

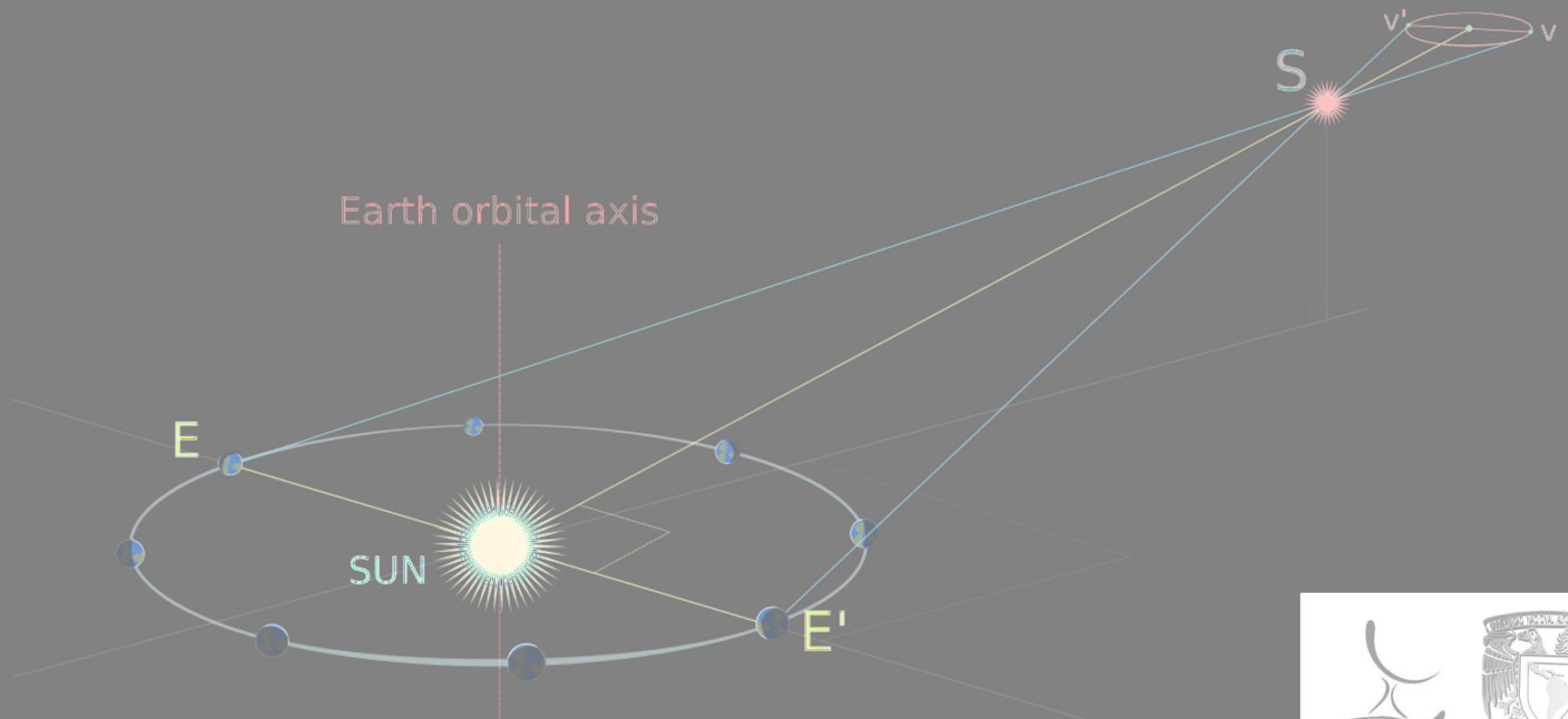
VLBI stellar astrometry in the era of Gaia

Star-formation and binaries

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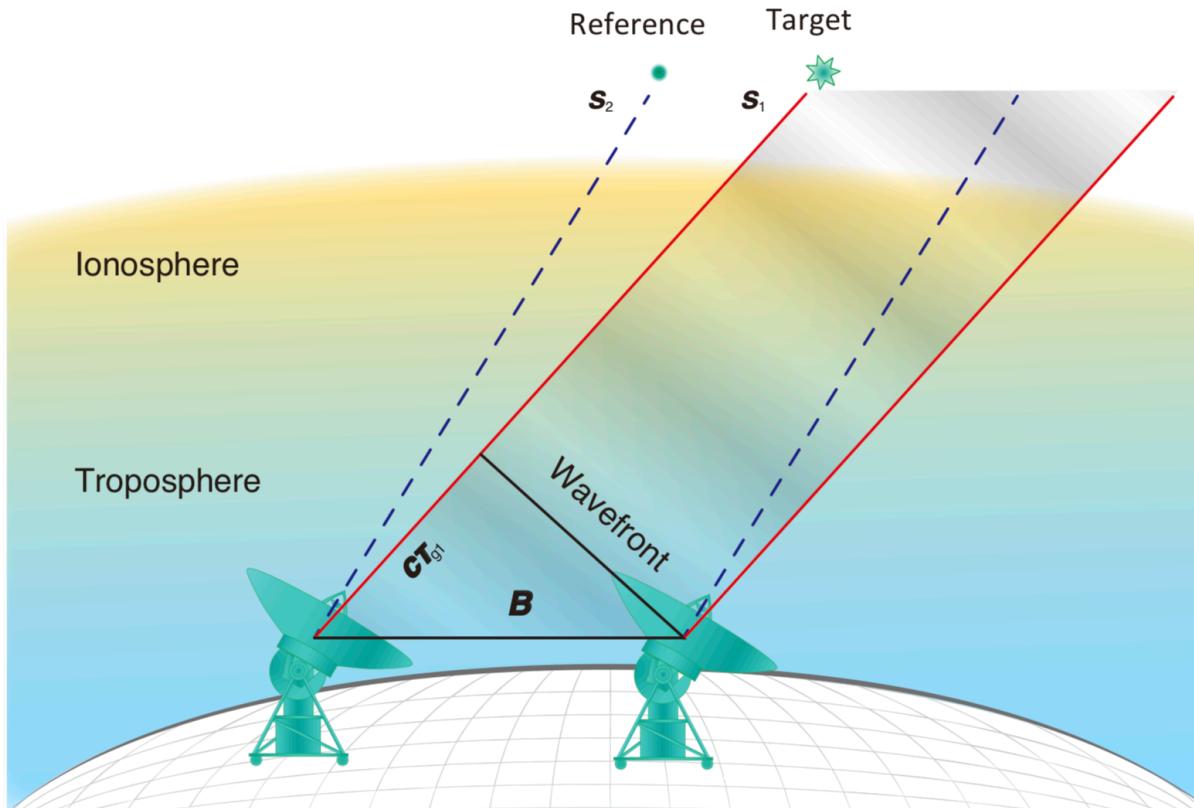
UNAM – Campus Morelia



Phase-referenced interferometry

$$\Delta s_{\text{rel}} \approx \theta_{\text{sep}} \frac{c\Delta\tau}{|B|}$$

For $|B| = 8,000$ km
and $\theta_{\text{sep}} = 1$ degree

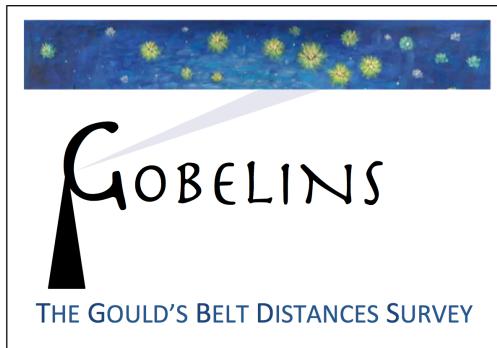


$\Delta s_{\text{rel}} \sim 10 \mu\text{as}$

(Comp. w/ Gaia)

Angular resolution
of order 1 mas

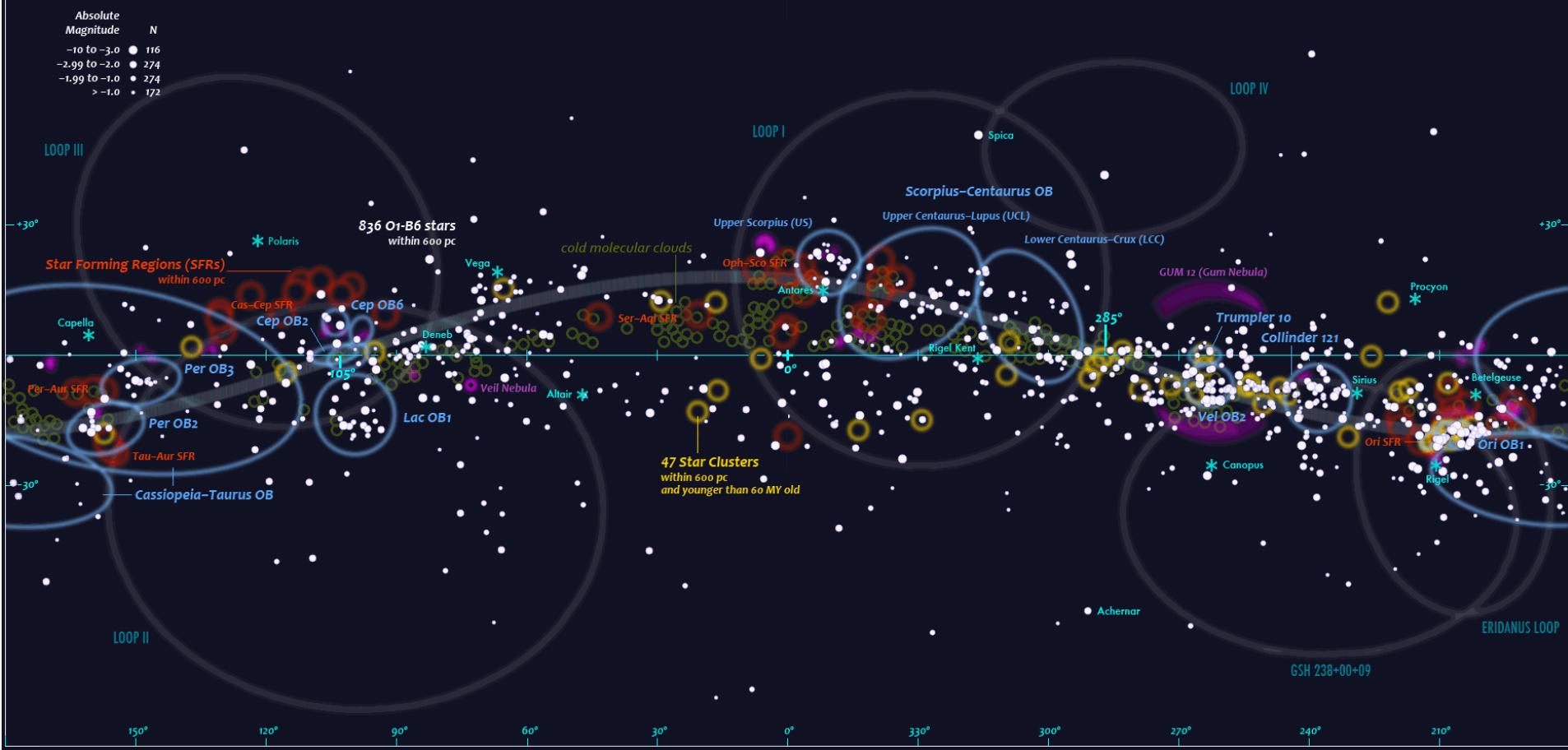
The Gould's Belt Distances Survey (GOBELINS)



GOULD'S BELT

A local (< 500 pc), expanding (age $\sim 2\text{-}3 \times 10^7$ yr) Galactic structure (ring, plane, disk, wave?) where most of nearby star-formation is occurring. Seen in young stars (in particular OB stars), gas, dust.

The Gould Belt



People



Rosy Torres (UNAM PhD. 2009)
U. Guadalajara
IRAM



Sergio Dzib (UNAM PhD. 2013)
MPIfR



Gisela Ortiz
(UNAM, PhD. 2016)



Gerardo Pech
(UNAM PhD. 2015)
U. TecMilenio



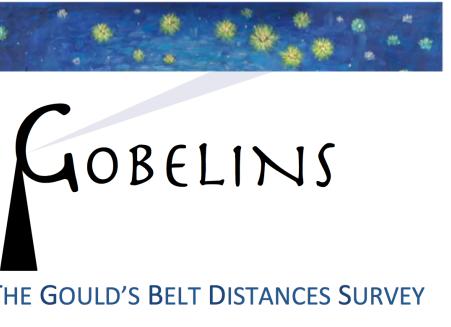
Juana Leticia Rivera
(UNAM, PhD. 2017)



Marina Kounkel
(U. Michigan, PhD. 2017)
Western Washington



"Gely" Duran
(UNAM, PhD)



Andy Boden
(CalTech)

Cesar Briceño
(NOAO, Chile)

Neal Evans
(Texas)

Philip Galli
(USP, Brazil)

Lee Hartmann
(Michigan)

Laurent Loinard – PI
(UNAM)

Amy Mioduszewski – CO-PI
(NRAO)

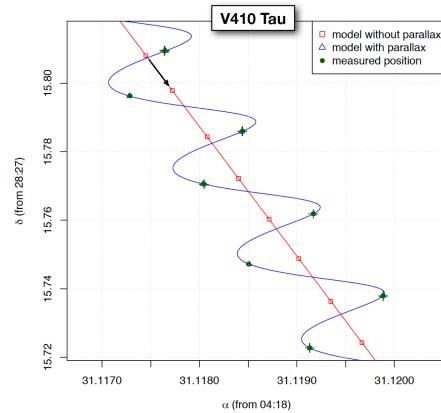
Luis F. Rodríguez
(UNAM)

Rama Teixeira
(USP, Brazil)

John Tobin
(NRAO)



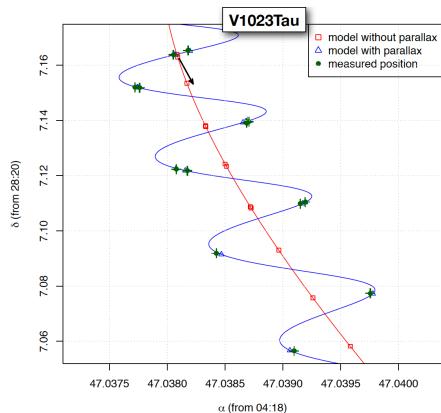
Astrometric fits



□ Single star

$$\alpha(t) = \alpha_0 + \mu_\alpha t + \varpi f_\alpha(t)$$

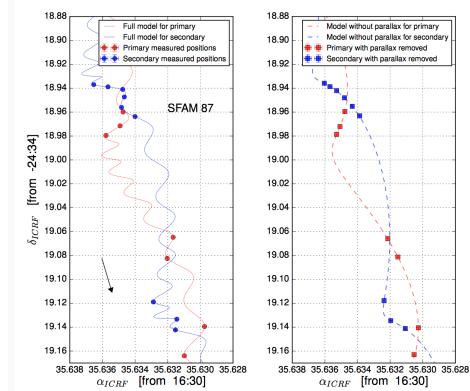
$$\delta(t) = \delta_0 + \mu_\delta t + \varpi f_\delta(t)$$



□ Long-period binary

$$\alpha(t) = \alpha_0 + \mu_\alpha t + \frac{1}{2}a_\alpha t^2 + \varpi f_\alpha(t)$$

$$\delta(t) = \delta_0 + \mu_\delta t + \frac{1}{2}a_\delta t^2 + \varpi f_\delta(t)$$



□ Short-period binary

$$\alpha(t) = \alpha_0 + \mu_\alpha t + \frac{1}{2}a_\alpha t^2 + aQ_\alpha(t) + \varpi f_\alpha(t)$$

$$\delta(t) = \delta_0 + \mu_\delta t + \frac{1}{2}a_\delta t^2 + aQ_\delta(t) + \varpi f_\delta(t)$$

Hipparchos

$$\begin{aligned}\mu_\alpha \cos \delta &= 7.28 \pm 2.75 \text{ mas yr}^{-1} \\ \mu_\delta &= -27.77 \pm 2.03 \text{ mas yr}^{-1} \\ \varpi &= 10.18 \pm 2.40 \text{ mas} \\ d &= 98^{+30}_{-19} \text{ pc}\end{aligned}$$

Gaia DR1

$$\begin{aligned}\mu_\alpha \cos \delta &= 8.610 \pm 0.154 \text{ mas yr}^{-1} \\ \mu_\delta &= -24.918 \pm 0.107 \text{ mas yr}^{-1} \\ \varpi &= 7.78 \pm 0.29 \text{ mas} \\ d &= 128.5^{+5.0}_{-4.6} \text{ pc}\end{aligned}$$

Gaia DR2

$$\begin{aligned}\mu_\alpha \cos \delta &= 8.683 \pm 0.128 \text{ mas yr}^{-1} \\ \mu_\delta &= -25.100 \pm 0.061 \text{ mas yr}^{-1} \\ \varpi &= 7.667 \pm 0.053 \text{ mas} \\ d &= 130.44^{+0.90}_{-0.89} \text{ pc}\end{aligned}$$

Gaia DR3

$$\begin{aligned}\mu_\alpha \cos \delta &= 8.846 \pm 0.025 \text{ mas yr}^{-1} \\ \mu_\delta &= -25.129 \pm 0.0016 \text{ mas yr}^{-1} \\ \varpi &= 7.730 \pm 0.021 \text{ mas} \\ d &= 129.37^{+0.35}_{-0.35} \text{ pc} \quad \text{ruwe} = 1.17\end{aligned}$$

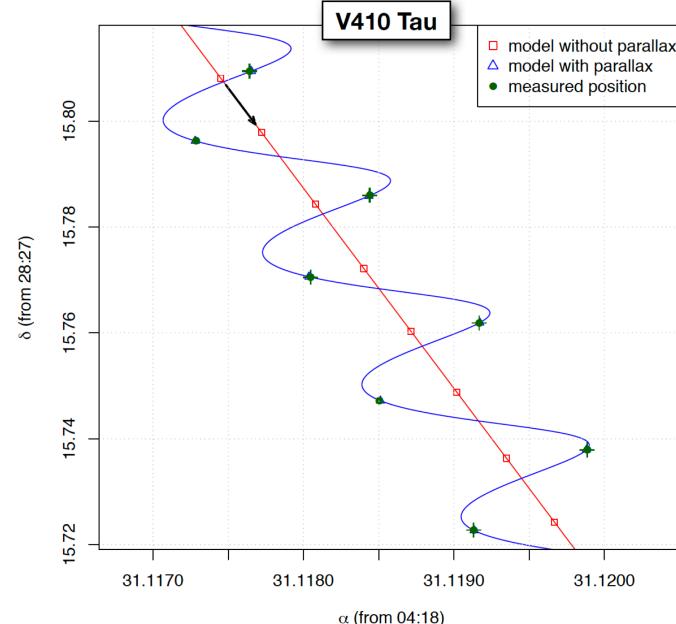
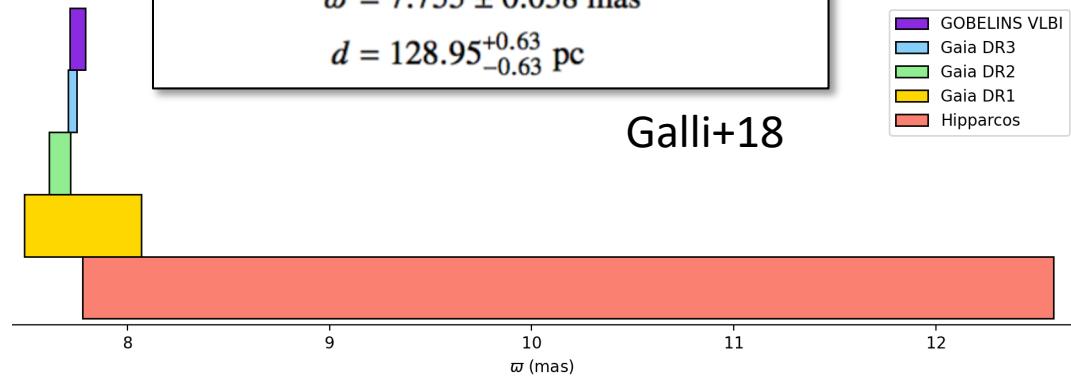
Single Star

GOBELINS

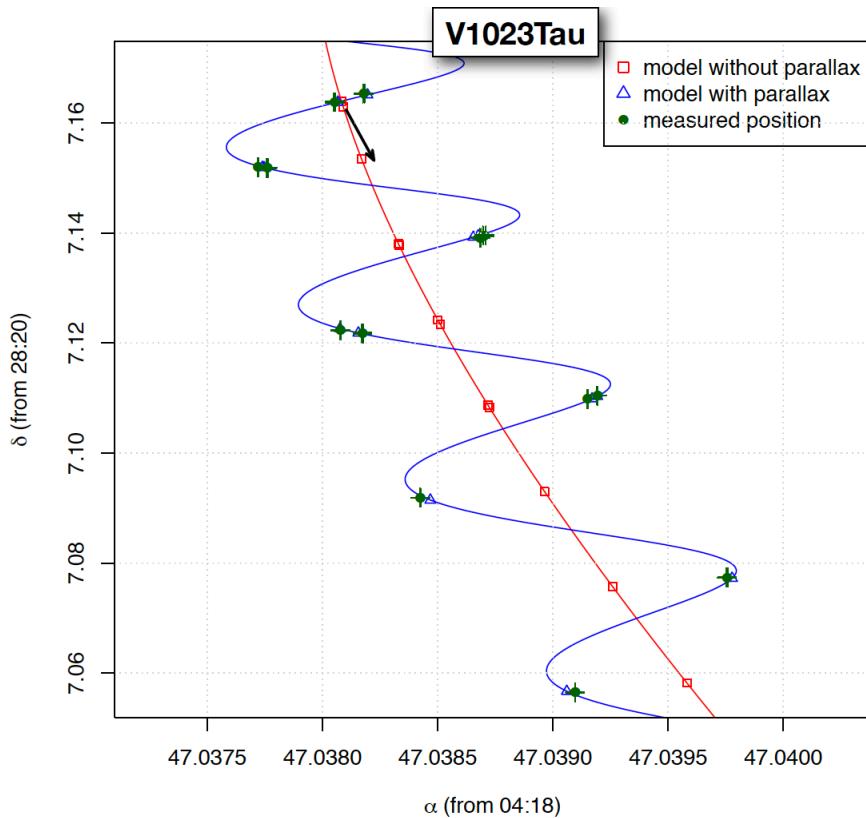
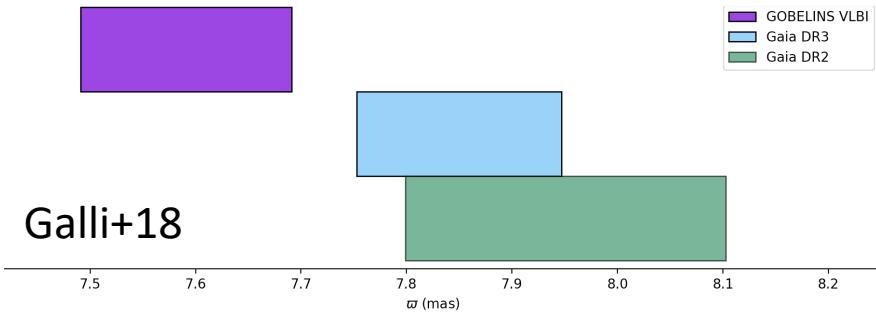
$$\begin{aligned}\mu_\alpha \cos \delta &= 8.708 \pm 0.027 \text{ mas yr}^{-1} \\ \mu_\delta &= -24.969 \pm 0.0021 \text{ mas yr}^{-1} \\ \varpi &= 7.755 \pm 0.038 \text{ mas} \\ d &= 128.95^{+0.63}_{-0.63} \text{ pc}\end{aligned}$$

Galli+18

- GOBELINS VLBI
- Gaia DR3
- Gaia DR2
- Gaia DR1
- Hipparchos



Long period binaries



GOBELINS

$$\mu_\alpha \cos \delta = 5.344 \pm 0.080 \text{ mas yr}^{-1}$$

$$\mu_\delta = -30.797 \pm 0.047 \text{ mas yr}^{-1}$$

$$a_\alpha \cos \delta = 1.011 \pm 0.153 \text{ mas yr}^{-2}$$

$$a_\delta = -3.115 \pm 0.086 \text{ mas yr}^{-2}$$

$$\varpi = 7.591 \pm 0.100 \text{ mas}$$

$$d = 131.73^{+1.76}_{-1.71} \text{ pc}$$

Gaia DR2

$$\mu_\alpha \cos \delta = 8.296 \pm 0.356 \text{ mas yr}^{-1}$$

$$\mu_\delta = -25.309 \pm 0.229 \text{ mas yr}^{-1}$$

$$\varpi = 7.951 \pm 0.152 \text{ mas}$$

$$d = 125.77^{+2.45}_{-2.36} \text{ pc}$$

Gaia DR3

$$\mu_\alpha \cos \delta = 8.707 \pm 0.112 \text{ mas yr}^{-1}$$

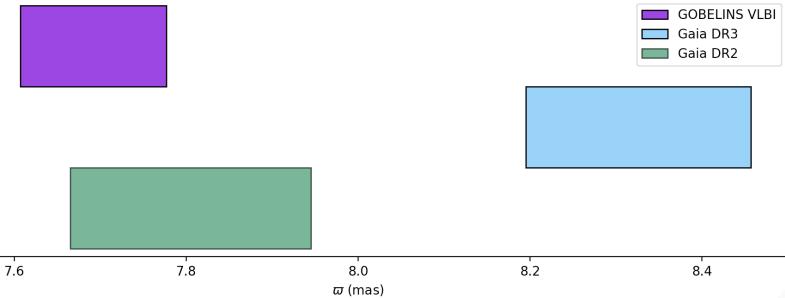
$$\mu_\delta = -25.483 \pm 0.083 \text{ mas yr}^{-1}$$

$$\varpi = 7.850 \pm 0.097 \text{ mas}$$

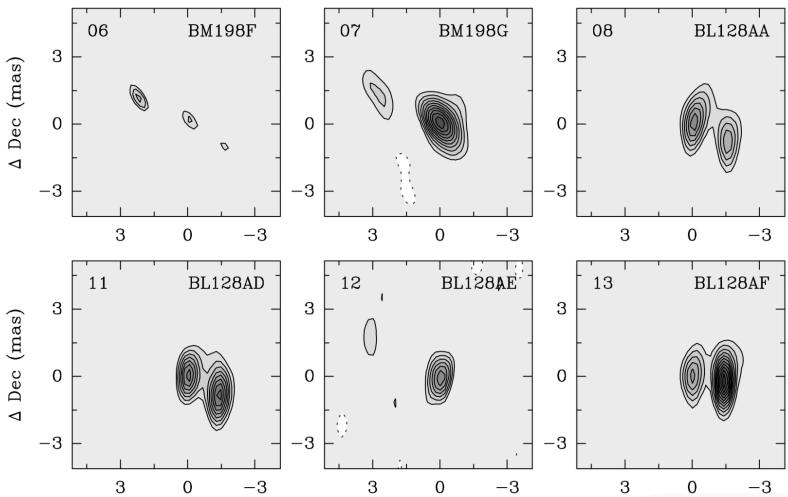
$$d = 127.39^{+0.89}_{-0.85} \text{ pc}$$

$$\text{ruwe} = 5.50$$

Short period binaries



Galli+18,
Torres+12



GOBELINS

$$\mu_\alpha \cos \delta = 10.25 \pm 0.84 \text{ mas yr}^{-1}$$

$$\mu_\delta = -25.12 \pm 0.30 \text{ mas yr}^{-1}$$

$$\varpi = 7.692 \pm 0.085 \text{ mas}$$

$$d = 130.00^{+1.46}_{-1.42} \text{ pc}$$

Gaia DR2

$$\mu_\alpha \cos \delta = 8.932 \pm 0.390 \text{ mas yr}^{-1}$$

$$\mu_\delta = -29.054 \pm 0.250 \text{ mas yr}^{-1}$$

$$\varpi = 7.805 \pm 0.140 \text{ mas}$$

$$d = 128.12^{+2.34}_{-2.25} \text{ pc}$$

Gaia DR3

$$\mu_\alpha \cos \delta = 6.540 \pm 0.163 \text{ mas yr}^{-1}$$

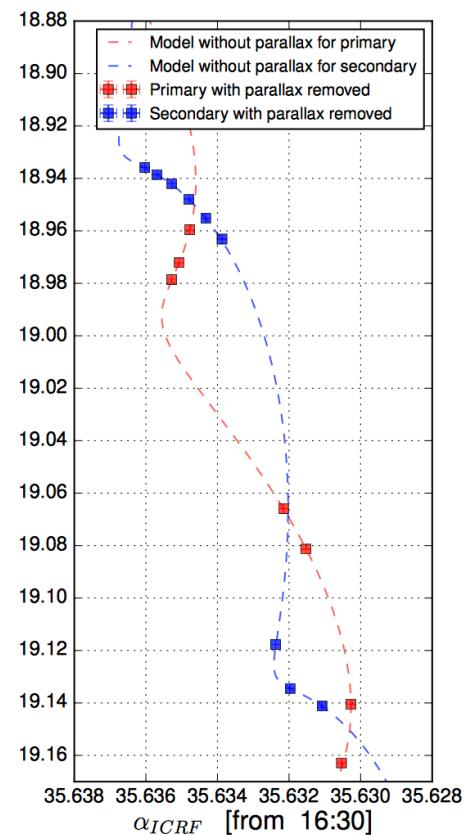
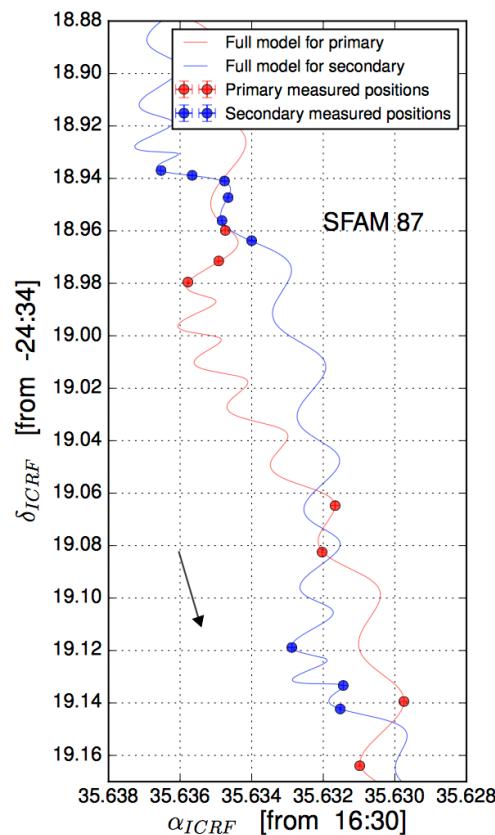
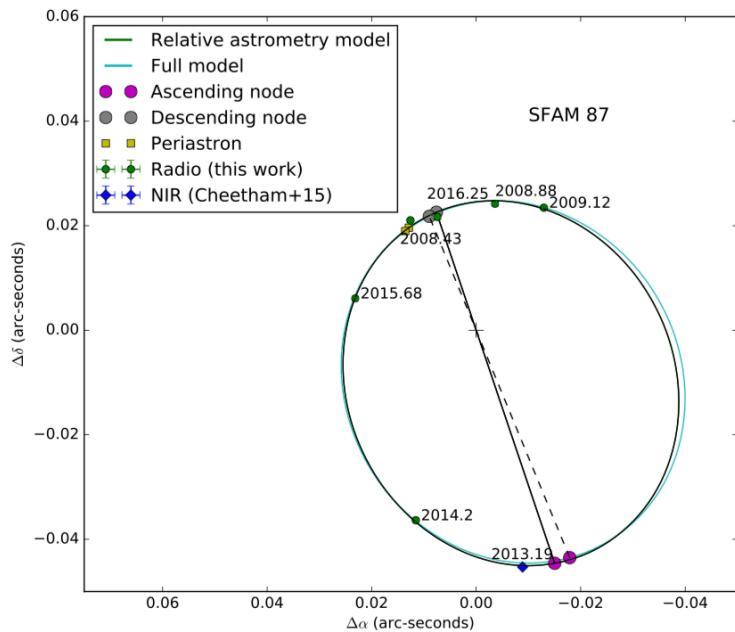
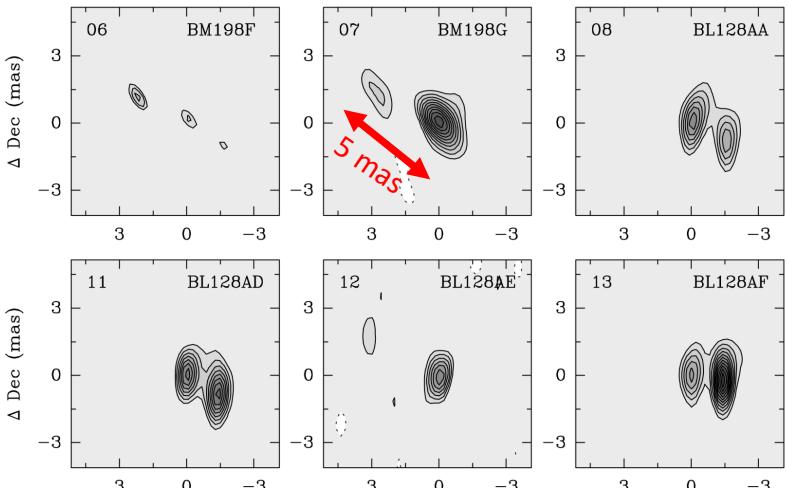
$$\mu_\delta = -27.792 \pm 0.110 \text{ mas yr}^{-1}$$

$$\varpi = 8.326 \pm 0.131 \text{ mas}$$

$$d = 120.11^{+1.92}_{-1.86} \text{ pc}$$

ruwe = 7.53

More about short period binaries: angular resolution also matters



Ortiz-Leon+17

Motion of sources around
the center of mass

Short period binaries @ VLBI:

individual masses at sub-percent levels

Ortiz-Leon+17

Name	a (mas)	P (yr)	T_0	e	Ω ($^{\circ}$)	i ($^{\circ}$)	ω ($^{\circ}$)	M_1 (M_{\odot})	M_2 (M_{\odot})	M_T (M_{\odot})	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
LFAM 15											
Full	16.40 ± 0.13	3.591 ± 0.0183	2007.008 ± 0.039	0.528 ± 0.005	337.93 ± 0.81	110.30 ± 0.49	235.54 ± 1.02	0.4687 ± 0.0146	0.421 ± 0.010	0.89 ± 0.01	
Rel. astr.	16.98 ± 0.16	3.598 ± 0.0099	2010.626 ± 0.011	0.561 ± 0.007	340.05 ± 0.49	109.77 ± 0.27	239.60 ± 0.64	—	—	0.99 ± 0.27	
YLW 12Bab											
Full	12.70 ± 0.09	1.425 ± 0.0012	2005.174 ± 0.009	0.444 ± 0.003	135.15 ± 1.03	75.60 ± 1.25	158.69 ± 1.47	1.3969 ± 0.0194	1.258 ± 0.006	2.66 ± 0.02	
Rel. astr.	12.54 ± 0.06	1.424 ± 0.0005	2013.720 ± 0.003	0.442 ± 0.003	135.38 ± 0.32	74.32 ± 0.48	160.11 ± 0.99	—	—	2.58 ± 0.39	
SFAM 87											
Full	35.58 ± 0.31	7.691 ± 0.007	2023.781 ± 0.006	0.343 ± 0.001	22.36 ± 8.57	-162.66 ± 2.84	346.19 ± 8.83	1.0207 ± 0.0224	0.999 ± 0.038	2.02 ± 0.04	
Rel. astr.	35.79 ± 0.30	7.719 ± 0.019	2008.404 ± 0.015	0.341 ± 0.005	18.62 ± 4.32	-157.95 ± 2.59	344.25 ± 4.91	—	—	2.06 ± 0.51	

Gaia:

- accurate absolute positions
- “low” angular resolution

IR aperture synthesis:

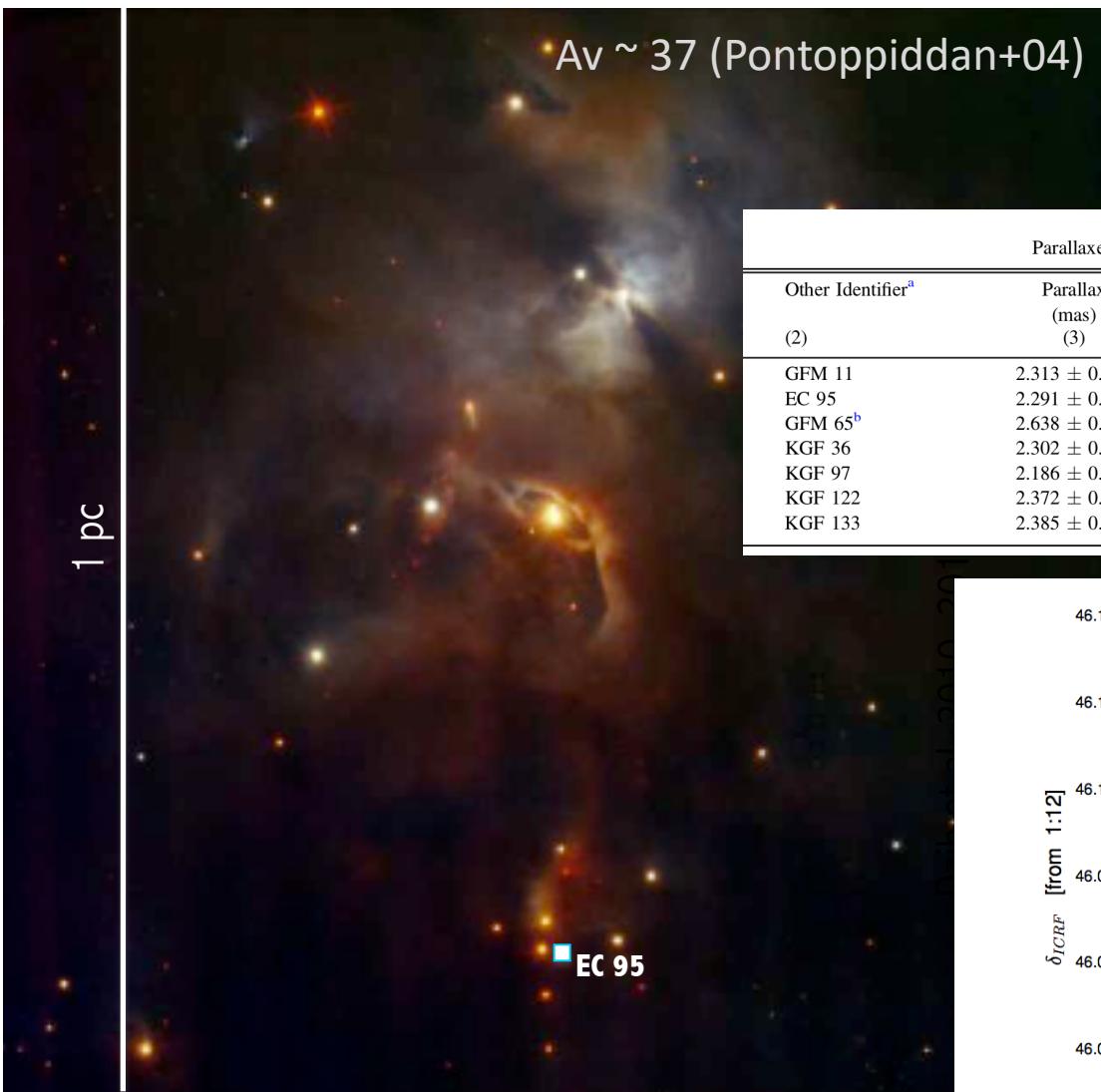
- no absolute positions
- high angular resolution

VLBI:

- accurate “absolute” positions
- high angular resolution



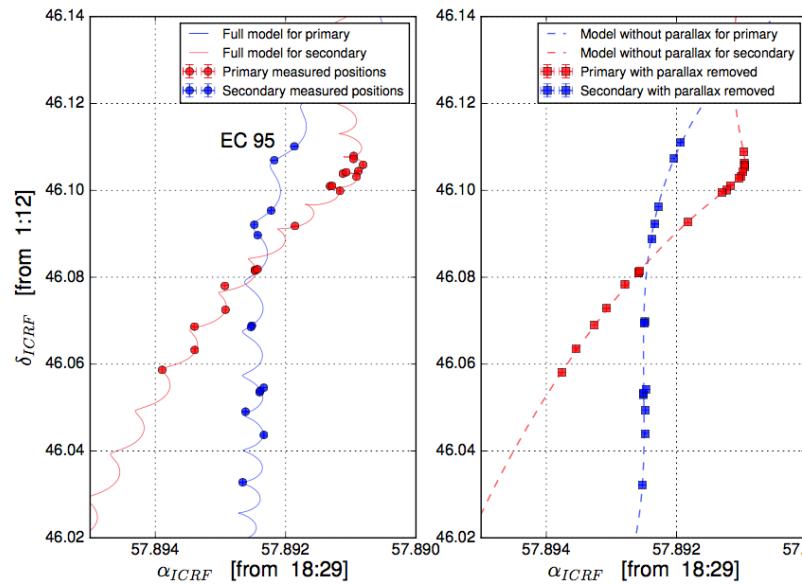
Deeply embedded young stars



Ortiz-Leon+17

Table 5
Parallaxes and Proper Motions

Other Identifier ^a (2)	Parallax (mas) (3)	$\mu_\alpha \cos \delta$ (mas yr ⁻¹) (4)	μ_δ (mas yr ⁻¹) (5)	Distance (pc) (6)
GFM 11	2.313 ± 0.078	3.634 ± 0.050	-8.864 ± 0.127	432.3 ± 14.6
EC 95	2.291 ± 0.038	3.599 ± 0.026	-8.336 ± 0.030	436.4 ± 7.1
GFM 65 ^b	2.638 ± 0.118	1.573 ± 0.070	-6.513 ± 0.152	379.1 ± 17.0
KGF 36	2.302 ± 0.063	0.186 ± 0.053	-6.726 ± 0.121	434.5 ± 11.8
KGF 97	2.186 ± 0.076	-0.258 ± 0.058	-7.514 ± 0.135	457.5 ± 16.0
KGF 122	2.372 ± 0.120	4.586 ± 0.074	-7.946 ± 0.167	421.5 ± 21.4
KGF 133	2.385 ± 0.098	-0.330 ± 0.049	-7.746 ± 0.111	419.3 ± 17.3



Conclusions and perspectives

- ❑ For deeply embedded sources VLBI enables astrometry as accurate as Gaia DR3 for optically bright stars
- ❑ For long period binaries, VLBI remains more accurate than Gaia
- ❑ For short-period binaries, VLBI enables accurate distances and **individual** mass determinations
- ❑ VLBI is time-consuming, but...
- ❑ ngVLA will enable enhanced astrometric accuracy and faster parallax determinations

Take-home message

- ❑ If your source is a binary or deeply embedded, VLBI astrometry is here for you!