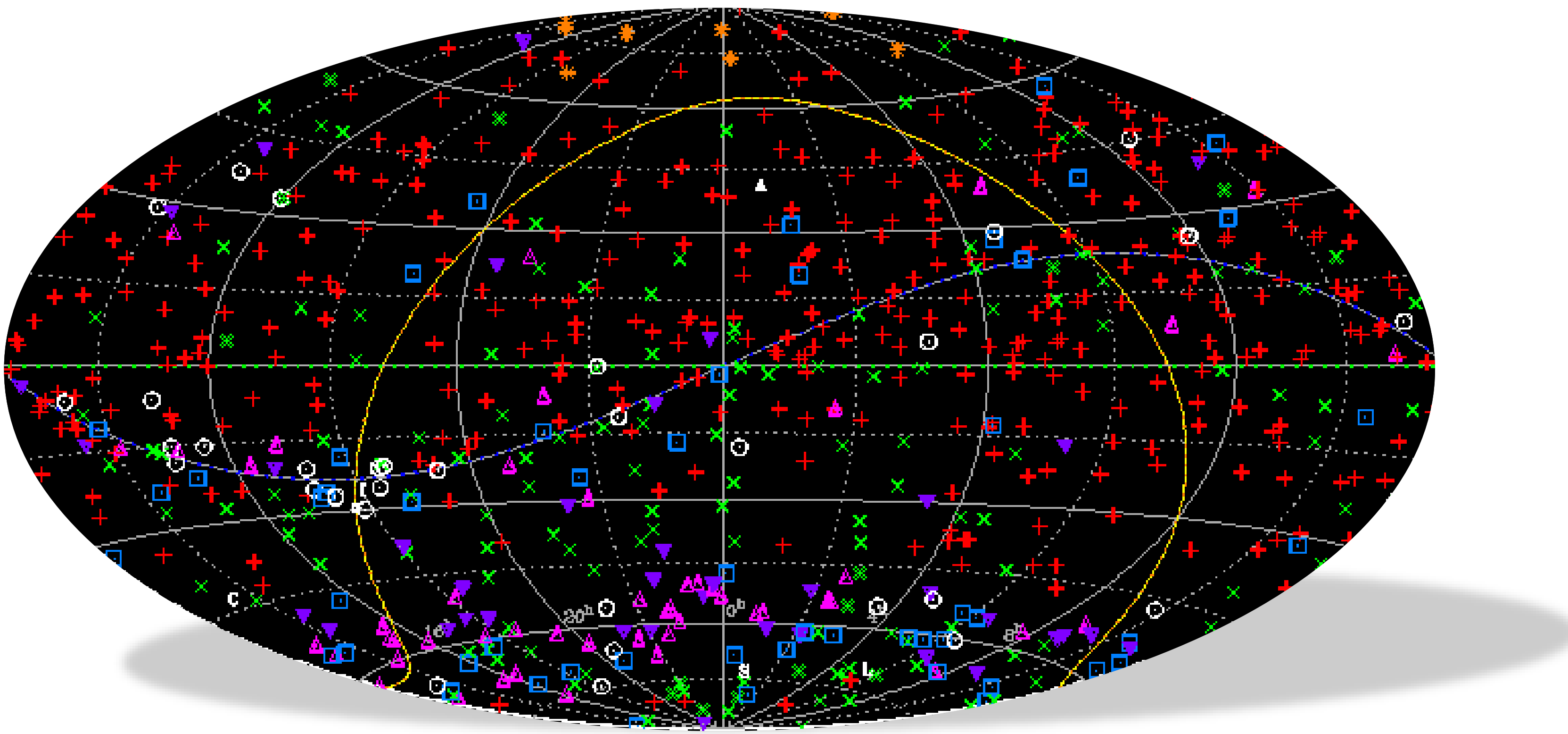
JPL, Pasadena CA, 2018 Jan 24

X/Ka (8.4/32 GHz) Celestial Frame: Potential for collaboration with Usuda



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

C. Garcia-Miro, S. Horiuchi, M. Mercolino, L. Snedeker.

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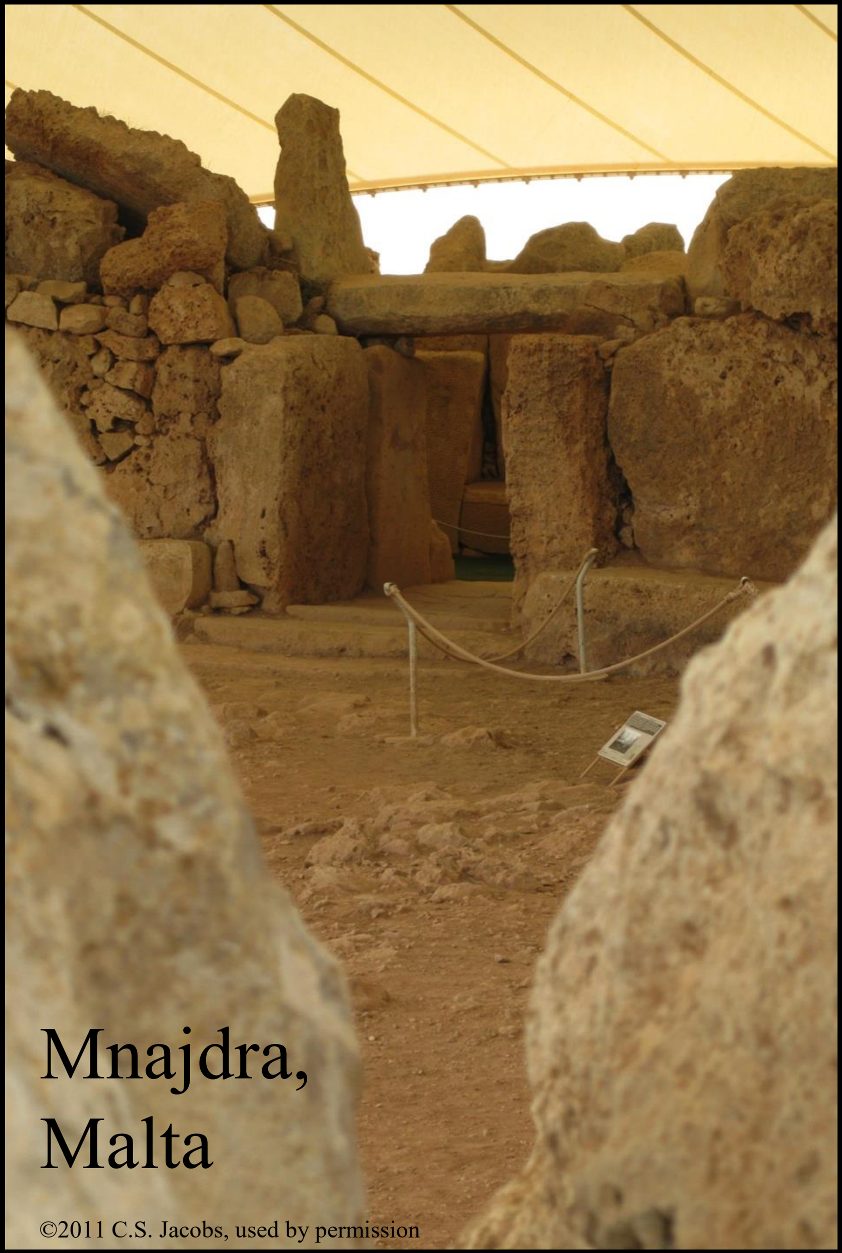
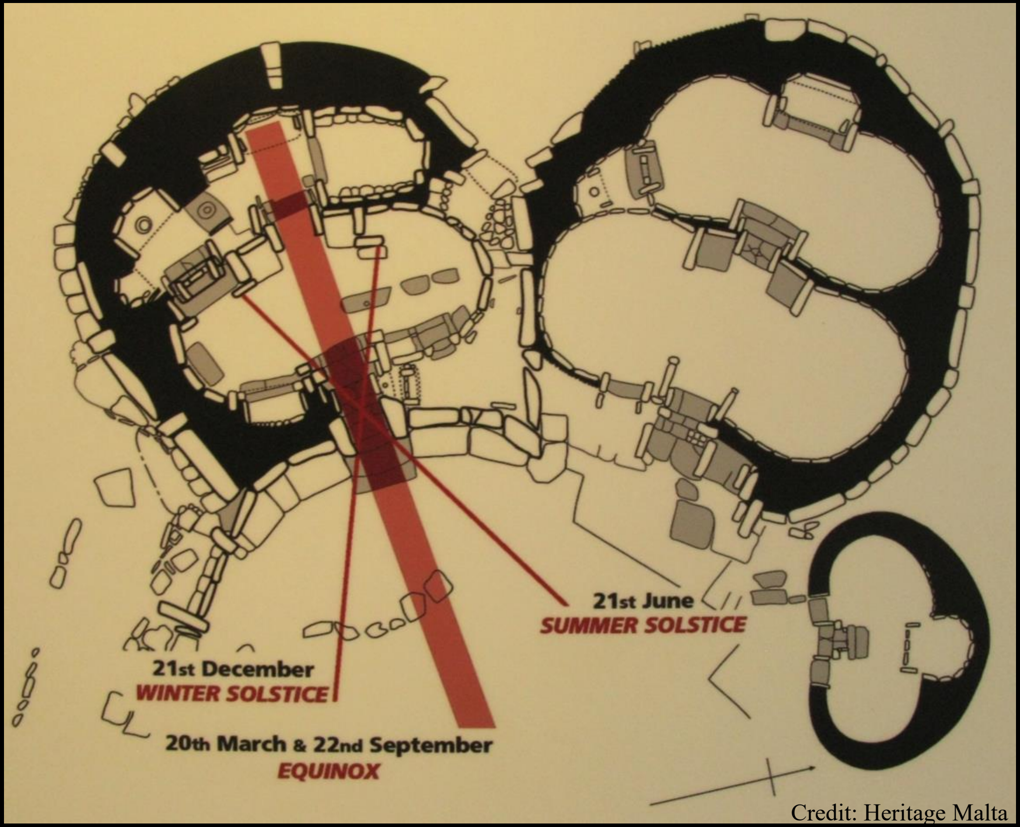
Astrometry: measures positions in the sky, 5000+ years history!

Credit: Heritage Malta



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

Mnajdra solar alignments



Why build a Celestial Reference Frame?

- Reference points with known coordinates for spacecraft navigation (DDOR)

- Reference directions for determining Earth Orientation:
  UT1-UTC, Polar motion, Nutation

- Reference directions for determining station locations

- Reference directions for determining planetary ephemerides (e.g. Jones et al, 2018)

- Desire point sources at infinity to define ultra-stable directions
  Quasars are point-like to sub-nanoradian level
  Quasars are typically at redshift z ~ 1 (billions of light years)

Historical Context: Celestial Reference Frames

- Optical Frames: Used stars up through FK5 (Fricke+, 1988). Proper motions an issue. Hipparcos (Perryman+, 1997) had 100K stars mas precision but mas/yr PM precision. In late 1980s, early 1990s IAU started a move to quasars to leverage zero parallax & PM

- 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, 2017*)

- X/Ka (32 GHz, 9mm) also sub-mas (*Jacobs+, 2016, 2017*)

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

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

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

Why build a Celestial Reference Frame at X/Ka?

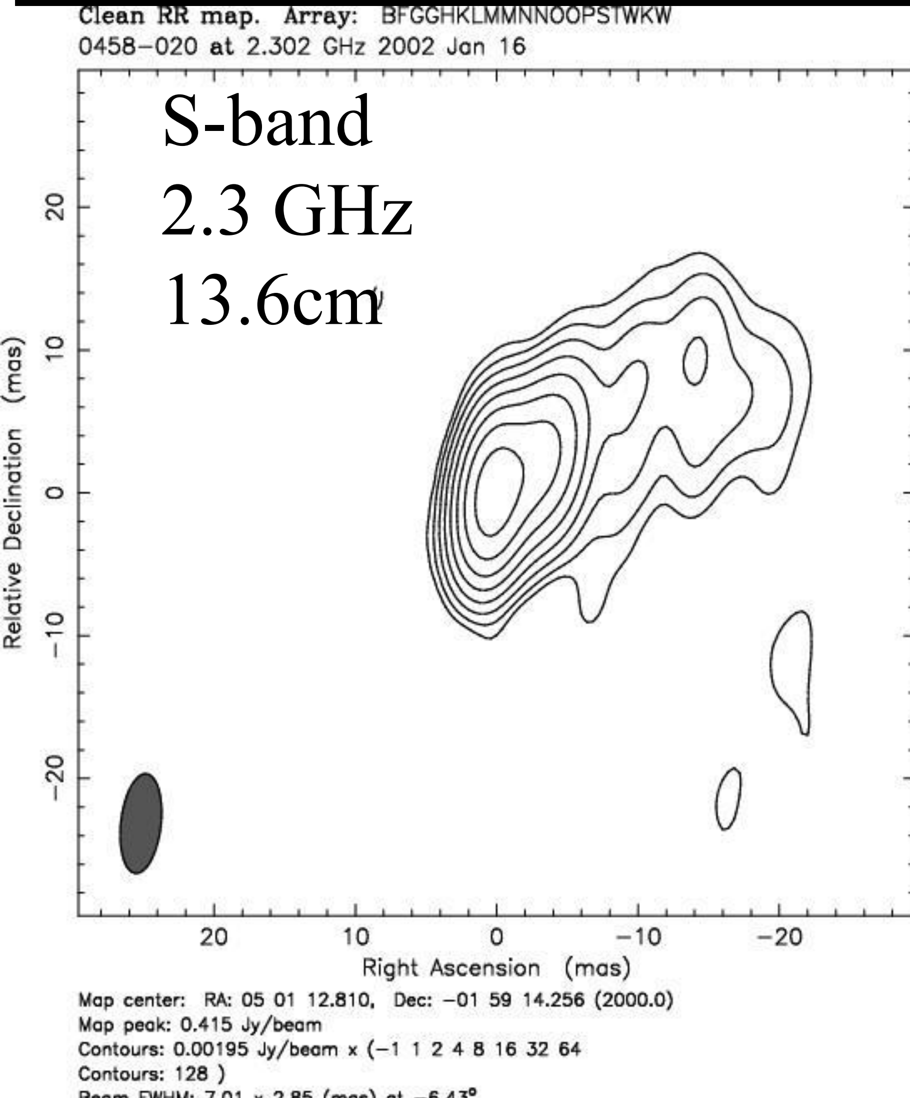
- Spacecraft are allocated three frequencies: S (2 GHz), X (8 GHz), Ka (32 GHz)

- S-band usefulness is decreasing rapidly
  Very few new missions at S-band
  RFI at S-band is degrading the band (Wif-Fi etc.)
  Source structure worse at low frequencies
  Plasma calibrations much more difficult at low frequencies

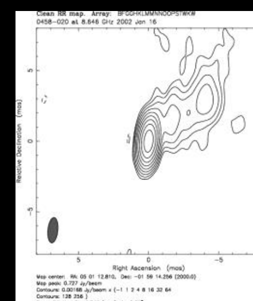
- X-band is now the "workhorse" frequency

- Ka-band advantages:
  More bandwidth: 500 MHz allocation, DDOR tones can spread up to 200 MHz
  Higher telemetry rates
  Solar plasmas effect reduced as 1/ frequency squared
    This allows tracking much closer to the Sun e.g. Parker Solar Probe
    When optical tracking becomes operational,
      still need capability close the Sun—exactly where Ka-band excels!

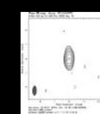
Why Xka? Source Structure vs. Frequency



X-band
8.6 GHz
3.6cm



K-band
24 GHz
1.2cm



Q-band
43 GHz
0.7cm

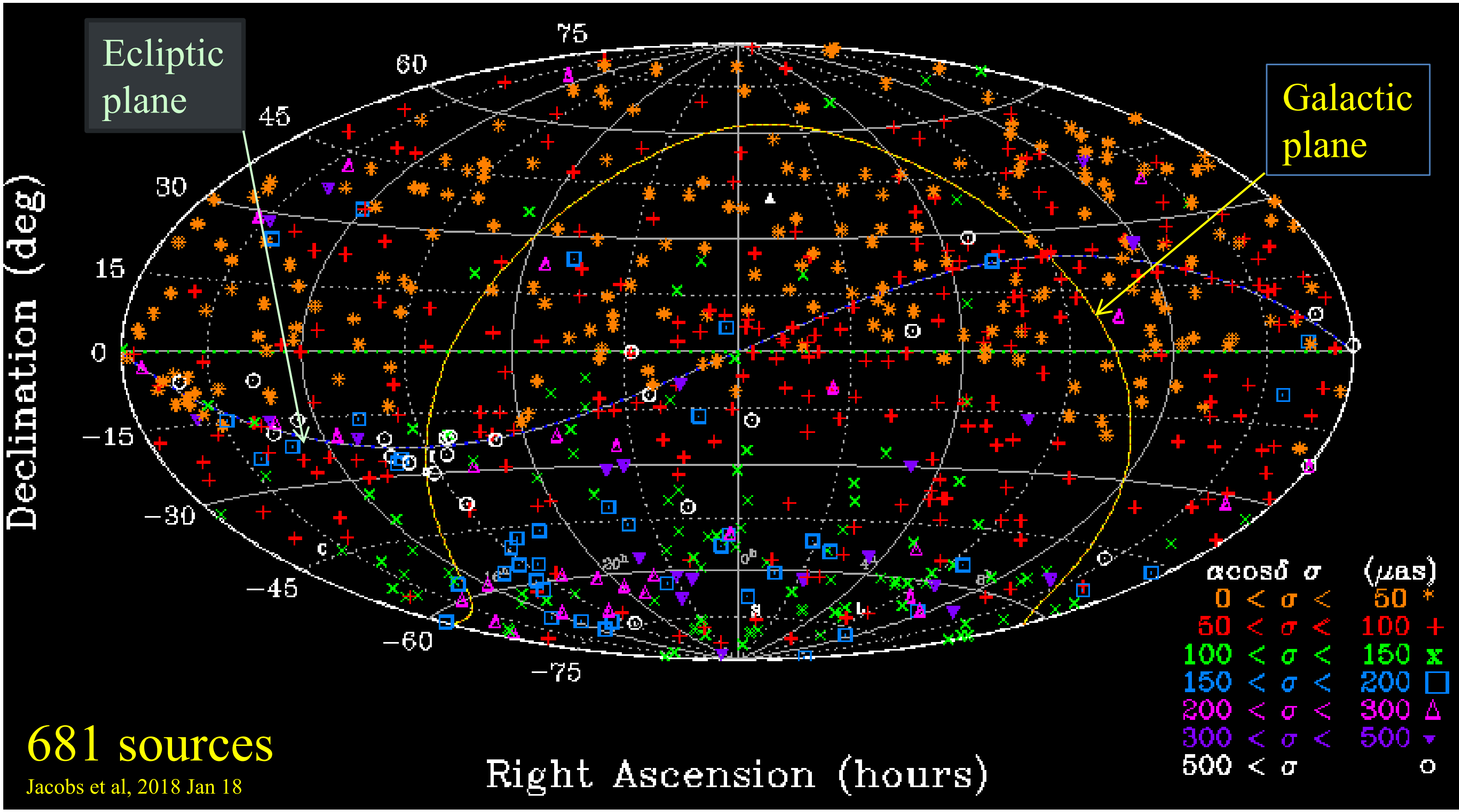
The sources become better →
Less structure

Ka-band
32 GHz
0.9cm

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

Current Status of XKa Celestial Frame

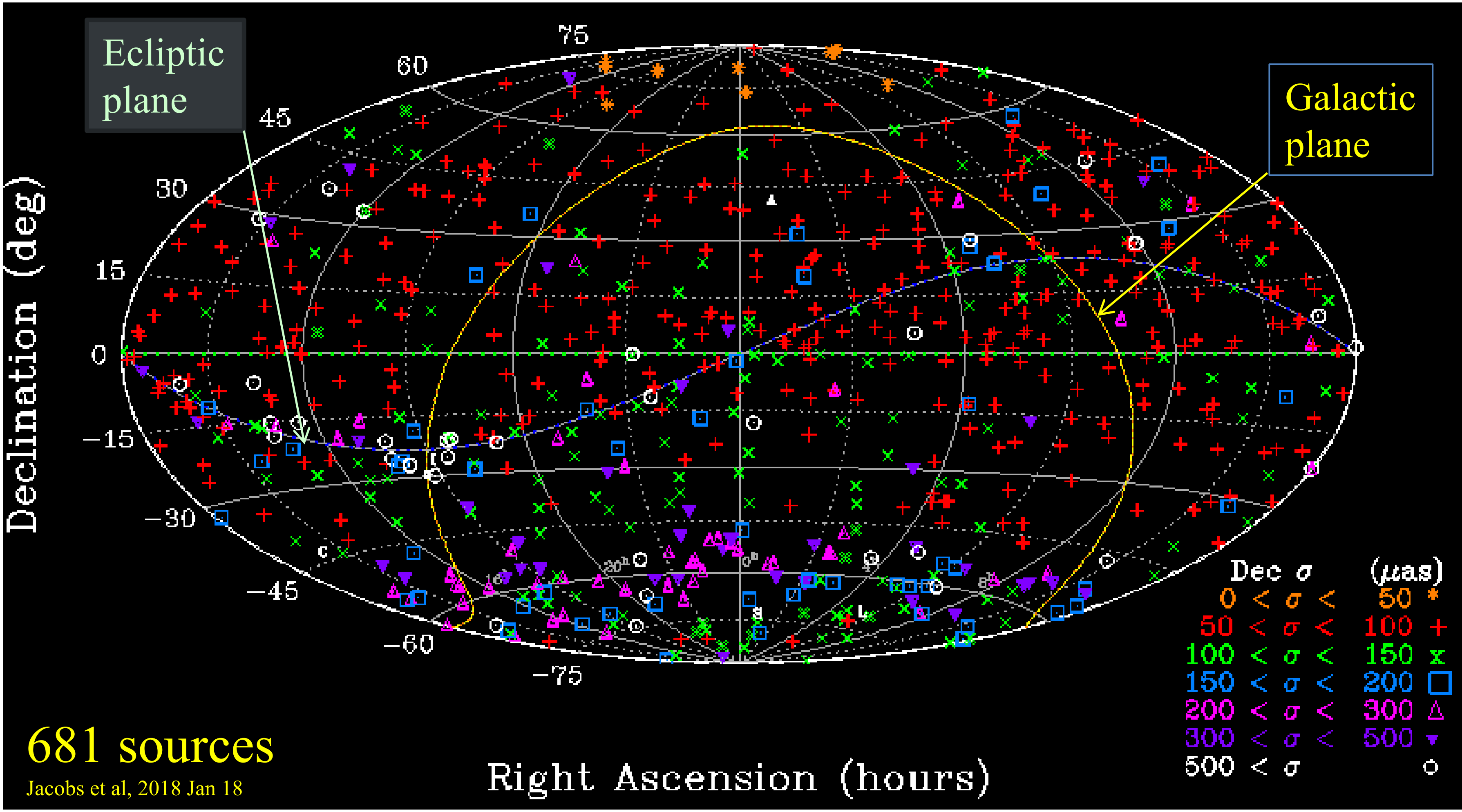
Ka (32 GHz, 9mm) Right Ascension sigmas (precision)



- Strengths:
  - Uniform spatial density
  - less structure than S/X (3.6cm)
  - needed only 67K observations vs. SX's 12 million!

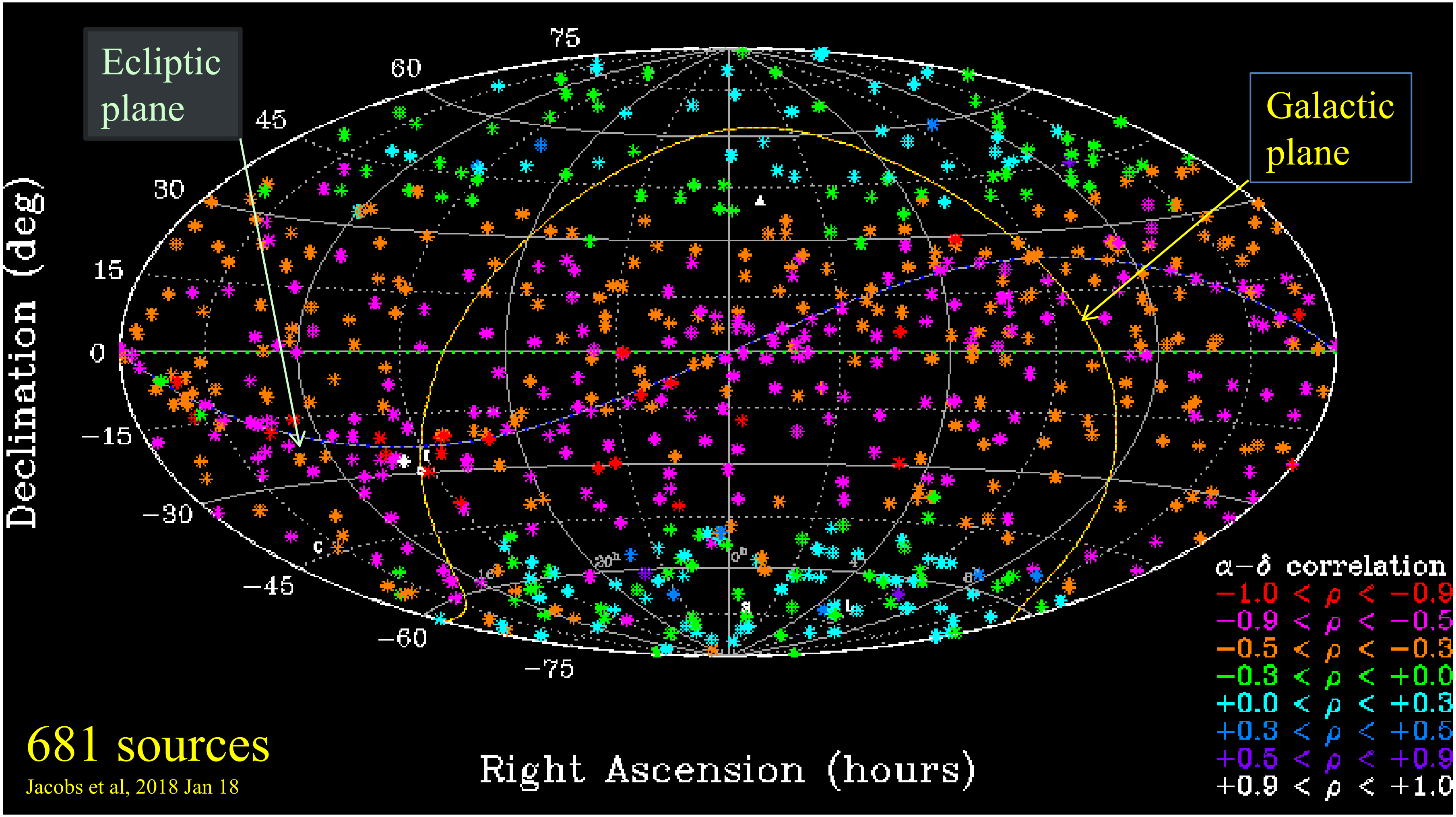
- Weaknesses:
  - Poor near Galactic center due to inter-stellar media scattering
  - South weak due to limited time on ESA's Argentina station
  - Limited Argentina-California data makes vulnerable to δ zonals
  - Limited Argentina-Australia weakens δ from -45 to -60 deg

Ka (32 GHz, 9mm) Declination sigma (precision)



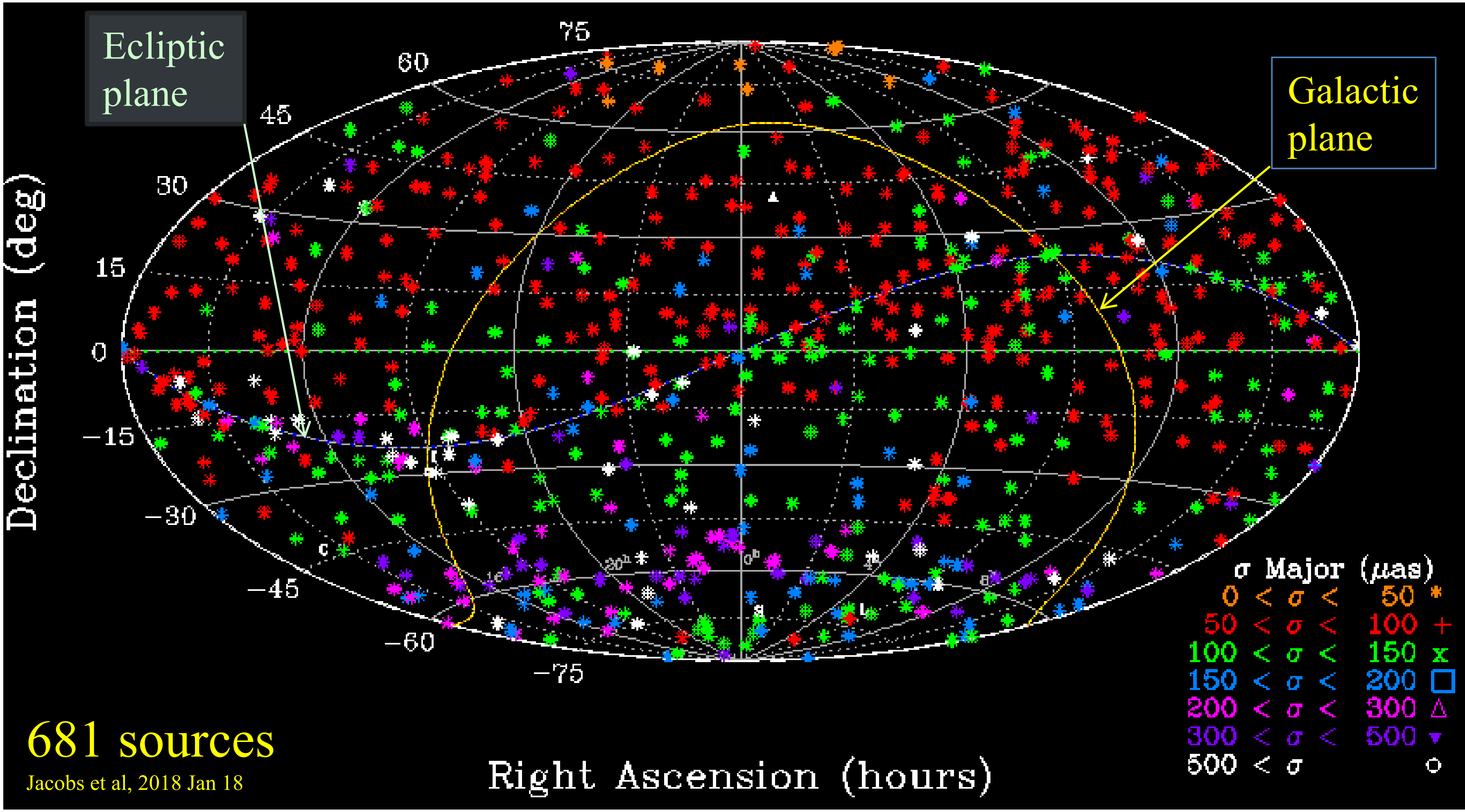
- Declination precision ~2 times worse than RA precision
- Especially weak in southern ecliptic and far south

Ka (32 GHz, 9mm) RA-Dec correlation



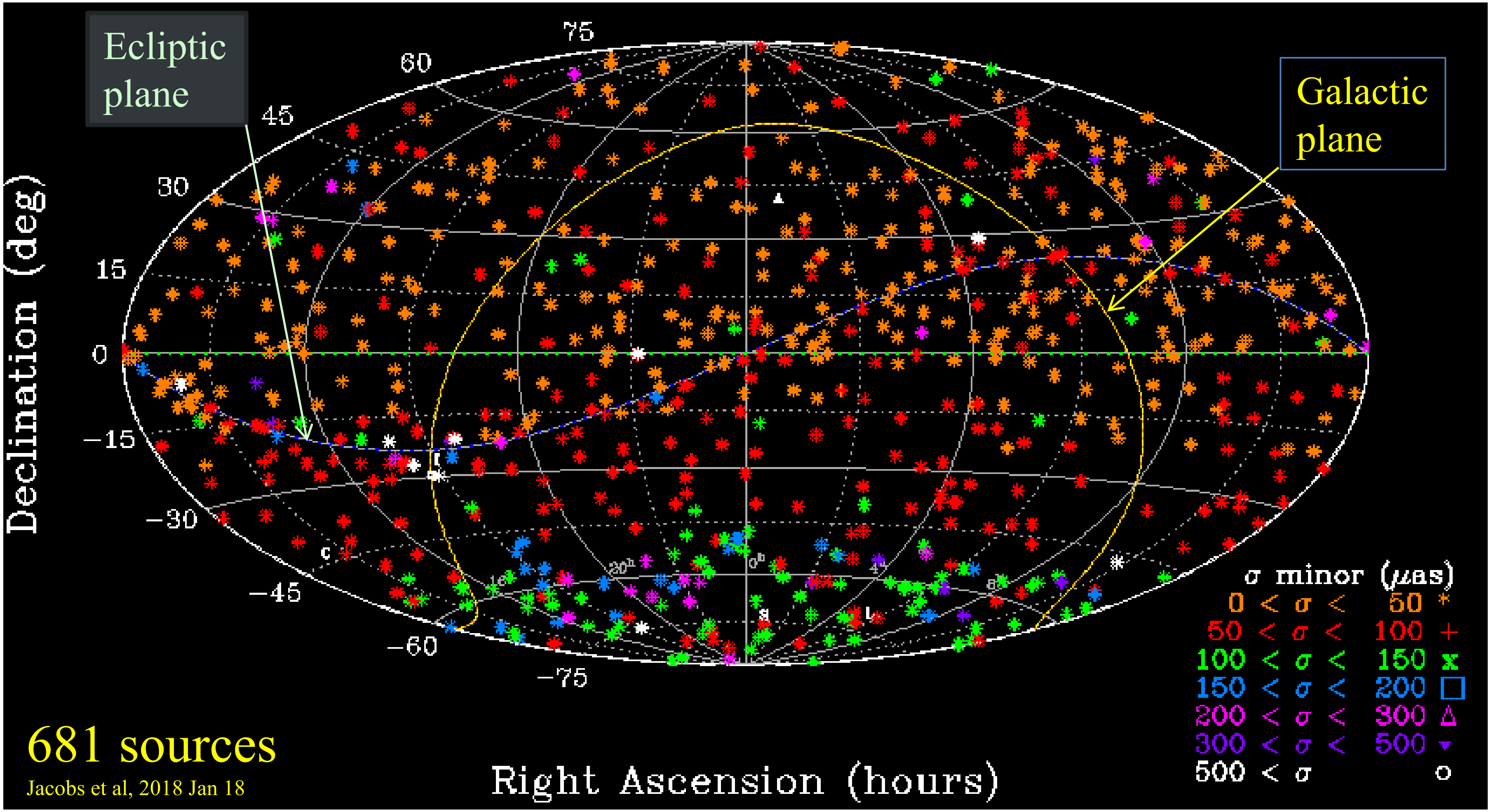
- Mid Declinations dominated by Goldstone-Tidbinbilla baseline
- Need more observations on a 2nd non-parallel North-South baseline

Ka (32 GHz, 9mm) Error Ellipse major Axis



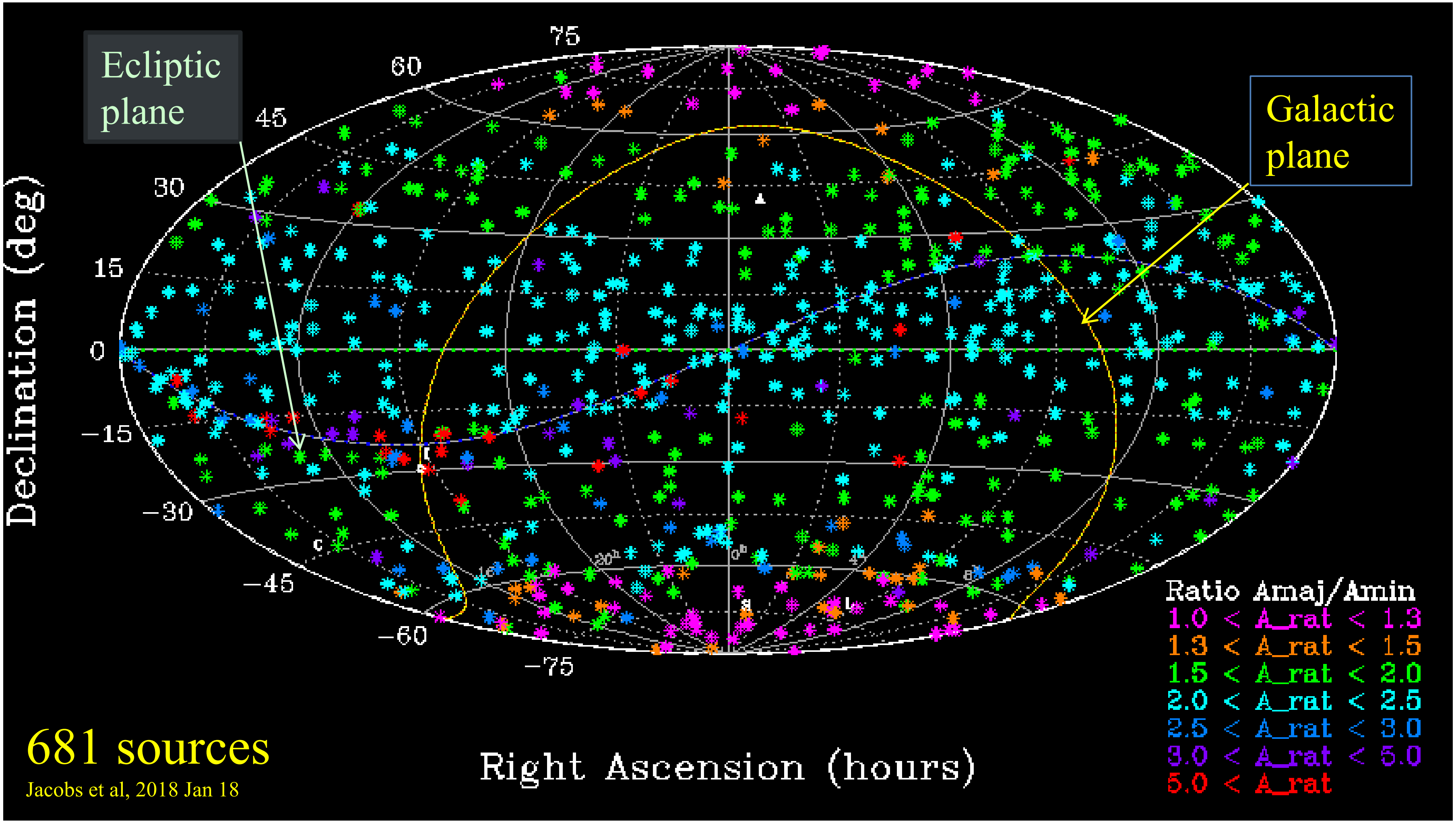
- Major axis shows precision in weak direction
- Major axis 2-3 times worse than required precision.

Ka (32 GHz, 9mm) Error Ellipse minor Axis



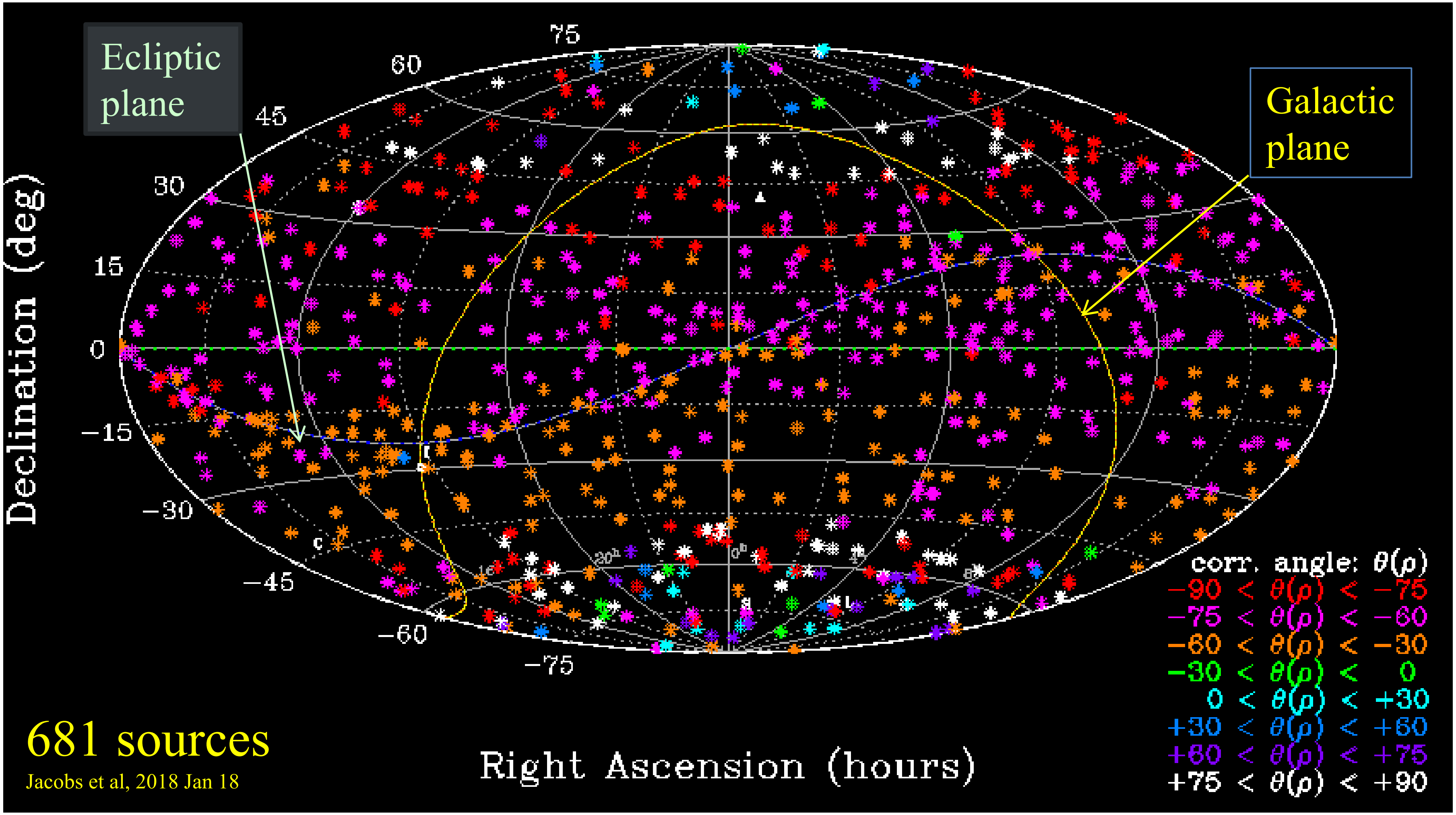
- Minor axis shows strong (precise) direction
- Meeting precision requirement in North but not south ecliptic

Ka (32 GHz, 9mm) Ellipse elongation: A_{maj}/A_{min}



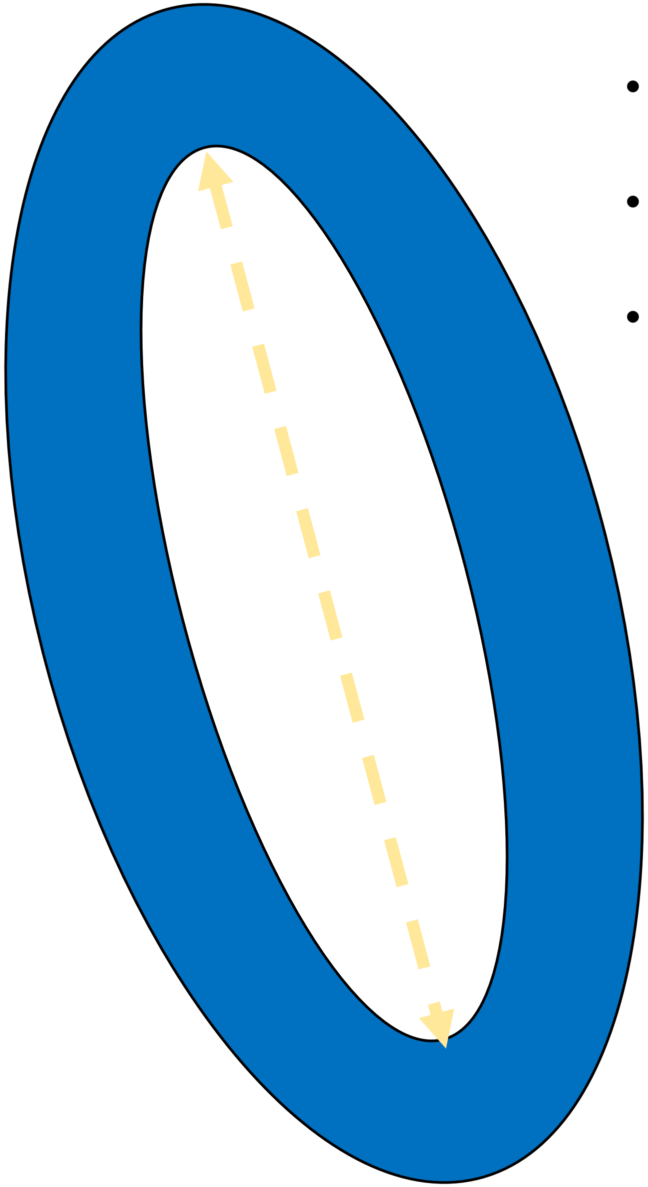
- Ratio Amaj/Amin shows how elongated ellipse is.
- Error ellipses typically asymmetric by factor ~2
- Southern Ecliptic is worse by a factor of 3-5 or more

Ka (32 GHz, 9mm) Direction of Major Axis (weak)



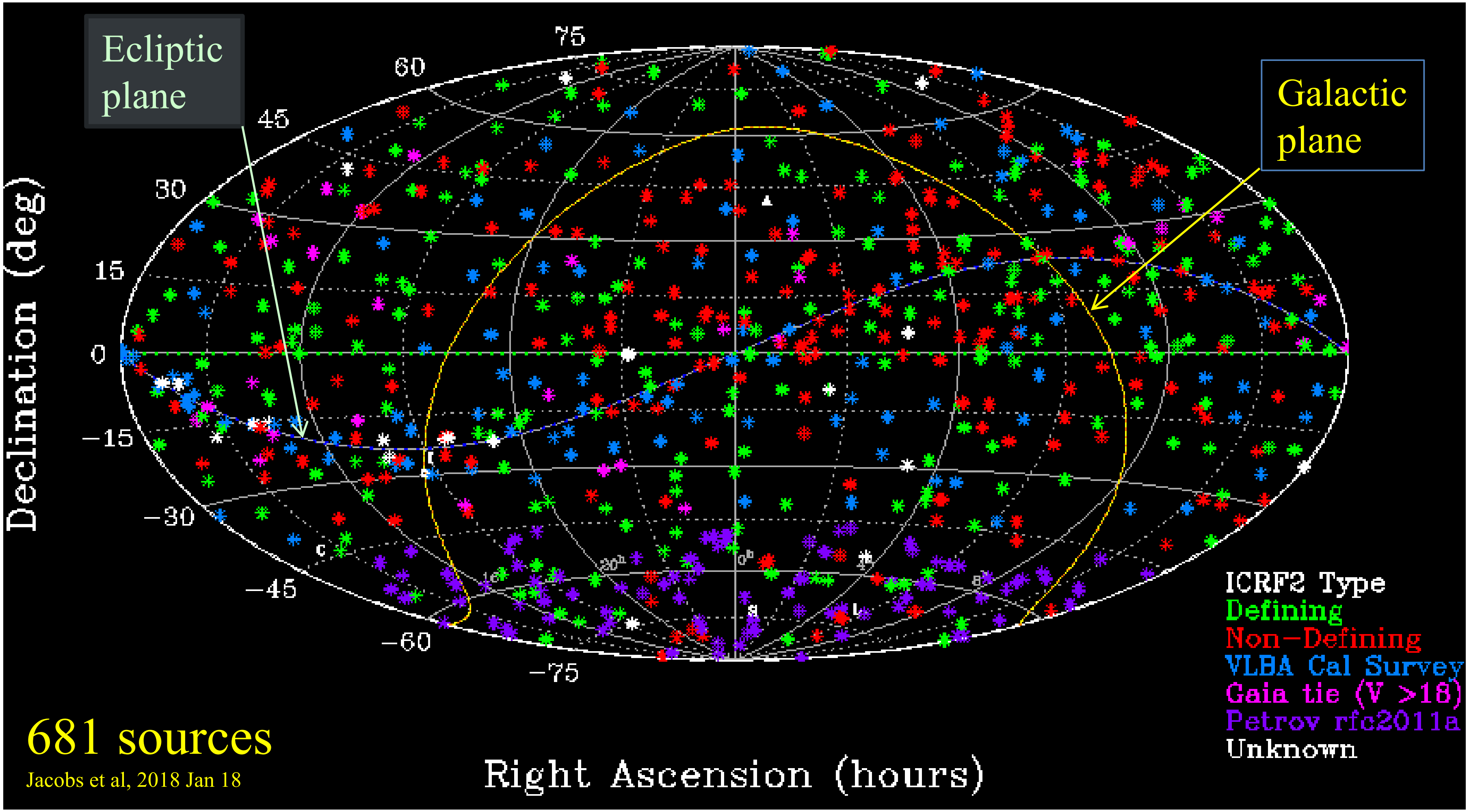
- Weak direction is close to North-South (red, magenta)
- Need North-South Baseline to correct the weakness

XKa: Typical Error Ellipse



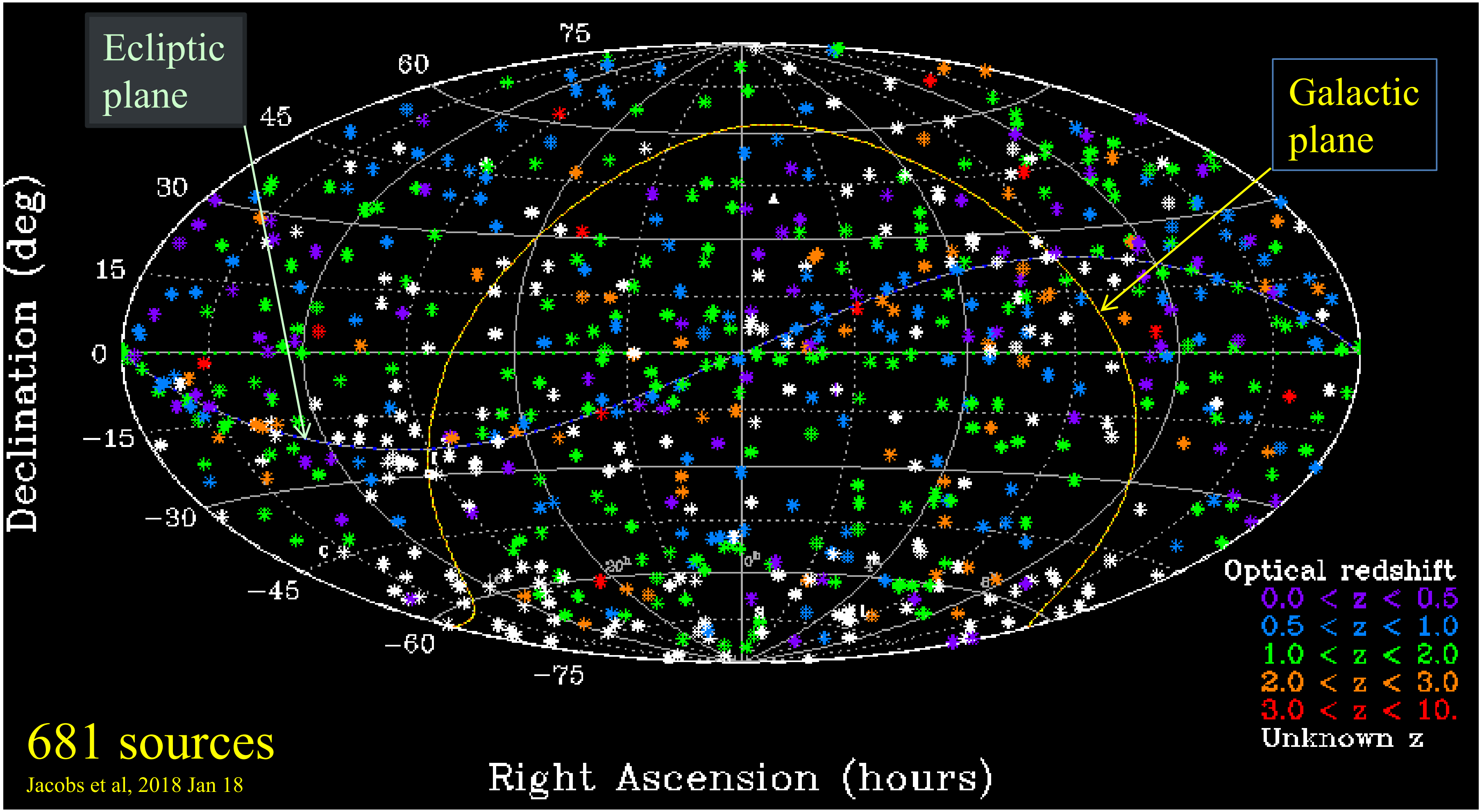
- Major axis is ~ 2 times larger than Minor axis
- Major axis direction is close to Declination direction
- **Usuda-Tidbinbilla baseline direction is a near perfect match to improve the weakest direction!!**

Ka (32 GHz, 9mm) ICRF-2 object class



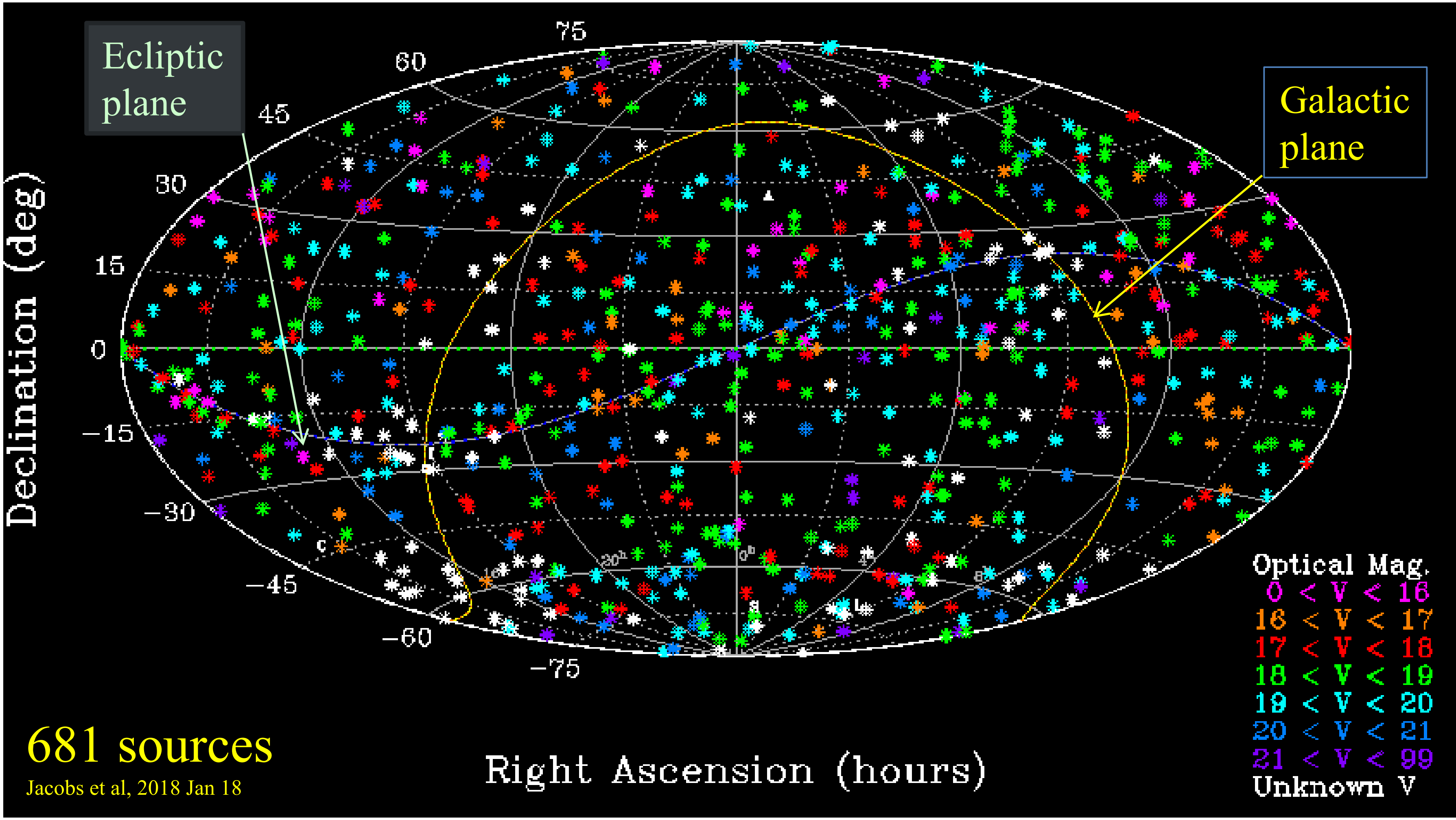
- More than 200 ICRf-2 “Defining” sources (green)
- Ensures a strong tie that aligns XKa to the ICRF-2

Ka (32 GHz, 9mm) Redshift (optical)



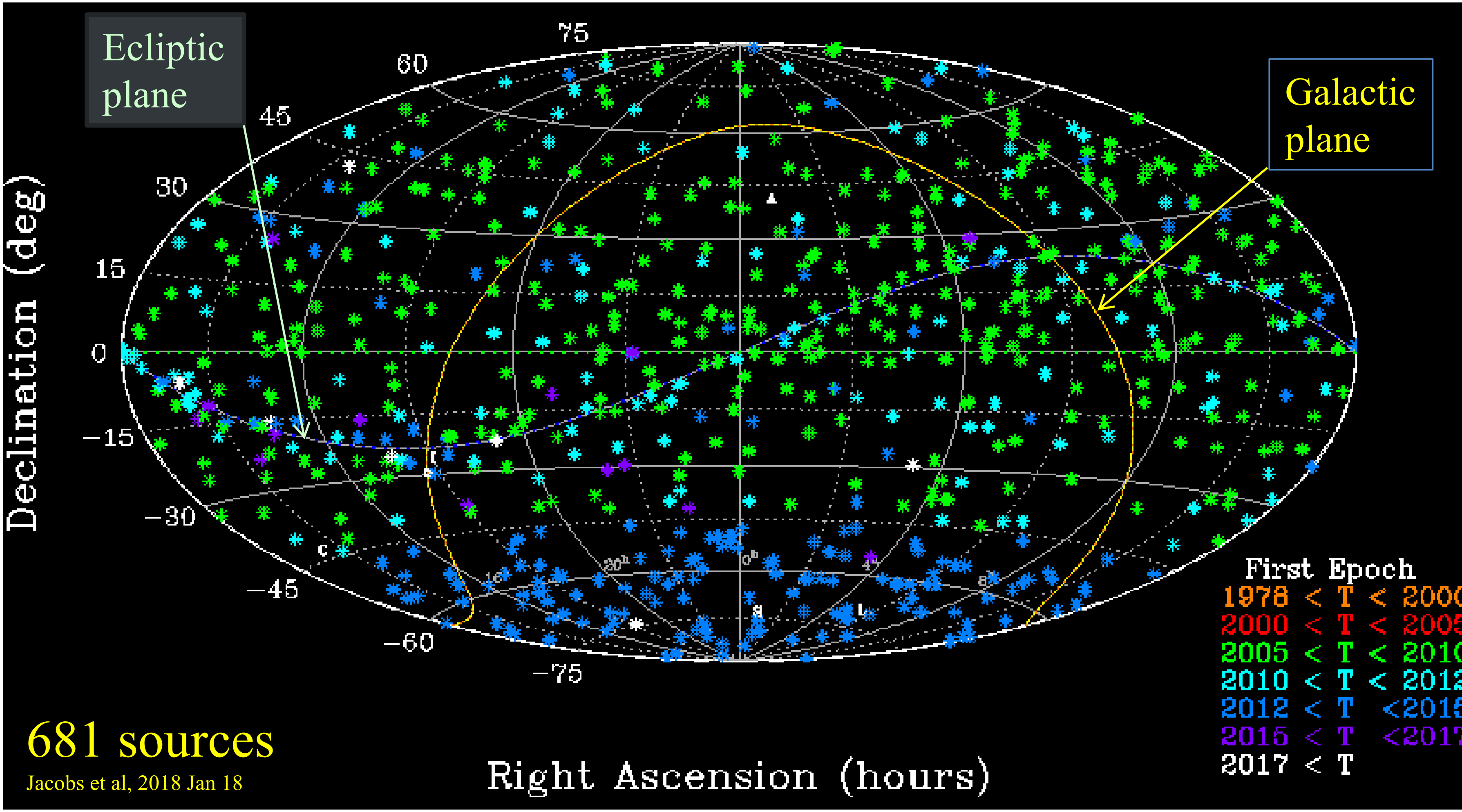
- Median redshift is ~1 (billions of light years)
- Farthest object is z = 5.5, several objects z > 3
- Allows verification of cosmological modelling

Ka (32 GHz, 9mm) Optical magnitude: <18 for Gaia tie



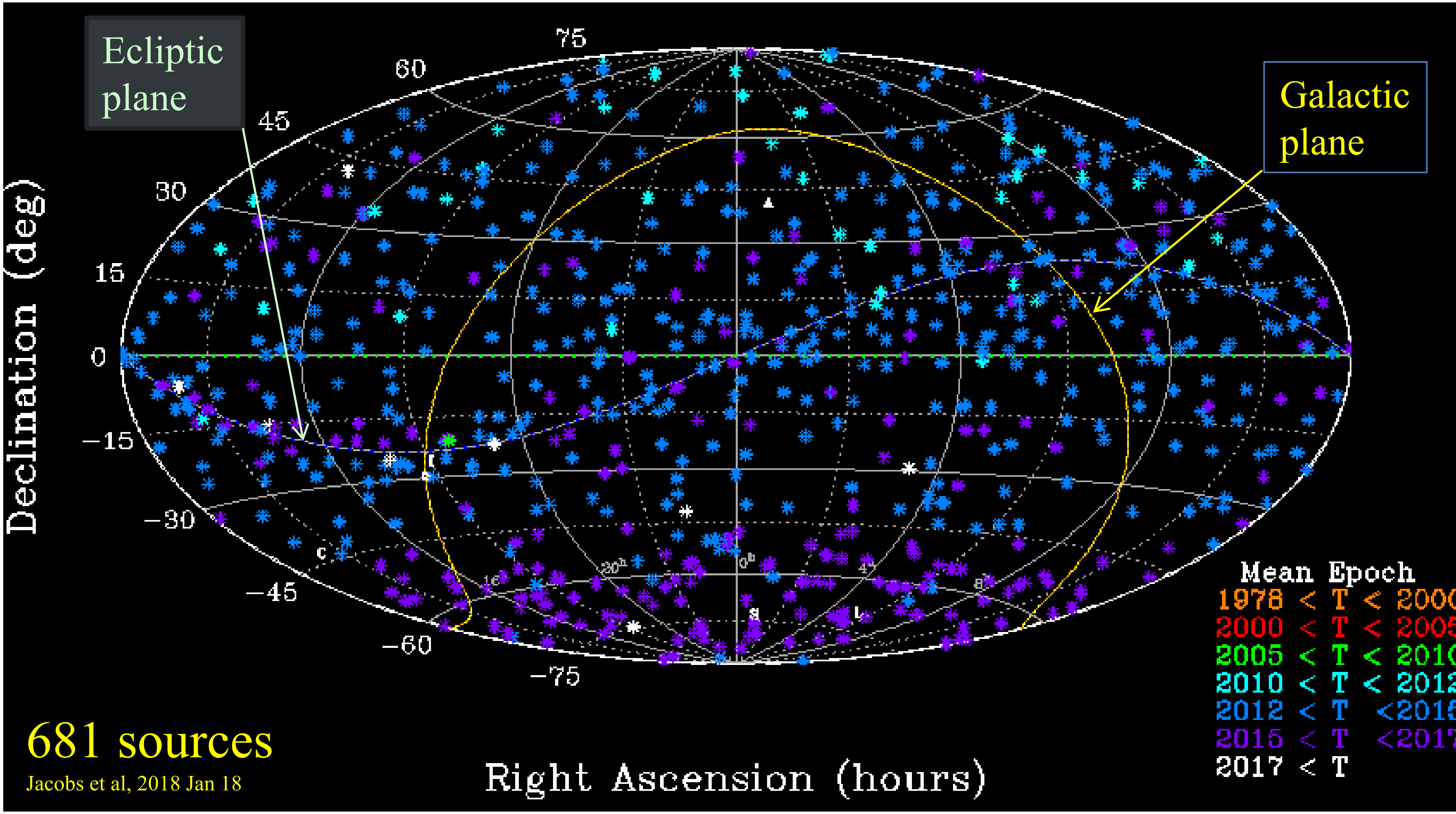
- Optical magnitudes brighter than V = 18th mag allow a strong tie to the Gaia optical frame(magenta, orange, red)
- Expected tie precision ~ 10 μas

Ka (32 GHz, 9mm) First observation Epoch



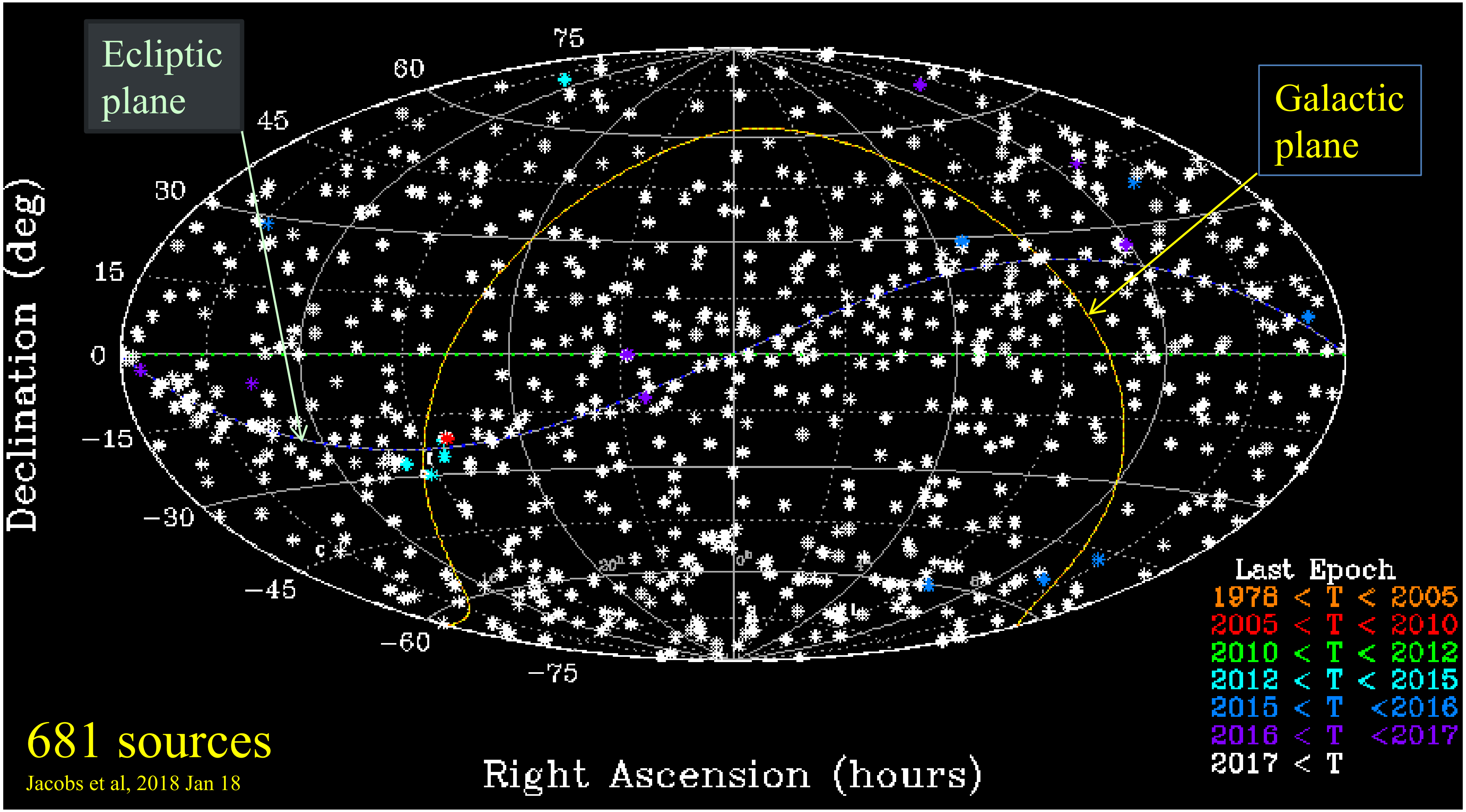
- Started in 2005 for "north" : Dec > -45 deg
- Started in 2012 for far south: Dec < -45 deg

Ka (32 GHz, 9mm) Mean observation Epoch



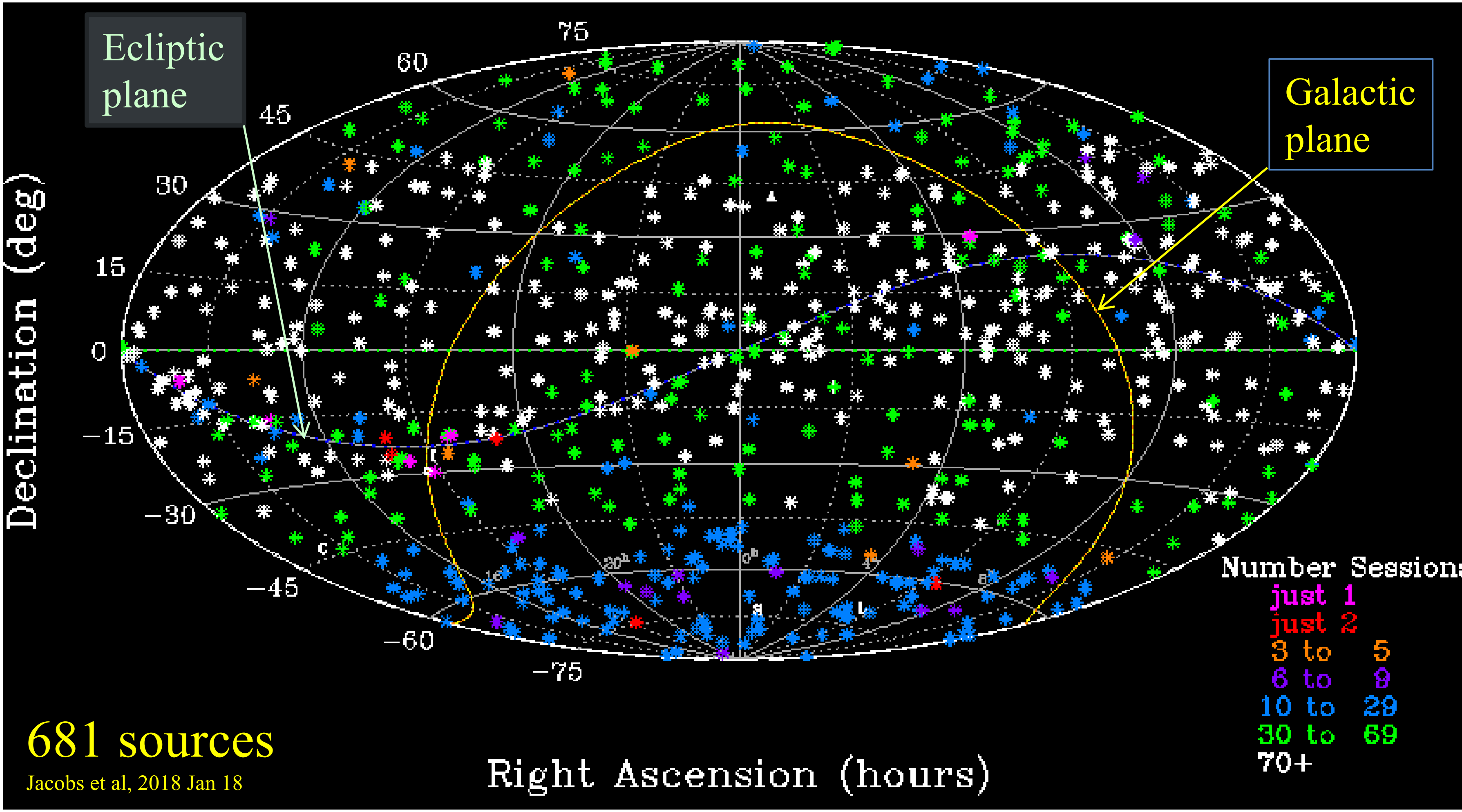
- Mean epoch of observation fairly uniform for Dec > -45 deg
- Biased toward more recent time in far south due to late start of Malargüe observations in late 2012

Ka (32 GHz, 9mm) Last observations Epoch



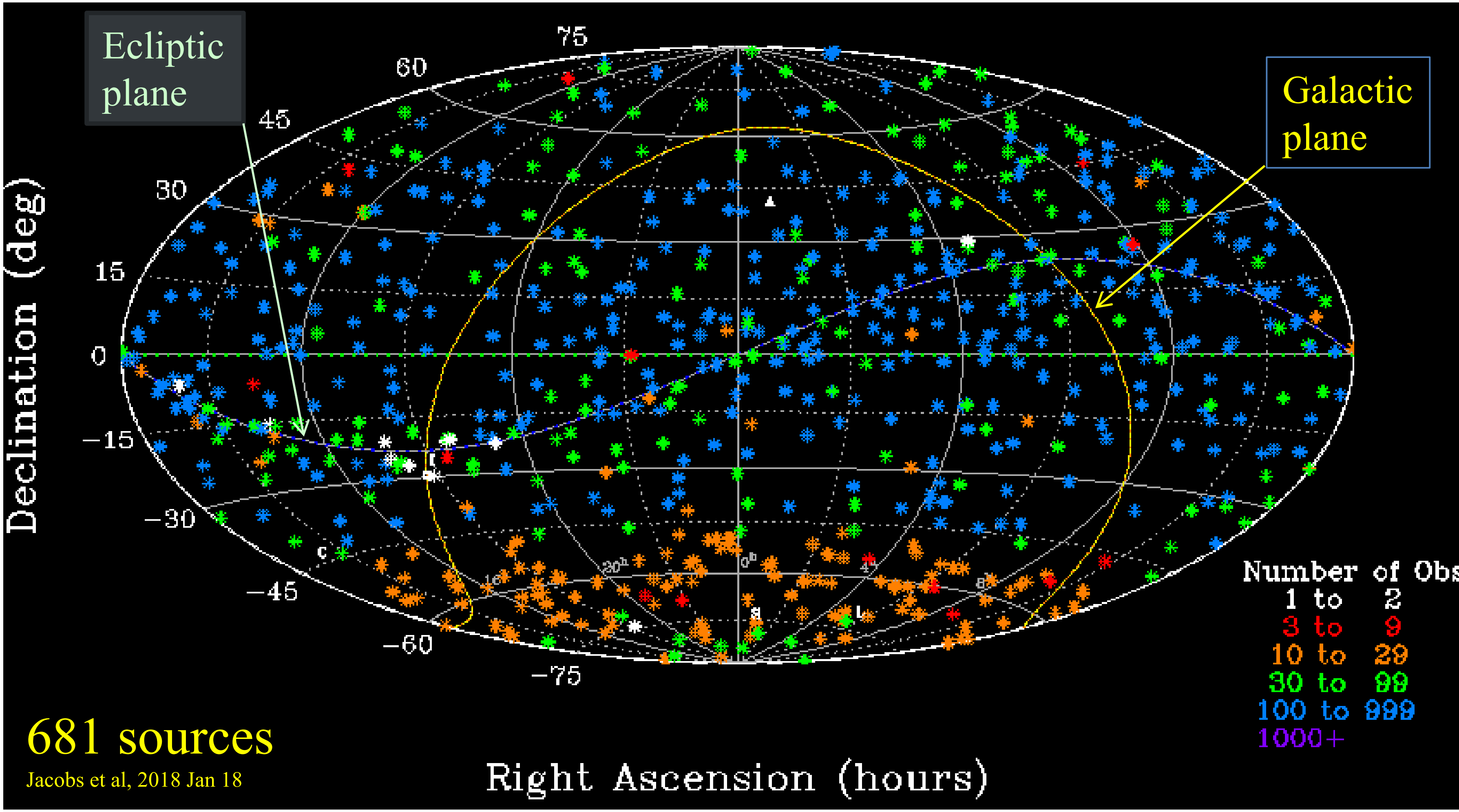
- Regular, uniform observations of all sources
- Almost all sources observed recently

Ka (32 GHz, 9mm) Number observing Sessions



- > 70 sessions for mid-Declinations where multiple baselines reach
- Far south now stable with $N_{sessions}$ > 10

Ka (32 GHz, 9mm) Number Delay Observations



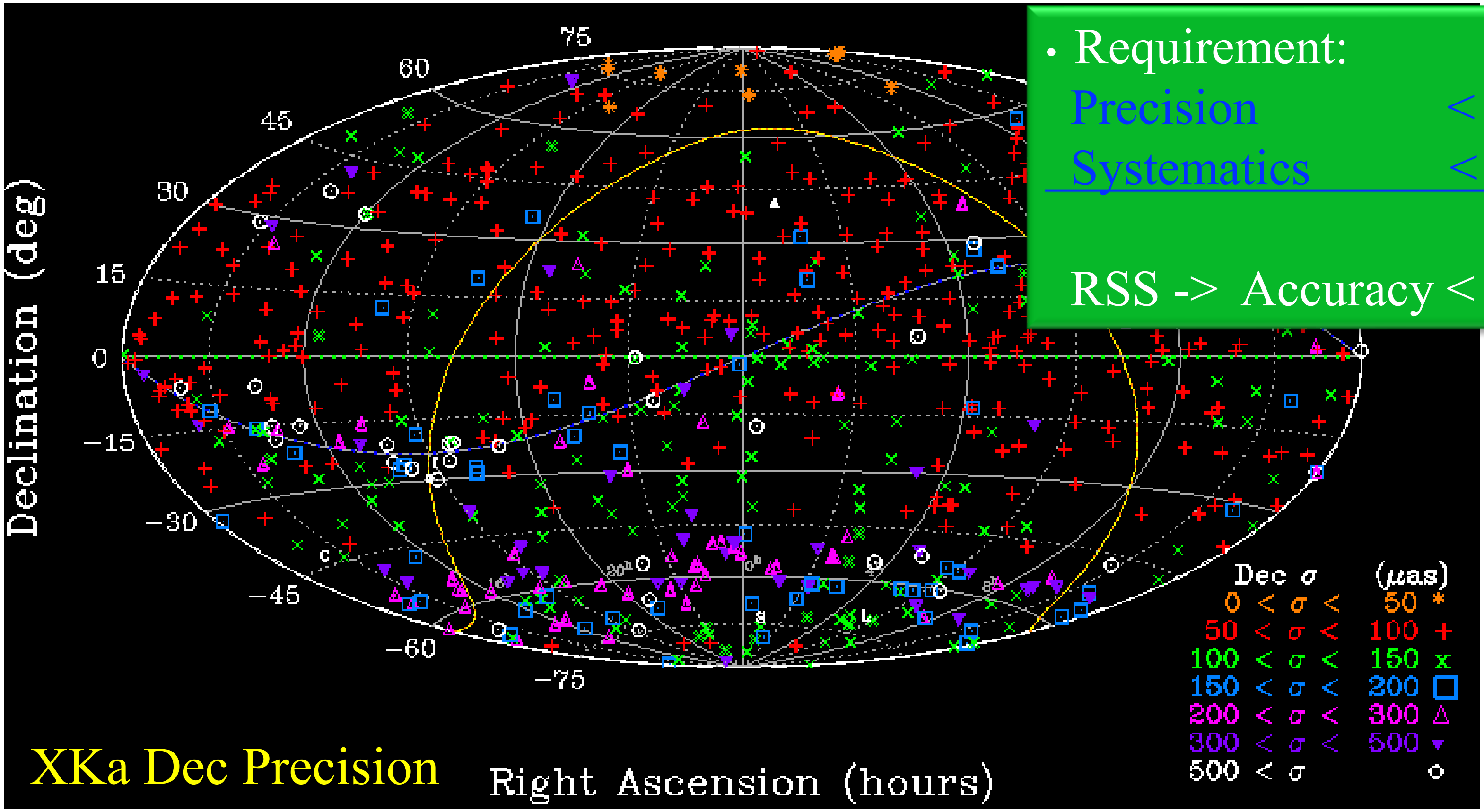
- Typically more than 100 delay observations
- Far south is 3-10 times worse

XKa Accuracy Assessment

Precision falls badly short of requirements in southern ecliptic.

Need more Goldstone-Malargüe data.

Usuda-Tidbinbilla (2019) has potential to make major improvements!



- Requirement:
  Precision < 50 μas
  Systematics < 85 μas

  RSS -> Accuracy < 100 μas

Ka-band combined NASA/ESA Deep Space Net

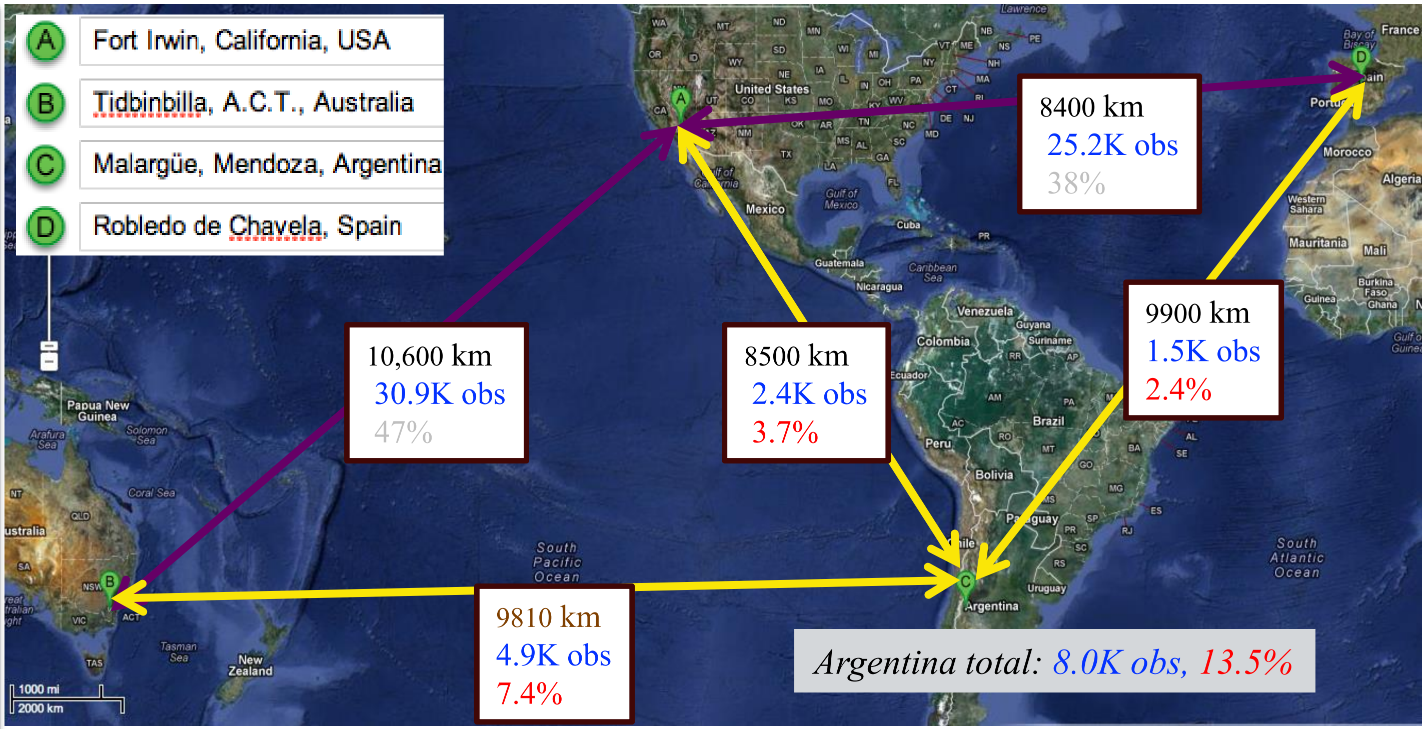
ESA Argentina to NASA-California under-observed by order of magnitude!

Baseline percentages

- Argentina is part of 3/5 baselines or 60% but only 13% of obs
- Aust- Argentina 7.4%
- 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!!



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

XKa vs/ SX: RA* Zonal errors ~500 μas

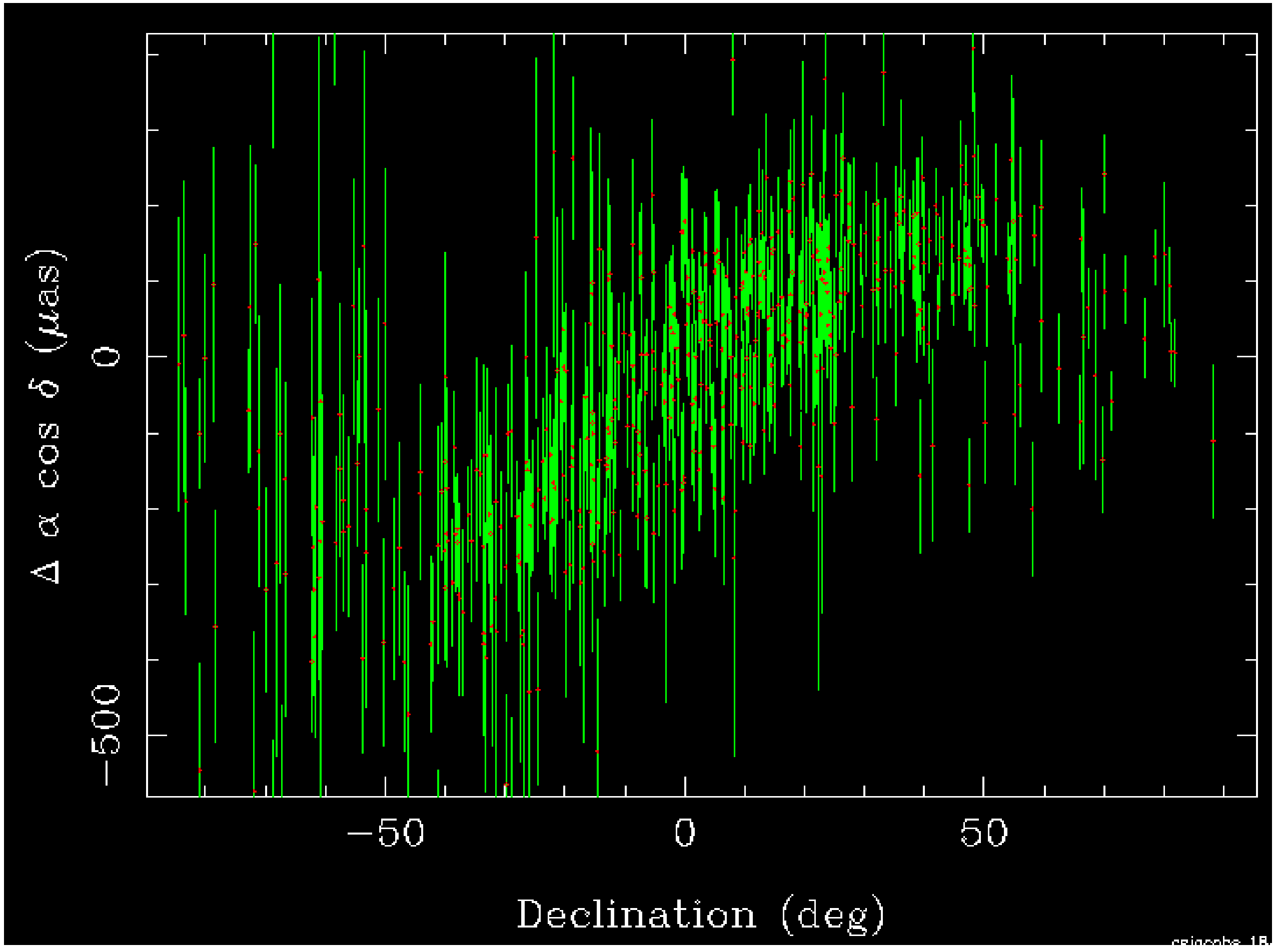
Zonal Errors

- ΔDec vs. Dec: -600 μas
  ΔRA* vs. Dec: -300 μas South
  +200 μas North

- Need at least 2 baselines to get 2 angles:
  Goldstone-Canberra: 31K obs
  Goldstone-Malargüe: 2K obs

-> Need more Goldstone-Malargüe data to overcome this 13 to 1 distortion in sampling geometry.

- Usuda 54-m XKa antenna (2019) would improve North-South sampling geometry and thus control Declination zonals.



XKa vs/ SX: Dec Zonal errors 600 μas

Zonal Errors

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  ΔRA* vs. Dec: -300 μas South
  +200 μas North

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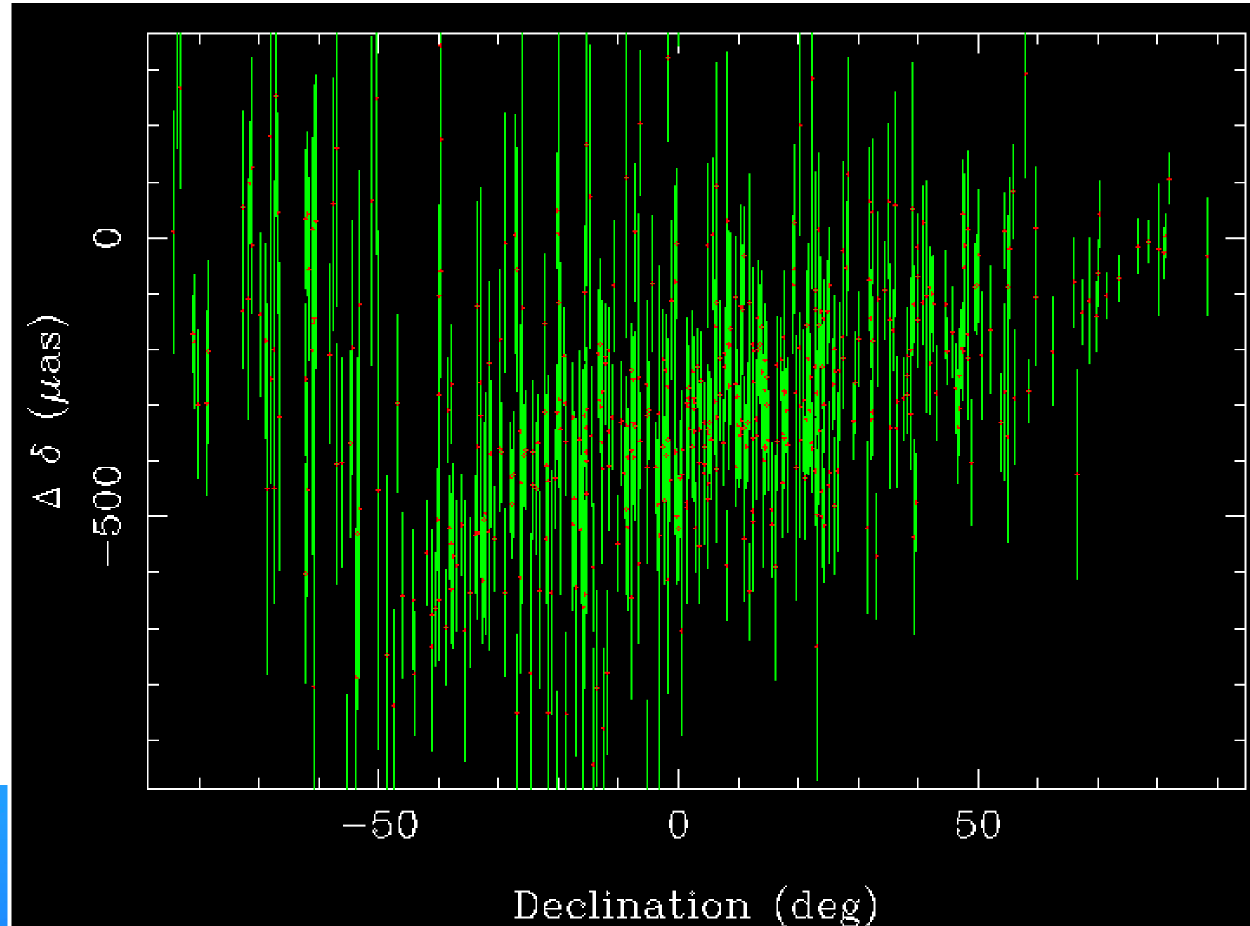
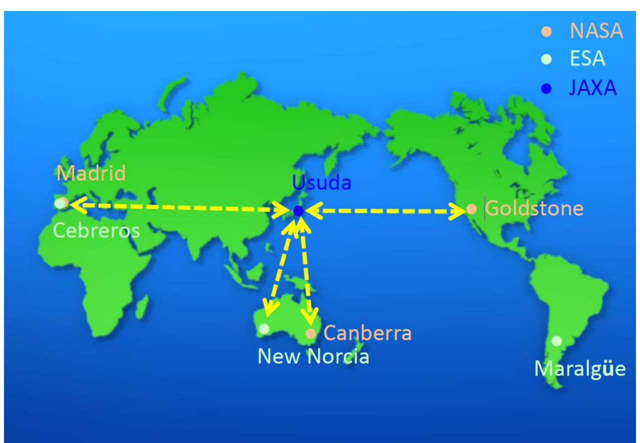
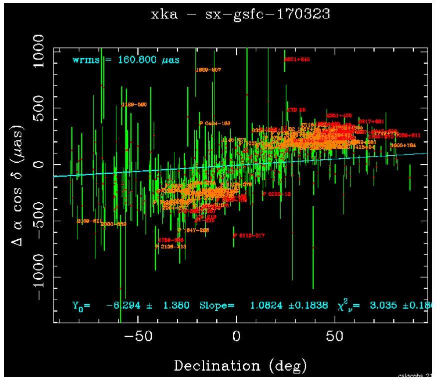




Usuda 54m will be in ideal location to address XKa's limiting error: Zonal distortions vs. Declination.



Credit: SX astrometry, D. Gordon

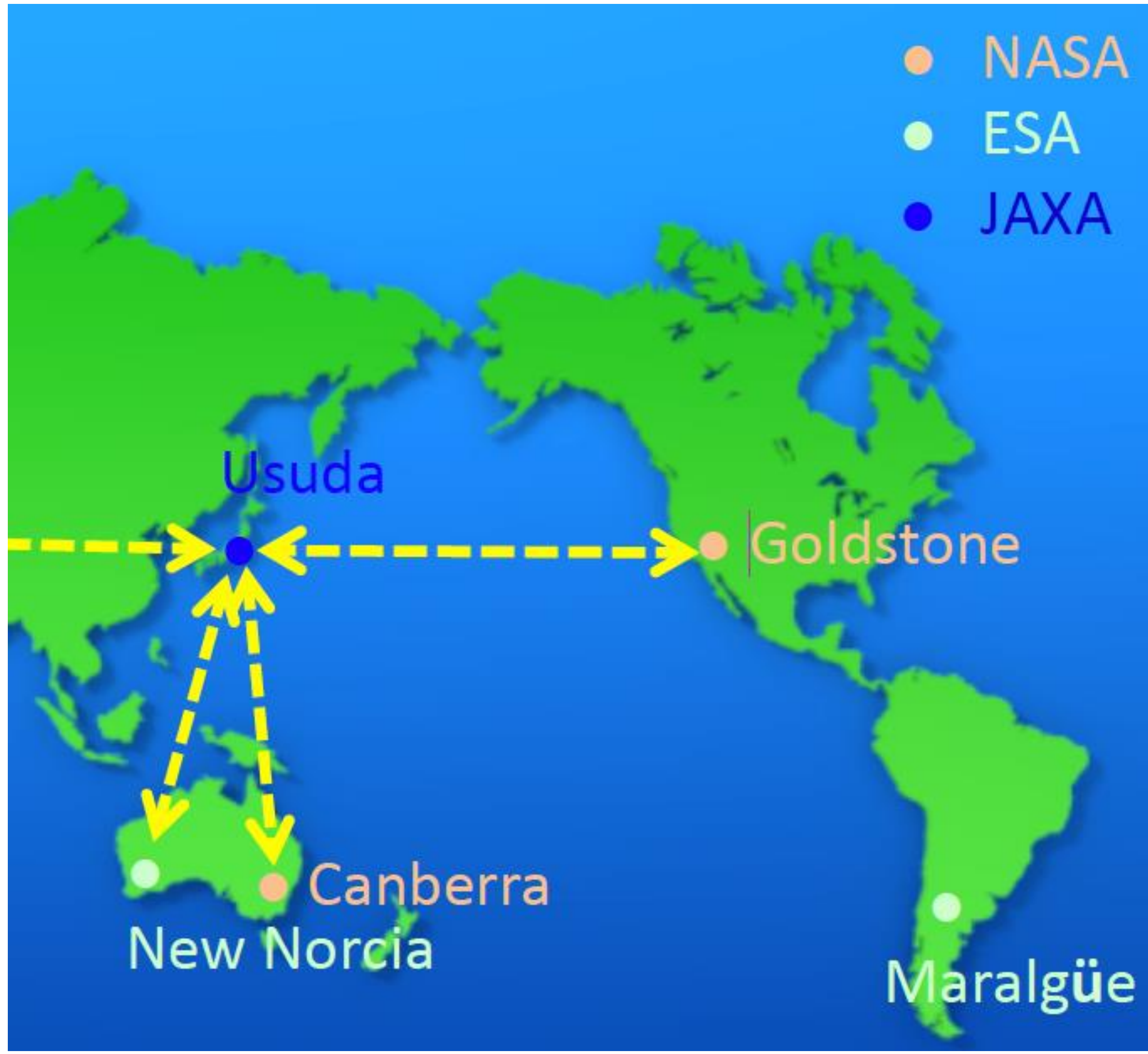
Zonal Errors

- 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.



Proposal to Strengthen XKa Celestial Frame

- Usuda 54m Celestial Frame observations about once per month
  Full 24 hour sweep of the sky for each session.
  - Usuda to Canberra ~ 6 times per year
  - Usuda to Madrid ~ 2 times per year
  - Usuda to Goldstone ~2 times per year
  - Usuda to Malargüe ~2 times per year

- JPL creates
  VEX 1.5 schedule

- JAXA records:
  VDIF format data
  2048 Mbps

- Correlated at JPL
- Analysis at JPL

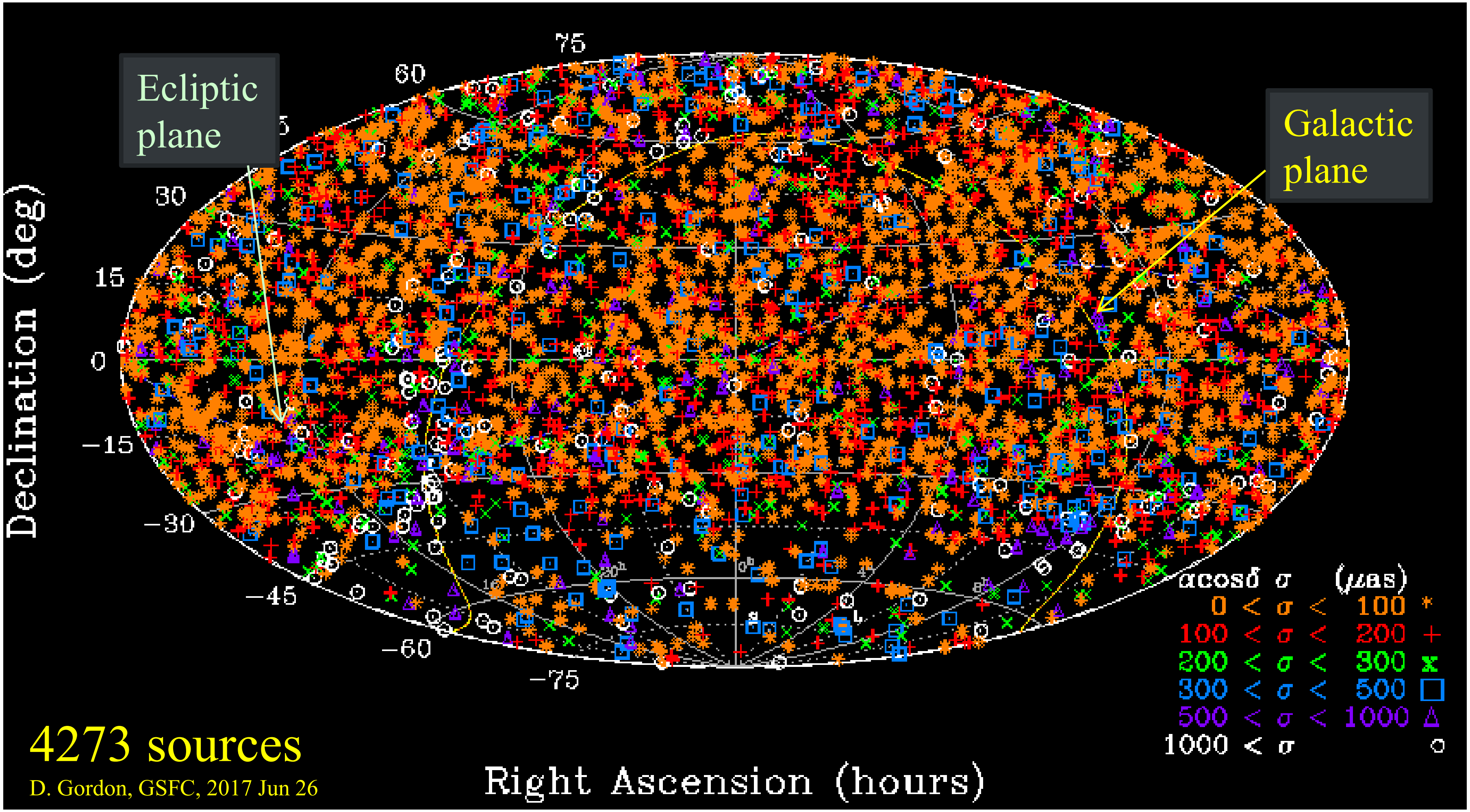
- Data shared
- Publications shared

XKa Celestial Frame Summary:

- **Goal: XKa frame accurate to 100 μas**
  Precision (random errors) 50 μas
  Systematic errors 85 μas
- **Roadmap:**
  - Initial data are very promising.
  - Accuracy limited by systematic zonal errors vs. Declination
  - Need more Goldstone-Malargüe, Argentina data
  - Need dual-band in Argentina, Need higher data rate >= 1 Gbps
  - **Usuda, Japan to Tidbinbilla, Australia baseline is in ideal direction!**
  - Usuda 54m can strengthen Declinations, constrain systematic zonal errors.
- **JAXA's 54m XKa antenna**
  Fills a major need for a North-South Baseline, addresses XKa limiting errors
  Allows tie of NASA/ESA/JAXA Terrestrial Frames (station locations)

Backup

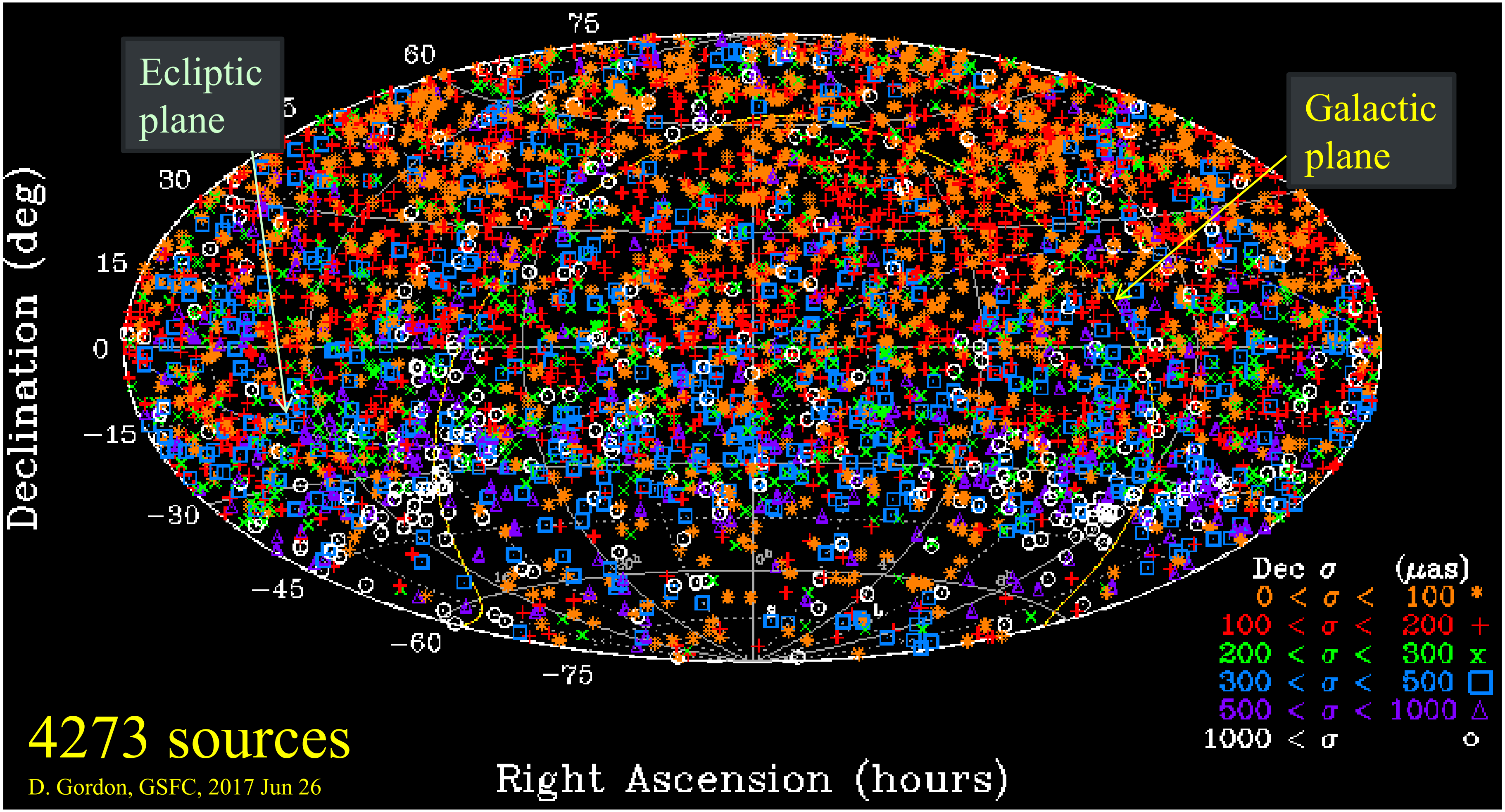
SX (8.4 GHz, 3.6cm) *VLBA+~ 100 other IVS*



- Strengths:
  - 4273 sources
  - Excellent coverage North of δ -30 deg
  - median precision < 50 μas
  - SX's 12 million observations, 40 years
  - over 100 stations contributed

- Weaknesses:
  - Poor coverage south of δ -40 deg
  - only 20% of sources in > 10 sessions
  - source structure worse than K or XKa.

SX (8.4 GHz, 3.6cm): Dec precision weaker than RA



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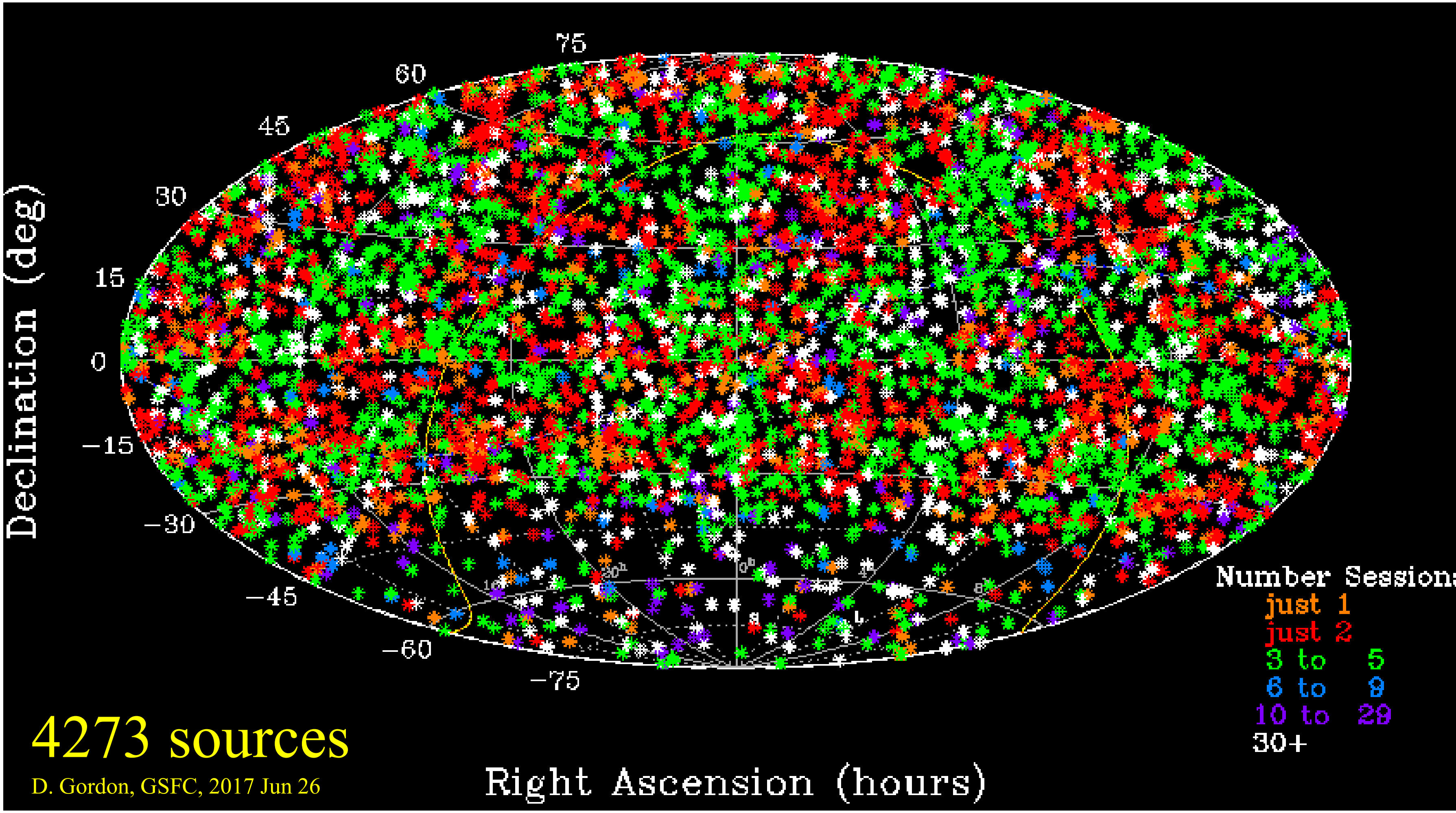
SX: Number Sessions, ~800 > 10 sessions, rest 2-5 survey sessions



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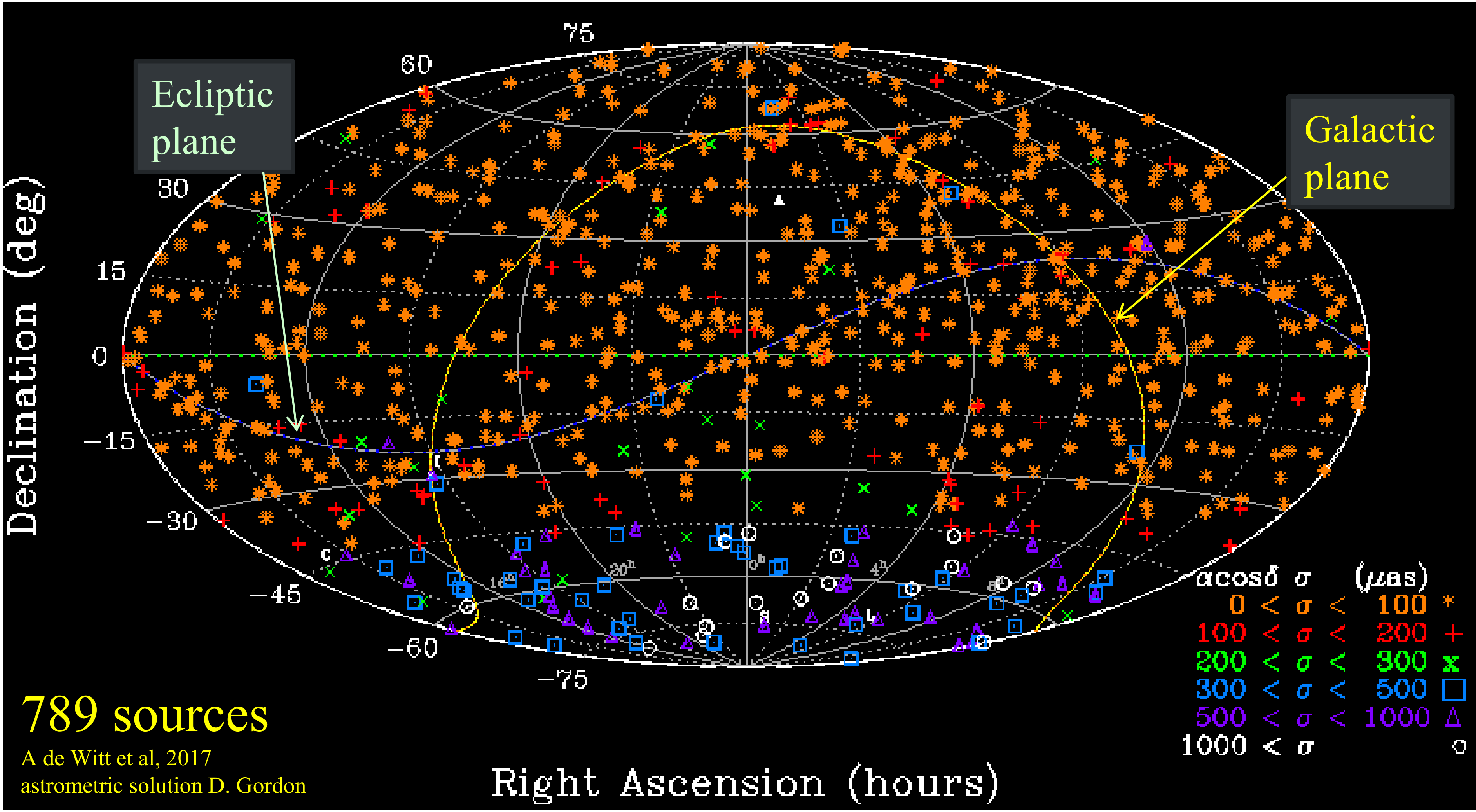
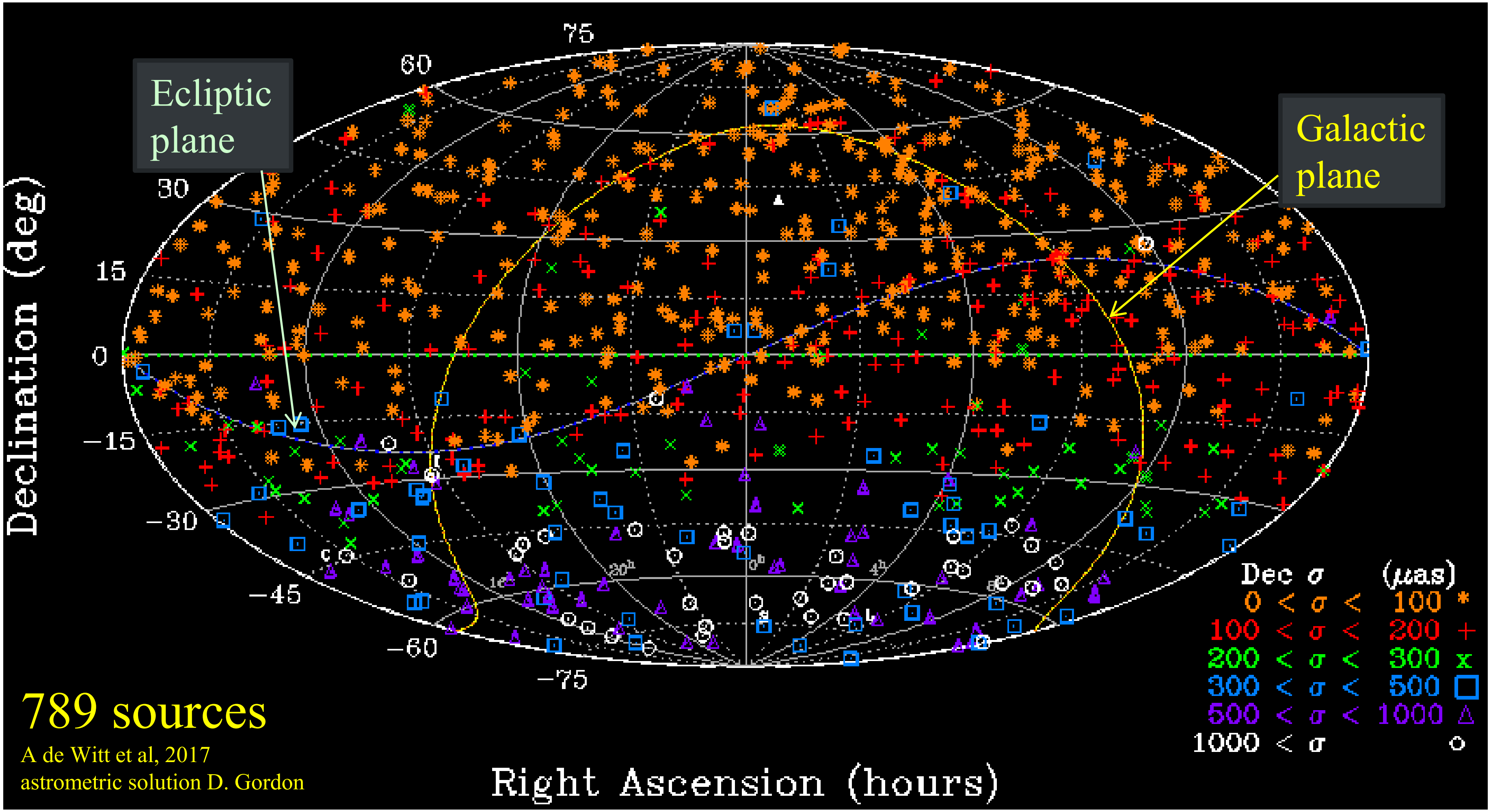
K (24 GHz, 1.2cm) *VLBA+ (S. Africa-Tasmania)*



- 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 ($\delta < -30$ deg) weak due to limited HartRAO, South Africa to Hobart, Tasmania data

K (24 GHz, 1.2cm): Dec precision weaker than RA



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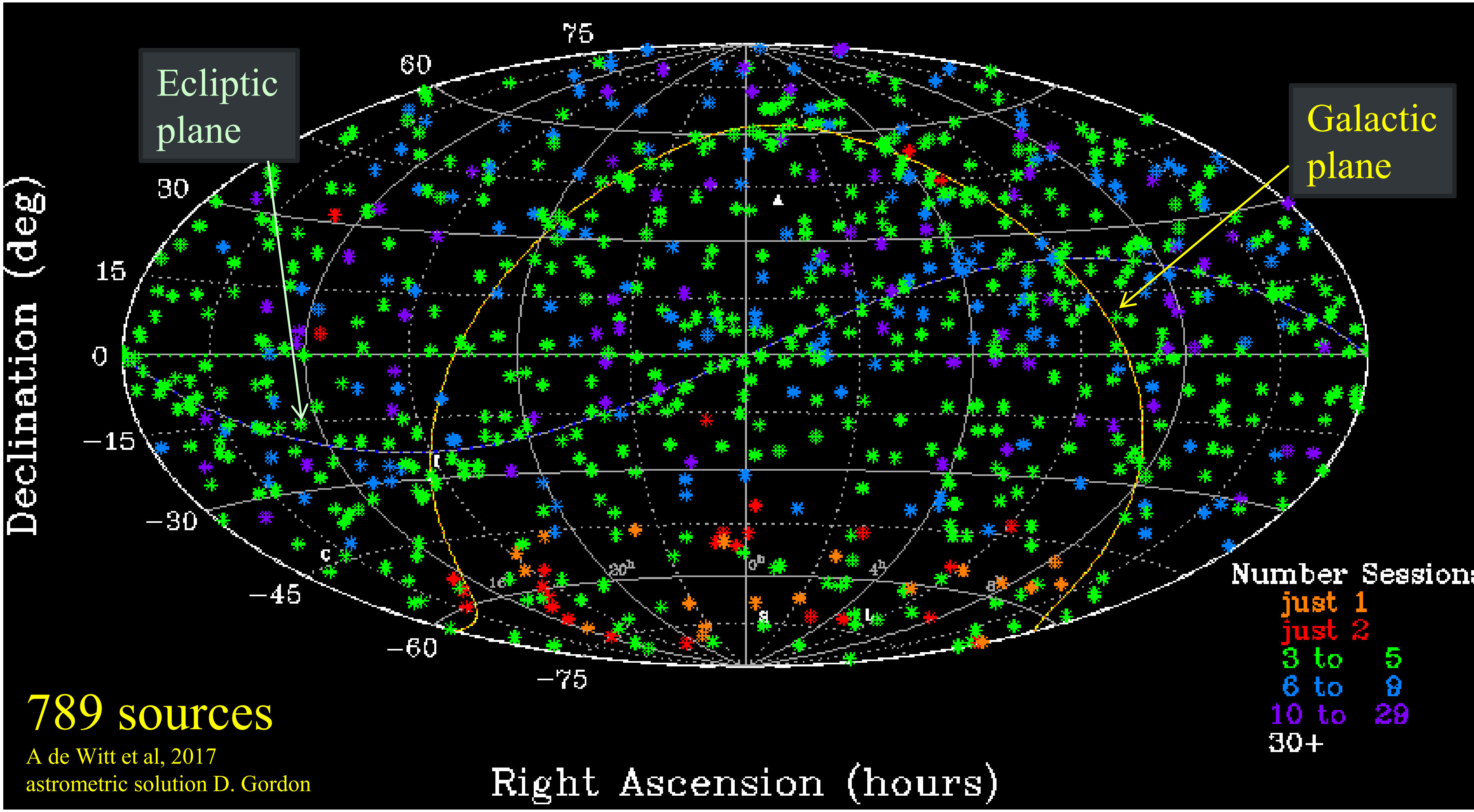
K (24 GHz, 1.2cm): Number sessions 3-10



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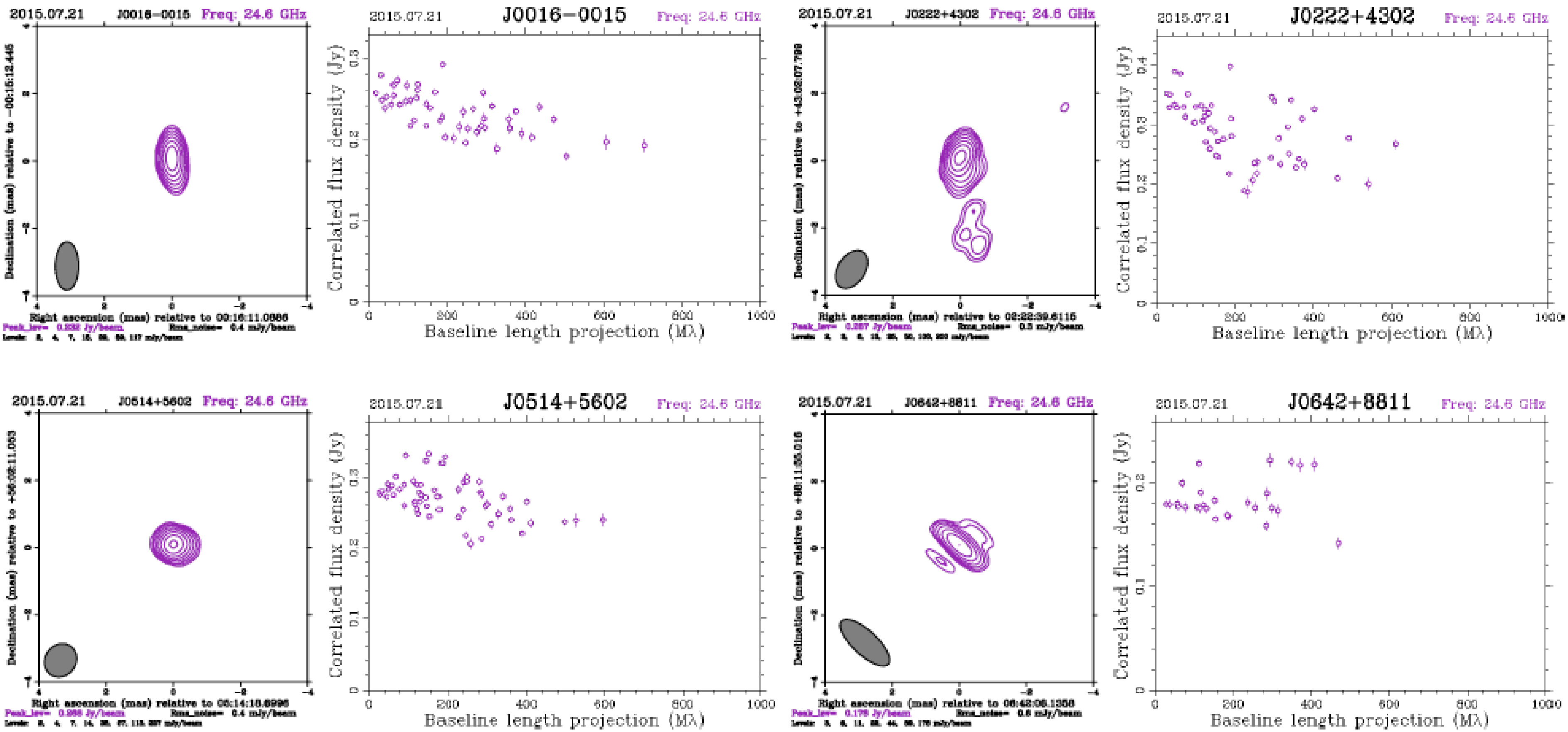
Imaging: VLBA at 24 GHz (1.2cm) (de Witt et al, 2016)



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.

The Source Objects

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) used radio stars to tie Hipaarcos & VLBI.

- **Thermal emission from regular stars:**

  350 GHz astrometry using Atacama Large Millimeter Array (ALMA)

  Fomalont et al. (pilot observations)

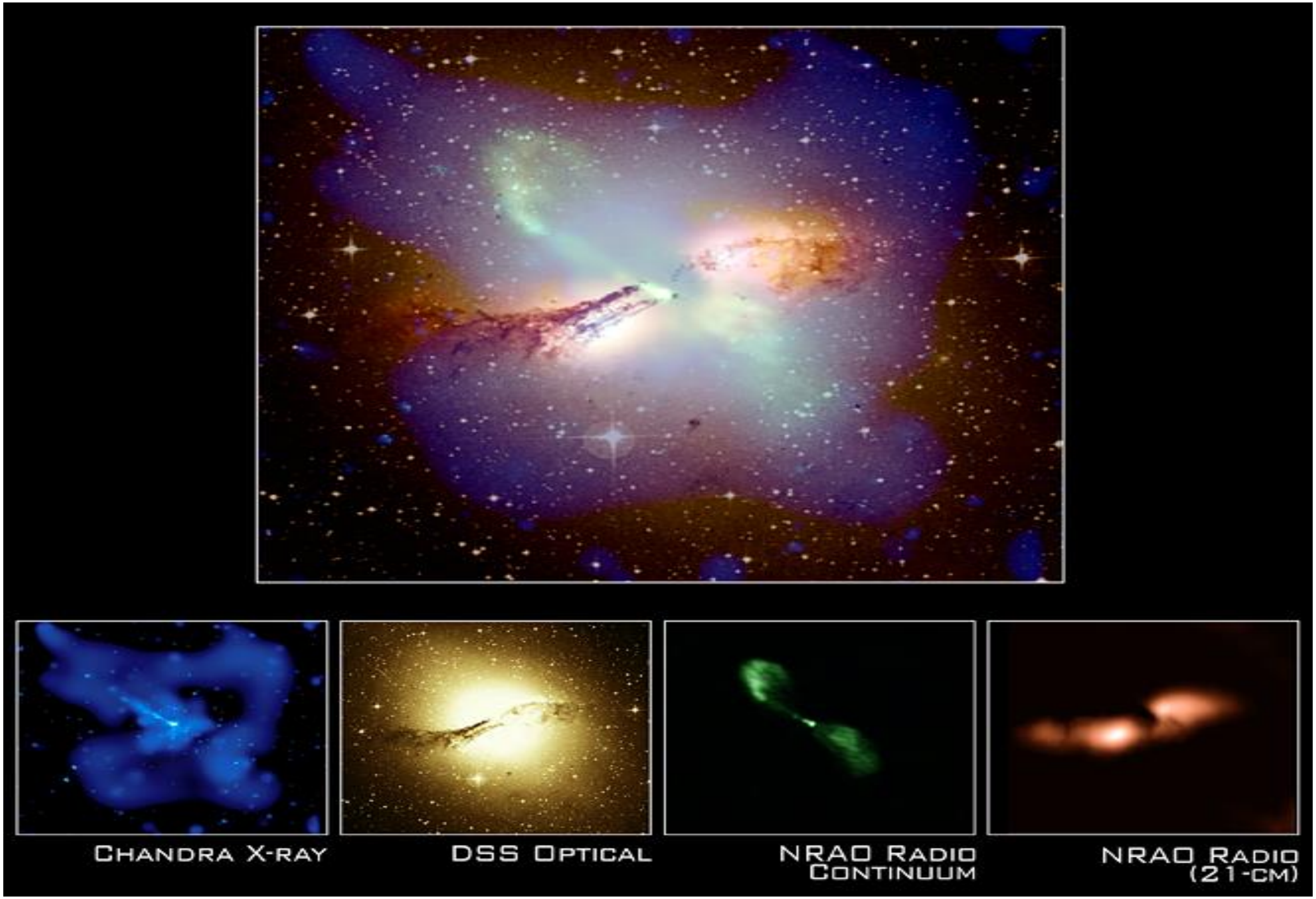
  Verifies bright end of optical, but likely limited to 500 – 1000 μas (2.5 to 5 ppb).

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

  potential for better than 100 μas to 20 μas (0.5 to 0.1 ppb).

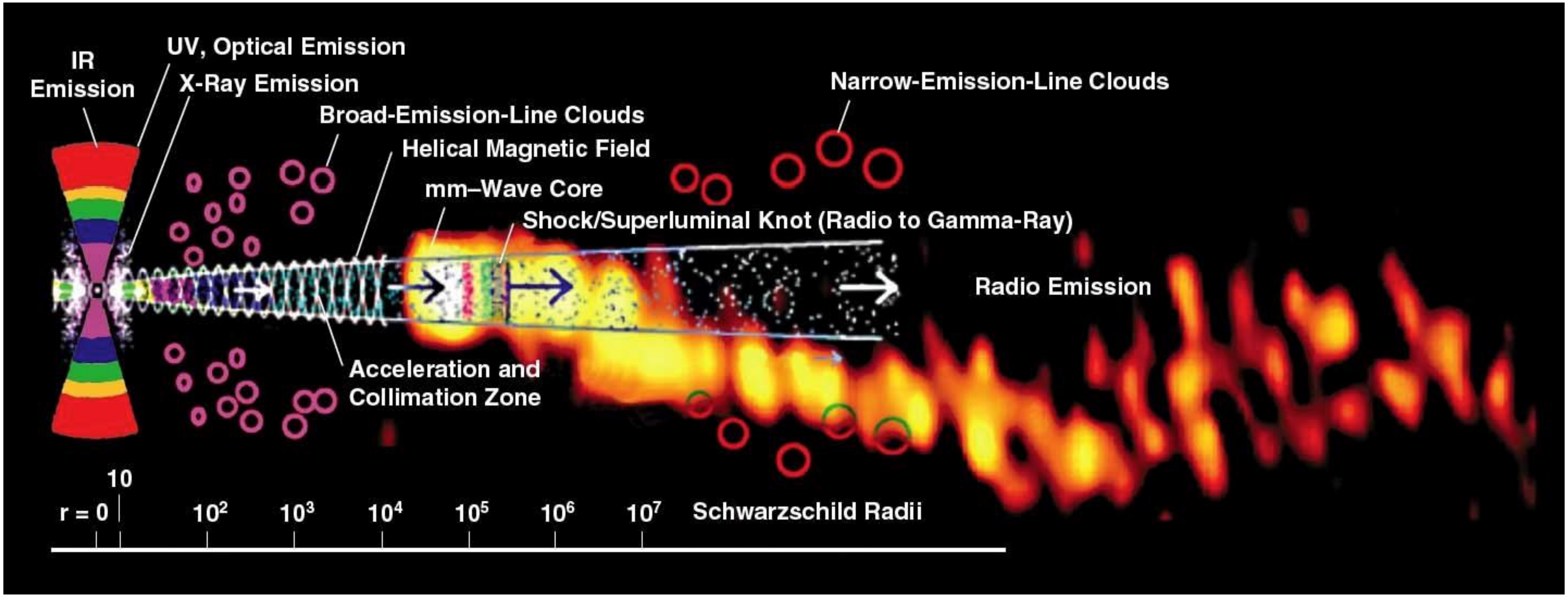
  Strengths: extreme distances (> 1 billion light years) means no parallax or proper motion

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)

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)

Optical vs. Radio positions

Positions differences from:

• Astrophysics of emission centroids

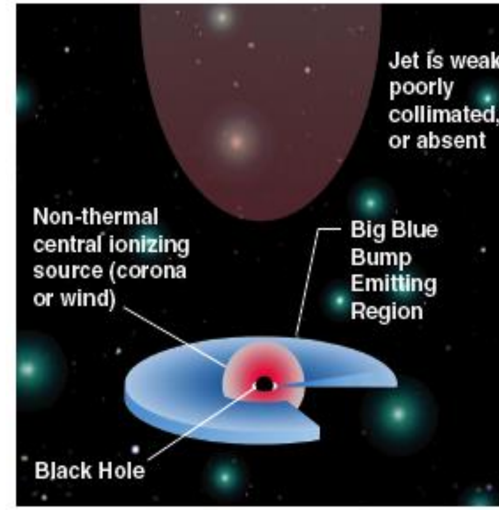
- radio: synchrotron from jet

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

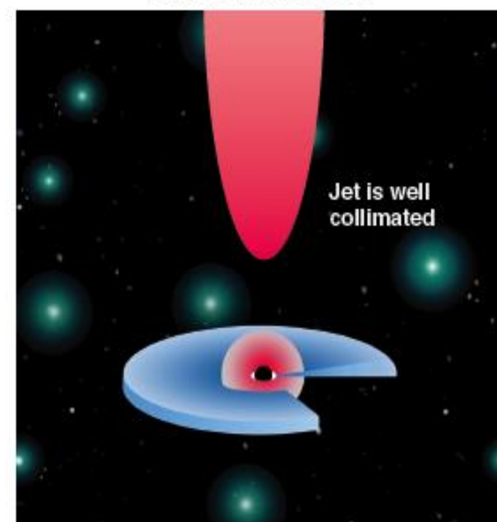
• Instrumental errors both radio & optical

• Analysis errors

Radio-quiet Quasar



Radio-loud Quasar

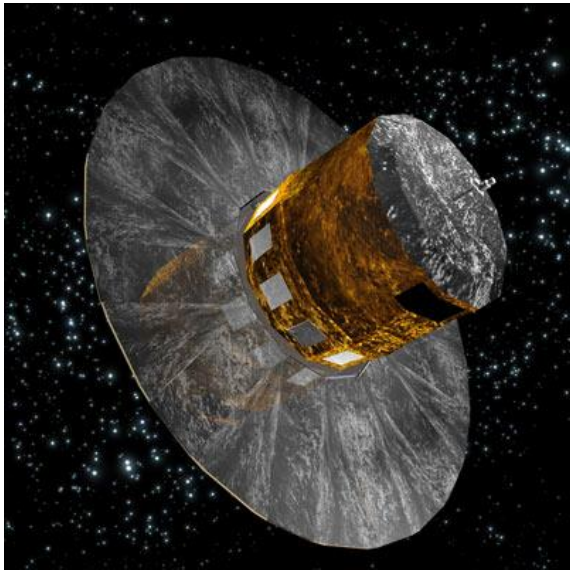


Credit: Wehrle et al, μas Science, Socorro, 2009
http://adsabs.harvard.edu/abs/2009astro2010S.310W

The Gaia Optical Frame

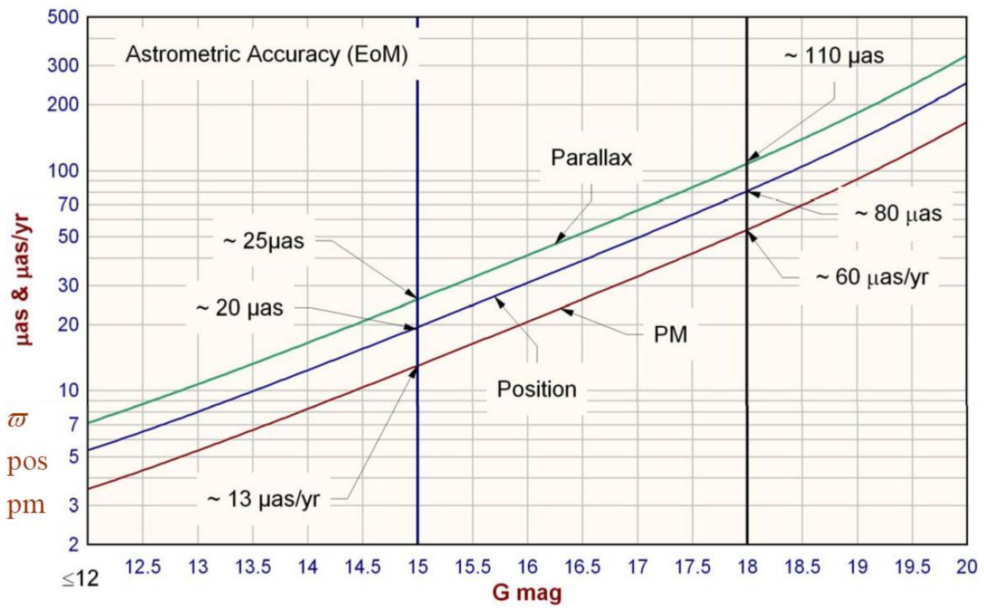
ESA's Gaia optical Astrometry

- 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 Data Release-1:

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

~10 mas for rest of the stars

~ 0.5 mas for ICRF2 quasars (auxiliary solution)

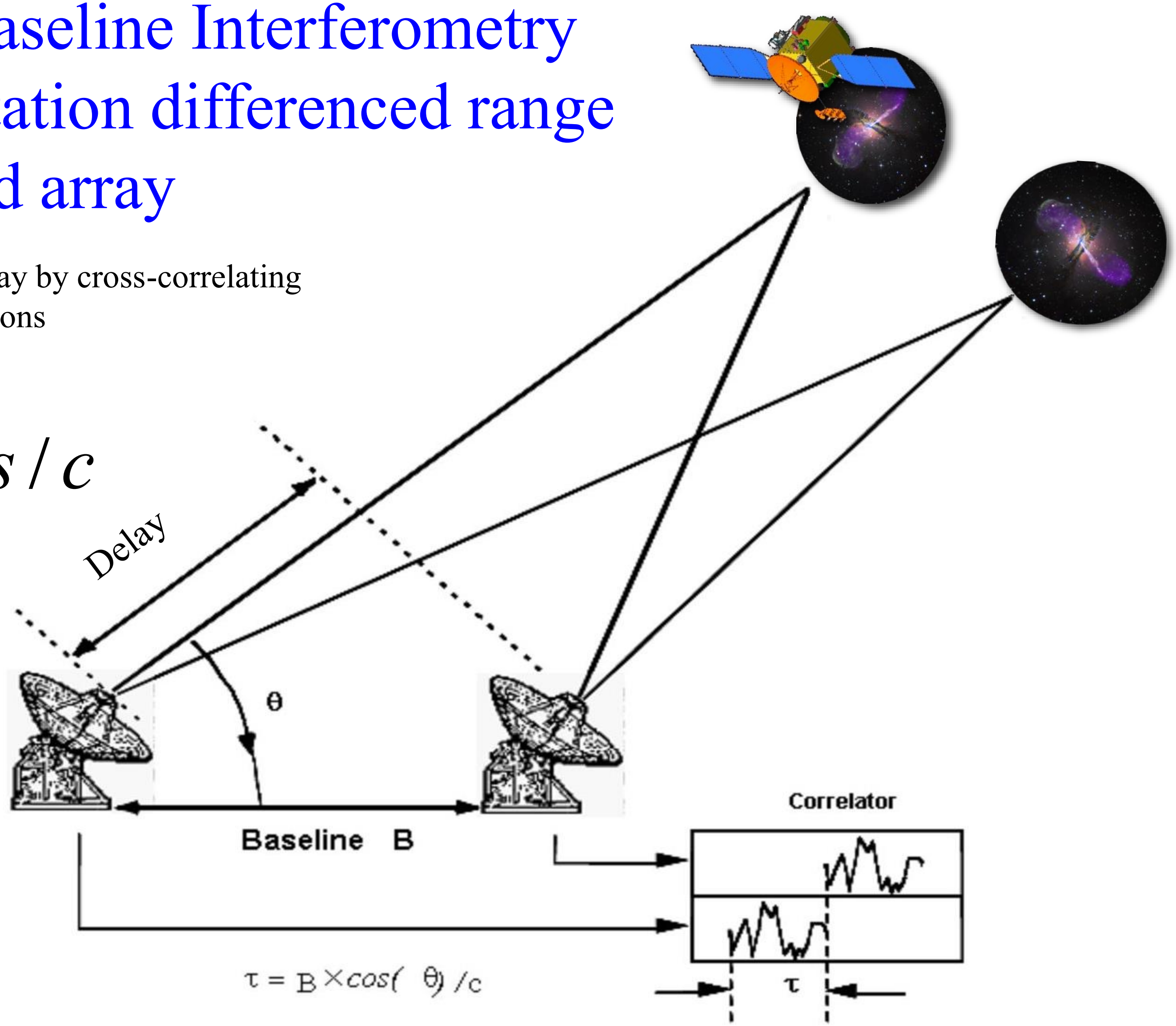
Celestial Frames using Radio Interferometry (VLBI)

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

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



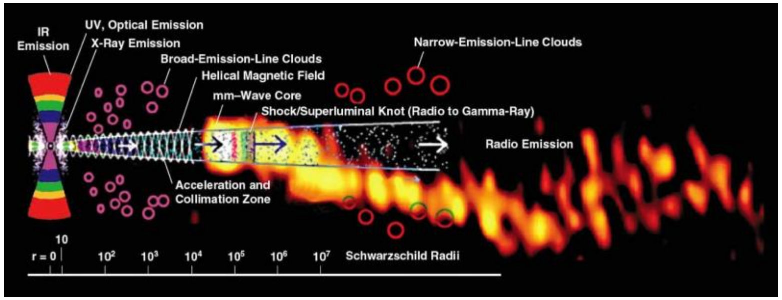
10,000 km baselines give resolution of λ/B ~ few nanoradian sub-mas beam !!

Resolves away all but galactic nucleus

The goal:

Alignment of Optical and Radio into Common Frame

Optical-Radio Frame Tie Geometry

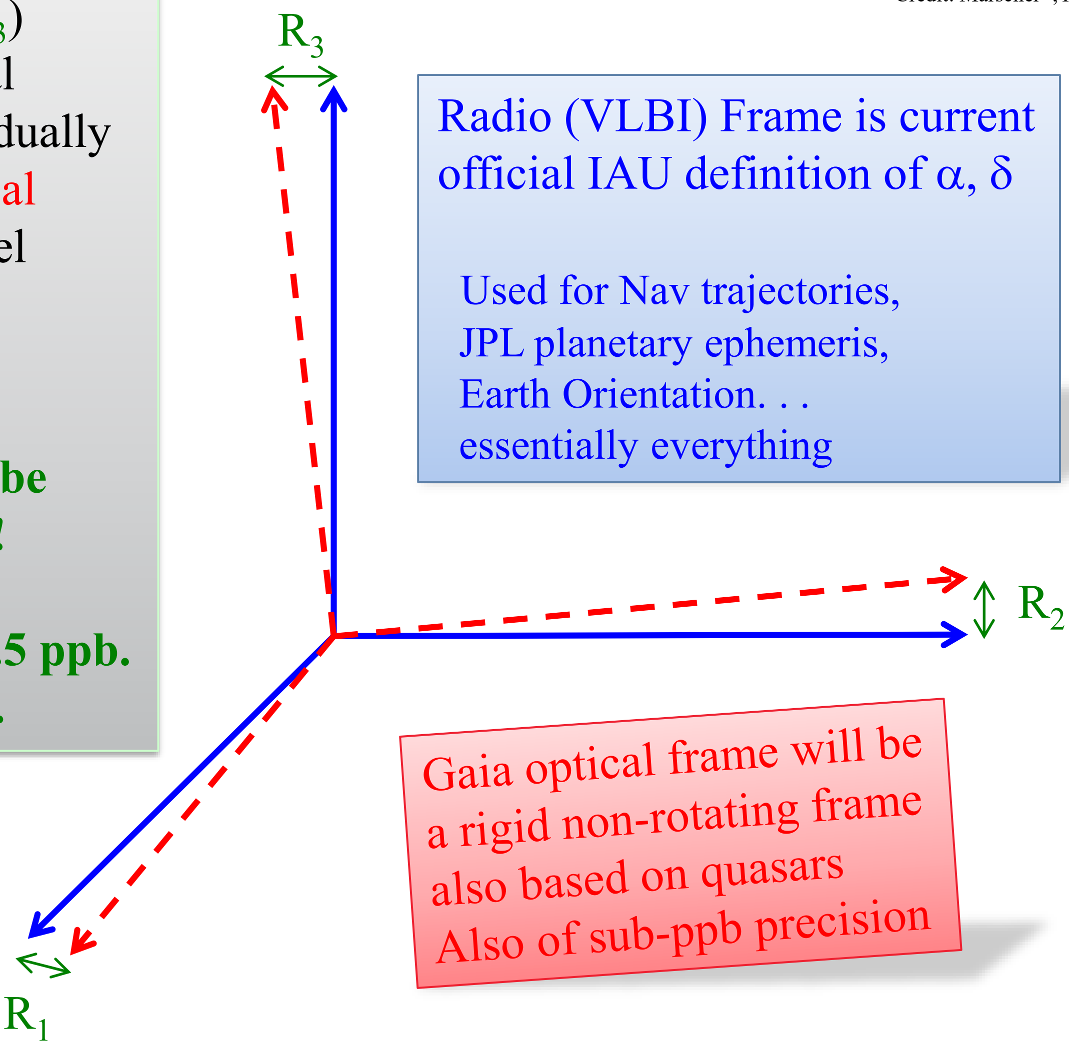


Credit: Marscher+, Krichbuam+

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

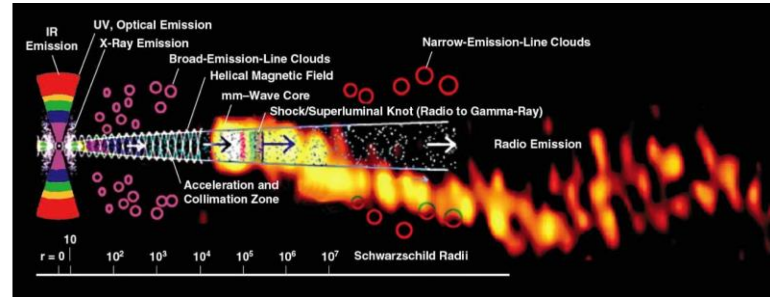
Used for Nav trajectories, JPL planetary ephemeris, Earth Orientation. . . essentially everything

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

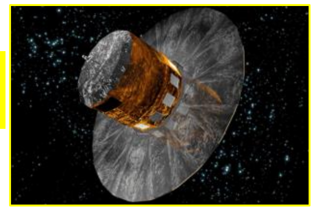
Frame Tie Comparisons

Tying Optical and Radio Celestial Frames

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

<u>Systematics:</u>

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

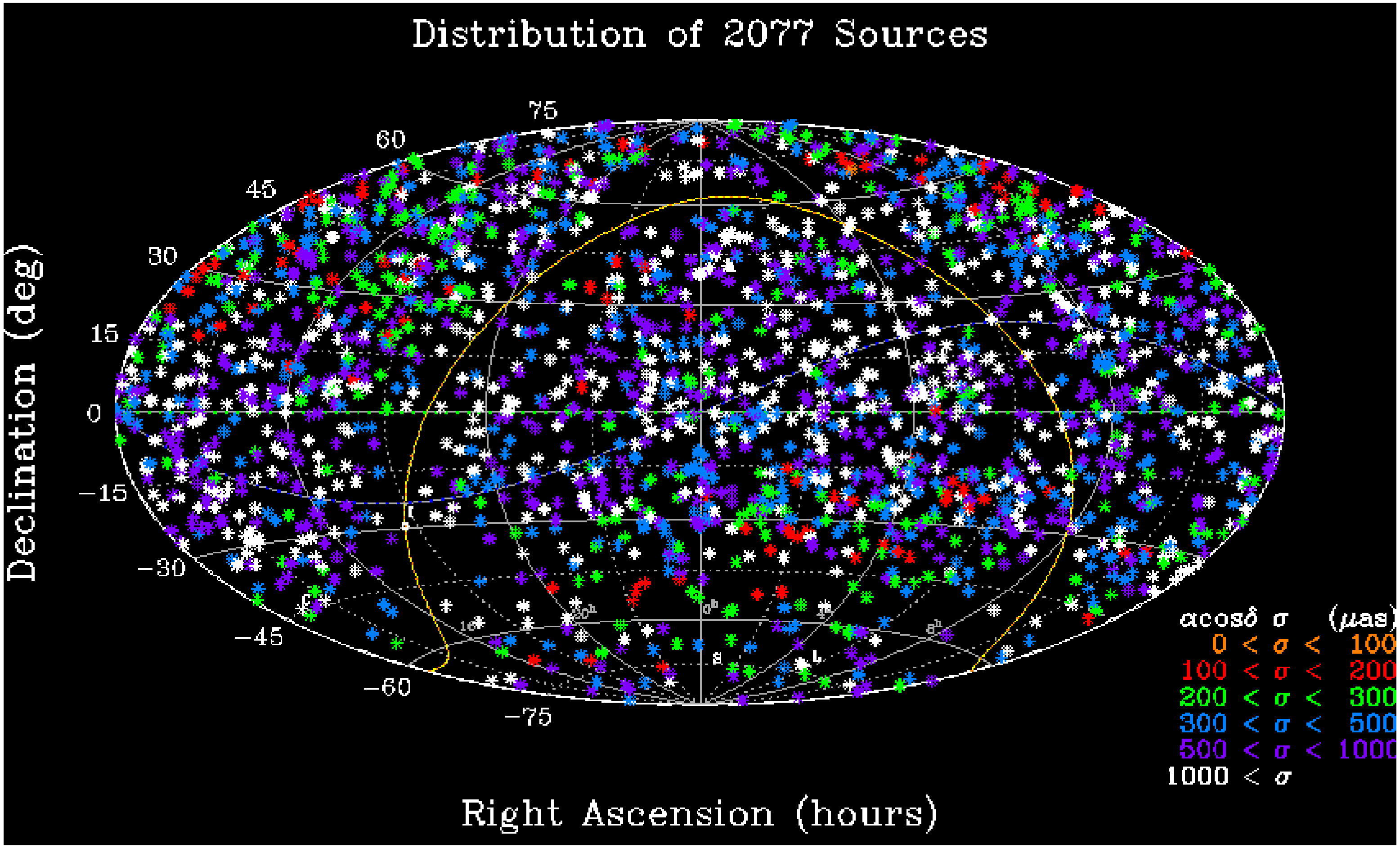
ALMA: pilot obs bright end ~5^{mag}
Waiting on 10km+ configurations

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. SX VLBI



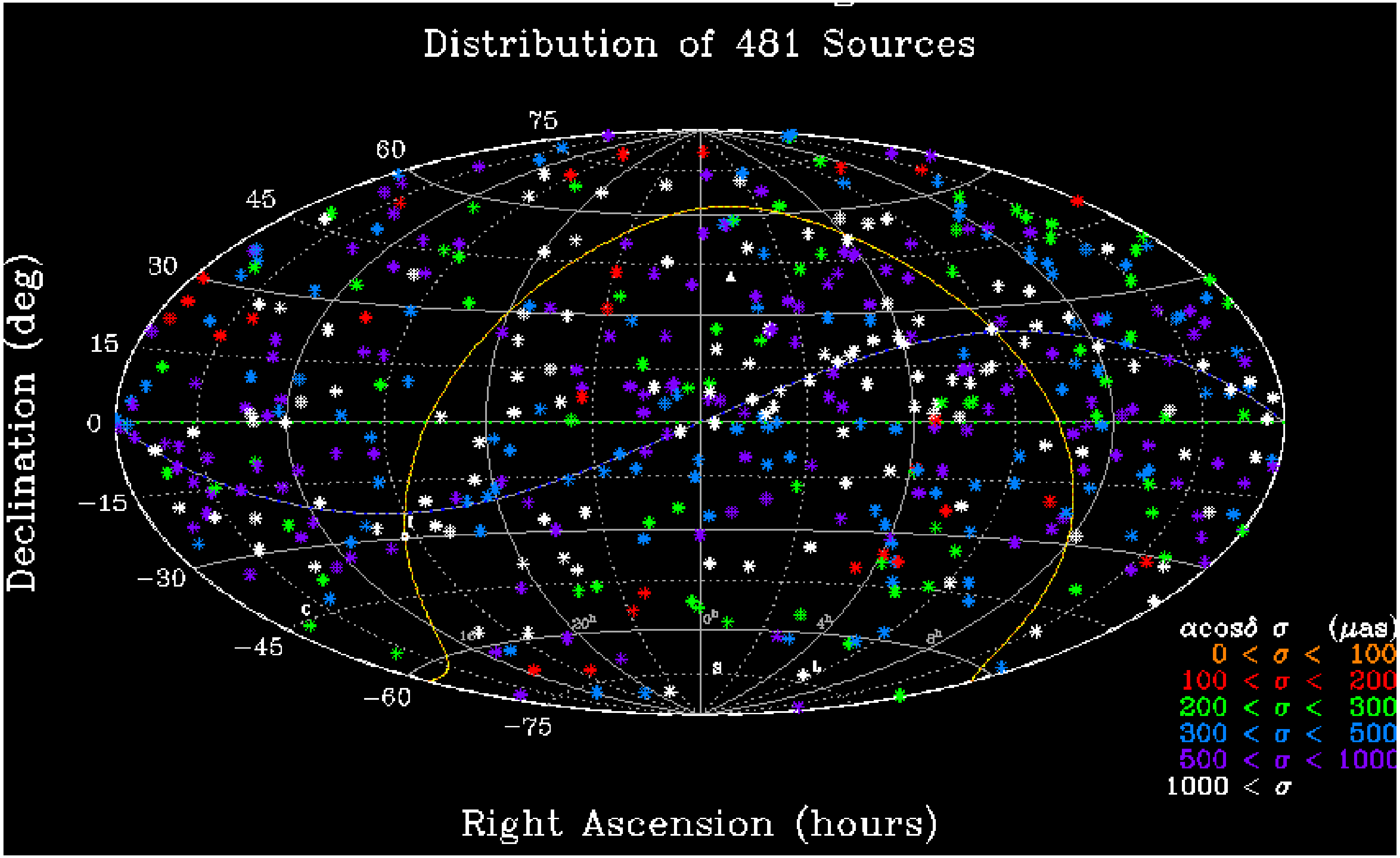
~5 times more sources than K or Ka

Fairly uniform distribution. A bit weaker in the south

Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

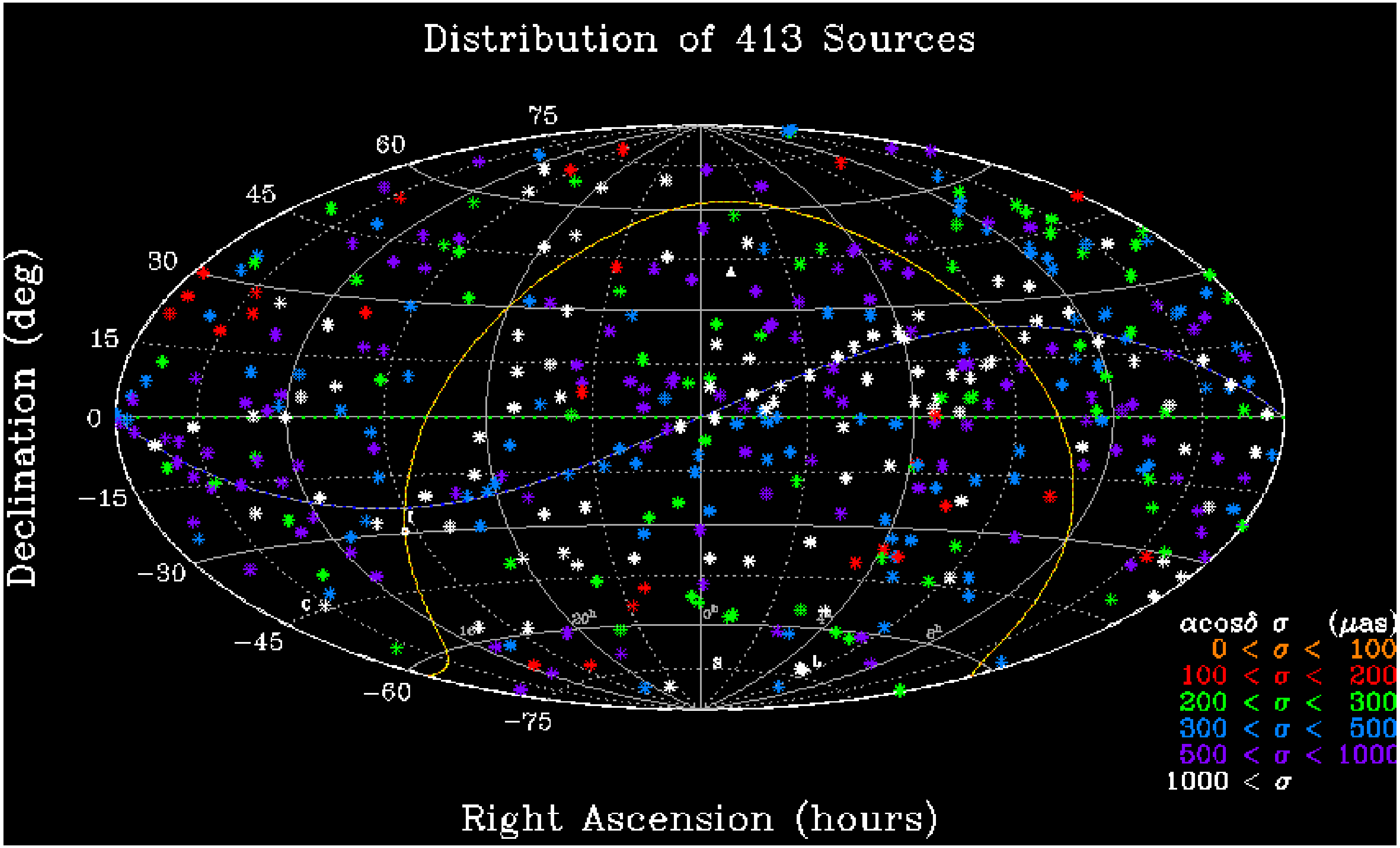
Gaia DR1-aux vs. K VLBI



Fairly uniform distribution.
Color code shows Gaia formal sigmas.

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. Ka VLBI



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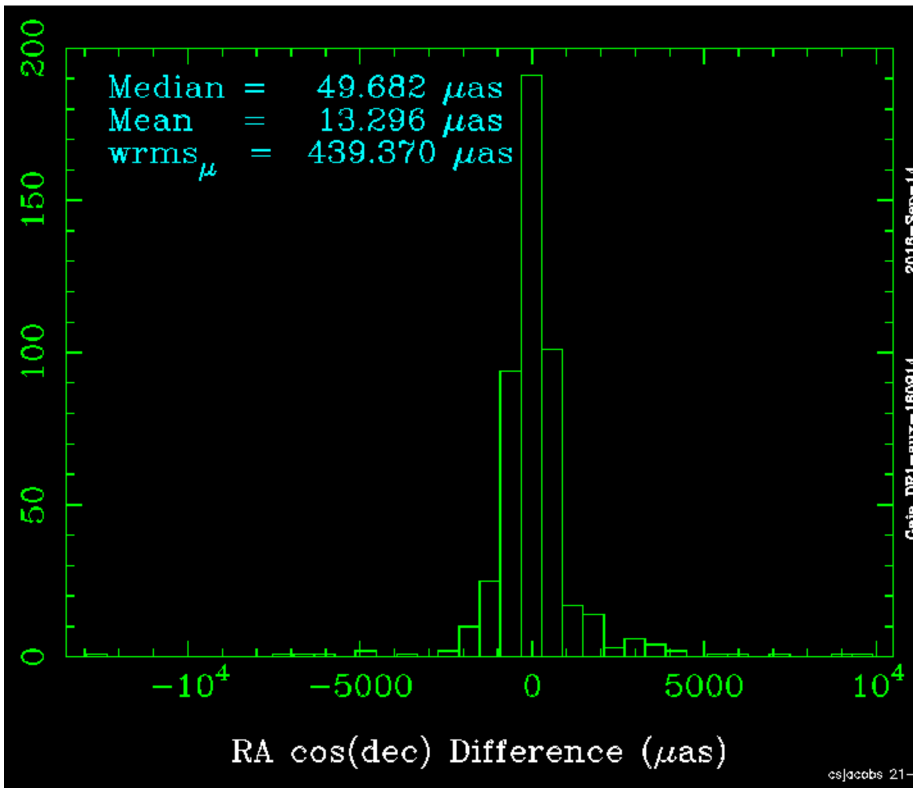
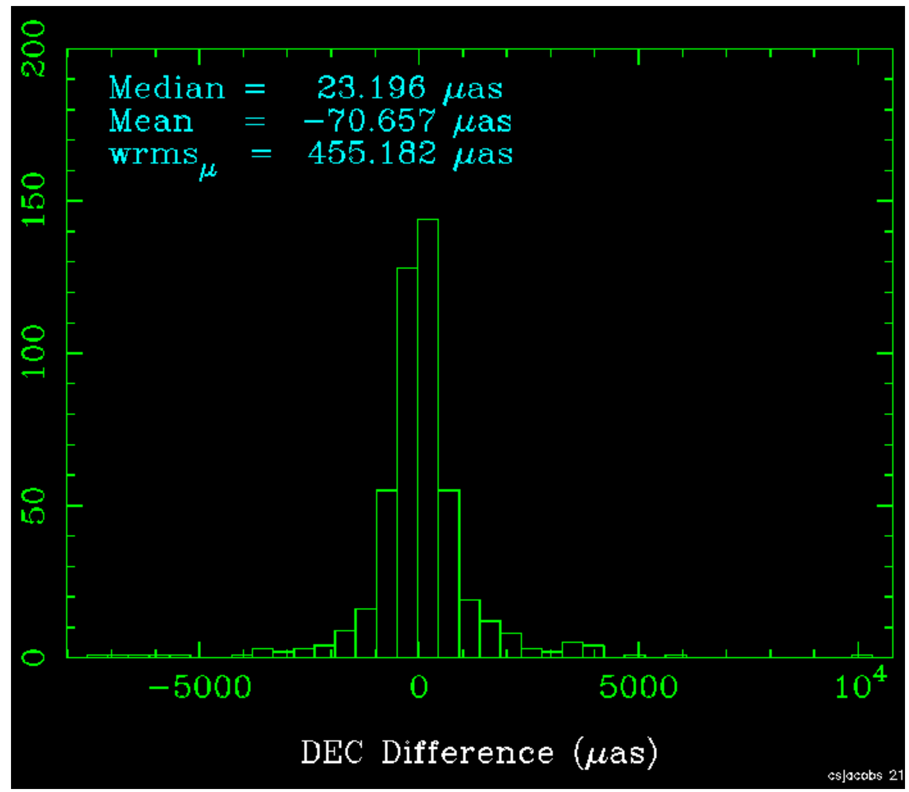
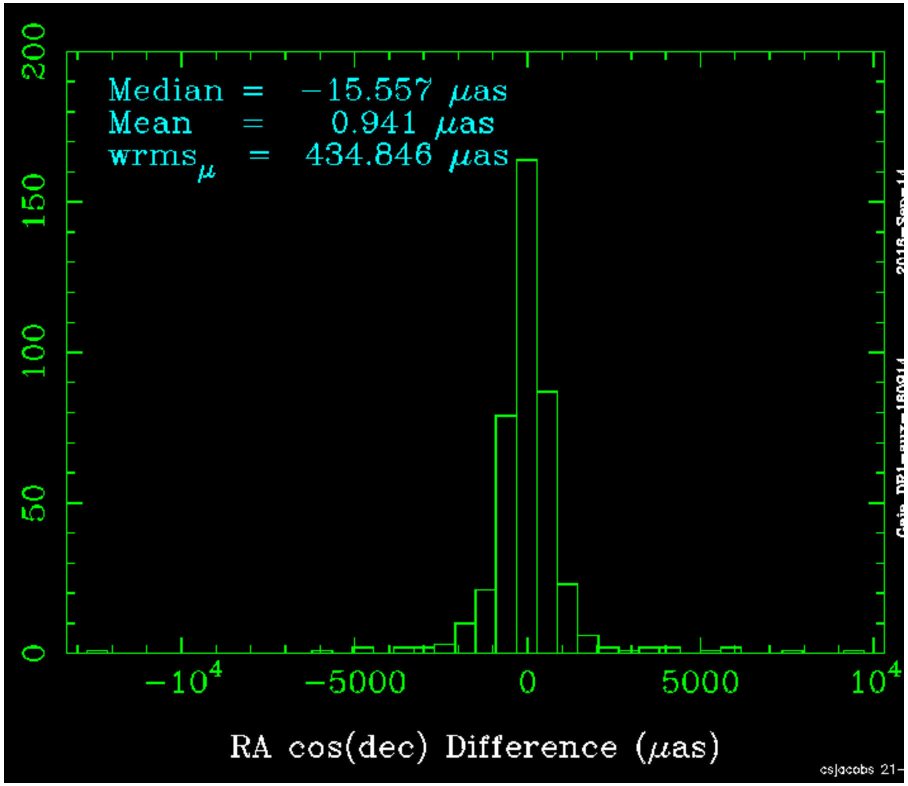


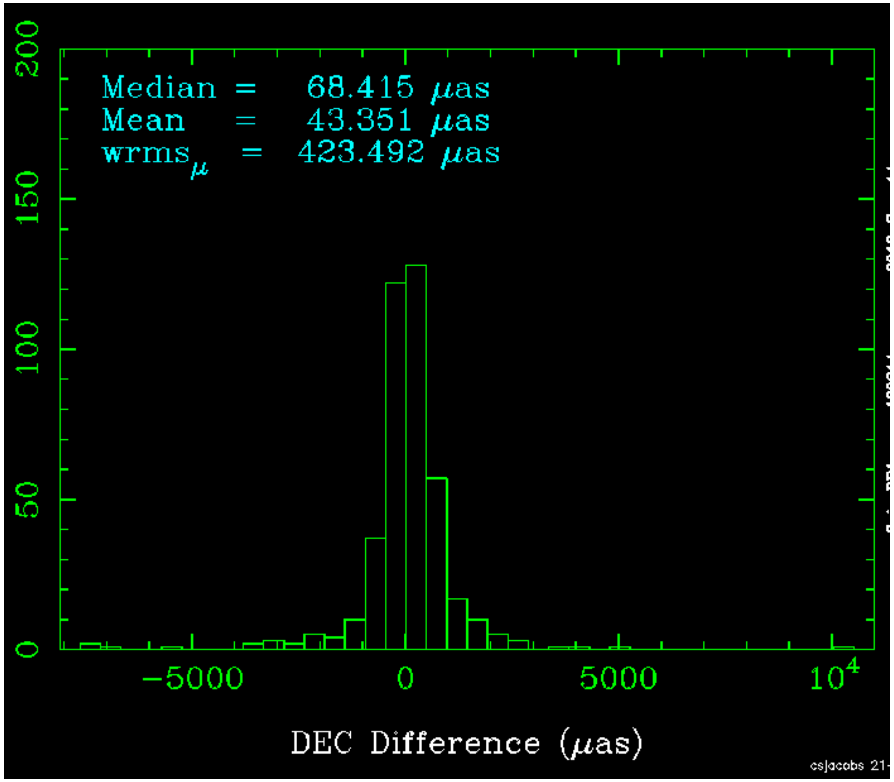


wRMS Ra and Dec differences about 440 μas (2 nrad)
Normalized differences are about 1.1 indicating realistic errors

Tying optical and Radio Celestial Frames

Gaia DR1-aux vs. Ka VLBI





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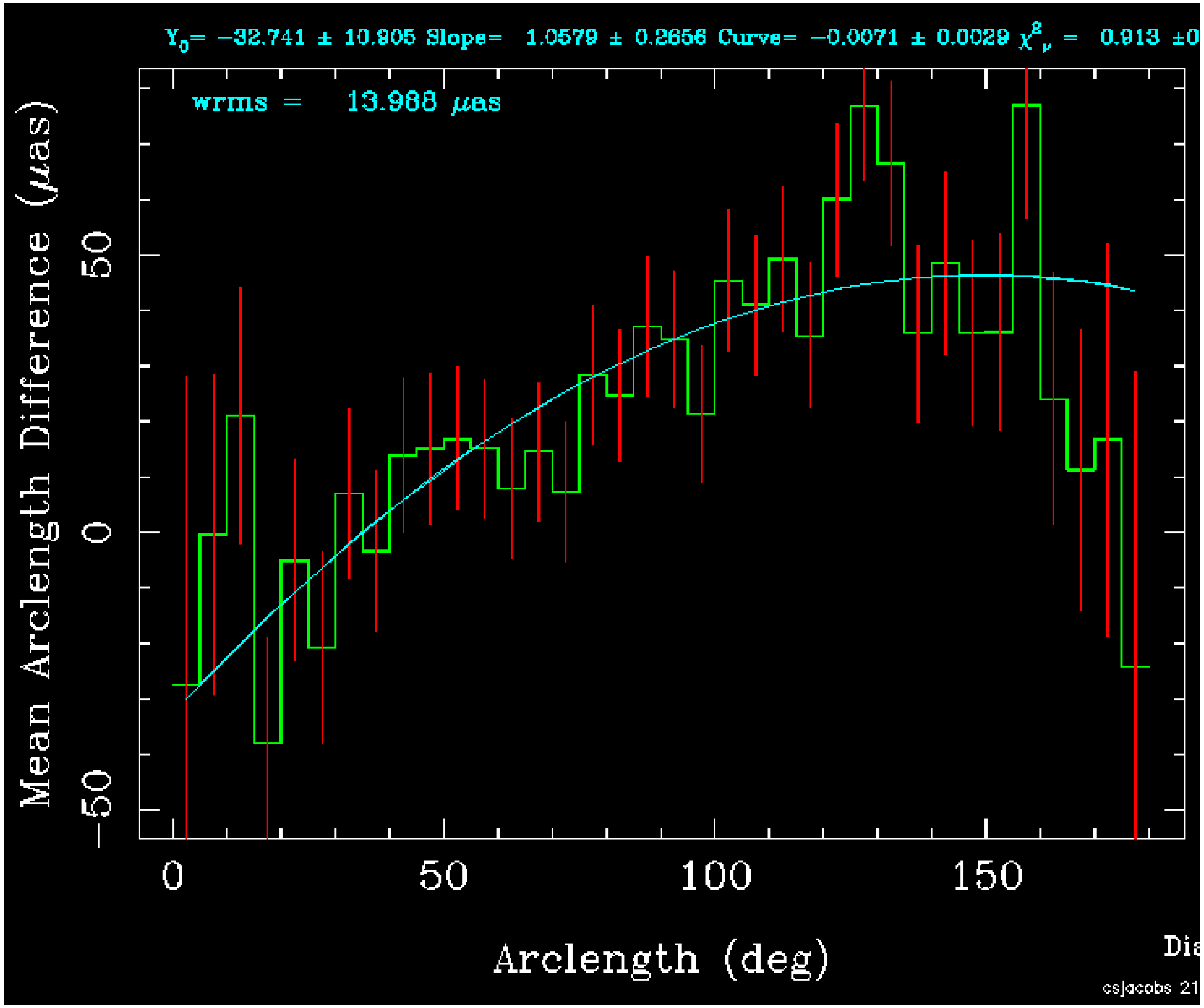
Tying optical and Radio Celestial Frames

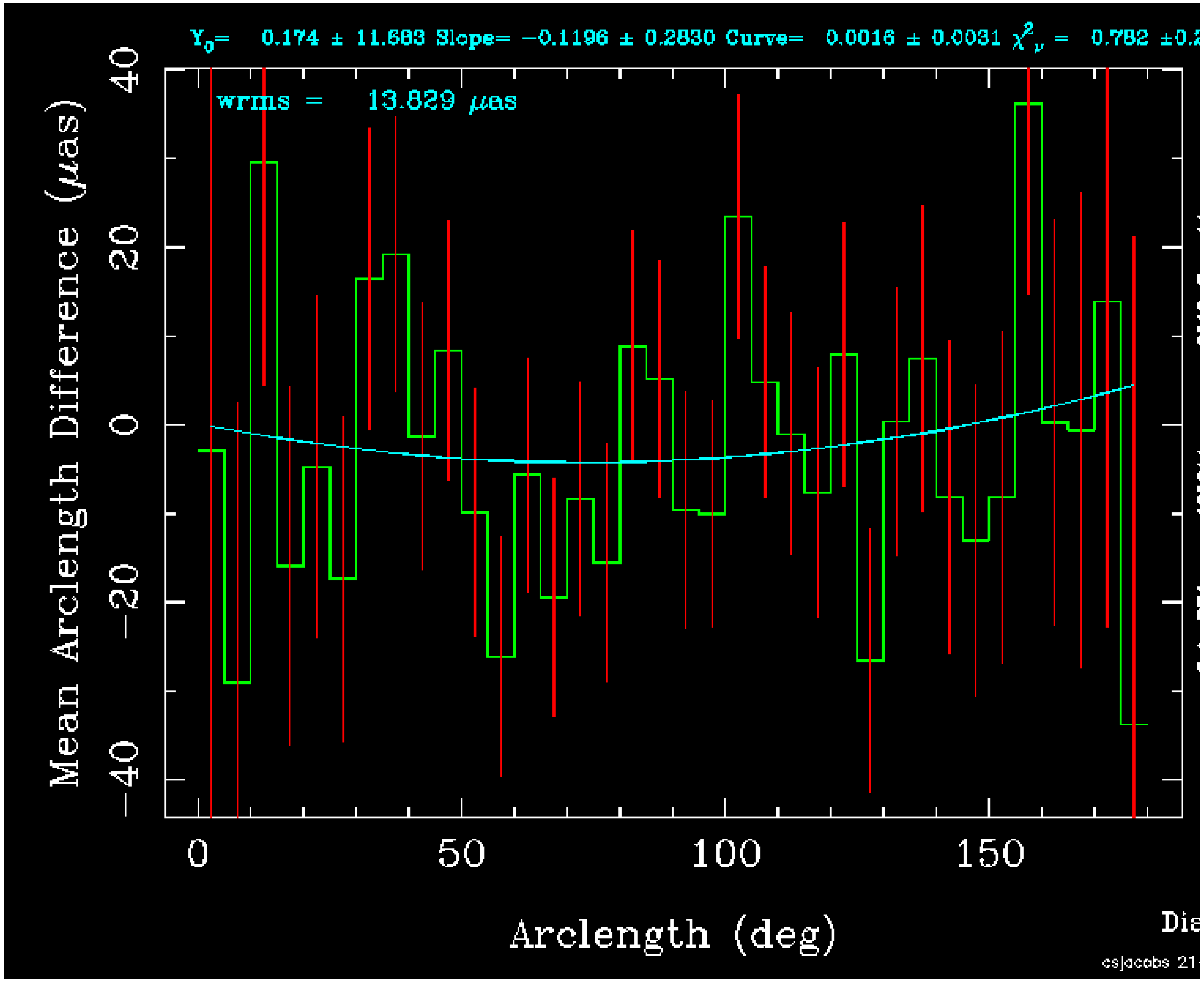
Gaia DR1-aux vs. K VLBI



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

Tying optical and Radio Celestial Frames

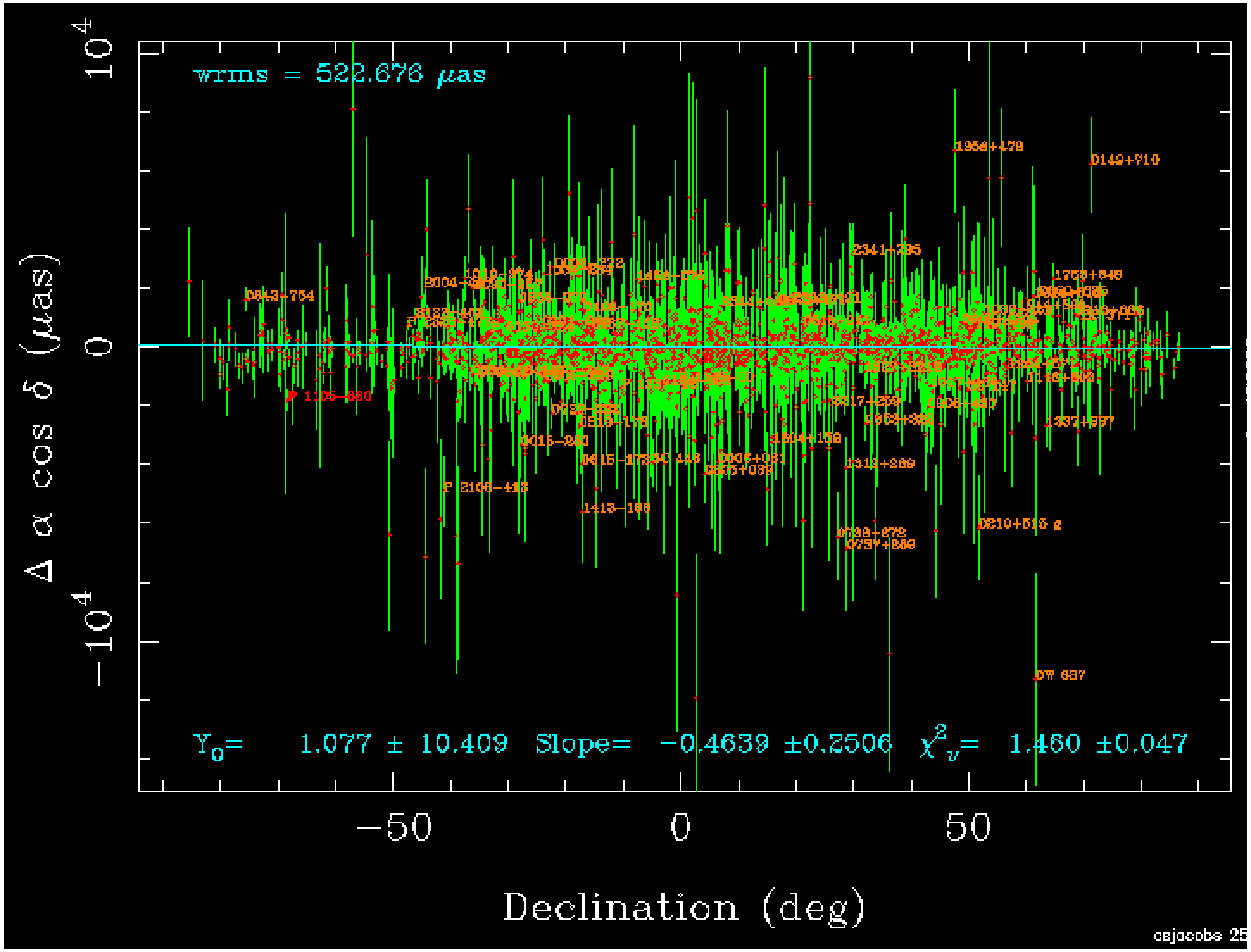
Gaia DR1-aux vs. Ka VLBI



Arc differences steady vs. arclength bins at 15 μas level

Tying optical and Radio Celestial Frames

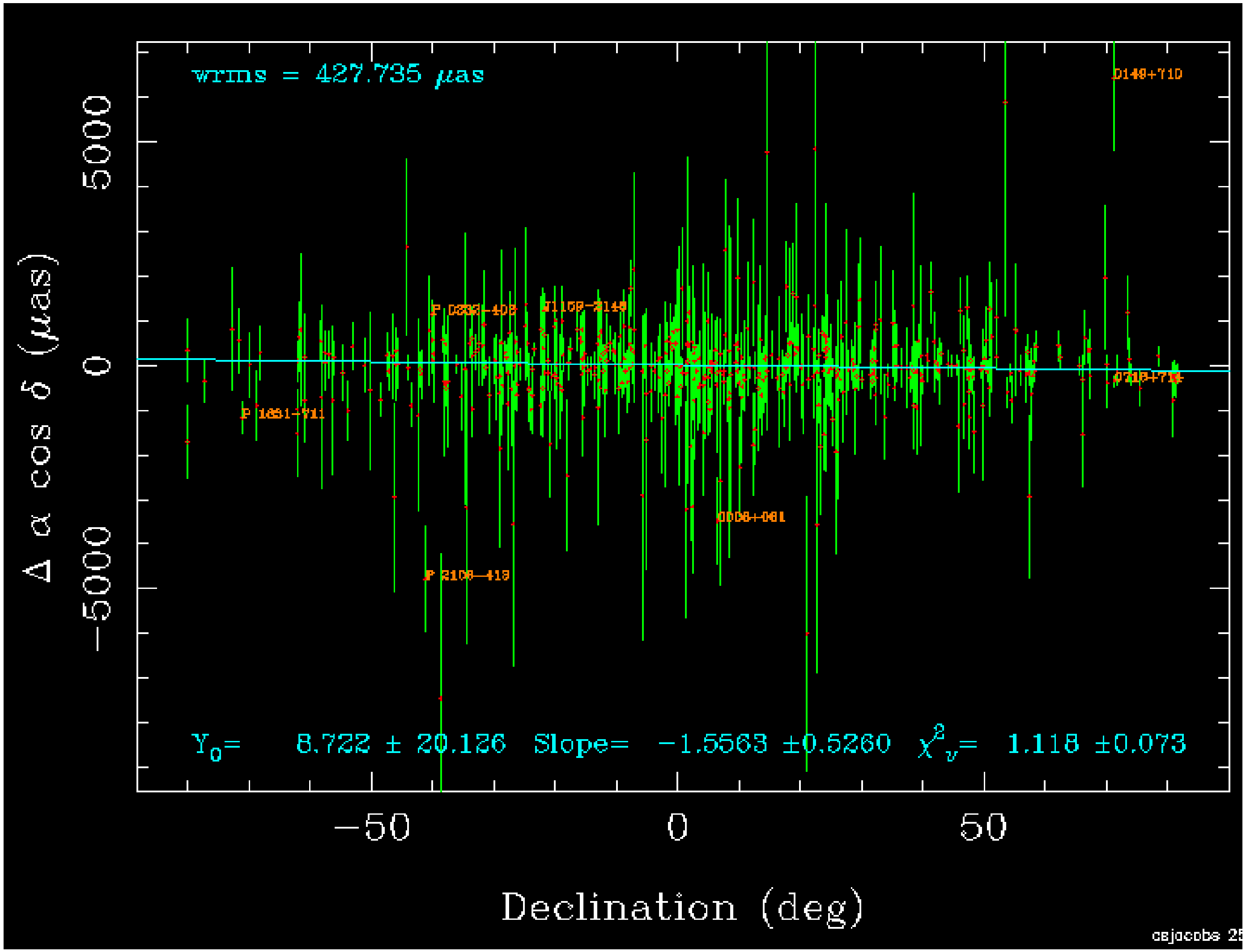
Gaia DR1-aux vs. SX VLBI



Systematic tilt: Δα vs. δ has 2 sigma slope of -0.46 +- 0.25 μas/deg

Tying optical and Radio Celestial Frames

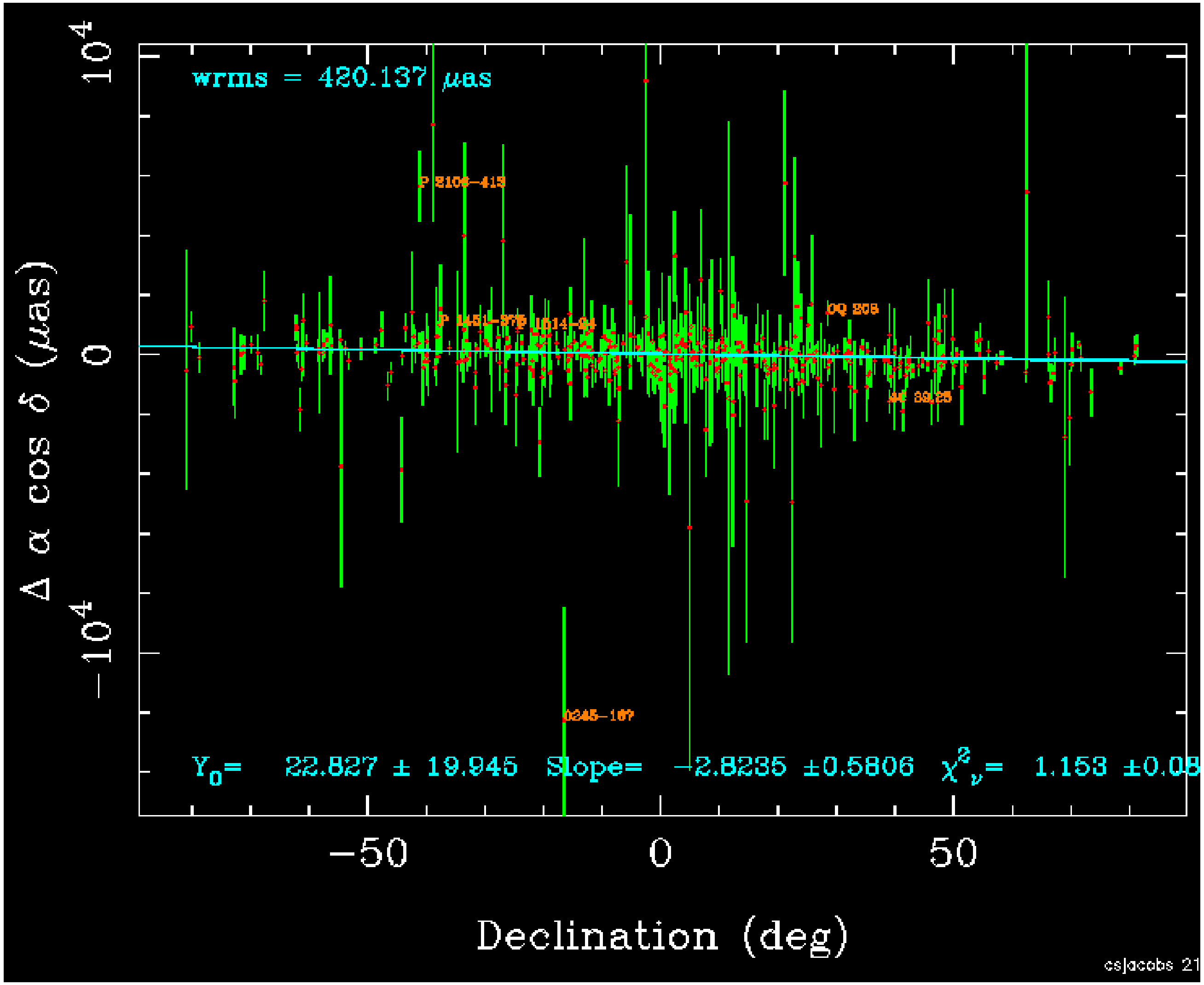
Gaia DR1-aux vs. K VLBI



Systematic tilt: Δα vs. δ has 3 sigma slope of -1.56 +- 0.53 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

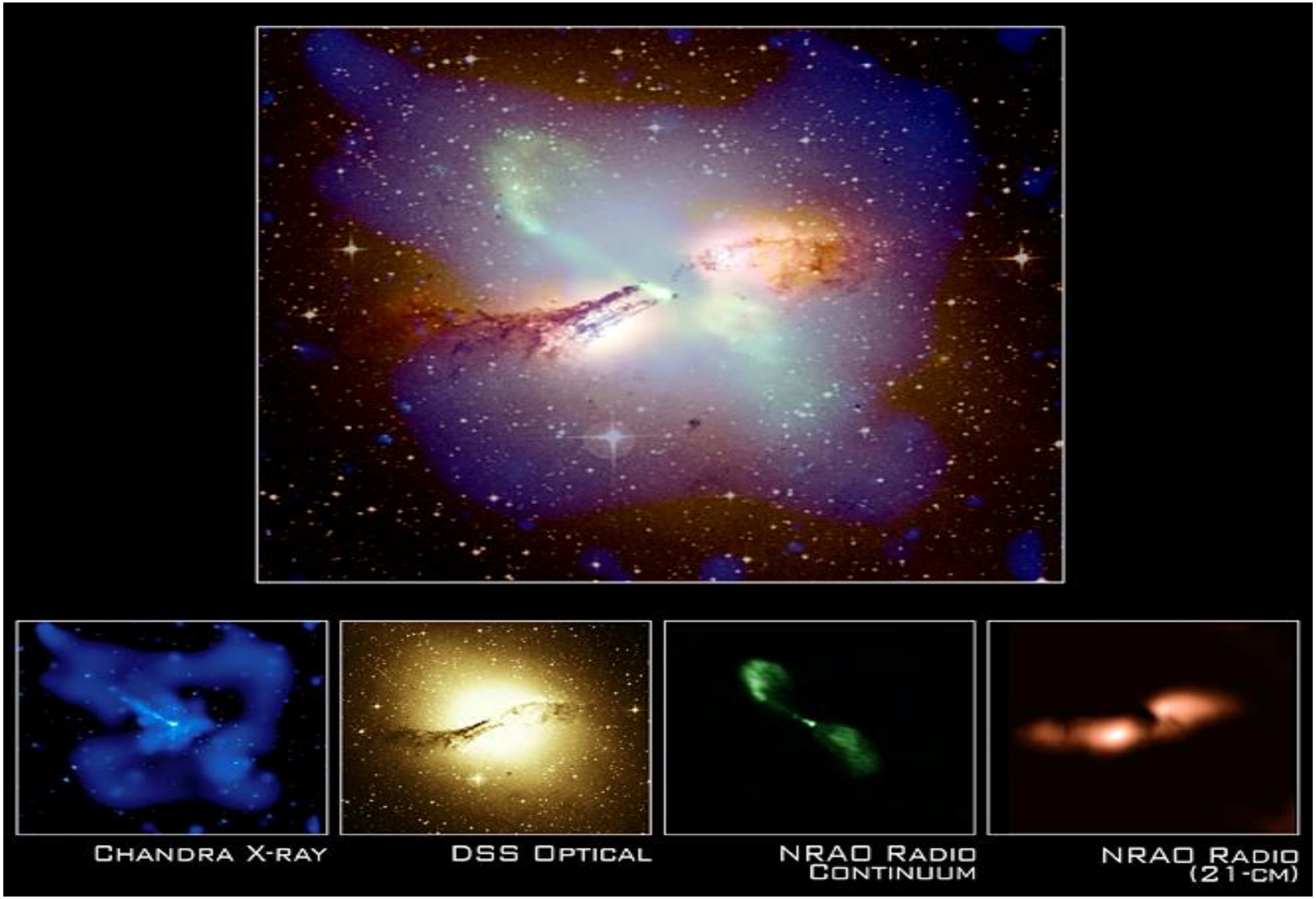
	SX-band 8 GHz 3.6cm	K-band 24 GHz 1.2 cm	XKa-band 32 GHz 0.9 cm
# Observations	12 million	0.25 million	0.06 million
# sources	1926	473	405
# outliers > 5σ	100	13	6
% outliers	5.2 %	2.7 %	1.5 %
α wRMS	523 μas	431 μas	433 μas
δ wRMS	531 μas	453 μas	418 μas
R_x	-37 +- 13	-89 +- 24	57 +- 24
R_y	0 +- 11	14 +- 21	32 +- 21
R_z	-29 +- 13	-13 +- 23	21 +- 24
Δα vs. δ tilt (μas/deg)	-0.46 +- 0.25	-1.55 +- 0.53	-2.83 +- 0.58

Rx vulnerable
To trop errors

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

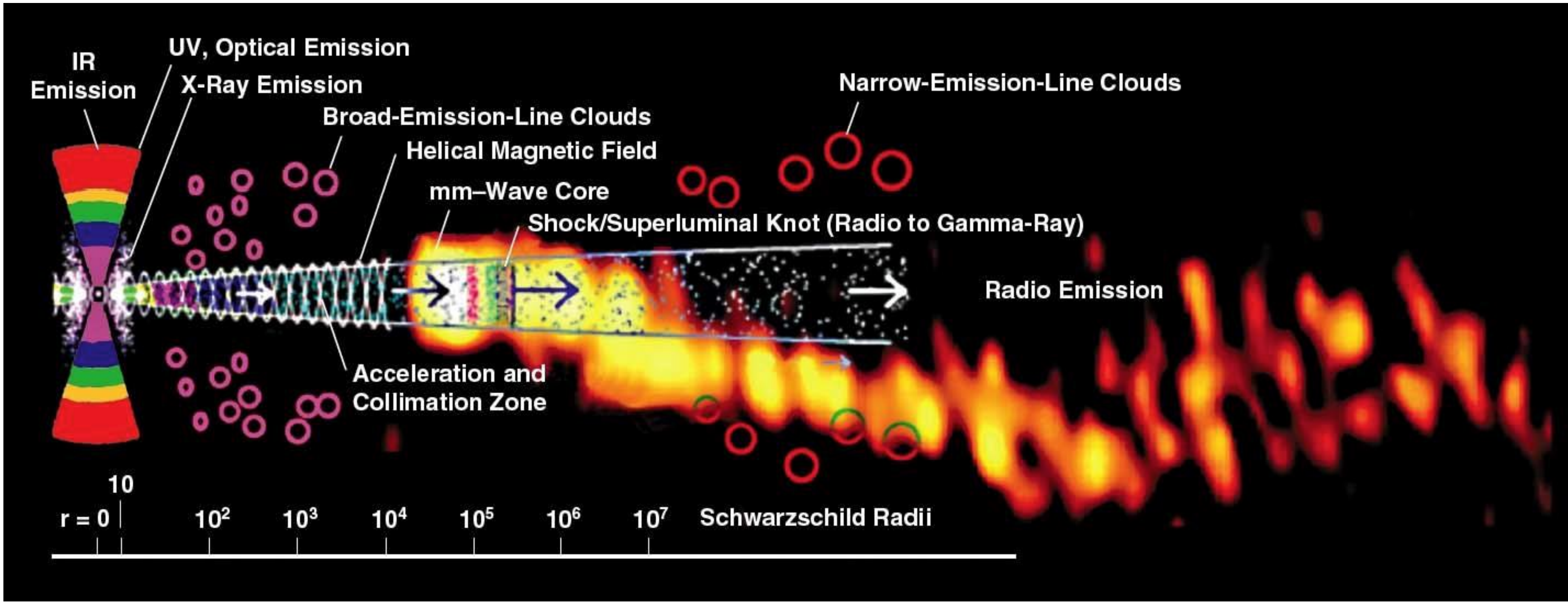
A last look at Optical vs. Radio Astrometric offsets

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)

Active Galactic Nuclei (*Marscher*)



R~0.1-1 μas 1mas

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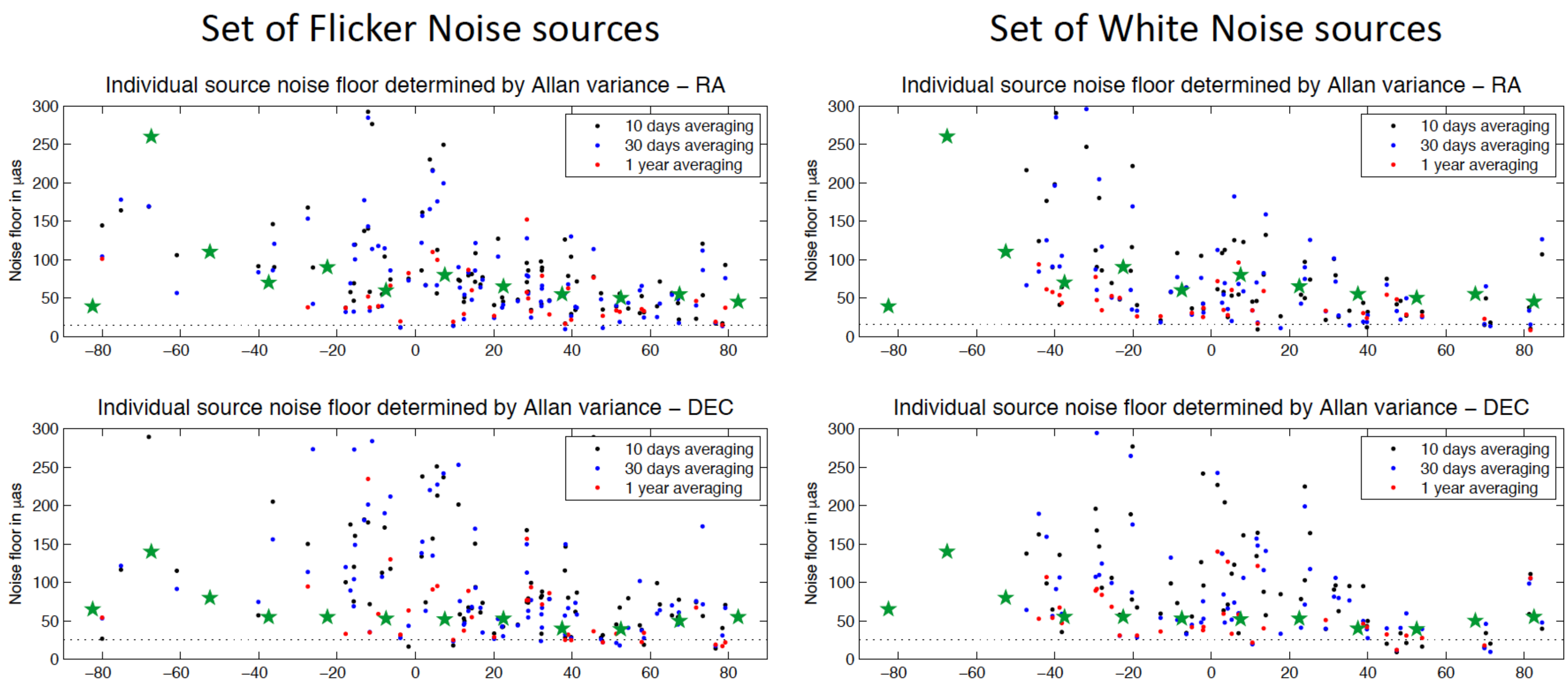
SX VLBI systematic Floor ~ 20 to 30 μas?



Green ★ : ICRF2 noise floor - average on sources in 15° declination bands.

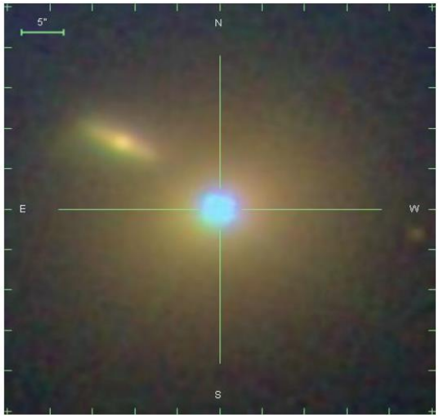
Attention! This method uses ALL "good" sessions, contrary to the decimation test.

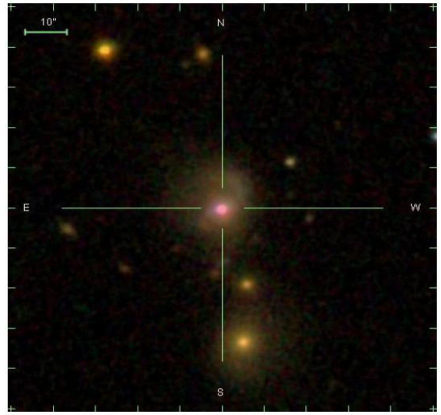
Le Bail+ (EVGA, 2017) use Allan variance test on position time histories to determine when averaging no longer helps—systematic floor is encountered.

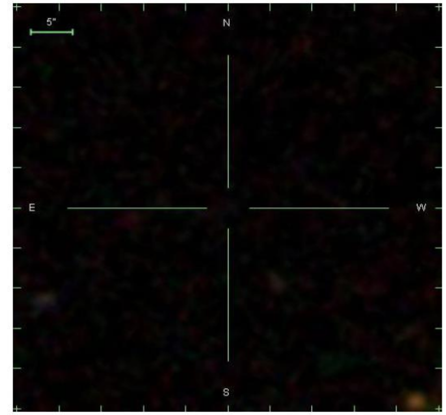
Structure part of this floor should be several times smaller at K (24 GHz) and Ka (32 GHz)

Optical vs. Radio systematics offsets

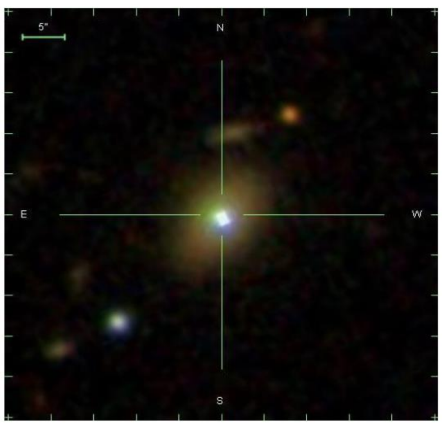
SDSS Optical images of quasars (scale 5-10 asec)

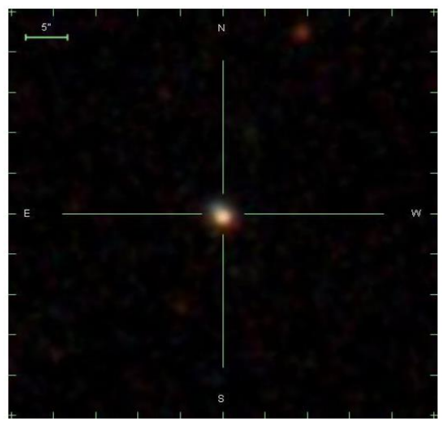


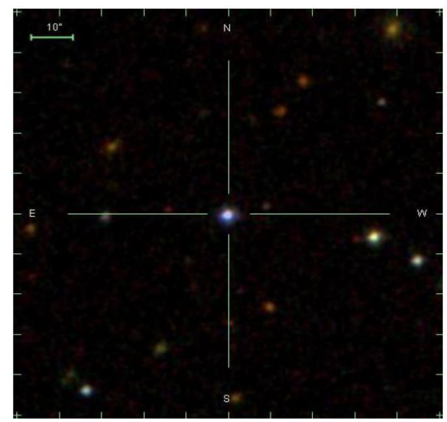




1101+384 0007+106 0920+390





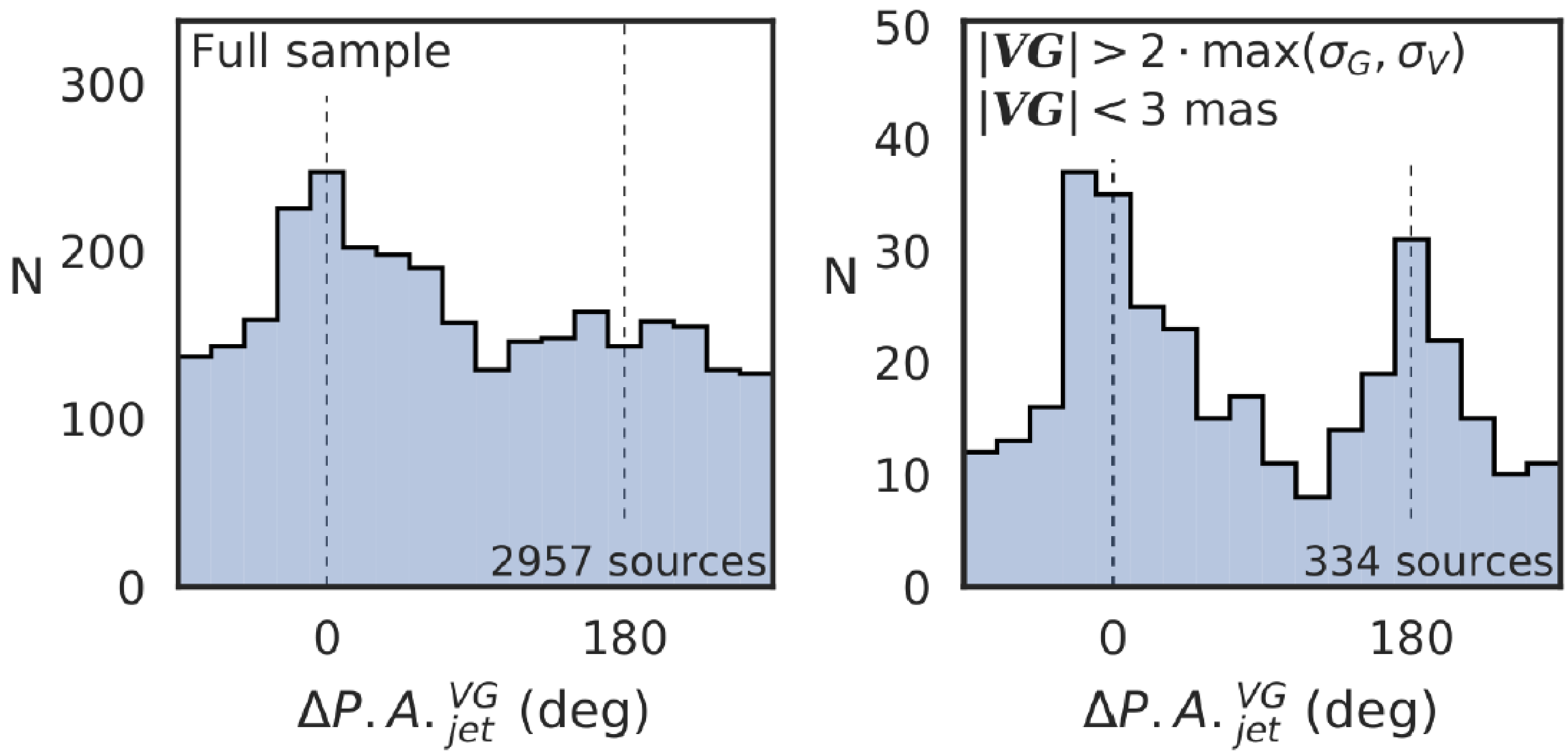


1418+546 1514+192 1546+027

Credit: SDSS

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

Optical vs. Radio systematics offsets



Petrov & Kovalev (MNRAS, 2017) show that optical-radio astrometric offsets Correlate with jet direction (or anti-direction).

They argue that the offsets are dominated by optical synchrotron jets.

Optical vs. Radio systematics offsets

Petrov & Kovalev (MNRAS, 2017)

- Example of optical jet in “nearby” 3C 264 would scale to ~milli-arsecond offsets at typical AGN distances.

- Optical synchrotron jets may be limiting factor in radio-optical astrometric agreement.

- VLBI interferometry “locks” onto the brightest component. Also extremely high resolution resolves out extended structures. So VLBI positions is close ot the core.

- Gaia optical image’s centroid averages all of the light distribution, jet included. “Beam” is 60 milliarcseconds.

- Optical may be more easily biased than radio.

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?

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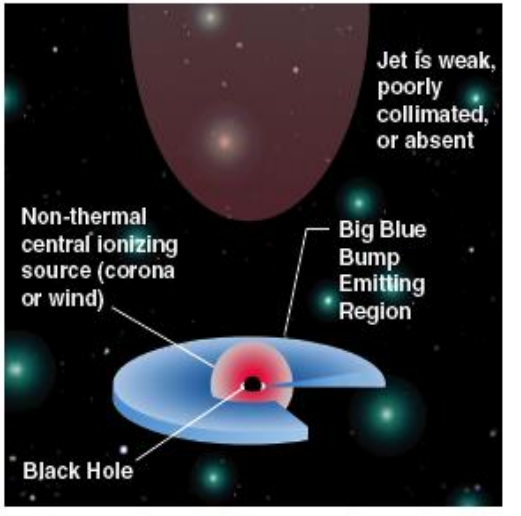
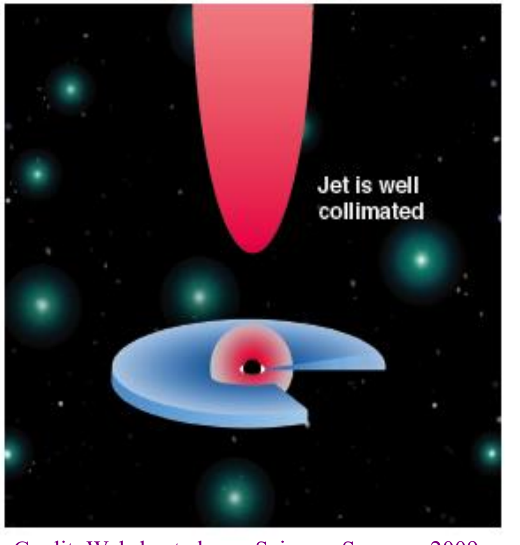
Radio-quiet Quasar



Radio-loud Quasar



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