Data Mining and Gravitationally Lensed Quasars

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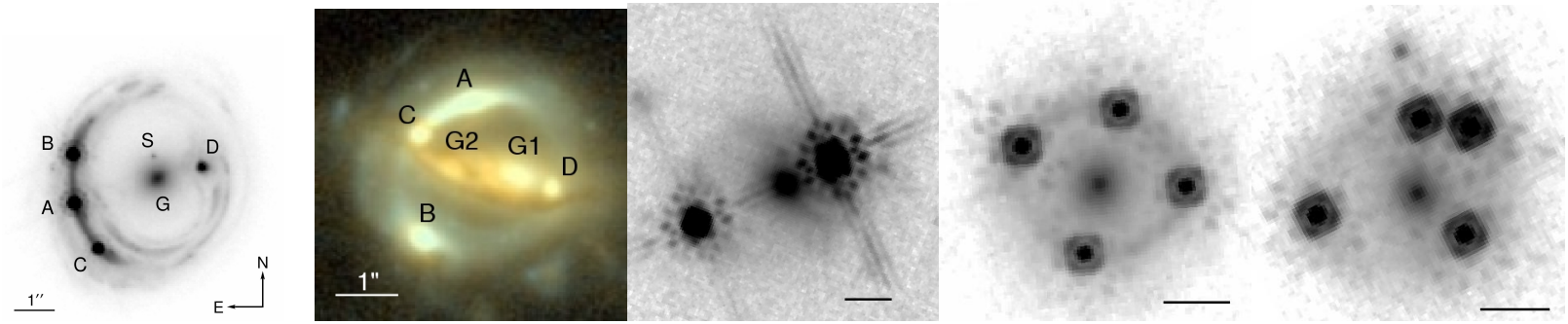
K-IPMU: Galaxies and Cosmology in Light of Strong Lensing

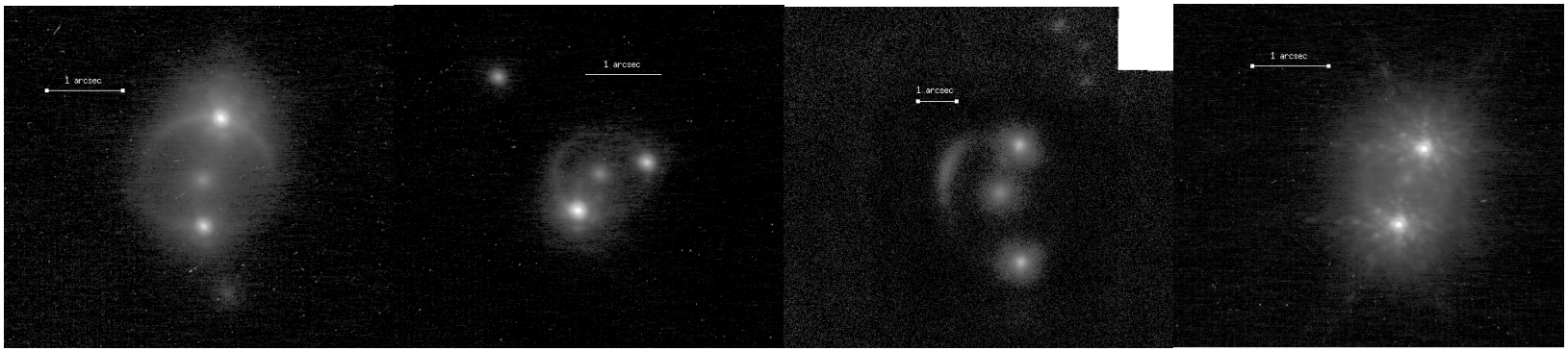
Why bother?

A few things that can be done with lensed quasars:

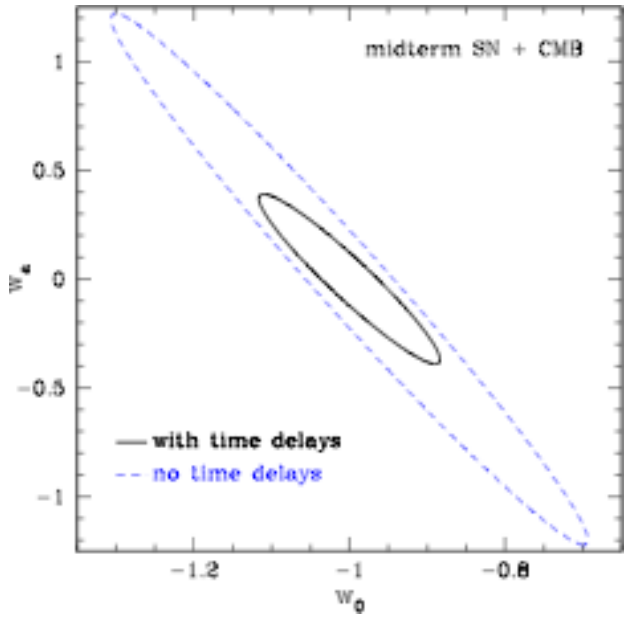
1. Do time-delay cosmography
2. Study properties of quasars and their hosts (cf Edi's talk)
3. Study massive galaxies, possibly as a population (Sonnenfeld & Marshall, in prep.)
4. Hints for substructure searches
5. ...

Systems currently being studied: 5 H0LiCOW + 4 Keck-AO



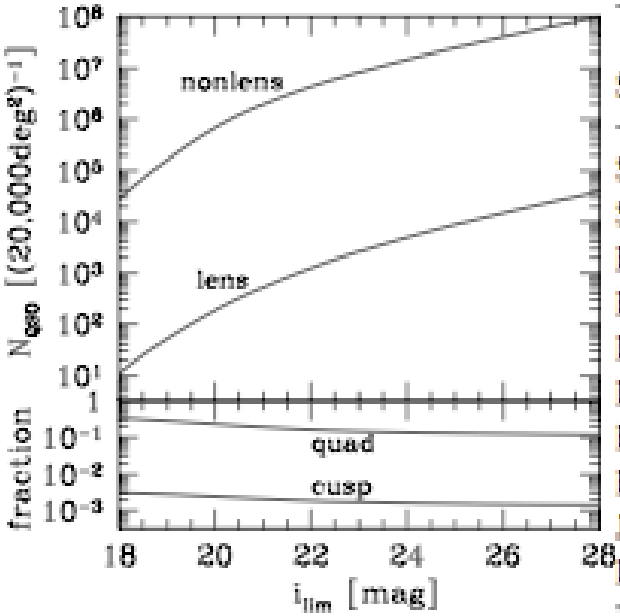


But how many systems do we need?



Linder (2011): When time-delay lensing data are exploited jointly with supernovae and CMB information, this enables the accurate measurement of the matter density Ω_m (to within 0.004), the Hubble constant h (to within 0.7%) and the variation of the dark energy equation of state w_a (to within 0.26). This requires a careful study of the systematics and a large enough sample of lenses.

How many systems do we expect? Oguri & Marshall (2010):

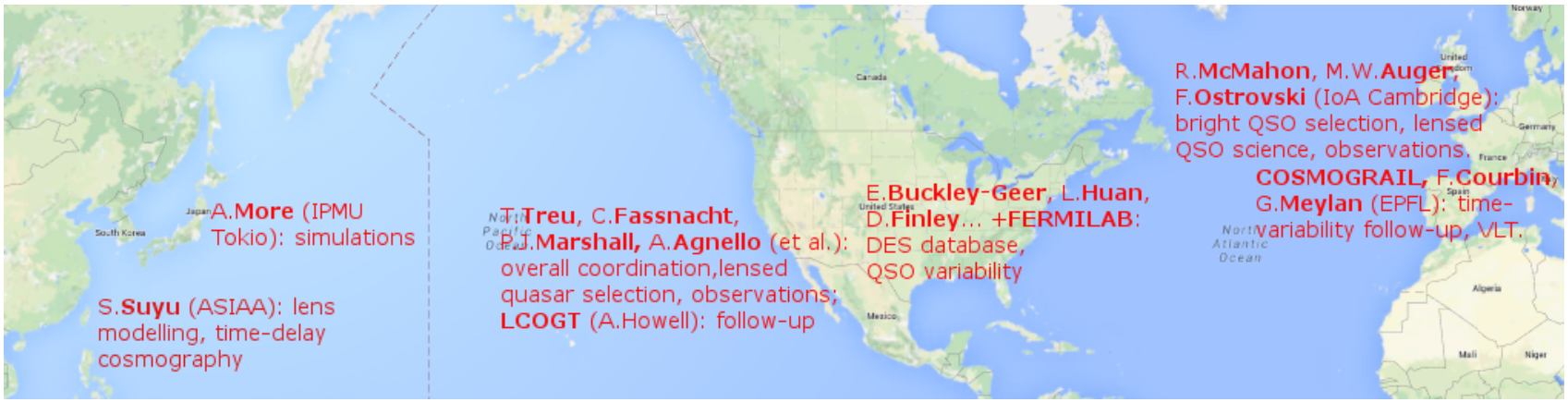


Survey	QSO (detected) $N_{non\text{-}lens}$	N_{lens}
SDSS-II	1.18×10^5	26.3 (15 per cent)
SNLS	9.23×10^3	3.2 (12 per cent)
PS1/3π	7.52×10^6	1963 (16 per cent)
PS1/MDS	9.55×10^4	30.3 (13 per cent)
DES/wide	3.68×10^6	1146 (14 per cent)
DES/deep	1.26×10^4	4.4 (12 per cent)
HSC/wide	1.76×10^6	614 (13 per cent)
HSC/deep	7.96×10^4	29.7 (12 per cent)
JDEM/SNAP	5.00×10^4	21.8 (12 per cent)
LSST	2.35×10^7	8191 (13 per cent)

[Simple extrapolations into GAIA:[1] expected $\approx 5 \times 10^5$ QSOs, of which ≈ 3000 strongly lensed.]

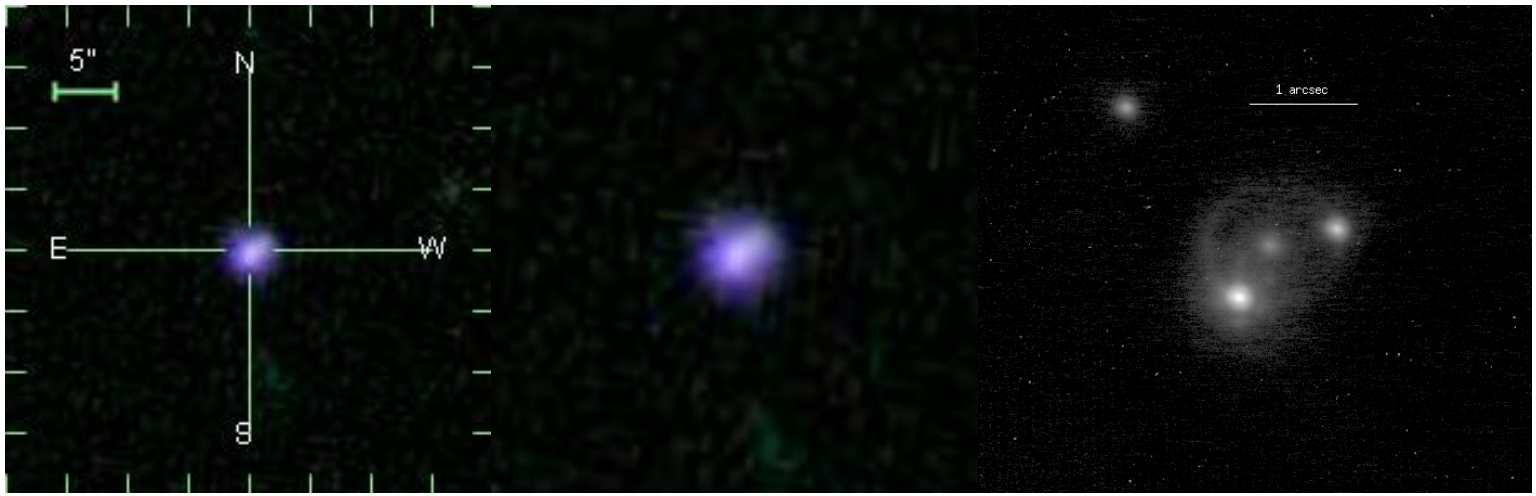
[1] Finet et al. (2012).

STRIDES: STRong lensing Insight into DES[2].
We expect $\approx 10^3$ lensed quasars in the DES footprint, ≈ 120 with $i < 21$.



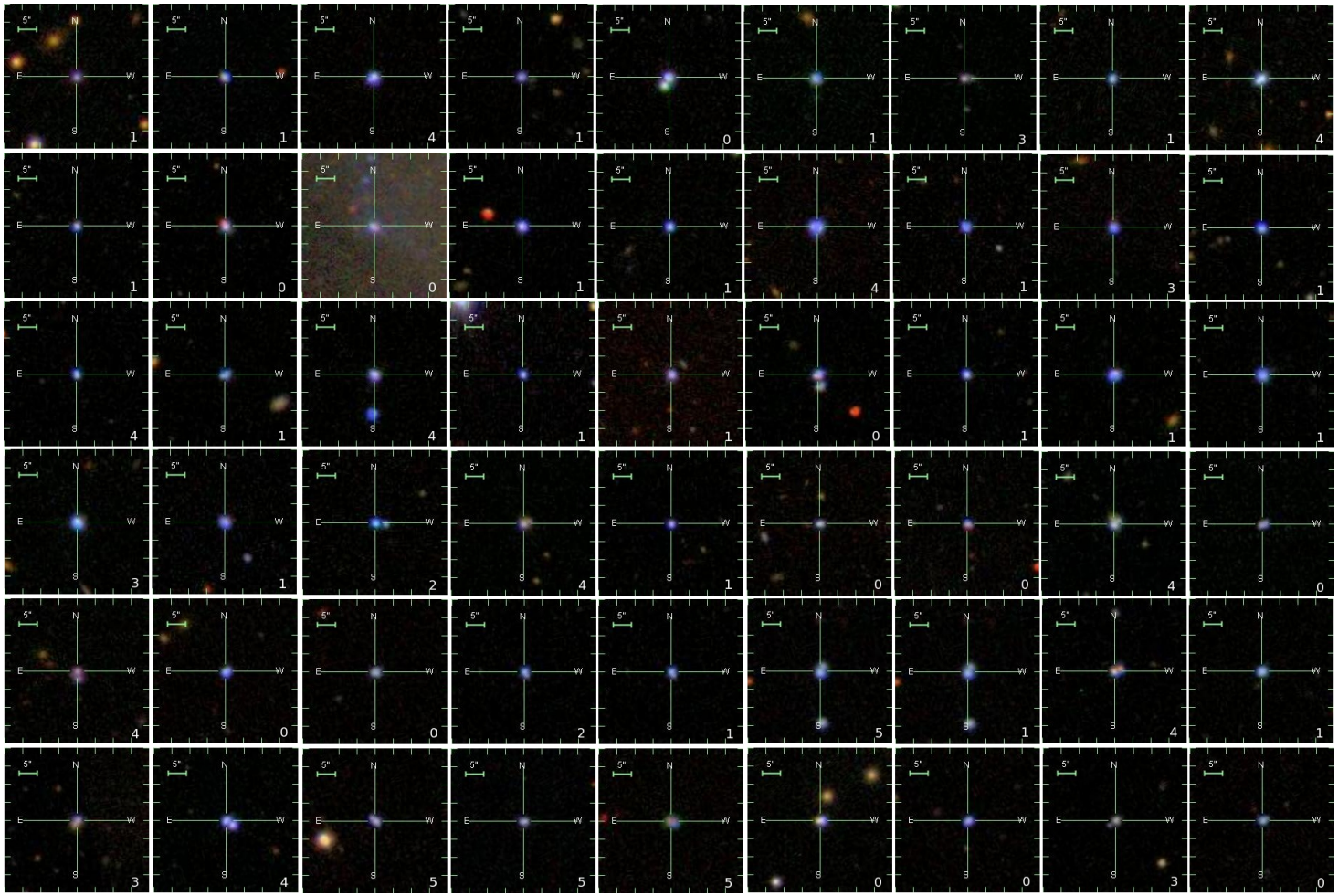
[2] strides.physics.ucsb.edu

What do they look like?



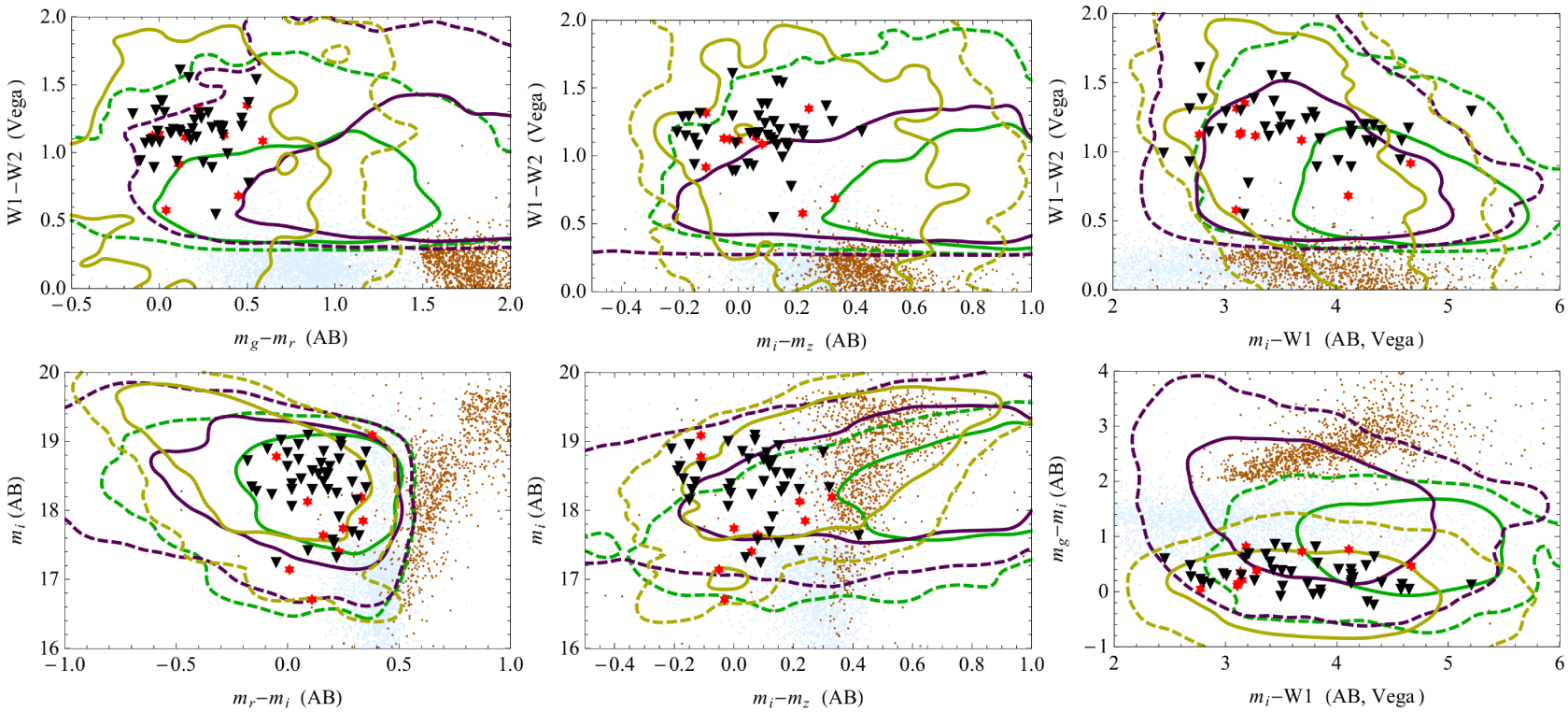
SQLS (Oguri et al.2006): look within SDSS's *spectroscopically confirmed* quasars, apply simple selection procedures at catalogue level (SQL queries) as much as possible.

- Unblended: Look for QSO-like objects with close companions of similar colours.
- Blended: Look for QSO-like objects that are poorly fit by a single PSF.



Limitations of SQLS in new/upcoming surveys

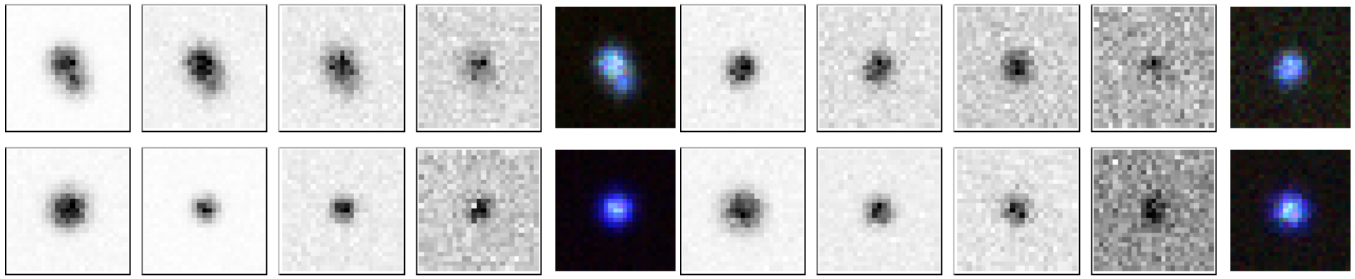
- Spectroscopically based: of limited use for new surveys like DES, where we have just *griz*+*Y*.
- DES has no $u-$band: different photometric strategies, need to match with infrared surveys (e.g. WISE).
- Lots of false positives in SQLS: mainly QSO pairs, unlensed QSO+ETG.
- What's the role e.g. of Blue Cloud galaxies in photometric-only selections?

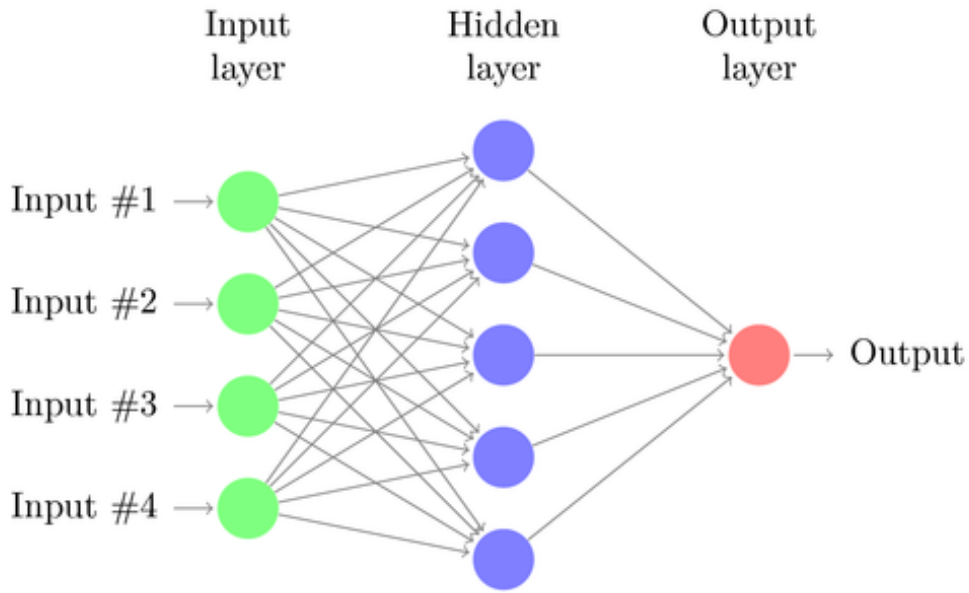

W1−W2 (Vega)
$m_g - m_r$ (AB)
W1−W2 (Vega)
$m_i - m_z$ (AB)
W1−W2 (Vega)
m_i−W1 (AB, Vega)
m_i (AB)
$m_r - m_i$ (AB)
m_i (AB)
$m_i - m_z$ (AB)
$m_g - m_i$ (AB)
m_i−W1 (AB, Vega)

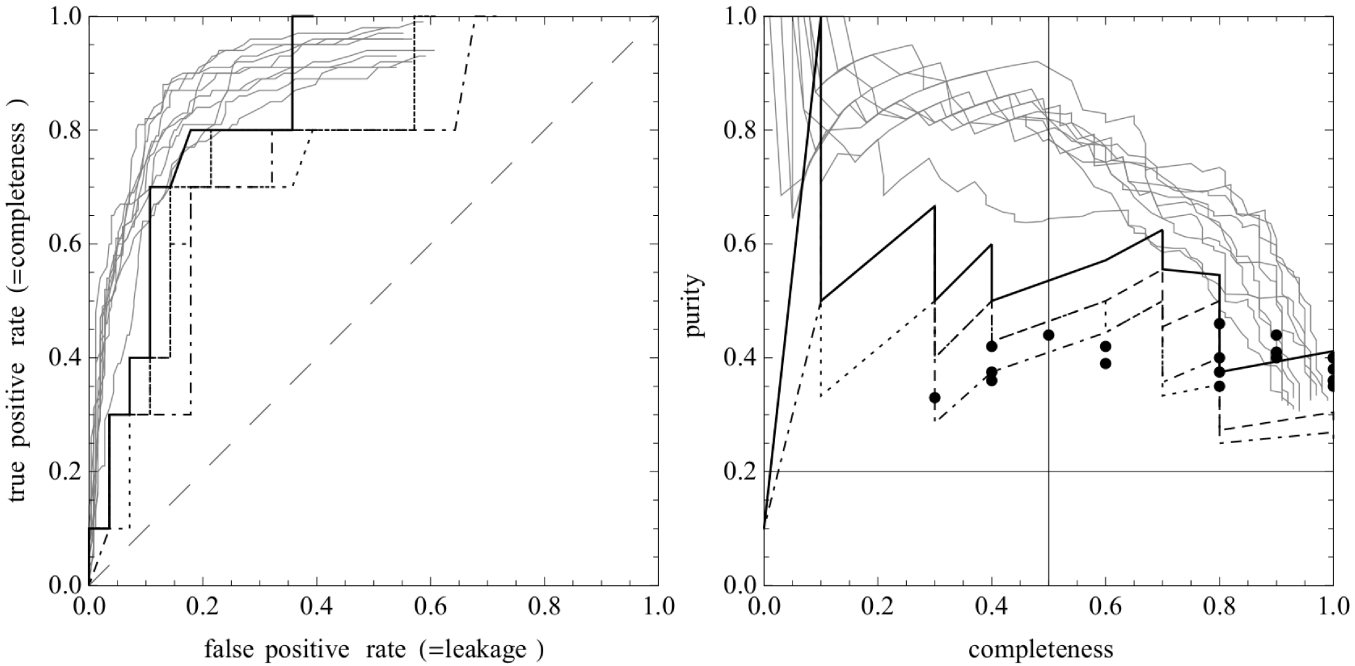
- **Step 0:** Query within **catalog**, with simple cuts in colours, possibly match to other surveys (e.g. WISE).
- **Step 1:** Use data mining on catalog parameters (photometry, second moments) to skim for **targets**.
- **Step 2:** Get the target cutouts and apply pixel-by-pixel techniques to rank the **candidates**.
- Can I model it as a lens?

AA, B. C. Kelly, T. Treu & P. J. Marshall 2014, arXiv:1410.4565

Target selection: *griz* photo+morph, W1,W2.






true positive rate (=completeness)
false positive rate (=leakage)
purity
completeness
0.0
0.2
0.4
0.6
0.8
1.0

Candidate selection:

kPCA, GBTs
(B.C.Kelly, AA)

- Data: coadd cutouts
- OM10 lens model in training set
- Classification based on lens score alone
- PSF asserted via training set
- Well tested on SQLS lenses and non-lenses
- 'Very' fast

Chitah
(J.Chan, S.H.Suyu)

- Data: lens and image positions, from color projections
- SIE model, returns chi-sq goodness of fit
- Classification based on chi-sq alone
- Well tested on bright quads
- Fast

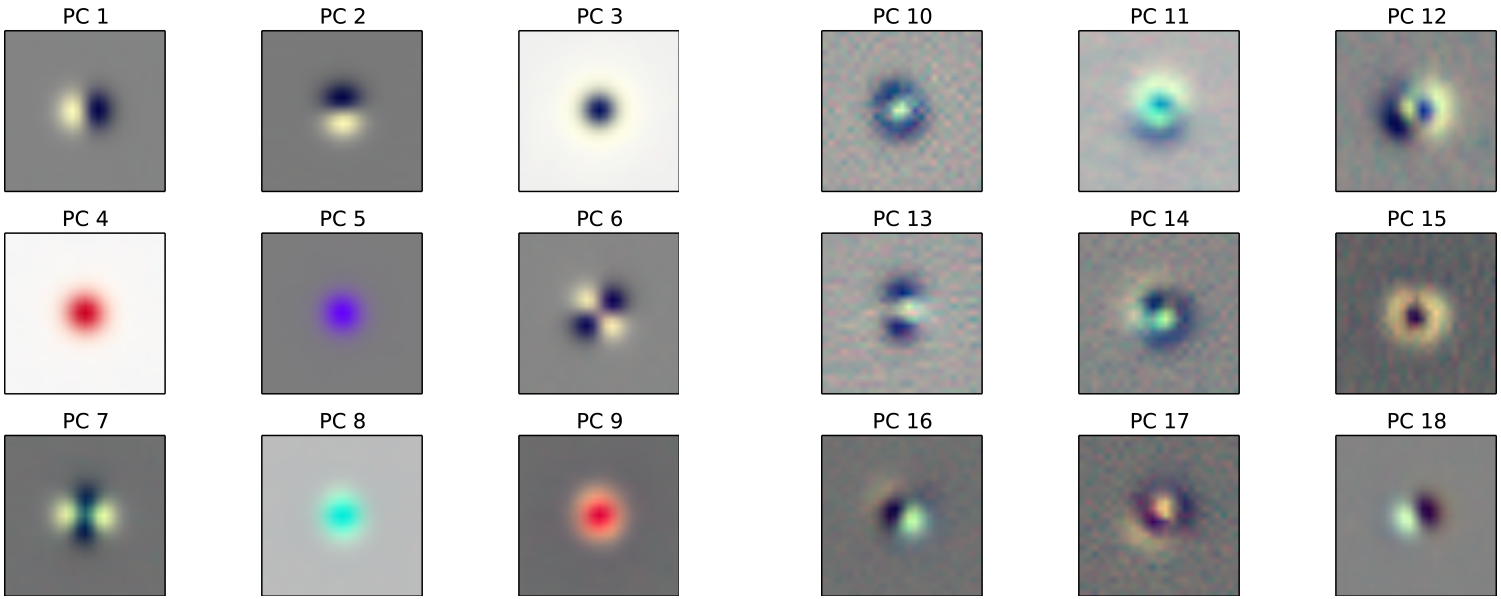
PyLens
(M.W.Auger)

- Data: coadd cutouts
- Lens and Nebula models available(?), returns posterior samples
- PSFs optimized, after point sources and galaxy
- Used in DES as aid to subjective expert classification
- Slow

LensTractor
(AA, P.J.Marshall, D.Lang, D.Hogg)

- Data: all images
- Nebula and Lens (SIS+shear) model, returns chi-sq, BIC, posterior samples
- PSFs optimized, after point sources and galaxy
- Classification by BIC or similar
- To be tested on large sample of mocks
- 'Very' slow

Example: GBTs[3]



[3] AA, Kelly, Treu & Marshall (2014).

Example: LensTractor[4]

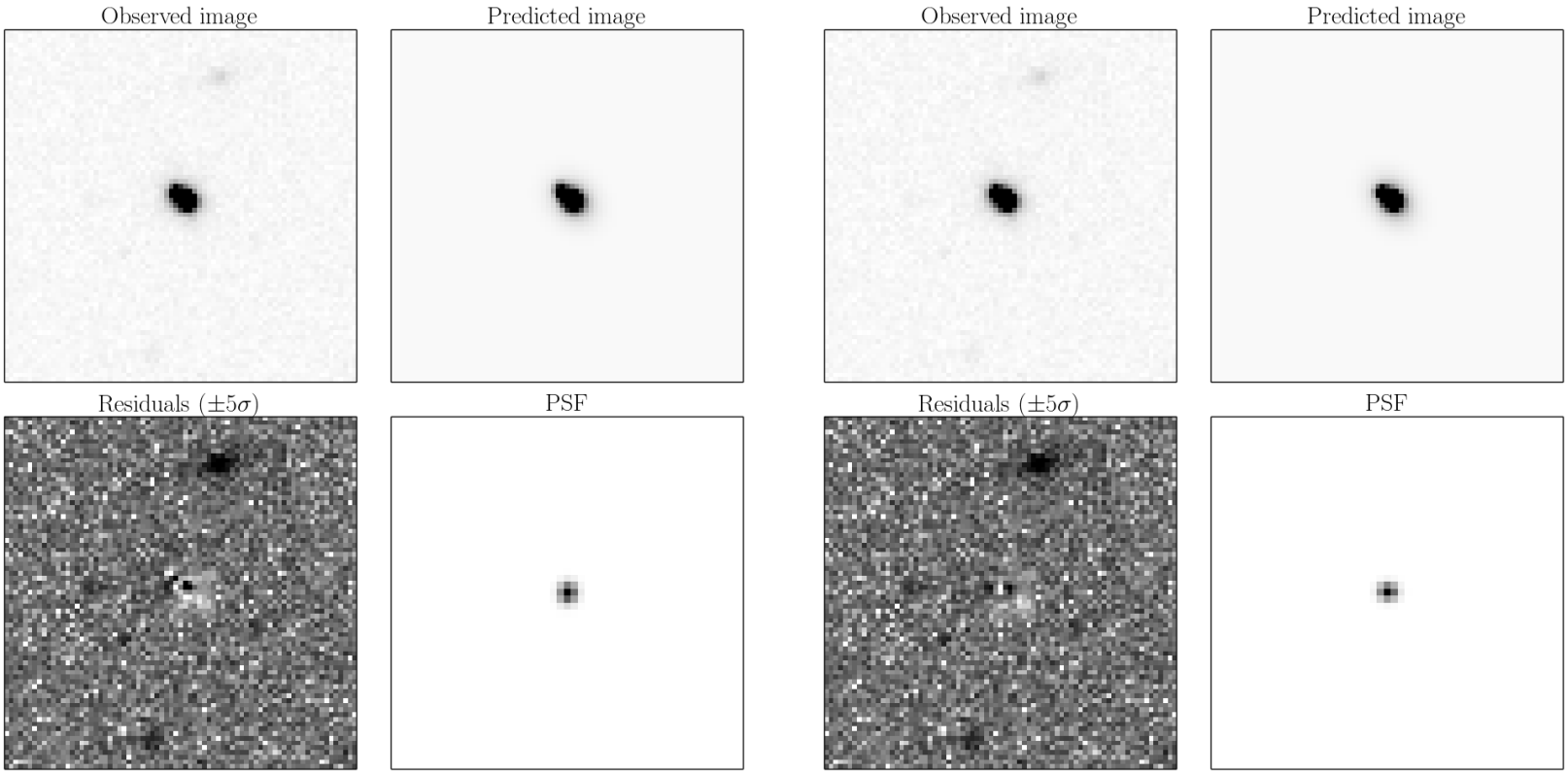
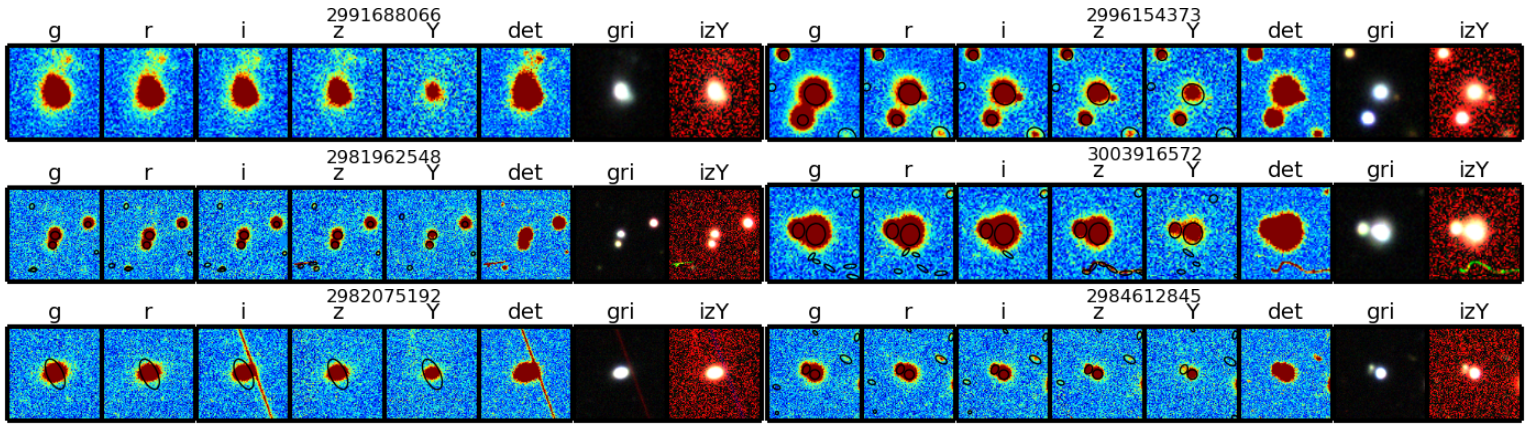


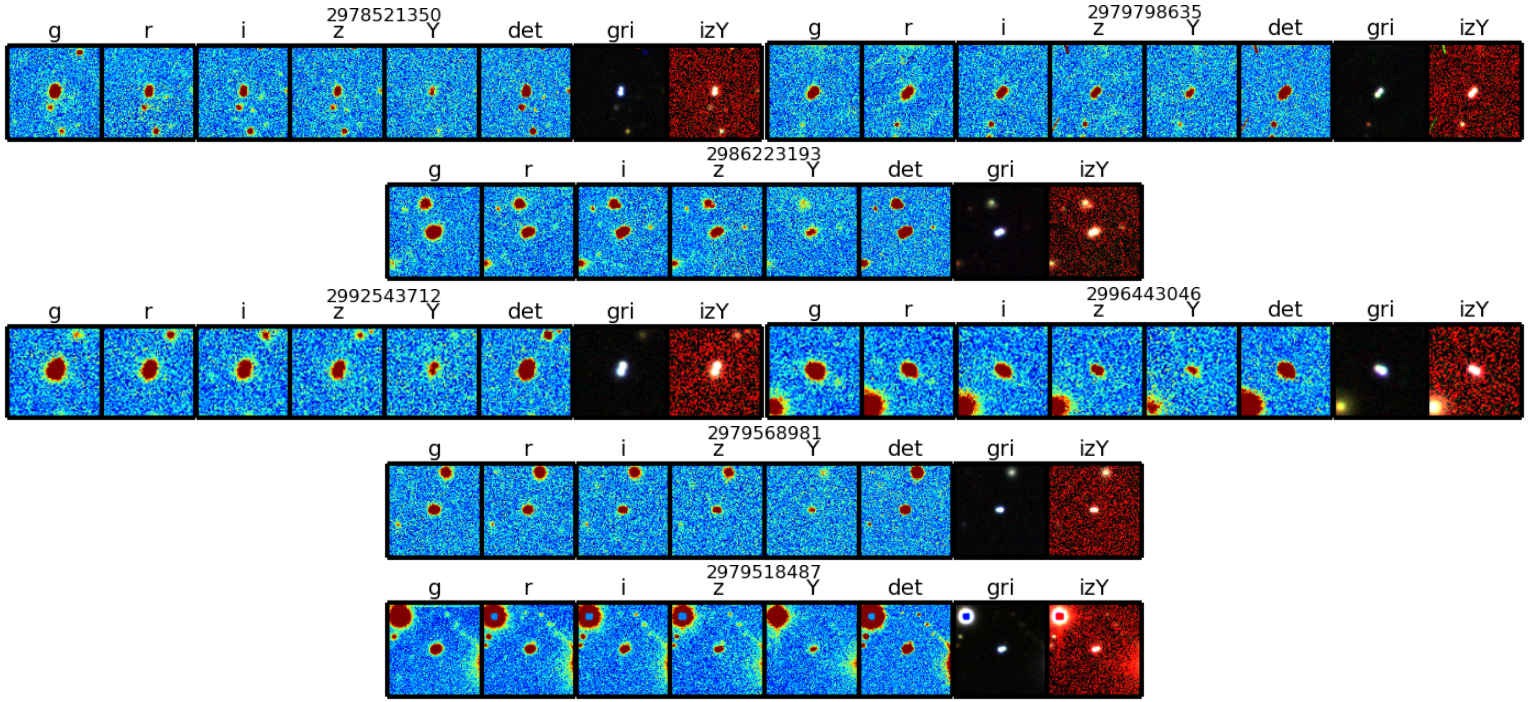
Figure : Left: Nebula 2; right: Lens. $BIC = \chi^2 + k \ln N$. The system is J0951+2635, a *true* lensed quasar in SDSS, in $r-$band, the *BIC* recognizes this as a lens. We fit the deflector and QSO, plus variation of the PSF across different bands. We can fit (almost) down to the noise.

[4] https://github.com/davidwhogg/LensTractor

Fernanda Ostrovski and I have started the search within DES. Systems with bright-QSO photometry from Fernanda's search, with extended morphology (psf_mag-model_mag>0.2 in g,r,i) in SVA1. 84 systems with $i < 19.1$, four flagged, two uncertain. With this small sample we could also eye-ball: the others (excluded by the robots) are in fact late-type or merging galaxies.



Fainter than 19, brighter than 20



Summing up...

- Goal: measure cosmological parameters from time-delay lenses with competitive precision and accuracy.
- Means: hundreds of lensed quasars in deep and wide surveys.
- Problem: 10^3 lensed quasars in 10^7 quasars, how do we find them?
- Build upon previous strategies (SQLS), without spectroscopic information, with higher purity.
- Method: Data mining
- First results: 'candidates' in DES from combined search with F.Ostrovski (IoA).
- Robots skim a lot but may need some further tuning, we need to go down to $m_i \sim 21$.