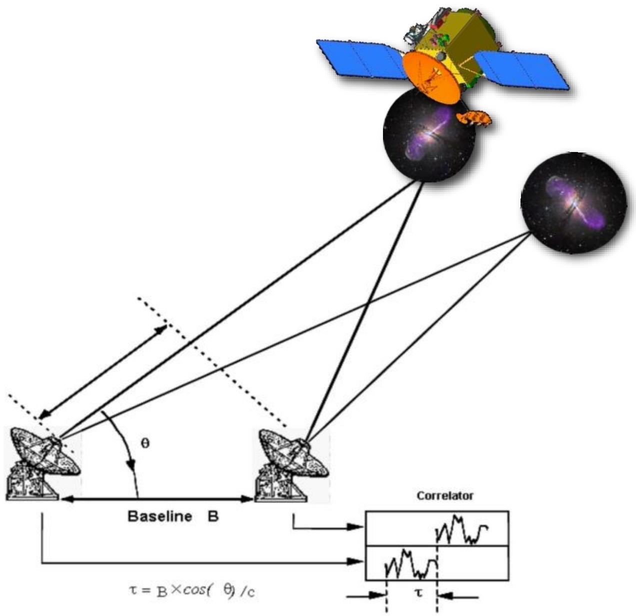
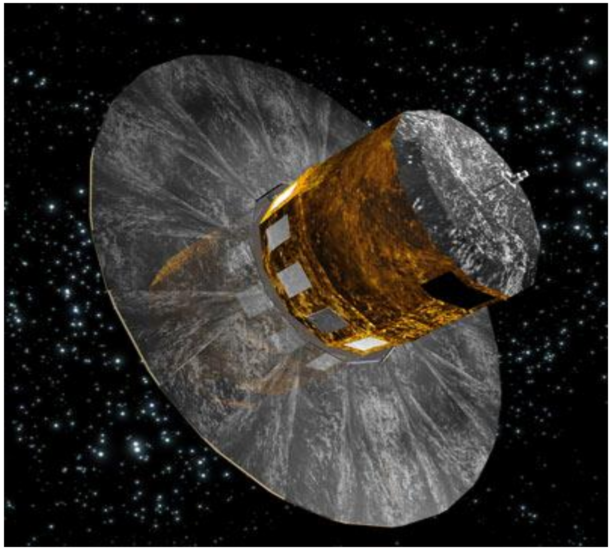
Tying multiple Radio Wavelength Celestial Frames to the Gaia Optical Frame





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Overview: Optical vs. Radio Celestial Frames

- **History:** VLBI at SX (8 GHz, 3.6cm) has been only sub-mas frame until last 10 years (e.g. *Ma+, ICRF1, 1998, Ma+, ICRF2, 2009*)

- K-band (24 GHz, 1.2cm) now sub-mas (*Lanyi+, 2010; de Witt+, 2016*)

- X/Ka (32 GHz, 9mm) also sub-mas (*Jacobs+, 2016*)

- Gaia optical: data release #1 is sub-mas for auxiliary quasar solution (*Prusti+, 2017*)

- Precision is excellent allowing 3-D rotational alignment precision of 10 to 20 μas

- Accuracy limited by VLBI systematics due to weak southern geometry, tropopshere, etc. at few 100 μas

- Gaia precision limited to ~ 500 μas by short span of data in DR#1.

What objects can we use?

Methods for Tying Optical and Radio Celestial Frames

- Need common objects well measured in both optical and radio

- **Radio stars:** Previous generation used galactic stars that emit in radio,
  Crude by today's standards: difficult to achieve desired accuracy level.
  e.g. Lestrade et al. (1995).

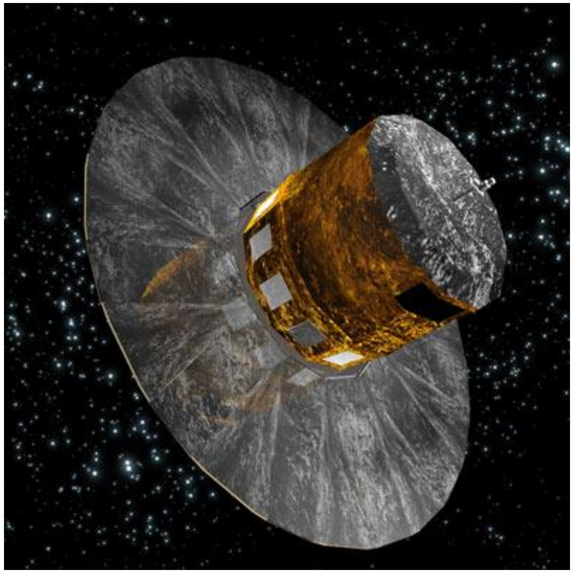
- **Thermal emission from regular stars:**
  350 GHz astrometry using Atacama Large Millimeter Array (ALMA)
  Fomalont et al. (pilot observations)
  Verifies bright end of optical, but likely limited to 500 – 1000 μas (2.5 to 5 ppb).

- **Extra-galactic Quasars:** detectable in both radio and optical
  potential for better than 100 μas to 20 μas (0.5 to 0.1 ppb).
  Strengths: extreme distances (> 1 billion light years) means no parallax or proper motion

The Gaia Optical Frame

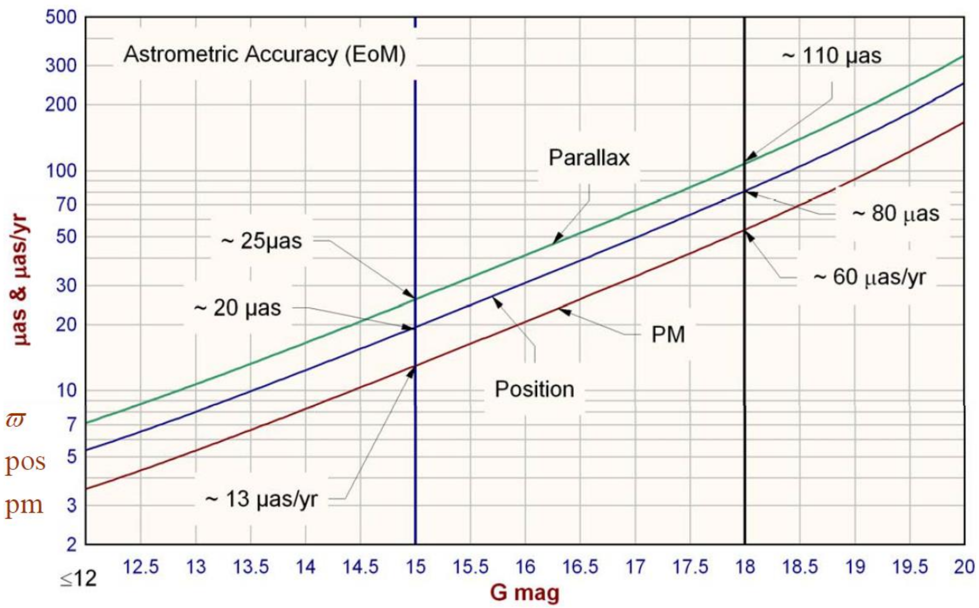
ESA's Gaia optical Astrometry

- Method: extremely accurate centroid of 60 mas pixels. Compare to VLBI sub-mas beam.
- **Astrometry & photometric survey to V = 20.7^{mag}**
  - ~10^9 objects: stars, QSOs, solar system, galaxies.
- **Gaia Celestial Reference Frame (GCRF):**
  - Optically bright objects (V< 18mag) give best precision
  - 1st release Gaia astrometric catalog DR1 Sep 2016,
  - DR2 Apr 2018.



Credit: F. Mignard (2013)

Anticipated precision of Gaia catalogue

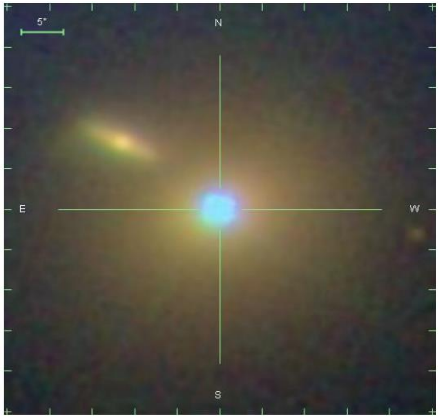
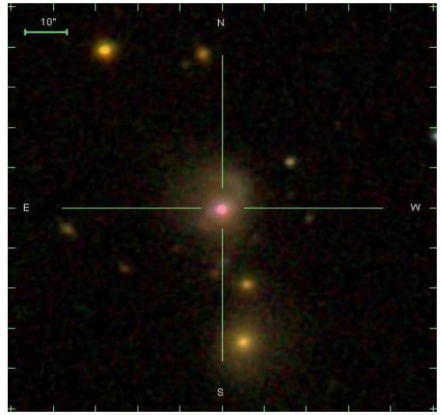
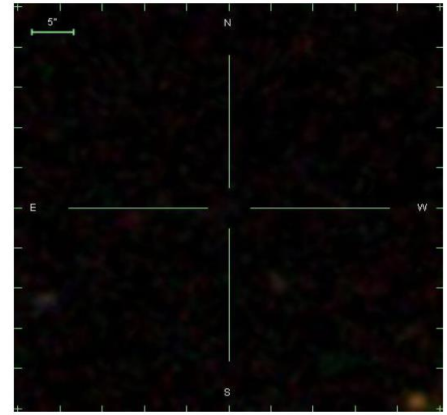


Gaia release-1:

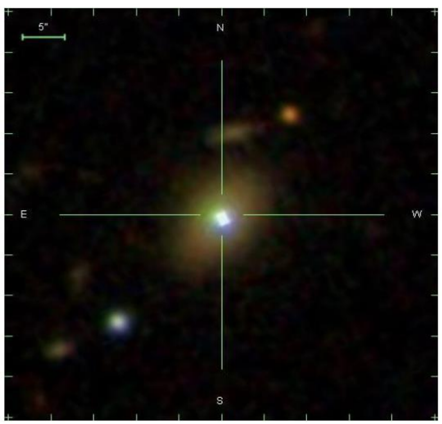
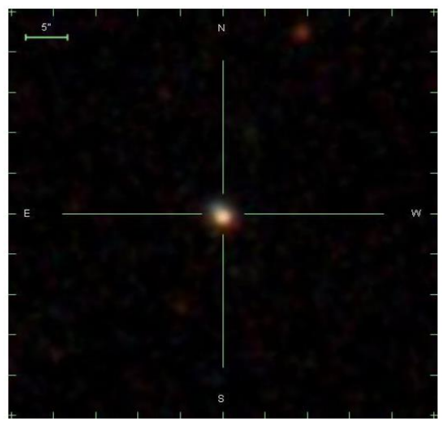
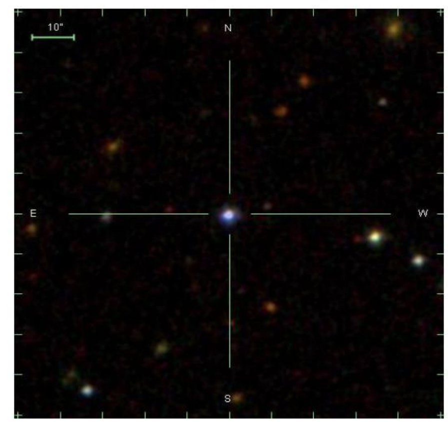
~0.3 mas in positions and parallaxes for 2 million brightest stars **~10 mas for rest of the stars**

Optical vs. Radio systematics offsets

SDSS Optical images of quasars (scale 5-10 asec)

1101+384 0007+106 0920+390

1418+546 1514+192 1546+027

Credit: SDSS

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric.
- Optical systematics unknown, fraction of millarcsecond optical centroid offset?
- Optical imaging generally 10s of milliarcsecond. In general, no sub-mas optical imaging.

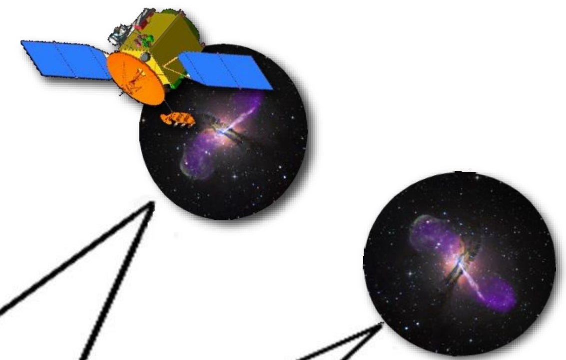
Celestial Frames using Radio Interferometry (VLBI)

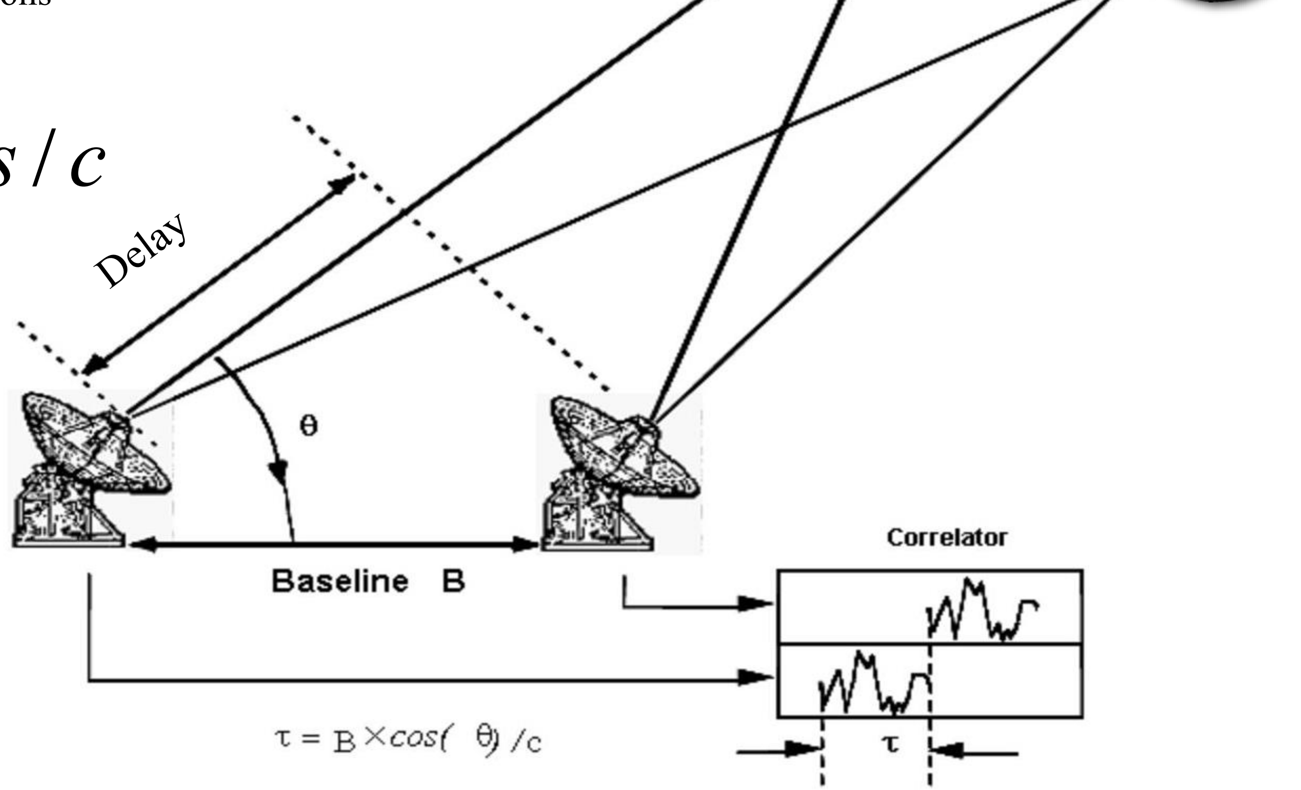
Radio Interferometry: Long distance phased arrays

Very Long Baseline Interferometry is a type of station differenced range from a phased array

- Measures geometric delay by cross-correlating signal from two (2) stations

$$t = B \cdot s / c$$

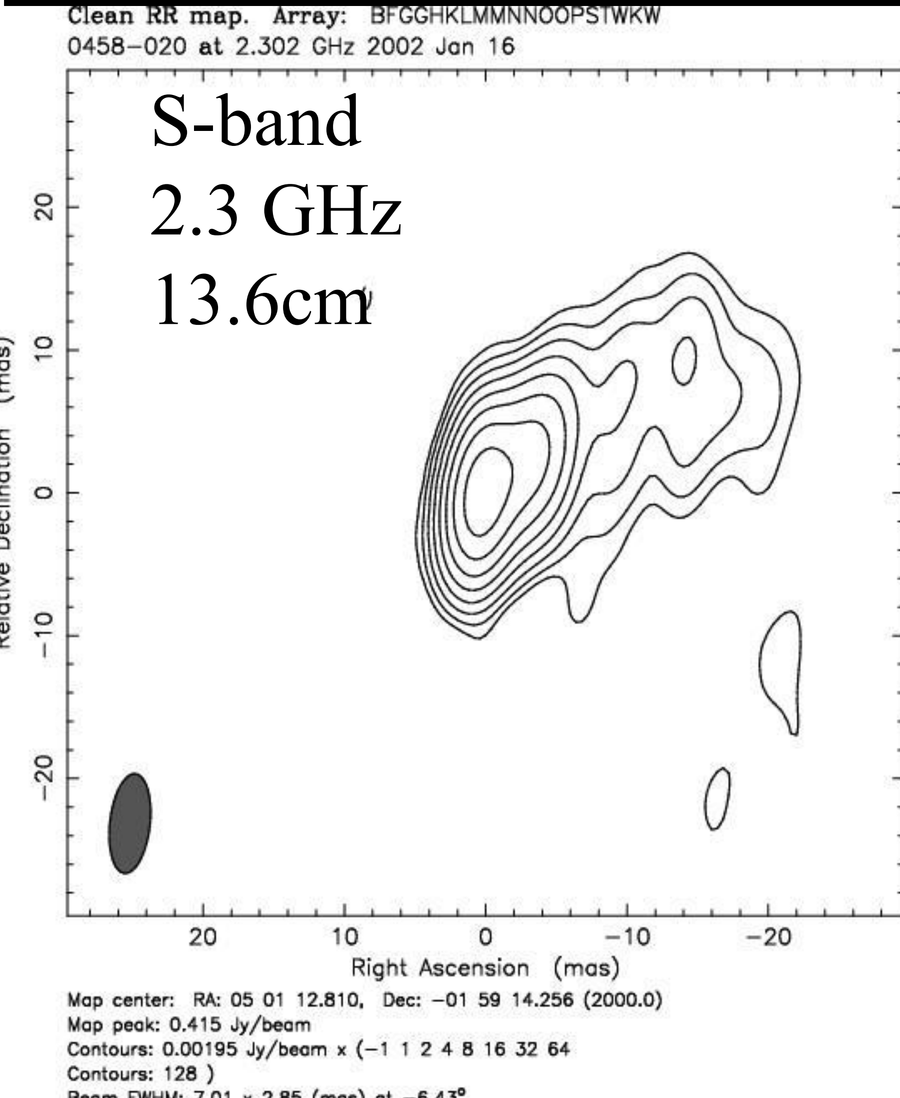




10,000 km baselines give resolution of λ/B ~ few nanoradian sub-mas beam !!

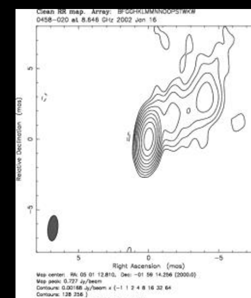
Resolves away all but galactic nucleus

Radio Source Structure vs. Frequency

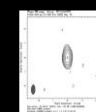


S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm



K-band
24 GHz
1.2cm



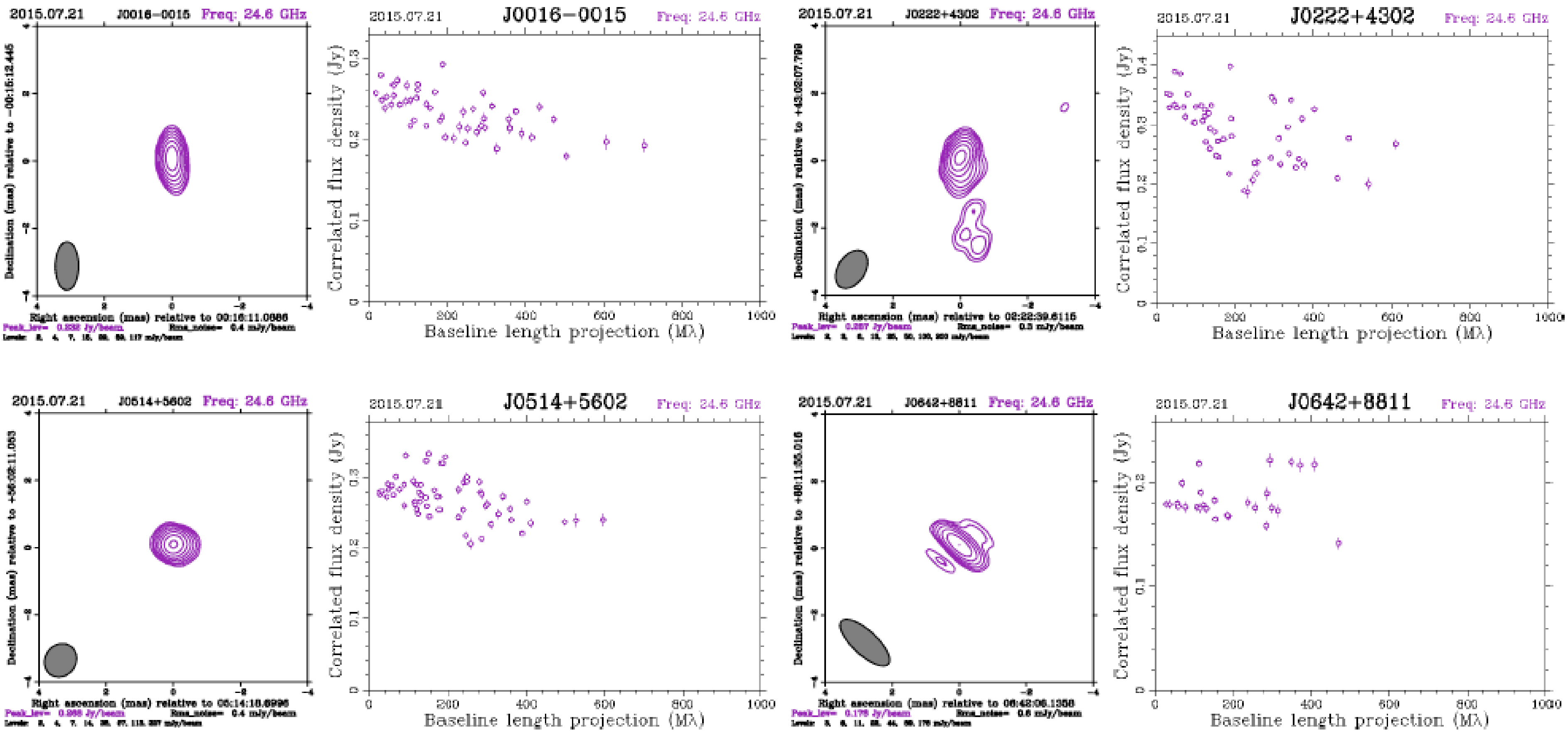
Q-band
43 GHz
0.7cm

The sources become better →
Less structure

Ka-band
32 GHz
0.9cm

Images credit: Pushkarev & Kovalev A&A, 544, 2012 (SX); Charlot et al, AJ, 139, 2010 (KQ)

Imaging: VLBA at 24 GHz (1.2cm) (de Witt et al, 2016)

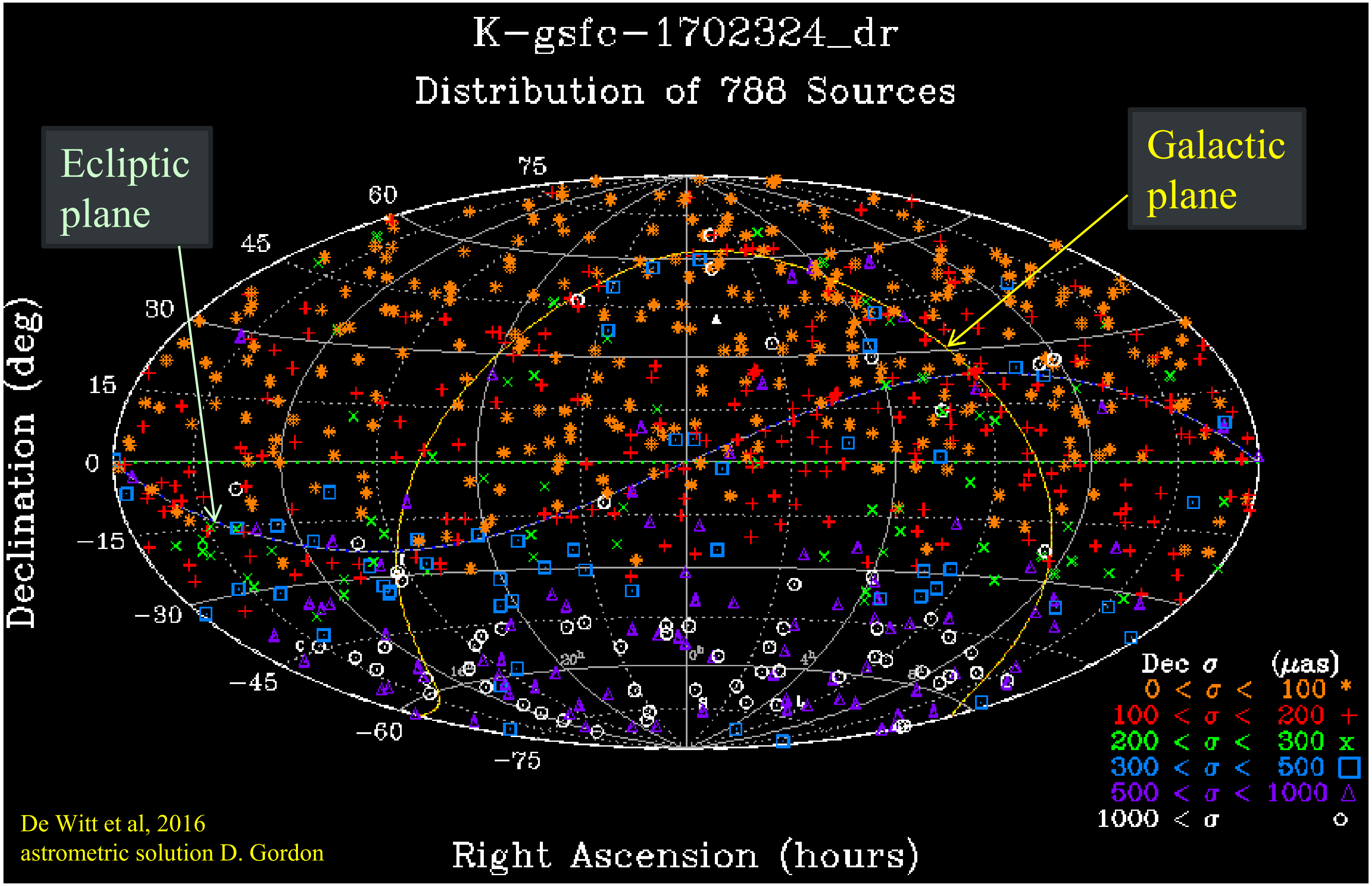


K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales.

Data for 500+ sources acquired. Processing limited by available analyst resources.

Imaging will be prioritized as comparison outliers pinpoint sources of interest

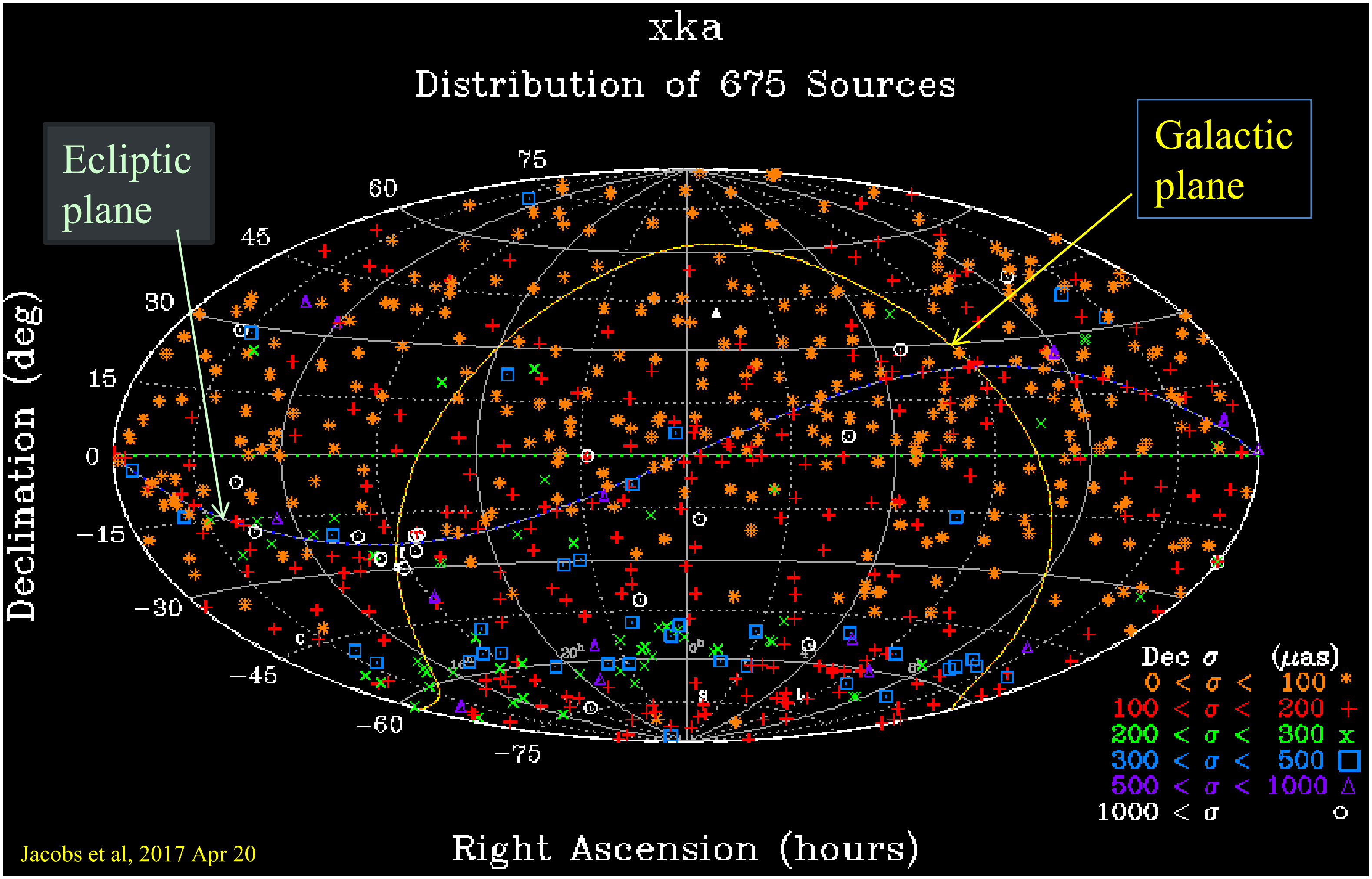
K (24 GHz, 1.2cm) *VLBA+ (S. Africa-Tasmania)*



- Strengths:
  - Uniform spatial density
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - precision < 100 µas
  - needed ~ 0.25 million observations vs. SX's 12 million!

- Weaknesses:
  - Ionosphere only partially calibrated by GPS.
  - No solar plasma calibrations
  - South (δ < -30 deg) weak due to limited South Africa-Tasmania data

Ka (32 GHz, 9mm) Combined NASA/ESA Network



- Strengths:
  - Uniform spatial density
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed only 60K observations vs. SX's 12 million!

- Weaknesses:
  - Poor near Galactic center due to inter-stellar media scattering
  - South weak due to limited time on ESA's Argentina station
  - Limited Argentina-California data makes vulnerable to δ zonals
  - Limited Argentina-Australia weakens δ from -45 to -60 deg

Ka-band combined NASA/ESA Deep Space Net

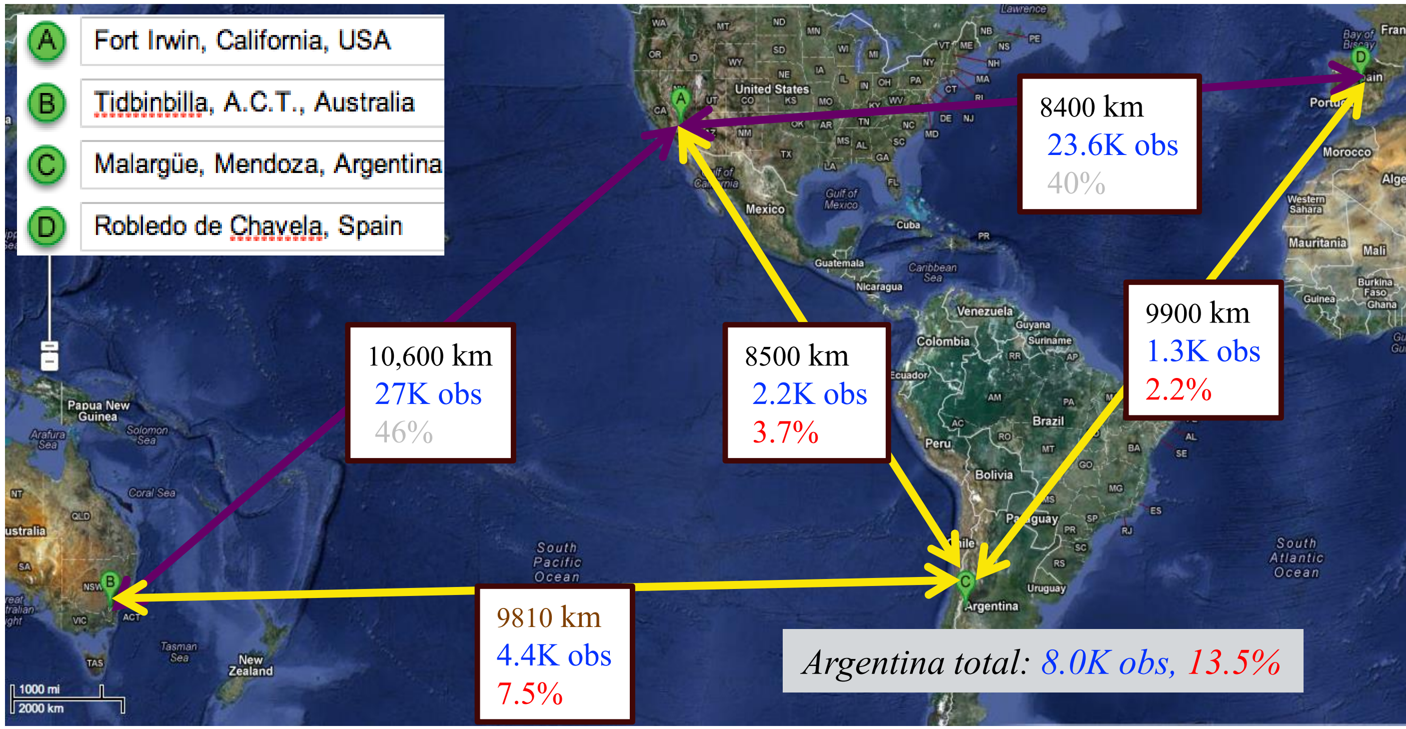
ESA Argentina to NASA-California under-observed by order of magnitude!

Baseline percentages

- Argentina is part of 3/5 baselines or 60% but only 13% of obs
- Aust- Argentina 7.5%
- Spain-Argentina 2.2%
- Calif- Argentina 3.7%

This baseline is under-observed by a factor of ~ 12.

More time on ESA's Argentina station would have a huge, immediate impact!!



Maps credit: Google maps

ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina

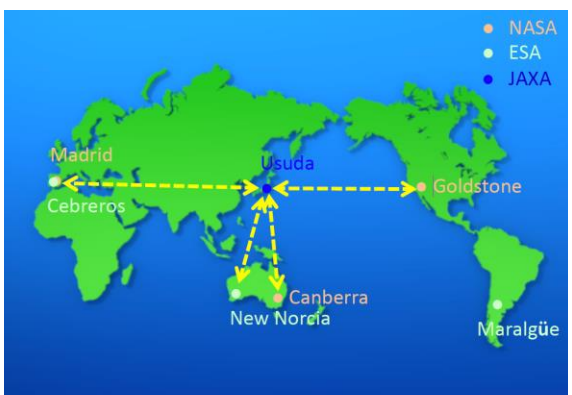
Three VLBI bands compare to better than 200 µas RMS
Gaia DR-1 precision ~ 500 µas. DR-2 vs. VLBI may reveal zonals

Zonal Errors

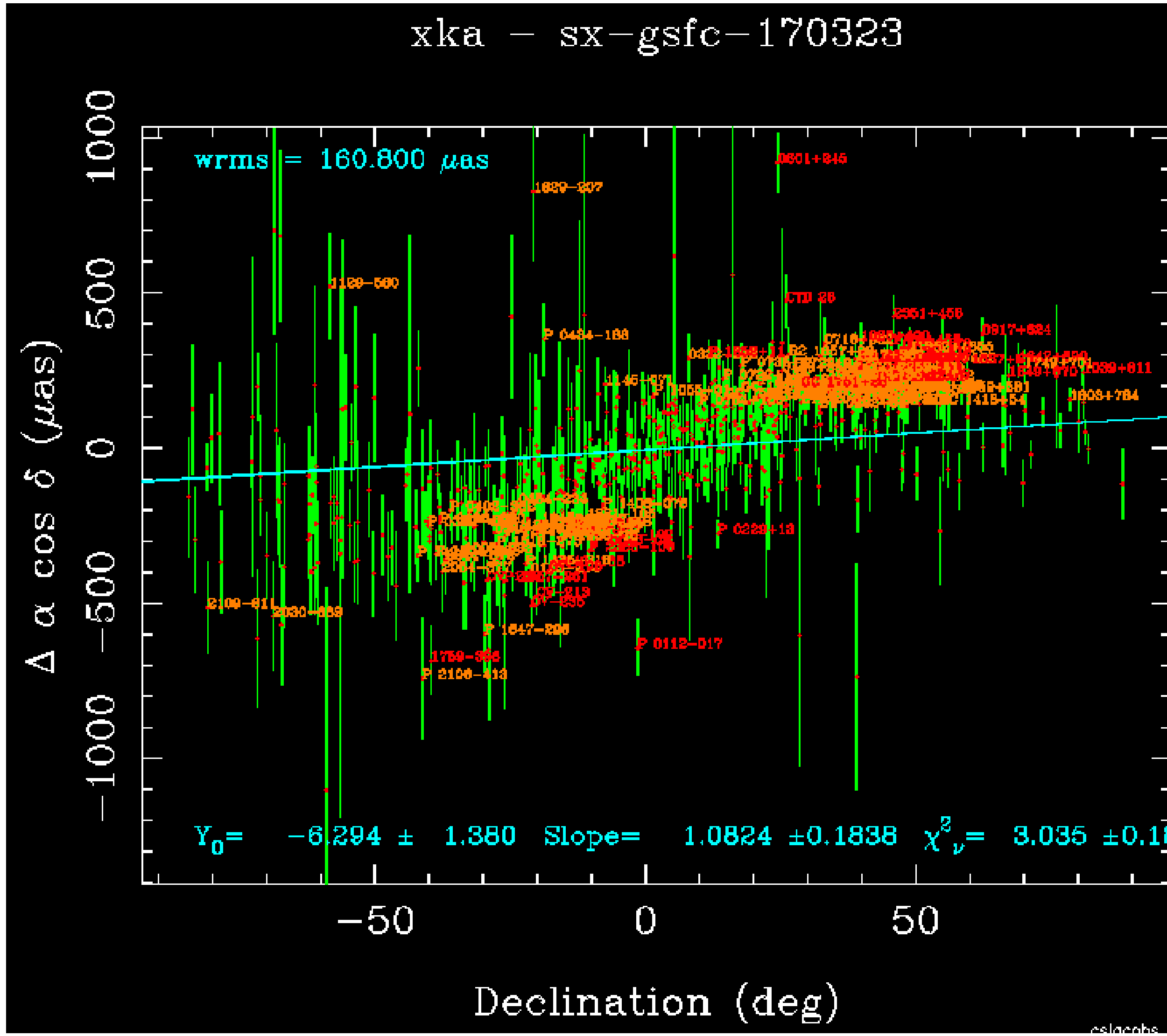
- ΔRA vs. Dec:
  ~300 µas in south, 200 µas in north
- Need 2 baselines to get 2 angles:
  California-Canberra: 24K obs
  California-Argentina: 2K obs

-> Need more California-Argentina data to overcome this 12 to 1 distortion in sampling geometry. ESA's Malargüe is key.

- Usuda, Japan 54-m XKa (2019) would improve North-South sampling geometry and thus control declination zonal differences.



XKa vs. SX: Zonal errors

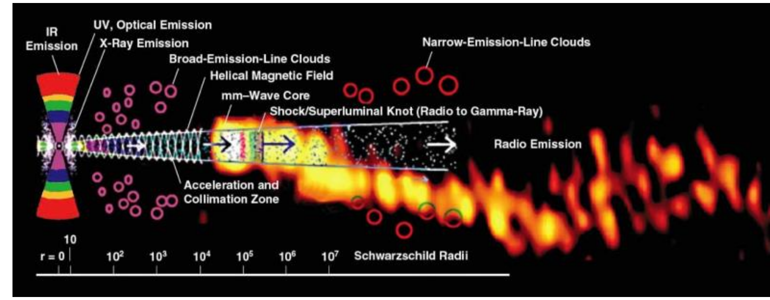


Credit: SX astrometry, D. Gordon

The goal:

Alignment of Optical and Radio into Common Frame

Optical-Radio Frame Tie Geometry



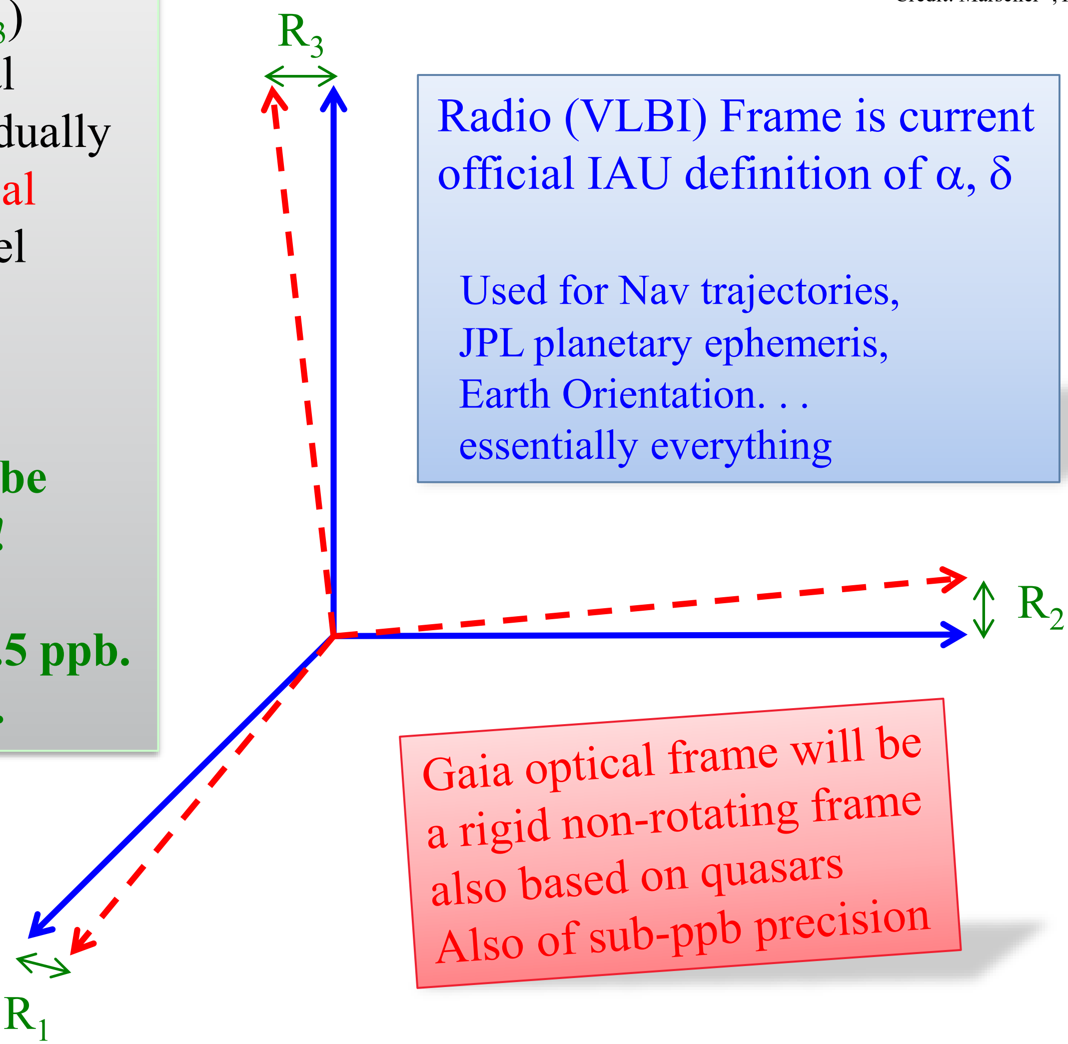
Credit: Marscher+, Krichbuam+

Determine 3 small rotations ($R_{1,2,3}$) and zonal differences i.e. spherical harmonics Y_{lm} between the individually rigid, non-rotating radio and optical frames to sub-part per billion level

Allows seamless integration into united frame.

More than 1 billion objects will be integrated into common frame!!

Object precision to < 100 μas, 0.5 ppb. want tie errors 10 times smaller.



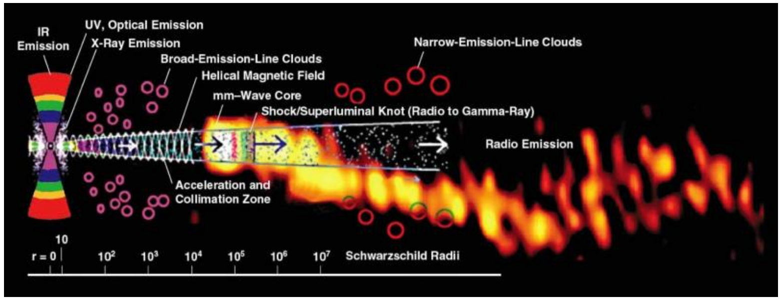
Radio (VLBI) Frame is current official IAU definition of α, δ

Used for Nav trajectories, JPL planetary ephemeris, Earth Orientation. . . essentially everything

Gaia optical frame will be a rigid non-rotating frame also based on quasars Also of sub-ppb precision

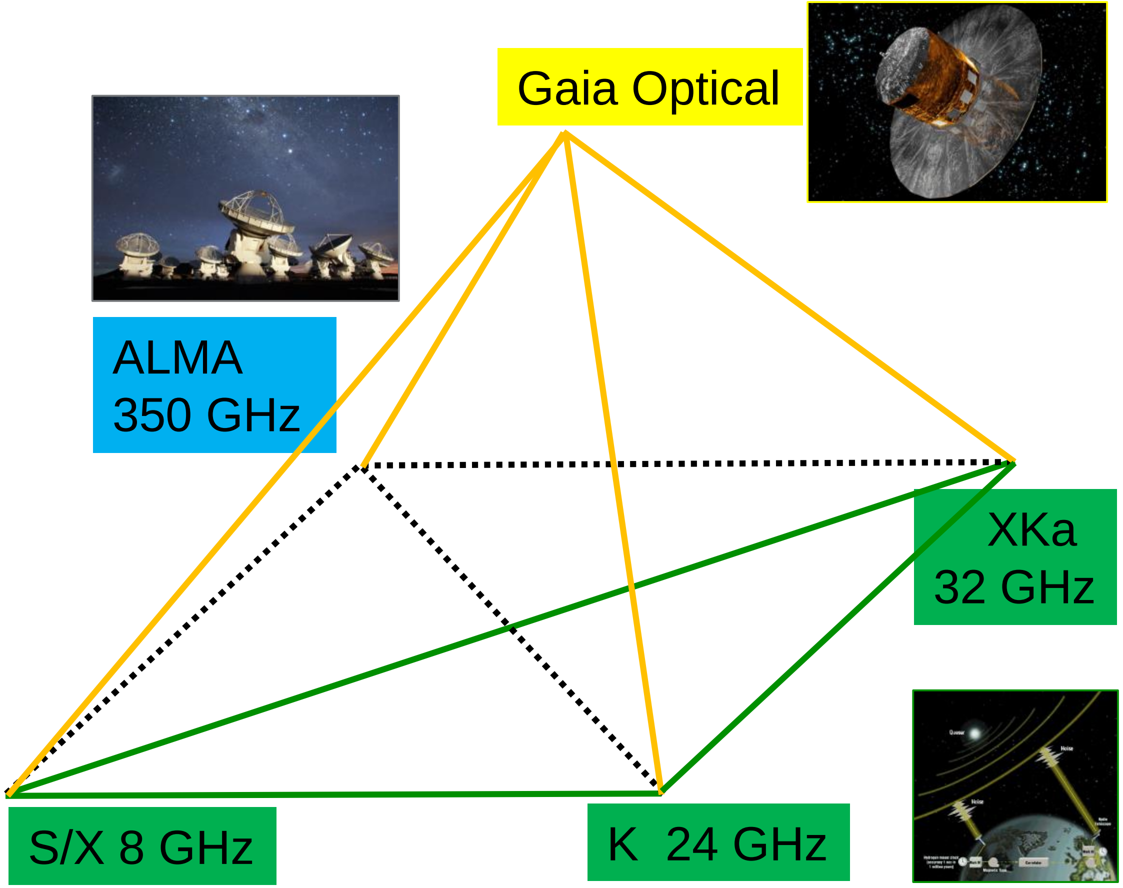
Frame Tie Comparisons

Tying Optical and Radio Celestial Frames



Credit: Marscher+, Krichbaum+

Systematics to be flushed out via Inter-comparison of multiple high precision frames.



Systematics:

Gaia: 60 mas beam sees
Host galaxy, foreground stars, etc.

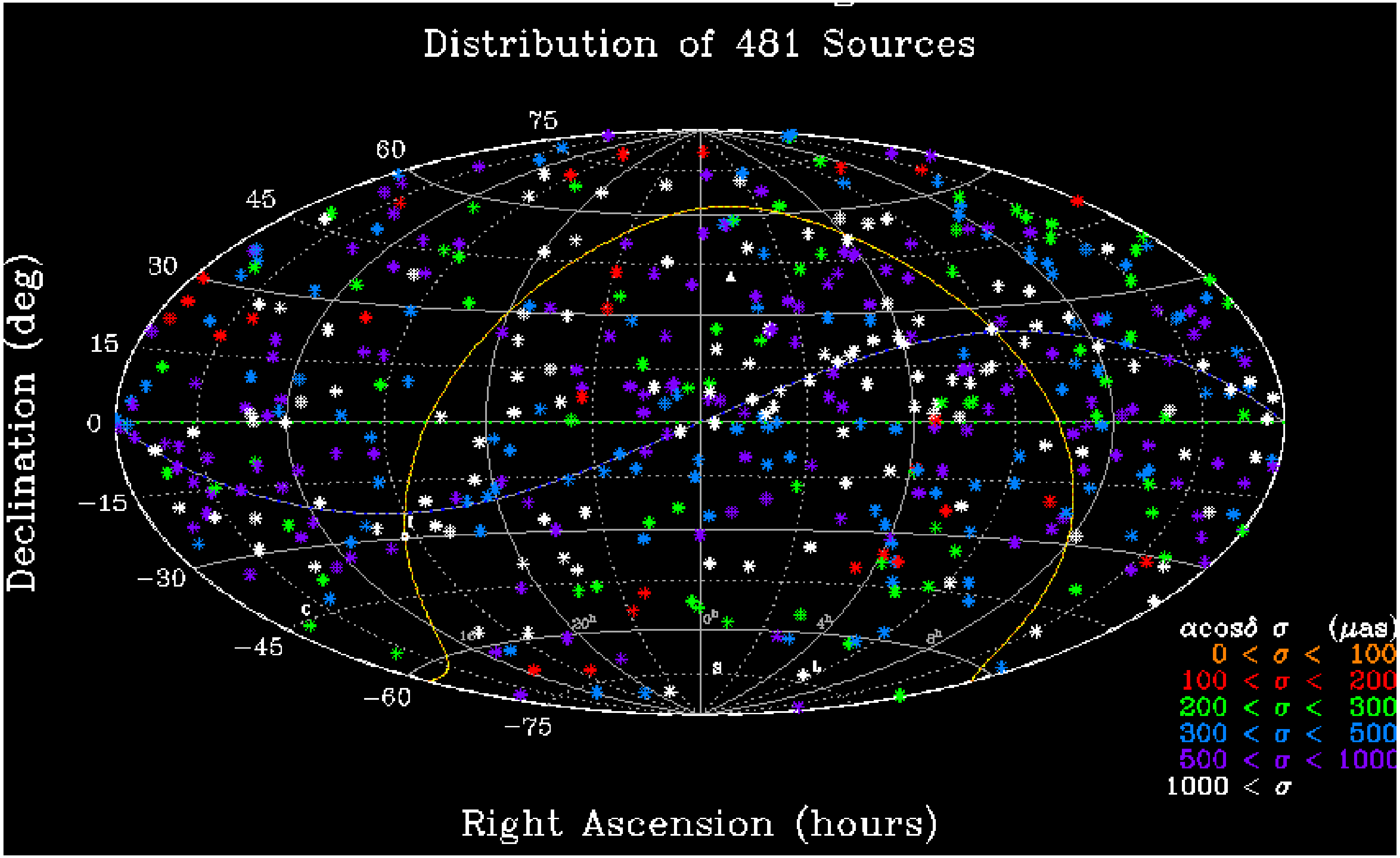
ALMA: pilot obs bright end ~5^{mag}
Waiting on 10km+ configurations

VLBI: All bands need more
southern data

S/X: Source structure
K: Ionosphere
XKa: Argentina baselines
under-observed

Tying optical and Radio Celestial Frames

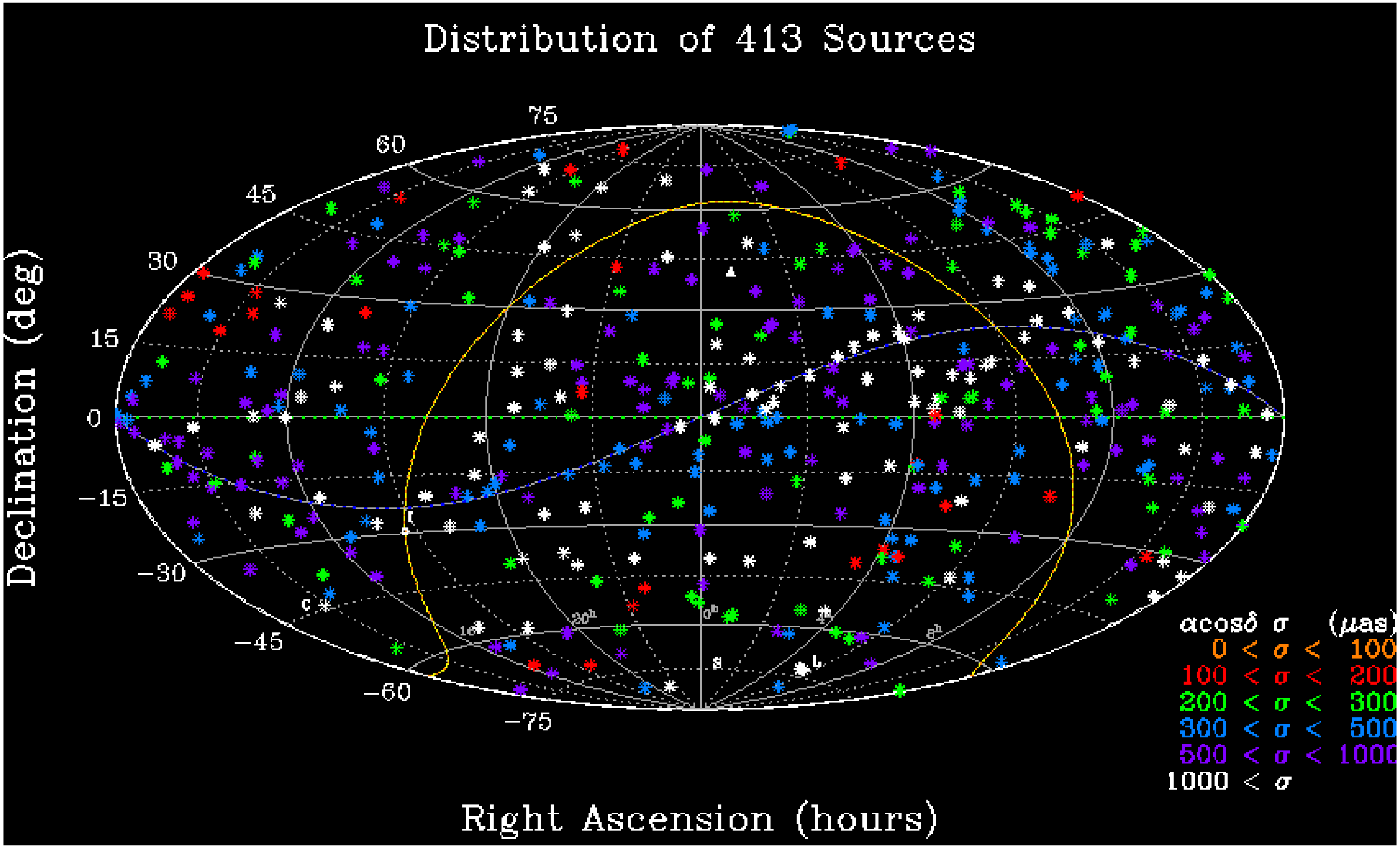
Gaia DR1-aux vs. K VLBI



Fairly uniform distribution.
Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. Ka VLBI



Fairly uniform distribution.
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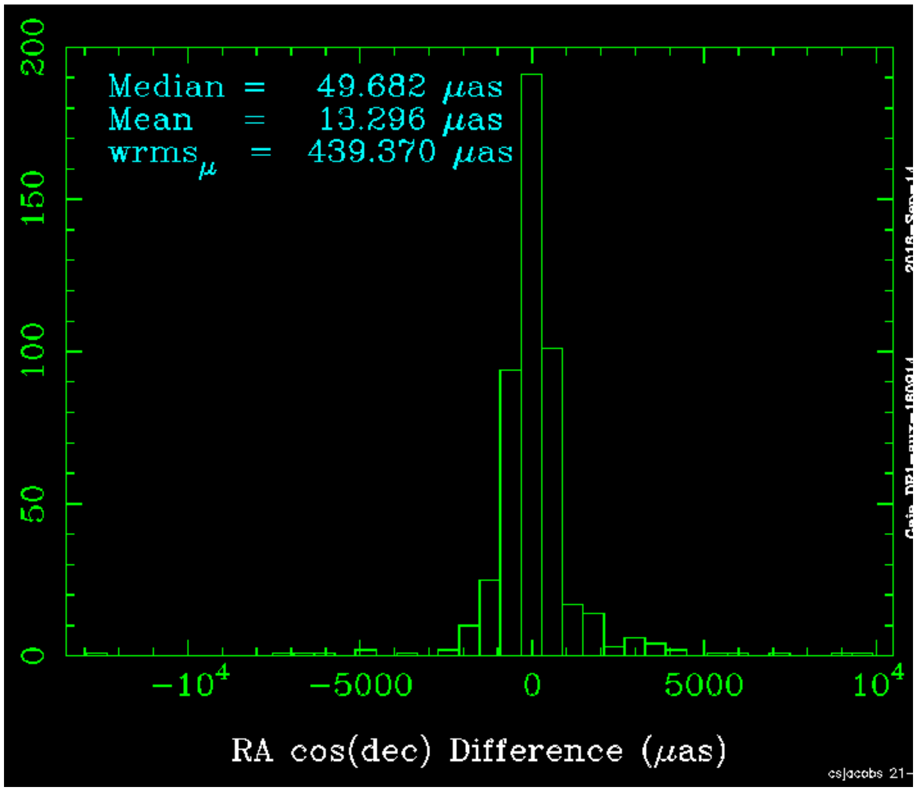
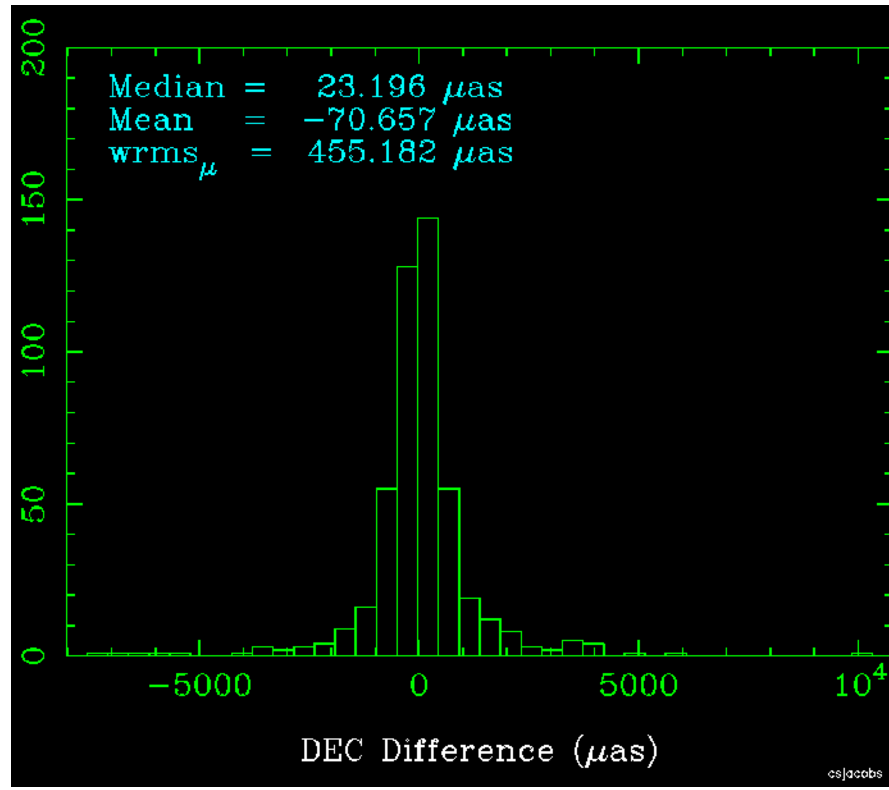
Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. K VLBI

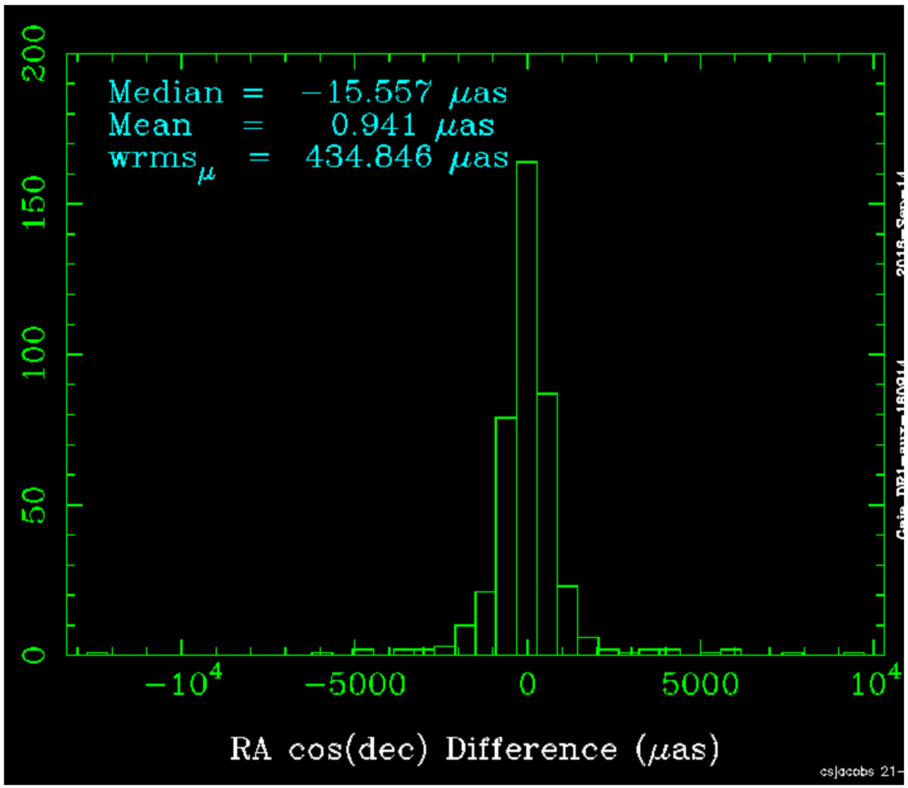


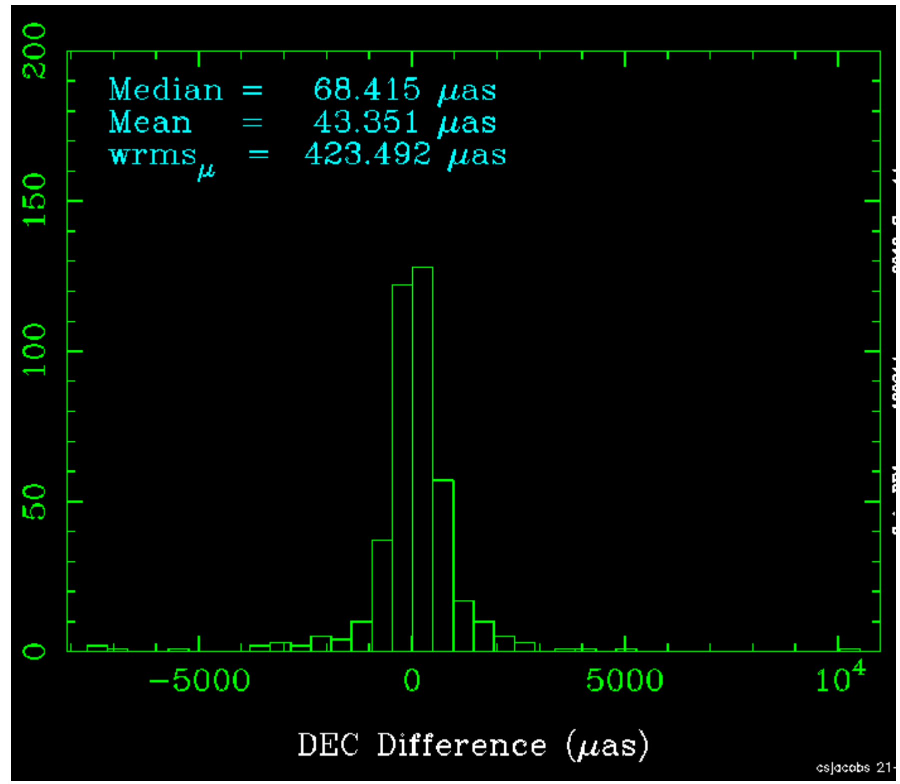


wRMS Ra and Dec differences about 440 μas (2 nrad)
Normalized differences are about 1.1 indicating realistic errors

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. Ka VLBI





wRMS Ra and Dec differences about 400 μas (2 nrad)
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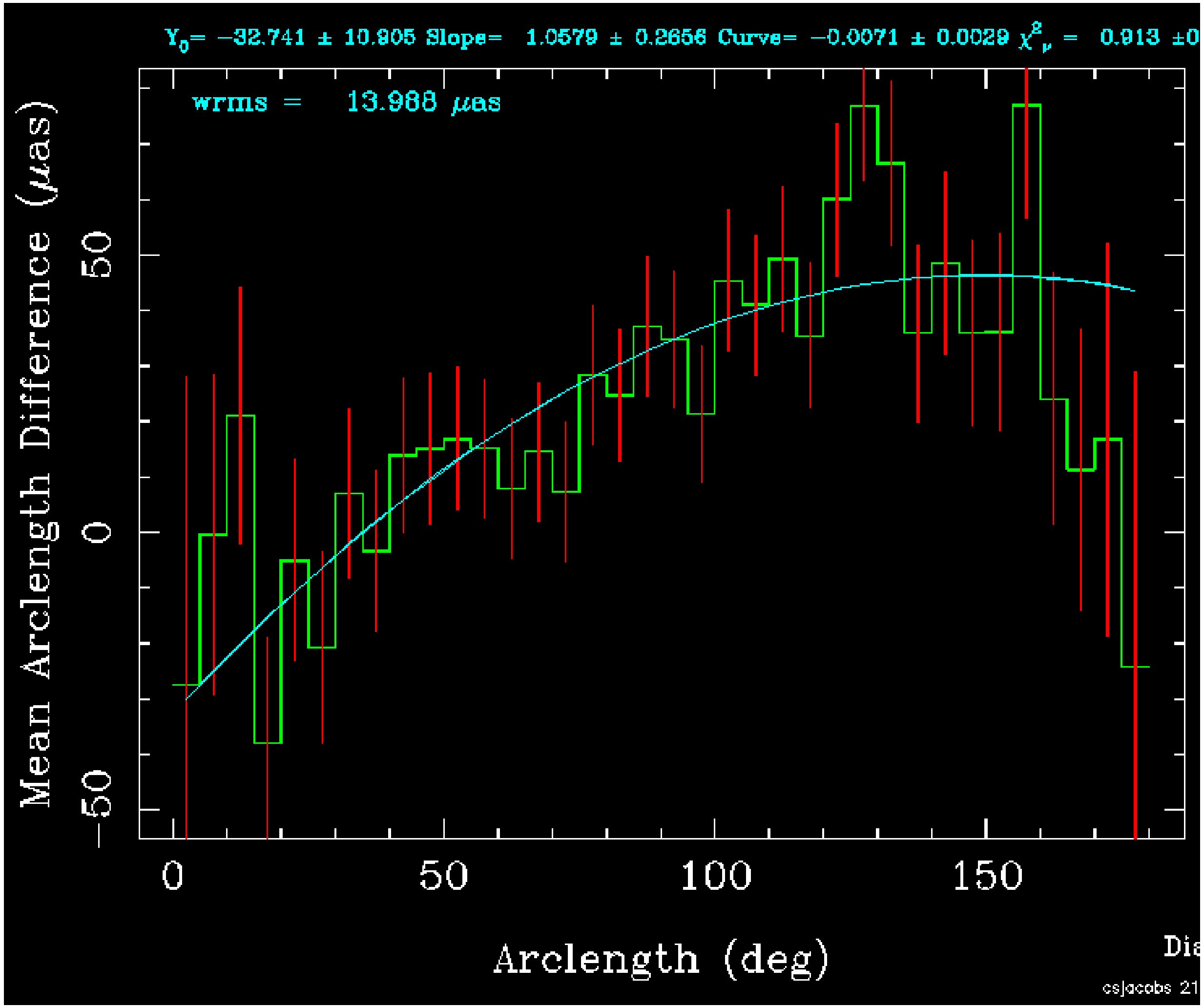
Tying optical and Radio Celestial Frames

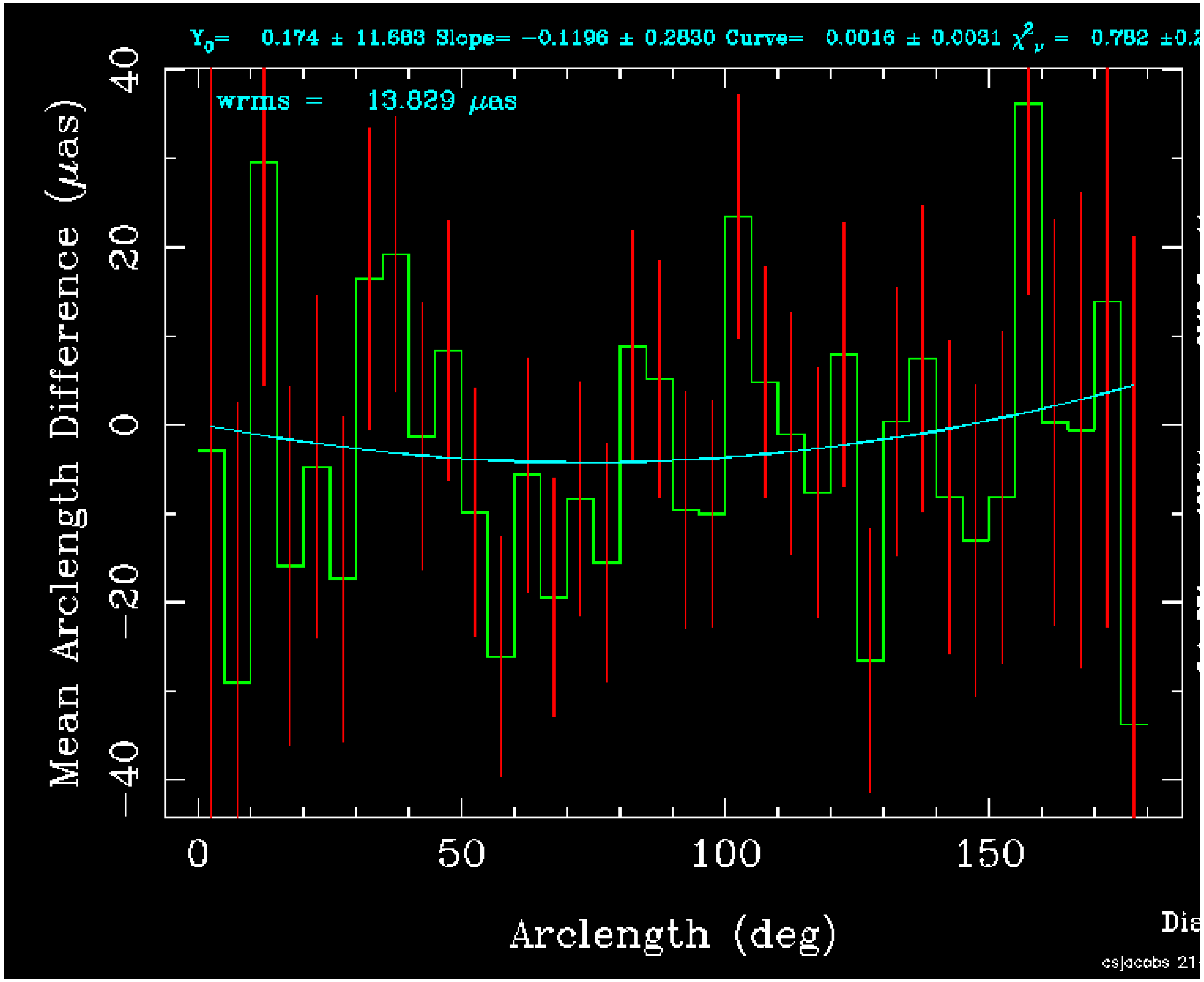
Gaia DR1-aux vs. K VLBI



Arc differences vs. arclength bins show distortion at 50 μas level

Tying optical and Radio Celestial Frames

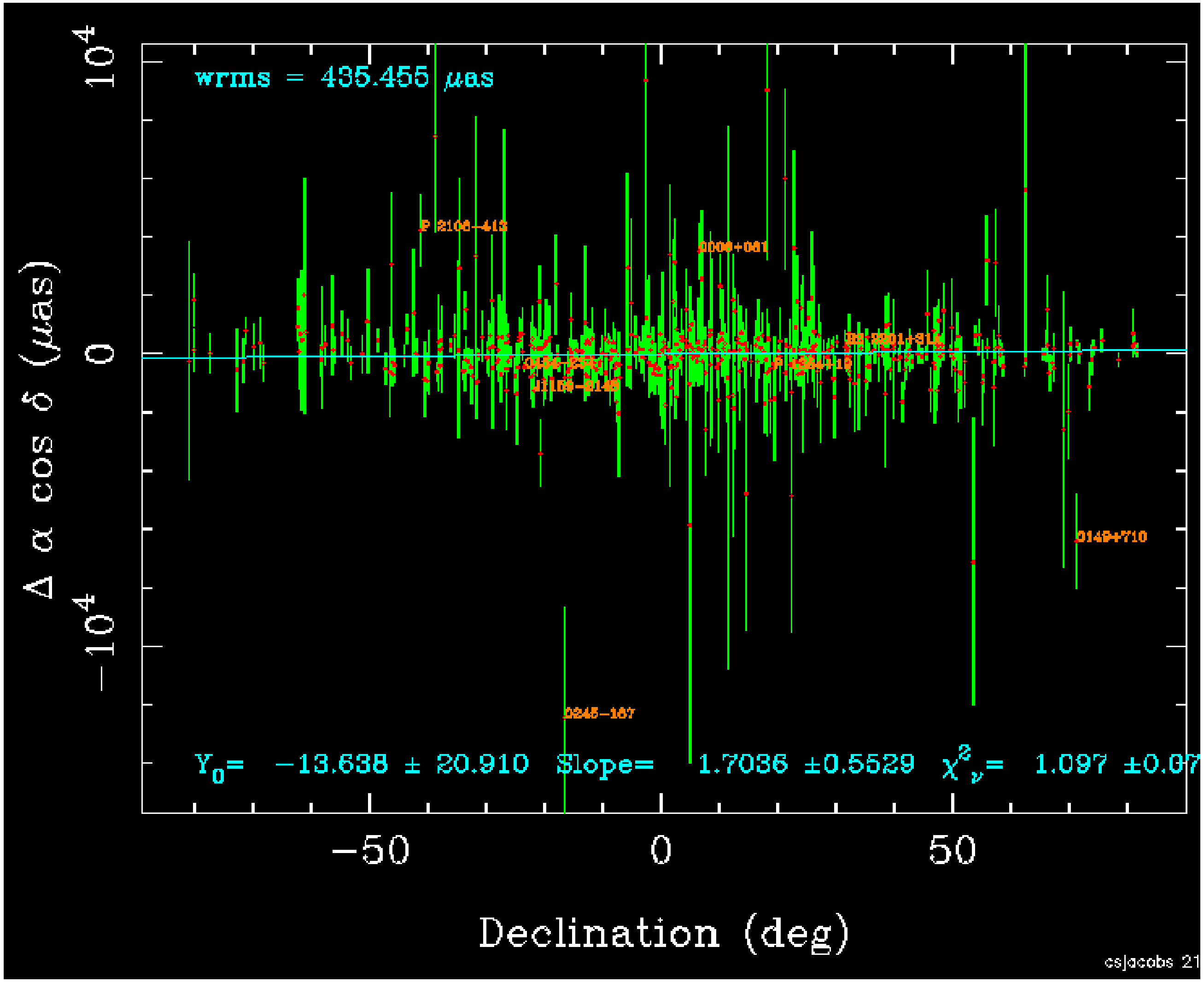
Gaia DR1-aux vs. Ka VLBI



Arc differences steady vs. arclength bins at 15 μas level

Tying optical and Radio Celestial Frames

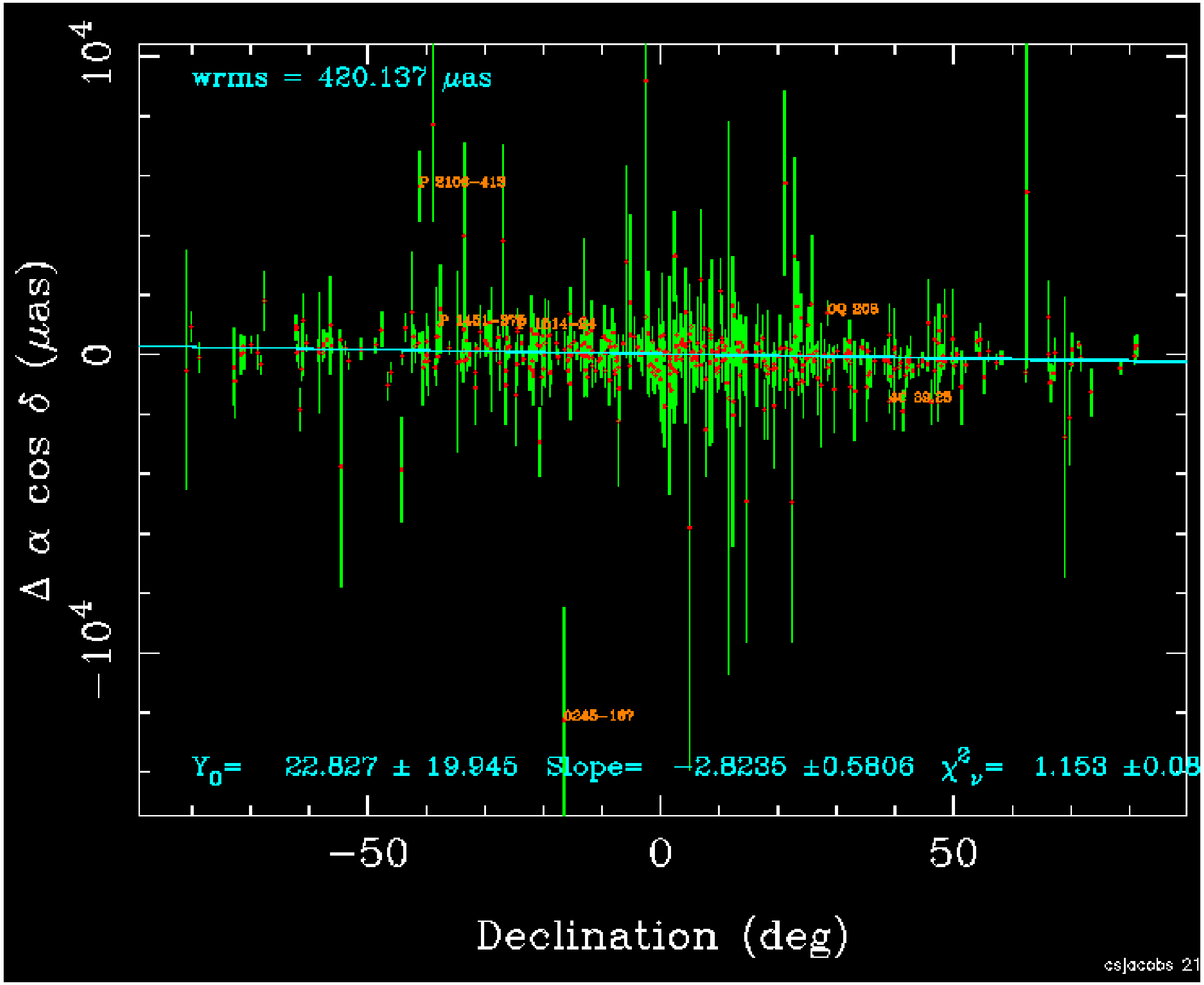
Gaia DR1-aux vs. K VLBI



Systematic tilt: Δα vs. δ has 3 sigma slope of 1.7 +- 0.6 μas/deg

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. Ka VLBI



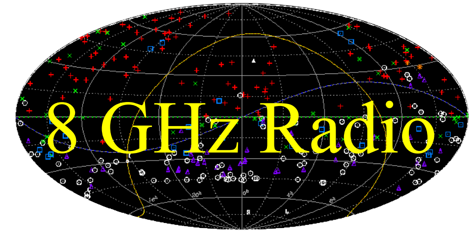
Systematic tilt: Δα vs. δ has 4.9 sigma slope of -2.8 +- 0.6 μas/deg

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. VLBI

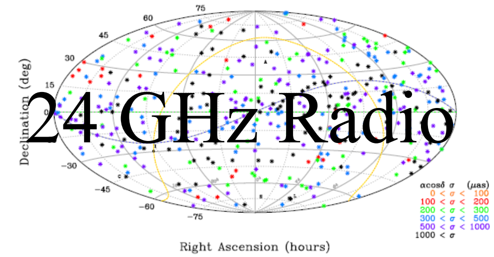
	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# sources	1984	481	413
# outliers > 5σ	106	13	7
% outliers	5.0 %	2.6 %	1.7 %
α wRMS	536 μas	439 μas	434 μas
δ wRMS	544 μas	455 μas	423 μas
R_x	32 +- 13	100 +- 24	56 +- 24
R_y	5 +- 11	-7 +- 21	32 +- 21
R_z	28 +-13	0 +- 23	15 +- 24

Hints that results improve by going to higher radio frequency
However, the above results do not use exact same objects

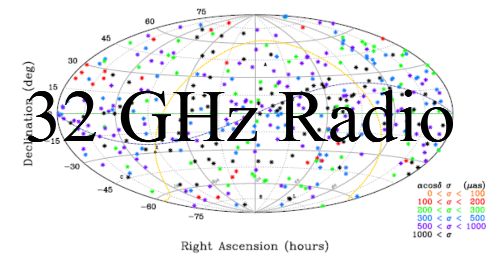


Summary: Tying Optical & Radio

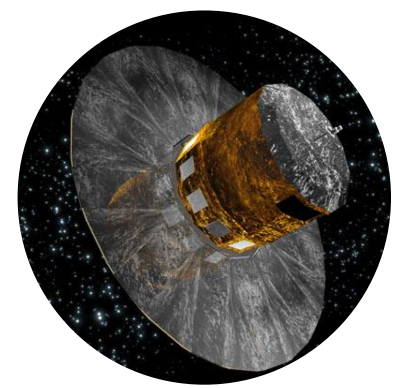
- **Goal:** Tie of optical and radio celestial frames for deep space navigation and astronomical applications.



- **Roadmap:**
  - — Preliminary optical & radio data are in-hand.
  - — Increase number of sources in common between optical and radio
  - — Expect to be limited by systematic calibration errors
  - — Quantify and reducing systematics by
    - — getting data in three radio bands (8, 24, 32 GHz)
    - — Compare independent analysis chains
    - — Image sources in radio to quantify non-pointlike structure

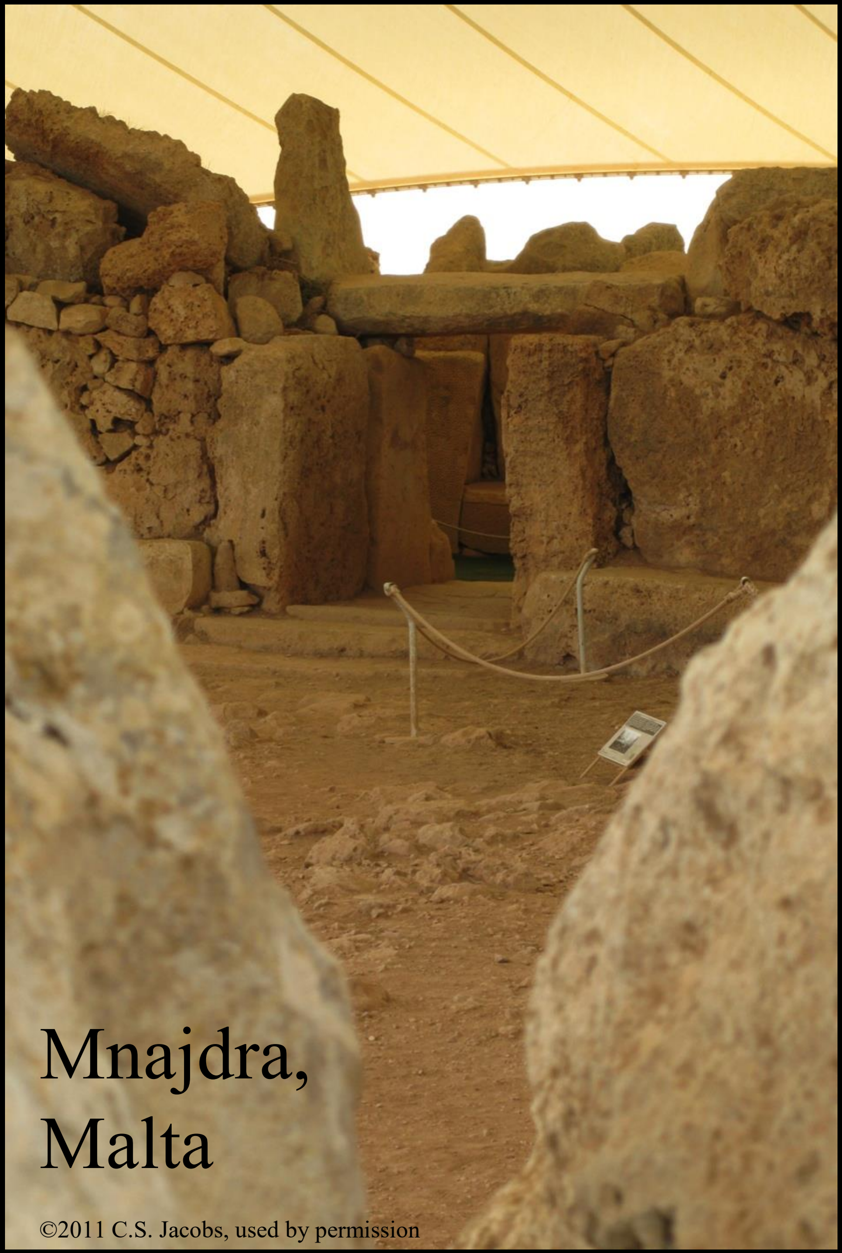


- **Preliminary results: Gaia DR1-aux vs. VLBI**
  - — Excellent 3-D tie precision of ~ 20 µas.
  - — Accuracy limited by systematic errors at 200 – 500 µas.
  - — Hints that 24 and 32 GHz VLBI are cleaner than 8 GHz
  - — Lower percentage outliers, smaller scatter vs Gaia
  - — Control of VLBI systematics will require increased southern observations.


Gaia Optical

BACKUP

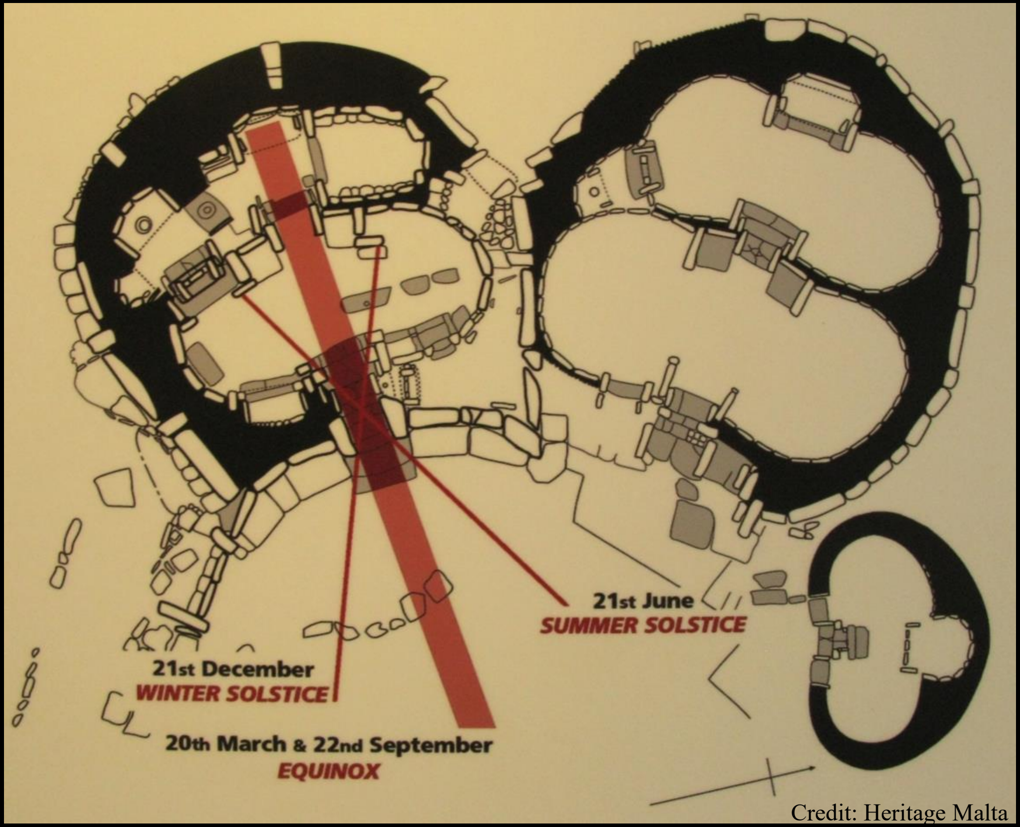
Astrometry: measures positions in the sky, 5000+ years history!



Credit: Heritage Malta

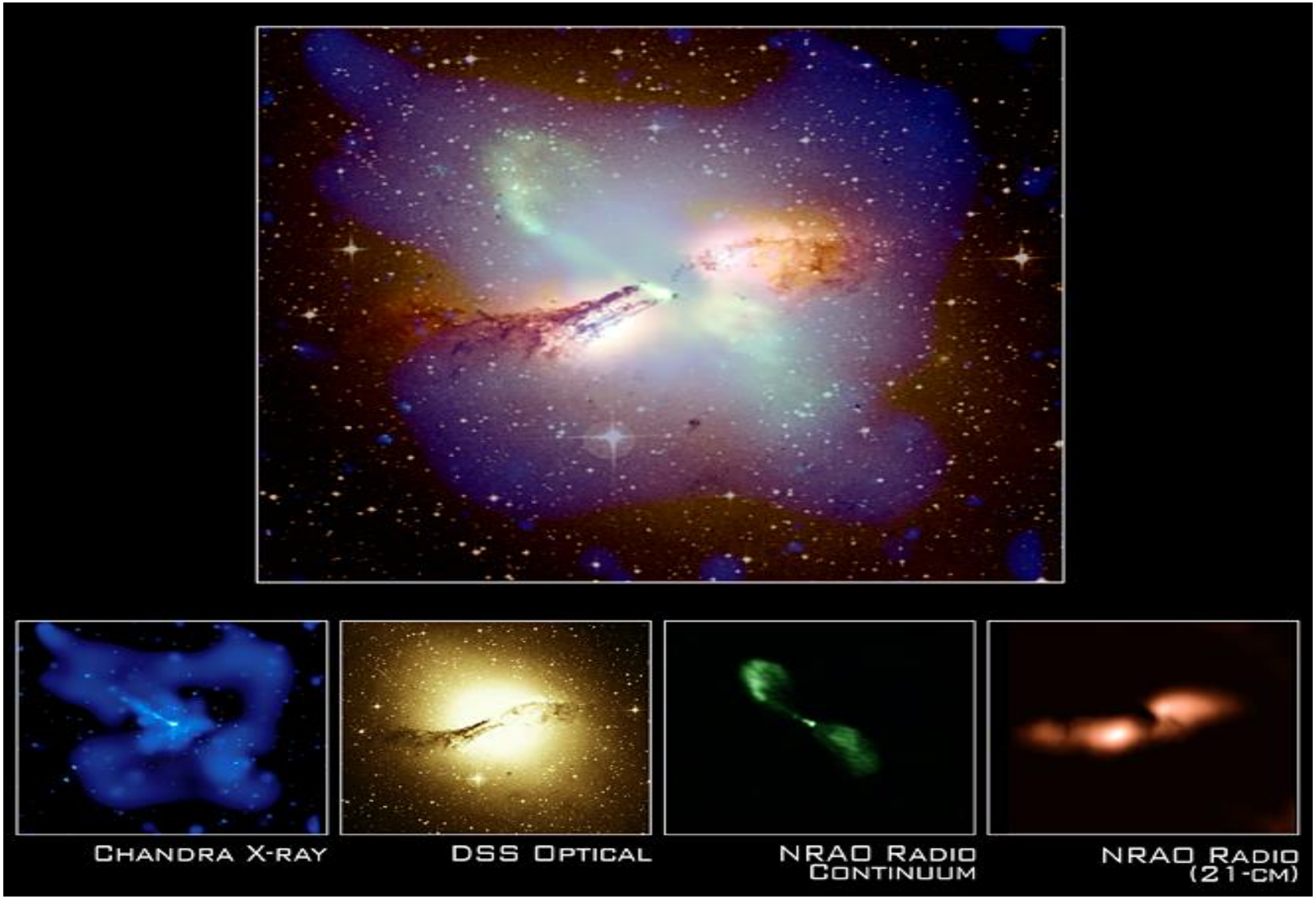
Island of Malta
Ggantija ~3500 B.C.
Mnajdra ~3200 B.C.

Mnajdra solar alignments



The Source Objects

Example Extragalactic Source: Centaurus-A in X-ray, Optical, Radio

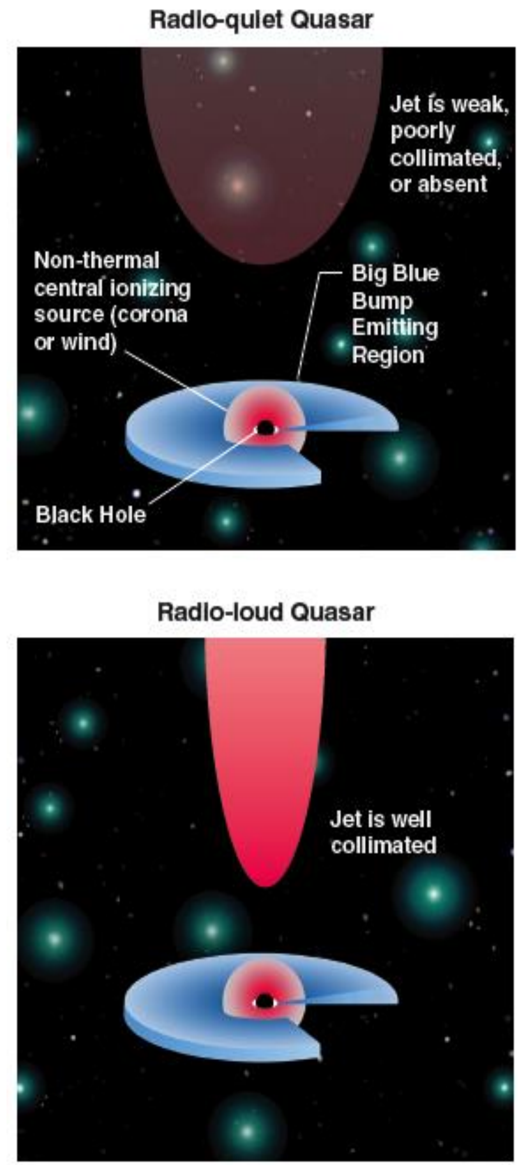


Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.), Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

Optical vs. Radio positions

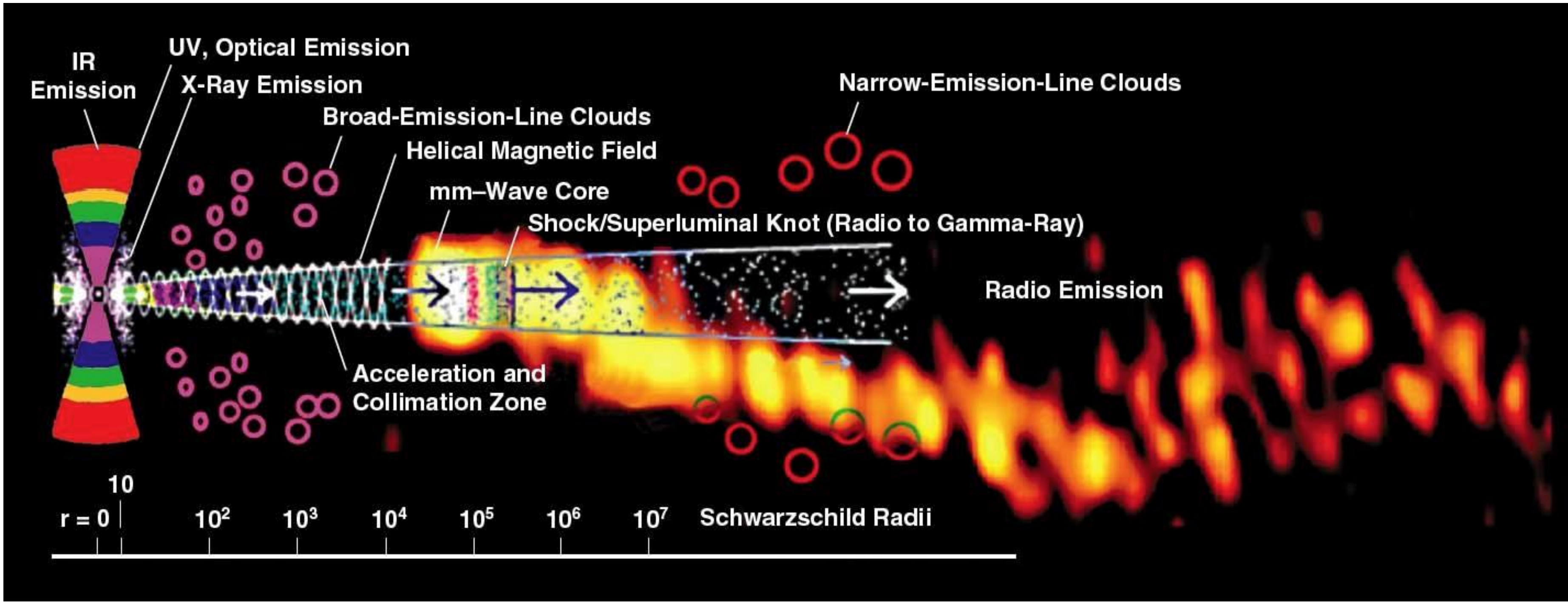
Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
  - optical: synchrotron from jet?
    non-thermal ionization from corona?
    big blue bump from accretion disk?
- Instrumental errors both radio & optical
- Analysis errors



Credit: Wehrle et al, μas Science, Socorro, 2009
http://adsabs.harvard.edu/abs/2009astro2010S.310W

Active Galactic Nuclei (*Marscher*)



R~0.1-1 μas 1mas

Features of AGN: *Note the Logarithmic length scale.*
"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credits: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)