Quasar Selection Techniques going into the Gaia Era

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Why Quasars?

How do you define "motion"?
- Motion of Earth about its axis
- Motion of Earth about the Sun

Need: Celestial Reference Frame (CRF)
→ **Stars** (okay for a few decades)

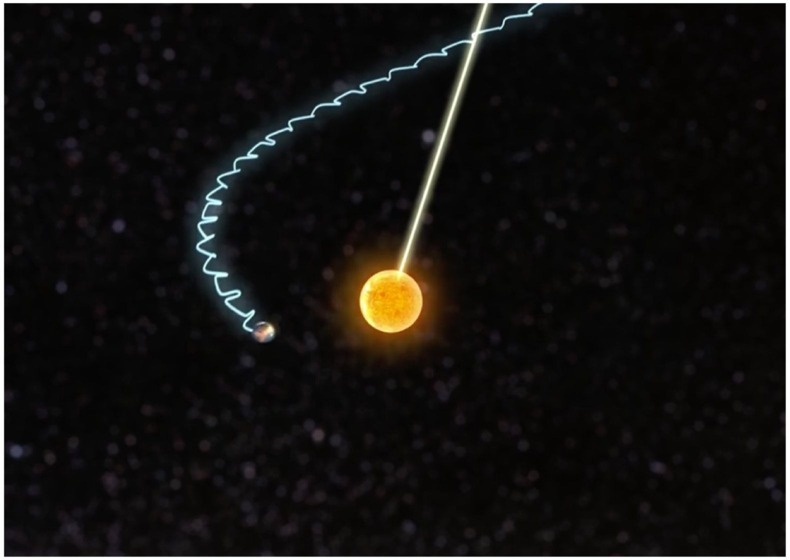
- Motion of stars around the Galaxy (including Sun)
- Also: geodesy over time (tectonics, tides, etc.)

Need: "stars" that do not move!

→ **Quasars**

- Extremely distant (negligible proper motion/extent)
- Extremely luminous (easy to observe)
- Randomly distributed (quasi-uniform sky distribution)

⇒ Ideal for defining a reference frame (in principle)



Credit: M. Stevens (Vsauce)

Credit: esa/*Gaia*

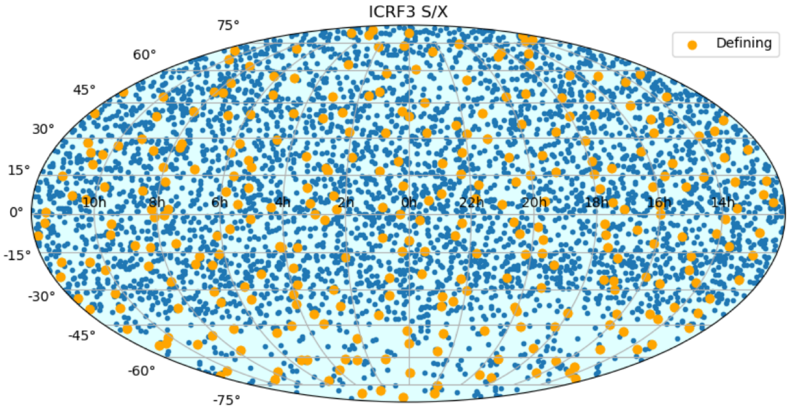
Why Quasars?

"The International Astronomical Union (IAU) has charged the International Earth Rotation and Reference Systems Service (IERS) with the responsibility of monitoring the International Celestial Reference System (ICRS) and maintaining its current realization, the International Celestial Reference Frame (ICRF), and links with other celestial reference frames. Starting in 2001, these activities are run jointly by the ICRS Centre (Observatoire de Paris and U.S. Naval Observatory) of the IERS and the International VLBI Service for Geodesy and Astrometry (IVS), in coordination with the IAU Working Group on the Reference System."

Quasars bright in radio:

Radio interferometry (VLBI)

- few micro-arcsec precision
- positions ***define*** the ICRF



Charlot et al.

Why Quasars?

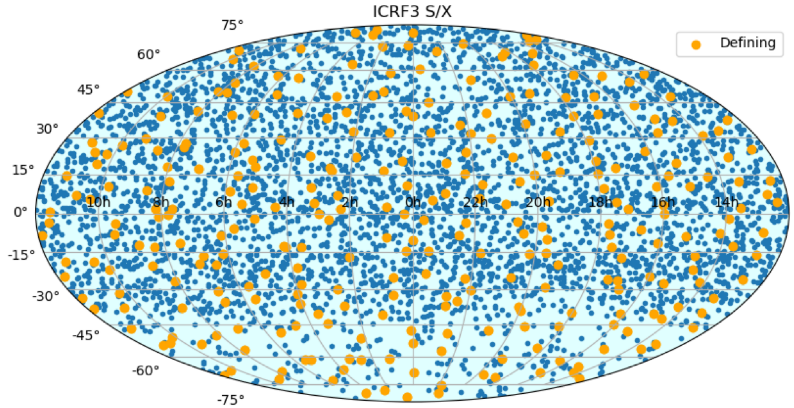
Radio positions → No direct visual CRF!

Gaia-CRF2 (micro-arcsec precision)

Alignment onto ICRS: use ICRF visual counterparts (2843)

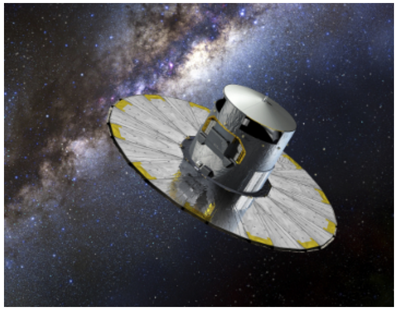
How to make Gaia-CRF2 **non-rotating**?

Need: large set of quasars assumed to be non-rotating



Charlot et al.

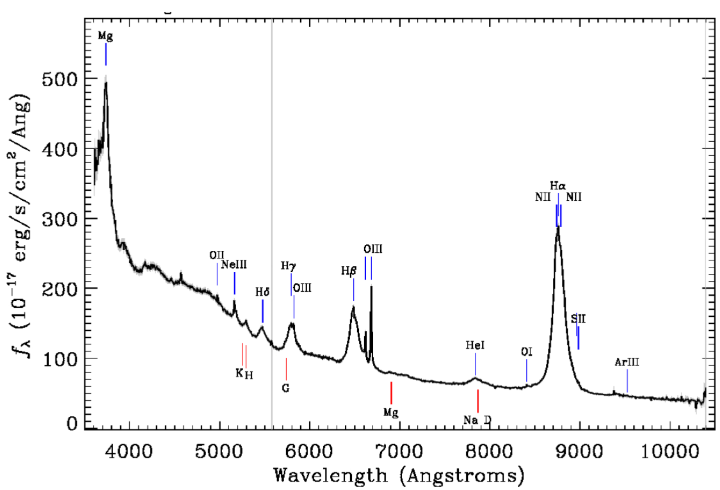
???

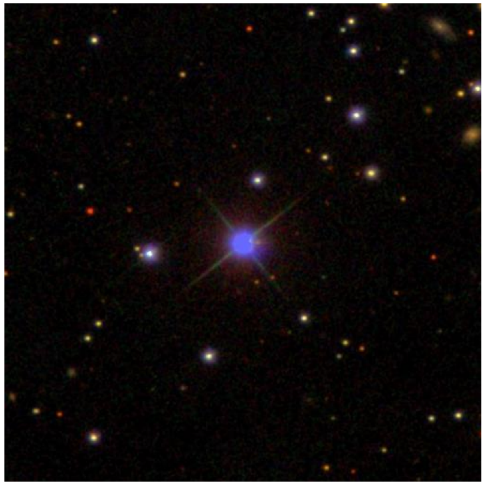


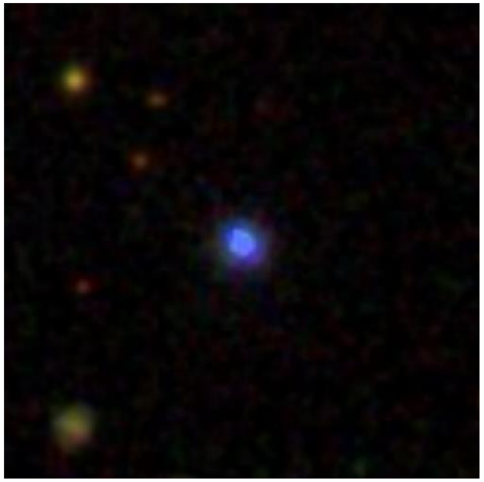
Finding Quasars

How do you know if something is a quasar?

Ideally: take a spectrum of it!
- In practice: observationally too expensive



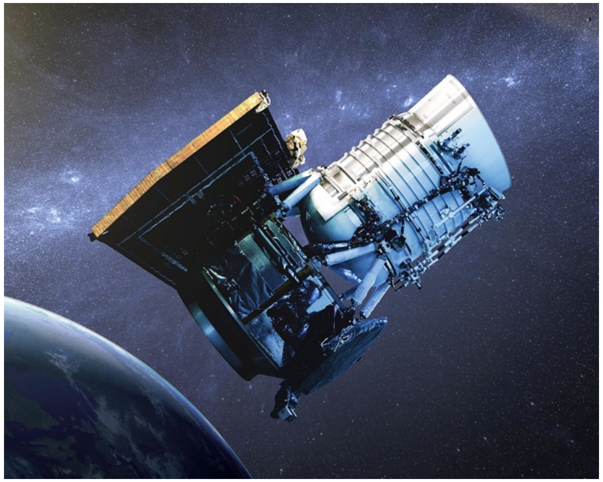




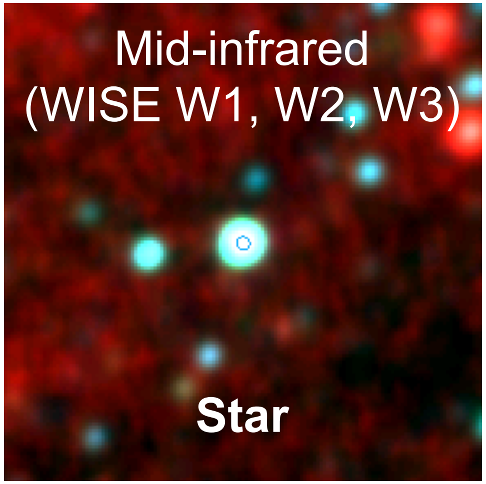
Finding Quasars

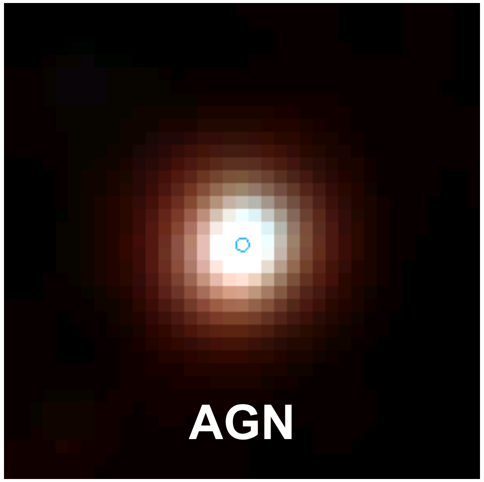
How do you know if something is a quasar?

Ideally: take a spectrum of it!
- In practice: observationally too expensive
➔ **Use the infrared**

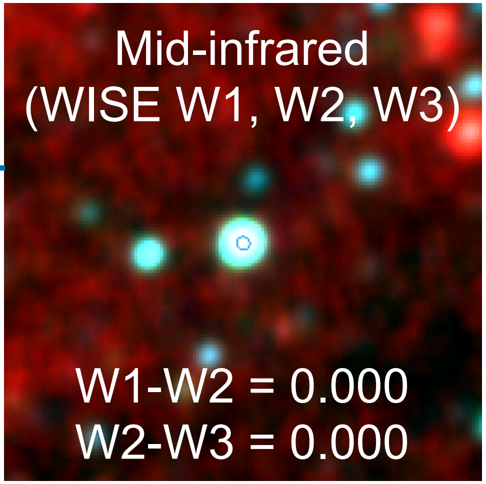


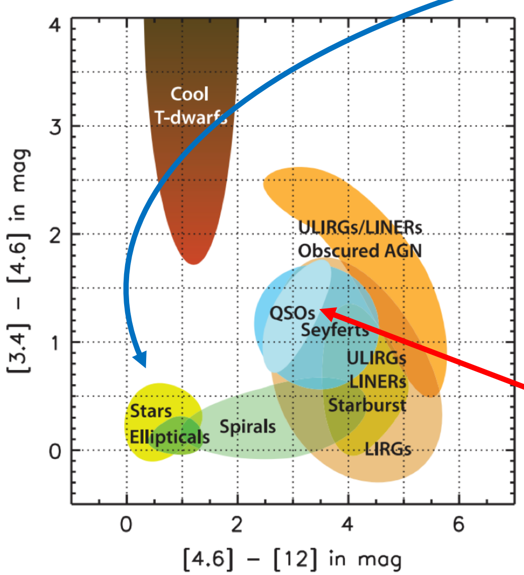
Wide-field Infrared Survey Explorer
(WISE)



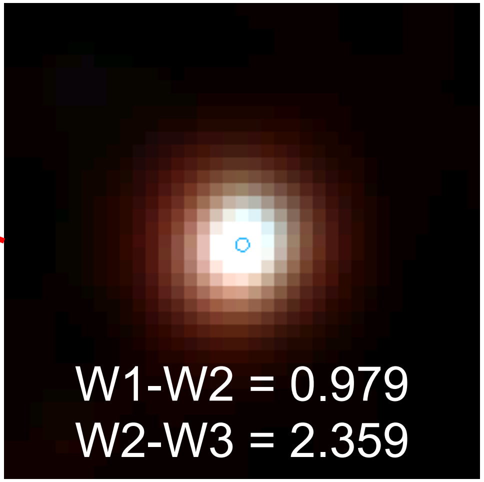


Finding Quasars



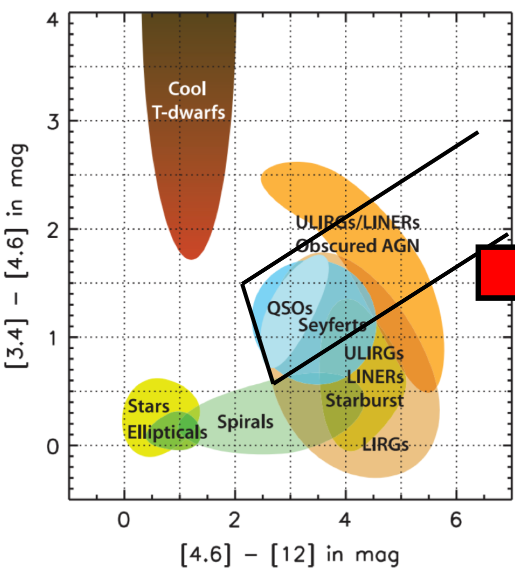


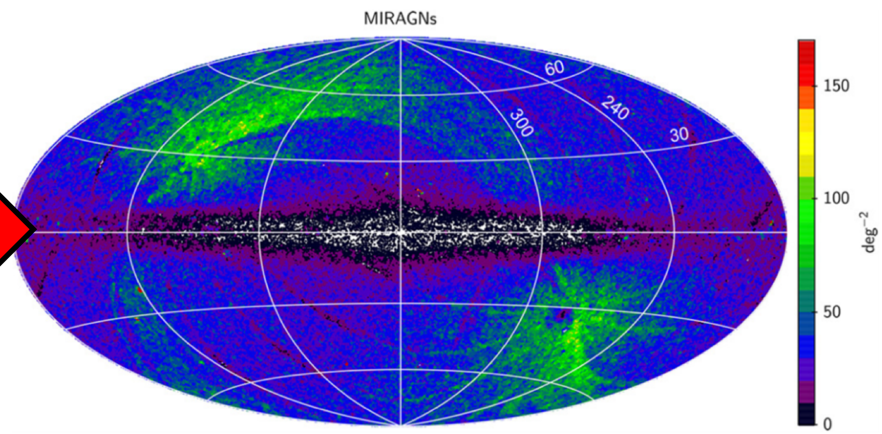
Wright et al. (2010)



- Get reliable, all-sky sample of non-stars by picking out AGNs
- Literature color cut → **1.4 million Mid-IR AGNs (MIRAGNs)**

Wright et al. (2010)



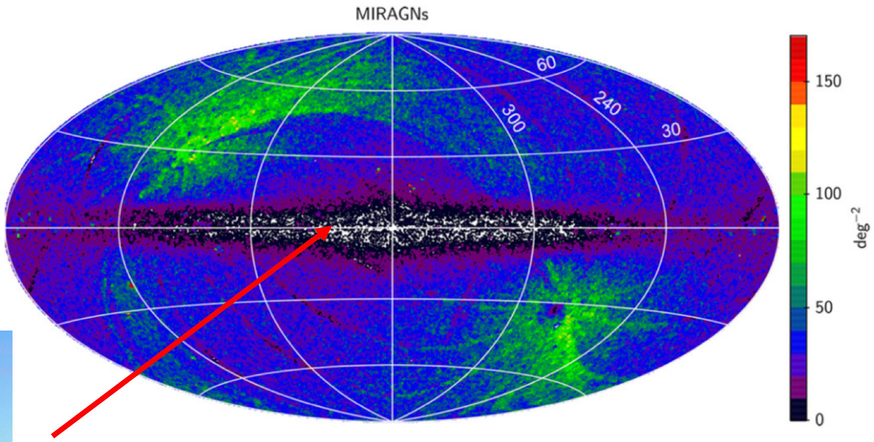


Secrest et al. (2015)

Gaia-CRF2 non-rotating
(**Lindegren et al. 2018**)

Near-IR for source confusion along Galactic plane

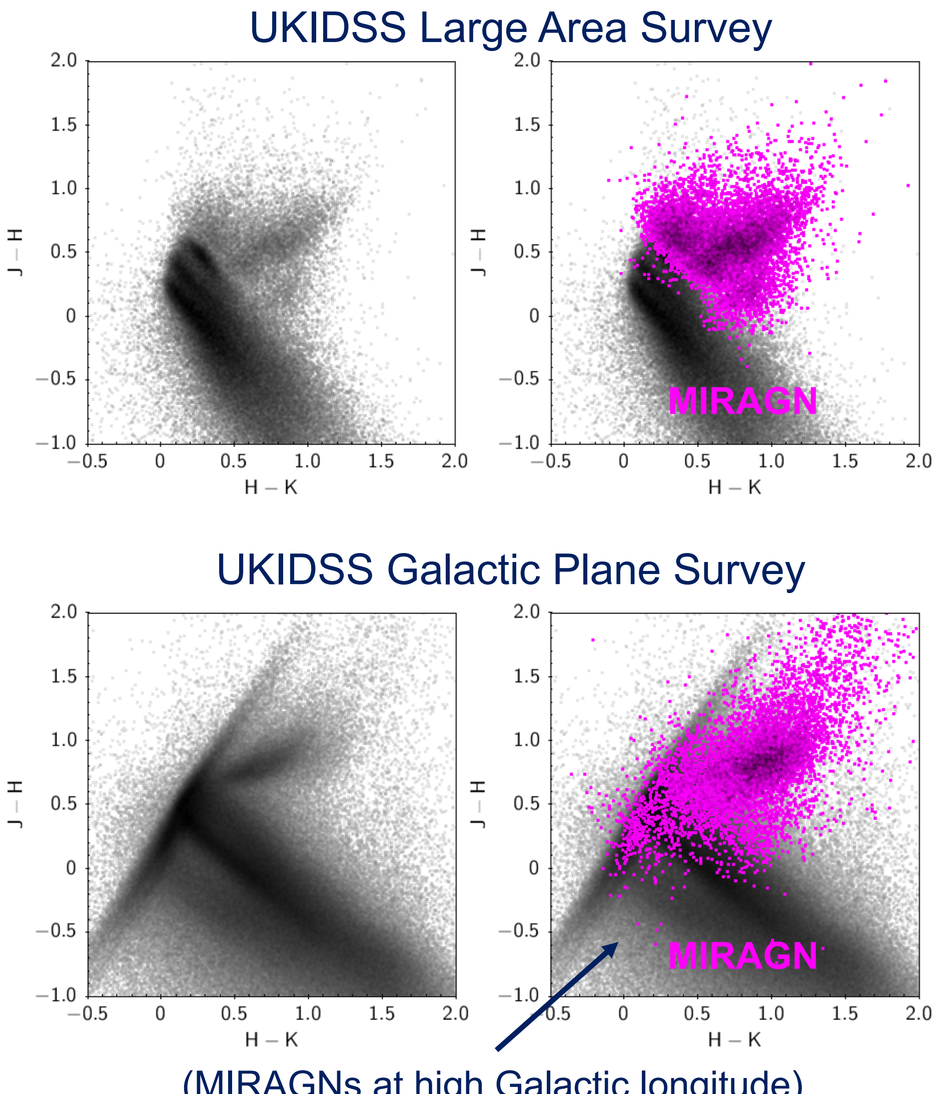
- **UKIRT** did survey of Galactic plane in J, H, Ks (UKIDSS GPS)
- Angular resolution **much** better:
  < 1” vs. 8” for AllWISE



Methodology:

- AGNs do not occupy J-H, H-K color space as cleanly as W1-W2, W2-W3 (*especially* along Galactic Plane)
- Fold in additional information, such as morphology, apparent mag, Galactic extinction, etc.

High dimension problem
➔ **Use machine learning**



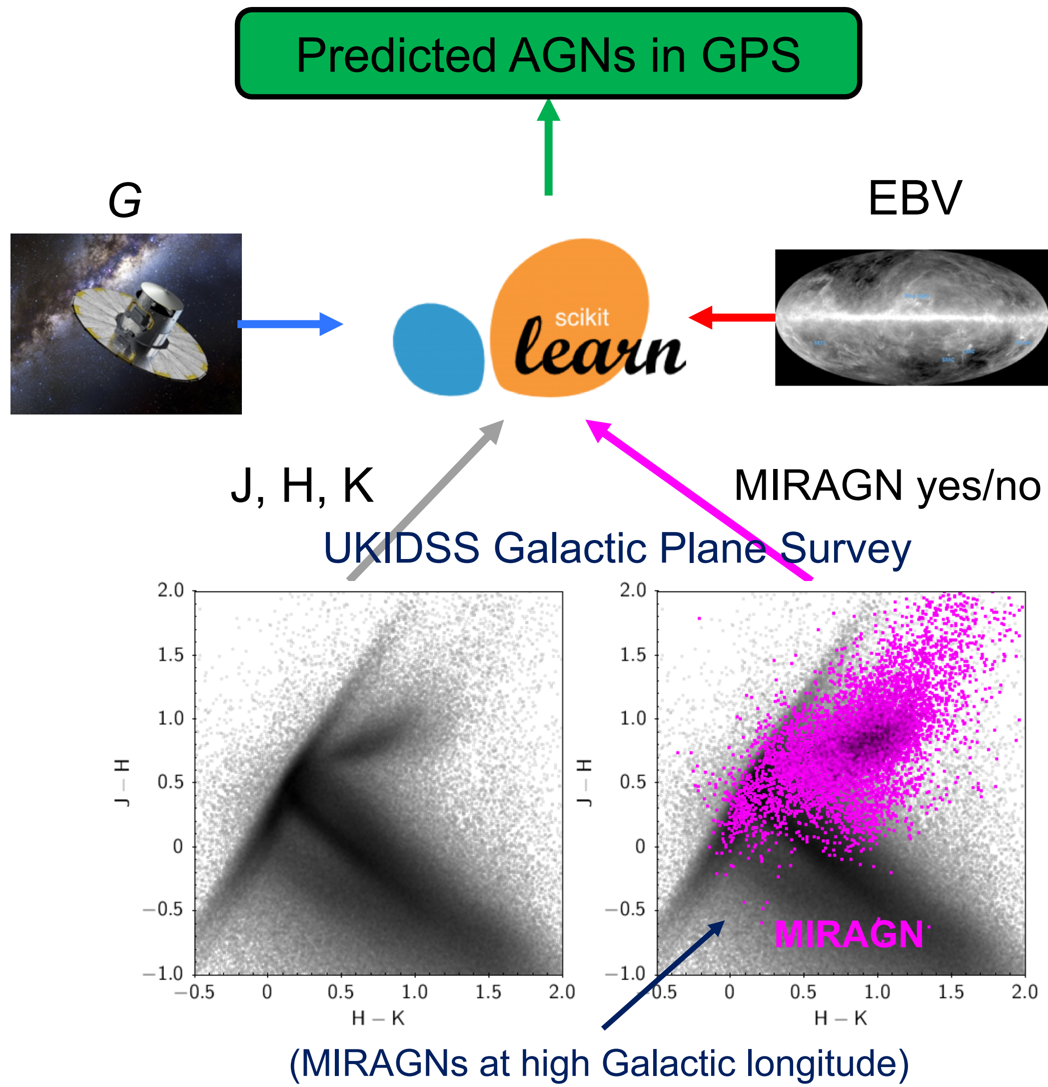
Training set: High Galactic longitude MIRAGNs in UKIDSS GPS

Parameters: ***un***corrected J-H, H-K, G-J, EBV

- G = *Gaia* G (to tie to *Gaia* frame)
- EBV from **Schlafly & Finkbeiner (2011)**

Magnitudes uncorrected for EBV to let ML handle uncertainties in Rv (which is dust dependent). (Given AGN SED, Rv*EBV *implicit* in uncorrected G-J, J-H, H-K)

Python scikit-learn k-nearest neighbors used for training, prediction



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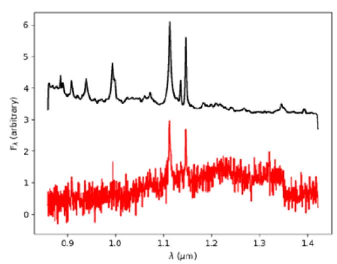
➔ Accepted UKIRT UIST observing proposal!



Predicted AGNs in GPS

↓

Validation against training set

↓

Reliability: **70%**
Completeness: **30%**

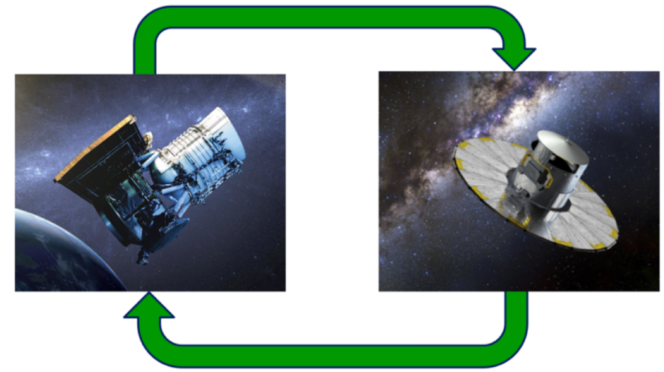
Percentage of AGNs in training set: **0.45%**

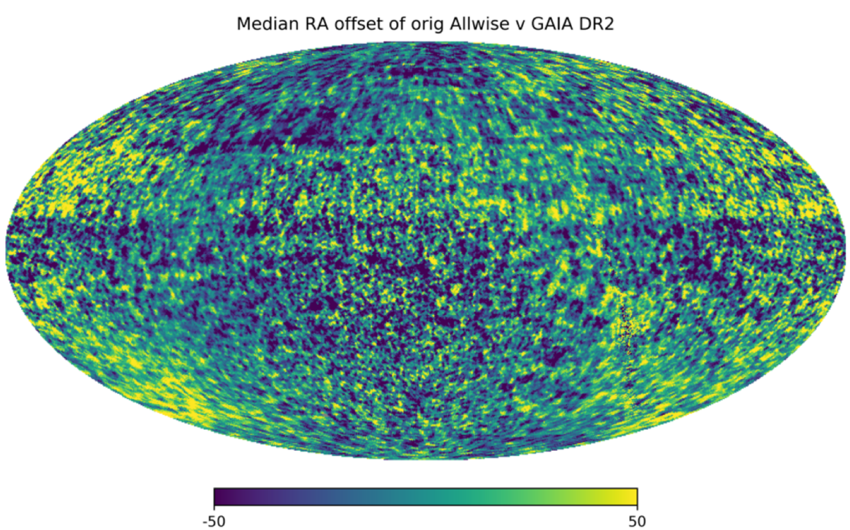
➔ ~ 160 times better than chance!

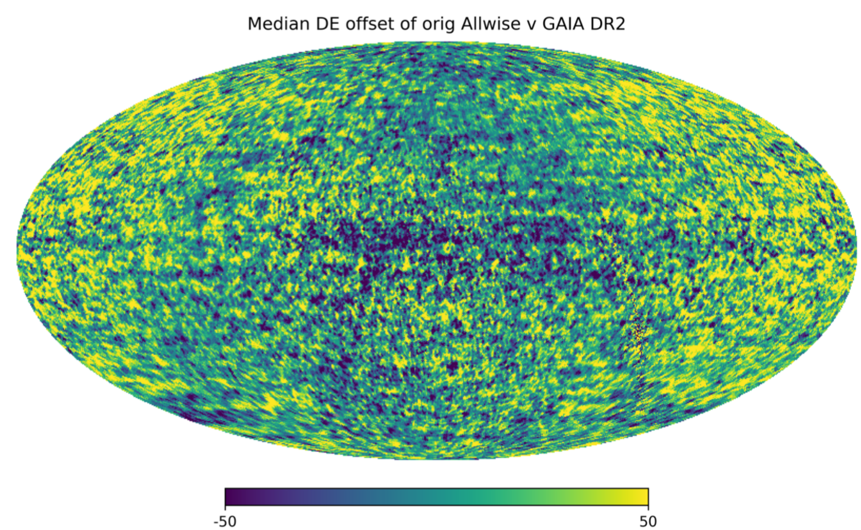
Gaia giving back to WISE!

AllWISE astrometry based on 2MASS positions + UCAC proper motions

→ Zonal errors → Position dependent bias





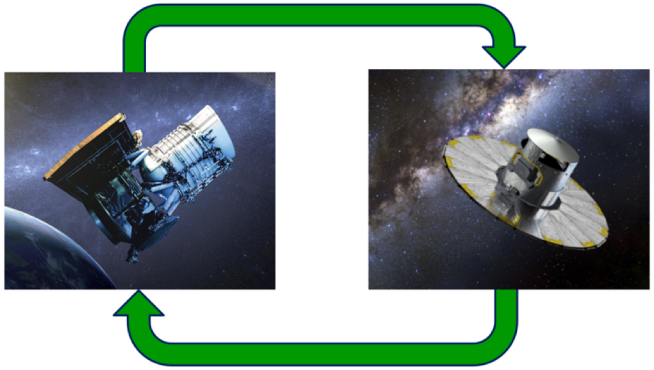


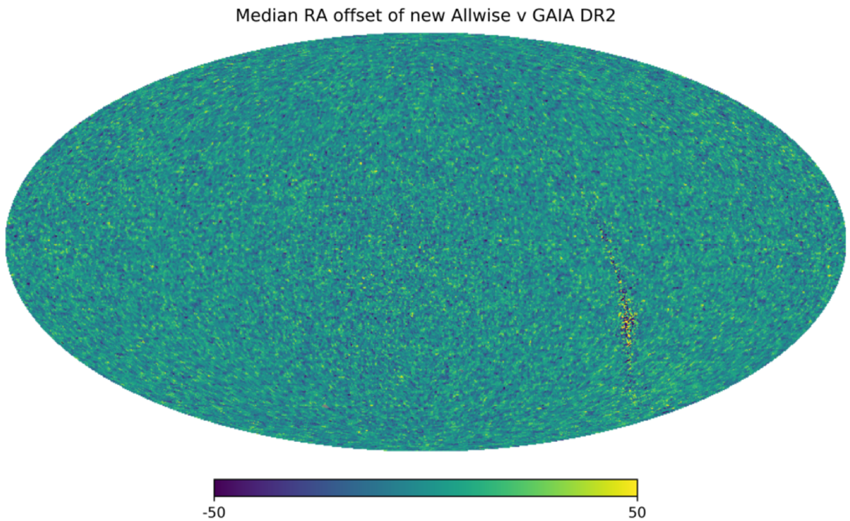
Gaia giving back to WISE!

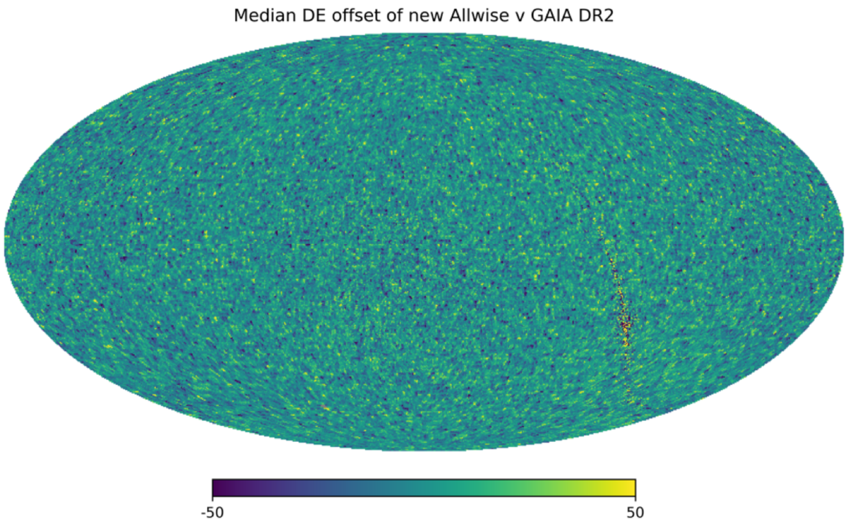
Re-do WISE astrometry w/*Gaia:*

→ Zonal errors gone!

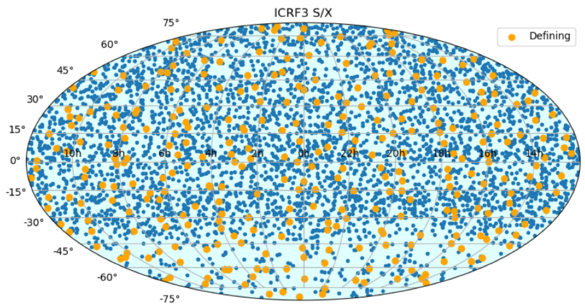
Beneficiaries: CRF, quasar clustering, CMB dipole studies, multi-wavelength catalogs, etc.

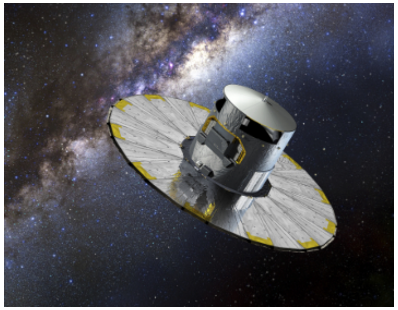


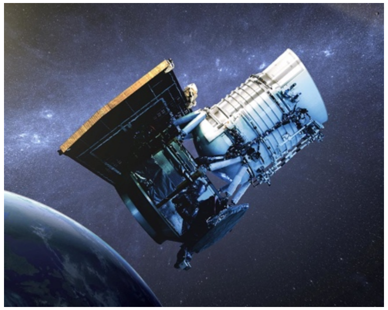


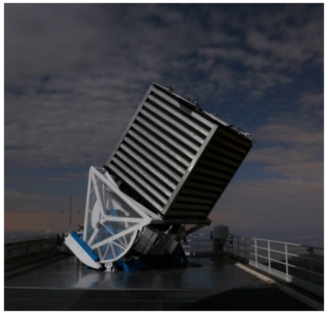


Multi-wavelength, iterative refinement.









VLBI
- Micro-arcsec positions
- Realization of ICRS

Gaia
- Micro-arcsec precision
- visual-wavelength CRF

WISE
- Uniform, reliable extragalactic objects/AGN

SDSS
-Spectroscopy for bona fide AGN/quasars, redshifts

Large Quasar Astrometric Catalog (LQAC)

Authoritative catalog of bone fide AGN/quasars with optimized positions

Now in version 5 **(Souchay et al. 2019)**

Summary

- Infrared photometric selection is an excellent method to separate stars from AGNs and assist with CRF work.
- Low angular resolution of existing mid-infrared data motivates using ground-based near-infrared facilities with machine learning.
  → Fill-in Galactic plane
  → **Small-JASMINE**
  → ***Gaia*NIR**
- Harmony between WISE and *Gaia*… New WISE astrometry on the way!
- Multi-wavelength → CRF