# Towards an accurate alignment of the VLBI frame and the future Gaia optical frame

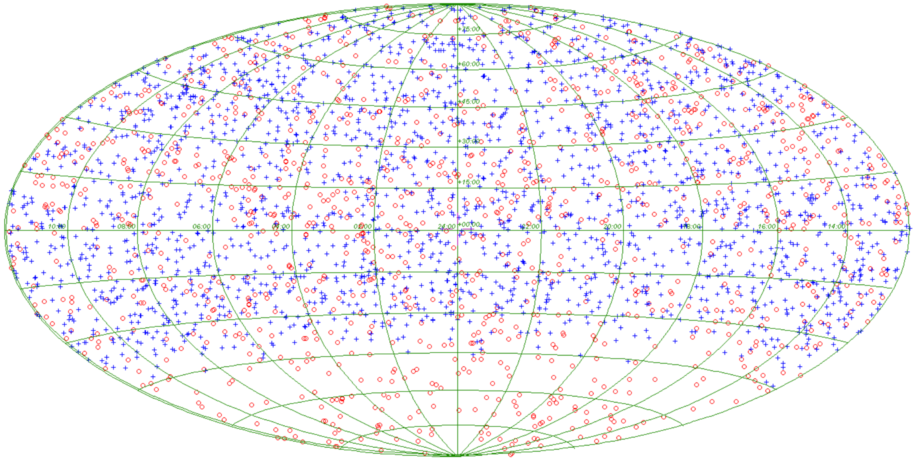
## Global VLBI imaging observations of a sample of candidate sources


| | |
|---|---|
| **G. Bourda** | Laboratoire d'Astrophysique de Bordeaux (LAB), France |
| **A. Collioud** | LAB, France |
| **P. Charlot** | LAB, France |
| **R. Porcas** | MPIfR, Bonn, Germany |
| **S. Garrington** | Jodrell Bank Observatory, UK |

# Context

By 2015-2020: Two extragalactic celestial reference frames available

**VLBI** (Radio)



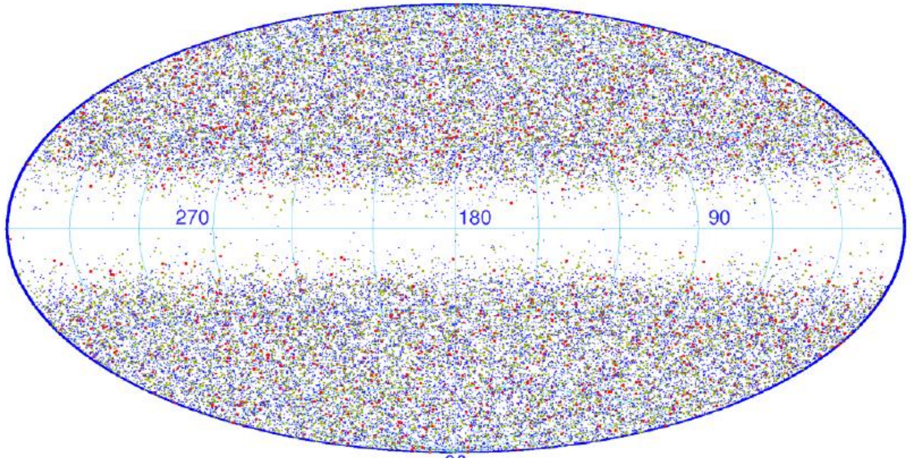
Position accuracy:

1997: ICRF1 − 717 sources − $\sigma \geq 250$ µas

2009: ICRF2 − 3414 sources − $\sigma \geq 60$ µas

2015-2020: ICRF3 ???

**Gaia** (Optical magnitude ≤ 20)




Anticipated position accuracy: 2015−2020

20 000 QSOs @ V≤18 → 16 µas ≤ σ ≤ 70 µas

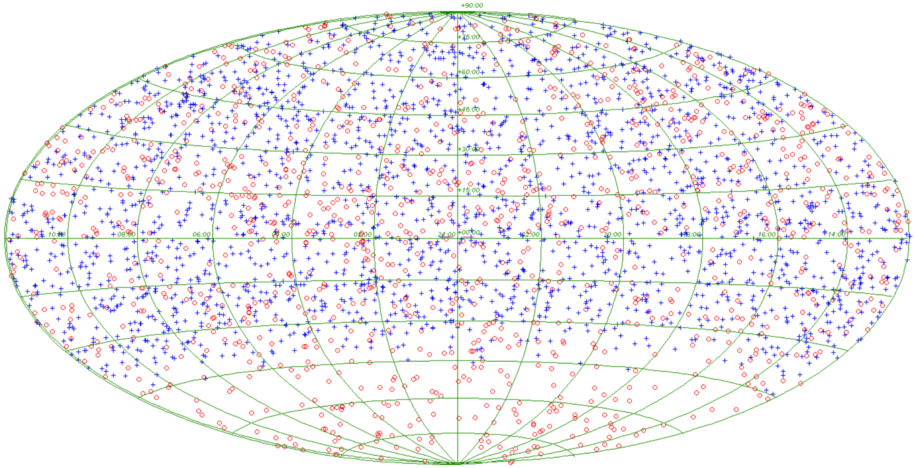
500 000 QSOs @ V≤20 → 16 µas ≤ σ ≤ 200 µas

*Lindegren et al., 2008*

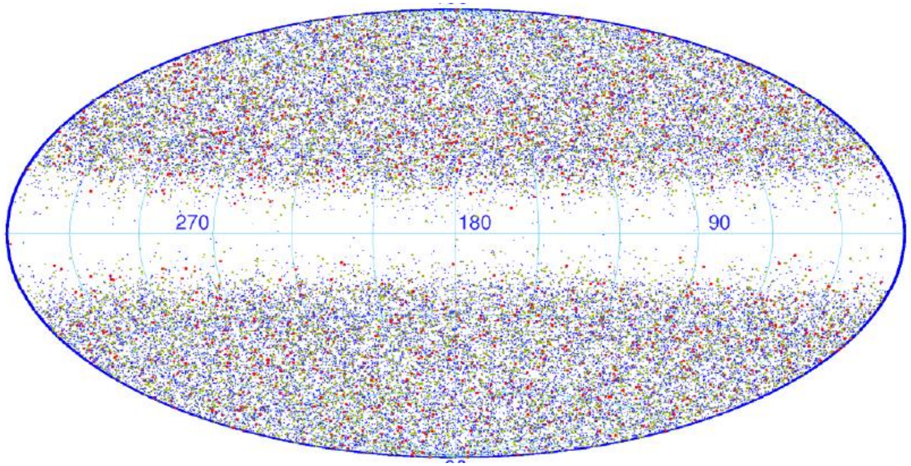
# Context

By 2015-2020: Two extragalactic celestial reference frames available

**VLBI** (Radio)



**Gaia** (Optical magnitude ≤ 20)




Position accuracy:

1997: ICRF1 − 717 sources − $\sigma \geq 250$ µas

2009: ICRF2 − 3414 sources − $\sigma \geq 60$ µas

2015-2020: ICRF3 ???

Anticipated position accuracy: 2015−2020

20 000 QSOs @ V≤18 → 16 µas ≤ σ ≤ 70 µas

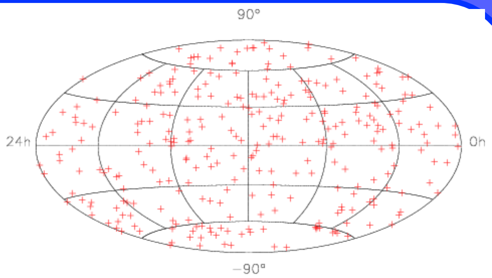
500 000 QSOs @ V≤20 → 16 µas ≤ σ ≤ 200 µas

*Lindegren et al., 2008*

Linking these 2 frames is important:

- to ensure continuity of the fundamental celestial reference frame
- to register optical & radio positions with the highest accuracy

# Gaia-Radio frames alignment




- **Some requirements:**

✓ Several hundreds of common sources

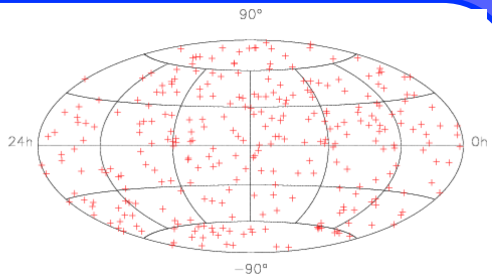
✓ With a uniform sky coverage

✓ Link sources must have:

Accurate Gaia position → Optically-bright ($V \leq 18$)

Accurate VLBI position → Good astrometric quality (no extended VLBI structure)

# Gaia-Radio frames alignment




- **Some requirements:**

✓ Several hundreds of common sources

✓ With a uniform sky coverage

✓ Link sources must have:

Accurate Gaia position → Optically-bright (V ≤ 18)

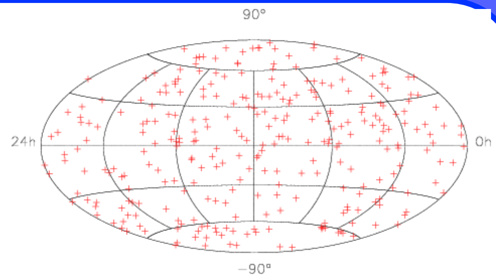
Accurate VLBI position → Good astrometric quality (no extended VLBI structure)

- **Current status:**

✓ ICRF1: 70 sources suitable (*Bourda et al., 2008*)

✓ ICRF2: 201 sources suitable (*Bourda et al., 2012, Proc. Porto Workshop*)

# Gaia-Radio frames alignment




- **Some requirements:**

✓ Several hundreds of common sources

✓ With a uniform sky coverage

✓ Link sources must have:

Accurate Gaia position → Optically-bright (V ≤ 18)

Accurate VLBI position → Good astrometric quality (no extended VLBI structure)

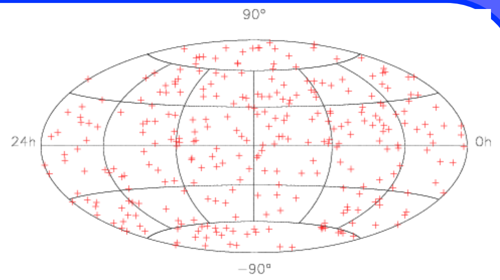
- **Current status:**

✓ ICRF1: 70 sources suitable (*Bourda et al., 2008*)

✓ ICRF2: 201 sources suitable (*Bourda et al., 2012, Proc. Porto Workshop*)

➡ Need to monitor these ICRF2 sources suitable for the alignment

# Gaia-Radio frames alignment




- **Some requirements:**

✓ Several hundreds of common sources

✓ With a uniform sky coverage

✓ Link sources must have:

Accurate Gaia position → Optically-bright (V ≤ 18)
Accurate VLBI position → Good astrometric quality (no extended VLBI structure)

- **Current status:**

✓ ICRF1: 70 sources suitable (*Bourda et al., 2008*)

✓ ICRF2: 201 sources suitable (*Bourda et al., 2012, Proc. Porto Workshop*)

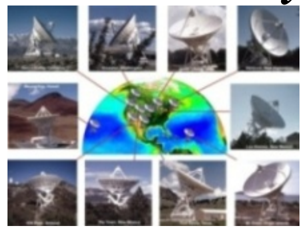
➡ Need to monitor these ICRF2 sources suitable for the alignment

➡ Need to find new radio sources suitable for accurate Gaia-VLBI alignment

# Our project

EUROPEAN VLBI NETWORK

*Very Long Baseline Array*

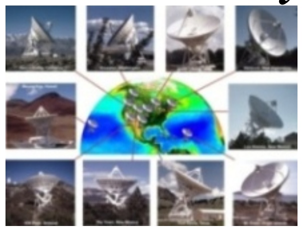


- Idea: New candidates → Weak sources (< 100 mJy)
- Specific VLBI observing program designed (with EVN & VLBA)

# Our project

EUROPEAN vlbi NETWORK

*Very Long Baseline Array*



- <u>Idea</u>: New candidates → Weak sources (< 100 mJy)
- Specific VLBI observing program designed (with EVN & VLBA)
- <u>Observing Sample</u>: 447 weak extragalactic radio sources

✓ NVSS catalog (excluding ICRF and VCS sources) → **Not in ICRF2!**

✓ Optical magnitude V ≤ 18

✓ Total flux density (NVSS) ≥ 20 mJy

✓ δ ≥ -10º

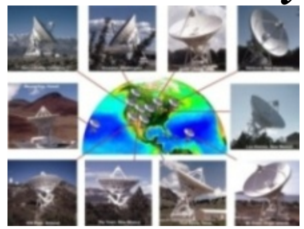
*NRAO VLA Sky Survey*

*(Condon et al., 1998)*

# Our project

EUROPEAN VLBI NETWORK

*Very Long Baseline Array*



- <u>Idea</u>: New candidates → Weak sources (< 100 mJy)
- Specific VLBI observing program designed (with EVN & VLBA)
- <u>Observing Sample</u>: 447 weak extragalactic radio sources

✓ NVSS catalog (excluding ICRF and VCS sources) → **Not in ICRF2!**
✓ Optical magnitude V ≤ 18
✓ Total flux density (NVSS) ≥ 20 mJy
✓ $\delta \geq -10^{o}$

*NRAO VLA Sky Survey*
*(Condon et al., 1998)*

- <u>Observing Strategy</u>:

1. VLBI detection (*Bourda et al., 2010, A&A 520, A113*)
2. Imaging (*Bourda et al., 2011, A&A 526, A102*) (*Bourda et al., 2012, in prep.*)
3. Accurate astrometry (for the most compact sources)

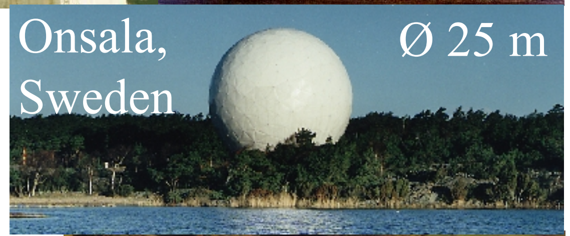
# Step 1: VLBI detection

- Two 48-hour EVN experiments (S/X @ 1Gbps)

  EC025A: June 2007 − 224 sources

  EC025B: October 2007 − 223 sources







# Step 1: VLBI detection

- Two 48-hour EVN experiments (S/X @ 1Gbps)

  EC025A: June 2007 − 224 sources

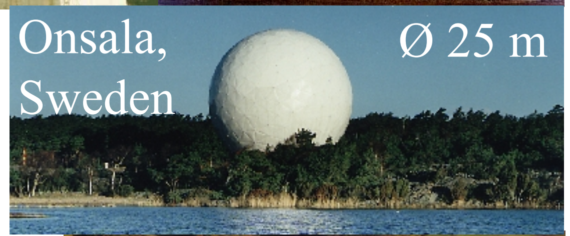
  EC025B: October 2007 − 223 sources

Weak sources in VLBI

➡ High sensitivity necessary

➡ Need large antennas & high recording rate







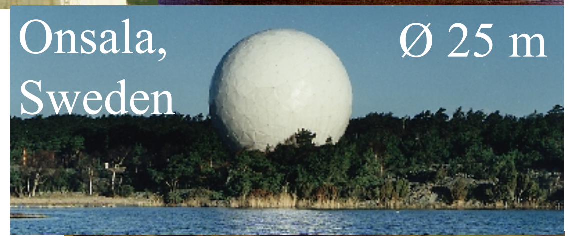
# Step 1: VLBI detection

- Two 48-hour EVN experiments (S/X @ 1Gbps)

  EC025A: June 2007 – 224 sources

  EC025B: October 2007 – 223 sources








Weak sources in VLBI

→ High sensitivity necessary

→ Need large antennas & high recording rate

- S/X detection rates:

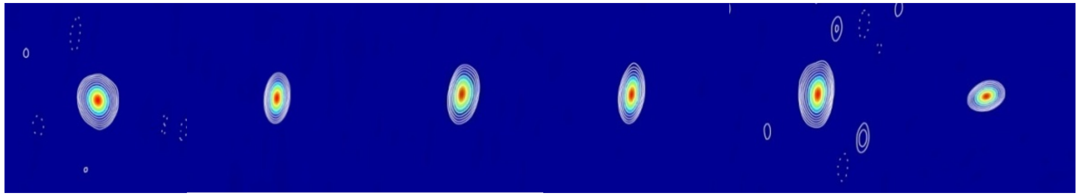
  EC025A ~ 96 %

  EC025B ~ 82 %

  Overall detection rate: **~ 89 %**
  (398 sources detected)

  (*Bourda et al., 2010, A&A 520, A113*)

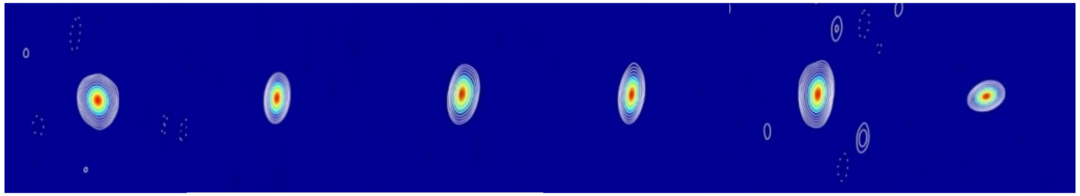
# Step 2: Imaging



- Four Global VLBI imaging experiments (EVN+VLBA) (S/X @ 512 Mbps)
  - ✓ GC030: March 2008 – 48-hrs – 105 sources
  - ✓ GC034A: March 2010 – 48-hrs – 97 sources
  - ✓ GC034BCD: November 2010 – 58-hrs – 118 sources
  - ✓ GC034EF: March 2011 – 38-hrs – 75 sources

→ In total, **192 hours** to observe **395 sources** (previously detected)

# Step 2: Imaging



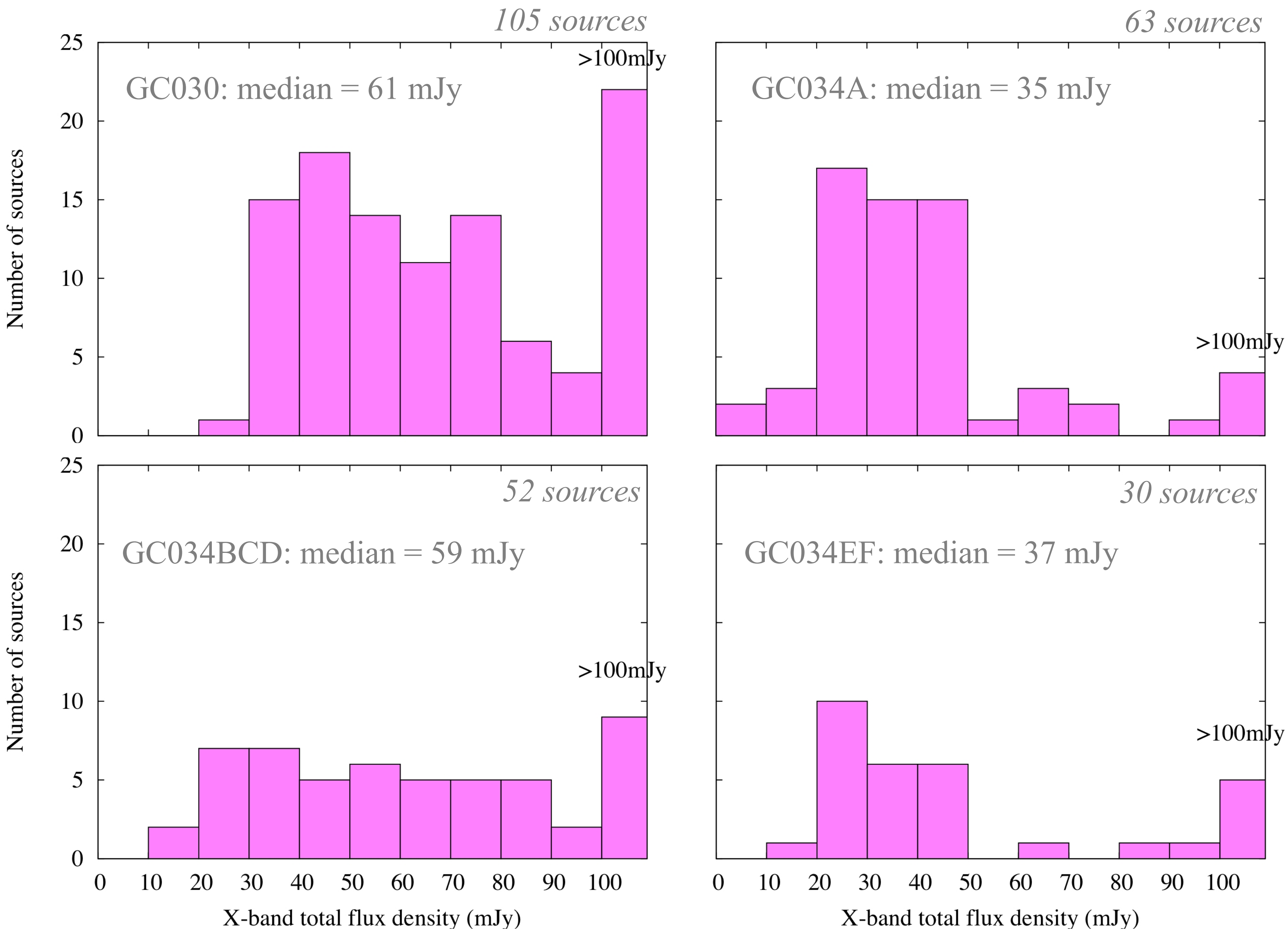
- Four Global VLBI imaging experiments (EVN+VLBA) (S/X @ 512 Mbps)
  - ✓ GC030: March 2008 – 48-hrs – 105 sources
  - ✓ GC034A: March 2010 – 48-hrs – 97 sources
  - ✓ GC034BCD: November 2010 – 58-hrs – 118 sources
  - ✓ GC034EF: March 2011 – 38-hrs – 75 sources

→ In total, **192 hours** to observe **395 sources** (previously detected)

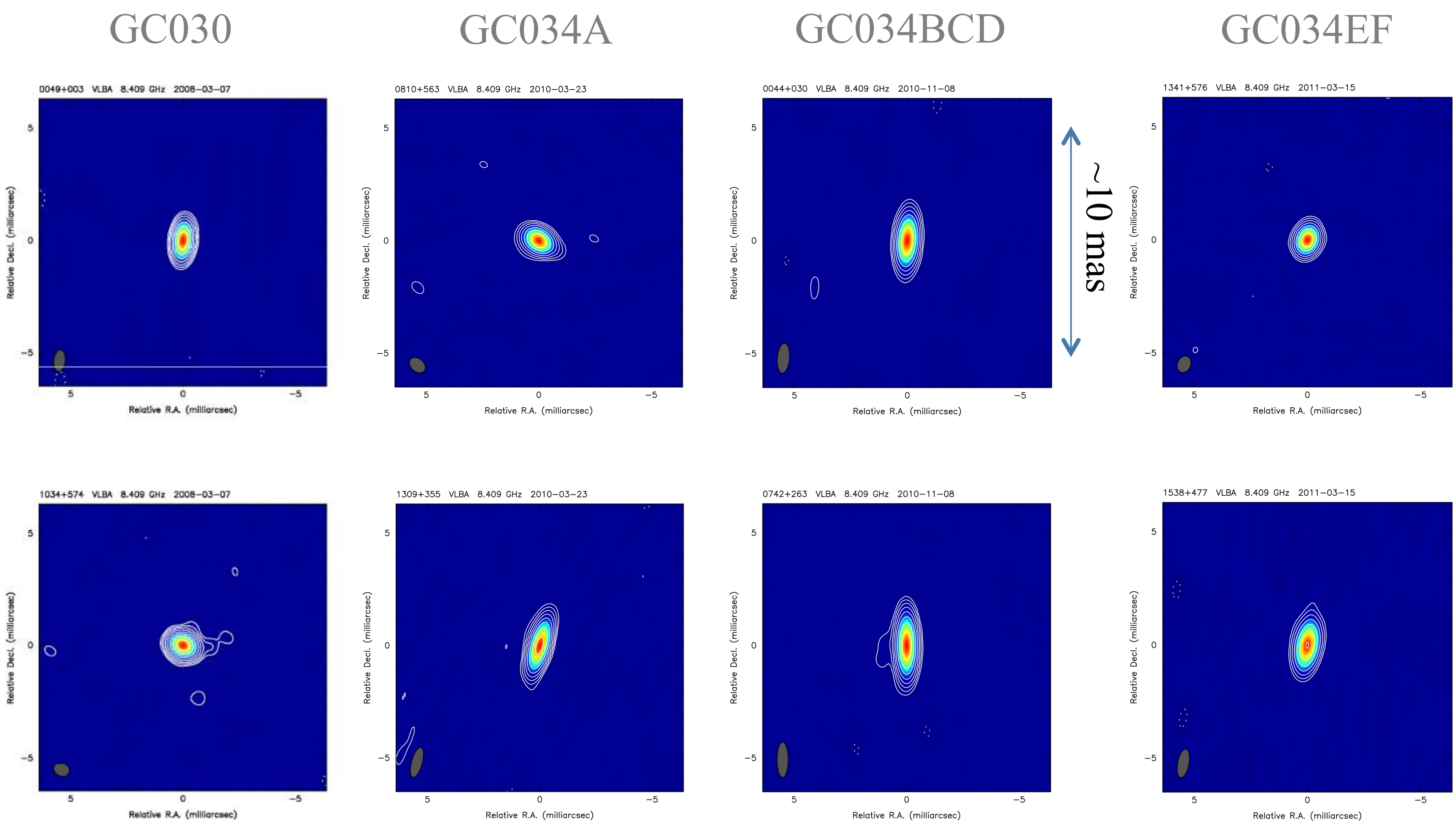
- **Results:** *(Bourda et al., 2011, A&A 526, A102)* *(Bourda et al., 2012, A&A, in prep.)* ★
  - ✓ GC030: All 105 sources successfully imaged at both X & S bands (100%)
  - ✓ GC034A: 63 VLBI maps (65%)
  - ✓ GC034BCD: 52 VLBI maps (44%) ★
  - ✓ GC034EF: 30 VLBI maps (40%)

→ In total, X-band VLBI maps determined for **250 sources** (63%)

# X-band Total Flux Density



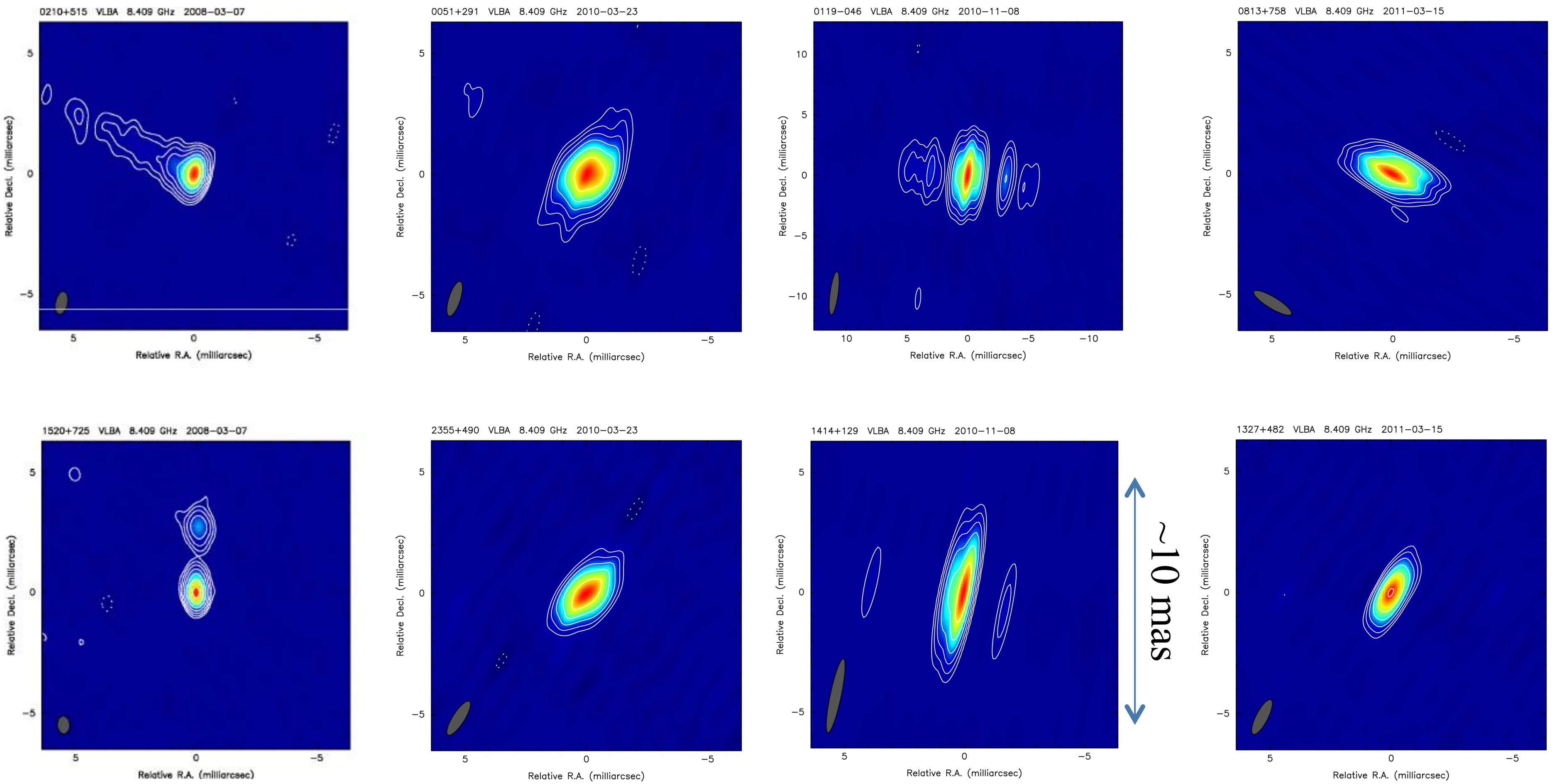
# Examples of VLBI maps for « good » sources




**X-band** $-1^{st}$ contour level @ 1 – 4%

# Examples of VLBI maps for « bad » sources

GC030 GC034A GC034BCD GC034EF




**X-band** – 1$^{st}$ contour level @ 1 – 4%

# VLBI Images in BVID

**The Bordeaux VLBI Image Database**

Home BVID | Database access

- Home BVID
- News
- BVID content
- **Database access**
- Citations
- Links
- Contact

Query by : Source name | Date | Coordinates

For GC030:

**105 sources have been found !**

http://www.obs.u-bordeaux1.fr/BVID/GC030

⇒ **VLBI image summary** *(in pdf)*

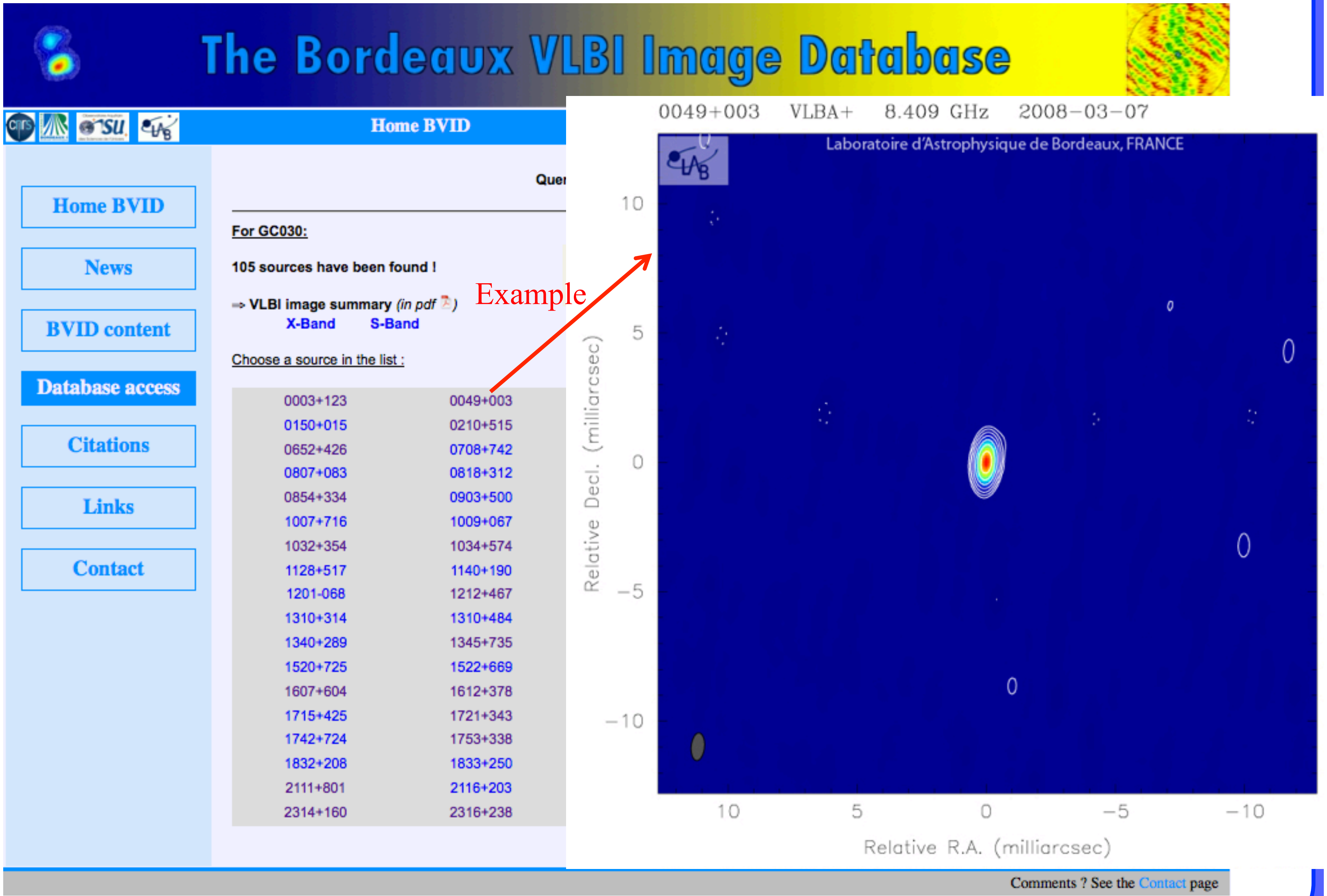
X-Band S-Band

Choose a source in the list :

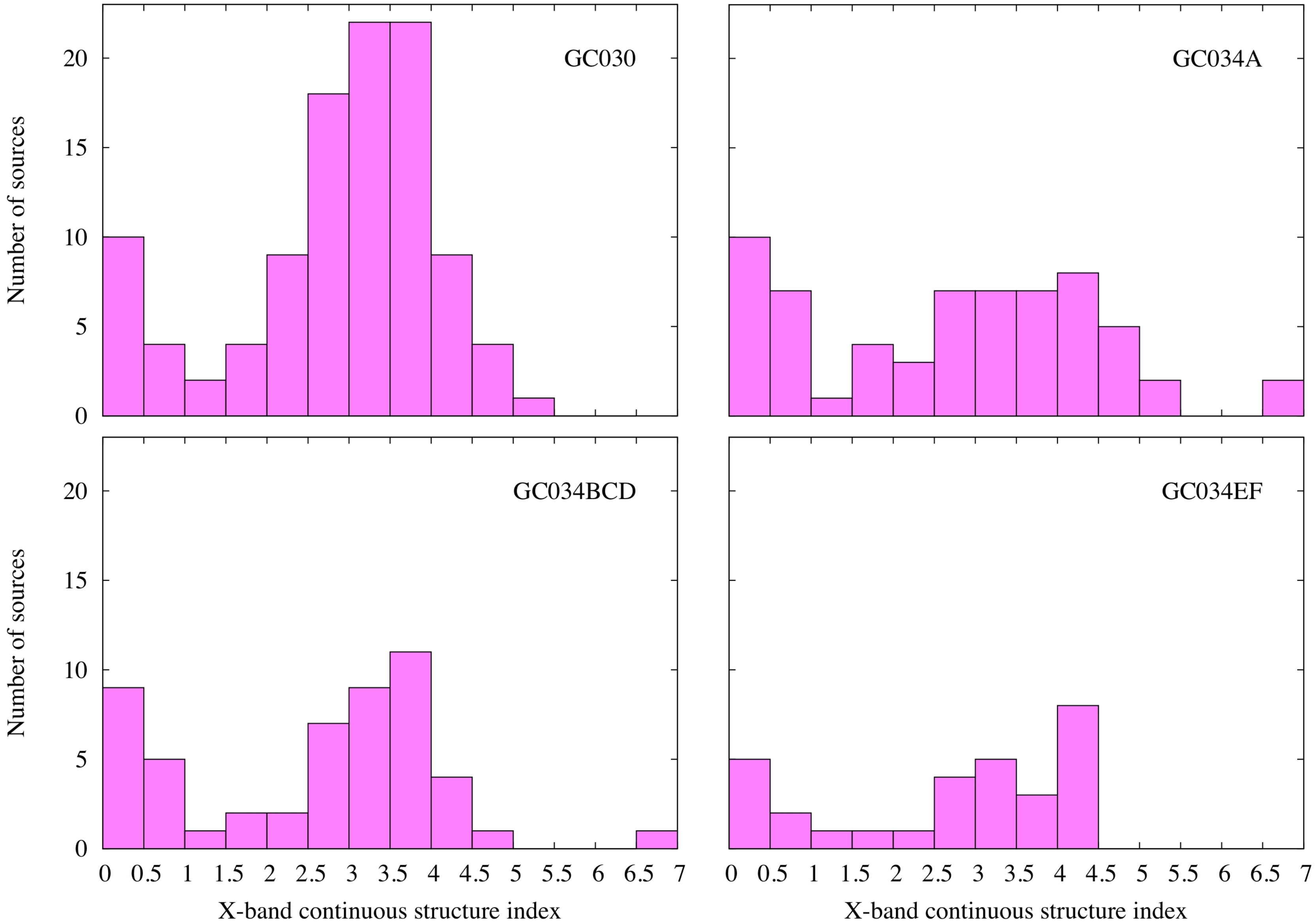
| | | | | | |
|---|---|---|---|---|---|
| 0003+123 | 0049+003 | 0107-025 | 0109+200 | 0130-083 | 0145+210 |
| 0150+015 | 0210+515 | 0446+074 | 0502+041 | 0519-074 | 0651+428 |
| 0652+426 | 0708+742 | 0741+294 | 0751+306 | 0757+477 | 0806+350 |
| 0807+083 | 0818+312 | 0821+411 | 0838+235 | 0838+456 | 0850+284 |
| 0854+334 | 0903+500 | 0907+336 | 0950+326 | 0950-084 | 0952+338 |
| 1007+716 | 1009+067 | 1009+334 | 1010+356 | 1020+292 | 1028+313 |
| 1032+354 | 1034+574 | 1040-056 | 1101+077 | 1126+237 | 1127+078 |
| 1128+517 | 1140+190 | 1141+235 | 1145+321 | 1148+592 | 1201+454 |
| 1201-068 | 1212+467 | 1228+077 | 1240+367 | 1242+574 | 1307+433 |
| 1310+314 | 1310+484 | 1312+240 | 1315+727 | 1319+006 | 1338+303 |
| 1340+289 | 1345+735 | 1411+746 | 1420+044 | 1429+249 | 1518+162 |
| 1520+725 | 1522+669 | 1535+231 | 1556+335 | 1603+699 | 1607+183 |
| 1607+604 | 1612+378 | 1618+530 | 1648+417 | 1653+198 | 1714+231 |
| 1715+425 | 1721+343 | 1722+119 | 1729+372 | 1730+604 | 1741+597 |
| 1742+724 | 1753+338 | 1759+756 | 1810+522 | 1811+317 | 1818+551 |
| 1832+208 | 1833+250 | 1838+575 | 2043+749 | 2052+239 | 2057+235 |
| 2111+801 | 2116+203 | 2128+333 | 2241+200 | 2247+381 | 2300+345 |
| 2314+160 | 2316+238 | 2322+396 | | | |

Comments ? See the Contact page

# VLBI Images in BVID

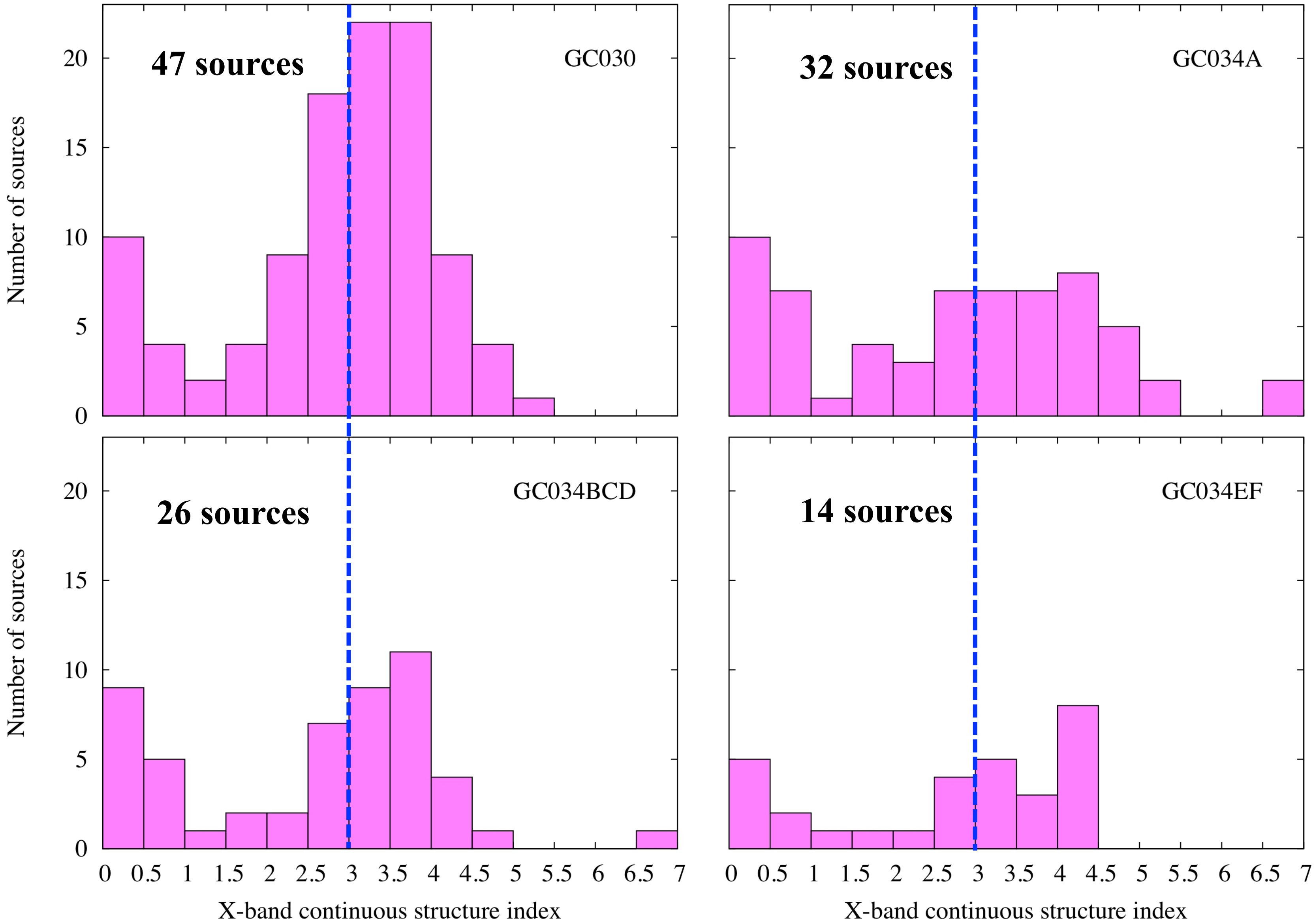


# Astrometric suitability



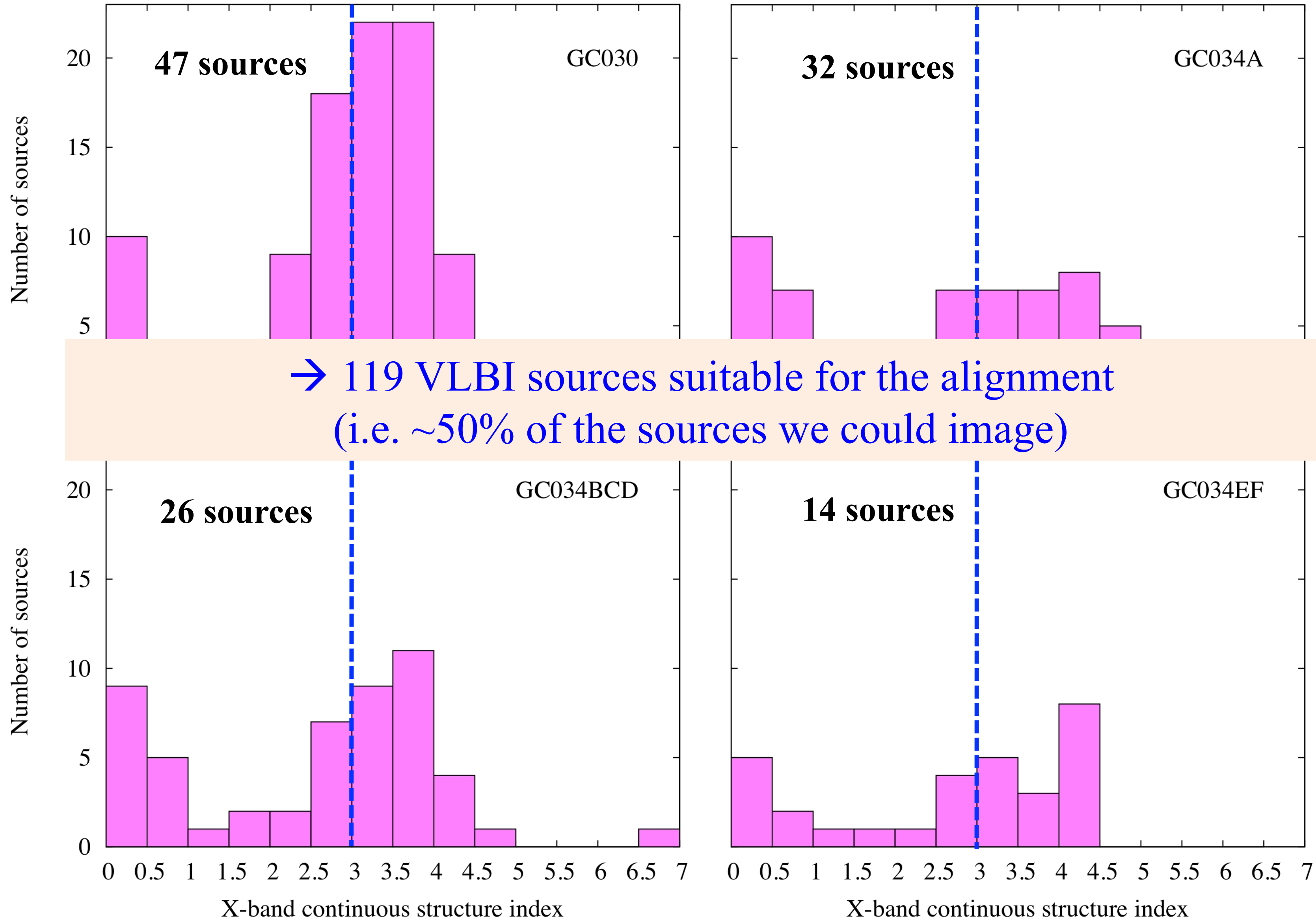
# Astrometric suitability

Same criterion as for the selection of ICRF2 defining sources (continuous structure index < 3.0)



# Astrometric suitability

Same criterion as for the selection of ICRF2 defining sources (continuous structure index < 3.0)




→ 119 VLBI sources suitable for the alignment
(i.e. ~50% of the sources we could image)

# Next stage

<u>Step 1</u>

VLBI detection

☑

<u>Step 2</u>

VLBI imaging

☑

<u>Step 3</u>

Astrometry

☐

- **Astrometry**

✓ Proposal submitted 1st February 2012

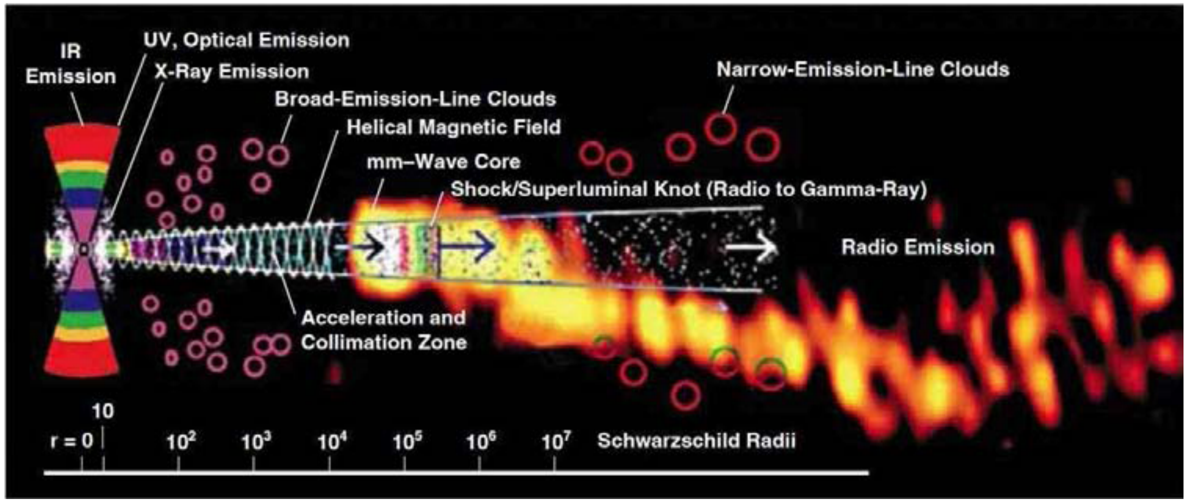
✓ Determine VLBI astrometric positions (for the most compact sources)
→ 119 point-like sources

✓ 72 hours asked

✓ Global VLBI array (EVN+VLBA)

# Future prospects

- ✓ Investigate further southern hemisphere
- ✓ Optical studies/observations for these candidates are on the way
- ✓ Quasi-simultaneous VLBI & Gaia observations will be carried out during the mission (*Gaia scanning law*) → Stability/Variability
- ✓ Astrophysics: Issues of core shifts




Thanks for your attention …

# The Gaia astrometric mission

- Gaia will observe 1 billion stars, 500 000 QSOs and 350 000 asteroids
- Astrometric accuracy

| V magnitude | 6 - 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | mag |
|---|---|---|---|---|---|---|---|---|---|
| Parallax | 8 | 13 | 21 | 34 | 55 | 90 | 155 | 275 | μas |
| Proper motion | 5 | 7 | 11 | 18 | 30 | 50 | 80 | 145 | μas / an |
| Position @2015 | 6 | 10 | 16 | 25 | 40 | 70 | 115 | 205 | μas |

- Launch: fall 2012
- Preliminary catalog: ~ 2015
- Final catalog: 2018-2020

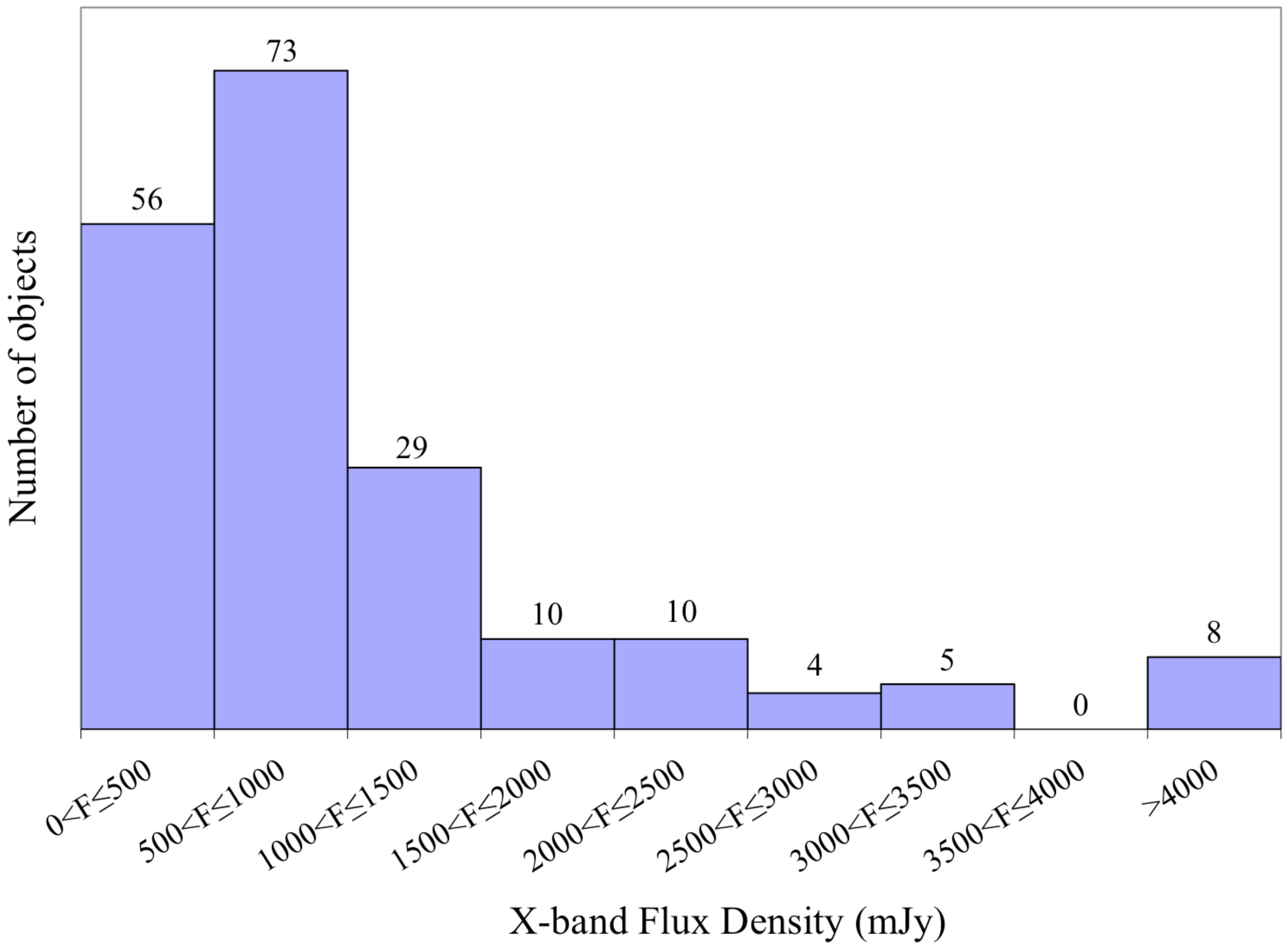
# ICRF2 optical counterparts

- Cross Identification: ICRF2 ∩ LQAC $\xrightarrow{3''}$ 3 195 sources
- From these: 276 *defining sources* (out of 295 ones within ICRF2)

| | $0 < mag$ | $0 < mag \leq 20$ | $0 < mag \leq 18$ |
|---|---|---|---|
| Magnitude V | 1120 | 1184 | 511 |
| Magnitude R | 2076 | 1938 | 755 |
| Magnitude I | 1806 | 1800 | 1013 |

Number of radio sources from ICRF2 with an optical counterpart within LQAC [*Large Quasar Astrometric Catalog*; Souchay et al. 2009]

# ICRF2 sources suitable for the alignement



# Structure Index

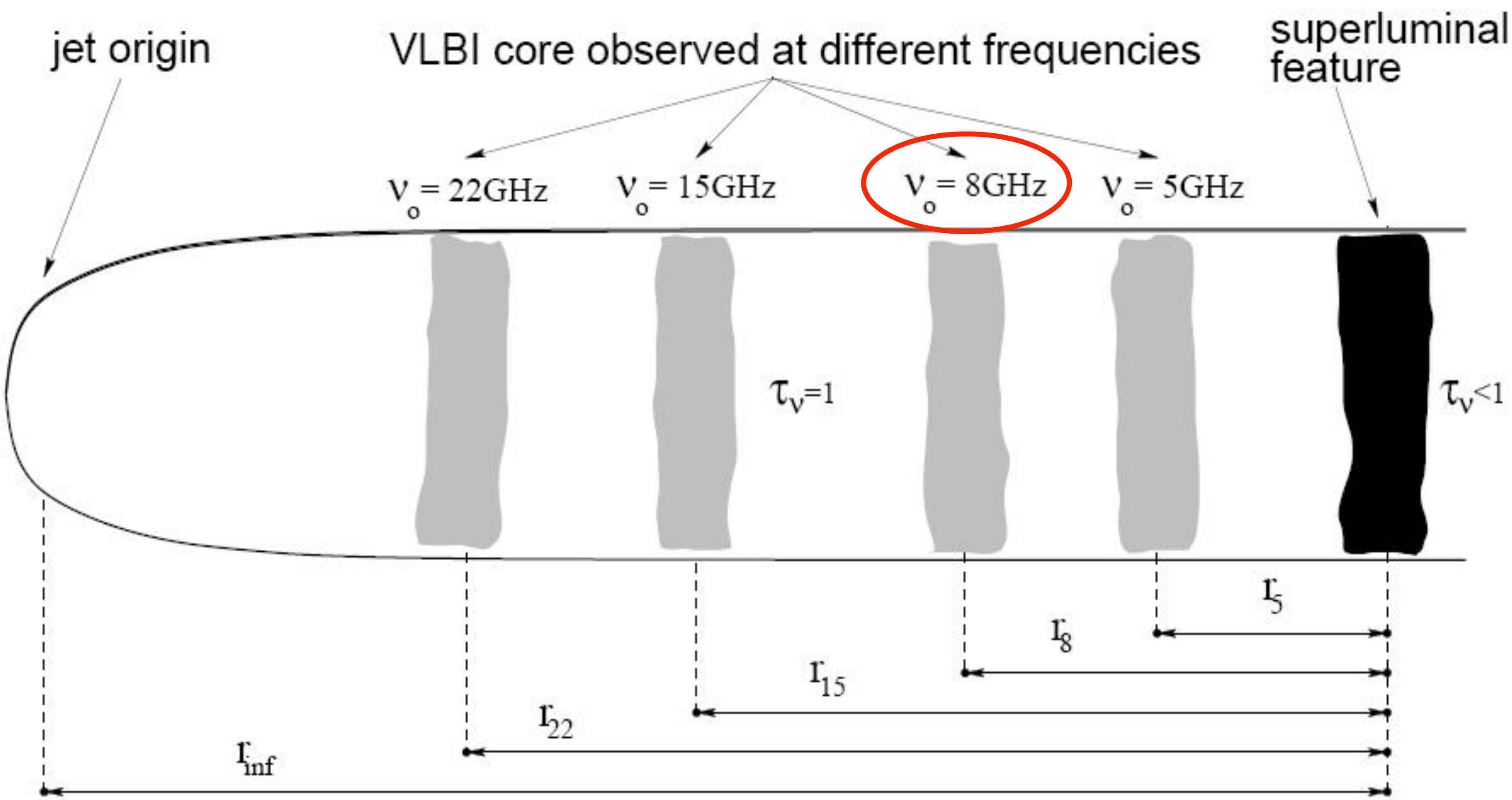
The structure index (SI) indicates the expected magnitude of the effects of intrinsic source structure on VLBI delay observations, according to the median value of the structure delay corrections ($\tau_{\mathrm{median}}$) calculated for all projected VLBI baselines that might be observed, using the algorithm devised by Charlot (1990). While Fey & Charlot (1997) separated sources into four categories, with values of the structure index ranging from 1 to 4, a continuous scale was adopted for the present work (as also done for the ICRF2; see IERS Technical Note 35). It is defined as follows:

$$\mathrm{SI} = 1 + 2\log(\tau_{\mathrm{median}}) \qquad (1)$$

where $\tau_{\mathrm{median}}$ is expressed in picoseconds (ps). Additionally, SI values are constrained to be always positive by setting SI = 0 when $\log(\tau_{\mathrm{median}}) < -0.5$ (i.e. $\tau_{\mathrm{median}} \lessapprox 0.3$ ps). There is close correspondence at the (discrete) SI boundaries between the continuous SI values defined here and the values defined in Fey & Charlot (1997) (SI = 1.95 vs. 2 for $\tau_{\mathrm{median}} = 3$ ps, SI = 3.00 vs. 3 for $\tau_{\mathrm{median}} = 10$ ps, SI = 3.95 vs. 4 for $\tau_{\mathrm{median}} = 30$ ps).

# Interests for the physics of QSOs

Core shifts → Put constraints on the physics of AGNs?




Kovalev et al. 2008

# Challenge:
## AGN radio-optical core-shift

AGN = Active Galactic Nuclei

Frequencies in VLBI:

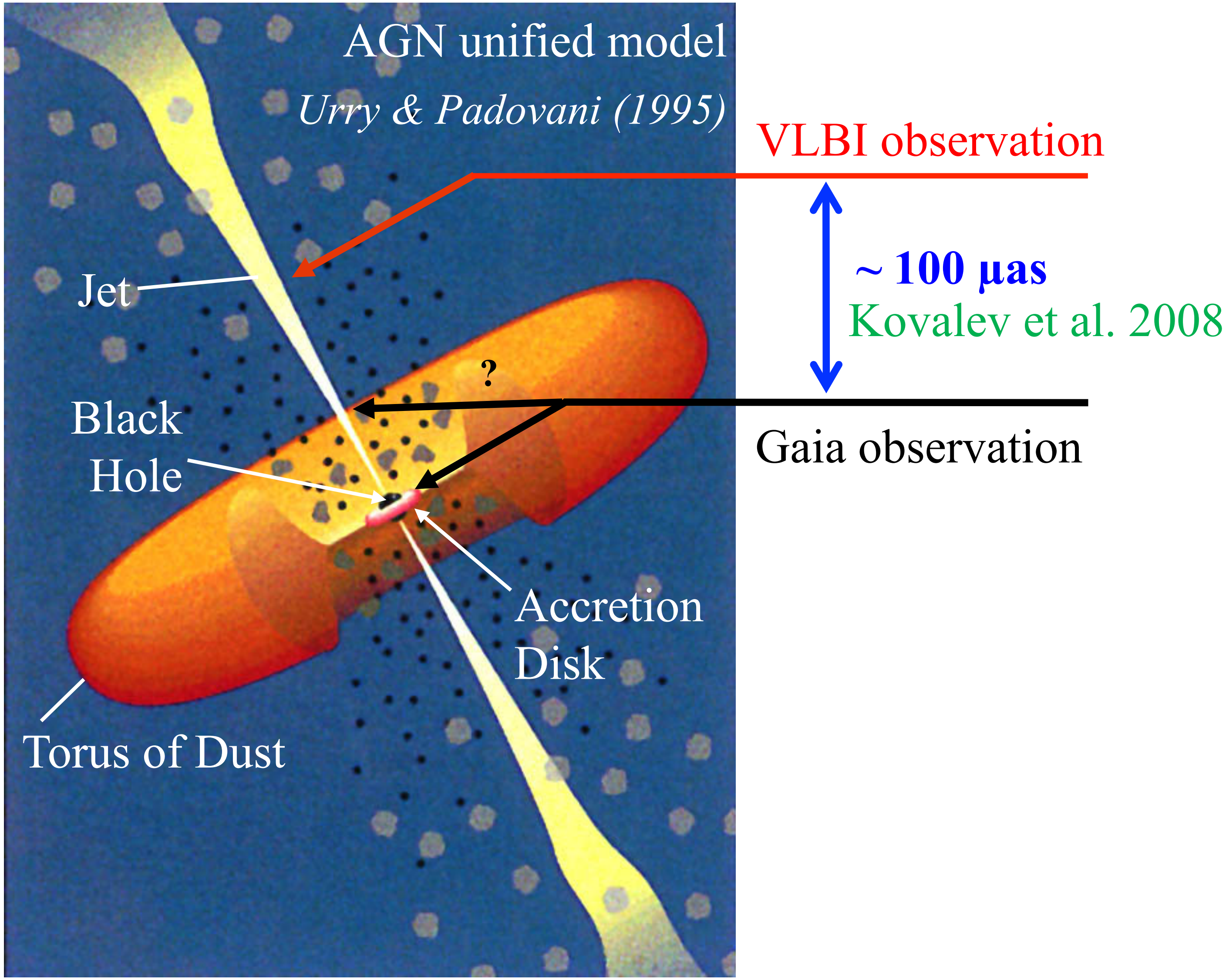
S ~ 2 GHz

X ~ 8 GHz

K ~ 24 GHz

Ka ~ 32 GHz

Q ~ 43 GHz



# Examples of related scientific questions

- Dominating optical emission mode within AGNs?

  Thermal emission (i.e. accretion disk) or non-thermal (relativistic jets)?

- Origin of the relativistic jets observed within AGNs?

- Is the core-shift within AGNs depending on frequencies? On time?