Celestial Reference Systems:

Stability and Alignment

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Outline

Image courtesy of NRAO/AUI

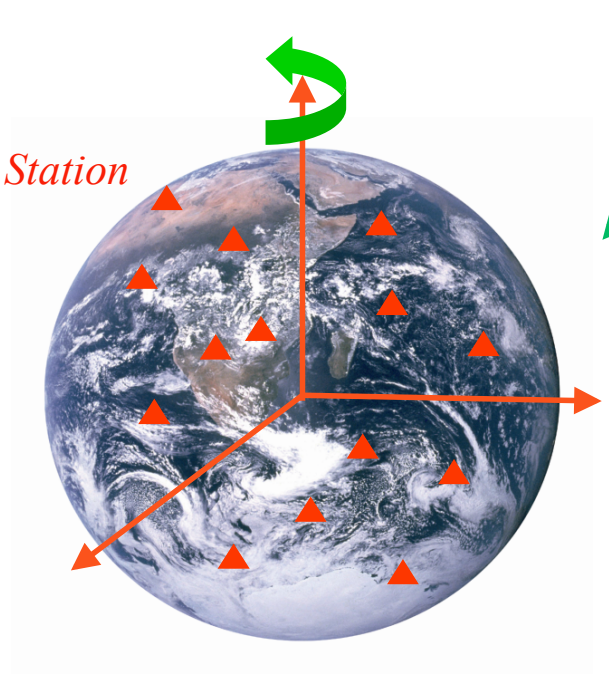
Reference systems

Celestial reference system/frame

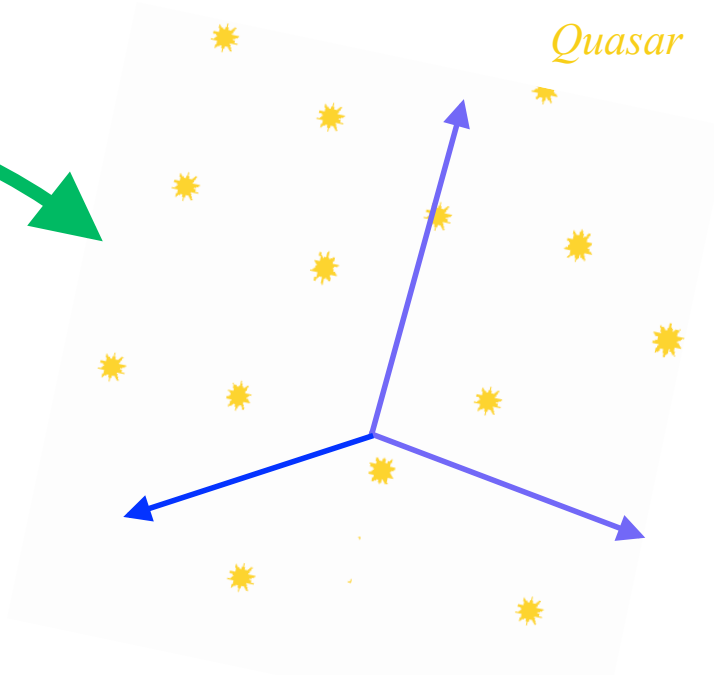
1. Definitions − Concepts − History
2. Current IAU fundamental celestial reference frame – VLBI
3. Astrometry
4. Imaging
5. Gaia era
6. Optical − radio frames alignment
7. Related science: From astrometry towards astrophysics

Conclusion

Reference systems



Earth Rotation



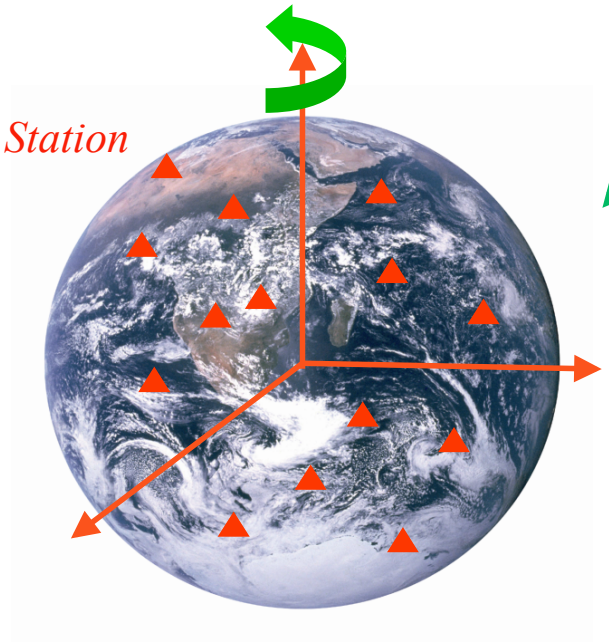
Terrestrial Reference Frame

Celestial Reference Frame

System = Concept

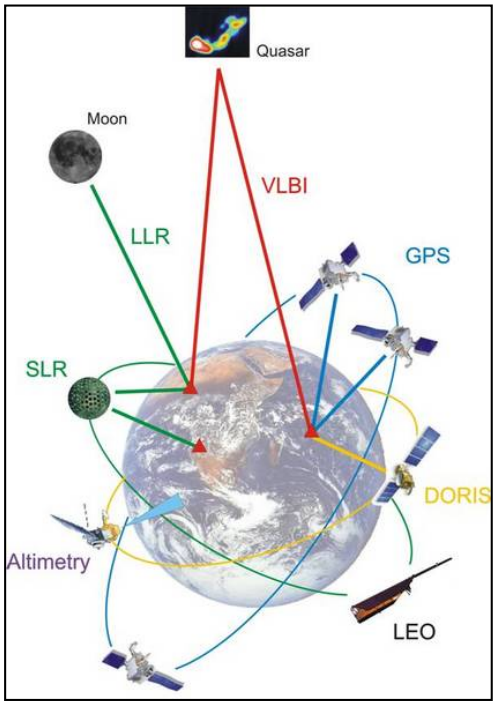
Frame = Materialization

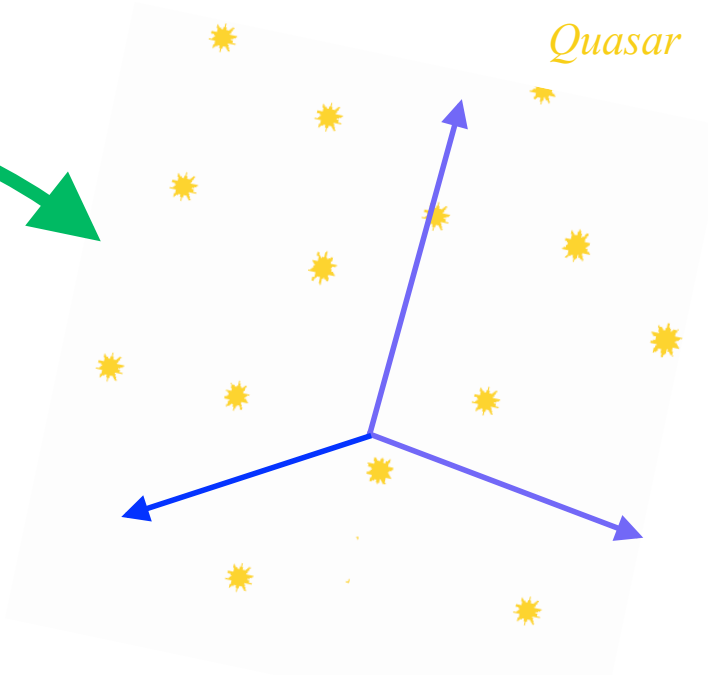
Reference systems



Earth Rotation

* Polar Motion
* Length-Of-Day
* Precession-Nutation





Terrestrial Reference Frame

ITRF

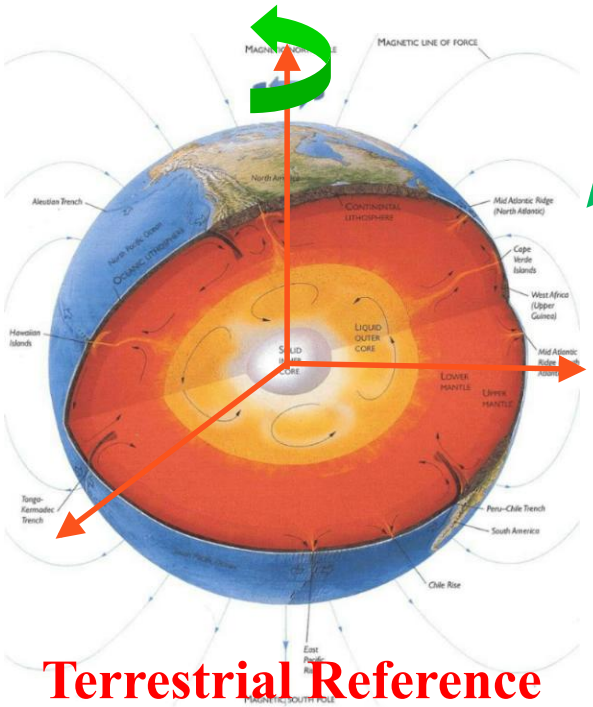
International Terrestrial Reference Frame

Celestial Reference Frame

ICRF

International Celestial Reference Frame

Reference systems



Earth Rotation

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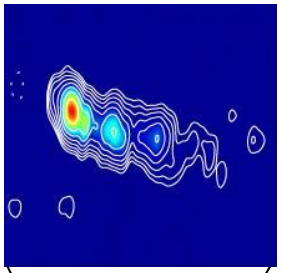
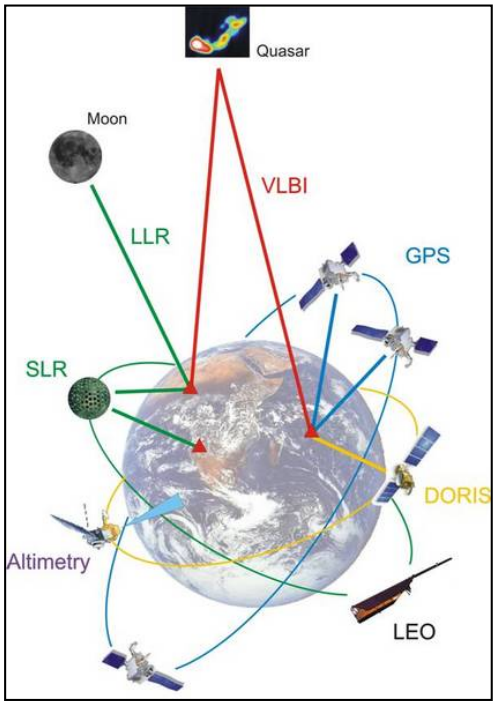


Quasar



Terrestrial Reference Frame

ITRF

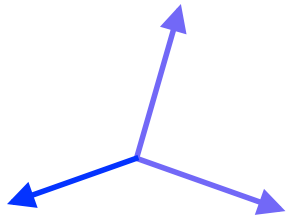
International Terrestrial Reference Frame

Celestial Reference Frame

ICRF

International Celestial Reference Frame

1. Celestial Reference System/Frame



Definitions − Concepts − History

- **Celestial reference system** = System of coordinate axes wrt which the positions of celestial bodies are referred (Kovalevsky, 2000)

  → Theoretical concept

- Celestial reference system materialized by a set of objects = **Celestial reference frame**

  → Practical materialization

- 1991: IAU celestial reference frame based on a **kinematical definition** rather than dynamical (e.g. FK5; Fricke et al., 1988)

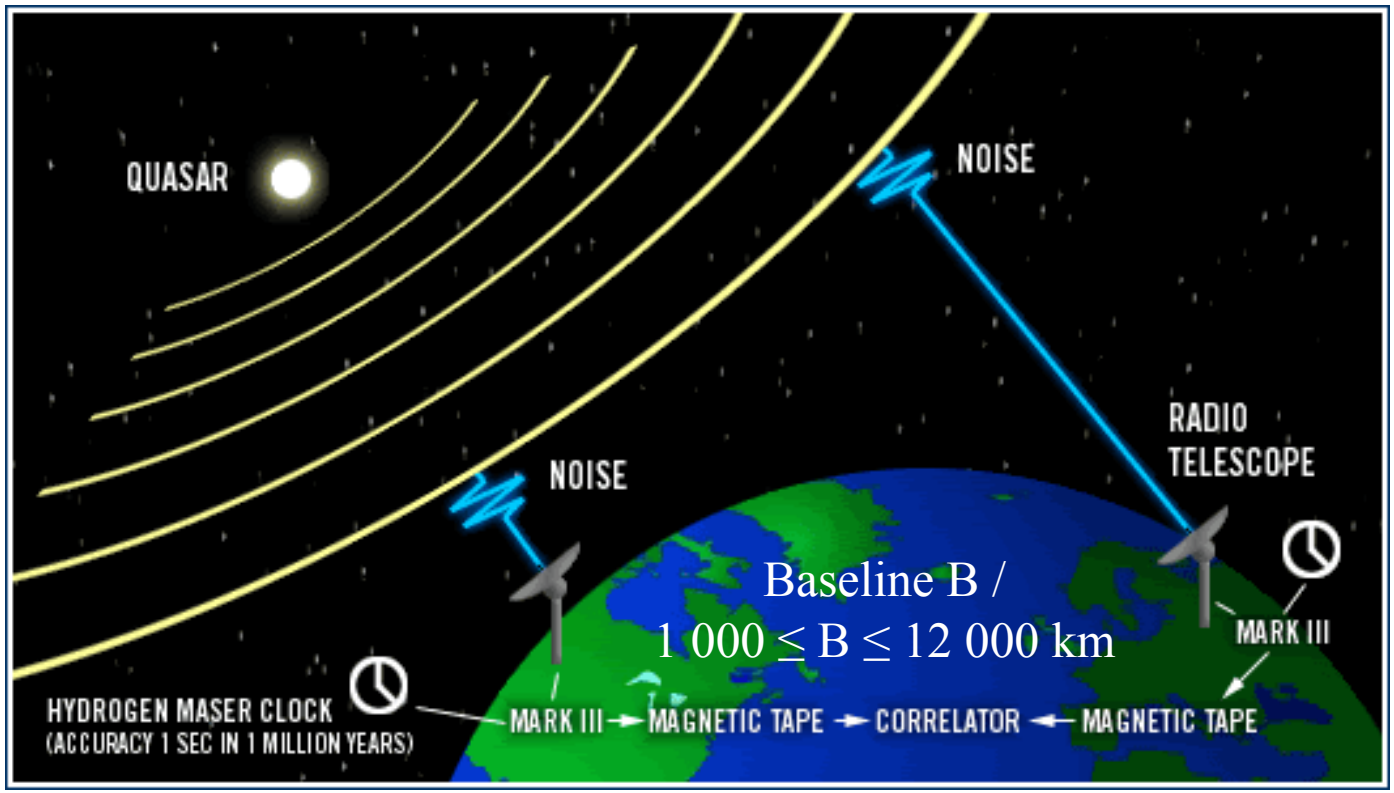
  → Use of quasars, no more stars

  → Coordinate axes fixed wrt distant matter in the Universe (no global rotation)

2. Celestial Reference Frame

VLBI

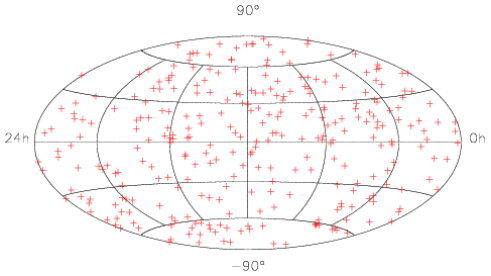
- Determine the extragalactic celestial reference frame in the radio domain
- **IAU fundamental celestial reference frame**
- ICRF2 = 3 414 radio sources [IERS Technical Note 35]



Angular resolution $\propto \lambda / B$

~ 1 mas @ X-band (8 GHz; 13 cm)

3. Celestial Reference Frame



Astrometry

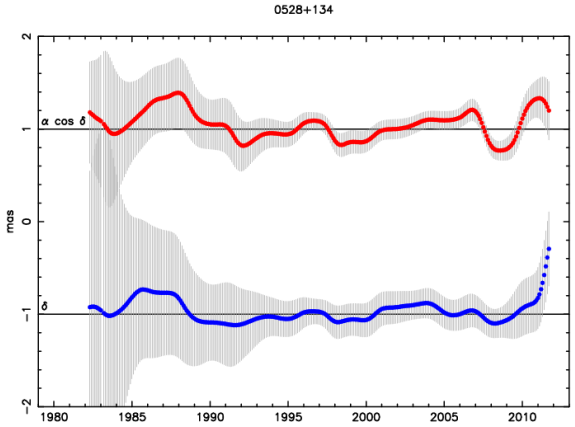
Sources with accurate and stable positions are necessary

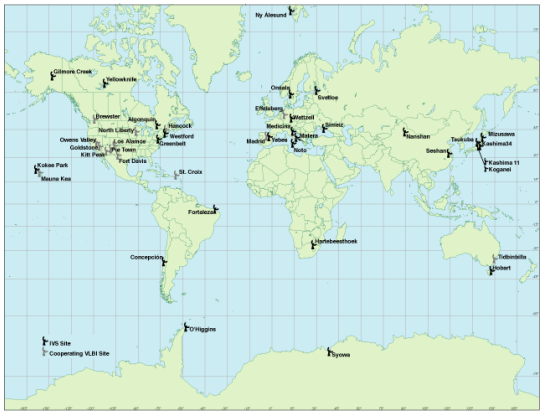
- **Position accuracy**

  Improve source position accuracy by regular observations

- **Position stability**

  Monitoring of source position

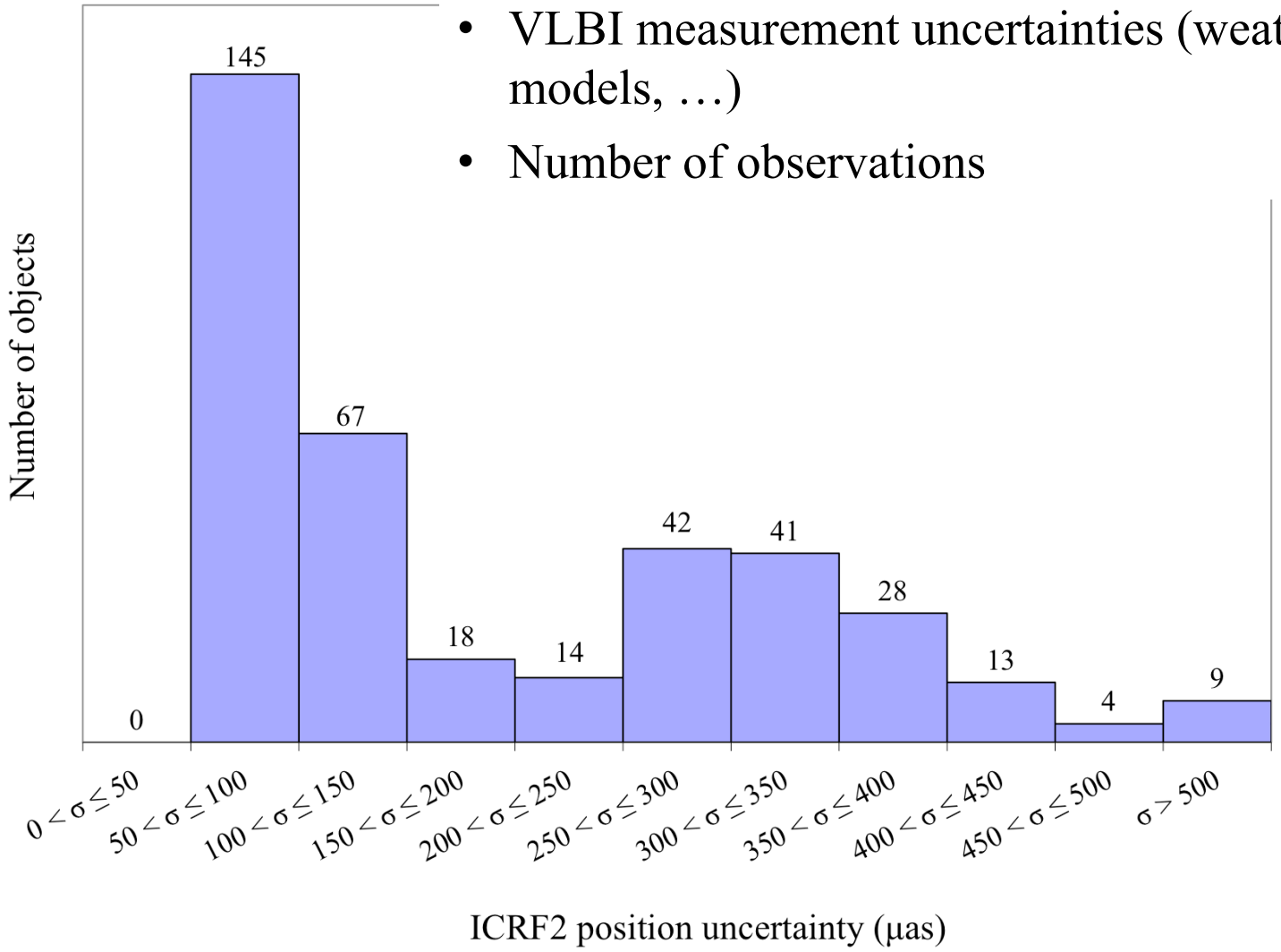




Position accuracy

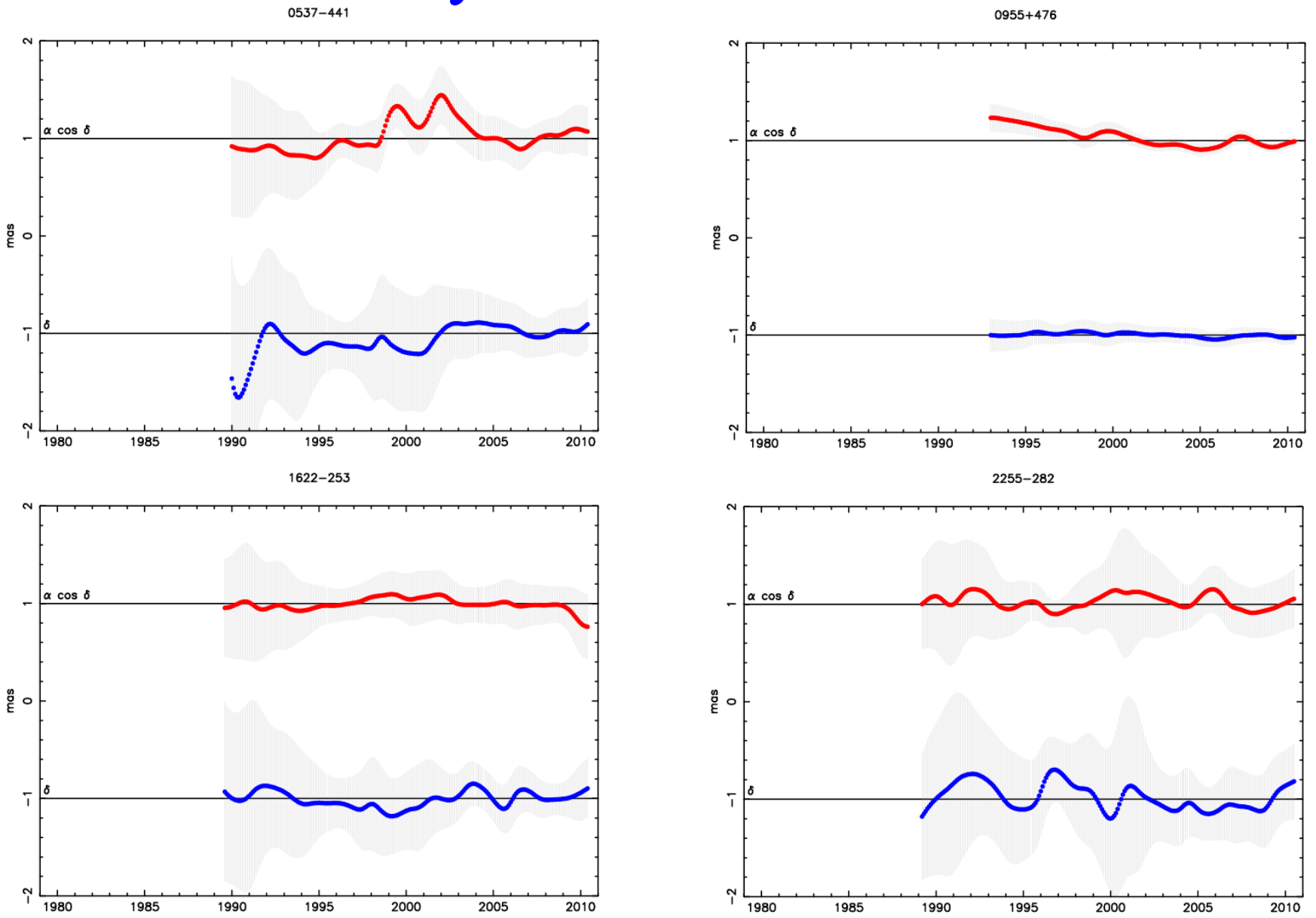
Depends mostly on:

- VLBI measurement uncertainties (weather conditions, models, …)
- Number of observations

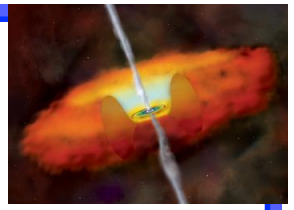


295 ICRF2 defining sources

Position stability



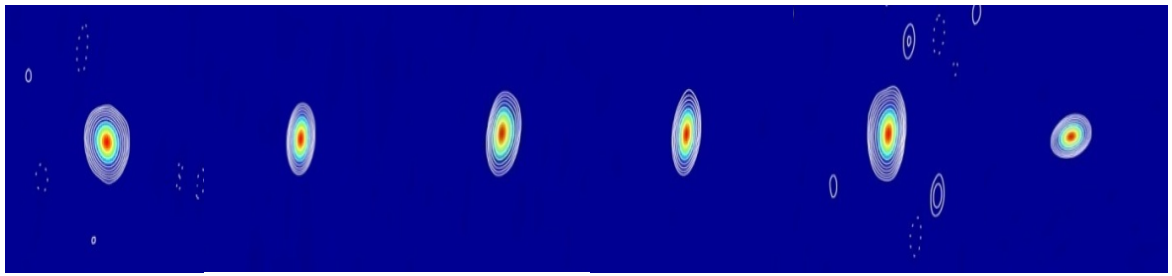
4. Celestial Reference Frame



Imaging

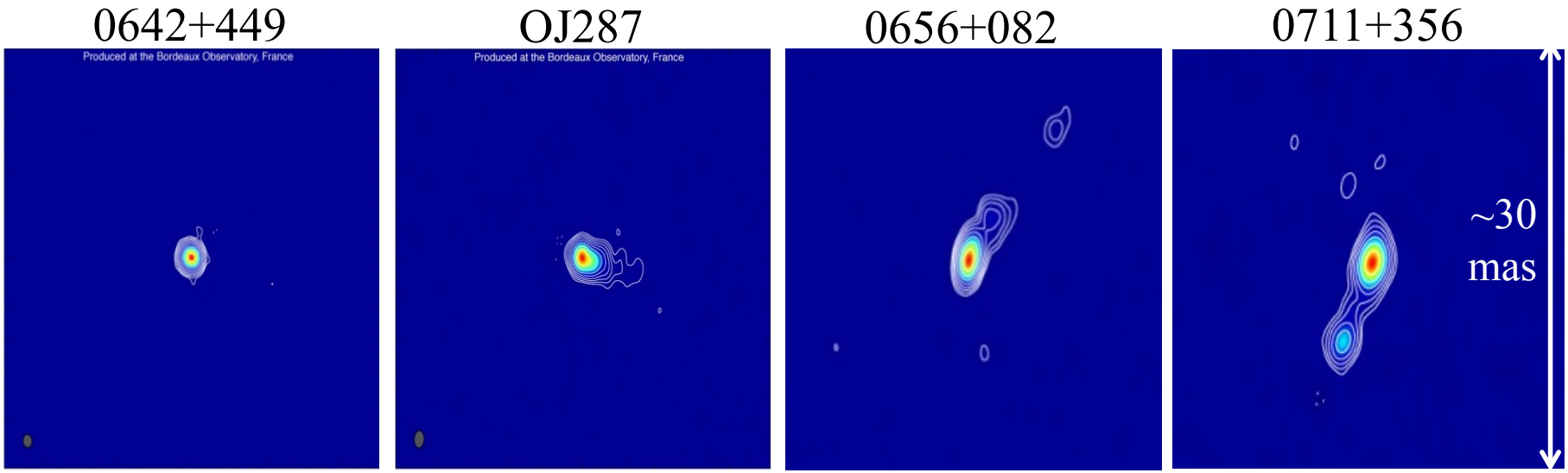
Point-like sources with stable VLBI structures are necessary

- **Source morphology**
  Image radio sources to reveal their structures on VLBI scales
- **Source structure variations**
  Monitoring of source structure



VLBI structure

Monitored through the "structure index" → Astrometric quality information



SI = 1

Point-like source

SI = 2

Source not extended

SI = 3

Extended source

SI = 4

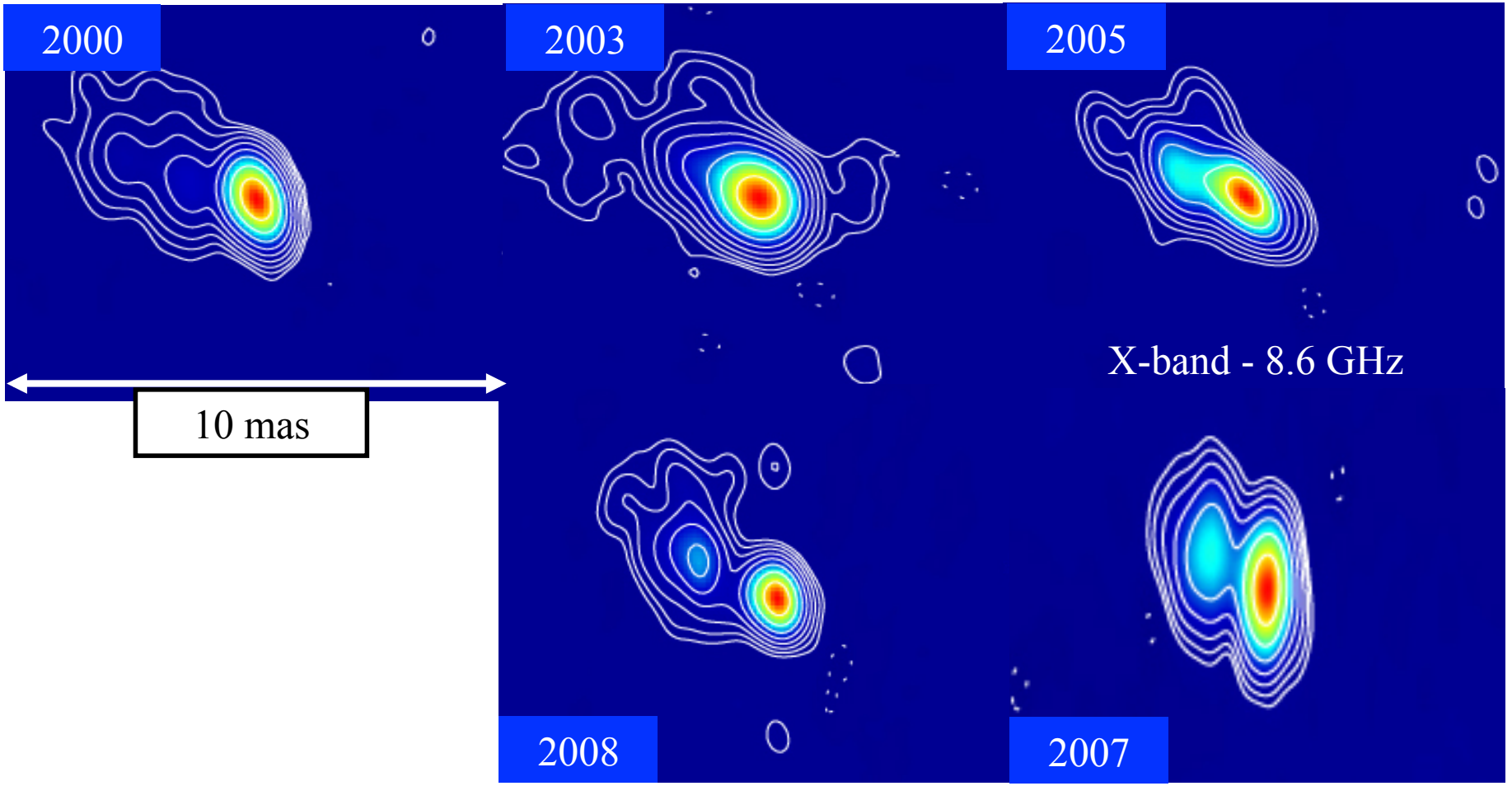
Source very extended

Bordeaux VLBI Image Database (BVID):

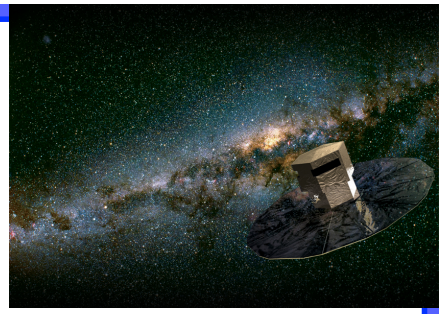
http://www.obs.u-bordeaux1.fr/BVID

Source structure variations

CTA26, source within ICRF catalogue, but not in ICRF2 (maps extracted from BVID)

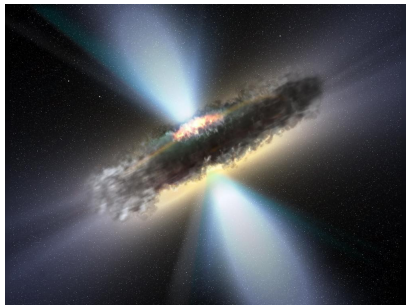


5. Celestial Reference Frame

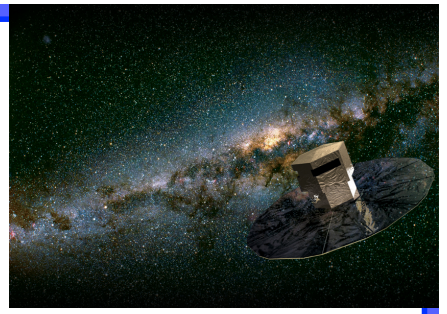


Gaia era

- Gaia will observe ~ 500 000 QSOs
- High percentage of *unknown* quasars (~2/3)
- Gaia will create its own extragalactic celestial reference frame directly at optical bands
- On the basis of a "clean sample" of QSOs with the most accurate positions
  → mag ≤ 18
  → ~20 000 objects (Mignard 2003)
- Kinematically non-rotating system
  → ~0.3−0.5 μas/yr
  → 20 000−50 000 objects
  (Mignard 2002, 2008)



Gaia Celestial Reference Frame



Conditions on QSOs like in radio

Highly accurate Gaia position

Stable position

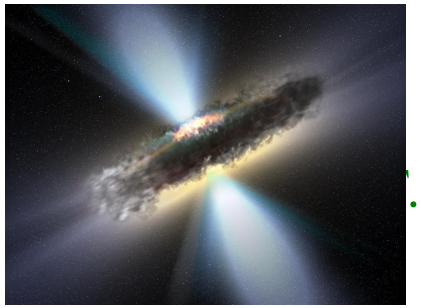
Point-like morphology at optical bands

→ Else it could deteriorate the optical position = astrometry

Stable photometry (magnitude)/morphological aspect

→ Observing programs are specifically devised to study/investigate/anticipate these morphological/photometric effects

A. Andrei (Brasil); S. Anton (Portugal); Taris & G. Bourda (France) …

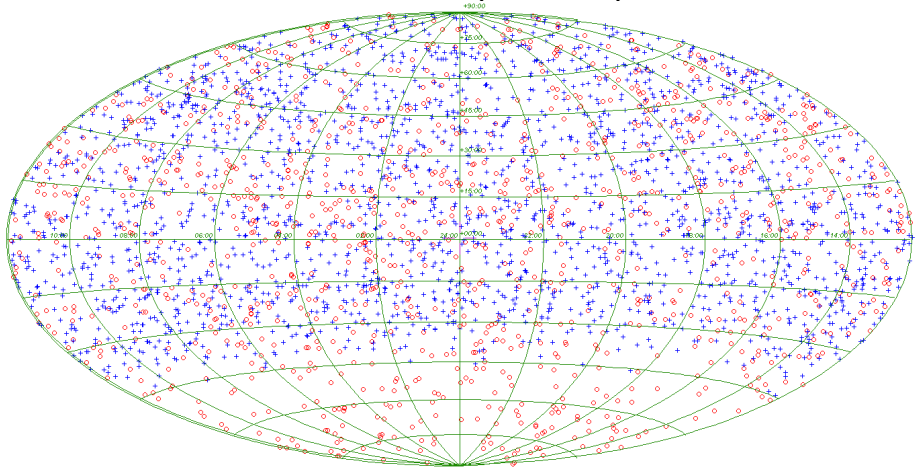


6. Celestial Reference Frame

Optical-Radio frames alignment

By 2015-2020: Two extragalactic celestial reference frames available

VLBI (Radio)



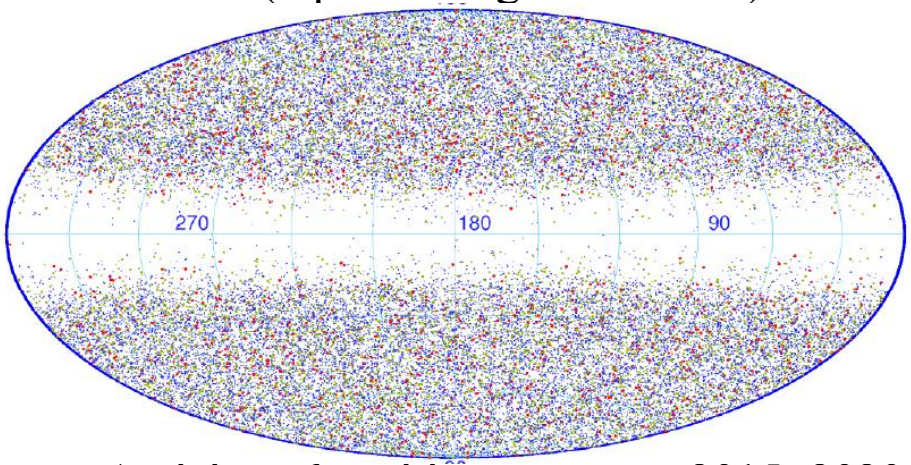
Position accuracy:

1997: ICRF1 – 717 sources – σ ≥ 250 μas

2009: ICRF2 – 3414 sources – σ ≥ 60 μas

2015-2020: ICRF3 ???

Gaia (Optical magnitude ≤ 20)



Anticipated position accuracy: 2015–2020

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

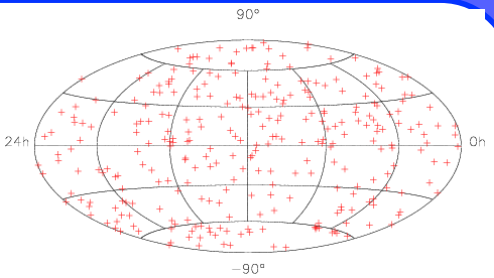
500 000 QSOs @ V≤20 → 16 μas ≤ σ ≤ 200 μas

Lindegren et al., 2008

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-VLBI 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: ~200 sources suitable (Bourda et al., 2012, Proc. Porto Workshop)

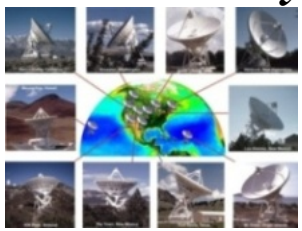
➡ Need to monitor these ICRF2 sources suitable for the alignment (IVS proposal)

➡ Need to find new radio sources suitable for accurate Gaia-VLBI alignment (EVN−VLBA observing program; PI = G. Bourda; Bourda et al., 2010, 2011)

Our project

EUROPEAN VLBI NETWORK

Very Long Baseline Array



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

✓ NVSS catalog (excluding ICRF2 sources)
✓ Optical magnitude V ≤ 18
✓ Total flux density (NVSS) ≥ 20 mJy
✓ δ ≥ -10°

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

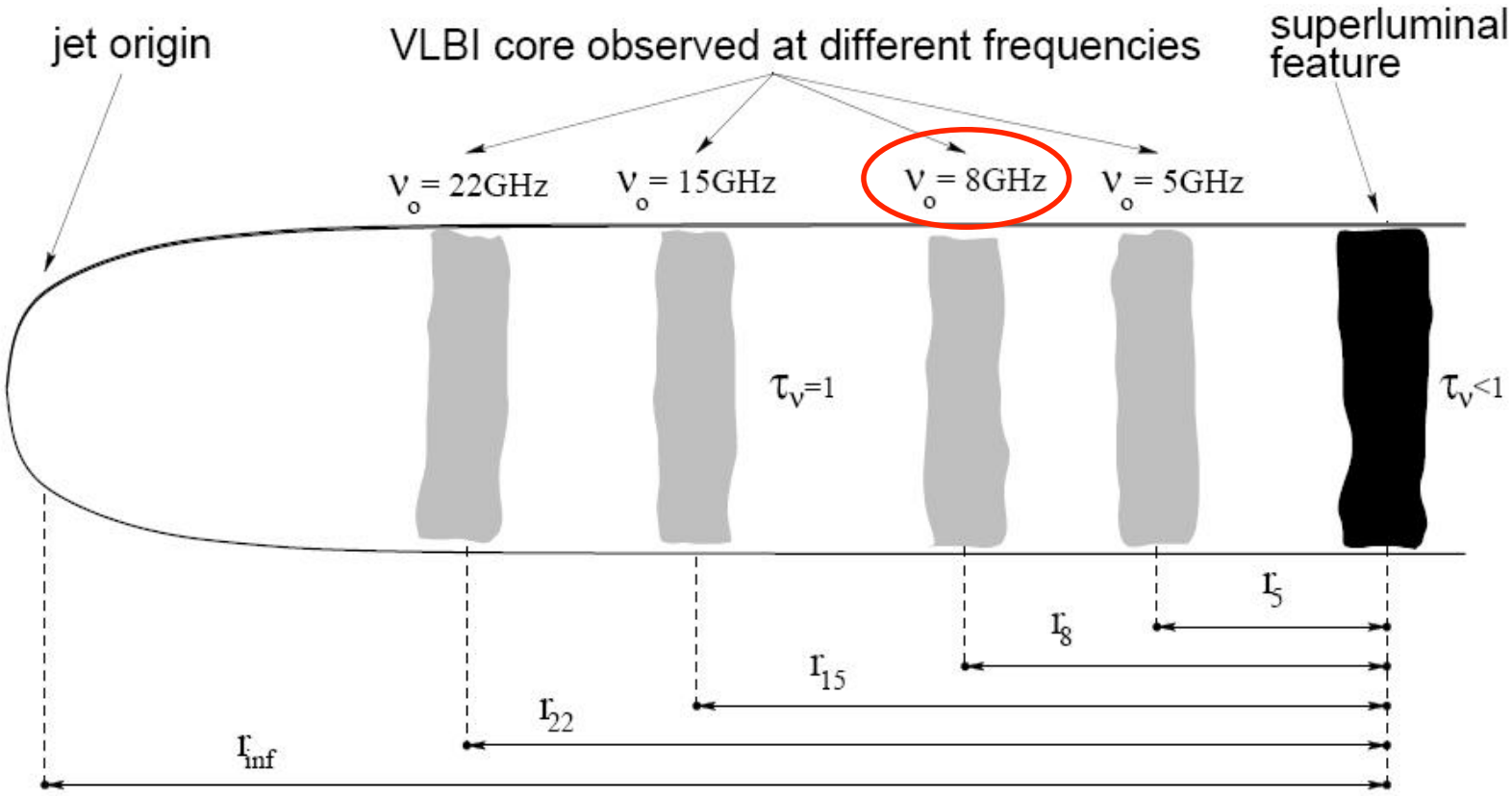
- Observing Strategy:

1. VLBI detection (Bourda et al., 2010) ☑
2. Imaging (Bourda et al., 2011; 2012 *in prep.*) ☑
3. Accurate astrometry (for the most compact sources) ☑

7. Celestial Reference Frame

From astrometry towards astrophysics

- 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

Frequencies in VLBI:

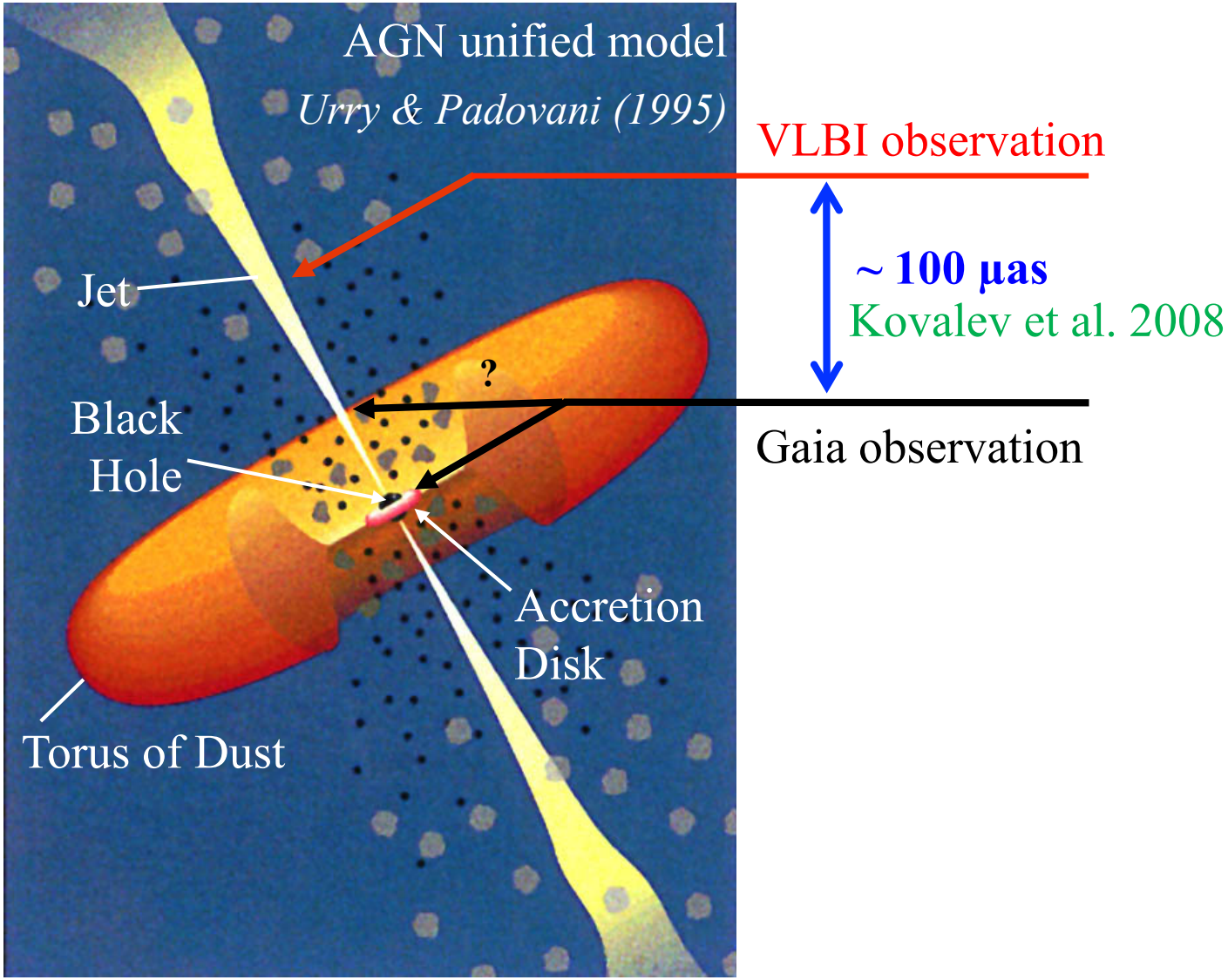
S ~ 2 GHz

X ~ 8 GHz

K ~ 24 GHz

Ka ~ 32 GHz

Q ~ 43 GHz



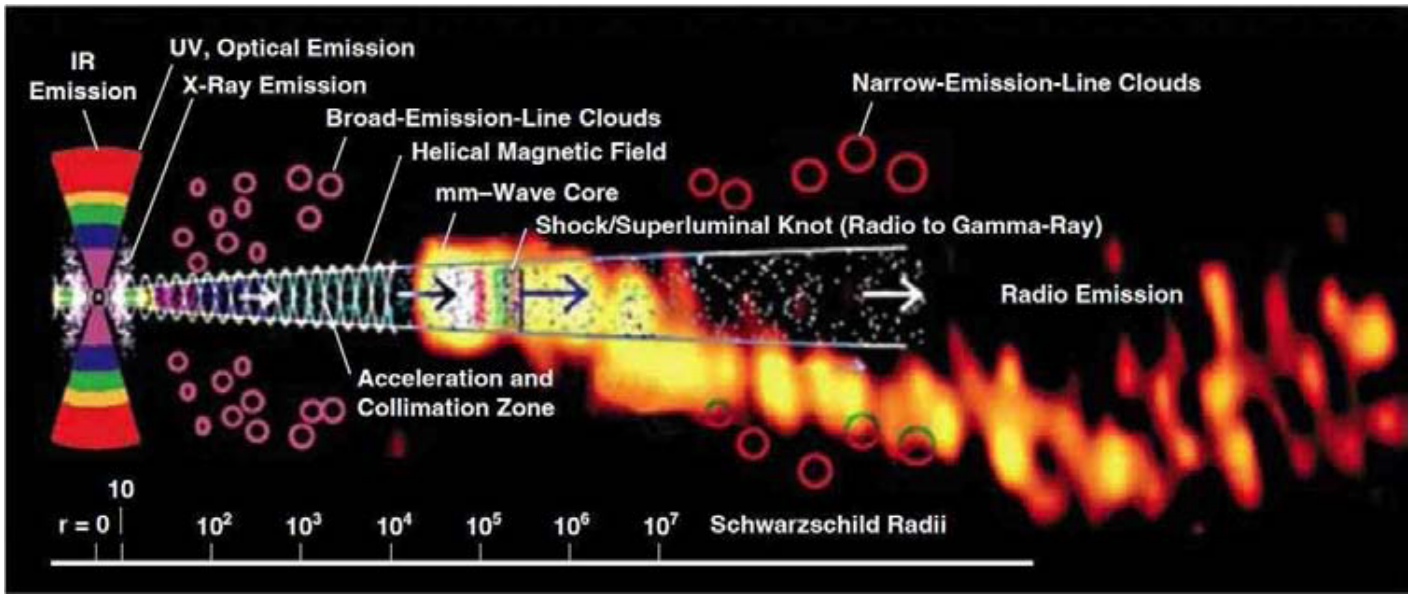
Examples of related scientific questions

- Dominating optical emission mode within AGNs?

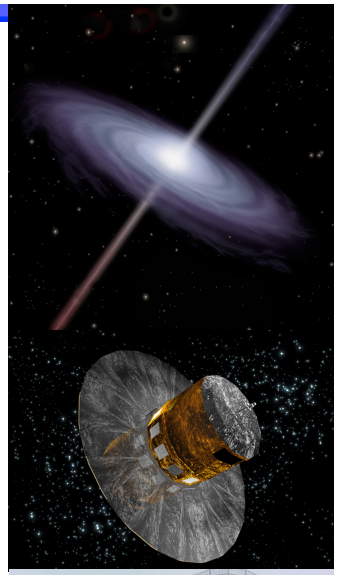
  Thermal emission (i.e. accretion disk) or non-thermal (relativistic jets)?

- Origin of the relativistic jets observed within AGNs?

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



Conclusion – Summary



<u>By 2020</u>: Gaia Celestial Reference Frame

~20 000–50 000 QSOs

~0.3–0.5 μas/yr

16 μas ≤ σ ≤ 70 μas (mag ≤ 18)

<u>Currently</u>: VLBI Celestial Reference Frame (ICRF2)

= IAU fundamental CRF

By 2020, probably improved → ICRF3

Optical-radio alignment

Fundamental point to ensure the continuity of the CRF

Feasible to better than 100 μas (Mignard 2008, 2012)

Before Gaia → Based on ICRF2 and dedicated VLBI & optical observations

During Gaia → Quasi-simultaneous observations planned (Gaia scanning law)

Astrophysical interest (core-shifts)

Thanks for your attention …