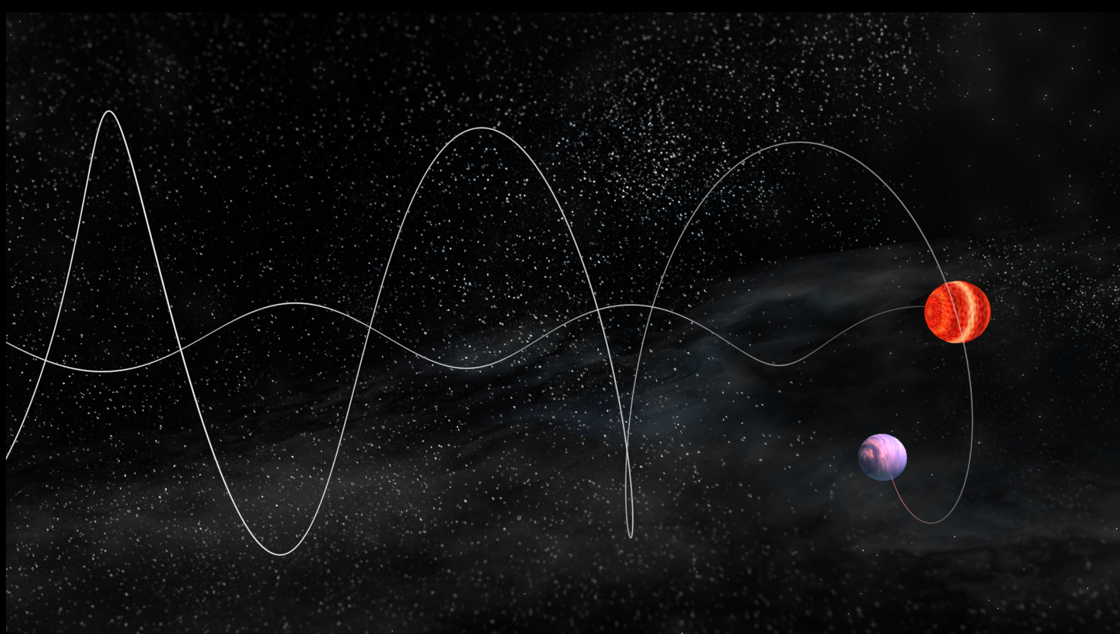
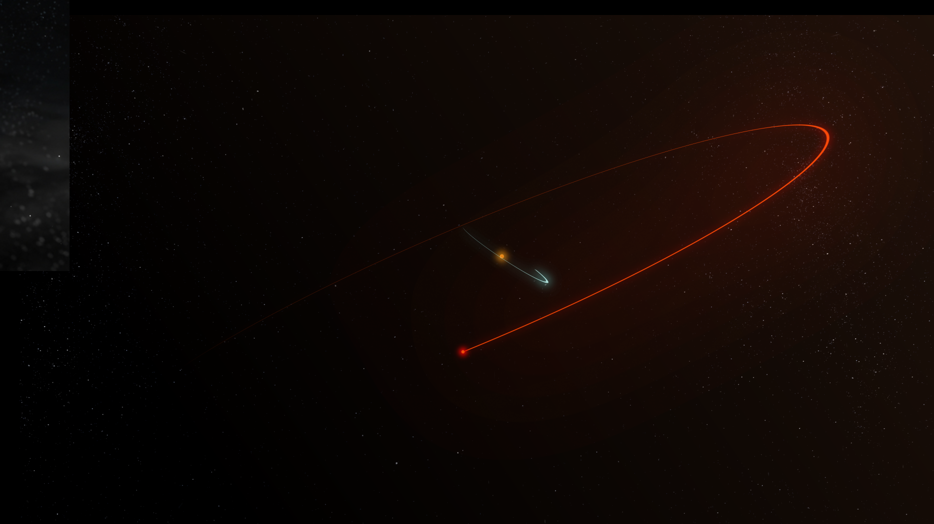
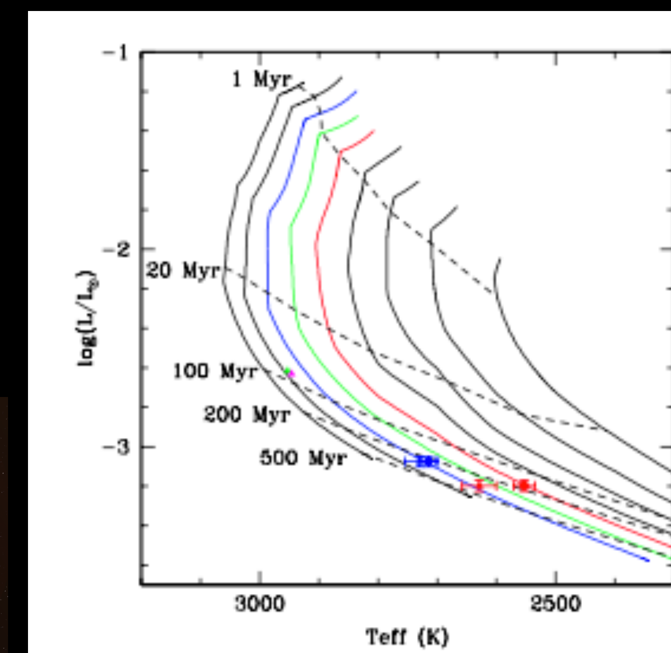
VLBI Astrometry as a Tool for Stellar Astrophysics







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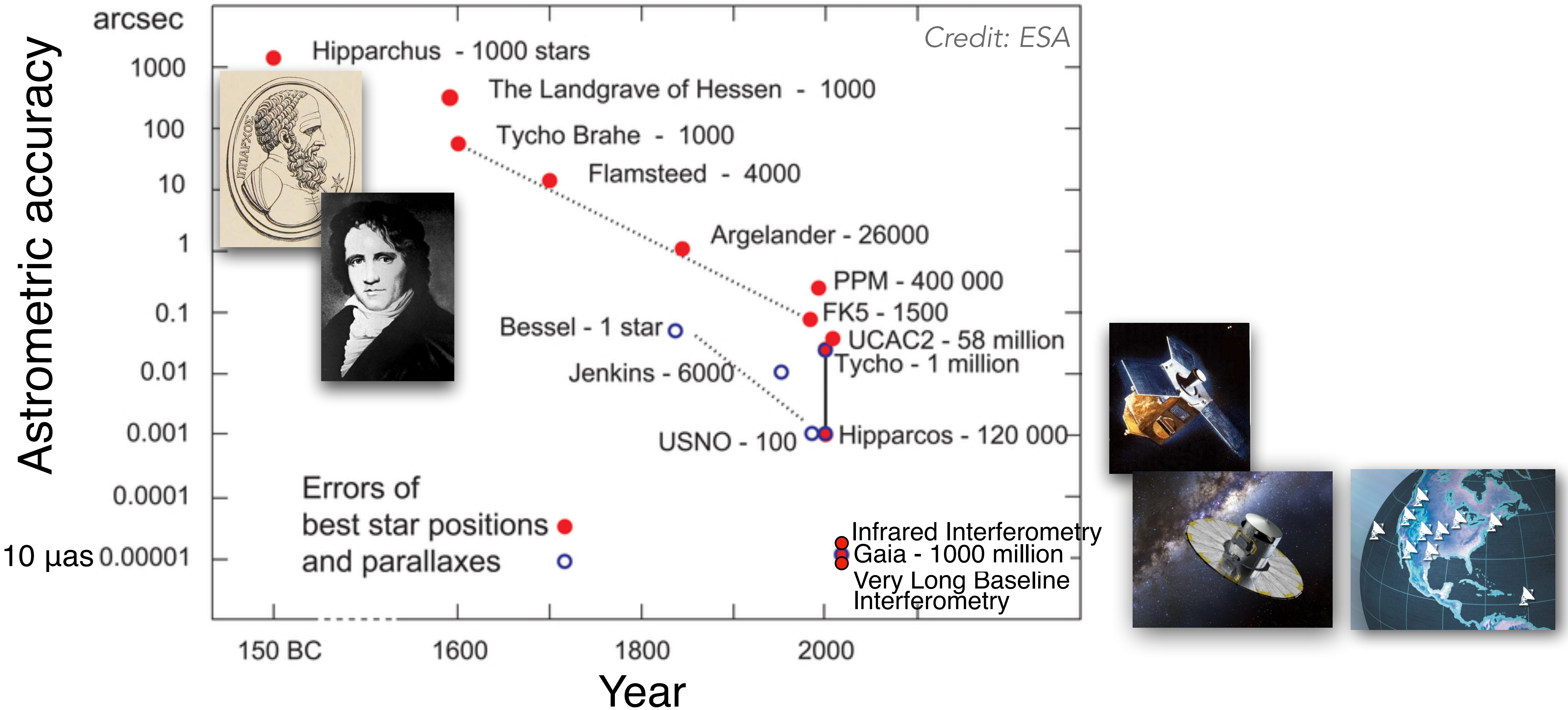
Instituto Nacional de Astrofísica, Óptica y Electrónica

Radio Stars in the Era of New Observatories
MIT Haystack Observatory, MA
April 18, 2024

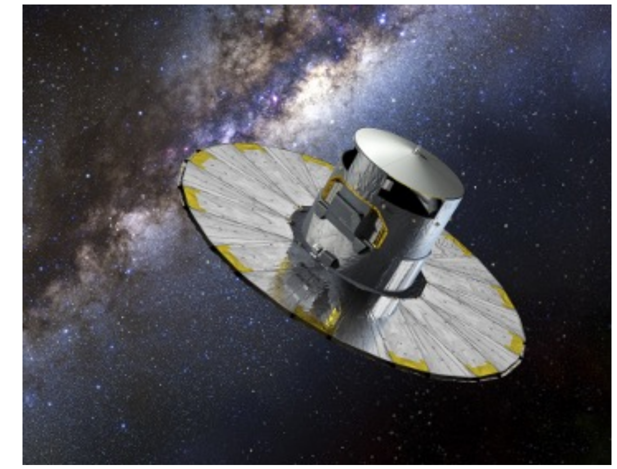
PROGRESS IN ASTROMETRIC ACCURACY

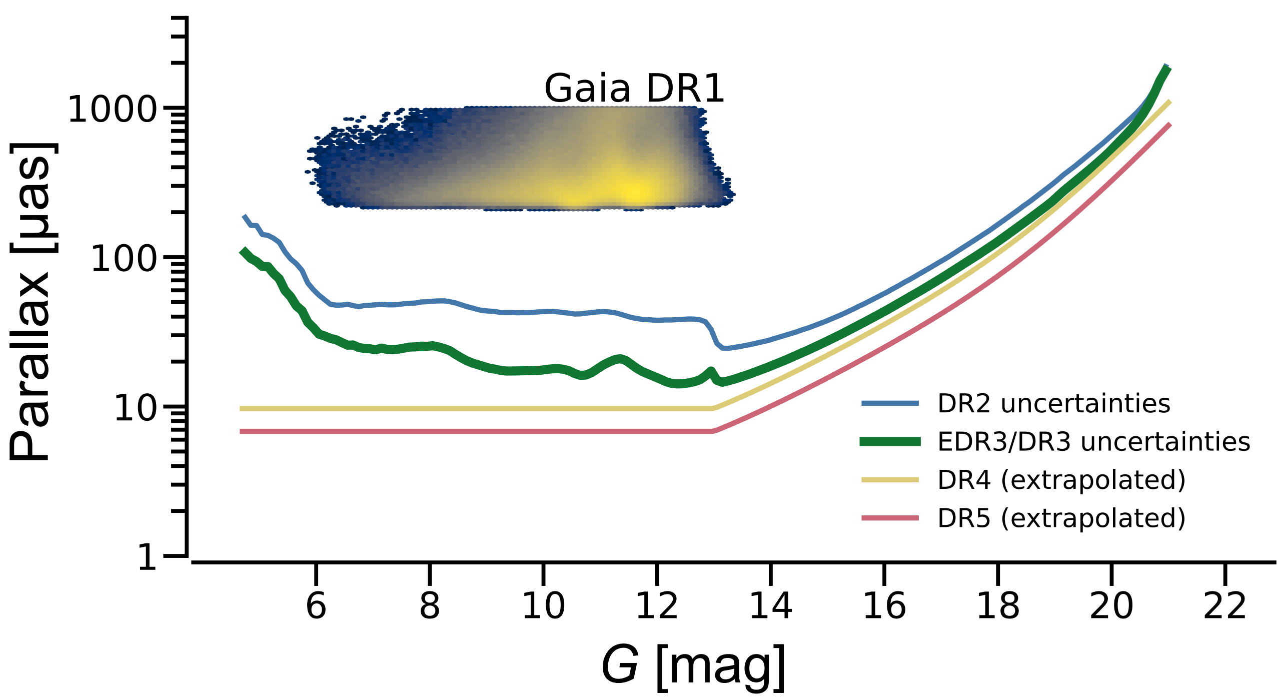


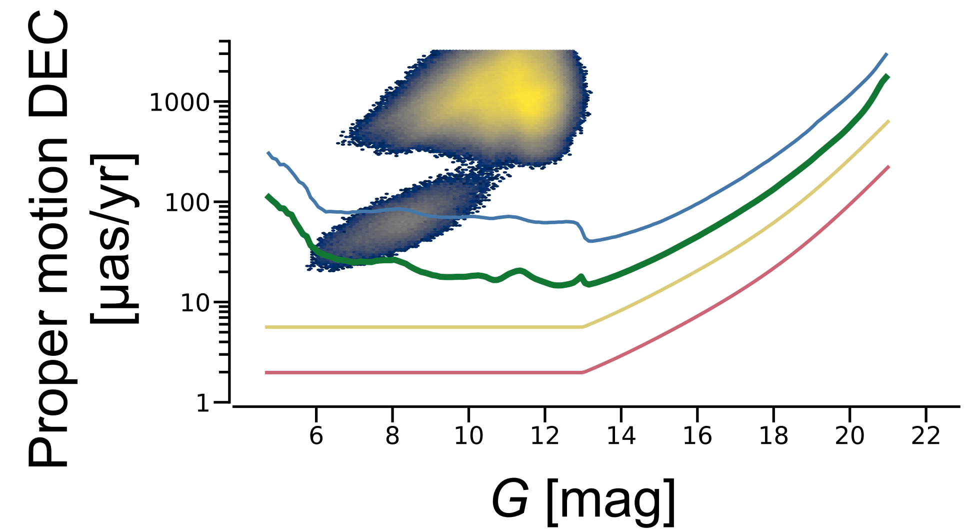
- **Relevance** for **stellar** astrophysics:
  - Accurate **stellar parameters**: parallaxes, distances, sizes, proper motions, spatial velocities, luminosities, **masses, ages**
  - Full **orbital characterization** of stellar binaries and planetary companions

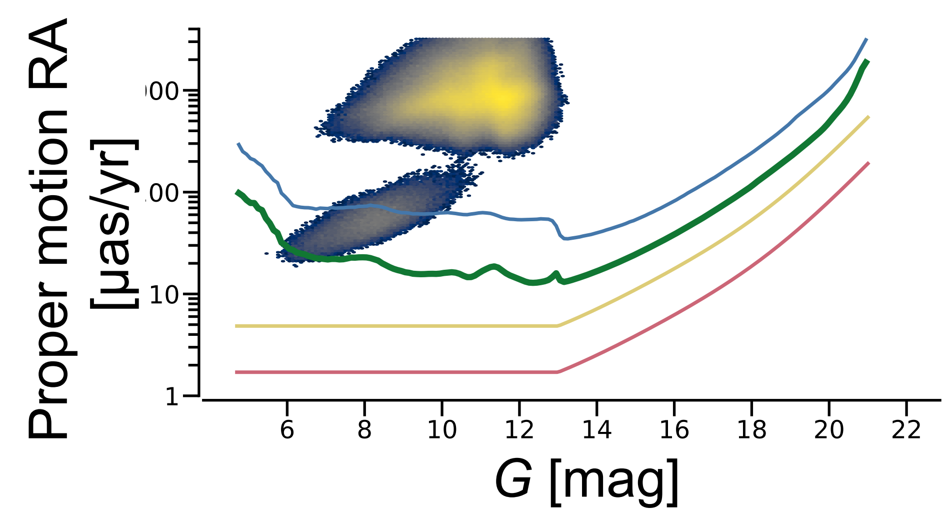
GAIA ASTROMETRY MISSION

- Powerful all-sky high-accuracy astrometric mission
- Parallax and proper motions of > 1000 million stars (~1% of the stars in the Galaxy)
- Limiting magnitude of G ≈ 21
- Mission duration of 5 years (extended to 10 years)



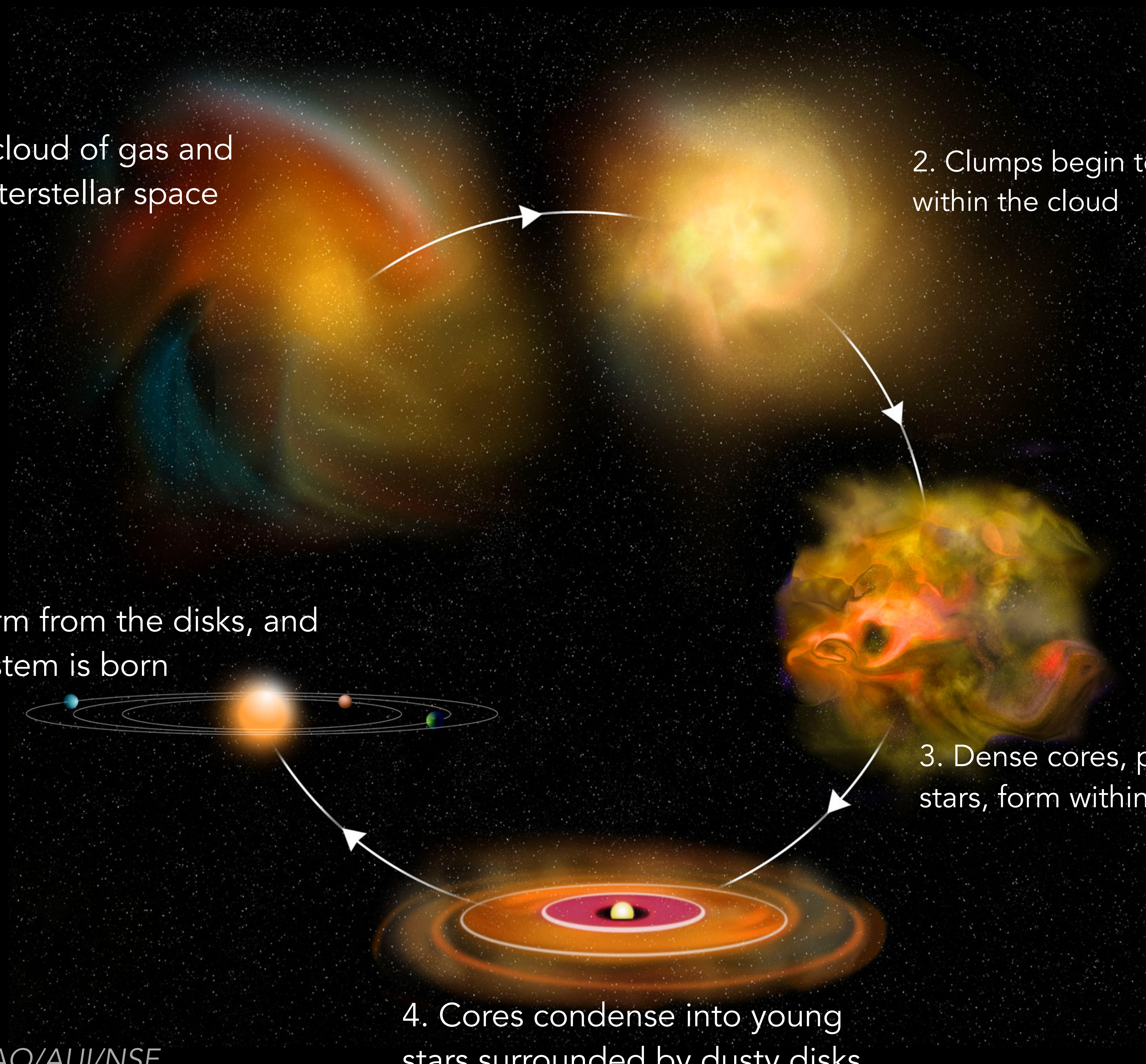






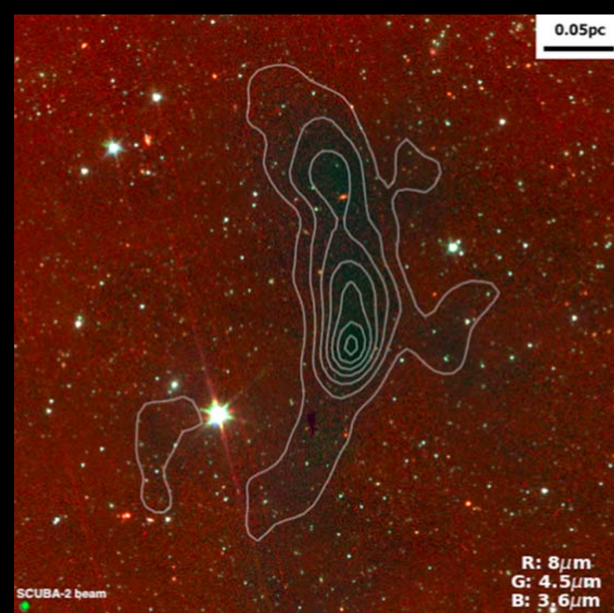
Gaia Collaboration et al. (2023, A&A…674A…1G)

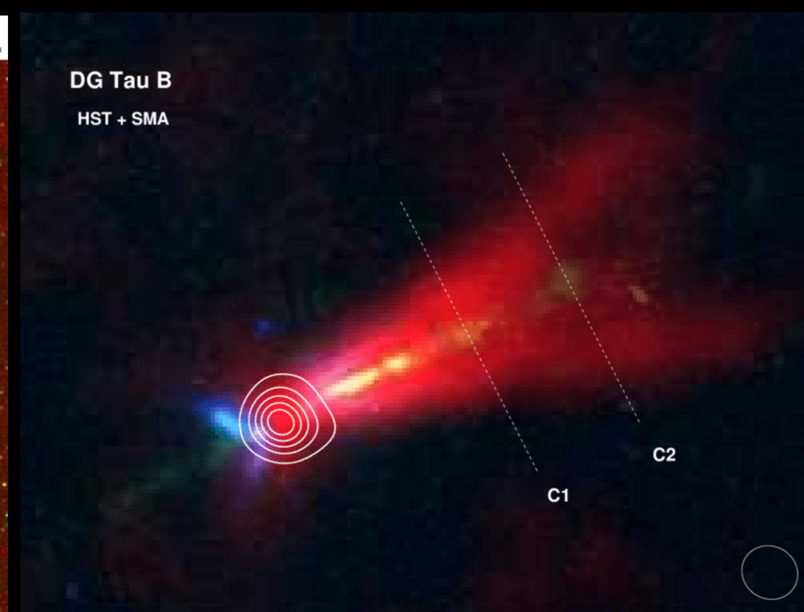
EARLY STAGES OF STELLAR EVOLUTION

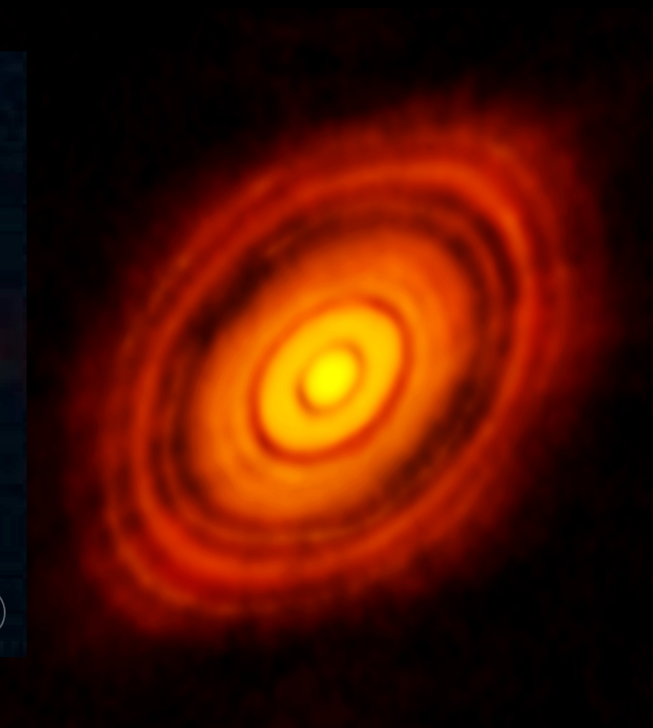


Credit: Bill Saxton/NRAO/AUI/NSF

EARLY STAGES OF STELLAR EVOLUTION



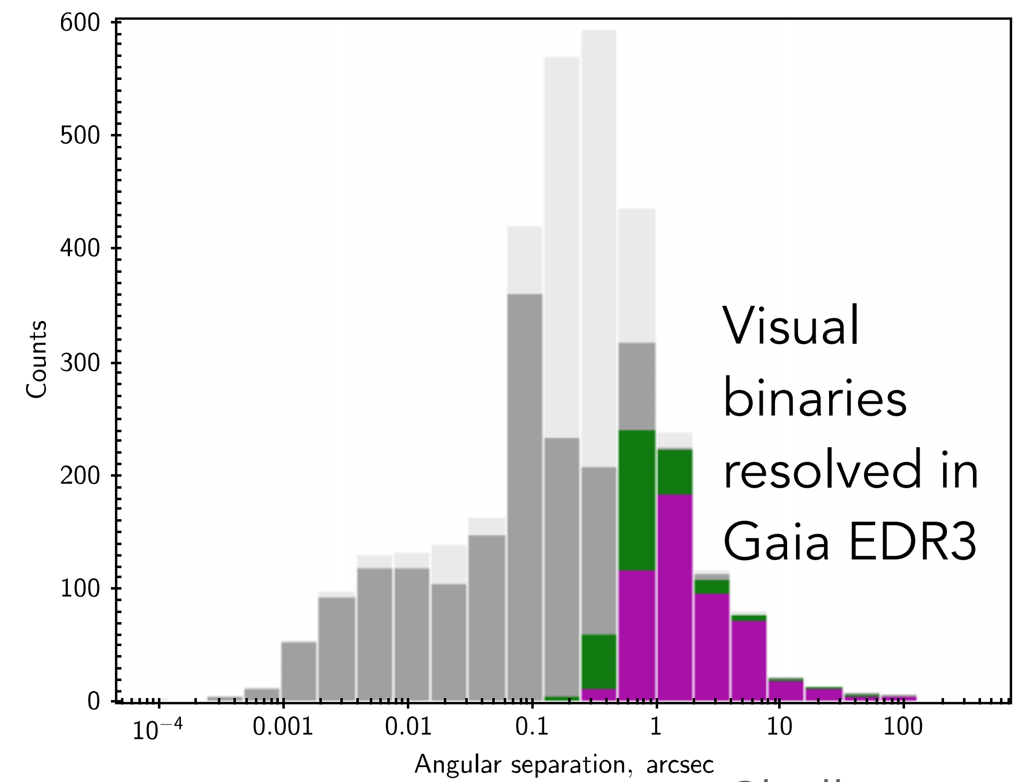




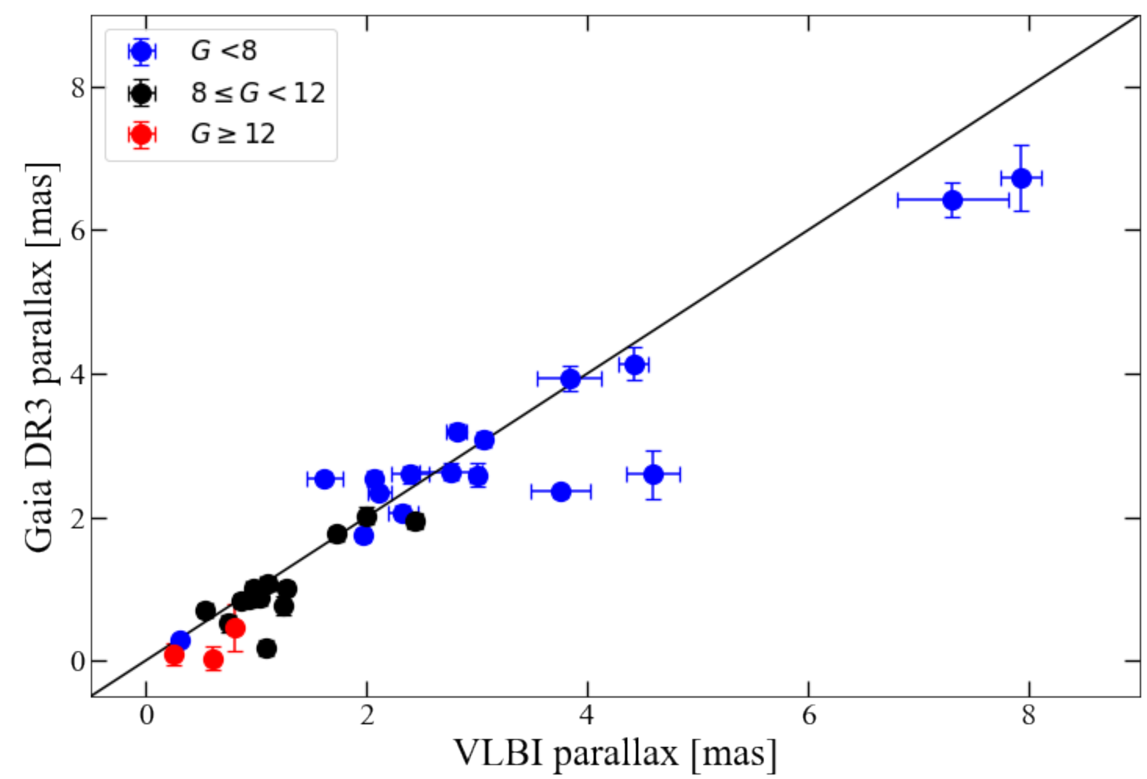
- Earliest stages of star formation are obscured by dust
- Hard to detect with Gaia

GAIA ISSUES IN STELLAR ASTROPHYSICS

- (young) binaries
  - Gaia angular resolution is 0.18″ cannot resolve compact binaries
- AGB stars
  - Uncertainties in Gaia astrometry introduced by dusty envelopes, large angular sizes, and surface brightness variability



Chulkov et al. (2022)



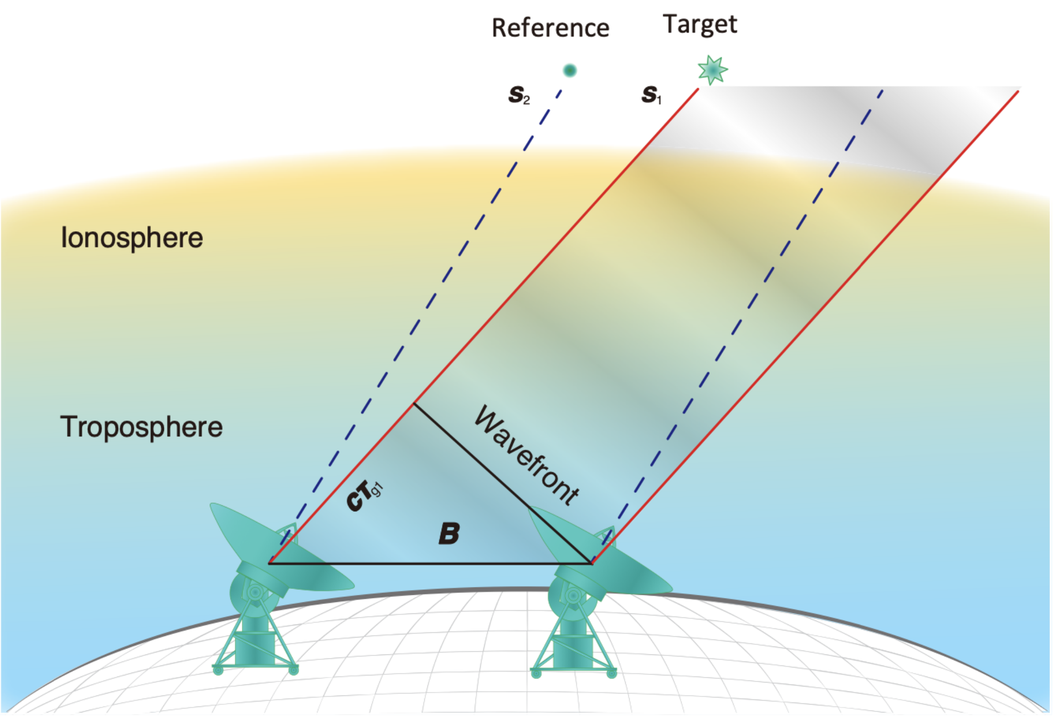
Andriantsaralaza et al. (2022)

RADIO ASTROMETRY

VERY LONG BASELINE INTERFEROMETRY (VLBI)

- Can see through dust
- Baselines of thousands of km
- Angular resolution ~ λ / B

  (1 milliarcsecond @ λ = 5 cm)
- Astrometry accurate to **~10 µas**
- Galactic-scale distances of up to 10 kpc
- Only non-thermal emission
  - Masers lines (e.g. CH_3OH, H_2O, OH, SiO)
  - Continuum stars (e.g. YSOs, M-dwarfs, ultracool dwarfs)



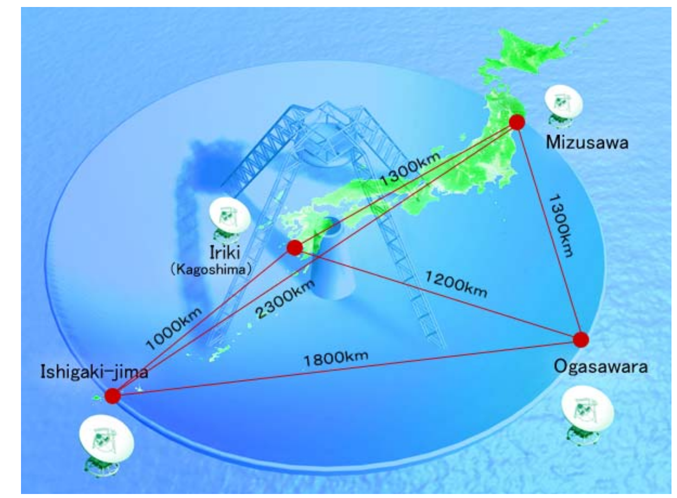
Reid & Honma (2014); see also Rioja & Dodson (2020)

RADIO ASTROMETRY

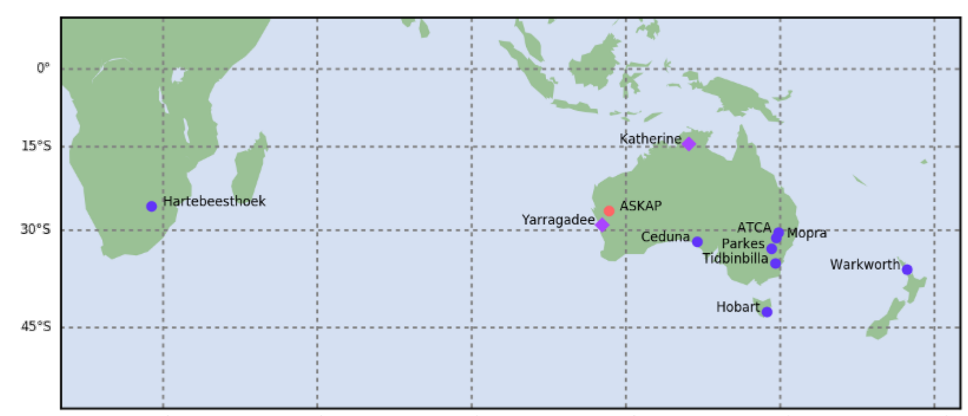
VLBI ARRAYS FOR ASTROMETRY

Very Long Baseline Array (VLBA), USA

European VLBI Network (EVN), Europe, Asia & South Africa



VLBI Exploration of Radio Astrometry (VERA), Japan



Long Baseline Array (LBA), Australia, New Zealand & South Africa

I. 6D STRUCTURE OF MOLECULAR CLOUDS

THE GOULD'S BELT DISTANCES SURVEY (GOBELINS)

Loinard (PI), Ortiz-León, Kounkel, Galli, Dzib, et al.

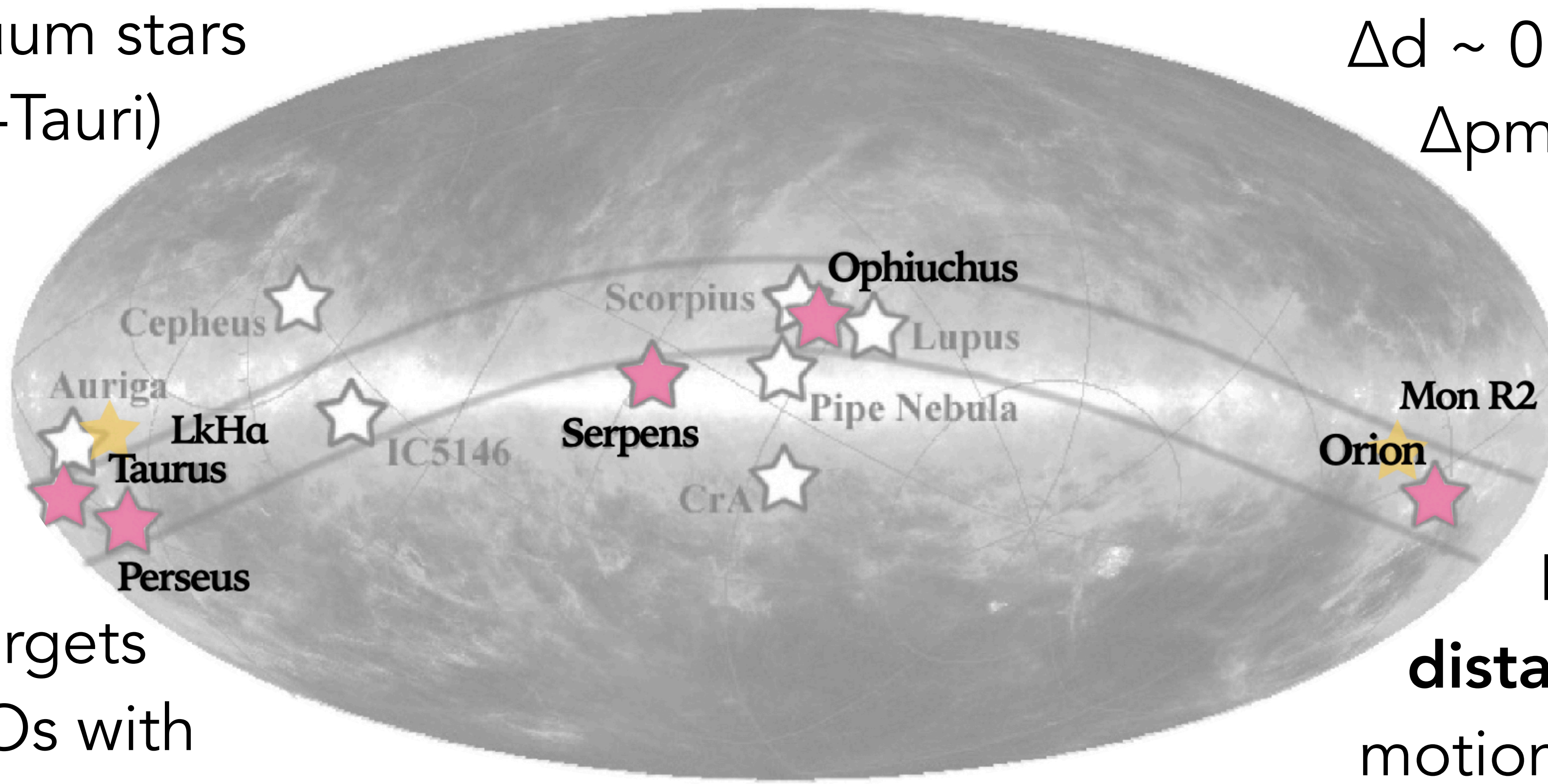
Radio astrometric survey of (embedded) young stellar objects (YSOs)

Continuum stars (Class II, T-Tauri)

$\Delta d \sim 0.3 - 10$ %

$\Delta pm < 0.2$ mas/yr

~ 0.1 km/s



Adapted from Ward-Thompson et al. (2007)

~270 targets

~100 YSOs with accurate astrometry

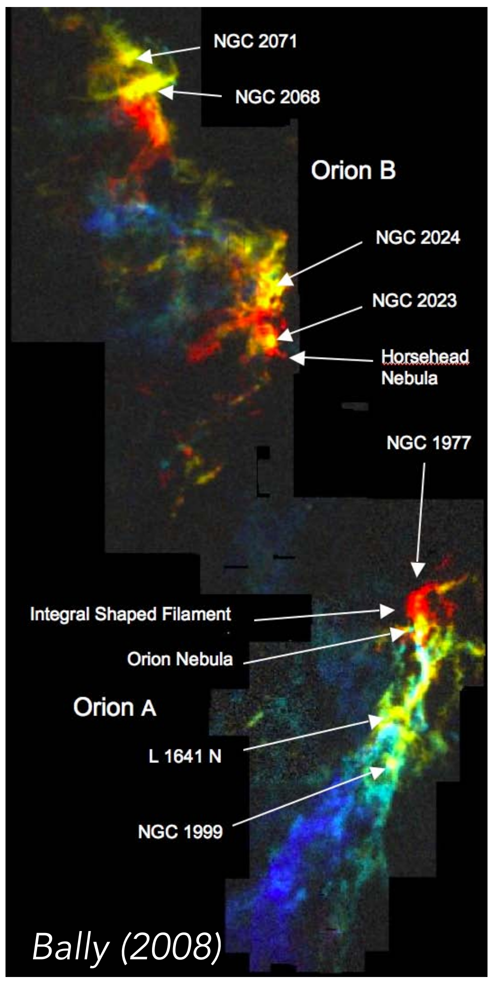
Parallaxes, **distances**, proper motions, spatial velocities, binary masses

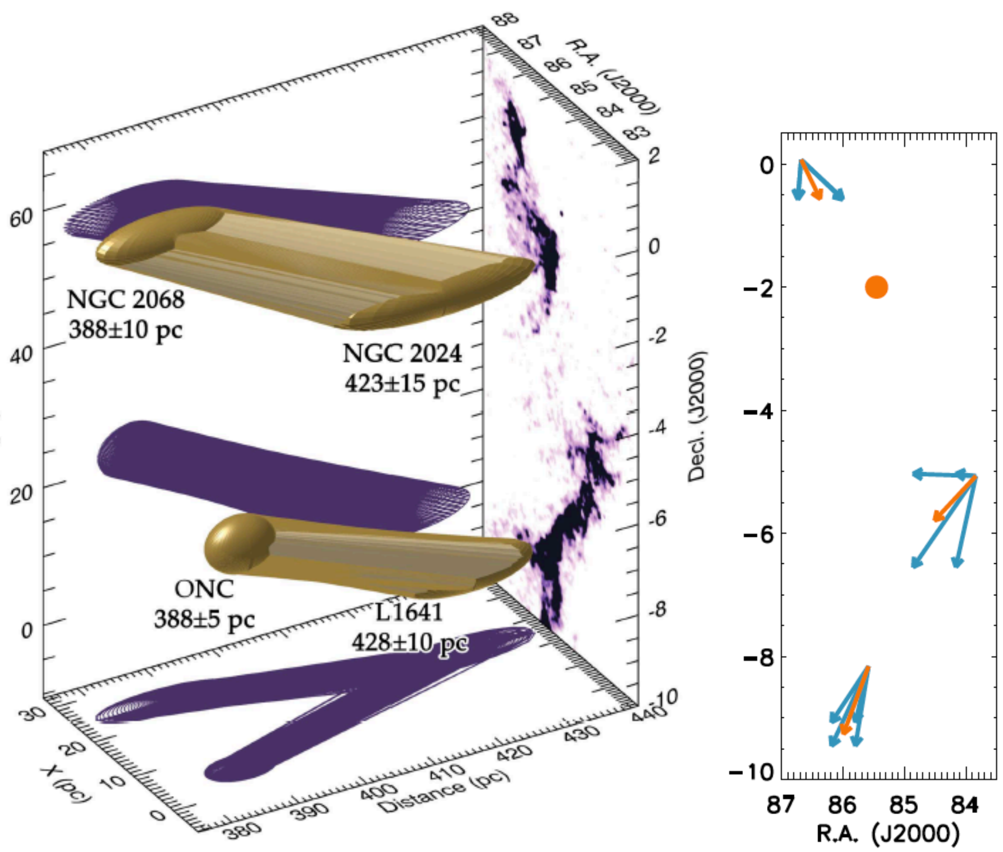
Loinard et al. (2007); Torres et al. (2007, 2009, 2012); Dzib et al. (2010, 2016, 2018); Ortiz-León et al. (2017a,b, 2018a,b); Kounkel et al. (2017); Galli et al. (2018)

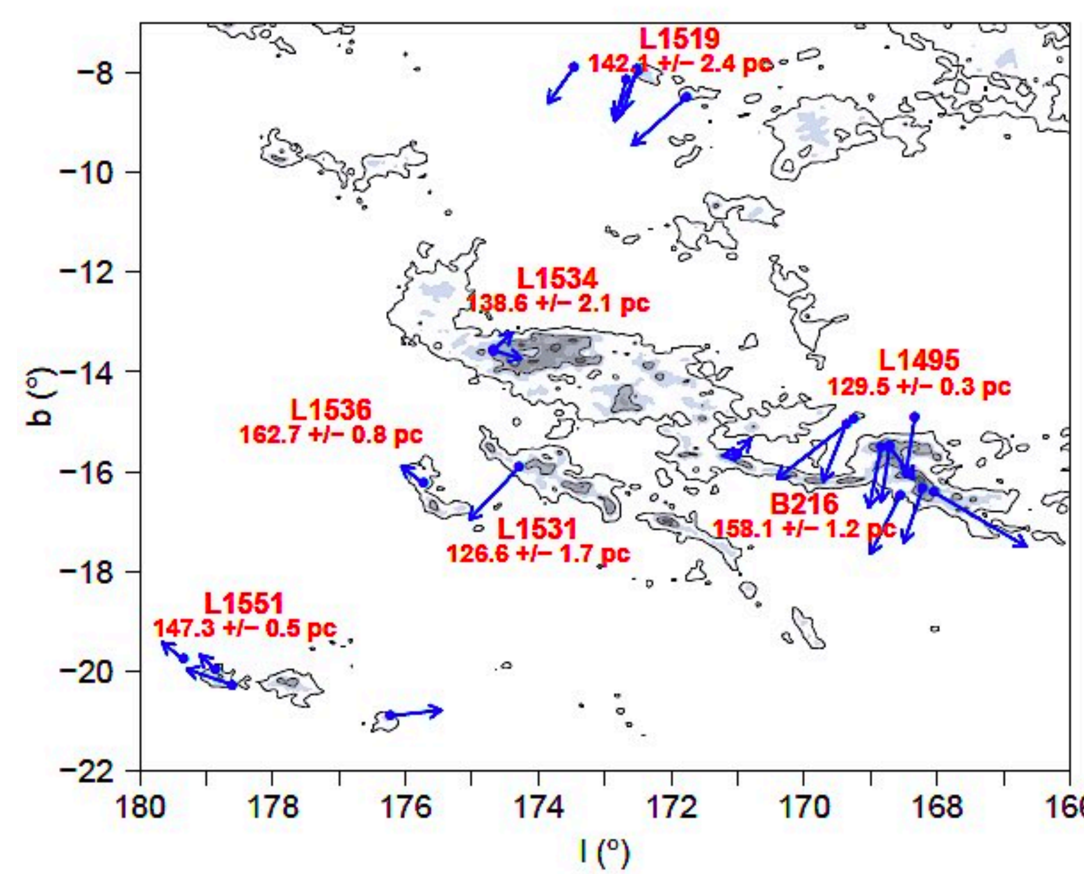
I. 6D STRUCTURE OF MOLECULAR CLOUDS

Orion *(Kounkel et al. 2017)*

Taurus *(Galli et al. 2018)*







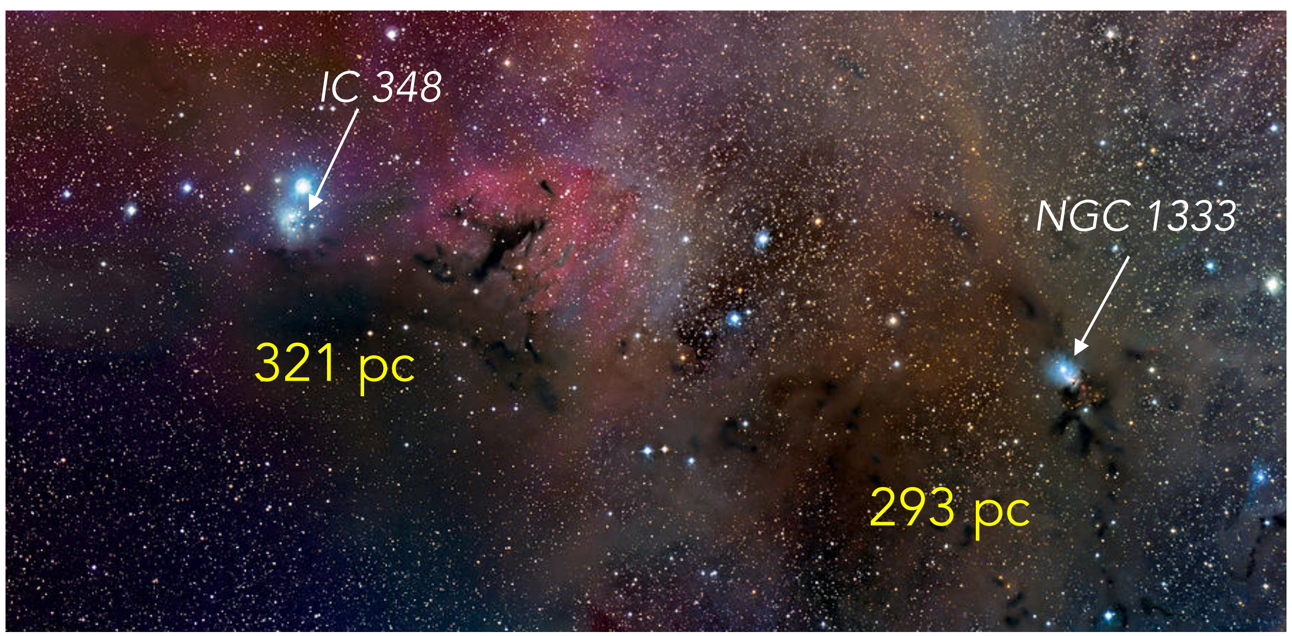
- Presence of multiple components
- **Orion** structure: distance difference of ~40 pc (see also *Großschedl et al. 2018*)
- **Taurus** structure revealed with **Radio + Gaia DR1** astrometry: distance to individual clouds ranges from 127 to 163 pc

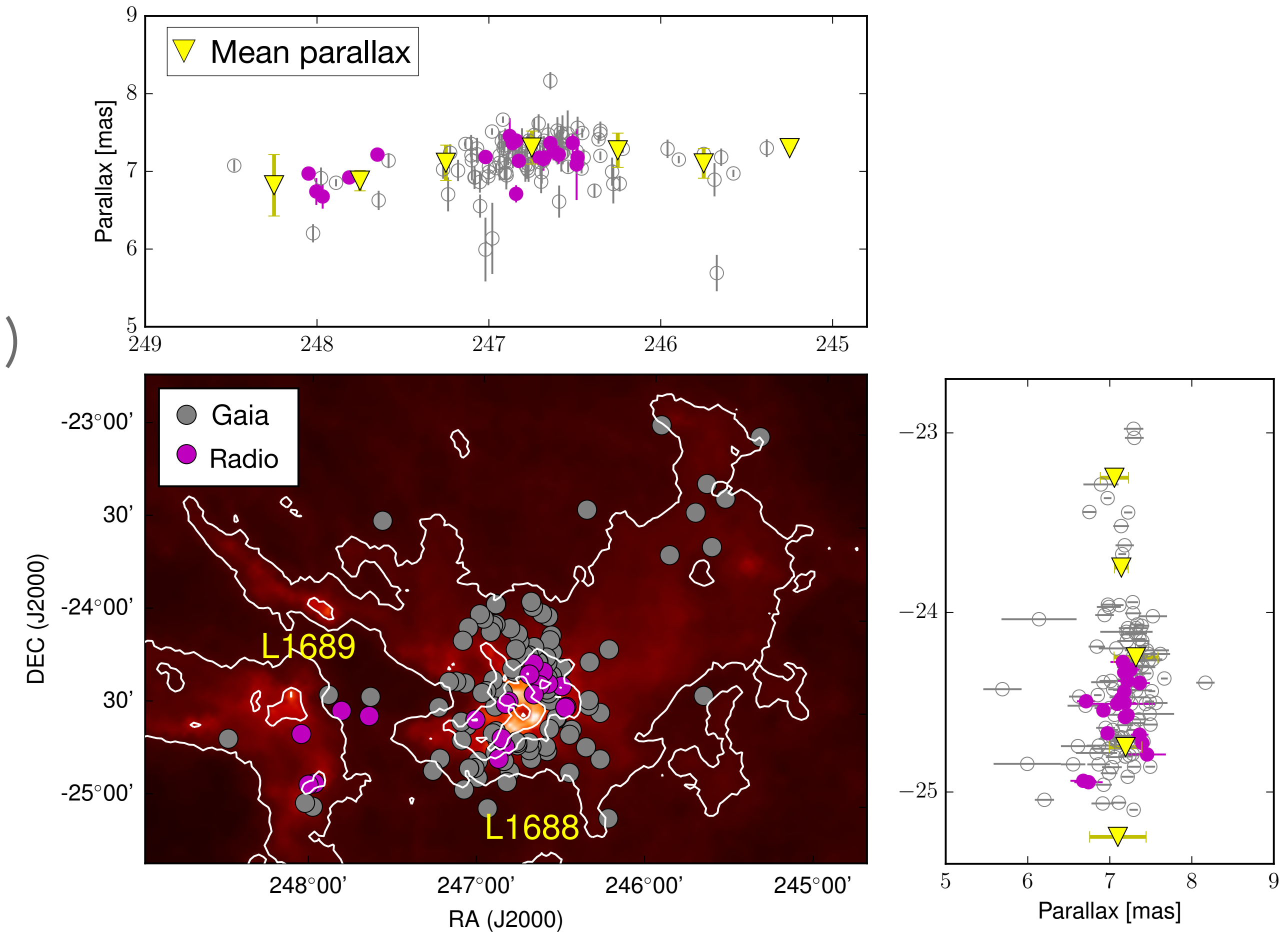
I. 6D STRUCTURE OF MOLECULAR CLOUDS

Perseus (*Ortiz-León et al. 2018a*)

Radio + Gaia DR2

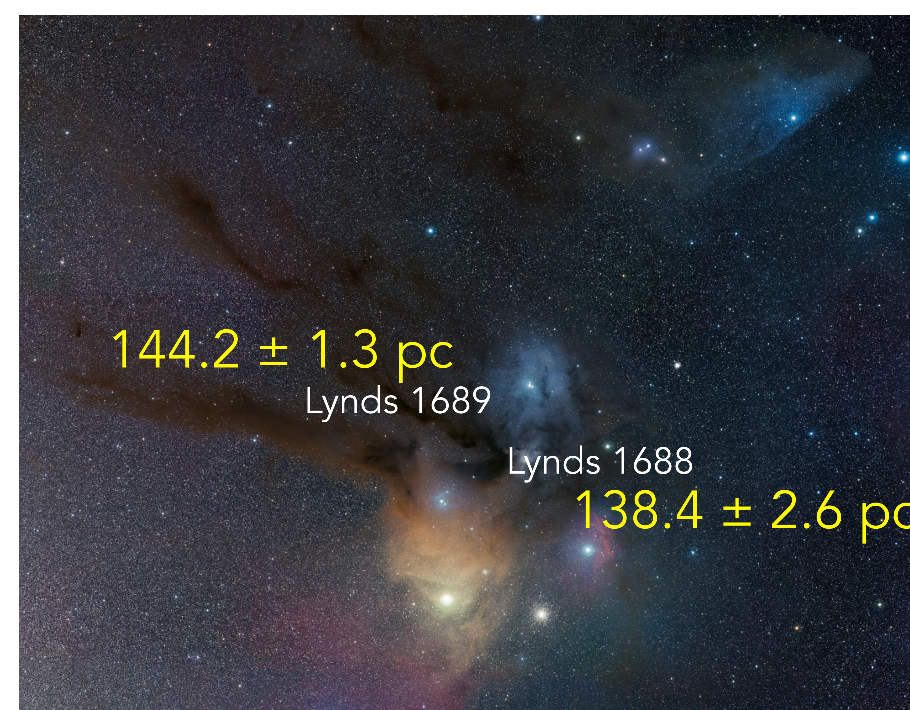
Prominent distance gradient of ~30 pc from east to west (see also *Pezzuto et al. 2021*)





Ophiuchus (*Ortiz-León et al. 2018b*)

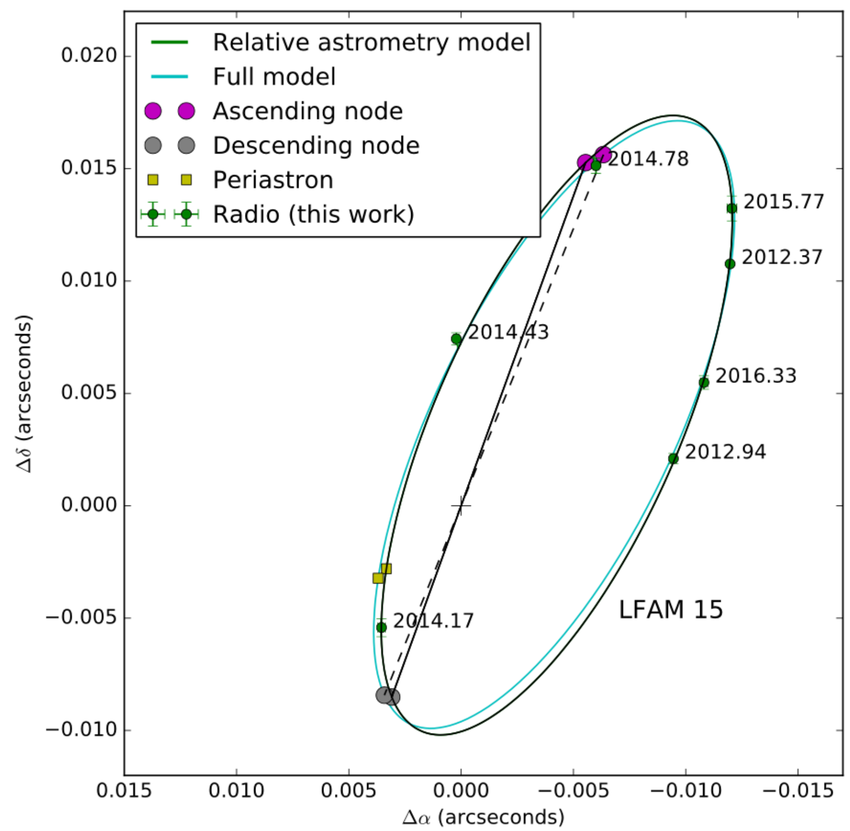
Small distance gradient across the cloud (see also *Zucker et al. 2021*)

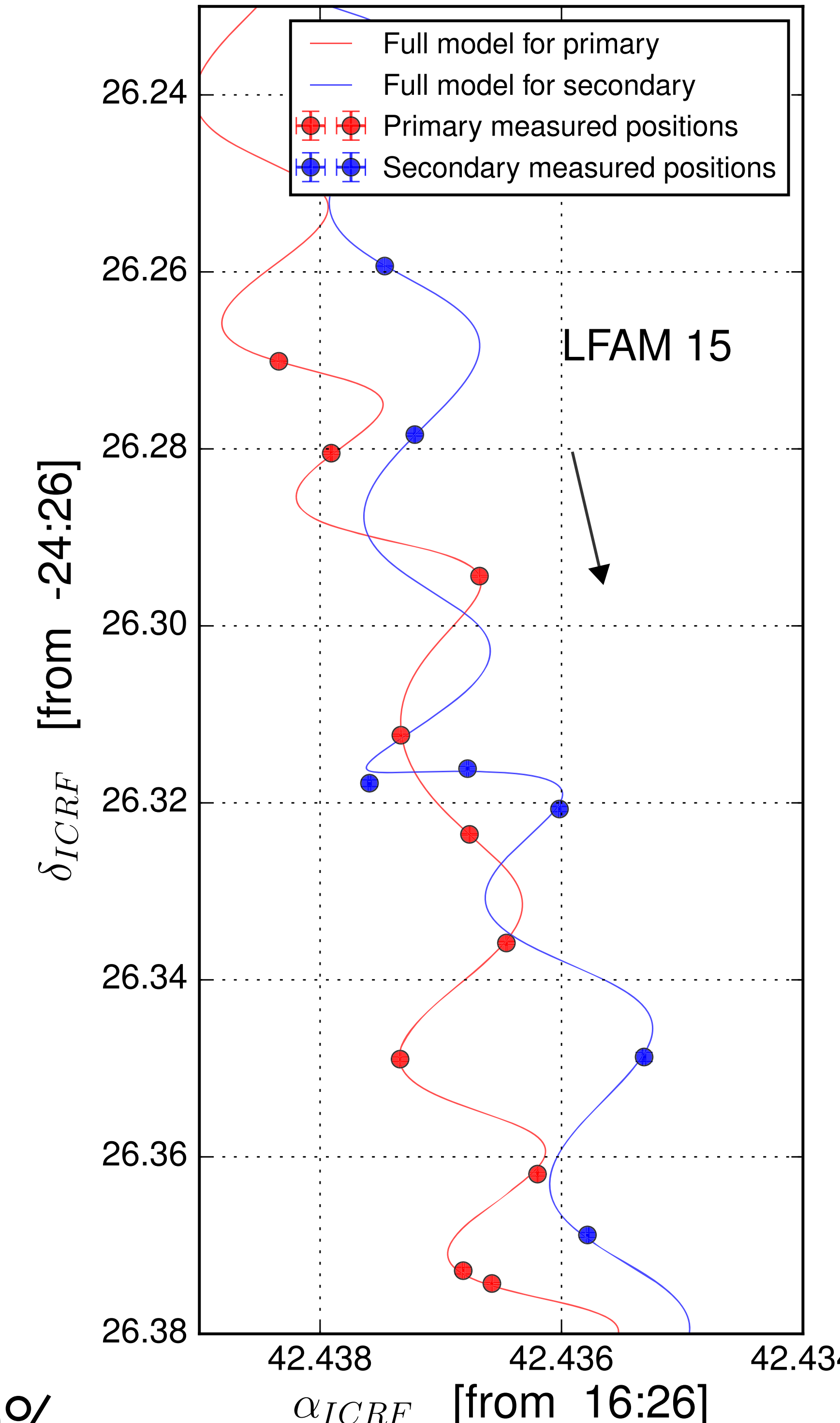


II. BINARY MASSES

COMPACT BINARIES

1 au = 0.007″ at 138 pc





Ortiz-León et al. (2017)

Young compact binaries resolved with VLBI

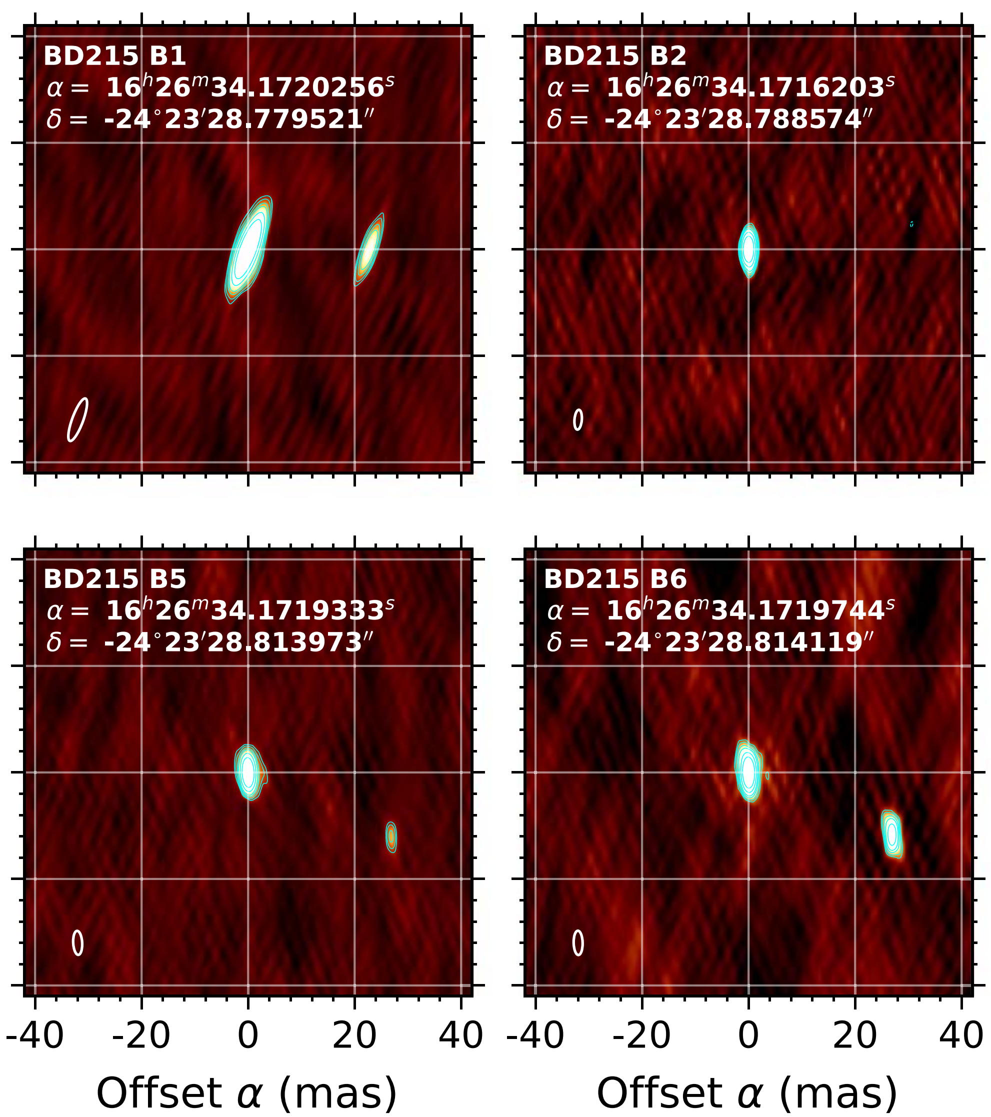
- Astrometric parameters + orbital parameters + **individual masses**
- Accurate component masses (~5%)
- Fraction of binaries in radio-detected YSOs ~ 40%

II. BINARY MASSES

DYNAMICAL MASSES OF YOUNG STELLAR MULTIPLE SYSTEMS WITH THE VLBA

Dzib (PI), Ordoñez-Toro, Ortiz-León, Loinard, Kounkel, et al.

- Young protostellar systems only detectable in the radio
- About 20 systems already observed with the VLBA



Oph-S1

- Young binary in Ophiuchus at 137 pc
- B3 to B5 spectral type
- 35 VLBA observations used to model the astrometry and binary orbit

Ordoñez-Toro et al. (2024)

II. BINARY MASSES

$P = 1.734 \pm 0.001$ yr

$e = 0.65 \pm 0.01$

$i = 25.4 \pm 1.9$ deg

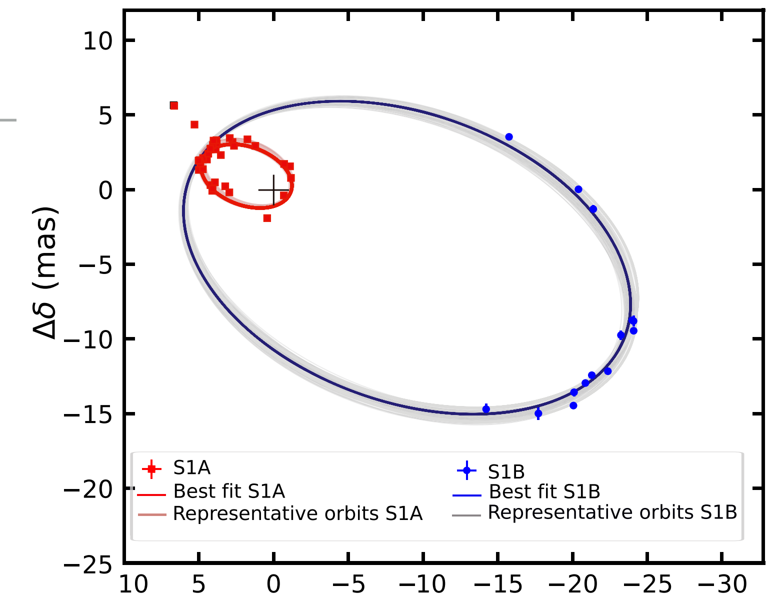
$a_A = 0.418 \pm 0.002$ au

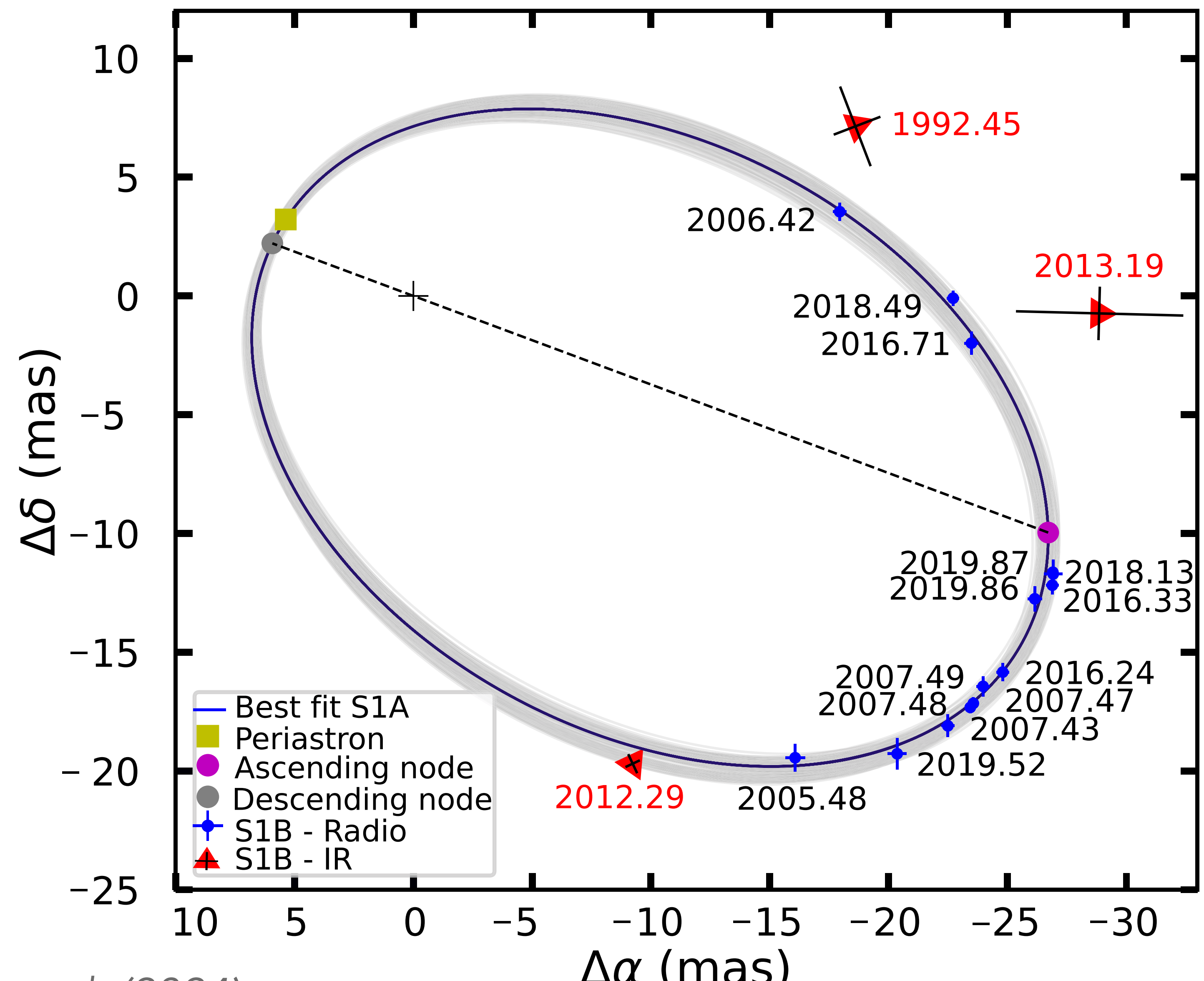
$a_B = 2.043 \pm 0.018$ au

$a = 0.018''$

$\mathbf{M_A = 4.11 \pm 0.1\ M_\odot}$

$\mathbf{M_B = 0.831 \pm 0.014\ M_\odot}$





Ordoñez-Toro et al. (2024)

II. BINARY MASSES

P = 1.734 ± 0.001 yr

e = 0.65 ± 0.01

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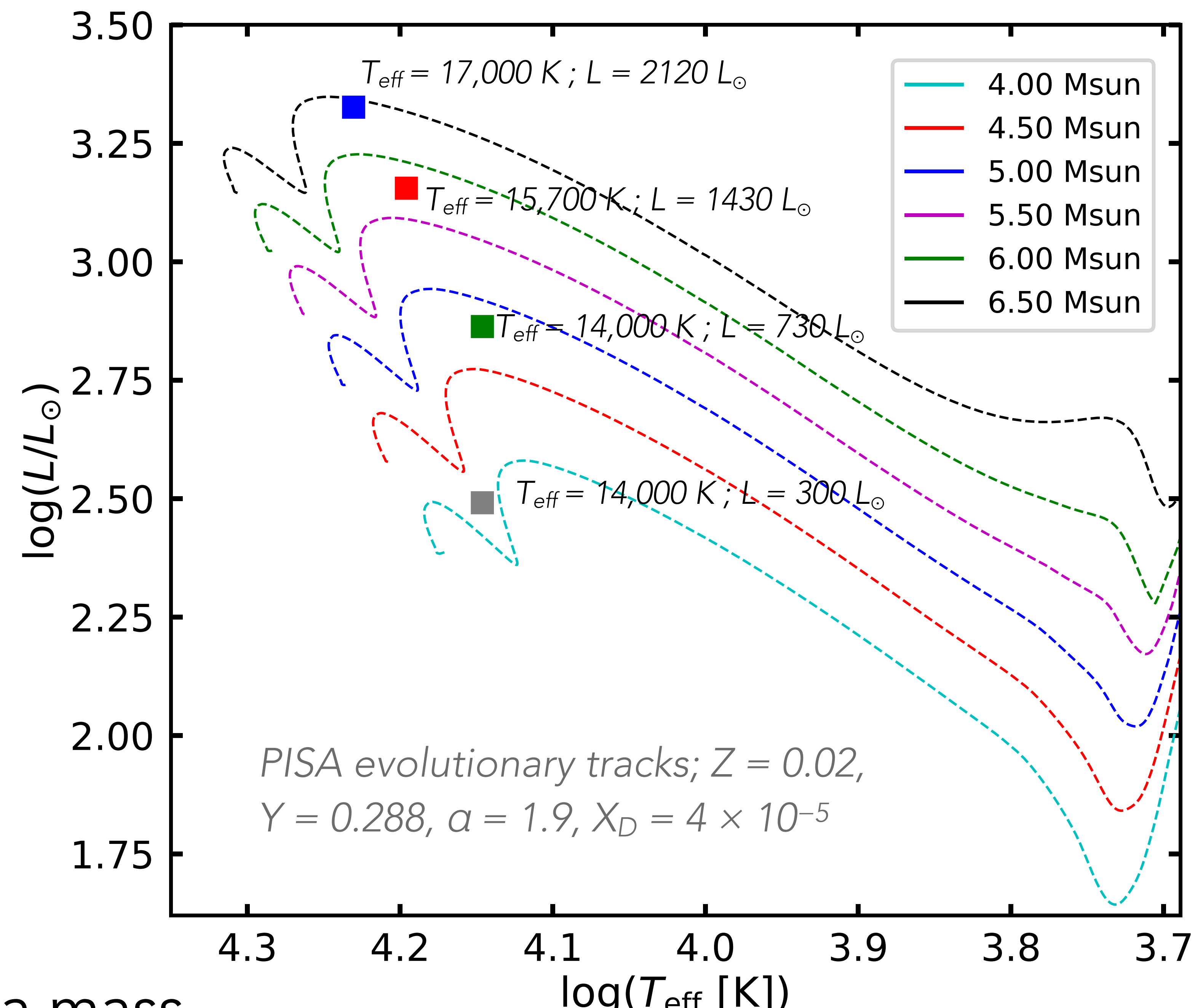
a_A = 0.418 ± 0.002 au

a_B = 2.043 ± 0.018 au

a = 0.018″

M_A = 4.11 ± 0.1 $M_\odot$

M_B = 0.831 ± 0.014 $M_\odot$



Theoretical models predict a mass of 5 to 6 $M_\odot$ (i.e. 25% higher)

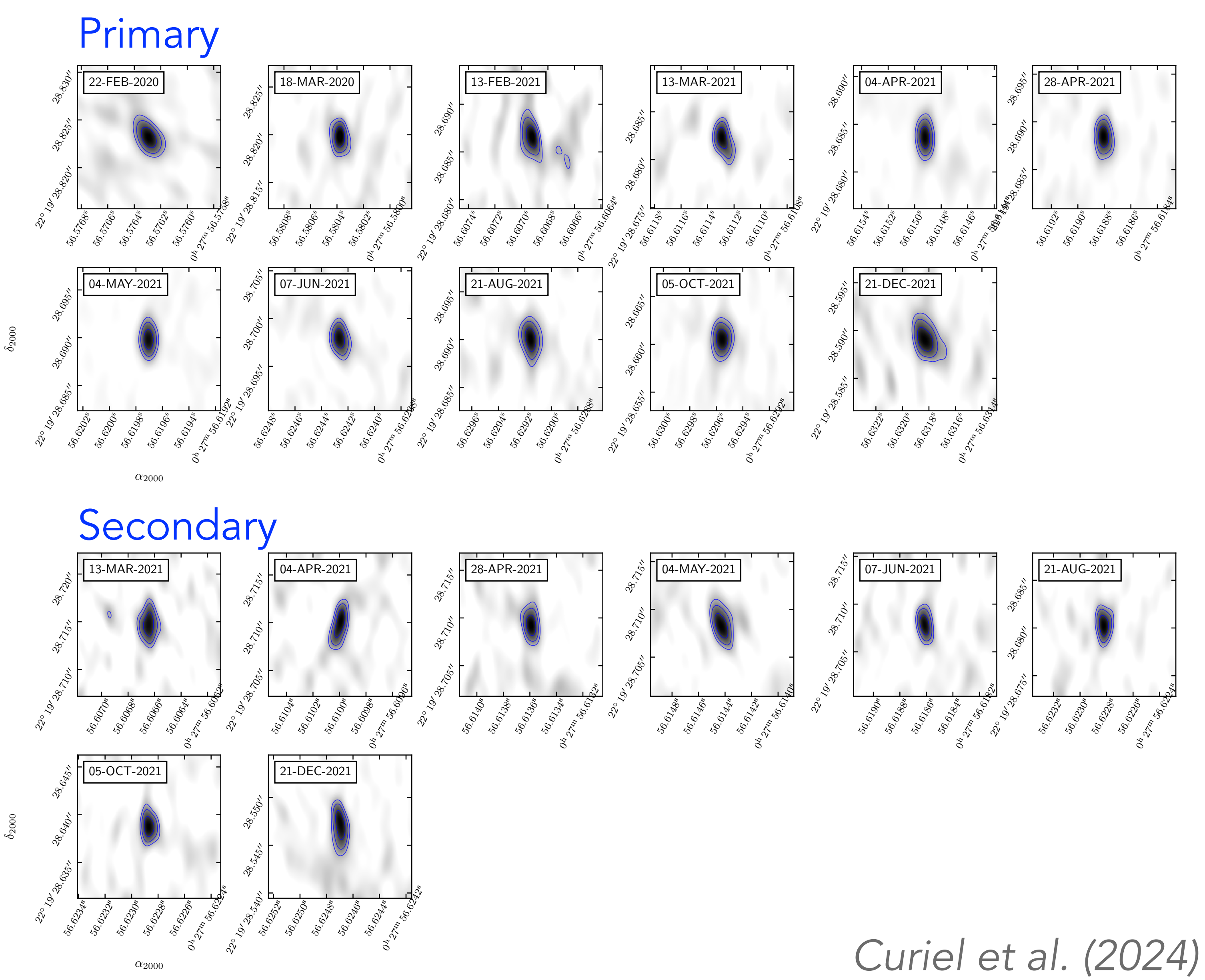
Ordoñez-Toro et al. (2024)

See also poster by Jazmin Ordoñez-Toro

II. BINARY MASSES

PRECISE ORBITAL MOTIONS OF M-DWARF BINARIES

Curiel, Ortiz-León, Mioduszewski, et al.



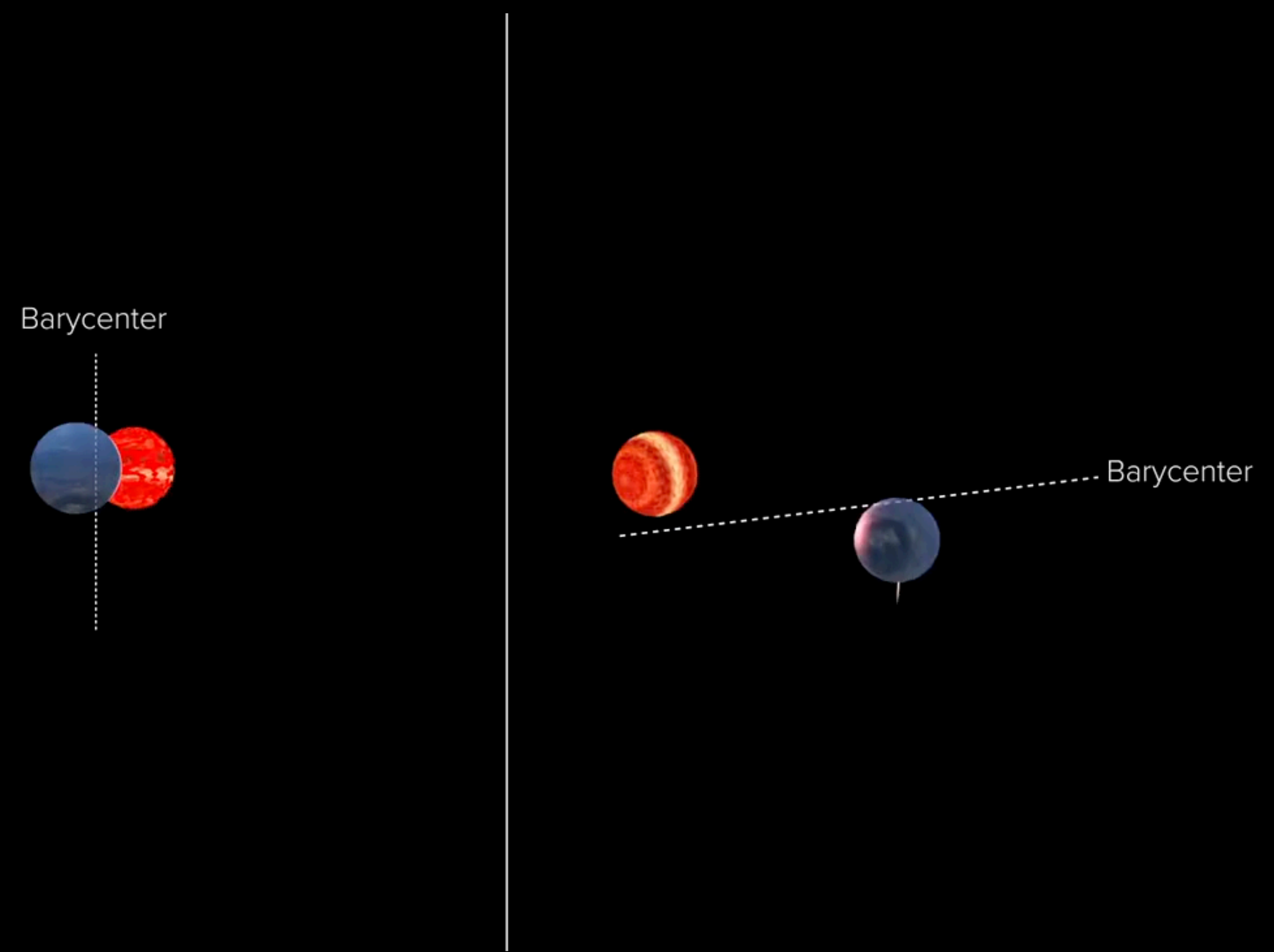
- M8 + M9
- *D* = 14.12 pc
- 11 VLBA observations
- 20 relative IR/optical positions
- 4 radial velocity observations

Curiel et al. (2024)

III. ASTROMETRIC PLANET SEARCHES

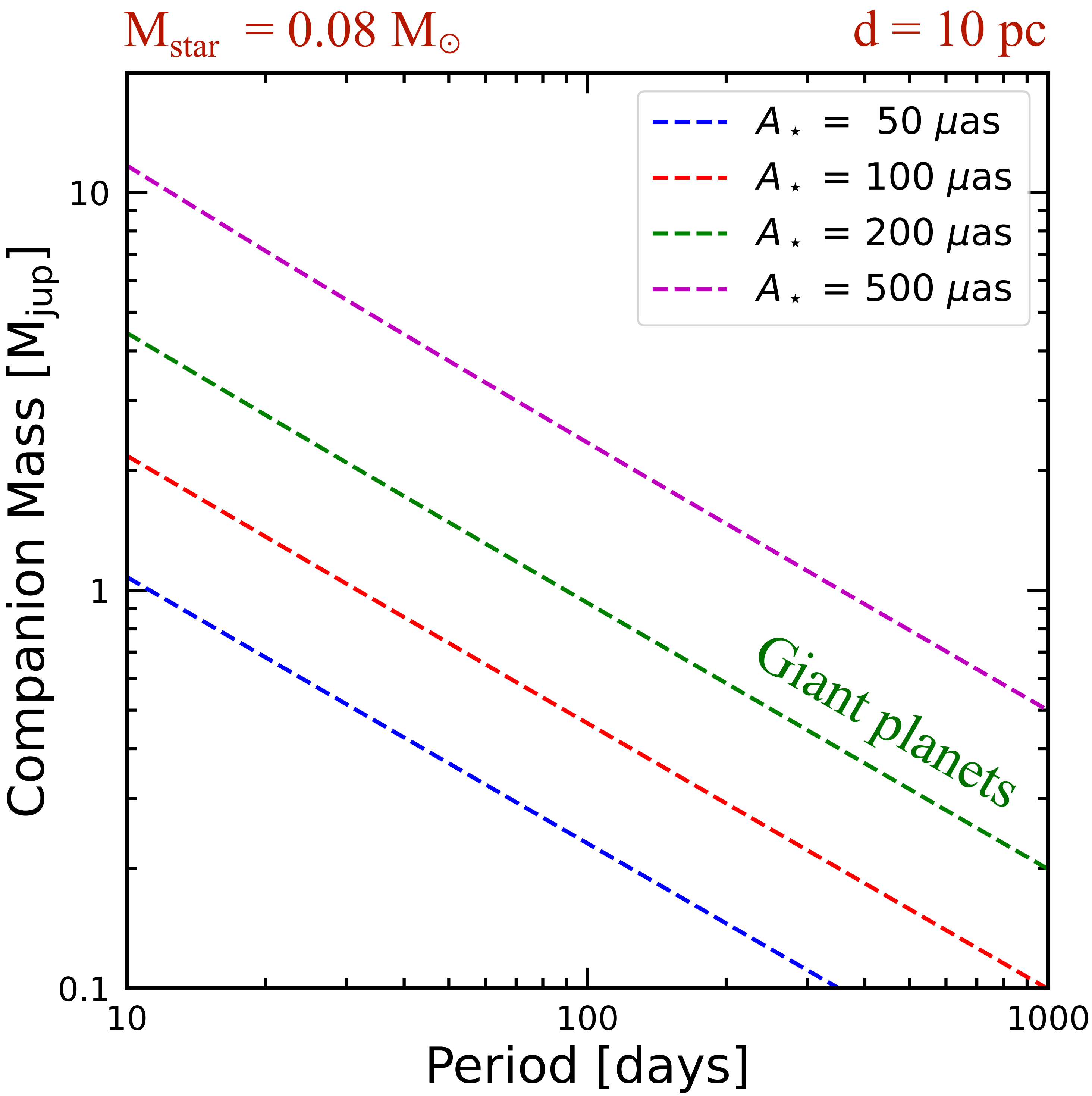
Indirect exoplanet detection by measuring the astrometric signature

$$A_\star = \frac{m_c}{M_\star} a_c$$



Credit: Bill Saxton, NRAO/AUI/NSF

III. ASTROMETRIC PLANET SEARCHES

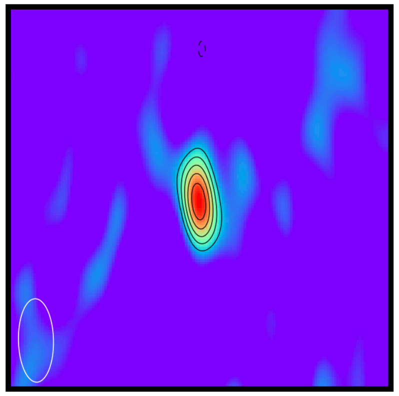


Required astrometric precision easily achieved with VLBI and Gaia

Radio emission from M dwarfs and young stars suitable for VLBI astrometry

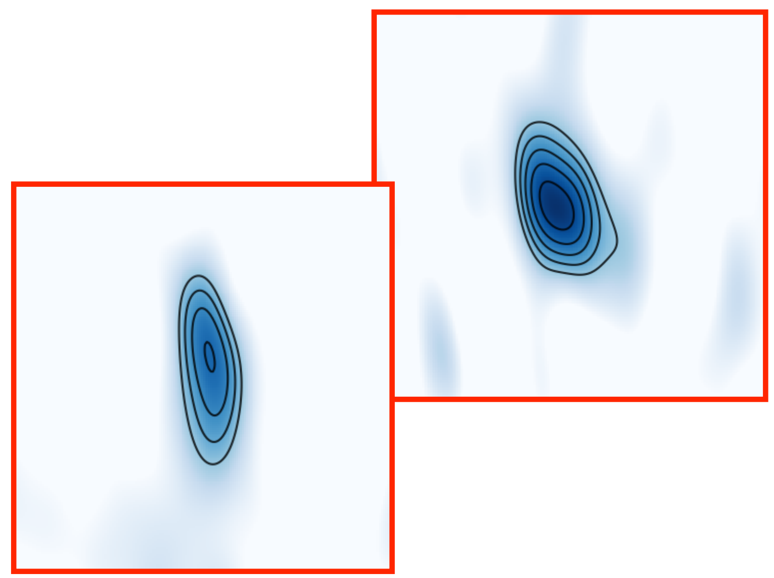
III. ASTROMETRIC PLANET SEARCHES

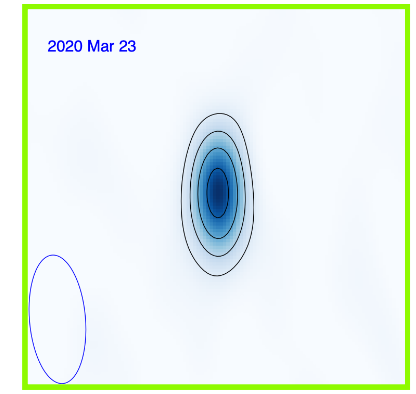
Curiel, Ortiz-León, Mioduszewski, Sánchez-Bermudez, et al.



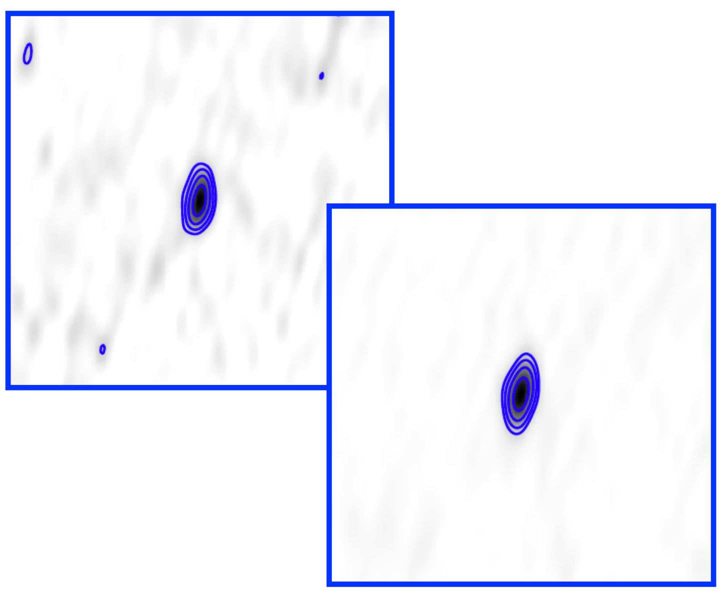
TVLM 513-46546
Ultracool dwarf (M9)
M ≈ 0.06-0.08 $M_{\odot}$
D =10 pc
Curiel et al. (2020)

M dwarf binary
(M7+M8)
Mtot ≈ 166 M_{Jup}
D =10 pc
Curiel et al. (2024)



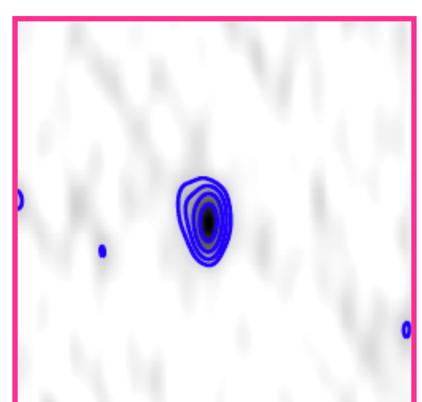


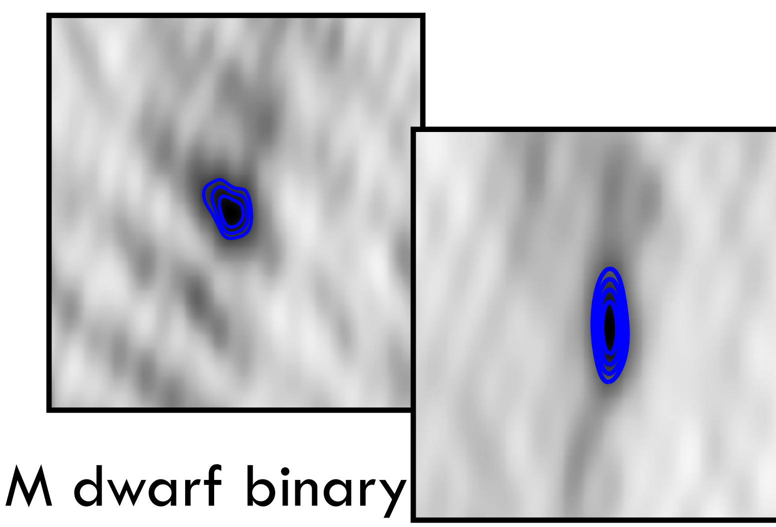
Brown dwarf
(L3.5)
M ≈ 66 M_{Jup}
D = 9 pc



GJ896 AB
M dwarf binary
(M3.5 +M4.5)
Mtot ≈ 0.6 $M_{\odot}$
D = 6.25 pc
Curiel et al. (2022)

M dwarf (M4)
M ≈ 0.23 $M_{\odot}$
D = 6 pc





M dwarf binary
(M5.5+M6)
Mtot ≈ 0.27 $M_{\odot}$
D = 2.7 pc
Ortiz-León et al. (in prep.)

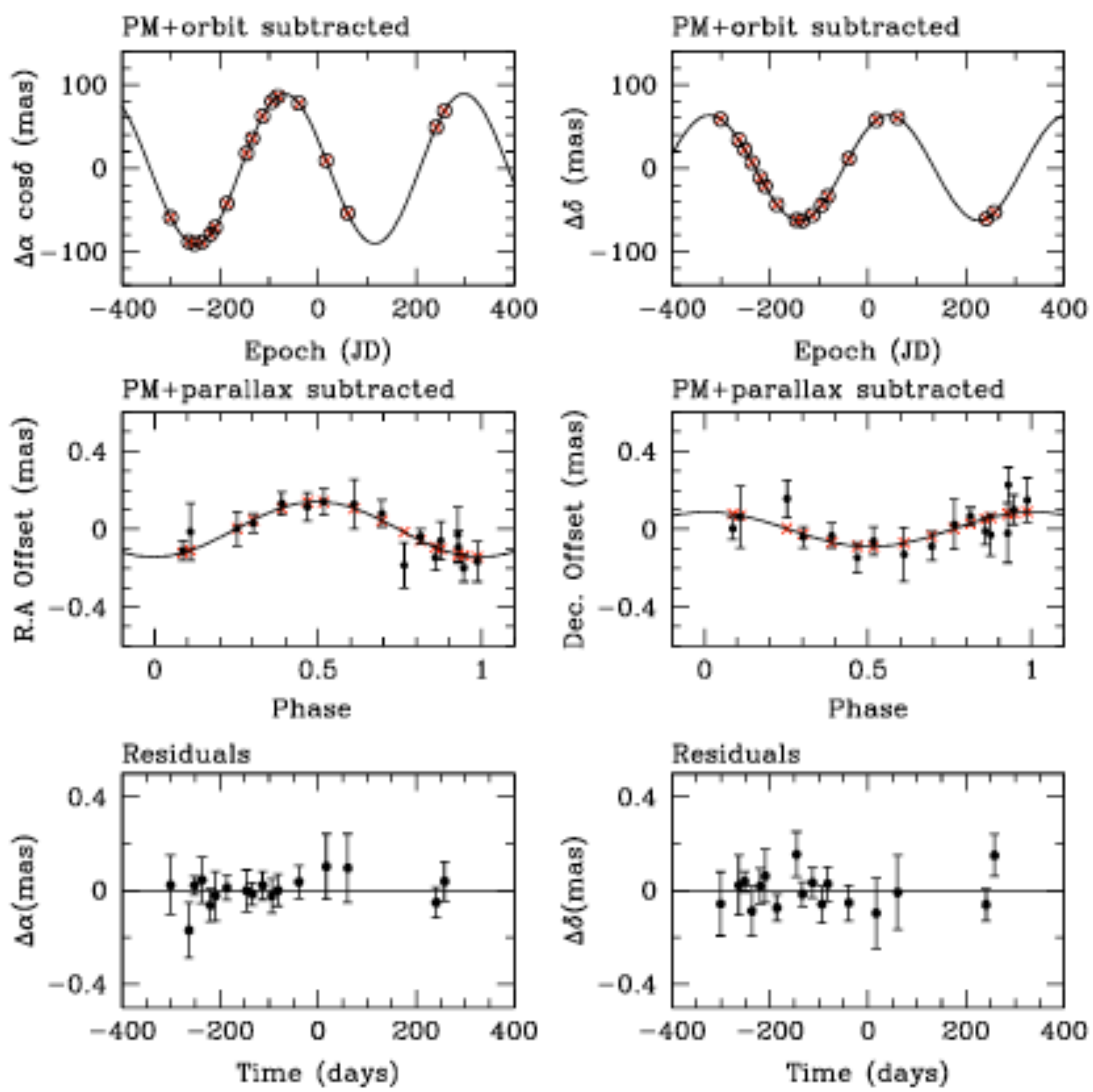
III. ASTROMETRIC PLANET SEARCHES

TVLM 513-46546

M9 ultracool dwarf

$M \approx 0.06 - 0.08\ M_{\odot}$

D =10 pc



Curiel et al. (2020)

$P \quad = 221 \pm 5$ days

$e \quad = 0$ (fixed)

$i \quad = 80 \pm 9^{\circ}$

$\Omega \quad = 130 \pm 8^{\circ}$

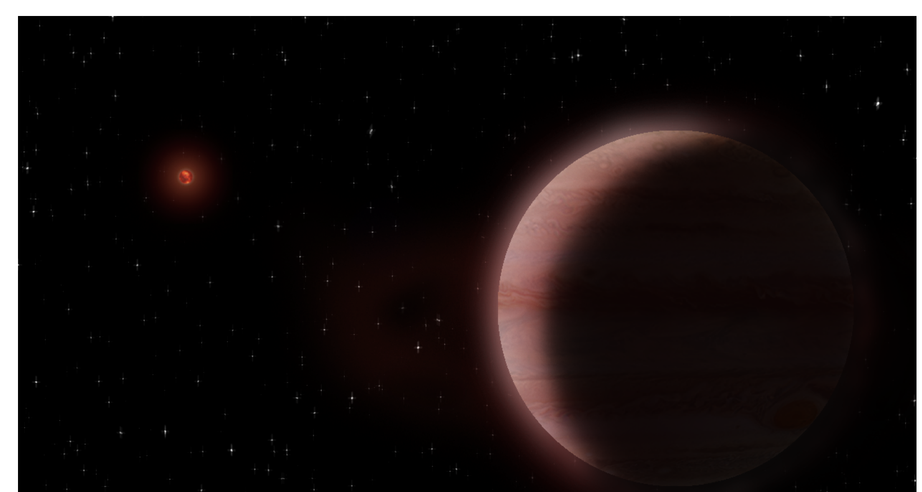
$a_{star} = 0.0016 \pm 0.0002$ au

$\quad\;\, =$ **145 ± 20 μas**

$a_{planet} = (0.28\text{-}0.31) \pm 0.004$ au

$\quad\quad\;\; = (28 - 29)$ mas

$m_{planet} = (0.35 - 0.42) \pm 0.04\ M_{Jup}$



III. ASTROMETRIC PLANET SEARCHES

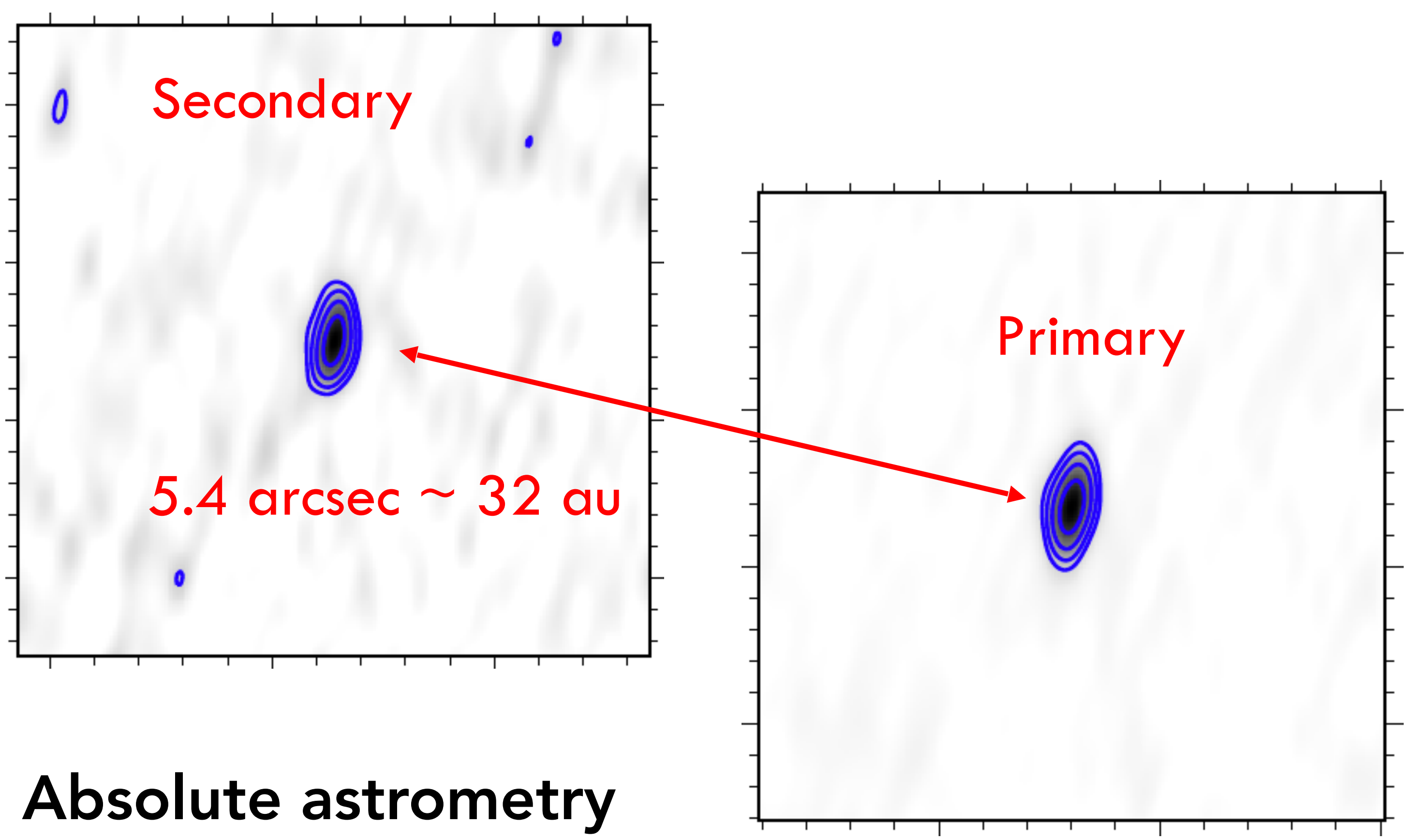
GJ 896AB

M3.5 + M4.5

m_A = 0.436 M_{Sun}

m_B = 0.165 M_{Sun}

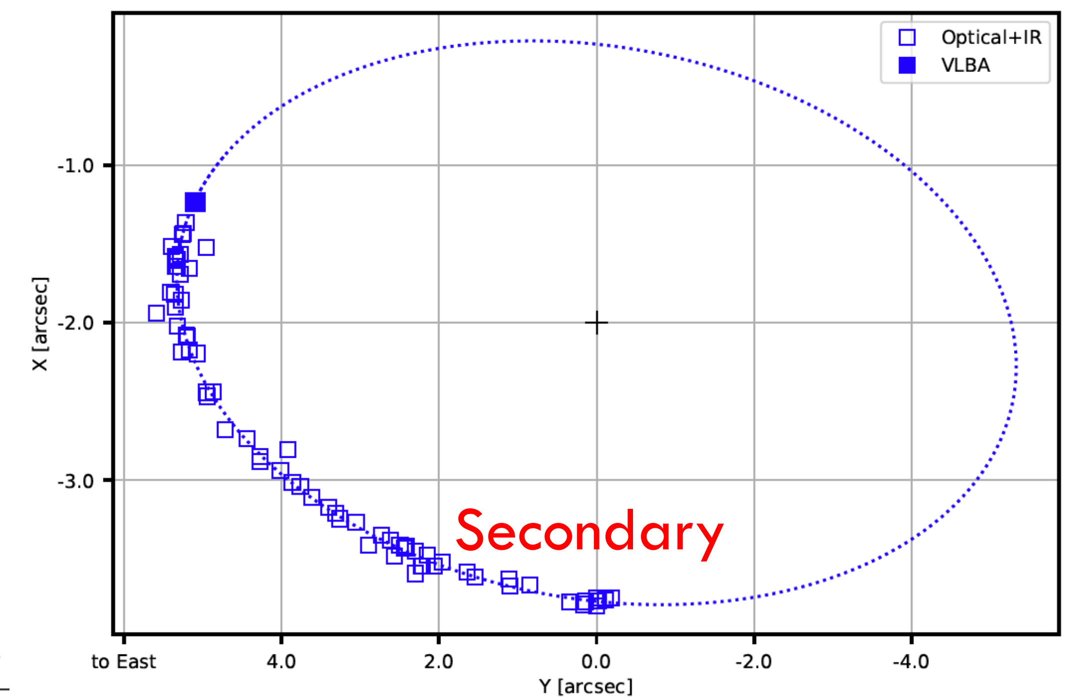
D = 6.25 pc



Absolute astrometry

Radio observations 2006 – 2020

Detections of both primary (in 16 epochs) and secondary (2 epochs)



Relative astrometry from optical and near-infrared data spanning ~80 yr + 2 radio detections; P_{AB} > 200 yr

Curiel et al. (2022)

III. ASTROMETRIC PLANET SEARCHES

GJ 896AB

M3.5 + M4.5

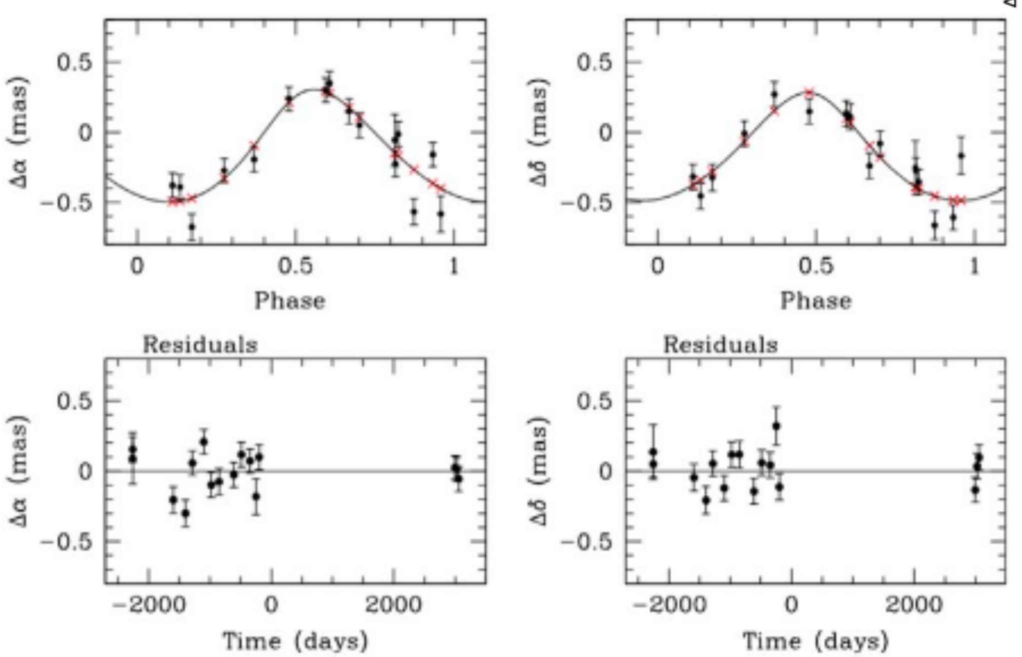
$m_A = 0.436\ M_{Sun}$

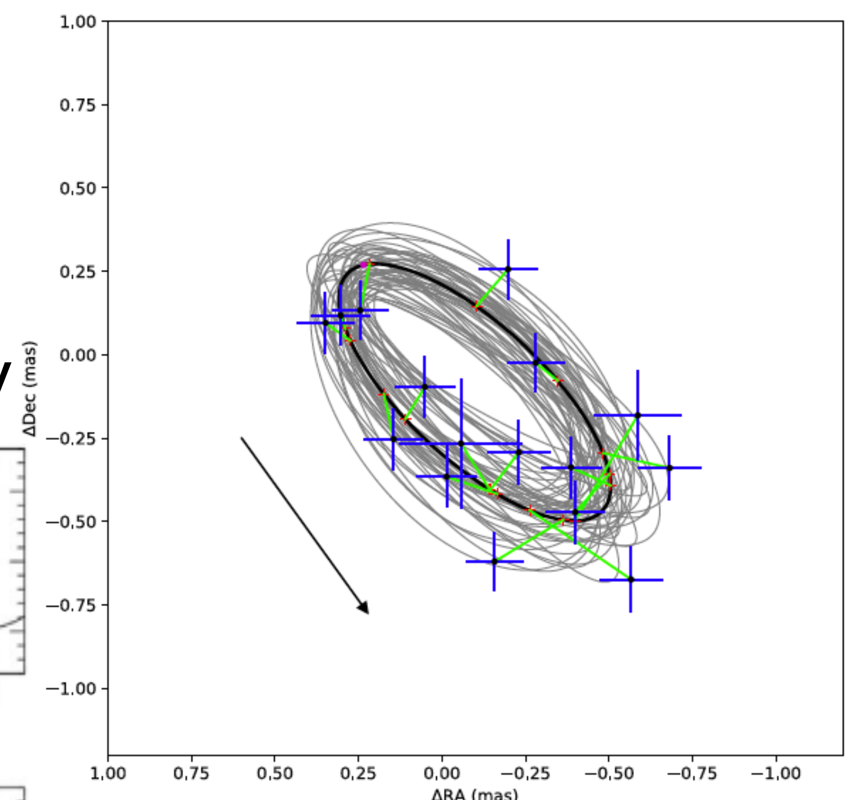
$m_B = 0.165\ M_{Sun}$

$D = 6.25$ pc

Fit to primary including a new companion and **acceleration terms** to take into account the perturbation of the secondary

Measured absolute positions of primary





New planetary companion around primary

$a_{primary}$ = 0.003 ± 0.001 au

= **520 ± 11 µas**

P_{planet} = 282 ± 2 days

e_{planet} = 0.30 ± 0.11

i_{planet} = 66 ± 15°

acc_α = 0.887 ± 0.005 mas yr^{-2}

acc_δ = 0.140 ± 0.005 mas yr^{-2}

a_{planet} = 0.635 ± 0.002 au

= 101.5 ± 0.4 mas

m_{planet} = 2.35 ± 0.49 M_{Jup}

Curiel et al. (2022)

III. ASTROMETRIC PLANET SEARCHES

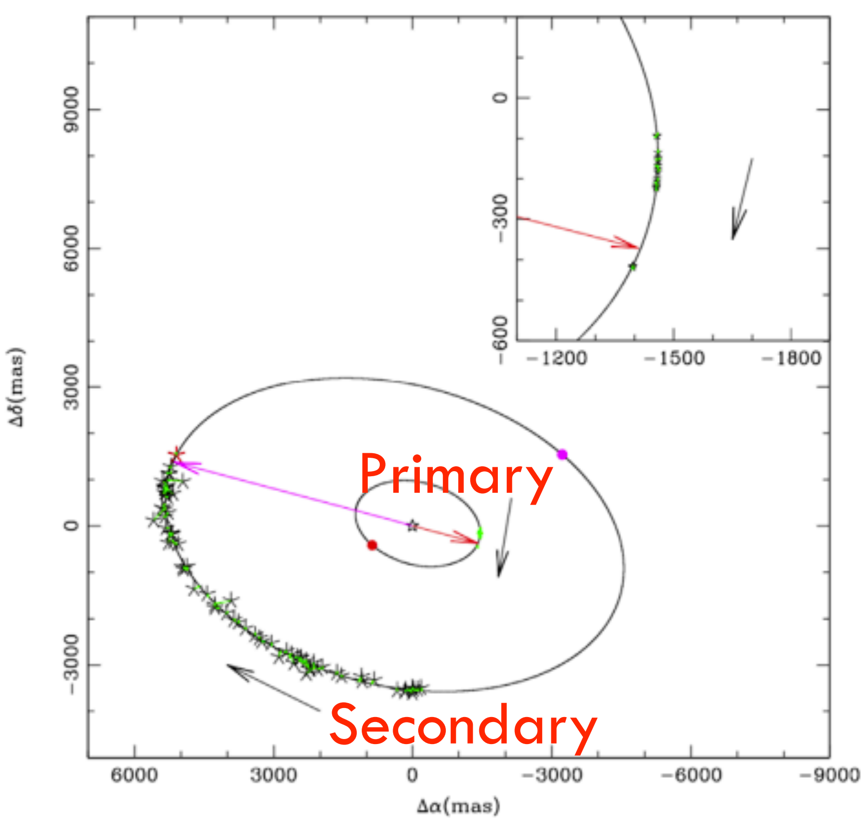
GJ 896AB

M3.5 + M4.5

$m_A = 0.436\ M_{Sun}$

$m_B = 0.165\ M_{Sun}$

$D = 6.25$ pc



Simultaneous fit to absolute positions of primary, including a new companion, absolute positions of secondary and relative **orbit of the binary**

New planetary companion around primary

$a_{primary} = 0.003 \pm 0.001$ au (**510 μas**)

$P_{planet} = 284 \pm 2$ days

$e_{planet} = 0.35 \pm 0.19$

$i_{planet} = 69 \pm 26^{\circ}$

$a_{planet} = 0.640 \pm 0.001$ au

$= 102.27 \pm 0.15$ mas

$m_{planet} = 2.26 \pm 0.57\ M_{jup}$

Binary

$P_{AB} = 229$ yr

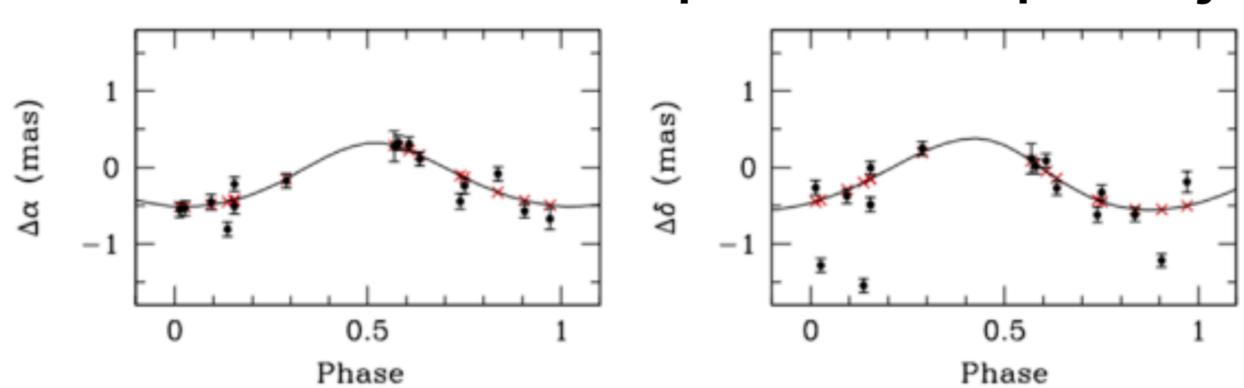
$a_{AB}(A) = 8.66 \pm 0.01$ au

$a_{AB}(B) = 22.97 \pm 0.02$ au

$e_{AB} = 0.1080 \pm 0.0001$

$i_{AB} = 130.07 \pm 0.01^{\circ}$

Measured absolute positions of primary



Curiel et al. (2022)

III. ASTROMETRIC PLANET SEARCHES

GJ 896AB

3-D orbital architecture of the binary system and its planetary companion

New planetary companion

$i_{planet} = 69 \pm 26^{\circ}$

$\Omega_{planet} = 46 \pm 10^{\circ}$

Binary

$i_{AB} = 130.07 \pm 0.01^{\circ}$

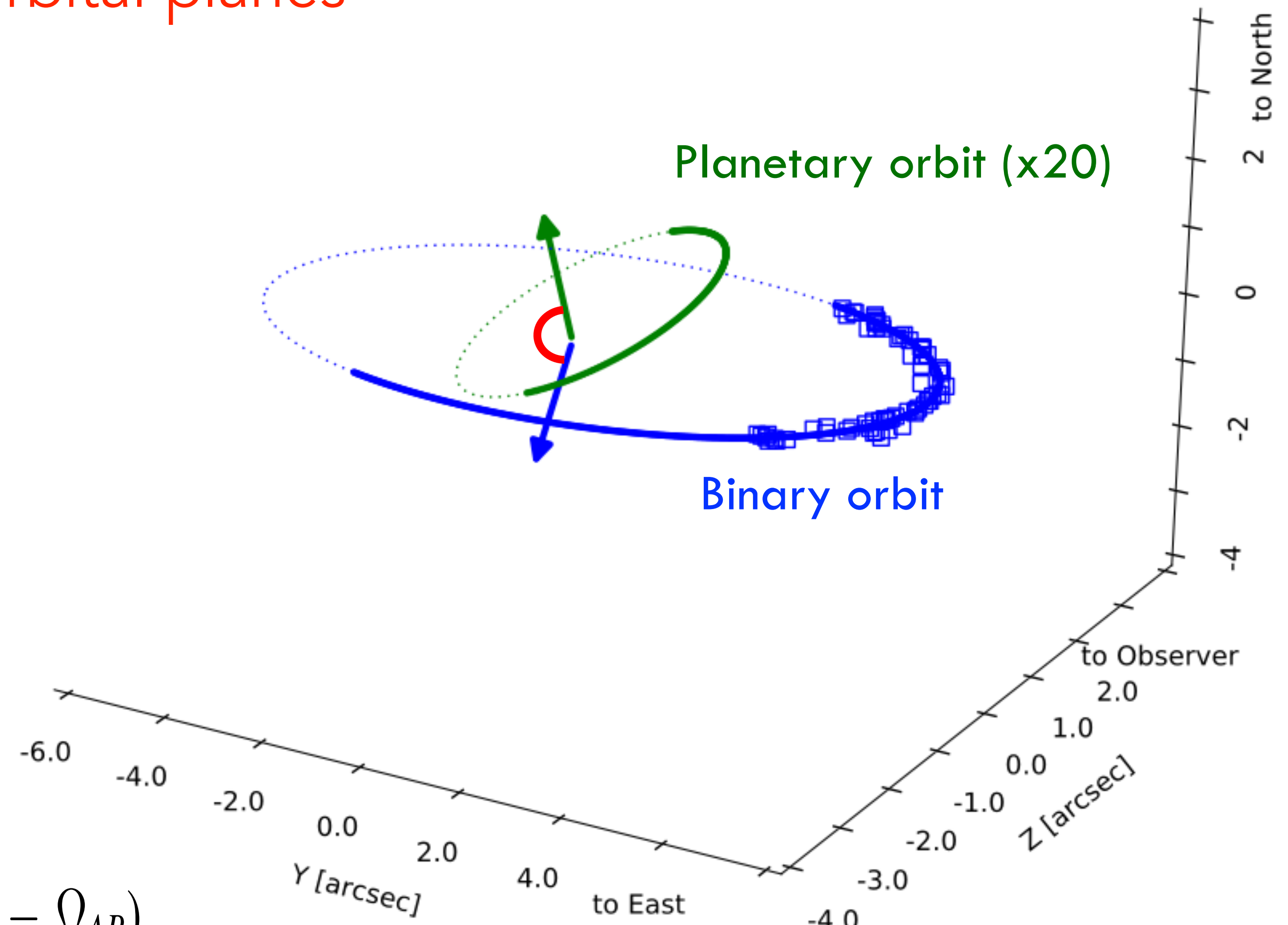
$\Omega_{AB} = 255.09 \pm 0.01^{\circ}$

Mutual inclination angle

148°

$$\cos \Phi = \cos i_{Ab} \cos i_{AB} + \sin i_{Ab} \sin i_{AB} \cos(\Omega_{Ab} - \Omega_{AB})$$

Large mutual inclination angle between both orbital planes



Curiel et al. (2022)

III. ASTROMETRIC PLANET SEARCHES

GJ 896AB

3-D orbital architecture of the binary system and its planetary companion

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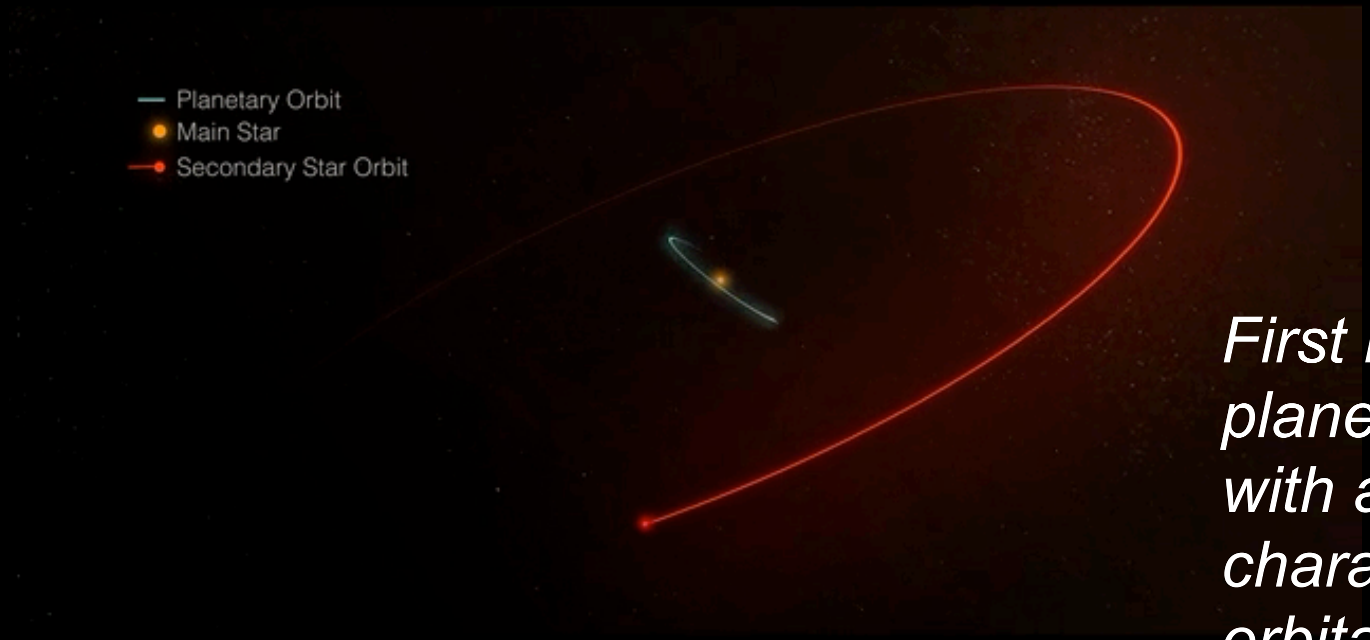
Torque by the secondary over the planetary orbital plane

Large mutual inclination angle between both orbital planes



Credit: Sophia Dagnello, NRAO/AUI/NSF

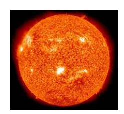
First binary planetary system with a fully characterized 3D orbital plane orientation

Curiel et al. (2022)

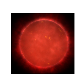
IV. FUTURE

ASTROMETRIC PLANET SEARCHES WITH GAIA

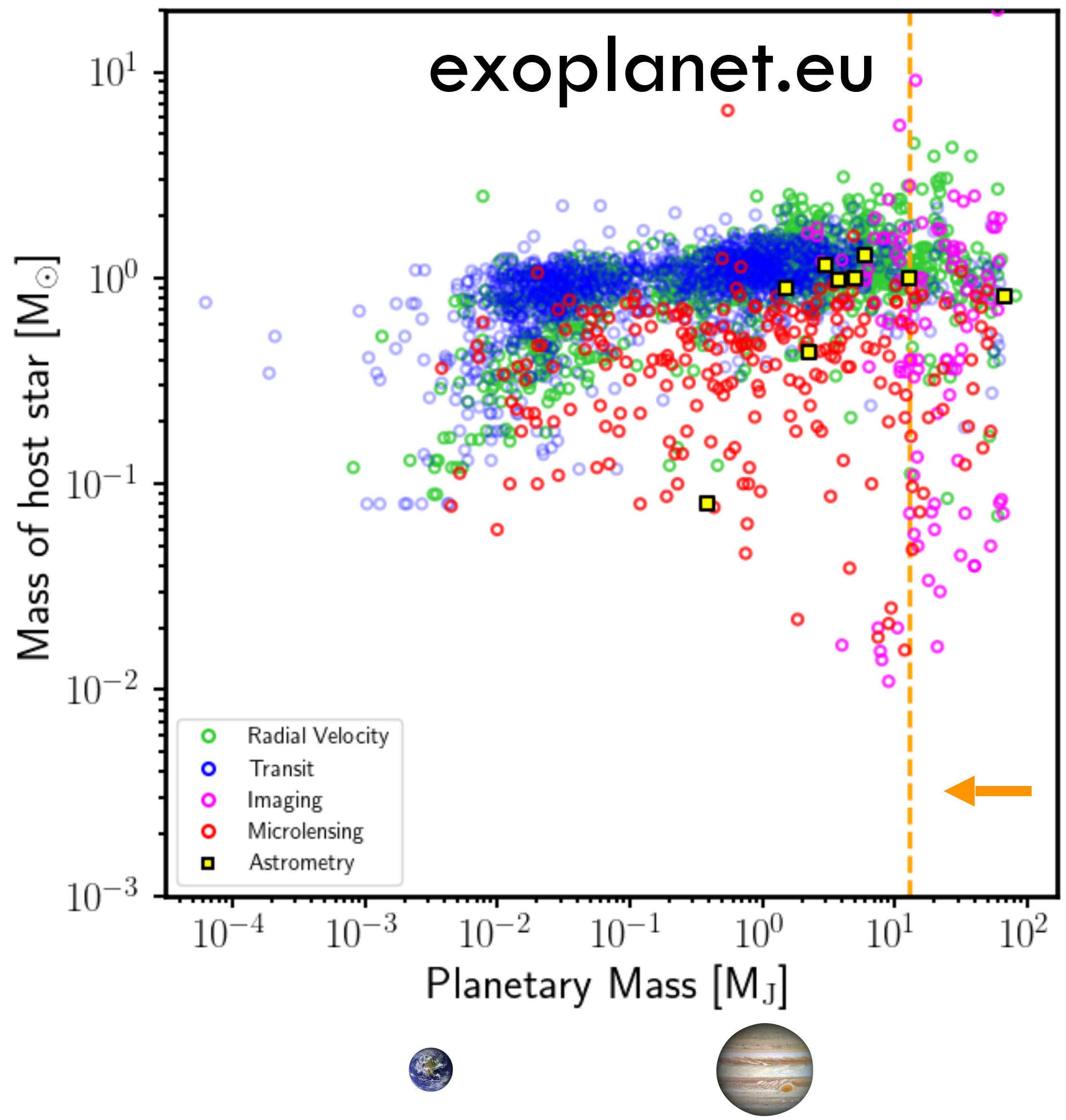
Estimates suggest *Gaia* will detect some **tens of thousands** of exoplanets out to 500 parsec (nominal 5 yr mission)



1000–1500 of these planets are expected to be orbiting **M-dwarfs** within 100 pc



72 candidates reported in DR3 (Gaia Collaboration et al. 2023, A&A…674A..34G)



Deuterium–burning mass limit (13 M_J)

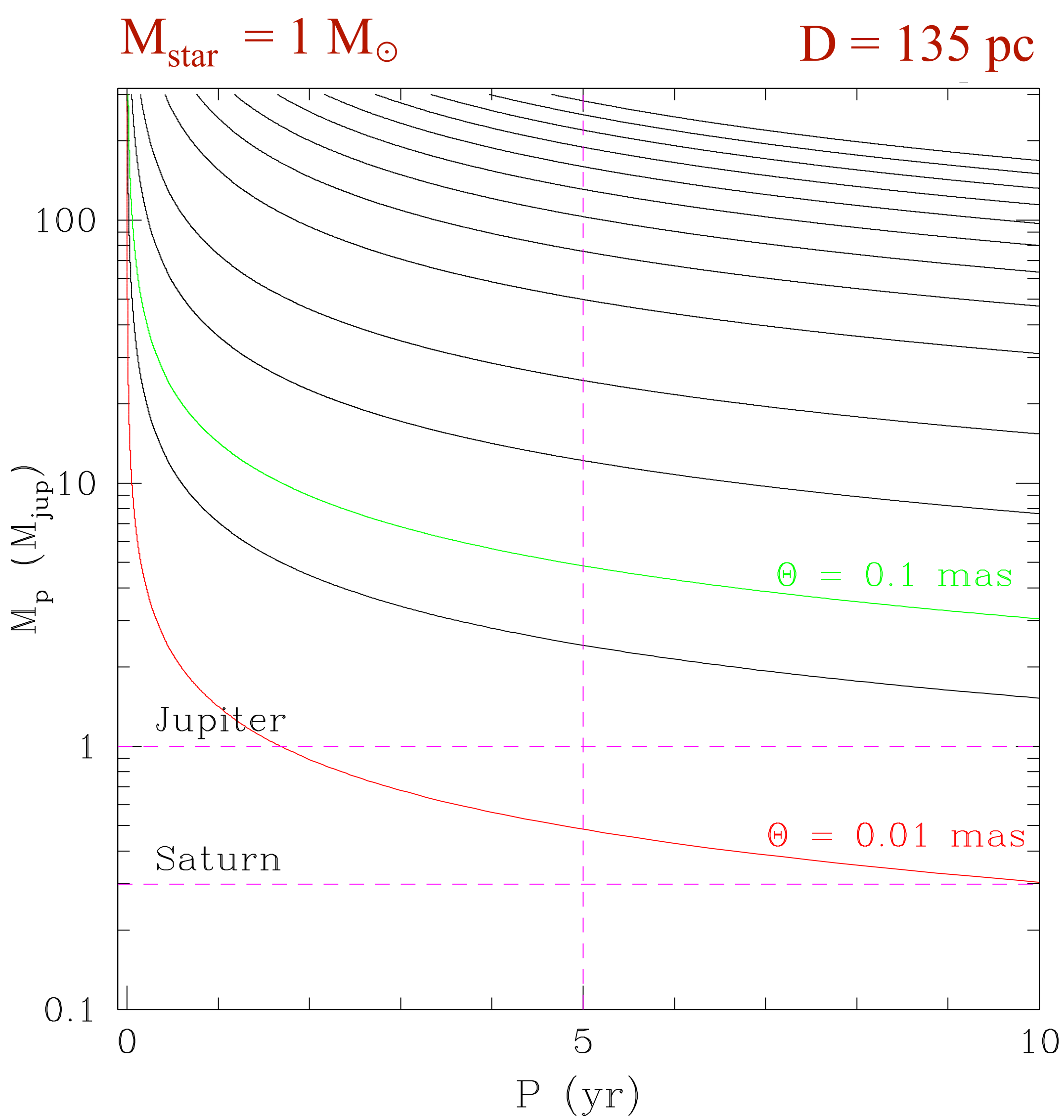
IV. FUTURE

NEXT GENERATION VERY LARGE ARRAY

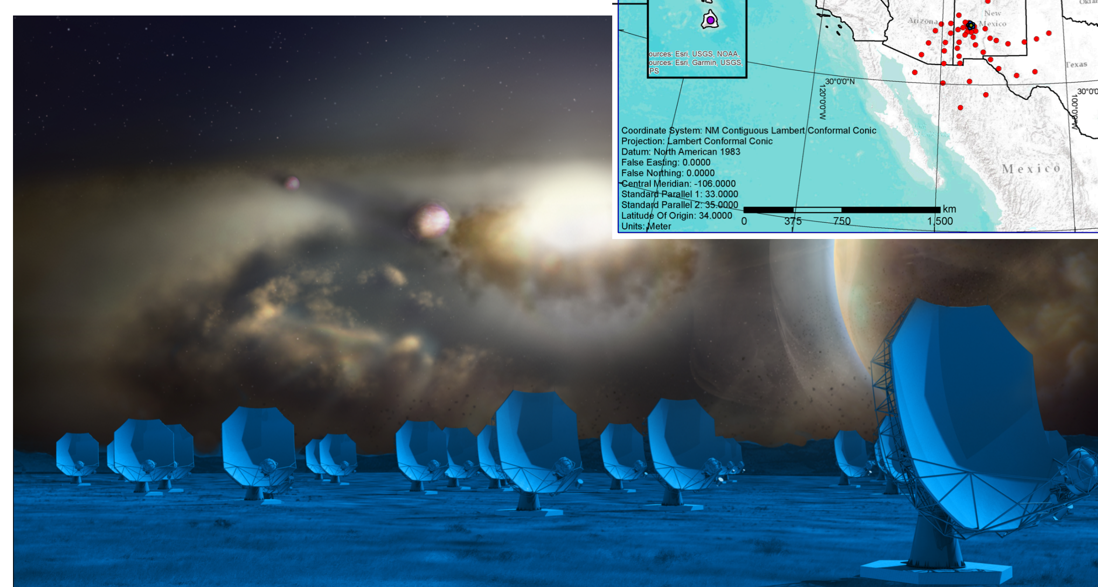
A transformative new facility that will replace the VLA and VLBA

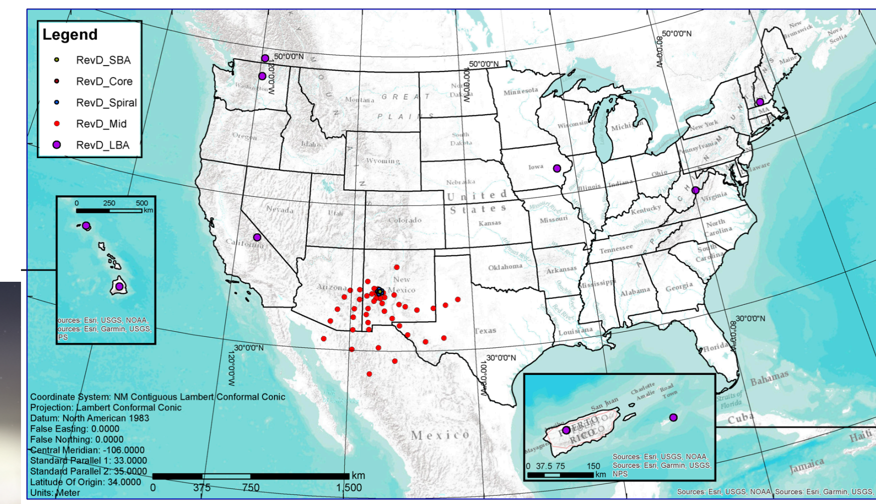
Will achieve **1 μas** astrometric accuracy! (NGVLA Memo 58)

Potential to reveal many more planets



User science case: Curiel, Ortiz-León & Mioduszewski





Frequency coverage: 1.2 - 116 GHz

Main array of 244x18m antennas

Core array of 19x6m antennas

Long baseline array of 30x18m antennas

10x the sensitivity of the VLA/ALMA

Early science operations ~ 2031

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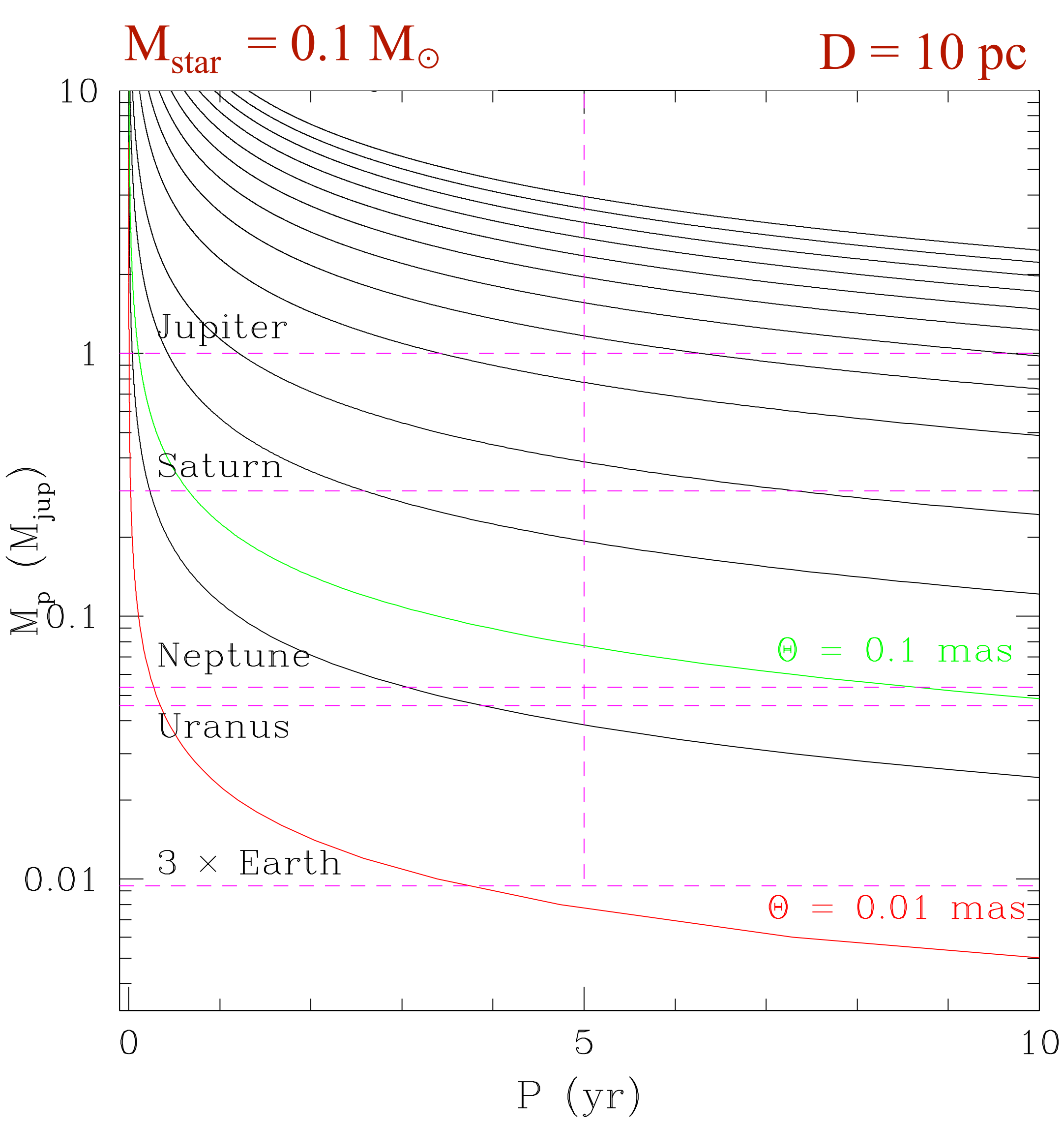
How many will be discovered by the ngVLA?



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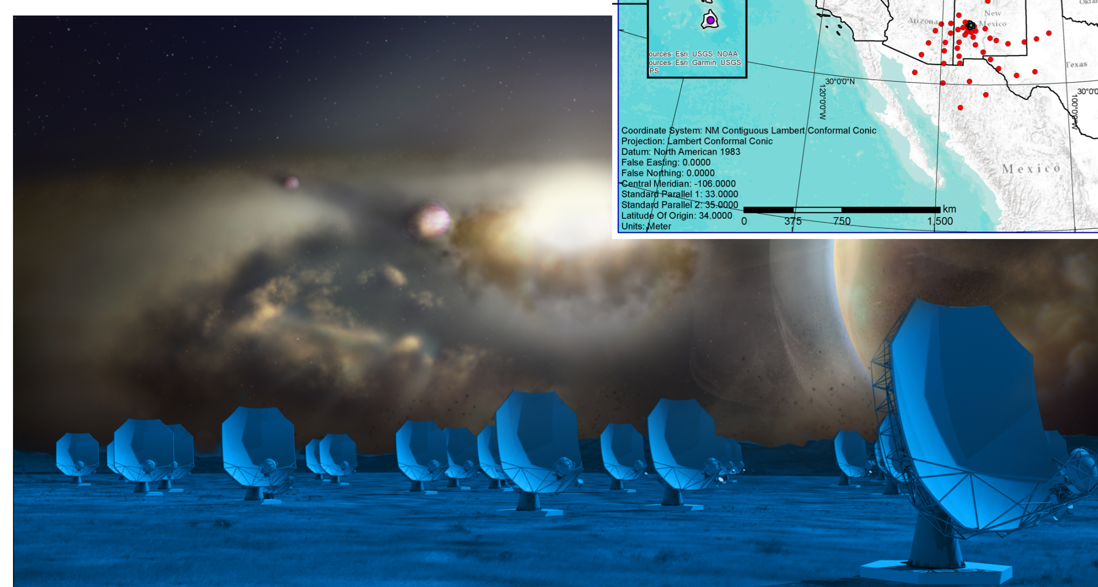

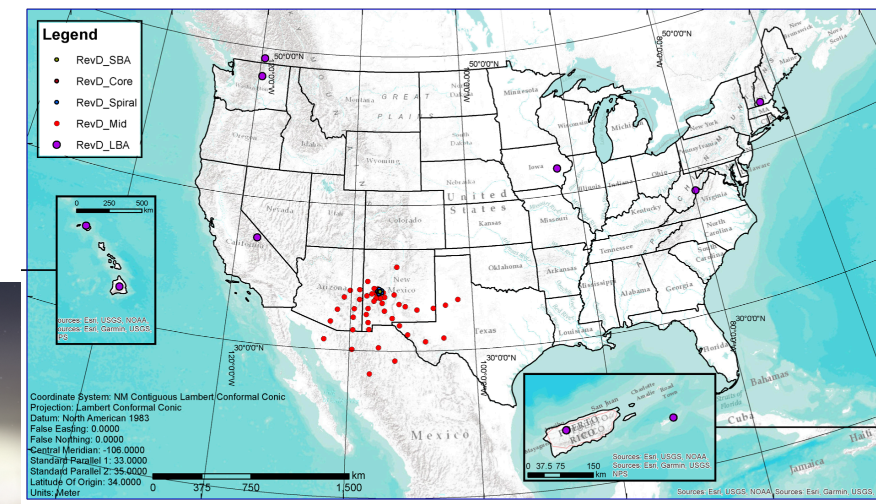

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SUMMARY

- VLBI astrometry (in combination with Gaia) has been fundamental for the characterization of molecular cloud 6D structure and the stellar systems that live within them.
- Astrometry of binary stars allow the determination of dynamical masses, which are being used to test evolutionary models and derive precise stellar parameters.
- VLBI astrometry could make a unique contribution to the field of exoplanet research:
  - Can constrain all the orbital parameters, including planetary mass
  - Can characterize the true 3D structure of binary planetary systems

THANK YOU

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