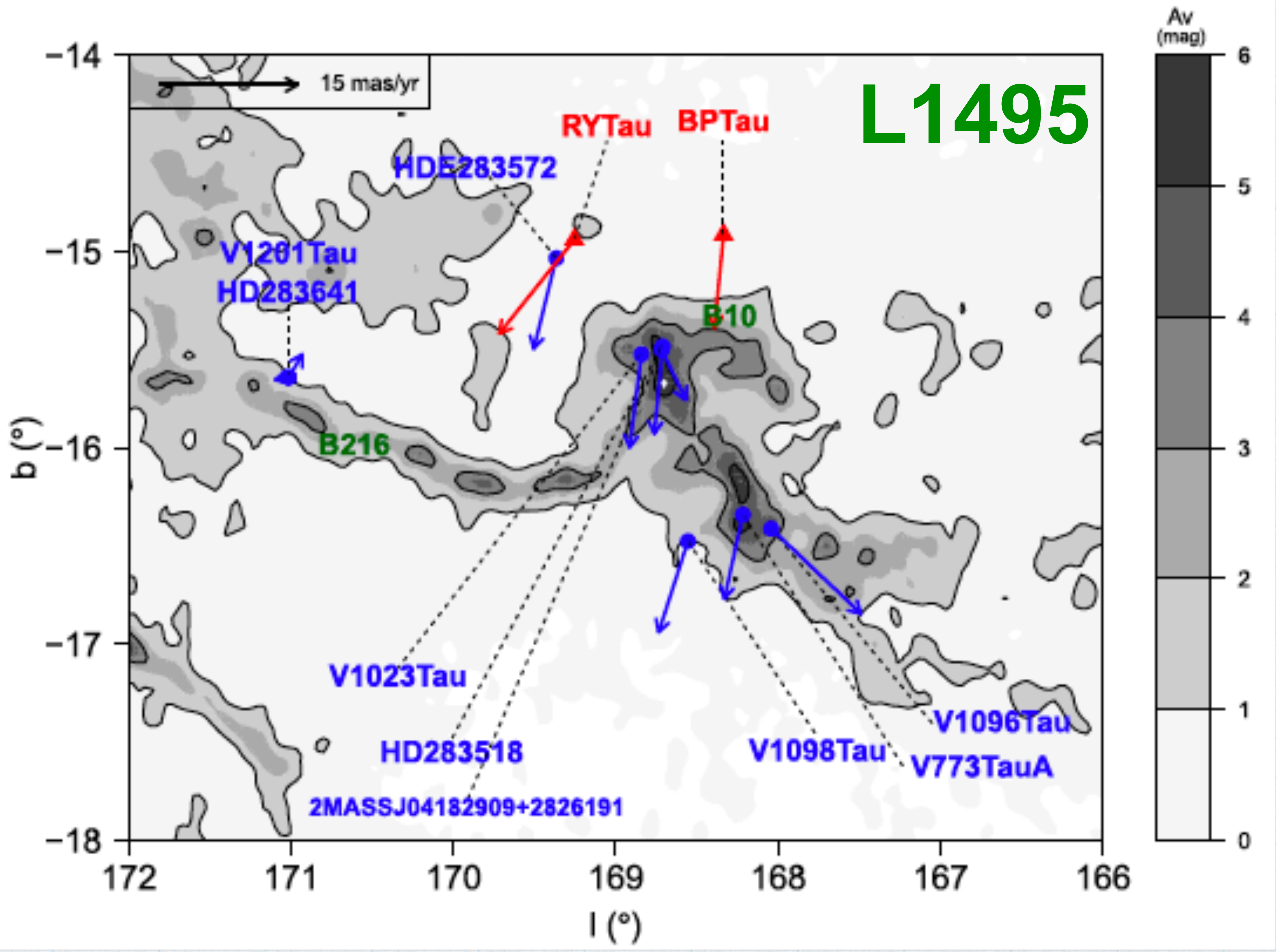


Galli+ (2018)

Taurus - VLBA + Gaia DR1

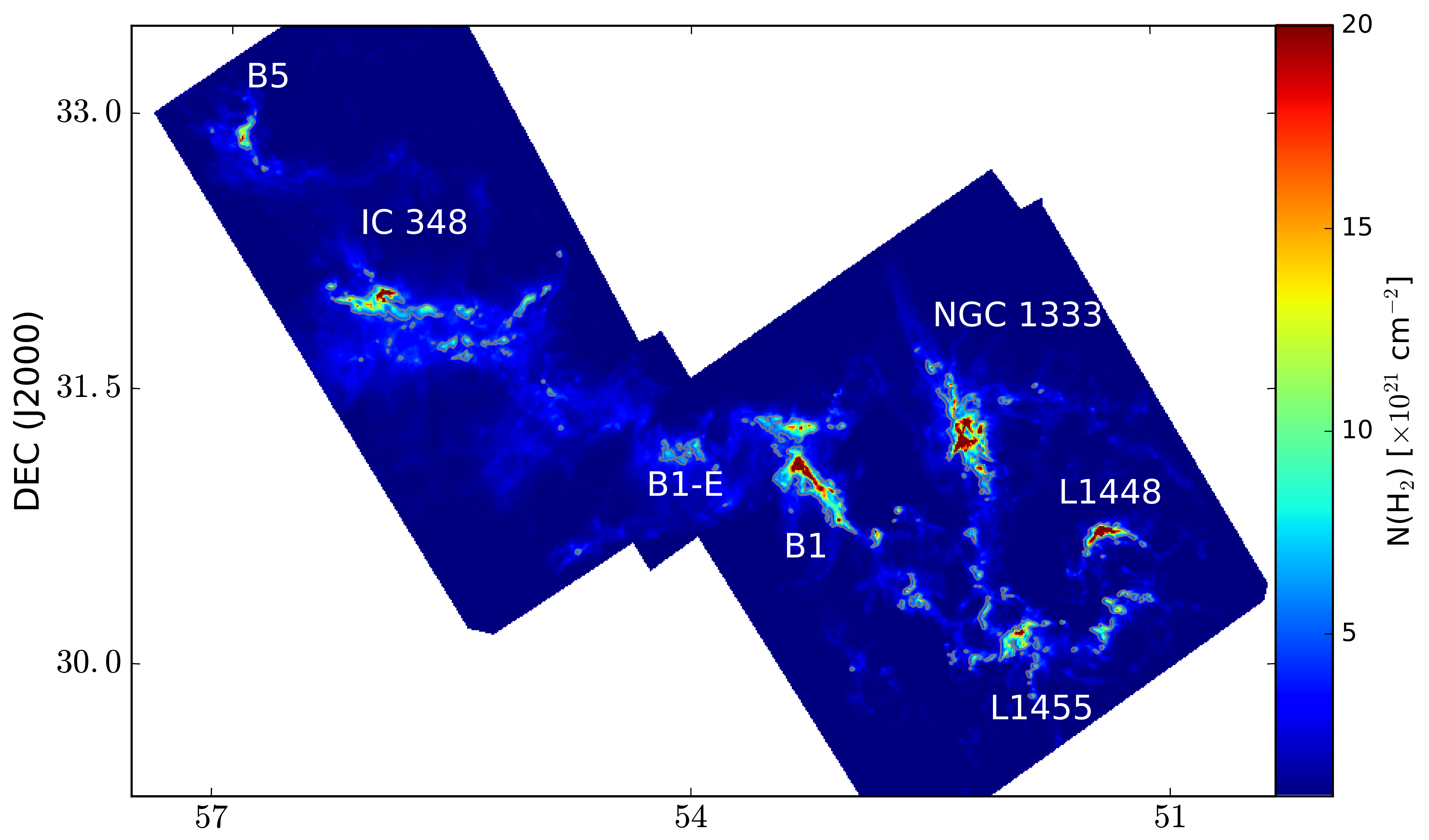
- Parallax distances reveal important depth effects within the cloud.
- Sub-structures also exhibit different kinematic properties.





The Perseus Molecular Cloud - VLBA + Gaia DR2

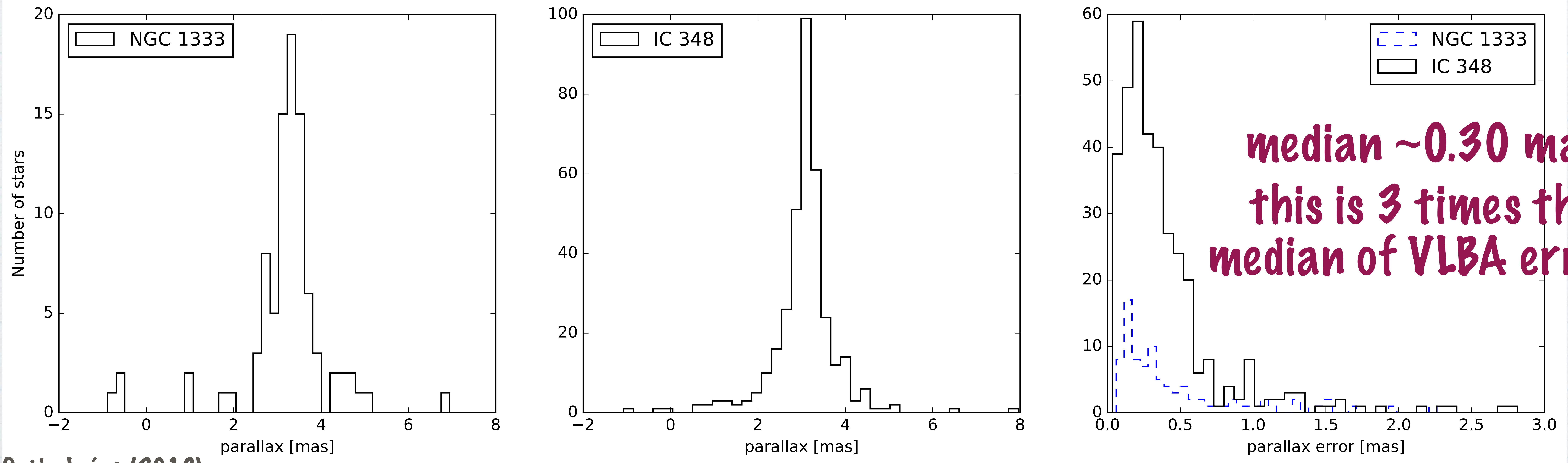
- The two main clusters, IC 348 and NGC 1333, contain together ~680 young stars (1-3 Myr).
- Only a small fraction of these are radio emitters (Pech+ 2016) and only seven were detected with the VLBA.



Ortiz-León+ (2018)

The Perseus Molecular Cloud - Gaia DR2 parallaxes

* Astrometric solutions in Gaia DR2 catalog for 351 (IC 348) and 90 (NGC 1333) stars.



Ortiz-León+ (2018)

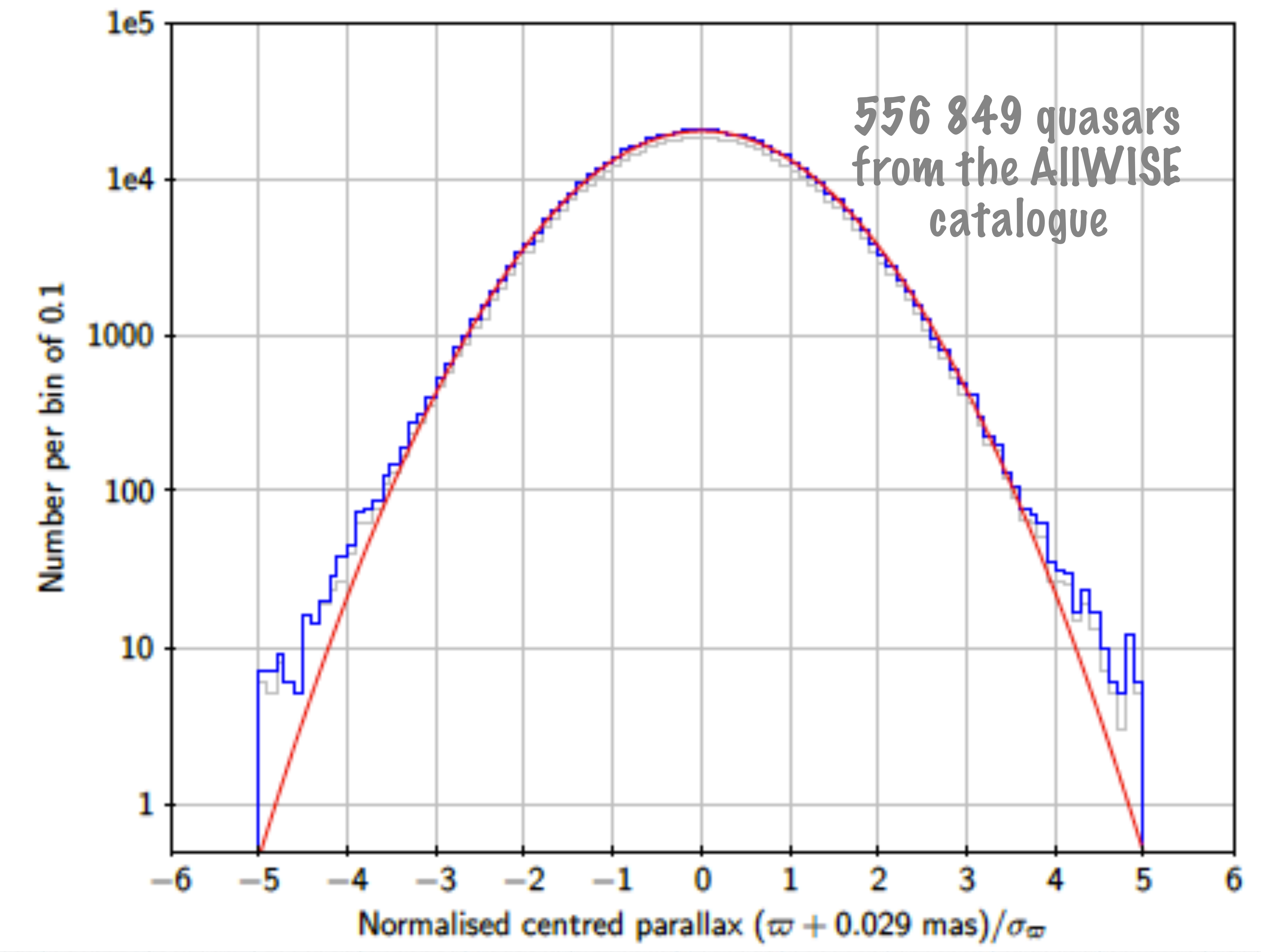
p = 3.38 ± 0.26 mas

p = 3.09 ± 0.25 mas

CONVERSION TO DISTANCES TOOK INTO ACCOUNT THE GAIA PARALLAX ZERO-POINT ERROR

Gaia parallax zero-point error

* "Gaia parallaxes are on the whole too small by about 0.03 mas" (Lindegren et al, 2018, p1).



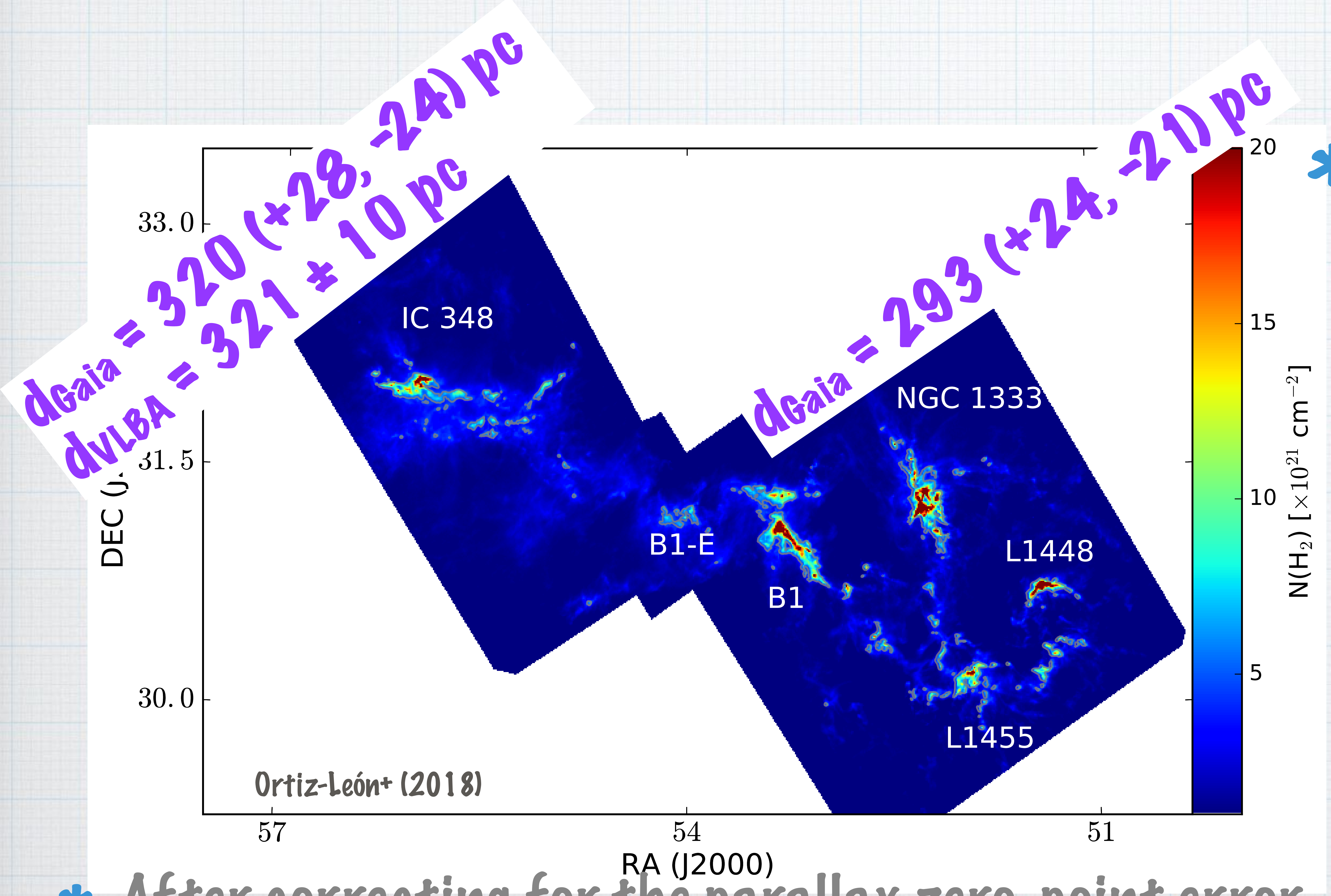
Lindegren et al (2018)

* This offset depends on magnitude, color and sky position.

* In IC 348 we found

p_gaia - p_vlba = -0.03 mas

Structure of the Perseus Molecular Cloud

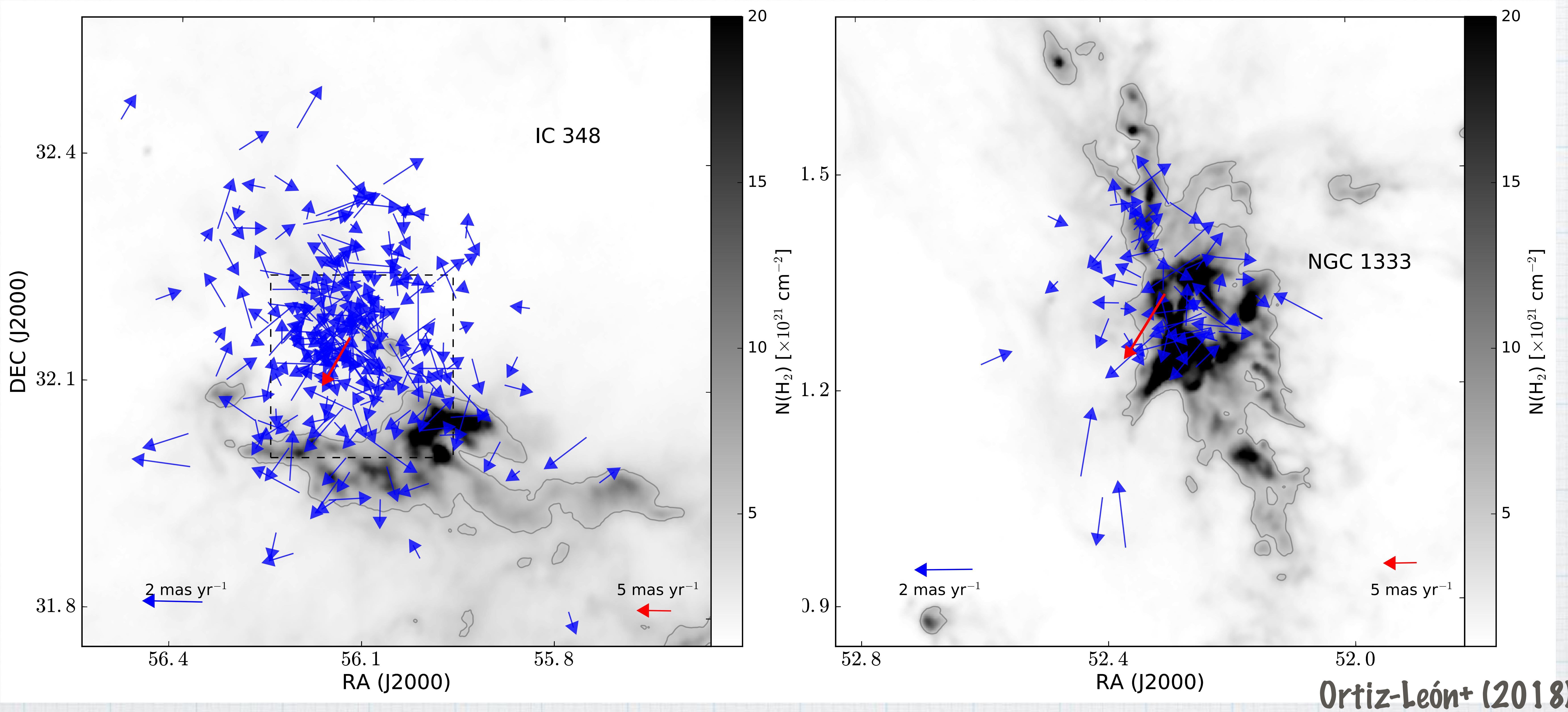


* Distance between the eastern and western edges of the cloud is only ~30 pc, which is significantly smaller than previously thought (e.g. Hirota et al 2008, 2011).

* After correcting for the parallax zero-point error.

The Perseus Molecular Cloud - Kinematics

* Cluster kinematics from proper motions and radial velocities



Ortiz-León+ (2018)

NO expansion or rotation

(A similar result was found independently by Kuhn et al 2018)

$$v_{\rm exp}\ ,\ \vec{v}_{\rm rot} < 2\ {\rm km\ s^{-1}}$$

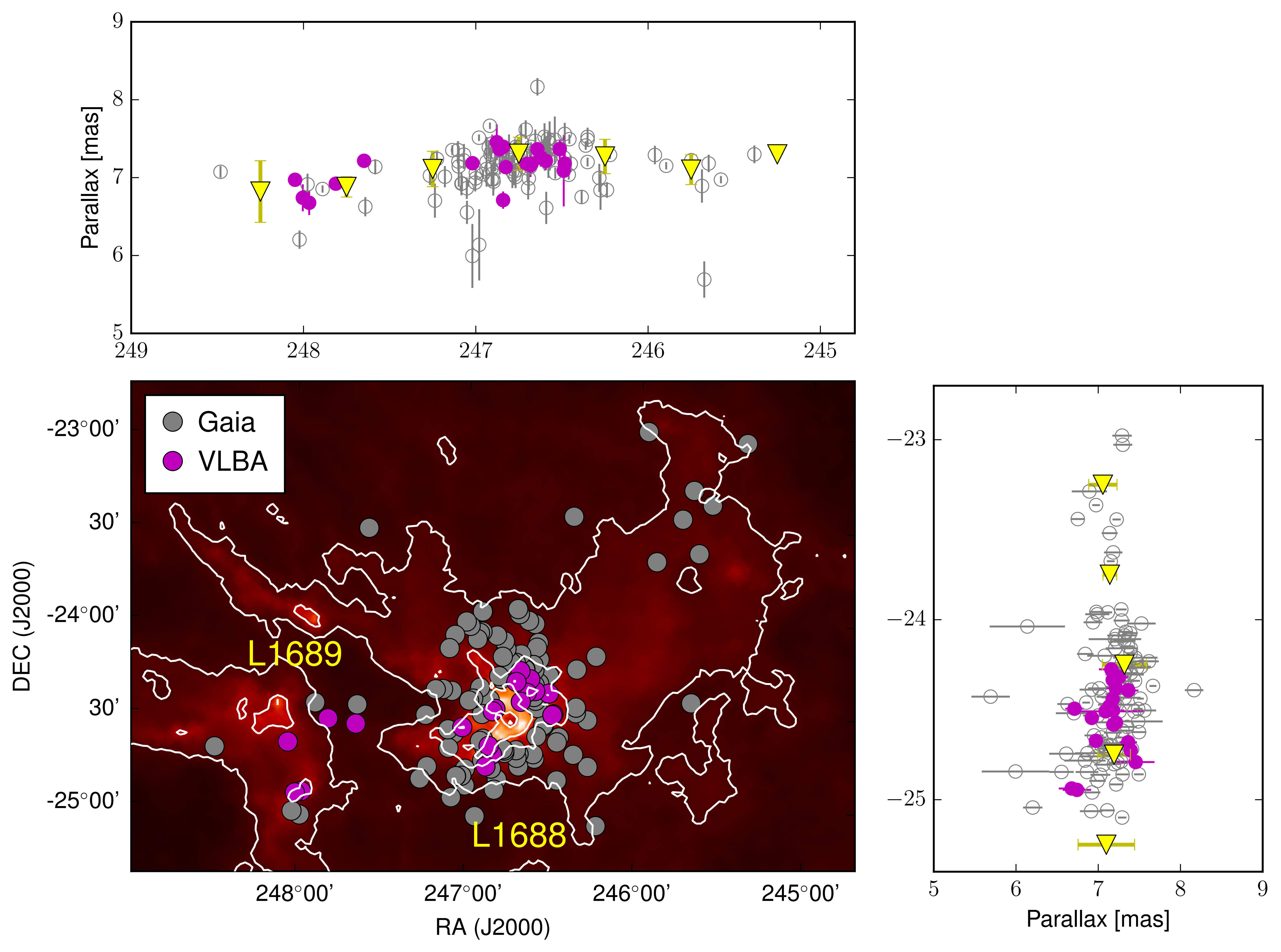
$$\vec{v}_{\rm rot} = (-0.16, 0.0, -0.10)\ {\rm km\ s^{-1}}$$
$$v_{\rm exp} = -0.06\ {\rm km\ s^{-1}}$$

$$\vec{v}_{\rm rot} = (-0.10, 0.10, 0.19)\ {\rm km\ s^{-1}}$$
$$v_{\rm exp} = 0.19\ {\rm km\ s^{-1}}$$

VLBA vs. Gaia DR2 - Ophiuchus

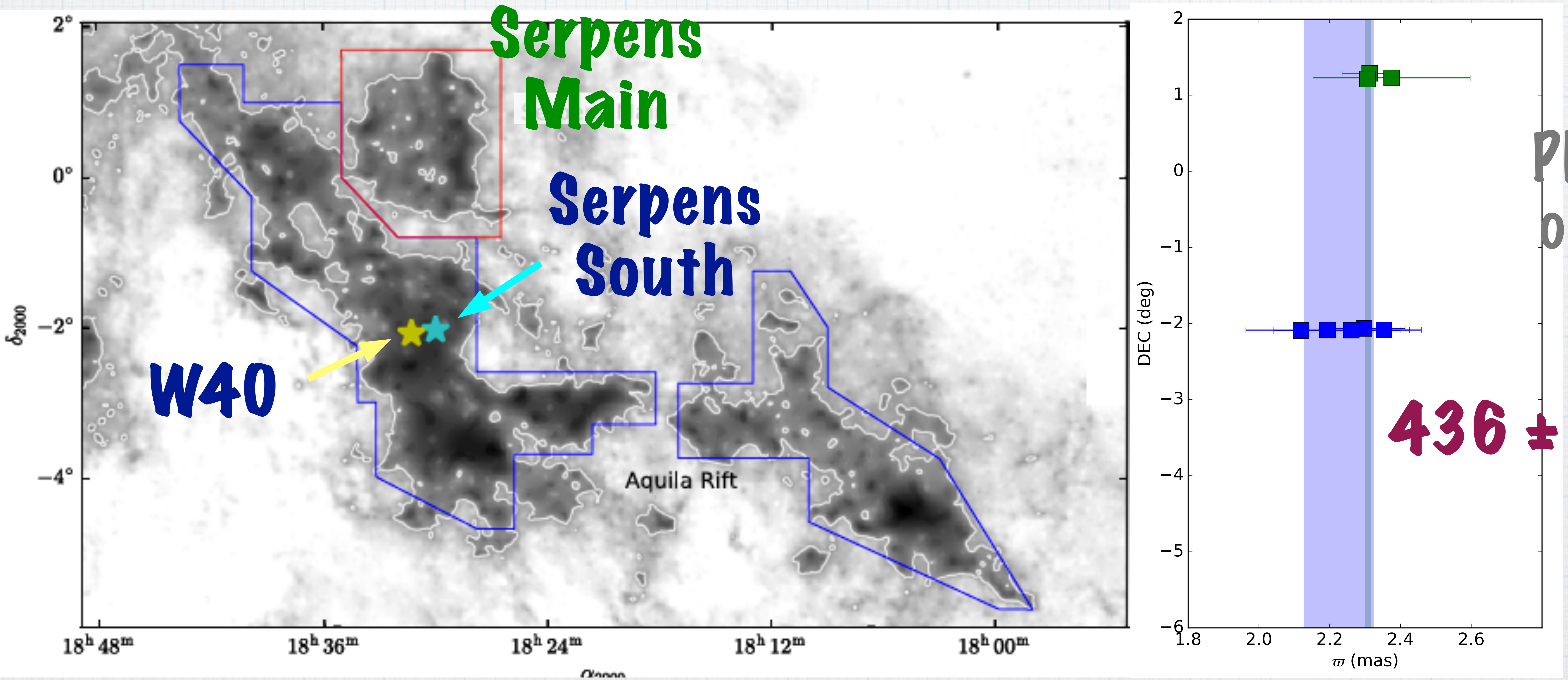
* Offset between Gaia and VLBA is positive for the most embedded part of the cloud, but negative outside.

* Gaia may be biased against the brightest sources (selection effect).



VLBA vs. Gaia DR2 - Serpens and Aquila

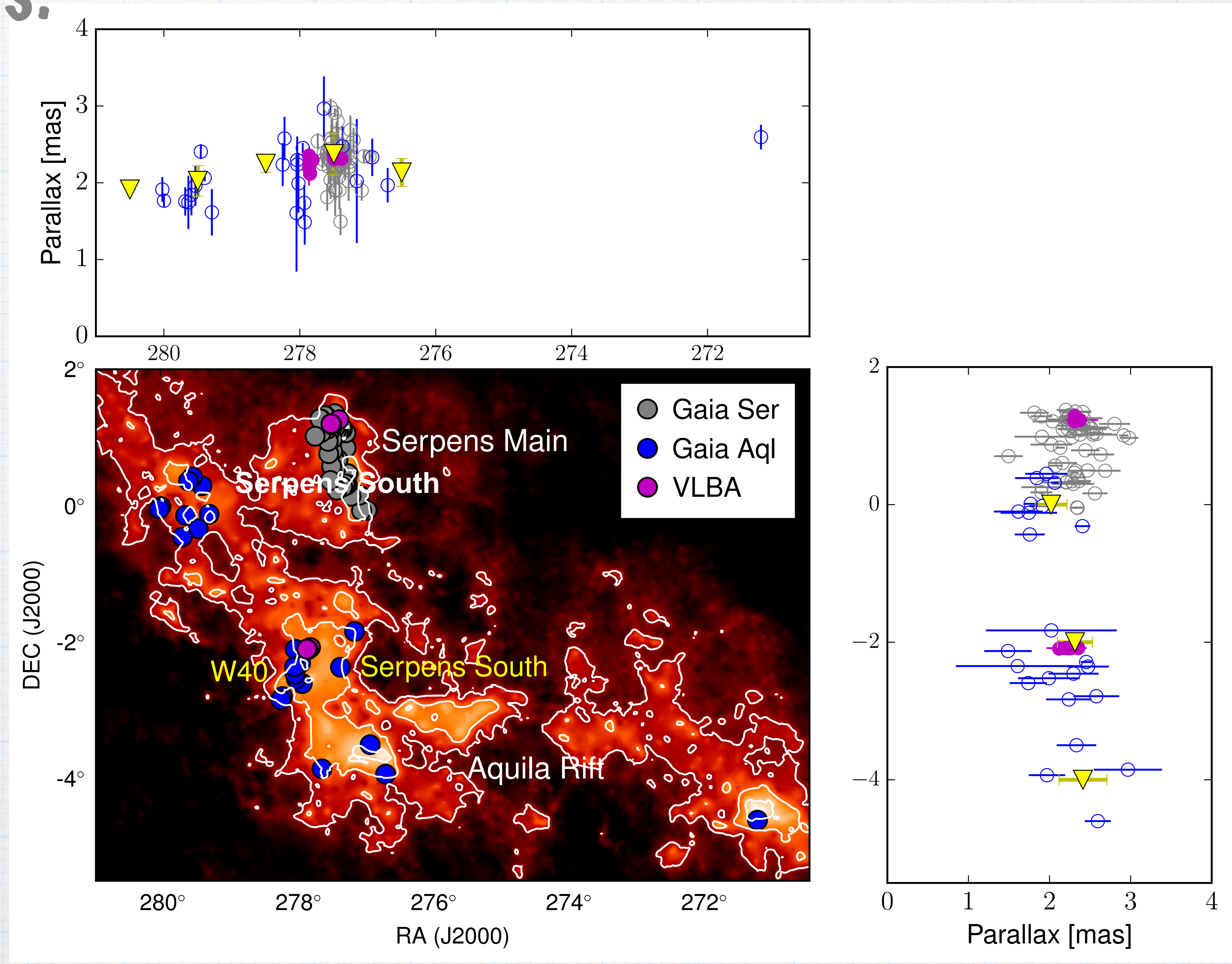
* A distance controversy in the Aquila Rift.
  * VLBA yielded a firm solution based on the astrometry to a few stars.



Photometric old distance ~260 pc

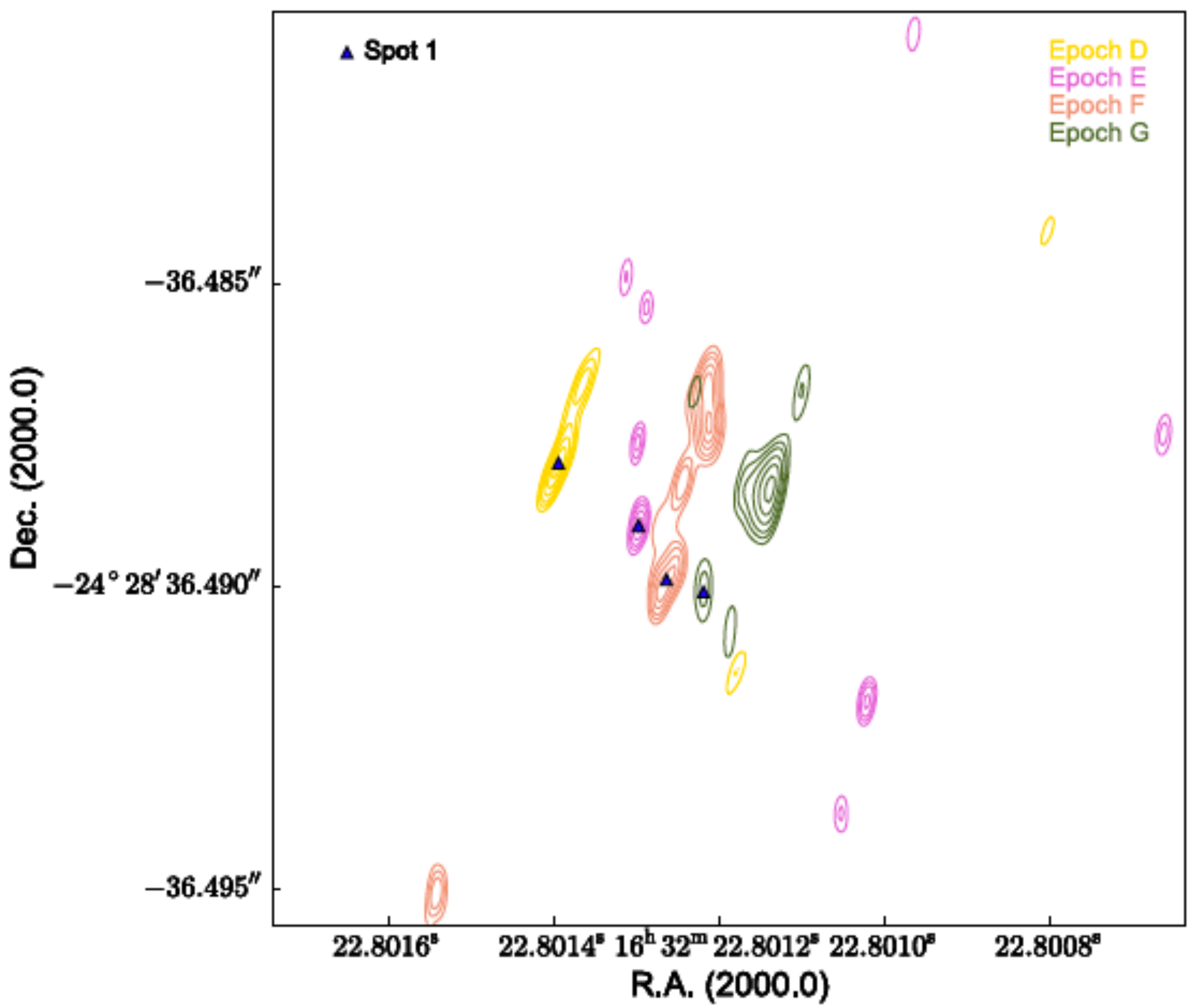
VLBA vs. Gaia DR2: Serpens and Aquila

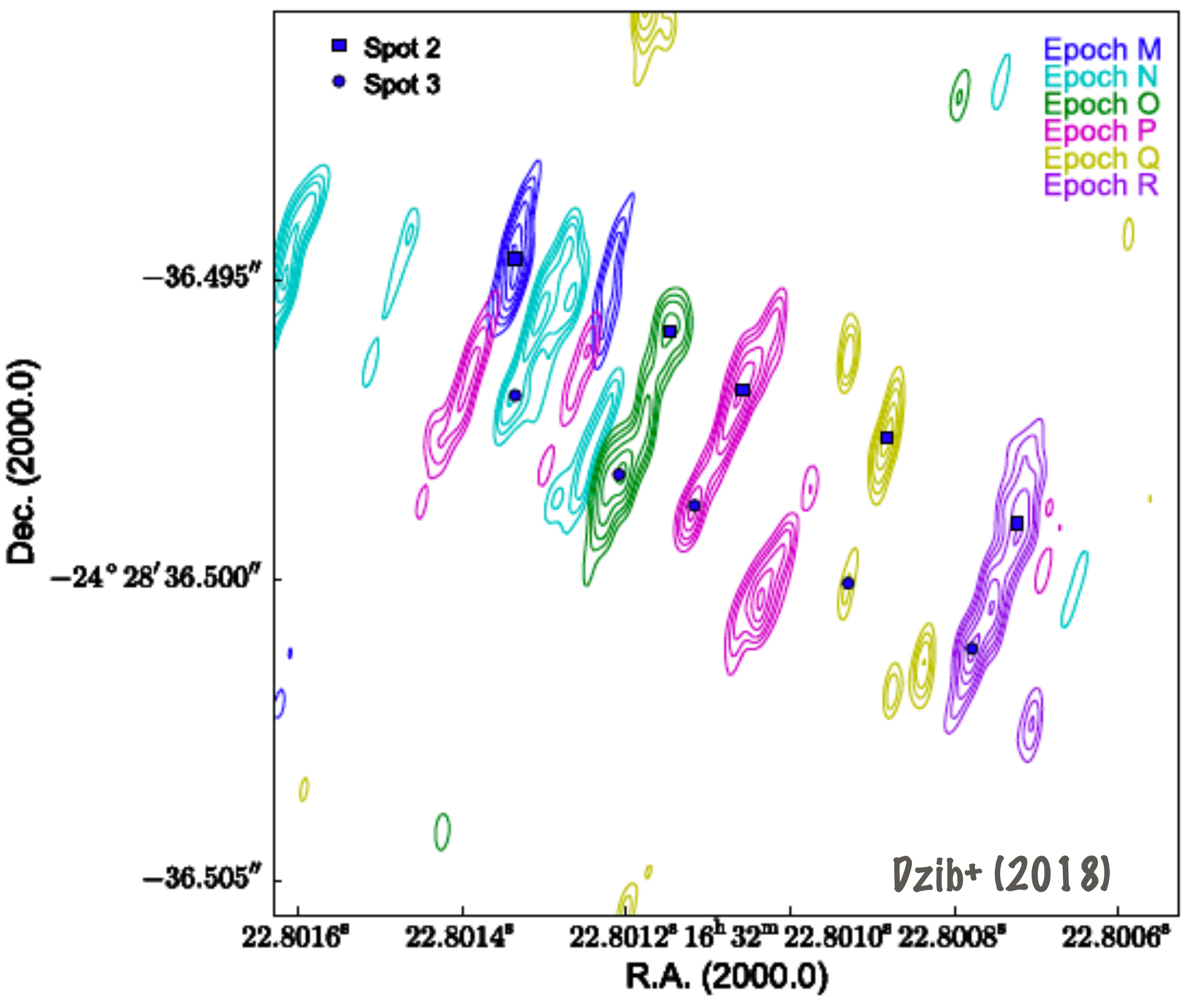
* Gaia confirms that Serpens South and Serpens Main are at very similar distances.
* Gaia parallaxes yield:
  * Serpens Main
    * d_Gaia = 423 ± 41 pc
  * Serpens South
    * d_Gaia = 425 ± 41 pc
* Offsets (with respect to VLBA):
  * +0.06 mas (Serpens Main)
  * +0.13 mas (Serpens South)



VLBA astrometry of water masers

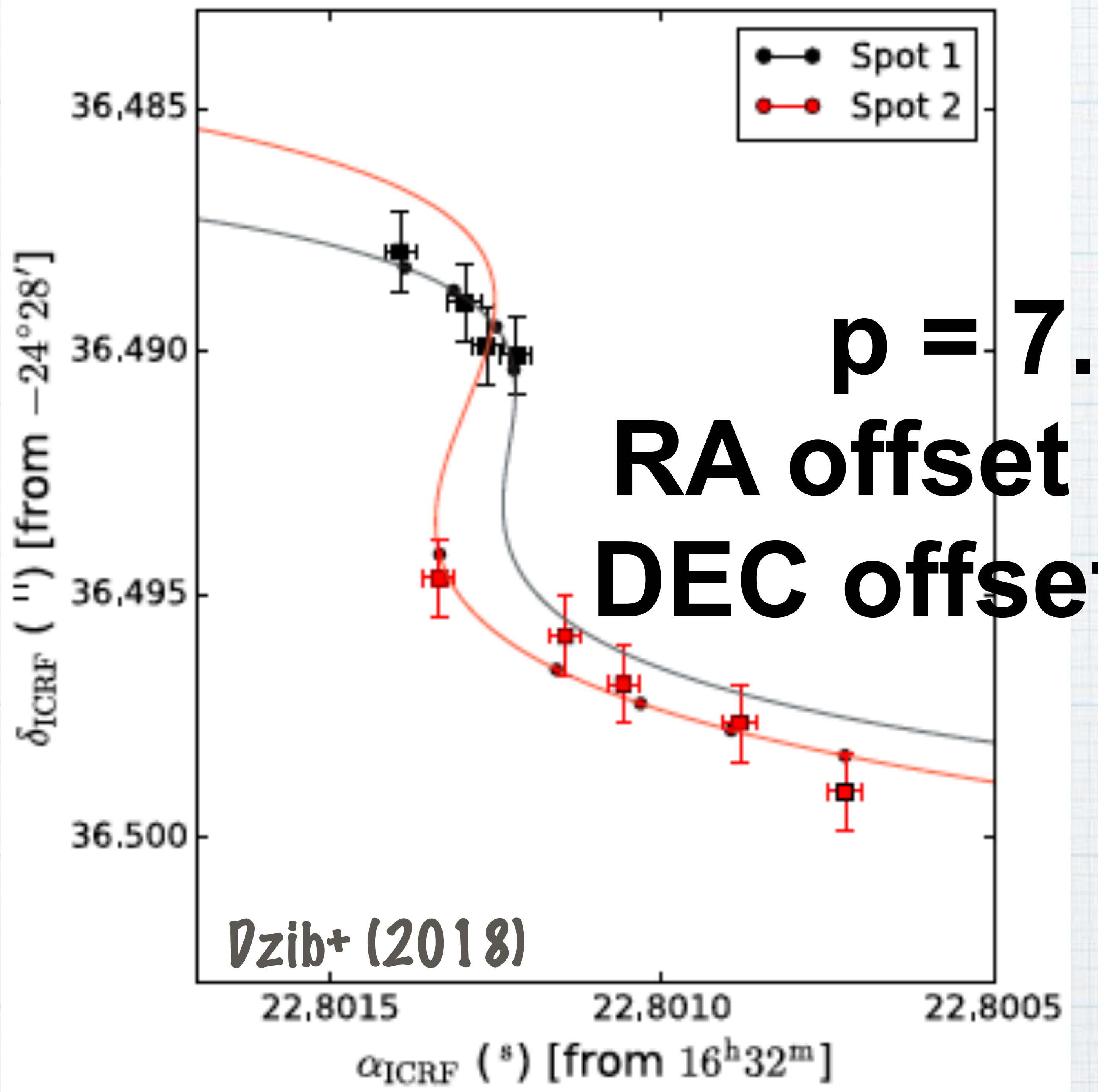
* IRAS 16293-2422
  * One of the bet studied systems of Class 0 objects



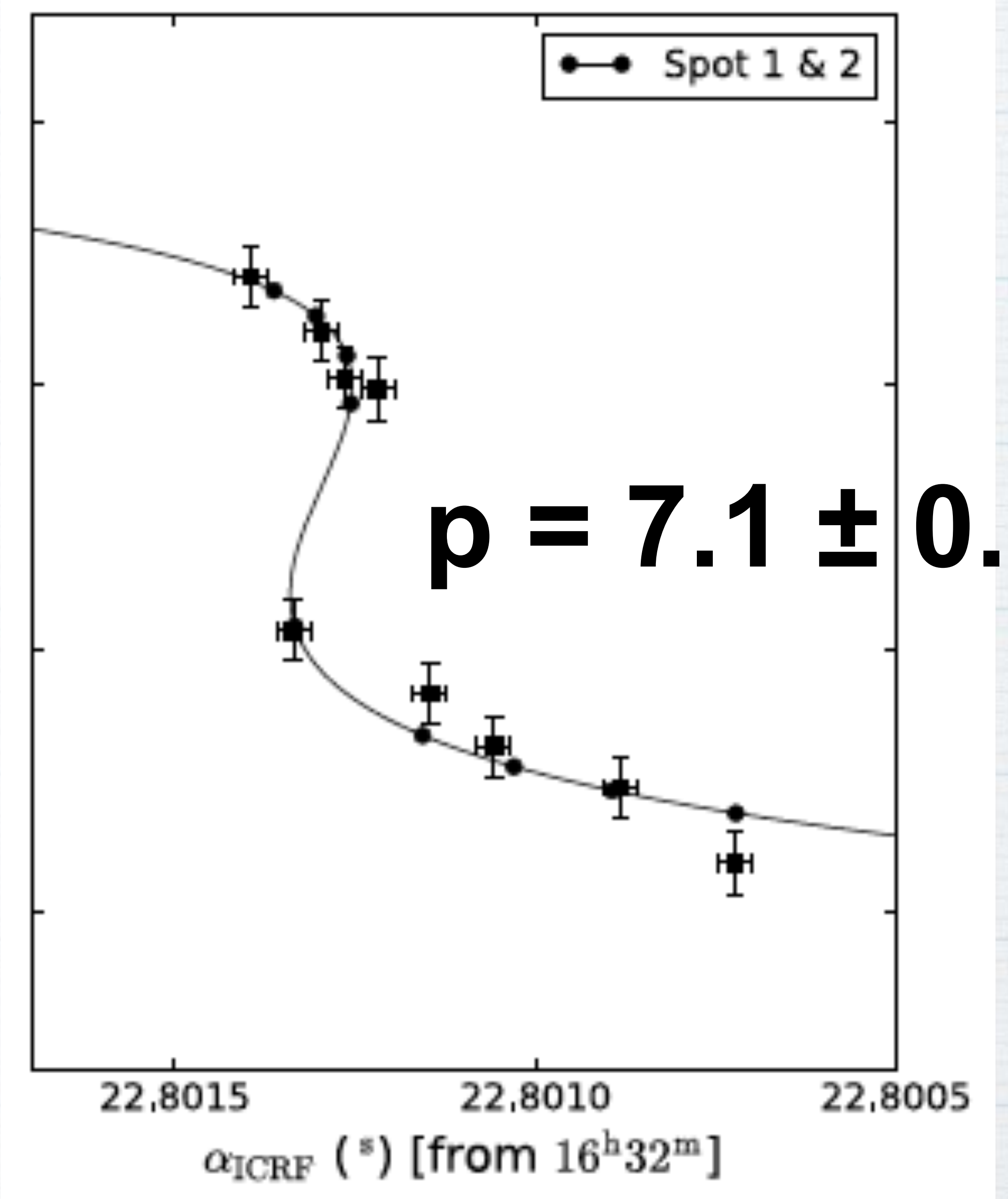


VLBA astrometry of water masers

* IRAS 16293-2422



p = 7.1 ± 1.3 mas
RA offset = -0.4 ± 1.0 mas
DEC offset = 1.4 ± 2.3 mas



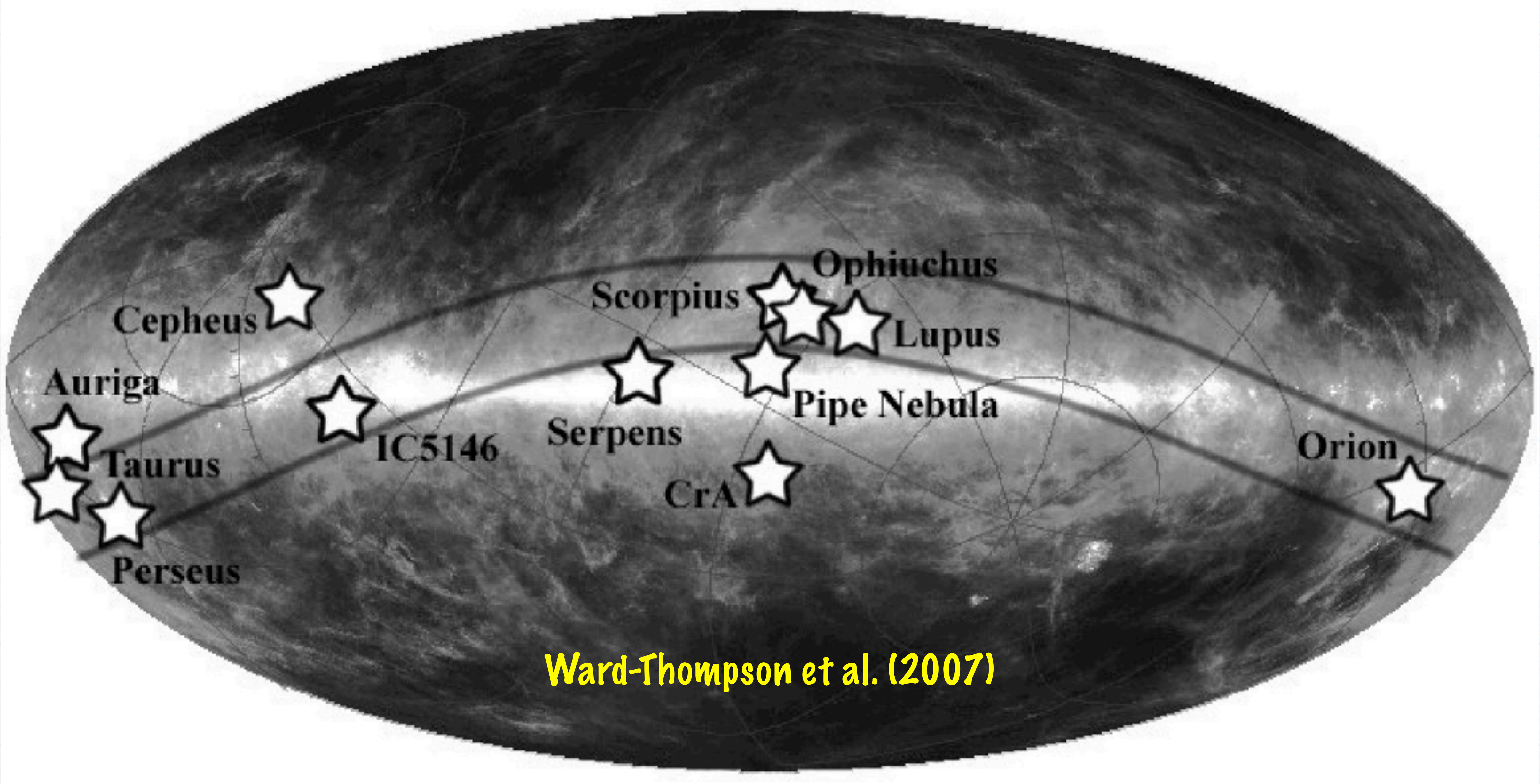
p = 7.1 ± 0.5 mas

* Simultaneous fit of two spots allowing them to have a positional offset.

* Simultaneous fit of two spots assuming they are the same.

The Gould's Belt

- Galactic structure (proposed to be an elliptical ring) containing most of the nearby young and OB stars.
- Estimated sizes are ~373 x 233 pc and its inclination to the Galactic plane is ~20° (Perrot & Greiner 2003; Bobylev 2016).

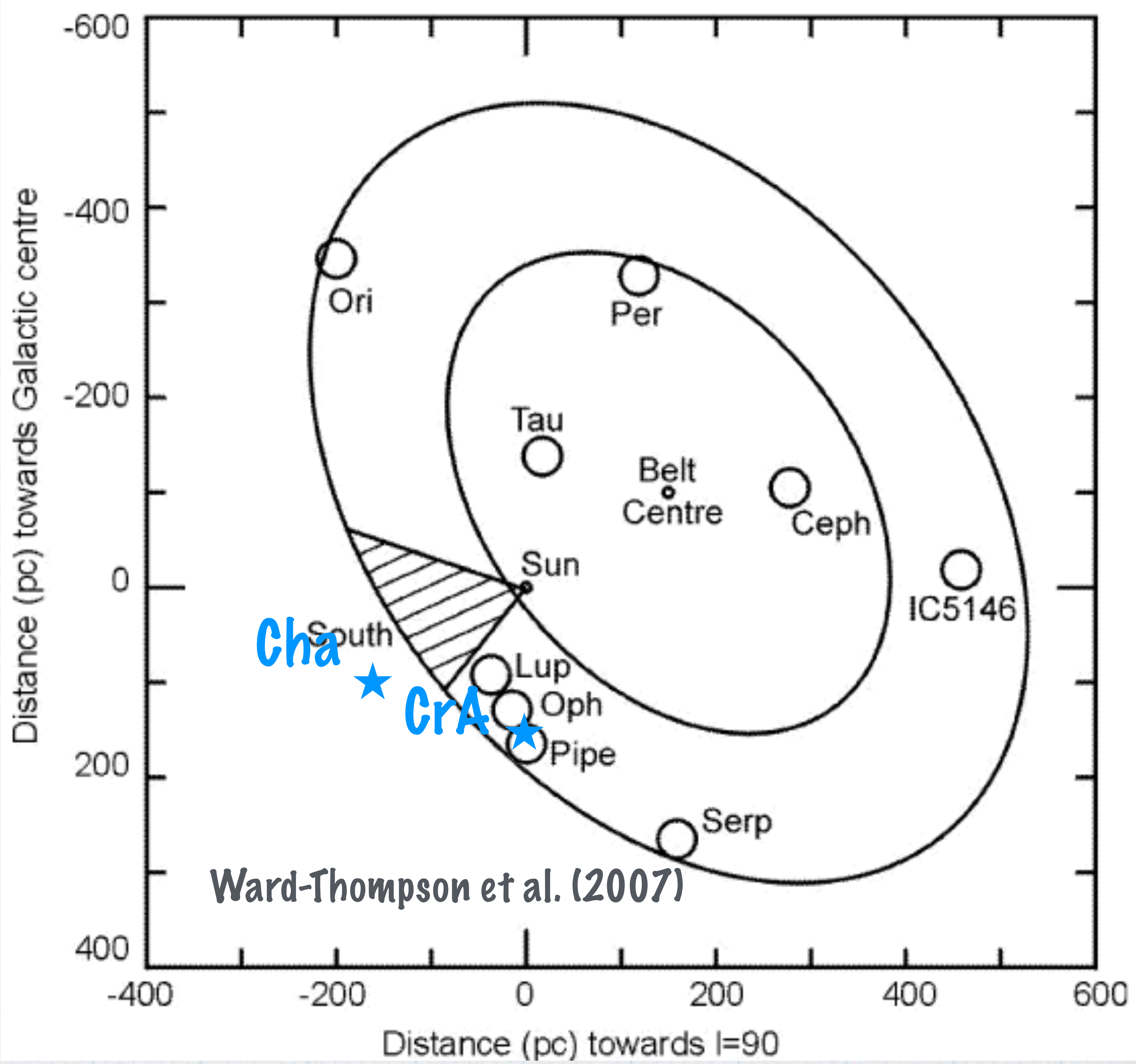


Star-Forming Regions associated to the Gould Belt

* To study the kinematics of the Gould Belt, we investigate the astrometry of **ALL** star-forming regions within 0.5 kpc, in addition to those observed by GOBELINS.

Region	l (°)	b (°)
Barnard 59	357.0	+07.1
Cepheus Flare	110.0	+15.0
Cepheus - NGC 7129	105.4	+09.9
Chamaeleon I	297.2	–15.4
Chamaeleon II	303.6	–14.4
ϵ Chamaeleontis	300.3	–14.0
Corona Australis	359.9	–17.8
IC 5146	094.4	–05.5
Lupus 1	338.8	+15.7
Lupus 2	338.9	+12.1
Lupus 3	339.6	+09.4
Lupus 4	336.3	+08.2

Dzib et al. (2018)



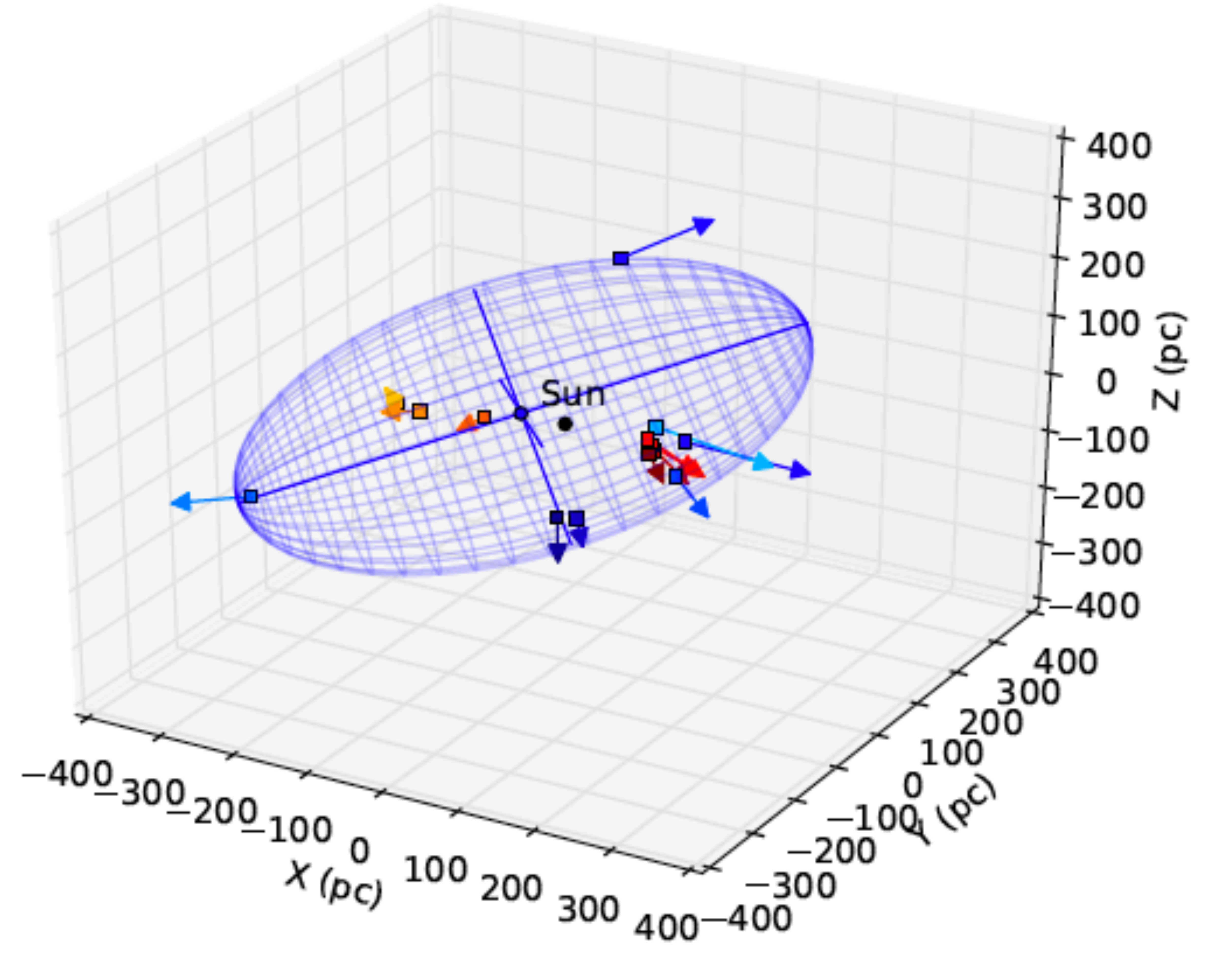
Ward-Thompson et al. (2007)

Structure and Kinematics of the Gould Belt

- Mean (X,Y,Z) positions are used to fit an ellipsoid that approximates the spatial distribution of the regions:

(358 ± 7) x (316 ± 3) x (70 ± 4) pc

(x_0, y_0, z_0) = (-82±15,39±7, -25±4) pc

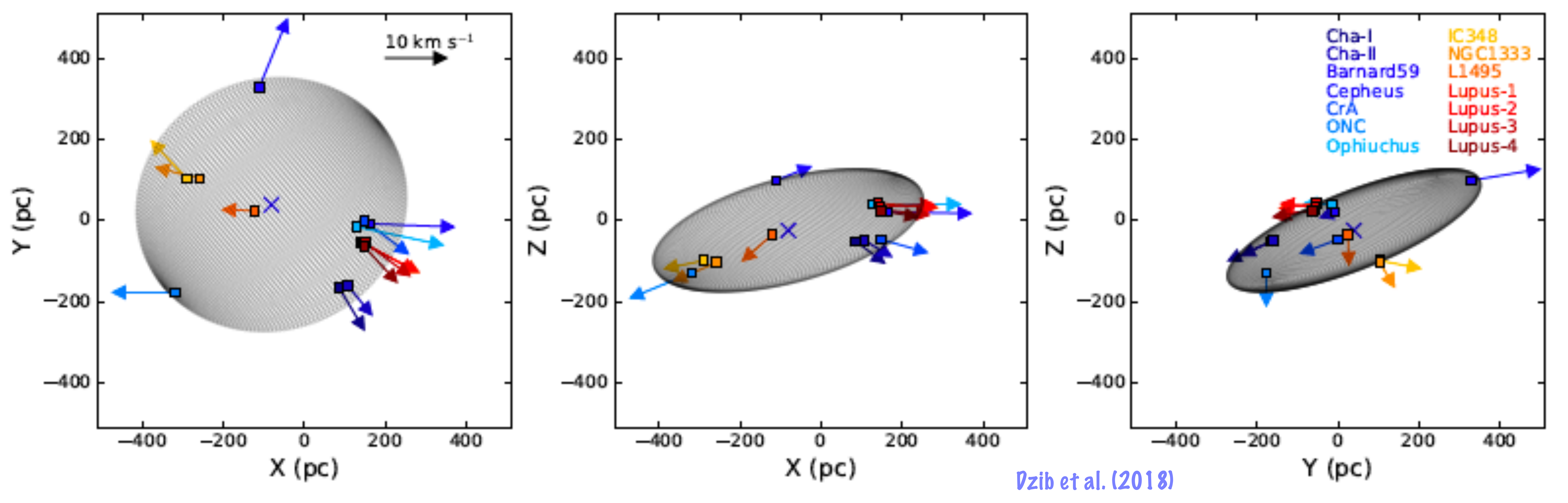


Dzib et al. (2018)

Structure and Kinematics of the Gould Belt

* Expansion motion relative to the center of the Gould Belt:

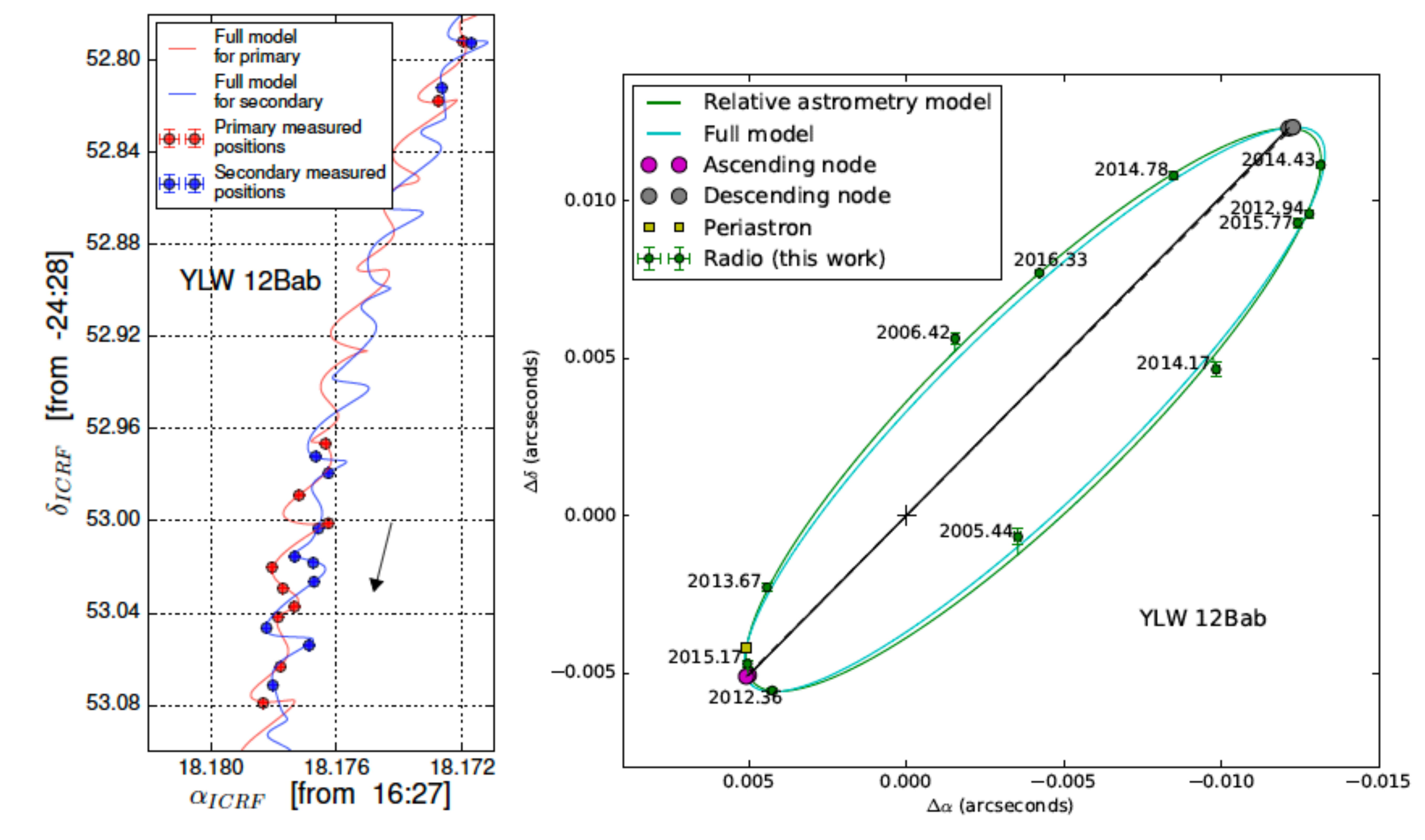
$$\hat{\mathbf{r}} \cdot \mathbf{v} = 2.5 \pm 0.1 \text{ km s}^{-1}$$
$$\sigma = 0.8 \text{ km s}^{-1}$$



Dzib et al. (2018)

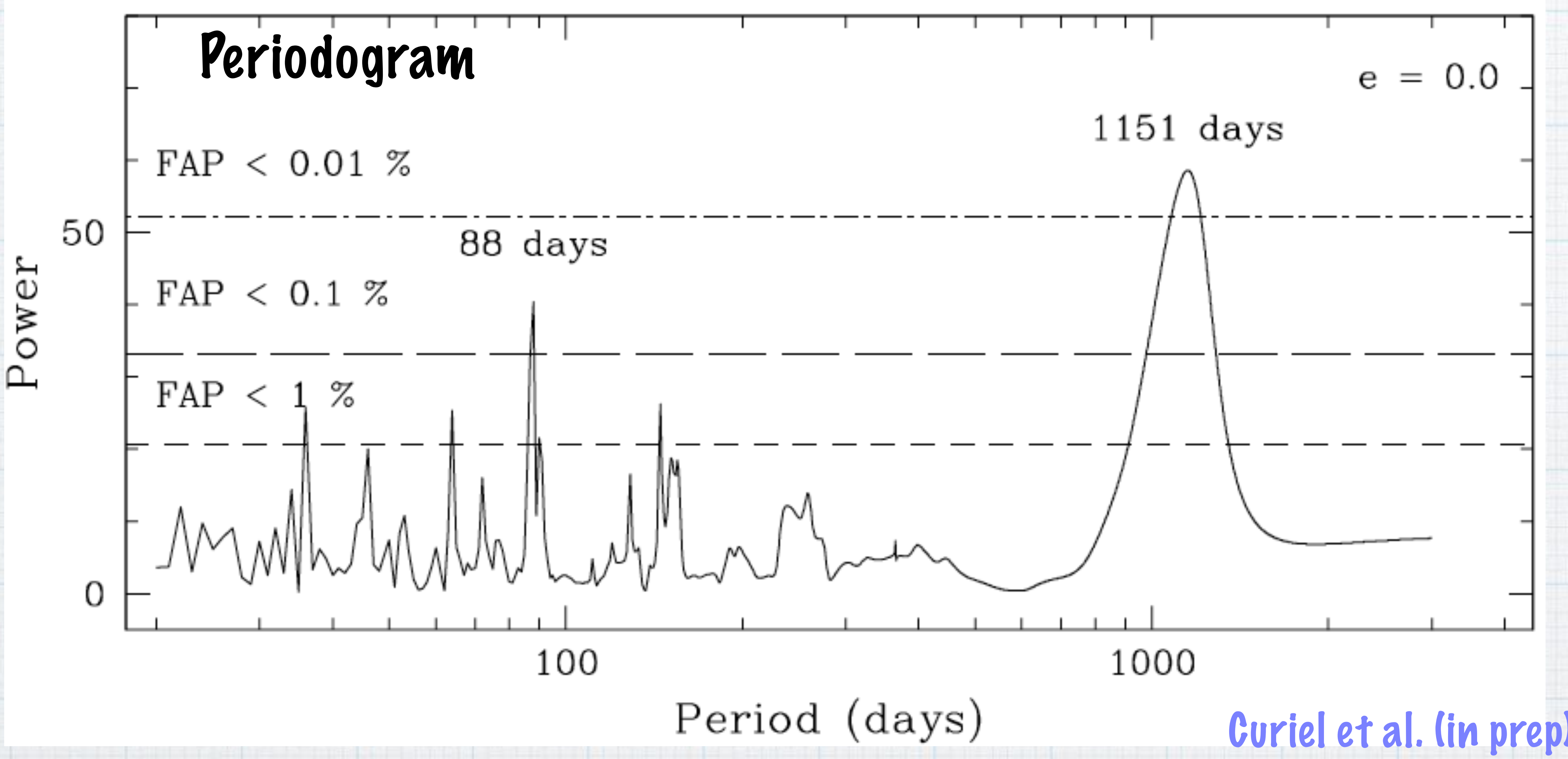
VLBI astrometry in the Gaia era - Dynamical masses

- Dynamical masses of YSOs from VLBA astrometry
- PI: S. Dzib + GOBELINS team.
  - 19 systems currently being observed
  - ~300 hours with the VLBA in **PRIORITY A** for a period of 3 years.

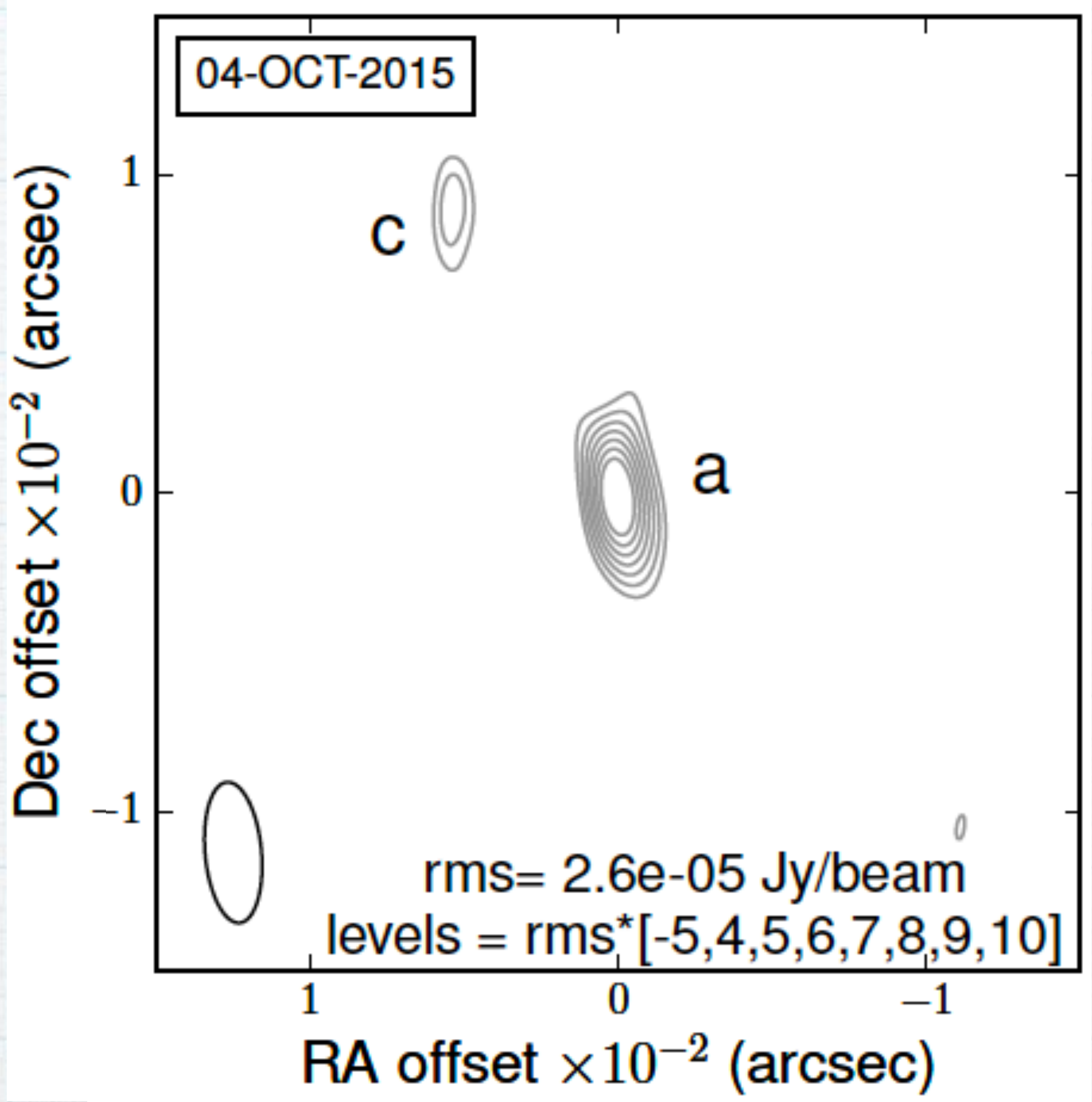


- Gaia will resolve all binaries (brighter than V=15) with separations above some 20 mas which have moderate magnitude differences between the components.

Brown dwarfs and sub-stellar companions



Curiel et al. (in prep)



- A novel method to search for brown dwarfs companions around young pre-main sequence stars.
- $m_p \sim 2\ M_{sun}$; $m_c \sim 50\ M_{jup}$