GRAVITATIONAL LENSES IN GAIA

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ORIGINS OF THE PROJECT

Firenze - CU4 meeting - 2013
Gaia observes many extragalactic objects (1 M Galaxies + 0.5 M QSOs)

Although designed for the Milky Way content, it is the first all-sky survey from space of gravitational lenses (GL) with the acuity of unprecedented resolving power!
Gravitational Lenses in Gaia

H1413+117
From Ground (SDSS9)

H1413+117
From space (HST)

Credit: Castles database, HST images
Gravitational Lenses in Gaia

- Depending on deflecting galaxy population *100 - ~1000 lensed quasars in Gaia*
- Most cases: 2 images, few 3 or 4 images, no arc!
- ~100 known today

➡ Counts will bring independent constraints on cosmological parameters $H_0, \Omega_0, \lambda_0$, mass distribution of the galaxy lenses…
Detection of lenses, how?

Specific (Δmag, Δpos) ——— Specific patterns

Same colour/spectra

Krone-Martins 2017

Inada 2003
1 - Look for known lenses

Updated Database
DRI + Gaia observations (IDT/IDU)

2 - Search around known quasars

Automatic search for optical projections around quasars

3 - Blind search in Gaia DR1

Search for lens configurations in DR1 ($\Delta$mag, $\Delta$pos)
Modeling of the detected candidate lenses
1 - Known Lenses : a new database

- **Castles** ([https://www.cfa.harvard.edu/castles/](https://www.cfa.harvard.edu/castles/)),
  - HST images (same resolution as Gaia), 100 lenses + 18 bin quasars (<2006)
- **SQLS** ([http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls/lens.html](http://www-utap.phys.s.u-tokyo.ac.jp/~sdss/sqls/lens.html))
  - SDSS, 49 additional lenses (<2012) → unresolved and resolved multi images
- **SDSS - III BOSS quasar lens survey**
  - 13 lensed quasars (2 images) + 11 quasar pairs
- **others** (BELLS, DES, CASSOWARY,…)

<table>
<thead>
<tr>
<th>276 lenses/candidates</th>
<th>165 - with 1 component</th>
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<tbody>
<tr>
<td></td>
<td>90 - with 2 components</td>
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<tr>
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<td>20 - with &gt;= 3 components</td>
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Heterogeneous database with sometimes poor astrometry
Sky coverage and detection

Database

Galactic
Sky coverage and detection

Database

DR1
Sky coverage and detection
Many more in DR2 !!!!
G magnitude

Database : 276 lenses
Detection : 147
(not all components)
• 79 partially in DR1
• 68 only in IDT

• Reliable astrometry
• Expect many more in DR2
2 - Automatic search around known quasars

➡ LQAC3 : Large Quasar Astrometric Catalogue  
(Souchay et al. 2015)  
• 322 000 entries (Quasars, 14 000 AGNs, 1200 BL Lac)
Mining and clustering Gaia observations

1 - Extraction of LQAC3 Quasars observations
- Explore 30 billions of Gaia transits
- 4.2 millions match with a LQAC source (< 3")

- 250,000 quasars detected (217 000 with 5+ observations)

2 - Clustering analysis
- identify groups of points in the area (rad=3") = sources
- identify cluster of sources (incl. quasar)

- unique source, no outlier, clustered 175,000 80%
- unique source, < 20% outliers 32,000 15%
- anomalous observations, large scatter ~ 2000

- 2 point sources ~ 1300
- 3 sources ~ 70
- >= 4 point sources or images 10
4 images configurations

\[
\Delta \delta \text{(mas)} \quad \Delta \alpha^* \text{(mas)}
\]

\[
\Delta \delta \text{(mas)} \quad \Delta \alpha^* \text{(mas)}
\]
4 images configurations

• Quasars + host galaxy

\[ \Delta \delta \text{ (mas)} \]

\[ \Delta \alpha^* \text{ (mas)} \]

HSWFI2033-4723

RXJ1131-1231
Others 4 images configurations

- Good Candidates:
  - 29 (3 or 4 components, <4”)
  - 39 (2 components, <1” high galactic latitude)

- Necessity to validate the new candidates with:
  1. Gaia photometry
  2. Lens modelling

→ Wait for DR2
3 - Automatic blind Detection in Gaia DR1

**SELenA : Systematic Exploration of Lenses from Astrometry**

- An “intelligent” and adaptable framework (kd-trees + machine learning based classifier + lens direct model) for searching lenses in **astrometric** catalogues.
- Can consider *additional* constrains: *photometry, spectroscopy, time-series*, ...

- Gaia DR1 = 1.5 G sources
- Processing time huge = 197 days in a single core ~4 days in 48 cores (*not including lens system modelling!*)

Dedicated UV30 machine in São Paulo (Gaia DR1 in memory + SSD disks)
SELenA method

Source Catalogue

Tree from similarity in (RA, Dec) space

Leaf similarity check in other param. spaces (Gmag, color, pm)

Not a lens

No

yes
SELenA method

Source Catalogue → Tree from similarity in (RA, Dec) space → Leaf similarity check in other param. spaces (Gmag, color, pm) → semi supervised Lens classifier

If not a lens, then No

If yes, then Yes

If not a lens, then No

If yes, then Yes
SELenA method

Source Catalogue → Tree from similarity in (RA, Dec) space → Leaf similarity check in other param. spaces (Gmag, color, pm)

· Not a lens (No)

Lens modelling

· converged? (Yes)

· semi-supervised Lens classifier (Yes)

Strong candidate (Yes)

· converged? (No)

Candidate lens (No)

Not a lens (No)
Lens modelling: the problem to be solved

**Gaia data**

**Deflector**: axis ratio, major axis, Einstein radius (H0+Mass+redshift), pos. angle, shear terms (g, ang.)

**Background QSO**: ang.dist to lens pos.angle

But to do that, we need something that allow us to do the inverse!

**Gaia data**

**Deflector**: axis ratio, major axis, Einstein radius (H0+Mass+redshift), pos. angle, shear terms (g, ang.)

**Background QSO**: ang.dist to lens pos.angle
Lens modelling: the problem to be solved

- Forward model implemented in OpenCL (runs in CPU, GPU or FPGA): millions of lens configurations can be simulated per second.

Efficient sampling of the parameter space for the Bayesian inference process

Parameter inference

Gaia data
Preliminary Results on DR1

- **Automatic processing outside Galactic Plane** \((D_{\text{pos}} < 1.5'', D_{\text{mag}} < 1 \text{ mag})\)

| \(|b|\) cut   | Individuals  | 2-sources | 3-sources | 4-sources |
|------------|--------------|-----------|-----------|-----------|
| 50° to 55° | 6 546 674   | 10 905    | 139       | 0         |
| 55° to 60° | 5 284 145   | 9 351     | 126       | 0         |
| > 60°      | 13 233 625  | 35 199    | 621       | 13        |

- **No classifier and lens modelling yet !**
4 images candidates from DR1

Possible @QSO
Possible Galaxy
Possible StarCluster
Possible BrightStar

Around BrightStar
StarCluster
StarCluster
StarCluster
@QSO LQAC 195+037_013
StarCluster
Galaxy
Possible
Almost resolved Galaxy
StarCluster
Conclusion

- List of good candidates with 3 and 4 images from DR1.
- Proposal at the DOT (Devasthal Optical Telescope) 3.6m telescope (India) for a multi-photometry validation of DR1 candidates.
- We expect many more/complete configurations in DR2.