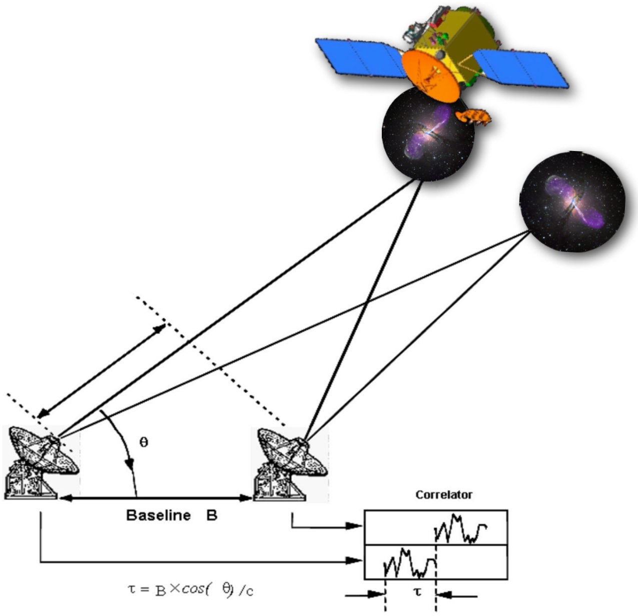
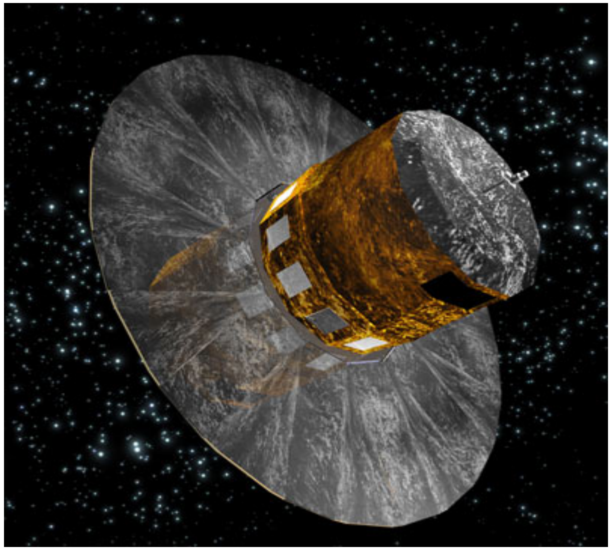
Astrometry & Astrophysics in the Gaia Sky, 24-28 April 2017 Nice, France

# Tying multiple Radio Wavelength Celestial Frames to the Gaia Optical Frame





**Christopher S. Jacobs,** *Jet Propulsion Laboratory, California Institute of Technology*

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L. Snedeker, G. Bourda, P. Charlot.

# **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 $\mu$as

- Accuracy limited by VLBI systematics due to weak southern geometry, tropopshere, etc. at few 100 $\mu$as

- Gaia precision limited to ~ 500 $\mu$as 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 $\mu$as (2.5 to 5 ppb).

- **Extra-galactic Quasars:** detectable in both radio and optical

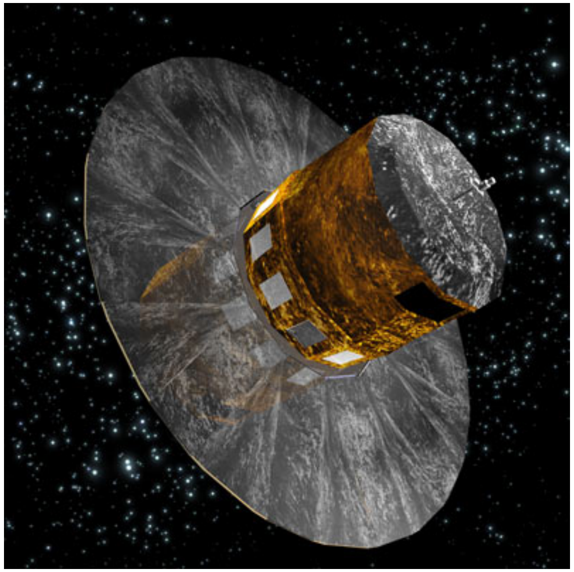
  potential for better than 100 $\mu$as to 20 $\mu$as (0.5 to 0.1 ppb).

  **Strengths: extreme distances (> 1 billion light years) means no parallax or proper motion**

# The Gaia Optical Frame

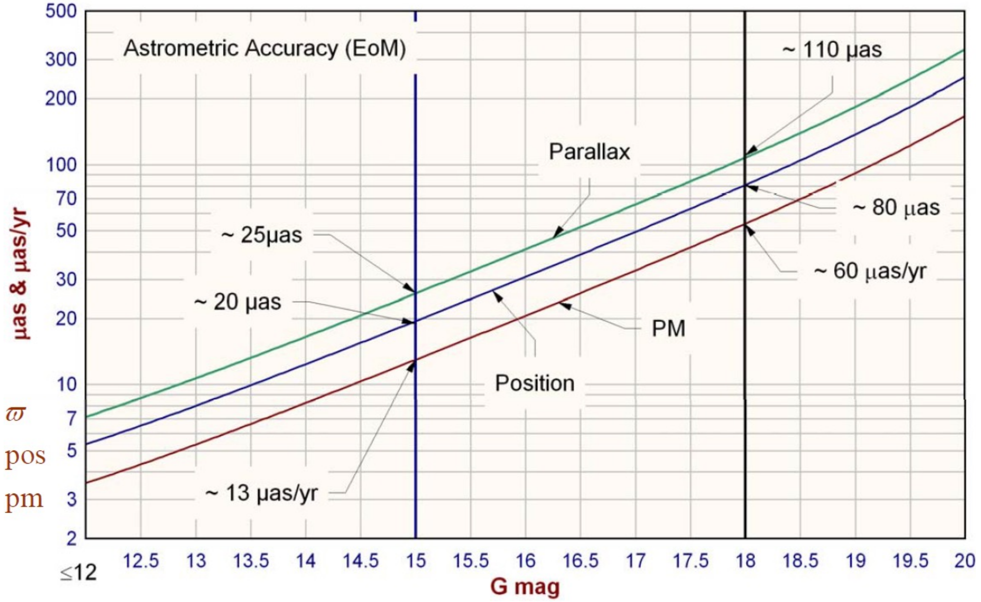
# ESA’s Gaia optical Astrometry

- 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**



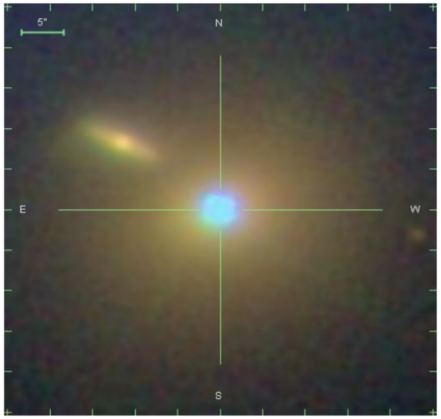
**Gaia release-1:**

**~0.3 mas in positions and parallaxes for 2 million brightest stars**

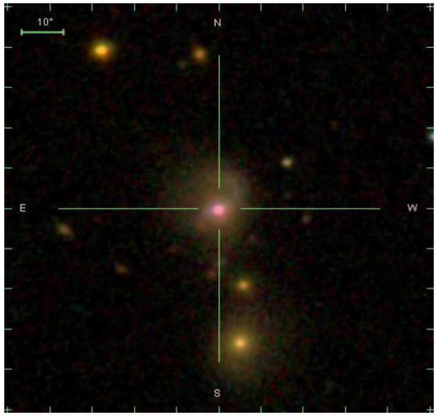
**~10 mas for rest of the stars**

# Optical vs. Radio systematics offsets

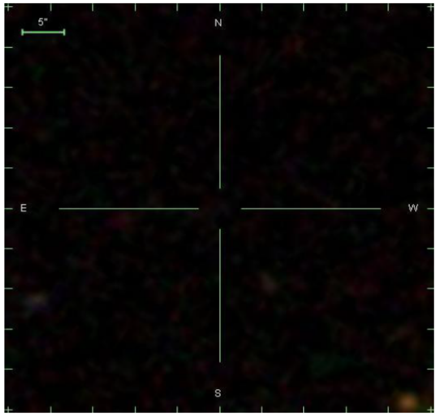
## SDSS Optical images of quasars (scale 5-10 asec)



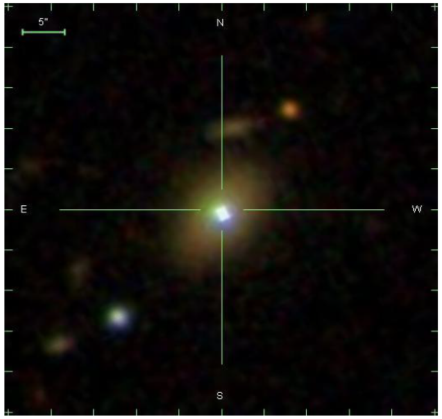
1101+384



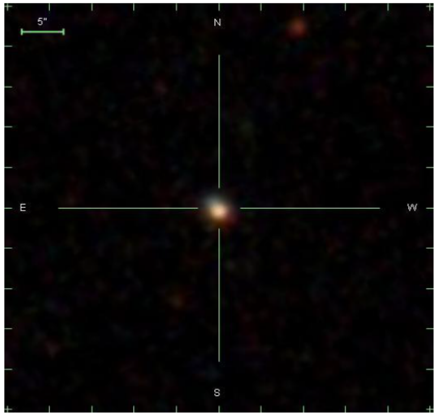
0007+106



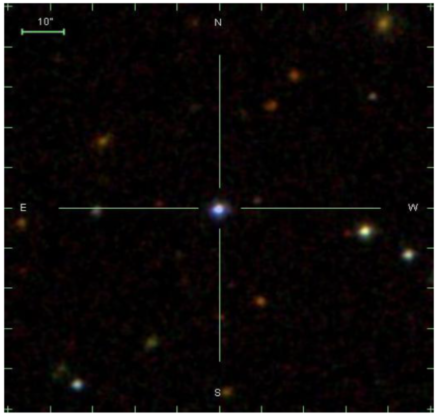
0920+390



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.

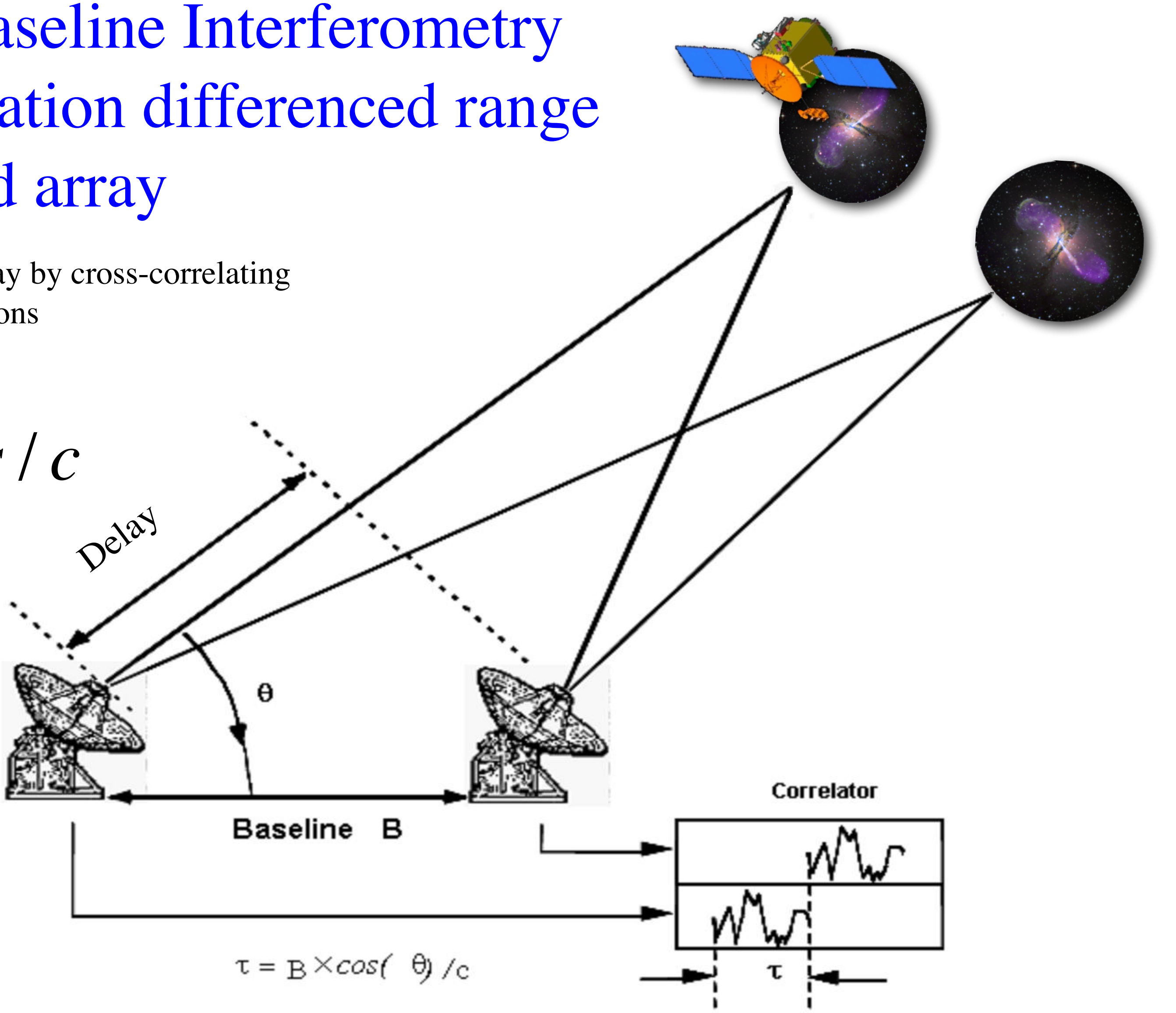
# Celestial Frames
# using
# Radio Interferometry
# (VLBI)

# 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

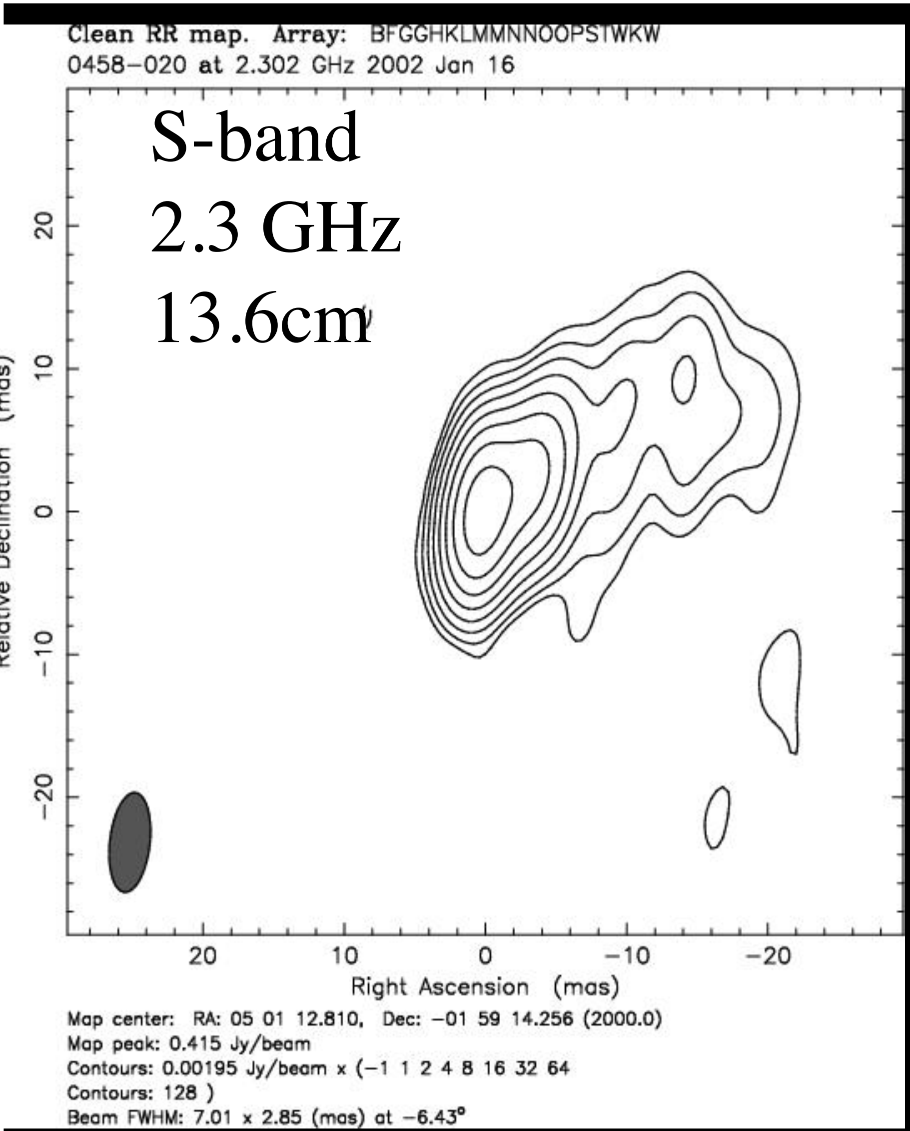
$$\tau = B \bullet s / c$$



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

Resolves away all but galactic nucleus

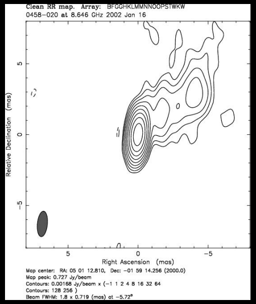
# Radio Source Structure vs. Frequency


Clean RR map. Array: BFGGHKLMMNNOOPSTWKW
0458−020 at 2.302 GHz 2002 Jan 16

Map center: RA: 05 01 12.810, Dec: −01 59 14.256 (2000.0)
Map peak: 0.415 Jy/beam
Contours: 0.00195 Jy/beam x (−1 1 2 4 8 16 32 64
Contours: 128 )
Beam FWHM: 7.01 x 2.85 (mas) at −6.43°

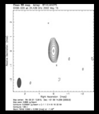
S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

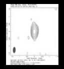

Clean RR map. Array: BFGGHKLMMNNOOPSTWKW
0458−020 at 8.646 GHz 2002 Jan 16

Map center: RA: 05 01 12.810, Dec: −01 59 14.256 (2000.0)
Map peak: 0.727 Jy/beam
Contours: 0.00168 Jy/beam x (−1 1 2 4 8 16 32 64
Contours: 128 256 )
Beam FWHM: 1.8 x 0.719 (mas) at −5.72°

K-band
24 GHz
1.2cm



Q-band
43 GHz
0.7cm

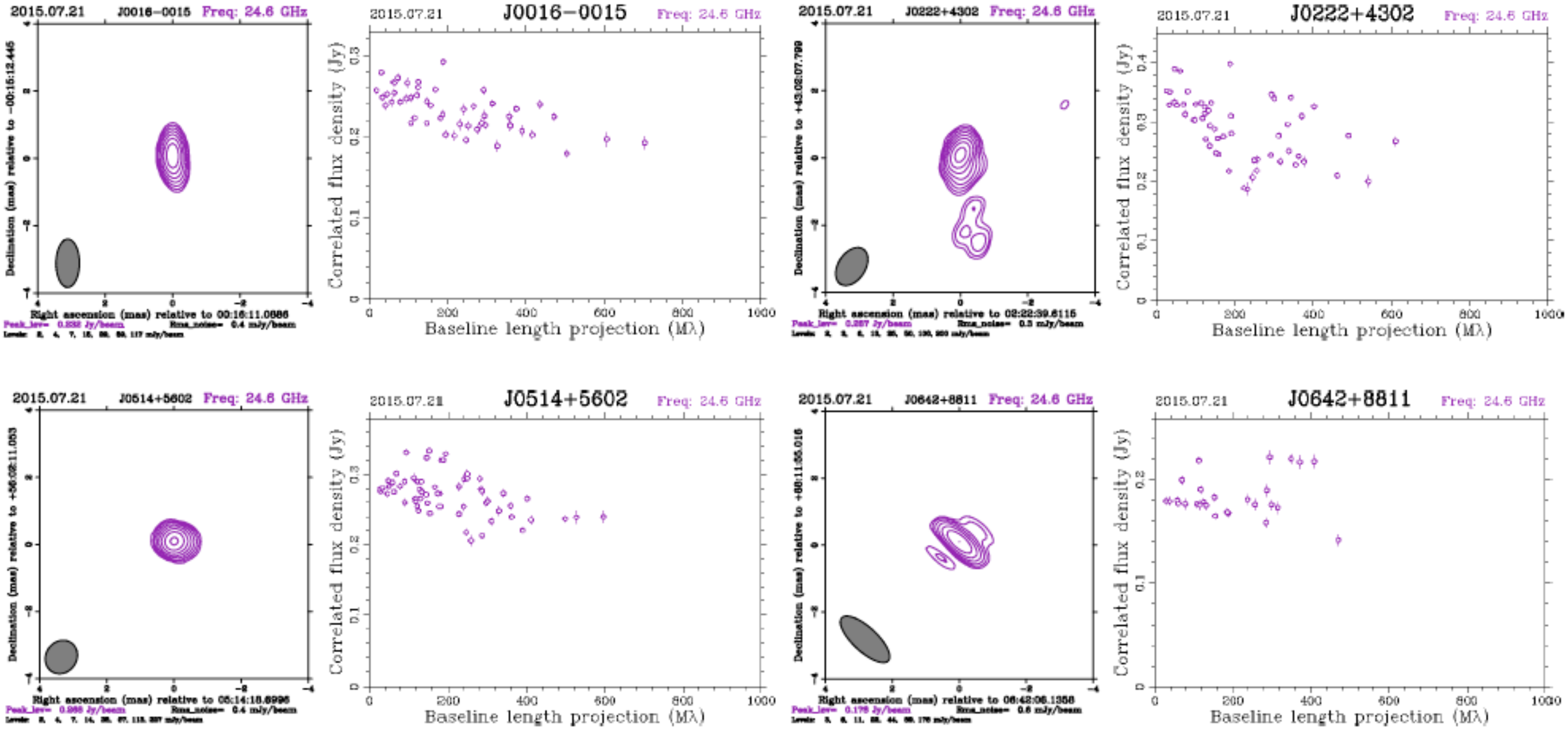


**The sources become better →**
Less structure

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)



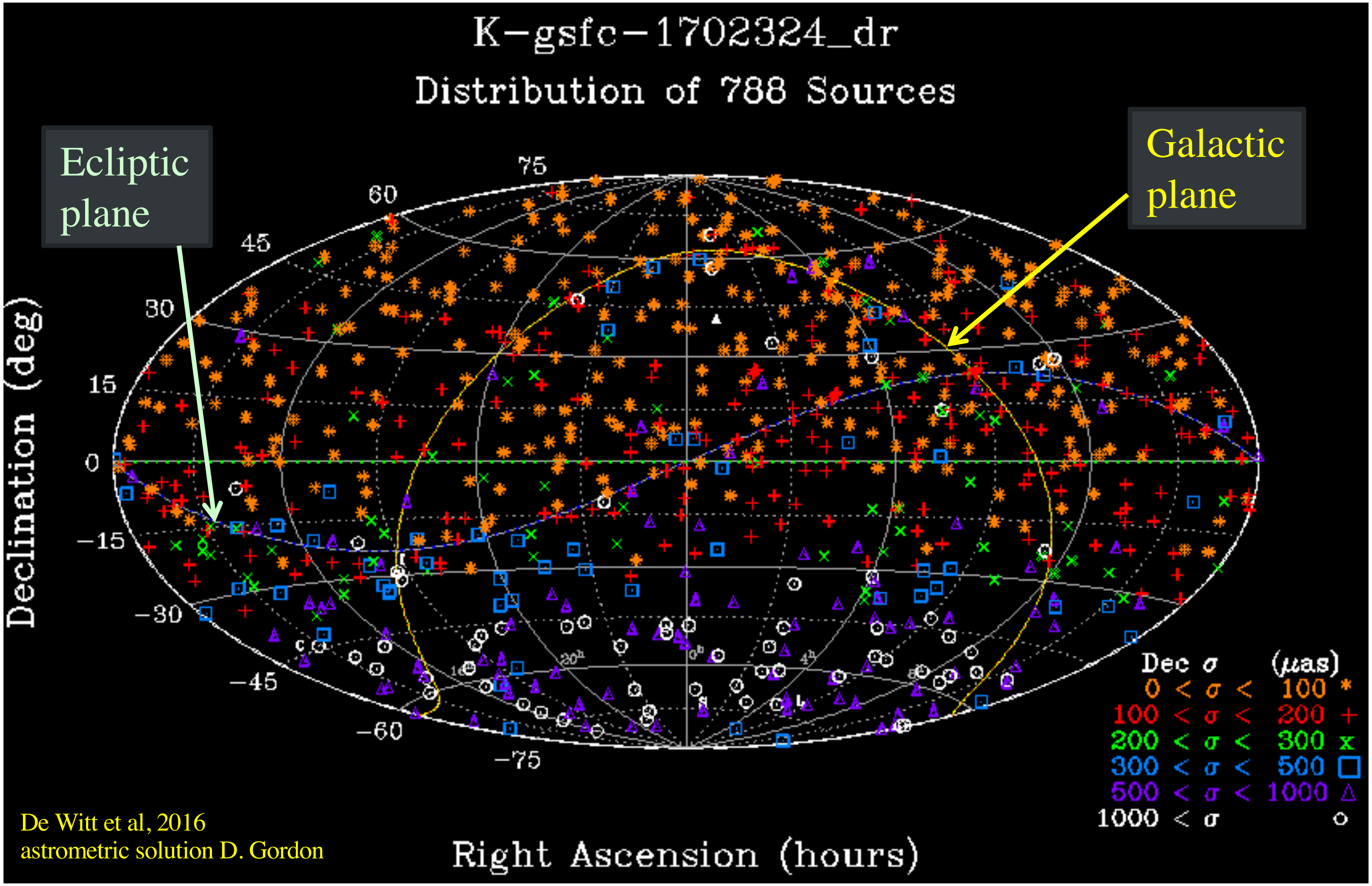
K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales.

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

Imaging will be prioritized as comparison outliers pinpoint sources of interest

The authors gratefully acknowledge use of the Very Long Baseline Array under the US Naval Observatory's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy.

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

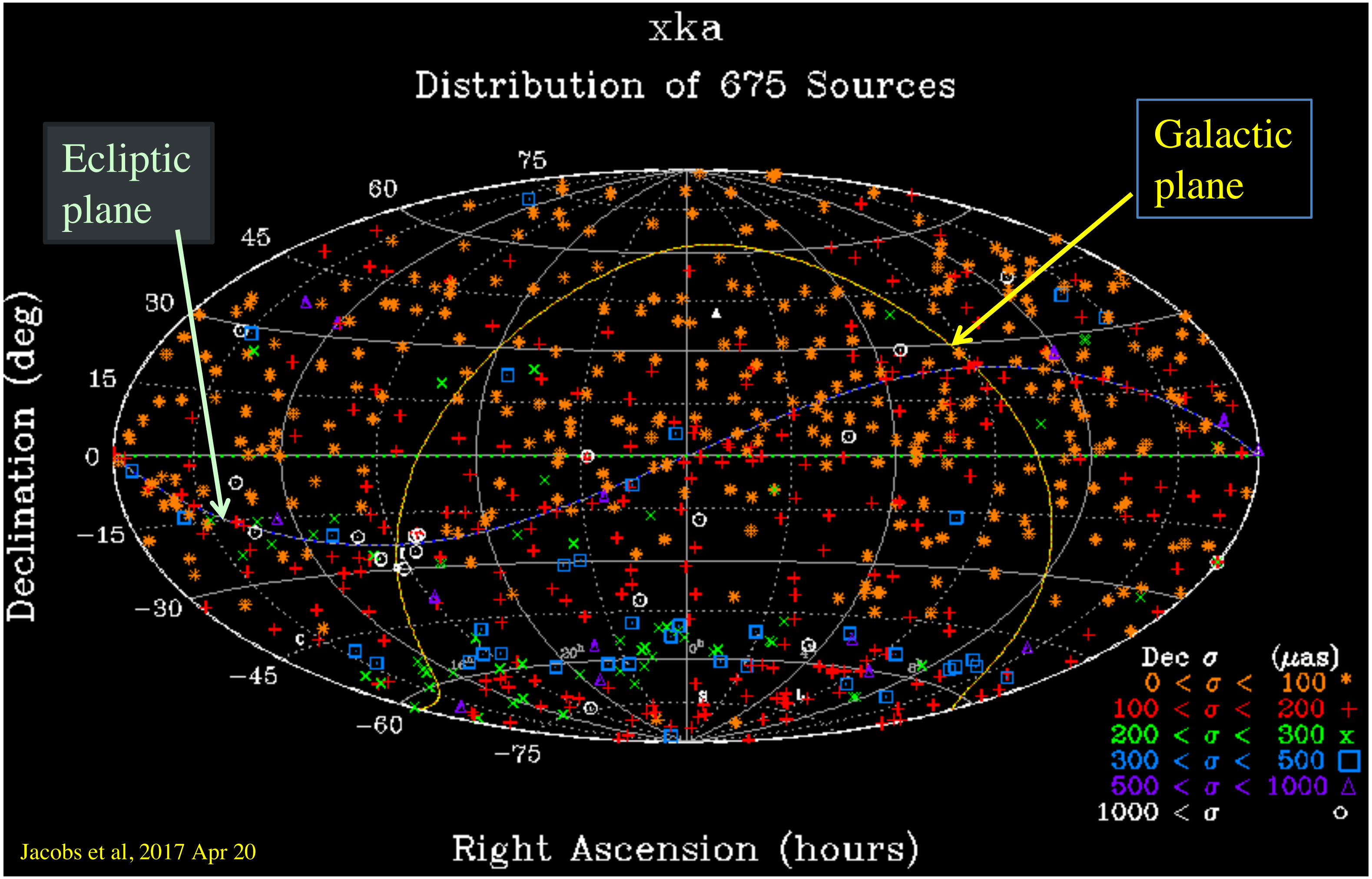


De Witt et al, 2016
astrometric solution D. Gordon

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

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

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



Ecliptic plane

Galactic plane

Jacobs et al, 2017 Apr 20

- 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

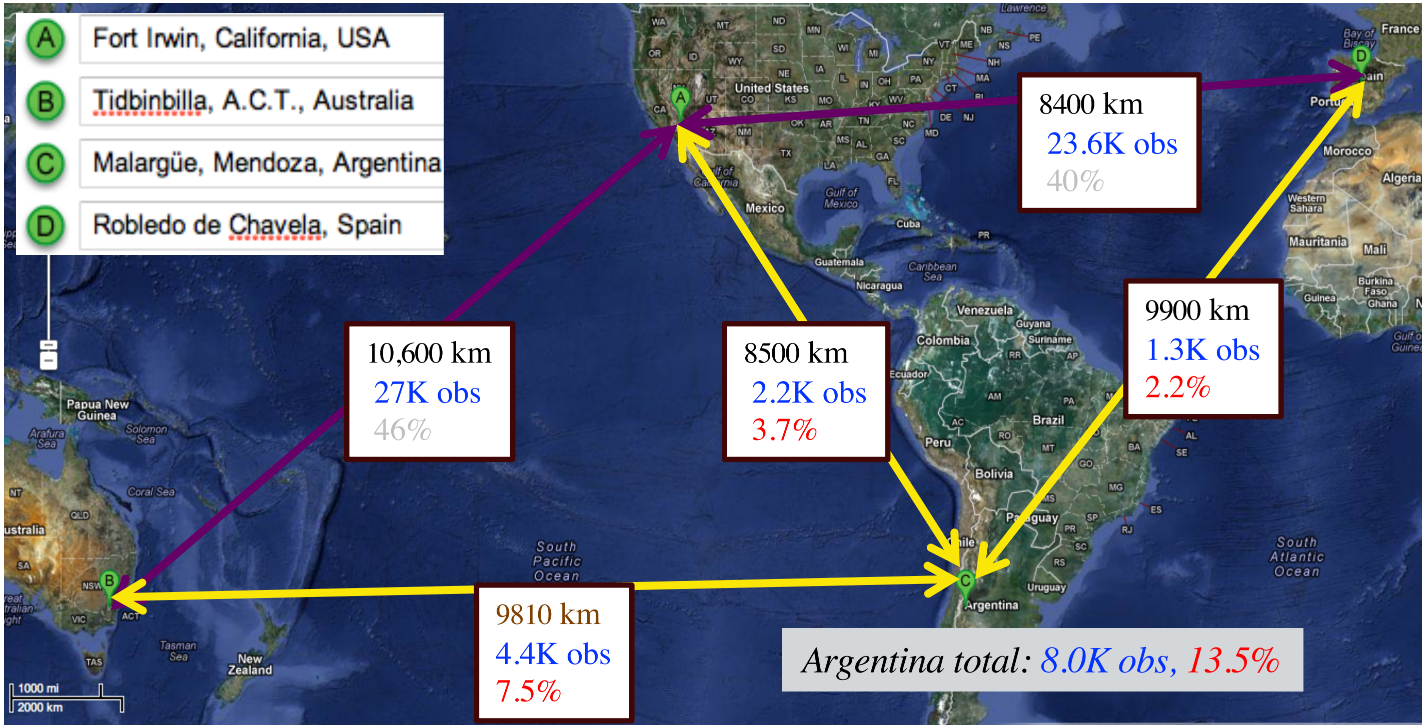
ESA Argentina to NASA-California under-observed by order of magnitude!

**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!!**



8400 km
23.6K obs
40%

10,600 km
27K obs
46%

8500 km
2.2K obs
3.7%

9900 km
1.3K obs
2.2%

9810 km
4.4K obs
7.5%

*Argentina total: 8.0K obs, 13.5%*

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 $\mu$as RMS
# Gaia DR-1 precision ~ 500 $\mu$as. DR-2 vs. VLBI may reveal zonals

**Zonal Errors**

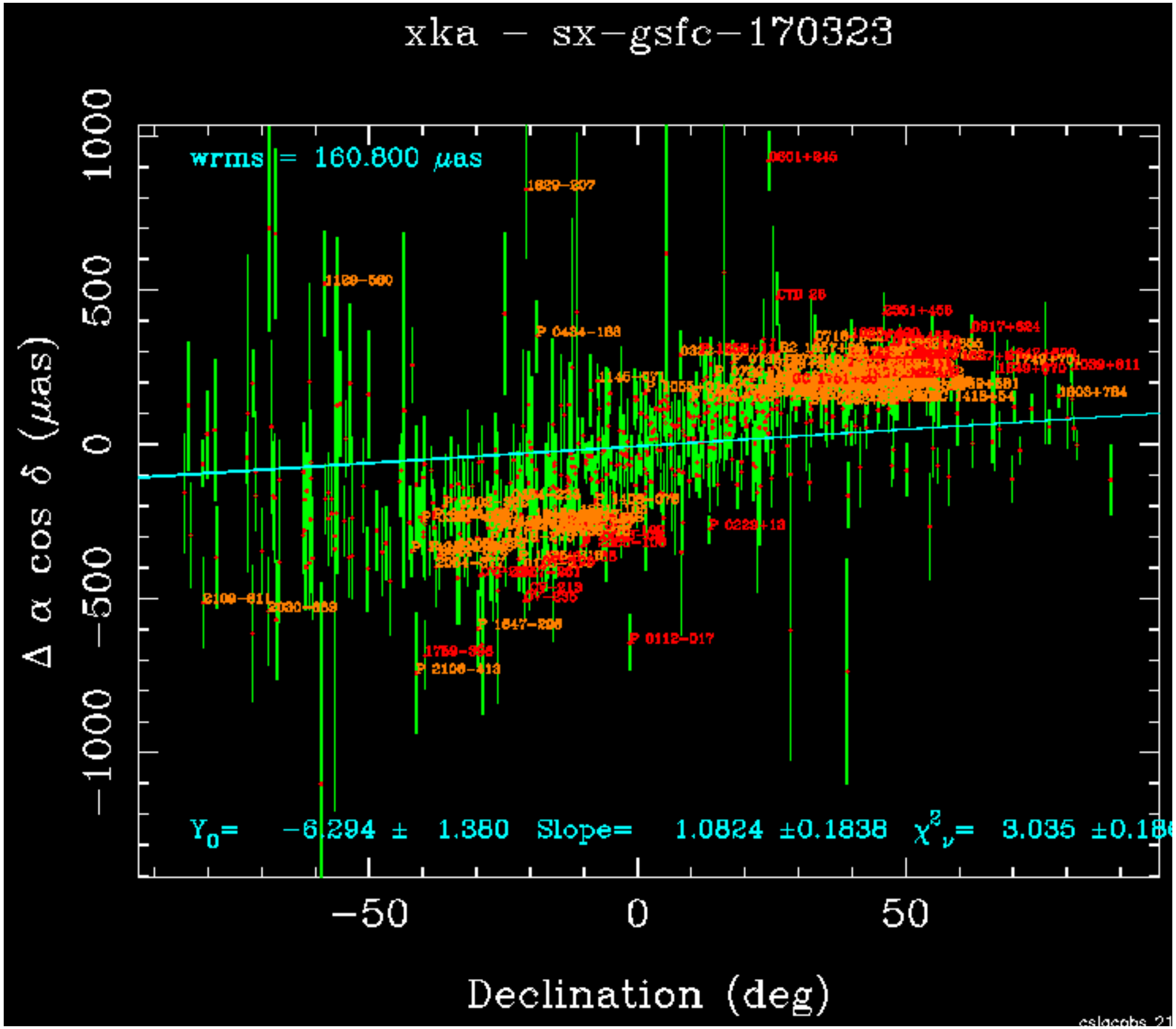
- ΔRA vs. Dec:
  ~300 $\mu$as in south, 200 $\mu$as in north

- 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

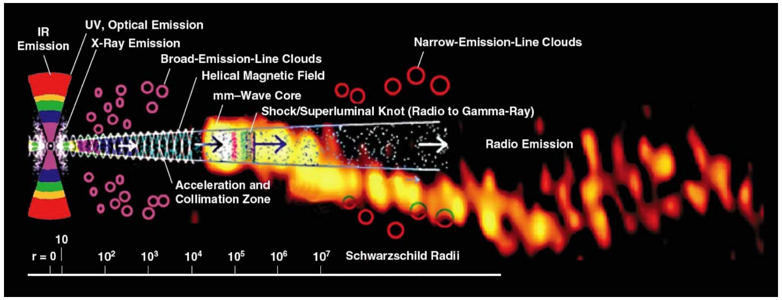
# Optical-Radio Frame Tie Geometry

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

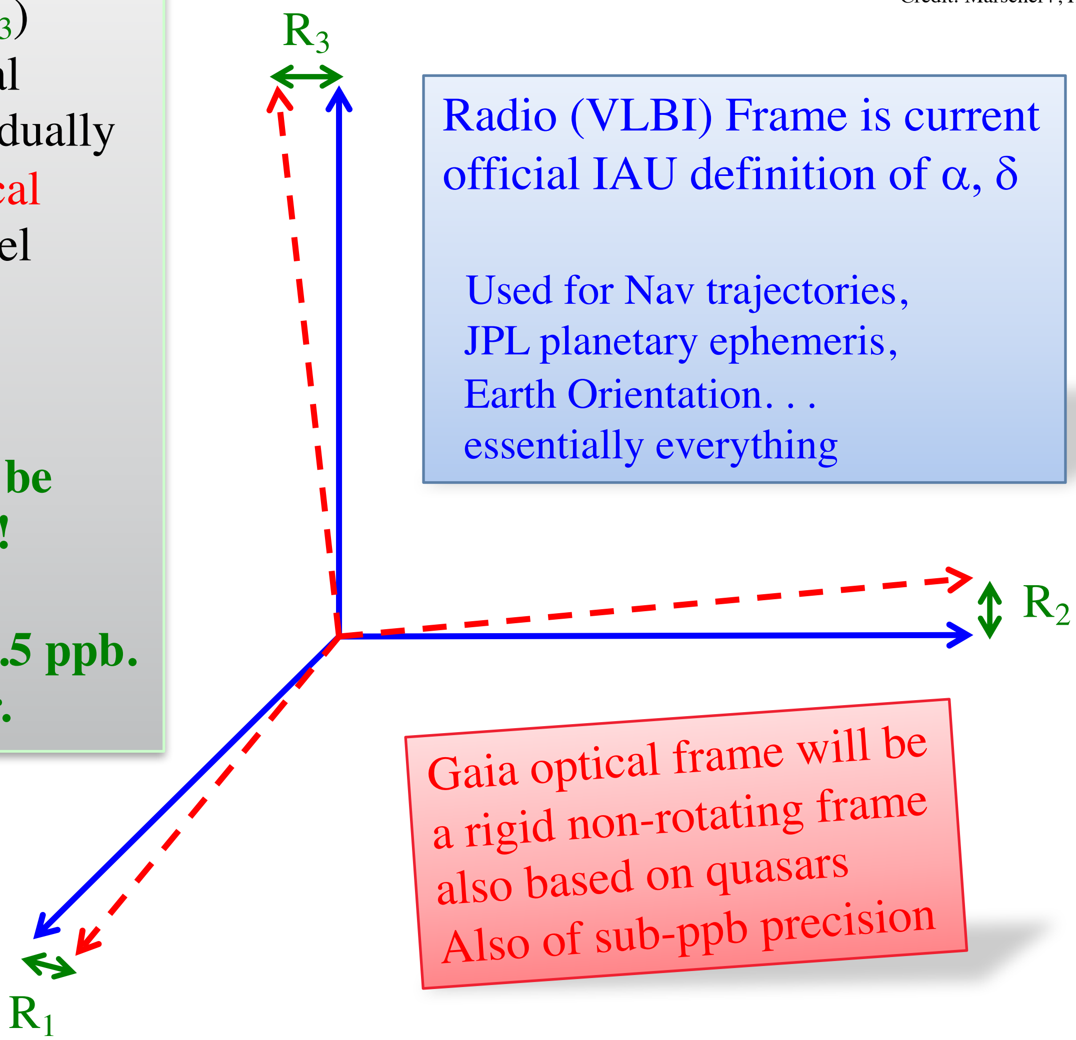
Allows seamless integration into united frame.

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

**Object precision to < 100 $\mu$as, 0.5 ppb. want tie errors 10 times smaller.**



Credit: Marscher+, Krichbuam+



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

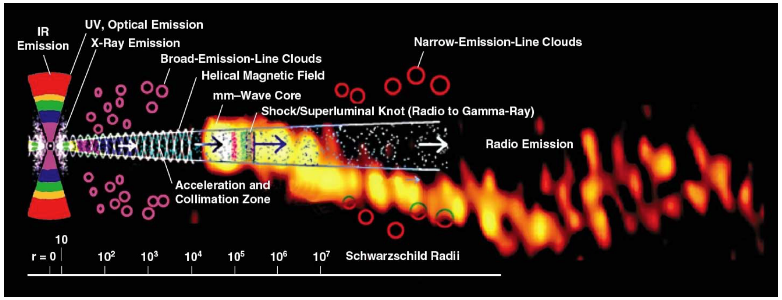
Used for Nav trajectories,
JPL planetary ephemeris,
Earth Orientation. . .
essentially everything

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

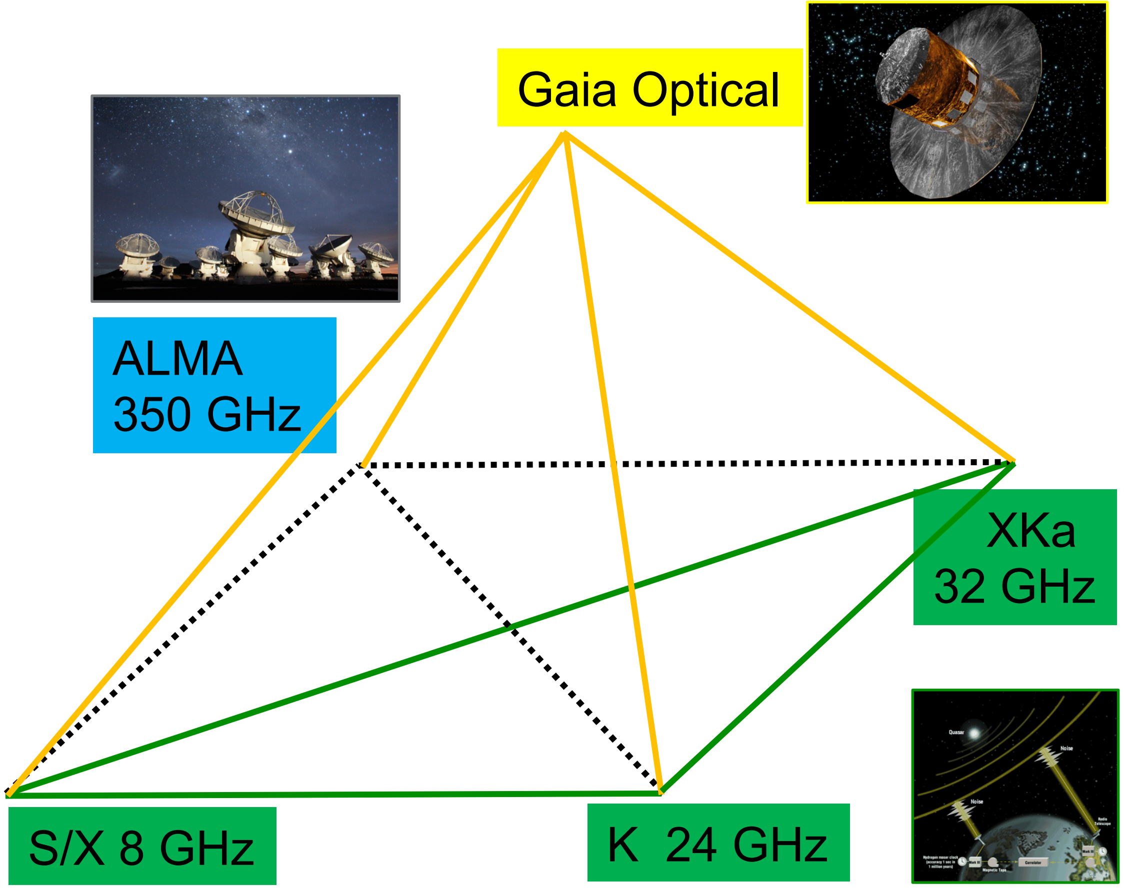
# Frame Tie Comparisons

## Tying Optical and Radio Celestial Frames

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



Credit: Marscher+, Krichbaum+



Gaia Optical

ALMA
350 GHz

XKa
32 GHz

S/X 8 GHz

K 24 GHz

Systematics:

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

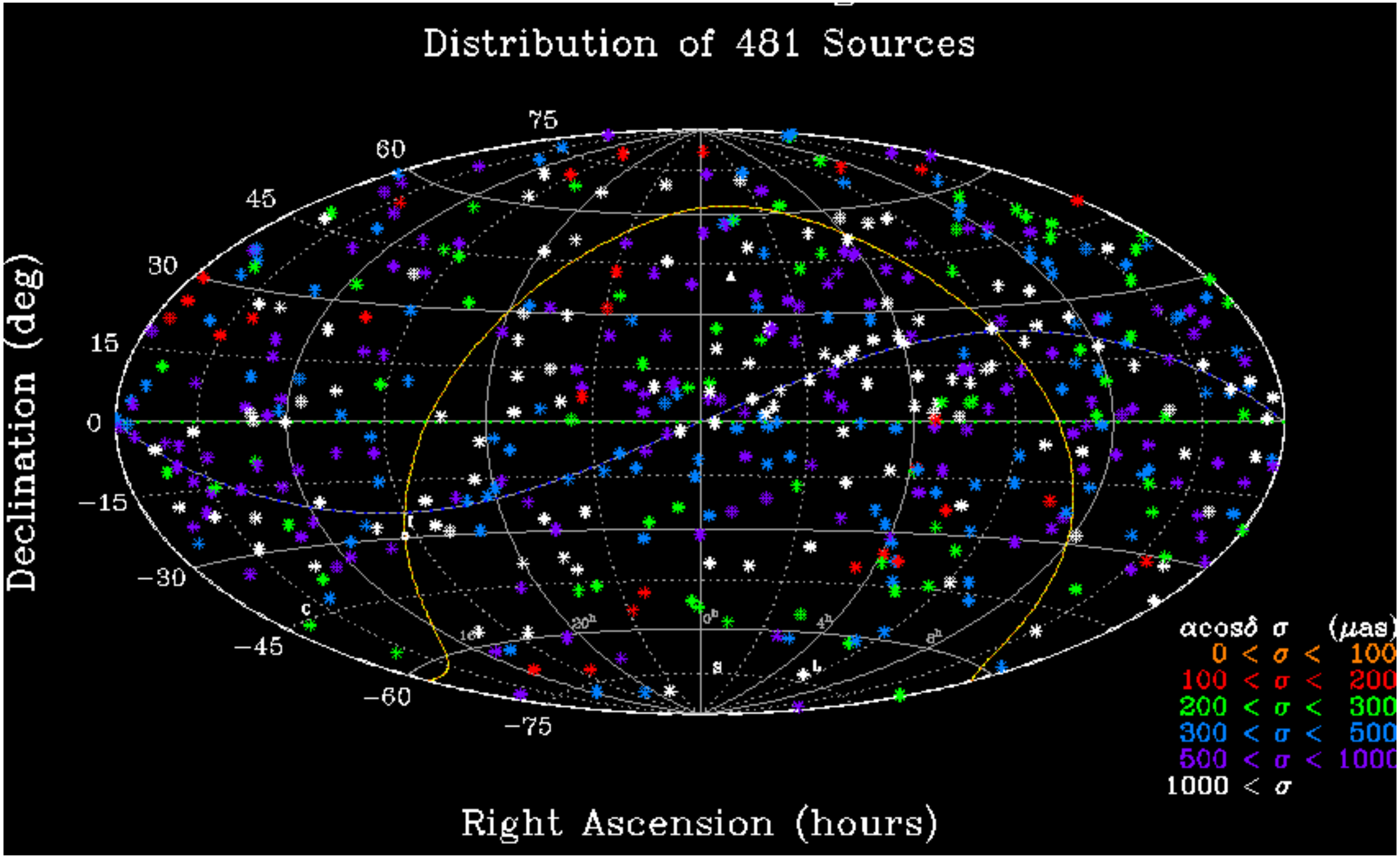
ALMA: pilot obs bright end ~$5^{\mathrm{mag}}$
Waiting on 10km+ configurations

VLBI: All bands need more
southern data

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

# Tying optical and Radio Celestial Frames

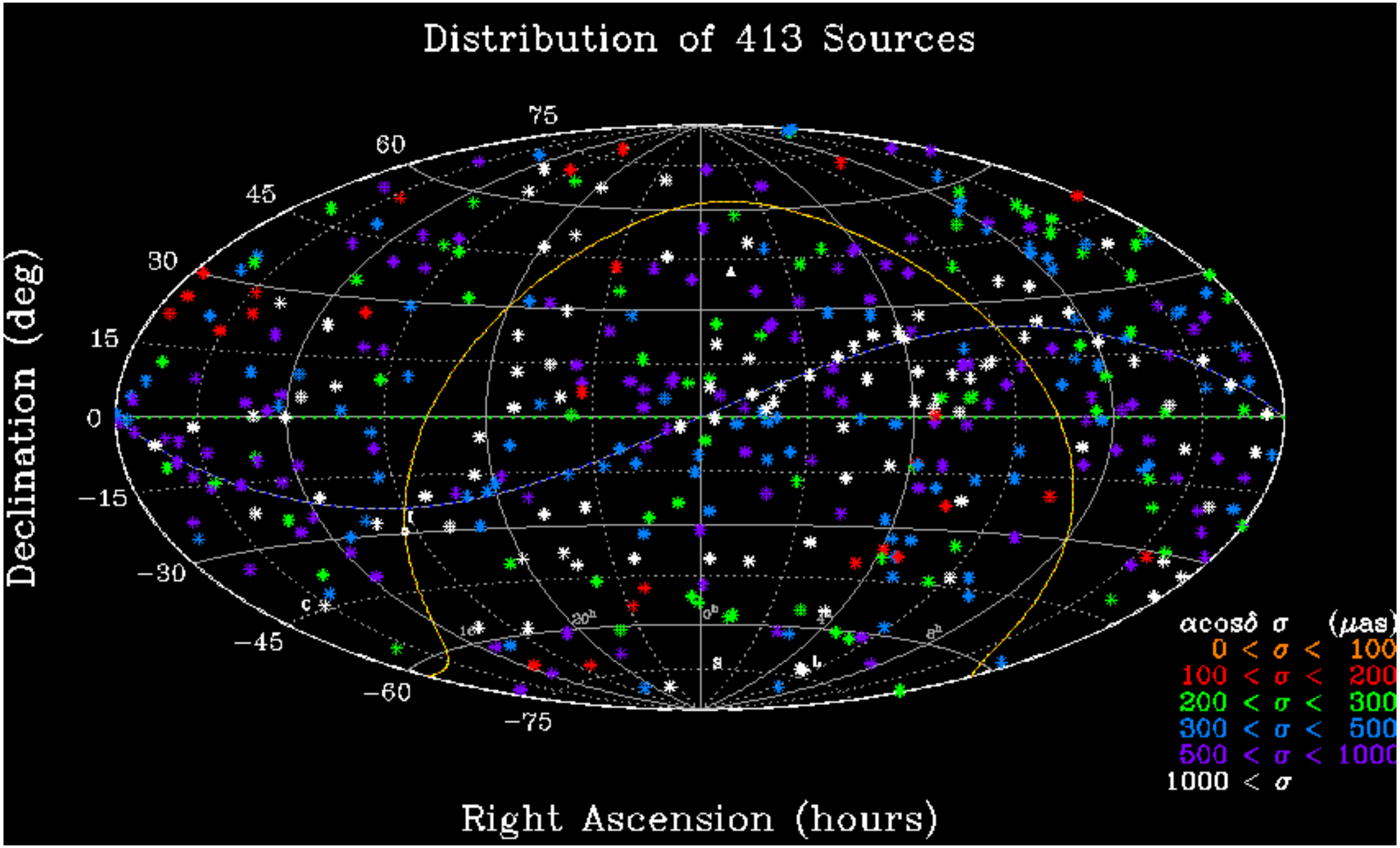
## Gaia DR1-aux vs. K VLBI



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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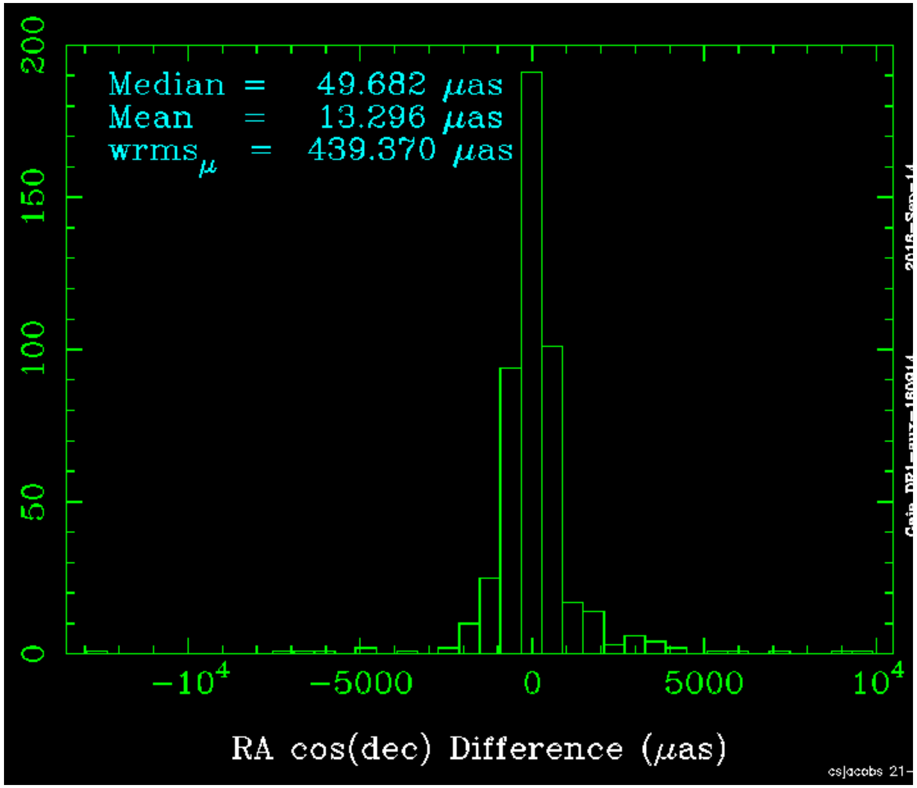
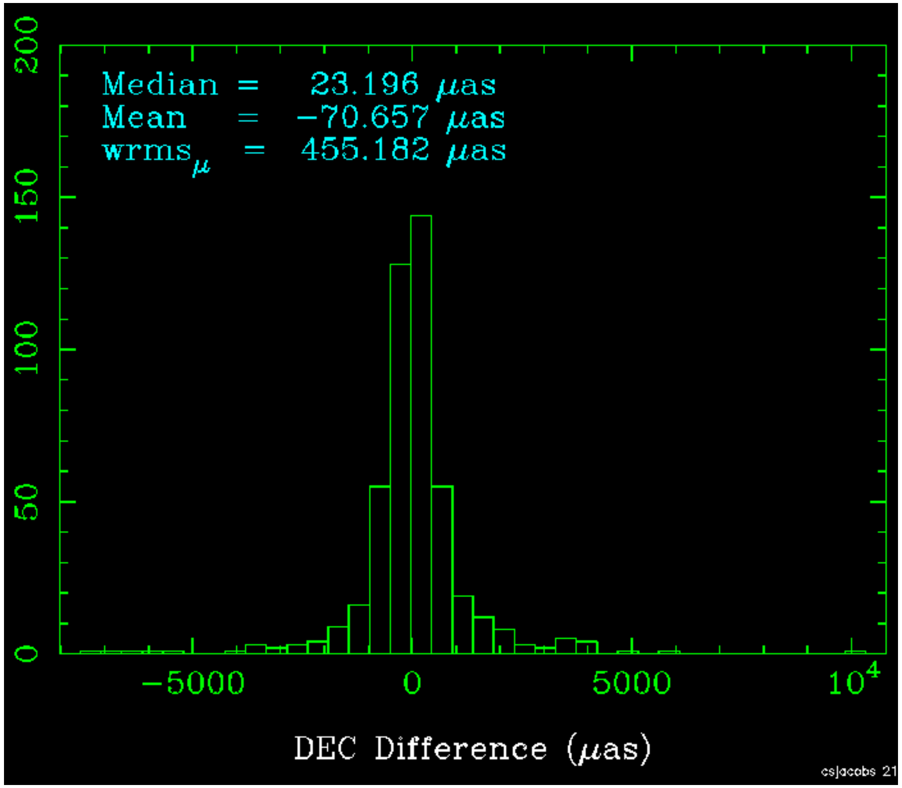
# Tying optical and Radio Celestial Frames

## Gaia DR1-aux vs. K VLBI



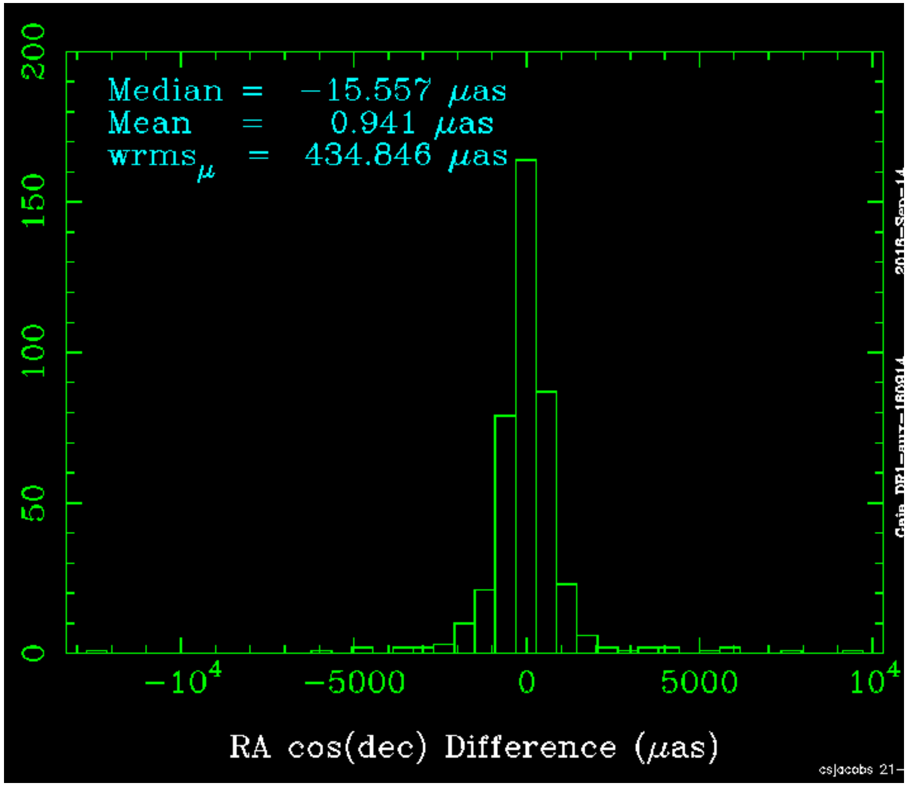


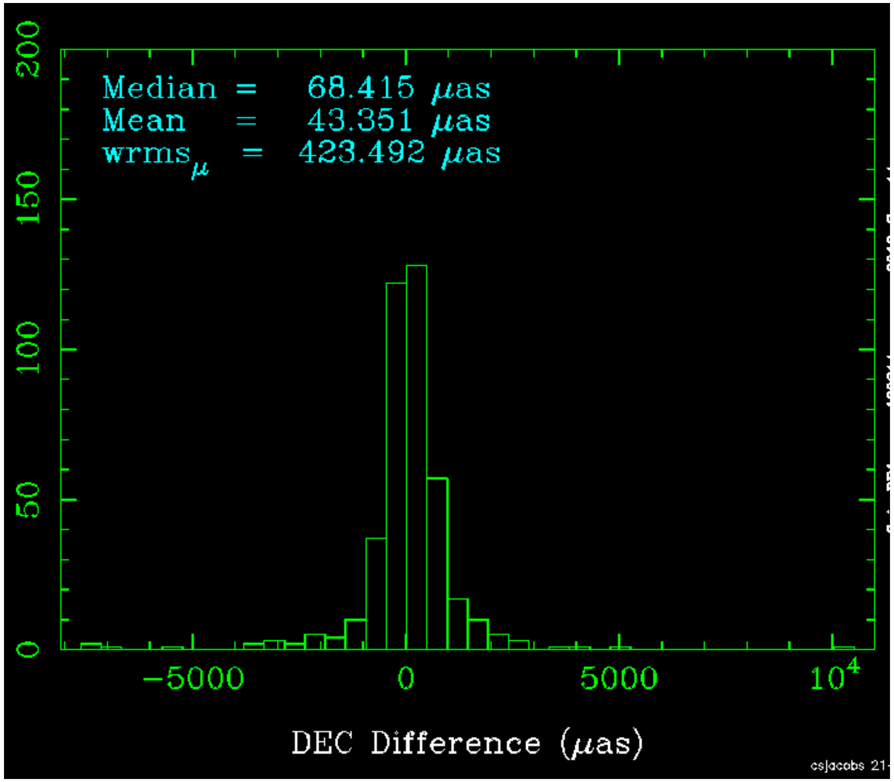
wRMS Ra and Dec differences about 440 $\mu$as (2 nrad)

Normalized differences are about 1.1 indicating realistic errors

# Tying optical and Radio Celestial Frames

## Gaia DR1-aux vs. Ka VLBI

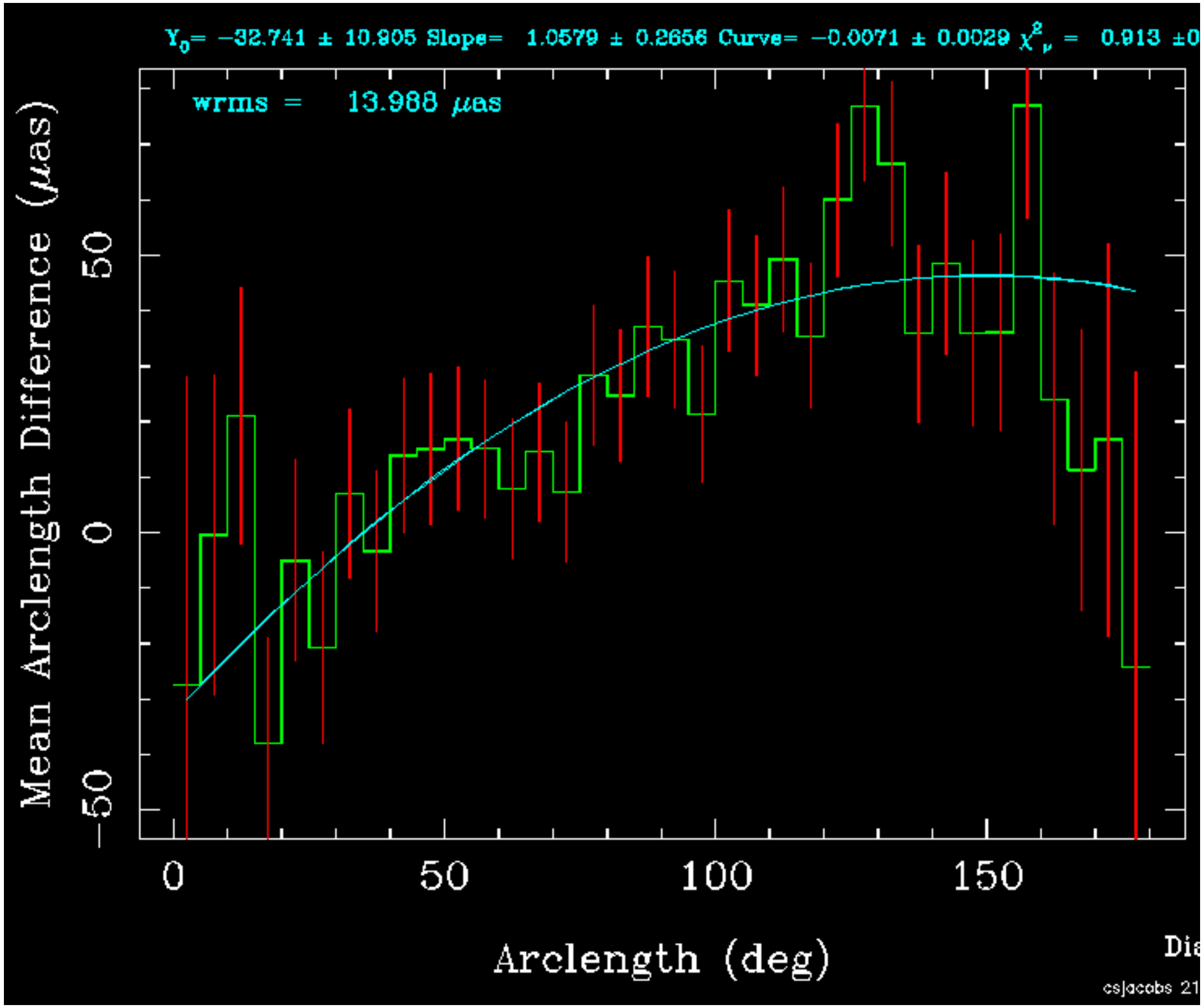




wRMS Ra and Dec differences about 400 $\mu$as (2 nrad)
Normalized differences are about 1.1 indicating realostic errors

# Tying optical and Radio Celestial Frames

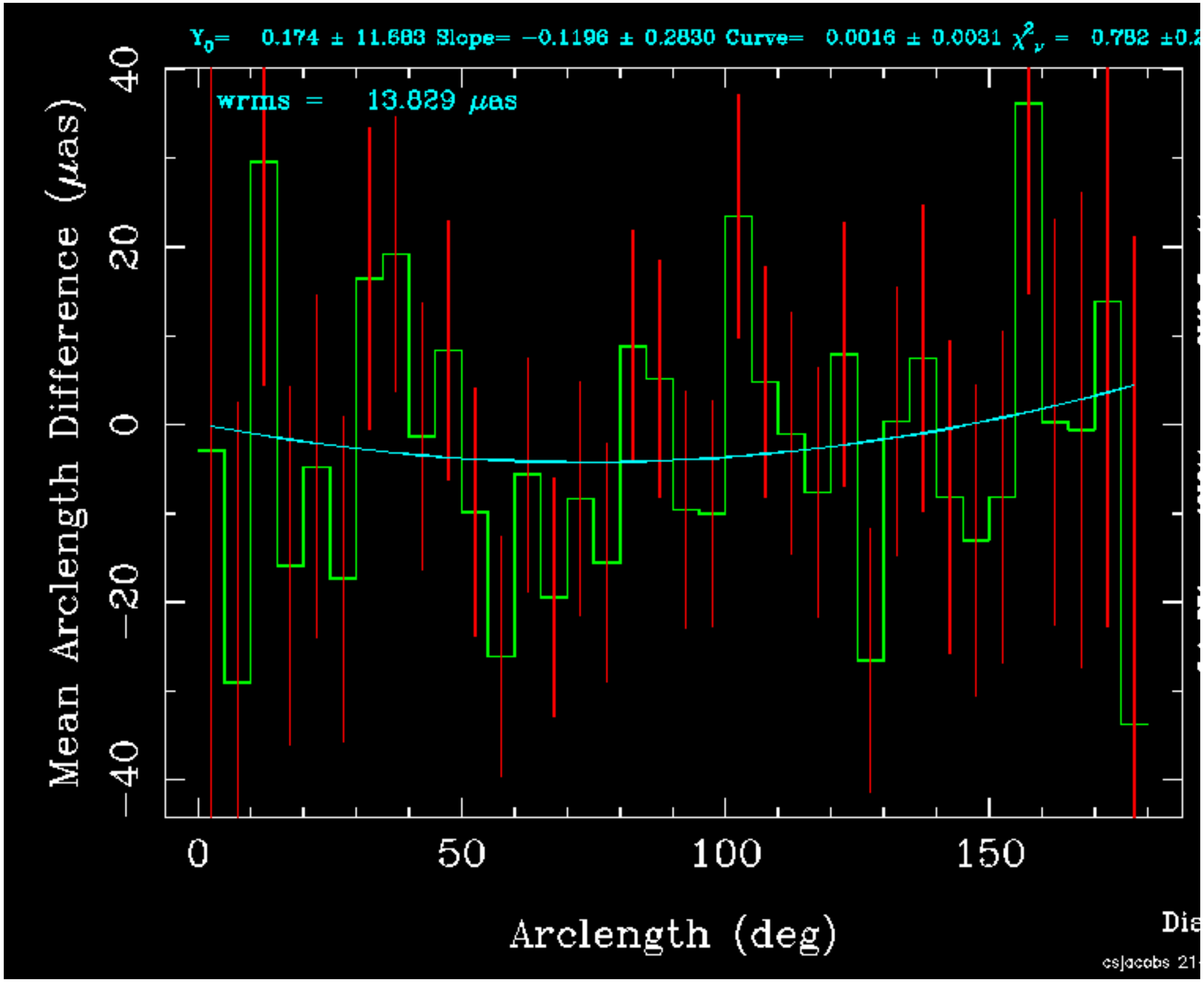
## Gaia DR1-aux vs. K VLBI



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

# Tying optical and Radio Celestial Frames

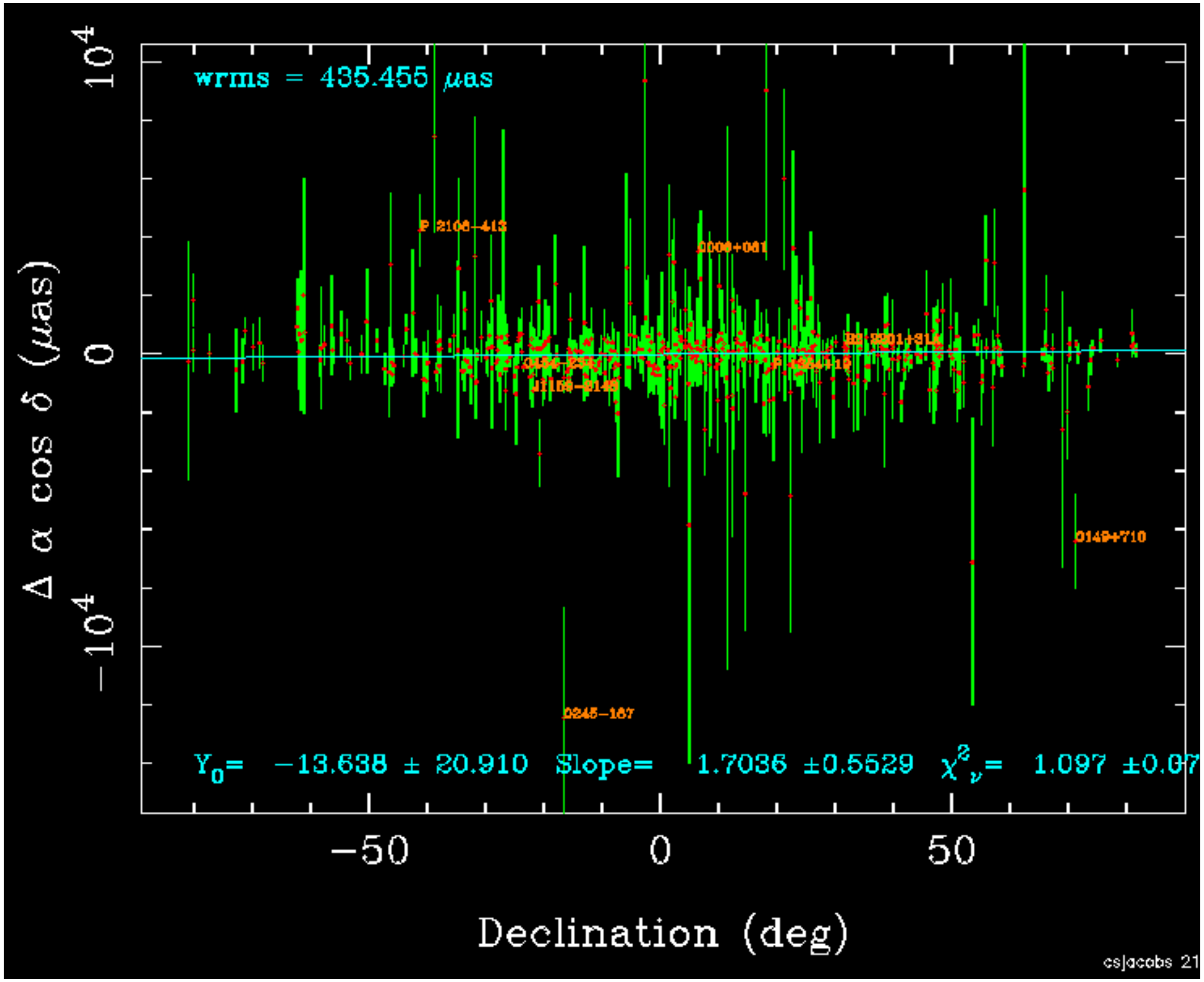
## **Gaia DR1-aux vs. Ka VLBI**



Arc differences steady vs. arclength bins at 15 μas level

# Tying optical and Radio Celestial Frames

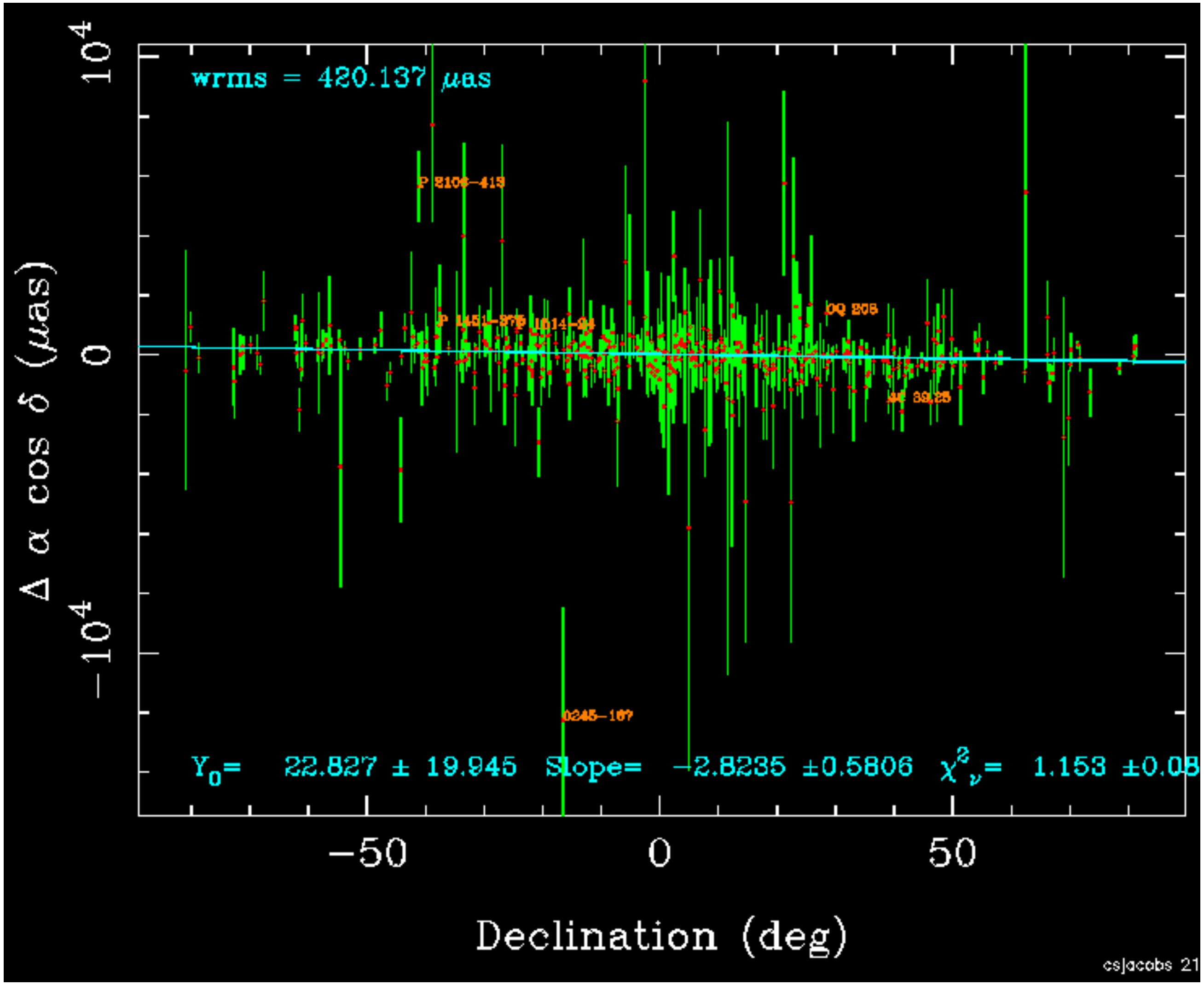
## Gaia DR1-aux vs. K VLBI



Systematic tilt: Δα vs. δ has 3 sigma slope of 1.7 +- 0.6 $\mu$as/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

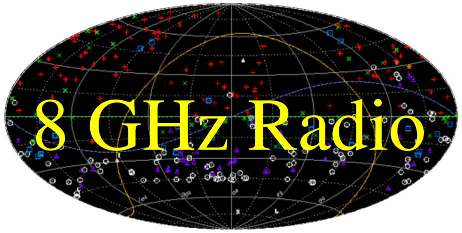
# Tying optical and Radio Celestial Frames

## Gaia DR1-aux vs. VLBI

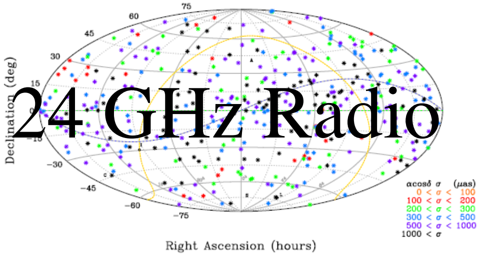
| | SX-band 8 GHz 3.6cm | K-band 24 GHz 1.2 cm | XKa-band 32 GHz 0.9 cm |
|---|---|---|---|
| # sources | 1984 | 481 | 413 |
| # outliers > 5σ | 106 | 13 | 7 |
| % outliers | 5.0 % | 2.6 % | 1.7 % |
| α wRMS | 536 µas | 439 µas | 434 µas |
| δ wRMS | 544 µas | 455 µas | 423 µas |
| $R_x$ | 32 +- 13 | 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

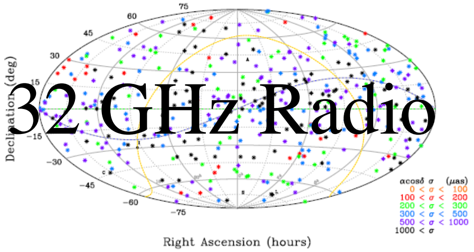
# Summary: Tying Optical & Radio



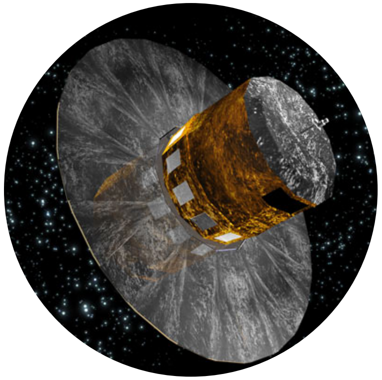
- **Goal:** Tie of optical and radio celestial frames for deep space navigation and astronomical applications.



- **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



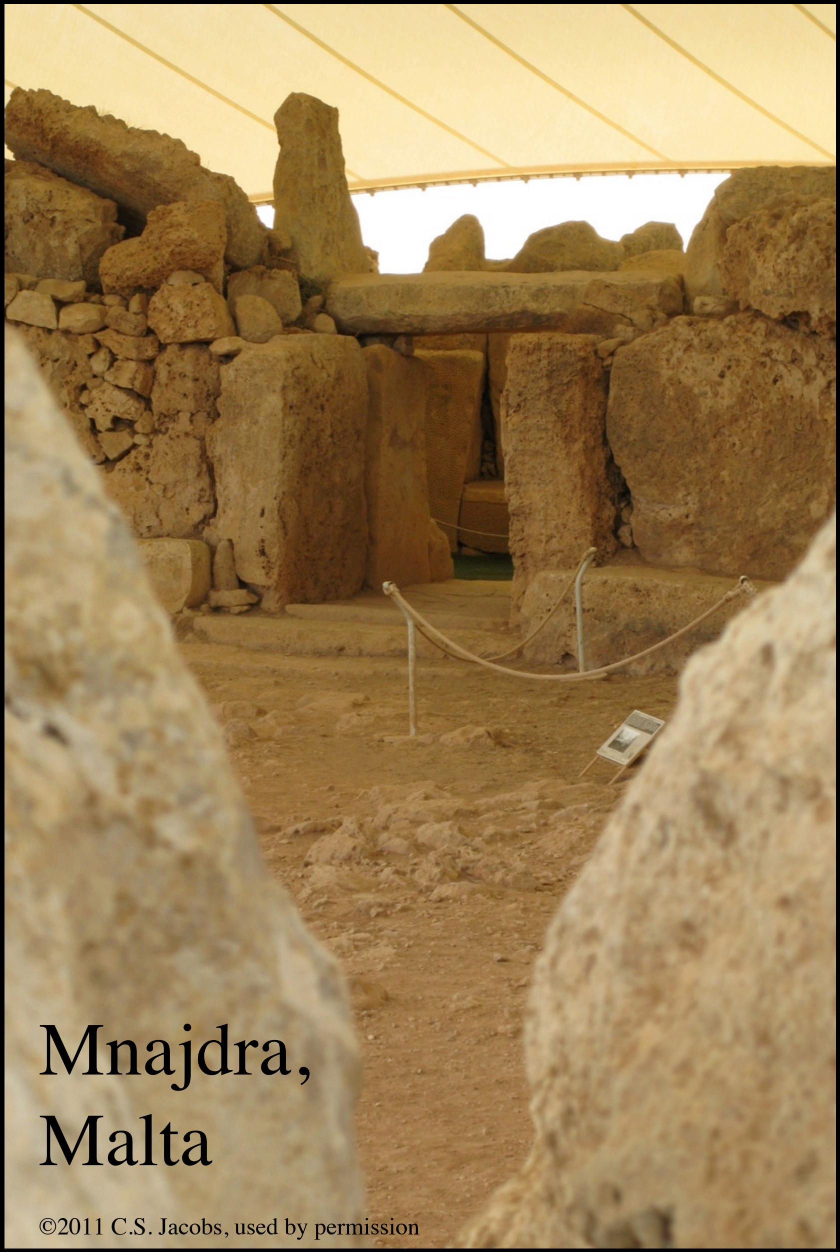
- **Preliminary results: Gaia DR1-aux vs. VLBI**
  - — Excellent 3-D tie precision of ~ 20 μas.
  - — Accuracy limited by systematic errors at 200 – 500 μas.
  - — Hints that 24 and 32 GHz VLBI are cleaner than 8 GHz
  - — Lower percentage outliers, smaller scatter vs Gaia
  - — Control of VLBI systematics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



Gaia Optical

# BACKUP

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



Mnajdra,
Malta

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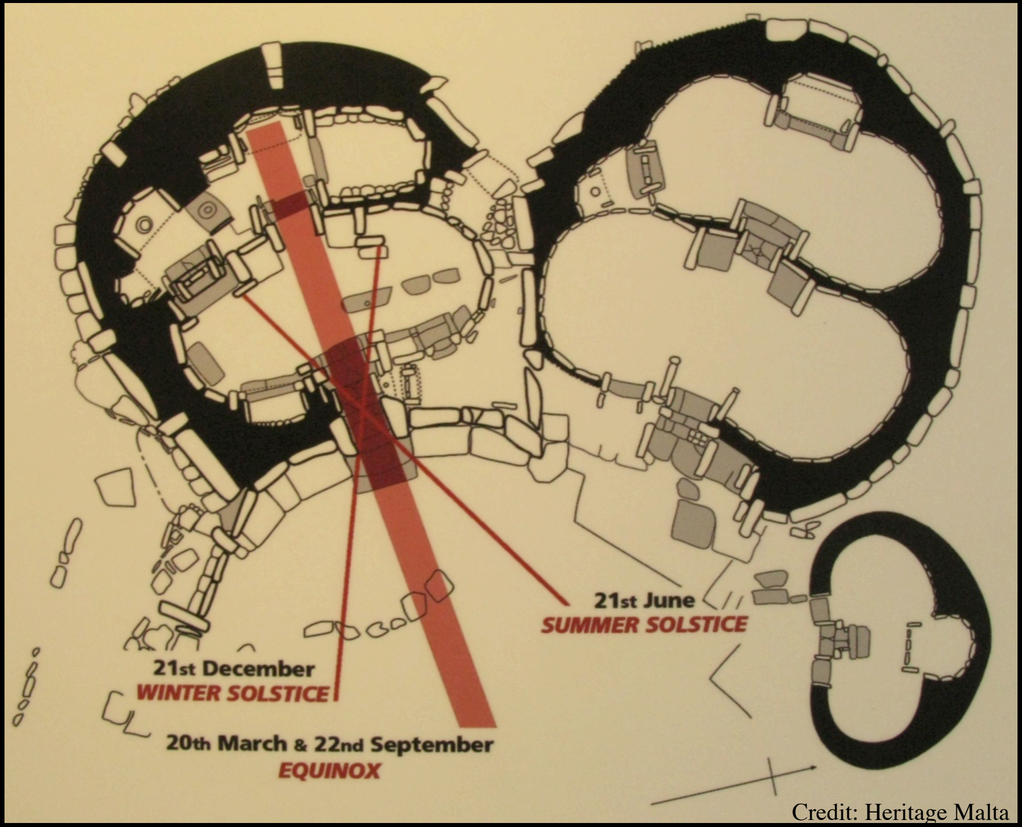
Island of Malta
Ggantija ~3500 B.C.
Mnajdra ~3200 B.C.

Credit: Heritage Malta

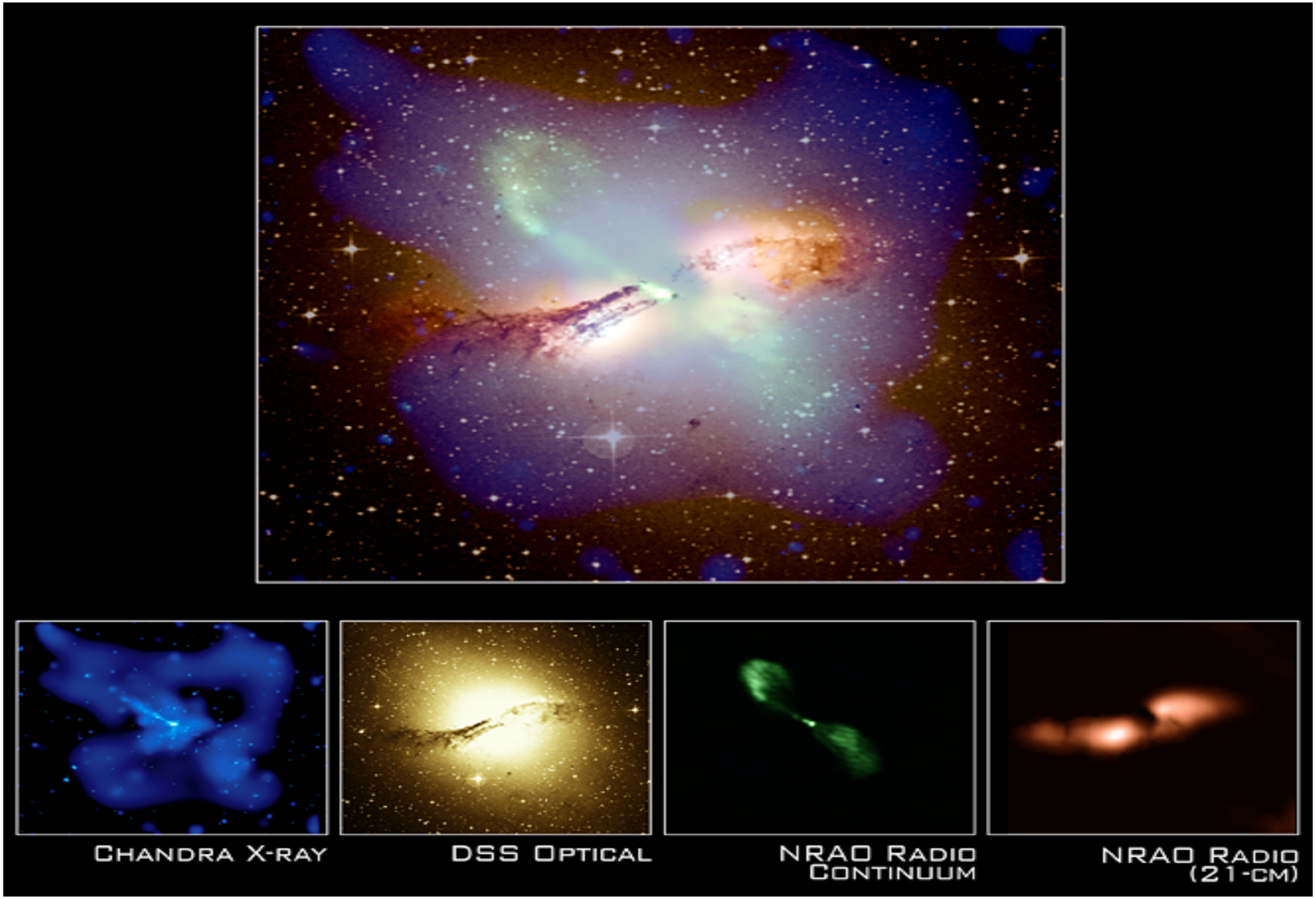
Mnajdra solar alignments



Credit: Heritage Malta

# The Source Objects

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



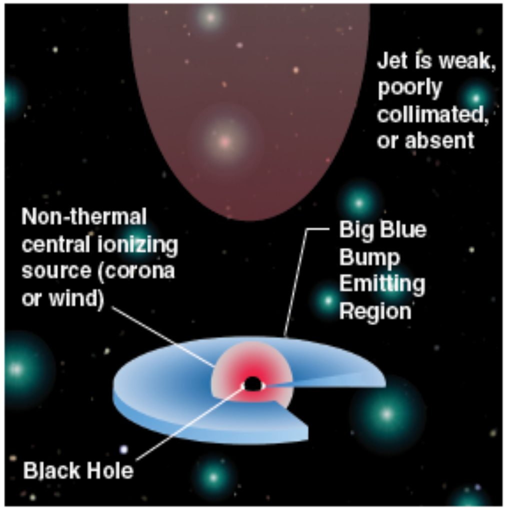
Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.),
Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

# Optical vs. Radio positions

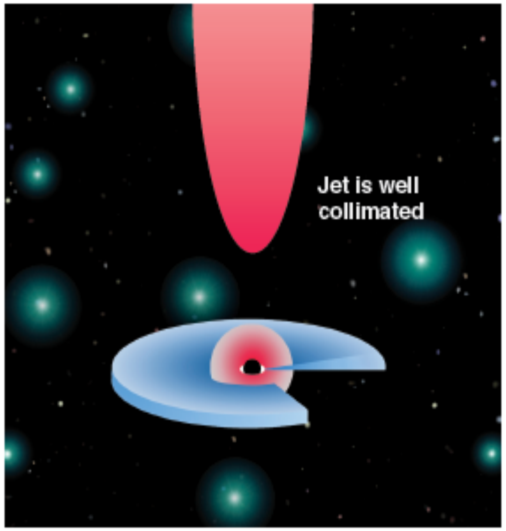
Positions differences from:

- 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

Radio-quiet Quasar

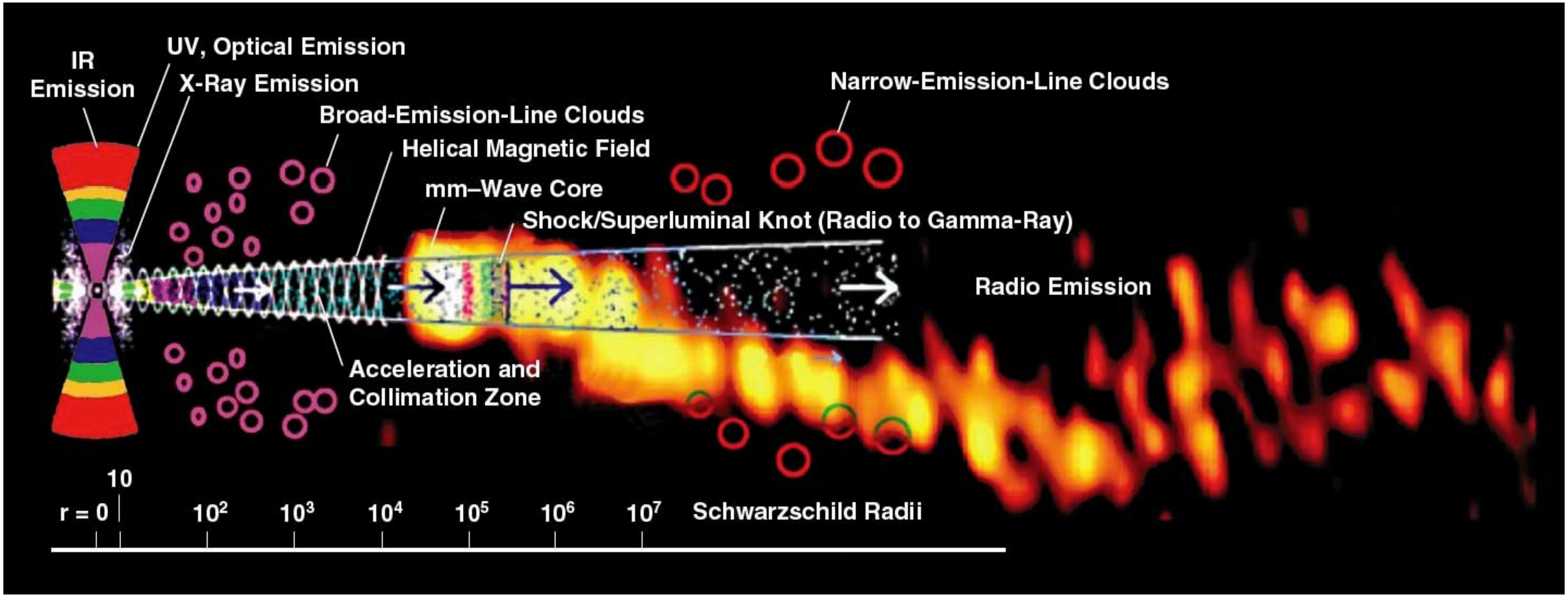


Radio-loud Quasar



Credit: Wehrle et al, $\mu$as Science, Socorro, 2009
http://adsabs.harvard.edu/abs/2009astro2010S.310W

# Active Galactic Nuclei (*Marscher*)



R~0.1-1 $\mu$as 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)*