# Building a CRF with Gaia

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CRF : Celestial Reference Frame

# Goal & Outline

- Explain the reference frame issue with Gaia and how one will construct an ICRF in the optical domain

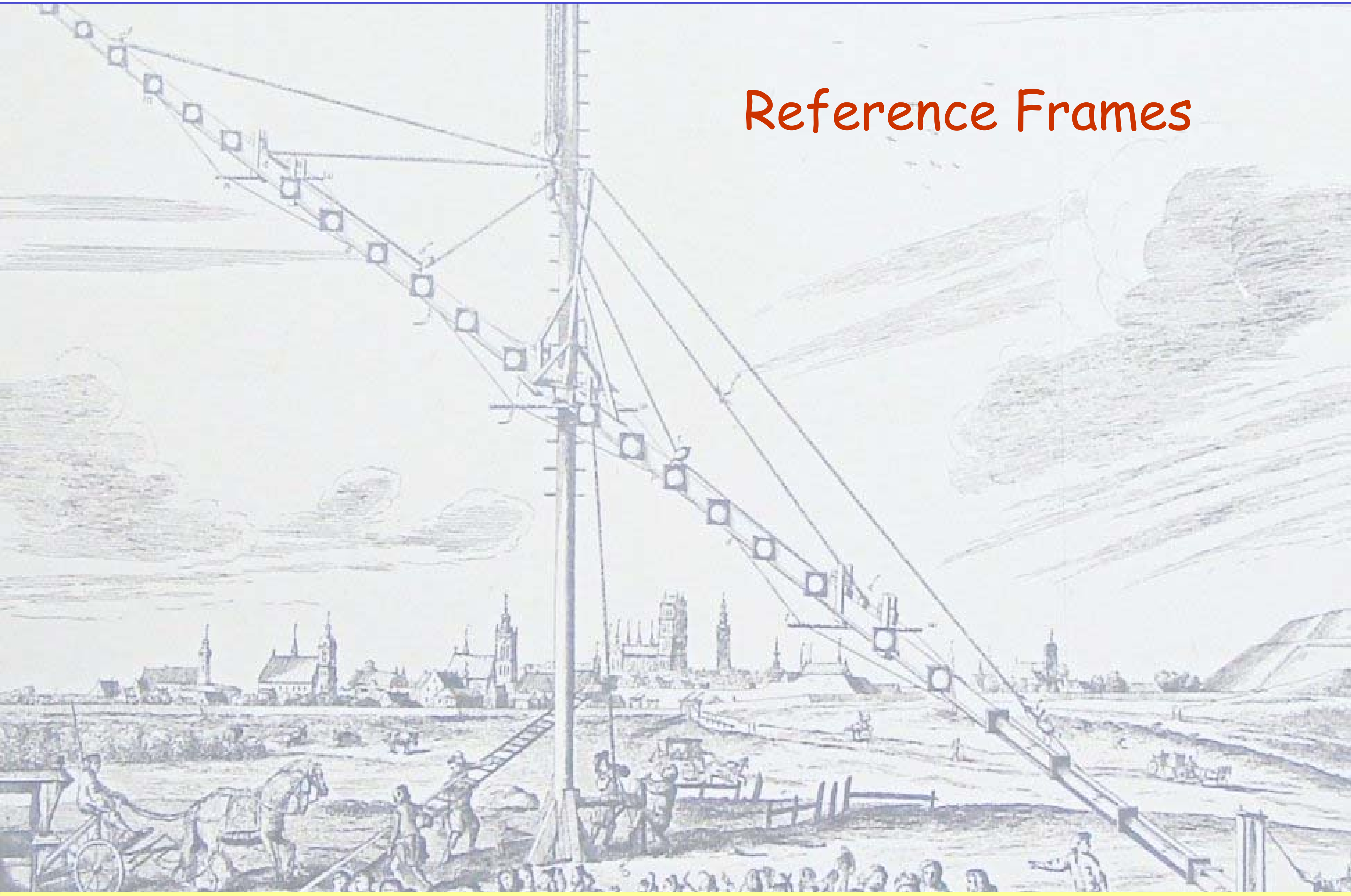
Lecture 1:

- reference frames and fundamental catalogues
- QSOs with Gaia
- QSO catalogues
- Building the Gaia ICRF : principles

Lecture 2:

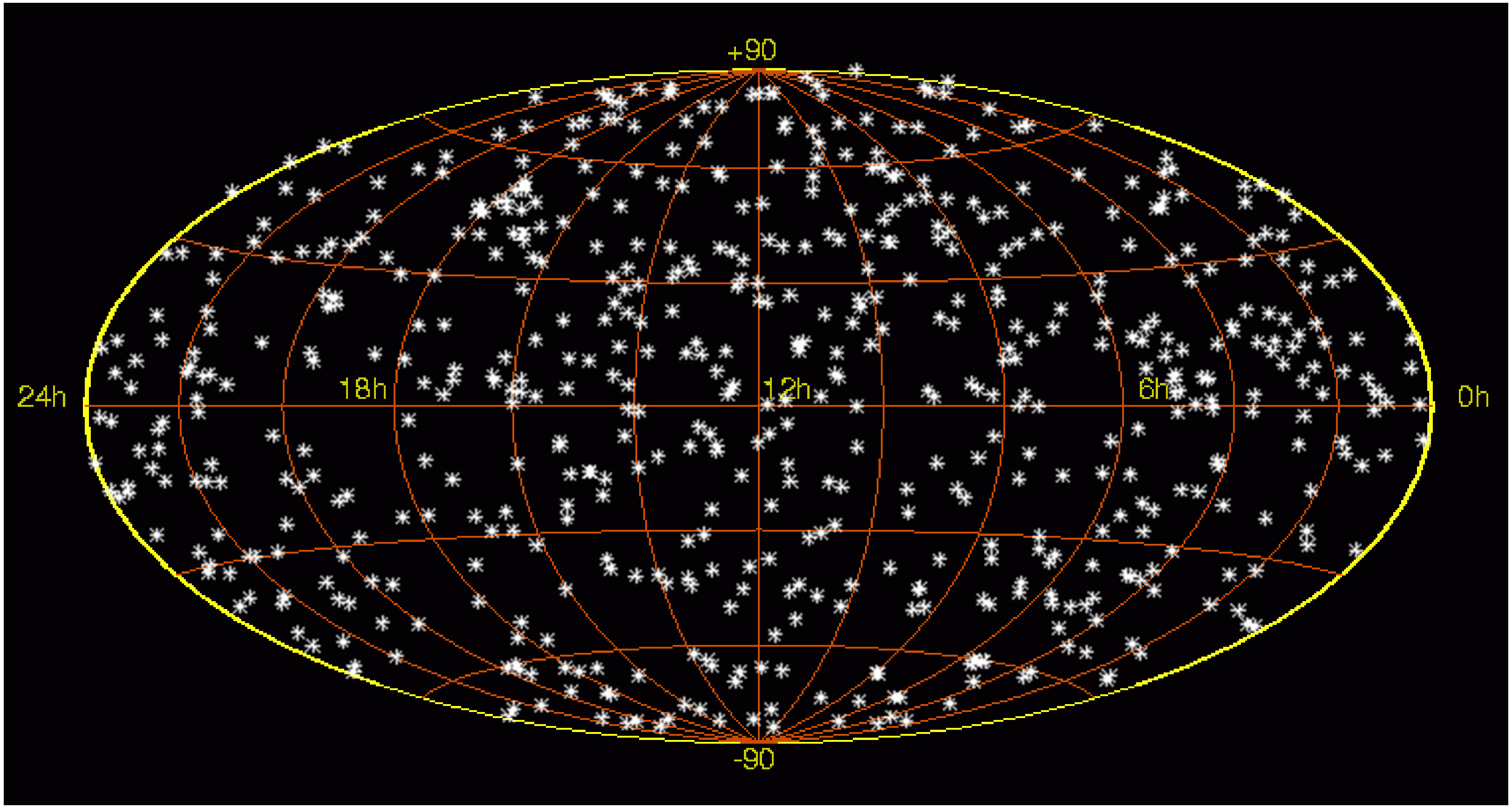
- Gaia Global Astrometry solution
- Infinitesimal rotations
- Spin of the Gaia frame
- Alignment of the Gaia frame to radio ICRF

# Reference Frames



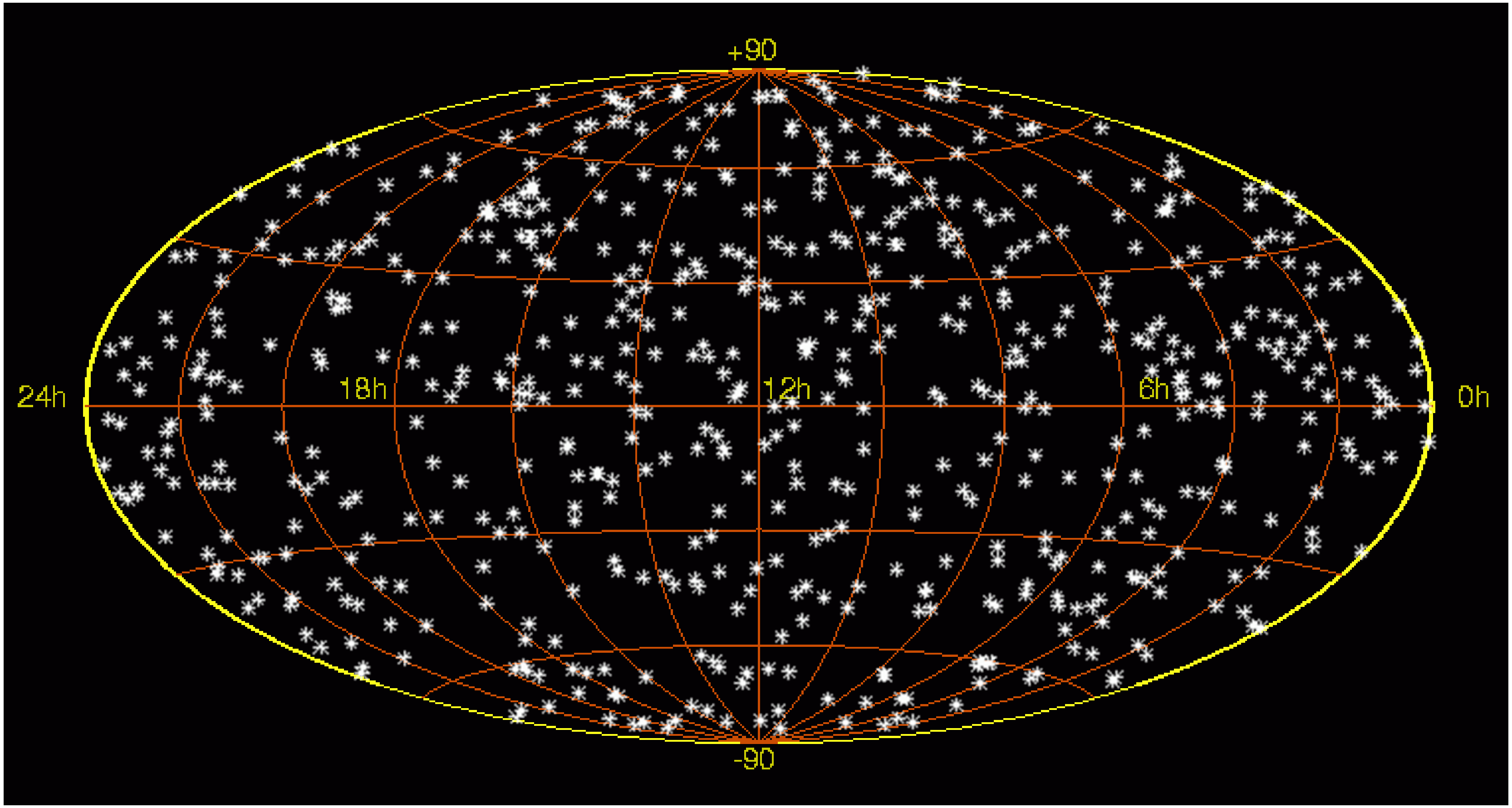
# Reference frame : standard view

- Pre-existing reference graticule

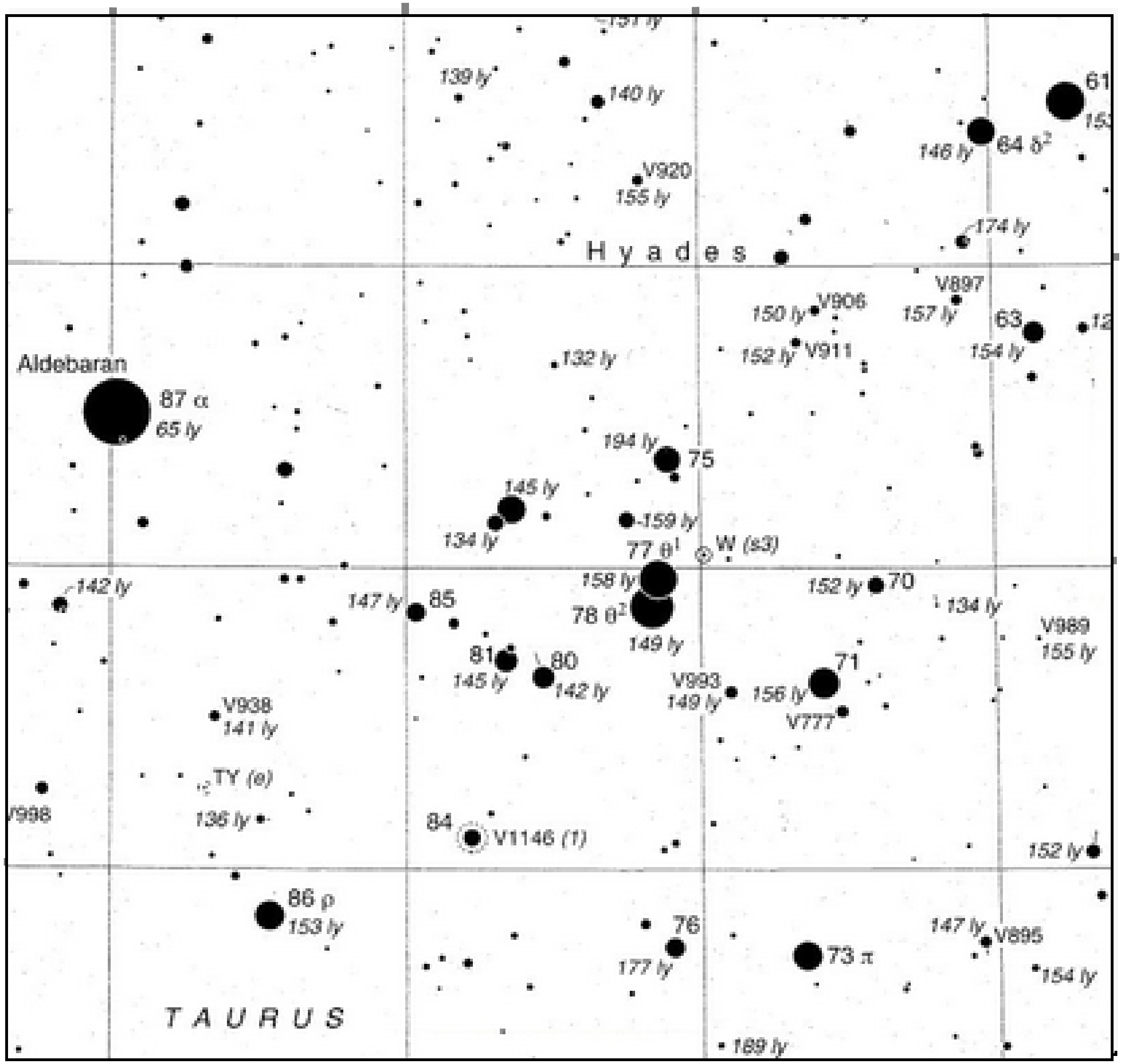


# Reference frame : fundamental view

- Stellar sources as fiducial points



# How to plot a star atlas




- One read star coordinates α, δ are read in a catalogue
- someone created this catalogue
- One must draw the map grid in the background
- No direct access on the sky
- What comes first : the stars or the reference grid ?
- One needs fundamental observations at some point
  - Hipparcos, Gaia

# Classical Astronomical Reference Frames

- Astronomical catalogues
  - Large full sky astronomical catalogues widely available in 1970
    - BD (1860) & Cordoba (1890) with 700,000 stars
    - HD (Henry Draper) since 1920, 230, 000 entries with spectral type
    - SAO (1966) with 270,000 stars with positions and PM
  - Positions and PM based on an existing reference frame
- Fundamental catalogues
  - Absolute observations with no reference to previous determinations
  - Historically tied to the equator and equinox at a particular epoch
    - assumed to provide absolute and inertial orientation
  - observations of the Sun or planets mandatory

# Fundamental Catalogues

- Small catalogues, many years of tedious labour to get absolute positions

| | | | |
|---|---|---|---|
| - 1790 | Maskelyne | 36 | zodiacal stars, one epoch |
| - 1818 | Bradley/Bessel | 3000 | no PM, nearly fundamental |
| - 1830 | Bessel | 36 | with PM, + precession |
| - 1878 | FK1 | 539 | |
| - 1898 | Newcomb | 1297 | Start of the GC series |
| - 1907 | FK2 | 925 | |
| - 1937 | FK3 | 873 | 1st IAU supported international RF |
| - 1963 | FK4 | 1535 | $\sigma_{1950}$ ~ 0"07- 0"15, $\sigma_{2000}$ ~ 0".15-0"30 |
| - 1988 | FK5 | 1535 | $\sigma_{2000}$ ~ 0".05 - 0"10 |
| - 1997 | Hipparcos | 100,000 | (quasi fundamental) |
| - 1998 | ICRF | 212 | |
| - 2009 | ICRF2 | 295 | |

# Limitations of the classical approach

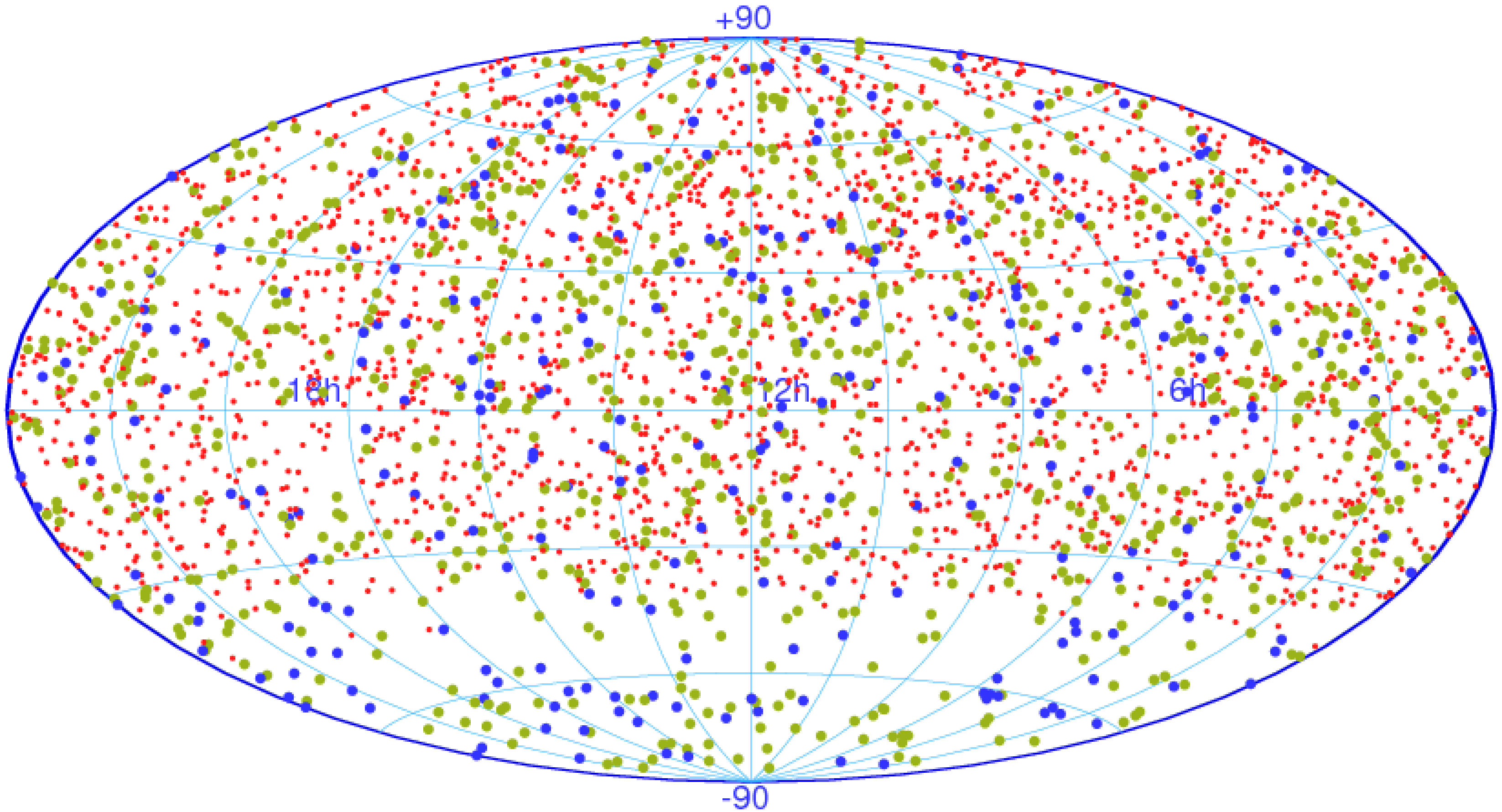
- System defined with equator and equinox
- precession and nutation modelling
  - fixed frame linked to solar system with equinox
- Observations from the ground
  - many stations needed to cover the sky
  - disturbances from the atmosphere
  - go to space for global astrometry ➔ Hipparcos
- System based on stars
  - problems with proper motions, multiplicity
- distant sources ➔ already considered by W. Herschel & Laplace
  - Adopted in ~ 1990 with ICRS and ICRF1 in 1998, ICRF2 in 2009

# *ICRF-2 (2009)*

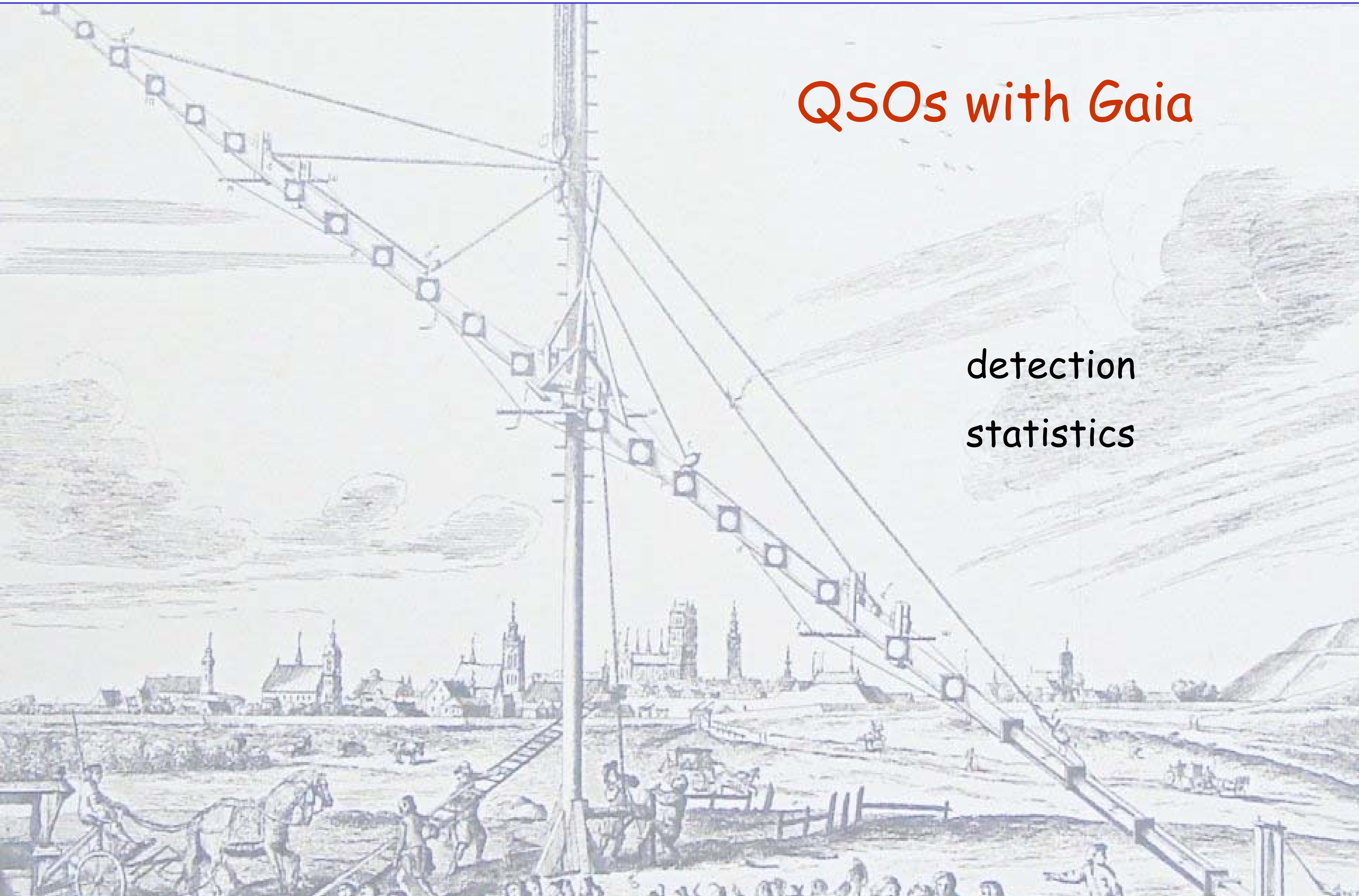
σ~ 50 to 150 μas

σ~ 0.2 to 2 mas

σ~ 0.5 to 10 mas




- defining (294)
- VLBI (923)
- VLBA Calib. (2197)



# QSOs with Gaia

detection

statistics

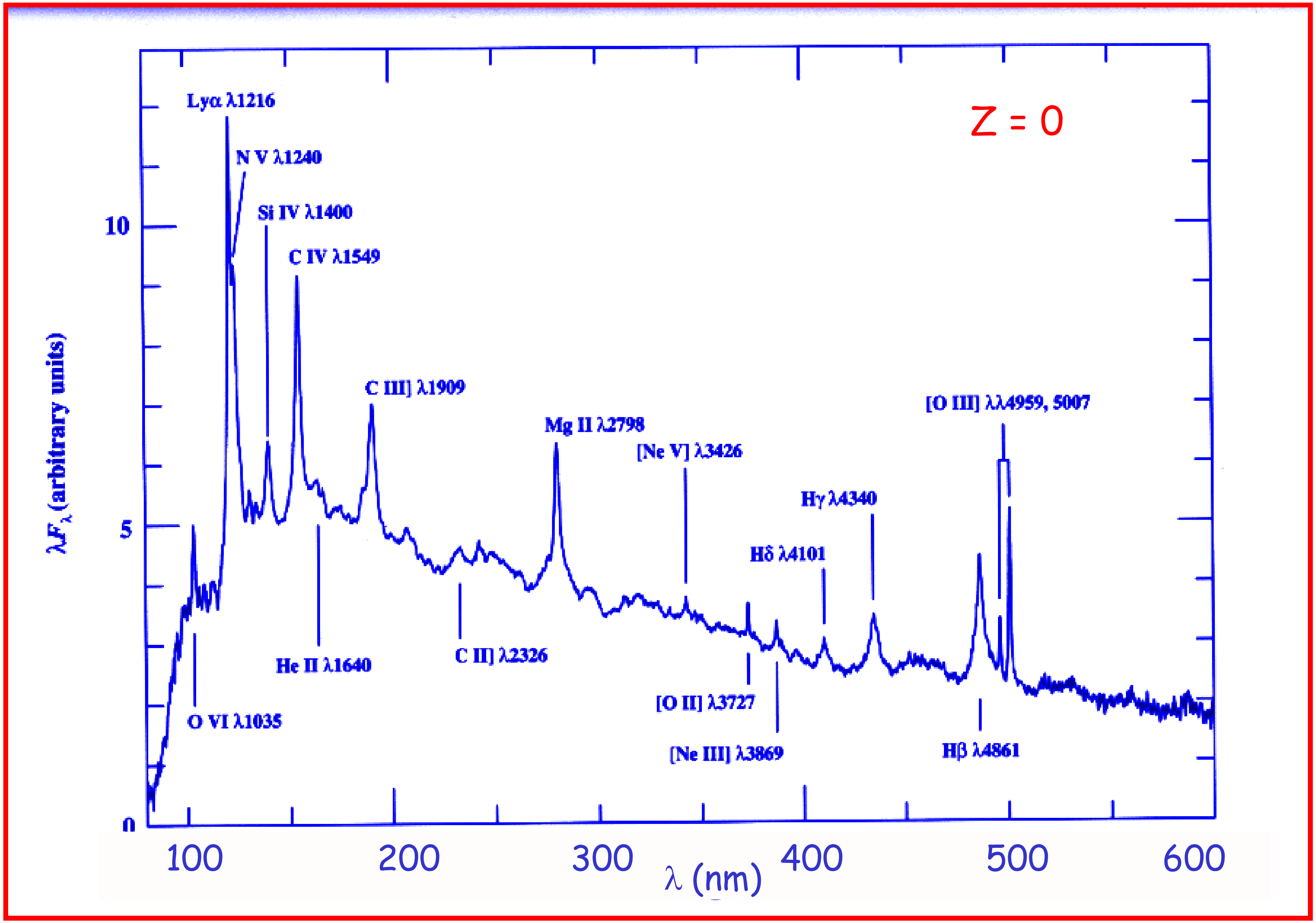
# Fact Sheet on QSOs

- Most luminous objects in the Universe
  - $10^{11}$ - $10^{14}$ $L_{sun}$ ; 1 to 1000 $L_{galaxy}$ ; $M_B$ ~ -23 to -30 ; $10^{37}$-$10^{41}$ W
- Radio loud ( *quasars*) or radio quiet (*QSO*)
- Variability over days to months
  - size of the emitting core ~ few solar systems to 0.1 pc
- Seen at great distance, then large redshift
  - $0 < z < 5$ ; > 10 billions years in the past
- Paradigm for their structure
  - accretion onto a massive black hole ($10^8$ solar mass)
  - one Sun per year is swallowed to sustain the luminosity
    - $Mc^2$ / 1 yr = 2x $10^{47}$ J / 3x$10^7$ s ~ $10^{40}$ W = $10^{47}$ erg $s^{-1}$

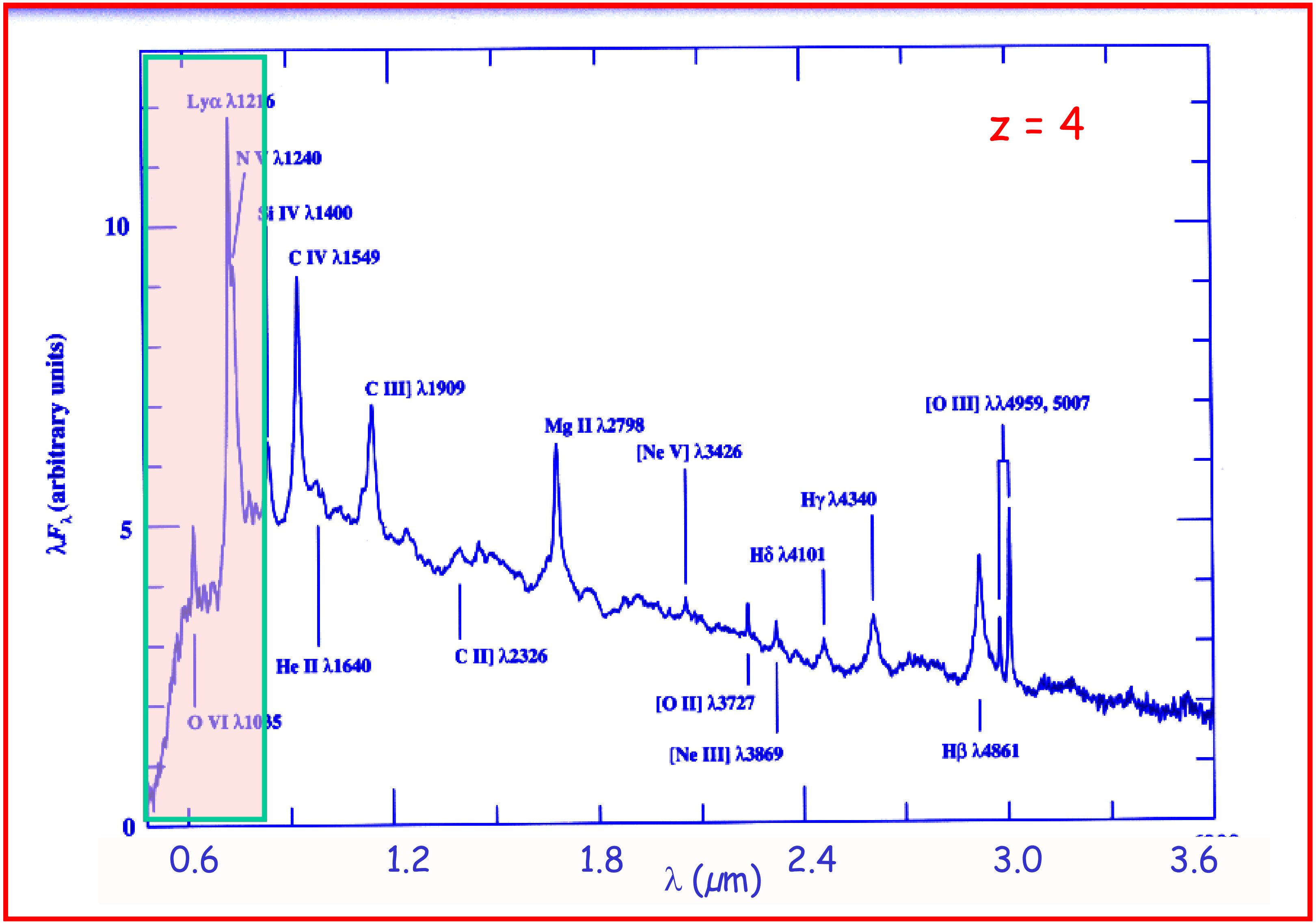
# Fact Sheet II

- Difficult to identify from the stars:
  - point like source, with faint and diffuse host galaxy
  - Faint, rare and starlight aspect on plates or CCDs
- Energy distribution : different from stars
  - $10^{11}$ - $10^{14}$ $L_{sun}$ ; 1 to 1000 $L_{galaxy}$ ; $M_B$ ~ -23 to -30
  - Strong and broad emission lines (E.W. ~ 60 Å ~ 10 000 km/s)
  - Blue bump
- This difference is the key feature for identification with Gaia

# Energy distribution



# Energy distribution

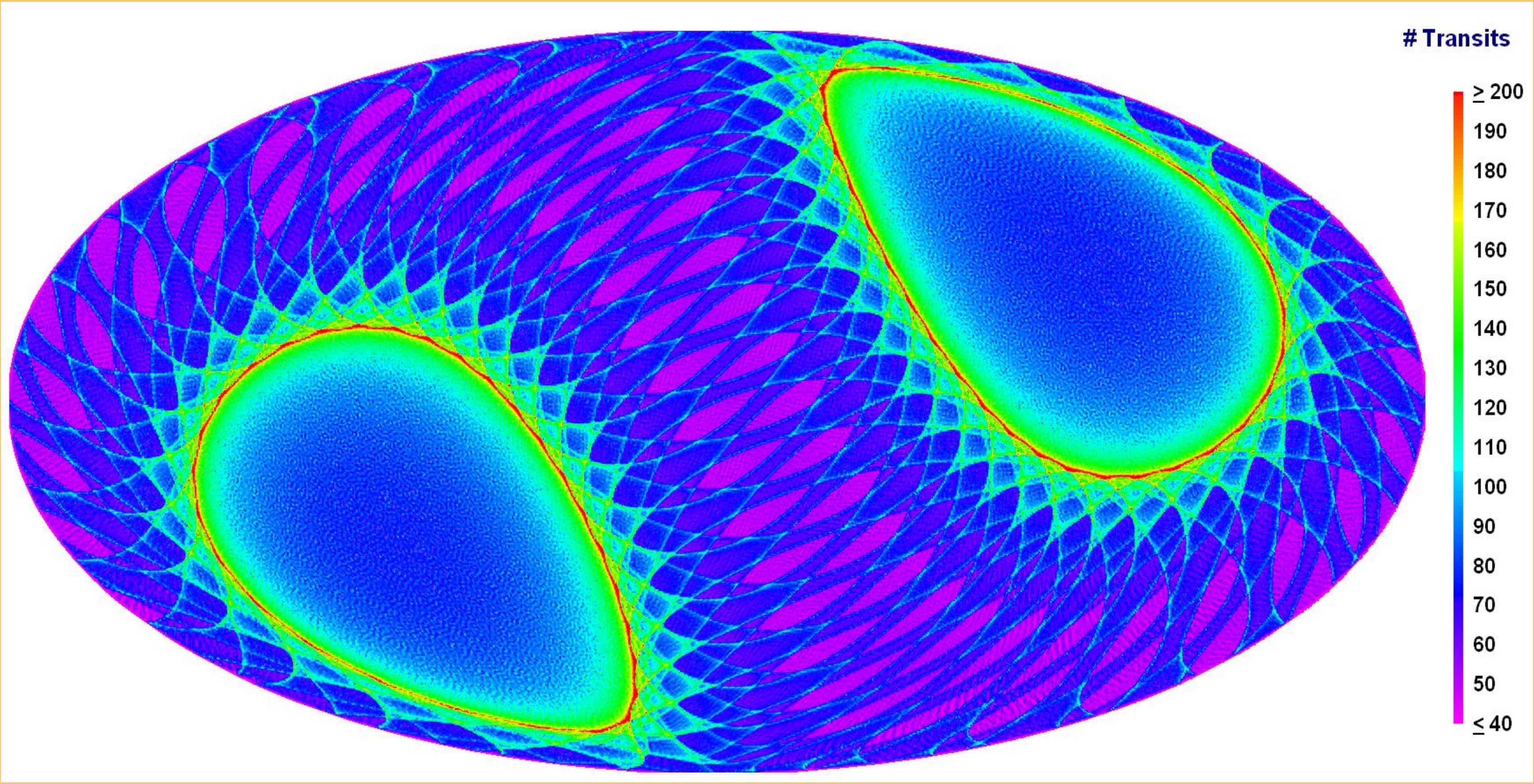


# Observation of QSOs with Gaia

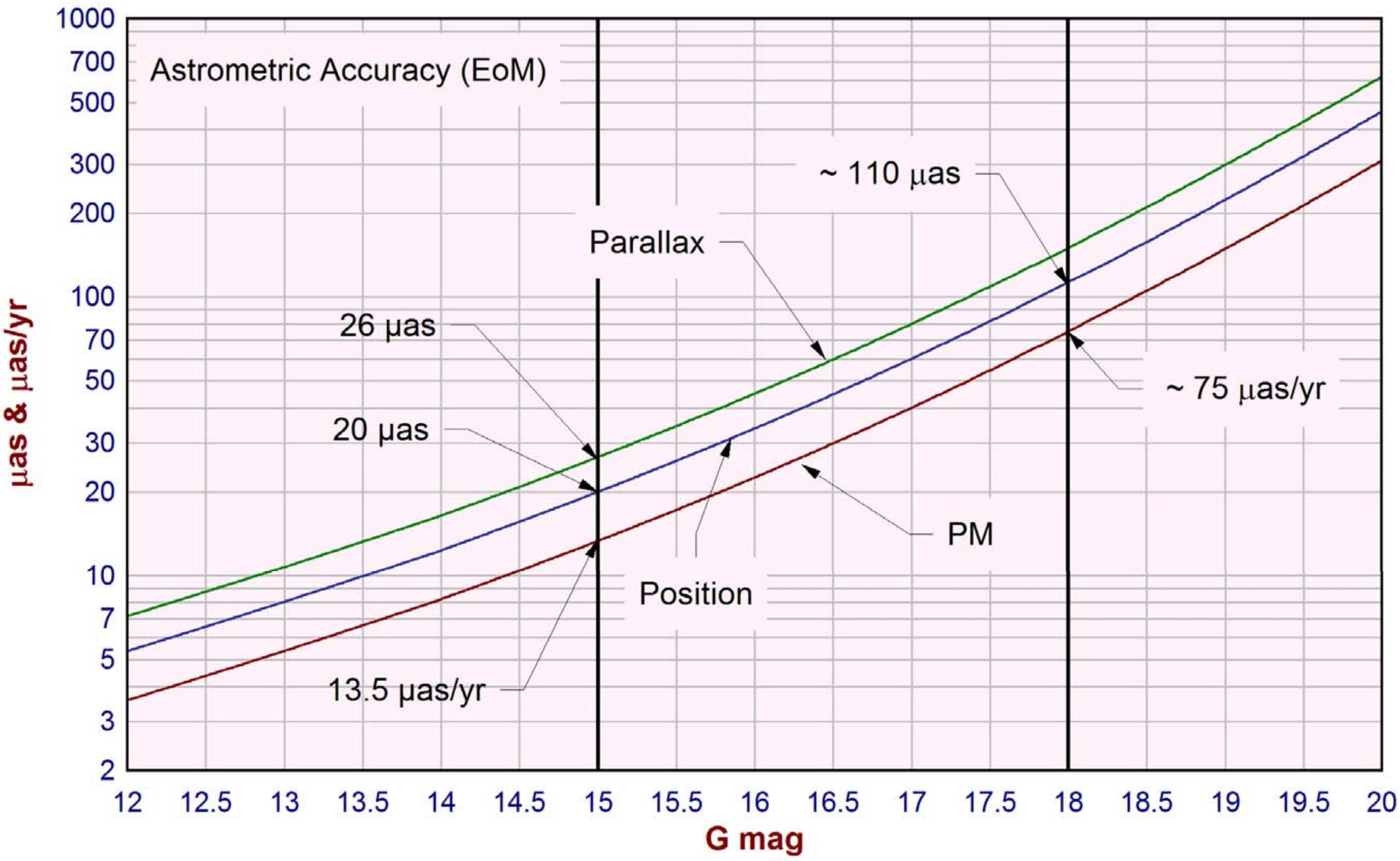
- QSOs will be observed like stars
  - point like sources
- They will be detected in the Sky Mapper when G < 20
- Sky coverage and astrometric performances will be the same as for stars of same magnitude
  - no specific colour problems are expected
- They will be observed about 80 times
  - distributed more or less regularly during the mission
  - min ~ 45 times, max ~ 150 times
- Astrometric and photometric processing will be standard
  - global solution for astrometry
  - epoch photometry at each transit

# Observation distribution (galactic coordinates)

- Time average is a combination of the sky distribution and the scanning law
  - two different symmetries: galactic plane and eclitpic plane

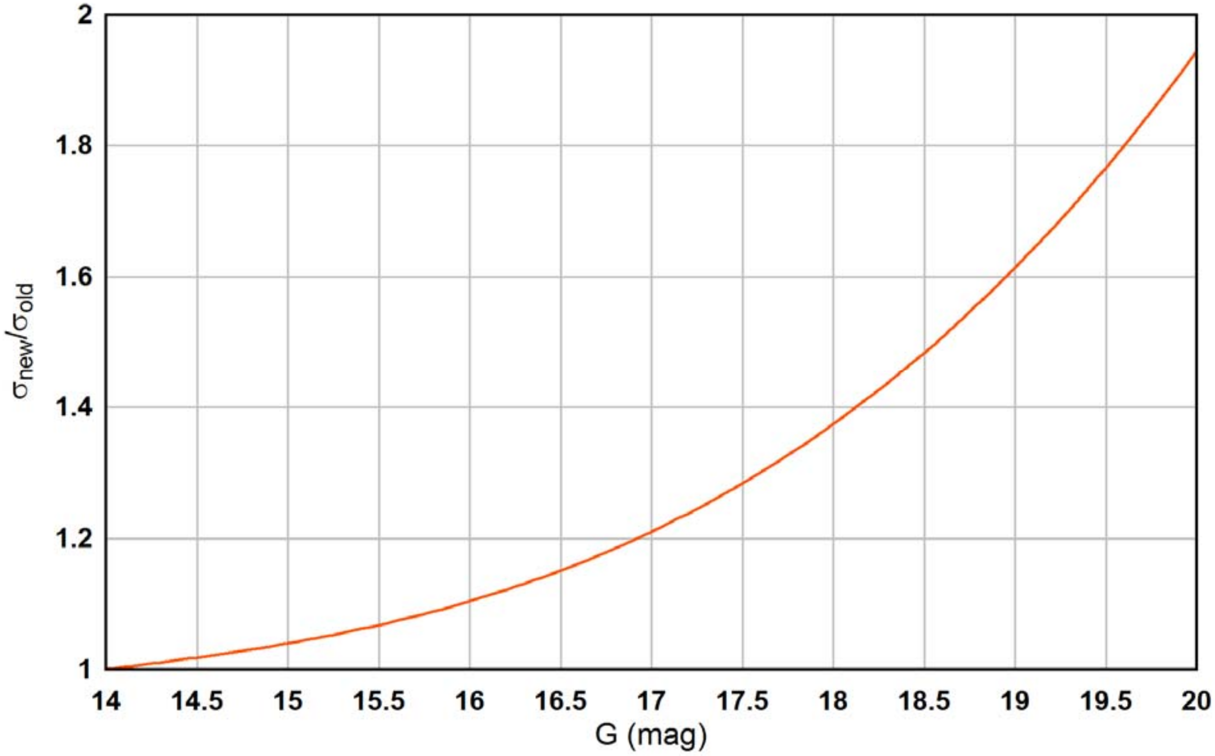


# Astrometric Accuracy : EOM (up-to-date)



# Actual mission: Astrometric loss

- Straylight coming from the Sun and the sky background
  - although this remains very small, it impacts the final accuracy
    - less for astrometry than photometry
    - less for photometry than for spectroscopy



# QSO recognition with Gaia- I

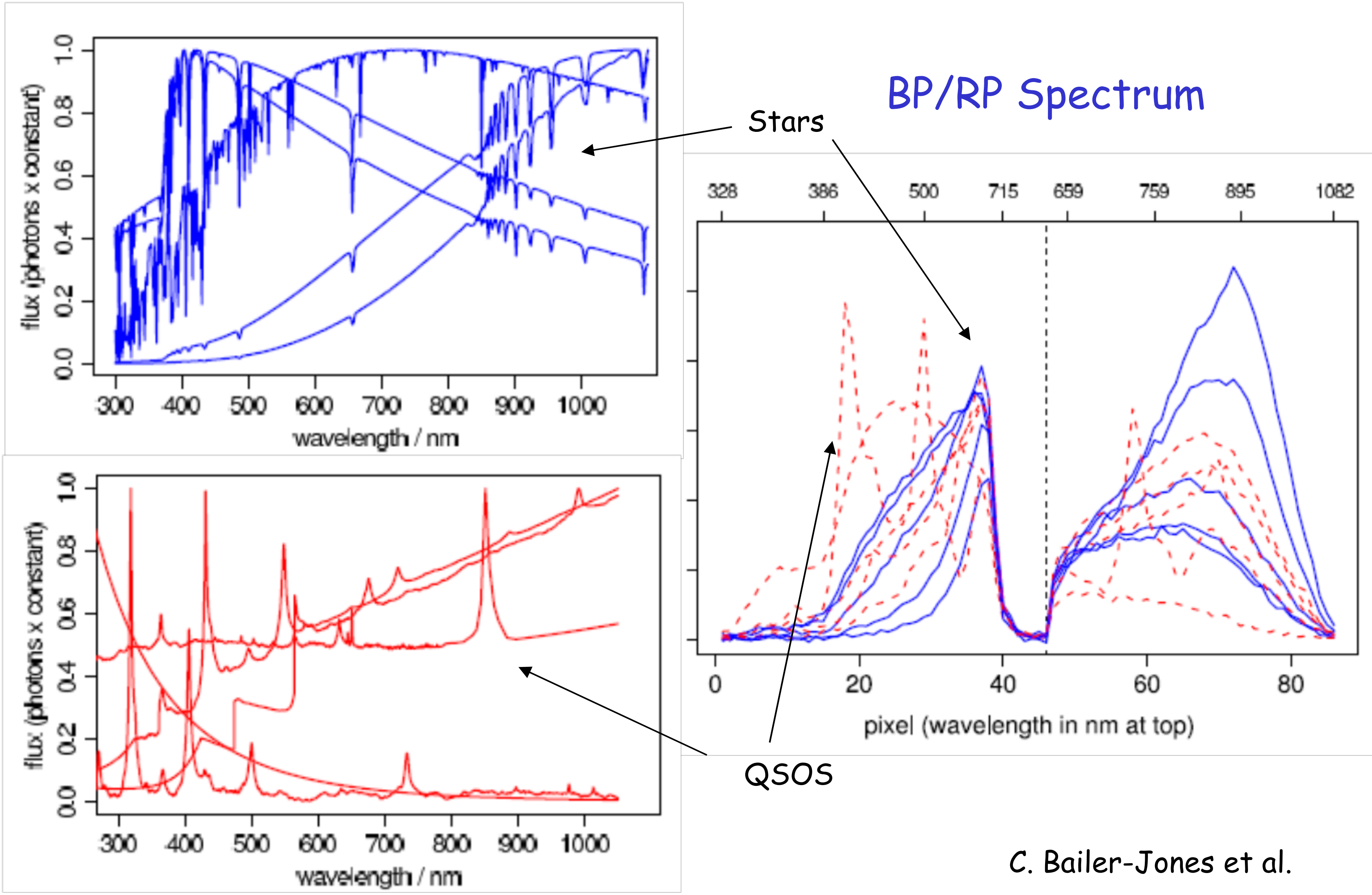
- ~ 2/3 of the QSOs of the Gaia survey will be new
- They must be identified by a built-in mechanism
- The baseline is photometric identification
  - use of the BP/RP dispersed images
- Additional hints
  - proper motion
  - parallaxes (of non QSOs)
  - host galaxy ?
  - ground based data

# QSO recognition with Gaia- II

- Two purposes:
  - Select a clean small sample of QSOs free of stellar contaminants
  - Identify the majority of the QSOs in not a so clean sample
- Remaining possible contaminants:
  - very red (M stars), or highly reddened stars
  - peculiar white dwarfs
    - could be removed with parallax and proper motions
- Classification methods very advanced

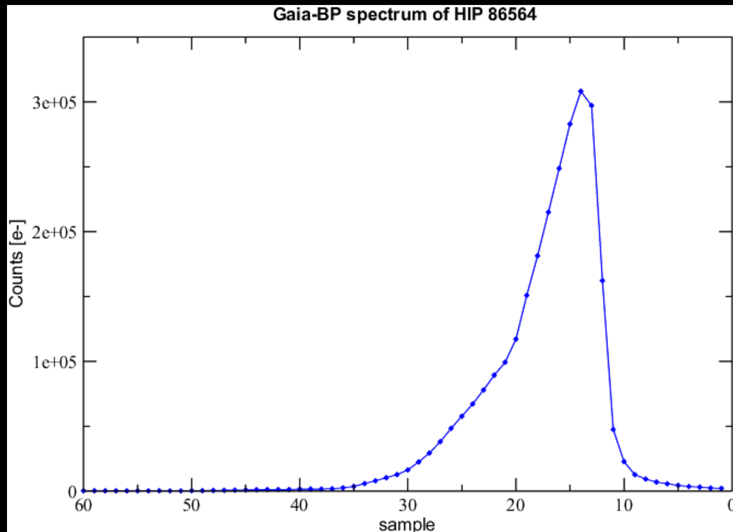
- Intensive activity over the last five years
  - led initially by J.F. Claeskens (Univ. of Liège, Belgium)
  - then continued by C. Bailer Jones and K. Smith in MPIA Heidelberg

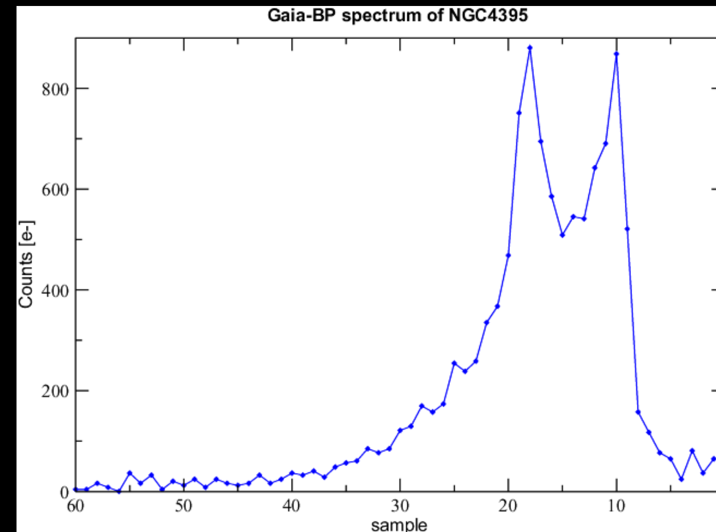
# QSOs in Gaia RP/BP - simulation

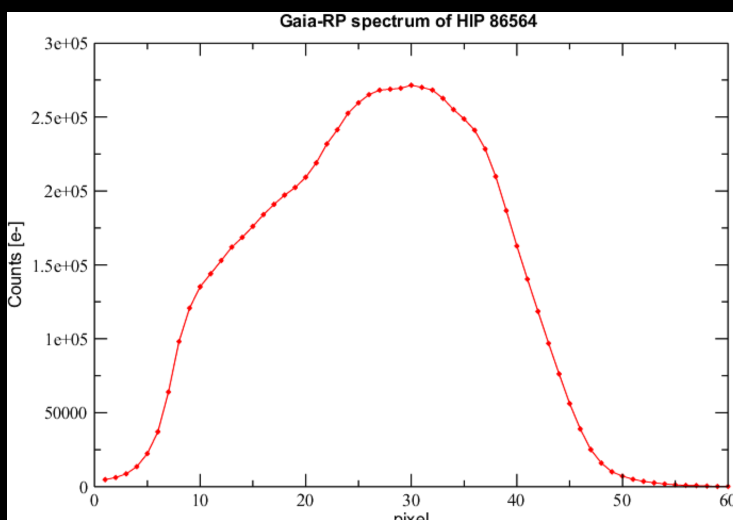


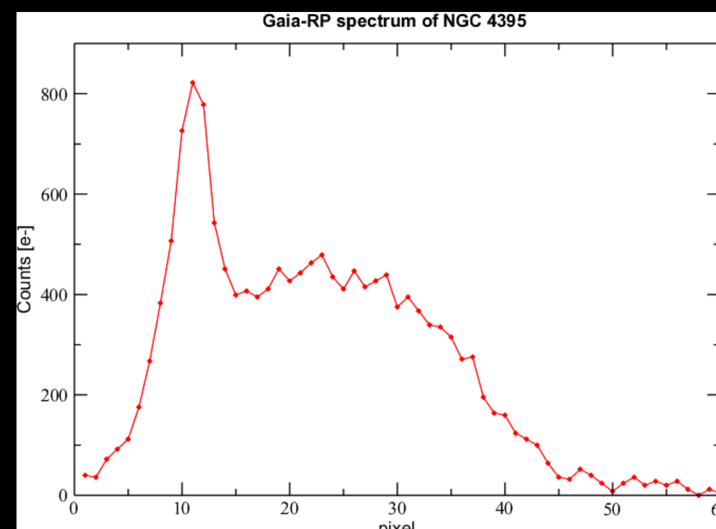

C. Bailer-Jones et al.

# *Etoile – Galaxie active avec Gaia*

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# Probability classification: principles

- An object will be a star, a galaxy or a QSO with a probability p
- Population with frequency ***f*** of QSOs and $H_0$ : source is a QSO
  - The test can wrongly reject a QSOs : risk of the test $\alpha$
    - 1- $\alpha$ : significance level
  - The test can keep a star in the QSO sample : risk of contamination $\beta$
    - 1 – $\beta$ : power of the test

| | | State | |
|---|---|---|---|
| | | QSO | Star |
| Found | QSO | $1-\alpha$ | $\beta$ |
| | Star | $\alpha$ | $1-\beta$ |

P(Q/FQ): this is a QSO when Found as a QSO

$$P(Q/FQ) = \frac{f(1-\alpha)}{f(1-\alpha)+(1-f)\beta}$$

P(S/FQ): this is a Star when Found as a QSO

$$P(S/FQ) = \frac{(1-f)\beta}{f(1-\alpha)+(1-f)\beta}$$

if $f \ll \beta$ then P(S/FQ) ~ 1 ! All purported to be quasars are indeed stars

**So the efficiency β must match the frequency of the QSOs**

With f ~ 1/2000 ➔ $\beta < 0.0005$

# Consequences

- A survey over 100 $deg^{-2}$ with a 1% error selection test will yield :
  - 2000 quasars (max) and
    - 30 000 stars at b = 0° ==> efficiency of 3%
    - 3000 stars at b = 60° ==> efficiency of 40%
- GAIA will observe ~ 500 000 QSOs G< 20
- ~ $10^9$ stars : so classification test better than $2 \times 10^{-3}$

# Current performances

- G > 17 for this test

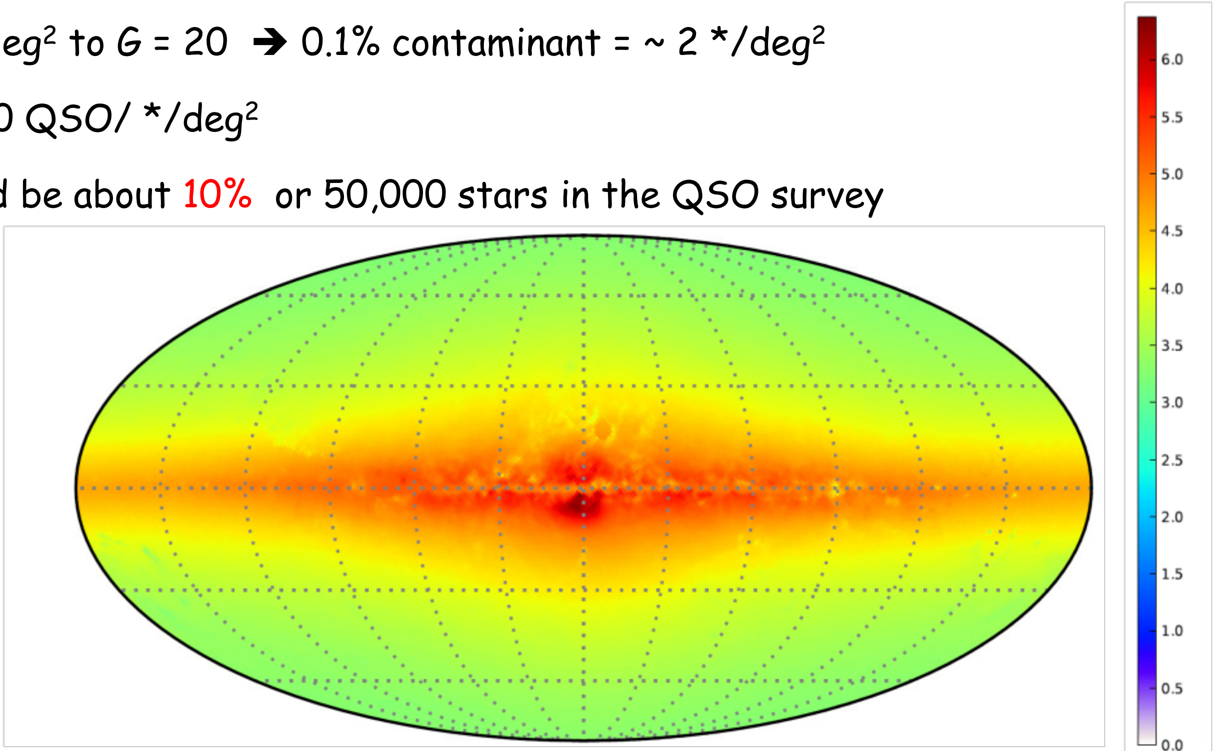
| kind \ found | Star | QSO | Galaxy | unknown | total |
|---|---|---|---|---|---|
| Star | 82 | 0.1 | 2 | 16 | 100 |
| QSO | 1.2 | 81 | 2 | 15 | 100 |
| Galaxy | 1.3 | 0.1 | 92 | 6.5 | 100 |

- For QSOs
  - Completeness ~ 80%
  - Contamination level ~ 0.1% by stars

credit: K. Smith

# *Absolute contamination*

- Pessimistic approach : 0.1% of the stars are wrongly classified as QSOs
  - $10^9$ stars ➔ 1 million will fall in the QSO basket !
  - This amounts to 200% contamination in the survey
- More realistic approach : most stars are close to the Galactic plane, where QSOs are not seen
  - Sky outside galactic plane, nearly empty
  - Typically 1000 – 3000 */deg$^2$ to $G$ = 20 ➔ 0.1% contaminant = ~ 2 */deg$^2$
  - for QSO one has about 20 QSO/ */deg$^2$
  - True contamination should be about 10% or 50,000 stars in the QSO survey




Robin et al., A&A, 2012

Gaia Universe Model to G =20

log n

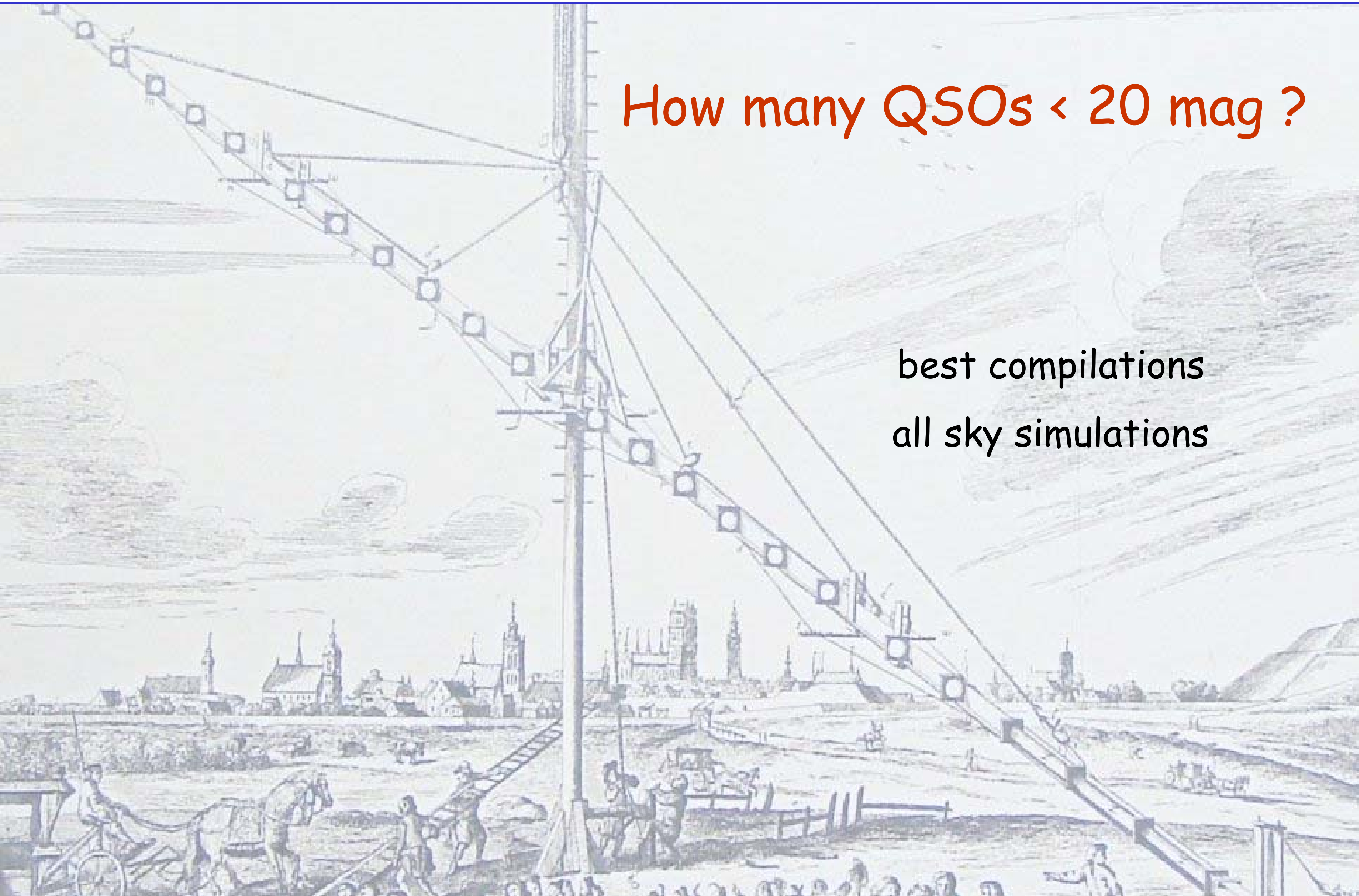
# Summary of the Selection

- Gaia detects and observes all the sources V < 20
- There are ~ $6 \times 10^5$ QSOs observable outside the galactic plane
- They are recognized from the stars with the photometric data
  - success rate > 99.9%
- A clean subset will be used for the primary reference frame
  - One assumes that there is a frame with no global rotation
- Systematic effects will be investigated in the residuals

# How many QSOs < 20 mag ?

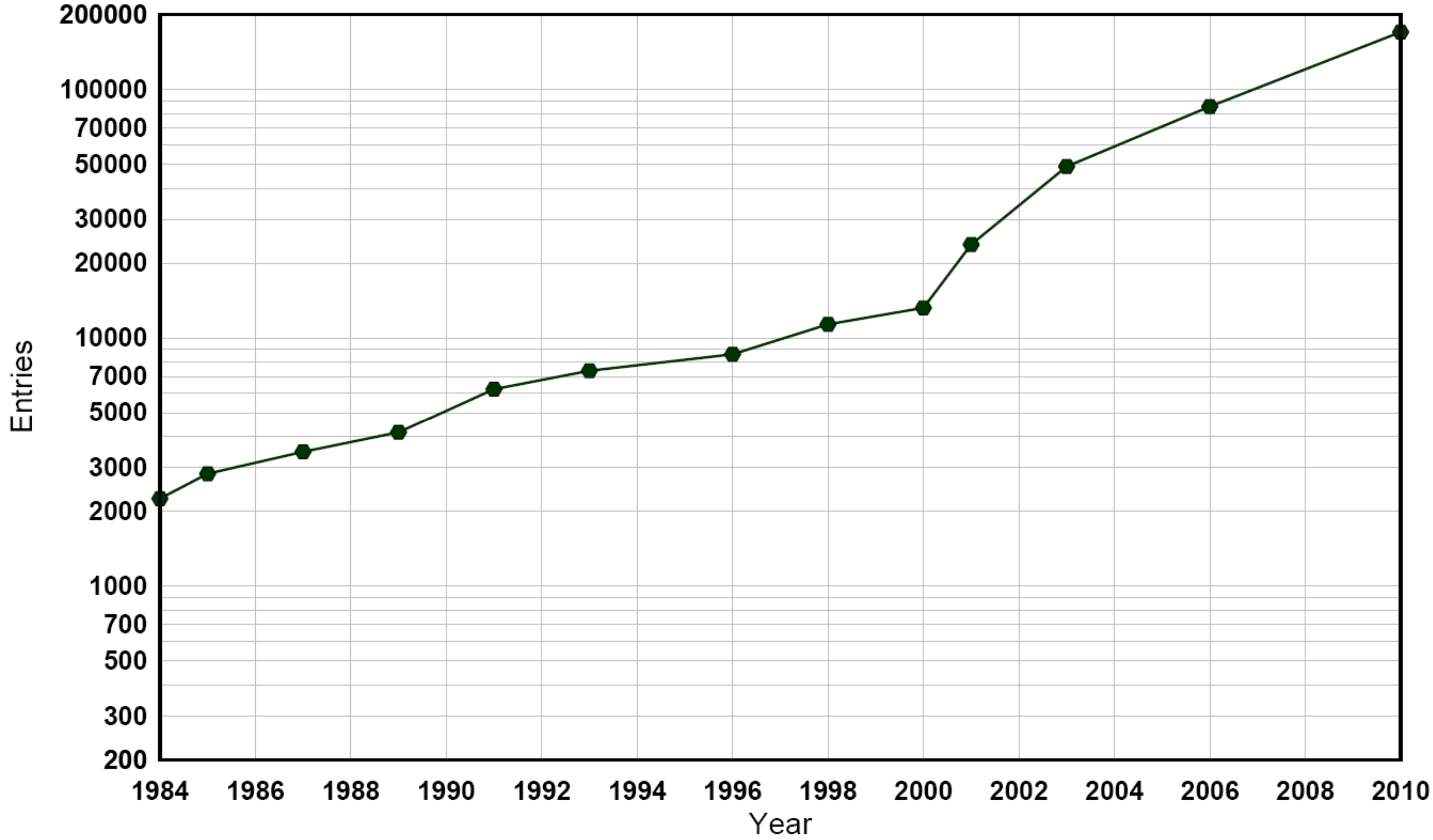
best compilations

all sky simulations



# Number of catalogued QSOs

- Number of entries in the Véron-Cetty – Véron releases
  - recent growth due mainly to SDSS

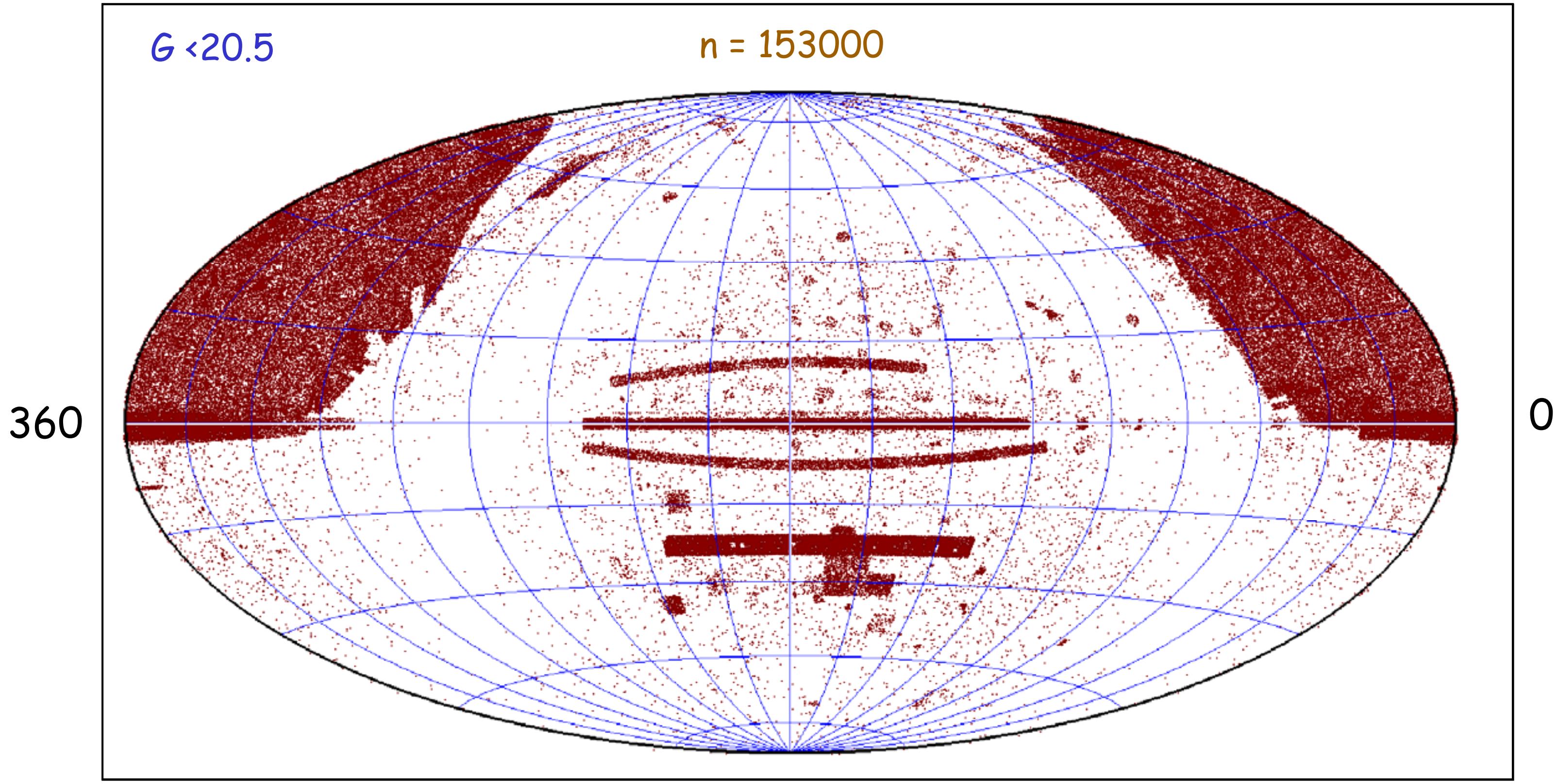



Mignard, 2012 - data from Véron-Cetty & Véron, A&A 2010

# Latest QSO compilation

Gaia DPAC

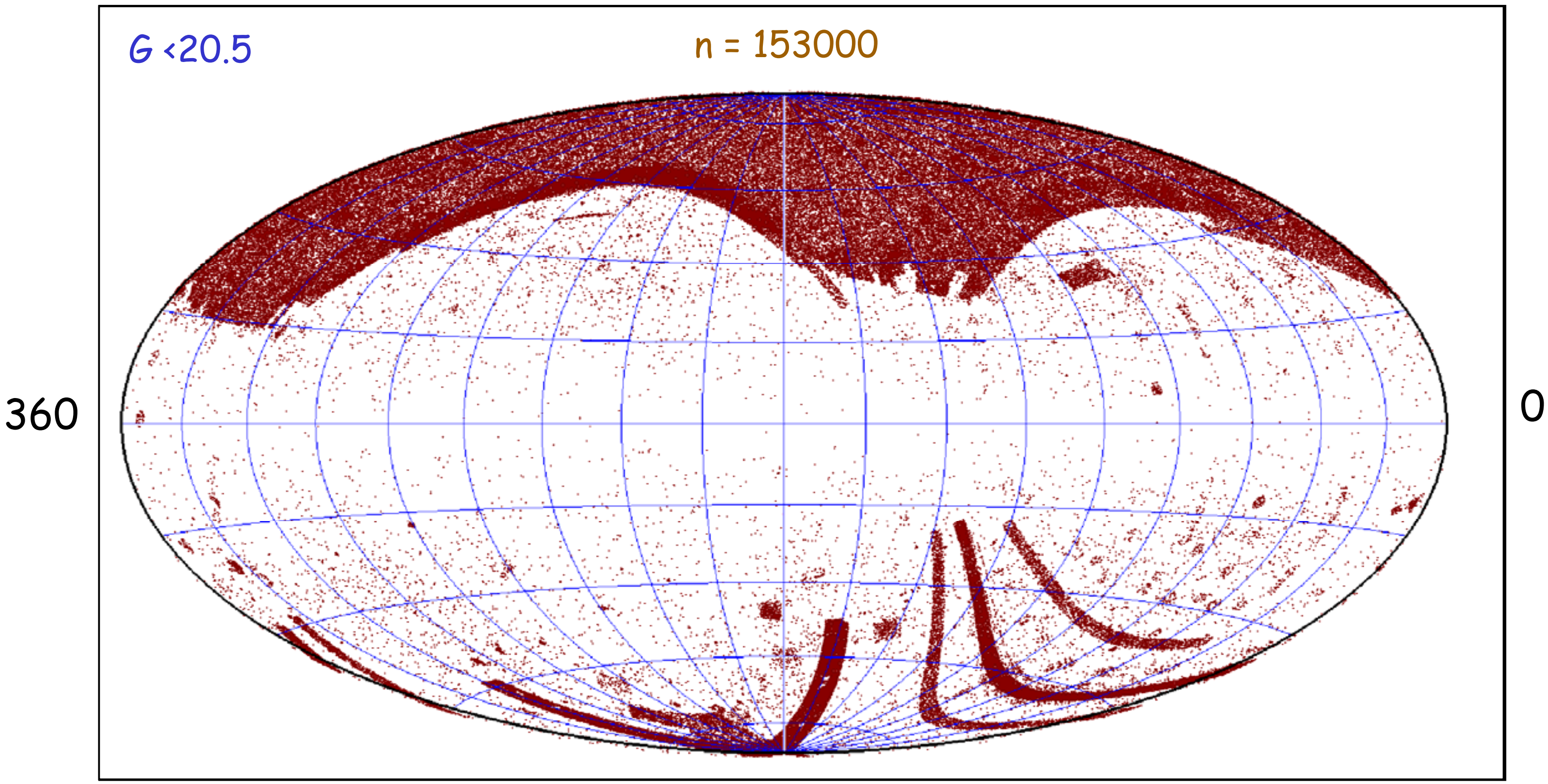
- Catalogue LQAC (Souchay et al, 2012)
  - Plots in equatorial coordinates
  - similar results with Véron & Véron (Véron et al., 2012)



# *Latest QSO compilation*

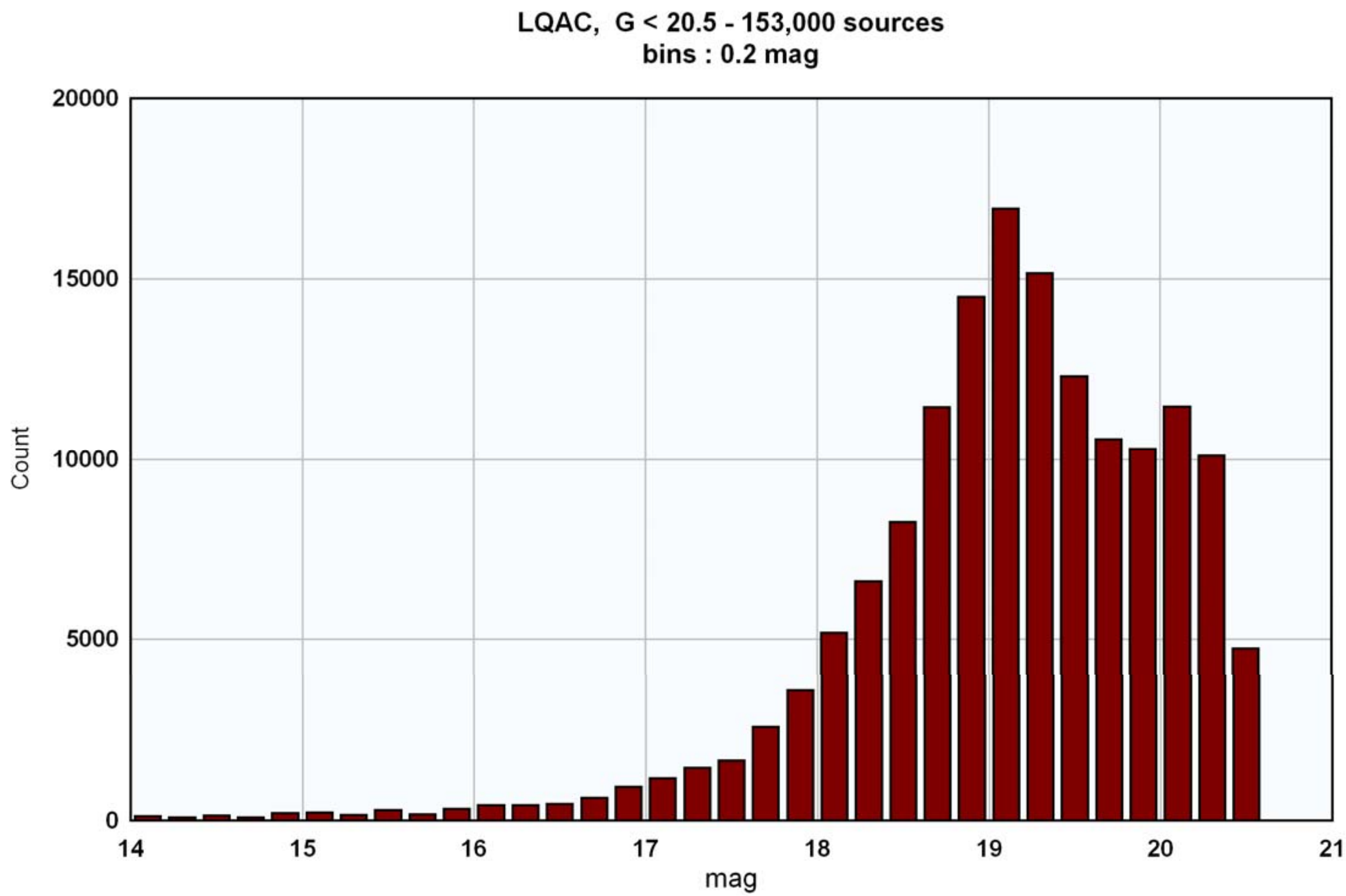
- Catalogue LQAC (Souchay et al, 2012)
  - Plots in equatorial and galactic coordinates

Equatorial Galactic



# G magnitude distribution

- Computed from colors available in LQAC
  - with magnitude transformations for Gaia (C. Jordi, 2008)
- Obvious completeness bias



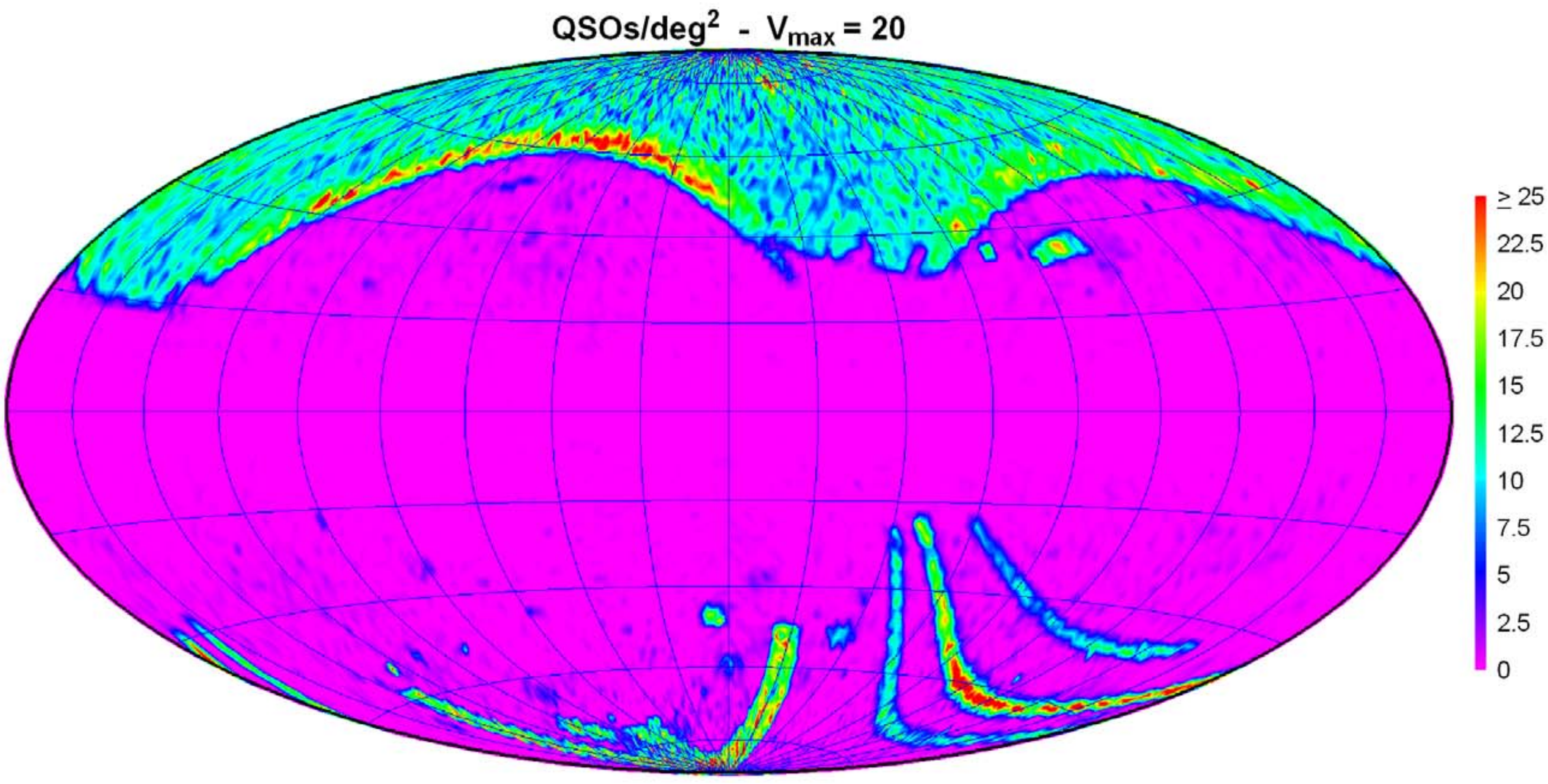
# How many QSOs on the whole celestial sphere

- Simple approach
  - LQAC has
    - 15800 G < 18 & 127000 G< 20
  - They cover roughly 25% of the sky
  - Therefore one may expect
    - 65000 G < 18 & 500, 000 G< 20

- Better evaluation
  - one assumes that the QSOs are uniformly distributed on the sky
  - Density in local deep surveys used to compute the expected number of QSOs per bin of magnitude and square degree
  - try to devise a robust estimate of this density

# Recent estimate of the density

- Robust estimate of the QSO density for G < 20




Mignard, 2012, Mem. Soc. Ast. It., 83,2012.

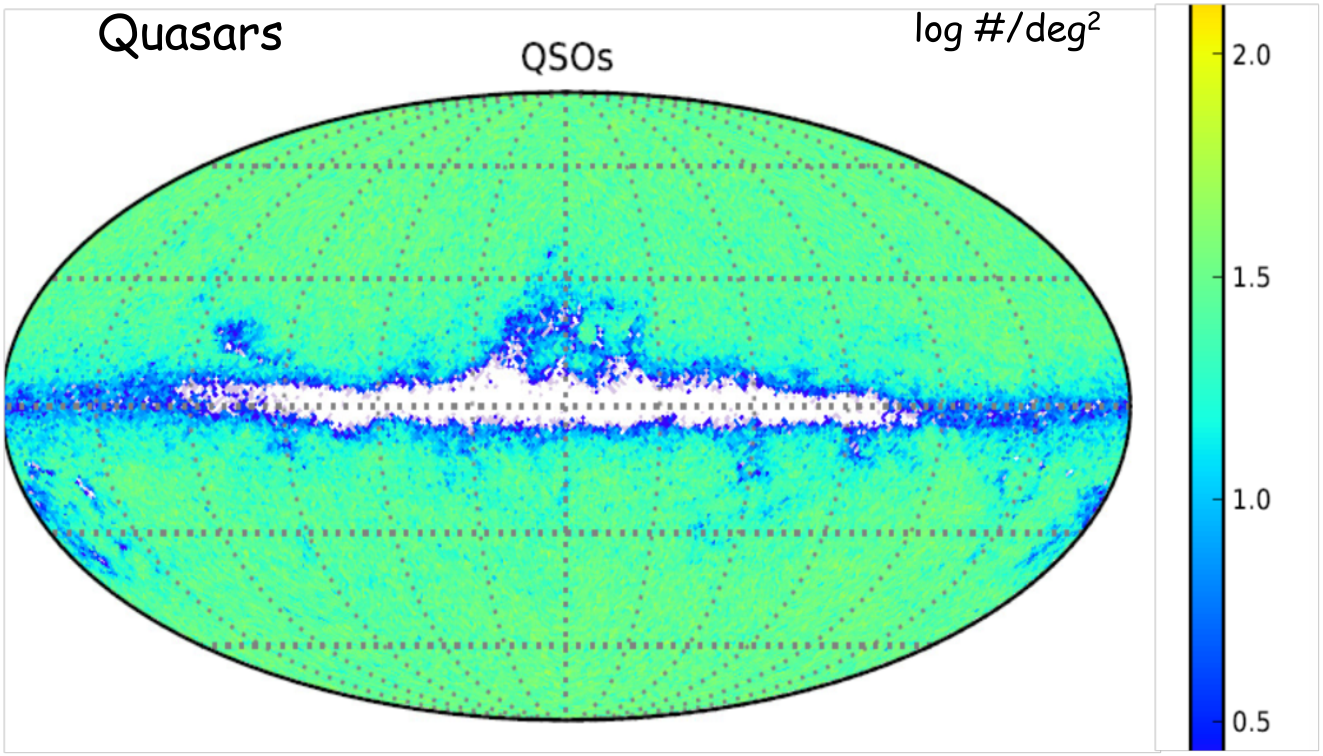
# How many new QSOs

- Density in local deep surveys used to compute the expected number of QSOs per bin of magnitude
- On subtracts the number in the current general catalogue
- assumption: QSOs have a uniform distribution on the sky

| V | density $deg^{-2}$ | Full sky # | 60% sky # | known # | new # | Slezak et.al # |
|---|---|---|---|---|---|---|
| 18.0 | 1.5 | 63 000 | 38 000 | 12 500 | 25 500 | 40 000 |
| 18.5 | 3 | 126 000 | 75 000 | 23 000 | 52 000 | 113 000 |
| 19.0 | 8 | 340 000 | 200 000 | 45 000 | 155 000 | 314 000 |
| 19.5 | 15 | 630 000 | 380 000 | 85 000 | 295 000 | 680 000 |
| 20.0 | 22 | 920 000 | 550 000 | 115 000 | 435 000 | 1 200 000 |
| 20.5 | 30 | 1 260 000 | 750 000 | 140 000 | 610 000 | 1 700 000 |

Mignard, 2012, Mem. Soc. Ast. It.,

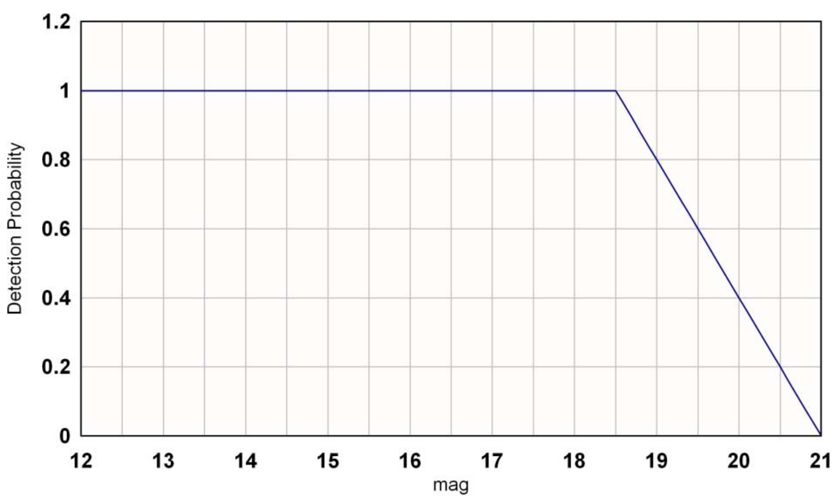
# Gaia Universe Model (GUM)



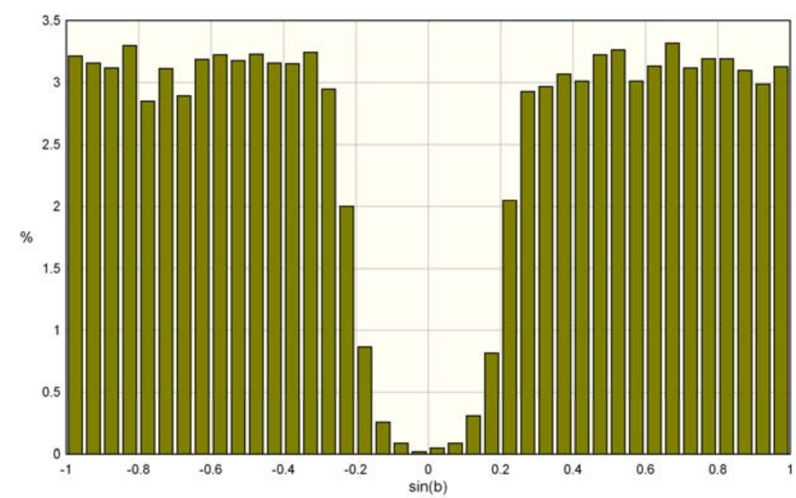

from Robin et al., 2012

# Selection of QSOs

- Start from the full-sky simulation to G = 20.5 from Slezak & Mignard
  - 1.7 x $10^6$ QSOs with realistic luminosity function
- Allow for a degrading recognition efficiency of Gaia at faint end
  - less sources will be recognized as genuine QSOs
- Lower the detection efficiency in the Galactic plane
  - crowding and absorption

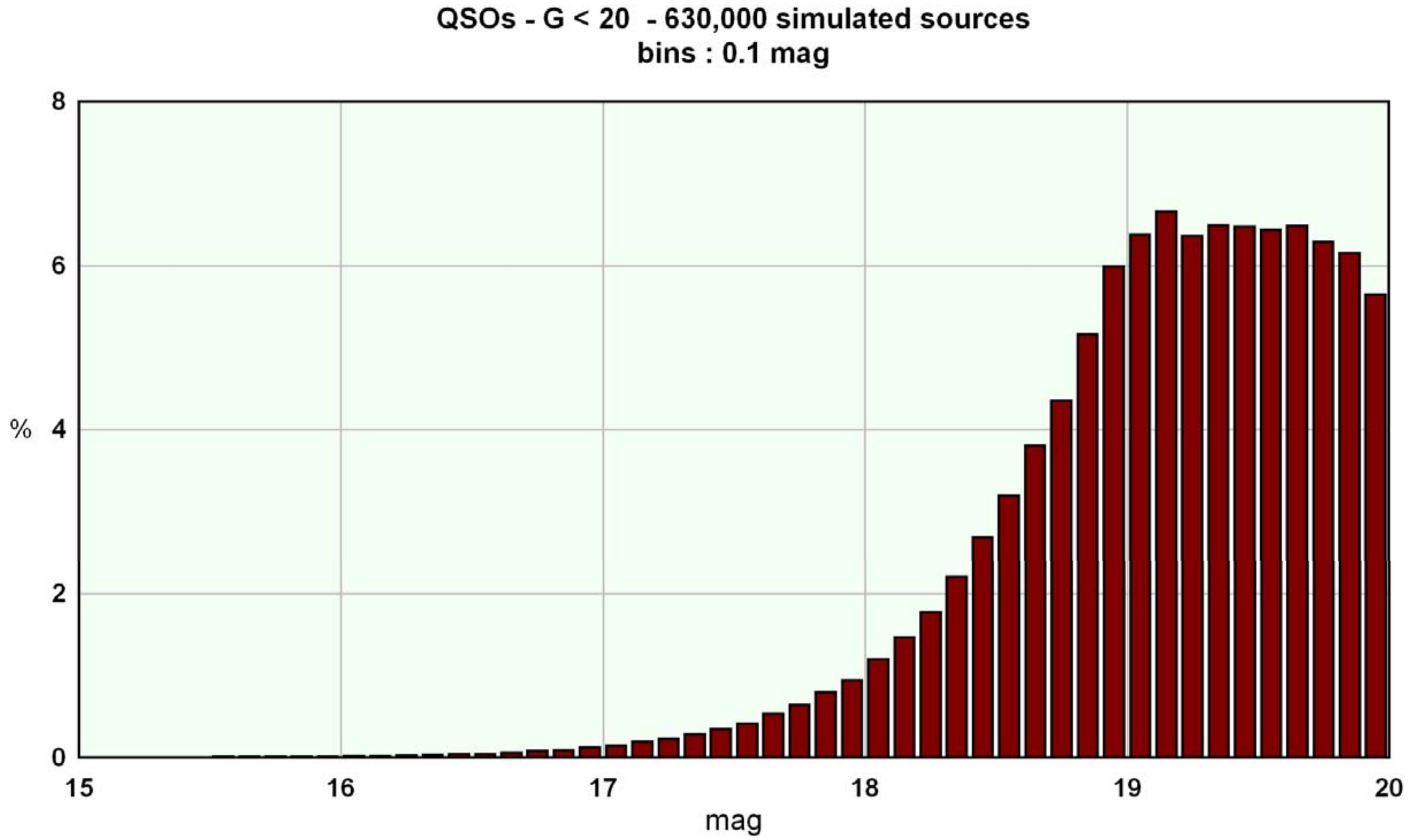


Probability that a QSO is selected by Gaia



Sin(b) distribution of selected QSOs

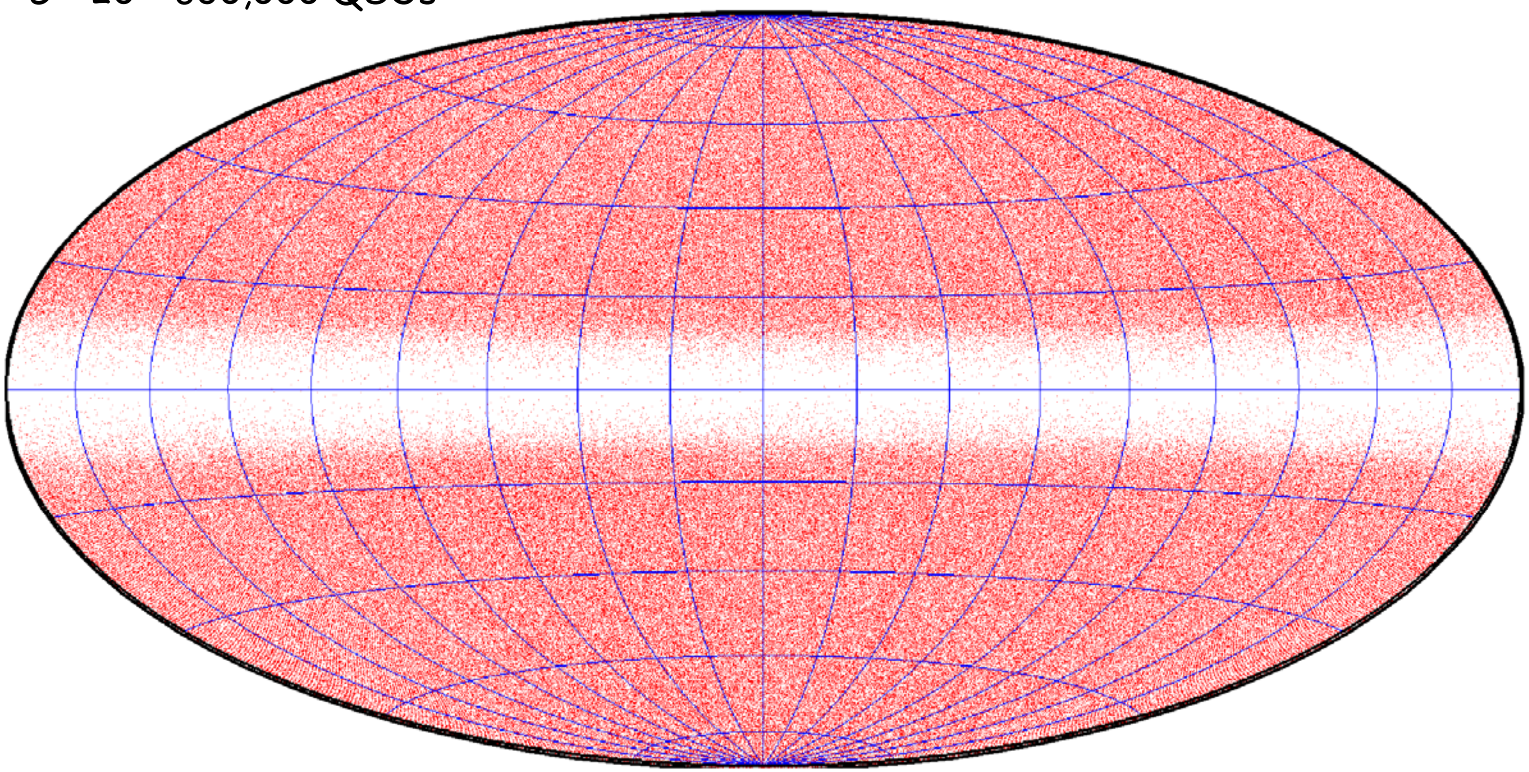
- Magnitude distribution, including the degrading detection efficiciency



# Sky distribution

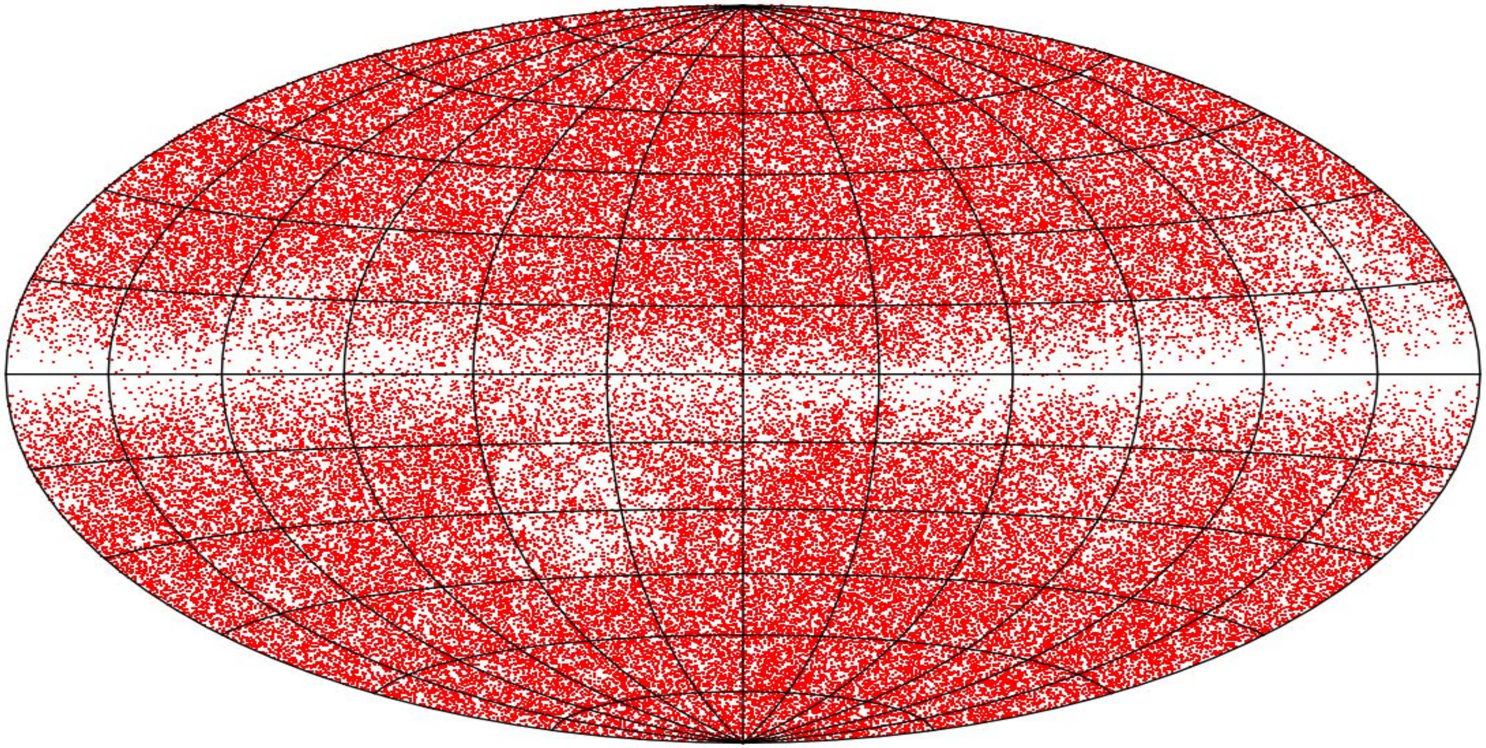
- about 650,000 QSOs with G <20
  - based on Slezak & Mignard simulated catalogue (2008)
  - Simple probabilistic extinction model
  - magnitude cut to account for the detection inefficiency

G < 20 – 630,000 QSOs



# QSO Simulation: alternative selection

- about 700,000 QSOs with G <20
  - based on Slezak & Mignard simulated catalogue (2008)
  - CU2 UM extinction model and realistic distribution in G
  - space distribution very similar to 7F QSOs

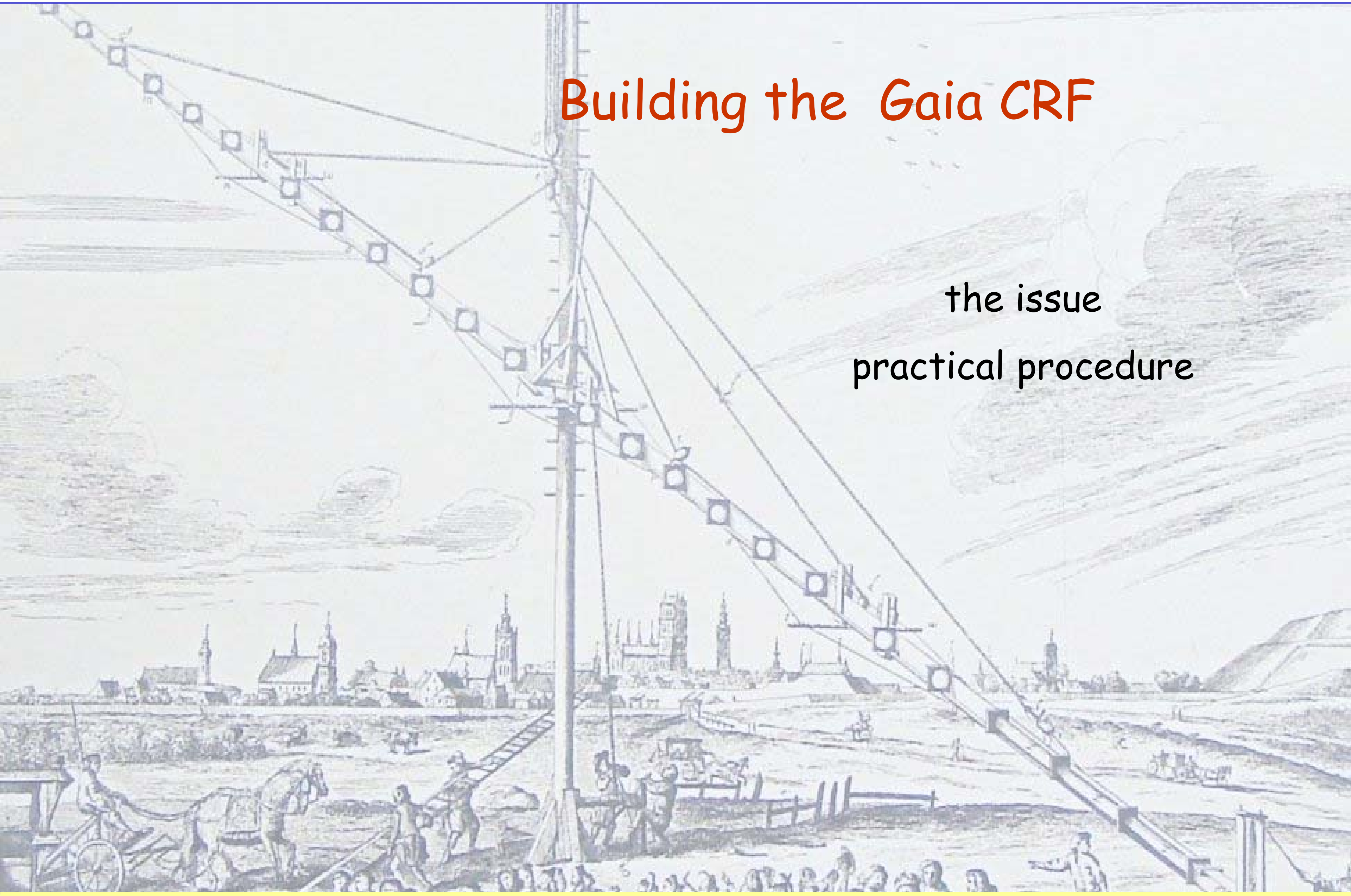


credit : S.Klioner

# Gaia pre-launch QSO List - A. Andrei

- GWP-S-335-13000 is the Work Package
  - GIQC : Gaia Initial QSO Catalogue
- Catalogue with 1.250,000 entries
  - 3 levels implemented: defining, candidates, and others
    - 190,000 defining with good spectroscopic redshifts
    - ➔174,000 entries in the IGSL released September 30th
  - astrometric accuracy ~1 arcsec.
    - except for the ICRF-2 sources
    - this is enough for matching observations
- Morphology and the signature of the host galaxy.
  - implemented flag from DSS images (92% R, 60% B, 56% IR).
  - automated SHARP, GROUND, SROUND IRAF's PSF analysis

# Building the Gaia CRF



the issue

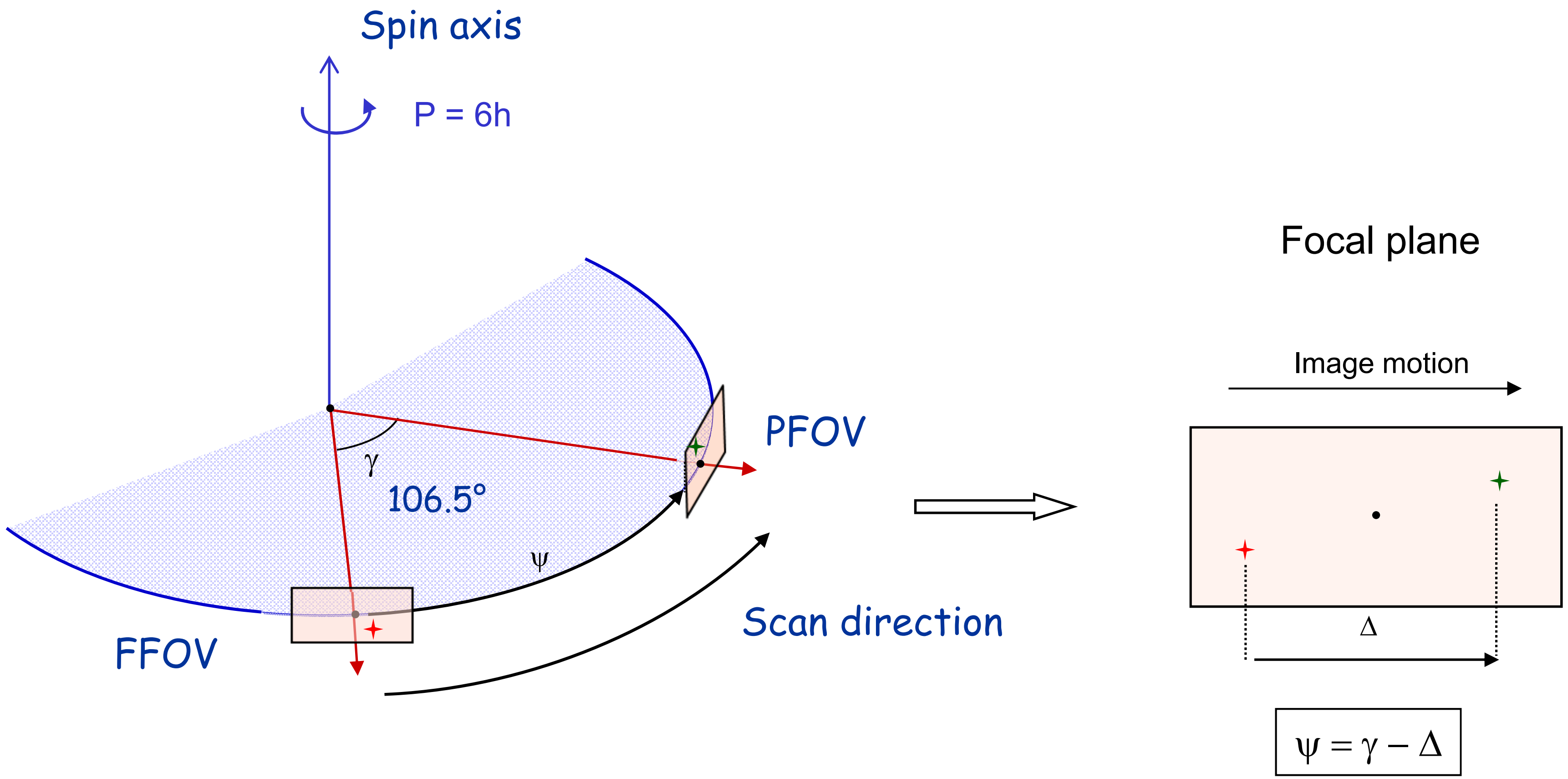
practical procedure

# Reference frame with Gaia: Principle

- Different from Hipparcos :
  - no link, primary frame determined➔ alignment to ICRF
- Gail will Observe extragalactic sources in the visible
- There are plenty brighter than V =20
  - about 500,000 observable with Gaia ➔ smaller sample selected
  - 20,000 V < 18
- Look for the anomalous proper motions to clean the sample
- The remaining set will display an overall spin
- Find $\omega$ and apply $-\omega$ everywhere
- The results will be referred to the best non-rotating frame
  - paradigm of the ICRS
- The orientation will be fixed with a small set of ICRF sources

# A simplified Gaia

- Wide angle measurements between two FOVs
- One common focal plane where local measurements are done
- A stable angular standard is the heart of the metrology



# Simplified Gaia and Reference Frame

- Assume stars are relatively fixed to each other
  - no parallax, no proper motion
  - a set of point sources on a 2D sphere
- Gaia is essentially measuring great circle distance between stars
- After 5 years of scans, arcs are accurately measured between each star and at least ~ 50 (much more for real Gaia)
- When all these arcs are combined together there is a single way to place the sources on the surface of a sphere, except for a global orientation
  - the network is very rigid but **can rotate** like a rigid body
- Therefore without additional constraint the absolute position cannot be deduced from the measurements alone
- The underlying mathematical structure is singular

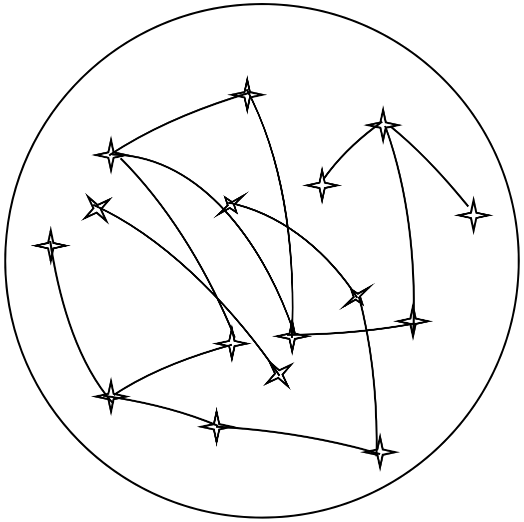
# Reference system with low-cost Gaia - I

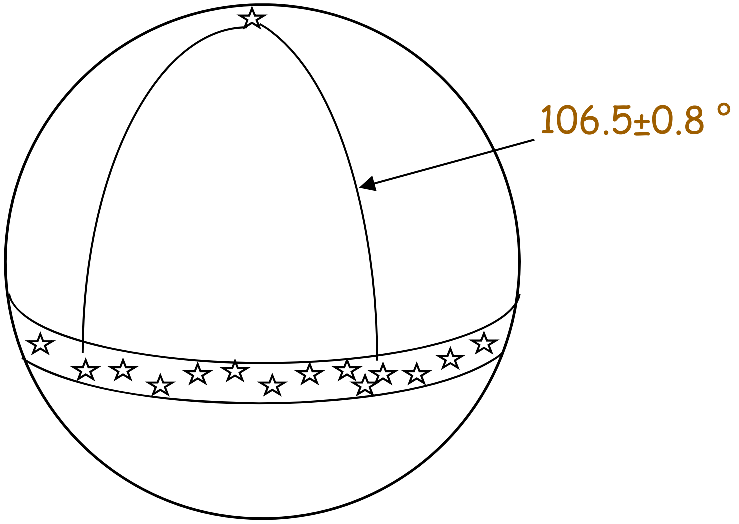
- Construction of a spherical networks of quasars
  - measure of arc between sources belonging to the two FOVs
  - the arc-lengths between sources are globally accurate and precise
    - the accuracy is typically the Gaia astrometric accuracy
  - there are many binary connections and the system is overdetermined

$$n \text{ stars} \Rightarrow \rho \sim \frac{n}{41200} * / \deg^2$$

$$FOV \text{ width } 0.8° \Rightarrow \delta n \sim \rho * 360 * 0.8 * \sin(106.5)$$

  - with the 40,000 brightest QSOs : each source directly connected to 250 others
    - many indirect connections with fainter sources and stars





# Reference system with low-cost Gaia - II

- This results into a rigid astrometric solution
  - the sphere of sources reproduces what we have on the sky
  - the overall rigidity is about $\sigma/\sqrt{\delta n}$
- But the overall system is rotationally invariant
  - arc-lengths are not tied to a particular orientation
  - the system is not tied the any privileged frame
    - inertial, ICRF … ➔ its orientation must be constrained to be useful
  - if the solution allows for proper motions, then there is a global rotation
    - rotation must constrained as well

# *Reference system with low-cost Gaia - II*

- For real Gaia :

  - rotation constrained by a physical assumption
    - QSOs have no global rotation wrt to cosmological restframe
    - this has a deep underlying physical significance
  - orientation is constrained to maintain continuity with previous frames
    - this has no particular physical meaning
    - but an overwhelming practical importance

# Gaia alignment to ICRF

- Orientation is performed by minimizing the distances between Gaia positions and ICRF positions of common sources

## True Gaia

- Stars have parallaxes
  - the parallactic displacements are geometrically tied to the Sun
  - they are very different between pair of connected stars
- The whole system is no longer rotationally invariant
  - the mathematical system is no longer singular but at least ill-conditioned
- Our mathematical model is linearised around approximate positions
  - the solution cannot be very very different from these initial values
- We use an attitude catalogue which materialises a reference frame
- The unconstrained solution is not fully free in orientation, but the frame is not robust against normally harmless changes:
  - weighting, attitude nodes, primary star selection ...

# True Gaia

- Astrometric solution is mathematically not singular
- For practical purposes the frame orientation must be constrained
  - with proper motions its rotation as well
- If we ignored 2000 years of astronomy, we could set the orientation to our fancy
- If we ignored 500 years of modern physics we could  make Gaia solution on  merry-go-round
- The best is to maintain metrological continuity and to adhere to the overall principles set by the ICRS

# What's next

- Global astrometric solution
- Making Gaia frame inertial
- Align Gaia frame to ICRF