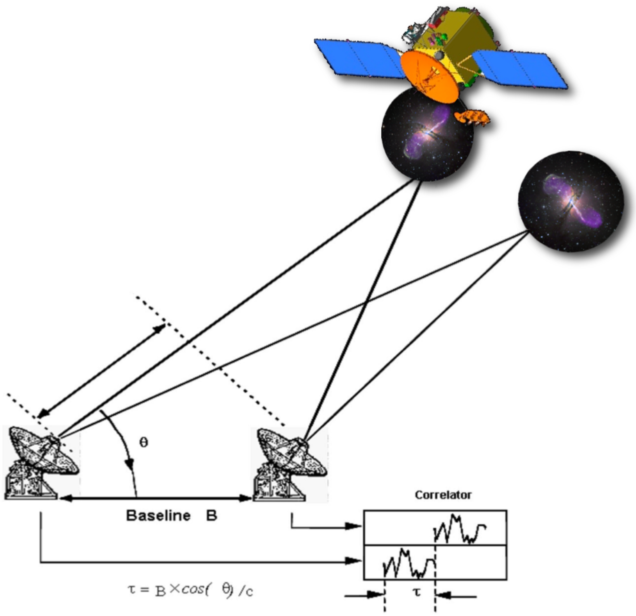
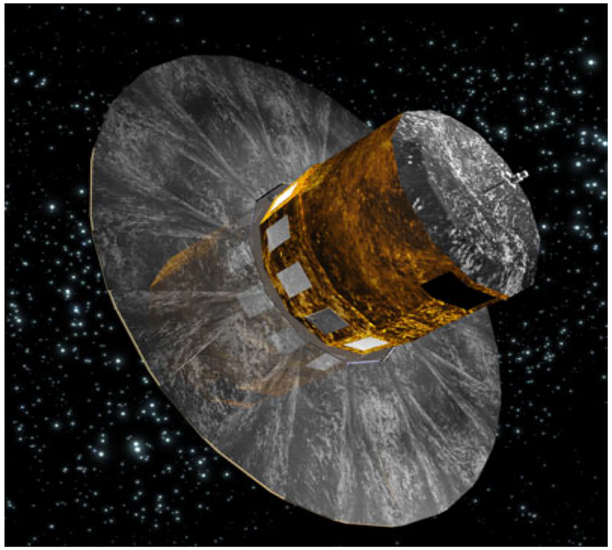
14 EVN Symposiums and Users Meeting, Granada, Spain, 8-11 Oct 2018

Tying multiple Radio Wavelength Celestial Frames to the Gaia Optical Frame





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

A. de Witt, C. Garcia-Miro, D. Gordon, S. Horiuchi, J. McCallum,
M. Mercolino, J. Quick, L. Snedeker

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,*)

VLBI:

- SX-band (8 GHz, 3.6cm) precision ~ 50 μas (Charlot et al, ICRF-3, 2018, in prep)
- K-band (24 GHz, 1.2cm) precision ~ 100 μas (*Lanyi+, 2010; de Witt+, 2018*)
- X/Ka-band (32 GHz, 9mm) precision ~ 100 μas (*Jacobs+, 2018*)

- Accuracy limited by VLBI systematics due to weak southern geometry, troposphere, etc. at 30 to 200 μas

Optical

- Gaia optical: Data Release #2 precision ~250 μas for radio loud quasars (*Mignard+, 2018*)

- Tie Precision is excellent allowing 3-D rotational alignment precision of ~15 μas

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

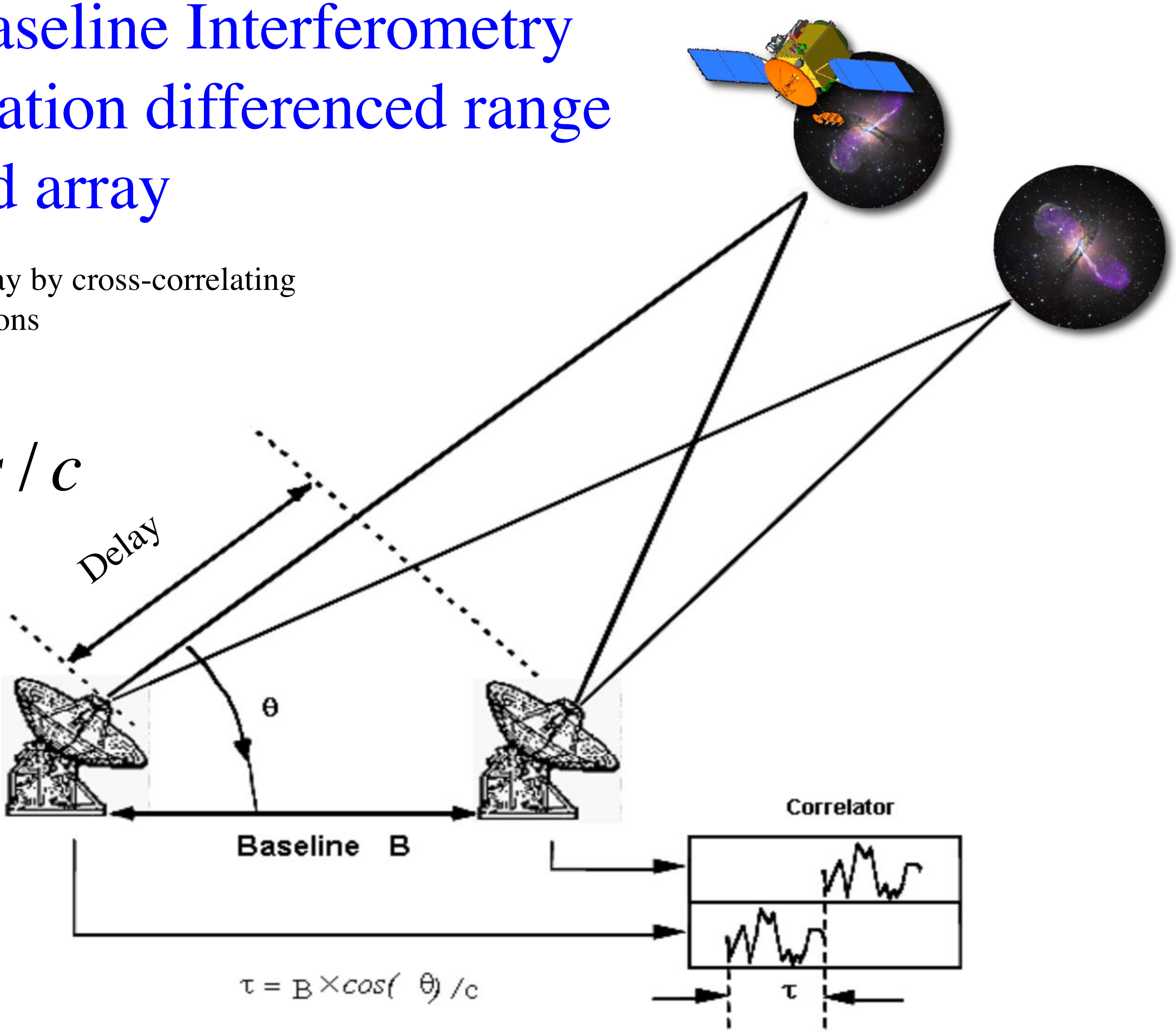
- Measures geometric delay by cross-correlating signal from two (2) stations

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

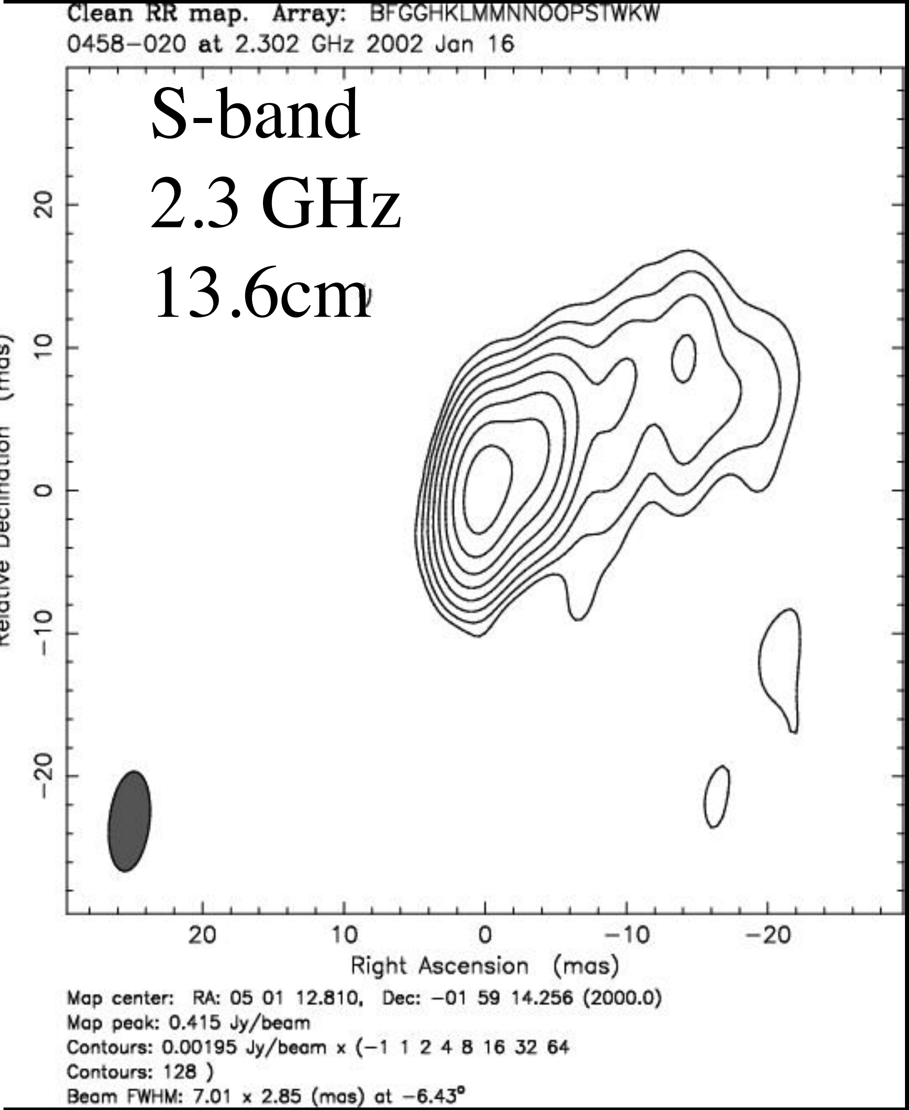
10,000 km baselines give resolution of λ/B ~ few nanoradian sub-mas beam !!

Resolves away all but galactic nucleus

Gaia beam ~60 mas



Radio Source Structure vs. Frequency



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

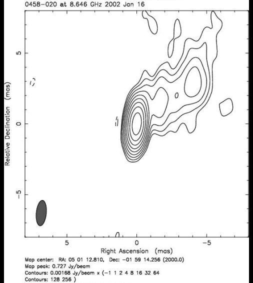
Map center: RA: 05 01 12.810, Dec: −01 59 14.256 (2000.0)
Map peak: 0.415 Jy/beam
Contours: 0.00195 Jy/beam x (−1 1 2 4 8 16 32 64
Contours: 128)
Beam FWHM: 7.01 x 2.85 (mas) at −6.43°

S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

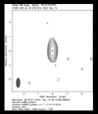
K-band
24 GHz
1.2cm

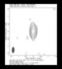
Q-band
43 GHz
0.7cm



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°





The sources
become better →
Less structure

Ka-band
32 GHz
0.9cm

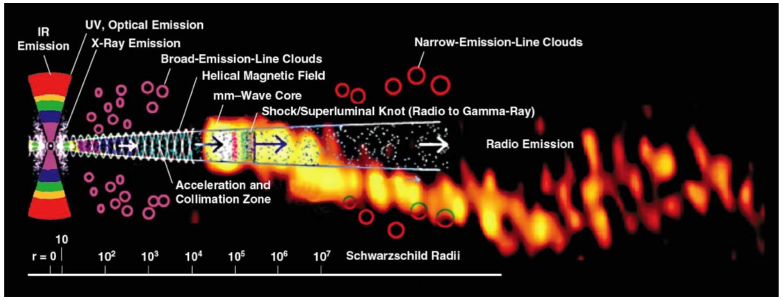
Images credit: Pushkarev & Kovalev A&A, 544, 2012 (SX); Charlot et al, AJ, 139, 2010 (KQ)

The goal:

Alignment of Optical and Radio into Common Frame

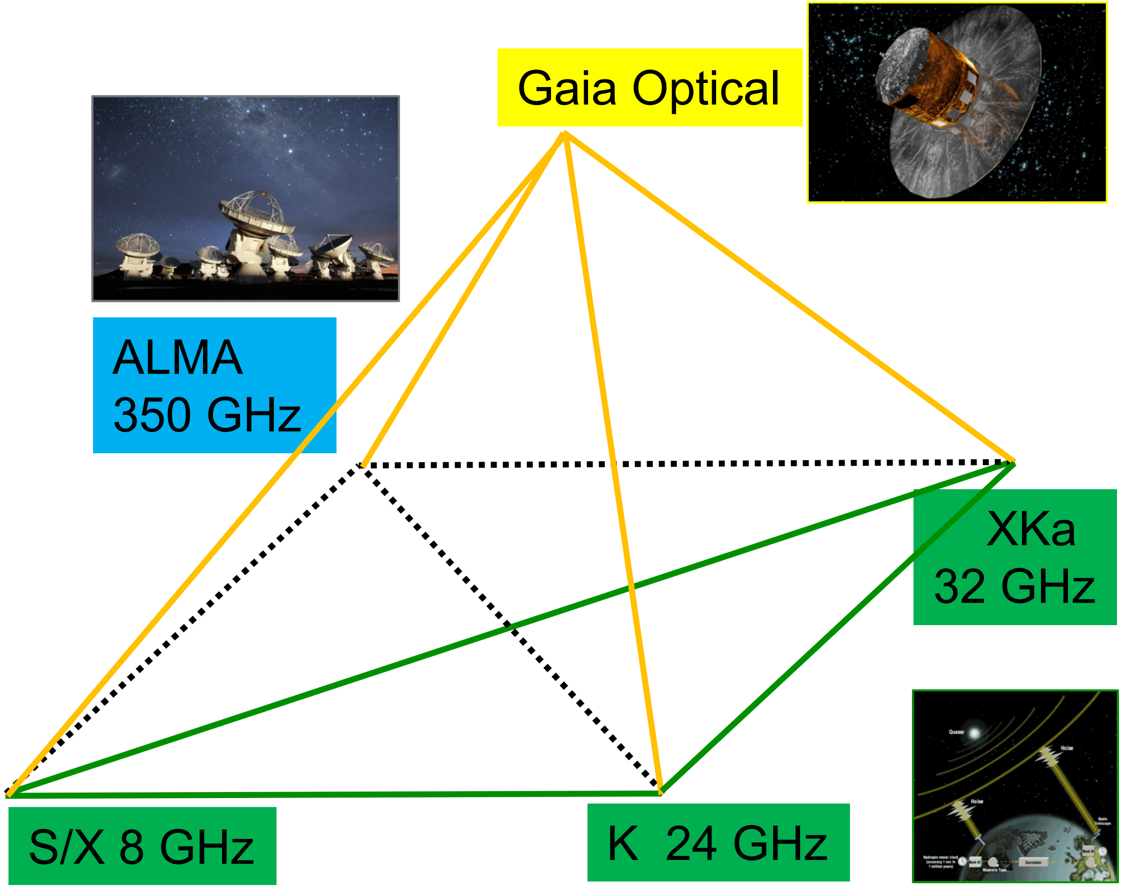
Frame Tie Comparisons

Tying Optical and Radio Celestial Frames



Credit: Marscher+, Krichbaum+

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



Gaia Optical

ALMA
350 GHz

XKa
32 GHz

S/X 8 GHz

K 24 GHz

Systematics:

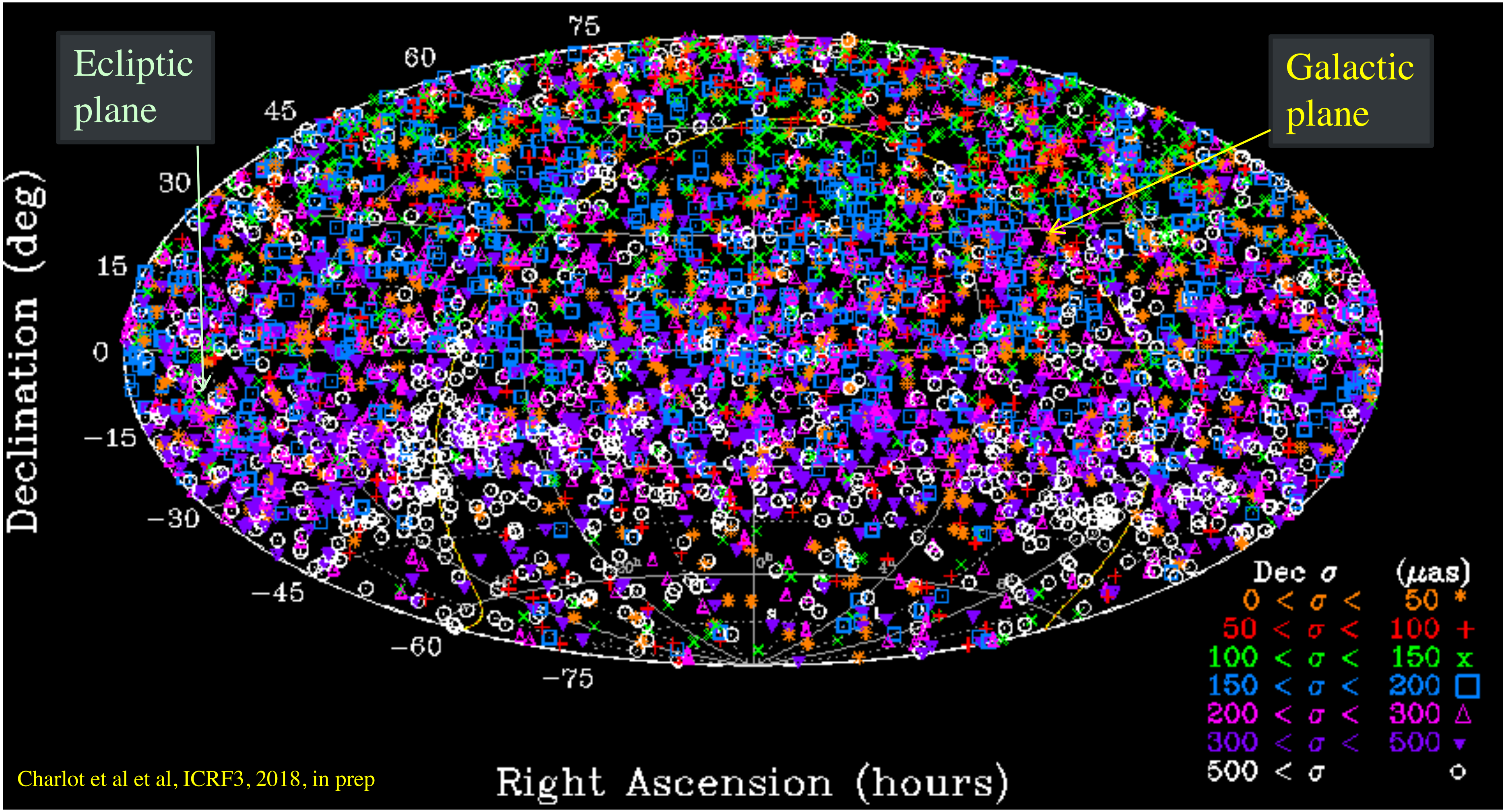
Gaia: 60 mas beam sees
Host galaxy, foreground stars, etc.

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

VLBI: All bands need more
southern data

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

SX (8 GHz, 3.6cm) *ICRF-3*



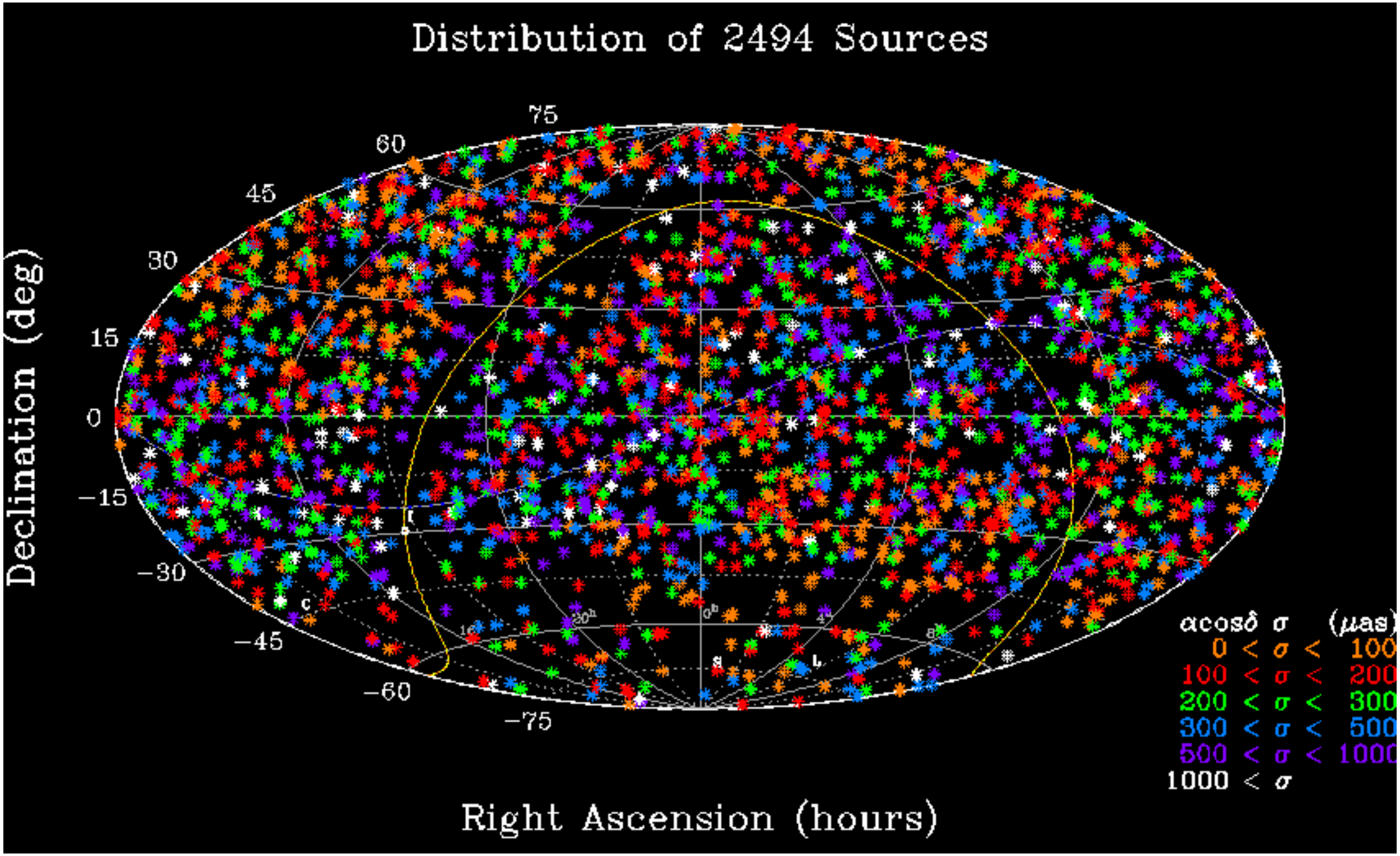
Charlot et al et al, ICRF3, 2018, in prep

- Strengths:
  - 4536 sources
  - Uniform spatial density
  - median RA precision ~40 μas
  - 40 years, 13 million obs averages many error down

- Weaknesses:
  - Source structure
  - South ($\delta < -30$ deg) weak due to limited South Africa-Australia data

Tying optical and Radio Celestial Frames

Gaia-DR2 vs. SX (8 GHz) VLBI



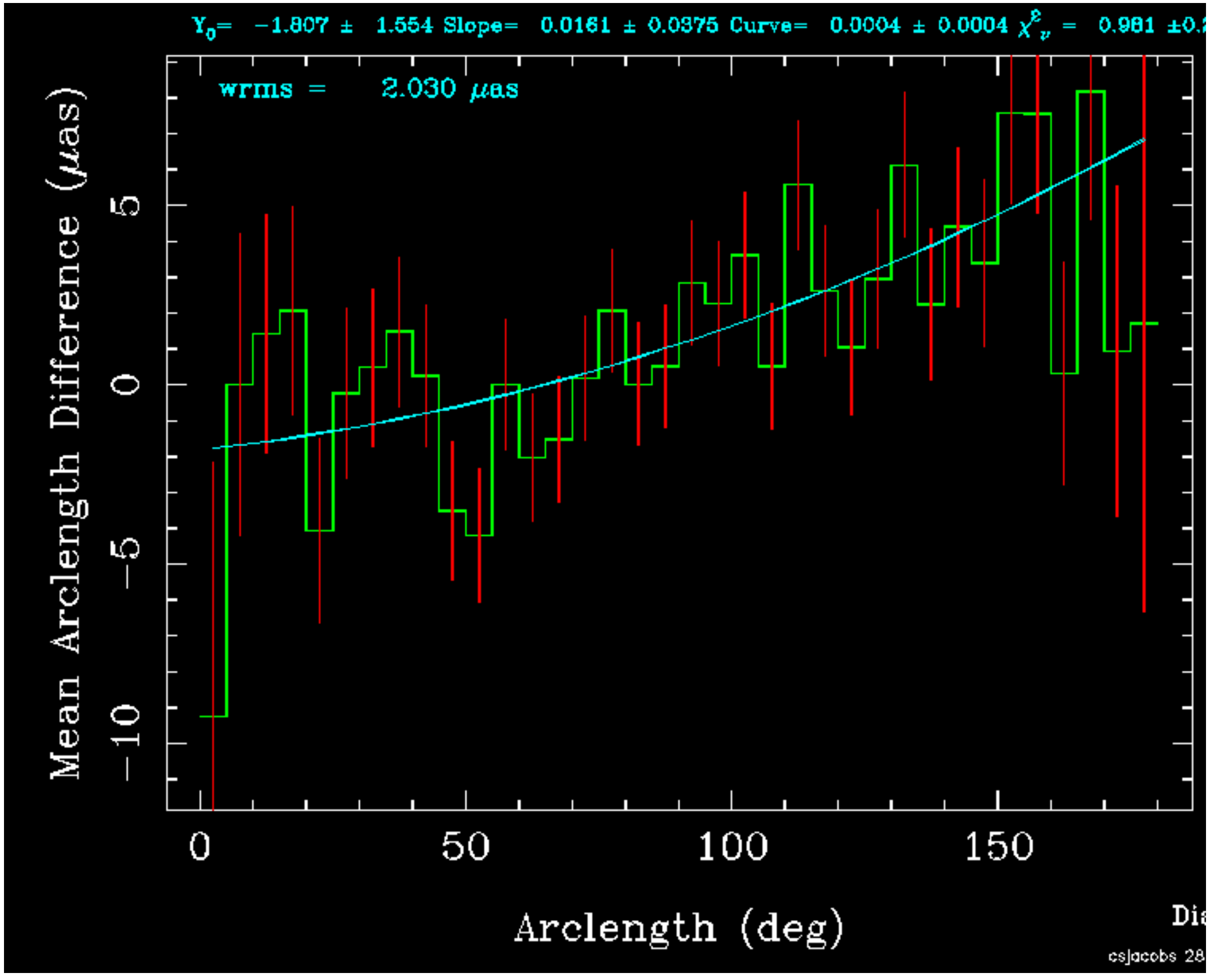
55% matches usable with Gaia, *but five times more total matches than K or Ka*

Weaker in the south. Gaps near galactic plane.

Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

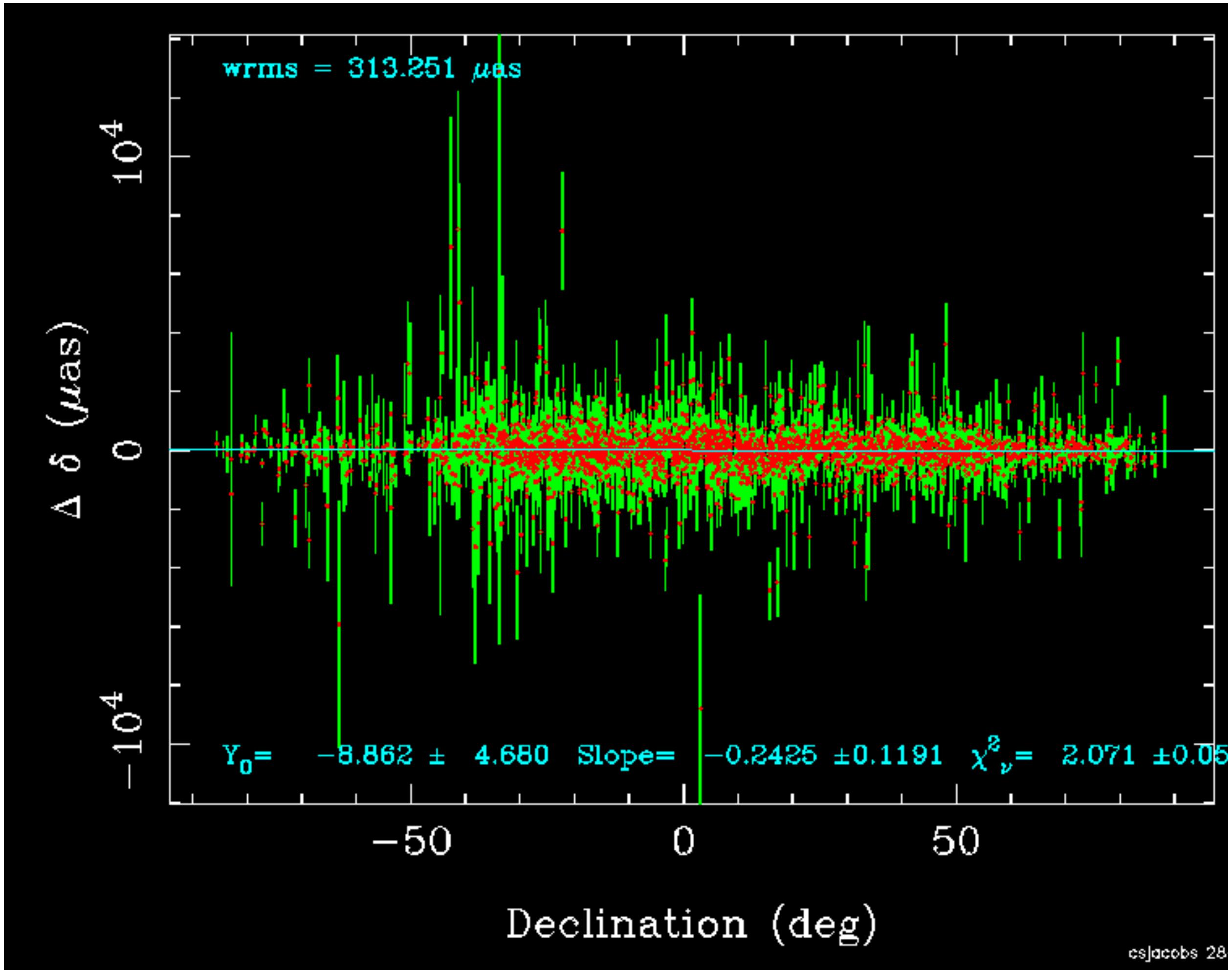
Gaia DR2 vs. SX VLBI



Arc differences vs. arclength shows distortion at 5 μas level *(2.4e-11)*

Tying optical and Radio Celestial Frames

Gaia DR2 vs. SX VLBI



Systematic tilt? Δδ vs. δ has 2 sigma slope of -0.2 +- 0.1 μas/deg

SX (Charlot et al, 2018, in prep) vs. Gaia Optical Frame *(Mignard+, 2018)*

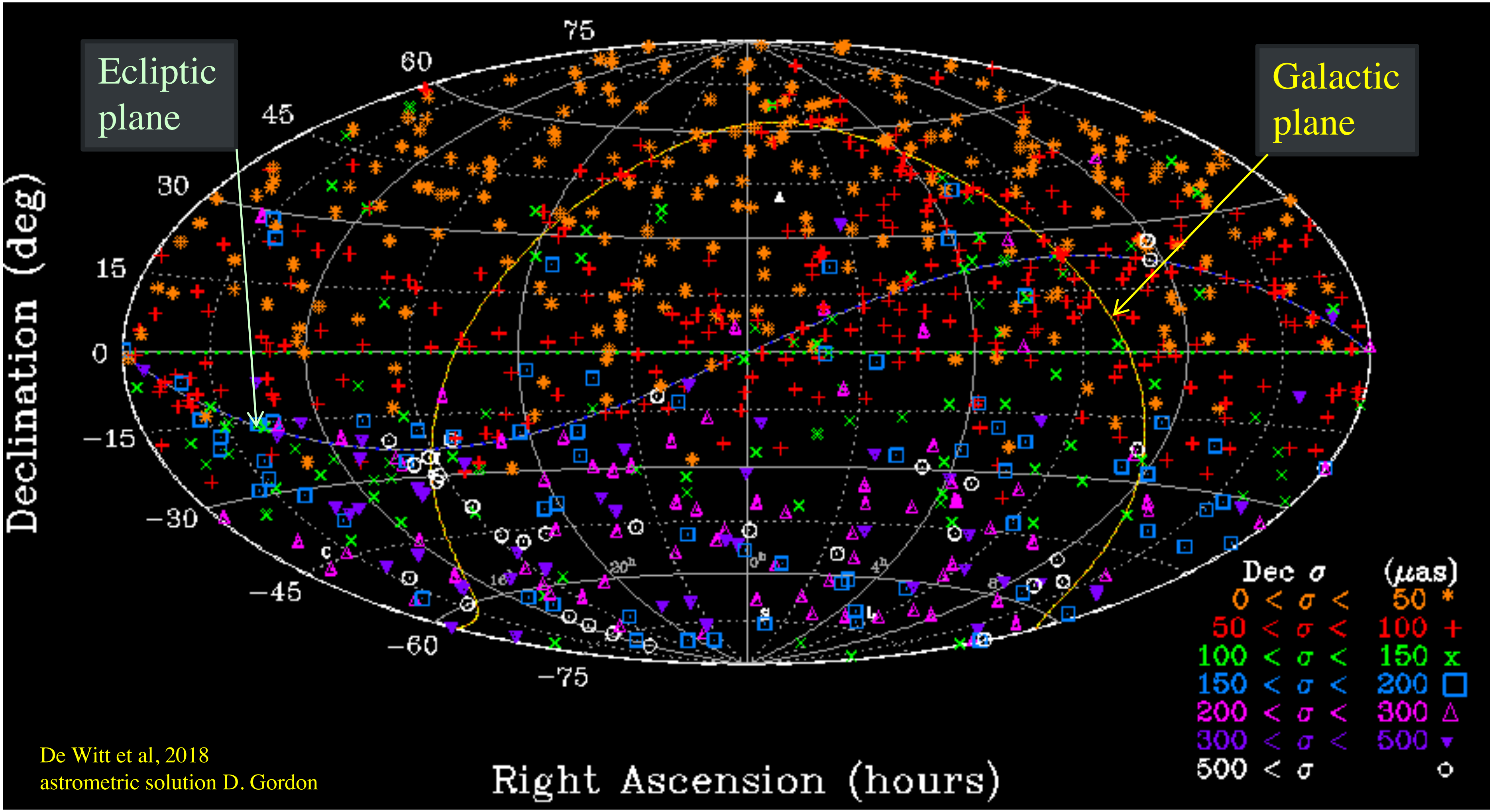
Spherical Harmonic Differences for 2494 common sources (10% outliers removed)

Largest terms ~ 30 µas (scheme of *Mignard & Kiloner, 2012*)

```
Parameter_name                value           sigma            scaled_σ
 R1 rotation_X           =    16.634     +-   6.0223     µas    8.9072
 R2 rotation_Y           =   -16.298     +-   5.9627     µas    8.8192
 R3 rotation_Z           =    9.6995     +-   5.2049     µas    7.6983

 Dipole-1                =    6.7523     +-   5.7940     µas    8.5696
 Dipole-2                =    8.9083     +-   5.6332     µas    8.3317
 Dipole-3                =   -6.5067     +-   5.7051     µas    8.4382

 Quad 20 Mag R(sin2Dec)=   -1.0679     +-   5.8846     µas    8.7036
 Quad 20 Elc R(sin2Dec)=   -32.995     +-   6.4831     µas    9.5888

 Quad 21 Elc Real        =    2.6989     +-   8.1422     µas    12.043
 Quad 21 Elc Imag        =   -29.171     +-   8.2085     µas    12.141
 Quad 21 Mag Real        =   -3.9236     +-   7.5641     µas    11.188
 Quad 21 Mag Imag        =   -18.812     +-   7.8110     µas    11.553

 Quad 22 Elc Real        =   0.97754     +-   3.7016     µas    5.4749
 Quad 22 Elc Imag        =   0.56704     +-   3.6267     µas    5.3640
 Quad 22 Mag Real        =   -1.0953     +-   3.6390     µas    5.3822
 Quad 22 Mag Imag        =    3.9390     +-   3.6769     µas    5.4383
```

Diagonal covariance

K (24 GHz, 1.2cm) *VLBA+ (HartRAO-Hobart)*



De Witt et al, 2018
astrometric solution D. Gordon

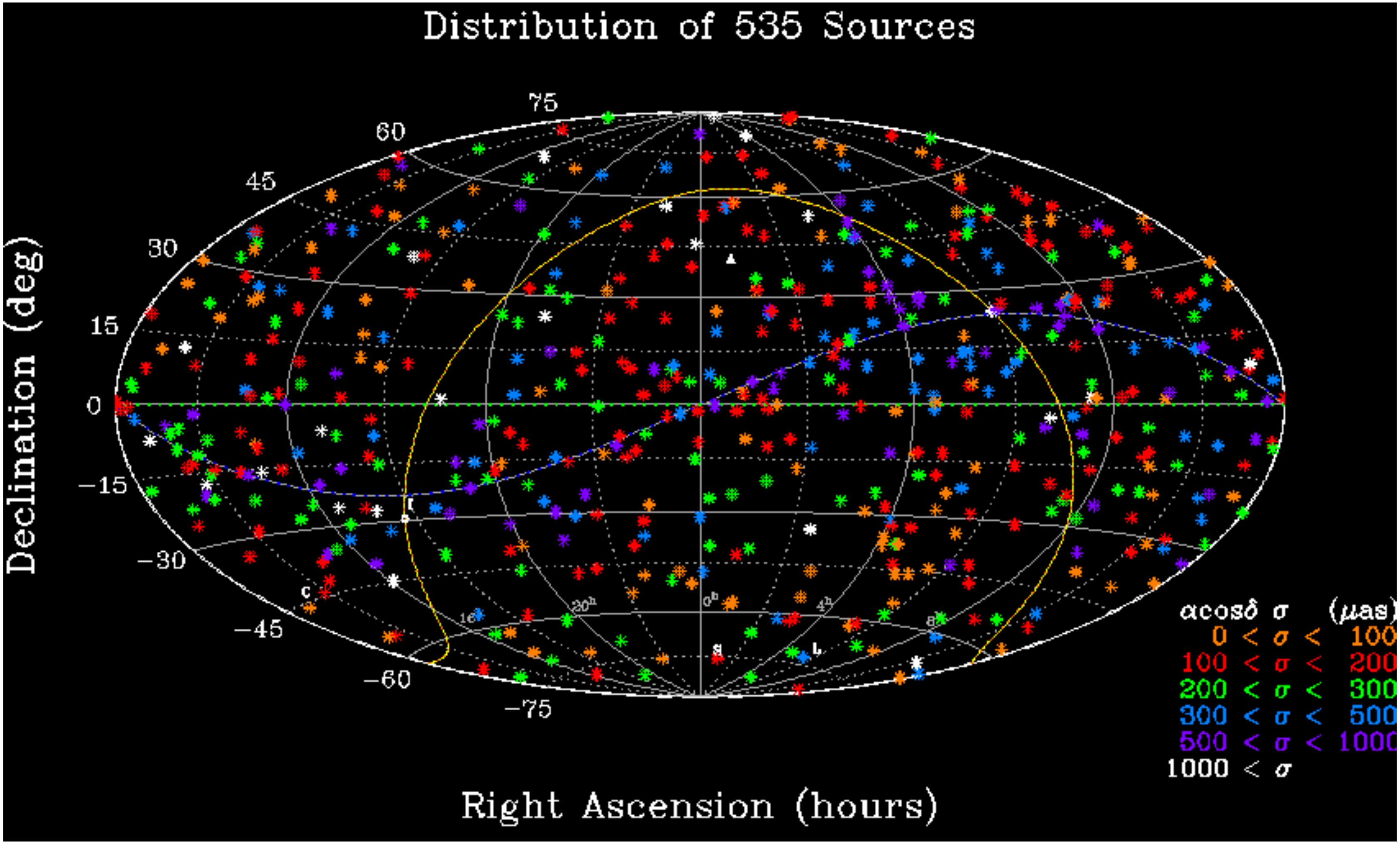
- Strengths:
  - Uniform spatial density, 824 sources
  - Galactic plane sources (Petrov+ 2006)
  - less structure than S/X (3.6cm)
  - median RA/Dec precision ~40 / 80 μas
  - needed ~ 0.5 million observations vs. SX's 13 million!

- Weaknesses:
  - Ionosphere only partially calibrated by GPS.
  - South ($\delta < -30$ deg) weak due to limited South Africa-Tasmania data

The VLBA is operated by the LBO since Oct. 2016 (previously by NRAO), both facilities of the National Science Foundation operated under cooperative agreement by Associated Universities.
The authors gratefully acknowledge use of the VLBA under the USNO's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy.
HartRAO is a facility of the National Research Foundation (NRF) of South Africa.
The Hobart telescope is operated by the University of Tasmania and this research has been supported by AuScope Ltd.,
funded under the National Collaborative Research Infrastructure Strategy (NCRIS)

Tying optical and Radio Celestial Frames

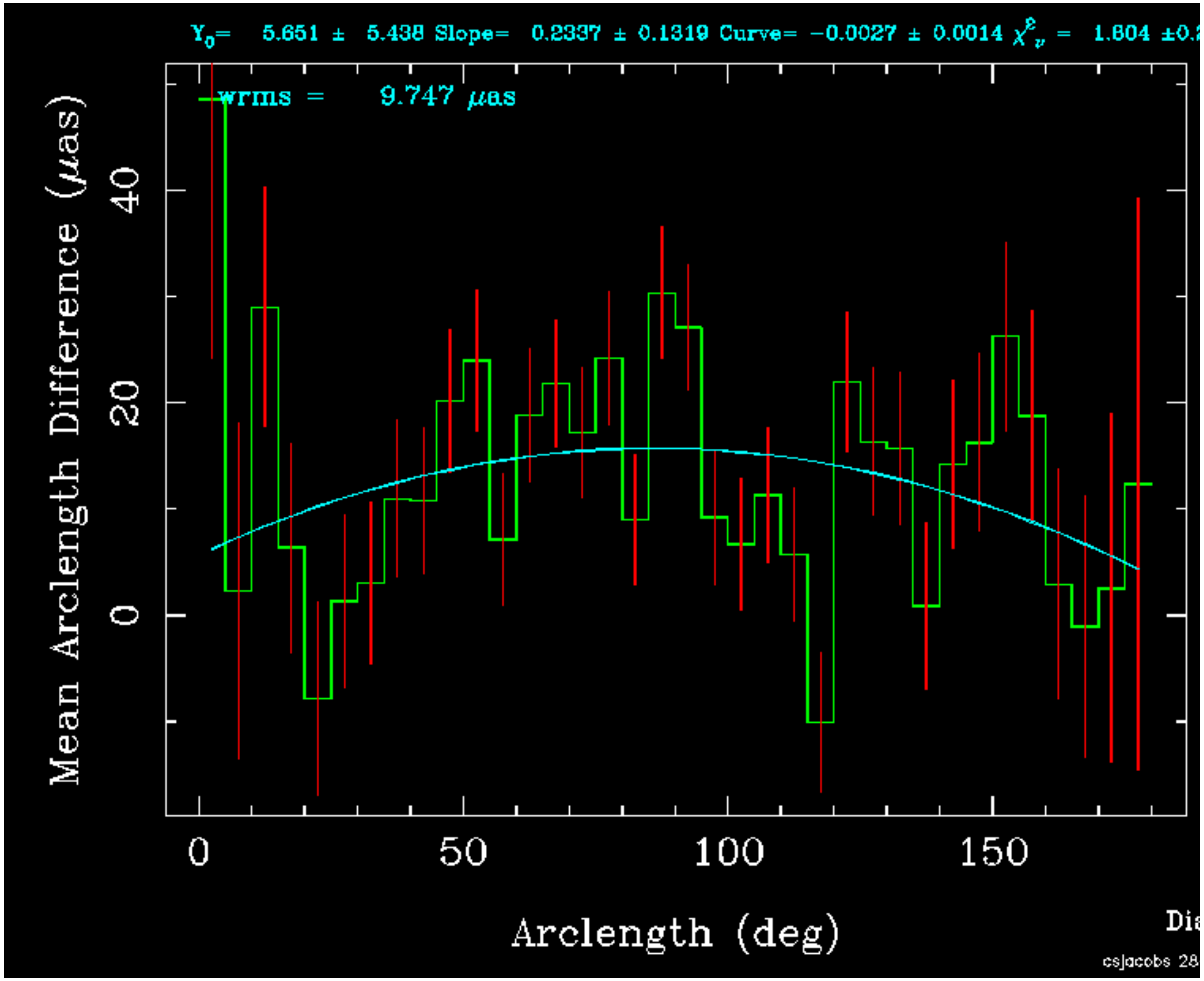
Gaia-DR2 vs. K (24 GHz) VLBI



Fairly uniform distribution. 65% usable matches with Gaia
Color code shows unevenness in Gaia formal sigmas.

Tying optical and Radio Celestial Frames

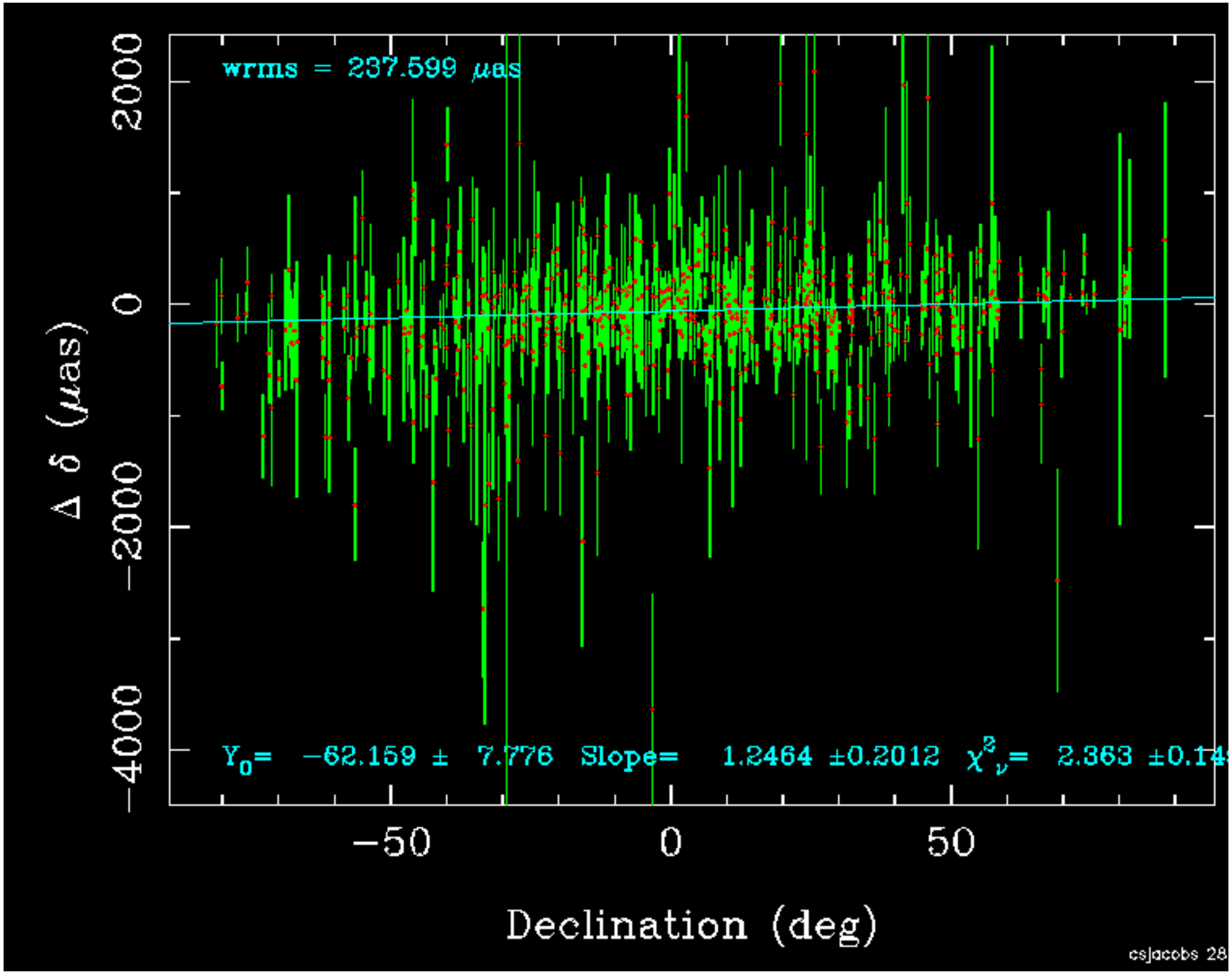
Gaia DR2 vs. K VLBI



Arc differences vs. arclength shows distortion at 10-20 μas level *(0.5 to 1.e-10)*

Tying optical and Radio Celestial Frames

Gaia DR2 vs. K VLBI



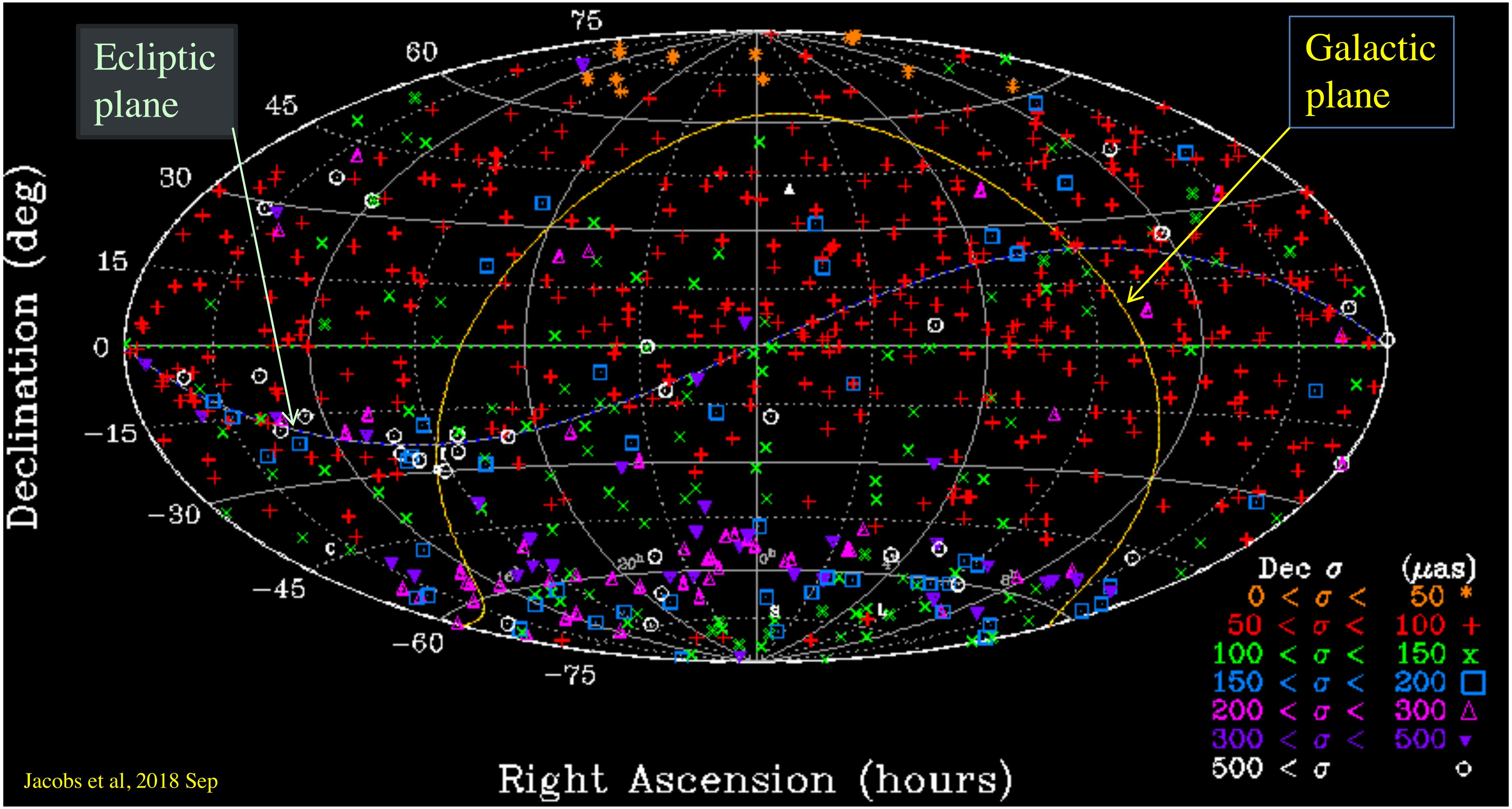
Systematic tilt: Δδ vs. δ has 6 sigma slope of 1.25 +- 0.2 μas/deg

K (de Witt et al, 2018) vs. Gaia Optical Frame *(Mignard+, 2018)*

Spherical Harmonic Differences for 535 common sources (10% outliers removed)

```
Largest term -84 µas (Diagonal covariance)

Parameter_name                  value           sigma           scaled_σ
 R1 rotation_X             =    34.742     +-   10.165    µas   15.410
 R2 rotation_Y             =    8.5640     +-   10.097    µas   15.307
 R3 rotation_Z             =    3.4207     +-   8.2059    µas   12.441

 Dipole-1                  =    26.536     +-   9.5931    µas   14.544
 Dipole-2                  =   -51.492     +-   9.5940    µas   14.545
 Dipole-3                  =   -24.847     +-   9.0398    µas   13.705

 Quad 20 Mag R(sin2Dec)=        27.345     +-   9.2511    µas   14.025
 Quad 20 Elc R(sin2Dec)=       -23.277     +-   10.754    µas   16.304

 Quad 21 Elc Real          =    17.858     +-   12.701    µas   19.255
 Quad 21 Elc Imag          =    61.432     +-   13.110    µas   19.876
 Quad 21 Mag Real          =   -83.783     +-   12.348    µas   18.720
 Quad 21 Mag Imag          =   -5.2426     +-   12.781    µas   19.377

 Quad 22 Elc Real          =    8.3740     +-   5.7978    µas   8.7898
 Quad 22 Elc Imag          =    19.566     +-   5.7173    µas   8.6677
 Quad 22 Mag Real          =   -24.686     +-   5.6310    µas   8.5369
 Quad 22 Mag Imag          =    1.6044     +-   5.7419    µas   8.7050
```

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



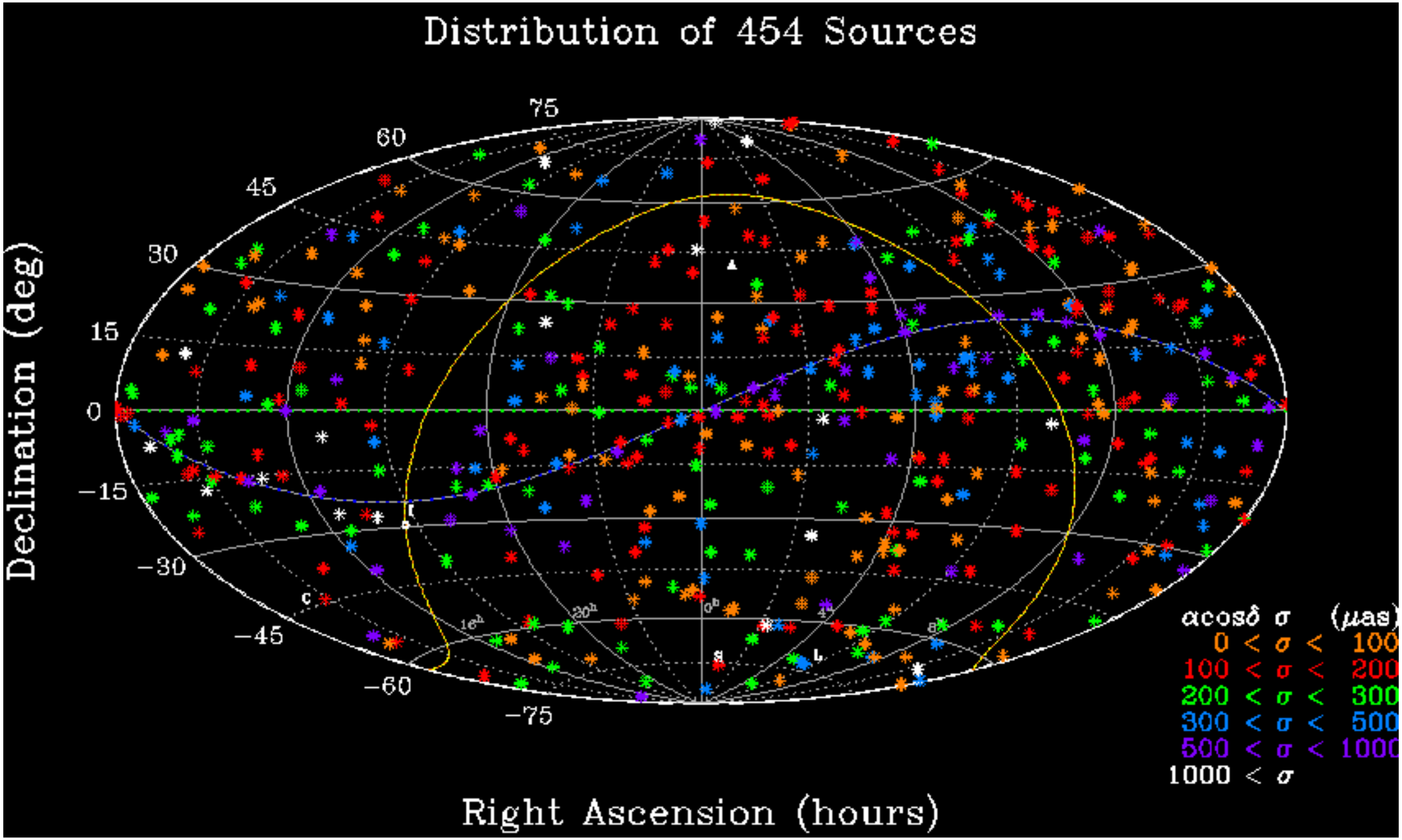
Jacobs et al, 2018 Sep

- **Strengths:**
  - Uniform spatial density, 678 sources
  - less structure than S/X (3.6cm)
  - precision < 100 μas
  - needed only 70K 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

Tying optical and Radio Celestial Frames

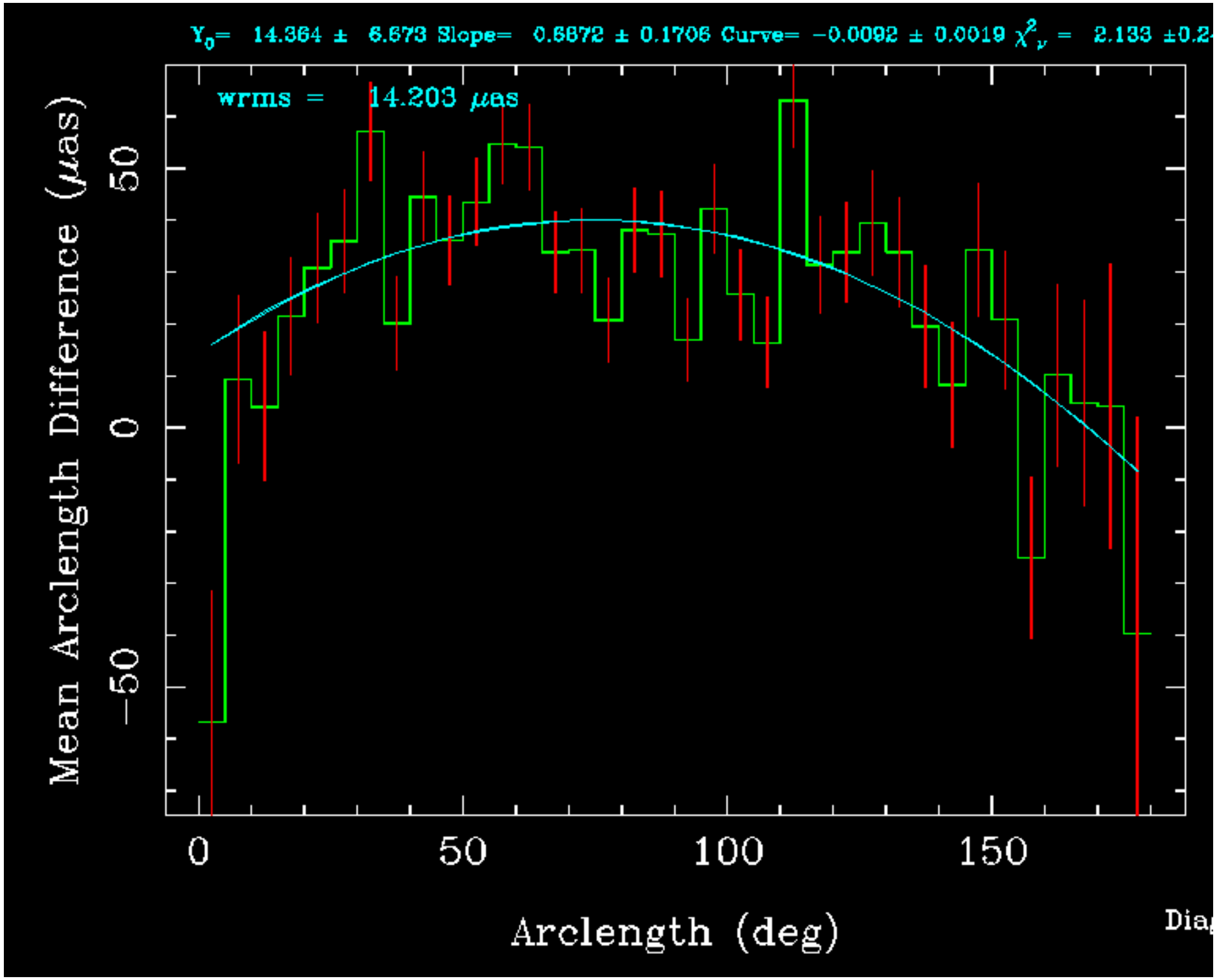
Gaia-DR2 vs. Ka (32 GHz) VLBI



67% usable matches. Fairly uniform distribution except near galactic plane
Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

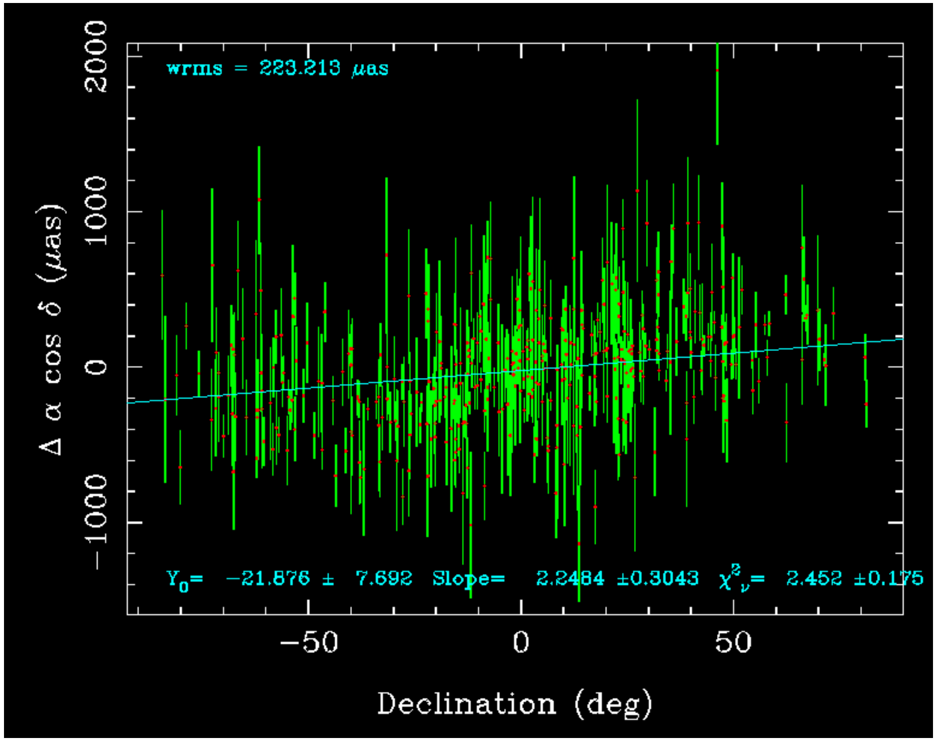
Ka VLBI vs. Gaia DR2



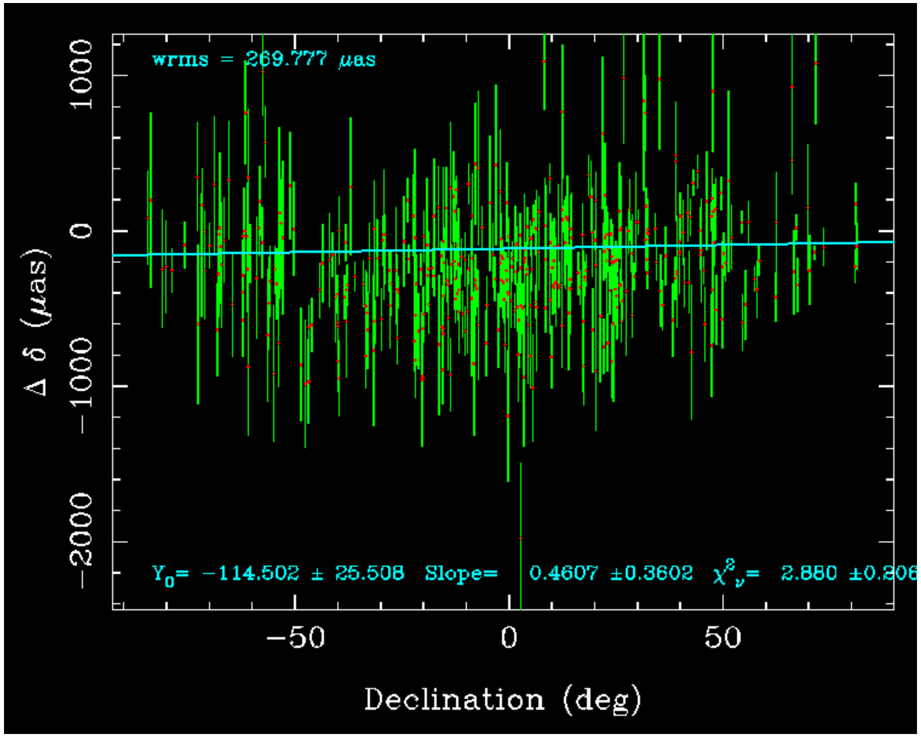
Arc differences vs. arclength bins scatter at 15-30 μas level

Tying optical and Radio Celestial Frames

Ka VLBI vs. Gaia DR2



$\Delta\alpha\cos\delta \sim \sin(2\ \delta)$ Quadrupole 2,0



$\Delta\delta \sim \cos(\delta)$ z-dipole

Ka vs. Gaia Optical Frame *(Mignard+, 2018)*

Spherical Harmonic Differences for 454 common sources (10% outliers removed)

```
With Diagonal covariance only

Parameter_name             value           sigma                 scaled_σ
 R1 rotation_X         =   13.871     +-   11.366     µas   18.100
 R2 rotation_Y         =  -7.6911     +-   12.072     µas   19.225
 R3 rotation_Z         =  -19.484     +-   9.4541     µas   15.056

 Dipole-1              =   19.008     +-   15.100     µas   24.047
 Dipole-2              =  -22.924     +-   14.795     µas   23.562
 Dipole-3              =   201.00     +-   47.962     µas   76.381

 Quad 20 Mag R(sin2Dec)=  -211.23     +-   18.148     µas   28.902
 Quad 20 Elc R(sin2Dec)=  -77.057     +-   24.744     µas   39.406

 Quad 21 Elc Real      =   76.938     +-   18.087     µas   28.805
 Quad 21 Elc Imag      =  -99.147     +-   17.774     µas   28.305
 Quad 21 Mag Real      =  -51.417     +-   13.944     µas   22.206
 Quad 21 Mag Imag      =  -59.487     +-   14.447     µas   23.007

 Quad 22 Elc Real      =   19.839     +-   6.7002     µas   10.670
 Quad 22 Elc Imag      =  0.38448     +-   6.9835     µas   11.122
 Quad 22 Mag Real      =  -1.4474     +-   6.3603     µas   10.129
 Quad 22 Mag Imag      =  -14.130     +-   6.3945     µas   10.184
```

Ka-band combined NASA/ESA Deep Space Net

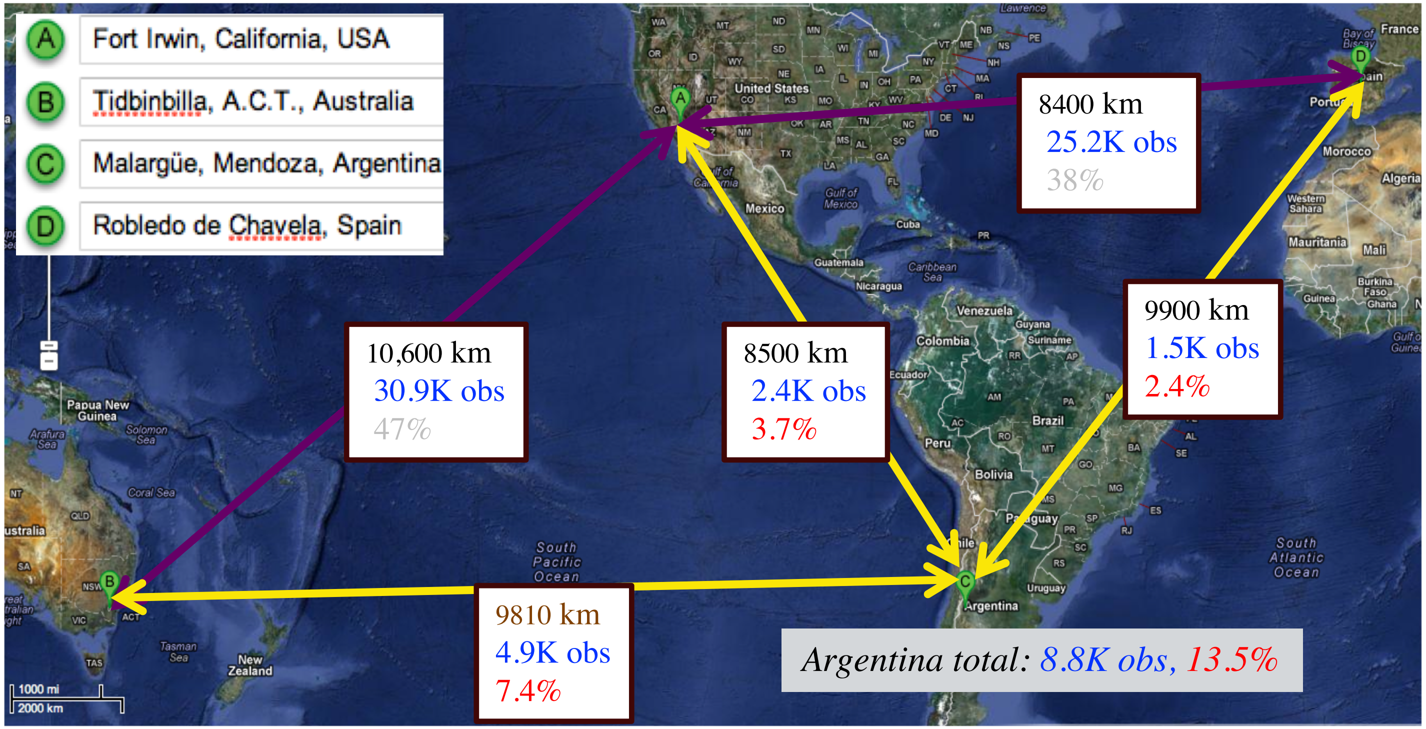
ESA Argentina to NASA-California under-observed by order of magnitude!

Baseline percentages

- Argentina is part of 3/5 baselines or 60% but only 14% of obs
- Aust- Argentina 7.4%
- Spain-Argentina 2.4%
- 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!!



A Fort Irwin, California, USA

B Tidbinbilla, A.C.T., Australia

C Malargüe, Mendoza, Argentina

D Robledo de Chavela, Spain

8400 km
25.2K obs
38%

10,600 km
30.9K obs
47%

8500 km
2.4K obs
3.7%

9900 km
1.5K obs
2.4%

9810 km
4.9K obs
7.4%

Argentina total: 8.8K obs, 13.5%

Maps credit: Google maps

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

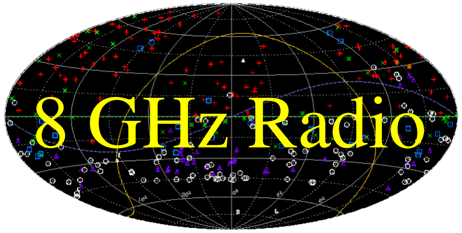
- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina

Tying optical and Radio Celestial Frames

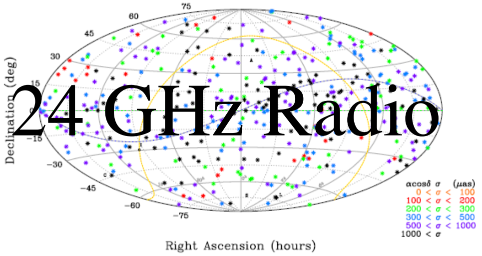
Gaia DR2 vs. VLBI

	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# Observations	13 million	0.5 million	0.07 million
# matched sources	2818	601	499
# outliers > 5σ	325	67	45
% outliers	11.5 %	11.1 %	9.0 %
α wRMS	305 μas	219 μas	259 μas
δ wRMS	315 μas	241 μas	276 μas
R_x	17 +- 9	35 +- 15	14 +- 19
R_y	-16 +- 9	9 +- 12	-8 +- 19
R_z	10 +-13	3 +- 12	-19 +- 15
Largest Vector Spherical Harmonic	-33 +- 10 μas Quad 2,0 E	-84 +- 19 μas Quad 2,1 M	-211 +- 29 μas Quad 2,0 M

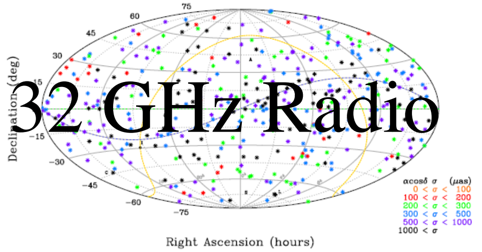
Summary: Tying Optical & Radio



8 GHz Radio



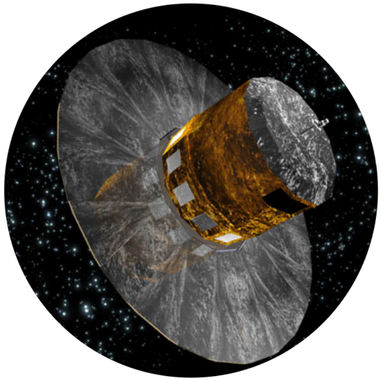
24 GHz Radio



32 GHz Radio

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

- **Results:**
  - Optical & radio data now allow multi-wavelength comparisons: Radio at 8, 24, 32 GHz and Gaia optical
  - Excellent 3-D rotational tie at 20 μas level.
  - Accuracy limited by systematic distortions at 30 – 300 μas.
  - SX (8 GHz) ~30 μas, K (24) 80 μas, Ka (32) 300 μas.
  - Control of VLBI systematics will require increased southern observations at all bands.
  - Gaia precision limited by partial mission. More data to come . . .
  - Gaia DR3 will add significantly more data and model non-linear motions



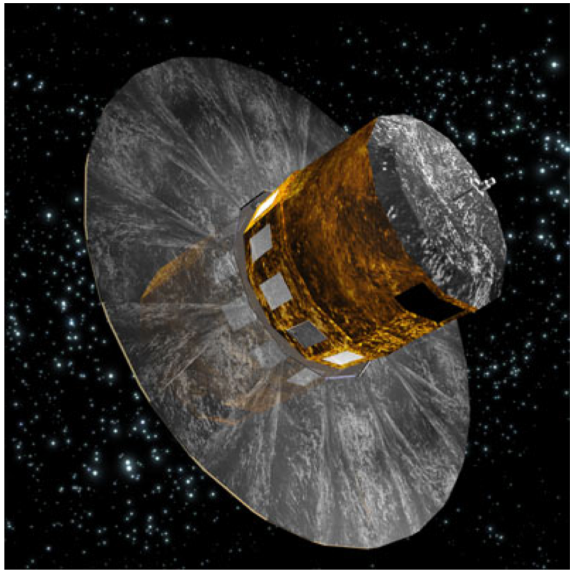
Gaia Optical

BACKUP

The Gaia Optical Frame

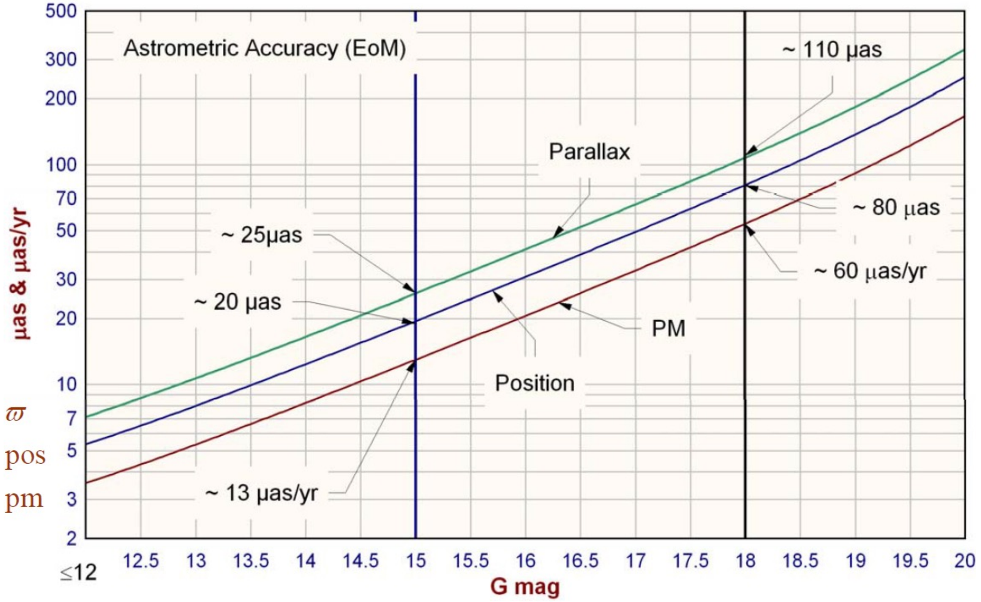
ESA's Gaia optical Astrometry

- 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
  - 2nd release Gaia astrometric catalog DR2 Apr 2018,
  - DR3 2020.



Credit: F. Mignard (2013)

Anticipated precision of Gaia catalogue

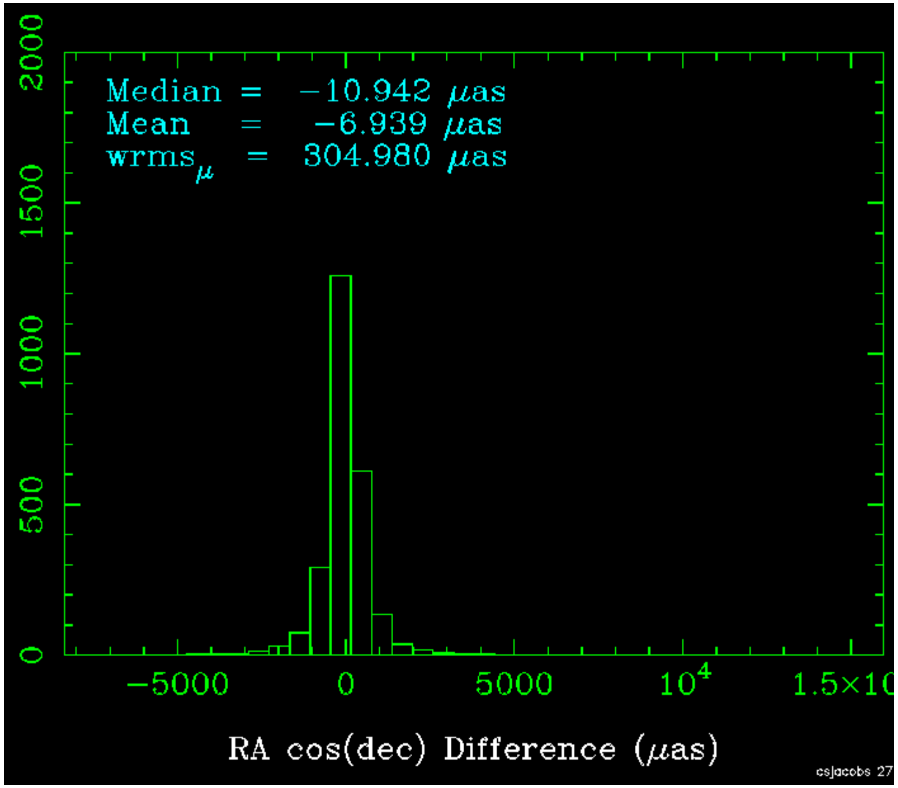


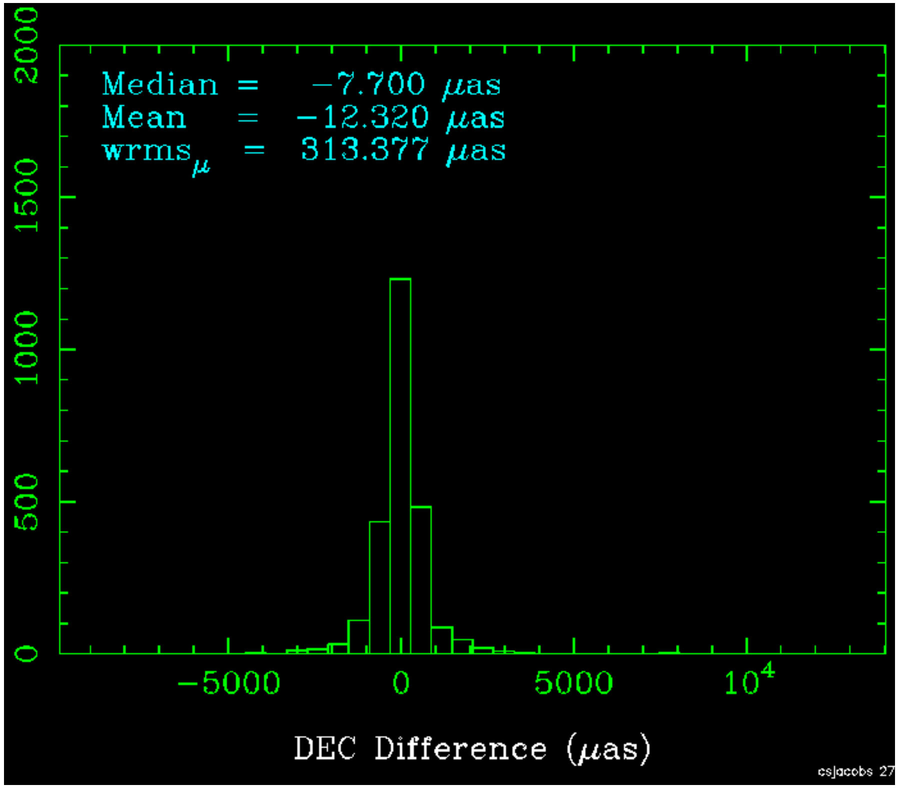
Gaia Data Release-2:

Precision ~ 250 µas for radio loud quasars

Tying optical and Radio Celestial Frames

Gaia DR2 vs. SX (8 GHz) VLBI

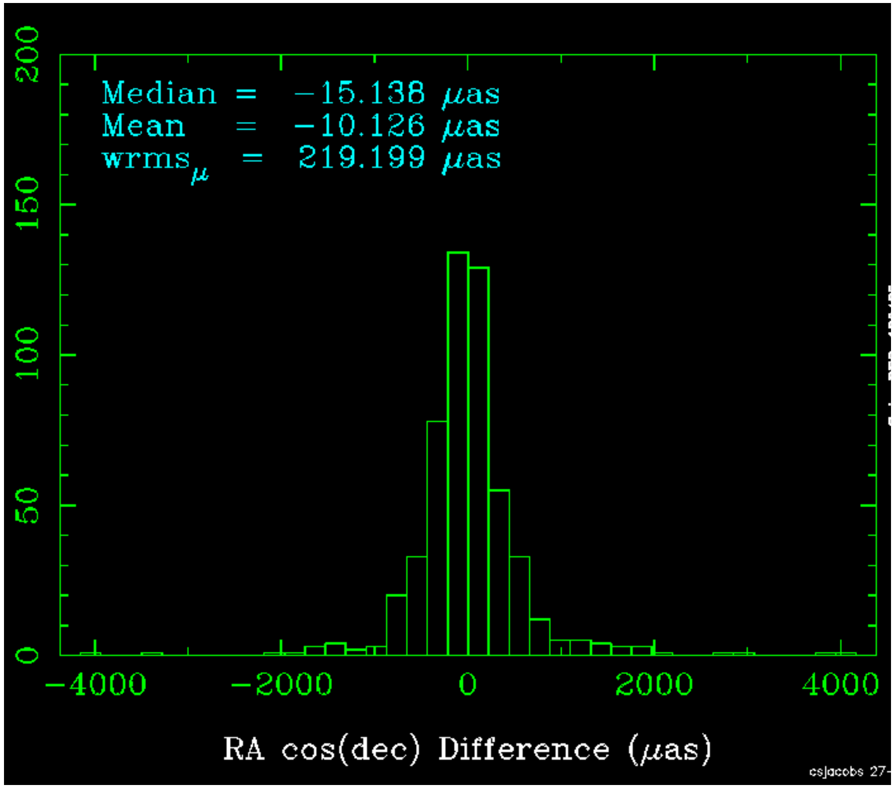


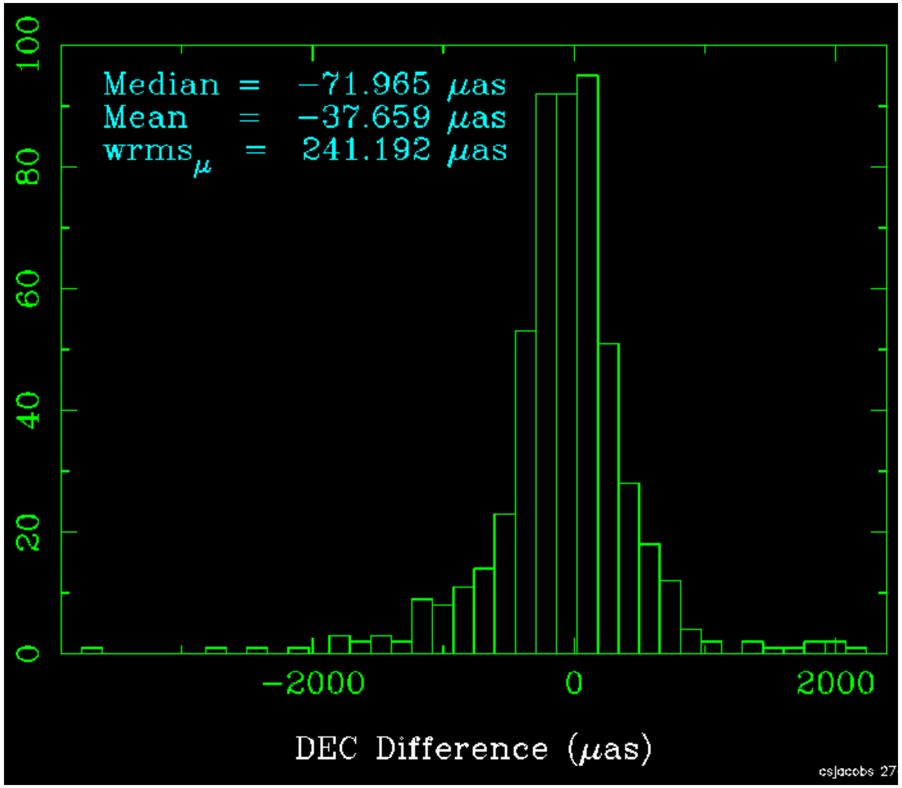


wRMS Ra and Dec differences about 300 μas (1.5 nrad)

Tying optical and Radio Celestial Frames

Gaia DR2 vs. K (24 GHz) VLBI

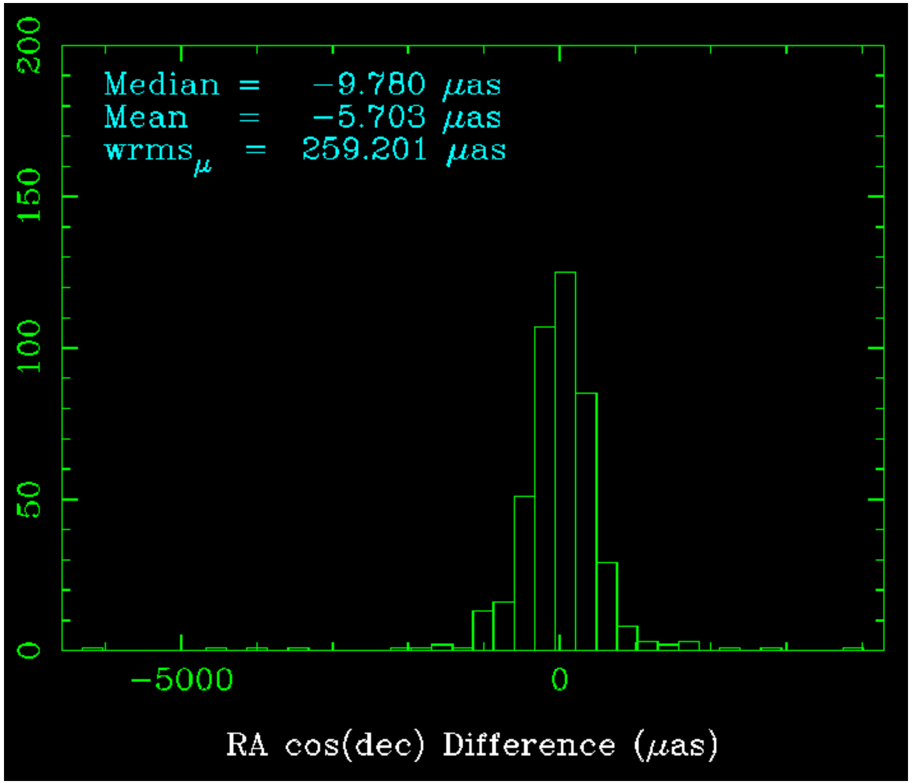


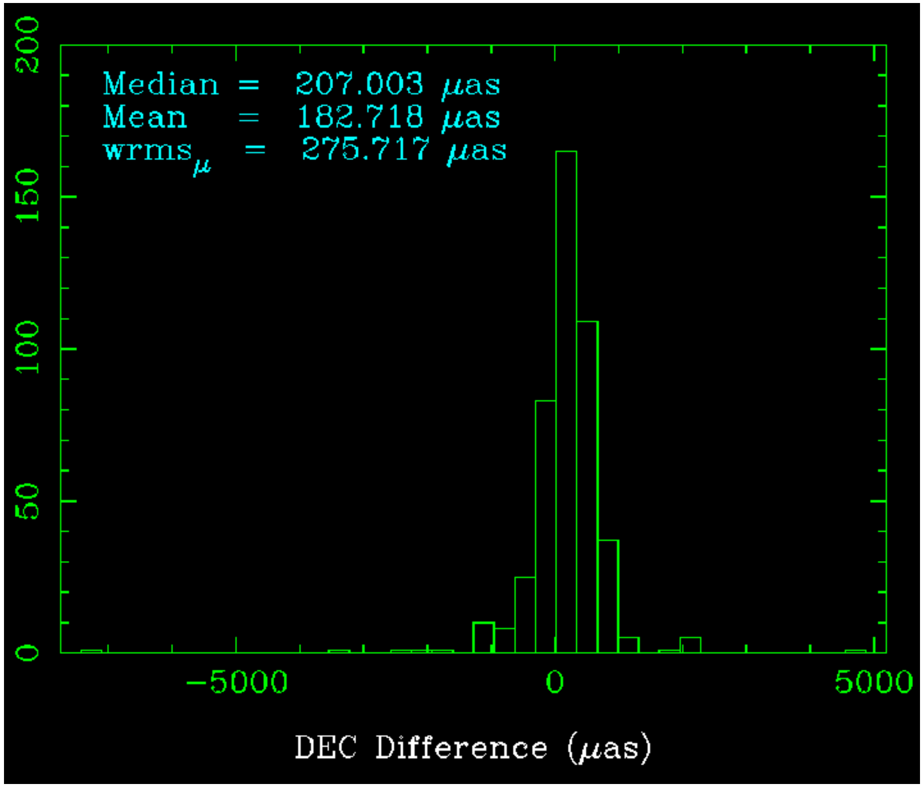


wRMS Ra and Dec differences about 230 μas (1.1 nrad)

Tying optical and Radio Celestial Frames

Gaia DR2 vs. Ka (32 GHz) VLBI

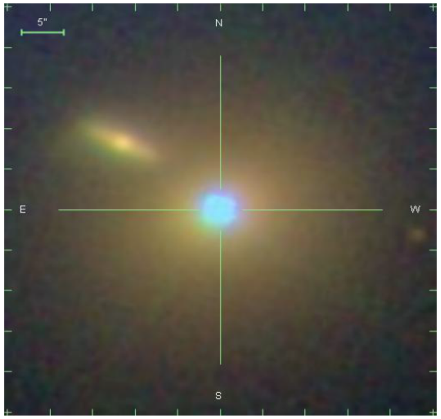




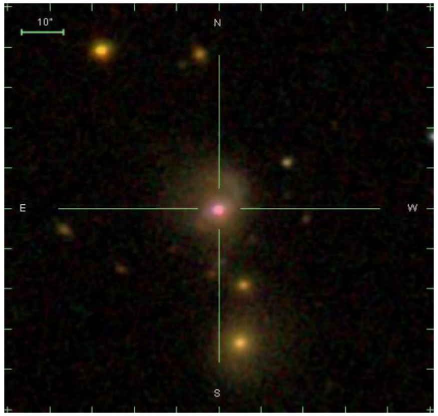
wRMS Ra and Dec differences about 270 μas (1.3 nrad)

Optical vs. Radio systematics offsets

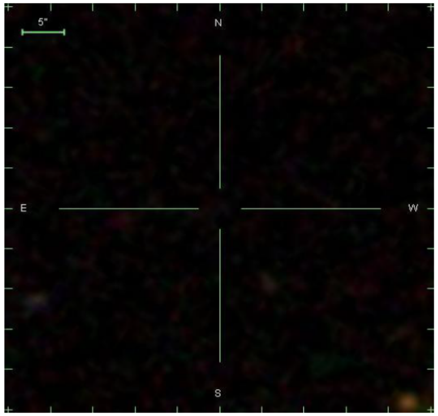
SDSS Optical images of quasars (scale 5-10 asec)



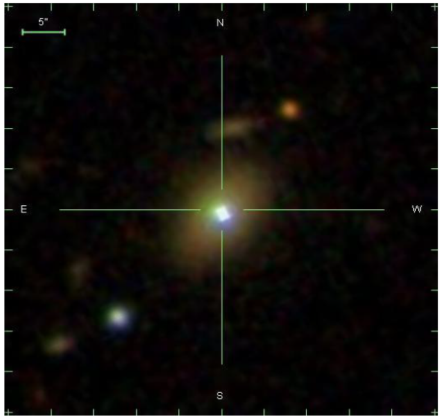
1101+384



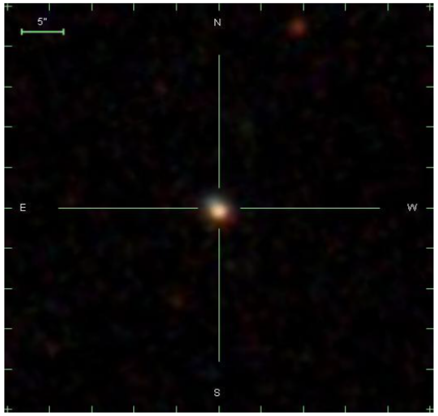
0007+106



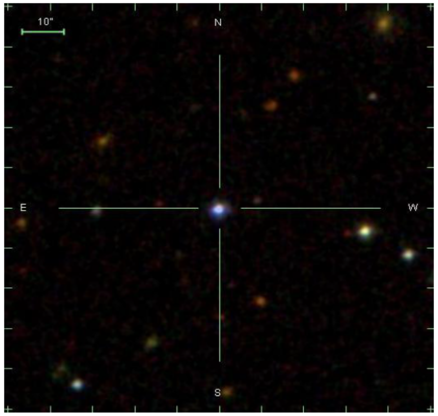
0920+390



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.

Three VLBI bands compare to better than 200 μas RMS
Gaia DR-2 precision ~ 250 μas.

XKa vs. SX: Zonal errors

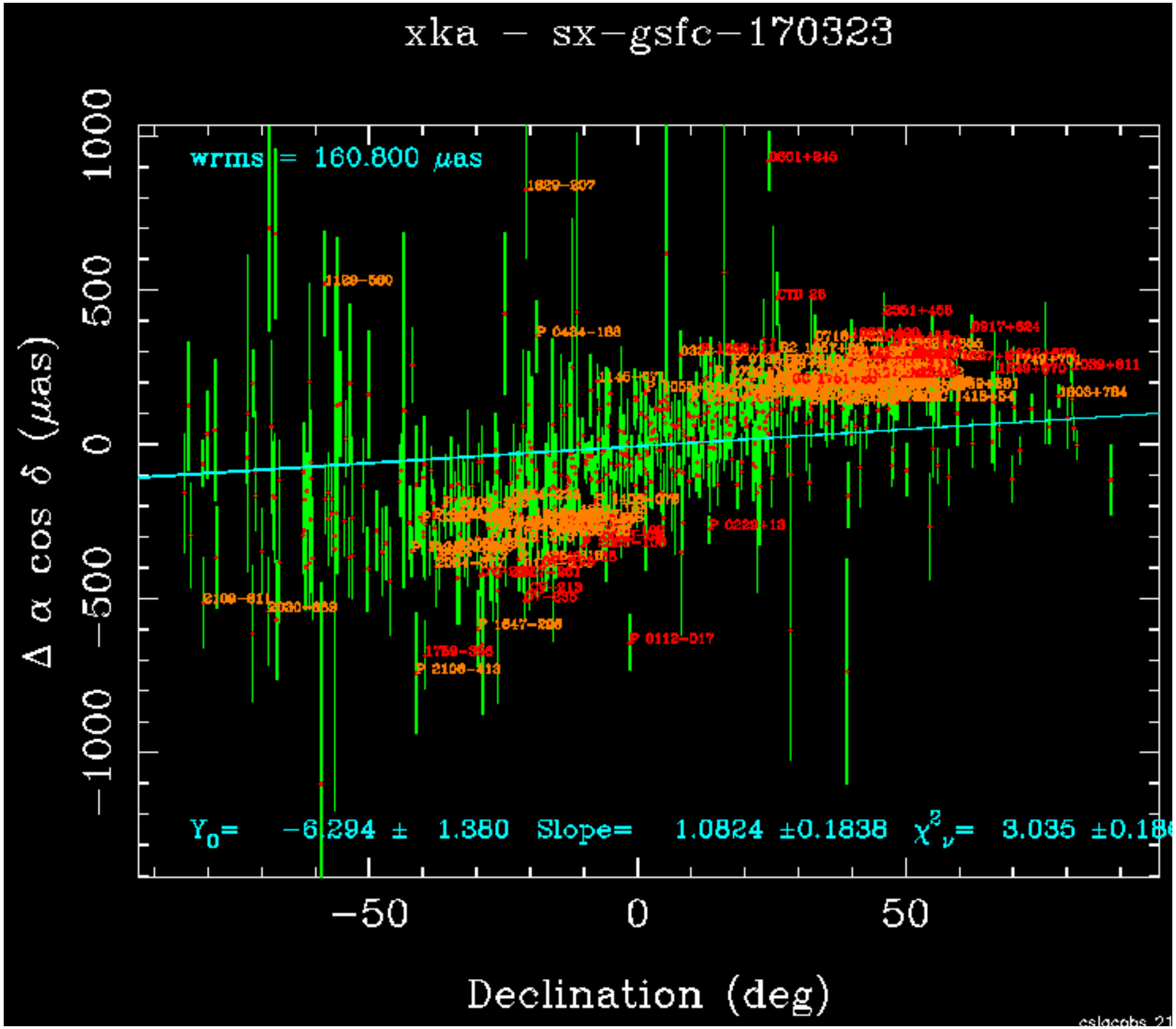
Zonal Errors

- 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.

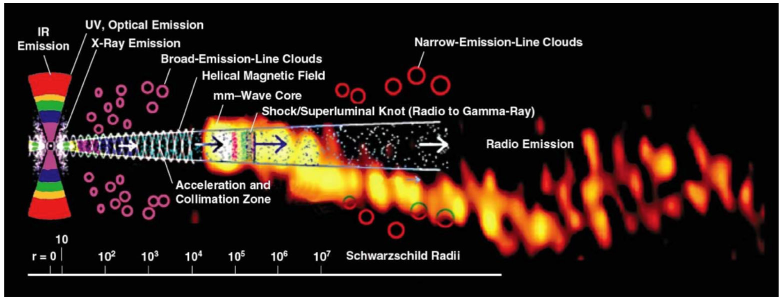
- Usuda, Japan 54-m XKa (2019) would improve North-South sampling geometry and thus control declination zonal differences.



Credit: SX astrometry, D. Gordon

The Source Objects

Optical-Radio
Frame Tie Geometry



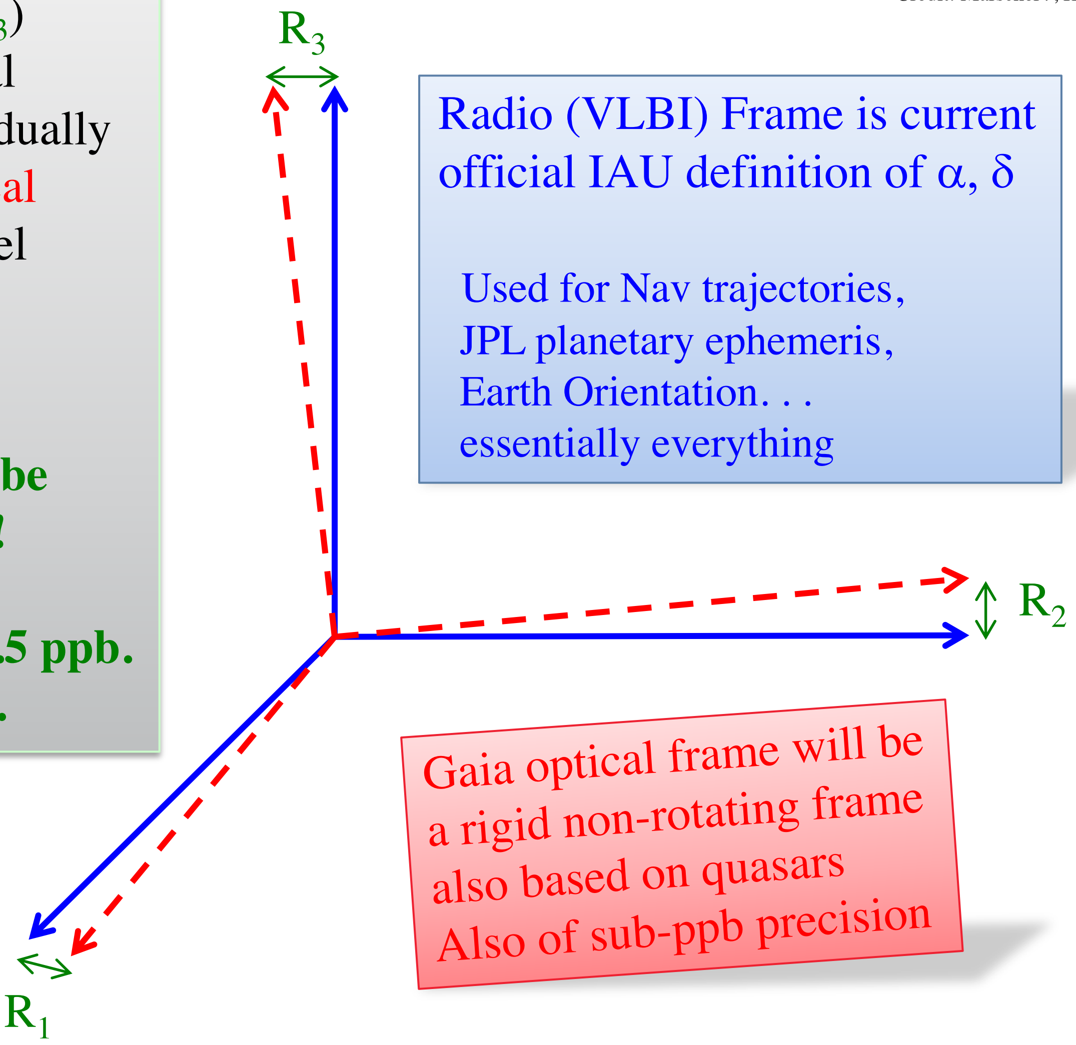
Credit: Marscher+, Krichbuam+

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

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

Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids

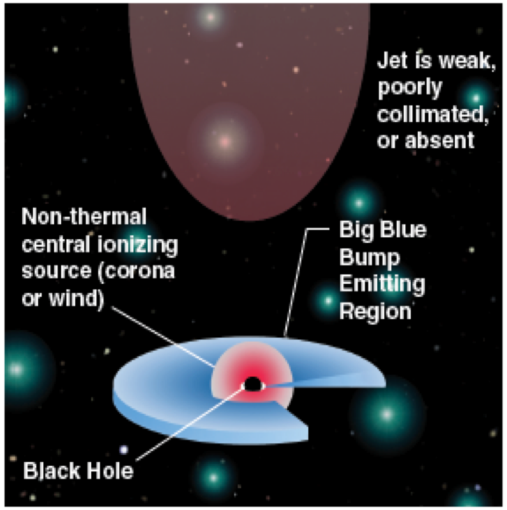
  - radio: synchrotron from jet

  - optical: synchrotron from jet?
    non-thermal ionization from corona?
    big blue bump from accretion disk?

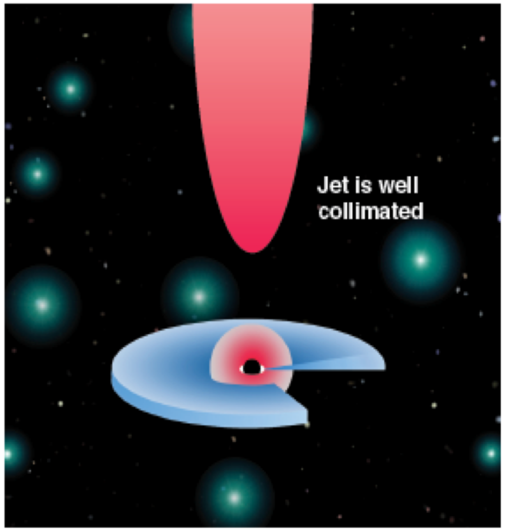
- Instrumental errors both radio & optical

- Analysis errors

Radio-quiet Quasar

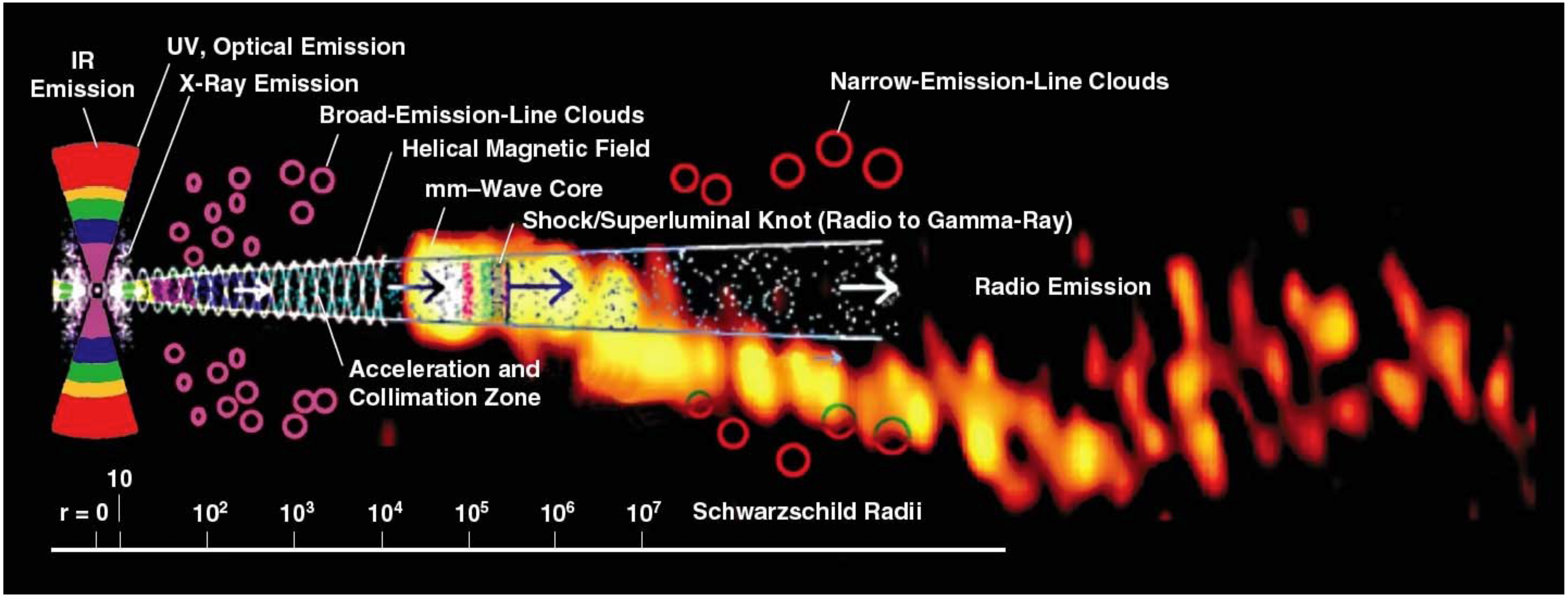


Radio-loud Quasar



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

Active Galactic Nuclei (*Marscher*)

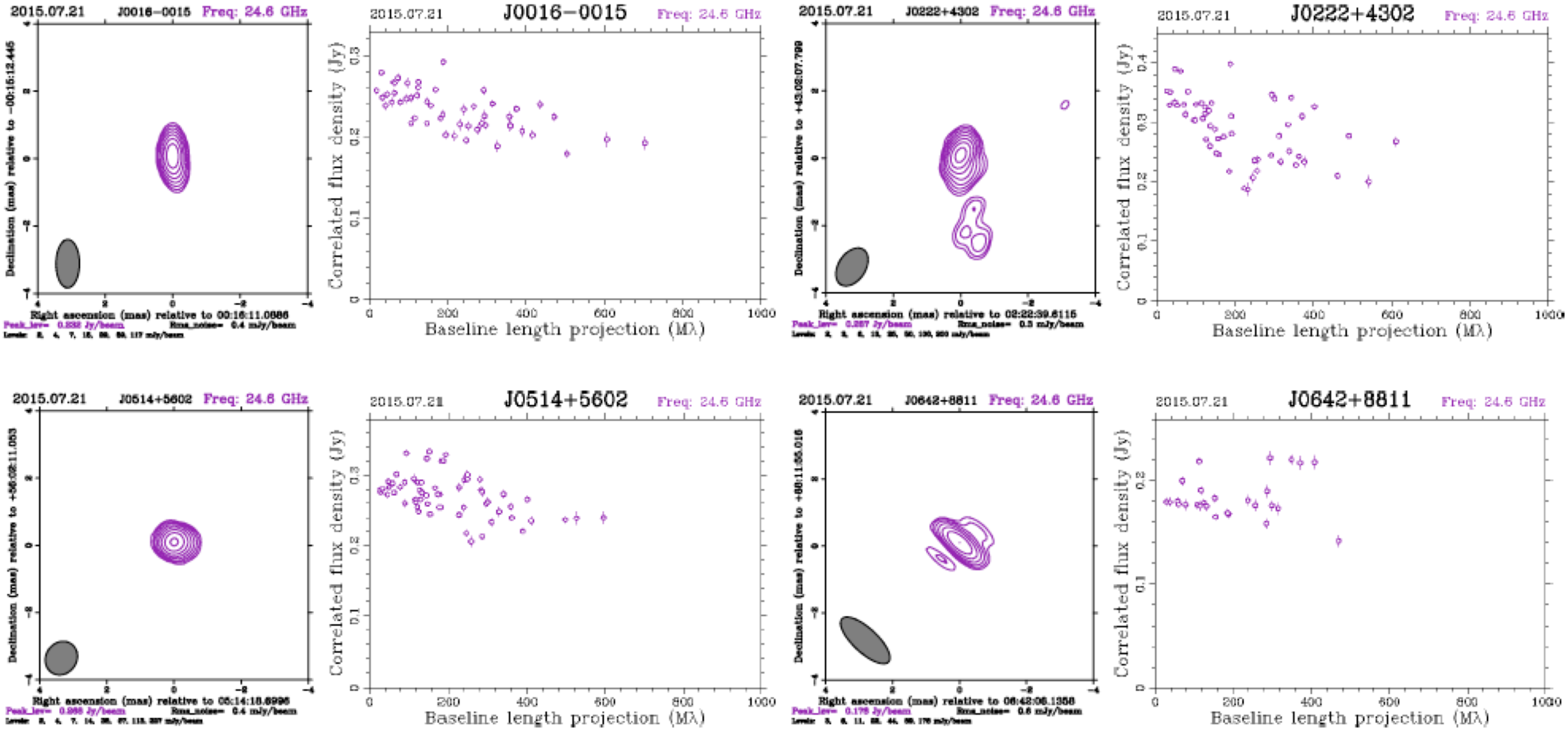


R~0.1-1 μas 1mas

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)

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



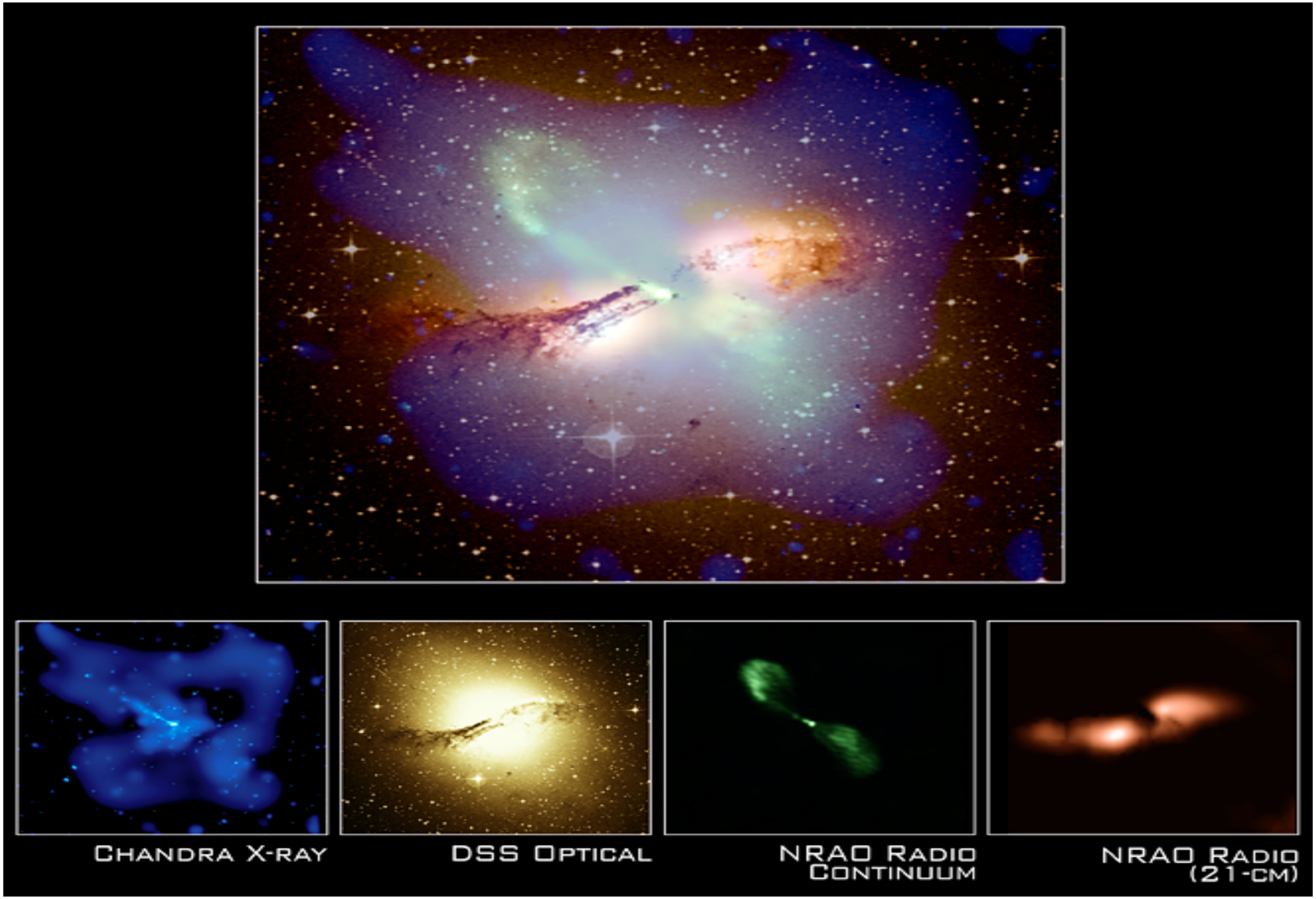
K-band (24 GHz) imaging shows VLBI sources are compact on millarcsec scales.

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.

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)