

Strongly Lensed Quasars: *Where Entropy meets Astrometry, Wavelets And Machine Learning*

Alberto Krone-Martins

CENTRA/SIM - Faculdade de Ciências
Universidade de Lisboa

In this talk

Why Strongly Lensed Quasars?

**How are we detecting
Strongly Lensed Quasars?**

In this talk

Why Strongly Lensed Quasars?

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Strongly Lensed Quasars?

Why Strongly Lensed Quasars?

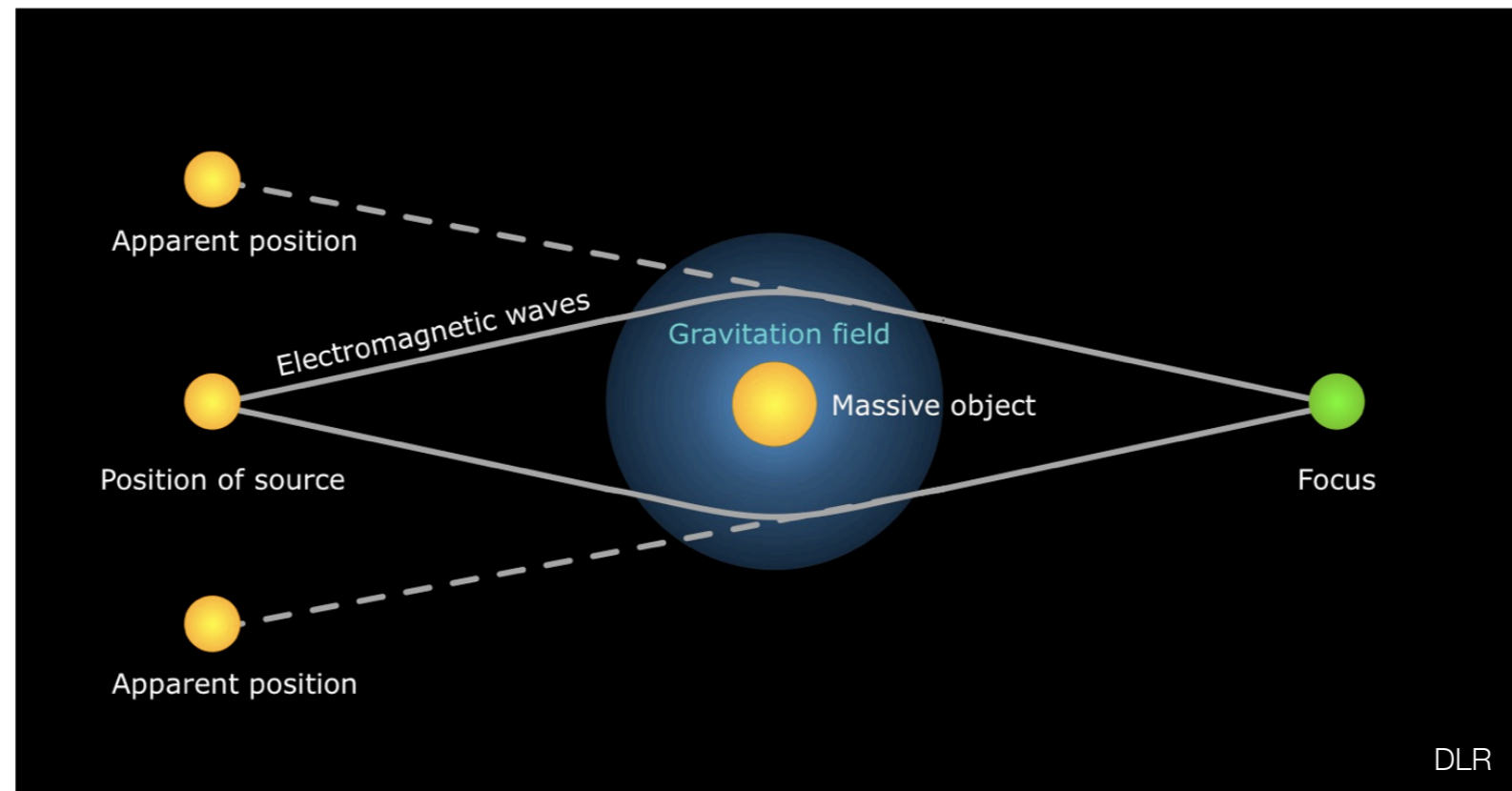


APOD 2017 December 17

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WIYN, AURA, NOAO, NSF

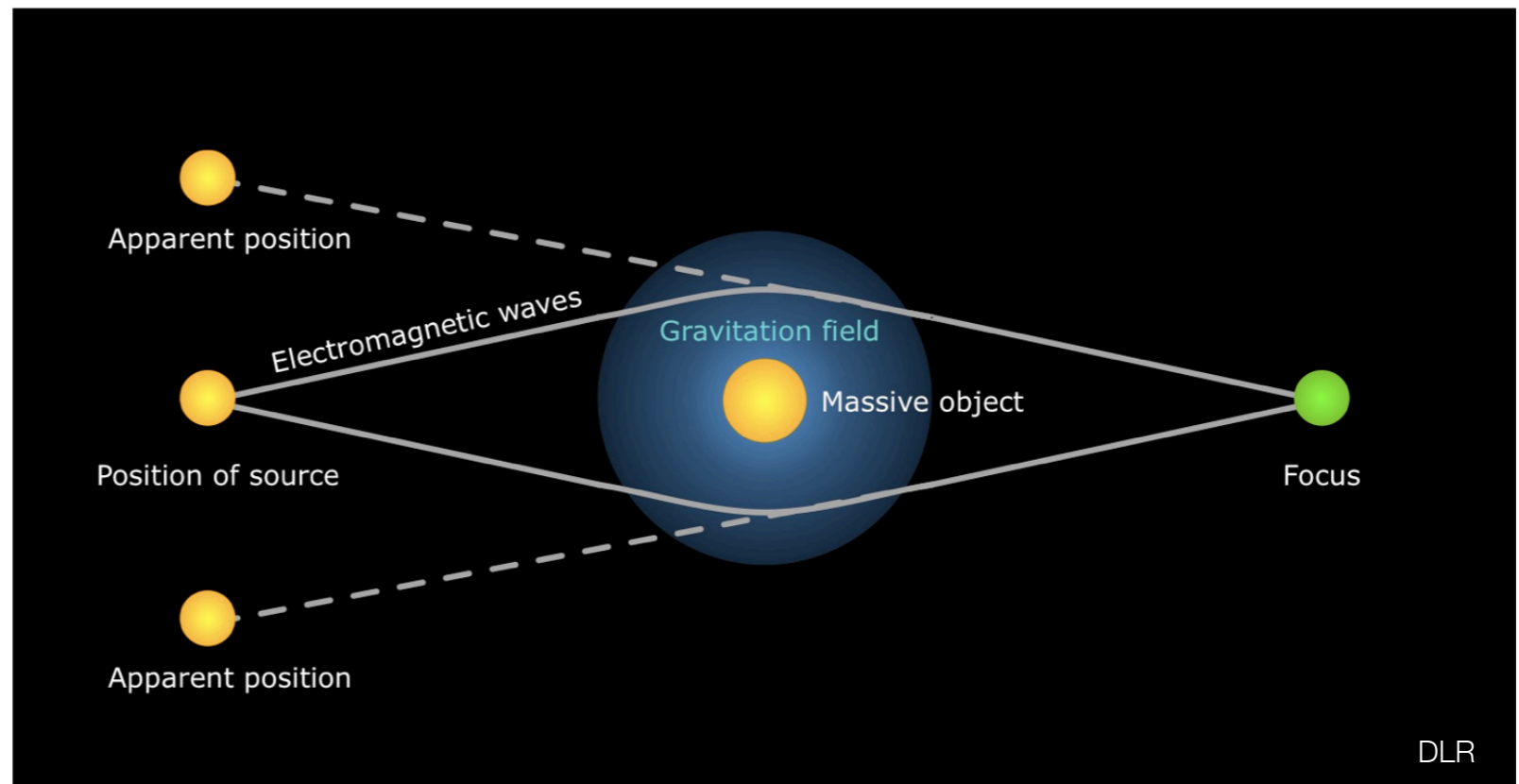
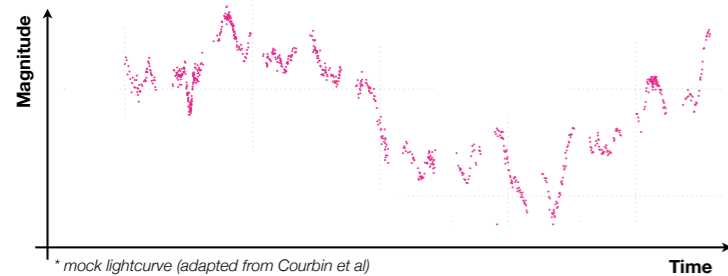
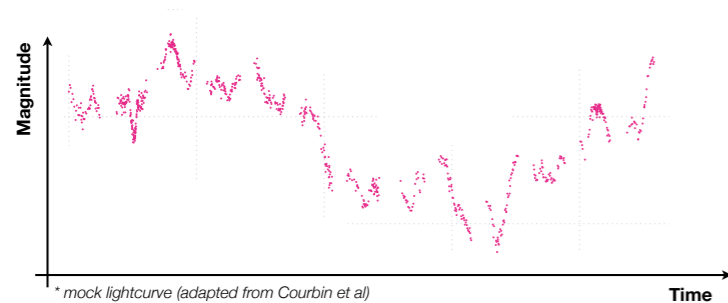
Why Strongly Lensed Quasars?

Among the most interesting (and useful) extragalactic phenomena...



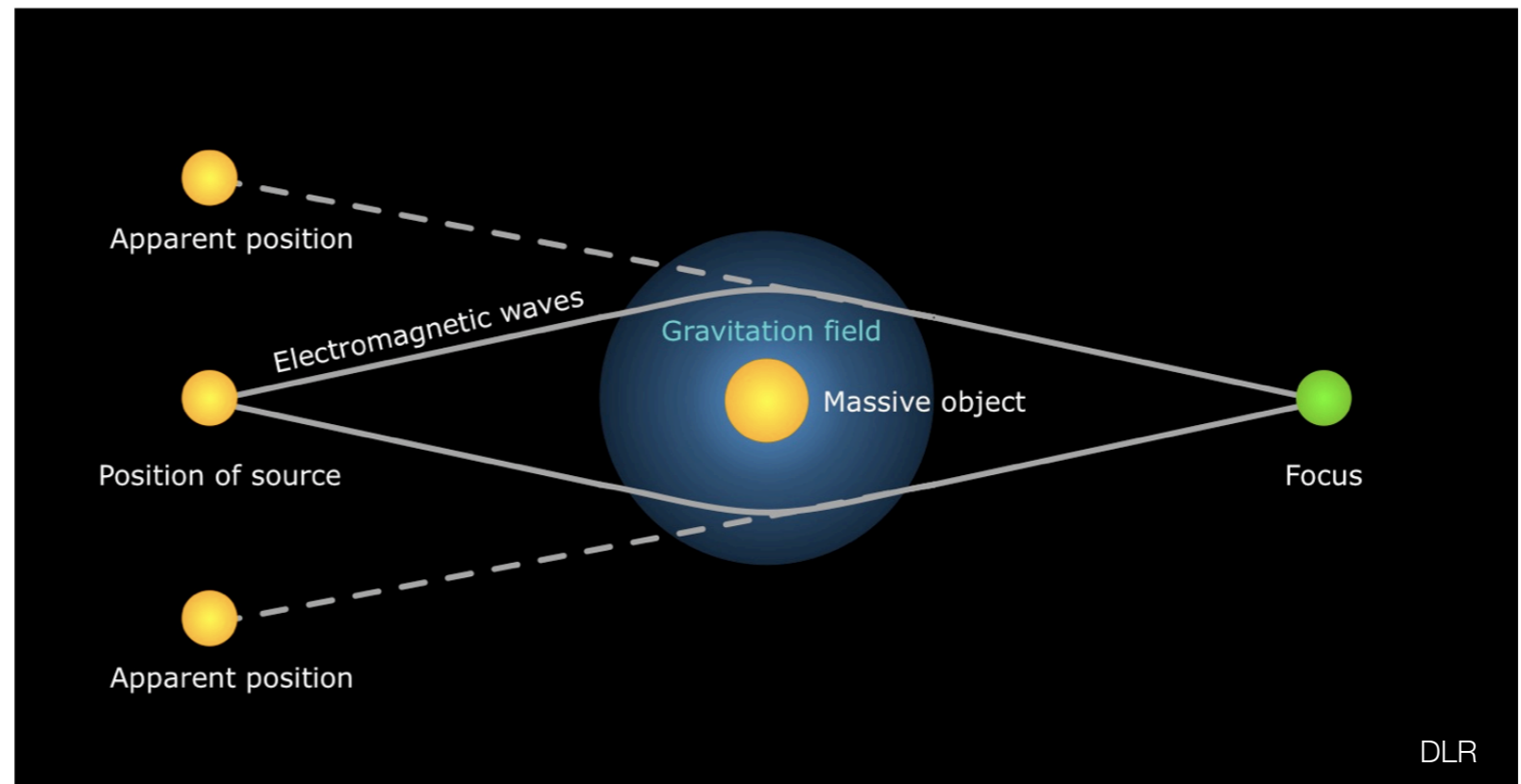
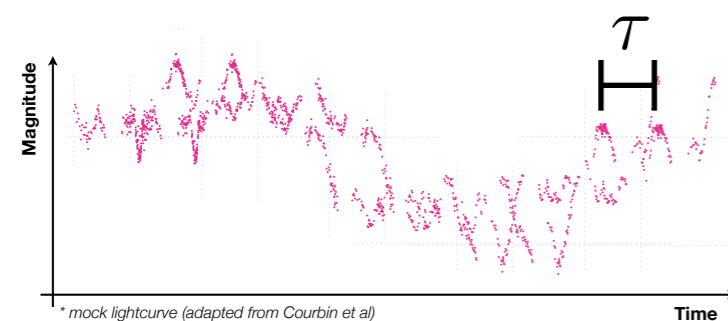
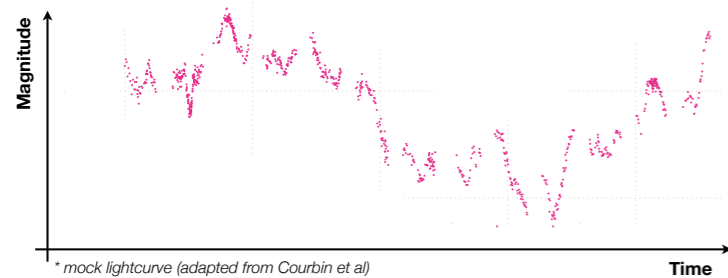
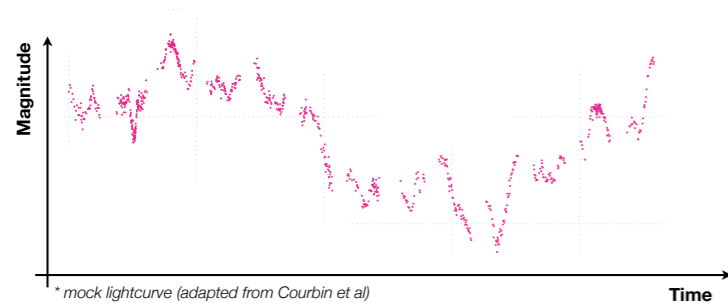
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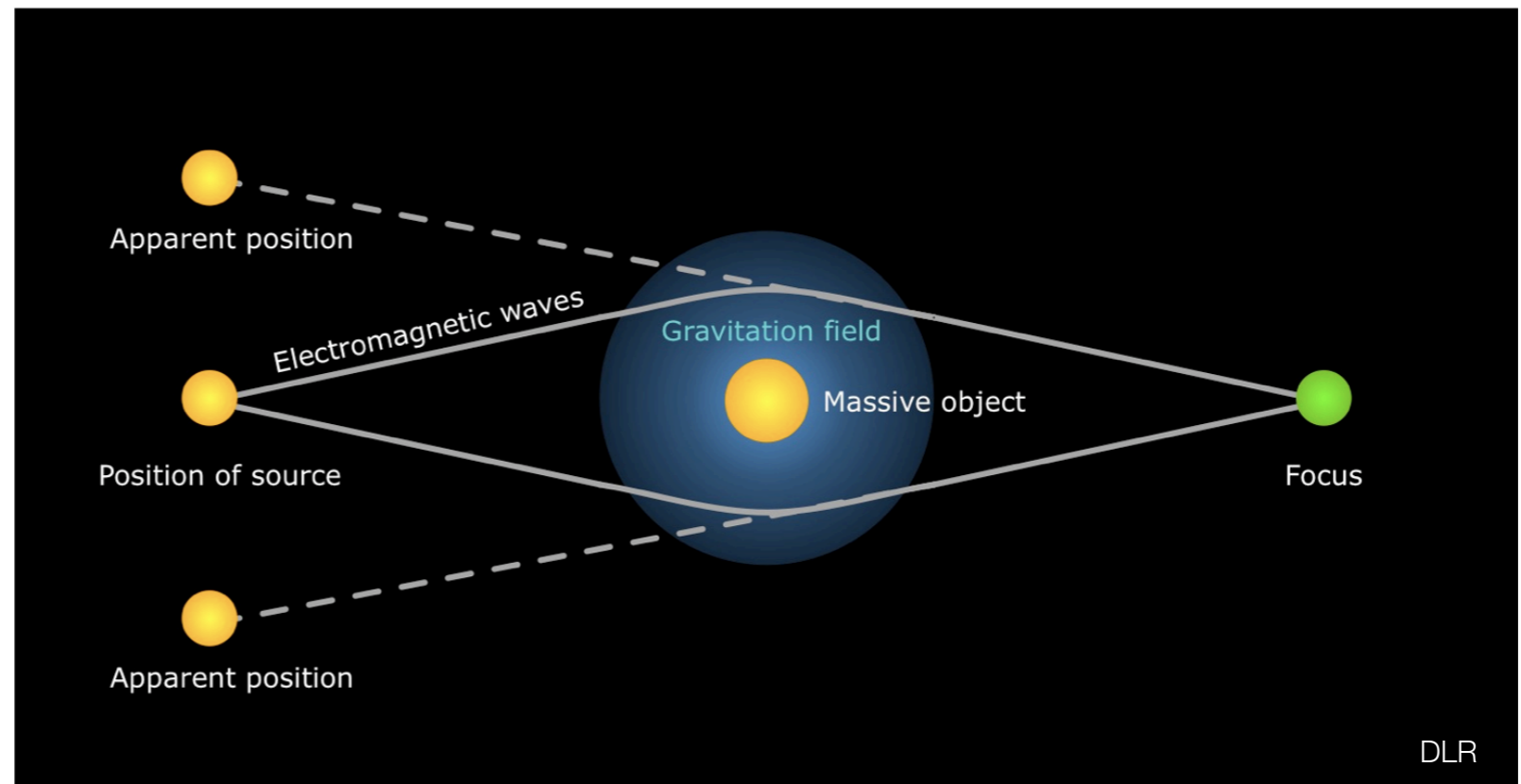
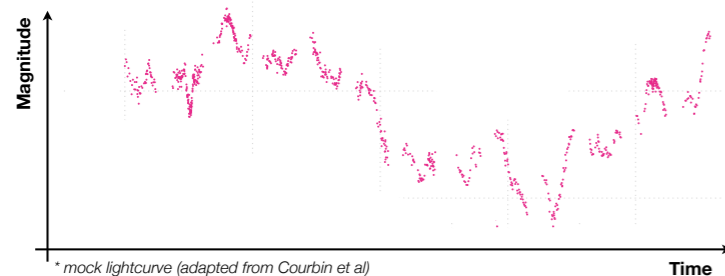
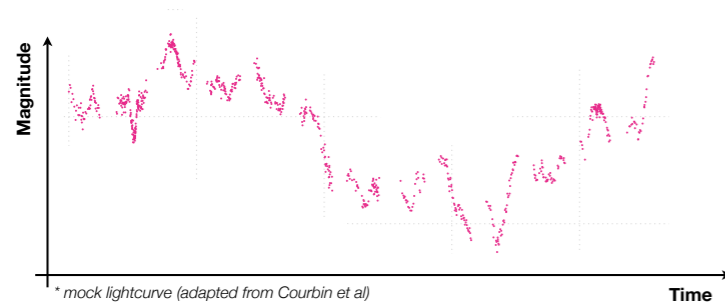
Why Strongly Lensed Quasars?

Among the most interesting (and useful) extragalactic phenomena...



Why Strongly Lensed Quasars?

Among the most interesting (and useful) extragalactic phenomena...



modelling: astrometry + photometry + spectroscopy

**measurement:
photometry
time-series**

$$\tau = \frac{(1 + z_L) d_L d_S}{d_{LS}} \left[\frac{1}{2} |\vec{\theta} - \vec{\beta}| - \psi_{2D}(\vec{\theta}) \right]$$

Why Strongly Lensed Quasars?

Among the most interesting (and useful) extragalactic phenomena...

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Why Strongly Lensed Quasars?

Among the most interesting (and useful) extragalactic phenomena...

measurement:
photometry
time-series

$$\tau = \frac{(1 + z_L) d_L d_S}{H_0} \left[1 - \dots \right]$$

modelling: astrometry + photometry

Very few multiply-imaged QSOs are known!

Problem



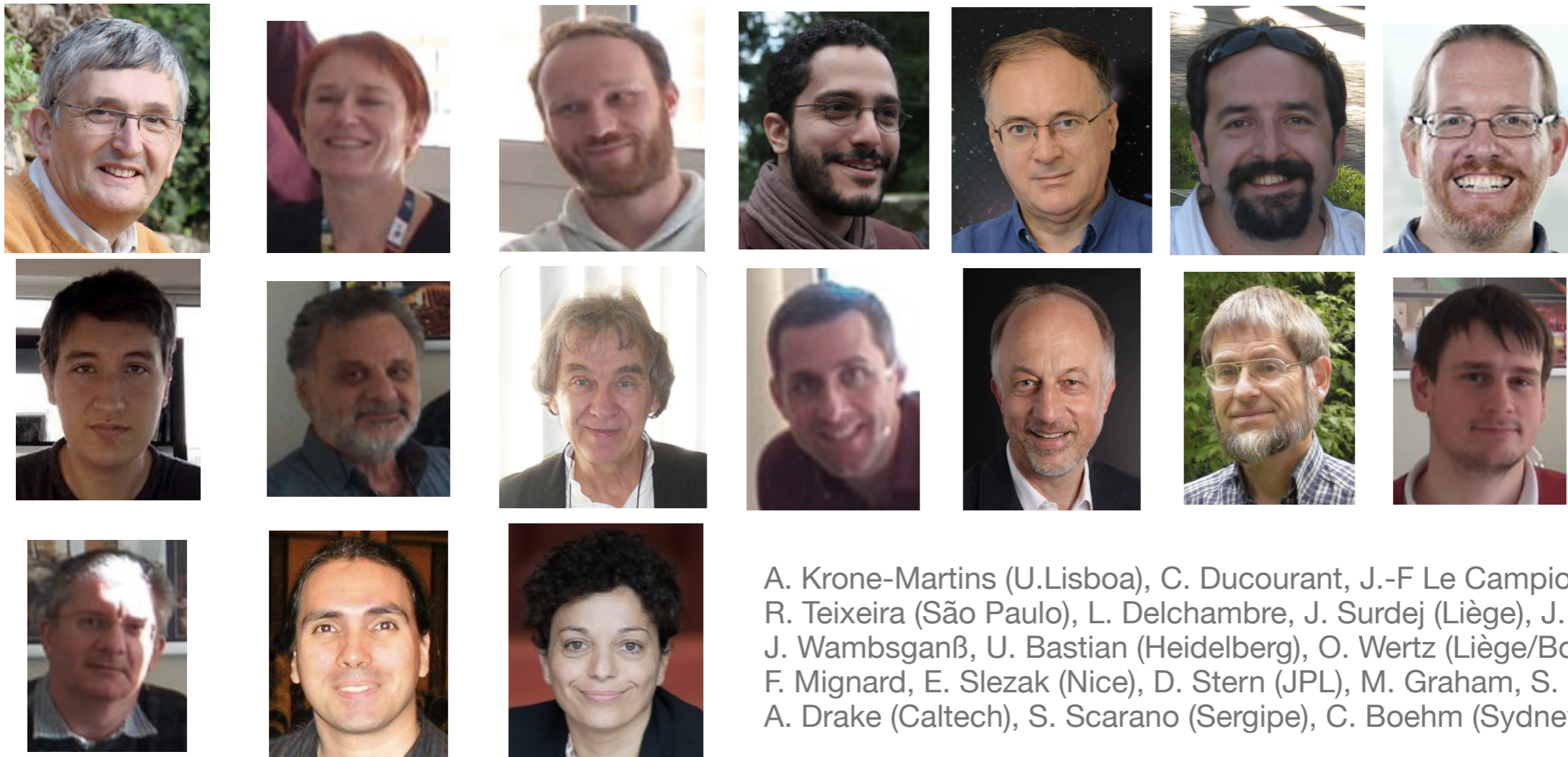
In this talk

Why Strongly Lensed Quasars?

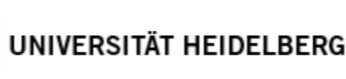
**How are we detecting
Strongly Lensed Quasars?**

We? *The Gaia GraL (Gravitational Lenses)*

ESA/DPAC/U.Lisboa/CENTRA

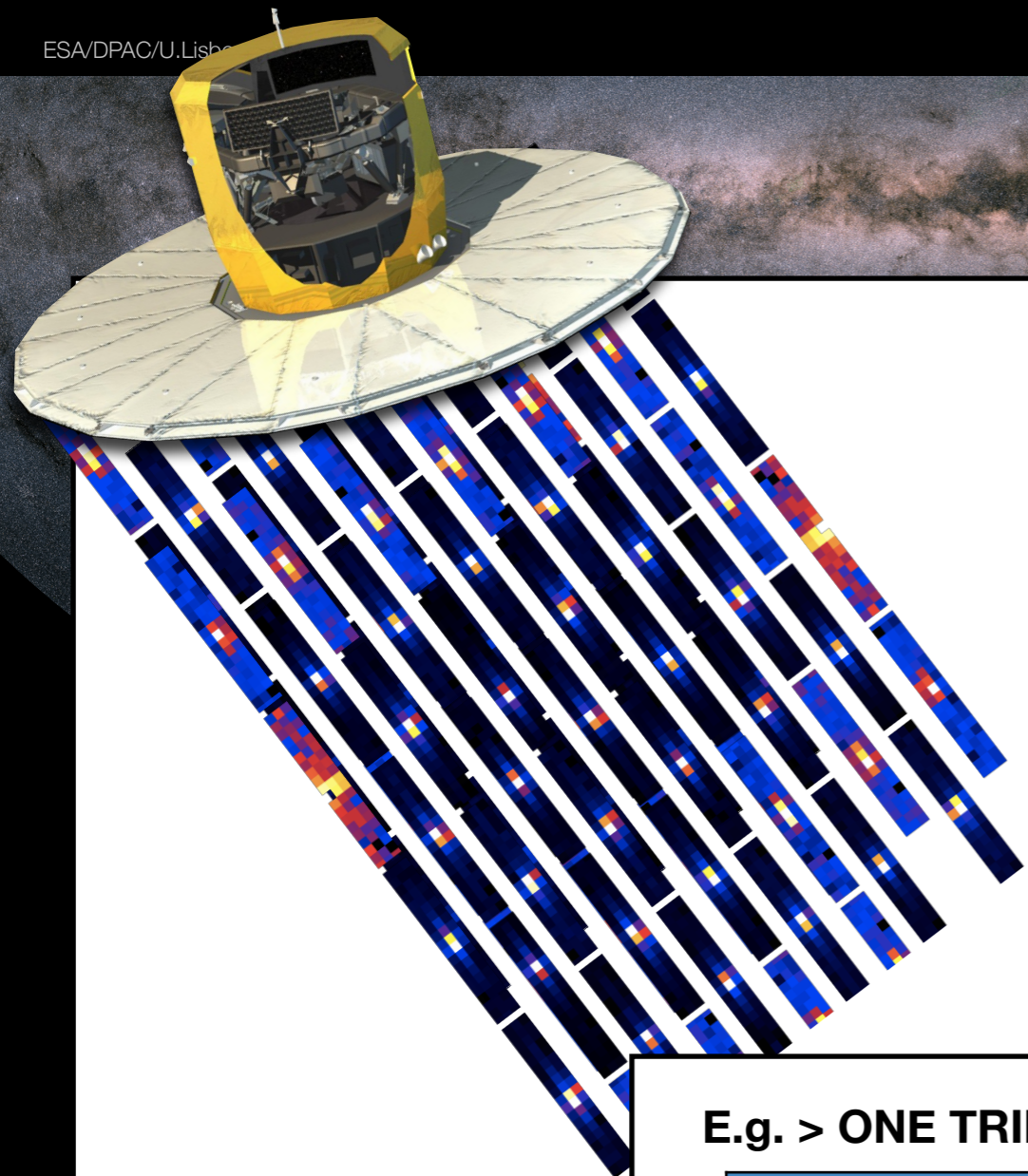


A. Krone-Martins (U.Lisboa), C. Ducourant, J.-F Le Campion (Bordeaux), R. Teixeira (São Paulo), L. Delchambre, J. Surdej (Liège), J. Klueter, J. Wambsganß, U. Bastian (Heidelberg), O. Wertz (Liège/Bonn), L. Galluccio, F. Mignard, E. Slezak (Nice), D. Stern (JPL), M. Graham, S. G. Djorgovski, A. Drake (Caltech), S. Scarano (Sergipe), C. Boehm (Sydney)



Why Gaia?

ESA/DPAC/U.Lisb



Fantastic potential for GL

All sky

Resolving power : 0.18"

Exception astrometric accuracy : $\sim 100 \mu\text{as}$

Lens expected

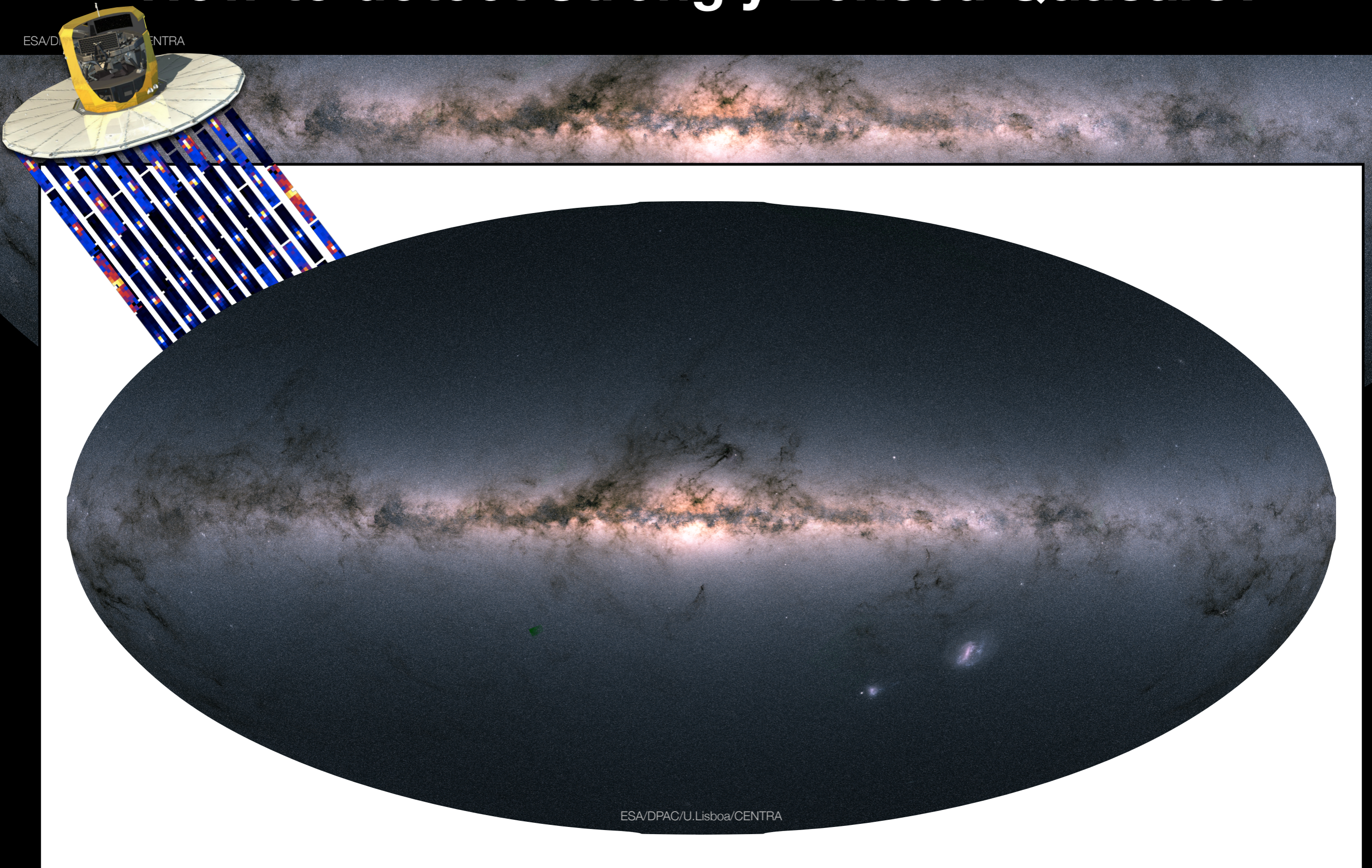
~ 2600 doubly imaged

~ 250 Quads

E.g. > ONE TRILLION Gaia measurements as of this morning (25th June 2019)

Astrometry + G-Photometry	$\sim 1.3 \times 10^{12}$
Spectrophotometry (300-1000 nm SEDs)	$\sim 2.6 \times 10^{11}$
Spectroscopy (R ~ 11500 , 847-874 nm)	$\sim 2.5 \times 10^{10}$

How to detect Strongly Lensed Quasars?



How to detect Strongly Lensed Quasars?



Astrometry + Single epoch photometry

Astrometry + Unresolved time-series

Astrometry + Imaging

How to detect Strongly Lensed Quasars?



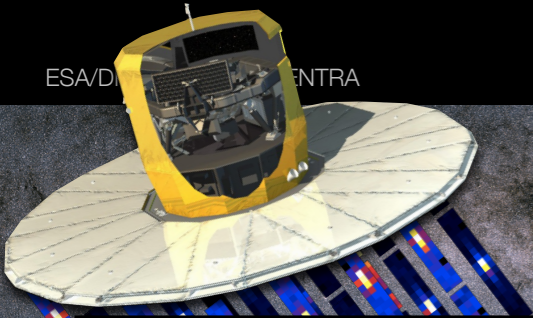
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How to detect Strongly Lensed Quasars?

ESA/D... ENTRA

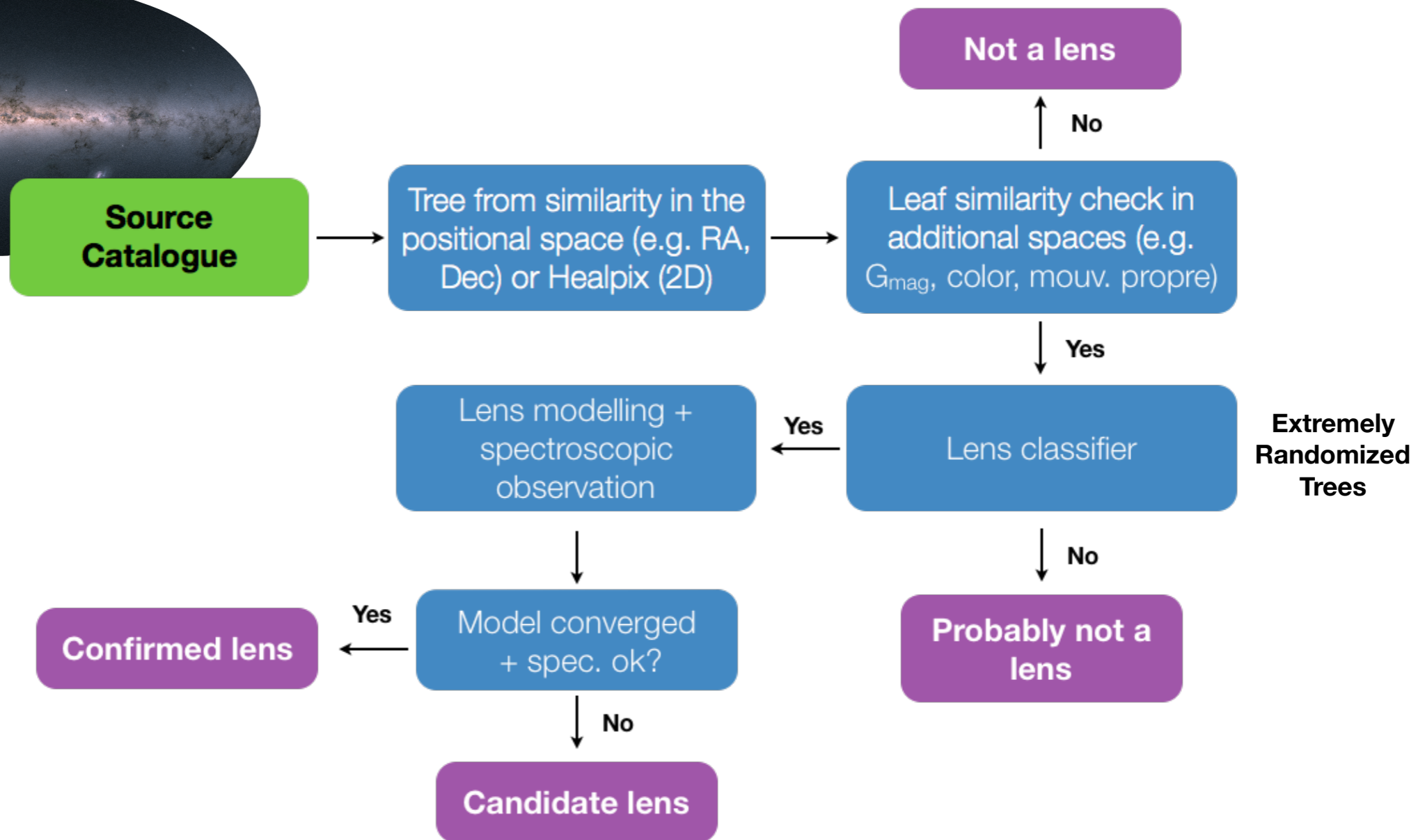
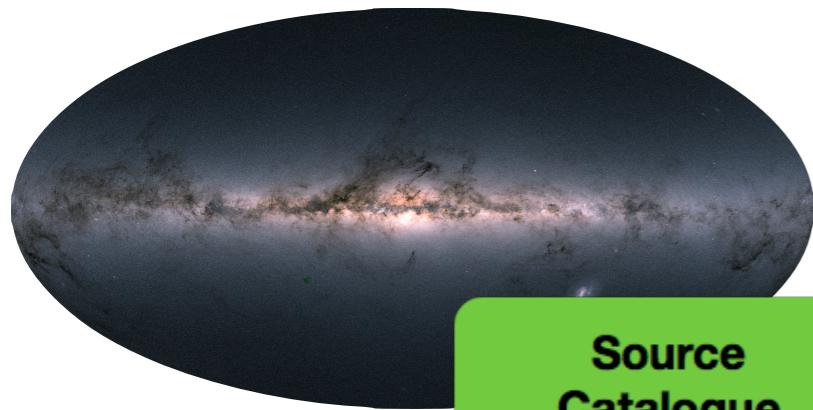


Astrometric + Photometric patterns



How to detect Strongly Lensed Quasars?

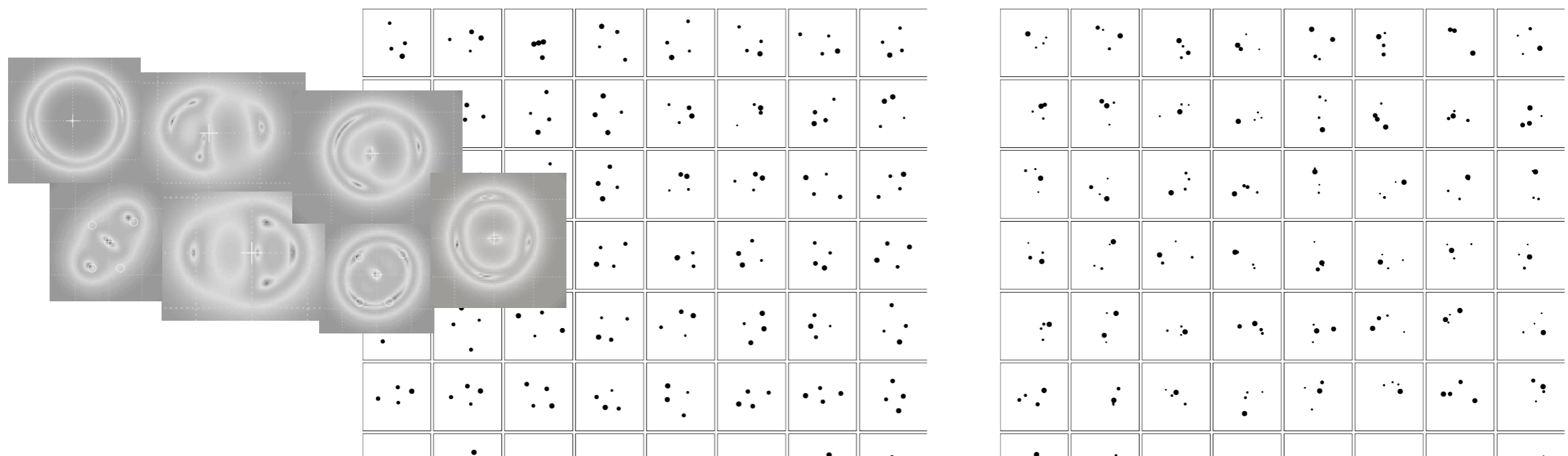
ESA/D... ENTRA



How to detect Strongly Lensed Quasars?

The learning set of observations

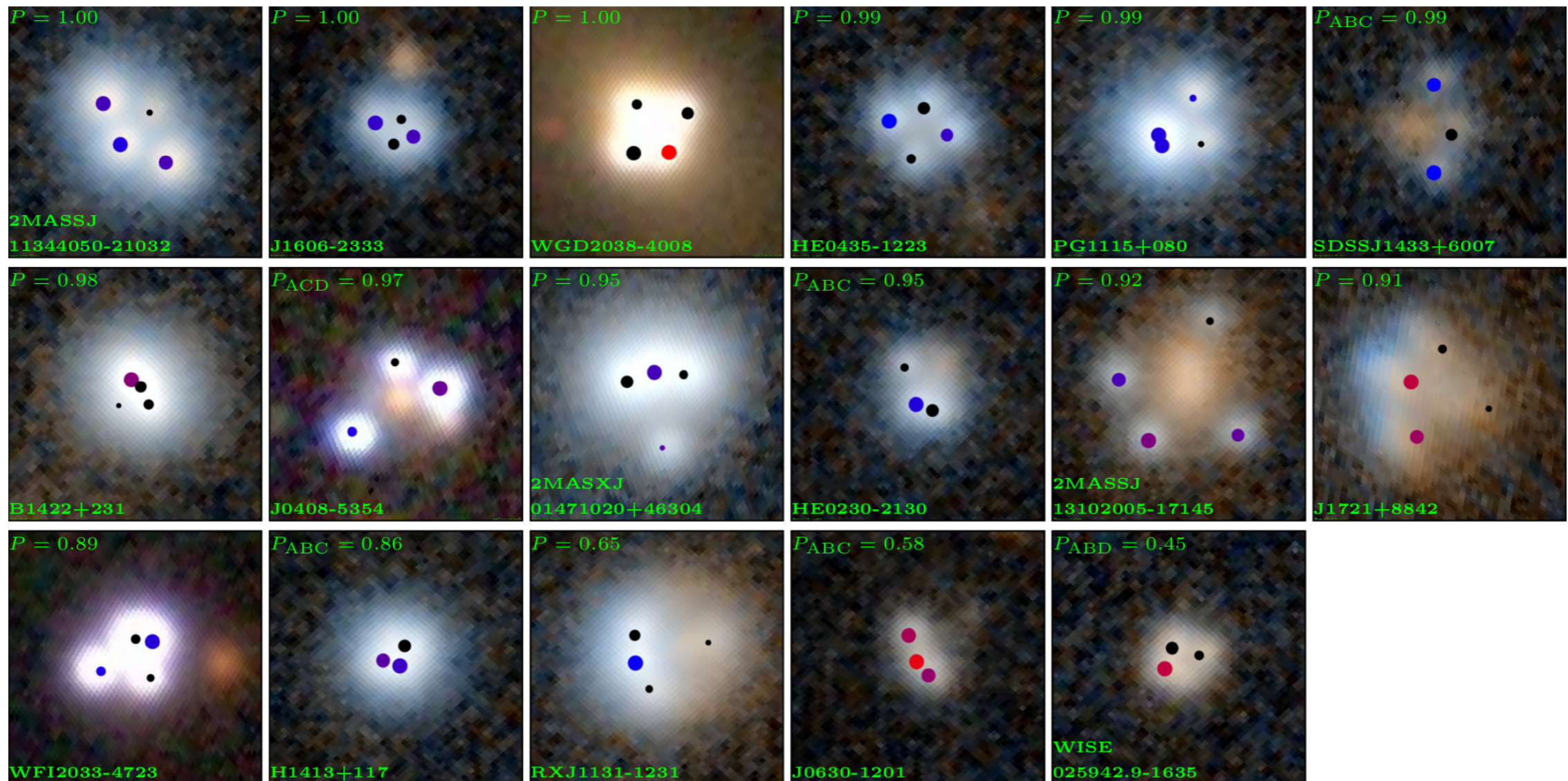
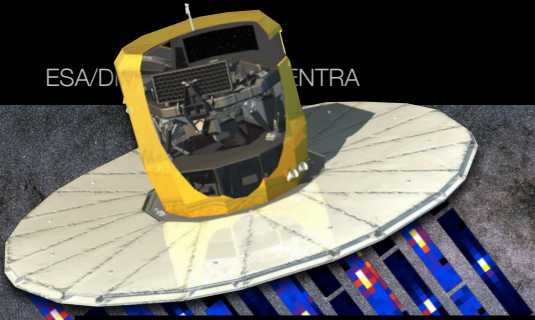
- 10^8 simulated GLs composed of four components (ABCD)
- + all combinations of three components (ABC, ABD, ACD, BCD)
- 10^8 configurations of random fluxes/positions



**including errors: Gaia DR2 + model misspecification
(train with a biased set!)**

How to detect Strongly Lensed Quasars?

ESA/D... ENTRA



How to detect Strongly Lensed Quasars?

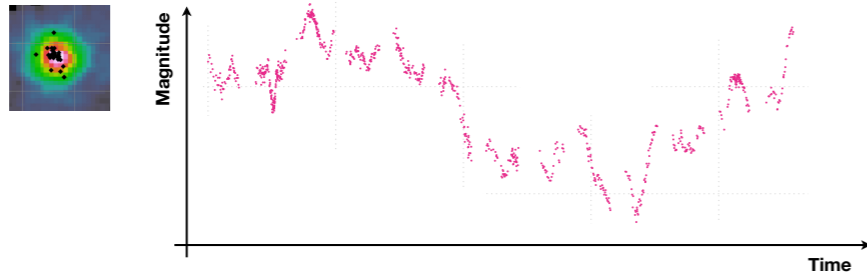
Astrometry + Single epoch photometry

Astrometry + Unresolved time-series

Astrometry + Imaging

How to detect Strongly Lensed Quasars?

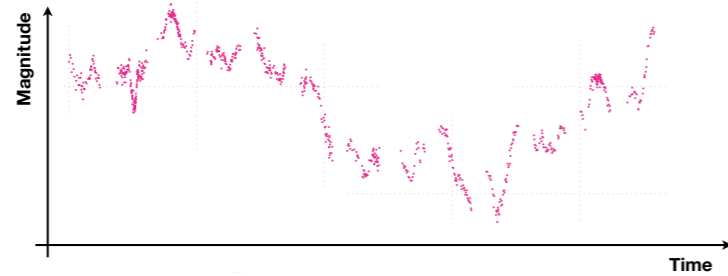
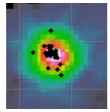
non-lensed QSO



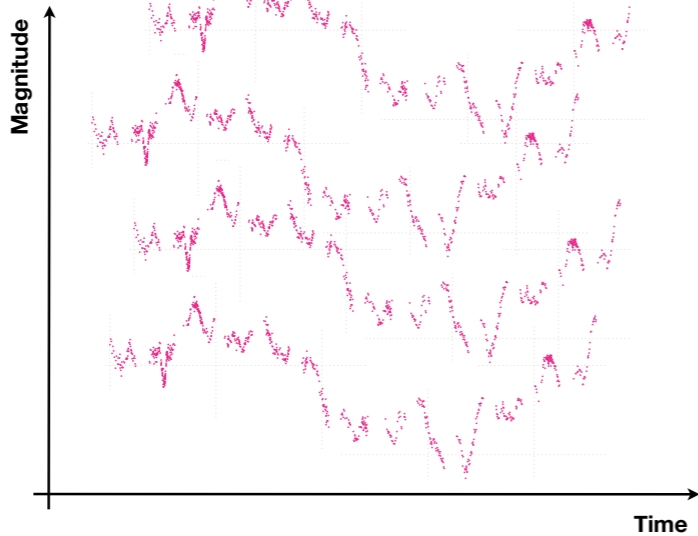
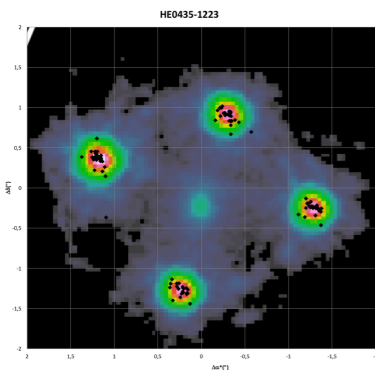
* real Gaia raw and HST data, mock lightcurve (from Courbin et al)

How to detect Strongly Lensed Quasars?

non-lensed QSO



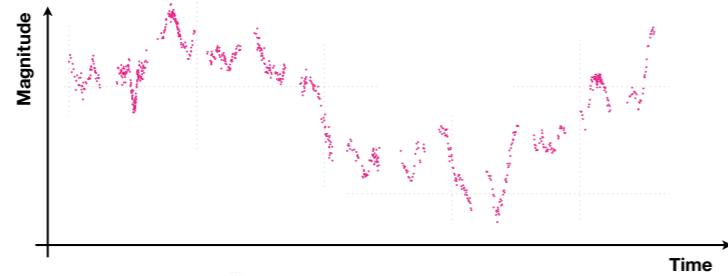
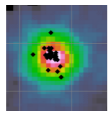
lensed and resolved QSO



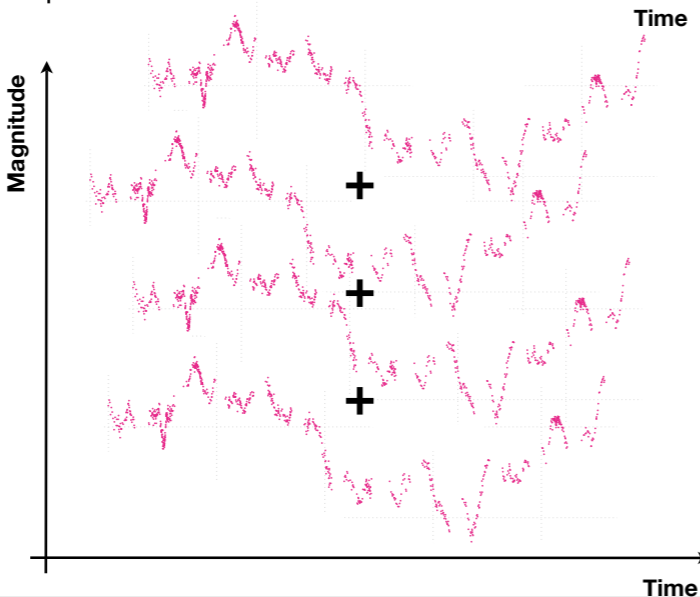
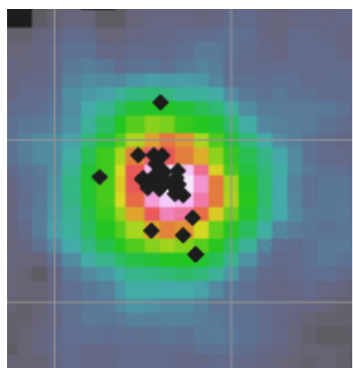
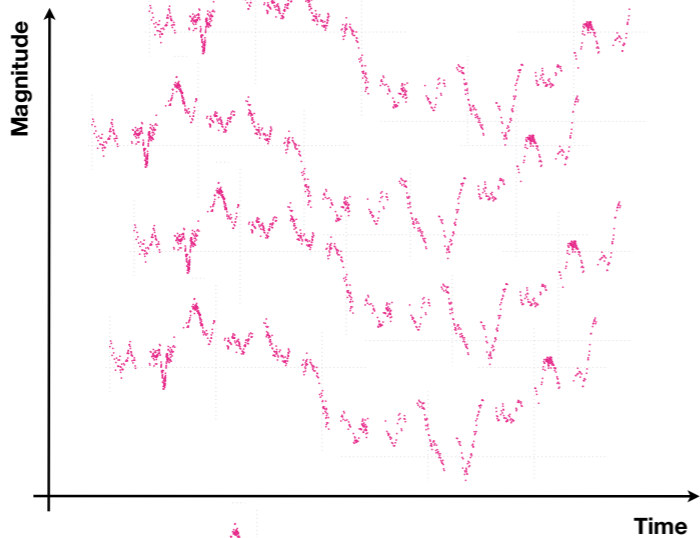
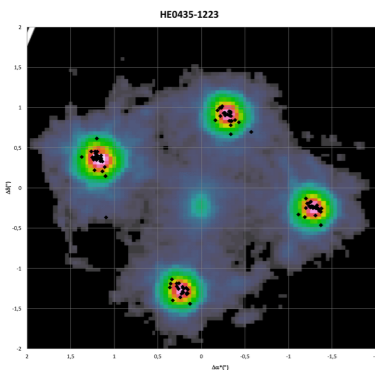
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non-lensed QSO



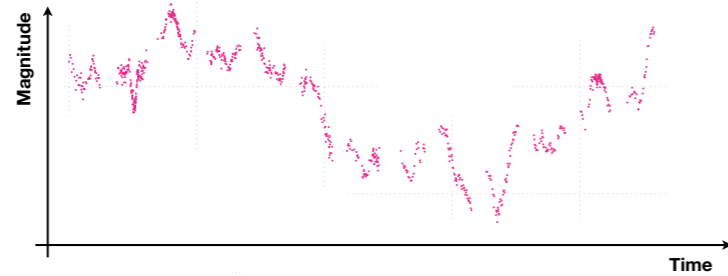
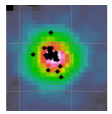
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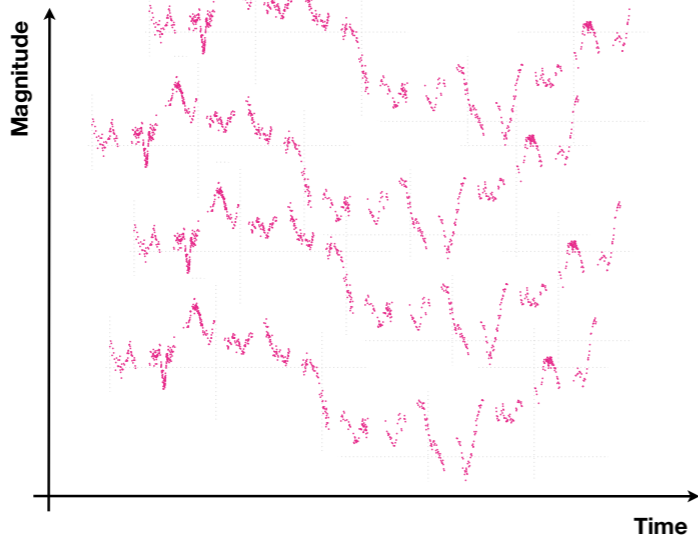
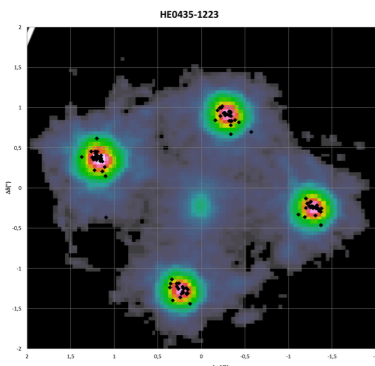
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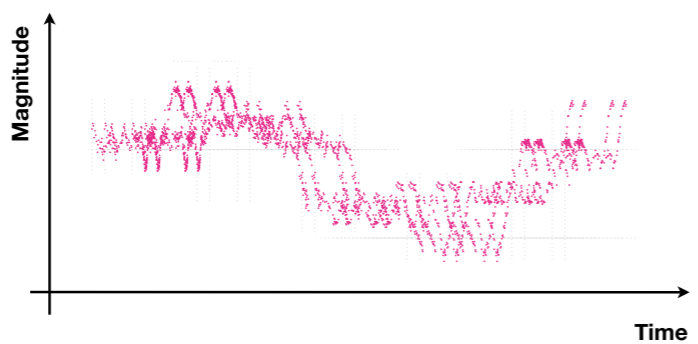
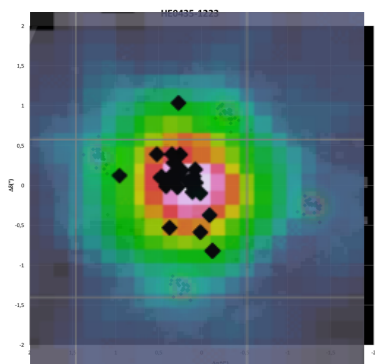
non-lensed QSO



lensed and resolved QSO



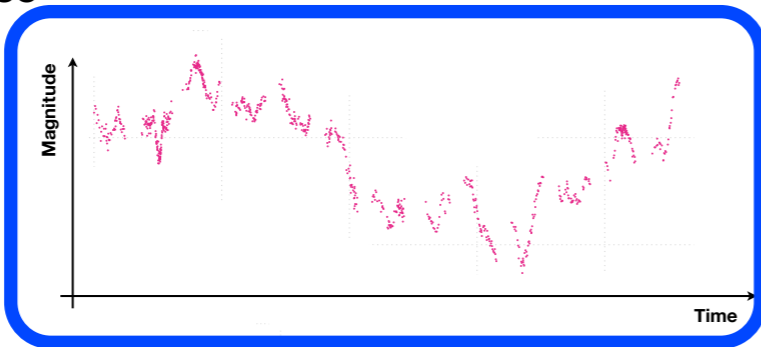
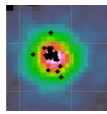
lensed and unresolved QSO



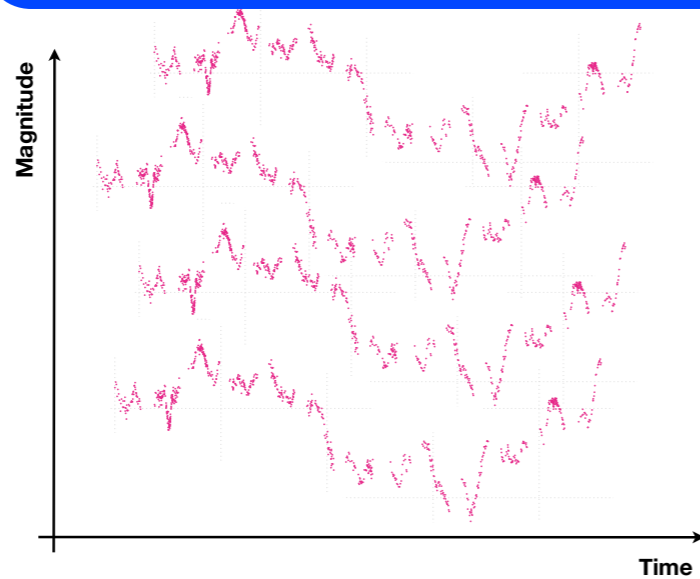
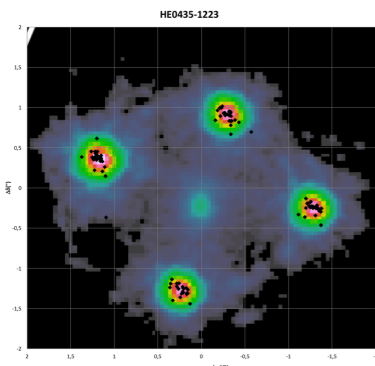
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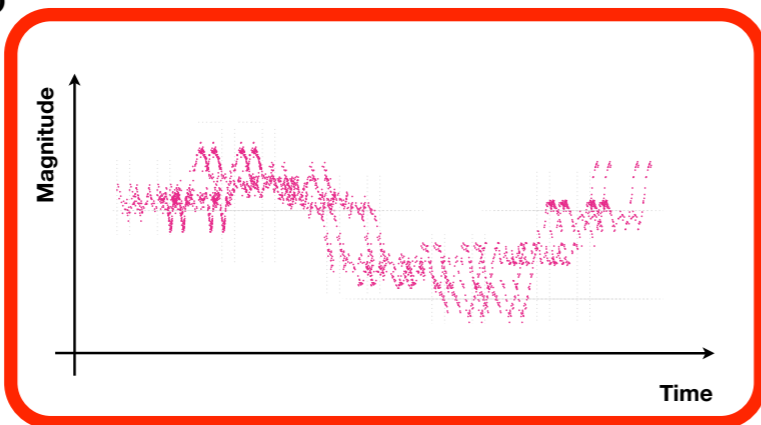
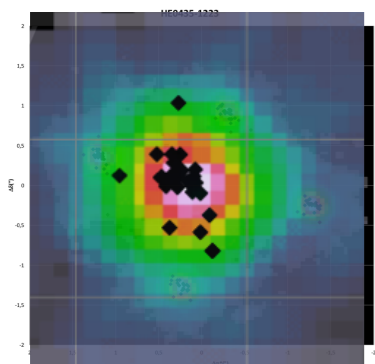
non-lensed QSO



lensed and resolved QSO



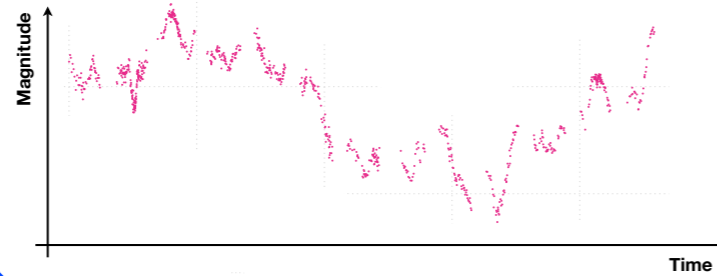
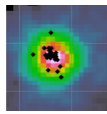
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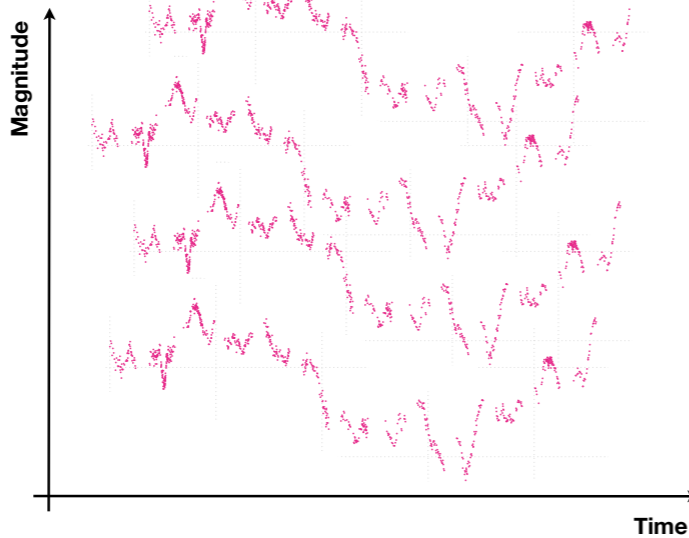
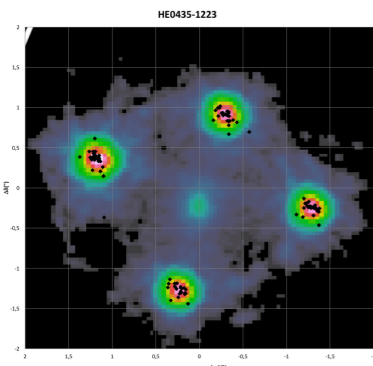
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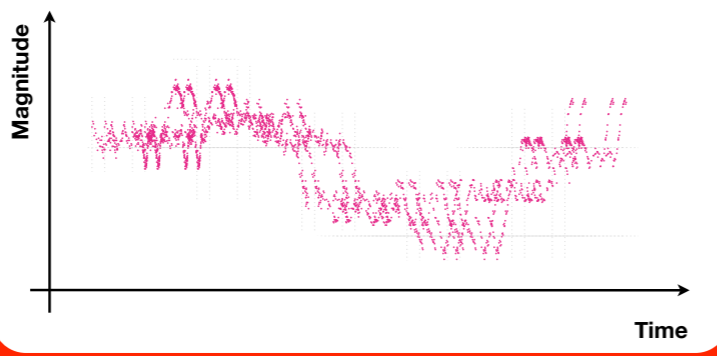
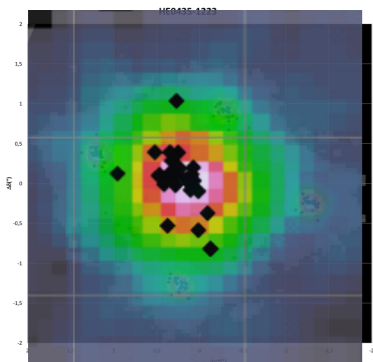
non-lensed QSO



lensed and resolved QSO



lensed and unresolved QSO



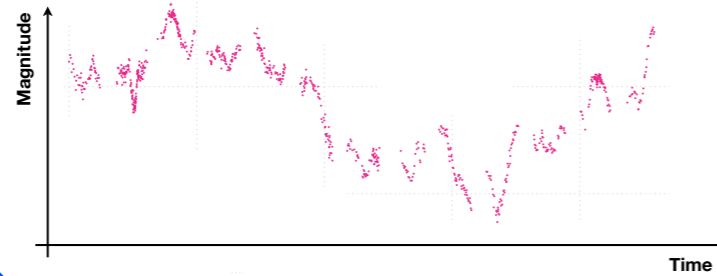
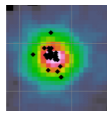
Principle

The **stochasticity** of non-lensed QSOs should be **higher** than the **stochasticity** of lensed, **but unresolved**, QSOs.

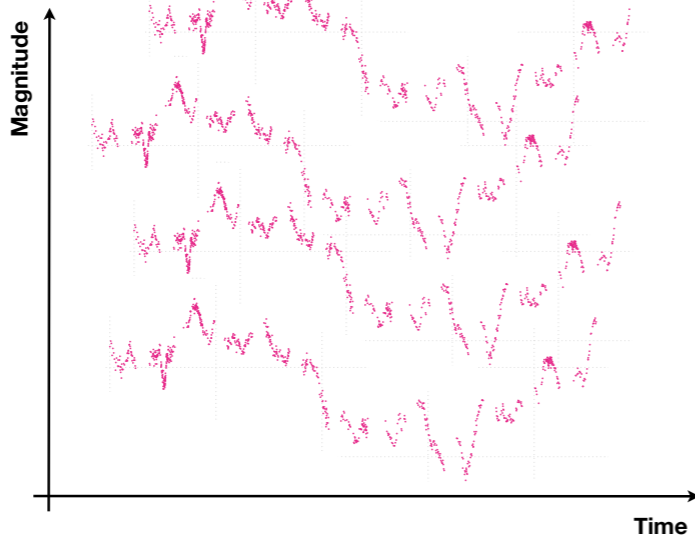
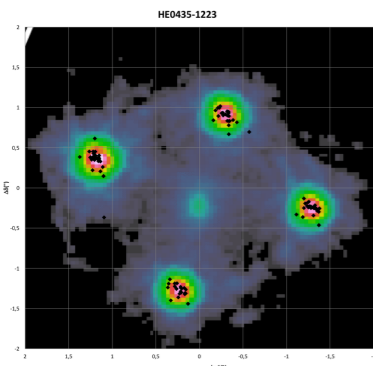
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How to detect Strongly Lensed Quasars?

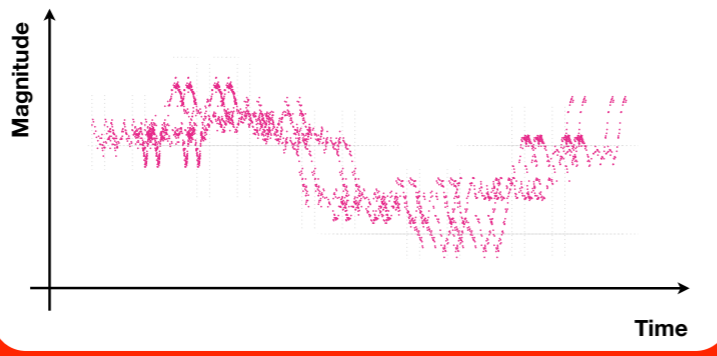
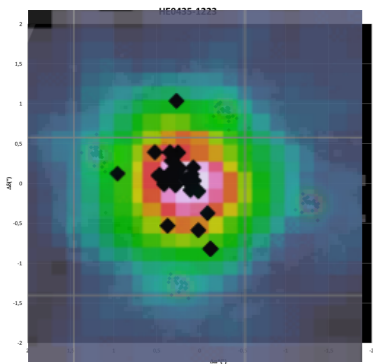
non-lensed QSO



lensed and resolved QSO

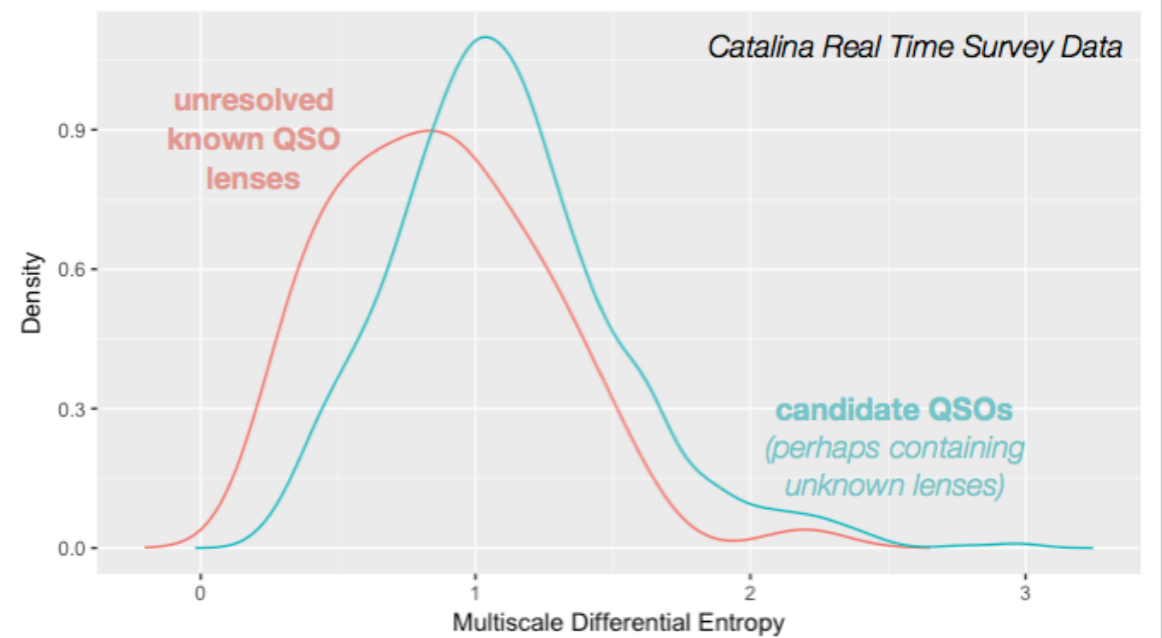


lensed and unresolved QSO



Principle

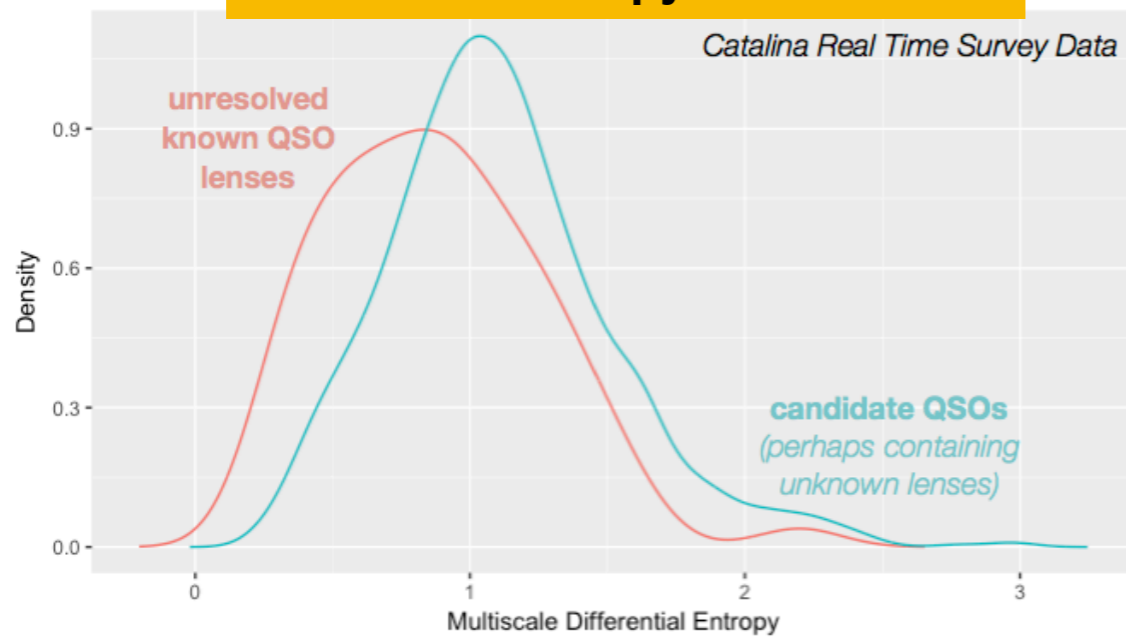
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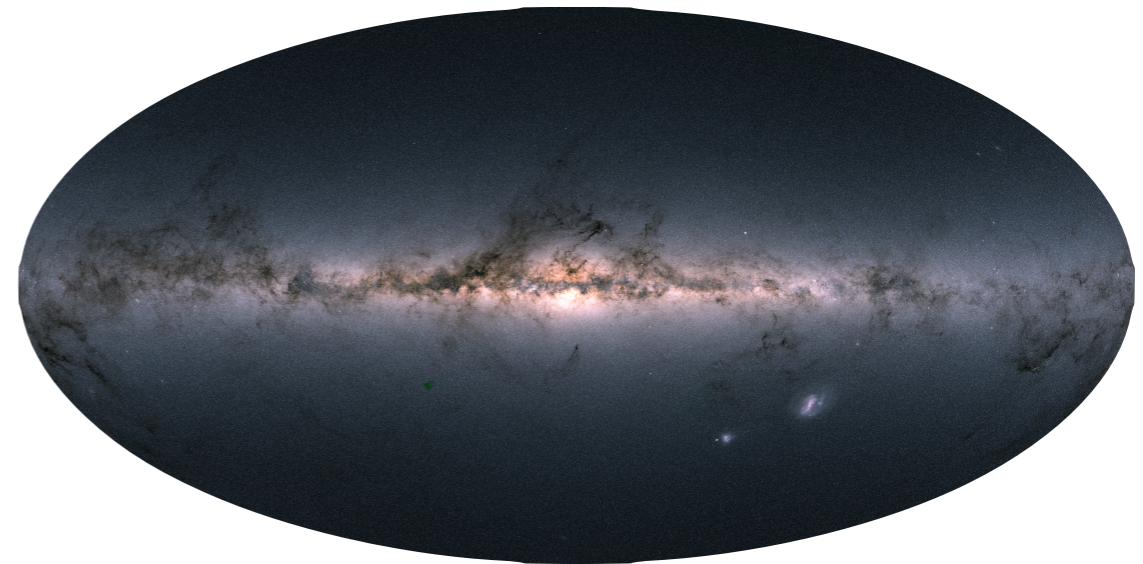
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How to detect Strongly Lensed Quasars?

Unresolved entropy measurement



Resolved astrometry and photometry



Not a lens

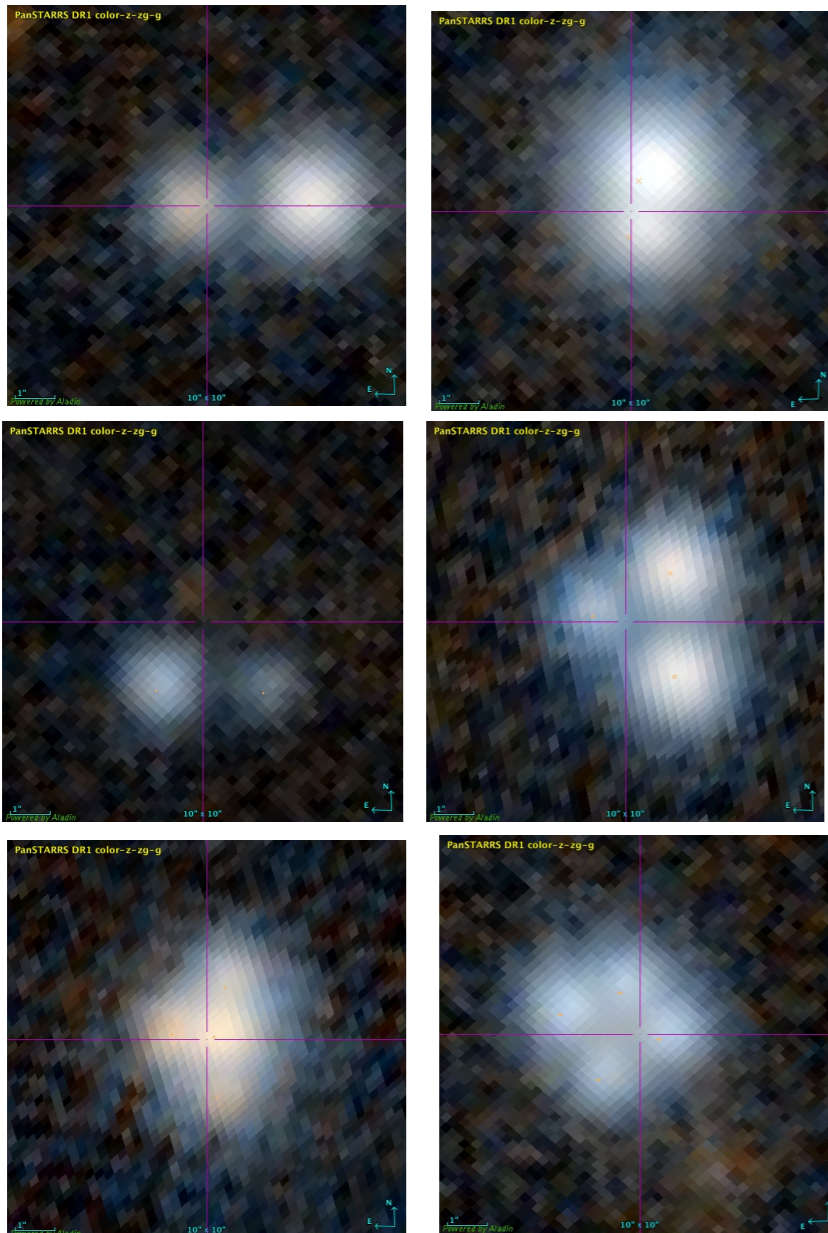
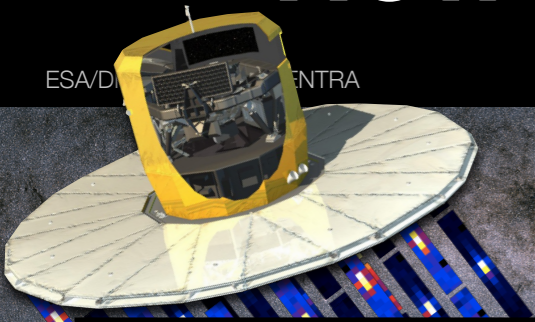
SVM + RBF kernel
grid + GPe hyperparameter optimization

Candidate

* real Gaia raw and HST data, mock lightcurve (from Courbin et al)

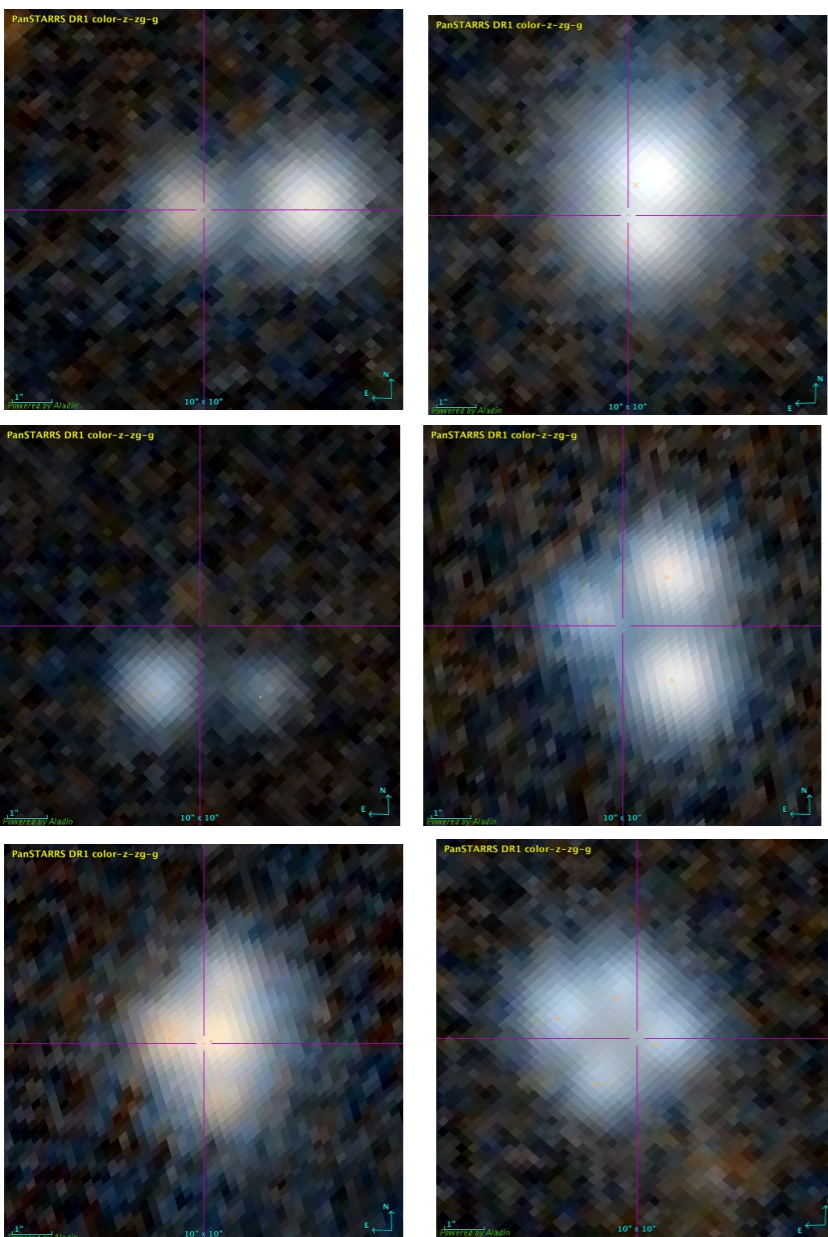
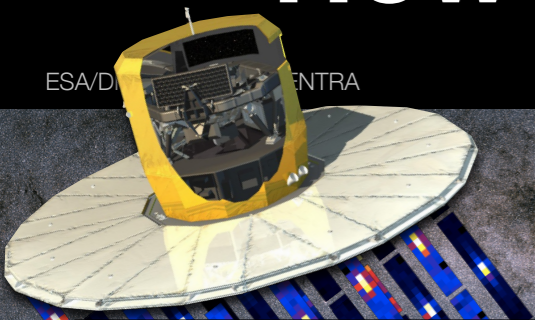
How to detect Strongly Lensed Quasars?

ESA/D... ENTRA

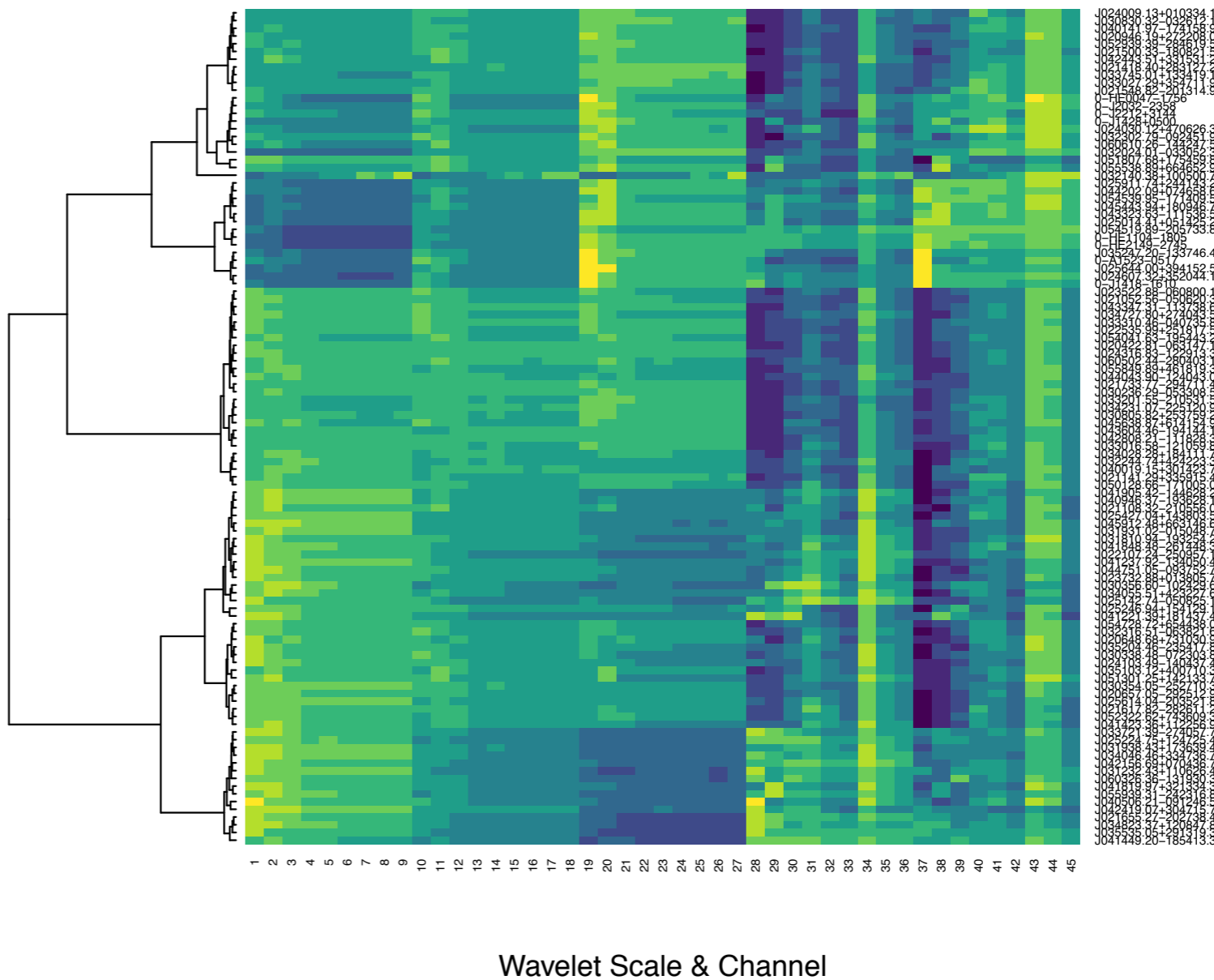


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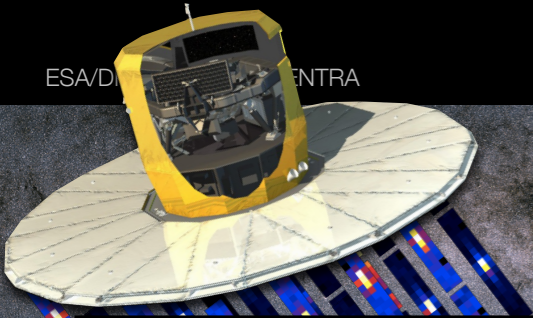


Total power per scale



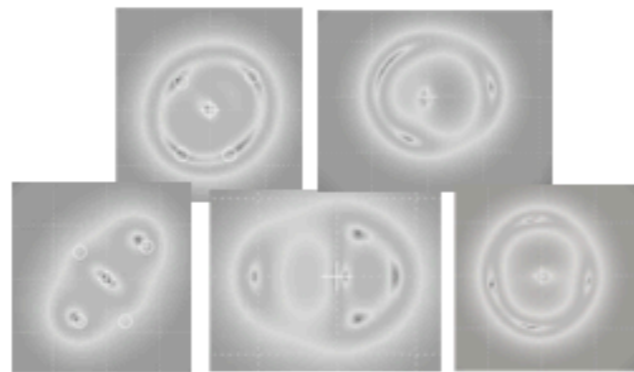
How to detect Strongly Lensed Quasars?

ESA/D... ENTRA



Lens candidate selection

Astrometric + photometric patterns + ERTs



Astrometry + lower lightcurve entropy + SVM

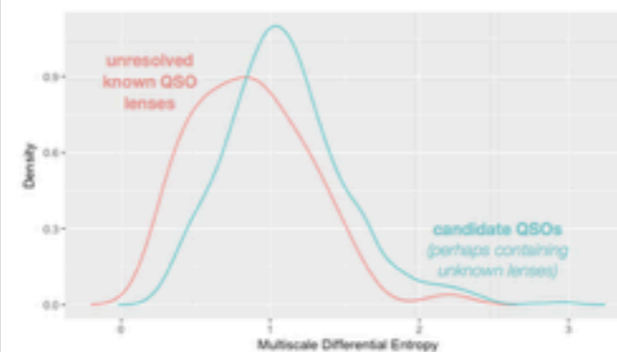
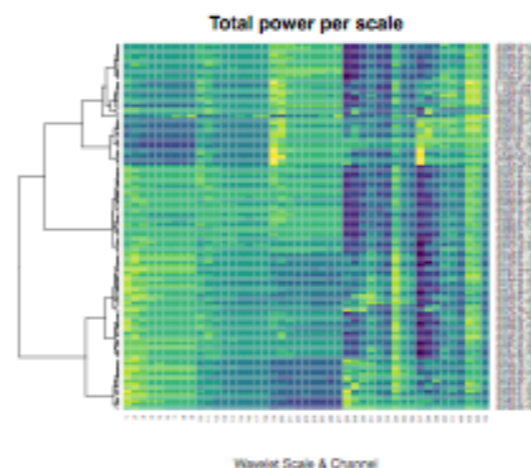
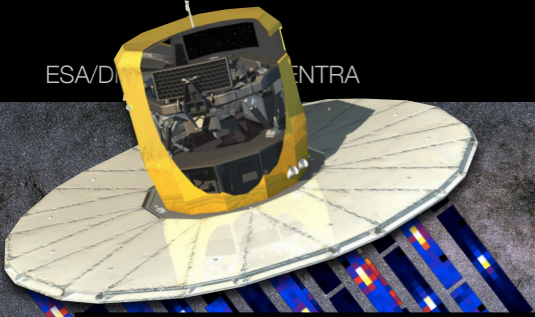


Image wavelet power spectrum signatures + hierarchical clustering
+Astrometry



How to detect Strongly Lensed Quasars?

ESA/D... ENTRA



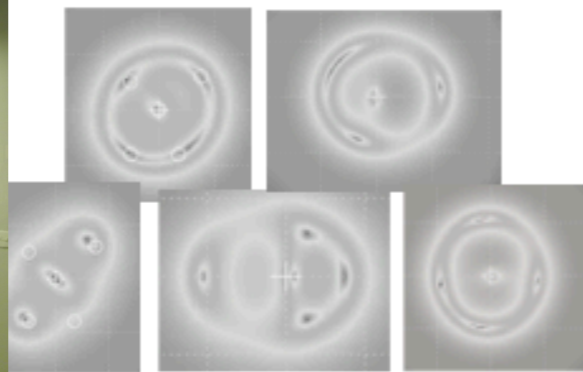
ESA CDN



48 cores
1TB RAM
2TB PCI-X SSD

Lens candidate selection

Astrometric + photometric
patterns + ERTs



Astrometry +
lower lightcurve entropy
+ SVM

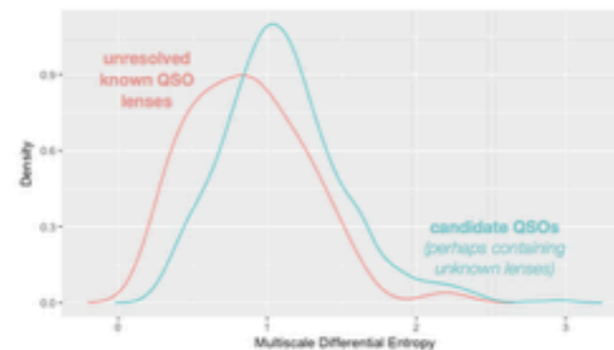
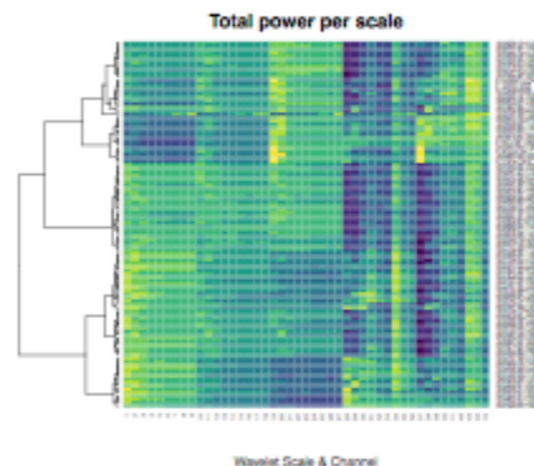


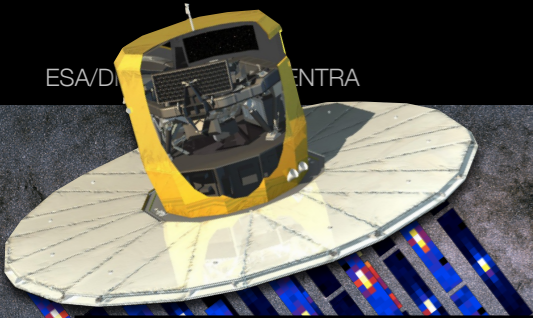
Image wavelet
power spectrum
signatures +
hierarchical
clustering

+Astrometry



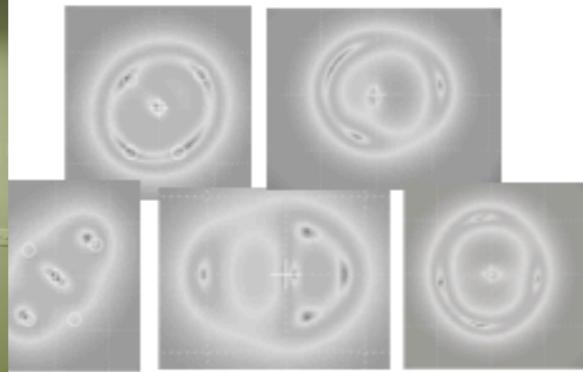
How to detect Strongly Lensed Quasars?

ESA/D... ENTRA



Lens candidate selection

Astrometric + photometric patterns + ERTs



Astrometry + lower lightcurve entropy + SVM

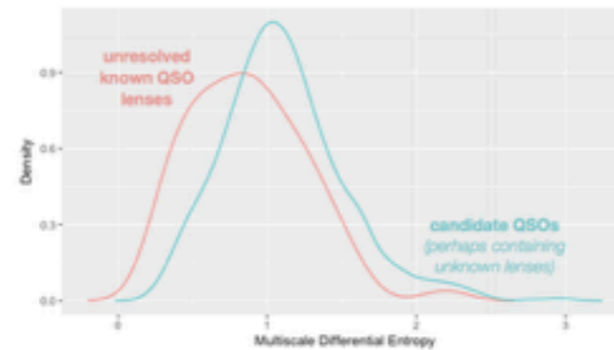
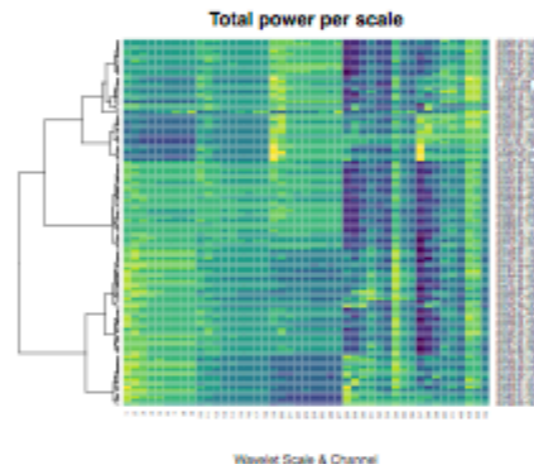
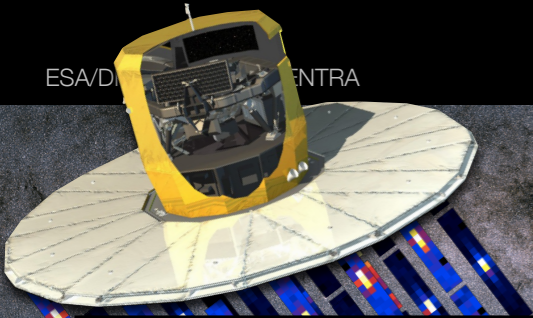


Image wavelet power spectrum signatures + hierarchical clustering + Astrometry



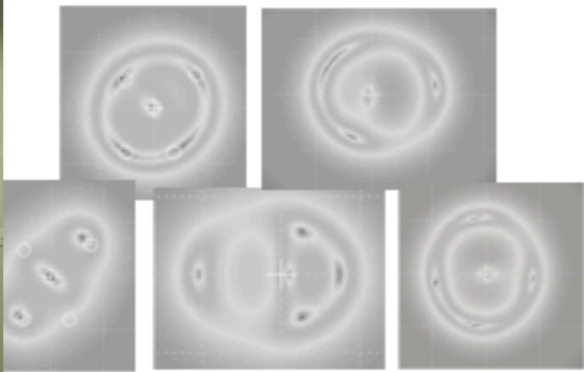
How to detect Strongly Lensed Quasars?

ESA/D... ENTRA

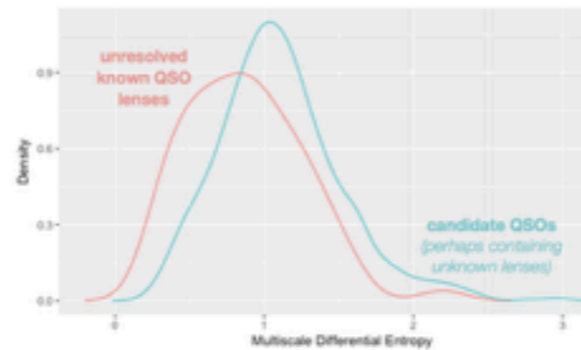


Lens candidate selection

Astrometric + photometric patterns + ERTs



Astrometry + lower lightcurve entropy + SVM



Candidates

Lens spectroscopic confirmation

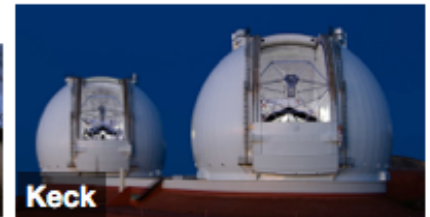
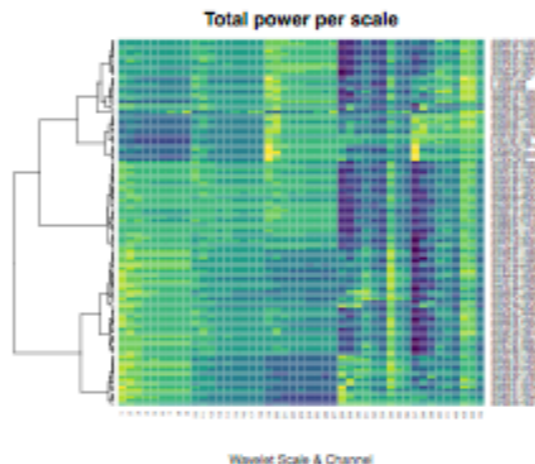
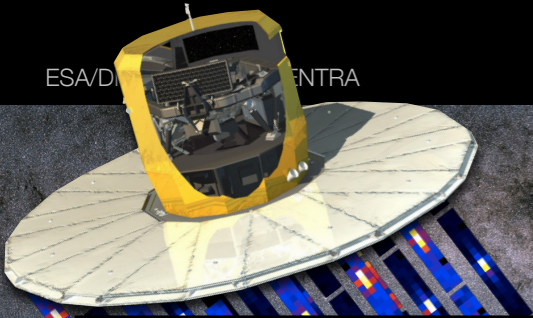


Image wavelet power spectrum signatures + hierarchical clustering + Astrometry



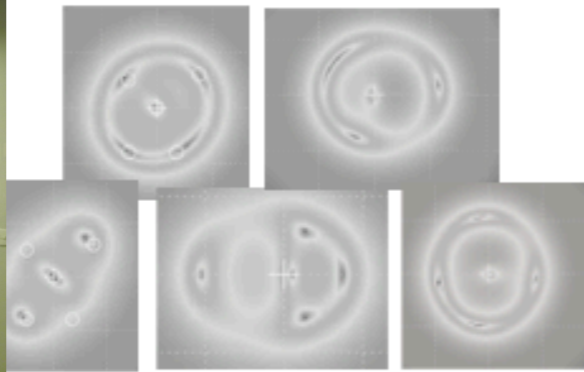
How to detect Strongly Lensed Quasars?

ESA/D... ENTRA

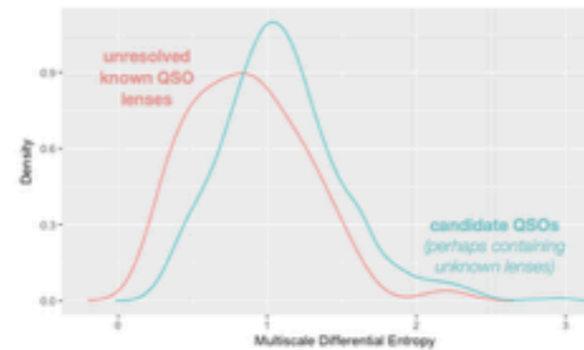


Lens candidate selection

Astrometric + photometric patterns + ERTs



Astrometry + lower lightcurve entropy + SVM

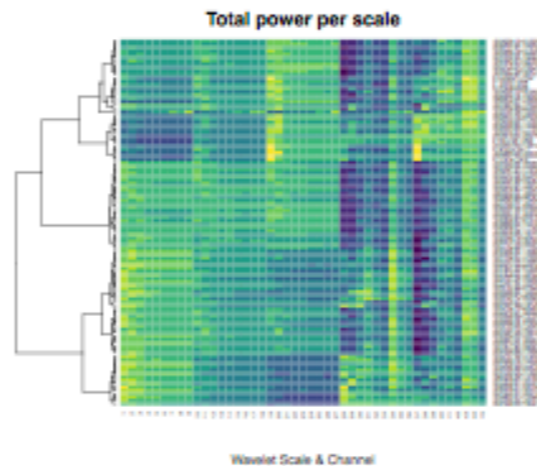


Candidates

Lens spectroscopic confirmation



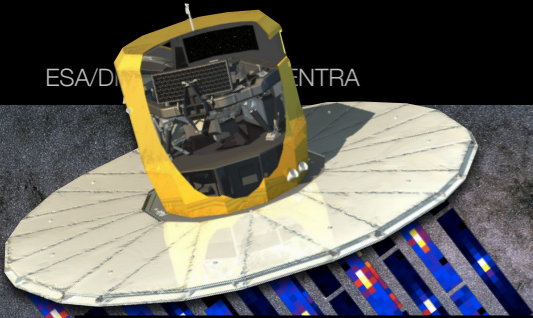
Image wavelet power spectrum signatures + hierarchical clustering + Astrometry



Results

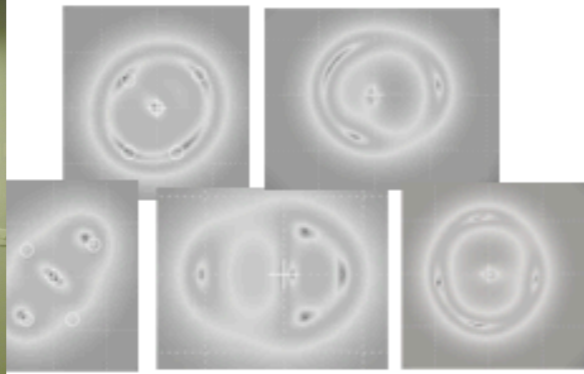
How to detect Strongly Lensed Quasars?

ESA/D... ENTRA

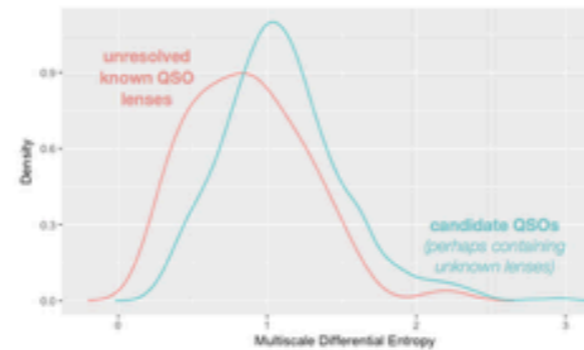


Lens candidate selection

Astrometric + photometric patterns + ERTs

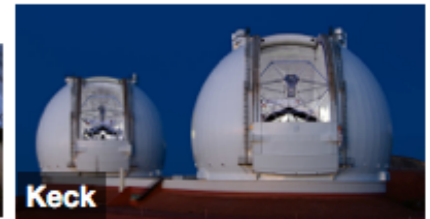


Astrometry + lower lightcurve entropy + SVM



Candidates

Lens spectroscopic confirmation



Results

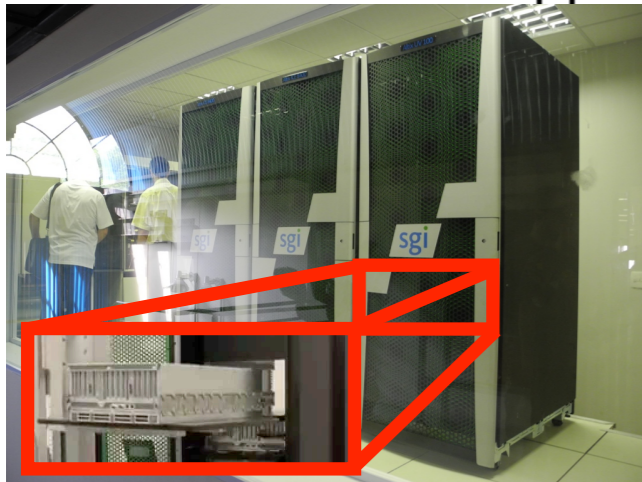
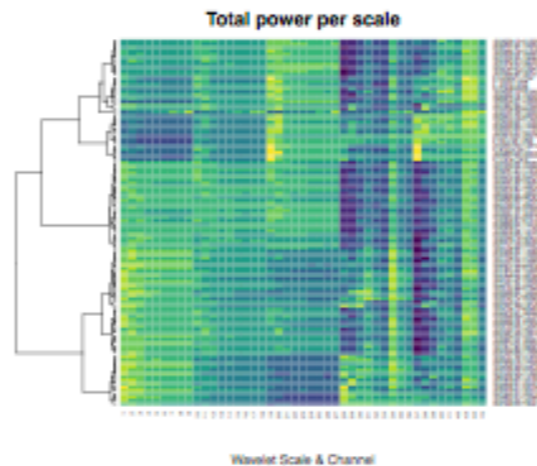


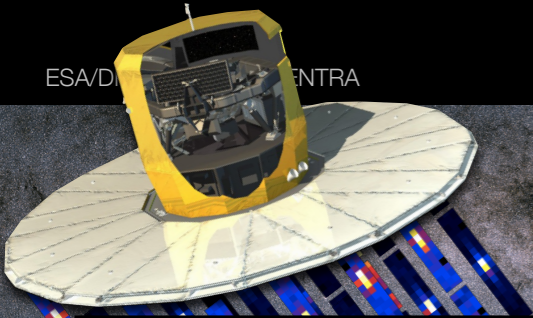
Image wavelet power spectrum signatures + hierarchical clustering + Astrometry



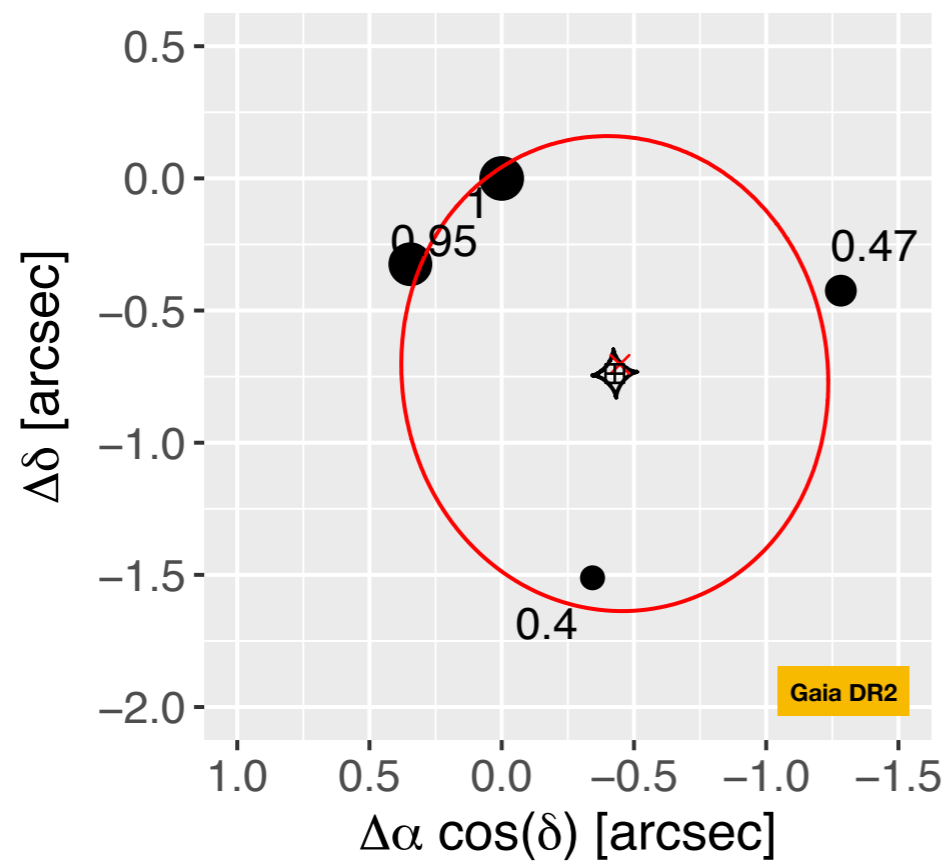
Exporting an Agile Software Engineering methodology approach to doing Science...

How to detect Strongly Lensed Quasars?

ESA/D... ENTRA



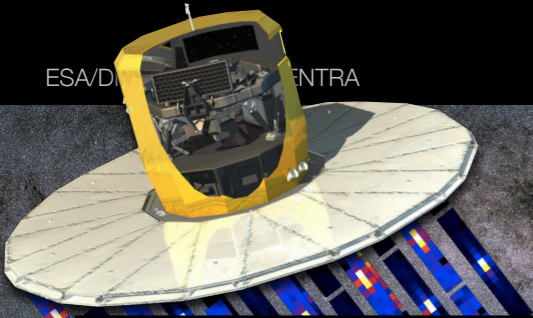
GRALJ1131-4419 : The first lens discovered from astrometry alone?



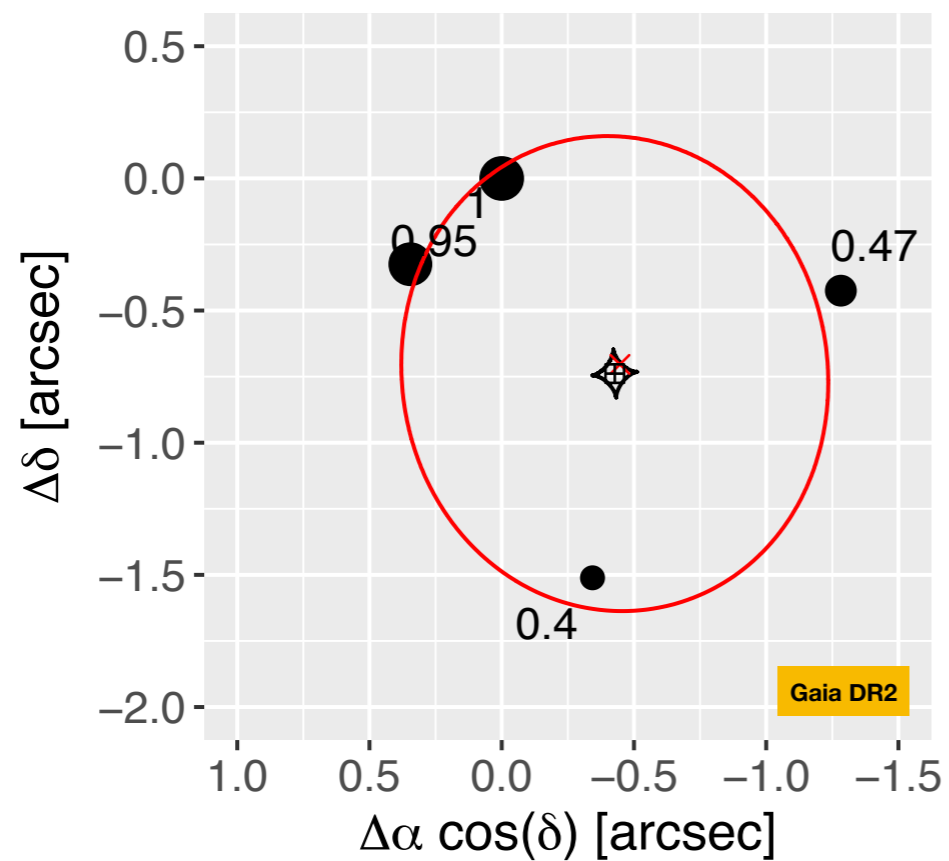
Keck

How to detect Strongly Lensed Quasars?

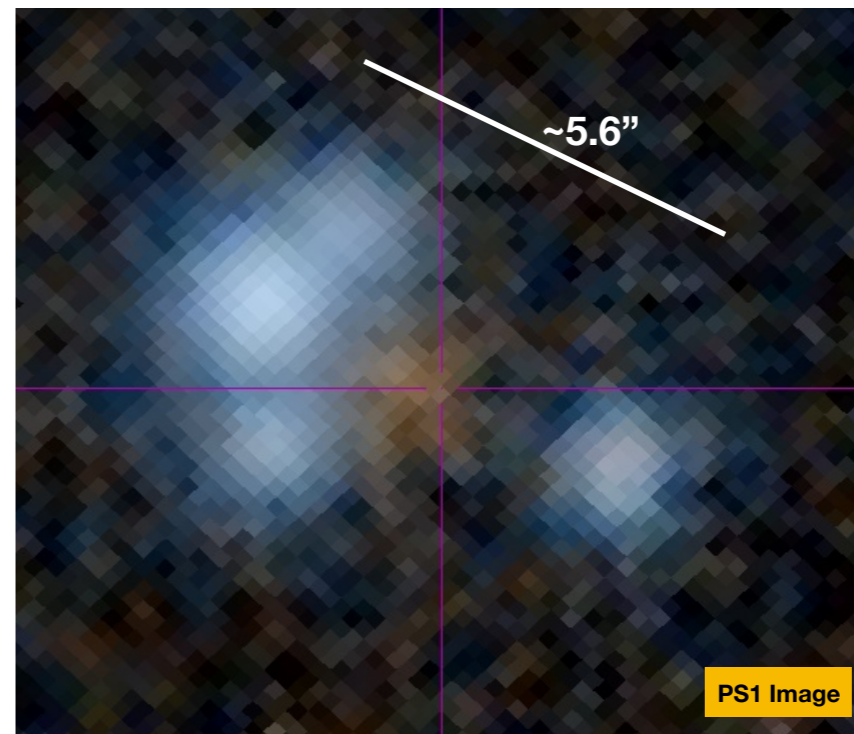
ESA/D... ENTRA



GRALJ1131-4419 : The first lens discovered from astrometry alone?



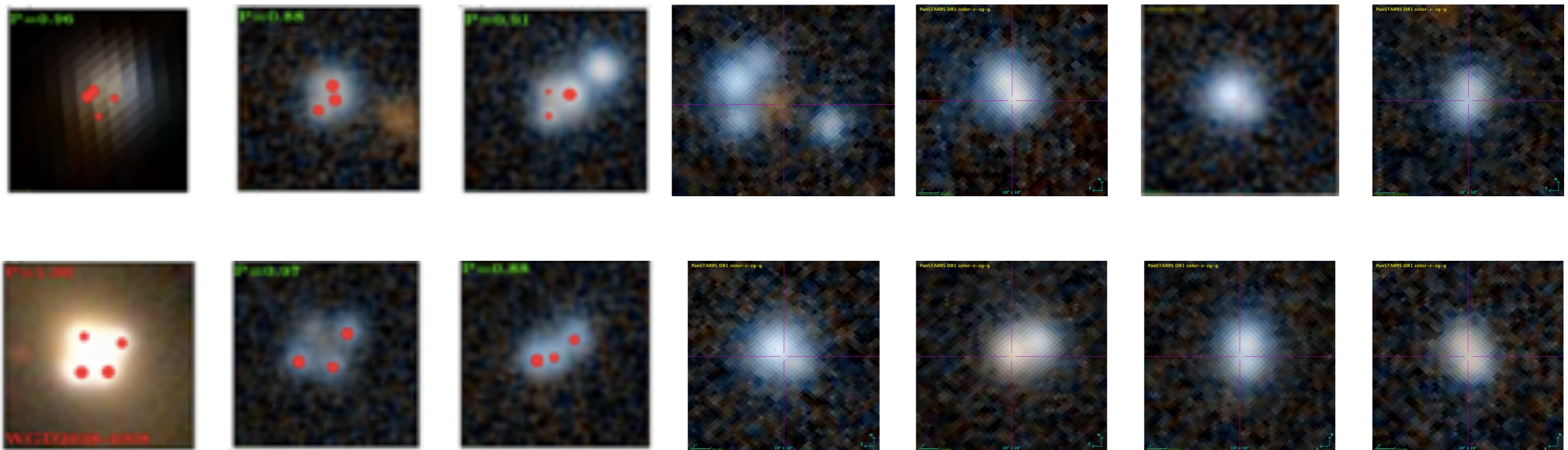
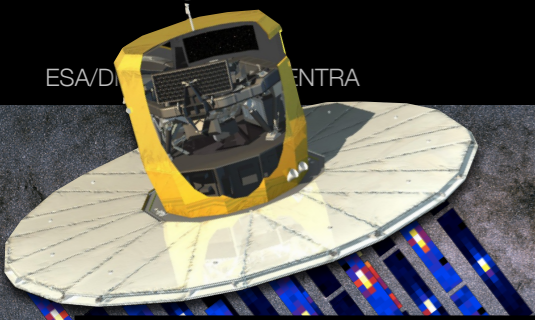
GRALJ0659+1629 : The Orion Crossbow



Keck

GraL confirmed lenses: May/2018 – April/2019

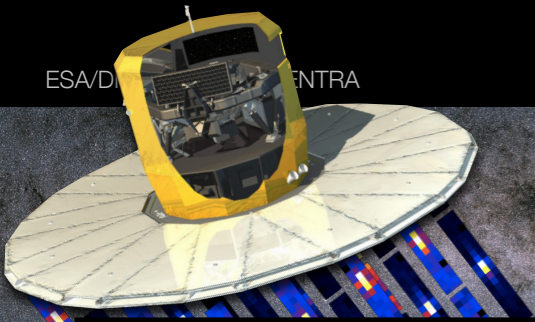
ESA/DG RSCG/INTRA



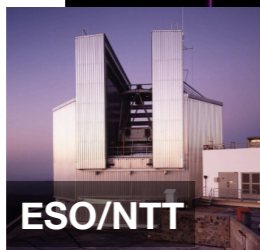
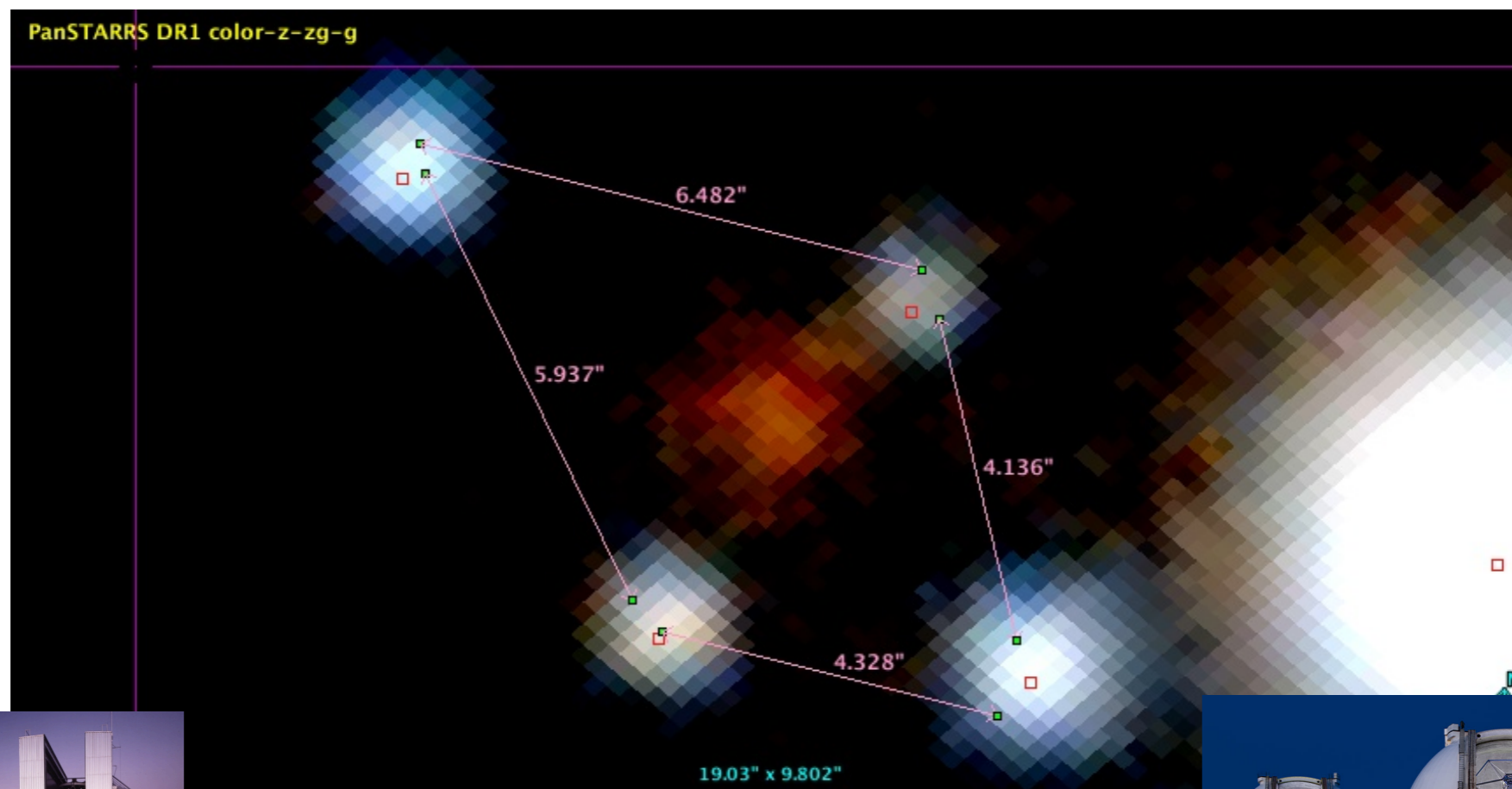
Many more are arriving...

A new beast...

ESA/D... ENTRA



The Arrow



Thank you!

Why Strongly Lensed Quasars?

How are we detecting Strongly Lensed Quasars?

References

- Krone-Martins, A. et al., in prep
- Stern, D. et al., in prep
- Wertz, O.; Stern, D.; Krone-Martins, A. et al., A&A accepted.
- 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.