Quasometry, Its Use and Purpose

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The use of quasars in global astrometry

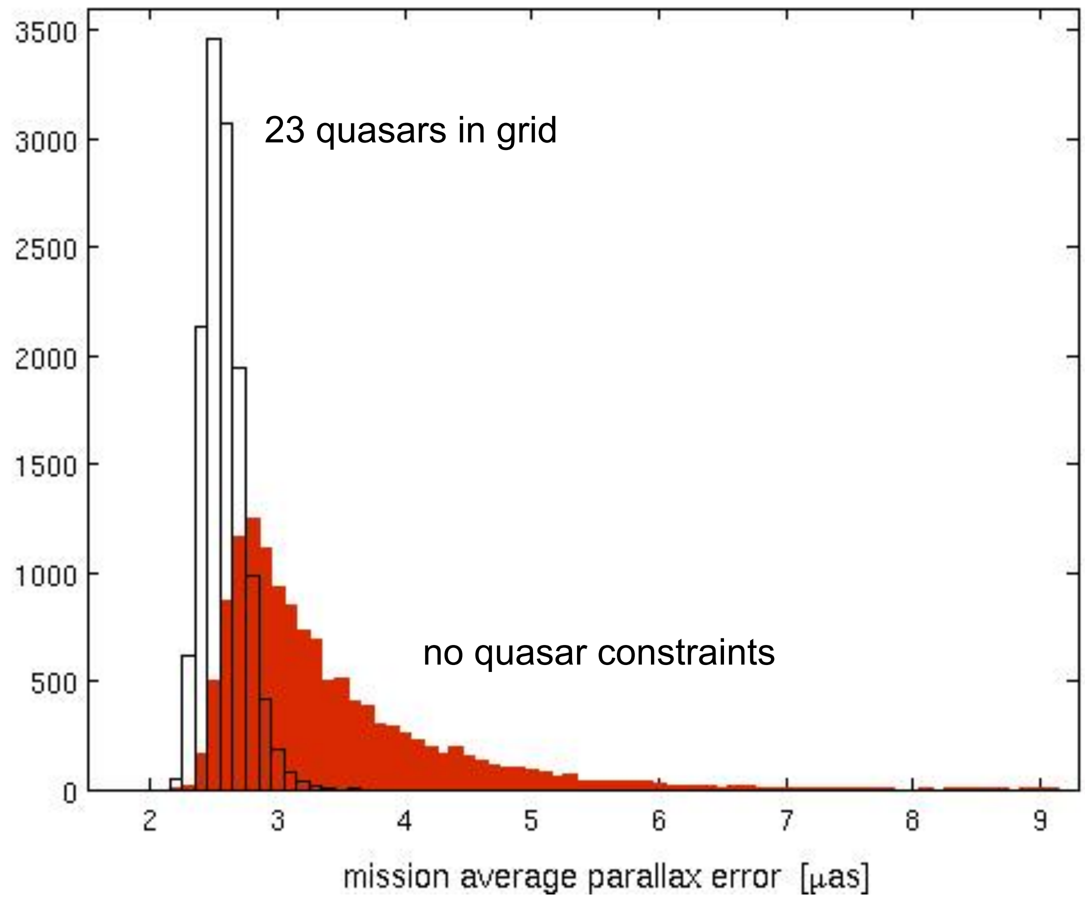
Performance of a global astrometric mission is characterized by a mission-average error (e.g., of parallax), which is a statistic

Confidence levels of mission average error are related to the uncertainty of the outcome, i.e., "the sigma of the sigma"

For *SIM*, using just 23 quasars in the grid solution, not only improves the mission expectancy, but practically eliminates the risk of a very bad outcome (through computation of singular values of the design matrix)

To fully realize this advantage, the quasar constraints should be hard-coded in the observational equations

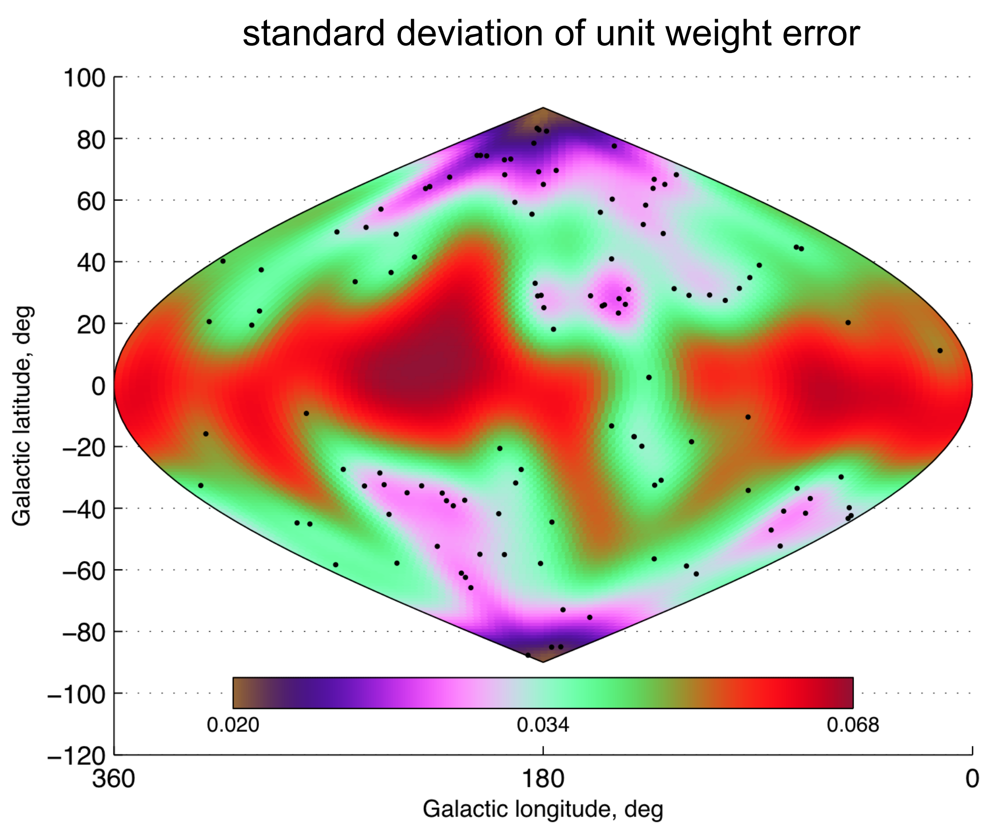
Space Interferometry Mission, distribution mission-average error



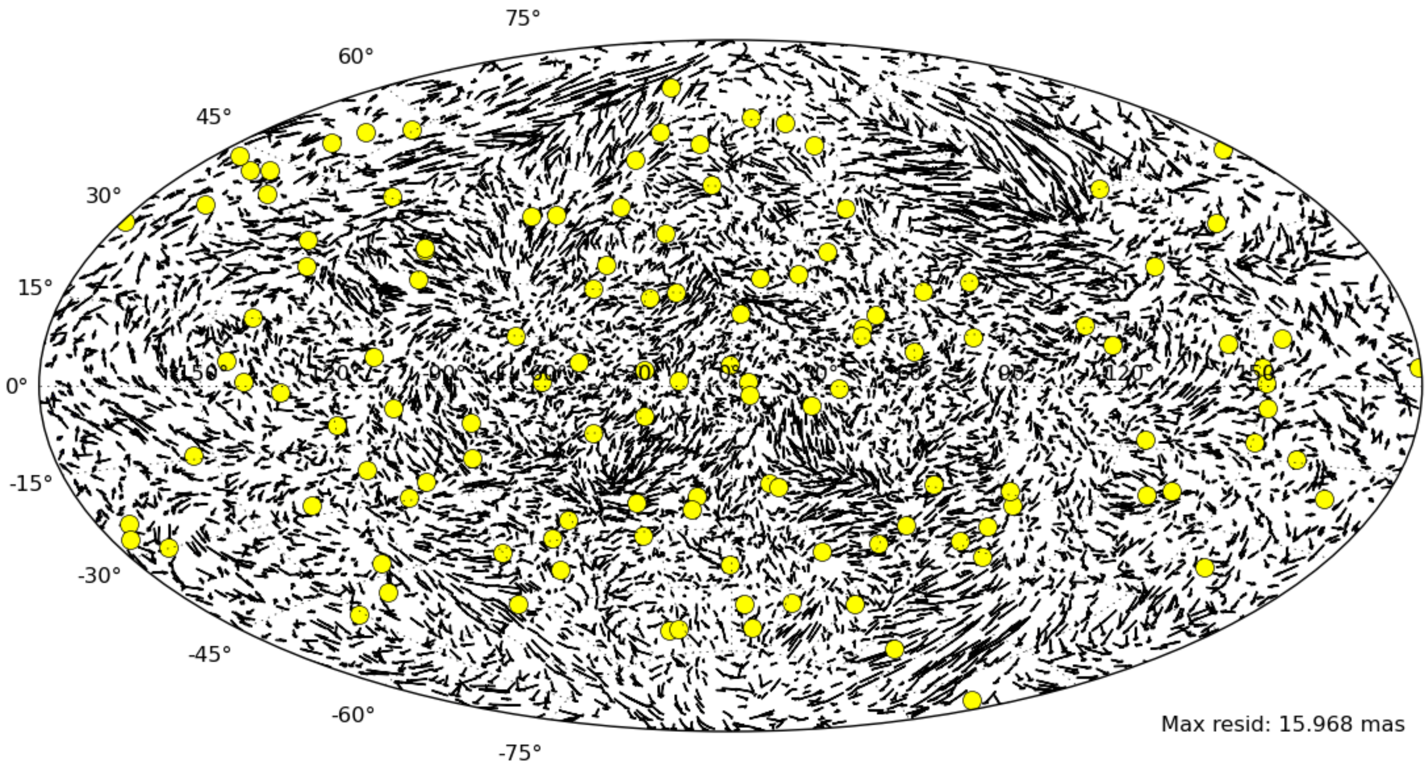
Anchoring the parallax

Simulation of a global astrometric mission, showing unit weight zonal error (std) of parallax

80 quasars are used as “hard” zero-parallax constraints

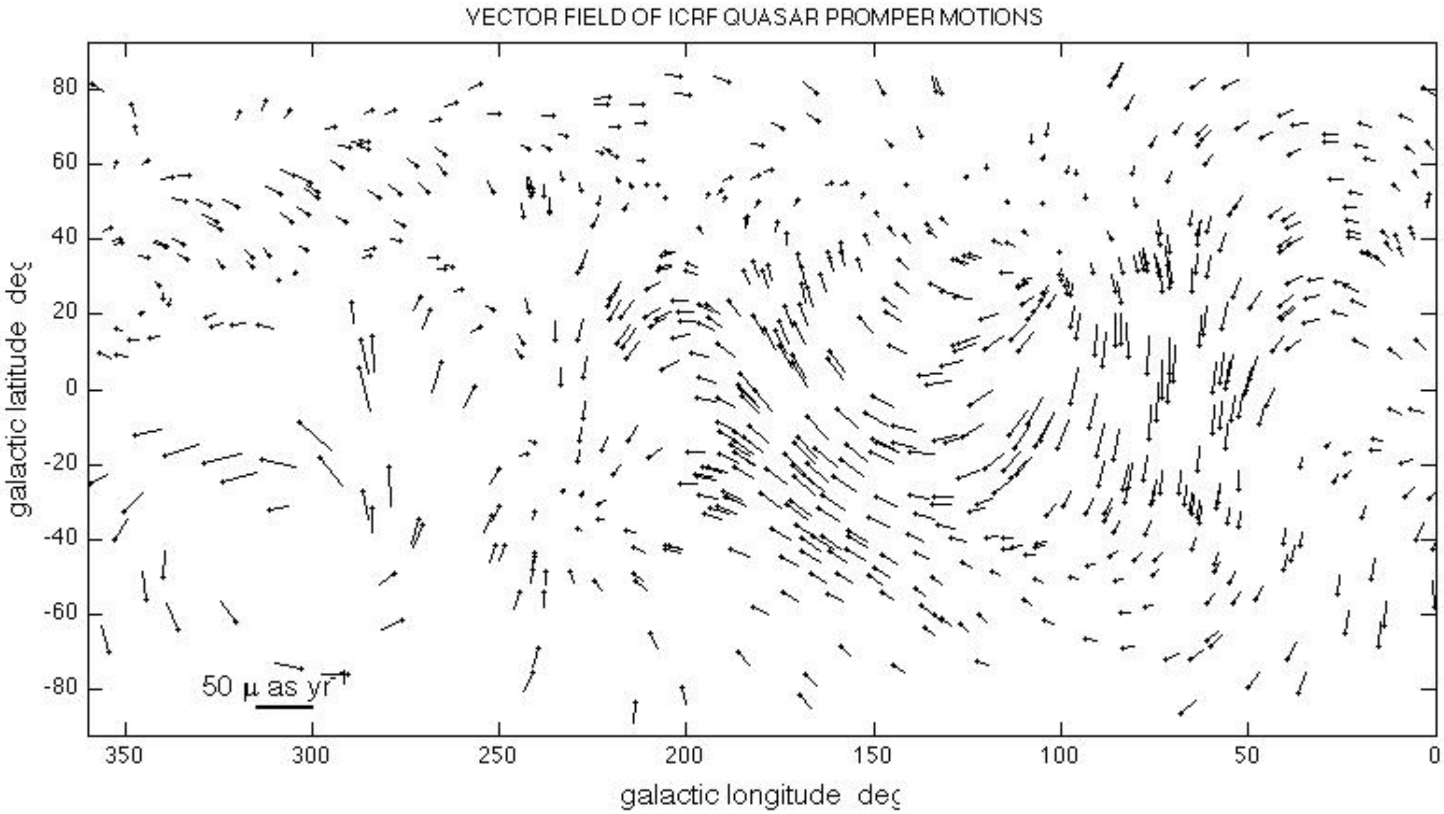


Anchoring proper motions



A global astrometric solution for 400 000 stars with 200 quasars used as zero-proper motion constraints

“Proper motions” of ICRF quasars

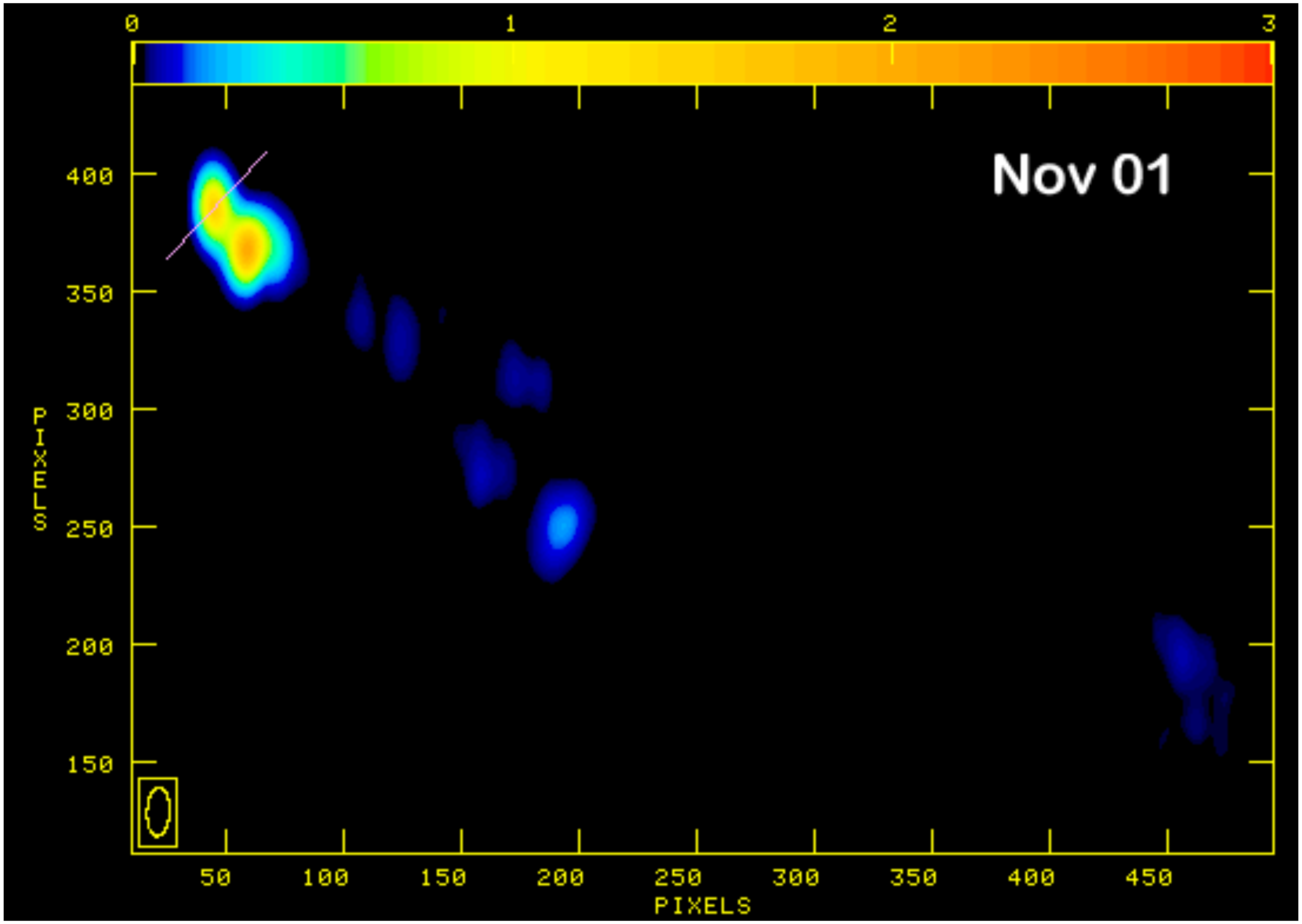


Systematic component of quasar proper motion field <50 µas/yr – absolute upper bound

None of the spherical harmonics (up to 3rd order) are statistically significant

Data courtesy of O. Titov 2011A&A...529A..91T

http://www.astro.cf.ac.uk/groups/instr/3C273_2B_Movie.gif



Global solutions on your laptop

- Global solutions are nontrivial for astrometric missions:
  - Number of unknowns $10^7 - 10^8$
  - NNZ of normal matrices ~$10^9 - 10^{10}$
  - Number of equations $10^8 - 10^9$
- Instead of solving for millions of star parameters, we can solve directly for zonal corrections

Least Squares solution $$\tilde{x} = (A^T A)^{-1} A^T y$$

Zonal errors represented by spherical harmonics:

$$\delta \vec{p}(\lambda,\beta) = \sum a_l^m \vec{V}_l^m (\lambda,\beta)$$

$$\delta \Pi(\lambda,\beta) = \sum b_l^m S_l^m (\lambda,\beta)$$

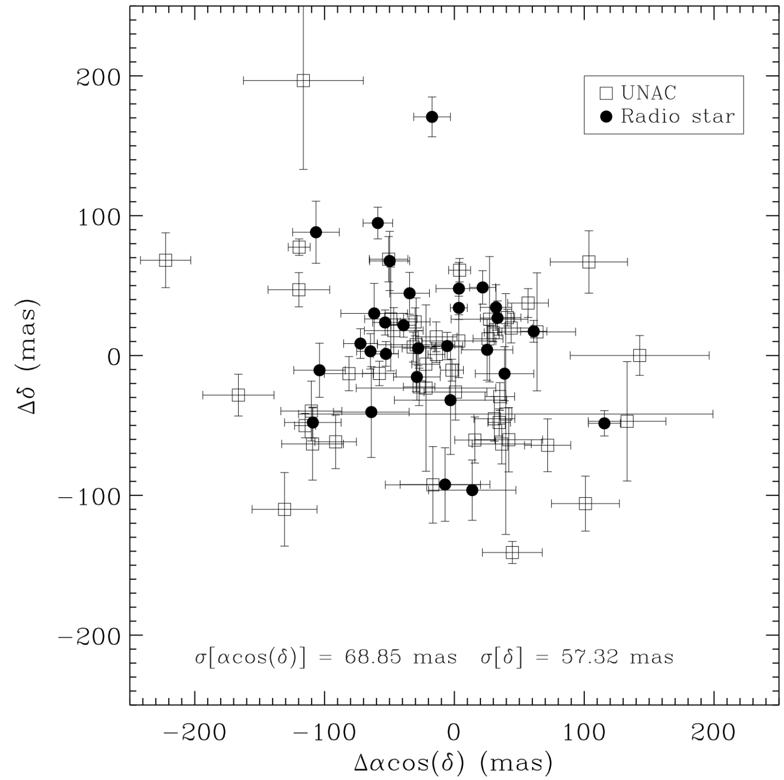
$$\delta \vec{\mu}(\lambda,\beta) = \sum c_l^m \vec{V}_l^m (\lambda,\beta)$$

- Spherical harmonics are orthogonal, therefore, solution is accurate for any limited number of them

Positions: hard constraints vs. a posteriori adjustment

- Alignment of the optical frame and ICRF and the *optimal* correction of positional zonal errors could be done in one step in a global solution via hard constraints
- But are the positions of ICRF quasars in the optical the same as in the radio?
- Camargo J.I.B. et al. 2011arXiv1105.0662C: the scatter of optical minus ICRF positions is up to 80 mas and seems correlated with the X-band structure index
- Two problems with this result:
  - Zonal errors of UCAC-2 are underestimated
  - Quasar images should be PSF centered
- Most likely, zonal errors of UCAC2 proper motions, cf. independent result by R. Zavala for bright Hipparcos and radio stars

observed minus Hipparcos positions

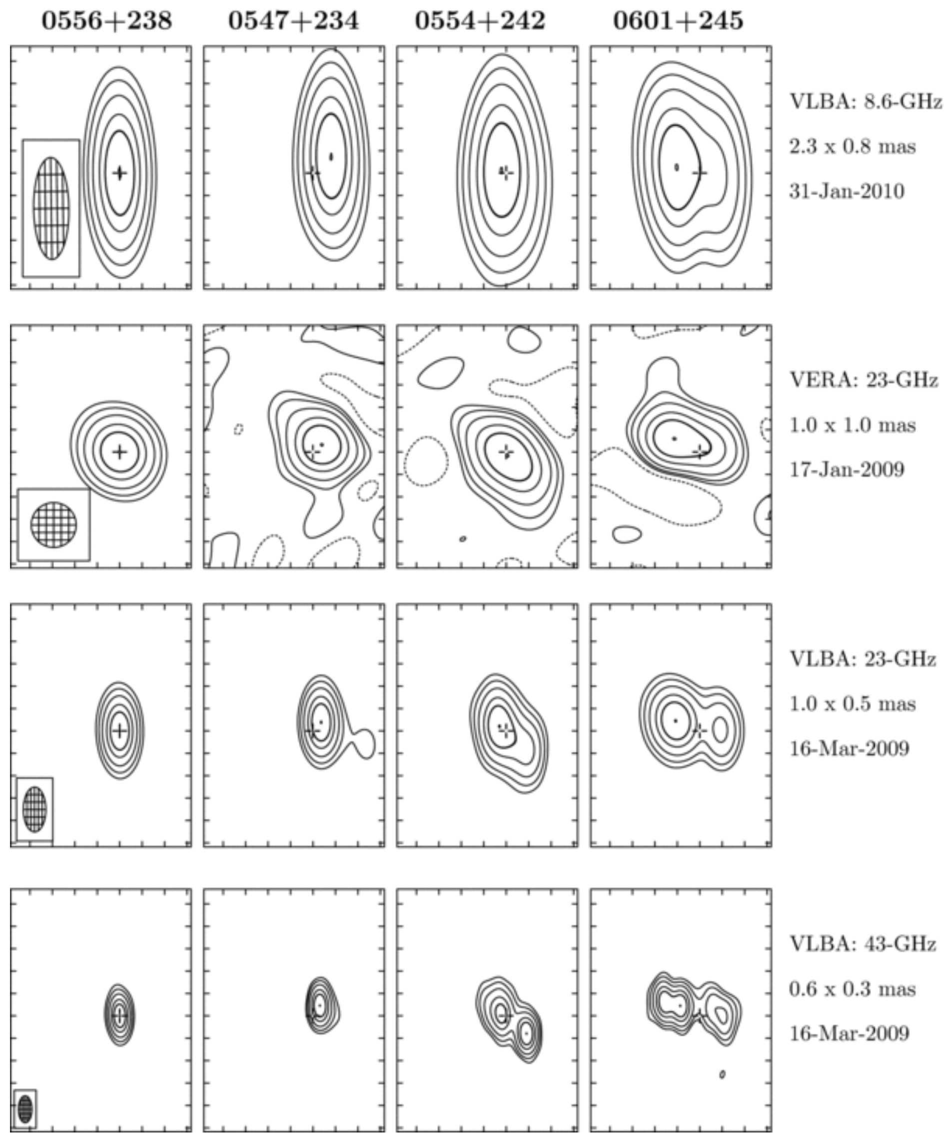


Data courtesy of R. Zavala, USNO

Radio cores and jet components

Fomalont, E. et al. 2011AJ....141...91F : some ICRF positions are dominated by a moving jet component and may be displaced up to 0.5 mas, reflecting the motion of the jet

Stay tuned for K. Johnston's talk on radio/optical offsets



Tidal features, host galaxies and companions

Not in ICRF but on the list of potential additions

Hamilton T.S. et al. **2008ApJ...678...22H** :

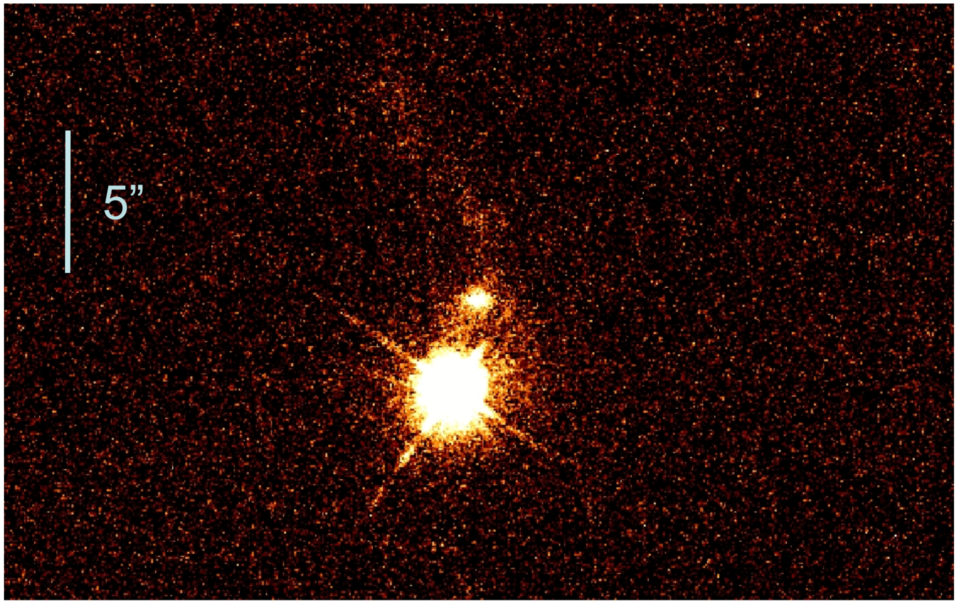
$$M_V(host) = (0.303 \pm 0.088) M_V(nuc) - (15.9 \pm 2.2)$$

Luminosities of host galaxies and nuclei are equal at M_V = -22.8, but all radio-loud QSOs are brighter.

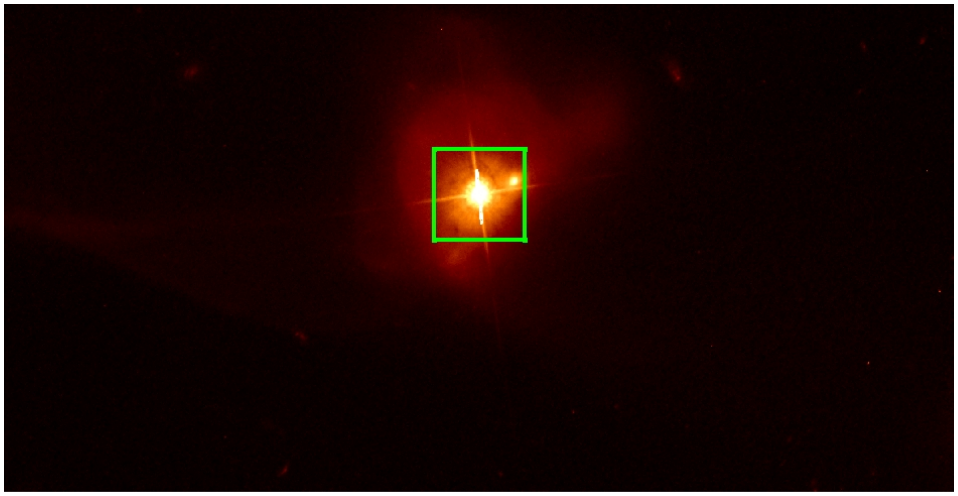
More luminous (i.e., higher-z at a given m_V) quasars are best for optical astrometry because they are less perturbed by the host galaxies

High-z quasars are also more compact on the sky, having roughly the same surface brightness relative to the nucleus.

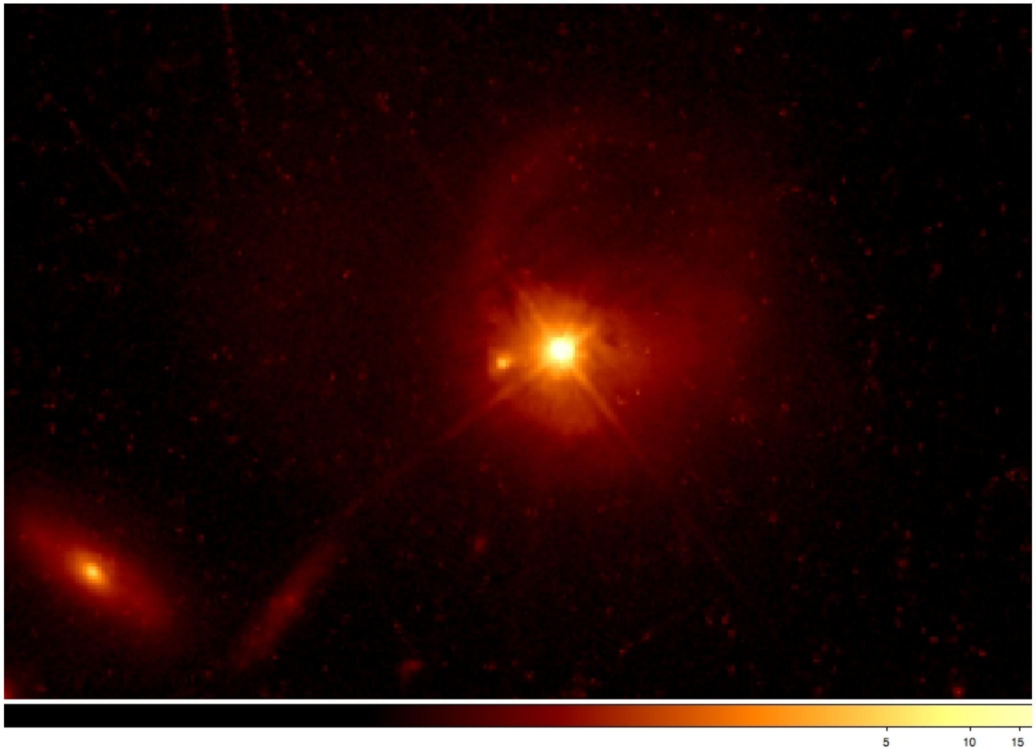
CSO 409, archival HST image

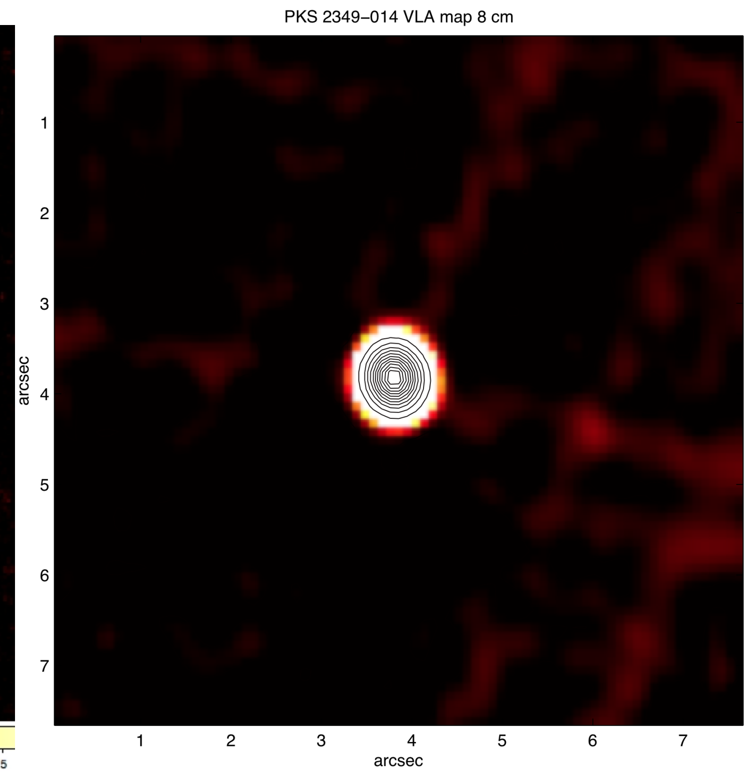


PG 1613+658



PKS 2349-014 at F606W and 8 cm





- HST map reveals a companion at ~2” and extended asymmetric structure
- VLA map indicates an unresolved point-like source

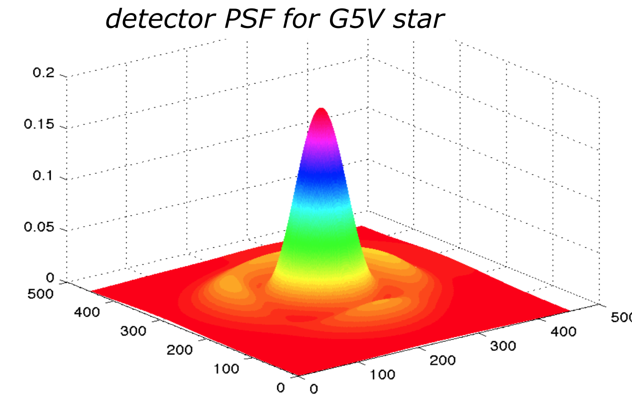
PSF centroiding

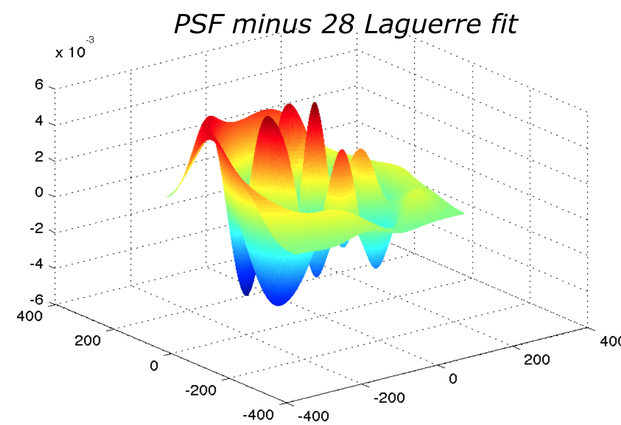
Predicted CoM centroiding errors for PKS 2349-014 from

data from Bahcall J.N. et al. 1995:

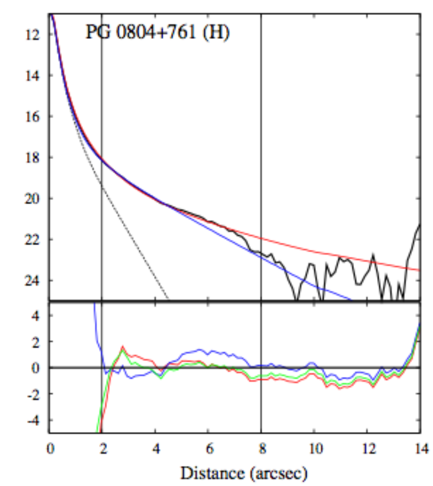
Component	m_{606W}	Centroid offset
Unresolved nucleus	15.3	0
Wisps (tidal tails?)	17.9	150 mas
Extended nebulosity (large, off-center galaxy?)	18.0	200 mas
Companion galaxy (similar to LMC)	21.0	10 mas
Host galaxy centered on nucleus	~18.6	0

Using exact PSF beats down the impact of extended components and companions by more than 2 orders of magnitude – still non-negligible for low-z quasars





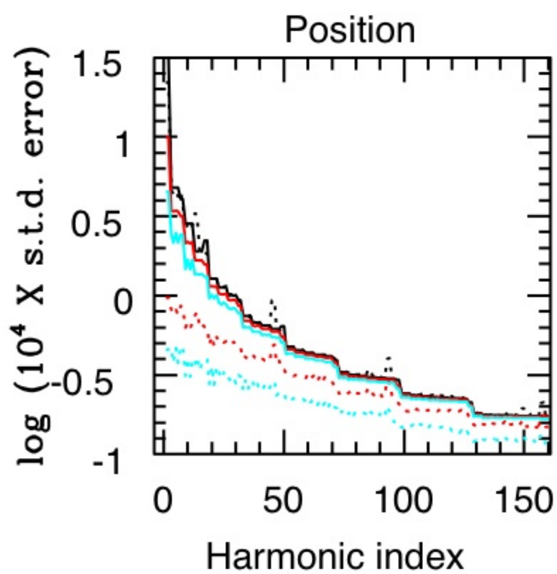
from Guyon, O. et al.
2006ApJS..166...89G



What's better: better quasars or more quasars?

- Andrei, A.H. et al. 2009A&A...505..385A: initial list of quasars for GAIA, 100 165 sources, incl. redshifts and photometry
- Alternative approach: invest in quality, carefully selected set of a few hundred QSOs, preferably prime ICRF sources

	Pro	Contra
more quasars	• smaller zonal errors	• confusion with stars, galaxies • bad objects can corrupt solution • hard constraints can not be used (loss of accuracy)
better quasars	• hard constraints for a global solution • simpler data reductions • no misidentification, ambiguity • possible direct tie to ICRF	• larger low-order zonal errors (loss of precision) • quasars can not be used for instrument calibration



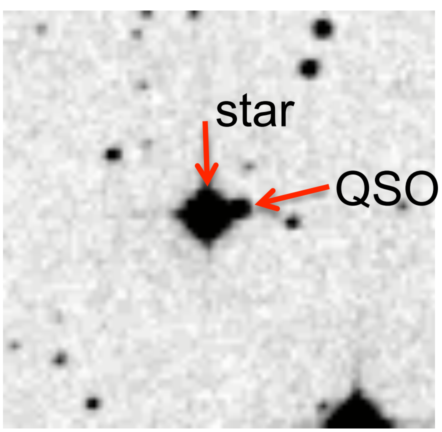
Zonal errors of ICRF-optical frame alignment with 5 (black), 200 (red) and 518 (cyan) ICRF quasars

Ongoing and future work at USNO

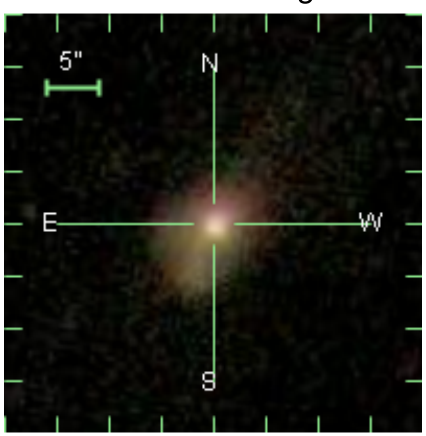
- Include new radio-loud, compact QSOs in the ICRF – new VLBI campaign (+ VLA images) (see G. Bourda's talk and 2011A&A...526A.102B about a parallel program)
- Photometric survey of ICRF and zero-parallax quasars at Chile and AZ, started in 2005 (R. Ojha et al.
2009AJ....138..845O) – differences of 1—3 mag found with previous data for some objects, nearby extended and extremely faint OSOs identified
- Screening of extended list using available archival information

A tempting but flawed solution: reject "bad" quasars by observational residuals

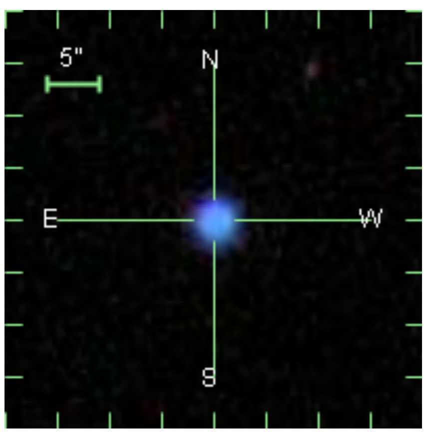
optical companions



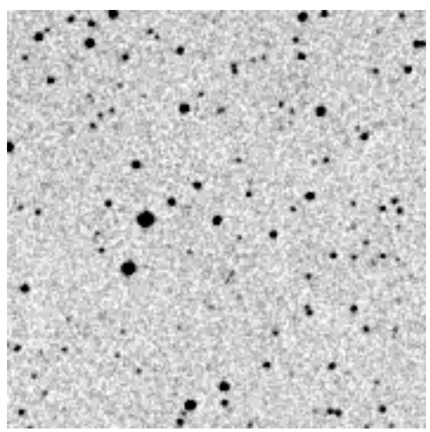
extended images



OK?



insufficient information



Dudik's list

DEC	RA	DEC	RA rounded	Dec Rounded	Galaxy Name	ICRF RA round	ICRF Dec Round	ICRF Type	Ciprian W4	SMP-1	Final Weight
32.12	21 58 52.065	-30 13 32.120	21 58 52	-30 13 32	[HB89] 2155-304	21 58 52	-30 13 32	non-VCS	20.83971913	1.677206385	0.175366736
08.60	12 29 6.700	2 3 8.600	12 29 7	2 3 9		12 29 7	2 3 9	non-VCS	25.16380284	1.726866147	0.98956125
59.05	15 58 21.948	-14 9 59.050	15 58 22	-14 9 59	PKS 1555-140	15 58 22	-14 9 59	non-VCS	24.32385719	1.840718496	0.779062197
00.73	17 51 32.819	9 39 0.730	17 51 33	9 39 1		17 51 33	9 39 1	non-VCS	21.76560209	2.052253015	0.290923198
24.69	13 37 39.783	-12 57 24.690	13 37 40	-12 57 25		13 37 40	-12 57 25	non-VCS	20.80798139	2.110346453	0.134453065
04.02	18 0 45.684	78 28 4.020	18 0 46	78 28 4		18 0 46	78 28 4	non-VCS	21.55282086	2.13459684	0.247087511
30.64	8 54 48.875	20 6 30.640	8 54 49	20 6 31		8 54 49	20 6 31	non-VCS	21.37072952	2.144610566	0.218154882
07.80	2 22 39.612	43 2 7.800	2 22 40	43 2 8		2 22 40	43 2 8	non-VCS	22.06495103	2.165192313	0.32098129
36.66	4 7 48.431	-12 11 36.660	4 7 48	-12 11 37		4 7 48	-12 11 37	non-VCS	25.47429887	2.231600971	0.811267365

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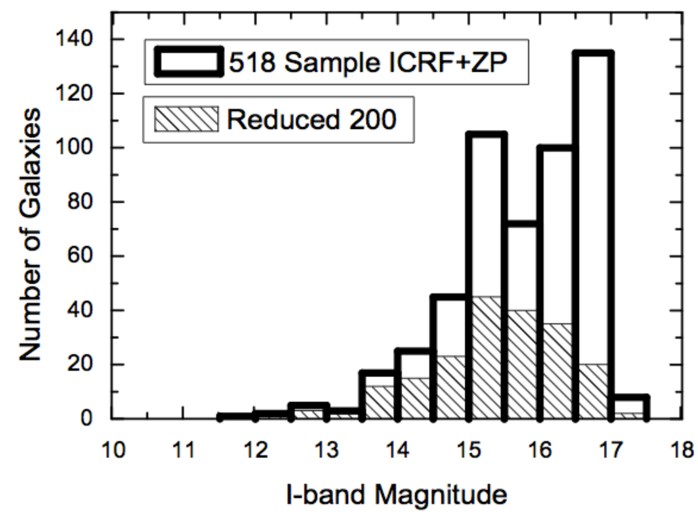
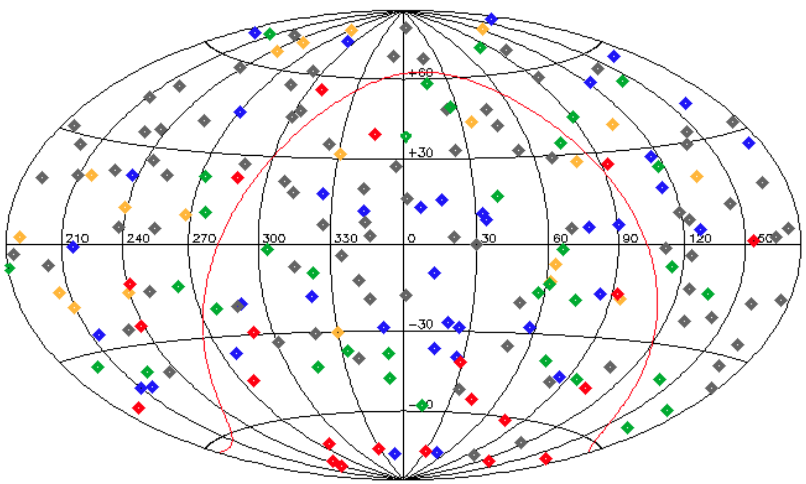
- 518 sources total
- 393 ICRF sources
- 125 zero-parallax sources
- Ranked by 2D metric:
  - optical brightness
  - distribution on the sky
- Cut at z > 0.10

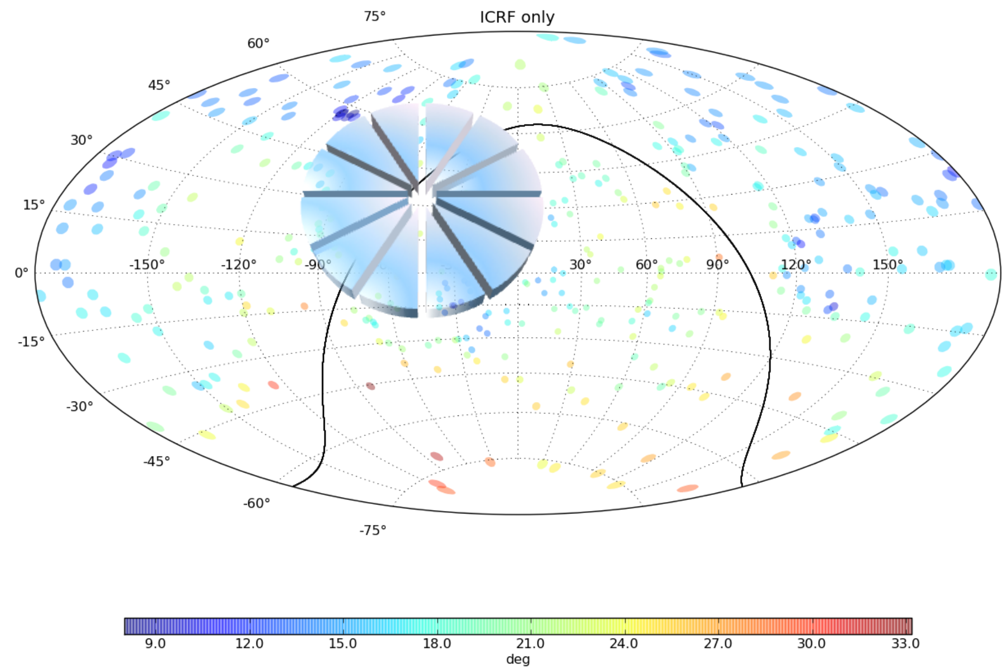


The “precious set”

- Currently 201 quasars (150 ICRF, 51 ZP)
- More distant than 425 Mpc (z > 0.10)
- Directional near neighbor statistics used to achieve most uniform sky distribution



Yellow = 12-14mag, blue = 14-15mag, green = 15-16mag, black = 16-16.5 mag, red = 16.5-17mag



Applications of quasometry in physics and cosmology

In the talks to follow…