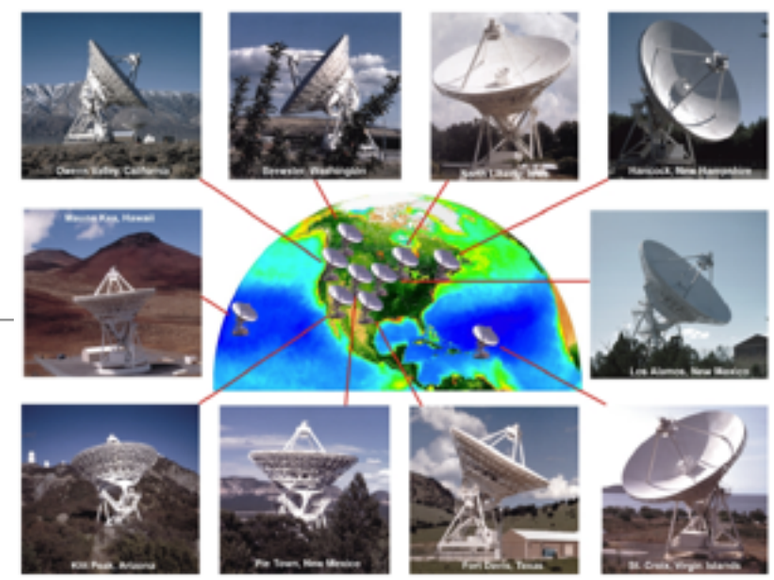
Ultra-high precision astrometry with centimeter and millimeter VLBI



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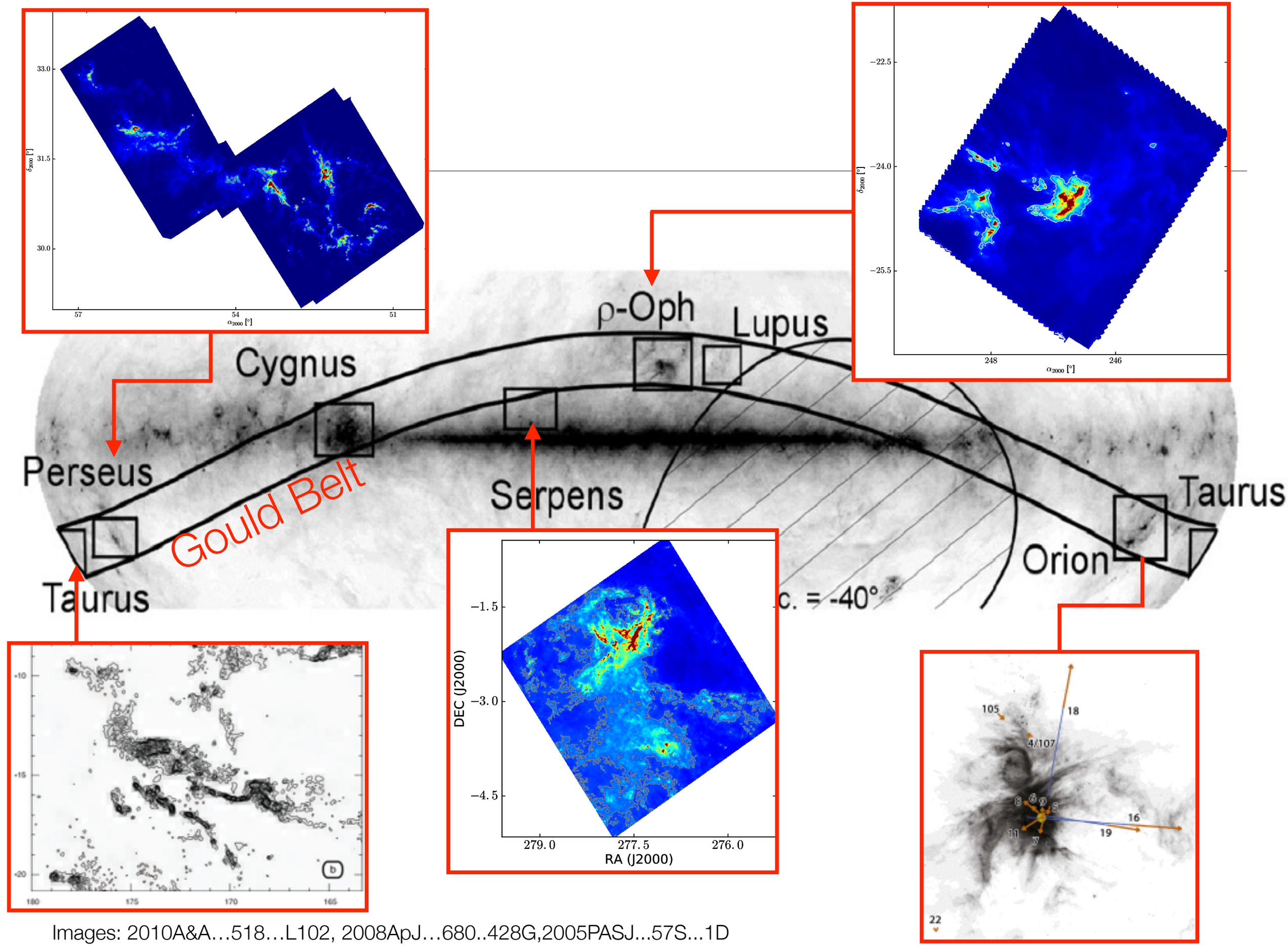
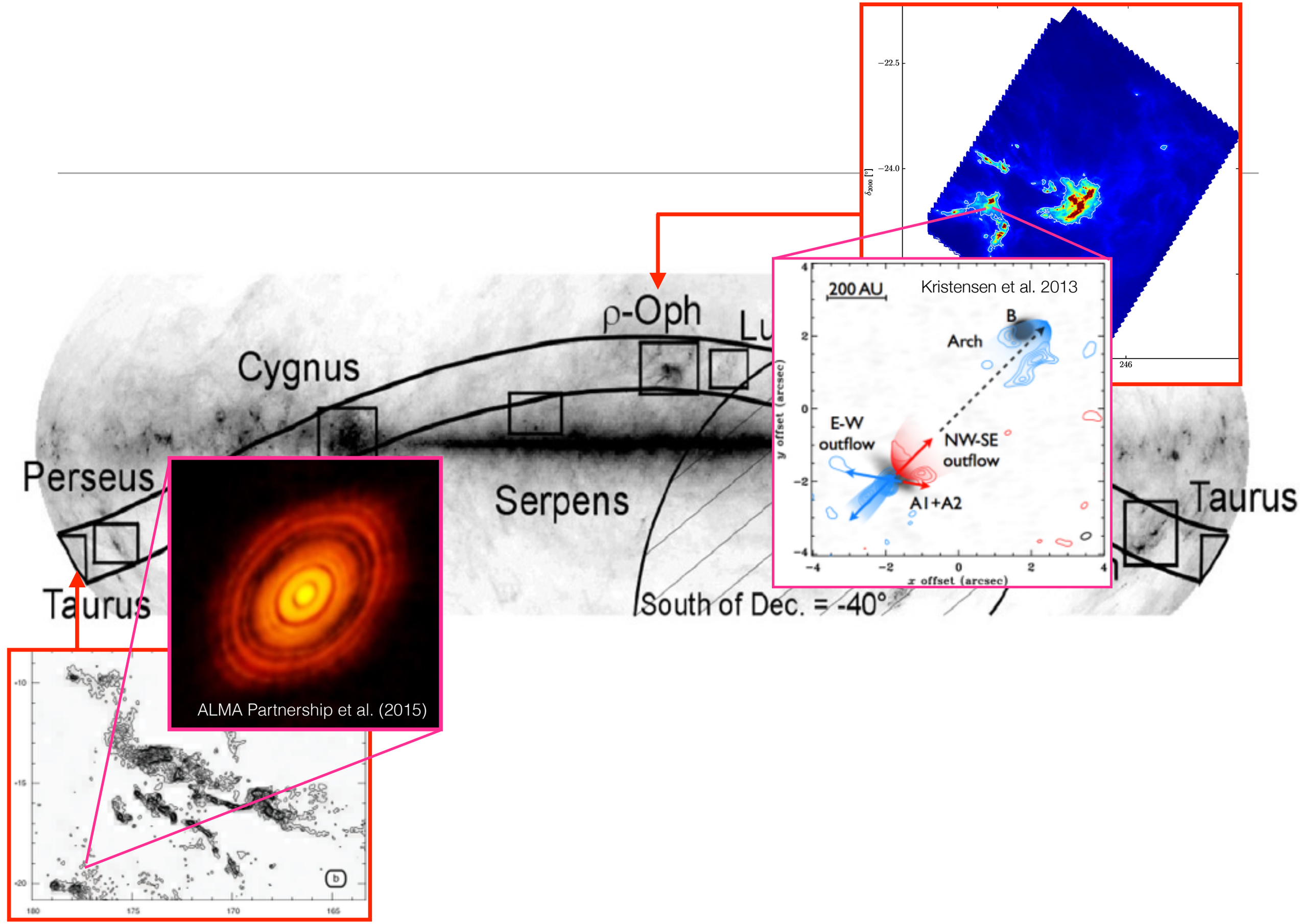
PhD supervisor: Laurent Loinard, Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México

Other collaborators: Andrew Boden, Cesar Briceño, Sergio Dzib, Neal Evans, Phillip Galli, Lee Hartman, Marina Kounkel, Amy Mioduszewski, Gerardo Pech, Juana Rivera, Luis F. Rodríguez, John Tobin & Rosa Torres

GA-IAU, Viena, August 27, 2018



Images: 2010A&A…518…L102, 2008ApJ…680..428G,2005PASJ...57S...1D



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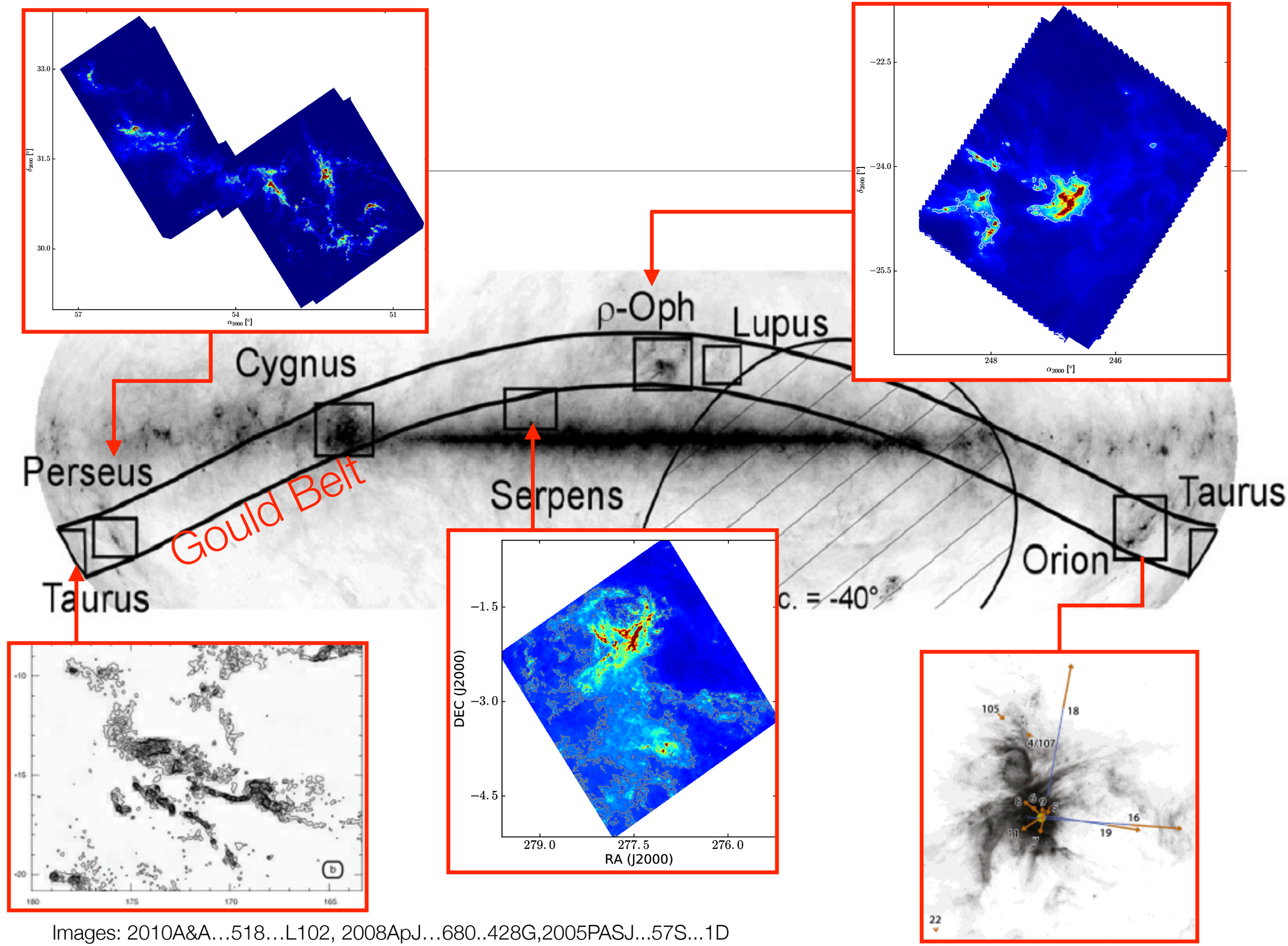


Images: 2010A&A…518…L102, 2008ApJ…680..428G,2005PASJ...57S...1D

Very Long Baseline Interferometry (VLBI)

- Angular resolution:

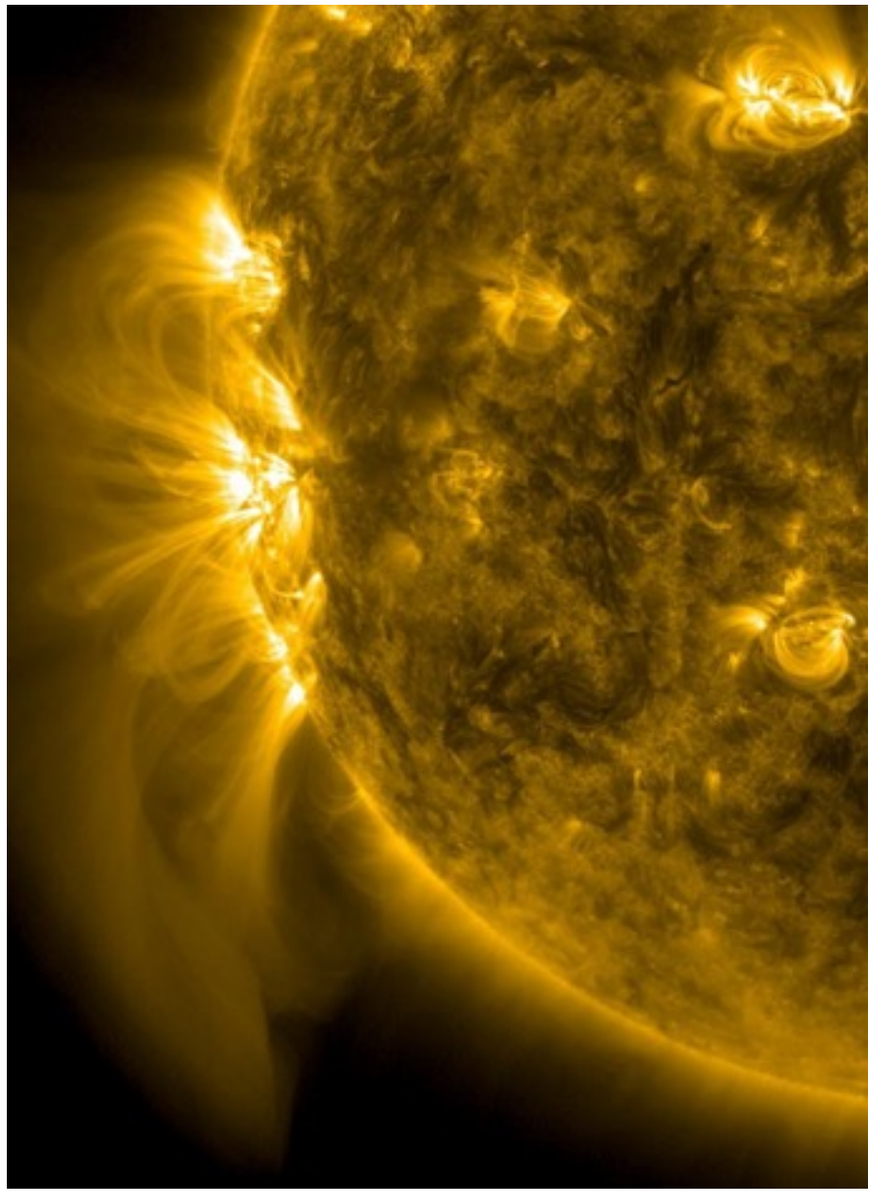
$\lambda\,(\mathrm{cm})$	5	3	1	0.7	0.3	0.1
$\theta_{\mathrm{res}}\,(\mathrm{mas})$	1.2	0.72	0.24	0.17	0.07	0.02

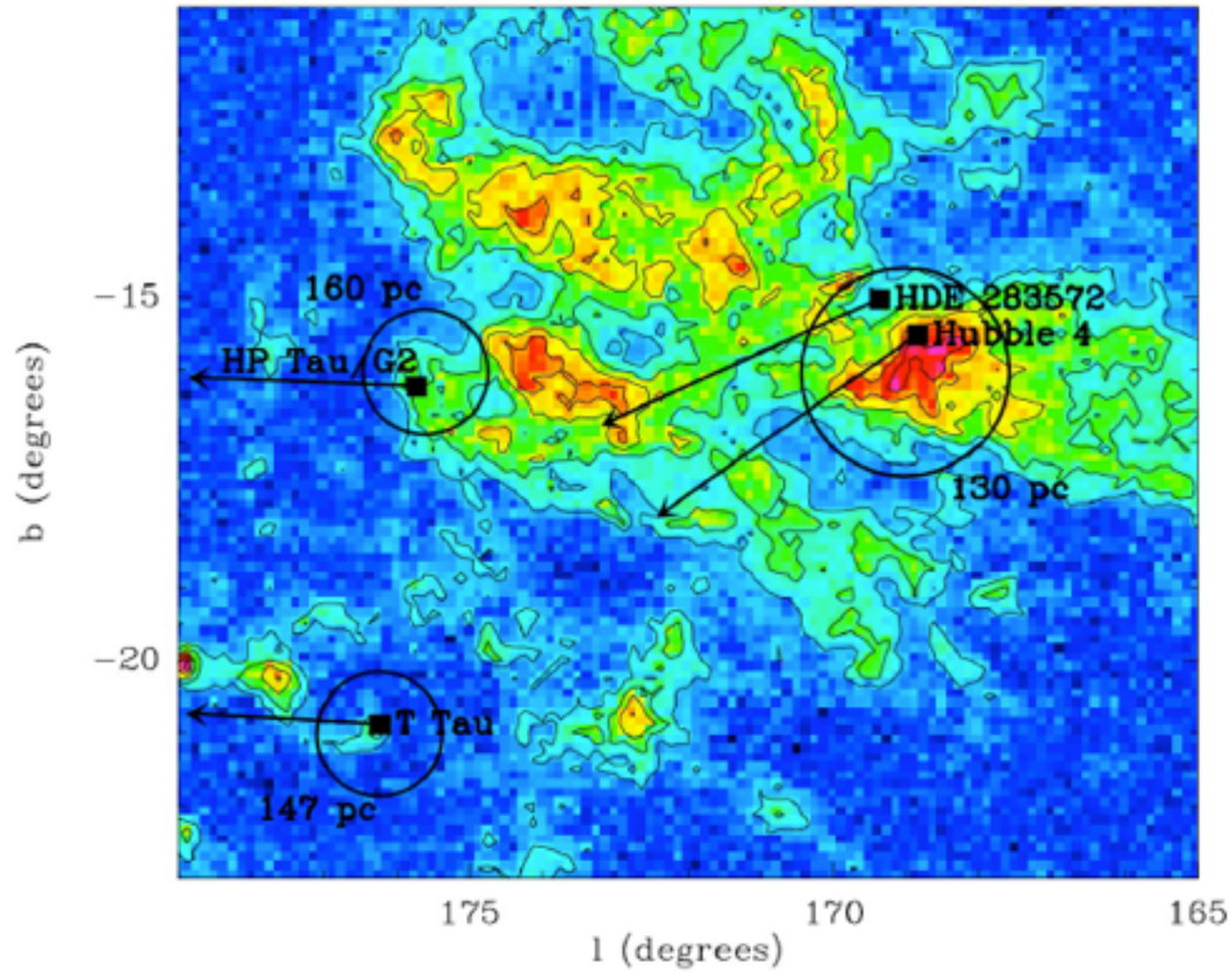
- Absolute astrometric precision:

  200 μas easily obtained

  20 μas with effort

Young stars with radio emission



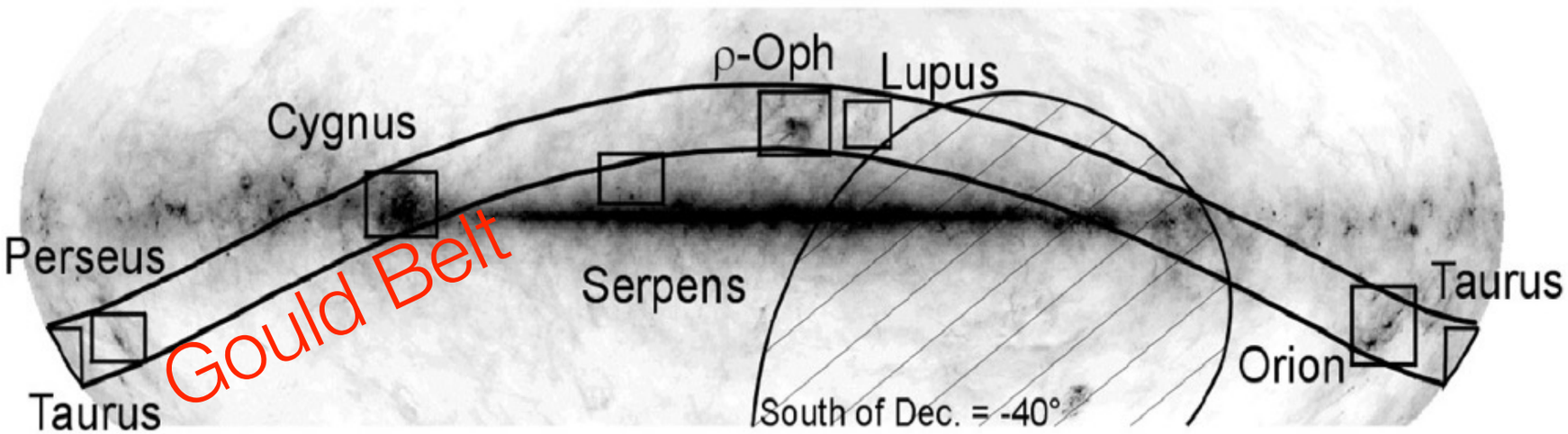


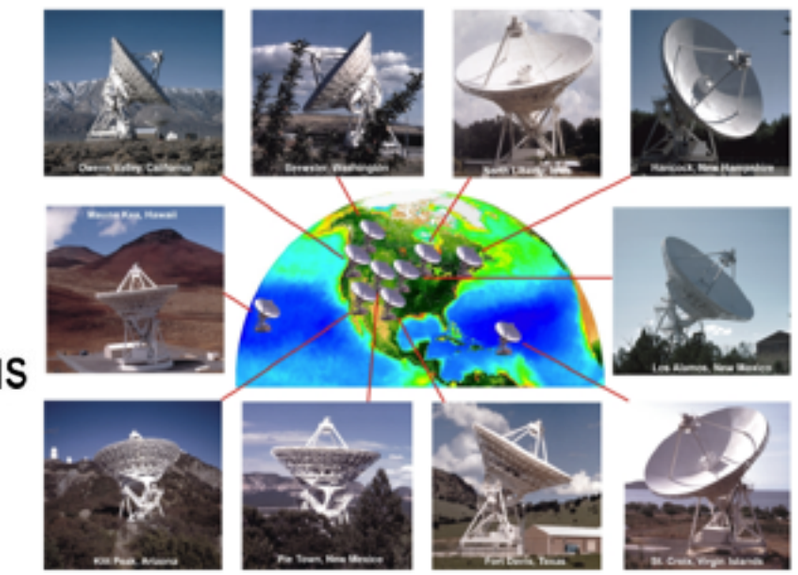
Taurus

Loinard et al. (2007, 2008), Torres et al. (2009, 2012)

- Stars with coronal activity, 10^5-10^7 yr old.
- Compact, non-thermal continuum radio emission.

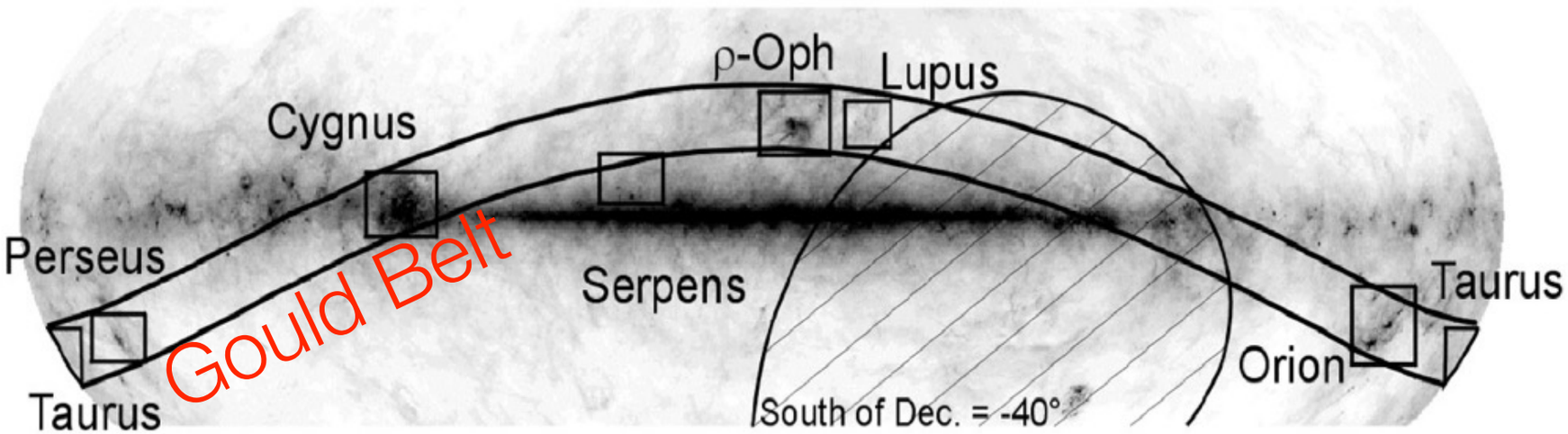
A *Very Long Baseline Array* Legacy Project

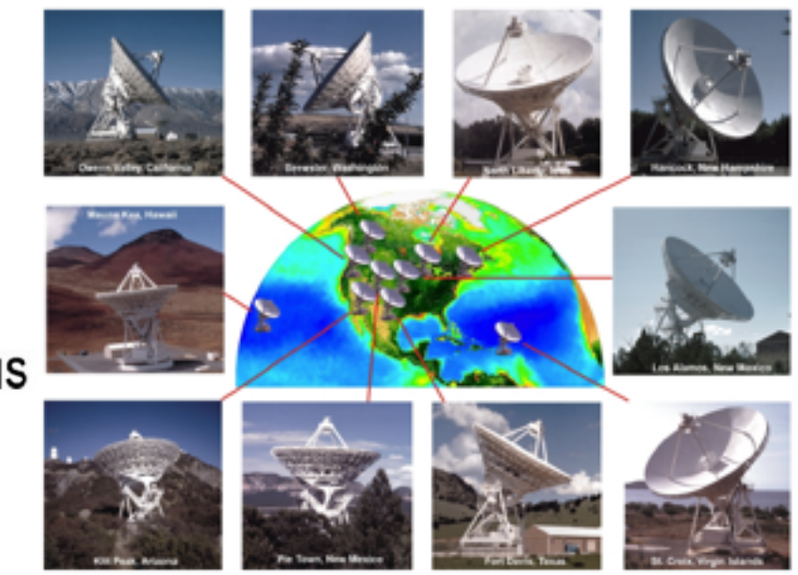




- VLA search to identify (non-thermal) radio emission associated to YSOs (~180 objects).
- 2200 hours of telescope time awarded to the project by the NRAO (period 2012-2018)
- Second largest project ever approved by the VLBA.

A *Very Long Baseline Array* Legacy Project

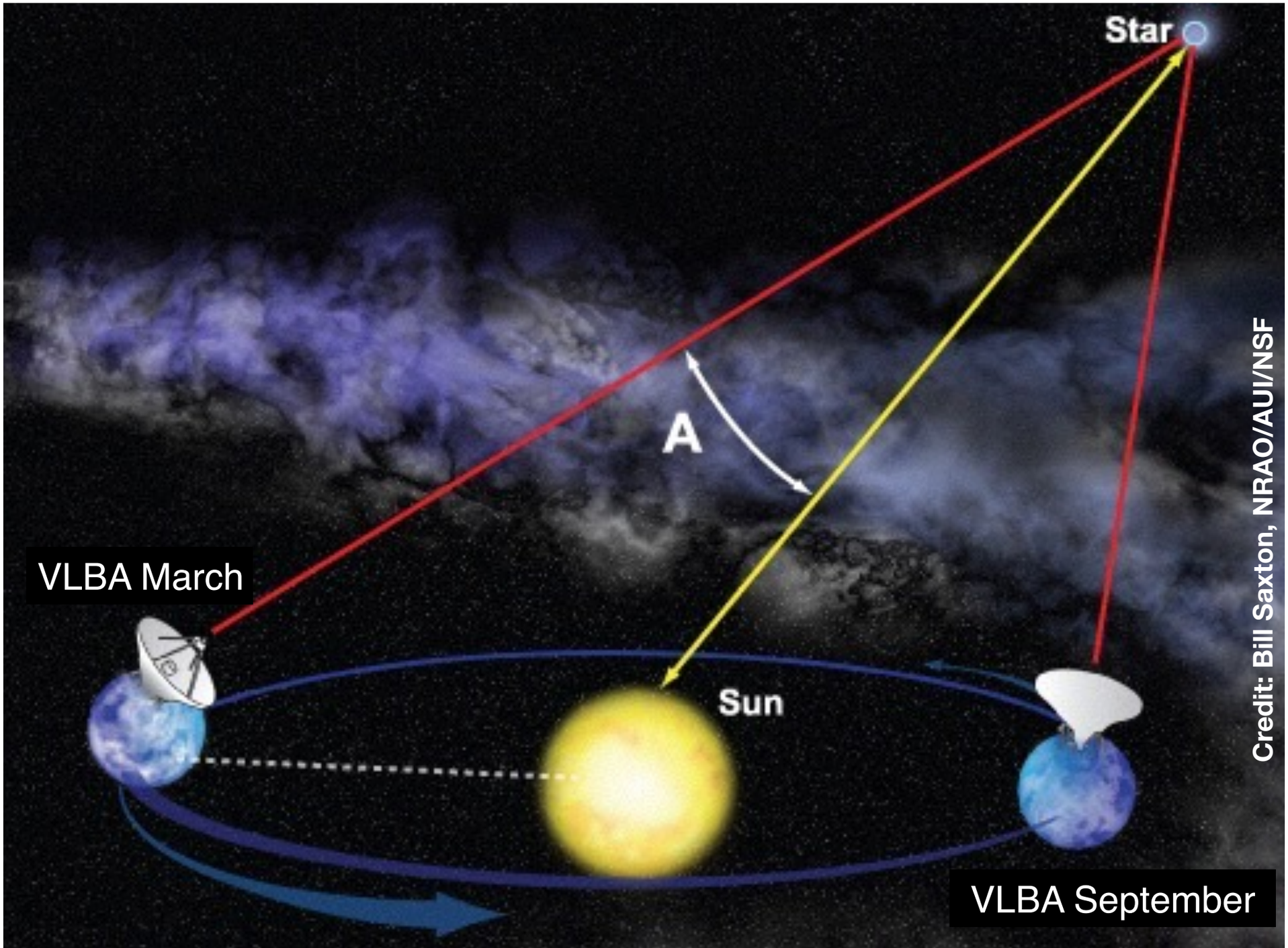




- *Main goals:*
  - Astrometric survey of (embedded) young stars.
  - 3D structure and kinematics of molecular clouds.
  - Constrain models for the origin/motion of the Gould's Belt.

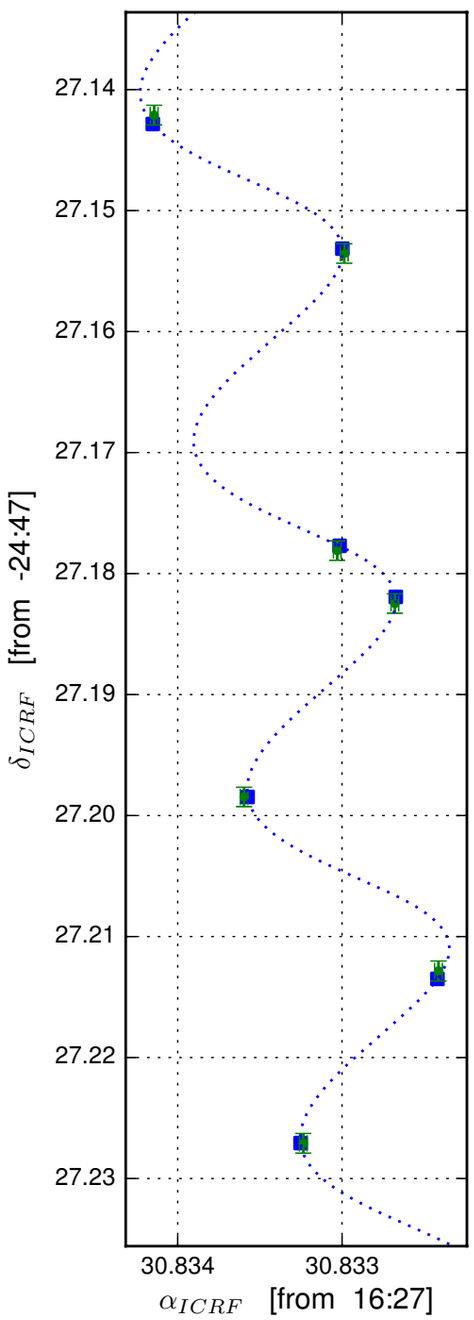
Very Long Baseline Array observations

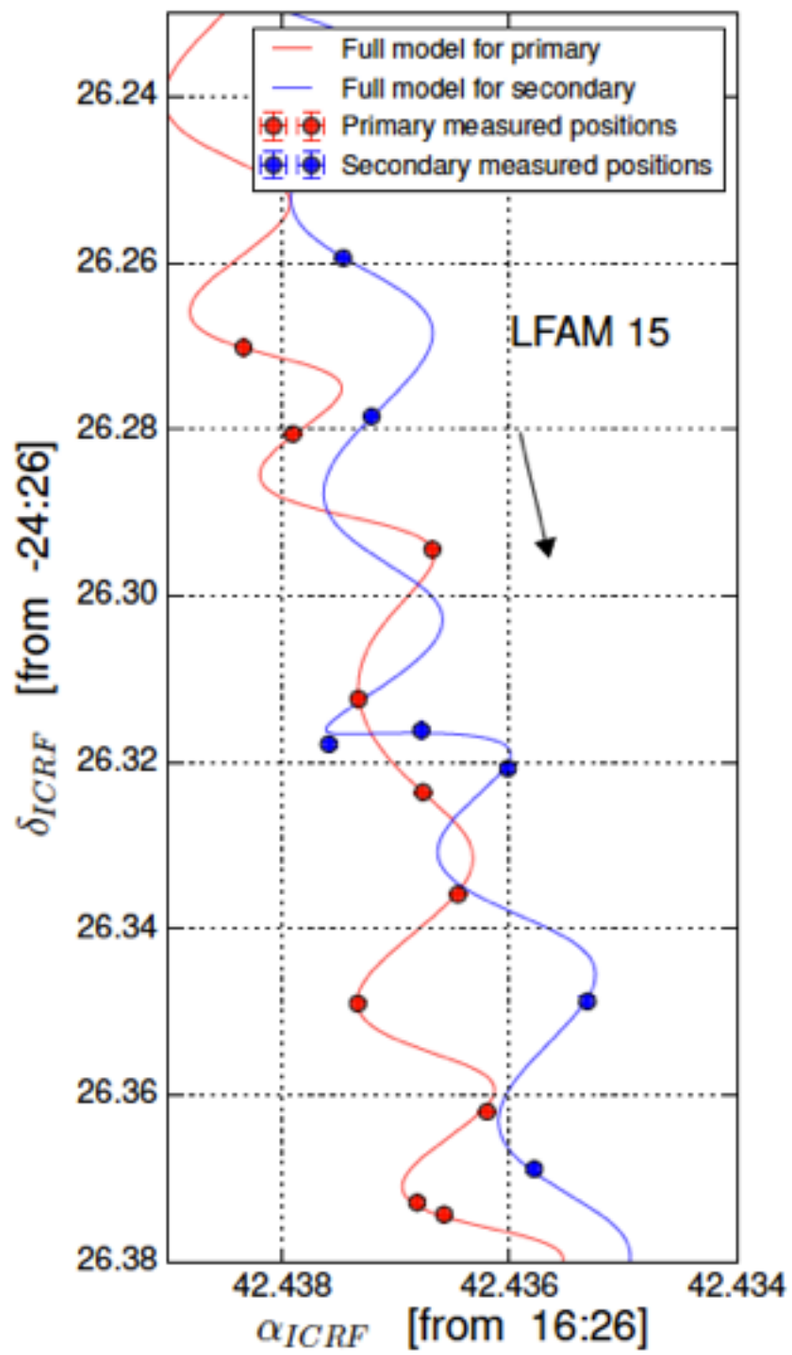
- 2 epochs/yr
- Observed frequency: 5 and 8 GHz.



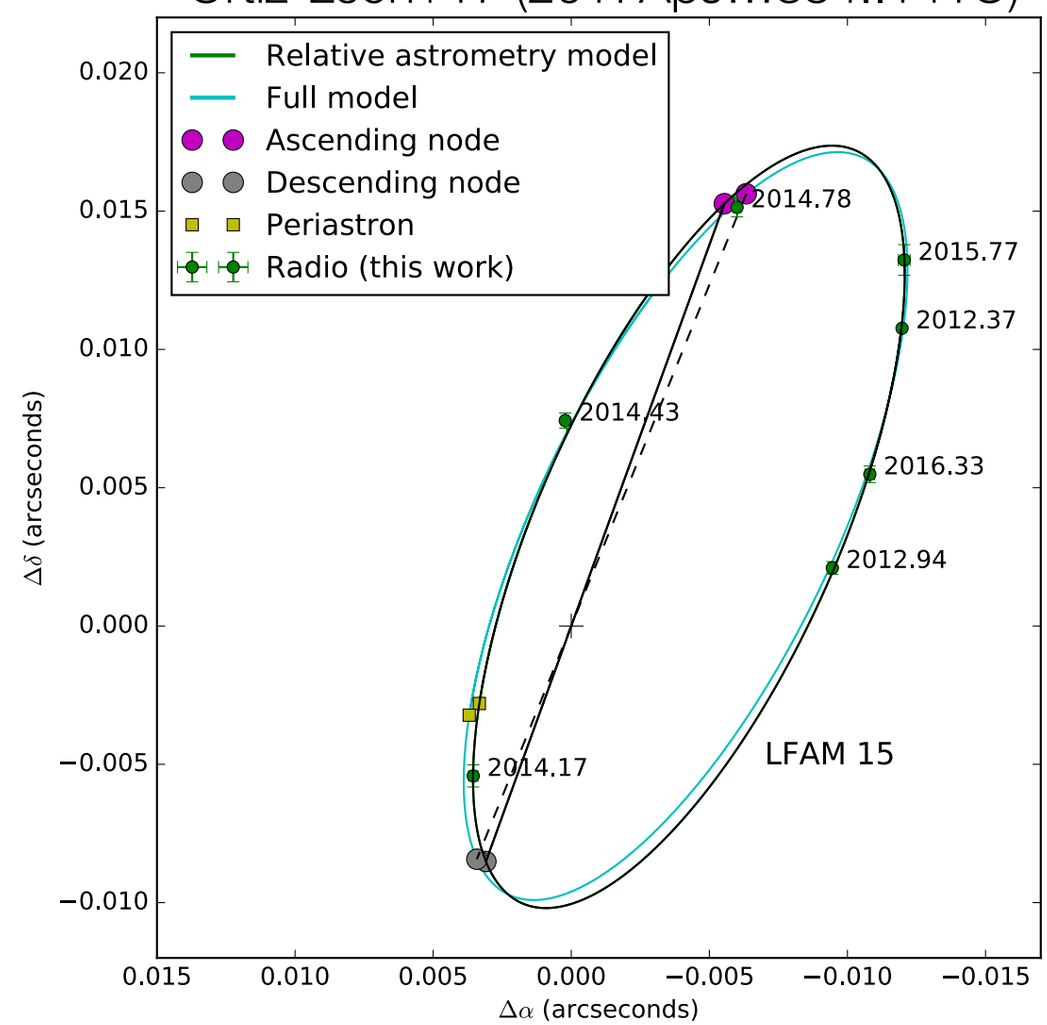
Astrometric fits: singles vs. binaries

- VLBI parallaxes





Ortiz-León+17 (2017ApJ…834..141O)



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

Dynamical masses

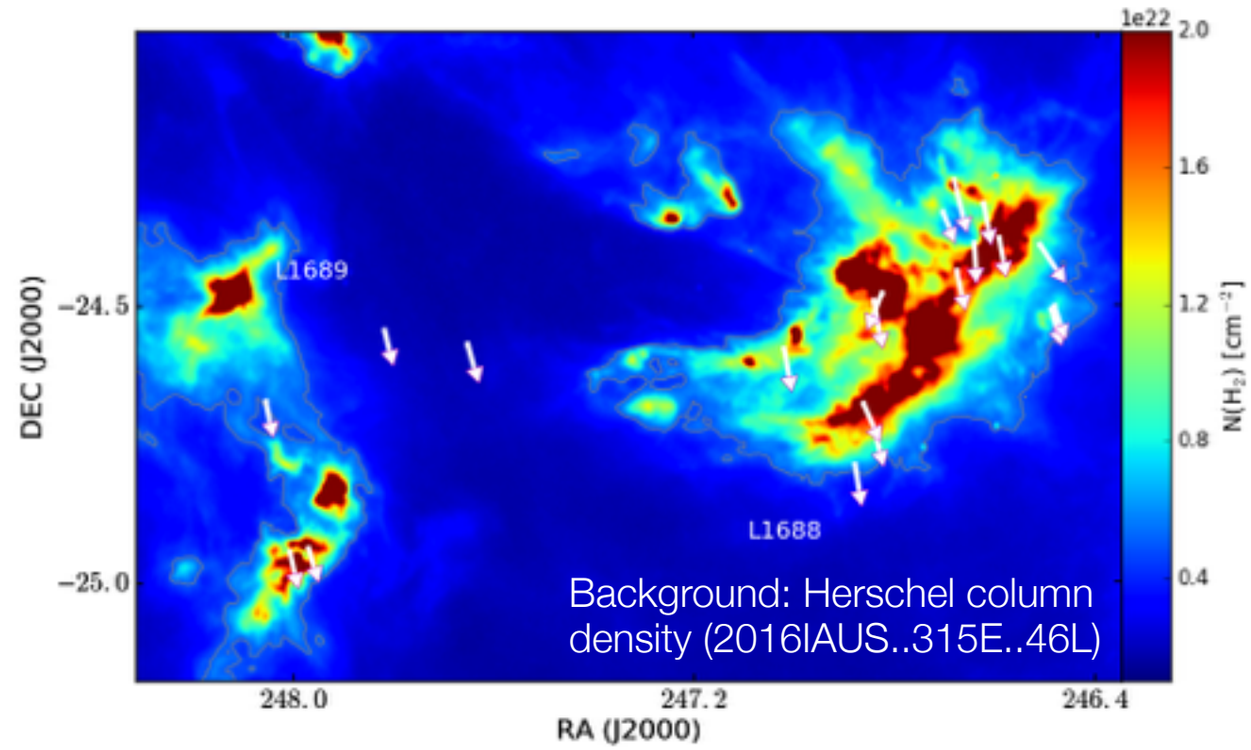
Name	*a* (au)	*P* (yr)	M_1	M_2
LFAM15	2.31 ± 0.02	3.598 ±0.005	0.506 ± 0.002	0.450 ± 0.010
YLW12Bab	1.74 ± 0.01	1.424 ± 0.001	1.244 ± 0.007	1.362 ± 0.017
SFAM87	4.98 ± 0.03	7.673 ± 0.005	1.076 ± 0.020	1.024 ± 0.027
DOAR51	4.71 ± 0.07	8.071 ± 0.030	0.815 ± 0.004	0.788 ± 0.034
ROXN39	6.9 ± 0.1	11.77 ± 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

Ortiz-León+17ab (2017ApJ…834..141O, 2017ApJ...834..143O)

- Excess of radio-bright binaries with separations below 10 au.
- Other 6 binaries in Taurus published by Galli+18 (2018ApJ…859…33G).
- 19 more currently being monitored (PI: S. Dzib).

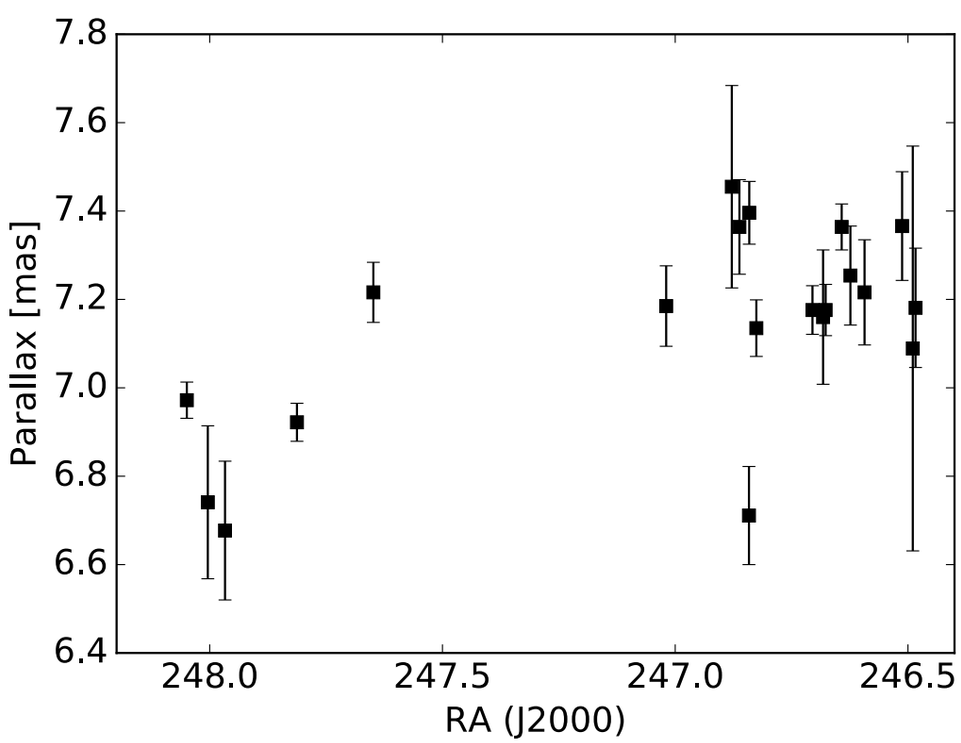
Astrometric results: Ophiuchus

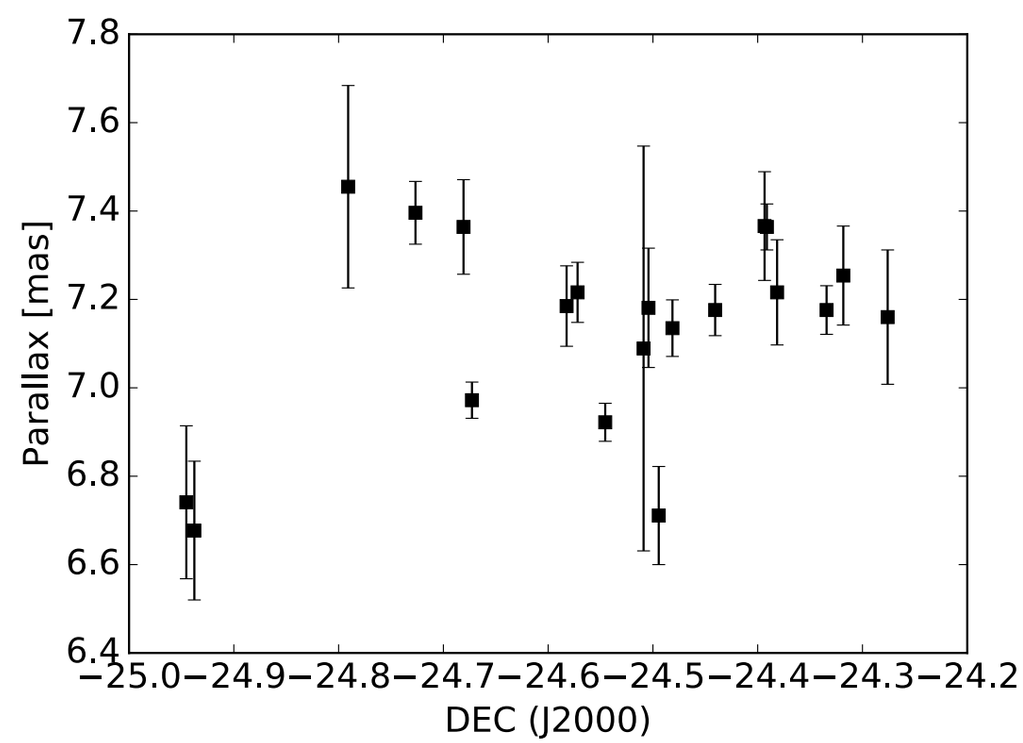
- 20 stars with VLBI parallaxes.
- Errors on the distance: 1.3-6%.
- Two separated cloud components.



Background: Herschel column density (2016IAUS..315E..46L)

Ortiz-León+17 (2017ApJ…834..141O)





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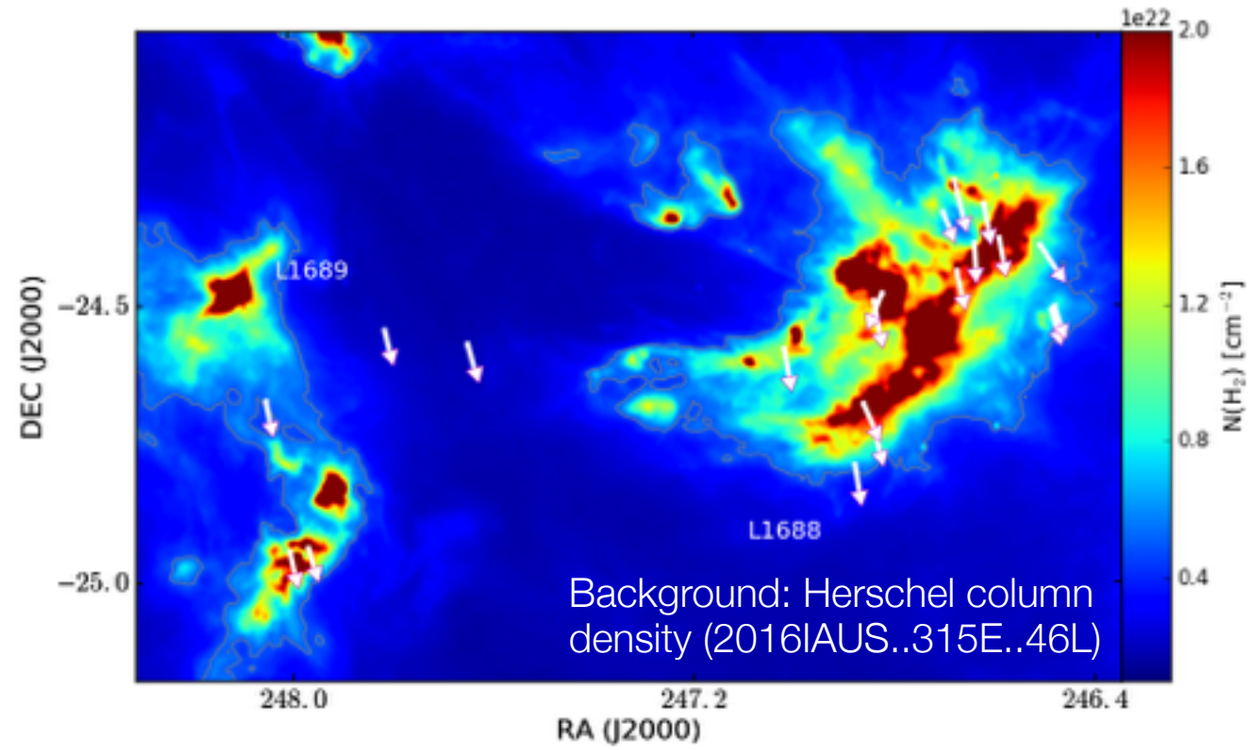

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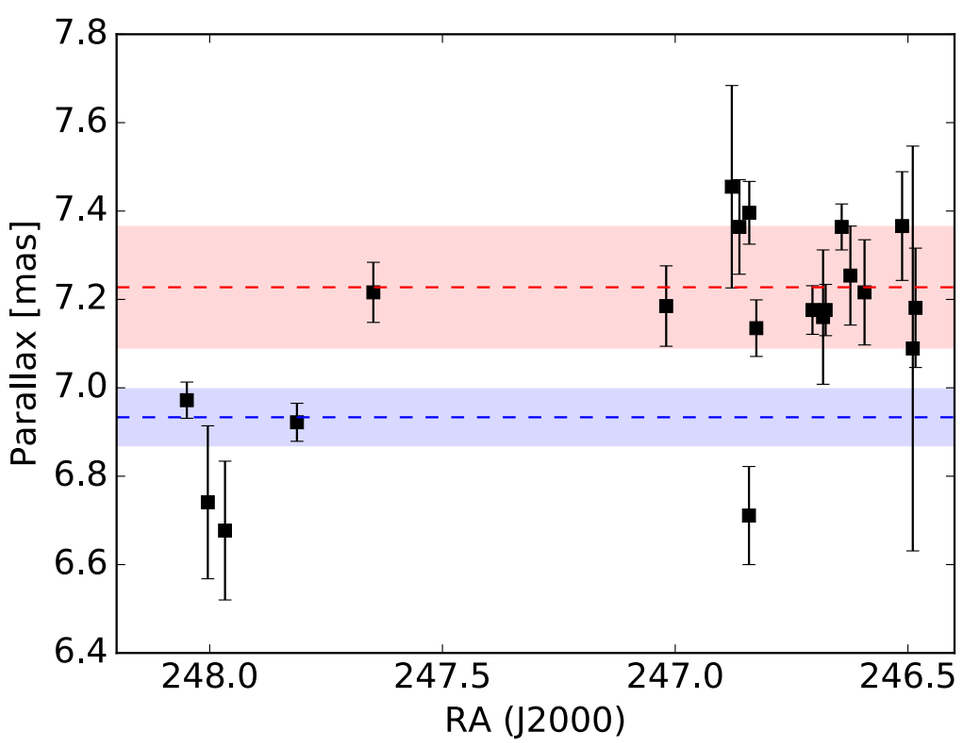
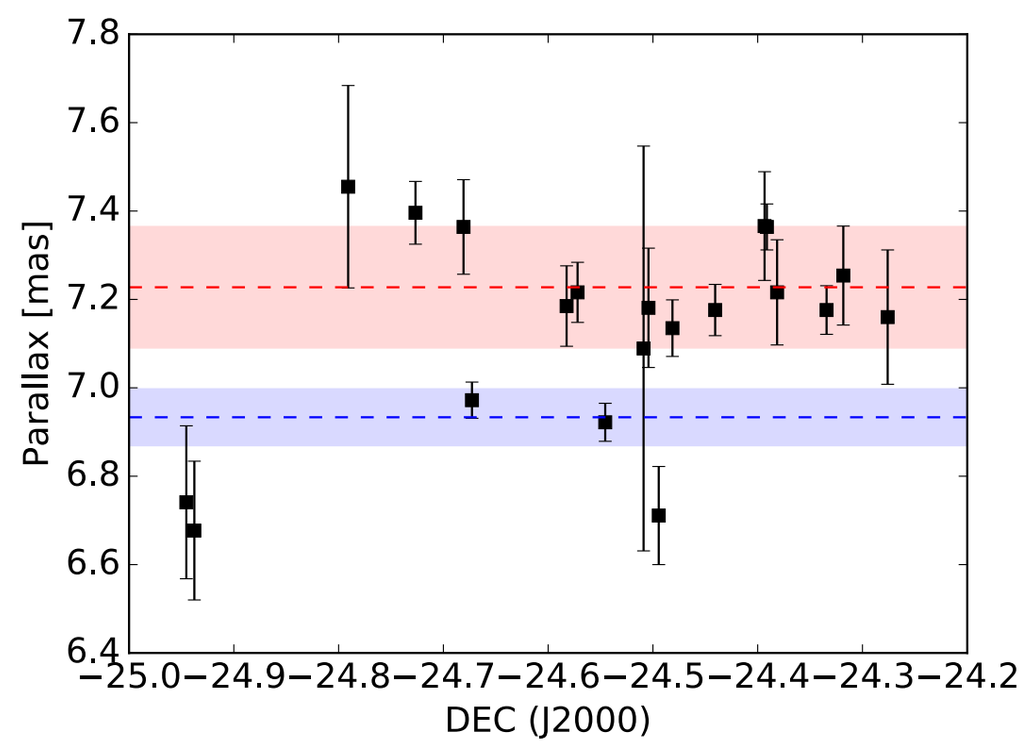
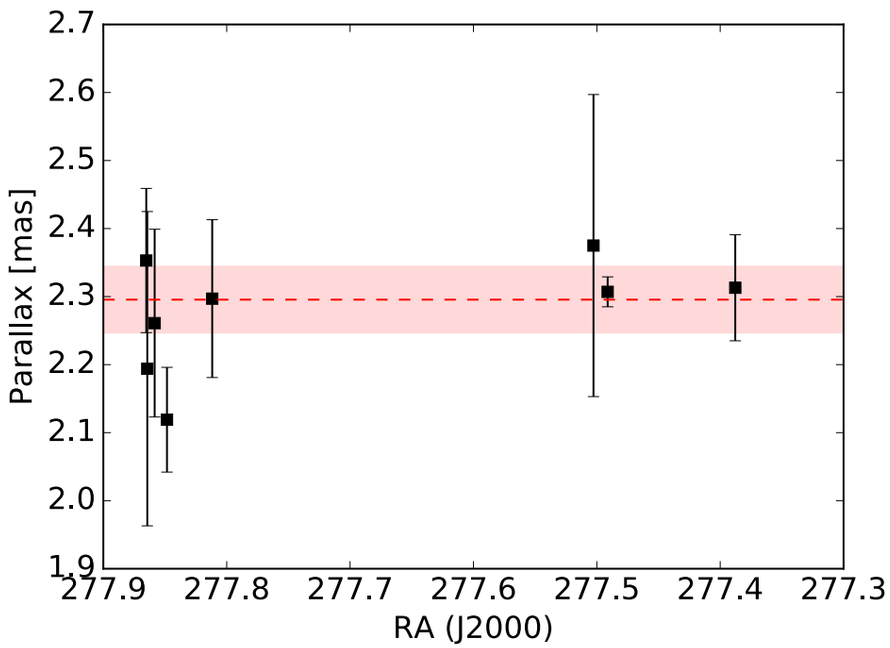
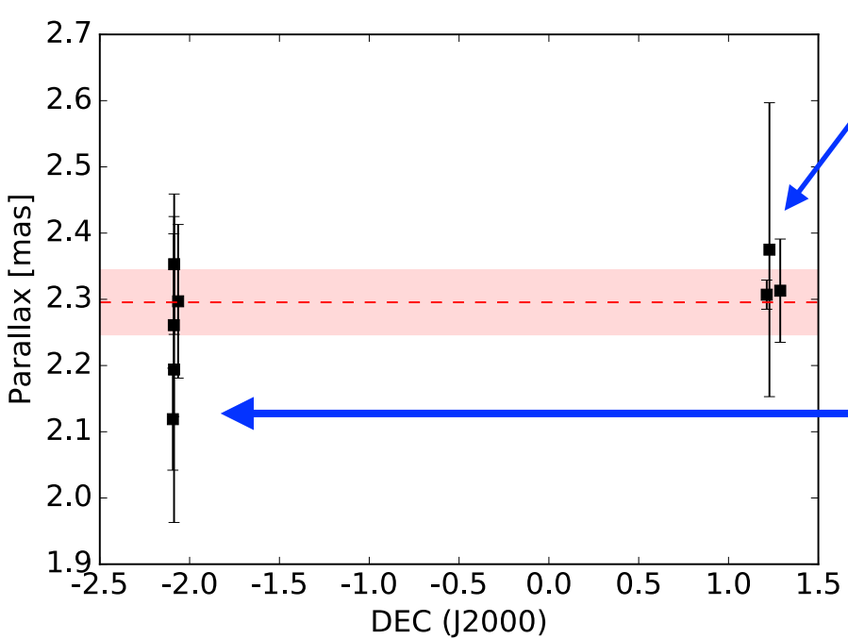
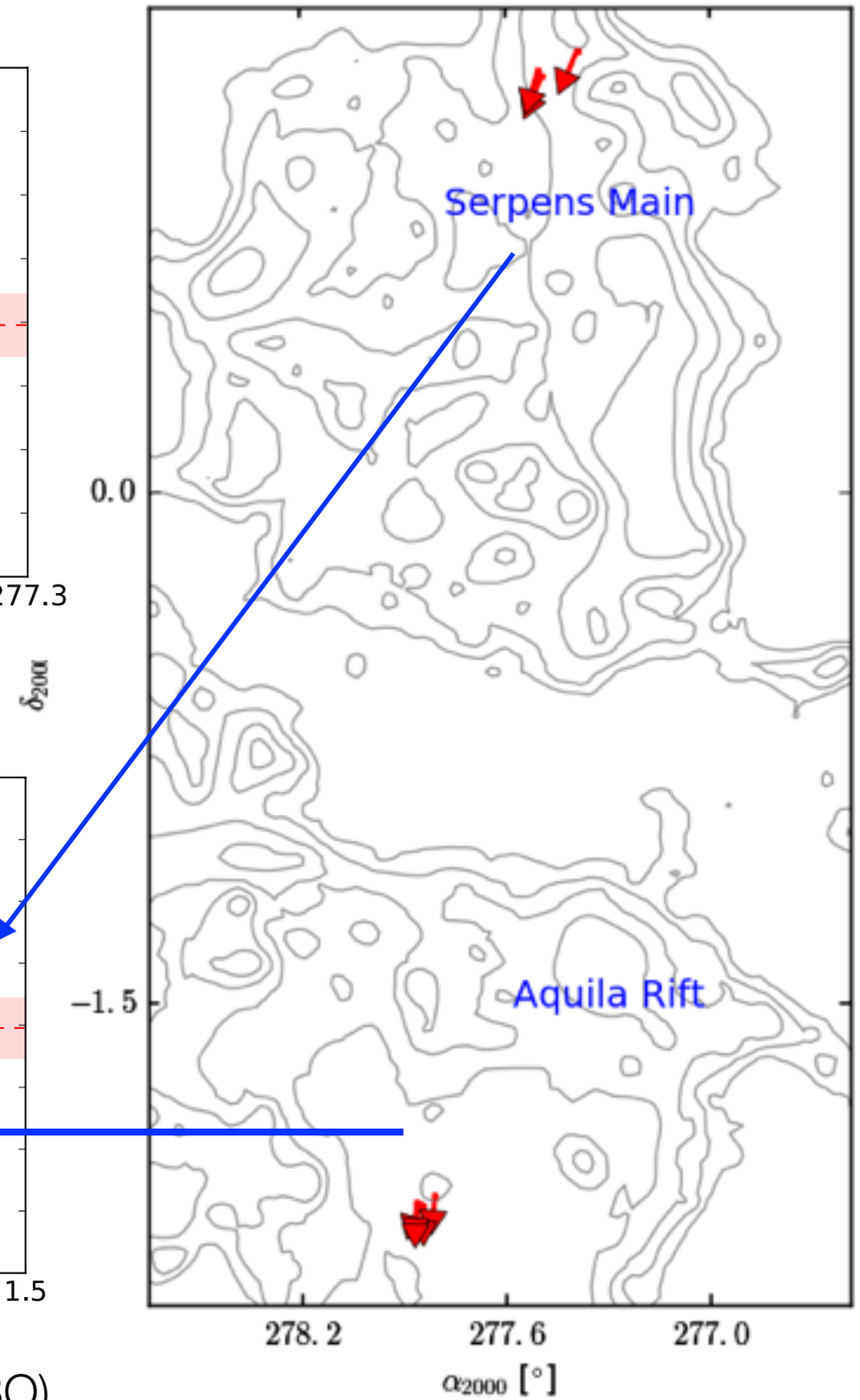




Astrometric results: Serpens and Aquila







- 8 stars with VLBI parallaxes.
- First direct proof of the physical association between Serpens and the Aquila.
- Distance is ~68% larger
- Objects are ~180% brighter
- Stars are ~79% younger

Ortiz-León+17 (2017ApJ...834..143O)

Distances: all regions

Cluster	Distance
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
L1688	138 ± 3 pc
L1699	144 ± 1 pc
Serpens Main	436 ± 9 pc
W40	436 ± 9 pc
IC348	321 ± 10 pc

Cluster	Distance
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

References: Ortiz-León+17ab (2017ApJ...834..141O, 2017ApJ...834..143O), Kounkel+17 (2017ApJ... 834..142K), Galli+18 (2018ApJ…859…33G), Ortiz-León+18 (2018arXiv180803499O).

Summary

- We have improved distances measurements toward young stars, many of which are invisible to Gaia.

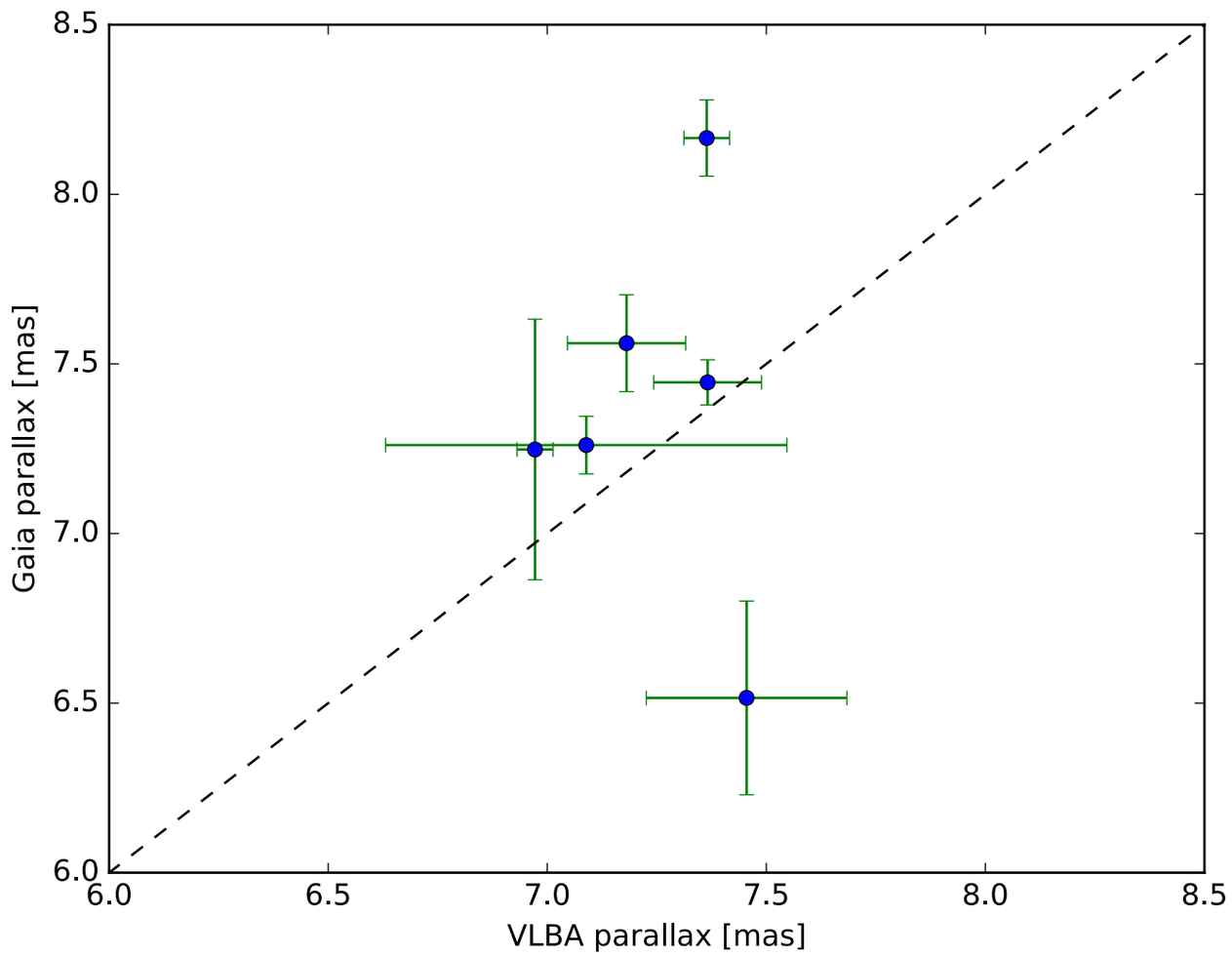
- For the first time distances with 0.3 - 6% accuracy have been measured, yielding important information about the three dimensional structure of molecular clouds.

- Stellar masses have been derived for individual components in several very binary systems.

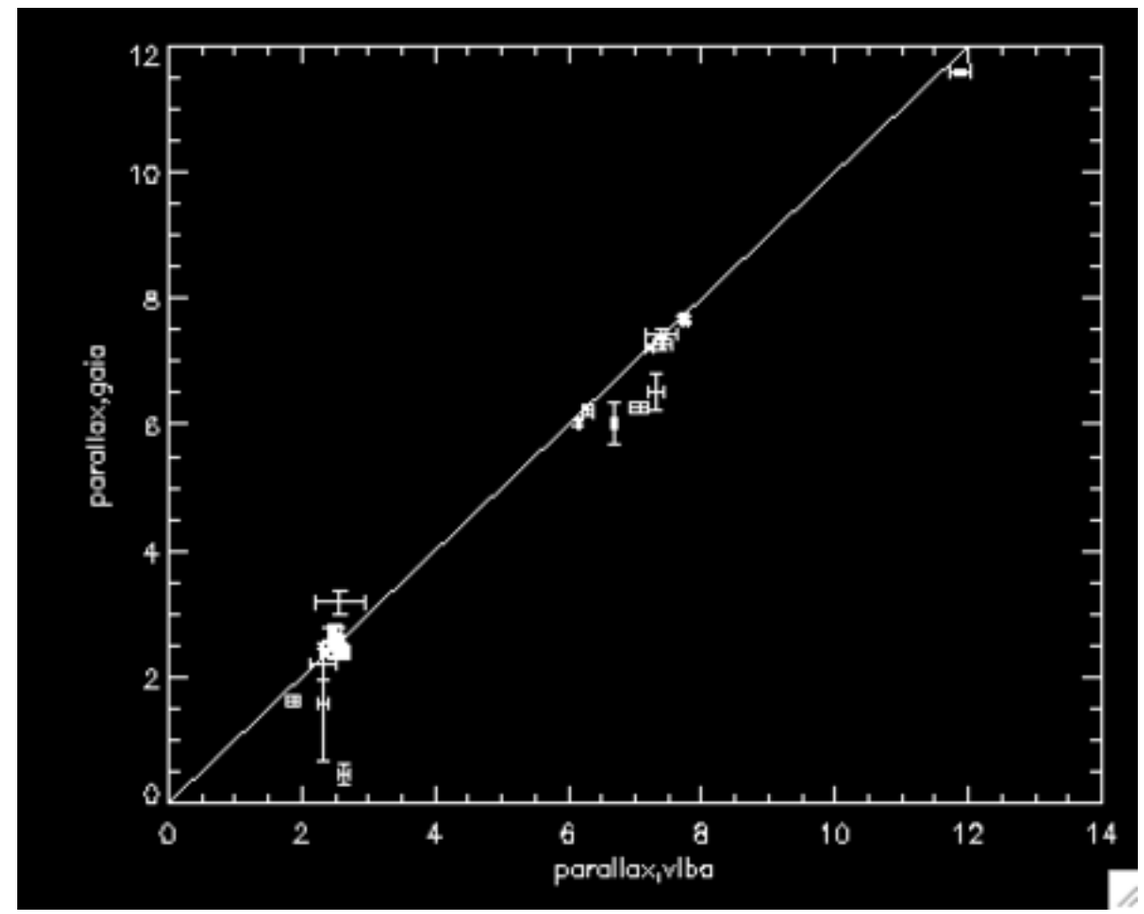
Backup slides

Comparison Gaia-VLBA

- Ophiuchus



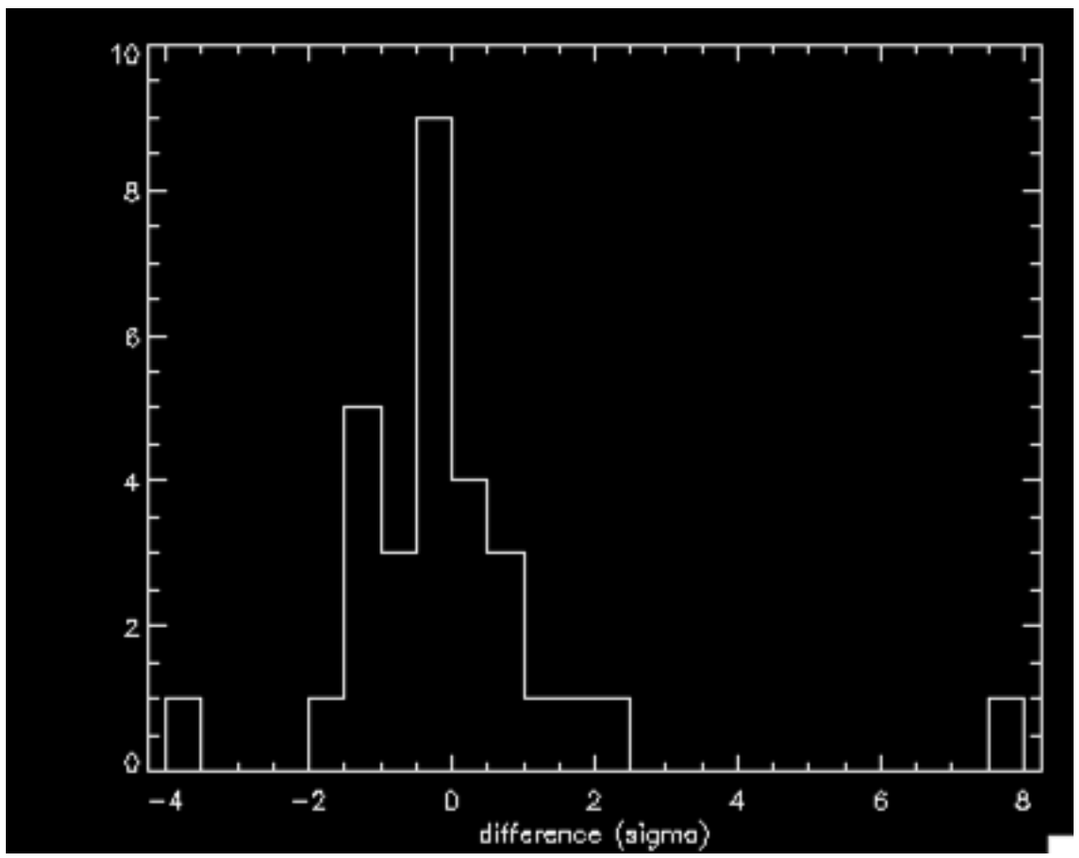
- All regions



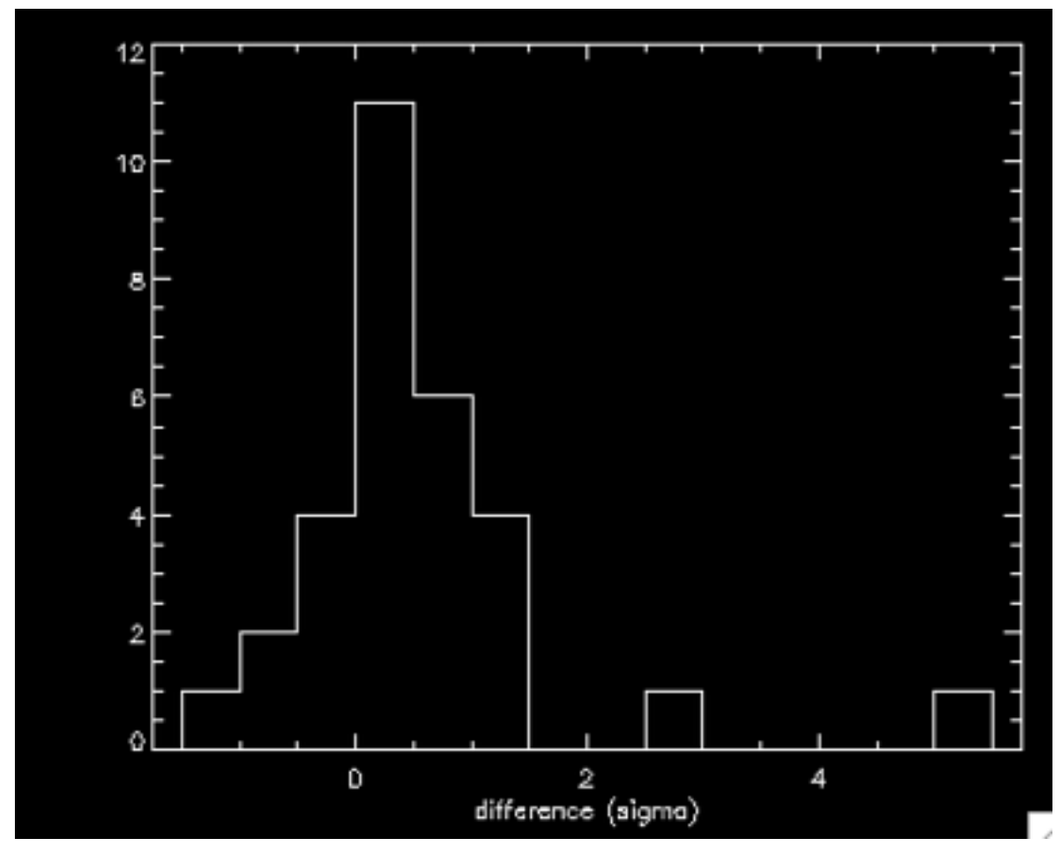
M. Kounkel

Comparison Gaia-VLBA

- All regions



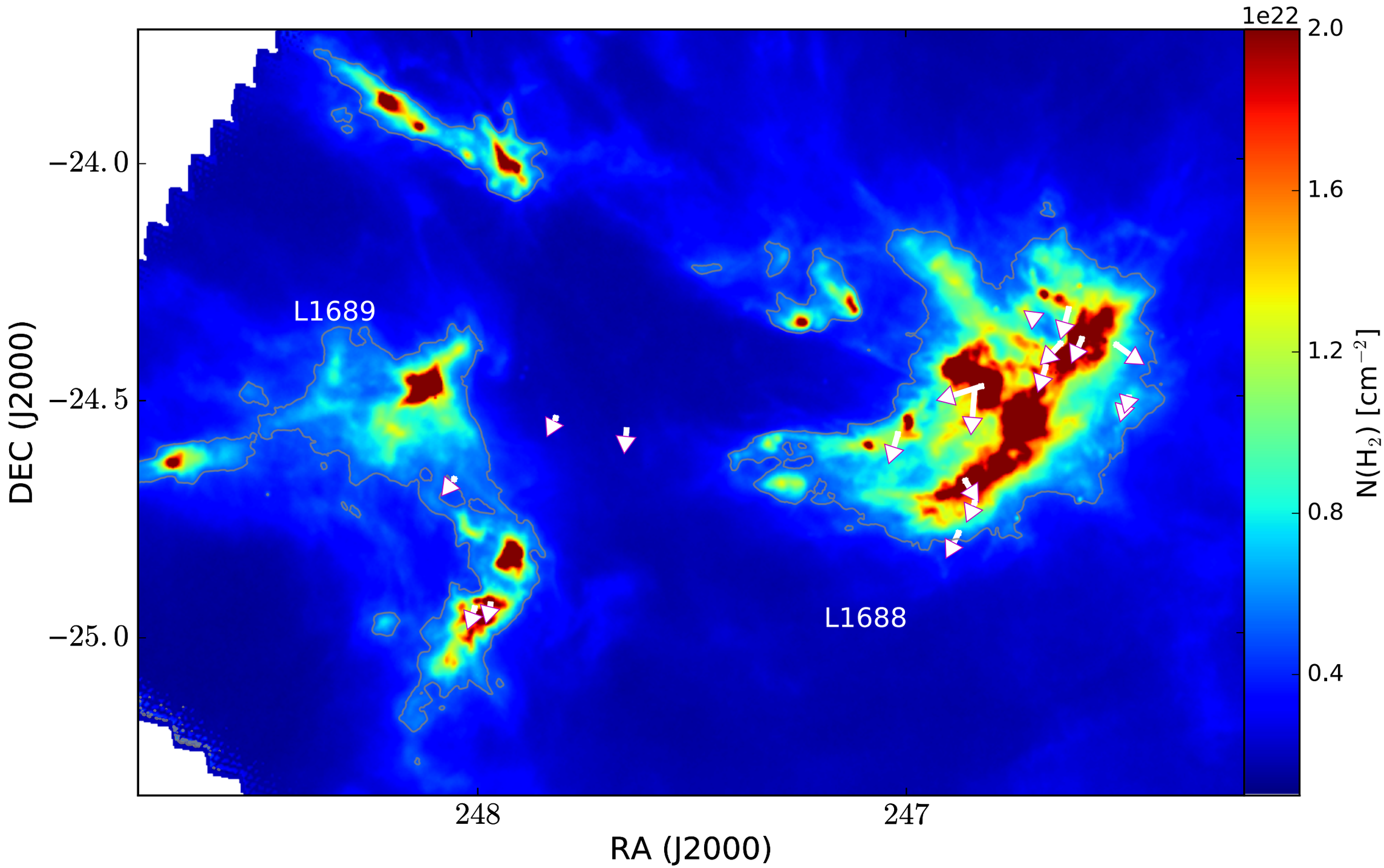
PM, R.A.



PM, Dec.

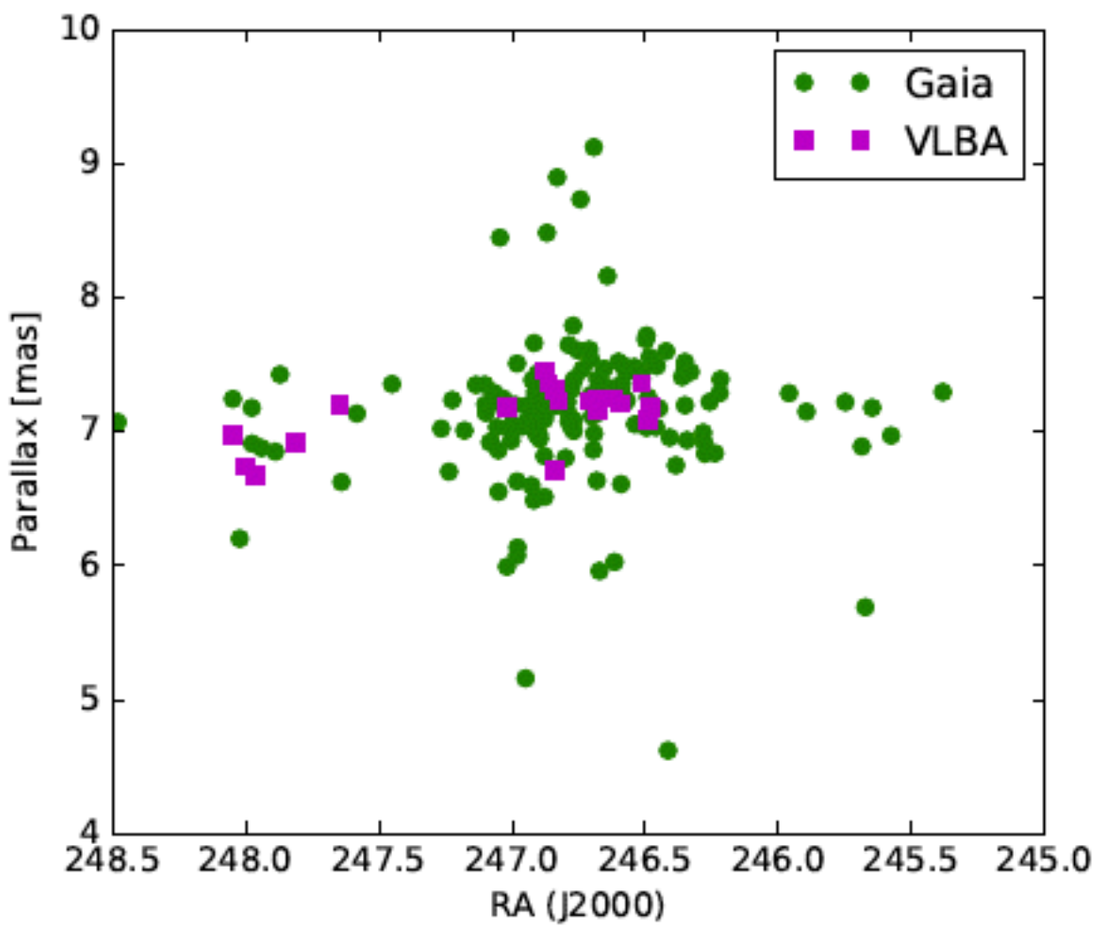
M. Kounkel

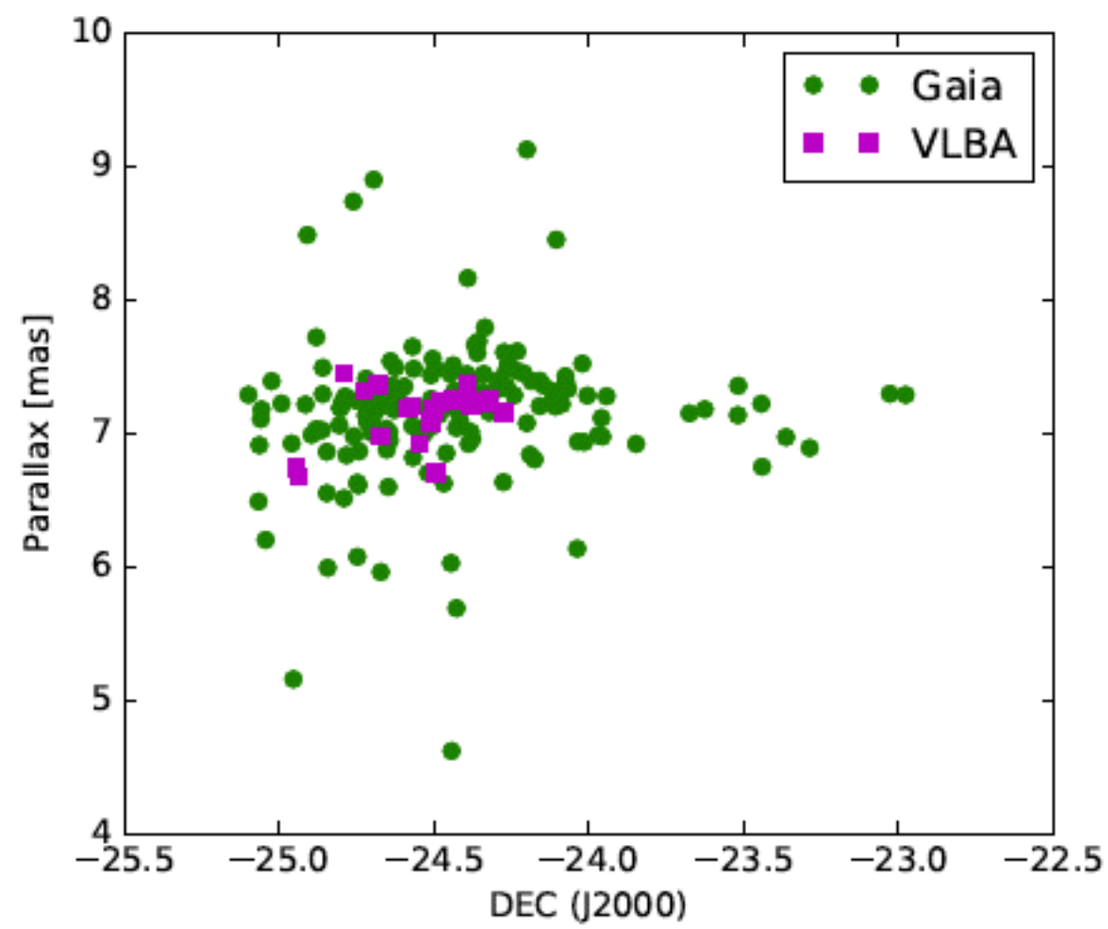
Ophiuchus proper motions



Gaia DR2

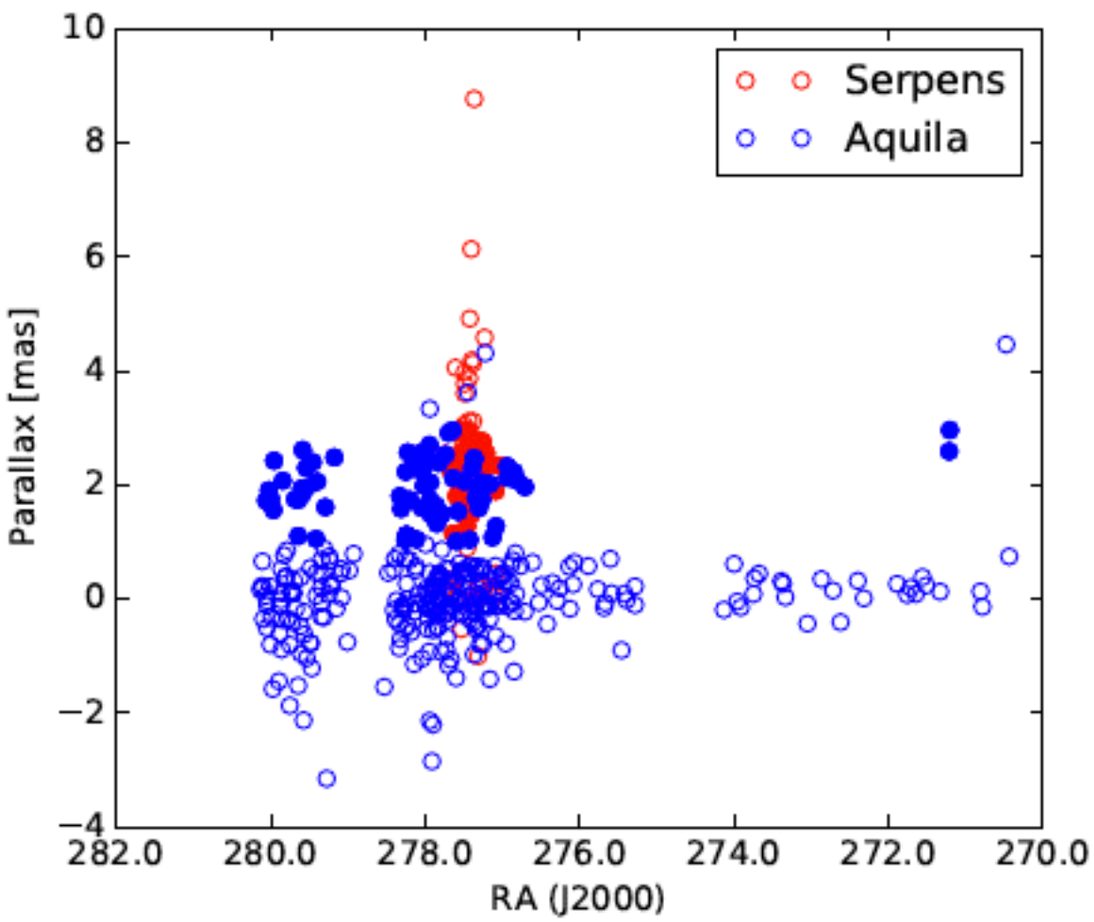
- Ophiuchus

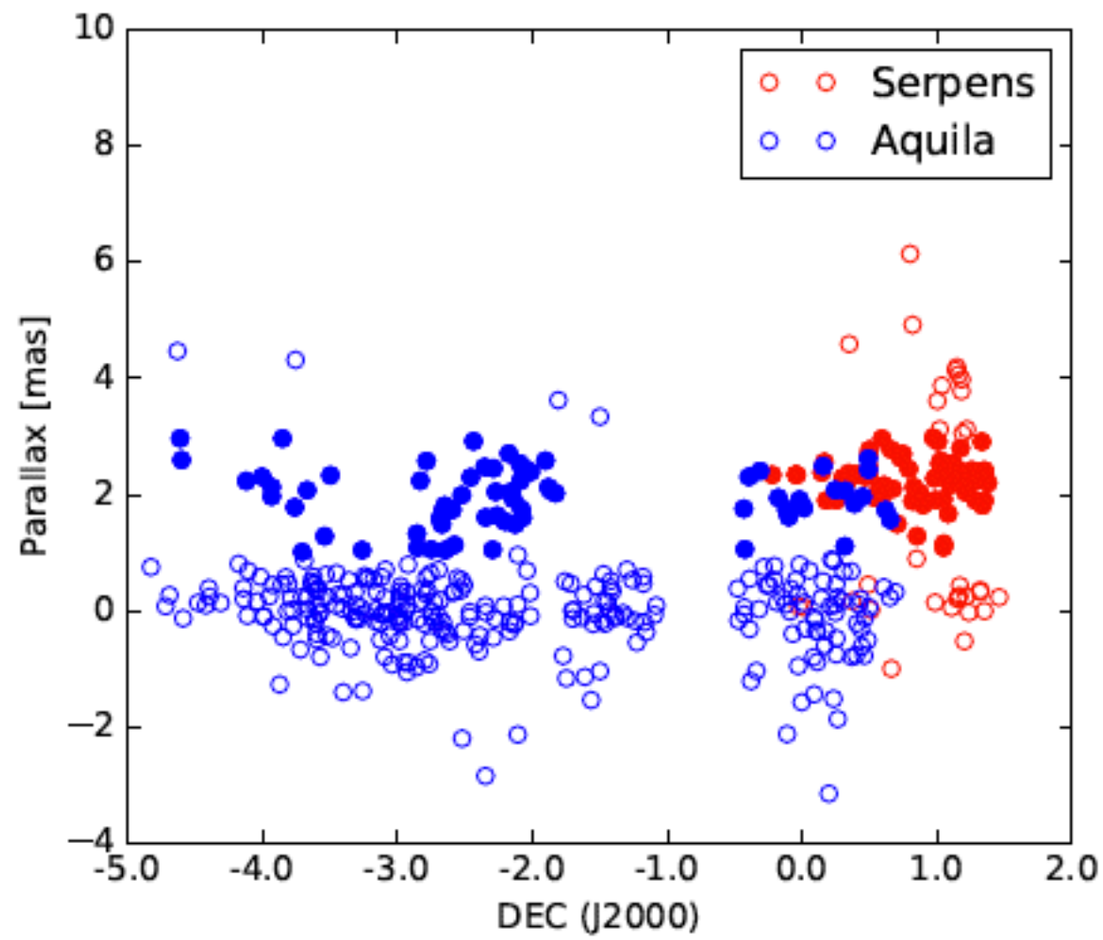




Gaia DR2

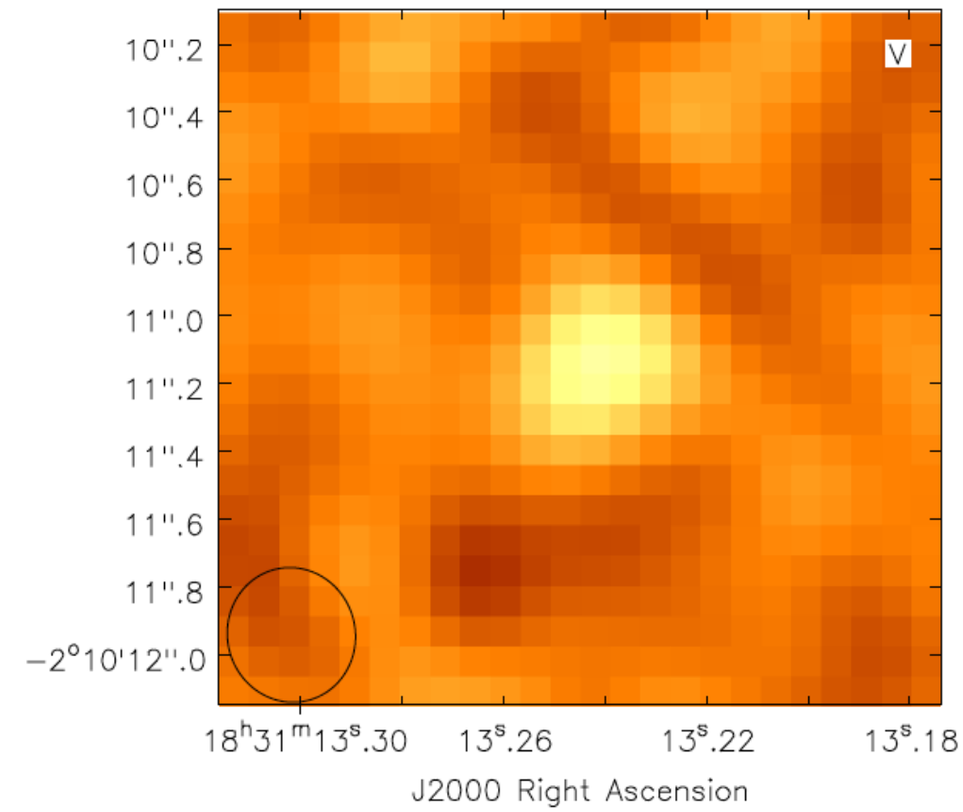
- Serpens/Aquila

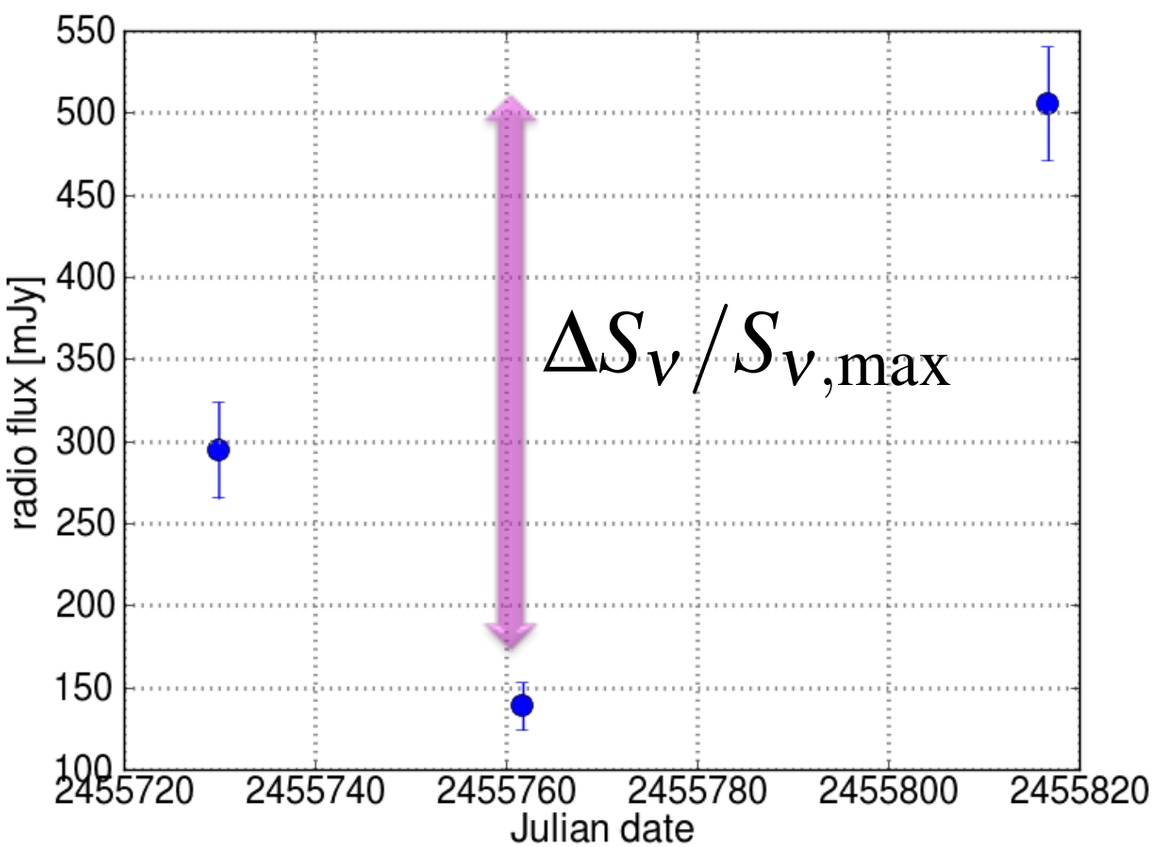




First phase: look for signatures of non-thermal emission

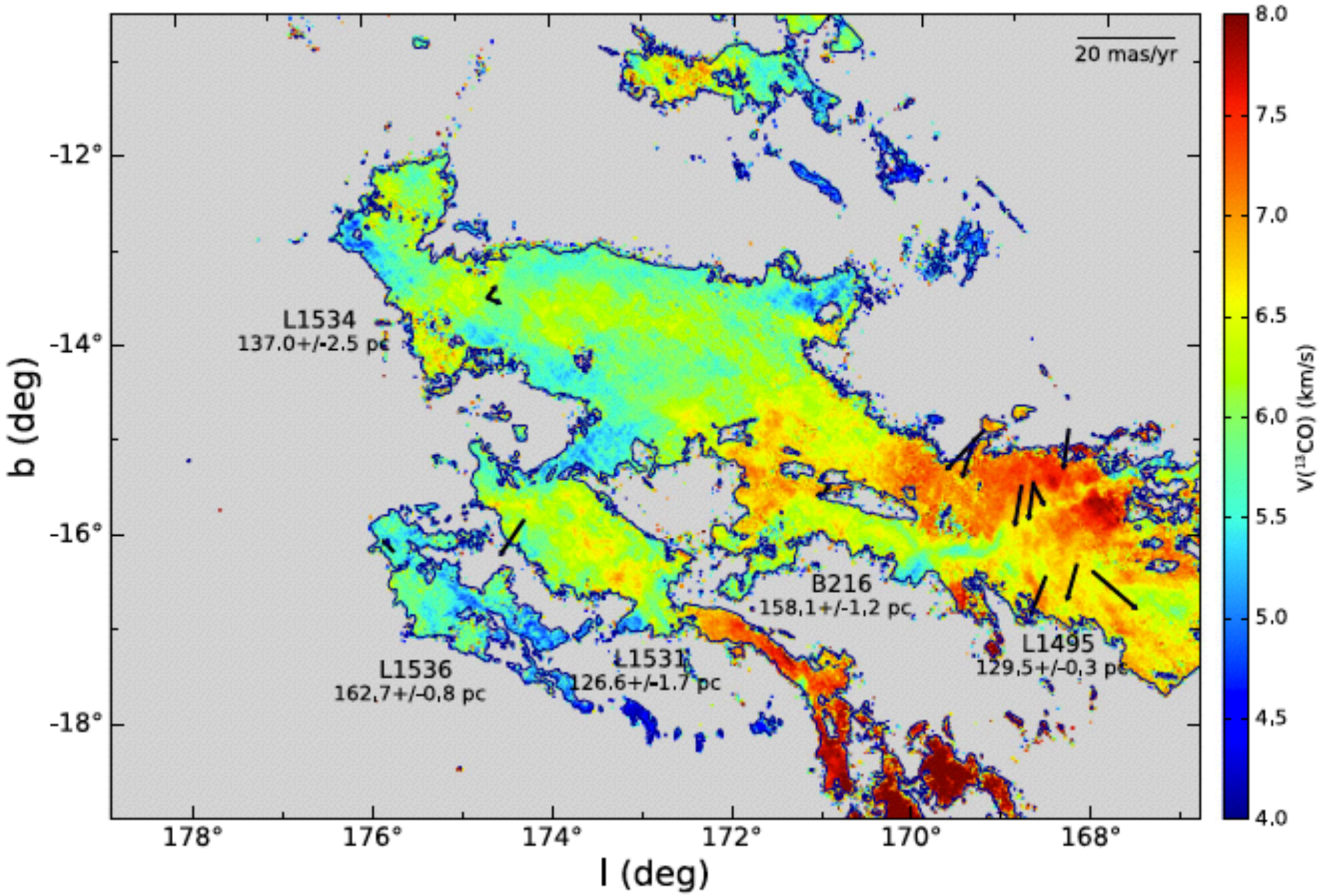
- Negative spectral index: $S_\nu \propto \nu^\alpha$
- Flux variability between epochs
- Circular polarization





- ~55% of the total number of YSOs are candidate non-thermal radio sources
- ~180 objects observed for astrometry

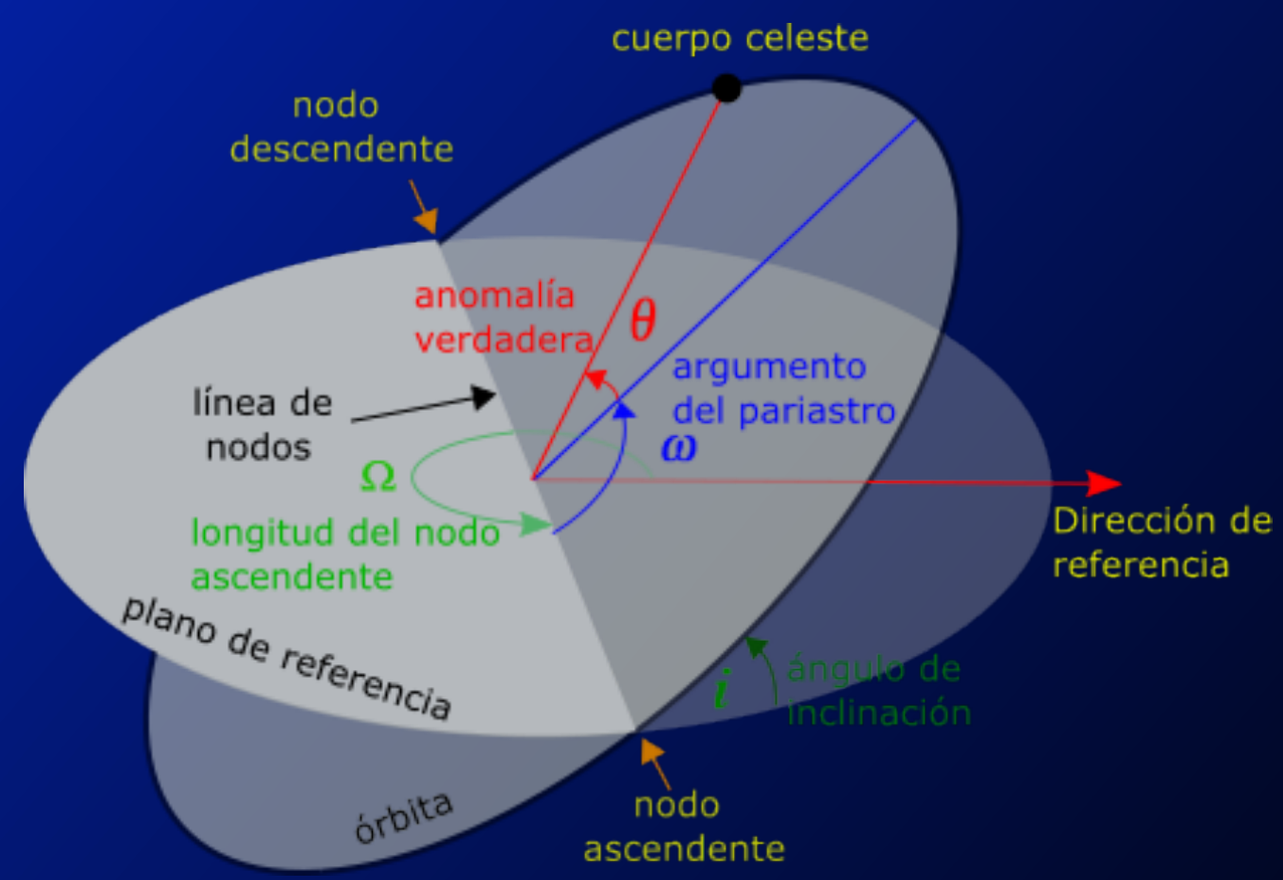
Taurus



Galli+18 (2018ApJ…859…33G)

Astrometric fits: binaries

- Short-period binaries
  - 5 astrometric parameters + 8 orbital parameters.
  - Individual masses are obtained, which are accurate to 2-5% in the best cases.



$$\alpha_{\mathrm{orb}}(t)\cos\delta = a_1 r(\cos(\theta+\omega)\sin\Omega - \sin(\theta+\omega)\cos\Omega\cos i)$$

$$\delta_{\mathrm{orb}}(t) = a_1 r(\sin(\theta+\omega)\sin\Omega\cos i + \cos(\theta+\omega)\cos\Omega)$$