QSOs with Gaia

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Outline

- QSOs fact sheet
- QSO recognition with Gaia
- Astrometric observation of QSOs with Gaia
- Properties of the Gaia Reference Frame

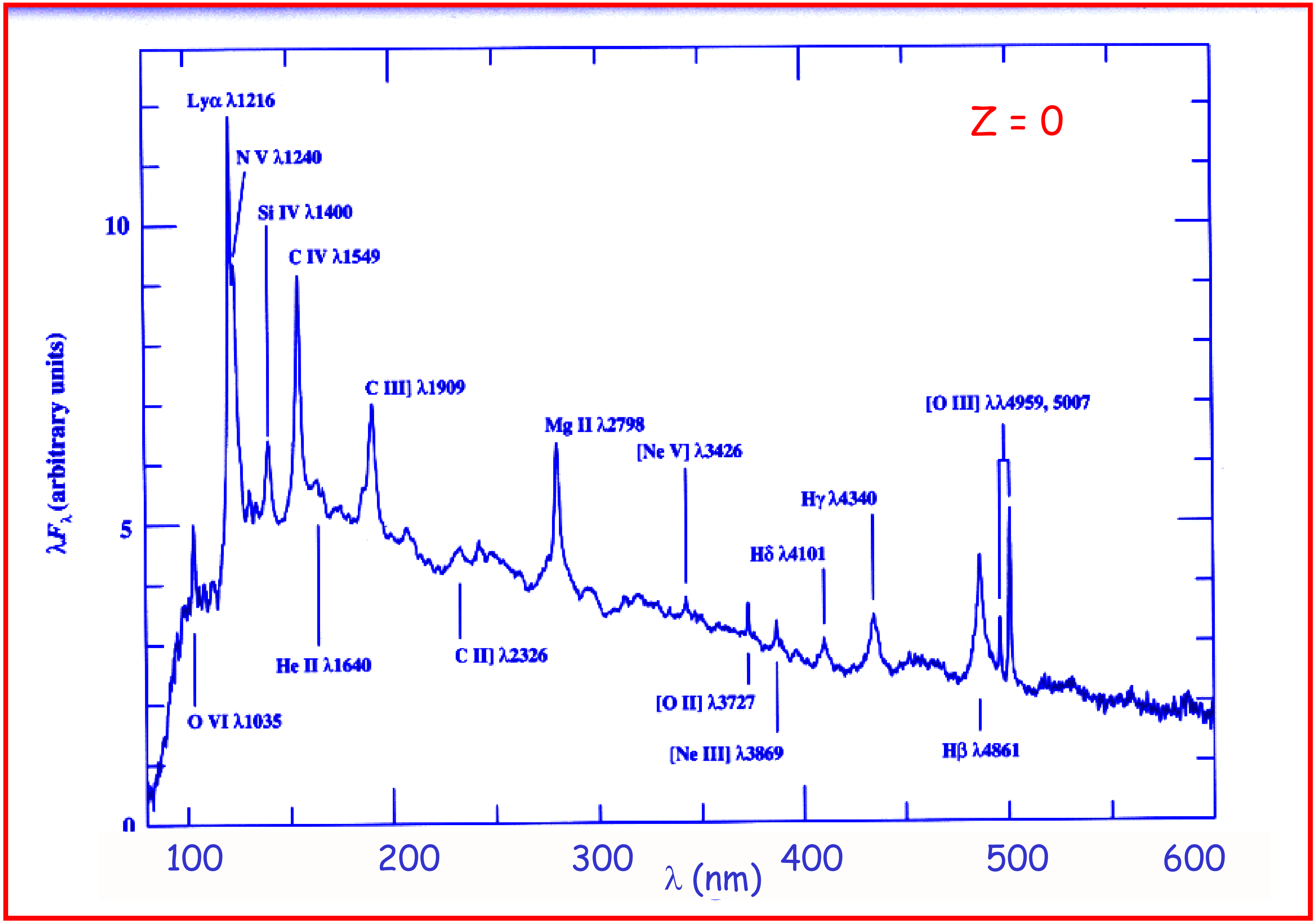
Fact Sheet on QSOs

- 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*)
  - no fully agreed terminology
- Variability over days to months
  - size of the emitting core ~ few solar systems to 0.1 pc
- Seen at great distance, then large redshift (compared to galaxies)
  - $0 < z < 5$; > 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 = 2×10^{47} J / 3×10^7 s ~ 10^{40} W = 10^{47} erg s^{-1}

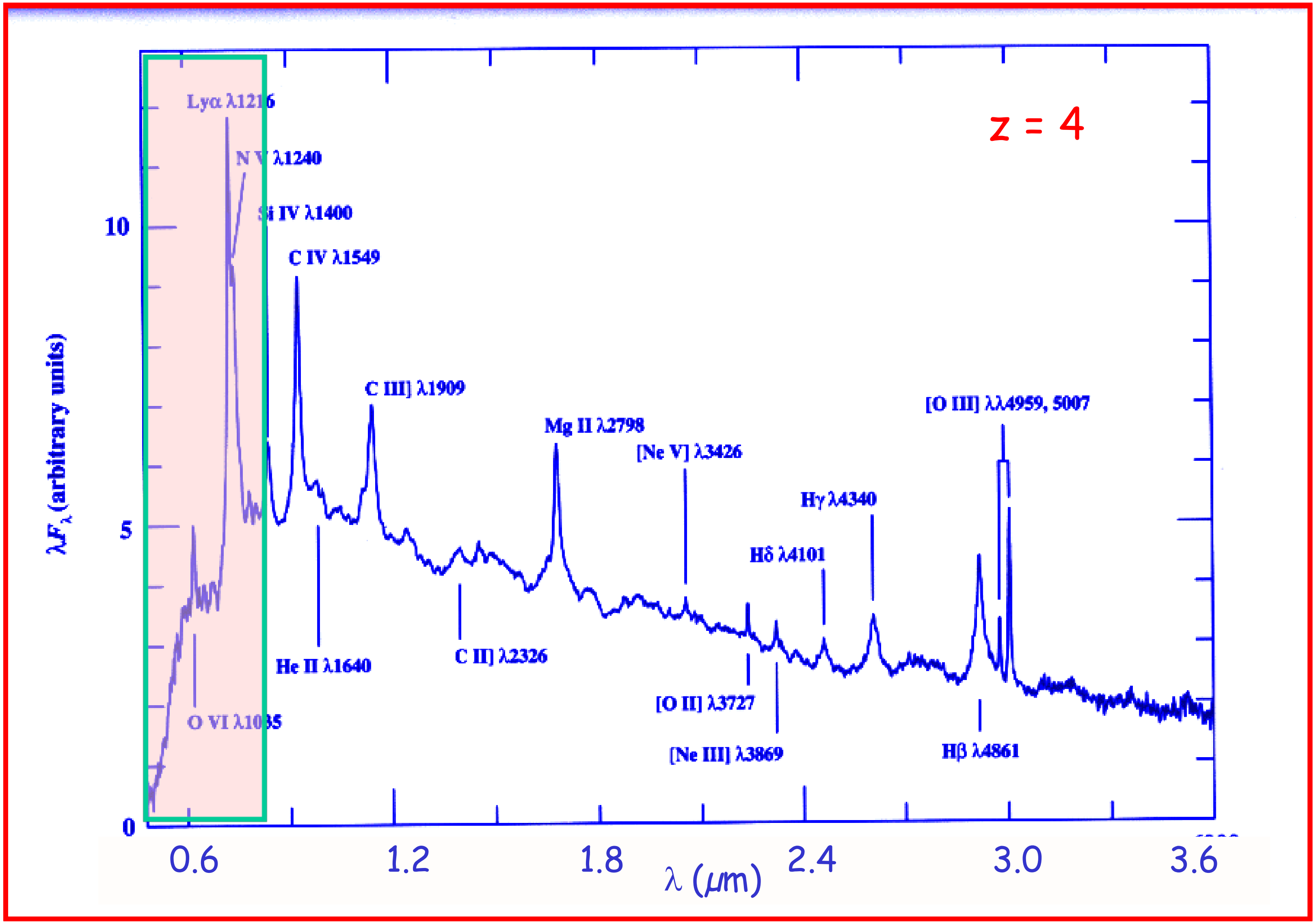
Fact Sheet II

- 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
  - and similarly for other surveys

Energy distribution



Energy distribution



Gaia and QSOs: Relevant activities I

- Identification and discrete classification
  - survey to G = 20 (~ R = 20)
  - clean subset (contaminant-free) for reference frame
  - automated classification of QSOs
- Supply of a well documented and clean initial QSO catalogue
- Extension of the potential sources usable for the orientation
  - additional ground based observations
- Survey of all the potential causes for tangential motion
  - timescale for these motion is crucial
- Theoretical studies related to the Inertial Frame
  - implementation in the Gaia processing

Gaia and QSOs: Relevant activities II

- Investigation on source stability
  - acquisition of basic data relevant for this issue
  - more theoretical investigations would be useful as well
- Photocentre – radiocentre offset
- Simulation of a Gaia ICRF
  - rotation, orientation, cosmic-acceleration
- Photometric redshifts with Gaia data
- Lensing and multiple imaging

Gaia and QSOs: Relevant activities III

- Production of a realistic simulated QSO list for simulation
  - good position distribution
  - fully representative photometric and z distribution
  - synthetic spectra
  - astrometric effect relevant for the reference frame

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

- Intensive activity over the last five years
  - led initially by J.F. Claeskens (Univ. of Liège, Belgium)
  - then continued by C. Bailer Jones and his team
- 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
- Classification methods very successful
  - see talk of Y. Damerdji

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 α
    - 1- α : significance level
  - The test can keep a star in the QSO sample : risk of contamination β
    - 1 – β : power of the test

		State	
		QSO	Star
Found	QSO	$1-\alpha$	β
	Star	α	$1-\beta$

Probability classification

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 ➔ β < 0.0005

Consequences

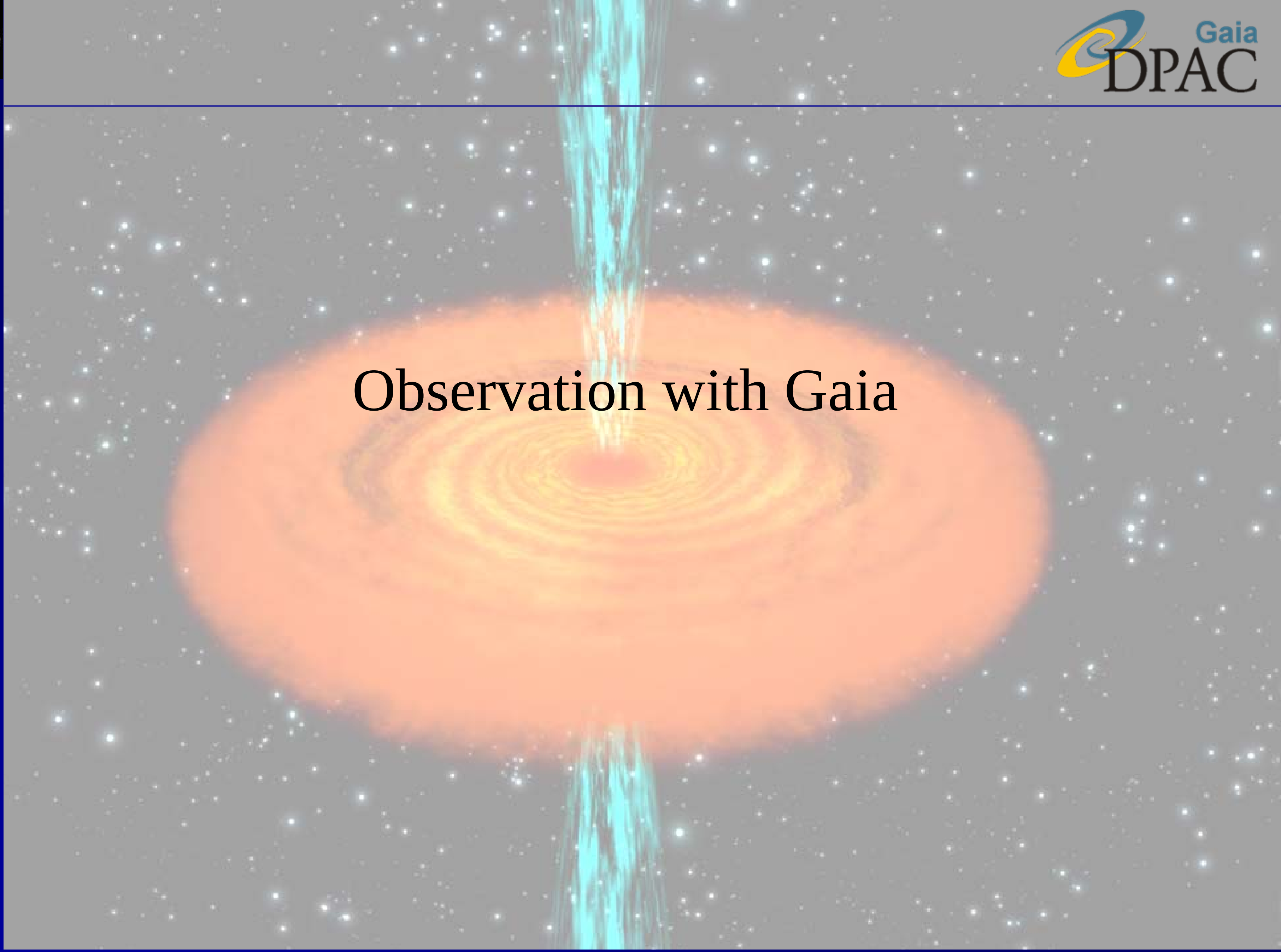
- A survey over 100 deg^{-2} with a 1% error selection test will yield :

  - 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 2×10^{-3}

Summary of the Selection

- Gaia detects and observed all the sources V < 20
- There are ~ 5×10^5 QSO 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



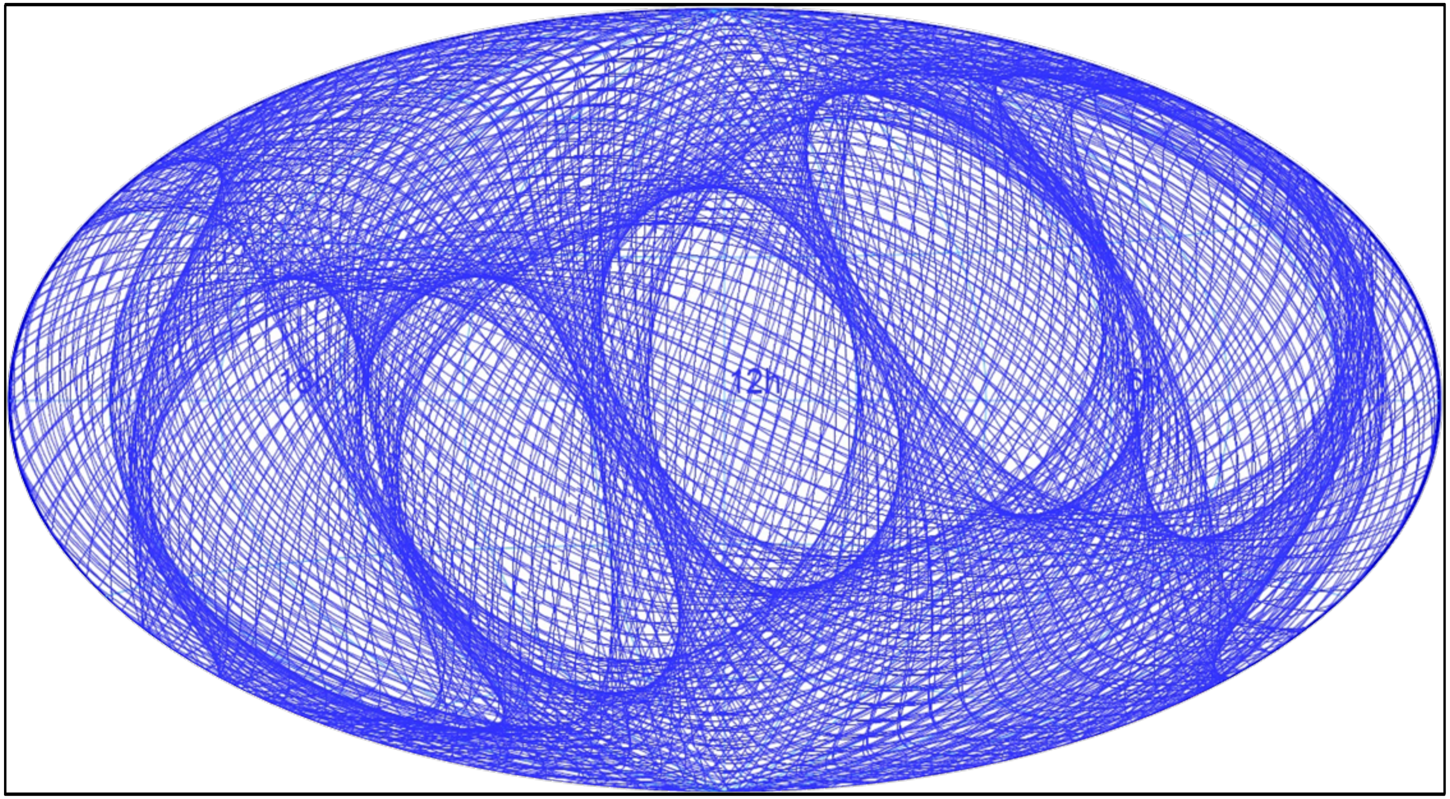
Observation with Gaia

Basic features

- 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
- Astrometric and photometric processing will be standard
  - global solution for astrometry
  - epoch photometry at each transit
- With enough photometric data, these sources will be flagged as non stellar

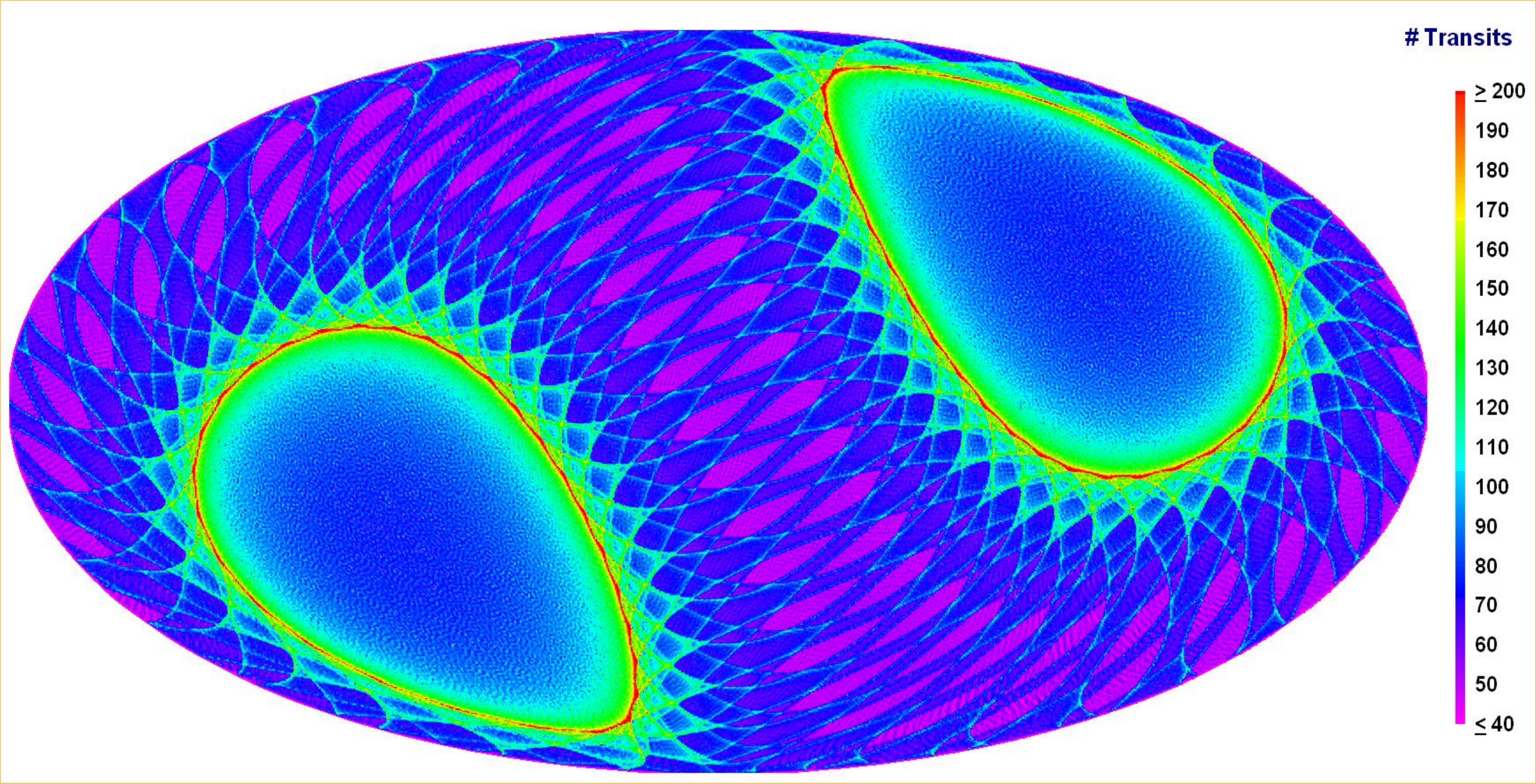
Sky Scanning with Gaia

- Sky coverage over 4 months and one year:
  - 4 months (one colour per month)
  - One full year (one scan per day plotted)



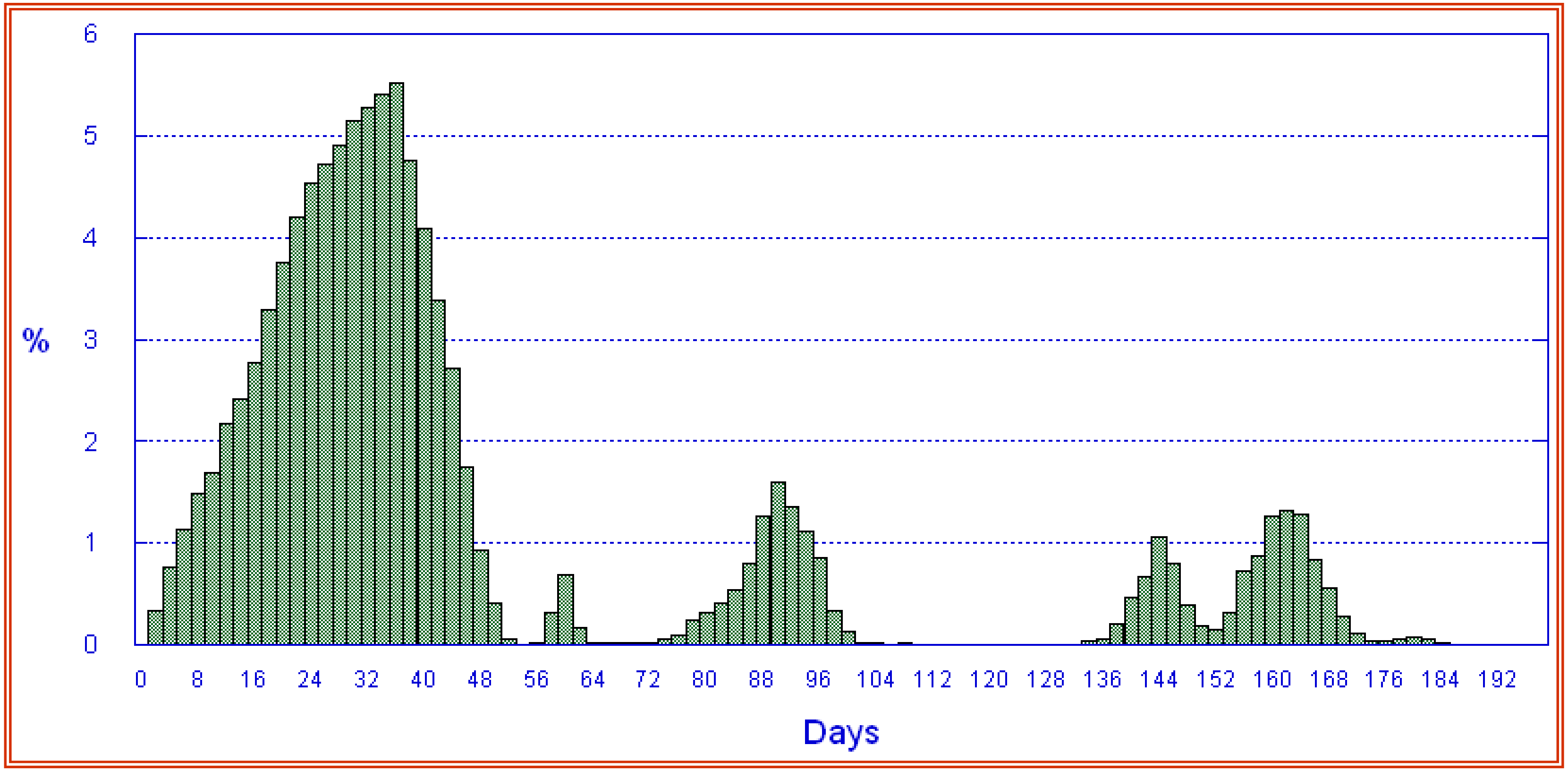
Sky coverage

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

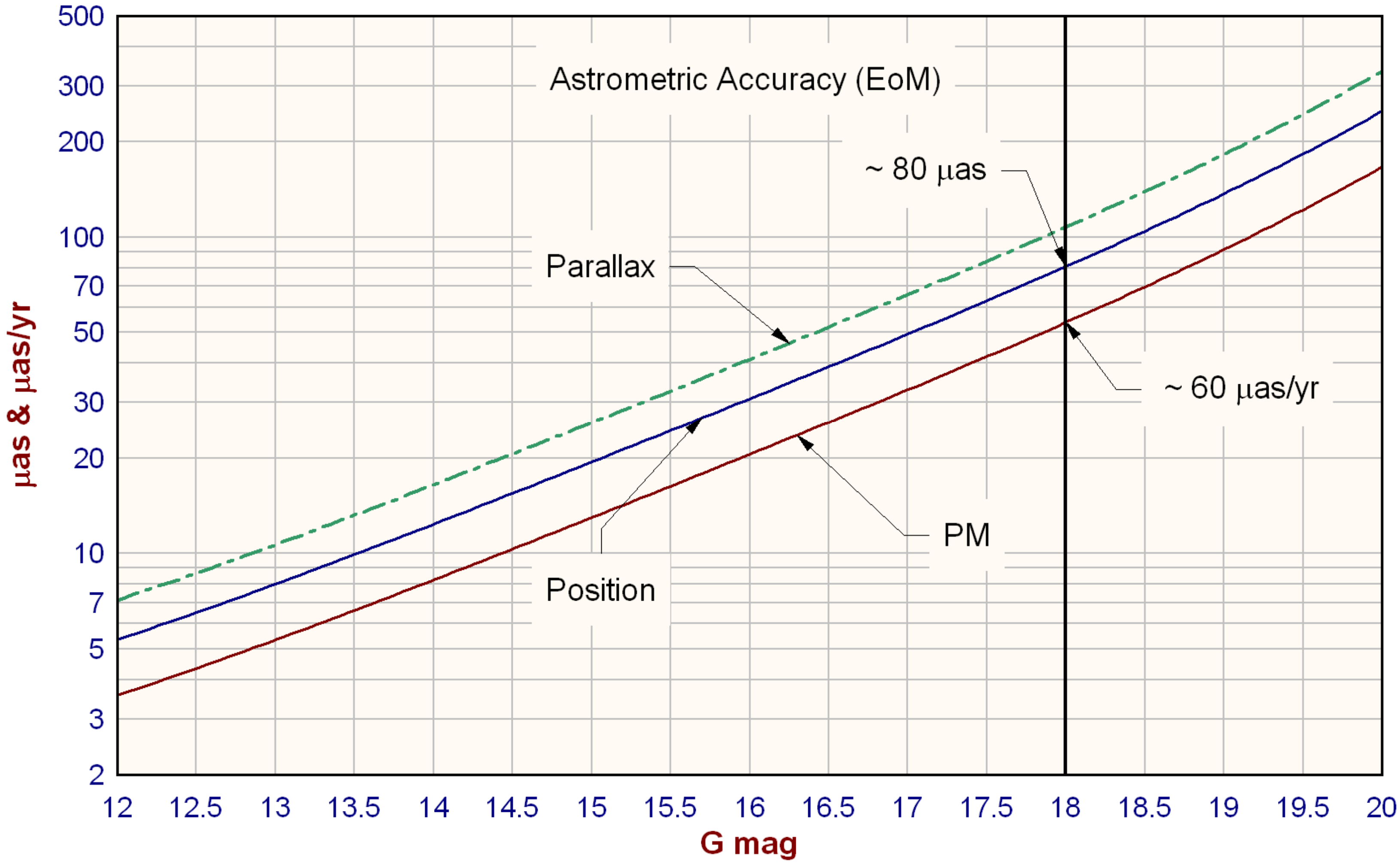


Distribution of long gaps

- Histogram of the gaplengths between two short sequences

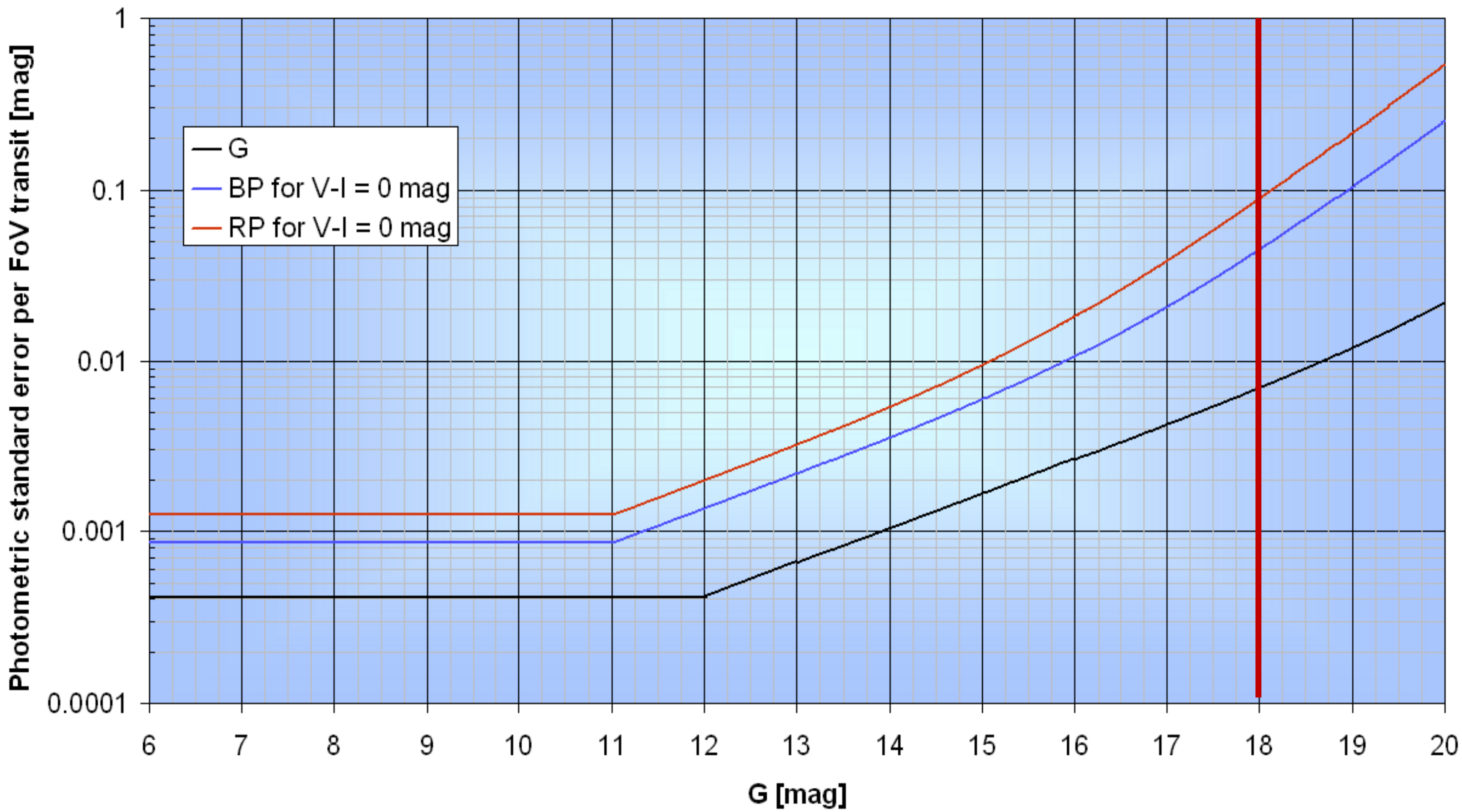


Astrometric Accuracy: QSOs

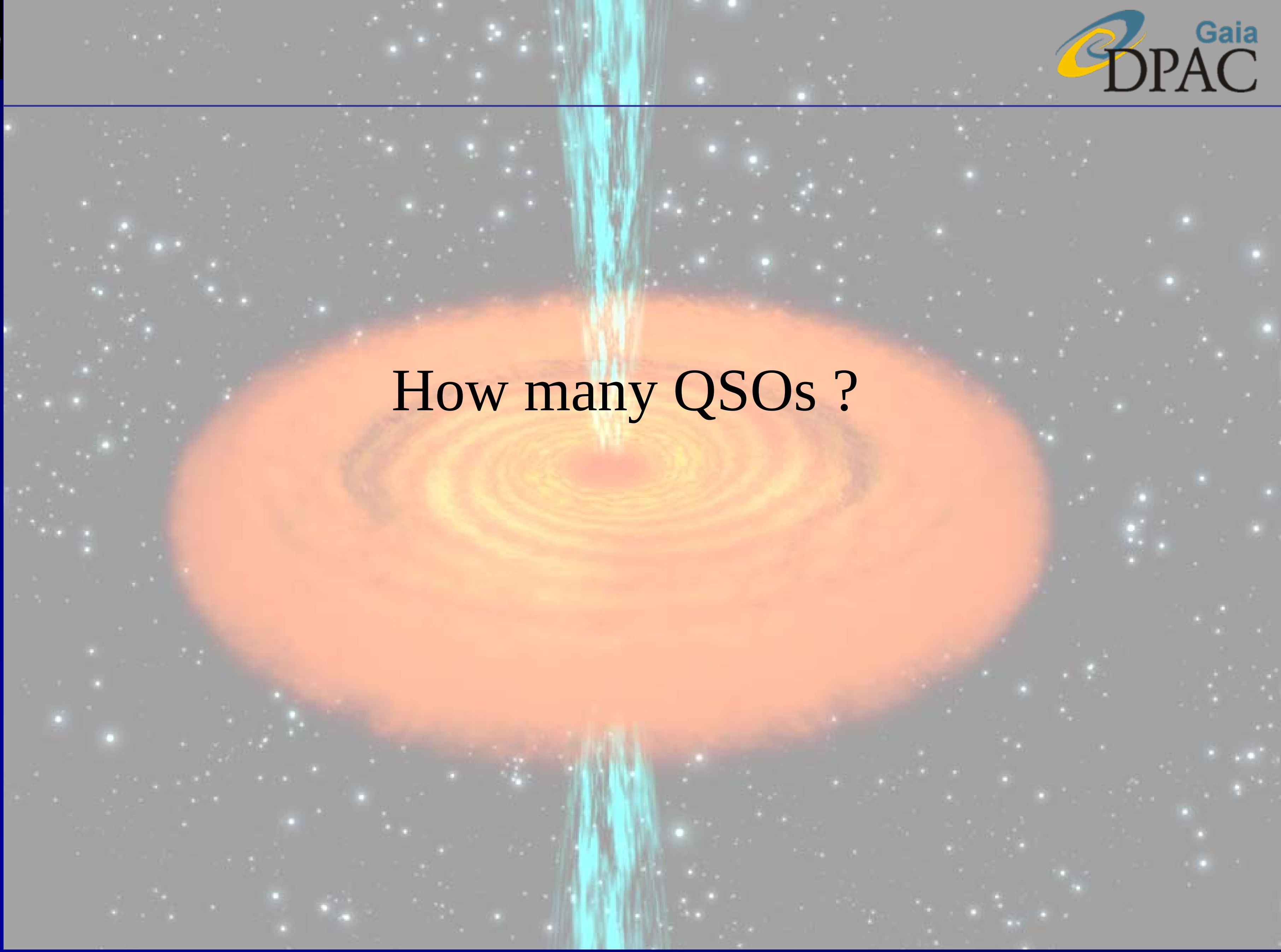


Photometric accuracy

- Epoch photometry : 1 transit over Astro CCDs or BP/RP
  - performances for photometric stability

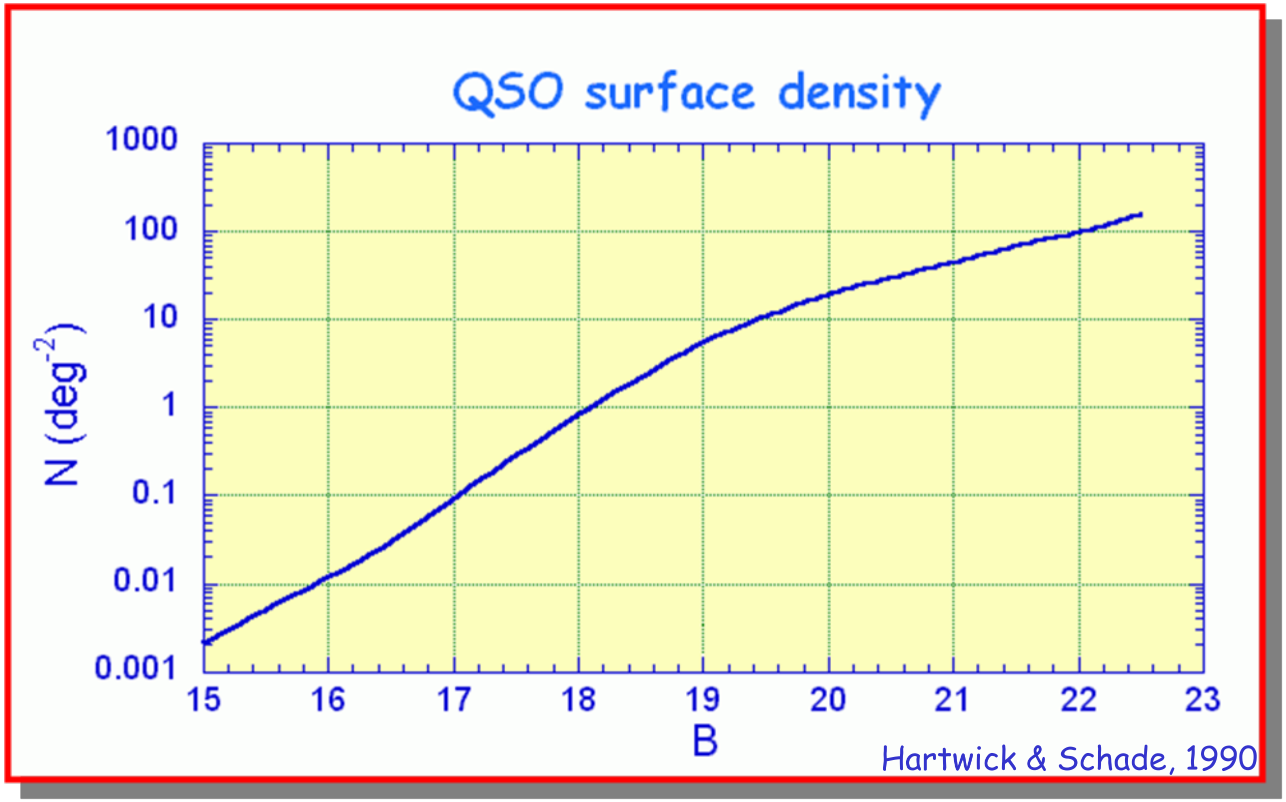


Credit : J. de Bruijne



How many QSOs ?

How many QSOs:



With a flawless selection : GAIA will observe on ~ 60% of the sky

- $B \leq 16$ 200
- $B \leq 18$ 25 000
- $B \leq 20$ 550 000

How many new QSOs

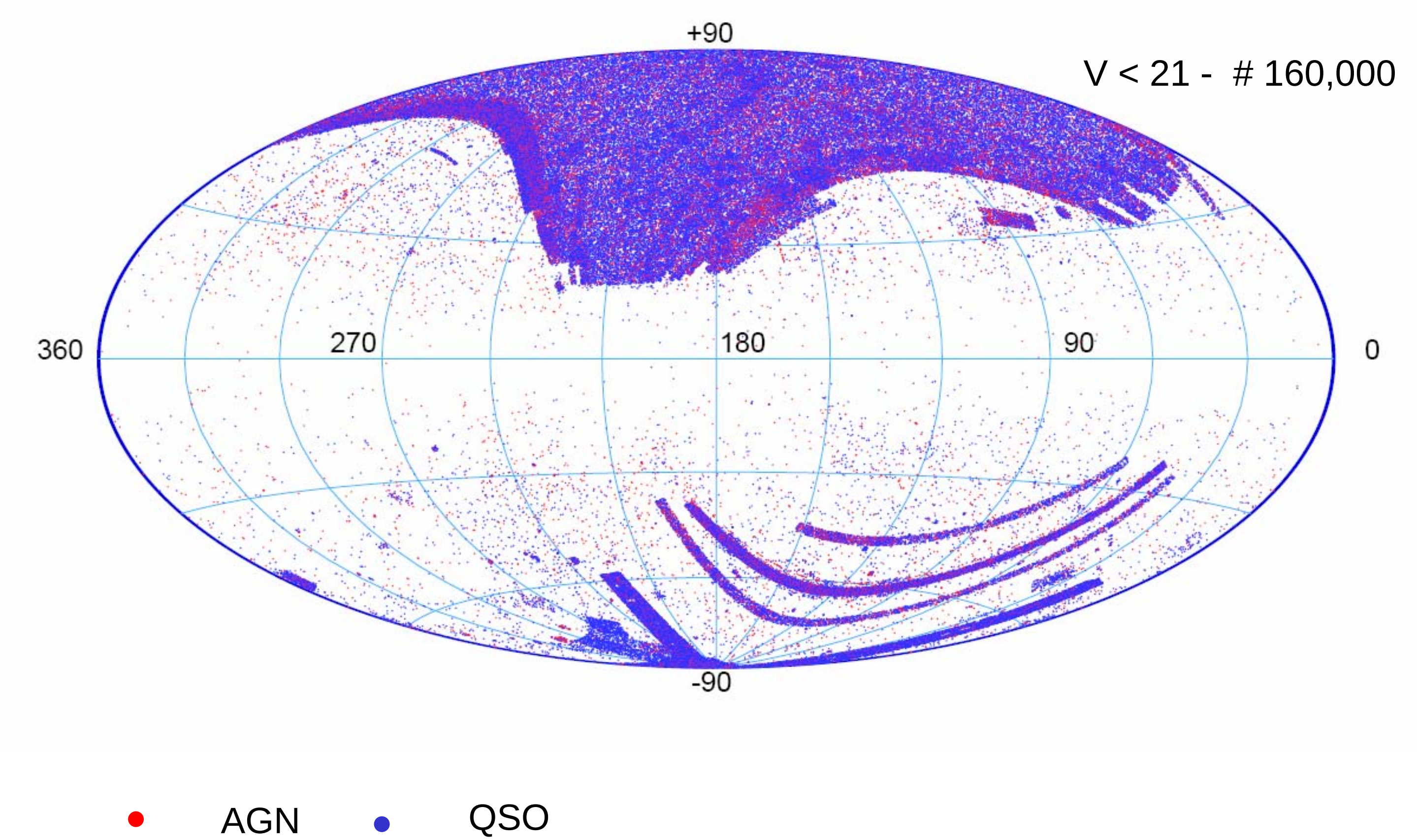
- Density in local deep surveys used to compute the expected number of QSOs per bin of magnitude
- On subtracts the number in the current general catalogue
- assumption: QSOs have a uniform distribution on the celestial sphere
- |b| > 25°

B	# new QSOs
< 17	0
17-18	15,000
18-19	100,000
19-20	300,000
20-20.5	*200,000*
17-20	415,000

Bourda, Mignard, Andrei, 2009

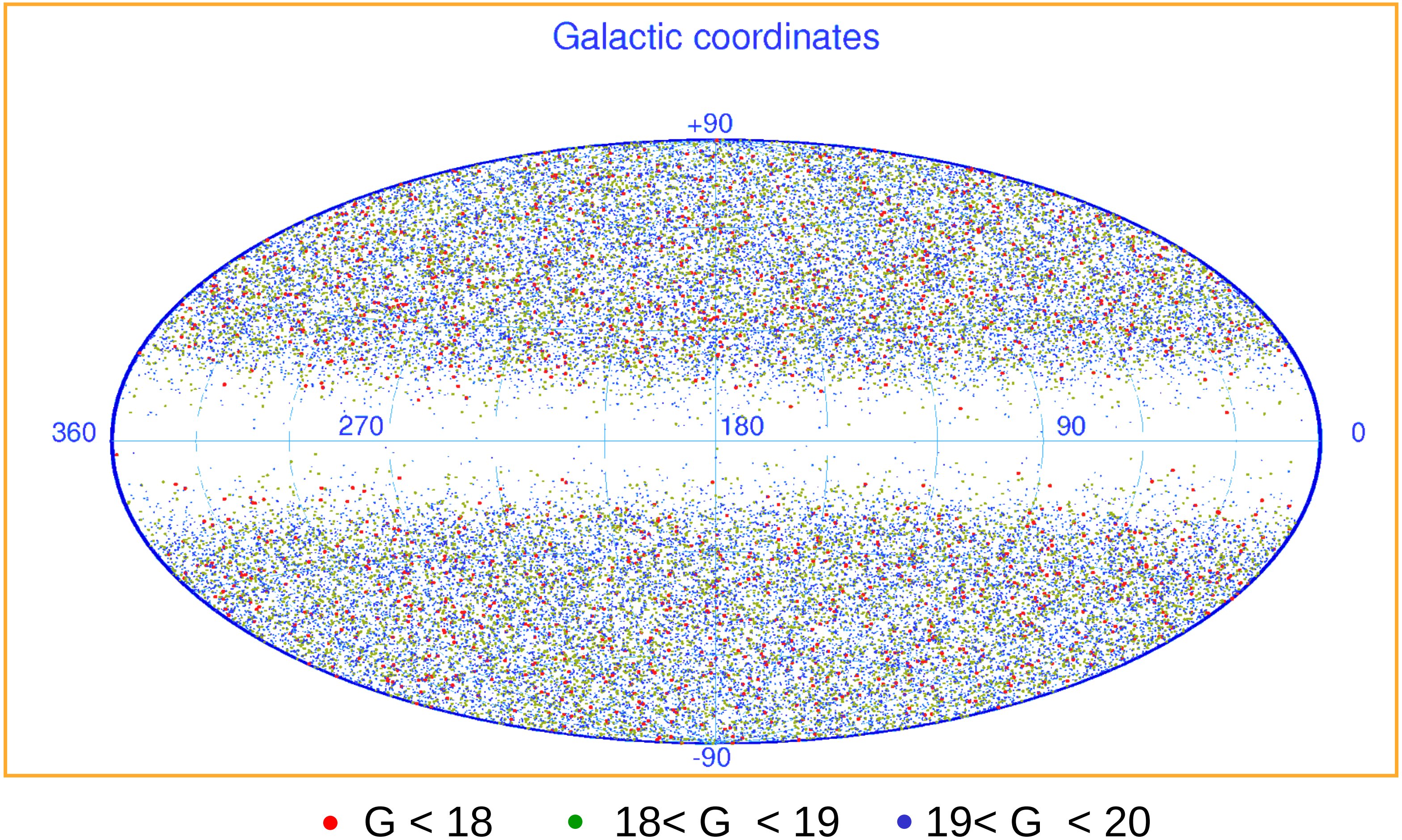
Latest QSO compilation

- Catalogue Veron-Cety & Veron V13 (2010)
  - Plots in galactic coordinates
  - similar results with LQAC (Souchay et al., 2008)



QSOs distribution with Gaia

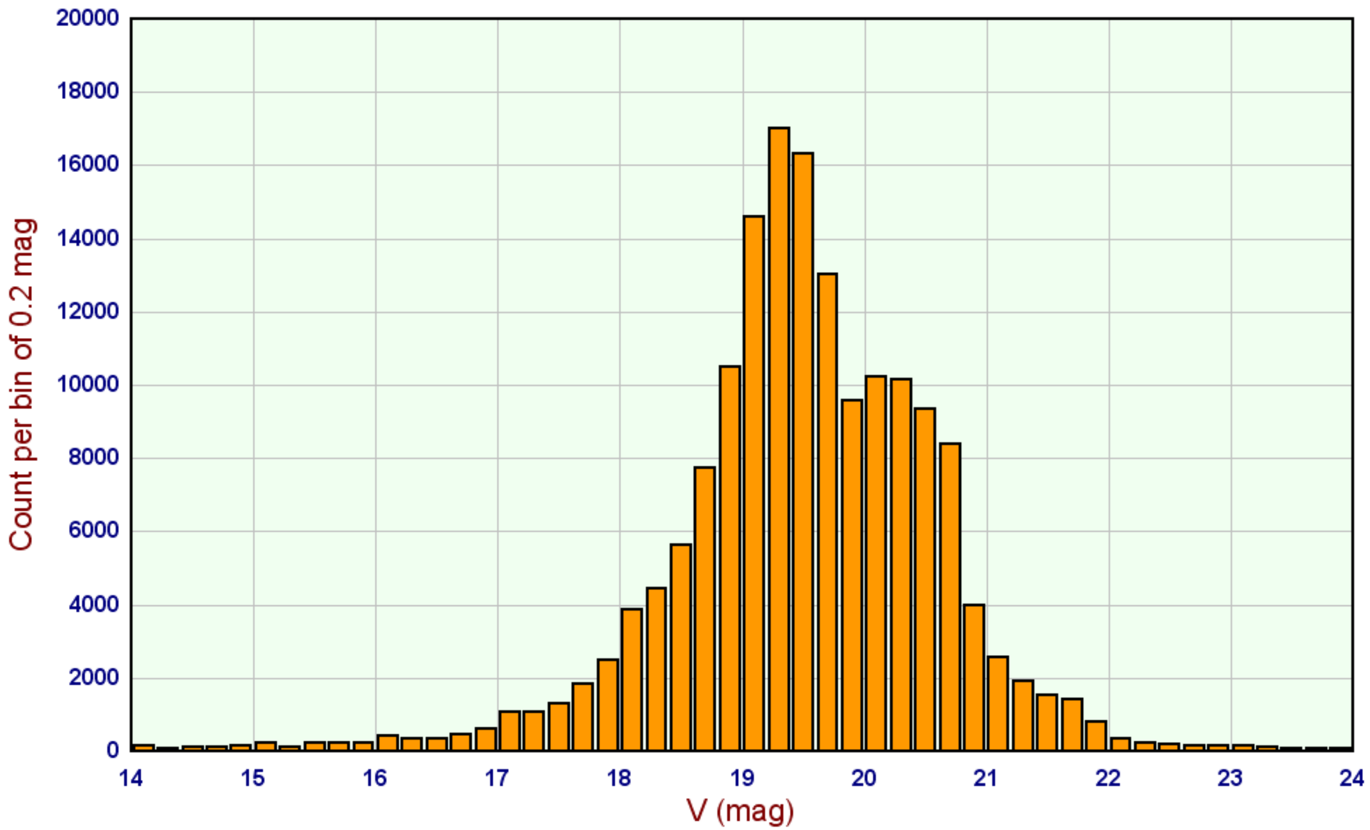
- Based on the simulation used in the DPAC Universe model
  - about 400,000 observable to G = 20



Slezak & Mignard, 2007

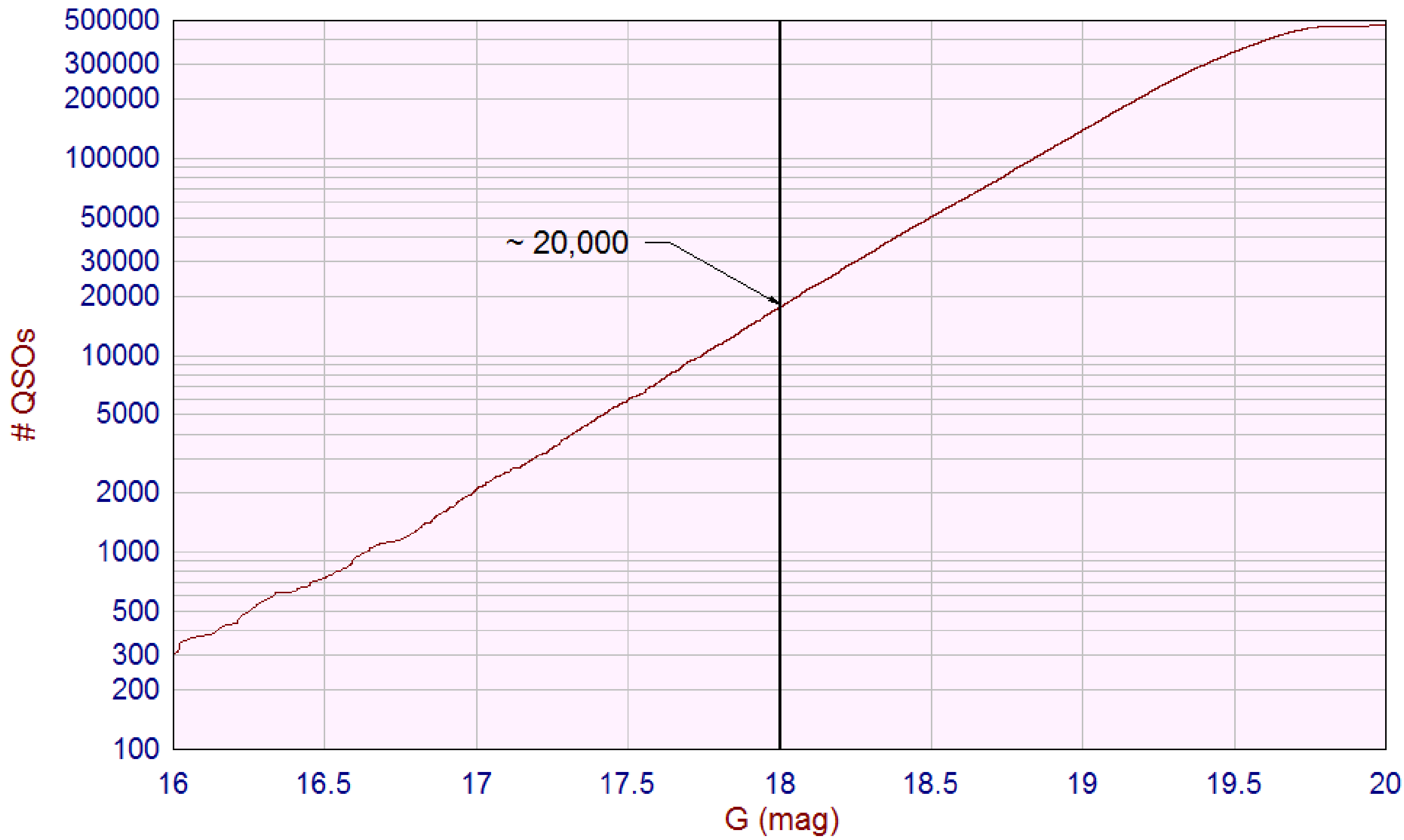
Magnitude distribution

- Magnitude distribution in Veron-Cety catalogue
  - unrealistic drop at V ~ 20



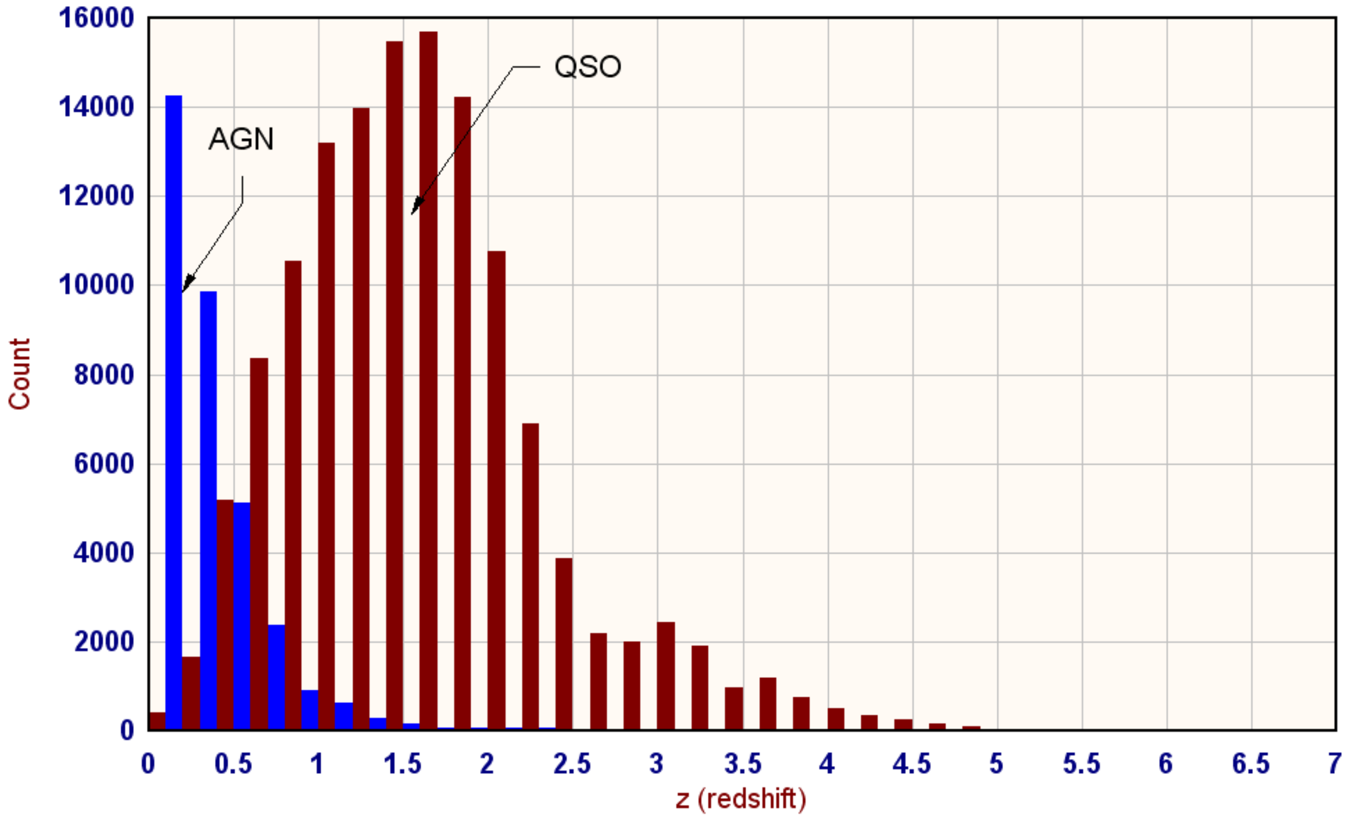
Magnitude distribution with Gaia

- Cumulated distribution over G magnitude
  - based on simulation by Slezak & Mignard, 2007



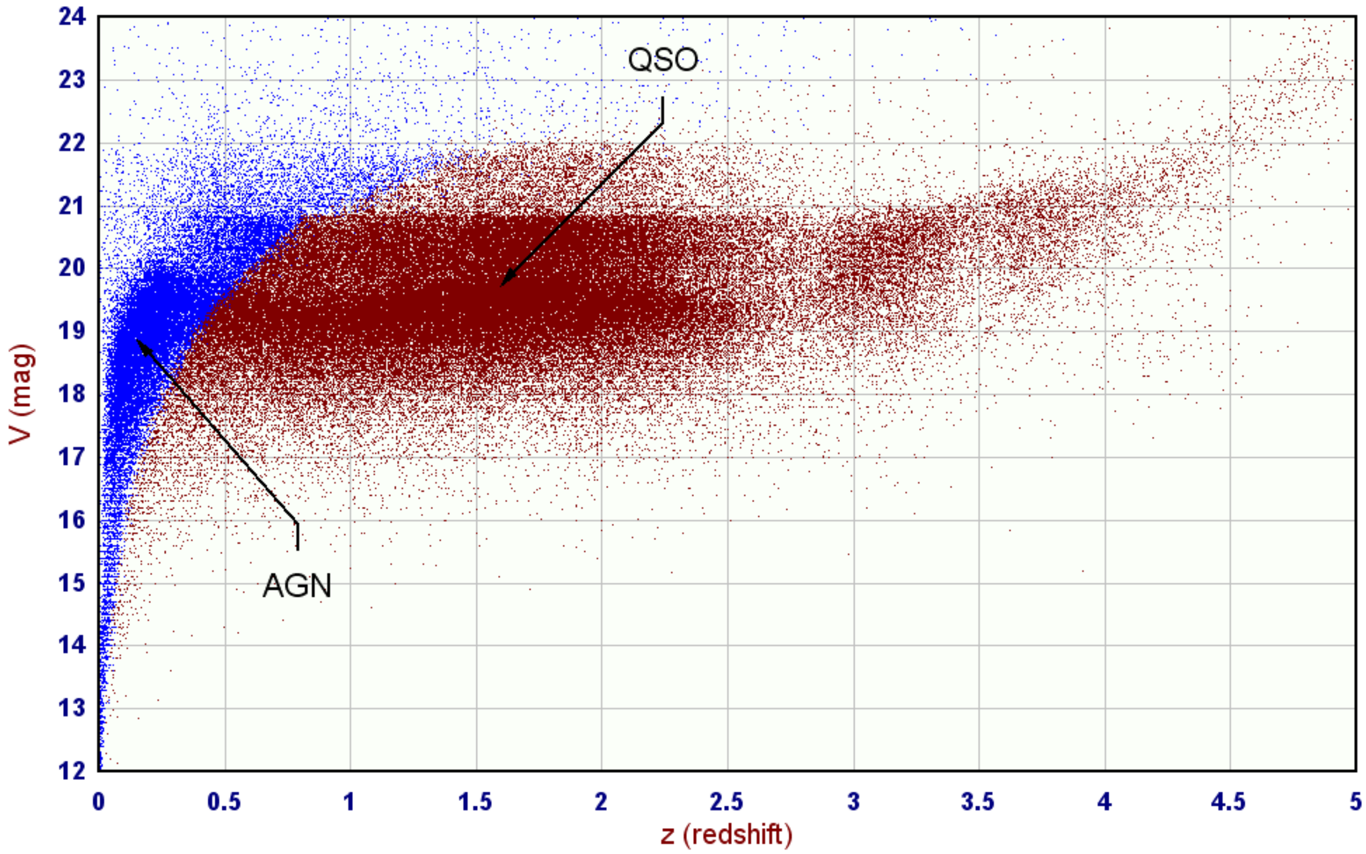
Redshift distribution

- data from Veron-Céty & Veron
- Artificial separation between AGN and QSOs



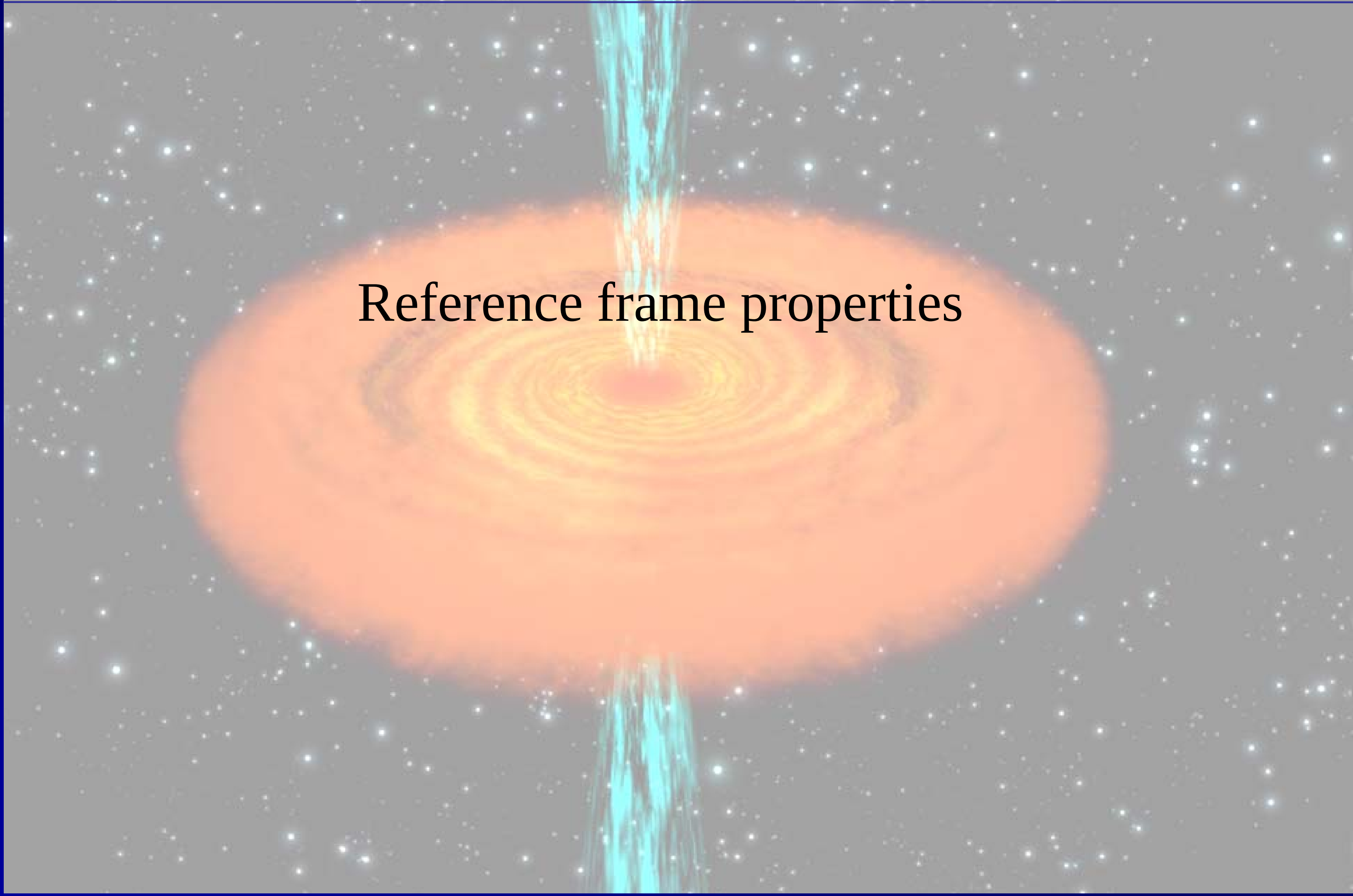
Correlation Magnitude-redshift

- Redshift in abscissa, V in ordinate



Initial QSO Catalogue for Gaia

- GWP-S- 335- 13000: **Initial QSO catalogue**
  - PI: A. Andrei ➔ his talk later this morning
- Produce the minimum clean sample from existing data
  - to train and validate the supervised classifiers
  - to assess the astrometry on QSOs with reference data
- Version 1.0 issued on December 2007 with 105,000 sources
  - based on LQAC (Large Quasar Astrometric Catalogue, Souchay et al., 2008)
  - several fields to be specialised for Gaia purpose



Reference frame properties

Reference frame

- Dense (> 15000 stars /deg^2) net of reference stars
  - Direct observations of extragalactic sources
    - ~ 500,000 quasars observable
    - **kinematically non-rotating system** (~0.3 muas/yr)
    - **acceleration** of the Solar System Barycentre in cosmological frame
  - Long-lived reference system:
    - based on a clean subset ~ 20,000 QSOs V < 18
    - 18 mag positions good to <1 mas over 1995 - 2035
- QSO physics
  - largest homogeneous survey to V ~ 20
  - Investigation of transverse motion to 20 muas/yr (individual), <1muas/yr (systematic)

Accuracy of the frame : Simulation

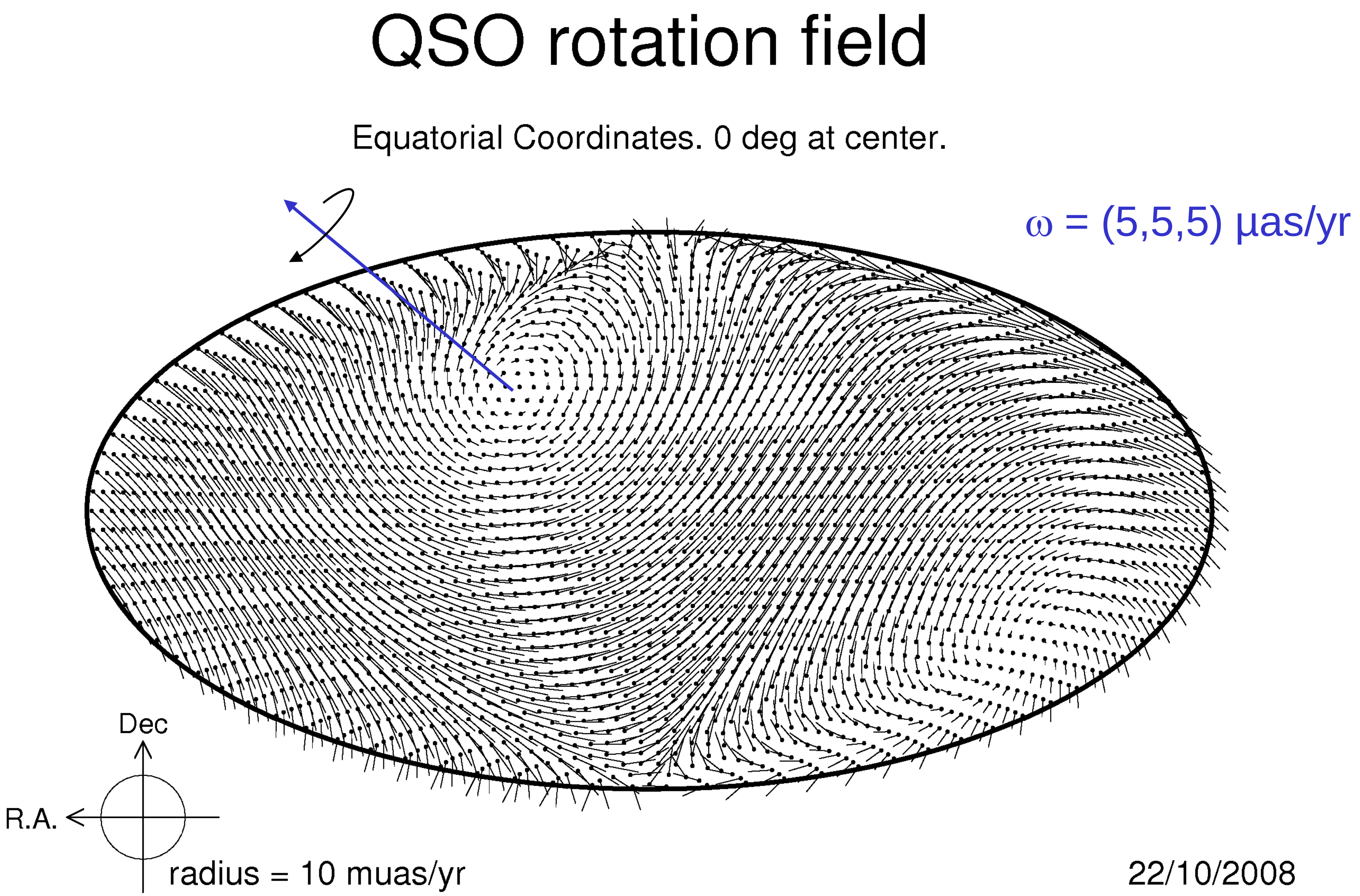
Assumptions :

- QSOs observed with the same accuracy as a normal star
- Additional noise included for source jitter : 20 μas/yr
  - larger than σ_{pos} for V < 16
- QSOs have no peculiar transverse motion
- Observed PM reveal the global rotation of the GAIA sphere

$$\begin{aligned} \mu_\alpha \cos\delta &= \omega_x \sin\delta\cos\alpha + \omega_y \sin\delta\sin\alpha - \omega_z \cos\delta \\ \mu_\delta &= -\omega_x \sin\alpha + \omega_y \cos\alpha \end{aligned}$$

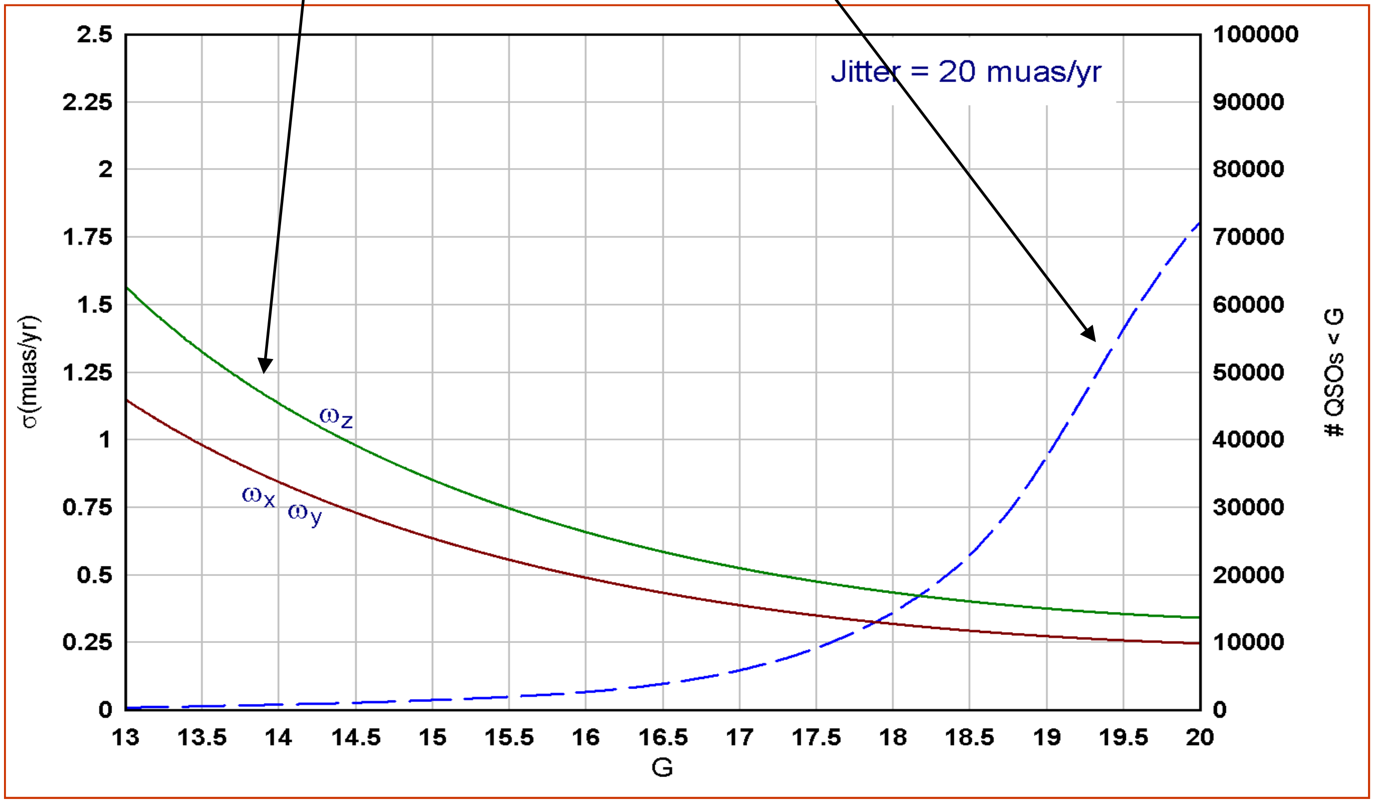
- Space and magnitude distribution from existing catalogues
- Inversion of the weighted normal matrix

Example of a typical rotation



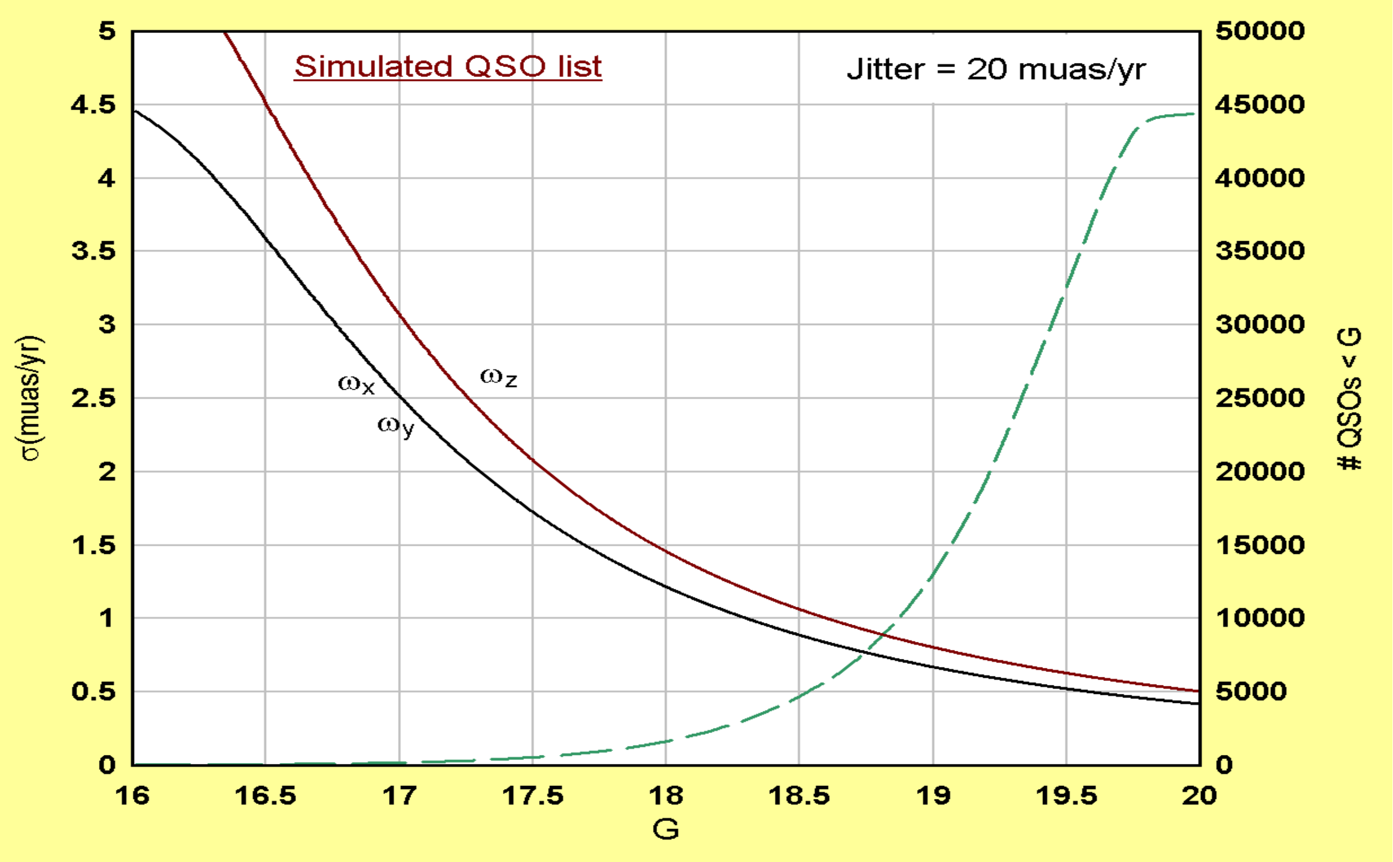
Main feature of the Gaia Frame

	today
• ICRF directly in the visible	radio
• Between 20,000 et 50,000 primary sources	295
• Inertiality < 0.3 muas/yr	20 muas/yr ?



More likely with Gaia

- With the simulated distribution
  - uniform outside |b| > 25 deg

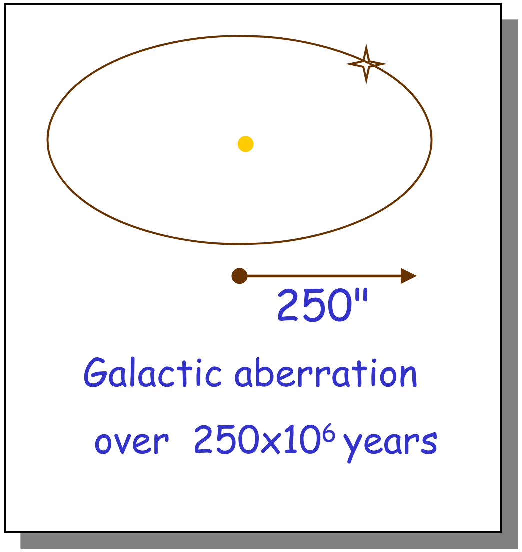


Transverse motions

- So far no systematic transverse motion detected
  - QSOs have fixed comoving coordinates
- If $V_t \sim H_0 D$ ➔ $\mu \sim 10\ \mu as/yr$
  - VLBI in 20 yrs with $\sigma_{pos} \sim 1$ mas ➔ $\mu < 50\ \mu as$
  - but sub-mas structure instabilities (P. Charlot, 2003)
- Other sources :
  - microlensing $P = 10^{-6}$ (Belokurov) ➔ only a handful
  - matter ejection, superluminous motion
  - Variable galactic aberration
  - Macrolensing $P = 10^{-2}$ (Mignard, 2003)➔ long timescale
  - Accelerated motion in the local group

Galactic Aberration

- The solar system is in motion in the Galaxy, $V \sim 220$ km s^{-1}
  - constant aberration of ~ 250" for the QSO wrt to comoving frame
  - not detectable (principle of relativity)
  - $\delta \mathbf{u} = \mathbf{v}/c$



- But the solar motion is not uniform
  - ~ circular motion of radius R ~ 8.5 kpc and period 250×10^6 yrs
  - the aberration is then variable

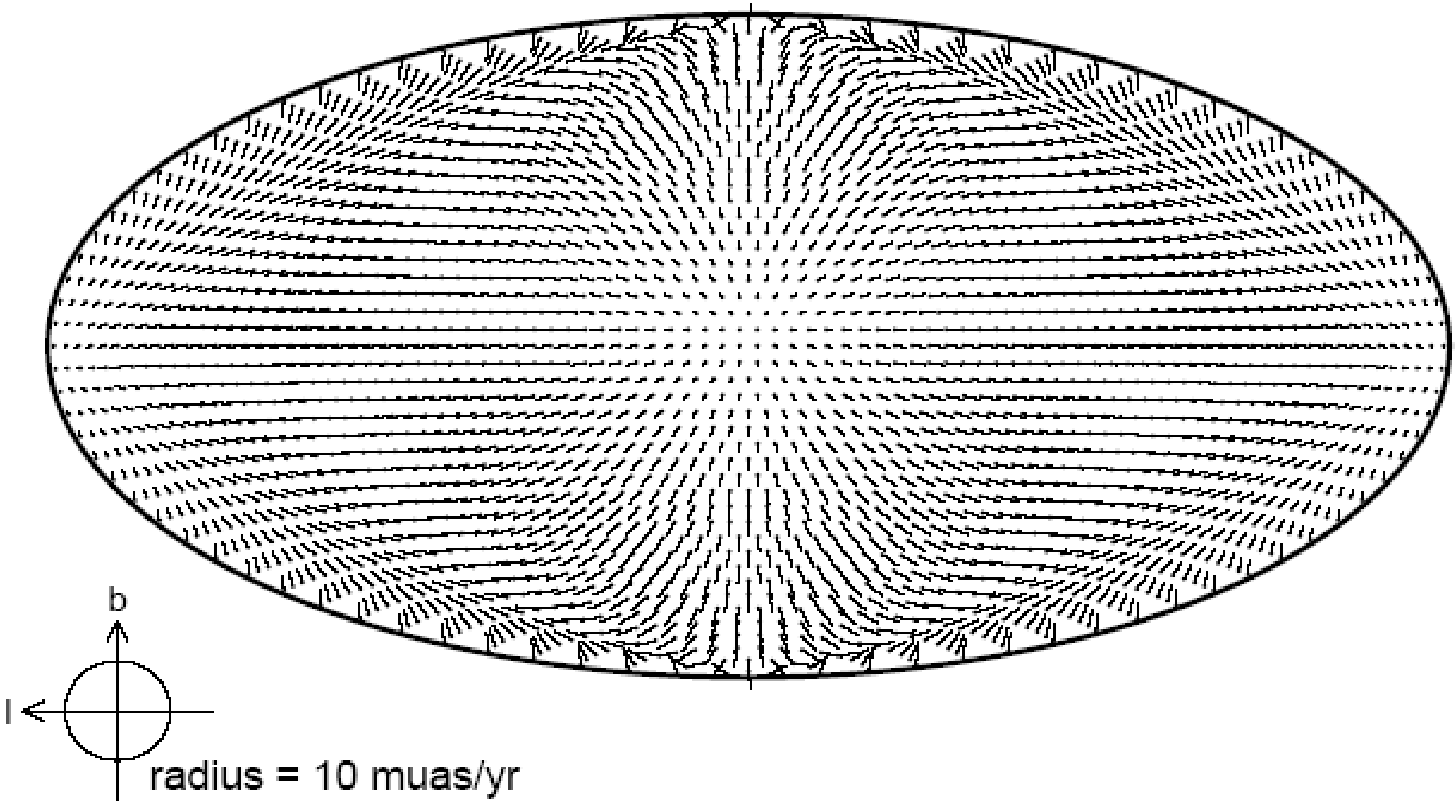
$$\boxed{\delta\mu = \frac{d(\delta\mathbf{u})}{dt} = \frac{\Gamma}{c} = \frac{V^2}{cR} \approx 4\mu as / yr}$$

Global pattern for galactic rotation

$$\mu_\alpha \cos\alpha = -3.464\cos\alpha \qquad \text{muas/yr}$$

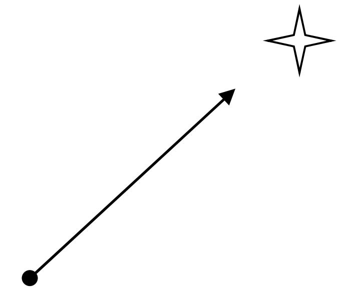
$$\mu_\delta \quad = \quad 3.464\sin\delta\sin\alpha - 2.0\cos\delta \qquad \text{muas/yr}$$

Galactic Coordinates. 0 deg at center.



General Case : detail

- For any acceleration of the SS wrt Quasars :



$$\frac{d\mathbf{u}}{dt} = \frac{\mathbf{\Gamma}}{c} - (\frac{\mathbf{\Gamma}}{c} \cdot \mathbf{u})\mathbf{u}$$

Observations

$$\mu_\alpha \cos\delta = -\frac{\Gamma_x}{c}\sin\alpha + \frac{\Gamma_y}{c}\cos\alpha$$

$$\mu_\delta = -\frac{\Gamma_x}{c}\sin\delta\cos\alpha - \frac{\Gamma_y}{c}\sin\delta\sin\alpha + \frac{\Gamma_z}{c}\cos\delta$$

- Equations similar to global rotation.
- Precision of ~ 0.4 μas/an (2 prad/yr) on Γ/c

  = 0.2x 10^{-10} m s^{-2} (γ Pionner/40)
- Galactic rotation (μ ~ 4 μas/yr)
- Acceleration of the Local Group➔ CDM ?

Gaia: Practical implementation

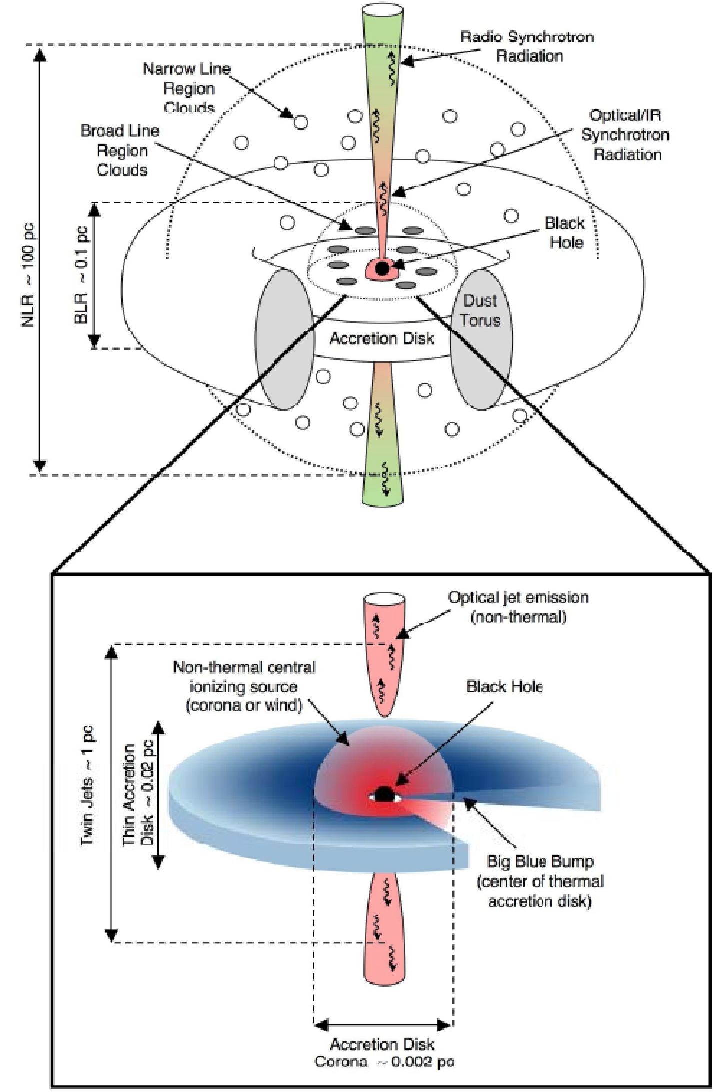
- No split between rotation and cosmic acceleration
- Orientation must be determined at the same time
  - cosmic proper motions to be included in the ICRF positions
  - they are not known, but can be computed
- Needs to carry out the alignment:
  - small subset of sources with positions in ICRS
    - ICRF sources and other observed in VLBI ➔ alignment
  - larger subset of EGSs with statistically zero proper motions
    - not necessarily observed with VLBI ➔ rotation

Gaia: Practical implementation

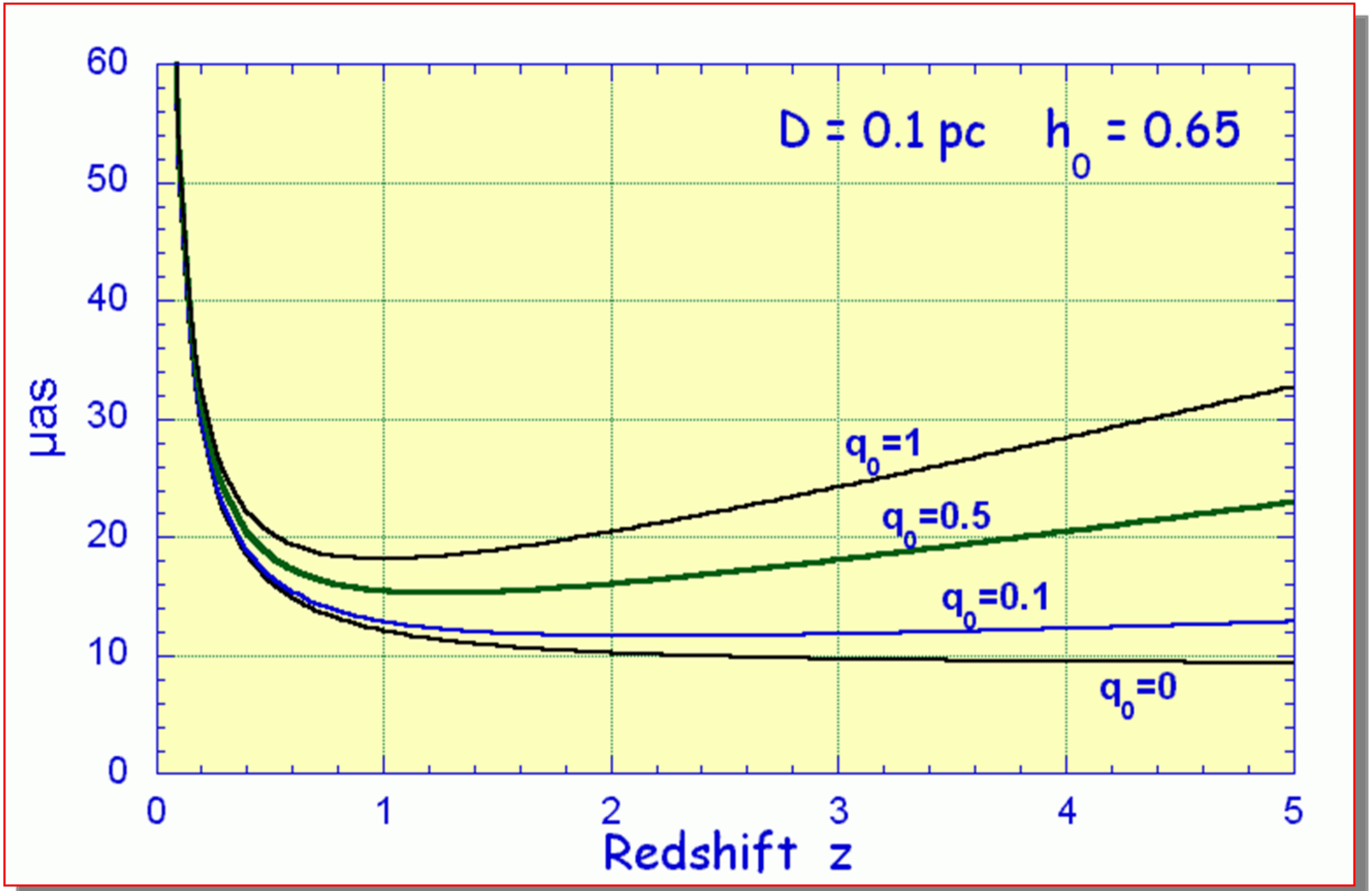
- There are 9 reference frame parameters
  - 3 for the orientation ε_x, ε_y, ε_z
  - 3 for the rotation ω_x, ω_y, ω_z
  - 3 for the cosmic acceleration a_x, a_y, a_z
- They are all determined within the astrometric global solution
  - attitude, position, proper motion will be referred to this frame
  - hopefully the ephemeris is given in a frame nearly identical
    - however the coupling is weak, and an error of 10 mas is acceptable
- This should be carried out in post-astrometric processing
- Full mathematical framework proposed by L. Lindegren

Radio-Optic offset

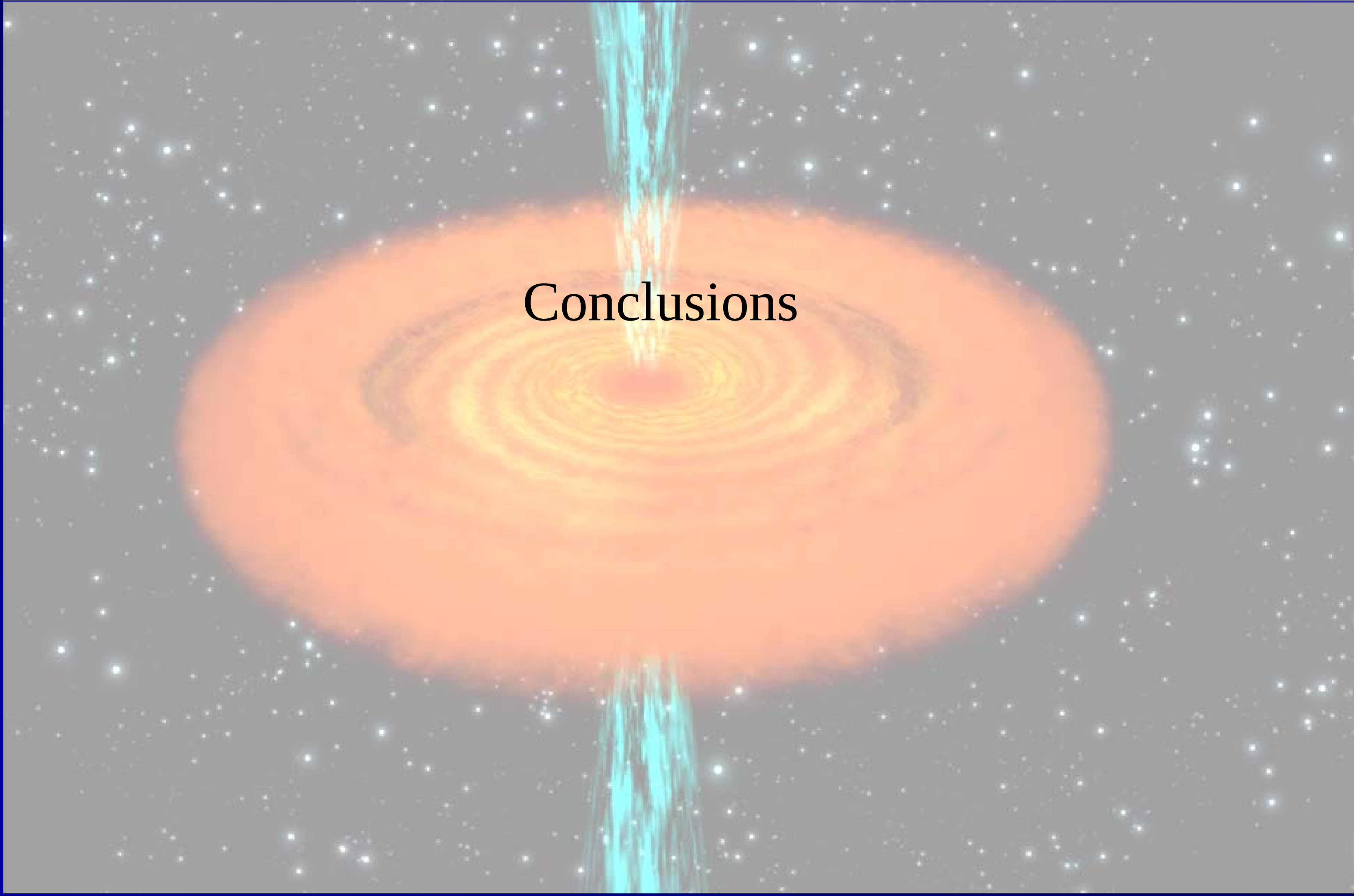
- No observational evidence
  - offset < 0.1 to 1 mas
- Emission model can provide insights
- For a distance of 0.1 pc between photocentre and radiocentre ➔ angular distance > 10 μas (z > 1)
  - becomes relevant for the alignment on radio ICRF
  - the offsets vectors should be randomly oriented ➔ act as an additional noise



Apparent diameter



Conclusions



Conclusions

- Extragalactic sources will be well observed by Gaia
  - resolved galaxies (eg : 5 to 10 Mios stars in LMC)
  - unresolved galaxies (~ 10^7 expected)
  - QSOs & AGNS
- QSOs will be recognised from stars primarily by photometry
  - astrometry will be used as well for difficult cases
- This will be the largest and most systematic full sky survey
- Classification of QSOs will be a major input for further physical studies
- A clean subset will be used as defining sources for the reference frame
- Imaging lensed QSOs will help constrain cosmological models

Thanks for your attention