Tie between extragalactic and planetary ephemeris reference frames: A perspective from the pulsar astrometry

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Content

01

Celestial reference frame

02

Pulsar timing astrometry

03

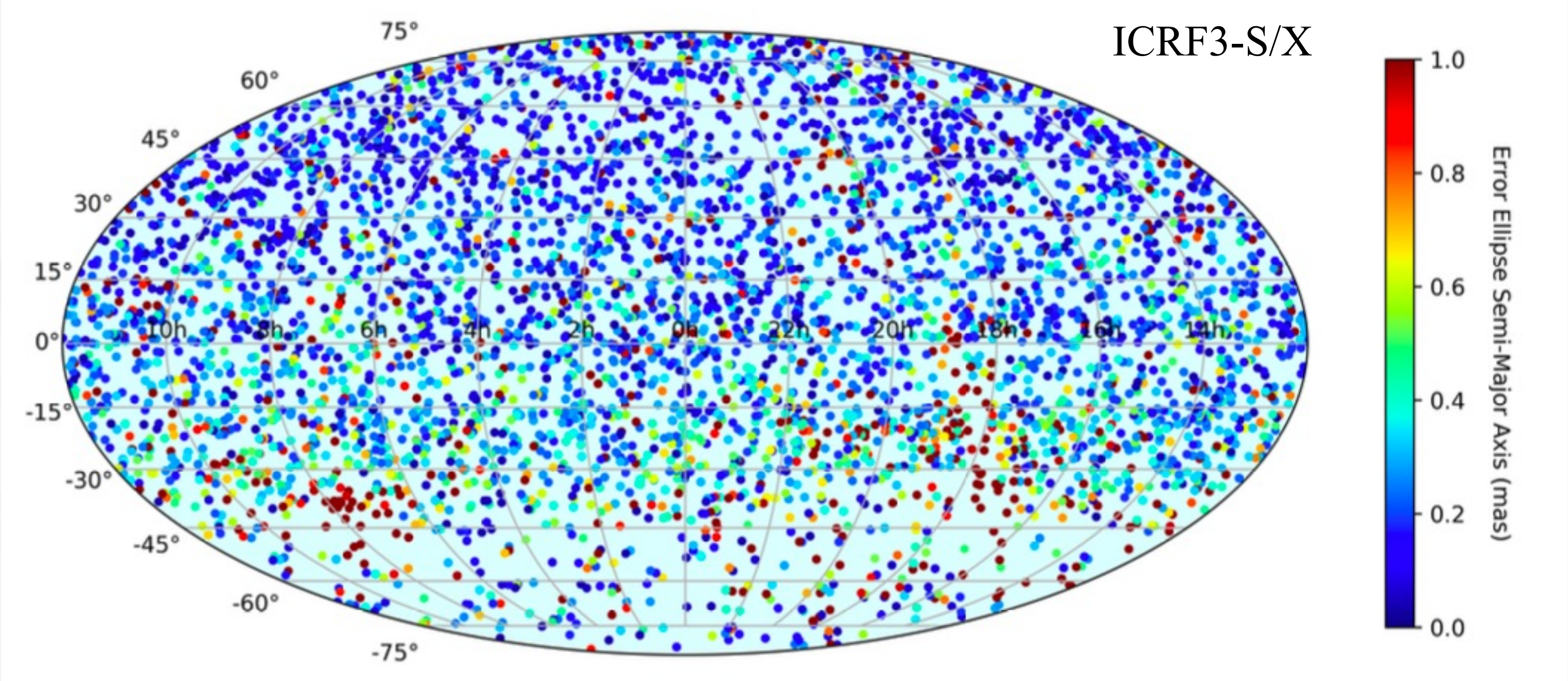
Materials &Results

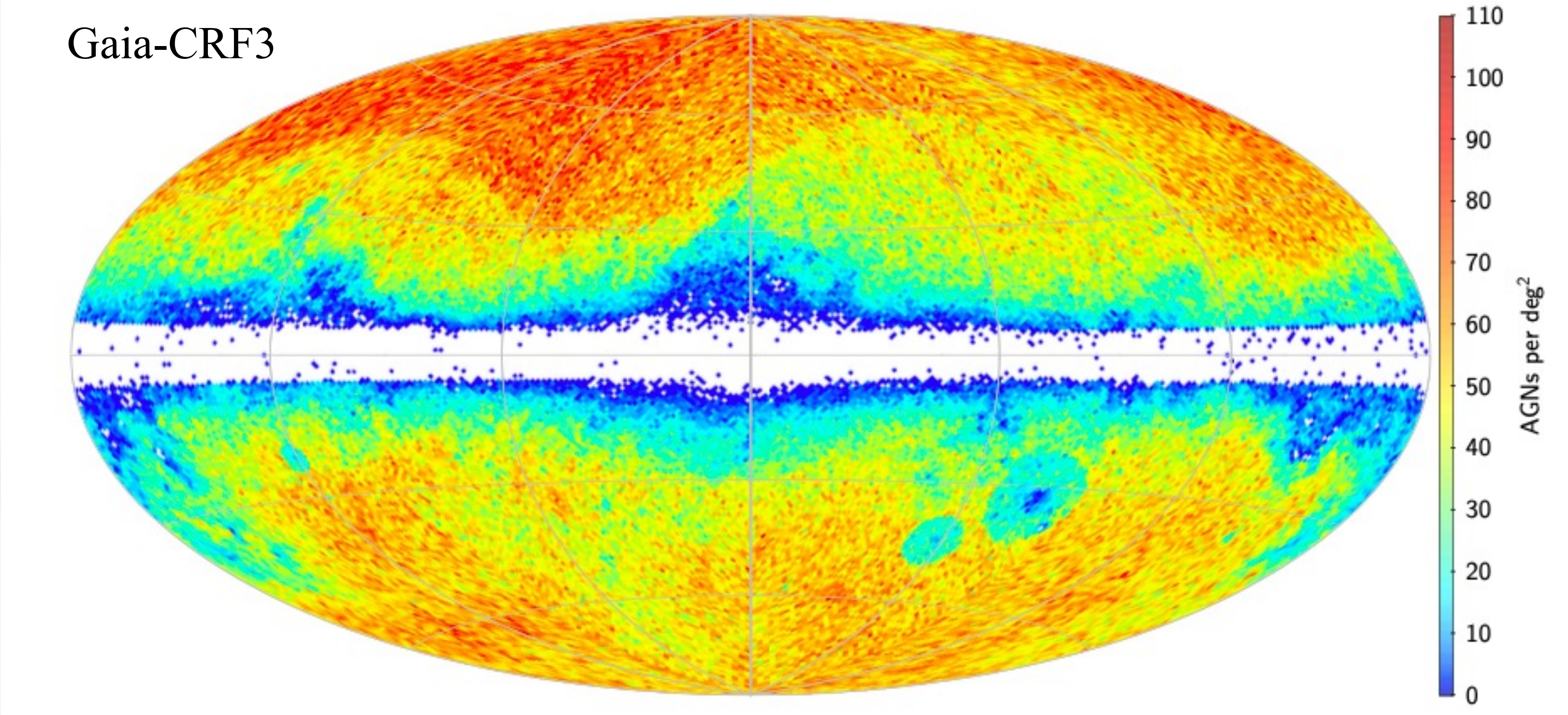
04

Summary

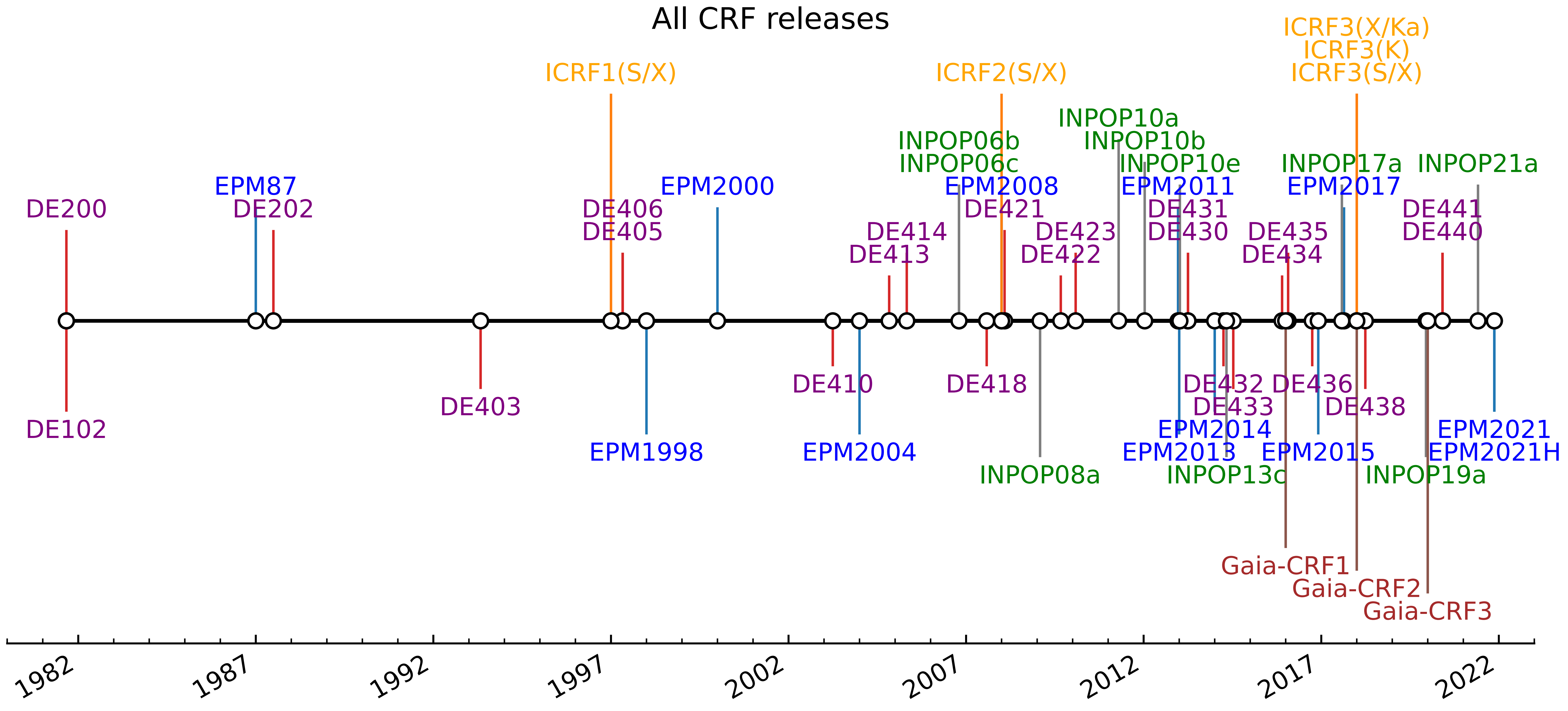
Celestial Reference System &Celestial Reference Frame

- The International Celestial Reference System (ICRS) provides the basic positioning standard, which is widely used in astrometry, geodesy, and navigation for spacecraft.
- The ICRS concept is built on the assumption that the Universe does not show a global rotation (kinematic definition).
- The planetary ephemeris reference frame realizes the ICRS in a dynamical sense with an assumption that the motions of (Solar System) objects do not present any acceleration reflected in the rotation of the celestial reference system (dynamical definition).





Solar System ephemerides & Planetary ephemeris frame



All these celestial reference frames should be tied without losing much their accuracies.

Orientation accuracy of ephmeris reference frames

RMS ~ 0.2 mas

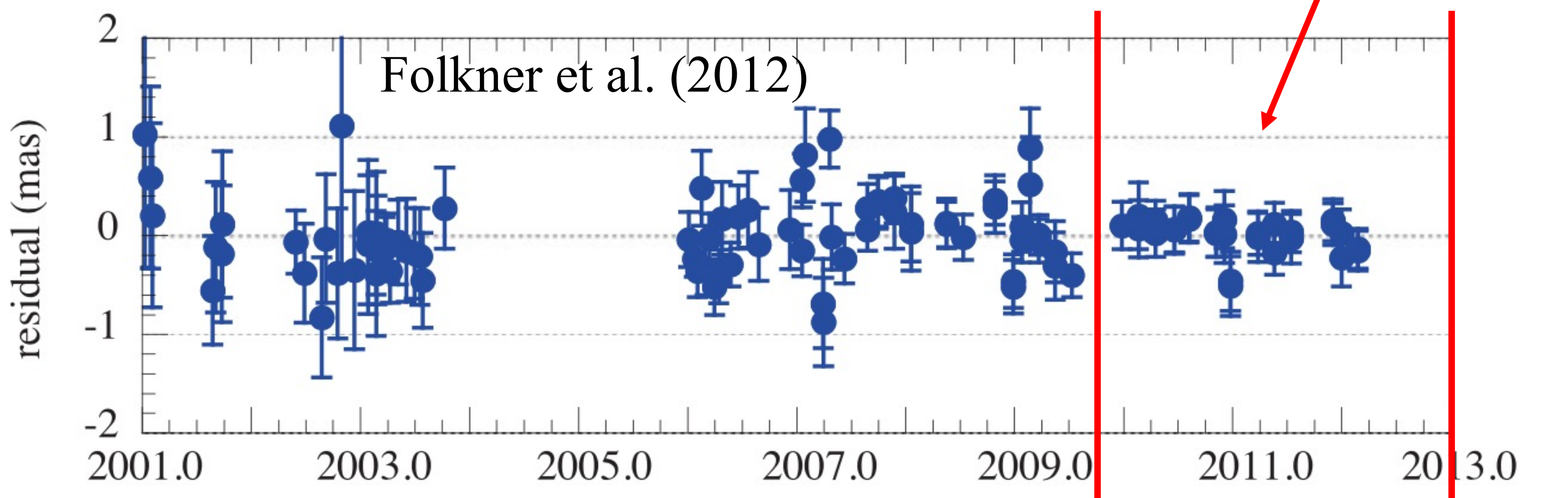


Figure 1. Residuals (milliarcseconds) of VLBI measurements of Mars-orbiting spacecraft on Goldstone-Madrid baseline

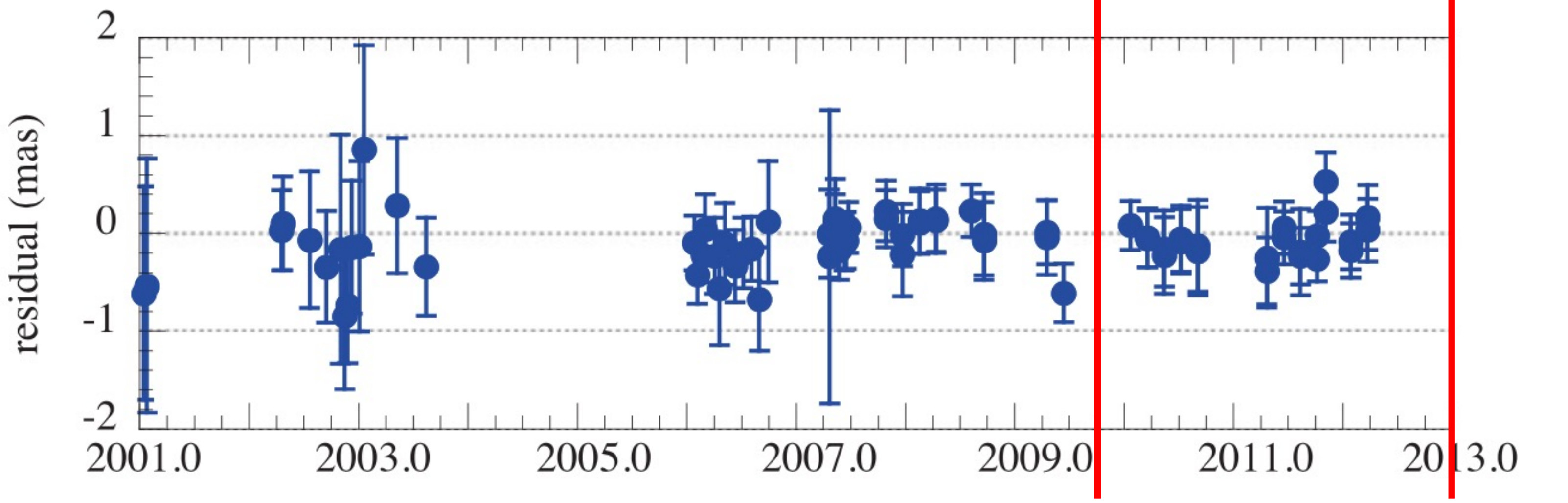


Figure 2. Residuals (milliarcseconds) of VLBI measurements of Mars-orbiting spacecraft on Goldstone-Canberra baseline

The inner orbit of DE440 is tied to ICRF3 with an accuracy of ~ 0.2 mas (Park et al. 2021).

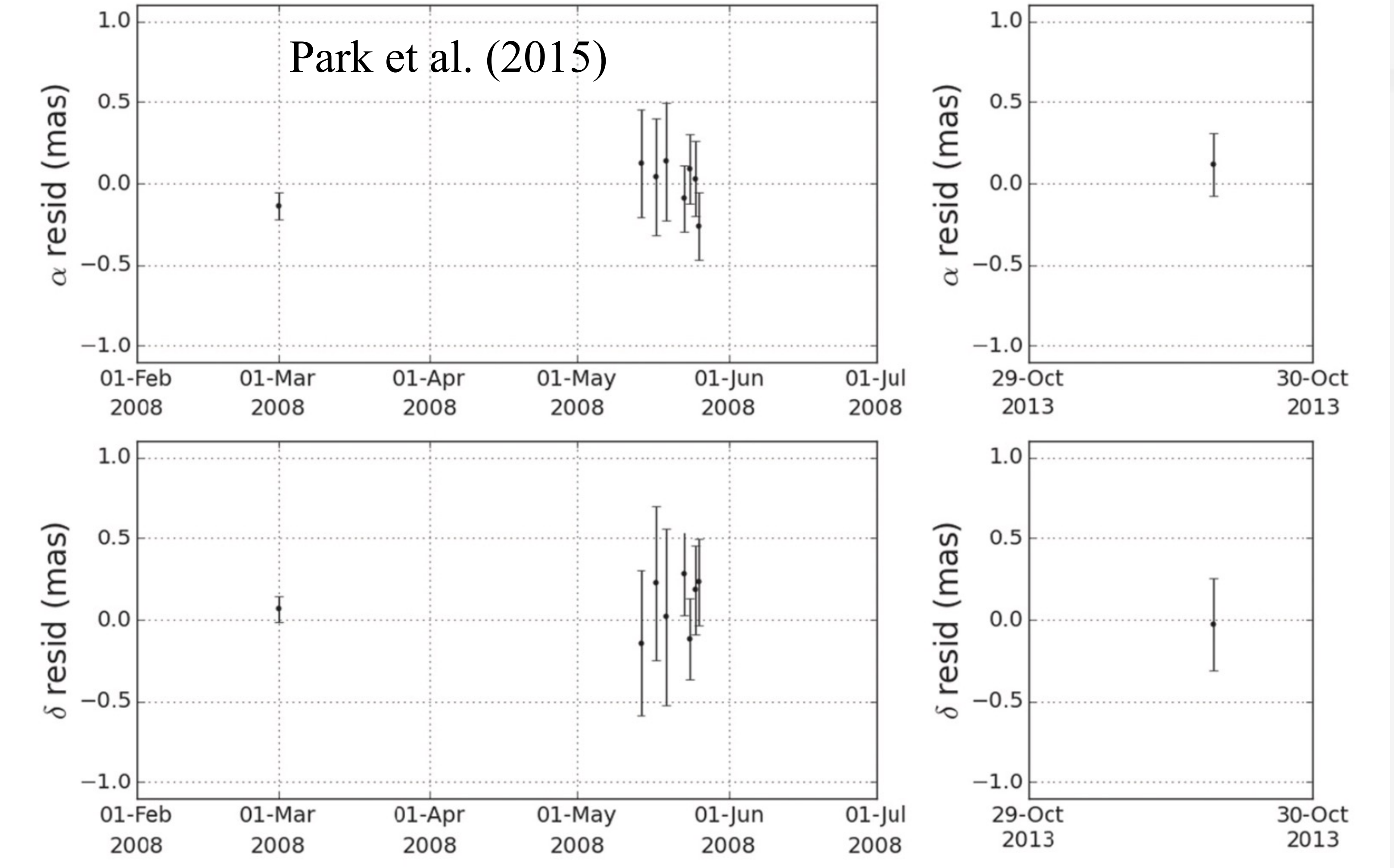


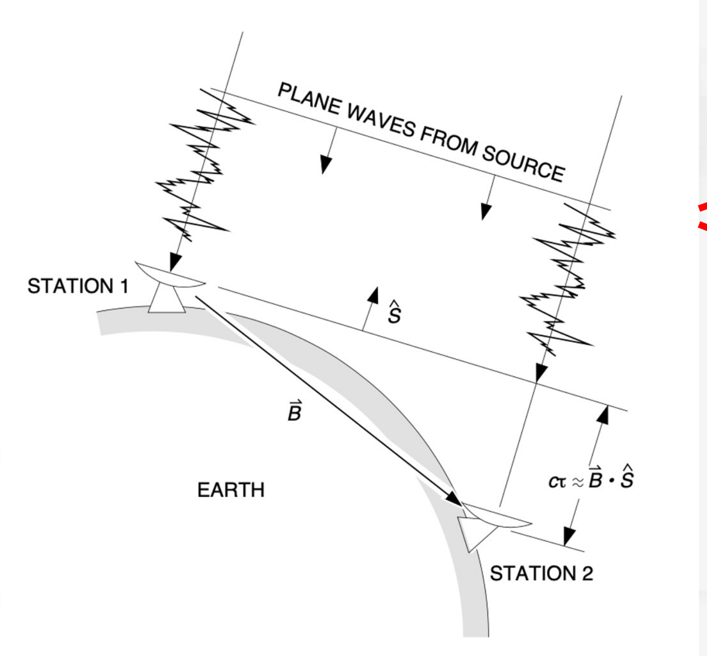
Figure 1. Mars positions based on VLBA data compared to the DE430 JPL Mars ephemeris positions. The error estimates include expected uncertainties in the quasar positions, station clock, and Earth media.

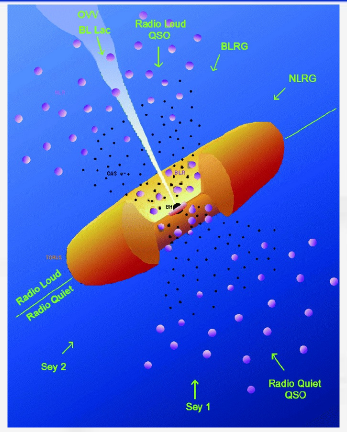
Estimated Orientation of the Earth Orbit (from Ephemeris DE430) with Respect to the ICRF

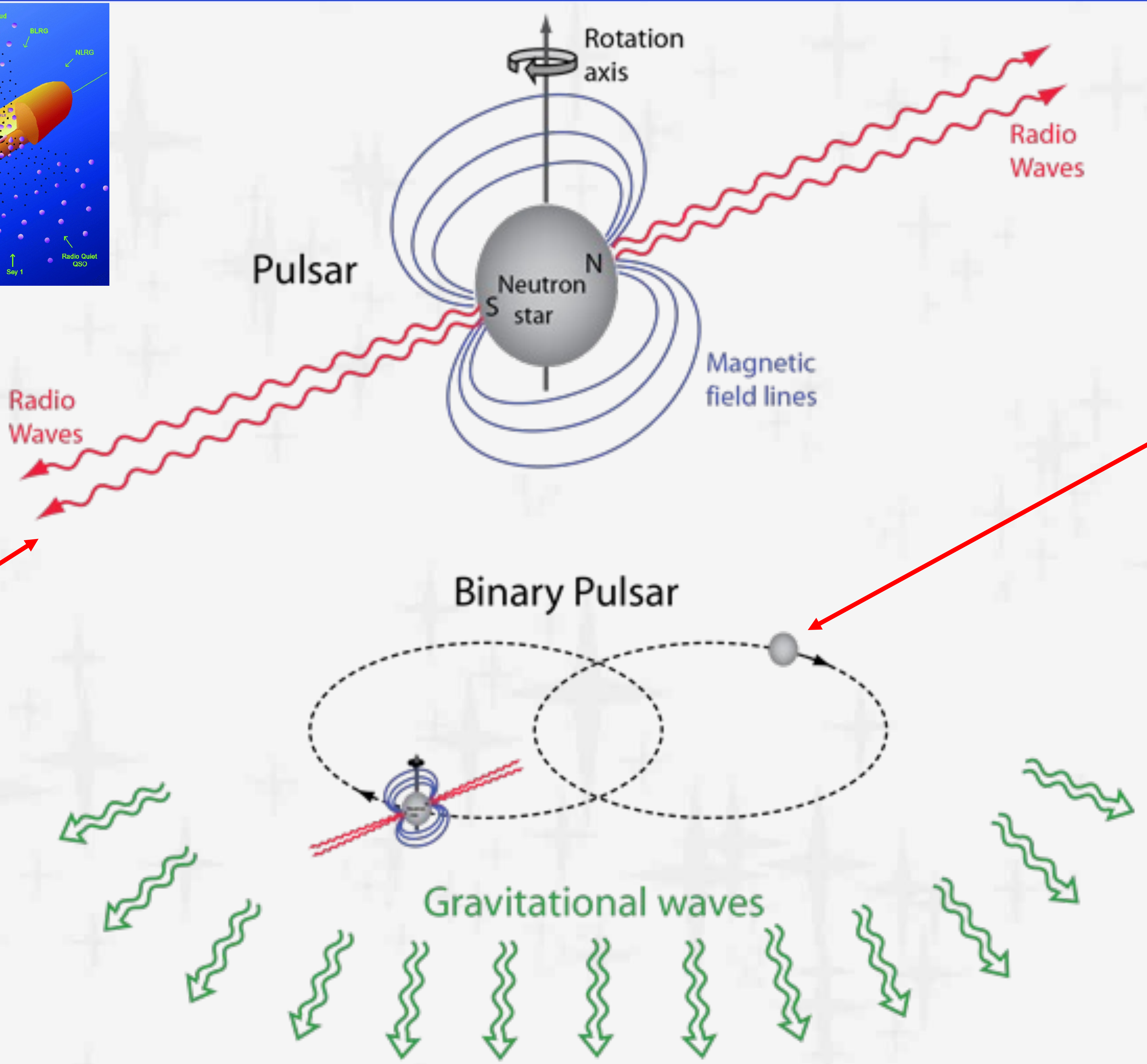
Name	Estimate (mas)	Uncertainty (mas)
θ_x	0.14	0.29
θ_y	0.03	0.25
θ_z	−0.19	0.12

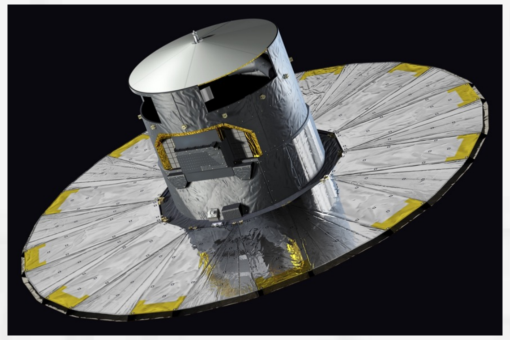
Pulsar astrometry

Differential VLBI (~ 1 mas)

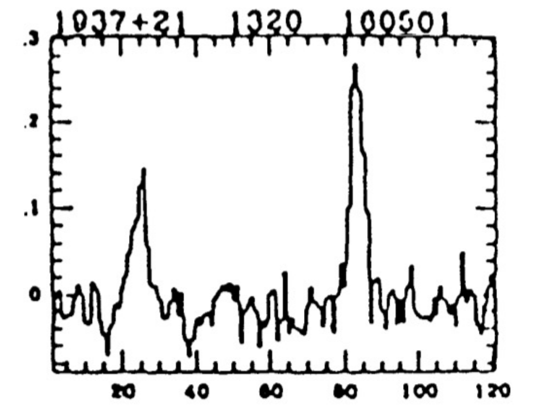


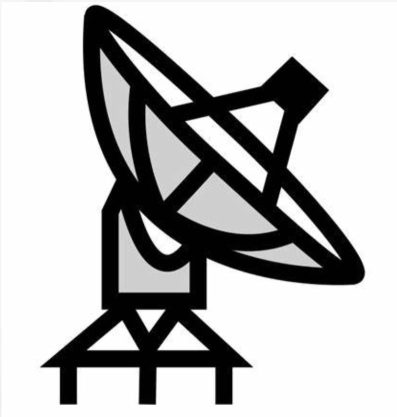






Gaia (~ 0.3 mas)





Pulse timing (millisecond pulsar ~ 0.2 mas; young pulsar ~ 10 mas)

Frame-tie via pulsar astrometry

Pros

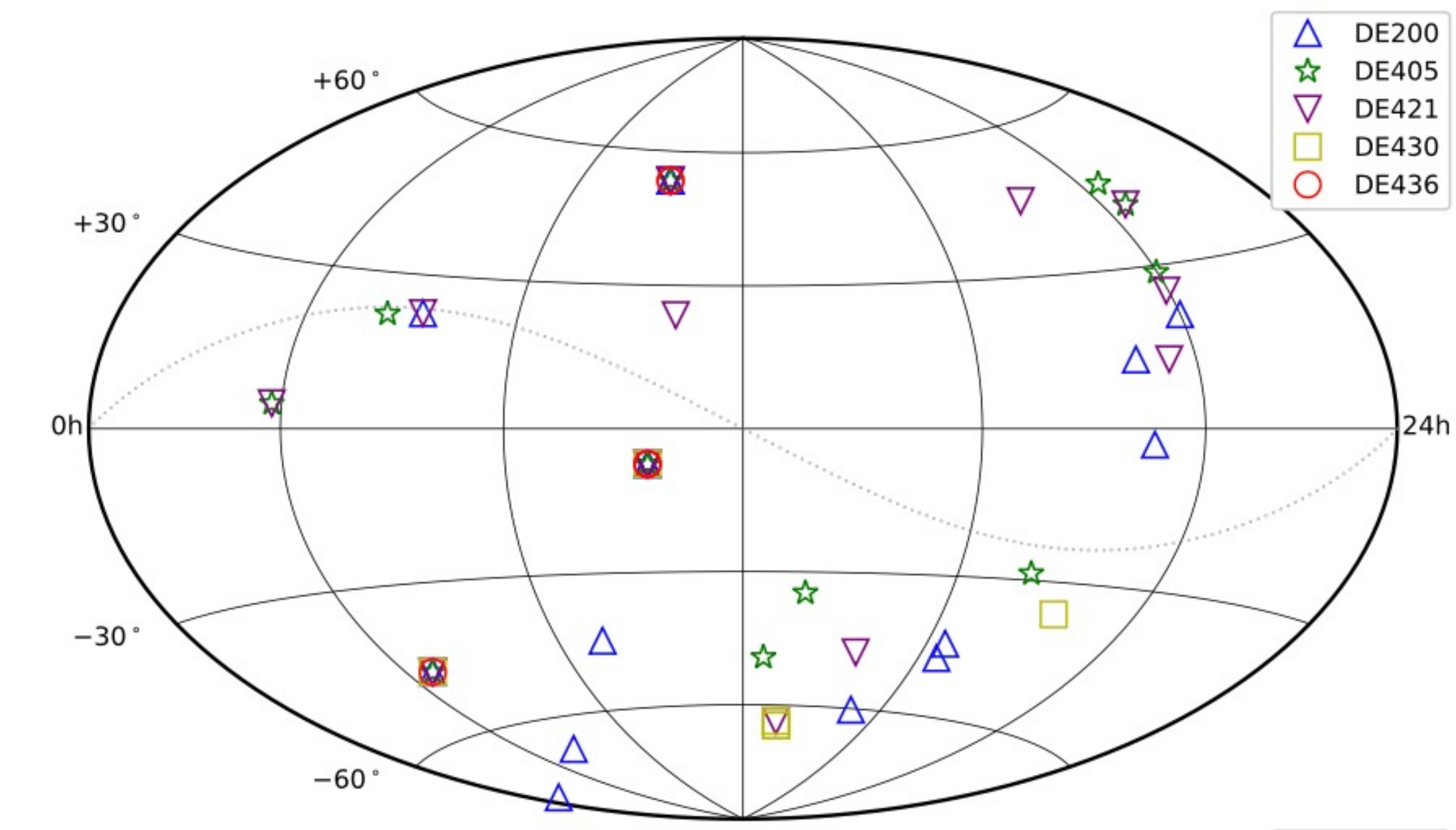
- Achieve a direct tie between the ephemeris and the extragalactic reference frames
- Provide an external check on the frame-tie since pulsar positions are fully independent of the production of the ephemerides
- May be less sensitive to the systematics along specific directions when using single baselines and a few targets thanks to the relatively uniform sky distribution of pulsars and the strong geometry of the observed VLBI networks
- Permit a regular monitoring of the frame-tie status with ongoing and future pulsar timing arrays (PTAs) and VLBI observing campaigns (PSRπ/MSPSPπ)
- …

Cons

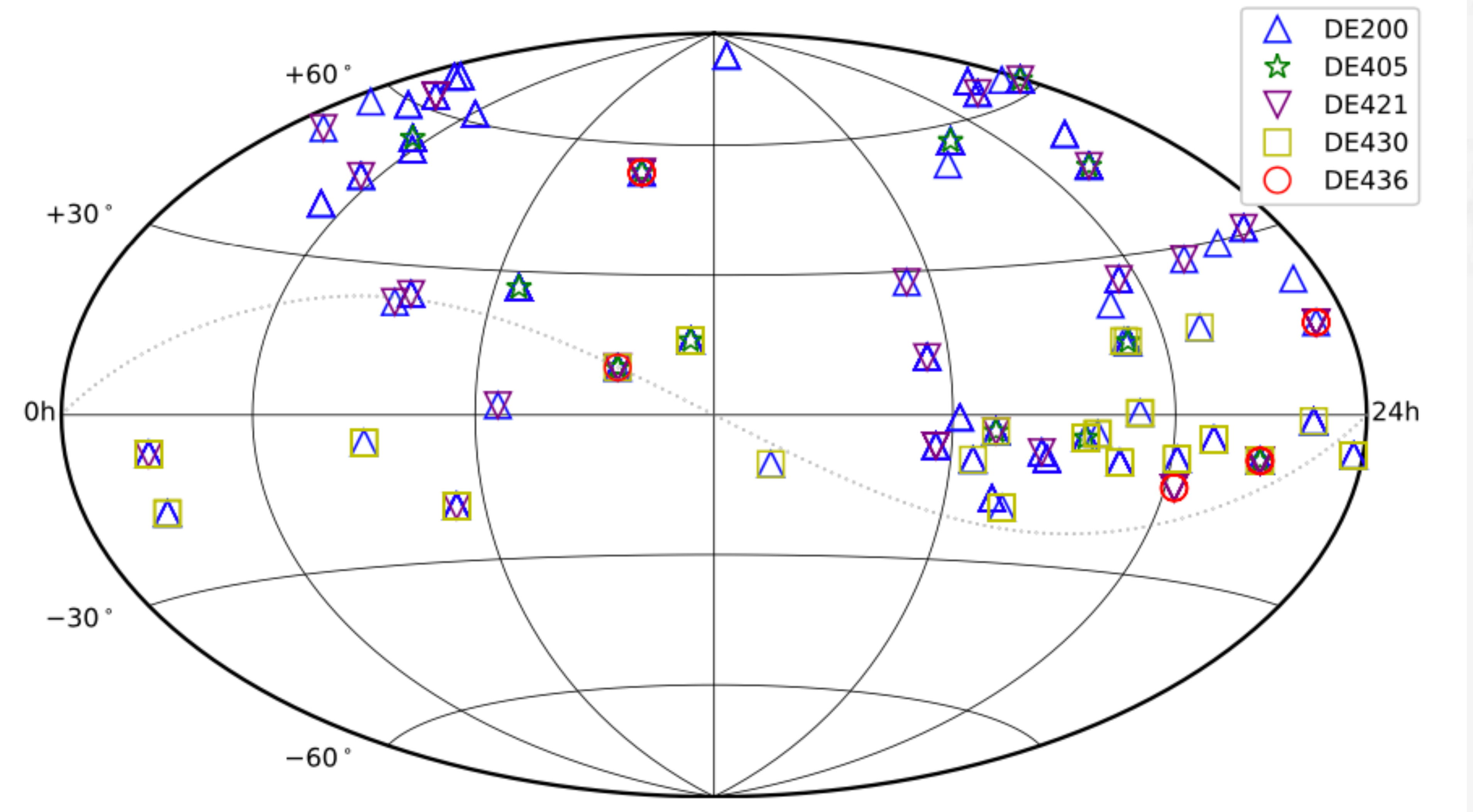
- Mainly limited by precision of VLBI astrometry (~ 1 mas)
- Genuine differences between timing (pulsar) and Gaia (companion) positions
- Gaia cannot observe pulsars being most precisely timed
- …

Pulsar sample

- Searched for pulsars in the Gaia DR3 using ANTF pulsar catalog and found 49 astrometric matches (two false associations: PSR J1435–6100 and PSR J1955+2908)
- Found 62 pulsars in the PSRπ/MSPSPπ data
- Searched for archival timing solutions using SIMBAD query service (283 solutions for 93 pulsars)



Gaia pulsar sample

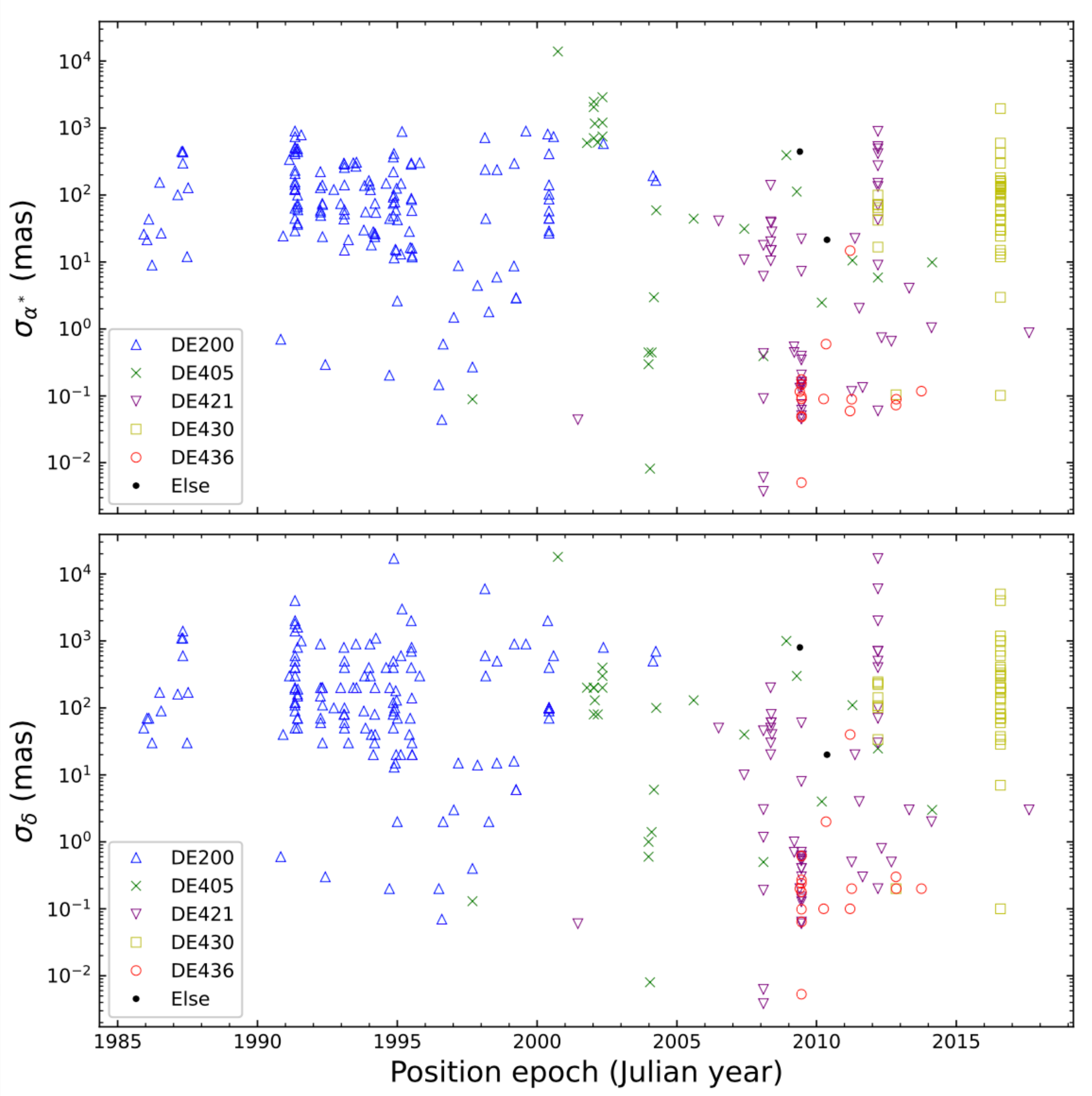


VLBI pulsar sample

Astrometric precision of pulsars

CRF	Subset	Epoch (yr)	N_{PSR}	N_{obs}	σ_{α^*} (mas)	σ_δ (mas)	$\sigma_{pos,max}$ (mas)	σ_ϖ (mas)	σ_{μ,α^*} (mas yr^{-1})	$\sigma_{\mu,\delta}$ (mas yr^{-1})	References
DE200	All	1994.1	75	142	75	120	173	5	8	13	1–23
	MSP	1996.9	10	20	2.8	4.5	5.0	5.0	0.7	1.4	
	Non-MSP	1993.5	65	122	99	165	194	… [a]	15	22	
DE405	All	2004.0	23	26	52	90	127	0.50	0.15	0.30	24–34
	MSP	2004.3	20	13	2.5	3.0	4.7	0.50	0.15	0.30	
	Non-MSP	2002.3	13	13	749	200	1075	… [a]	… [a]	… [a]	
DE421	All	2009.5	35	55	1.0	3.0	3.1	0.20	0.19	0.44	26, 35–51
	MSP	2009.5	15	33	0.16	0.50	0.59	0.20	0.08	0.17	
	Non-MSP	2010.4	20	22	41	65	76	… [a]	9.0	18.5	
DE430	All	2016.6	27	42	77	186	225	0.23	2.0	3.0	26,52–53
	MSP	2016.6	4	5	3.0	7.0	7.6	0.23	0.06	0.13	
	Non-MSP	2016.6	23	37	86	200	237	… [a]	3.0	4.5	
DE436 [b]	All (MSP)	2009.9	8	16	0.09	0.20	0.23	0.14	0.03	0.07	54–56
Gaia	All	2016.0	49	49	0.16	0.18	0.22	0.23	0.22	0.23	57
	MSP	2016.0	27	27	0.18	0.19	0.27	0.25	0.24	0.24	
	Non-MSP	2016.0	22	22	0.14	0.14	0.20	0.15	0.20	0.17	
VLBI	All	2012.2	62	62	1.4	1.0	1.8	0.06	0.09	0.12	58–61
	MSP	2012.2	6	6	1.5	1.5	2.1	0.08	0.07	0.12	
	Non-MSP	2012.2	56	56	1.4	1.0	1.8	0.05	0.09	0.12	

Archival timing solutions

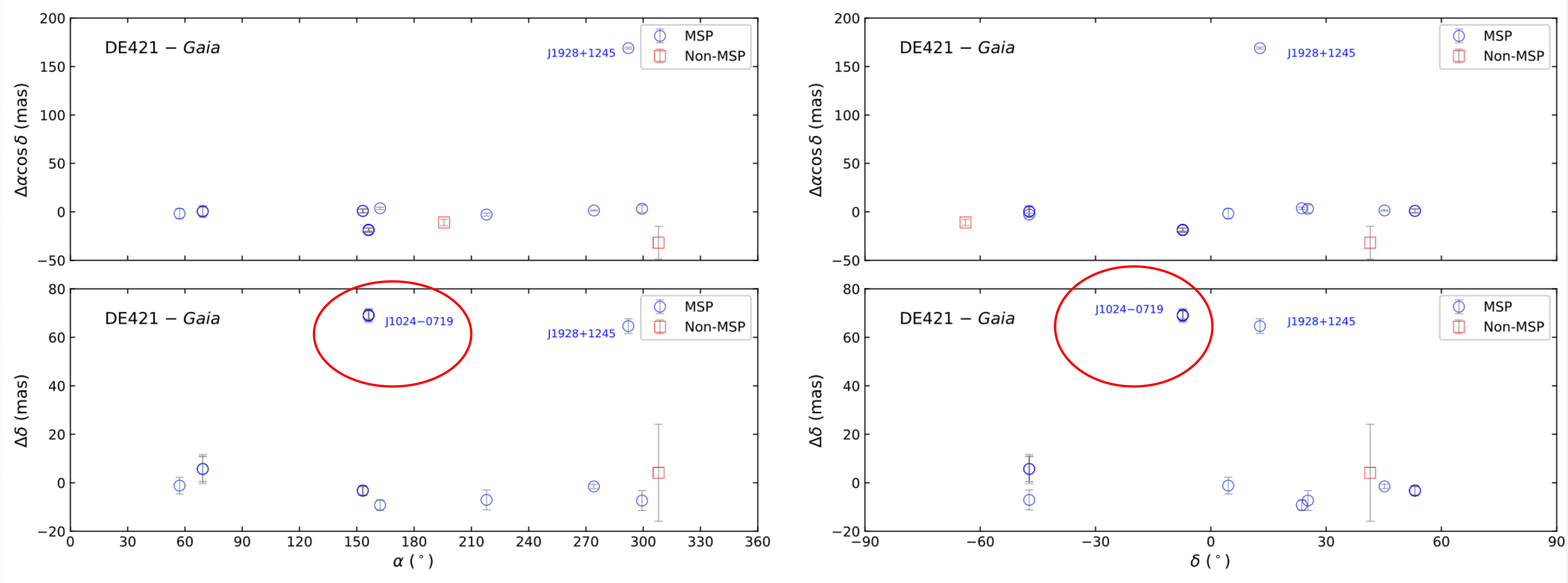


👈 Formal uncertainties of published timing solutions

- Choice of planetary ephemeris used in the timing solutions depends on the published time of the timing solutions (newly published solutions favor newer edition of planetary ephemerides)
- Precision of timing solutions also depends on the published time of the timing solutions (early solutions suffer from issues such as shorter data spans, narrower bandwidths, and less sophisticated data reduction techniques)
- One can hardly separate errors due to misalignment of ephemeris frames from errors caused by impection of timing solutions

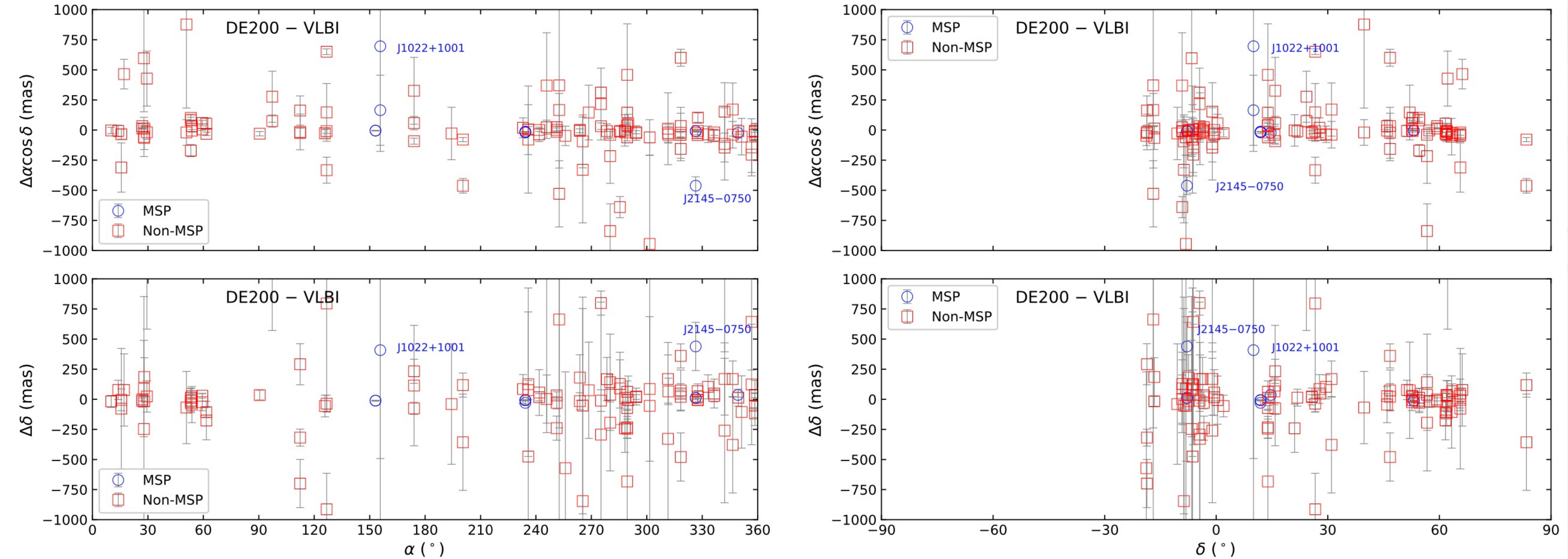
Position comparison:Timing vs. Gaia

Position offsets for MSPs and Non-MSPs



The timing positions yield genuine offsets to the Gaia positions for some pulsars.

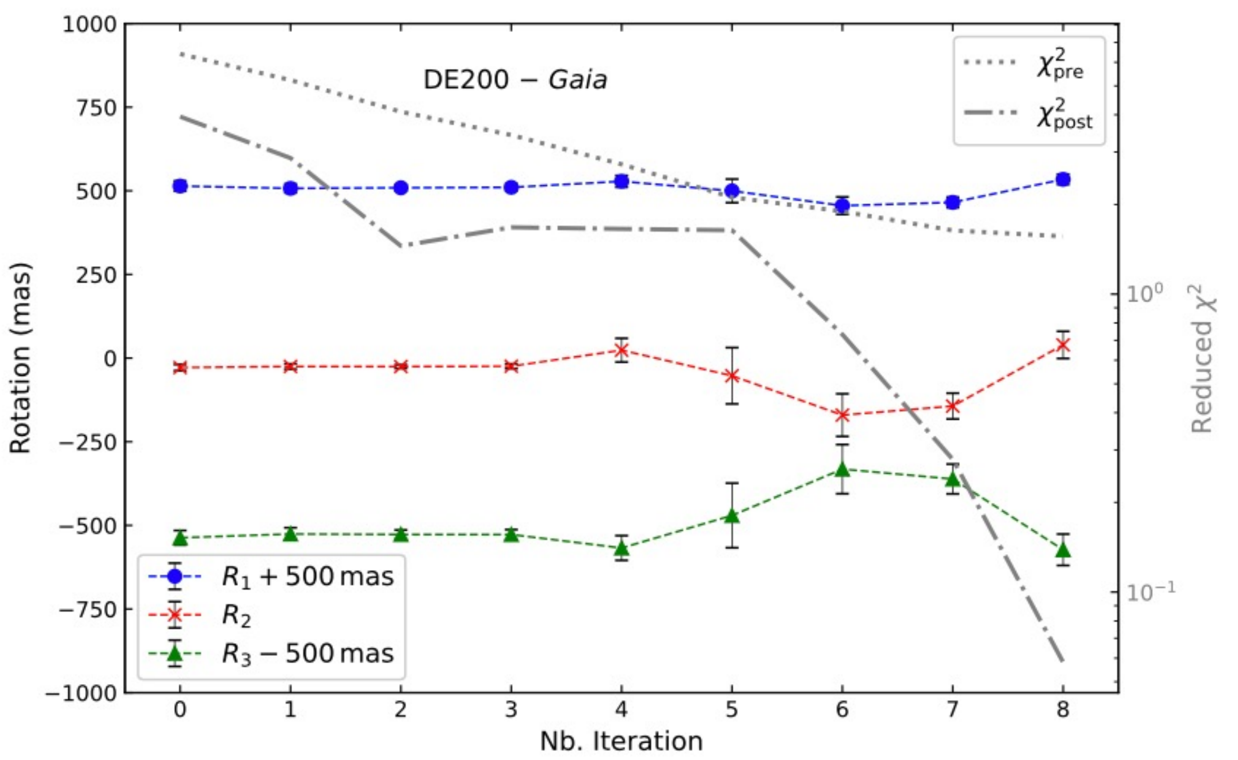
Position comparison:Timing vs. VLBI

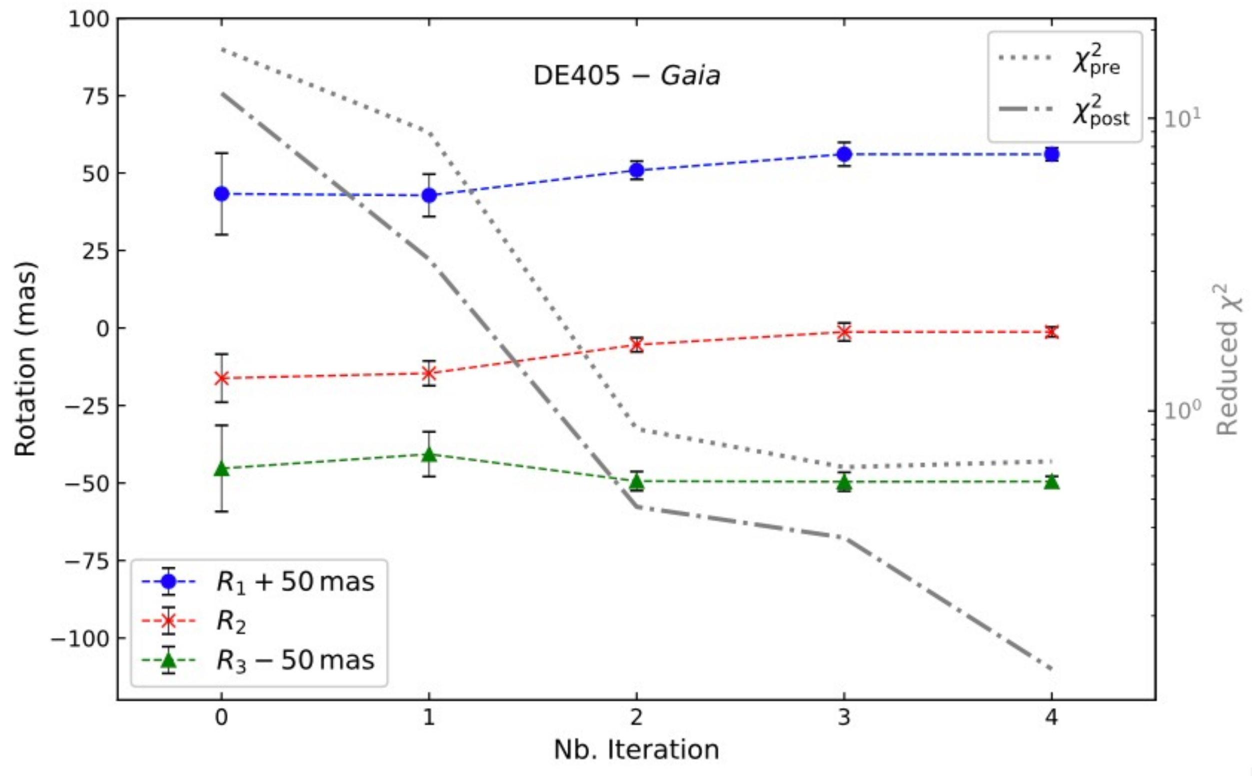


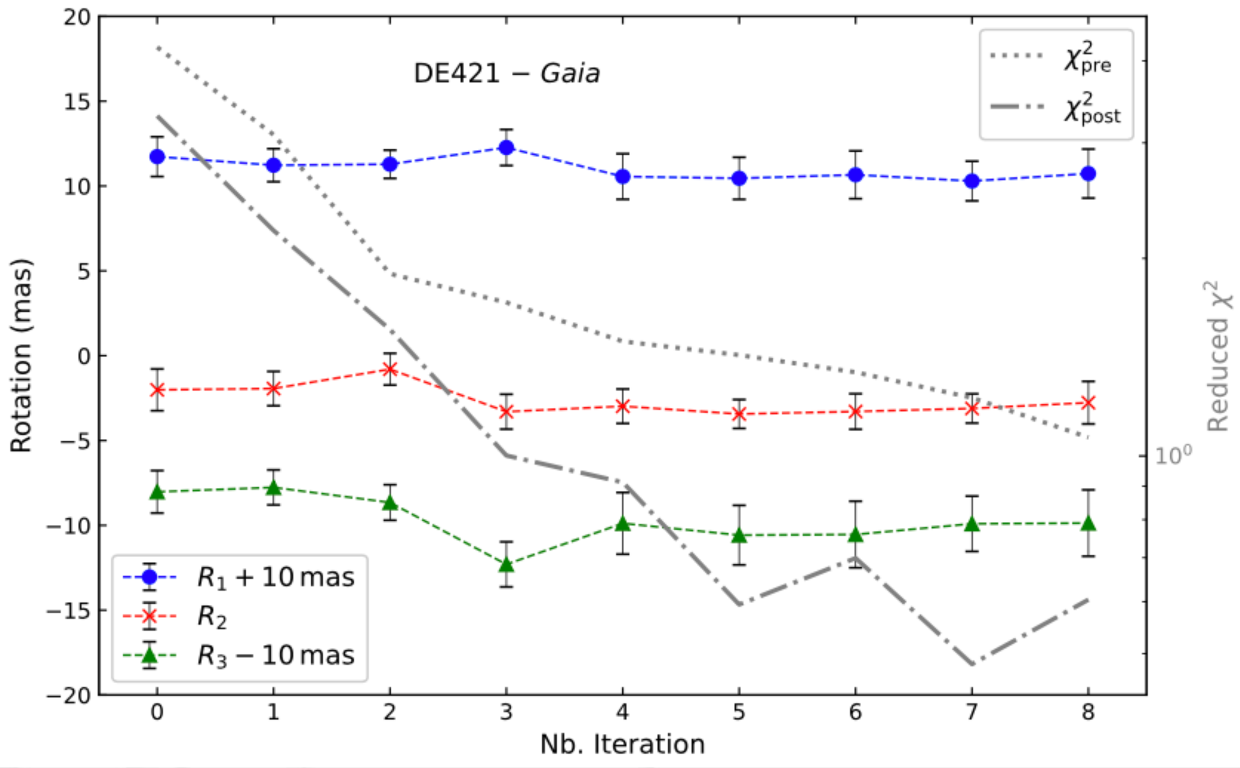
Use DE200 as an example, the behaviors of the non-MSPs differed significantly from the MSPs.

Frame rotation:Timing vs. Gaia

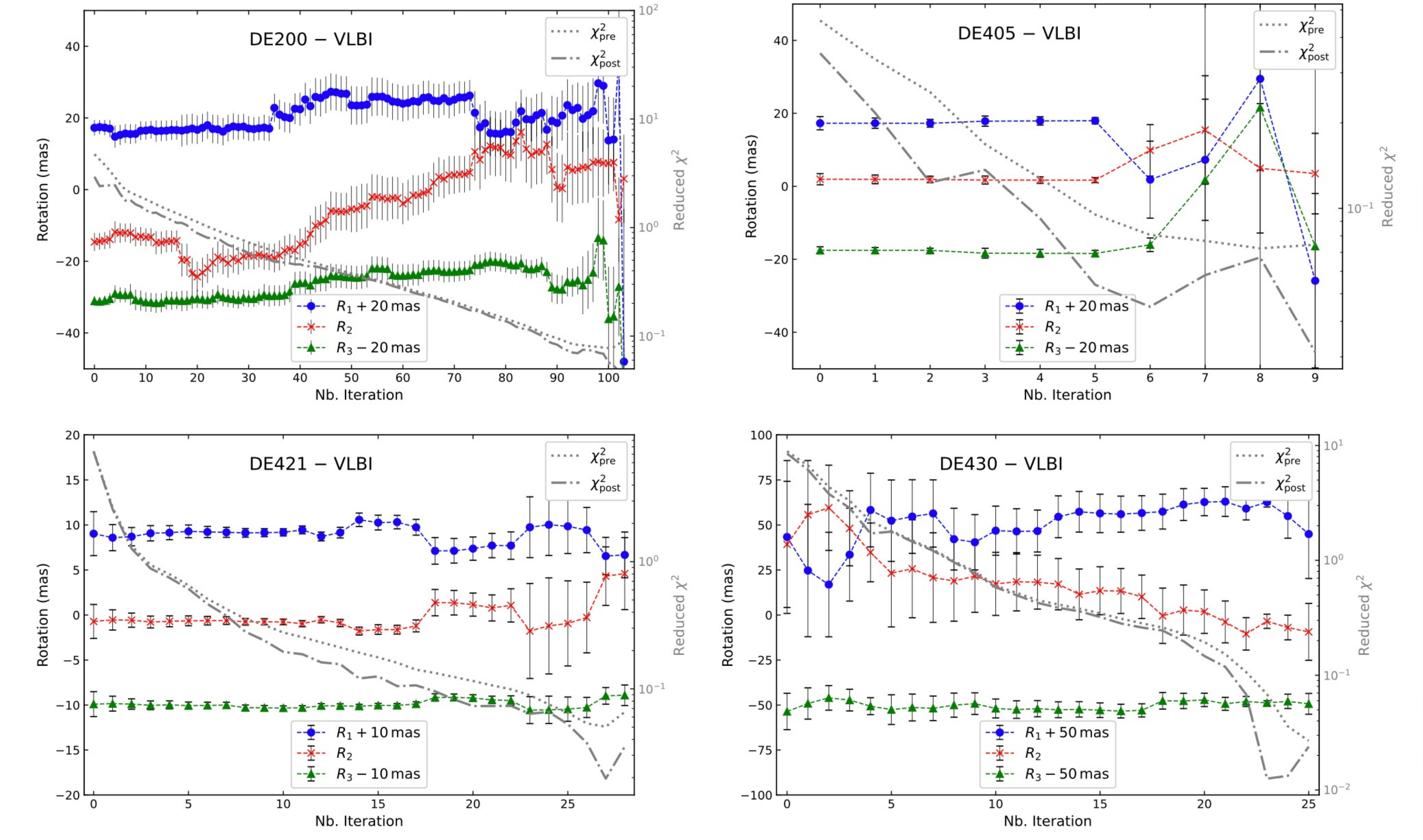
- A frame rotation was used to fit the positional offsets.
- An iterative LSQ fitting, by removing one outlier each time, was performed to get reliable estimates.
- The fitting converged at some stages.





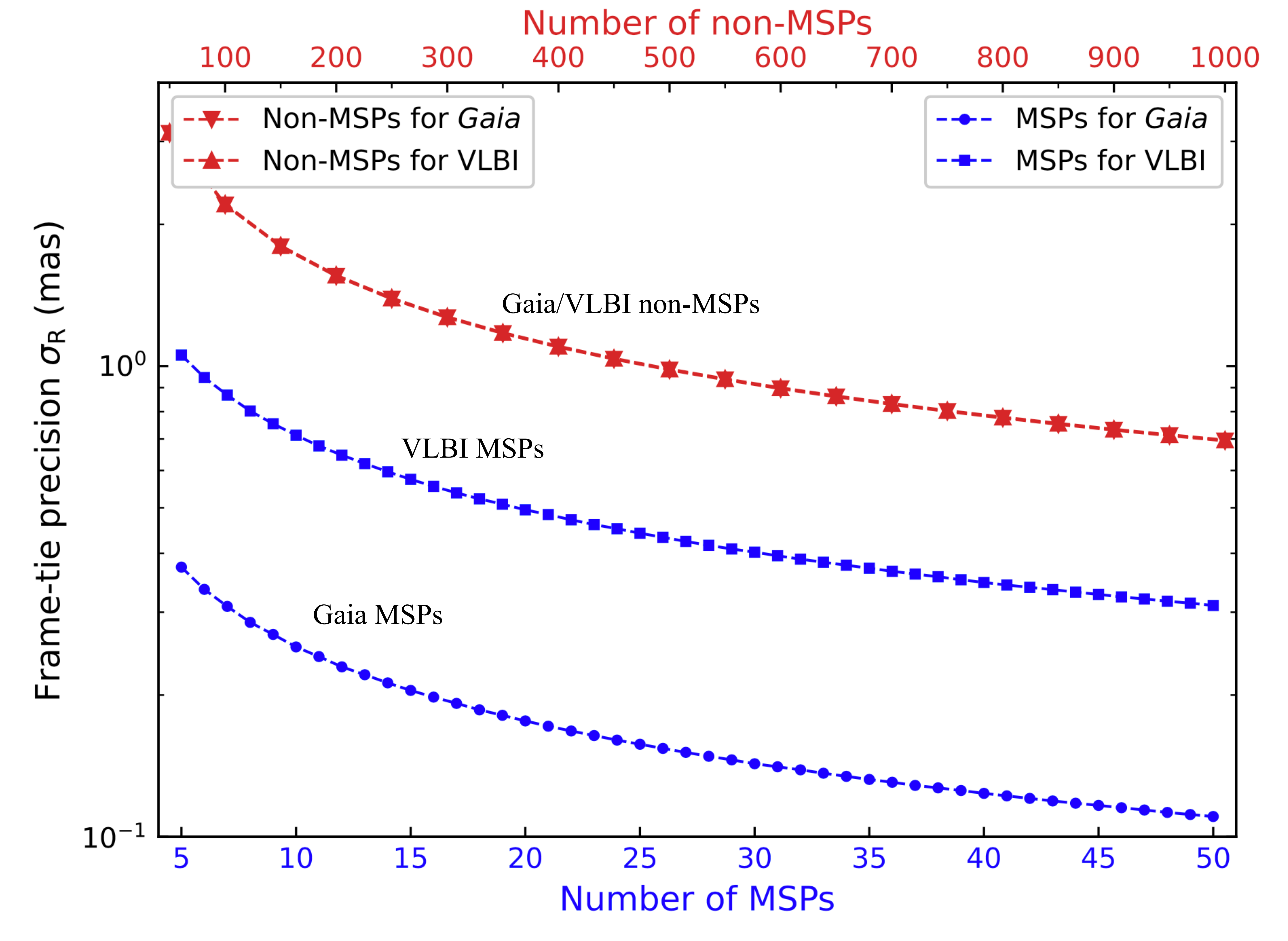


Frame rotation:Timing vs. VLBI



The results strongly depend on the subset used in the comparison and they could be biased by underestimated errors in the archival timing data, reflecting the limitation of using the literature timing solutions to determine the frame rotation.

How accurate is the frame-tie via pulsar?

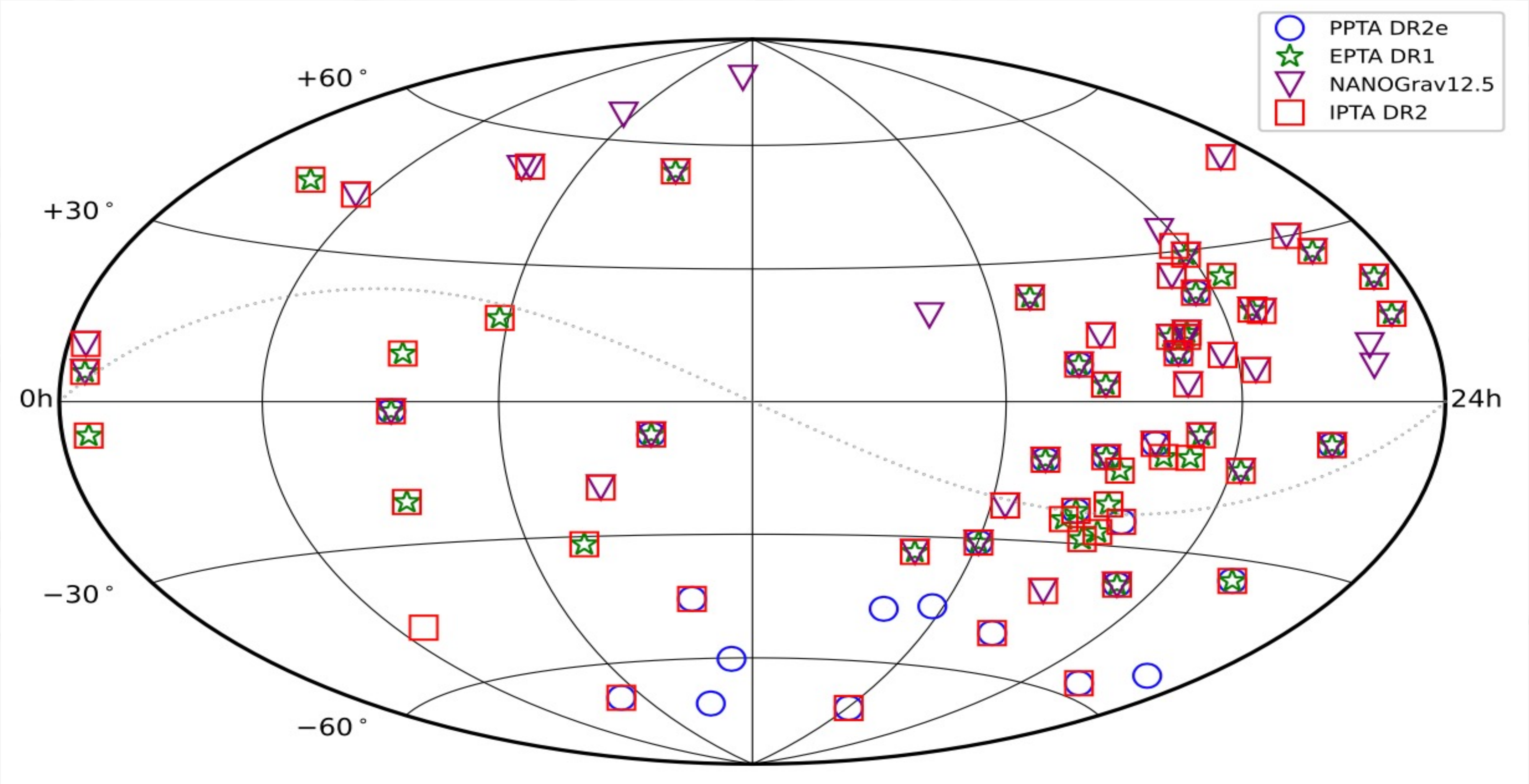


- Timing
  - millisecond pulsar ~ 0.2 mas
  - young pulsar ~ 10 mas
- VLBI ~ 1 mas
- Gaia ~ 0.3 mas

The frame tie via pulsar should focus on a subset of well-selected millisecond pulsars (MSPs).

Can we improve the results? Yes!

80 MSPs regularly monitored by pulsar timing arrays (PTAs, up to April 2022)

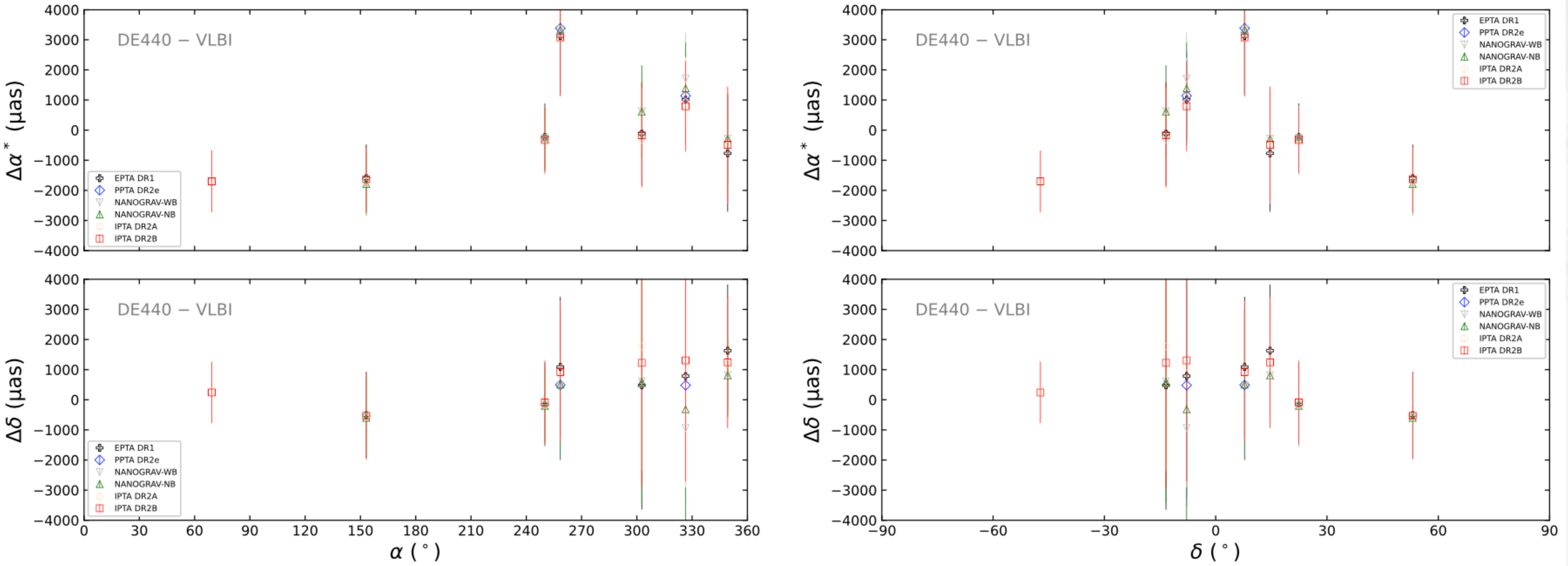


Data sets for new pulsar sample (MSPs only)

- Found seven MSPs observed by VLBA and LBA
- Only found two MSPs in common between PTA and Gaia DR3
- Reanalyzed the timing observations from PTAs using different planetary ephemerides (DE, EPM, and INPOP)

Pulsar	Timing					VLBI					Ref.
	Epoch	σ_{α^*} (μas)	σ_{δ} (μas)	$\sigma_{\mu_{\alpha^*}}$ (μas yr^{-1})	$\sigma_{\mu_{\delta}}$ (μas yr^{-1})	Eopch	σ_{α^*} (μas)	σ_{δ} (μas)	$\sigma_{\mu_{\alpha^*}}$ (μas yr^{-1})	$\sigma_{\mu_{\delta}}$ (μas yr^{-1})	
J0437−4715	2009.5	5	5	1	2	2007.0	1015	994	50	90	1
J1012+5307	2009.5	49	64	10	14	2016.9	900	1000	90	140	2
J1640+2224	2009.5	46	65	13	19	2016.3	971	1000	80	140	3
J1713+0747	2009.5	5	10	1	2	2002.0	1486	2000	170	160	4
J2010−1323	2009.5	148	614	56	237	2012.2	1459	4000	329	303	5
J2145−0750	2009.5	97	268	25	69	2012.2	1486	4000	52	90	5
J2317+1439	2009.5	88	173	25	49	2012.2	1451	1000	465	704	5

Position comparison:Timing vs. VLBI (new)



Some discrepancies among different PTAs but still consistent within the formal uncertainties

Orientation offsets of ephemeris frames vs. VLBI frame

Ephemeris	R_X (μas)	R_Y (μas)	R_Z (μas)
DE200	−3141(221)	−11806(216)	−14803(189)
DE405	−2478(219)	−372(210)	1200(187)
DE410	−929(212)	−1233(204)	−152(183)
DE421	−904(218)	−820(211)	4(187)
DE430	−1011(220)	−637(216)	431(189)
DE440	−896(221)	−587(217)	292(189)
EPM2011	−1013(221)	−472(217)	668(190)
EPM2015	−1106(221)	−523(217)	619(189)
EPM2017	−1070(218)	−505(212)	529(188)
EPM2021	−971(221)	−600(216)	412(189)
INPOP06c	−893(222)	−882(218)	61(190)
INPOP08a	−655(217)	−429(211)	−683(187)
INPOP10a	−769(217)	−763(211)	311(187)
INPOP10b	−900(221)	−286(216)	534(189)
INPOP10e	−1124(223)	−726(217)	242(190)
INPOP13c	−1002(221)	−732(217)	210(190)
INPOP17a	−1076(221)	−413(217)	281(190)
INPOP19a	−978(221)	−276(217)	130(189)
INPOP21a	−1170(221)	−164(216)	225(189)

- Improved results compared to previous studies
- Formal uncertainties of frame rotation estimation to be 0.2 mas but systematics may exist considering discrepancies between using different PTA data sets
- Misalignment of current planetary ephemeris celestial reference frames to be smaller than 0.4 mas, consistent with results based on other methods

Summary

- We explored the possibility of using pulsars to tie the planetary ephemeris reference frame with the extragalactic frame based on both the archival timing solutions and a reanalysis of measurements from PTAs.
- Our results showed improvements in the precision for determining the frame rotation; however, discrepancies were observed between timing solutions from different PTAs.
- The misalignment of current planetary ephemeris celestial reference frames was found to be smaller than 0.4 mas, roughly consistent with results based on other methods.
- For more details, please look at Liu et al., A&A 670, A173 (2023); A&A 674, A187 (2023).
- Future prospects
  - Future data releases from PTAs should be more consistent.
  - Absolute VLBI positions should be improved with reduced extrapolated errors of calibration or with a large beam.
  - Deeper and accurate optical observations of the companions in the binary MSP systems using Gaia sources as the reference may improve the frame tie.

Thank you for your attention!