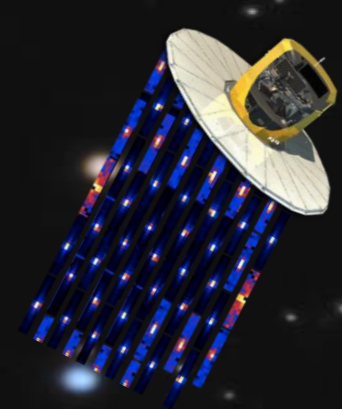


Gaia explores the Universe

*Morphology of galaxies and host galaxies of quasars
and the search for gravitational lenses*

CHRISTINE DUCOURANT

**LABORATOIRE D'ASTROPHYSIQUE DE BORDEAUX,
FRANCE**



GAIA SEES FAR

It observes millions of galaxies and quasars (with their host galaxy)

Galaxies

- Their morphology tells us about their evolution over cosmological time
- Statistics on their properties allow to investigate the local content of Universe

Quasars

- Define fixed directions, used to establish Gaia reference system
- Very few host galaxies studied yet
- Structure of host in the optics to better understand the coupling between the central black hole and its host

Gravitational lenses

- Result from quasar's light passing by a massive galaxy : multiple images of the quasar
- A few are known (<70 quadruply imaged quasars - quads)
- Help to provide independent, far-field measurements of H_0

SEVERAL GAIA GROUPS ANALYSE QUASARS AND GALAXIES

- How to identify quasars and galaxies?

- Classification from astrometric/photometric properties (GCRF3)
- Classification from photometric variability (Vari)
- Classification from spectro-photometric BP/RP spectra (DSC)

- What does Gaia measure?

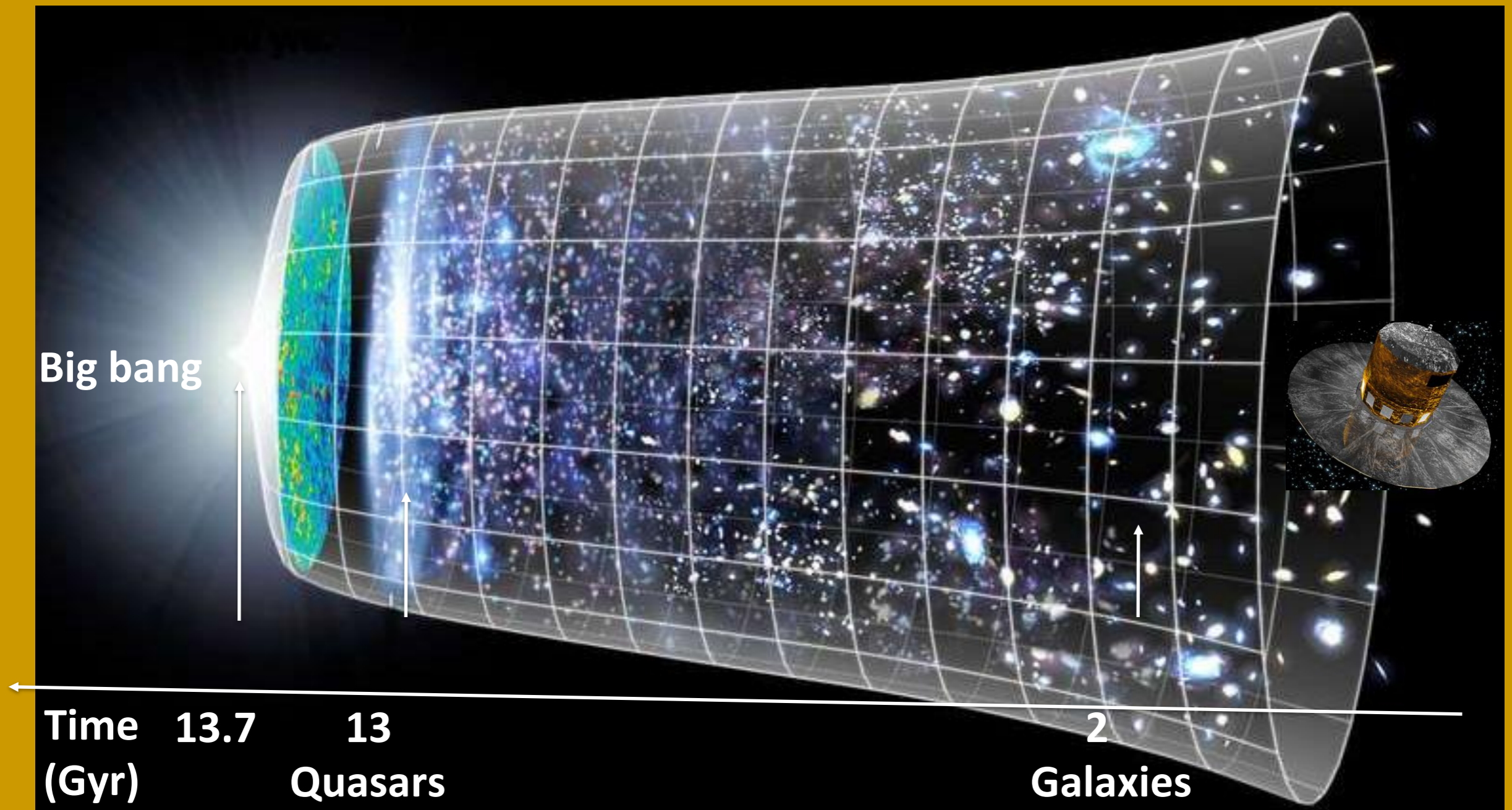
- spectro-photometric redshifts (QSOC, UGC)
- surface brightness profiles (EO)
- Photometric light curves (Vari)

- Two catalogues in DR3 (qso_candidates, galaxy_candidates)

- Several papers present the results/methods

- "Gaia DR3 : The extragalactic content" - *Gaia collaboration, Bailer Jone+2022*
- "Gaia DR3 : Surface brightness profiles of galaxies and host galaxies of quasars" - *Ducourant+2022*
- "Gaia DR3: The first catalogue of variable active galactic nuclei", *Carnerero+2022*
- "Gaia DR3: Apsis III - Non-stellar content and source classification", *Delchambre+2022*

DATA TO EXPLORE THE UNIVERSE

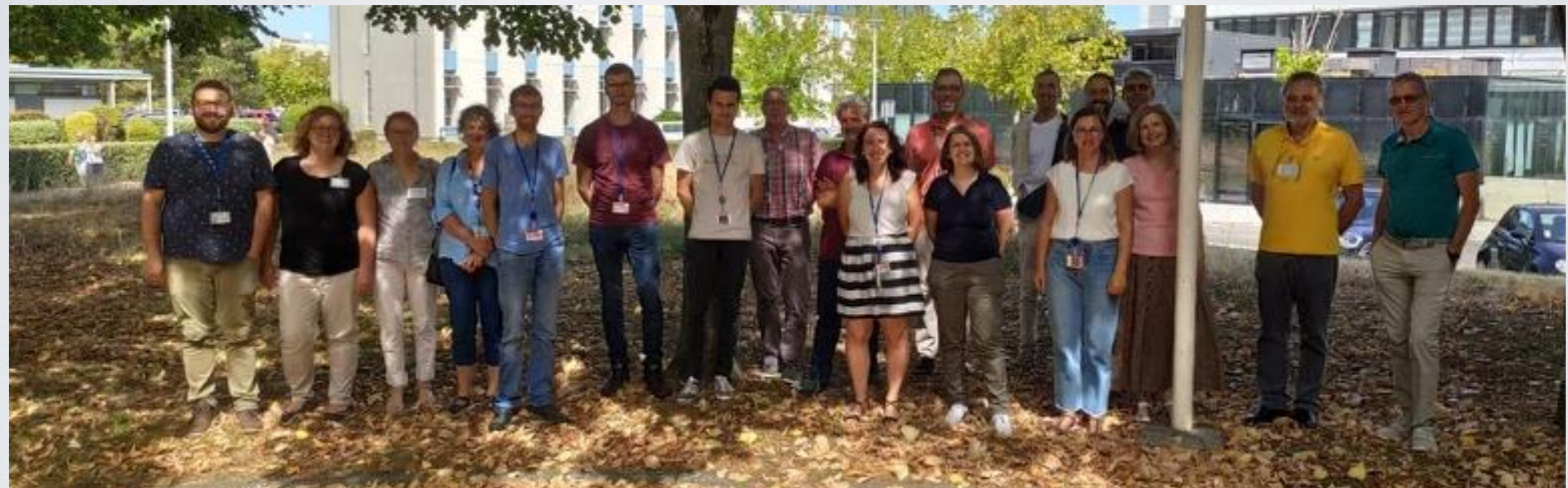


Crédit : NASA/WMAP

Outline

- **Surface brightness profiles of quasars and galaxies**
 - List of sources to be analysed
 - Specificity of Gaia observations
 - The direct model of fitting
 - Properties of quasars and galaxies' 2D light profiles
- **Gravitational lenses in Gaia**
 - The GraL group
 - Search for lenses : the methods
 - GravLens chain
 - Results

DPAC "Extended Objects" Group for surface brightness profiles



Scientific team: C. Ducourant (LAB), L. Galluccio (OCA), A. Krone-Martins (UC Irvine), J.F. Le Campion (LAB), I. Slezak (OCA), E. Slezak (OCA), R. Teixeira(USP), J. Braine (LAB), L. Delchambre (U. Liège) , R. de Souza (USP), F. Mignard (OCA), P. Gavras (ESAC)

Centre National Etudes Spatiales (CNES) team: A. Barbier, A. Blazere, W. Roux, A. Guerrier, C. Panem , J. Guiraud, S. Managau, N. Mary, A. Helmer

Quasar and Galaxy treatment

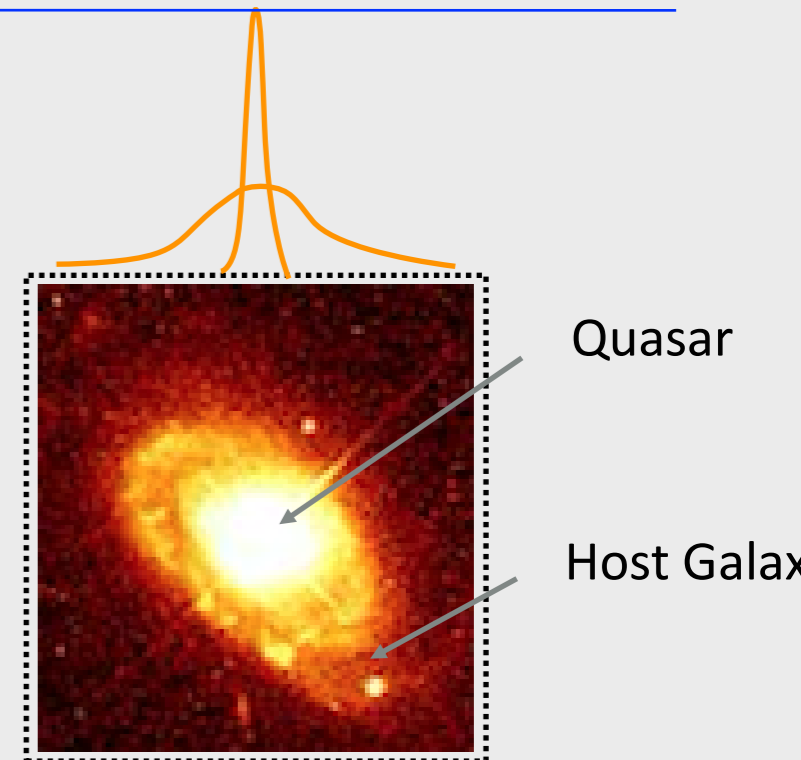
Quasar

➤ Scientific Objective

- First all-sky survey of Host Galaxies of Quasars (few tens with morphology from Hubble telescope and ~25 000 detected from ground spectroscopy)
- Study of the structure of host galaxy of quasars in optic
- Important for the link of Gaia celestial reference frame (optic) to International Celestial Reference Frame (radio)

➤ Product

- Give diagnostic of detection of host galaxy
- Fit luminosity profile of quasar + host galaxy (Quasar : exponential + galaxy : Sérsic)



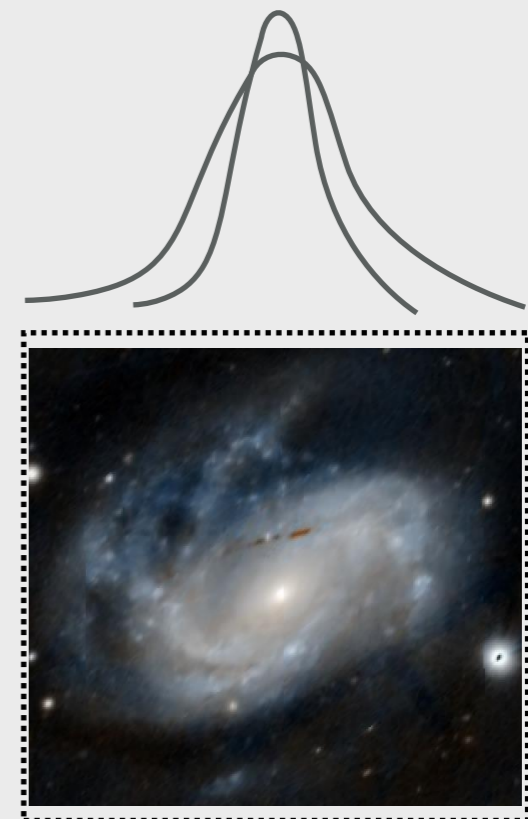
Galaxy

➤ Scientific Objective

- First space-based survey of morphology of galaxies at Gaia resolution (>180 mas)
- Study of the local Univers content
- Luminosity profiles of tiny galaxies never observed from ground

➤ Product

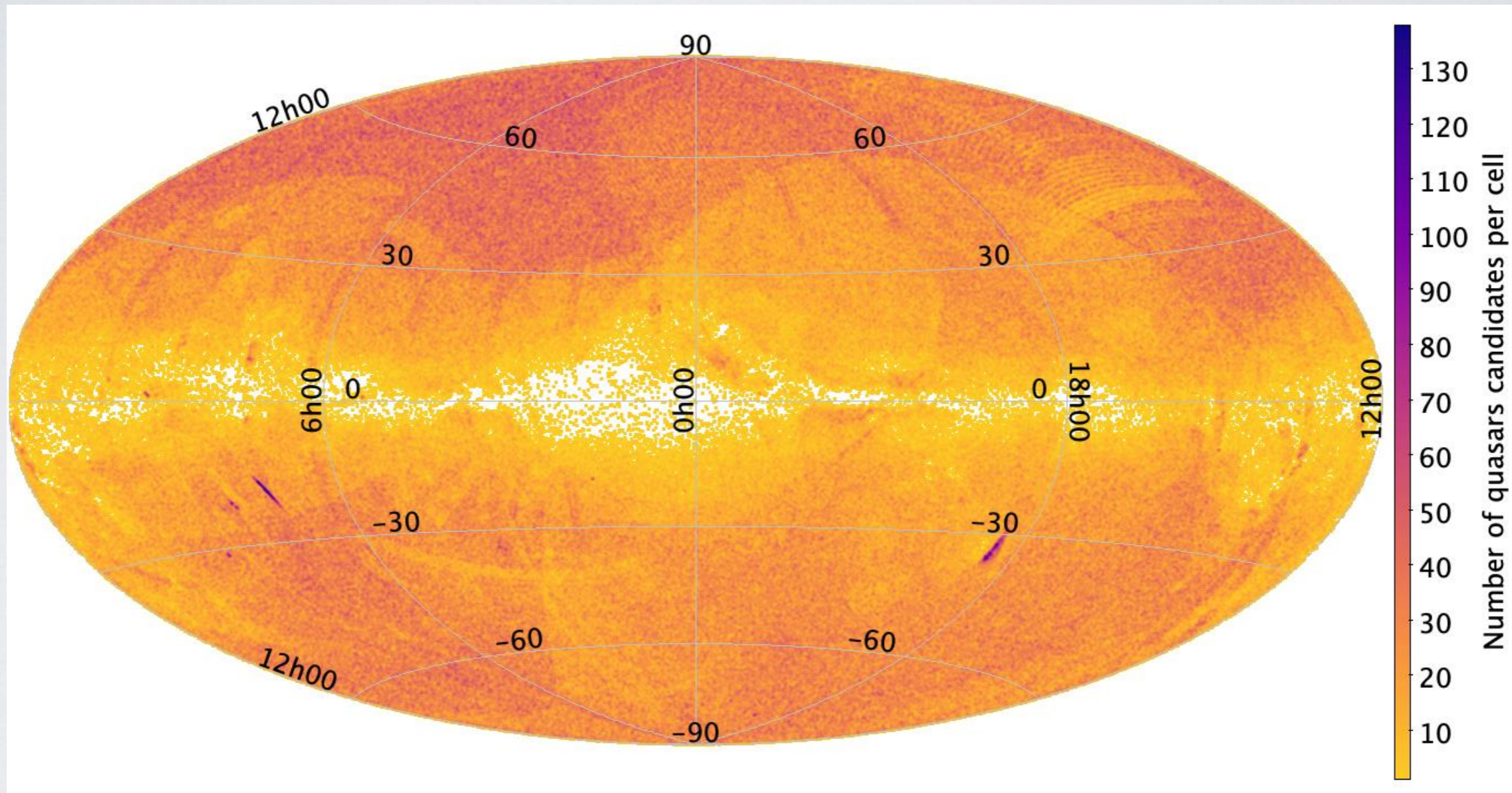
- Fit two luminosity profiles of galaxies (Sérsic, de Vaucouleurs profiles)



X 2 profiles

List of quasars

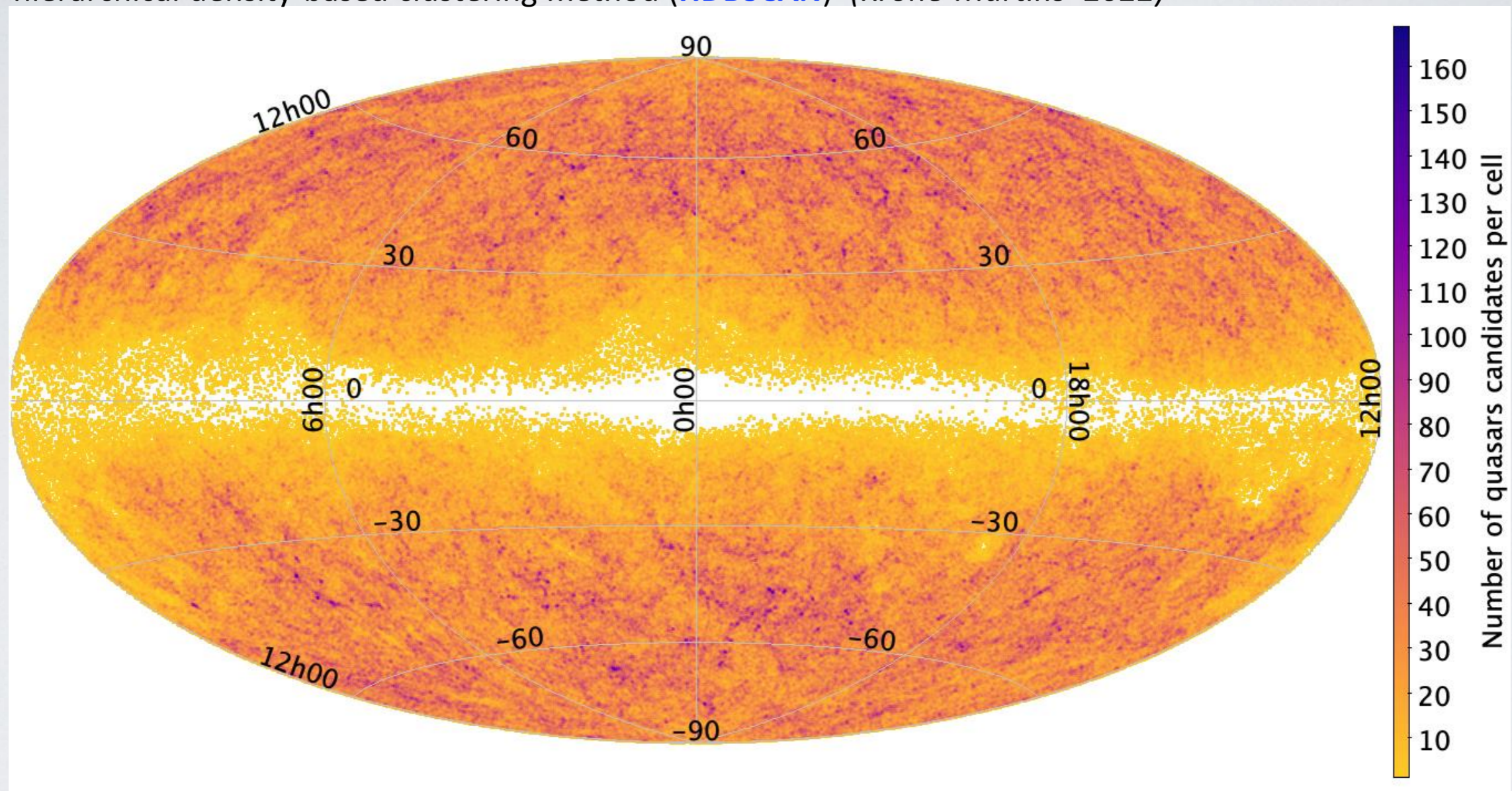
- **Compilation of major quasars or AGN catalogues** (*Ducourant+2022*) (MILLIQUAS (Flesh 2017), ALLWISE (Secrest 2015), ALLWISE (Assef 2018), Gaia-CU7 variability (Rimoldini+, 2019), QAC3 (Souhay 2015), ICRF2 (Ma 2009), SDSS DR12 (Pâris 2015))



- **1.3 M quasar candidates**
- Not very homogeneous catalogue (SDSS imprint...)
- Over-density (MC, Galactic plane) -> moderate stellar contamination

List of galaxies : Gaia DR2+AllWISE

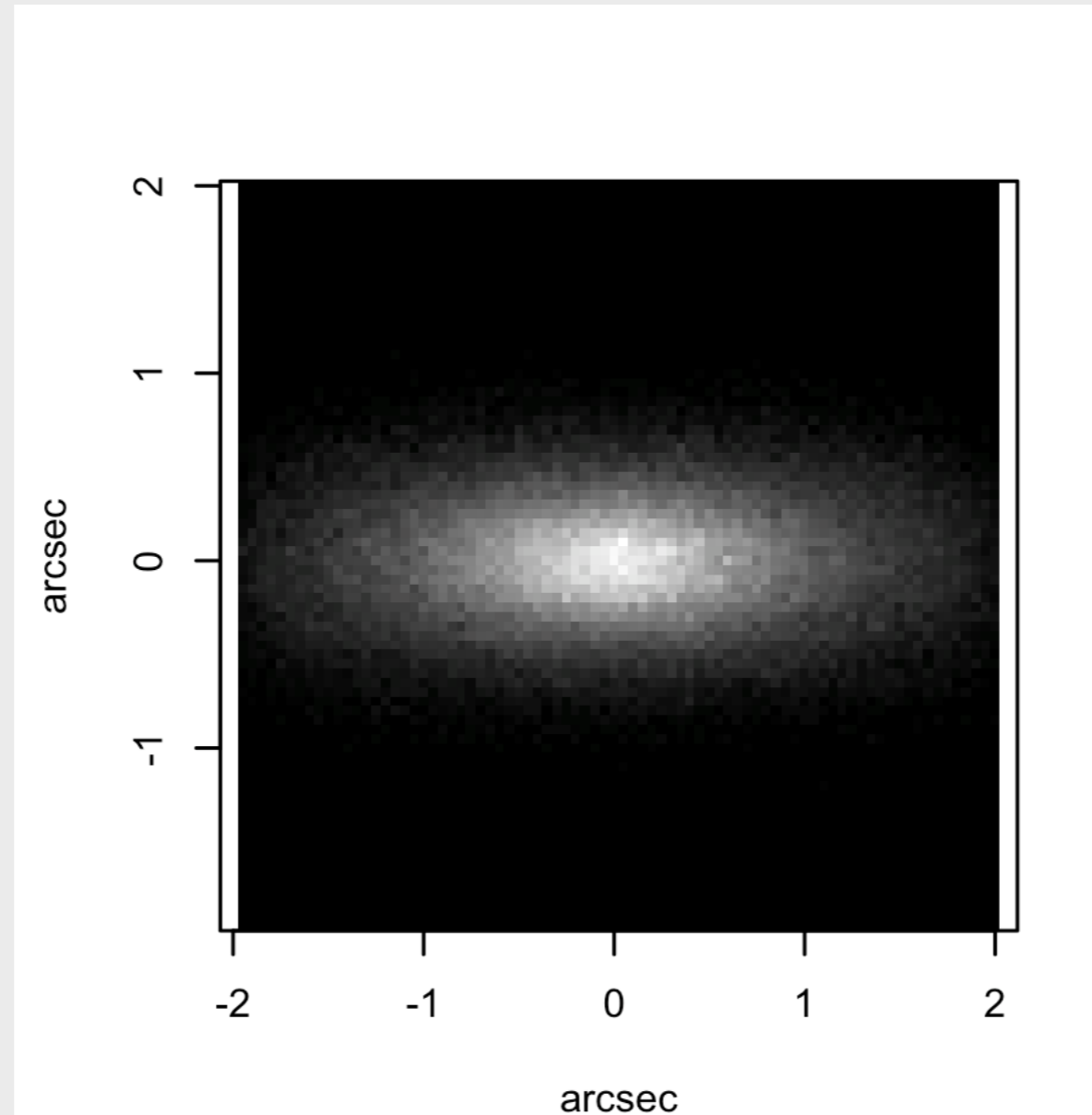
- Gaia DR2 + AllWISE
- **Unsupervised identification of galaxies** by iterative random sampling of the data (photometry+astrometry), random selection of the parameters analysed (dimension) and hierarchical density-based clustering method (**HDBSCAN**) (*Krone-Martins+2022*)



- **1.7 M quasar candidates**
- Homogeneous catalogue (purity= 98.5% and completeness =30.8%)
- No over-density (MC, GCs, Galactic plane) -> low stellar contamination
- Large scale structures

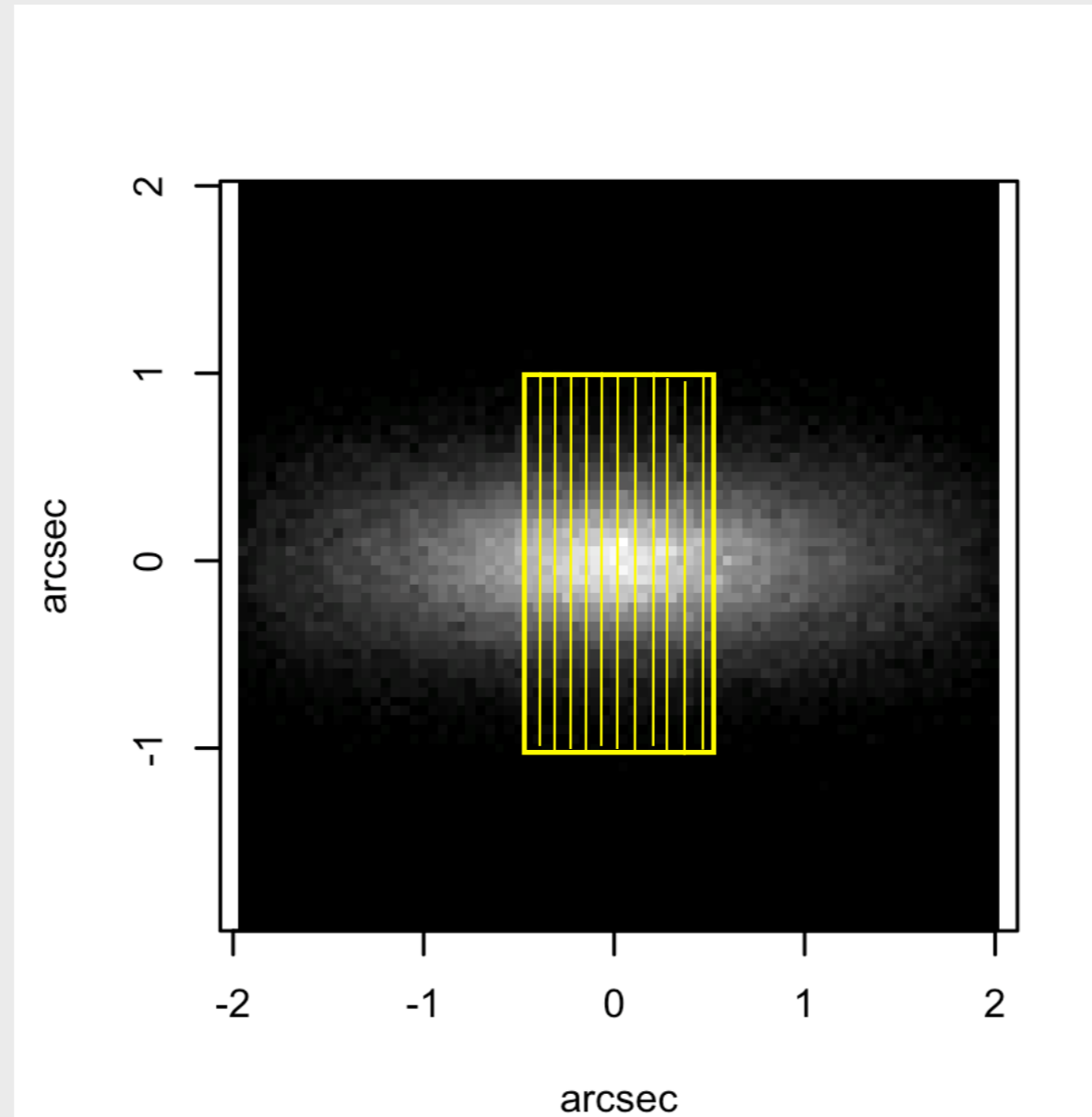
The observations of a galaxy by Gaia

- Gaia do not take pictures of the sources!



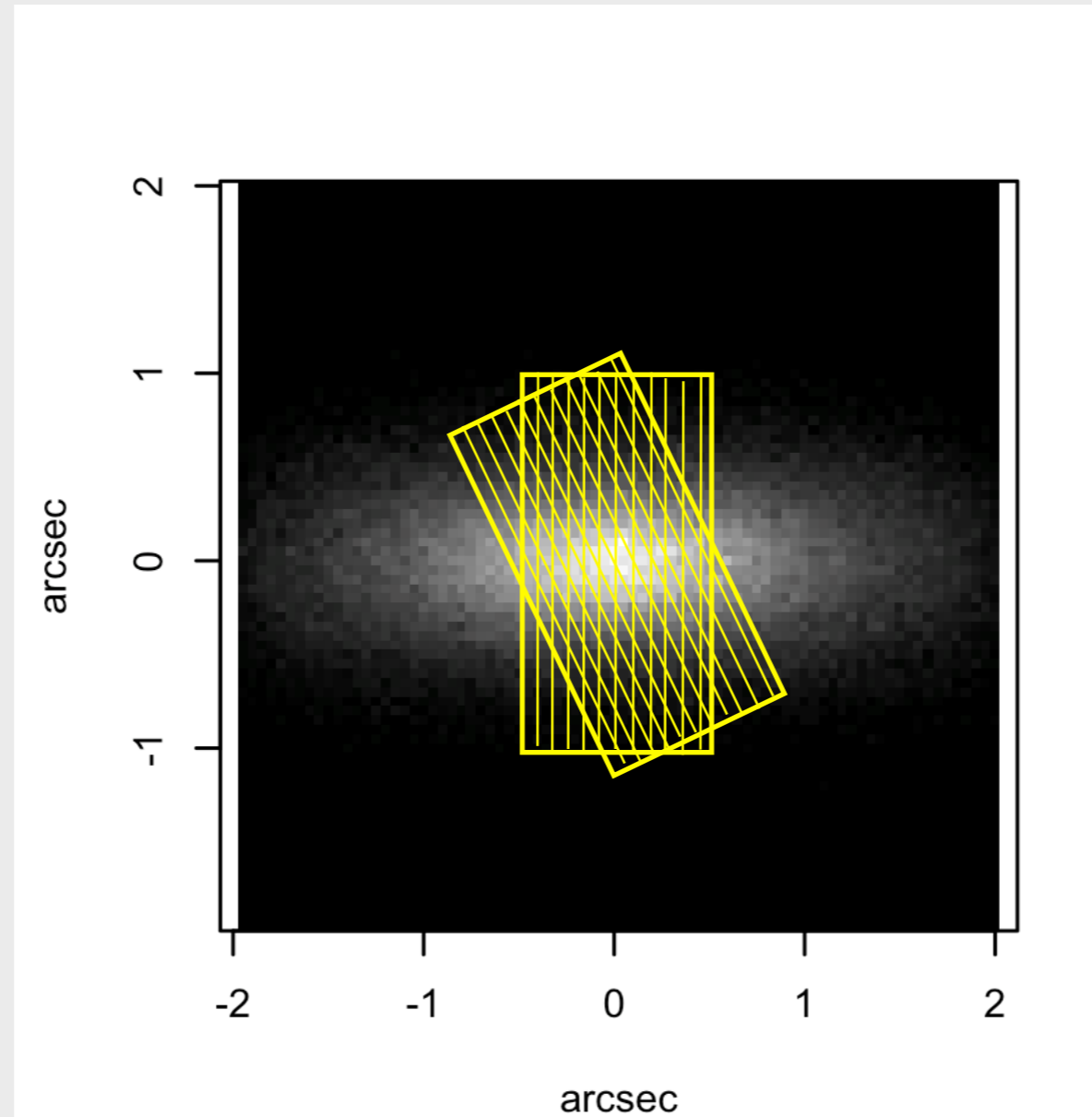
The observations of a galaxy by Gaia

- High resolution AFs detectors (1 dimension - 12 pixels : 707 mas x 2121 mas)
- pixel size : 59 mas x 2121 mas



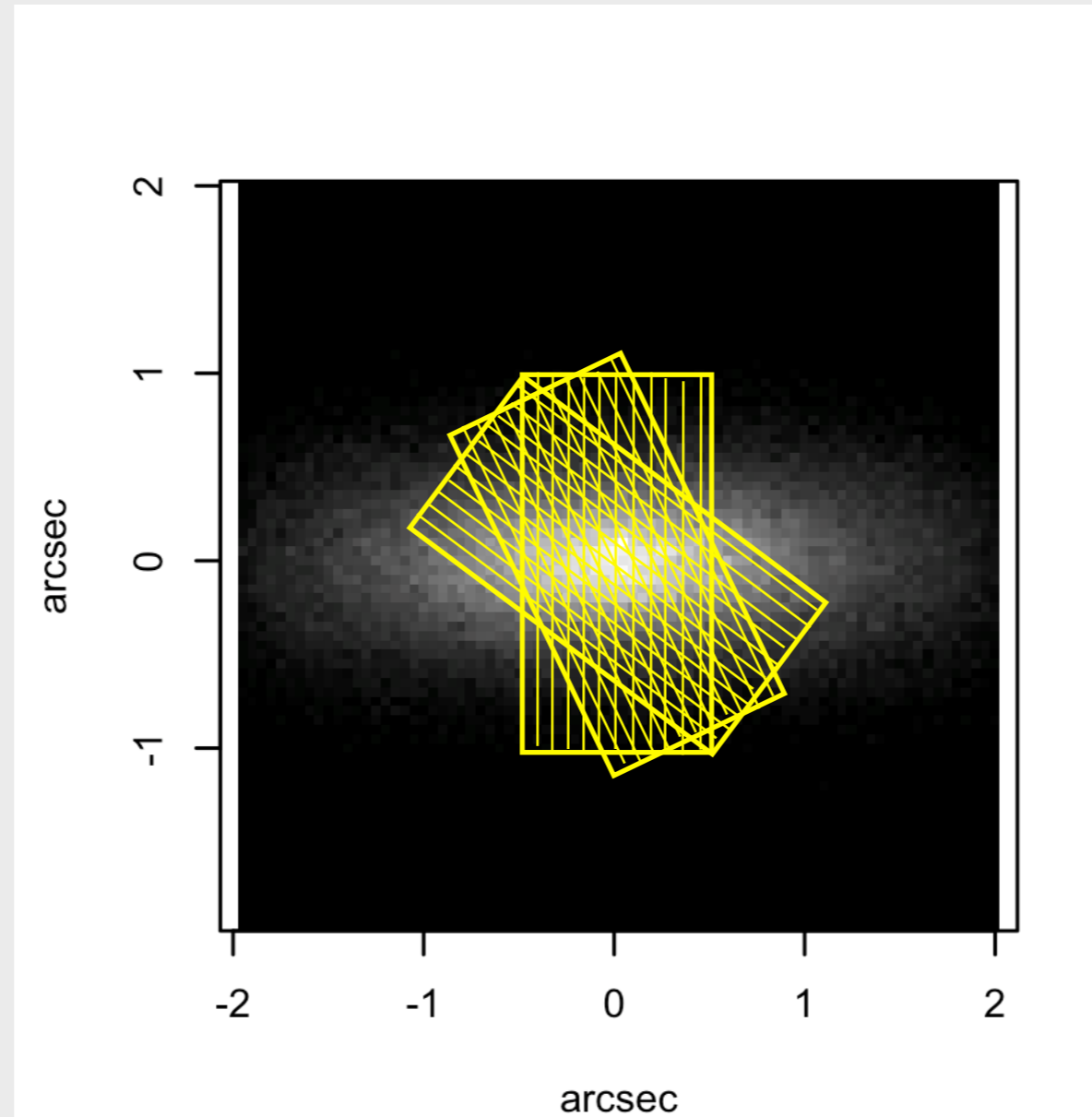
The observations of a galaxy by Gaia

- High resolution AFs detectors (1 dimension - 12 pixels : 707 mas x 2121 mas)
- pixel size : 59 mas x 2121 mas



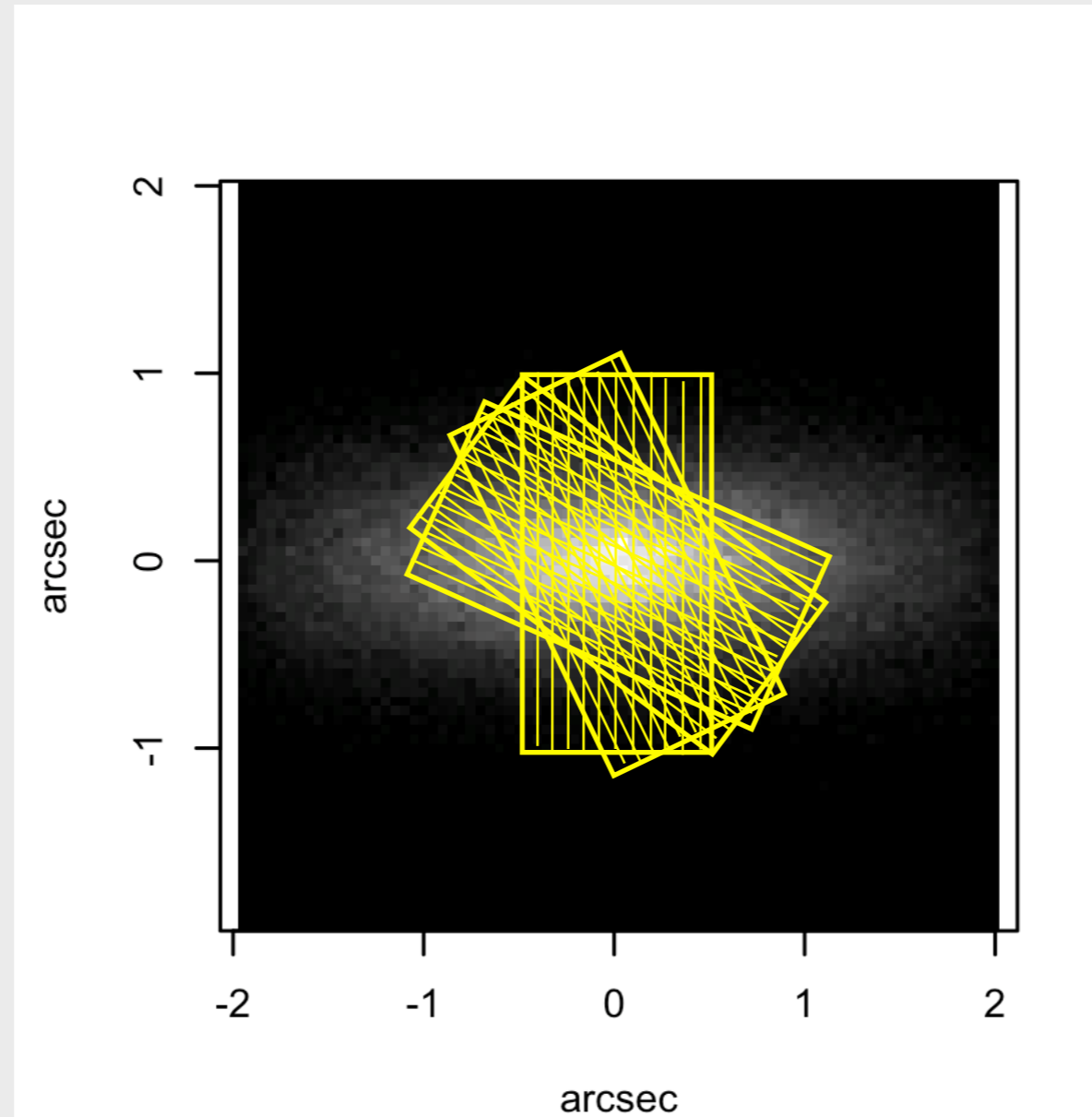
The observations of a galaxy by Gaia

- High resolution AFs detectors (1 dimension - 12 pixels : 707 mas x 2121 mas)
- pixel size : 59 mas x 2121 mas



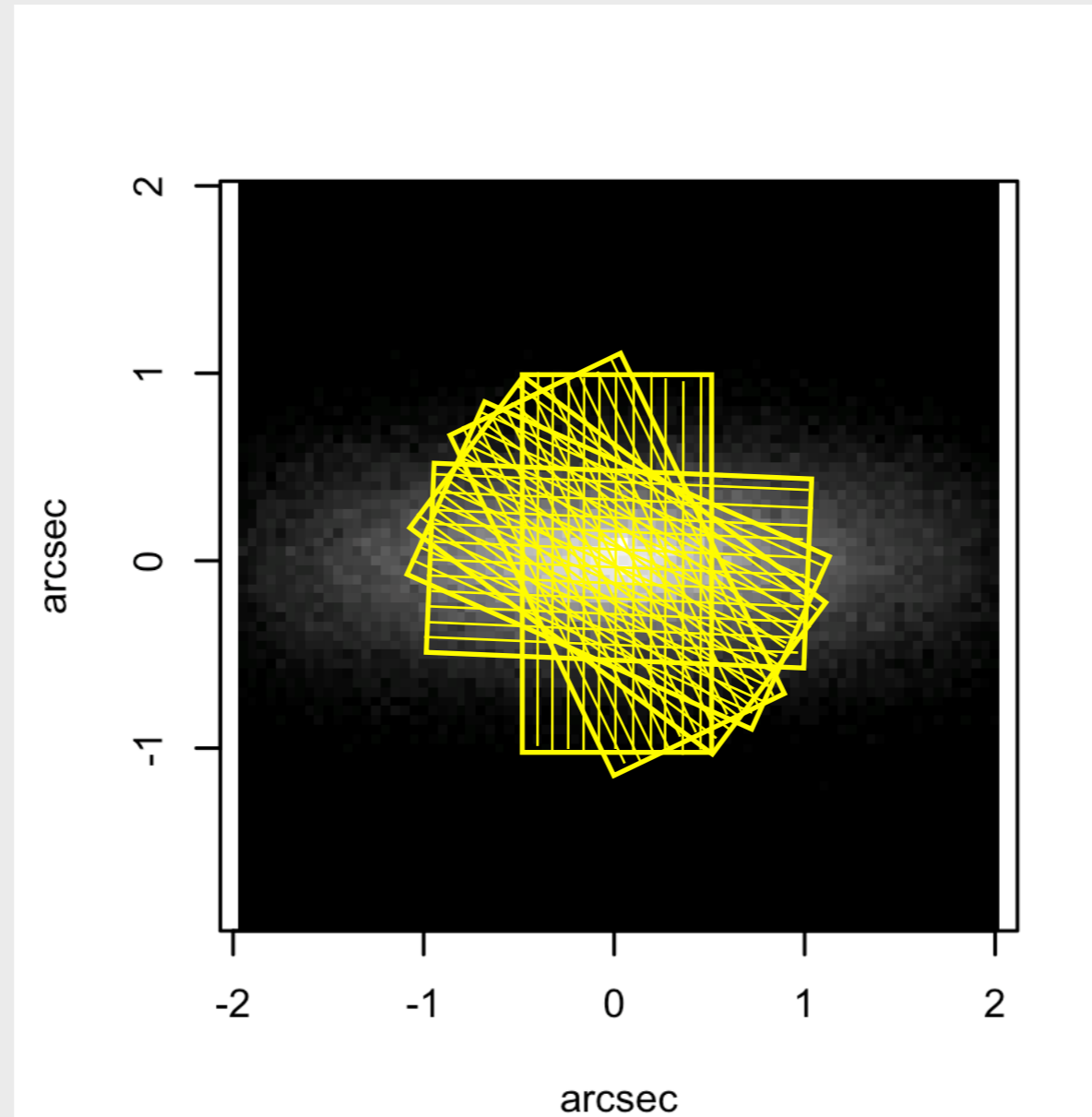
The observations of a galaxy by Gaia

- High resolution AFs detectors (1 dimension - 12 pixels : 707 mas x 2121 mas)
- pixel size : 59 mas x 2121 mas



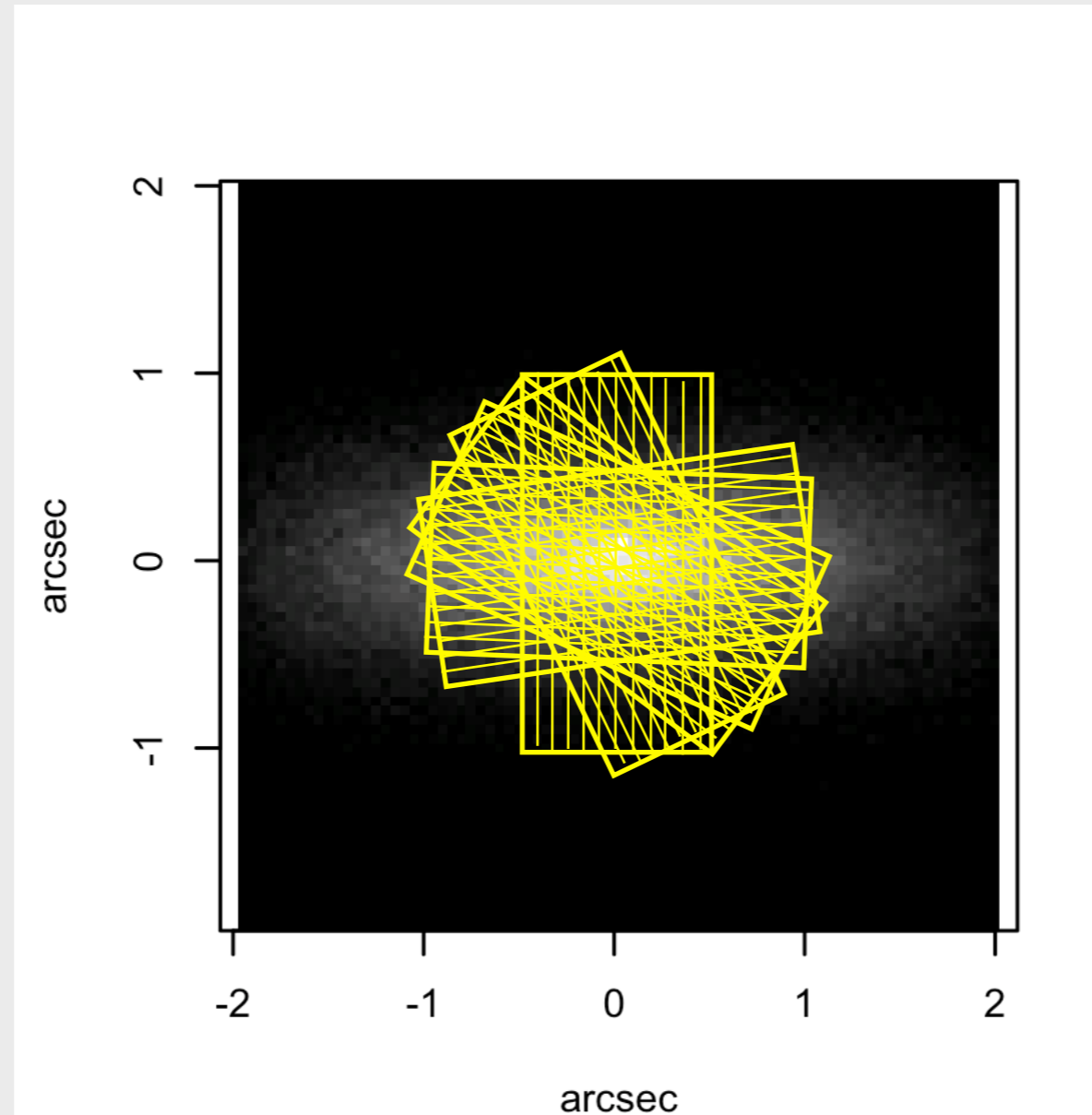
The observations of a galaxy by Gaia

- High resolution AFs detectors (1 dimension - 12 pixels : 707 mas x 2121 mas)
- pixel size : 59 mas x 2121 mas



The observations of a galaxy by Gaia

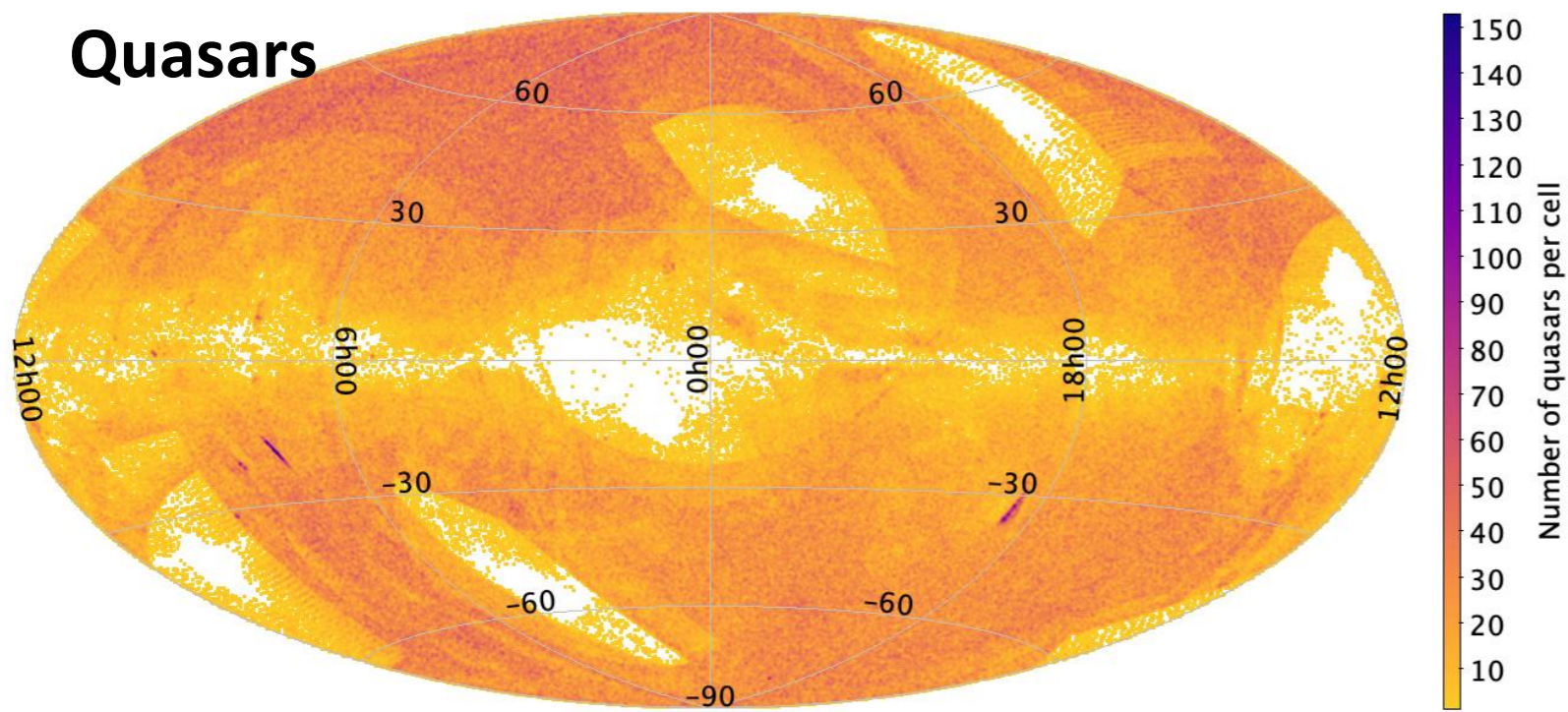
- High resolution AFs detectors (1 dimension - 12 pixels : 707 mas x 2121 mas)
- pixel size : 59 mas x 2121 mas



- 140 transits by the end of the mission with various transit angles (less for faint galaxies)
- A large surface coverage is necessary to retrieve the surface brightness profile of sources

Filtering the sources

Quasars

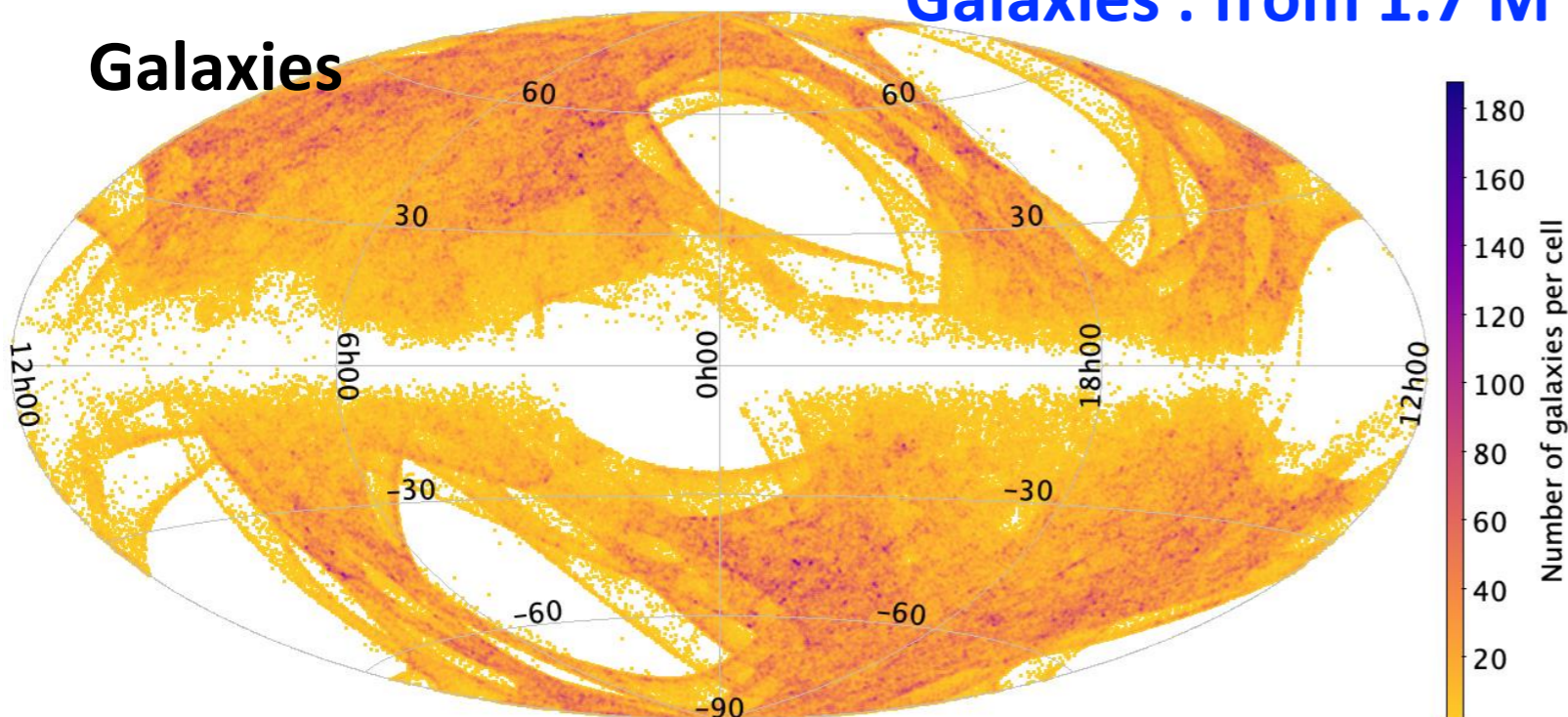


- **Filtering : nb transits >25 and large surface coverage**
- **Gaia scanning law appears evidently**
- **Filtering very severe for galaxies**

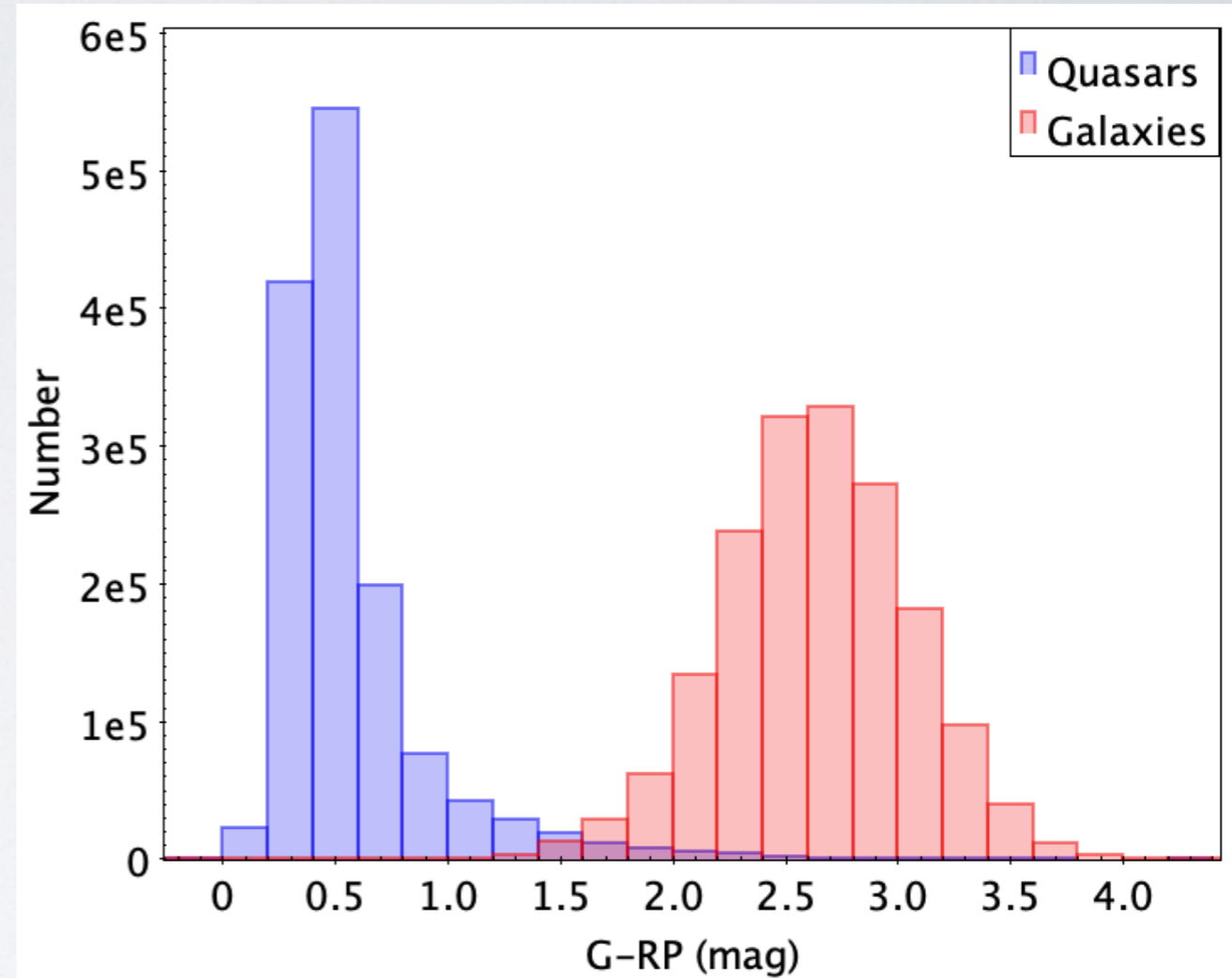
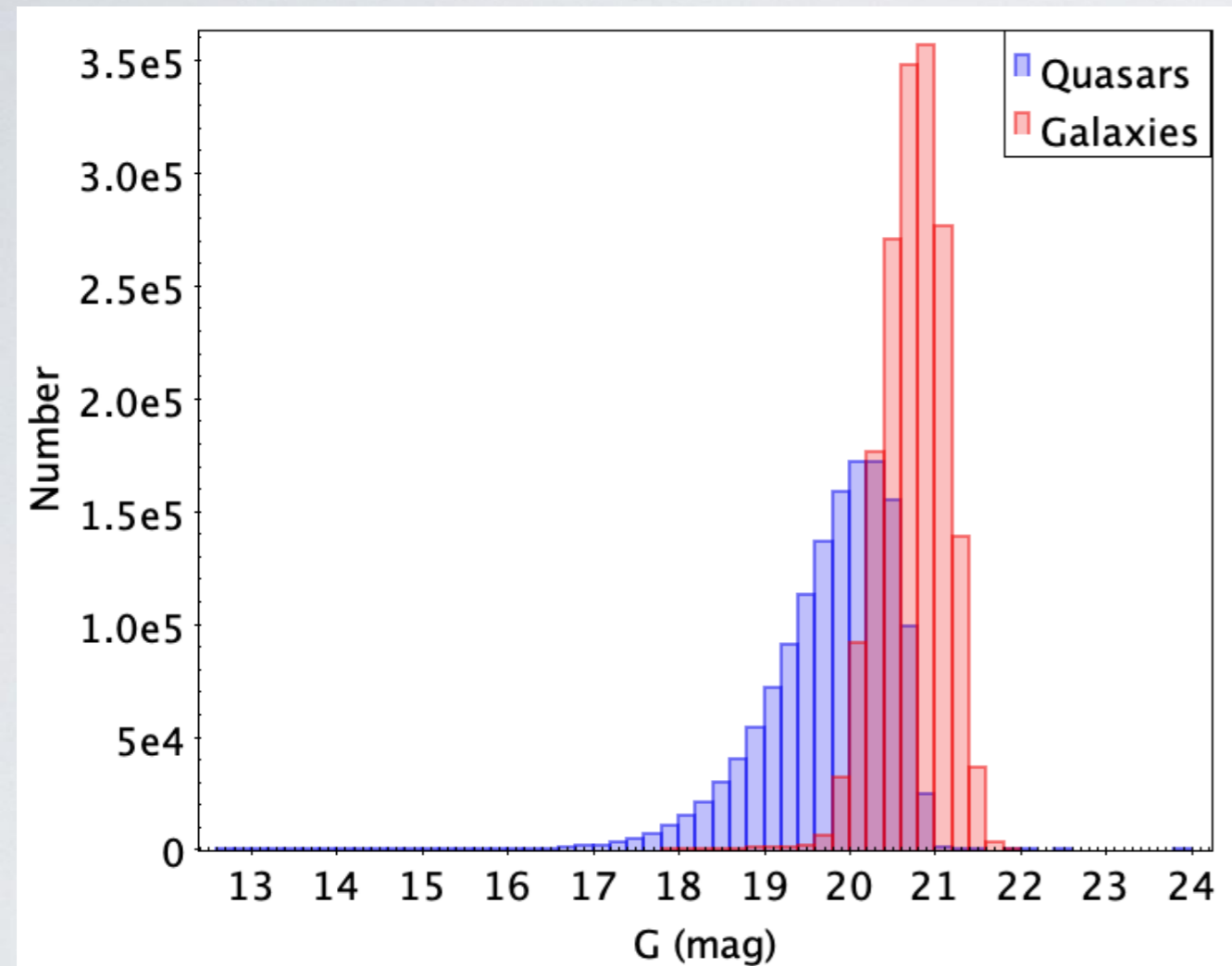
Quasars : from 1.3 M -> 1.1 M sources

Galaxies : from 1.7 M -> 0.9 M sources

Galaxies

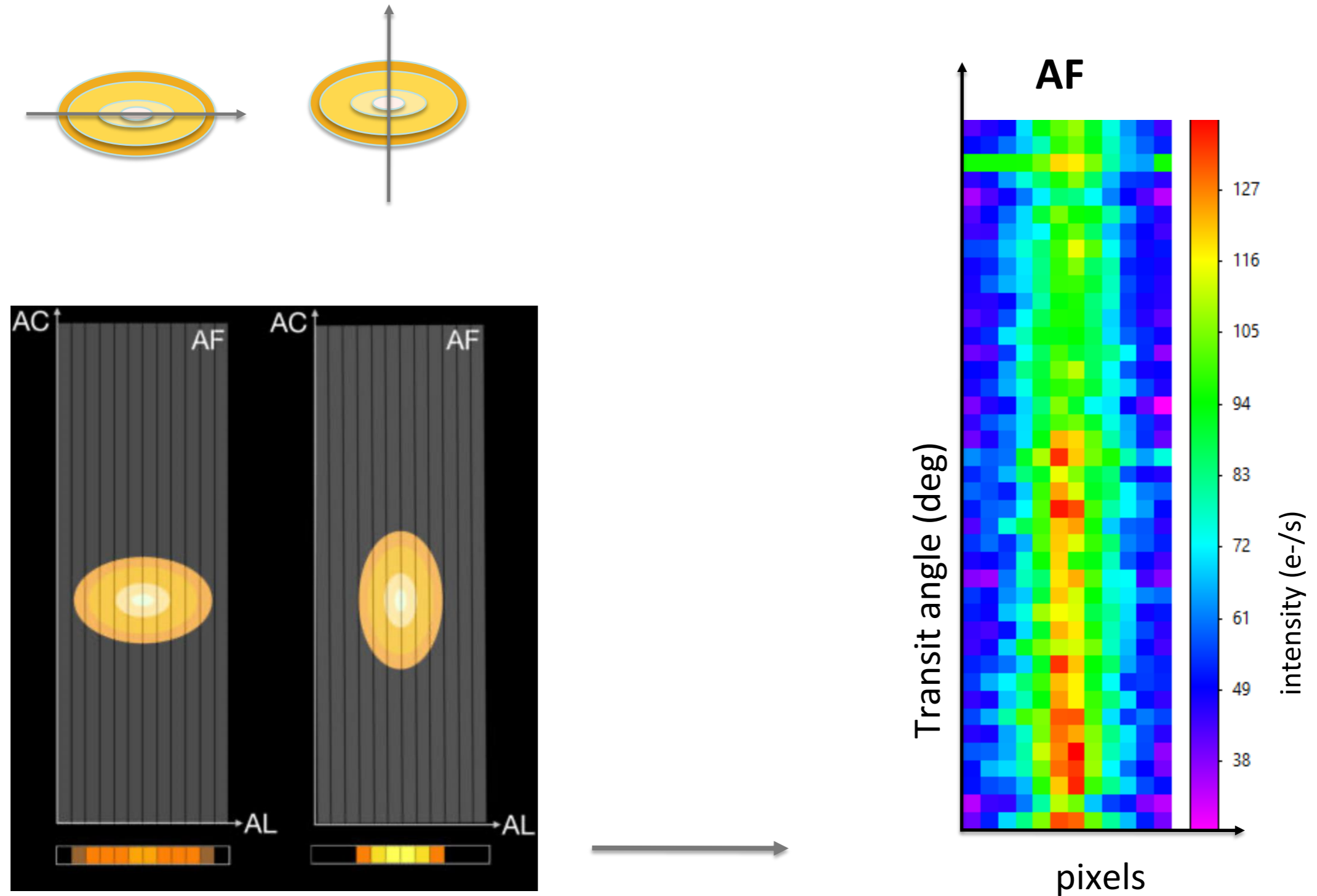


Properties of the sources



- Galaxies fainter (<21) than quasars (<22)
- Two lists with different colours and low overlapping

How to measure 2D profiles from 1D observations

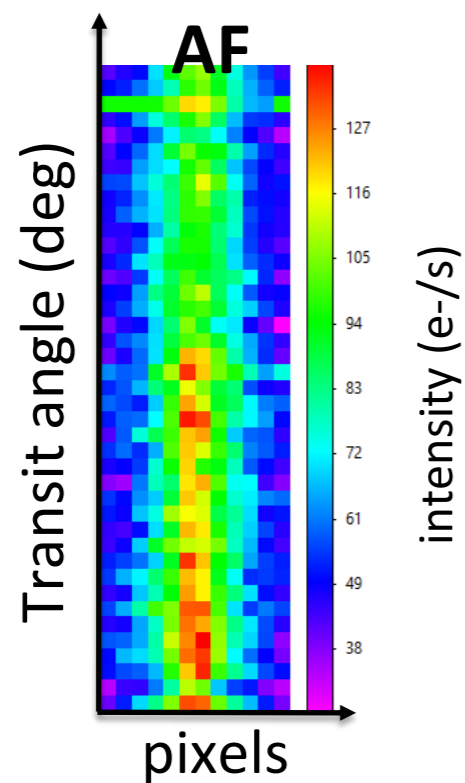


- Gaia scans galaxies under various transit angles
- Intensities are different for different transit angles

The forward model

Observations

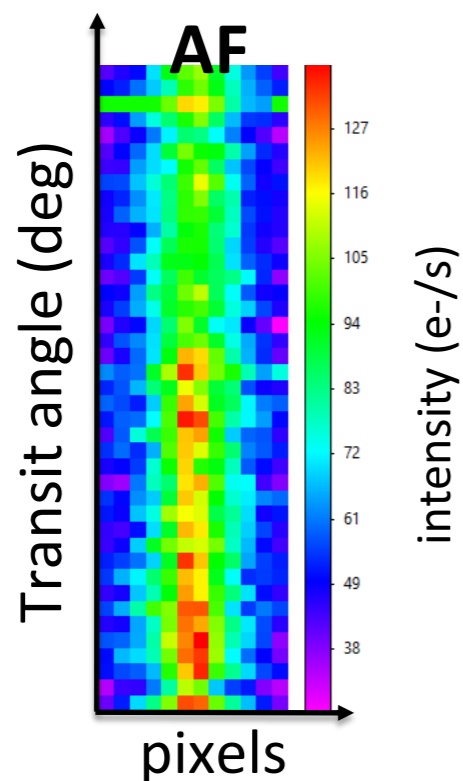
Organisation of observed windows in two sinograms (Radon transform)



The forward model

Observations

Organisation of observed windows in two sinograms (Radon transform)

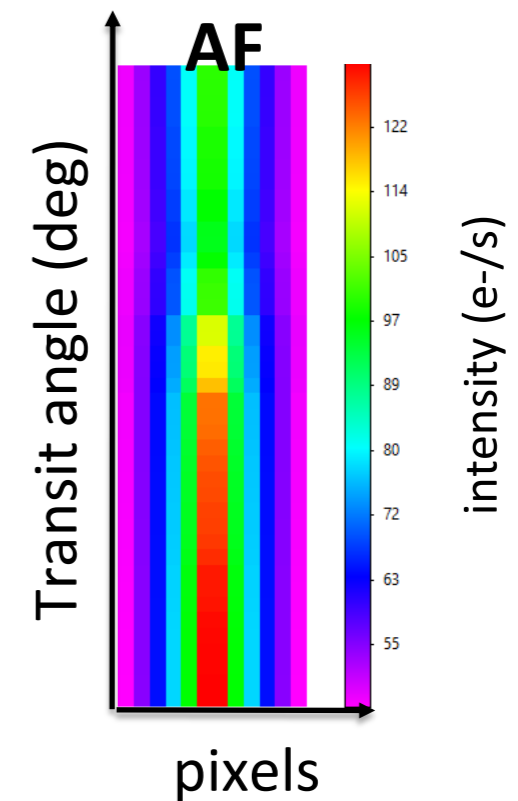


Forward Model

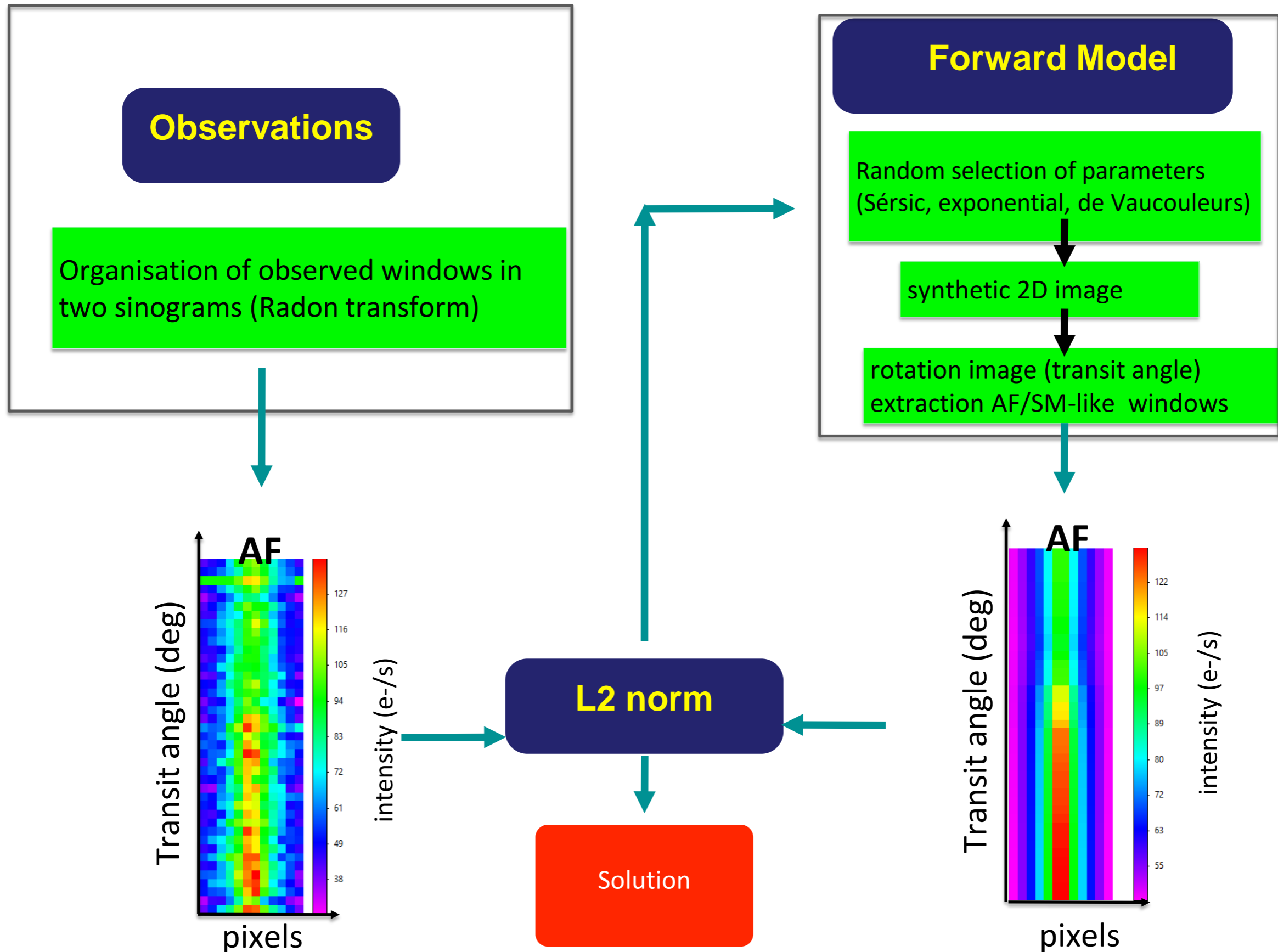
Random selection of parameters (Sérsic, exponential, de Vaucouleurs)

synthetic 2D image

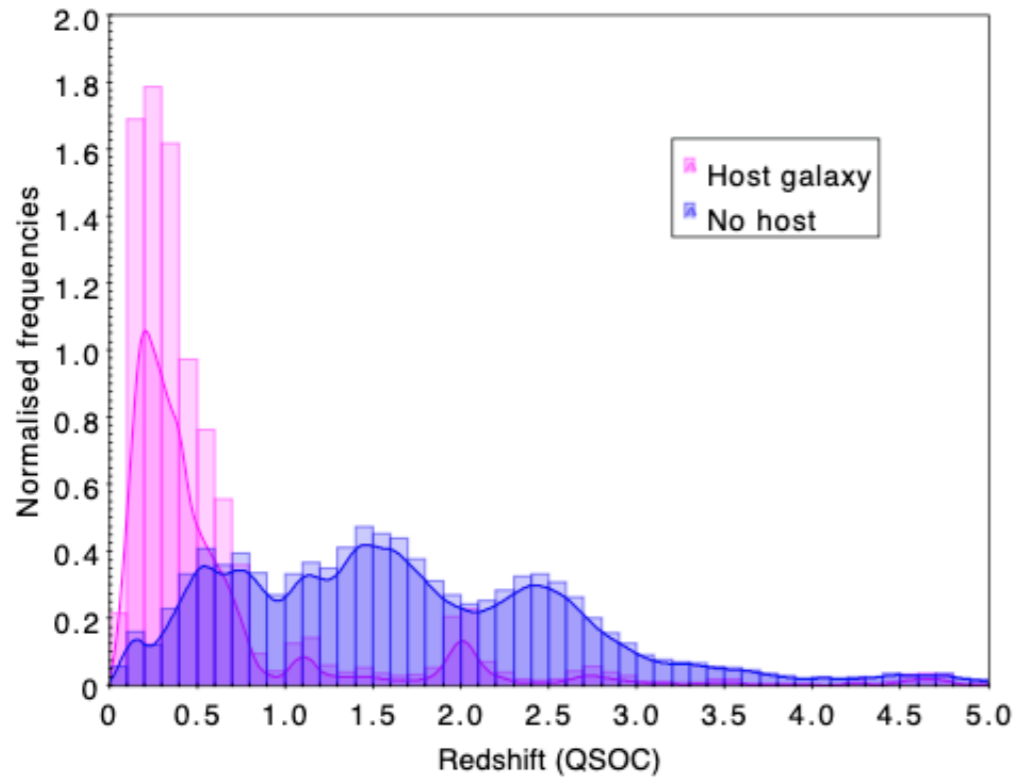
rotation image (transit angle)
extraction AF/SM-like windows



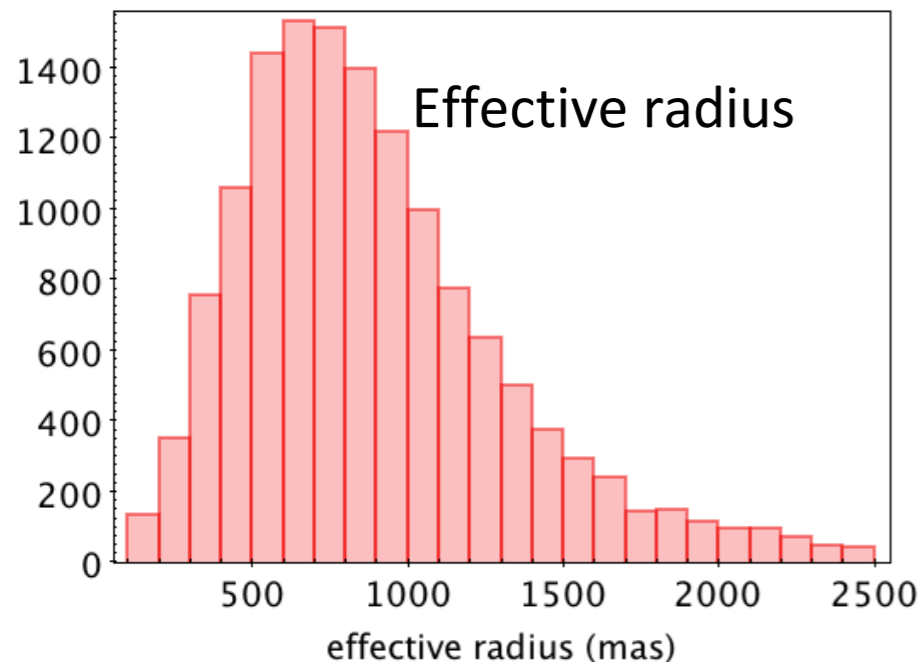
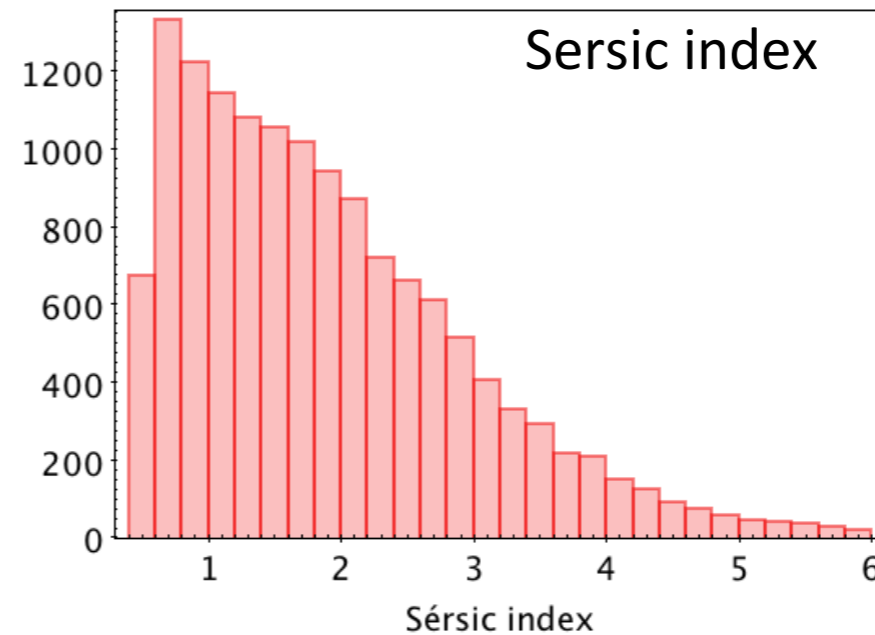
The forward model



2D profile of host galaxies of quasars



- 1.1 M quasars analysed
- 64 498 host galaxy detected (6%)
- 15 807 Published profiles

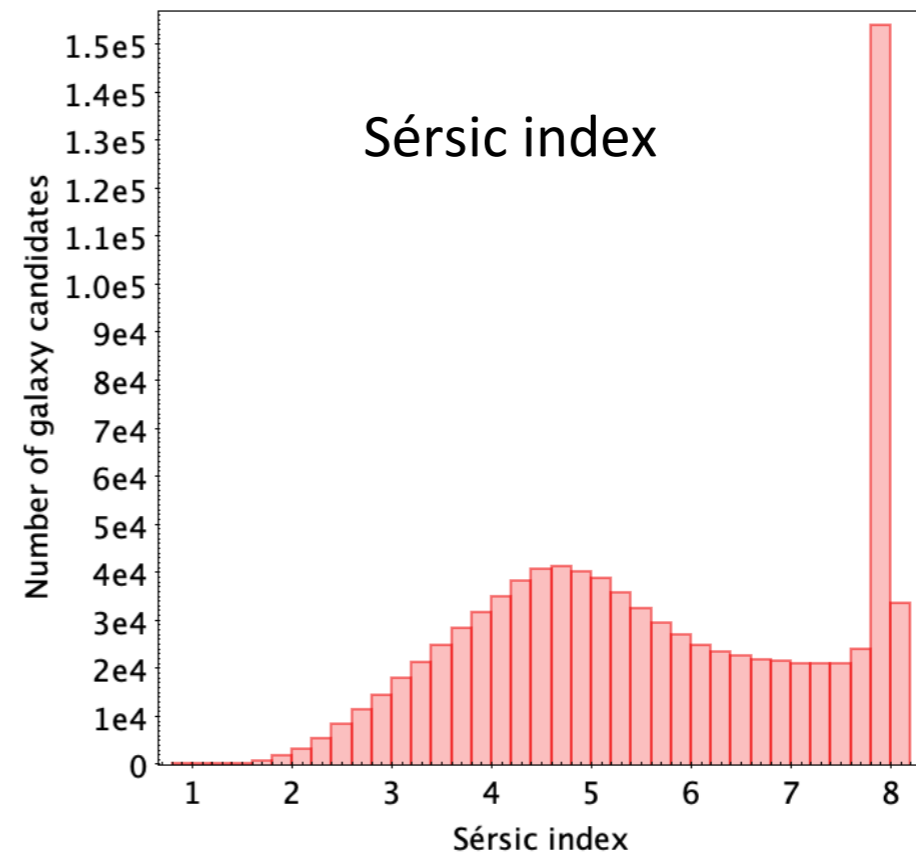
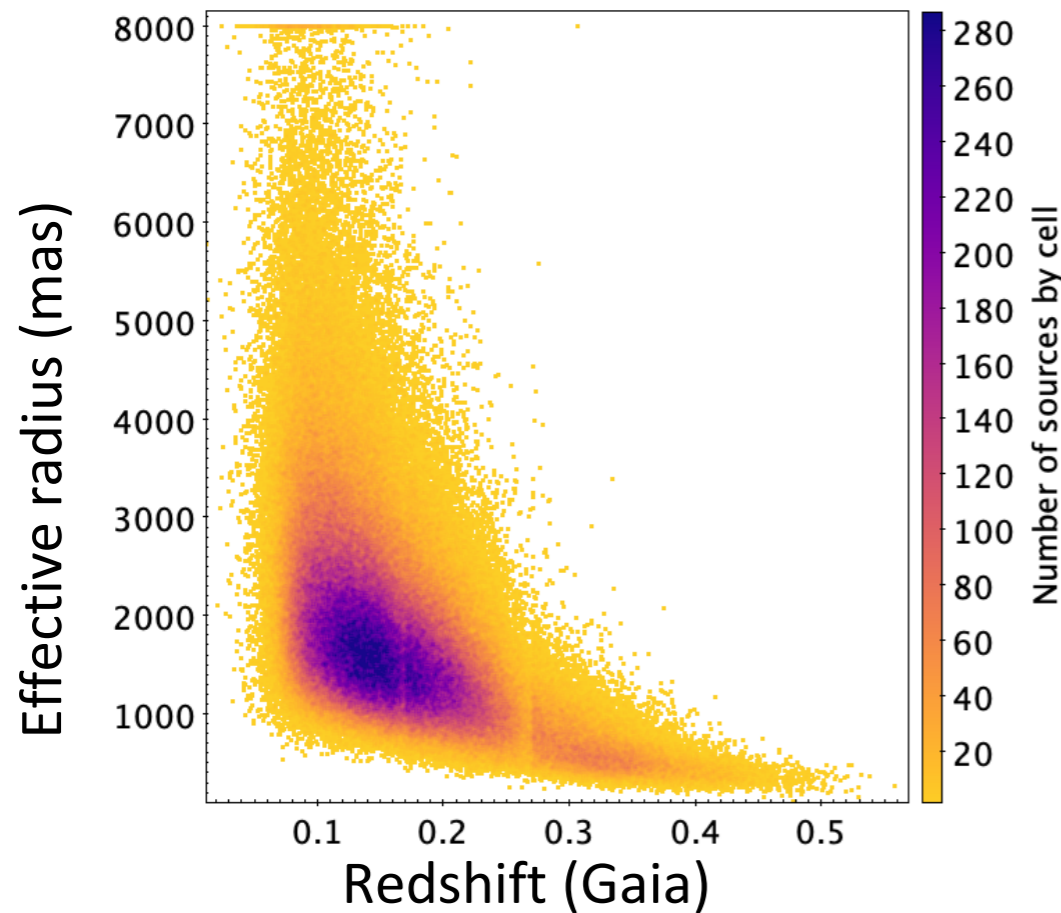


- **Host Galaxies** detected around quasars with **small redshifts**
- **Sérsic index ~1** : quasars are hosted by **disc-like galaxies**
- radius (Sérsic) peak ~0.7" : impossible to resolve from ground

Gaia provides the first morphologic survey of host galaxies of quasars

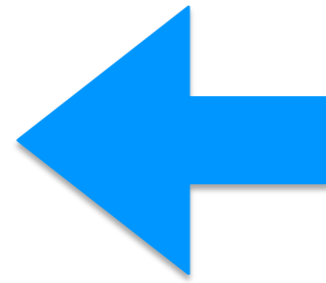
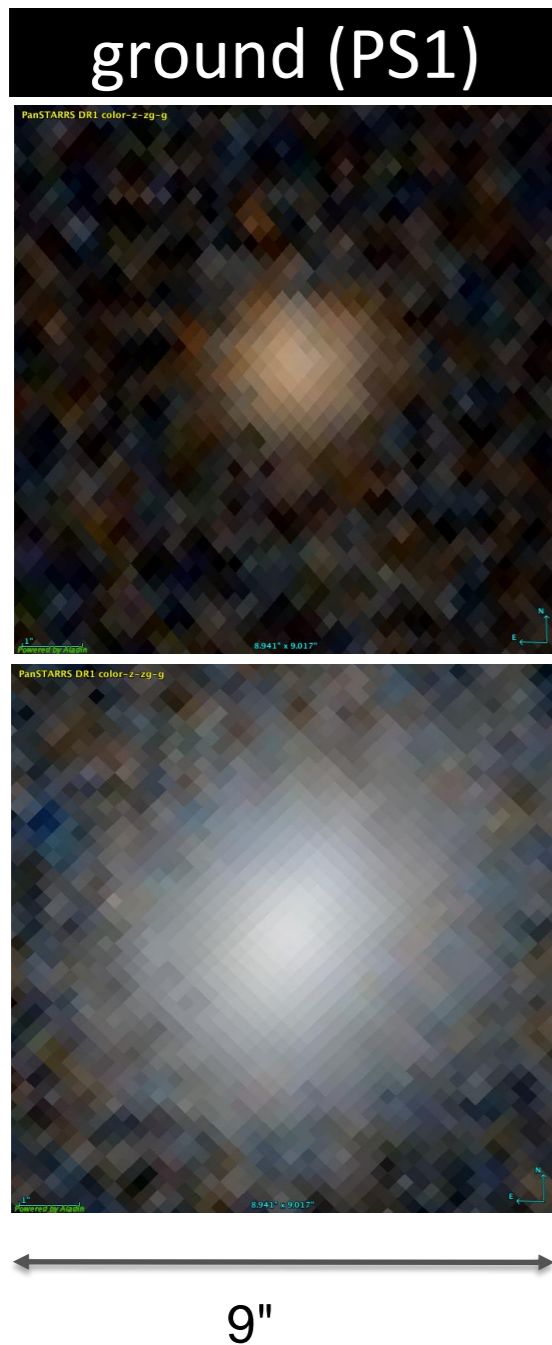
2D profile of galaxies

- 0.9 M galaxies analysed
- Sérsic profile and de Vaucouleurs profile for all

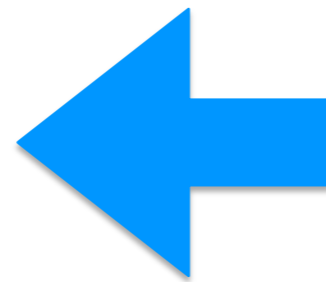


- Radius correlated to distance, **largest galaxies have the smallest redshifts (with mean $z \sim 0.13$)**
- **Radius $\sim 0.5''$ - $1.5''$ hardly resolved from ground**
- **Sersic index ~ 4 - 5 : majority of bulges, very few discs : Gaia filters out disc galaxies.**

Why Gaia has something to say about extragalactic

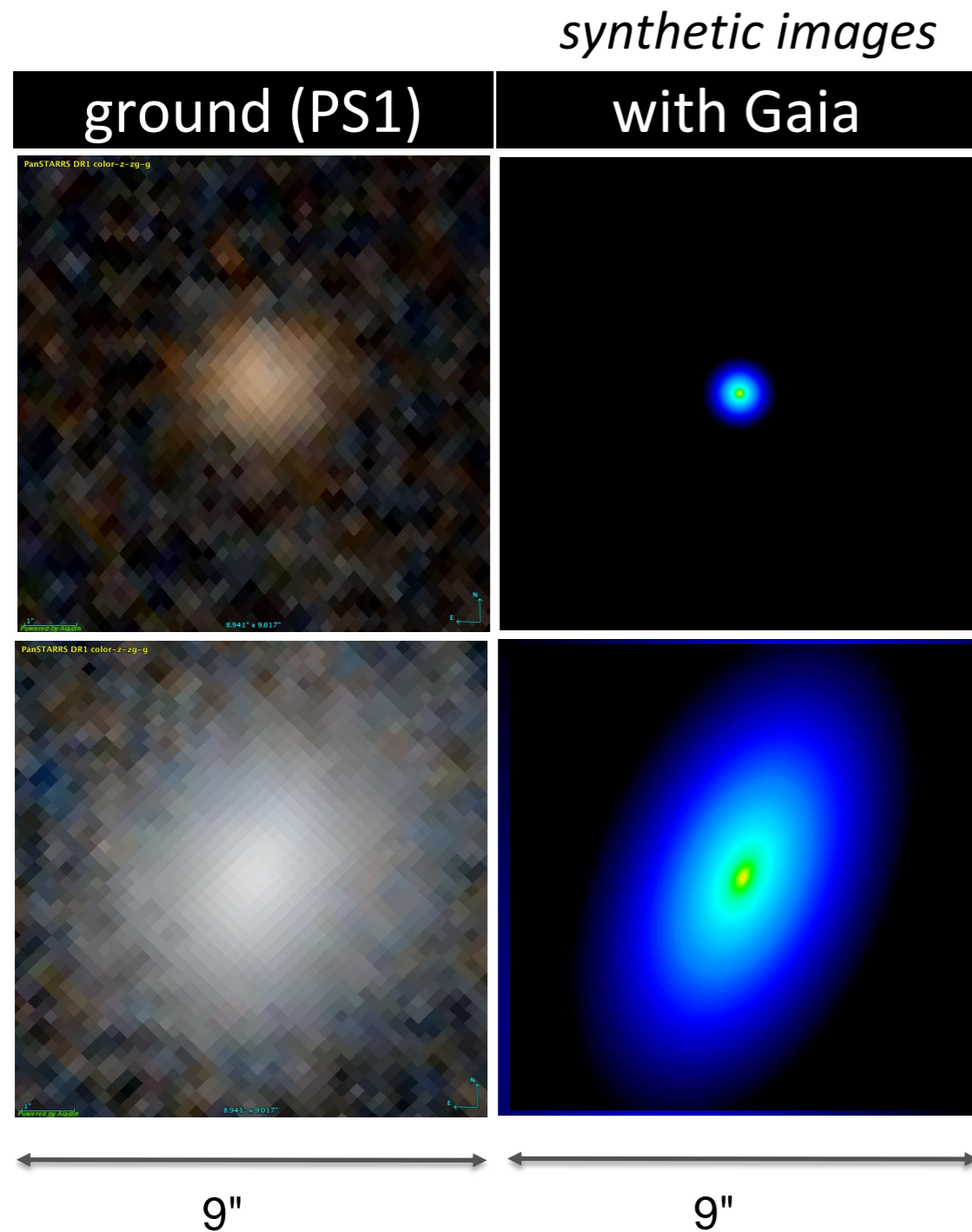


- The most distant galaxy analysed (5.3 G ly)



- The closest galaxy analysed (0.2 G ly)

Why Gaia has something to say about extragalactic



- The most distant galaxy analysed (5.3 G ly)

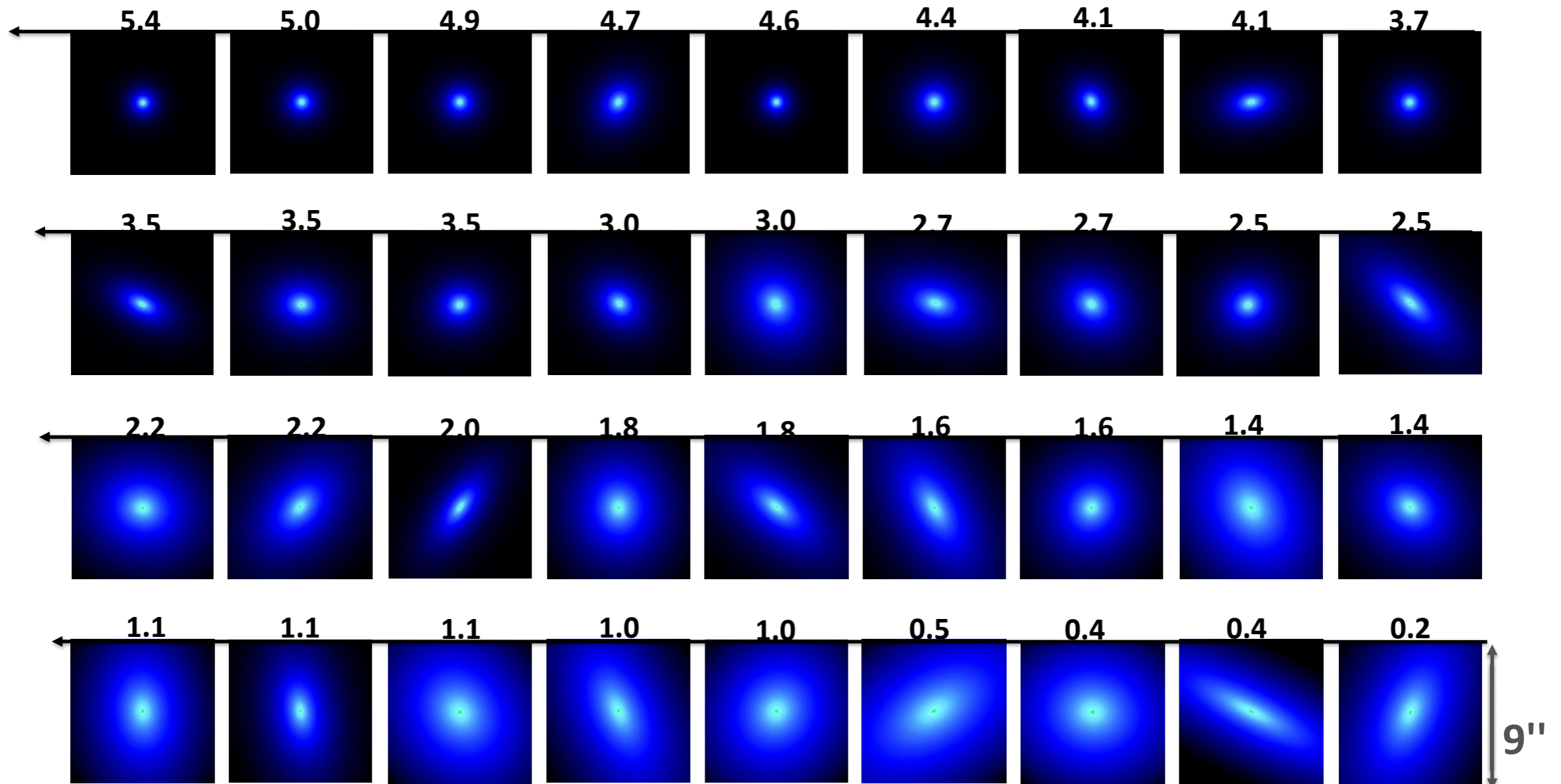
- The closest galaxy analysed (0.2 G ly)

Ground-based morphologic surveys of galaxies are limited and biased by the atmosphere

Synthetic images of galaxies

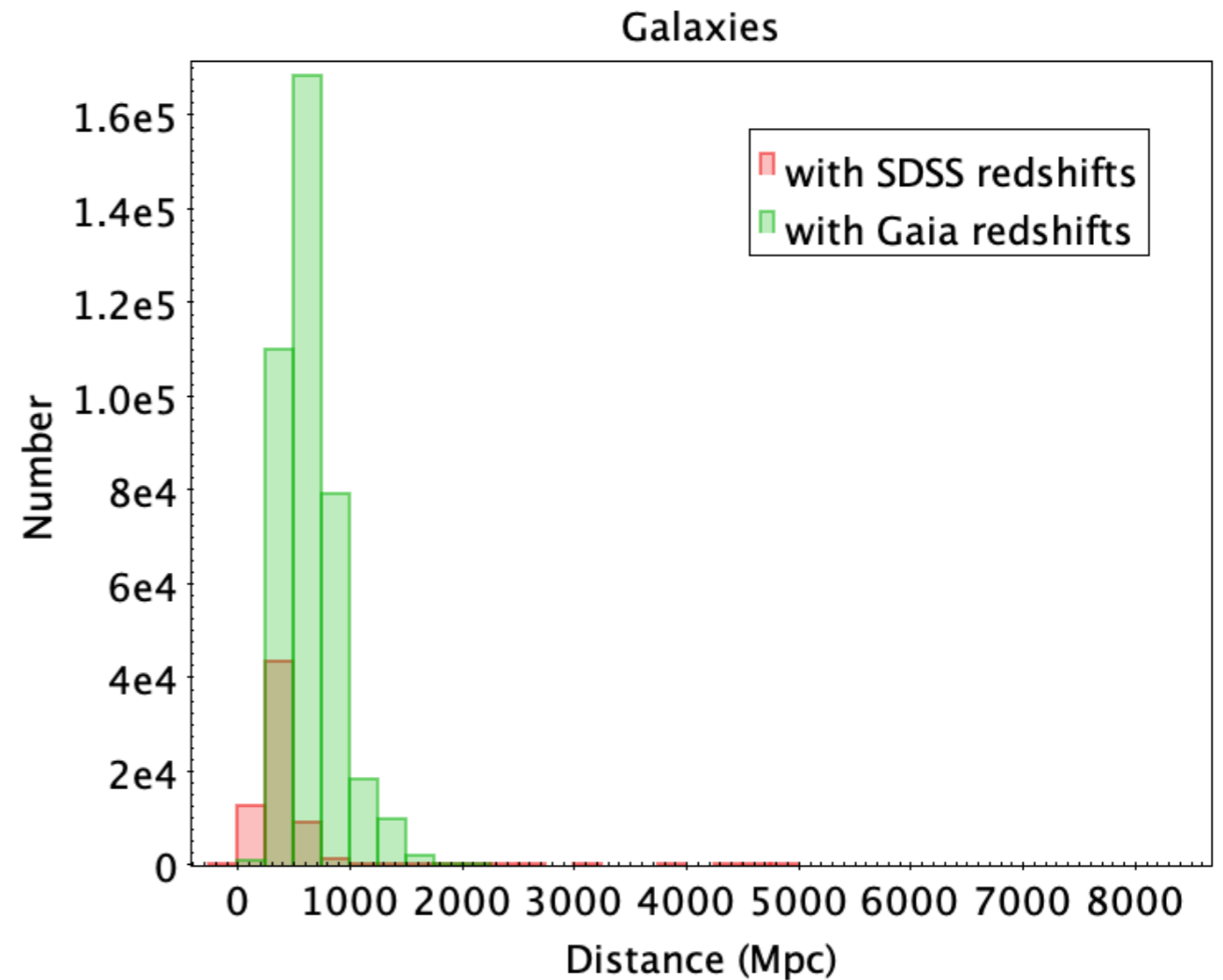
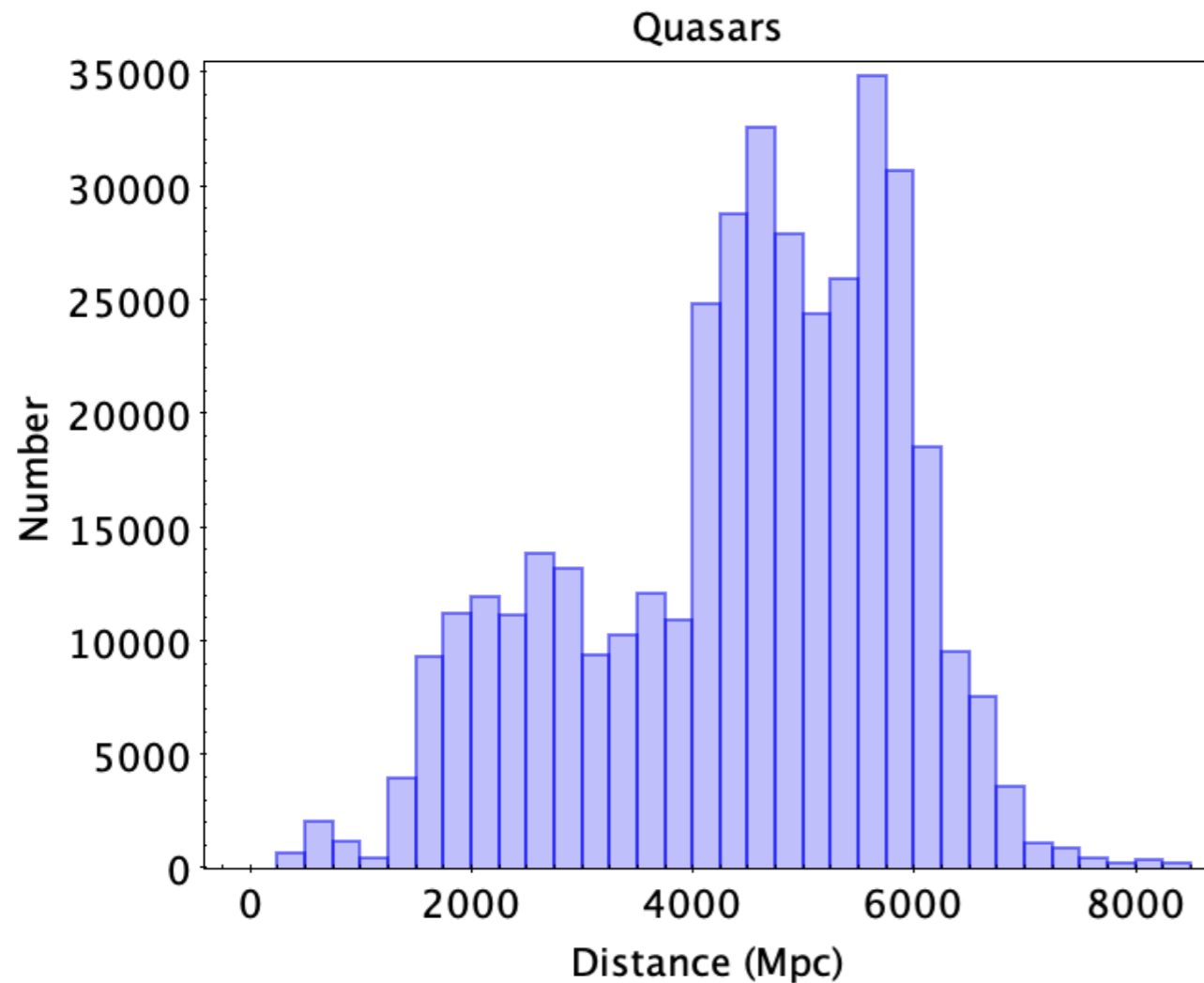
Lookback time (billion light years)

synthetic images



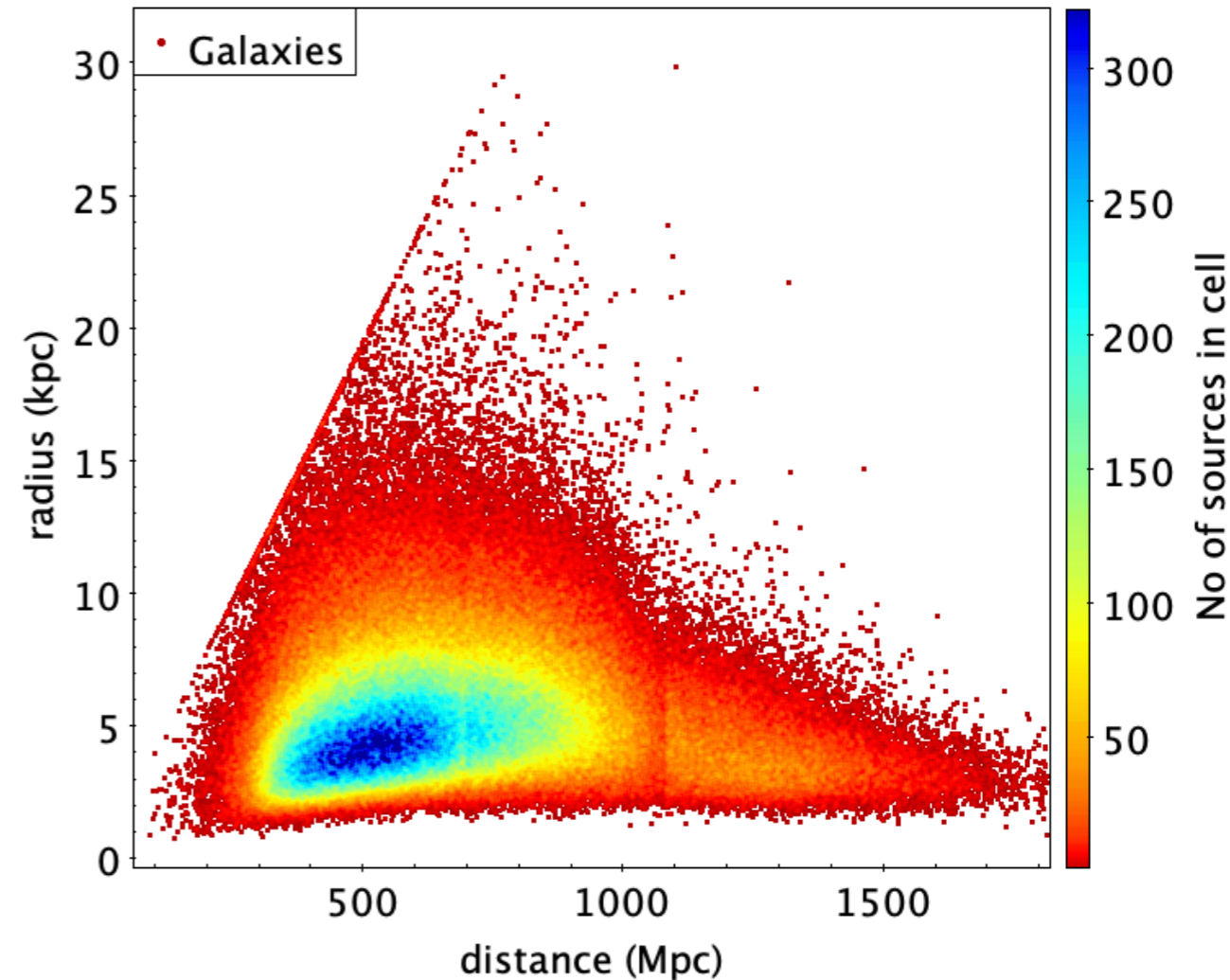
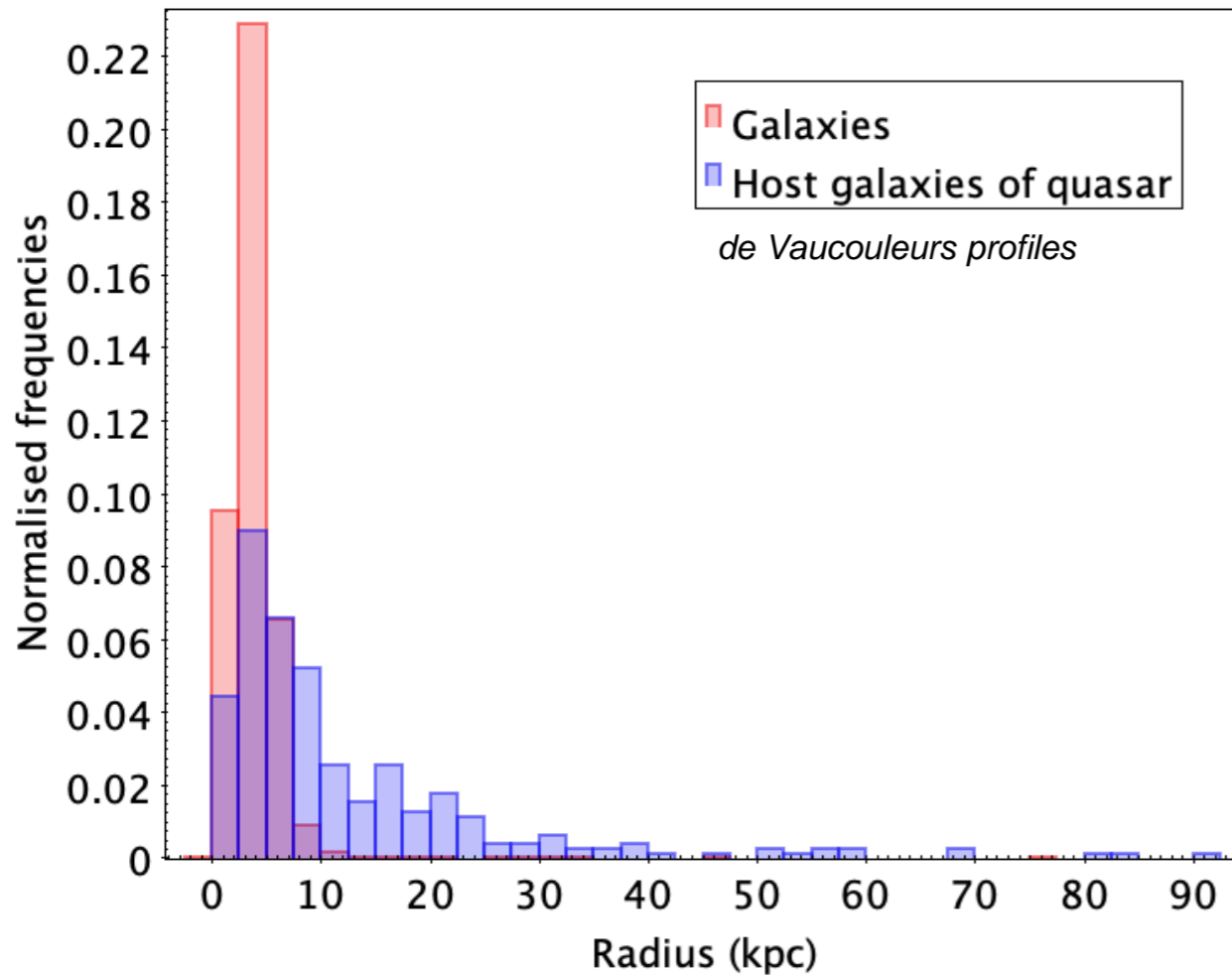
Gaia provides a space-based morphologic survey of local galaxies ($z < 0.5$)

Distance to extragalactic sources



- **Using redshifts** we can derive the **distance** to the extragalactic sources
- **Quasars** are detected **further than galaxies** (brighter)
- **Gaia** has less accurate **redshifts** than SDSS but **3X more abundant** and that allows to analyse **objects much farther**

Physical radius of extragalactic sources



- Using effective radius and distance, one can derive **physical radius of sources (Kpc)**
- **Gaia measures small galaxies** (rad<10 kpc) (due to size of detector 2" and bias in Gaia selection function)
- **Galaxies hosting quasars** tend to be **larger than elliptical galaxies** without AGN
- Galaxies with rad<5kpc can be studied at several distances/evolution states
- Bias in the radius along distance : **gaia seen farther the largest objects**

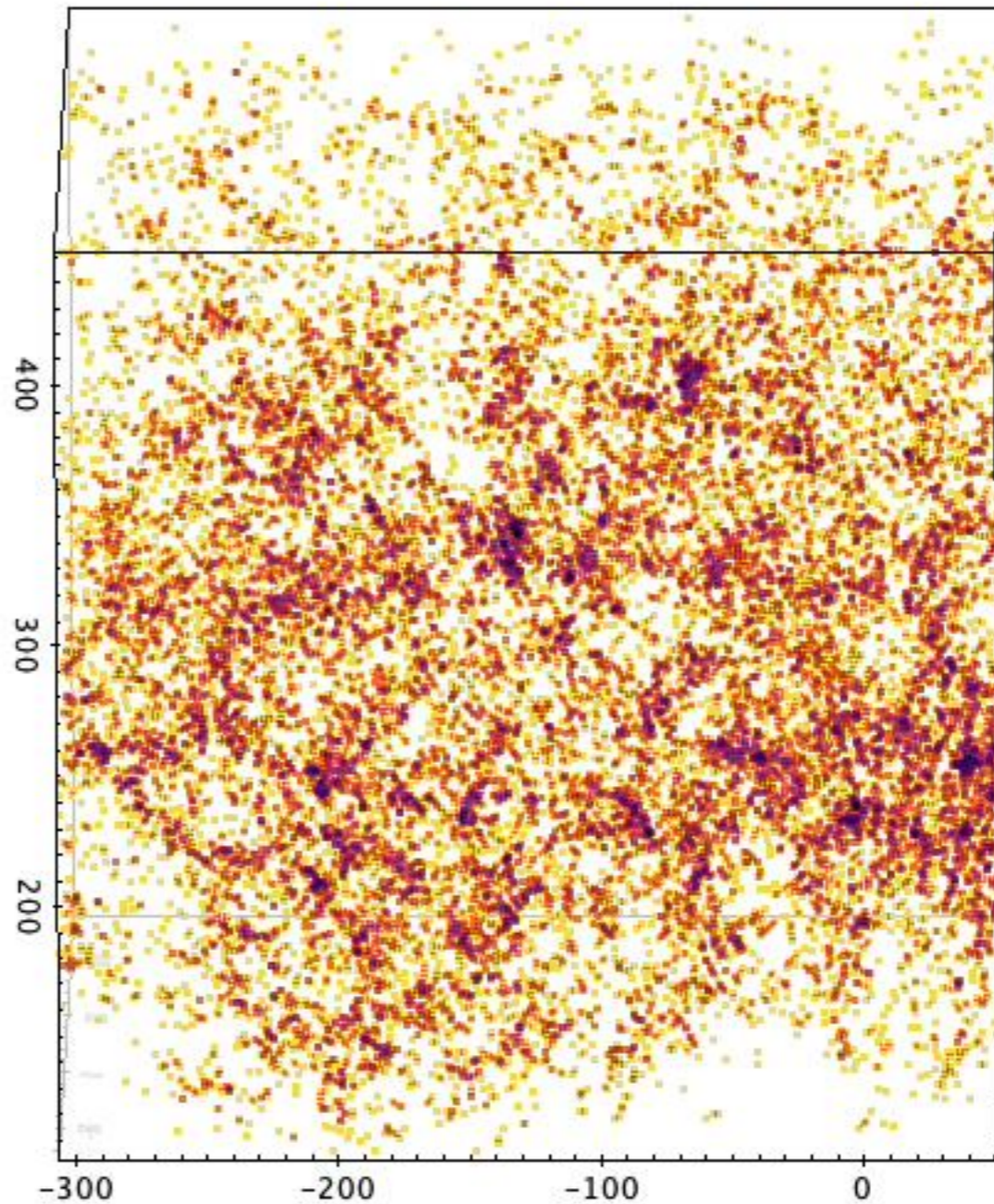
Distribution of galaxies in 3D

Zoom on a galactic northern region

- List of galaxies from Extended Objects
- Gaia astrometry
- Spectroscopic redshift (SDSS DR17)



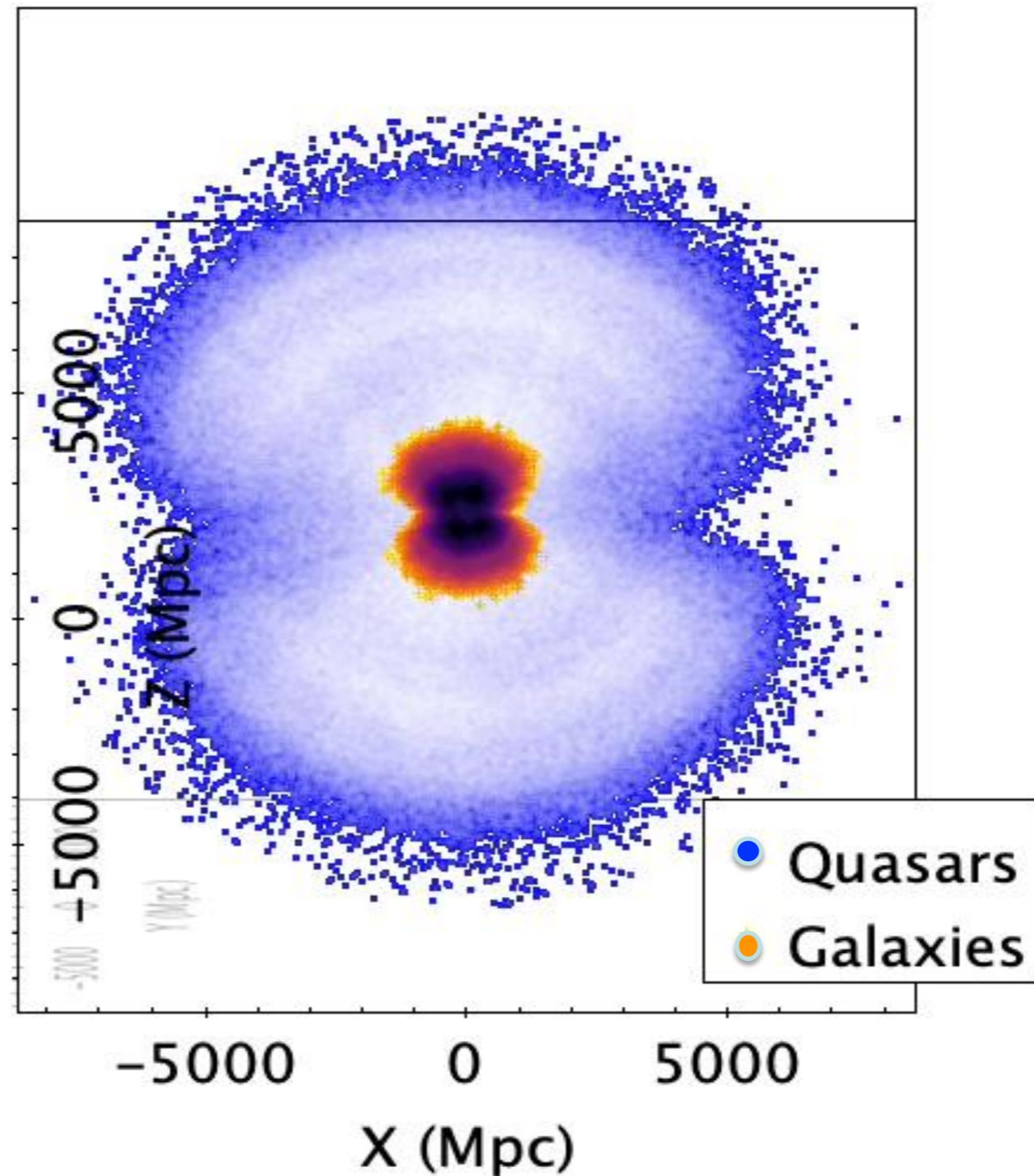
(X,Y,Z) Galactic coordinates



- **Filamentary repartition of the sources**

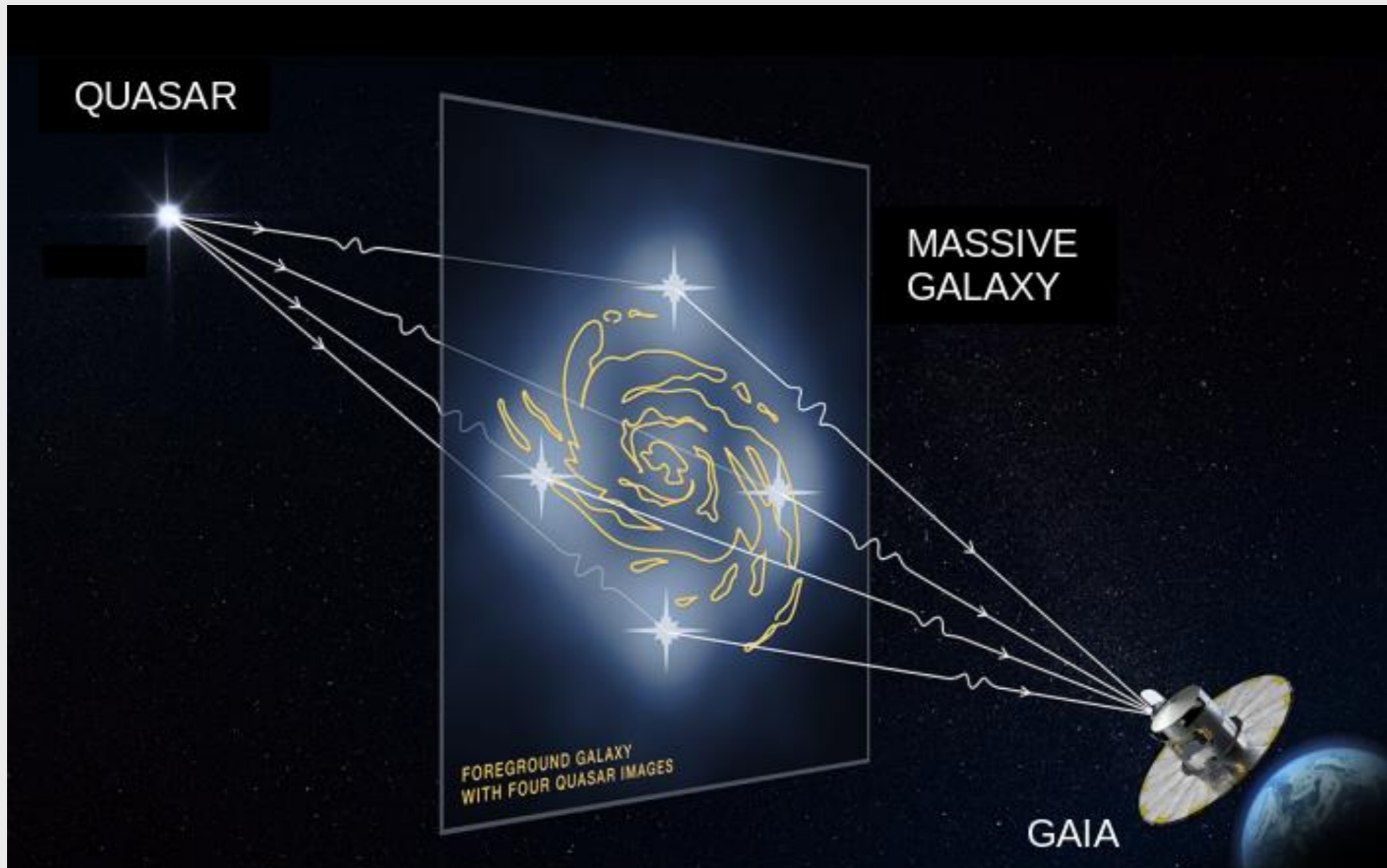
The universe explored by Gaia

- List of galaxies and quasars from Extended Objects
- Gaia astrometry
- Redshift (Gaia)



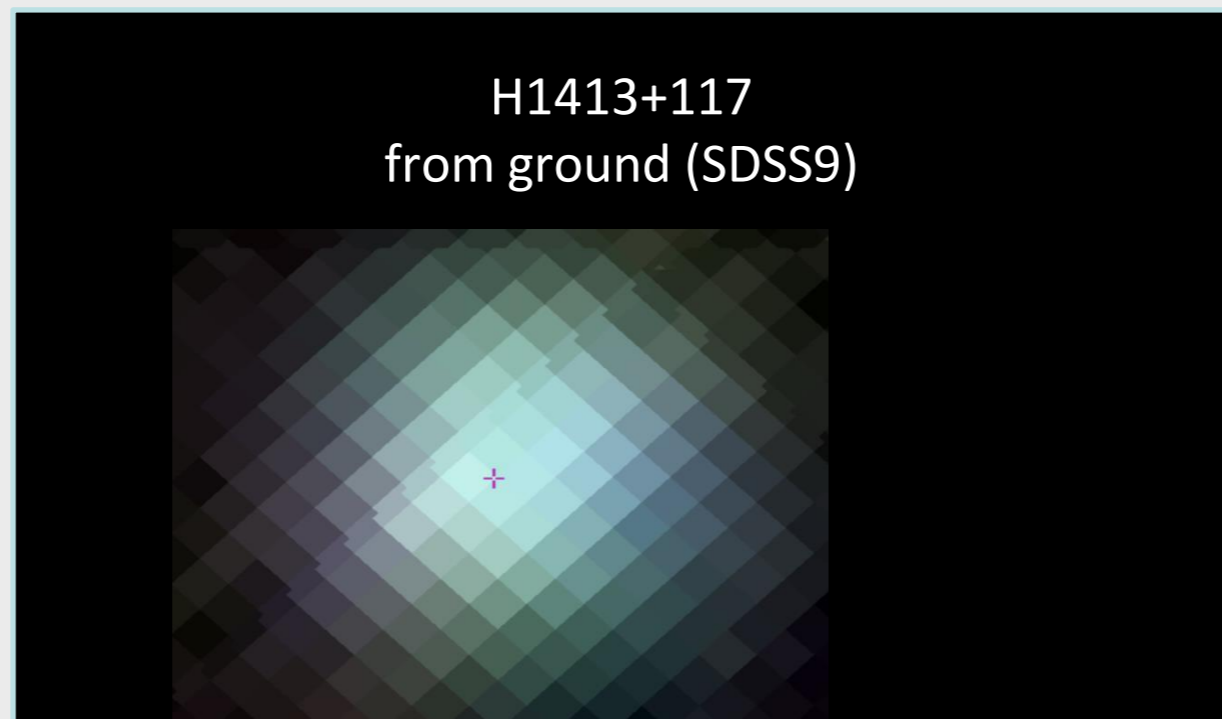
- 3D map of the local Universe, galaxies ($z < 0.5$), quasars ($z < 5$)

Gravitational lenses

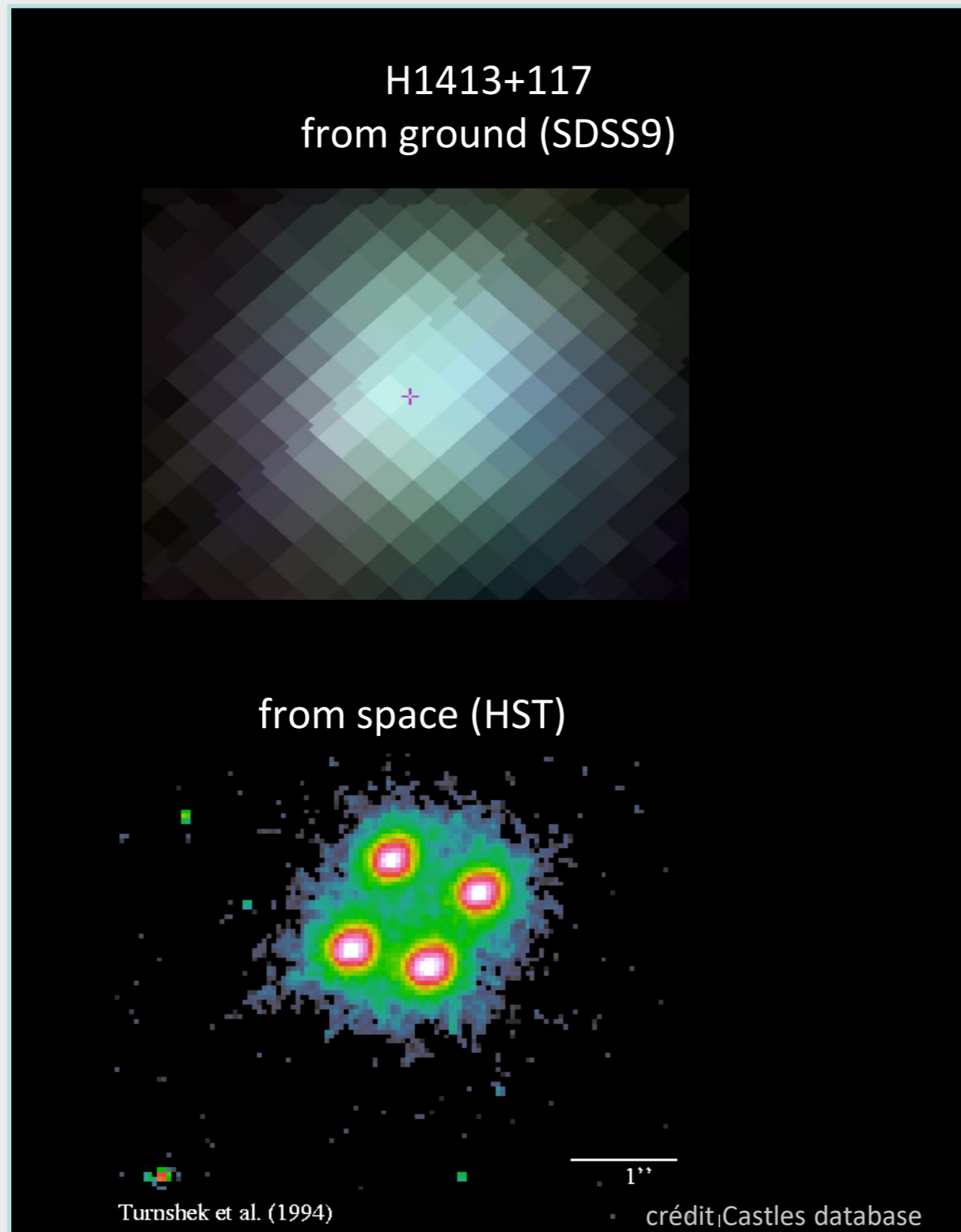


- The Gaia survey is also a survey of multi-imaged quasars by gravitational lensing
- 264 lensed quasars known today (68 quads and 196 doublets)

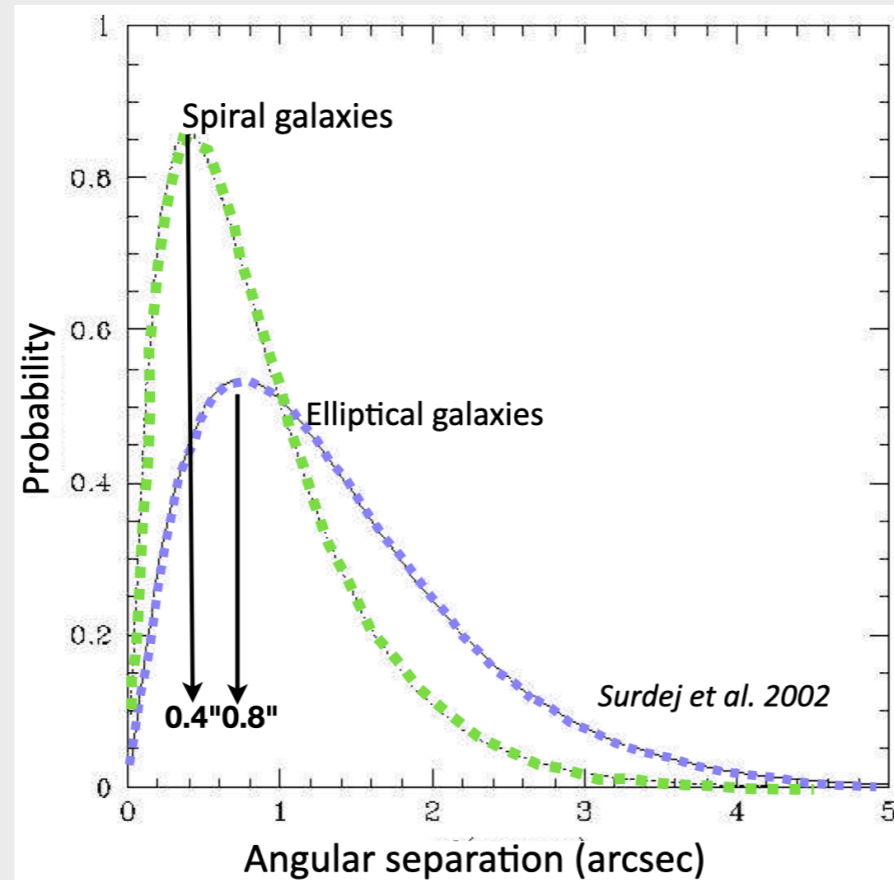
Lenses and atmosphere



Lenses and atmosphere



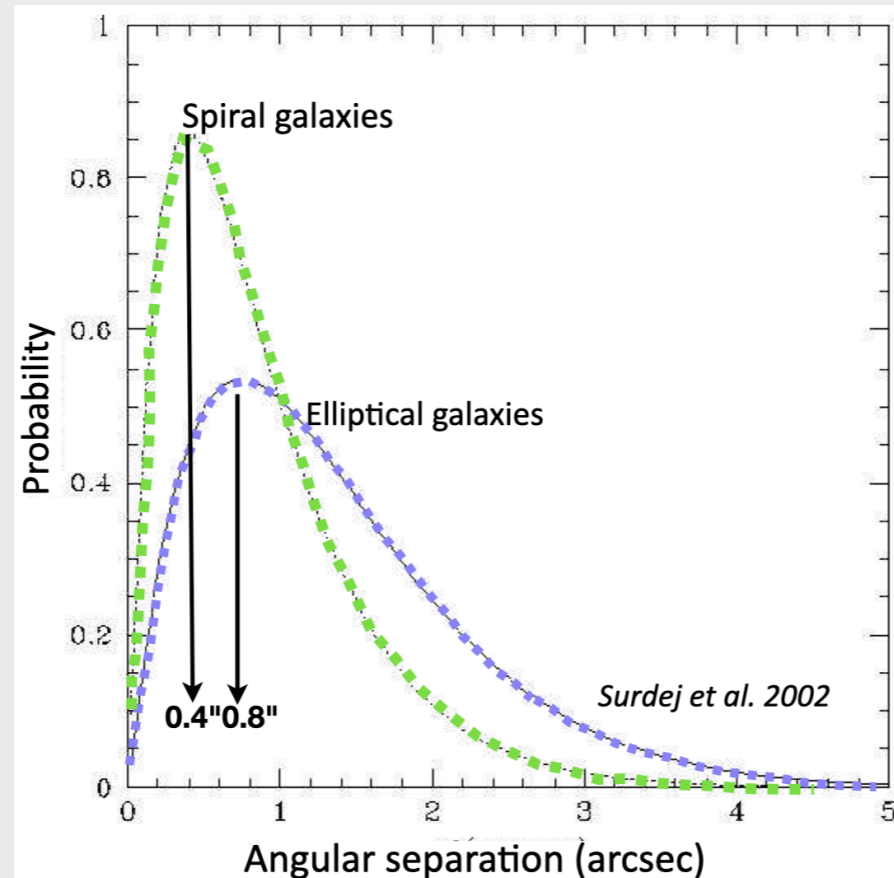
Gaia is a key survey for lenses



- Typical angular separation $< 1''$ not resolved in ground-based surveys

quasar at $z_q = 2$, lensed by a cosmological population of SIS galaxies (dots = spiral ones, continuous line = elliptical ones)

Gaia is a key survey for lenses

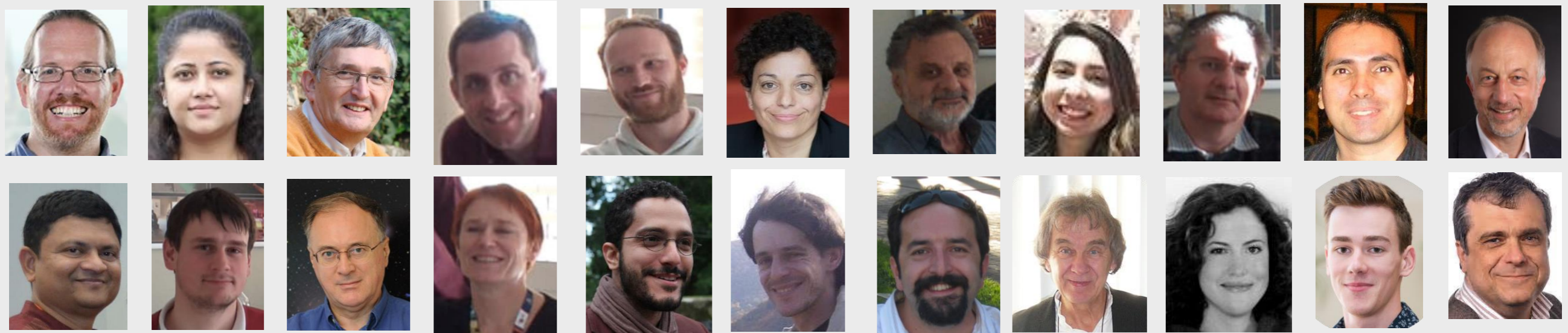


- Typical angular separation $< 1''$ not resolved in ground-based surveys

quasar at $z_q = 2$, lensed by a cosmological population of SIS galaxies (dots = spiral ones, continuous line = elliptical ones)

- **Gaia has a fantastic potential for GL**
 - spatial mission & all-sky survey
 - amazing resolving power $\sim 0.18''$
- **We expect Gaia to detect** (Finet & Surdej 2016)
 - ~ 3000 lenses
 - A large fraction compact configurations ($< 1''$)
 - no arc
- **Gaia is in condition to produce the first all-sky survey of lenses from space!!!!**

Gaia Gravitational Lenses (GraL) group



Current Members: A. Krone-Martins (U. California, Irvine); C. Ducourant (LAB Bordeaux), J. F. Le Campion (LAB Bordeaux), L. Delchambre (U. Liege), J. Surdej (U. Liege), D. Sluse (U. Liège); D. Stern (JPL/Caltech), S. G. Djorgovski (Caltech), M. J. Graham (Caltech), A. Drake (Caltech), A. Mahabal (Caltech), R. Teixeira (U. São Paulo), C. Spindola-Duarte (U. São Paulo); L. Galluccio (OCA), F. Mignard (OCA), E. Slezak, (OCA), S. Scarano (U. Sergipe), A. Nierenberg (U. California, Merced), D. Dobie, T. Murphy, C. Boehm (U. Sydney), P. Jalan (Aryabhata), J. Kluter (Louisiana), J. Wambsganss (U. Heidelberg), S. Klioner (T. U. Dresden)



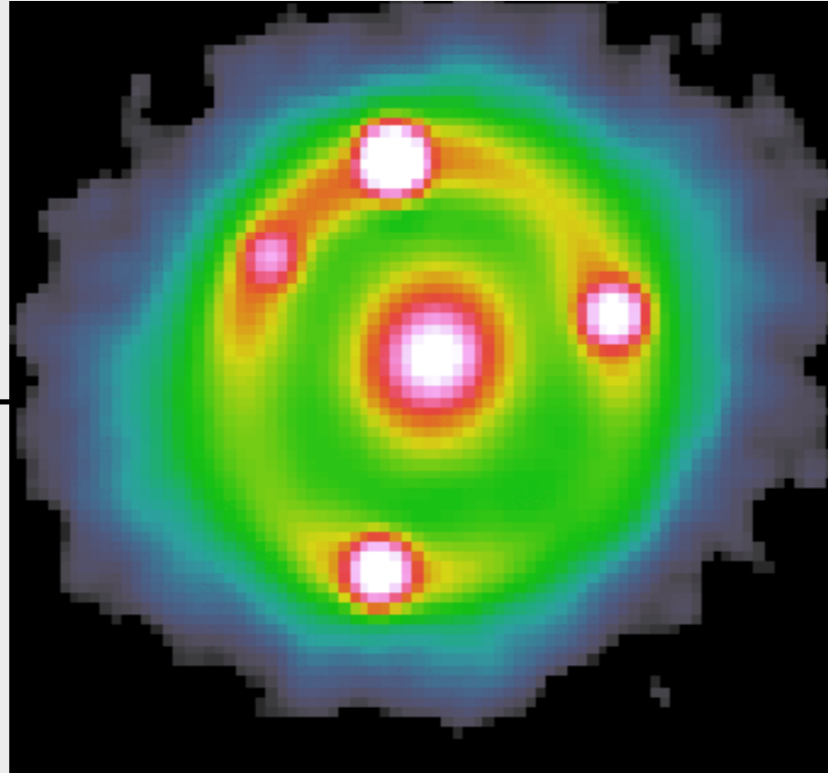
- **Constitution of GraL group in 2006**
- **Objective : Automatic search for lenses in Gaia catalogues and other surveys**



Previous Members:
O. Wertz (Argelander/Bonn)
U. Bastian (ARI/Heidelberg)

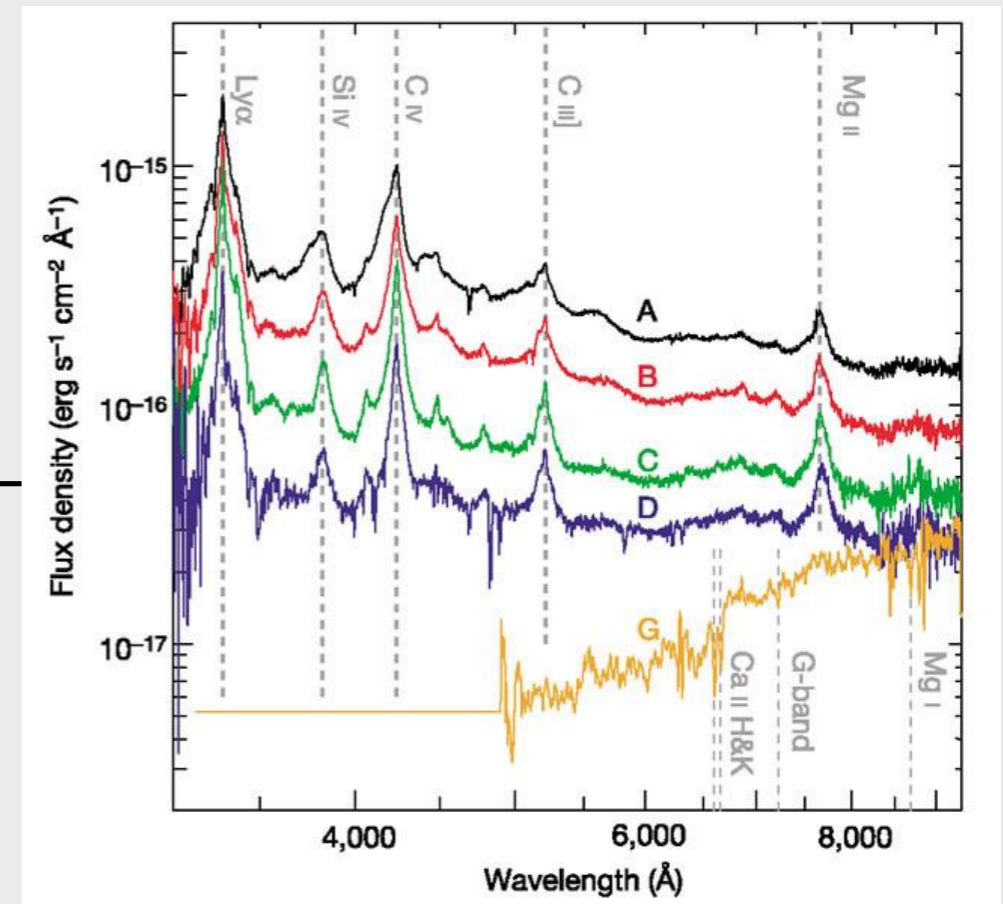
How to find lenses ?

Specific patterns



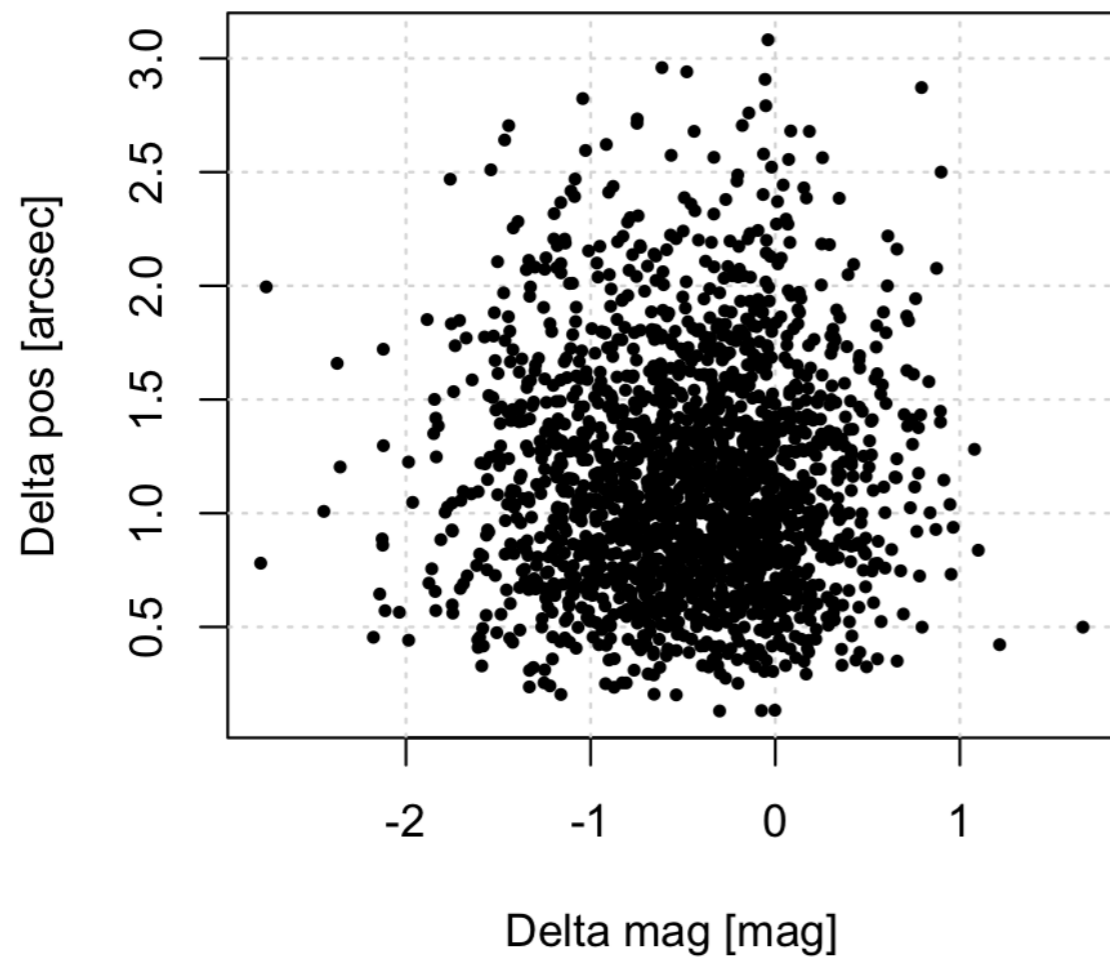
Credit : Castles database, HST images

Same colour/spectra



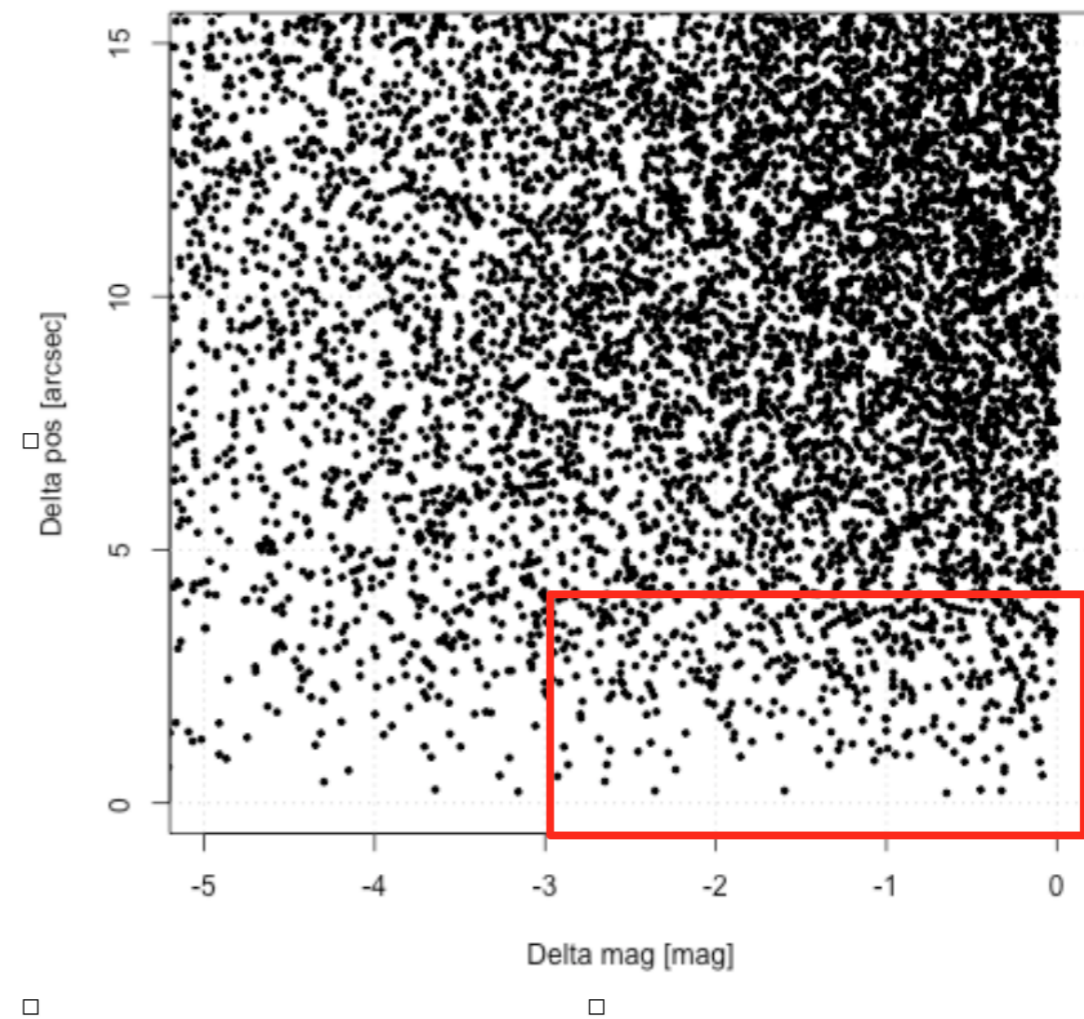
How to find lenses in Gaia catalogue ?

Parameters for lensed QSO
[two images]



2 images of a QSO

Parameters for Besancon
GaiaSimu2



2 Stars (l=0,b=45)

How to find lenses in Gaia data ?

Gaia GraL group for new methods:

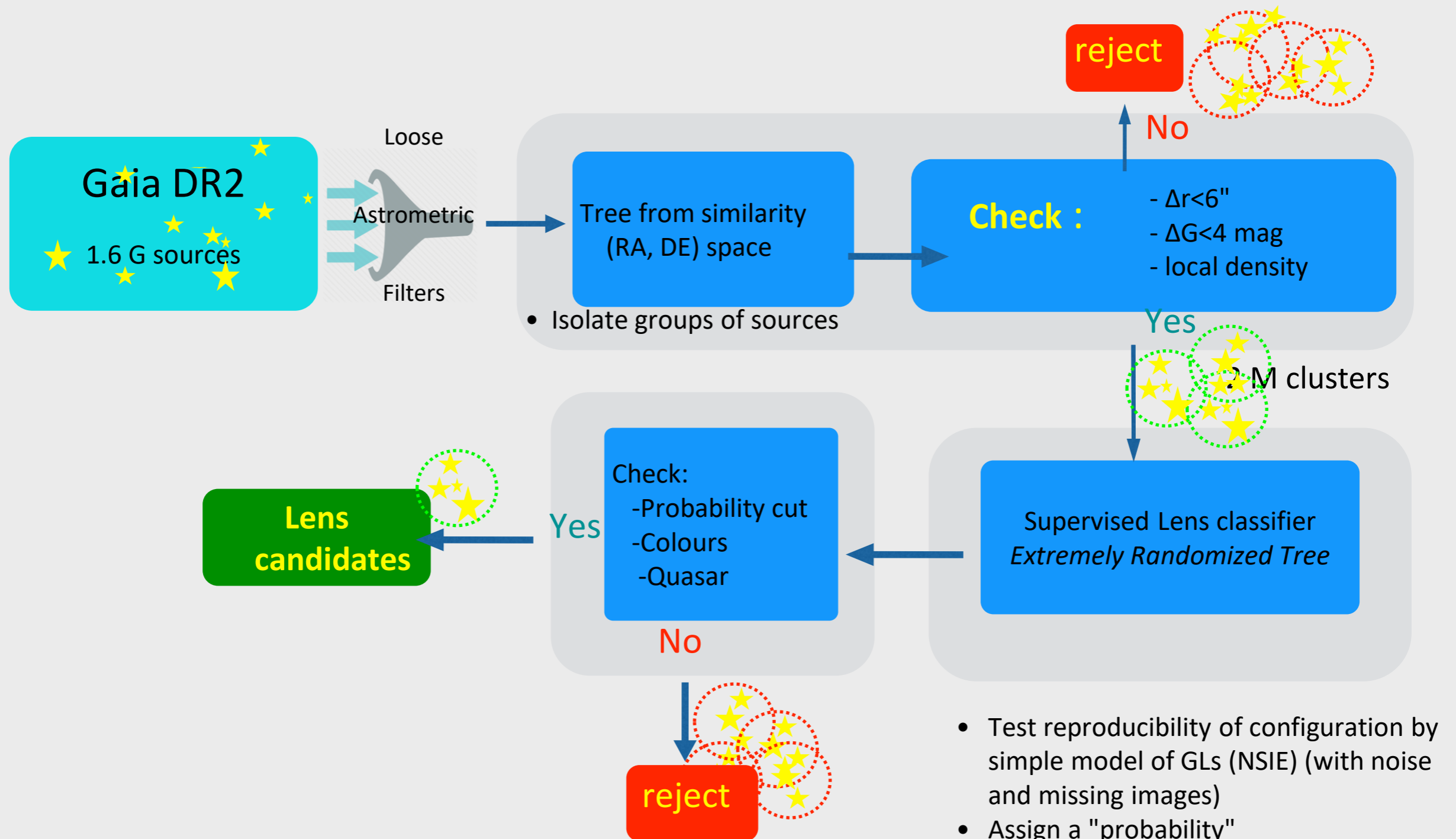
- Blind search in Gaia catalogue with extremely randomized trees (ERTs)
- Automatic search in Catalina photometric time series database (entropy)
- Validation candidates with ground-based spectroscopic observations
- Modelling of the confirmed lenses with Gaia astrometry

GravLens DPAC chain (@CNES) :

- **Motivation :**
 - Gaia DR2 and DR3 are incomplete at small angular separation ($<2''$) (*Arenou+2018A&A...616A..17A*)
 - Gaia detects more objects than are published in data releases
 - GLs are expected to be mostly with separations of $<1''$
- Exploration of quasars' environment
- Clustering of Gaia measurements to identify all sources (including the ones not published in DRs)
- Provide mean astrometry and onboard mean photometry for the sources detected
- Flagging of potential configurations

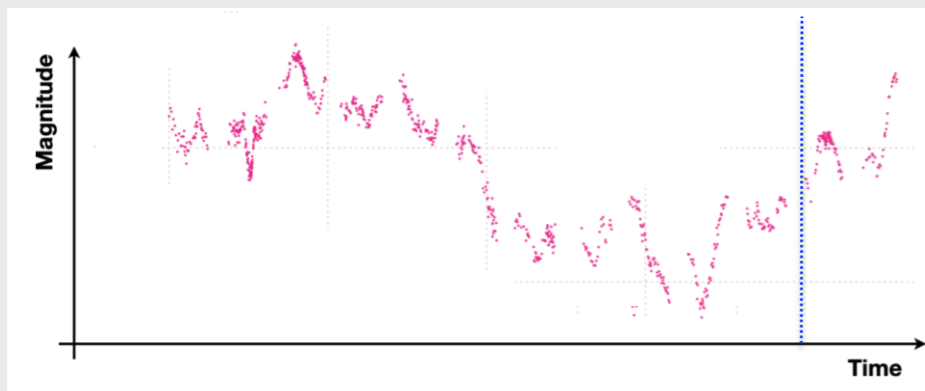
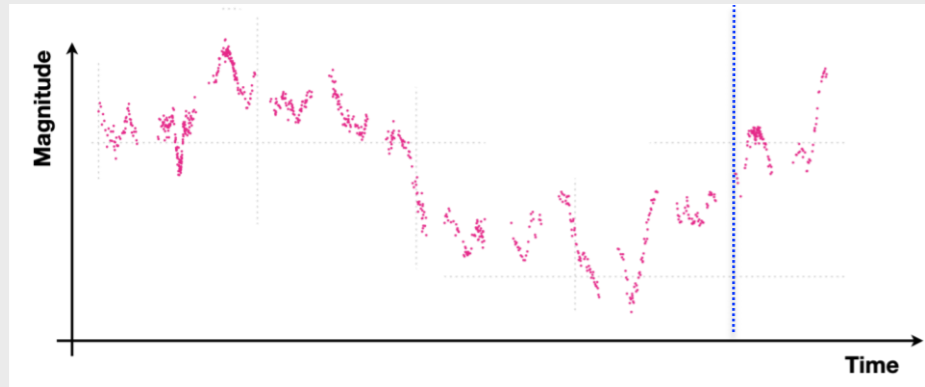
Blind search with ERTs in Gaia catalogue

Delchambre, L.; Krone-Martins, A.; Wertz, O., et al., A&A, 622, A165, 2019

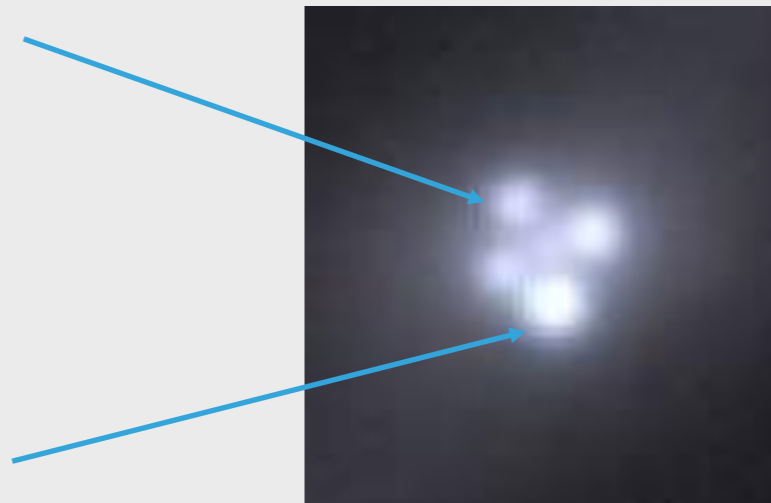


Entropy in Catalina photometric time series

Krone-Martins, A., Graham, M.; Stern D, et al., arXiv:1912.08977

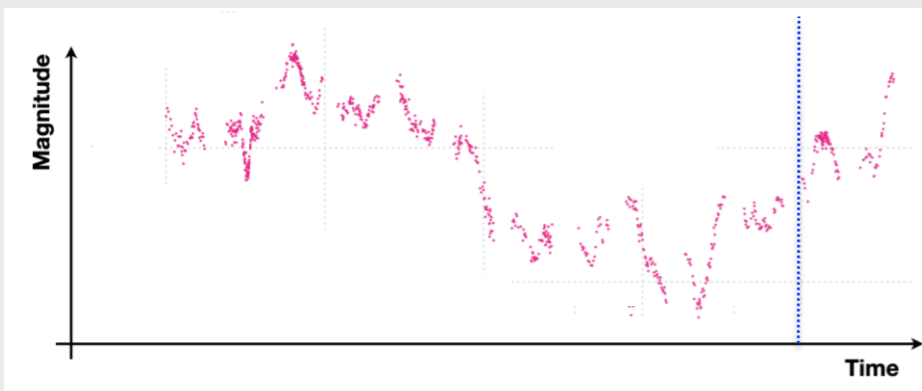
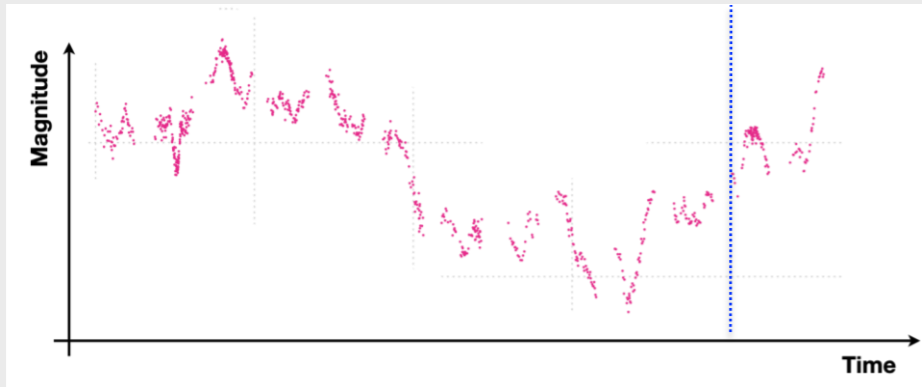


Quasars are variable sources



Entropy in Catalina photometric time series

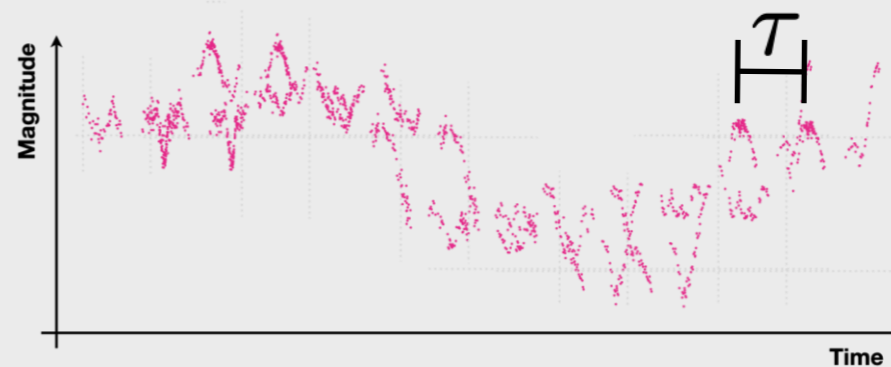
Krone-Martins, A., Graham, M.; Stern D, et al., arXiv:1912.08977



Quasars are variable sources

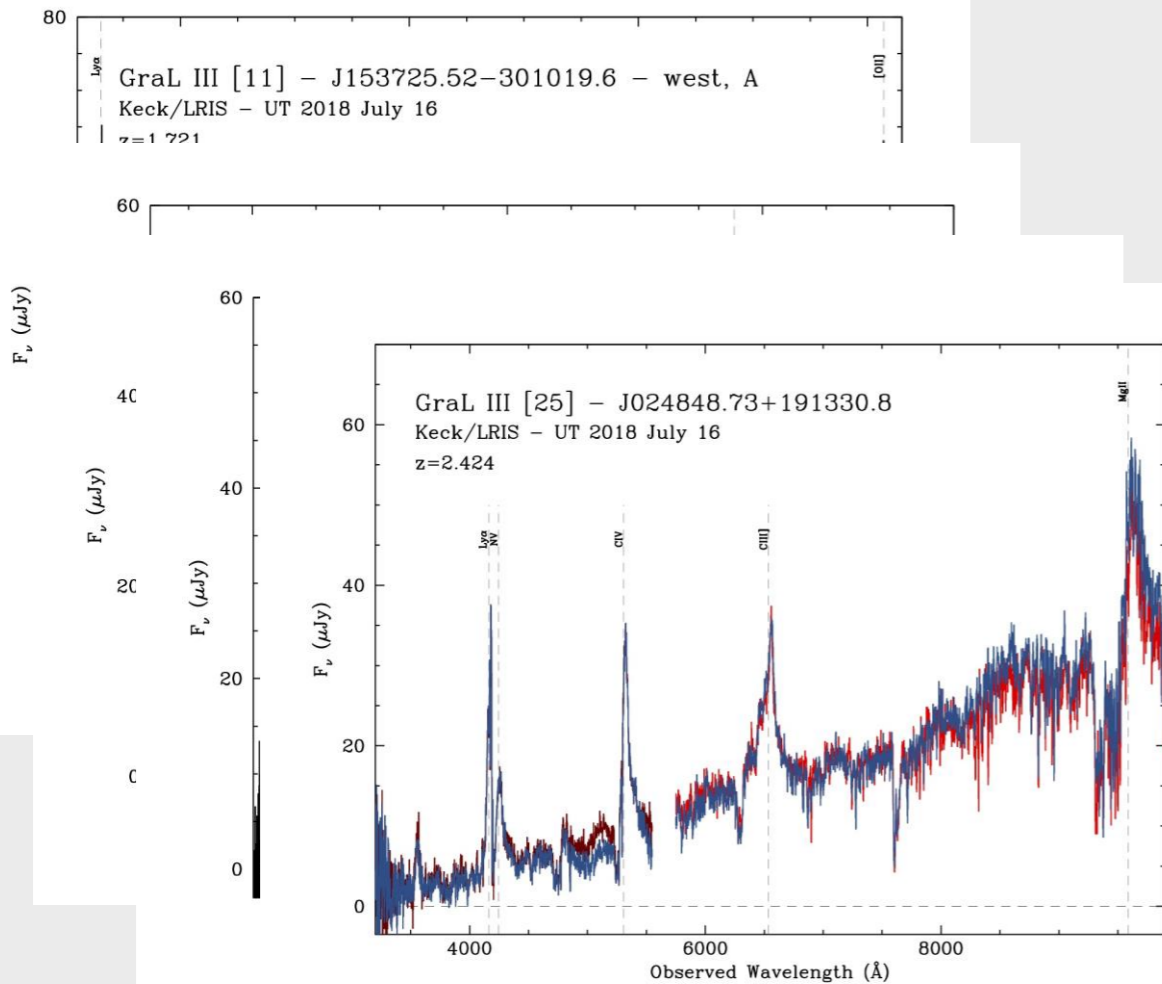


Catalina unresolved photometric time series



- Selection of candidates on low level of entropy in time series

Spectroscopic validation of candidates



Palomar



ESO-NTT



Gemini south



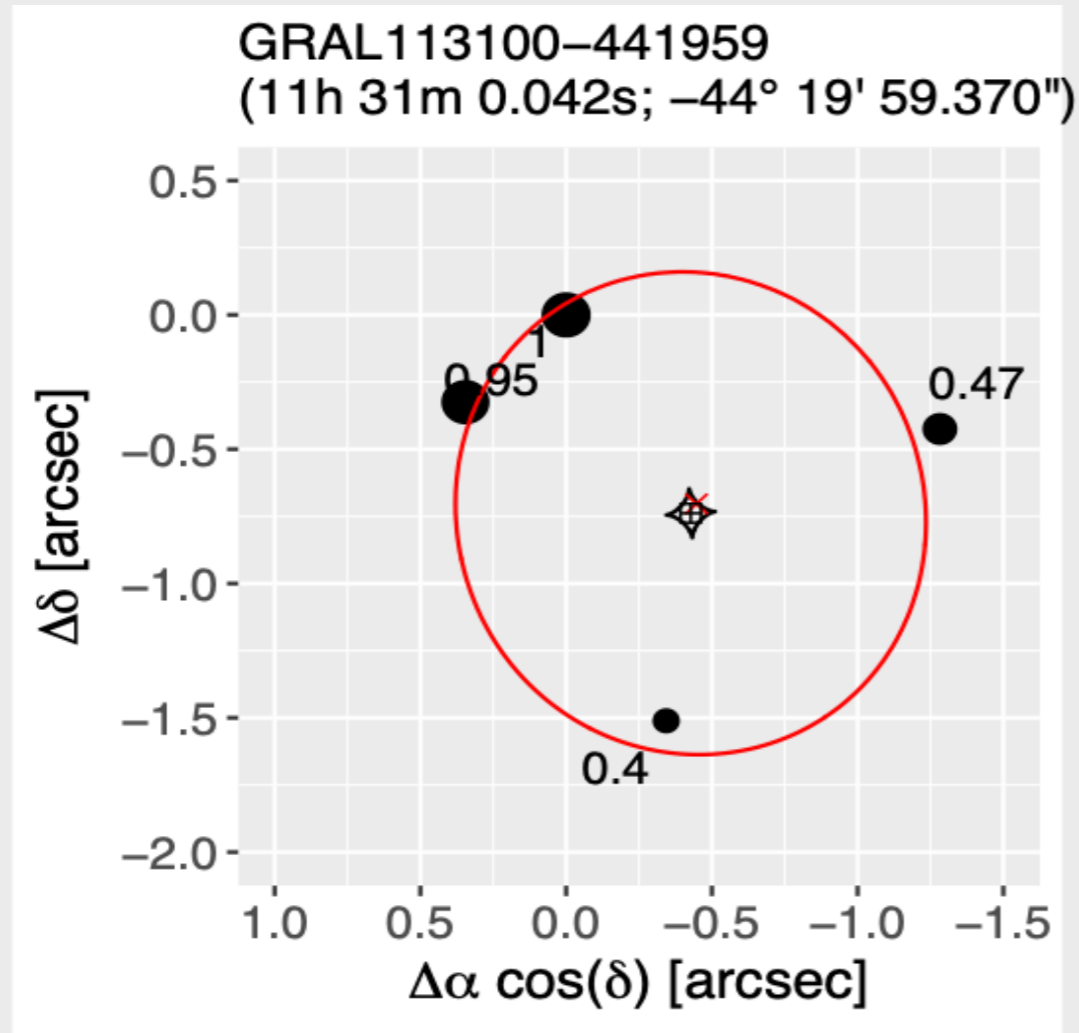
Keck



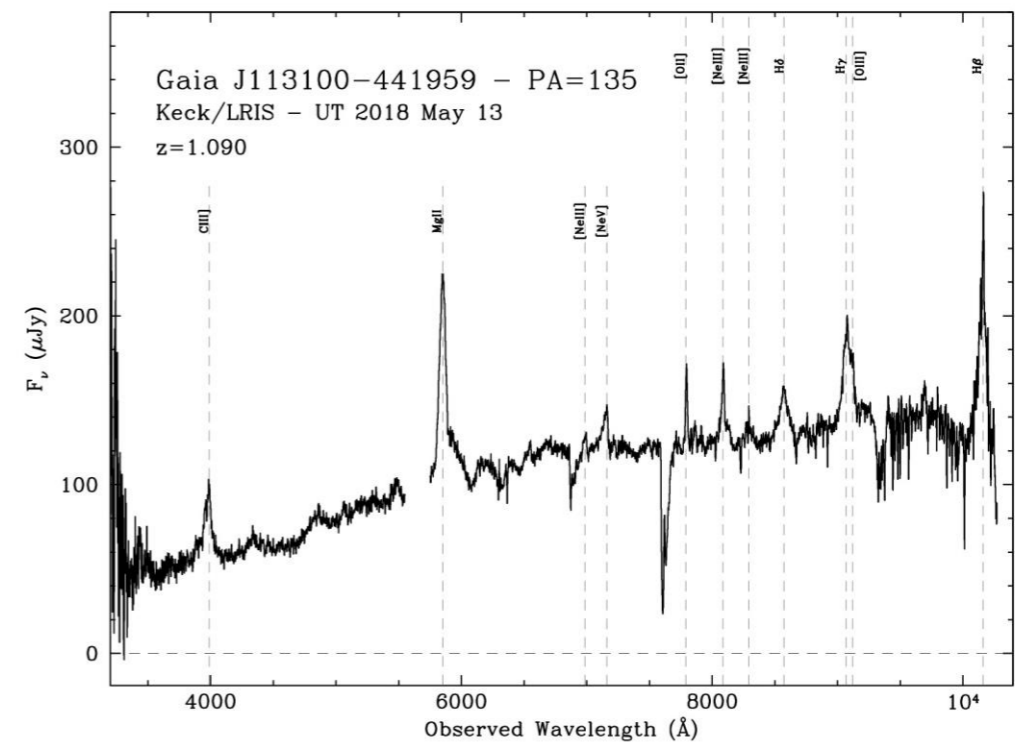
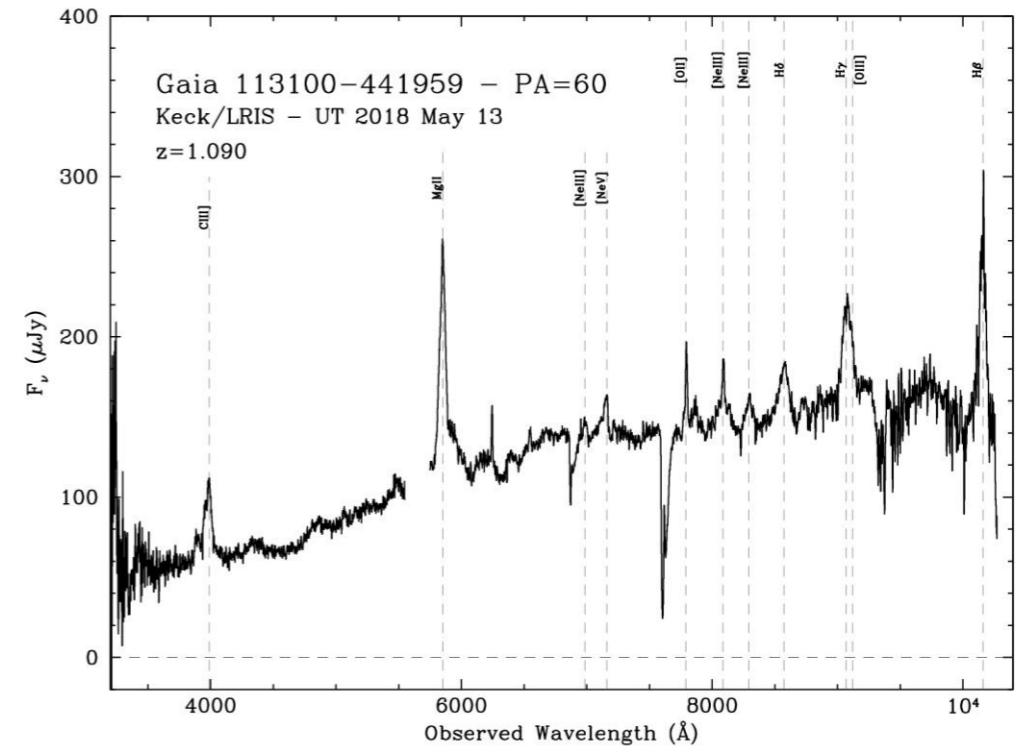
SOAR

- Spectroscopic validation with various telescopes
- Regular observing time at Keck since 2018

First lens discovered from astrometry



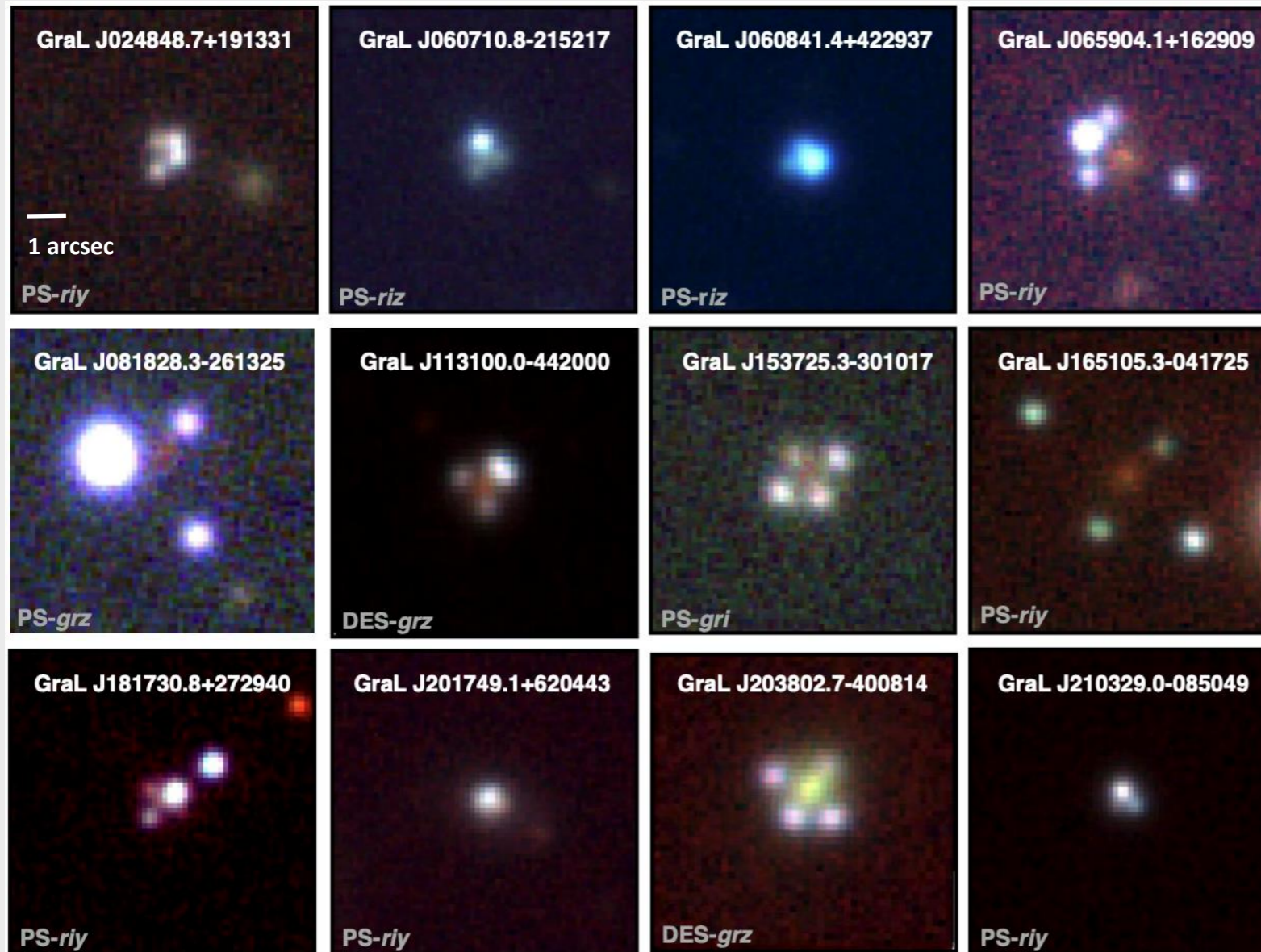
Krone-Martins, A.; Delchambre, L.; Wertz, O. et al., *A&A*, 616, L11, 2018



Wertz, O.; Stern, D.; Krone-Martins, A. et al., *A&A*, 628, A17, 2019

Gaia sees quadruple

- 12 spectroscopically confirmed quadruply imaged quasars + 4 not published
- 20% increase in the total number of confirmed quadruply-imaged quasars



Connor, T., Stern, D., Krone-Martins, A., arXiv:2109.14103

Stern, D. Djorgovski, S. G., Krone-Martins, A., et al., arXiv:2012.10051

Krone-Martins, A., Graham, M.; Stern D, et al., arXiv:1912.08977

Wertz, O.; Stern, D.; Krone-Martins, A. et al., A&A, 628, A17, 2019

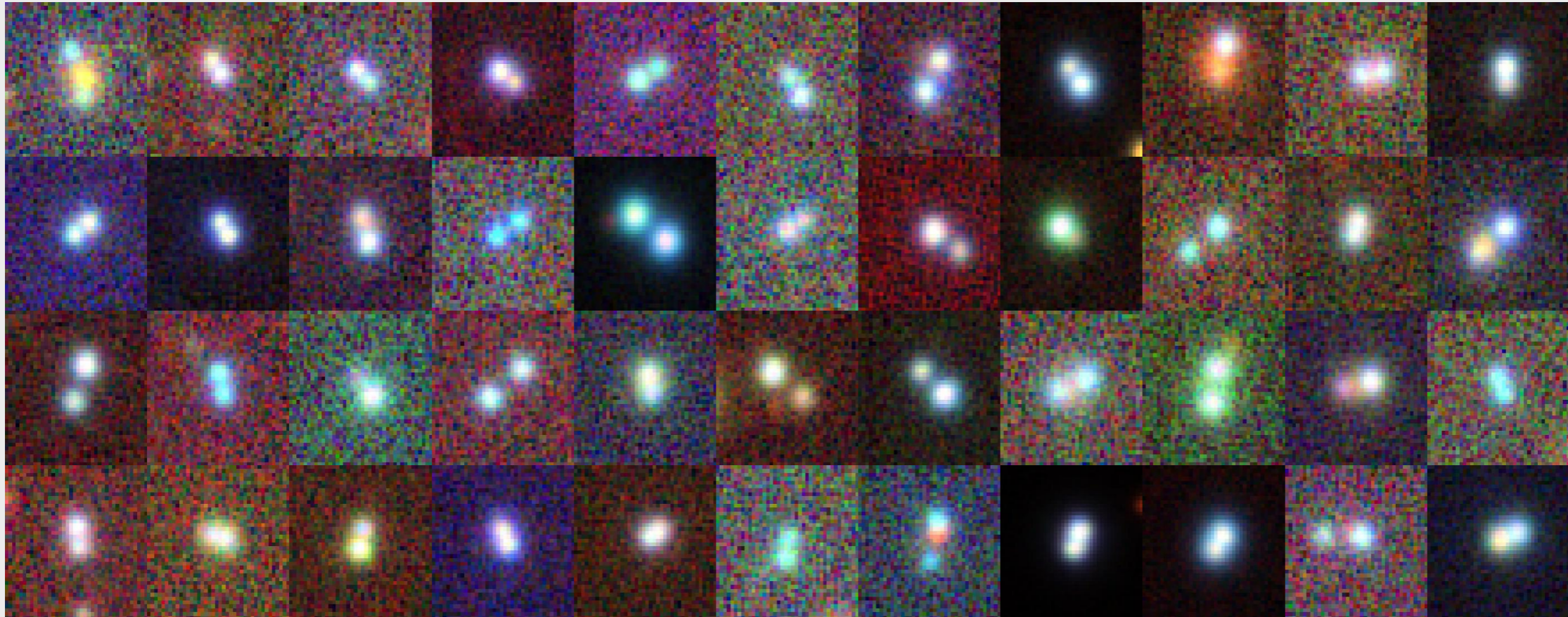
Delchambre, L.; Krone-Martins, A.; Wertz, O., et al., A&A, 622, A165, 2019

Ducourant, C.; Wertz, O.; Krone-Martins, A., et al., A&A, 618, A56, 2018

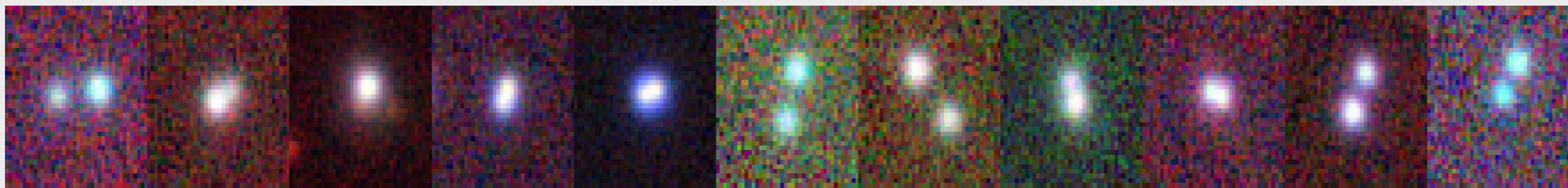
Krone-Martins, A.; Delchambre, L.; Wertz, O. et al., A&A, 616, L11, 2018

Gaia sees double

- 44 spectroscopically confirmed doubly imaged quasars
- 18% increase in the total number of confirmed doublets

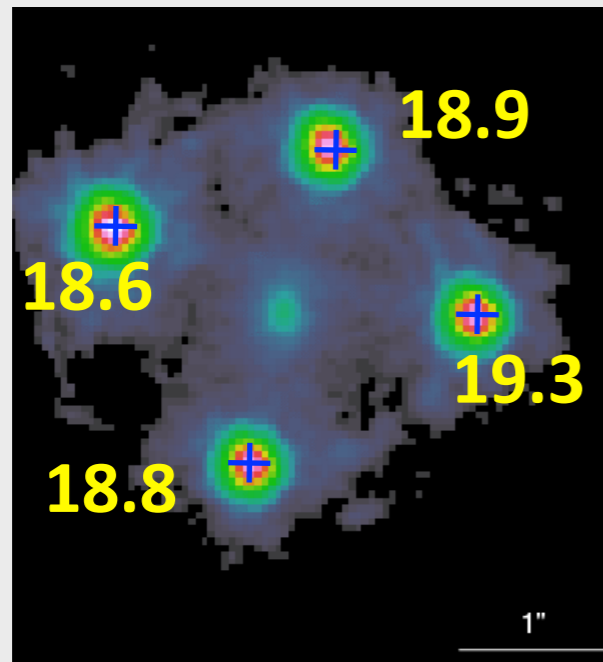


- 11 spectra indicate either lens or binary QSOs, TBC



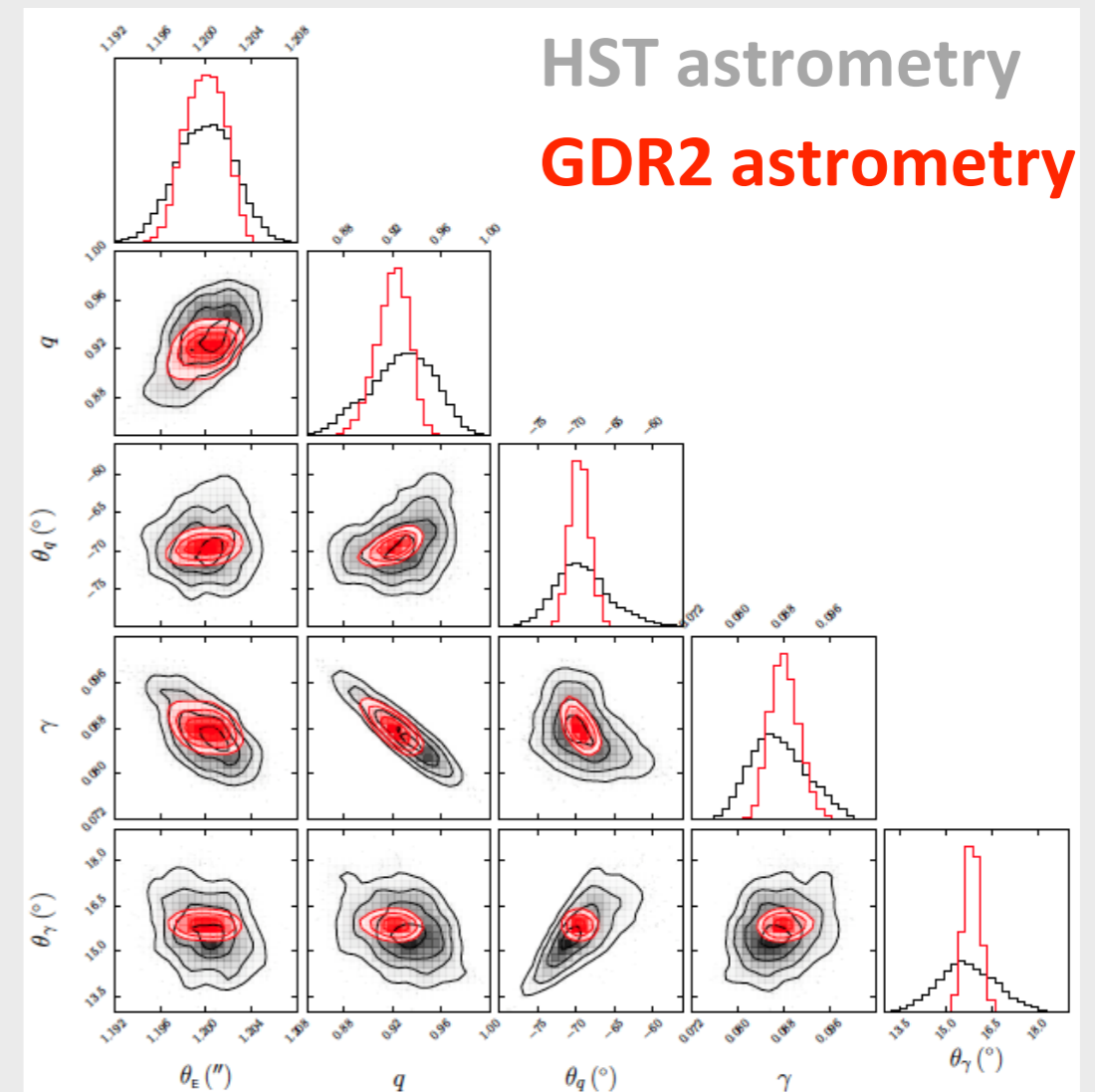
Krone-Martins, A., Graham, M.; Stern D, et al., arXiv:1912.08977

HE0435-1223



+ GDR2

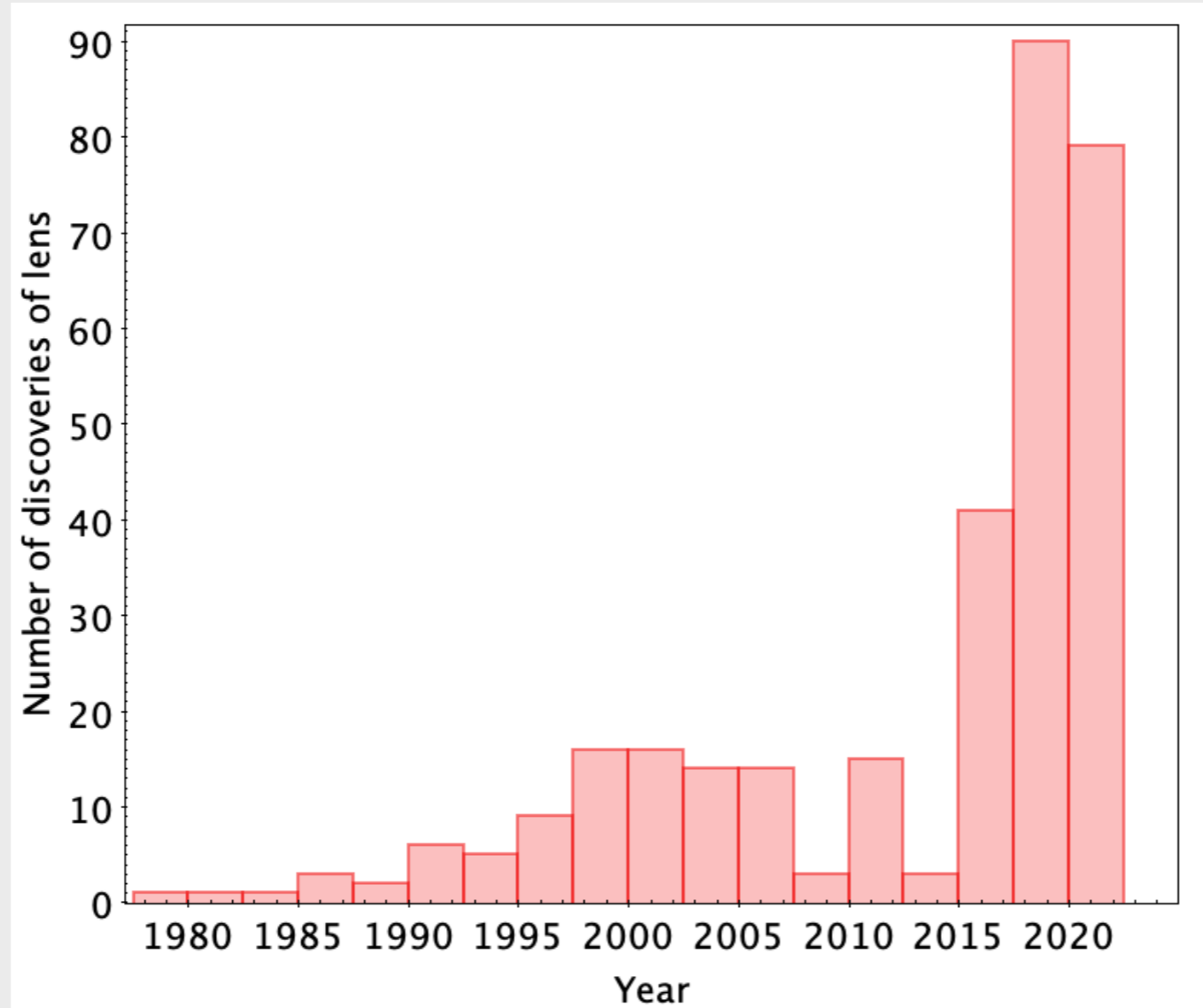
Credit : Castles database, HST images



Ducourant et GraL, A&A, 2018

- With sub-mas precisions
- Improved fitted parameters
- Great potential for realist modelling !

More and more lenses

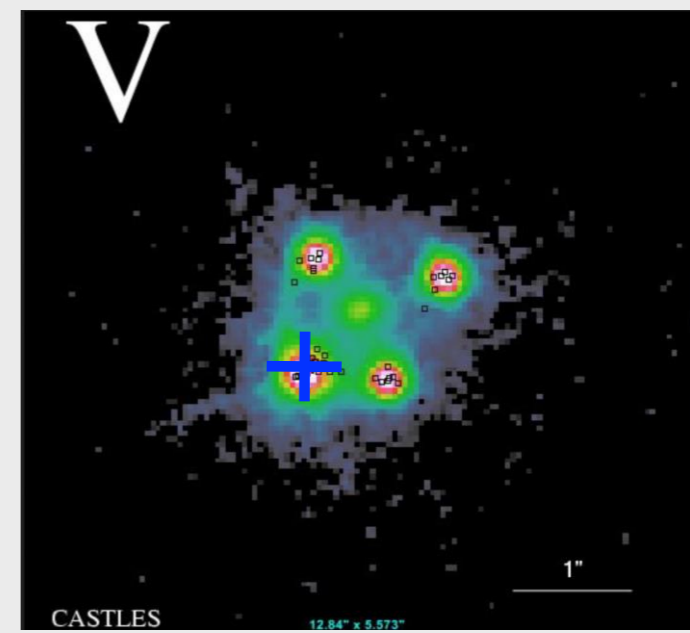
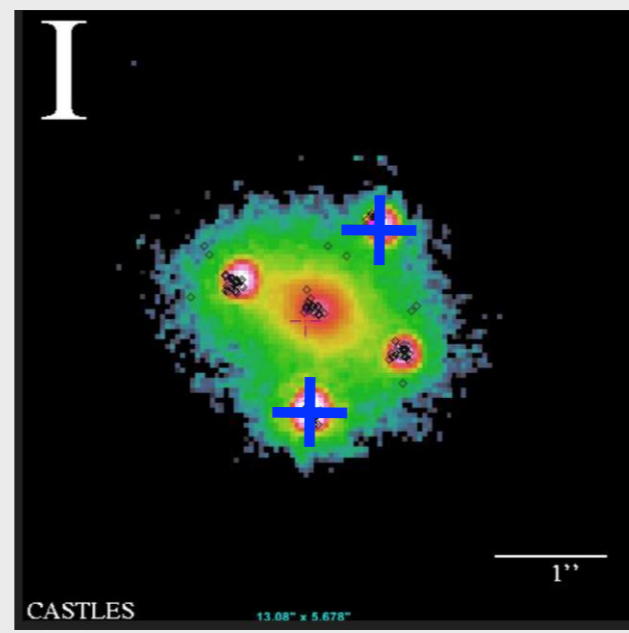
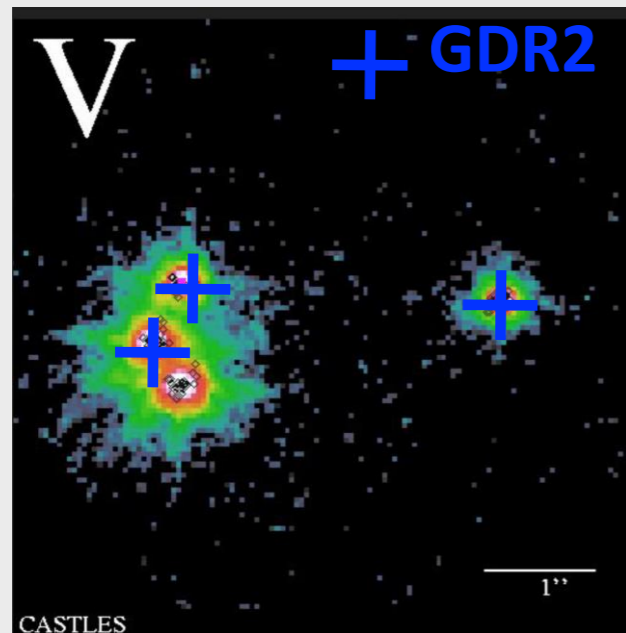


Several groups work hard on finding the lenses

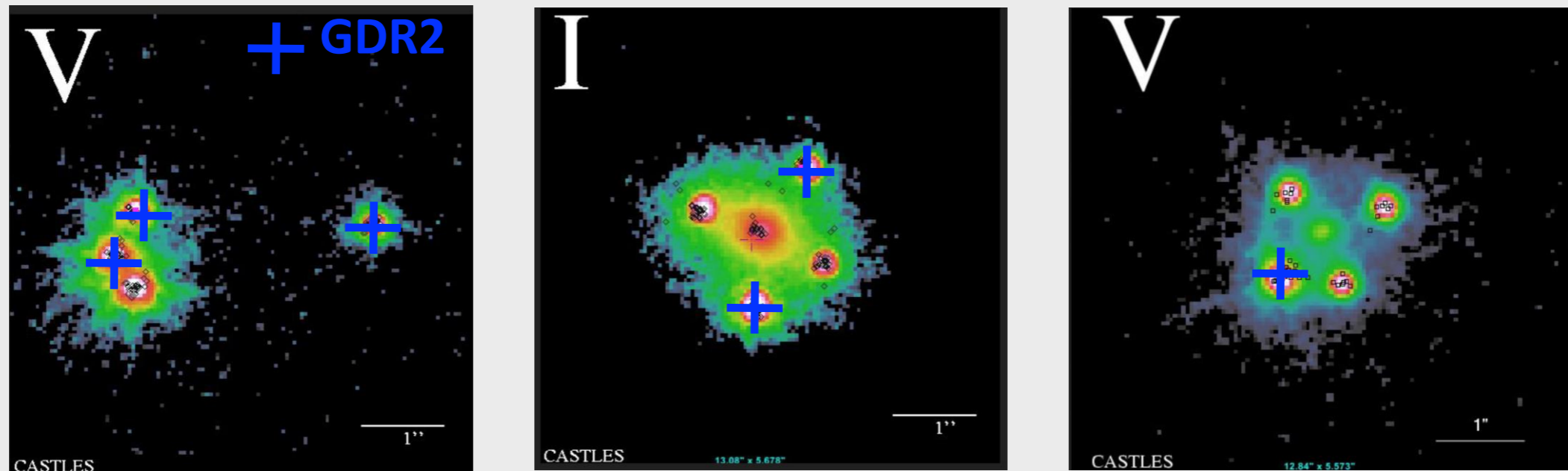
- **Blind search in Gaia data releases, times series**
- **Search in ground-base imaging surveys**
-

GDRs are incomplete at small separations

Arenou+2018A&A...616A..17A



GDRs are incomplete at small separations



➤ GravLens chain in DPAC

- Aims at detecting any additional source around known quasar within 6''
- Flag potential lenses

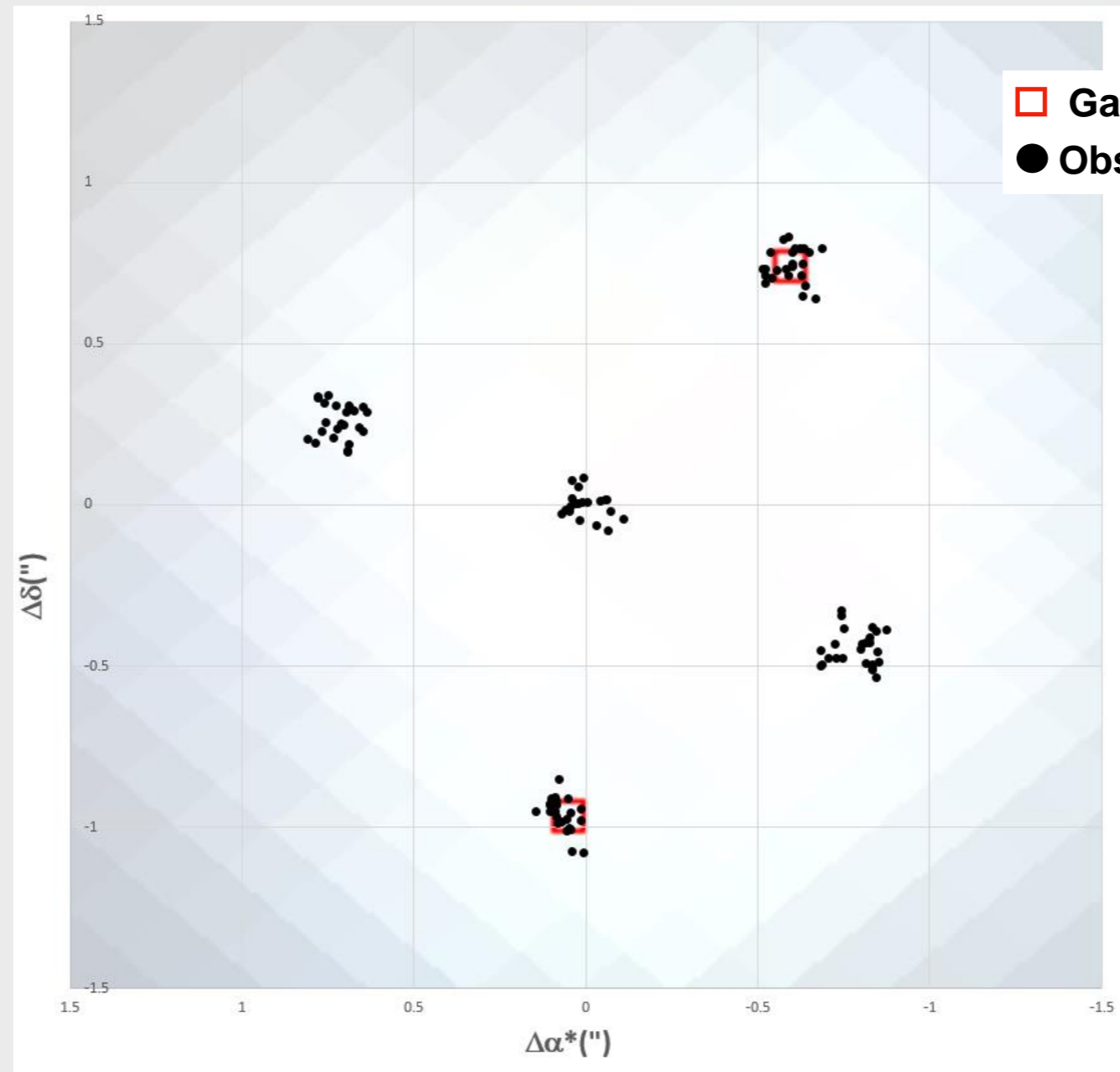
➤ How it works

- Constitution of an input list of quasar candidates (3.7 M sources)
- Clustering algorithm (DBSCAN) applied to Gaia measurements around candidates
- Determination of Mean (RA,DEC) + mean onboard G mag of all "clusters" found

➤ When

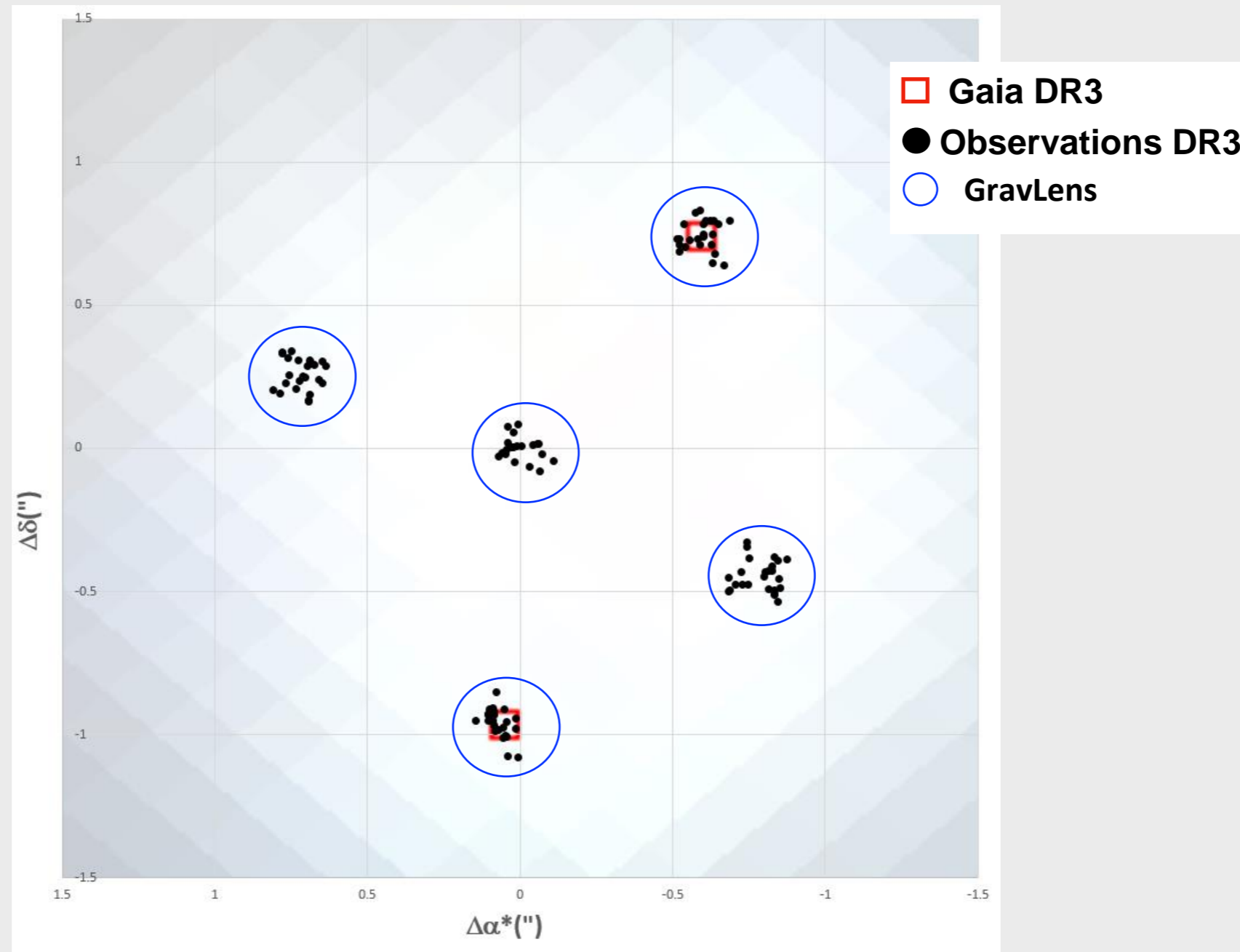
- Operations of the chain before end 2022
- Publication of results mid-end 2023 in Gaia Focus Products Release (FPR)

Known quad analysed by Gravlens



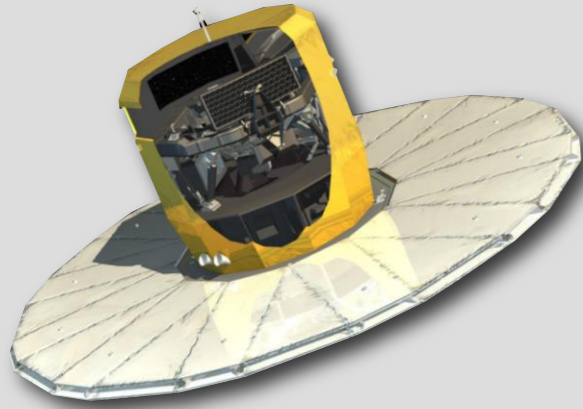
PanSTARRS image

Known quad analysed by GravLens

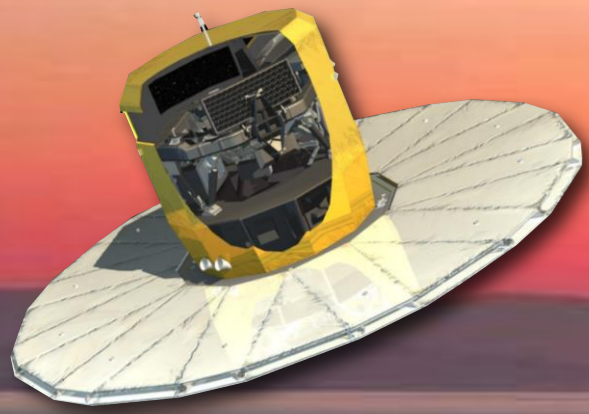


PanSTARRS image

- Catalogue of environment of 3M quasars expected mid-end 2023



- **Gaia provides in DR3 an all-sky, space-based survey of surface brightness profiles of quasars and galaxies that are mostly not resolved from ground.**
- **Gaia DR4 is already in preparation**
 - **should unveil much more of these extragalactic sources (2Xmore measurements)**
 - **with improved parameters**
- **Gaia is potentially the first survey of gravitational lenses from space**
 - **Several works exploit Gaia data and discovered ~20% of the known quads**
 - **DR3 already under analysis with ERTs for new candidates**
 - **GravLens chain exploring the environment of quasars with publication in Gaia FPR mid-end 2023**



Thank you!