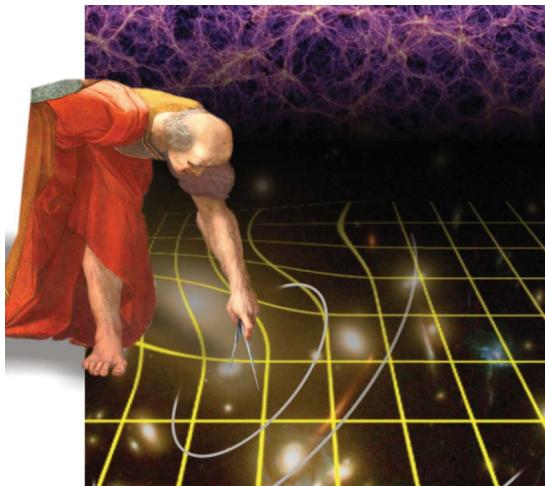


# Euclid Strong Lensing SWG



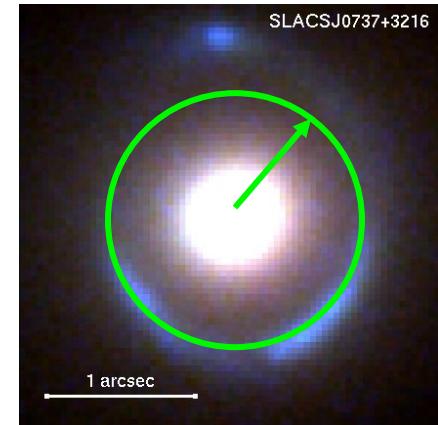
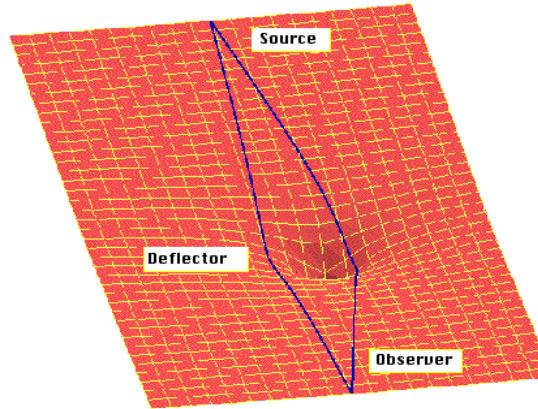
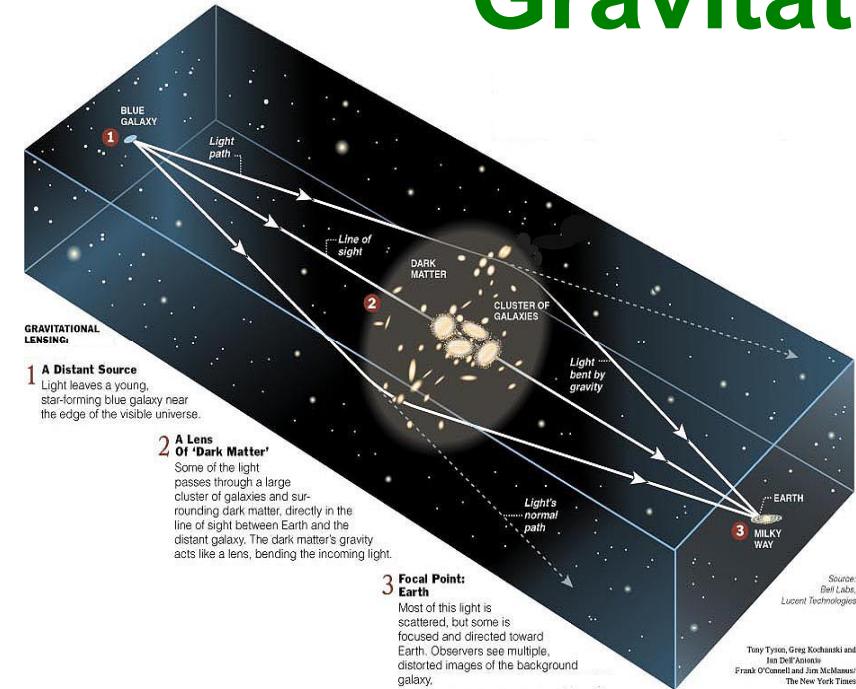
R. Gavazzi, (IAP)

Euclid France meeting, Paris, 5-6 dec. 2013

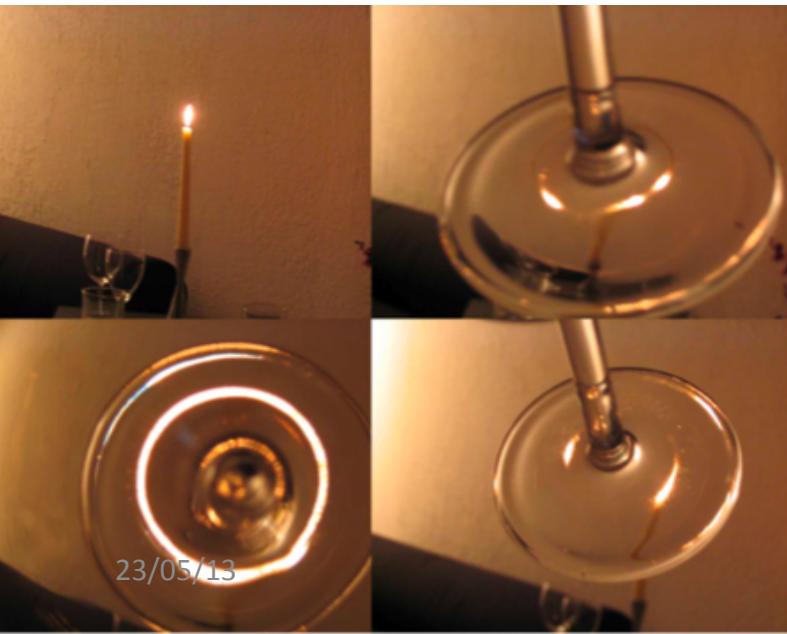
## Members

Manager: Jean-Paul kneib, Massimo Meneghetti  
Developer: Alexander Fritz, Anais Rassat, balasubramanian s, Ben Metcalf, Bogna Kubik, Carlo Giocoli, Cecile Faure, Claudio Grillo, Eric Jullo, Fabio Bellagamba, Frederic Courbin, Gijs Verdoes Kleijn, Giovanni Covone, Gregor Seidel, Hakim Atek, Jean-Claude Waizmann, Jean-Paul kneib, Jonathan Gardner, Leon Koopmans, Leonidas Moustakas, Marceau Limousin, Massimo Meneghetti, Neal Jackson, Oriana Mansutti, Phil Marshall, Pierre Dubath, Raphael Gavazzi, Rémi Cabanac, Stephen Serjeant, Stéphane Paltani

# Gravitational Lensing



Strong lensing regime!



Messier workshop, IAP

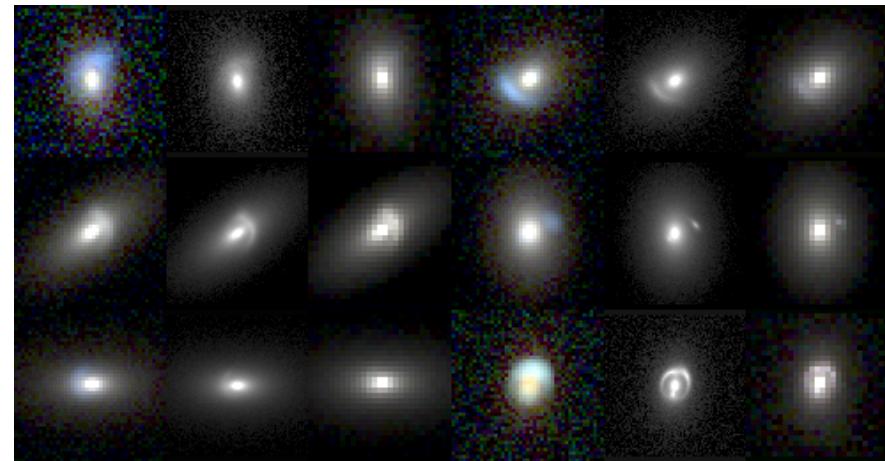


23/05/13

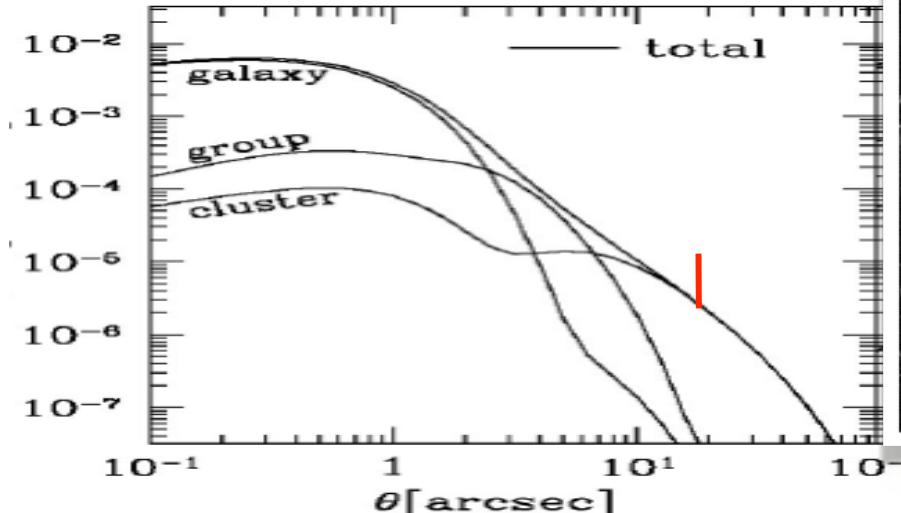
# SL Expectations from Euclid

## General Predictions:

- Galaxies lensed by galaxies:  $\sim 10 / \text{deg}^2$ ,  $\sim 1-2 \cdot 10^5$  over the  $15\text{k deg}^2$ .
- QSOs lensed by galaxies:  $\sim 10^3$
- Clusters/groups with giant arcs:  $\sim 0.5 / \text{deg}^2$ ,  $\sim 8 \cdot 10^3$  over  $15\text{k deg}^2$  (based on SL2S)
- Clusters with many multiple images:  $\sim 10^2$   
(the most massive clusters MACS type)
- DEEP ( $40\text{deg}^2$ , +2mag) : numbers/60



CFHTLS-like / EuclidVIS and Euclid YJH idealized sims



EUCLID simulation by Meneghetti

# From curiosity to a multi-purpose tool for unique galaxy structure & formation studies



# Euclid Strong Lensing SWG activities

- **Pipeline development for Lens finding algorithms with VIS (+EXT,+NISP)**
  - Find galaxy-scale lenses
  - Find group/cluster-scale elongated arcs

So far, only aspects covered at the OU-SHE strong lensing WP level
- **Develop and improve lens modeling tools**

Emphasis on automation / speed / robustness, making the most of the huge statistics!!
- **Coordinate Follow up**

Spectroscopy, other wavelengths
- **Statistical approaches**

Completeness/Purity for cosmology and galaxy/cluster evolution studies
- **Conduct simulations / predicate at the OU-SIM level**

Simplest instrumental signatures internally addressed (BLF++)  
Ensure OU-SIM able to degrade ray-traced mock image or any SB map

# Euclid Strong Lensing SWG activities

## Work Package Definitions -- Draft - 04062013

- WP 1 -- Theory: produce forecasts and interface models with strong lensing observations [link to THWG]
- WP 2 -- Strong lensing by galaxies: define and develop the science cases for galaxy-galaxy and galaxy-QSO lensing [link to GEWG]
- WP 3 -- Strong lensing by galaxy clusters: define and develop the science cases for lensing by galaxy clusters [link to CGWG, WLWG, PEWG]
- WP 4 -- Cosmology: define methods for extracting cosmological information from strong lensing data and combine SL with other probes
- WP 5 -- Exotic lenses: search and study exotic lenses
- WP 6 -- Image simulations: develop image simulations for supporting the activities of the group and of the ground segment [link to OU-SIM, WLWG]
- WP 7 -- Pipeline development: develop the pipeline for the strong lensing analysis, supporting the activities in the ground segment [with OU-SHE, OU-LE3]
- WP 8 -- Lens finders: search and classify strong gravitational lenses [within OU-SHE]

# *Internal structure of Galaxies*

# Galaxy Structure & Evolution

## Some Science Goals:

- Total-mass density profiles of galaxies in the inner several effective radii
- WL of strong-lenses on larger scales.
- The stellar and dark matter mass fraction in the inner regions of galaxies.
- The inner dark matter density distribution
- Scaling relations: e.g. Fundamental plane/TF
- The stellar IMF from combined lensing, dynamics & stellar pop. analysis.

*As a function of redshift, galaxy mass, type, etc.*

## Tool Kit:

- Lensing and dynamical modeling (spherical symmetry plus Jeans eqns)
- Bayesian self-consistent lensing & dynamics modeling of systems with kinematic data
- Bayesian grid-based gravitational lens modeling of source/potential
- Stellar pop. synthesis modeling

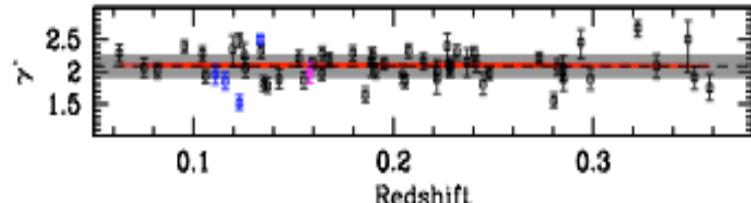
# Galaxy Structure & Evolution

Total Density profile

$$\rho(r) \propto r^{-\gamma'}$$

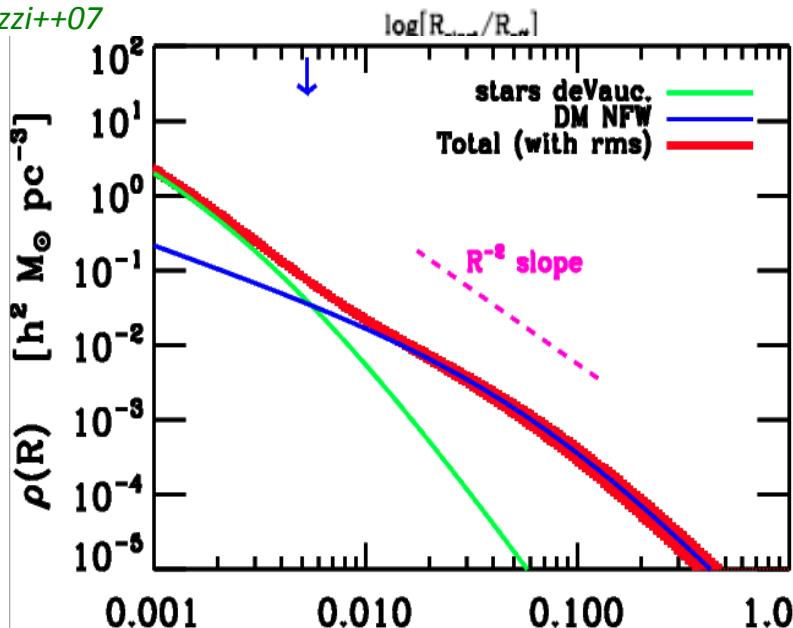
*SLACS only*

Koopmans++09



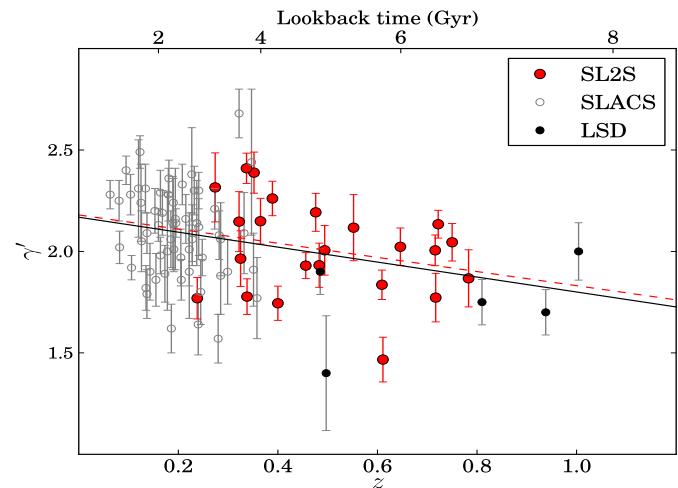
Isothermal behavior consistent with a mixture of stars and NFW dm halo

Gavazzi++07



*SLACS+SL2S*

*Better handle on time evolution*



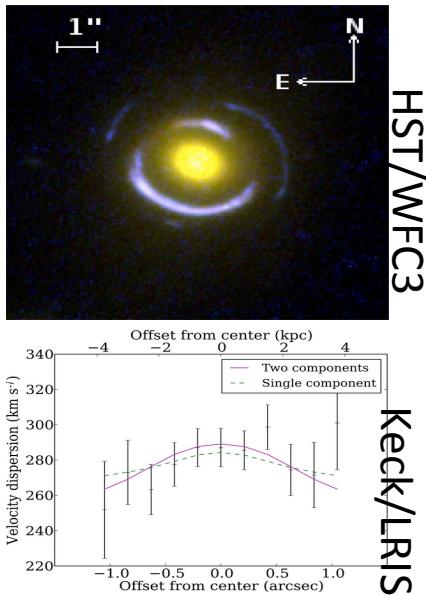
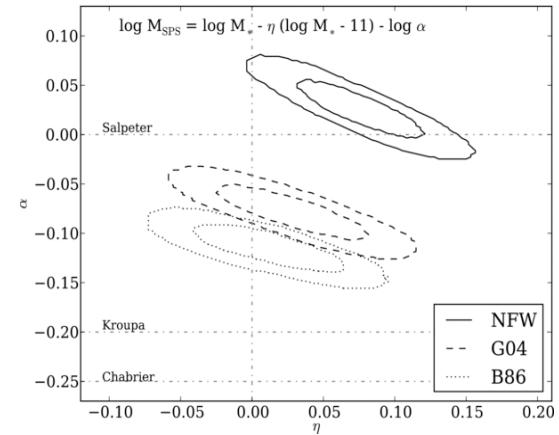
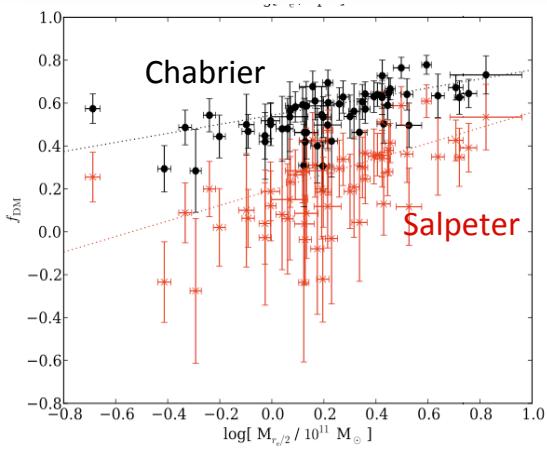
Ruff++11, Gavazzi++12, Sonnenfeld++13 (in prep)

~3.5 $\sigma$  evidence for steepening of the total density profile with time with 33 SL2S lenses + SLACS+LSD. (See also Bolton++12)

# Galaxy Structure & Evolution

*1<sup>st</sup> evidence from SLACS:  
stellar M/L ratios favor  
Salpeter-like IMFs (Treu+  
+10, Auger++10)*

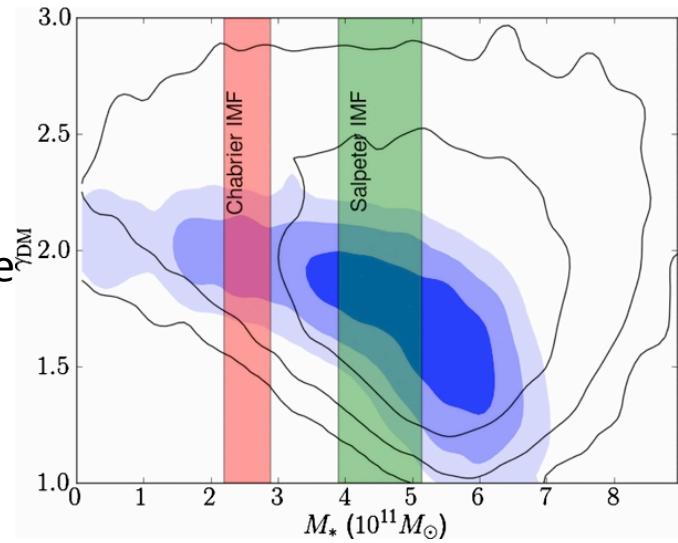
## DM/stellar mass budget



Double source plane lenses  
SDSSJ0946+1006, aka “Jackpot”  
Sonnenfeld++12, Gavazzi++08

Even greater handle on mass profile  
Still pointing toward high M\*/L

$$\frac{1}{\rho_*} \frac{d\rho_* \sigma_r^2}{dr} + 2 \frac{\sigma_\theta^2}{r} = - \frac{GM(r)}{r^2}, \quad (3)$$



# *CDM Substructure*

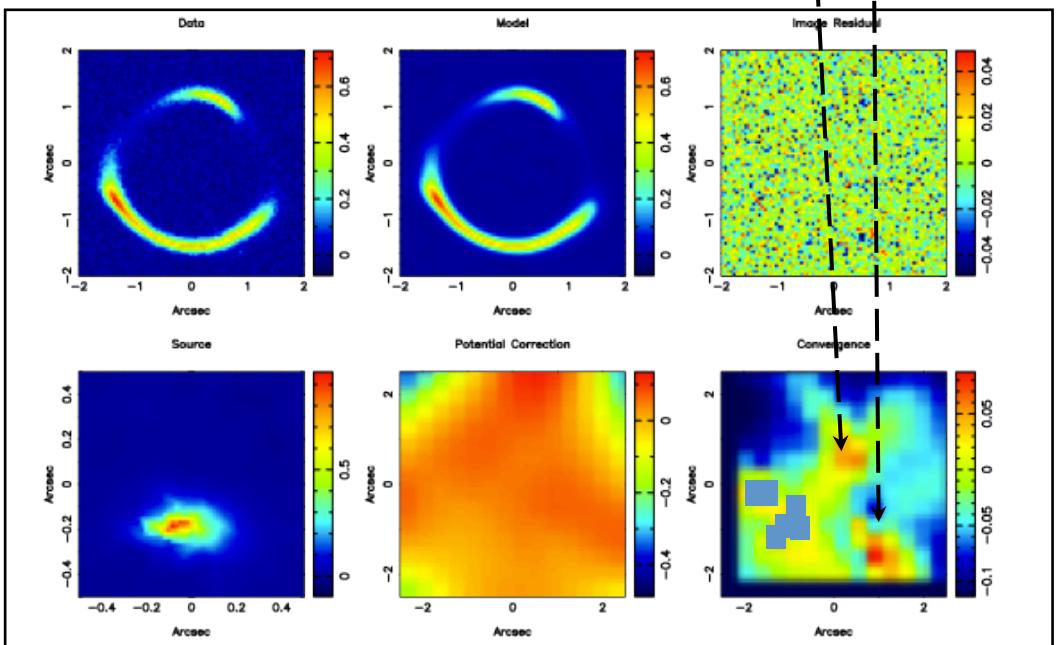
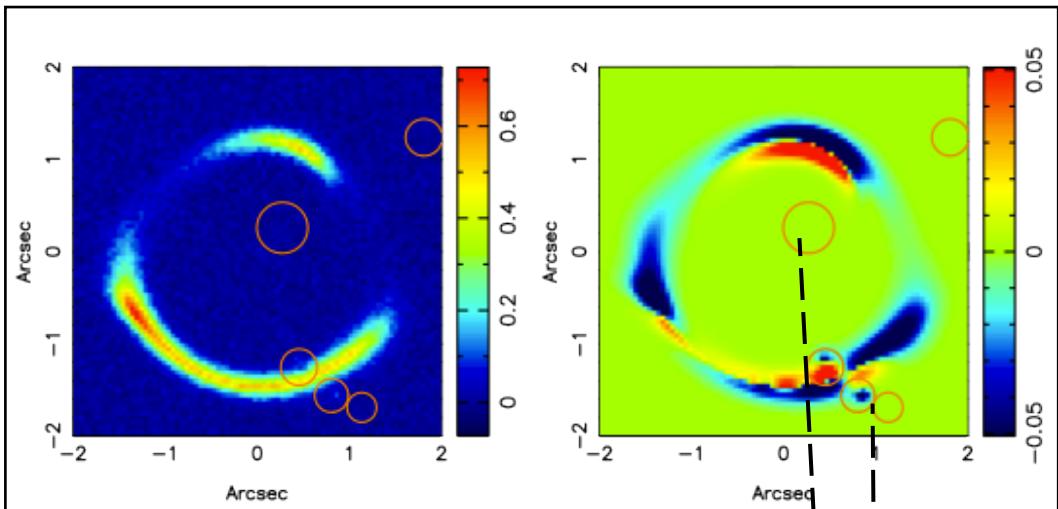
*(aka Missing satellites)*

# (CDM) Substructure

## Some Science Goals:

- The level of virialised (CDM) mass substructure/satellites
- Quantifying the mass/mass-to-light of luminous satellites
- Quantifying the power-spectrum of mass structure in galaxies

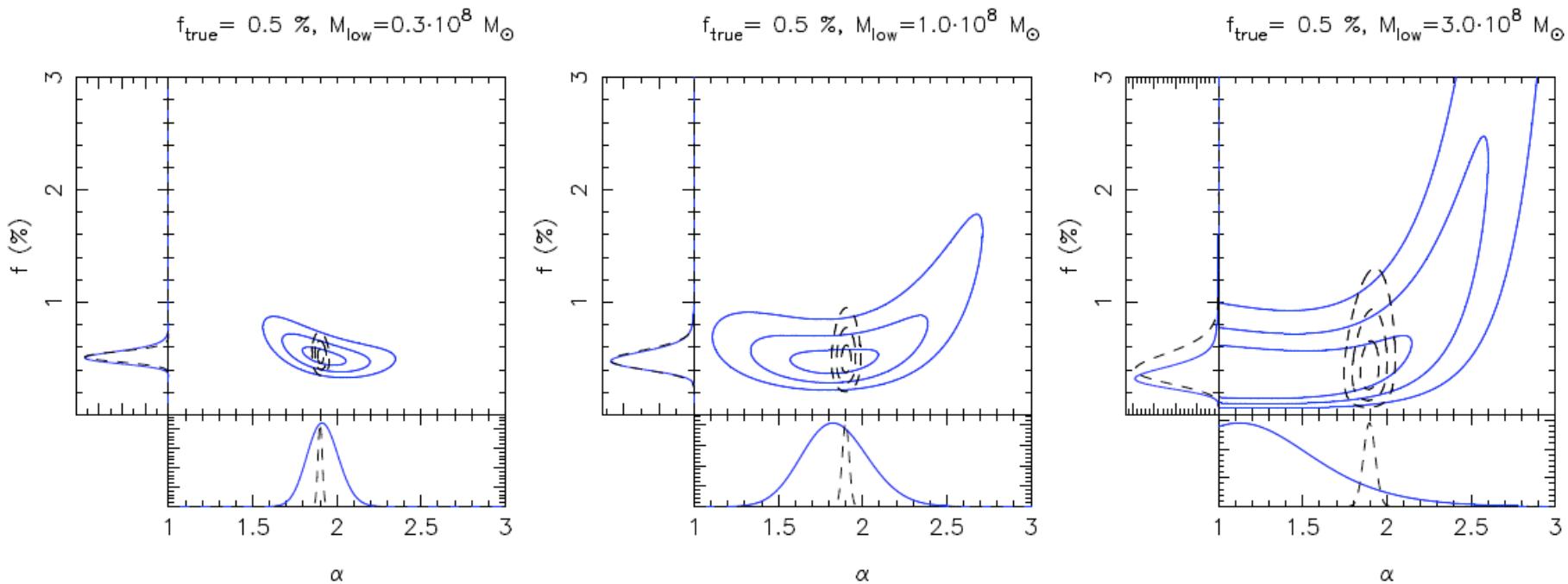
*As function of redshift, galaxy mass, type, etc.*



# (CDM) Substructure

Already  $\sim 1000$  EUCLID lenses of HST-like quality allow one to place limits on the level of mass substructure in lens-galaxies beyond  $\sim 10^9$  solar masses. (**DEEP can provide!!**)

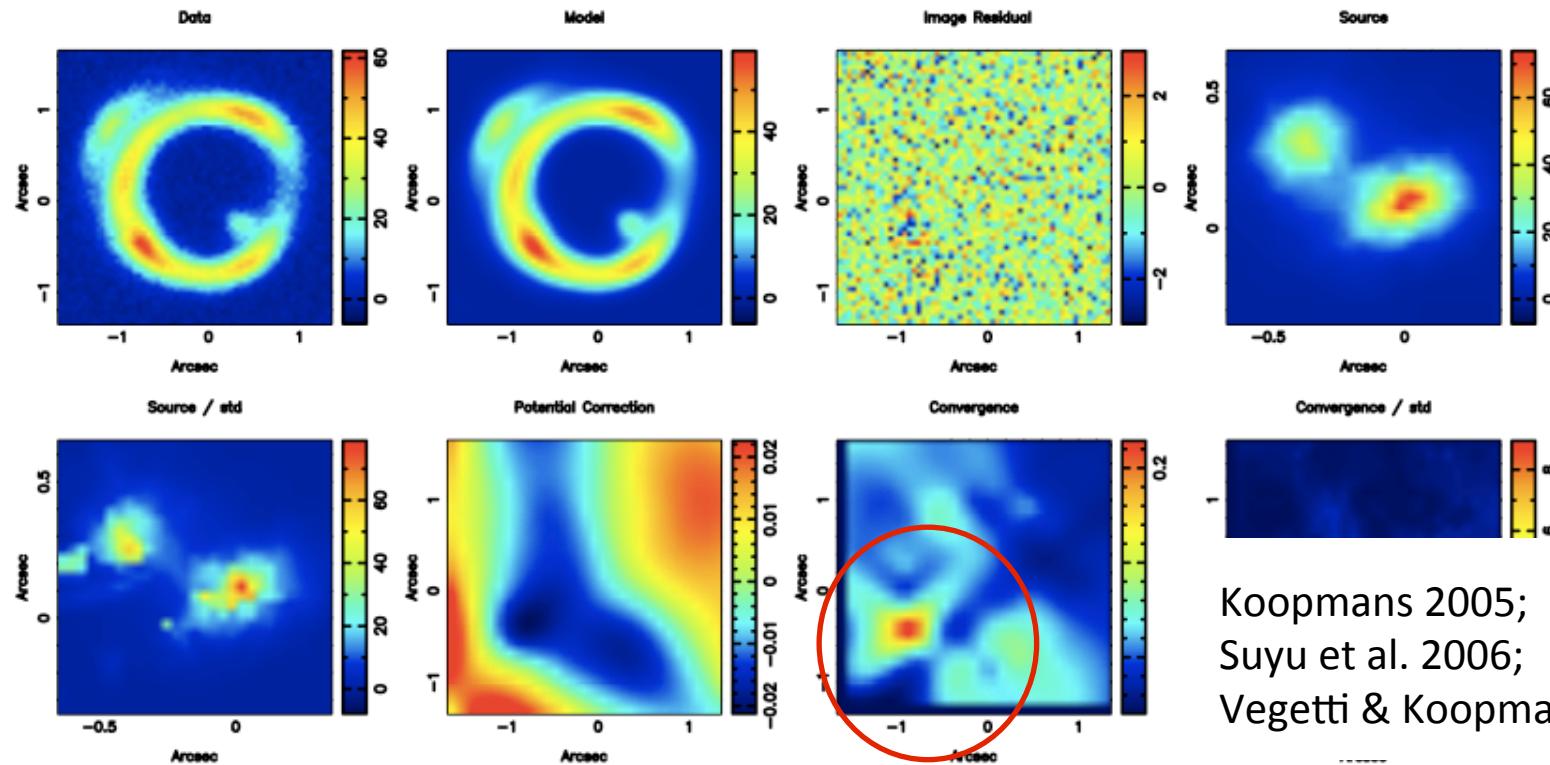
More systems allow this to be determined as a function of redshift, mass and galaxy-type.



Vegetti & Koopmans (2009)

# Fully (Adaptive) Grid-based Bayesian Lens Modeling (Vegetti & Koopmans 2009)

Extended images provide complementary information



Koopmans 2005;  
Suyu et al. 2006;  
Vegetti & Koopmans 2009

A full Bayesian analysis, using a Pseudo-Jaffe mass model for the substructure shows its impact on the smooth-model parameters

A perturbation of  $<0.01$  on the main galaxy indicates the extreme level of sensitivity to perturbations of this strong-lensing methodology

Vegetti et al. 2012, Nature

# *Galaxy clusters & groups*

# Galaxy Clusters

Some Science Goals (Cf Maurogordato's talk CGSWG)

- Total-mass density profiles in the inner  $\sim 100$  kpc.
- Combined with WL on larger scale.
- Mass concentration relation
- Azimuthal Shape
- Cosmic telescope
- Cosmography

As a function of redshift, mass, relaxation state, etc.

# *Sketching the chain of actions for SL*

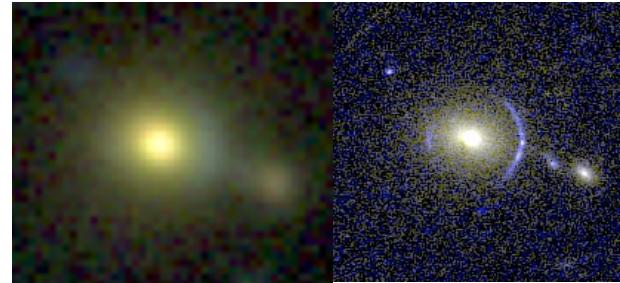
# Lens Selection Pipeline

- Automated selection pipeline based on multi-scale postage stamps & VIS-IR data.
  - ✓ Selection of gal-gal and gal-QSO systems
  - ✓ Selection of lenses over a wide range of galaxy-types: early/late
  - ✓ Selection over a wide range luminosities, masses and redshifts
- Automated selection pipeline based on H $\alpha$  near ETG at lower z (a la SLACS) in combination with images. Performance to be quantified...?
- Potential selection biases/effects: false positives & selection efficiency.
- Understanding of biases via simulations of realistic datasets passing through selection pipeline. Example: density slope evolution could be known to within few percent: are cosmological simulations ready? / are selection effects controlled to this level?



Sample of lens candidates based on very inclusive criteria (to be determined), in order to maximize selection efficiency. Crude modeling is an option! Minute modeling should then select against false positives!

# Galaxy-scale lens finders



goal:

(Fully) automated detection of complete/partial ring like feature around foreground galaxies:

- **4 flavors for ongoing method developments**

- RingFinder (Gavazzi) : difference imaging, evolving into fast model fitting
- PCA image subtraction (Courbin++)
- Galfit foreground subtraction + SExtractor analysis of residuals (Jackson)
- Community classification (Marshall, Spacewarps in the vein of GalaxyZoo)

Now performs **simultaneous** fit in all ugriz CFHTLS bands of a (red) deflector and a (blue) ring. Ability to deal with Euclid-VIS or Euclid-VIS + EXT to be tested!

Optimization over a many-parameter space (with strong priors on color of fg/bg).

$R_{\text{ein}}$ ,  $q$ , PA,

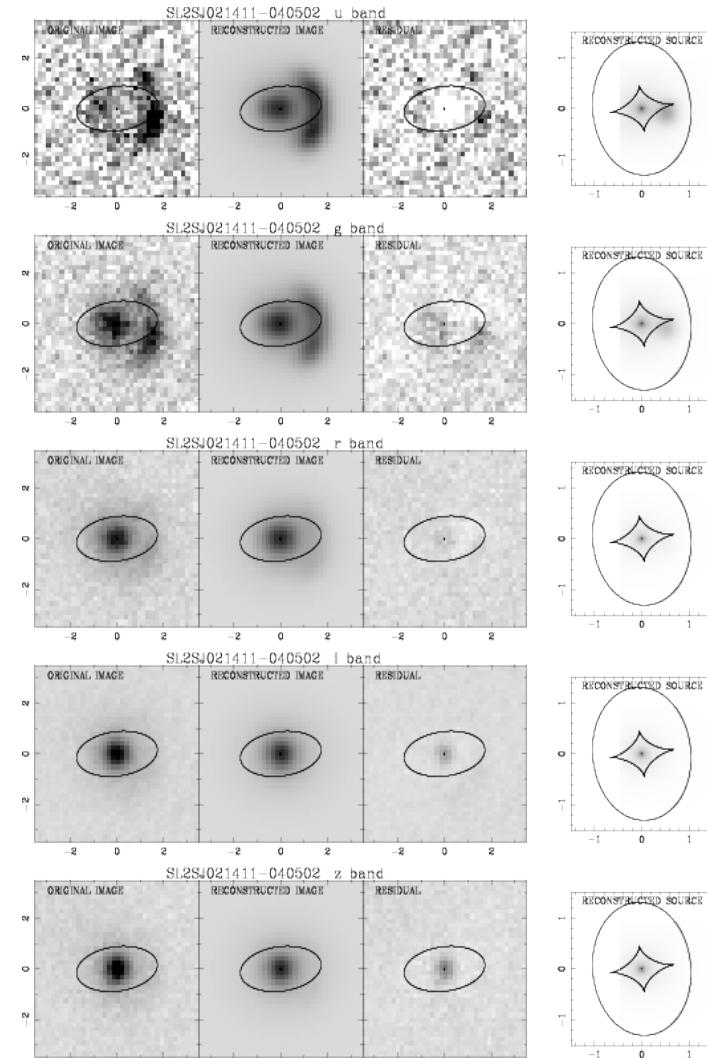
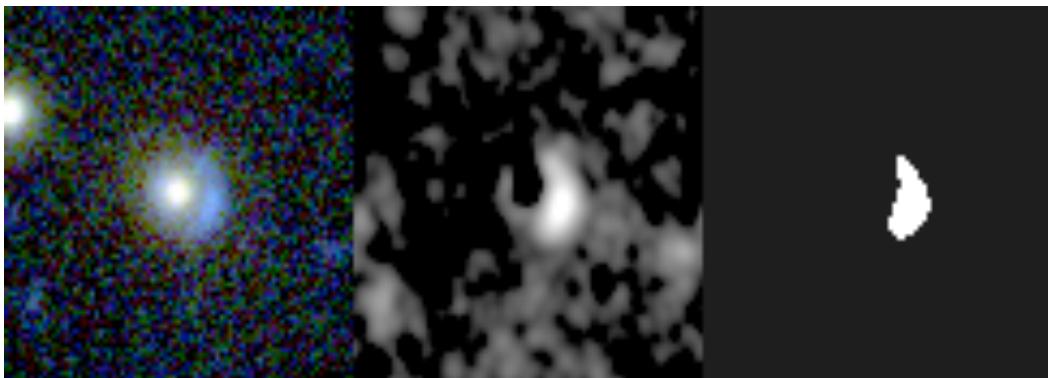
$q_d$ , PA<sub>d</sub>, Flux<sub>d1</sub>, Flux<sub>d2</sub>..., size<sub>d1</sub>, size<sub>d2</sub>...

$x_s$ ,  $y_s$ , [round], Flux<sub>s1</sub>, Flux<sub>s2</sub>..., size<sub>s1</sub>, size<sub>s2</sub>...

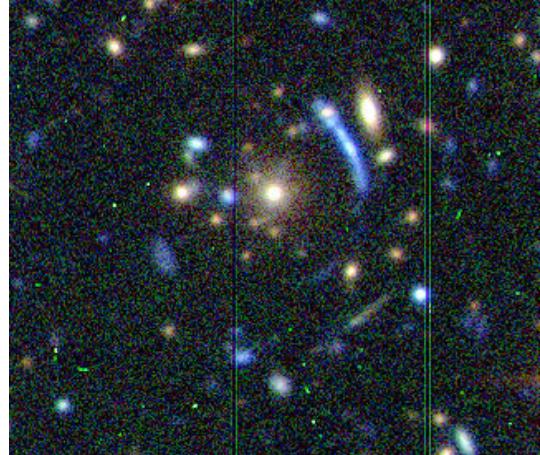
Environment still difficult to deal with.

Optimization time << 1 min.CPU

- Substantial parallelization effort underway.
- Build up of a more powerful covariance matrix for priors underway!



# Arc Finder



**goal:**

Fully automated detection of elongated objects and morphological analysis.

Remove spurious detections based on:

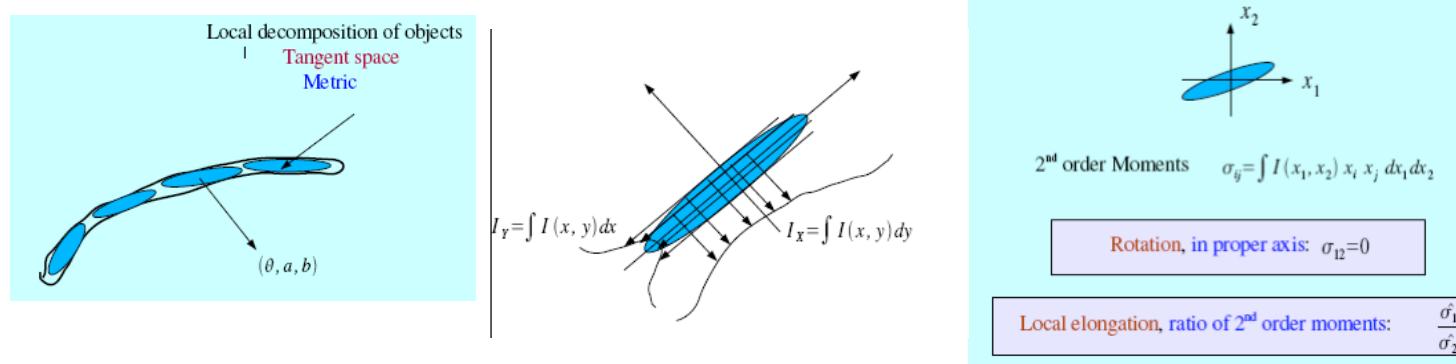
- (1) colour information in multi-band images
- (2) a priori data on galaxy and cluster positions

- **2 independent algorithms**

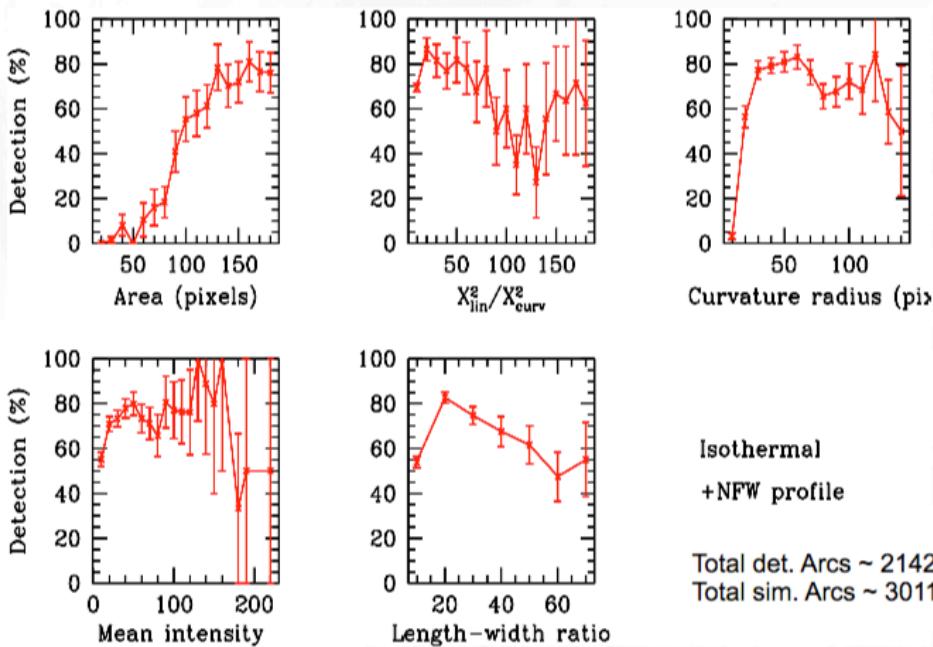
- G. Seidel et al. (Heidelberg)
- R. Cabanac (IRAP) (More, Cabanac, Alard et al 2012)

# ArcFinder

Automated detection of giant arcs (Alard 2009)  
R. Cabanac porting algorithm to Euclid VIS



Anupreeta More (in prep)

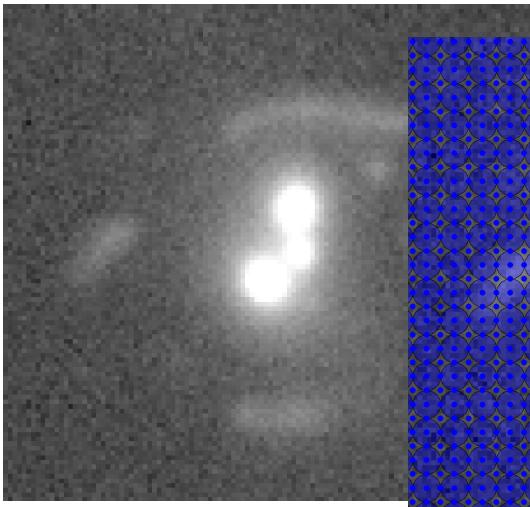


<- Assessment of detection efficiency  
(More et al 2012)

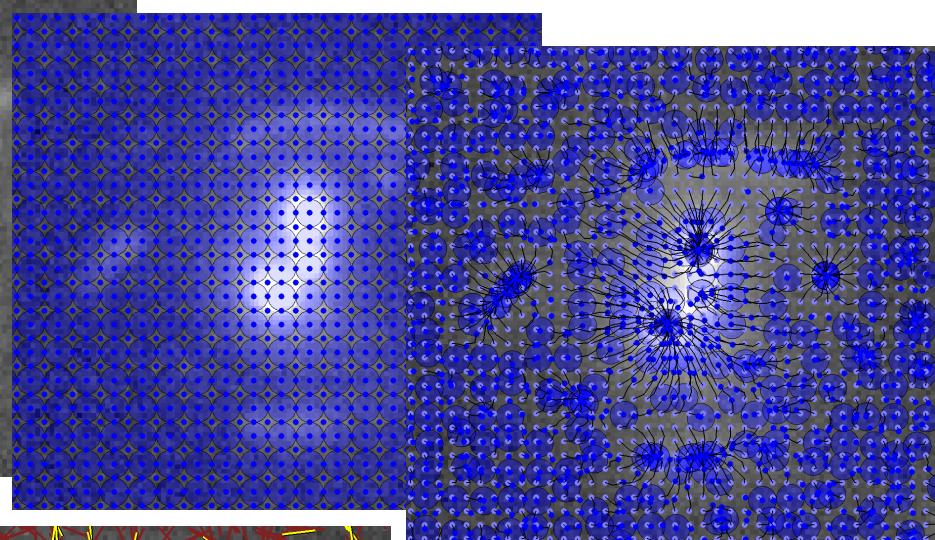
To be tuned to work on Euclid imaging

# G. Seidel's Arcfinder

- Distribute cells



- Cell transport



- Ellipticities

(1) initial objects

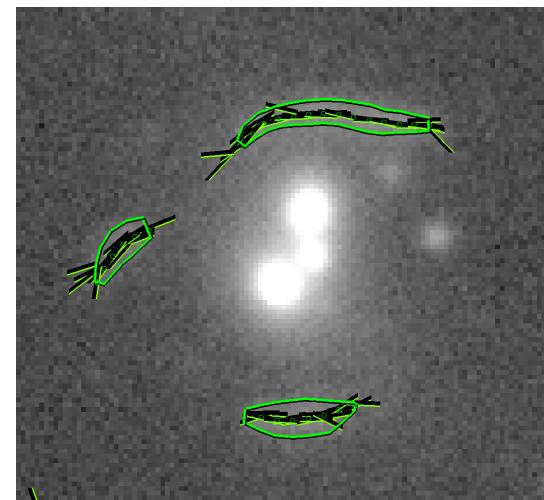
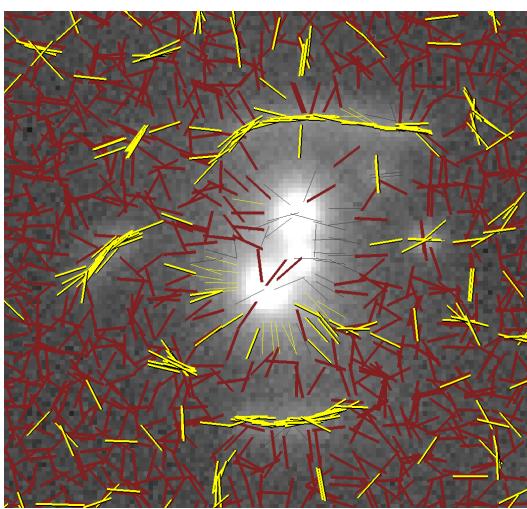
(2) apply primary filters

- Contour

(1) contour generation

(2) photometry

(3) apply secondary filters

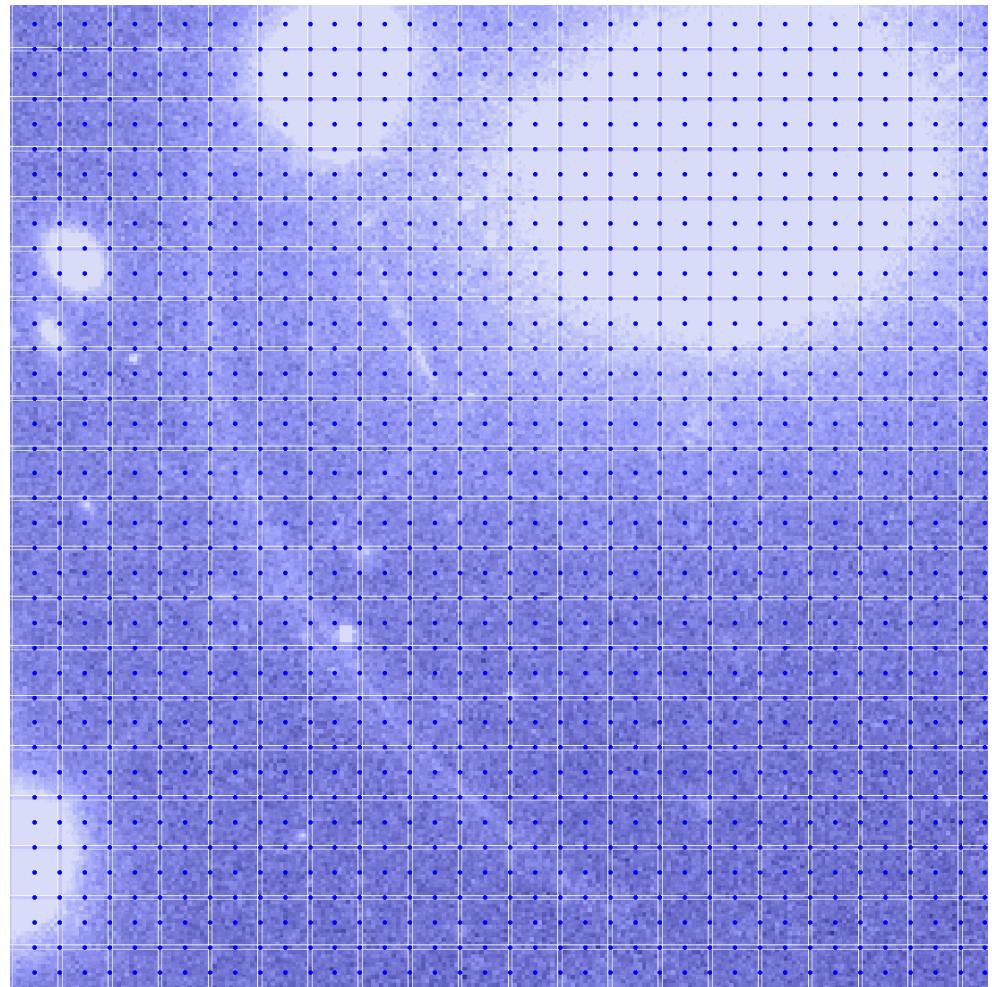


- **distribute cells on square grid**
- **shift to local centre of brightness**
- **compute ellipticities**

$$\chi = \frac{Q_{11} - Q_{22} + 2iQ_{12}}{Q_{11} + Q_{22}}$$

**from second moments**

$$Q_{ij} = \frac{\int_A (x_i - \bar{x}_i)(x_j - \bar{x}_j) d^2x}{\int_A q(I(x)) d^2x}$$

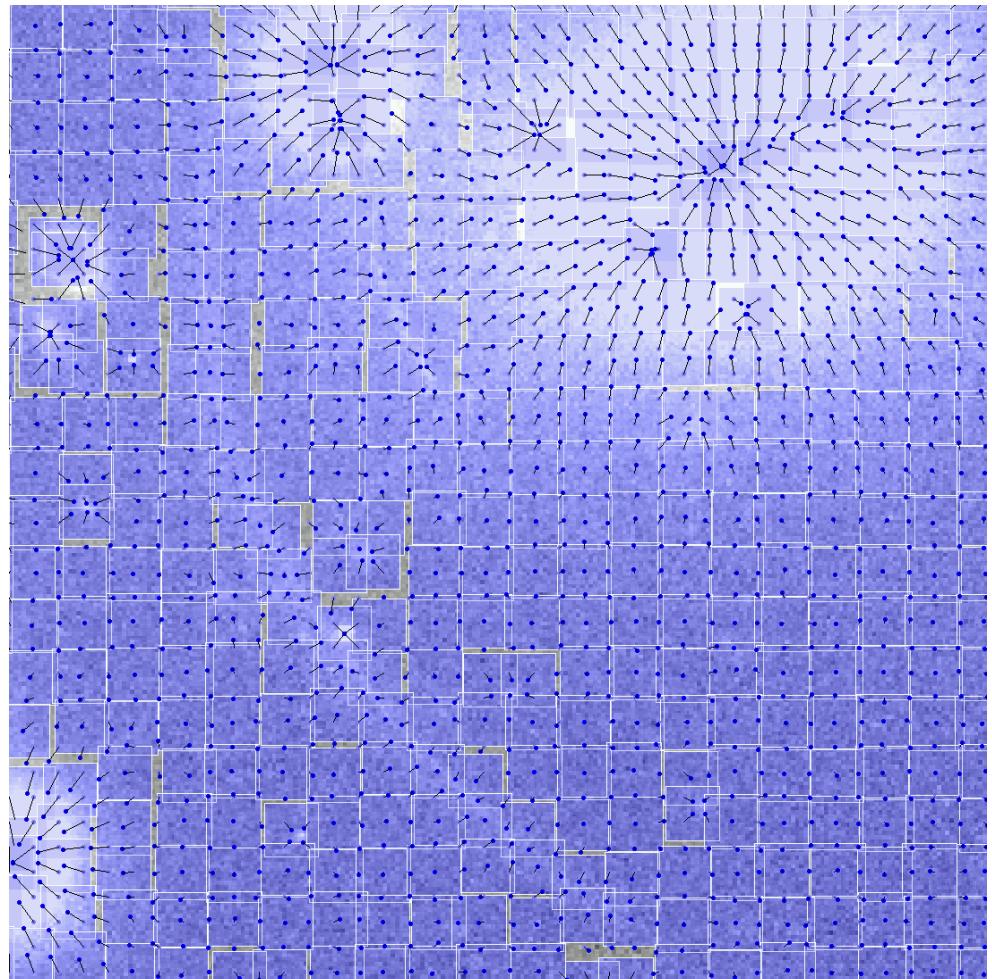


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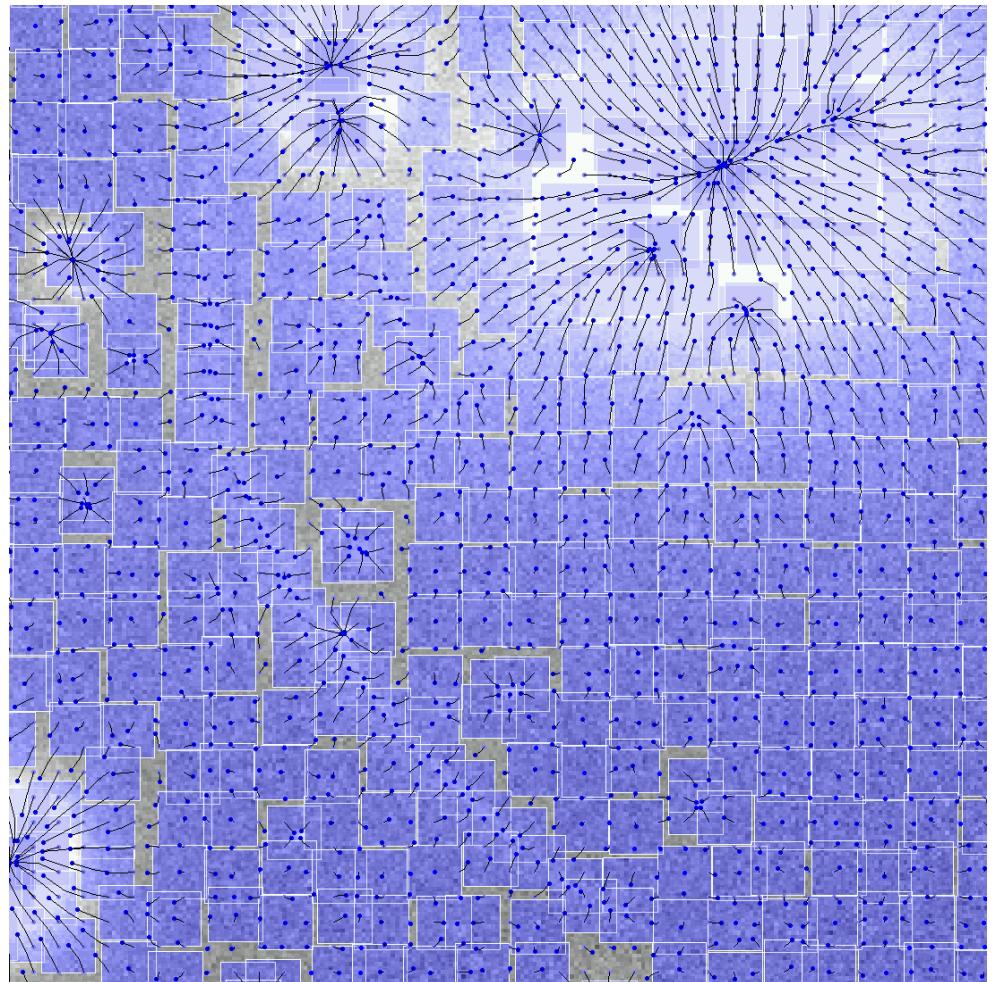


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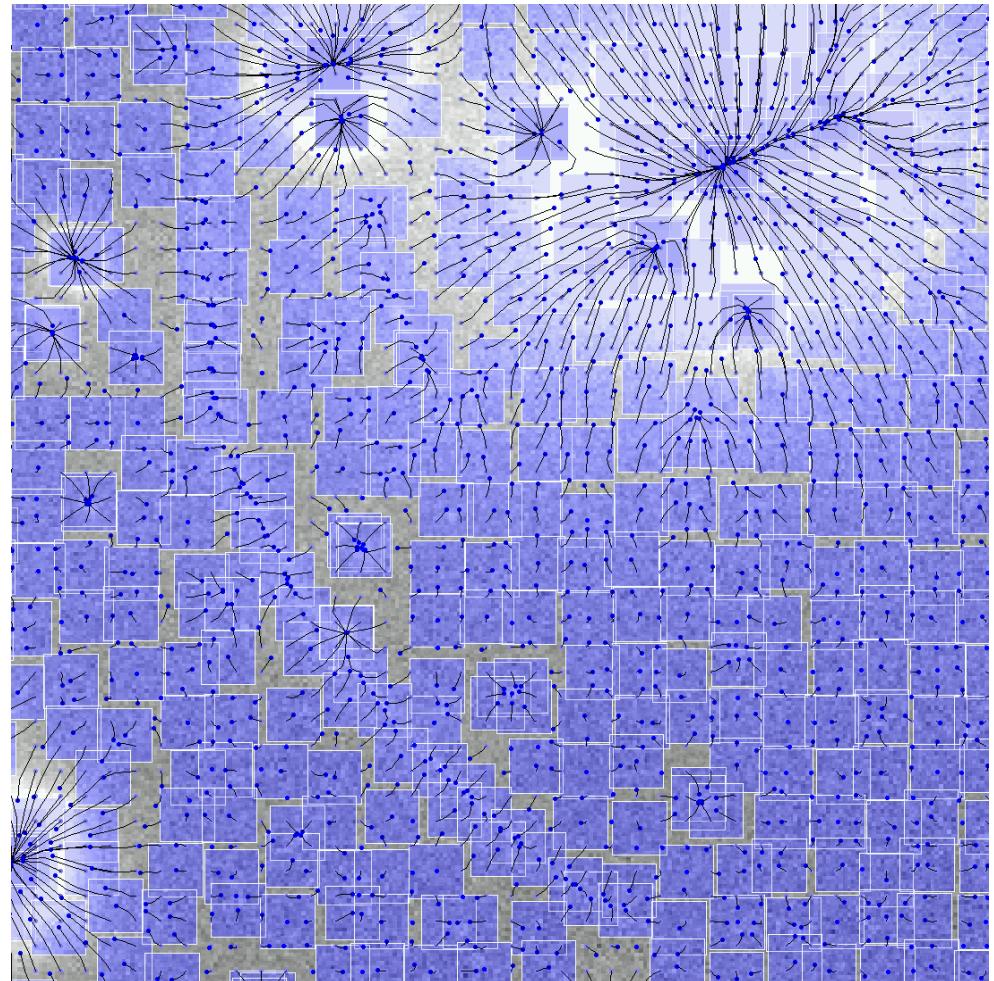


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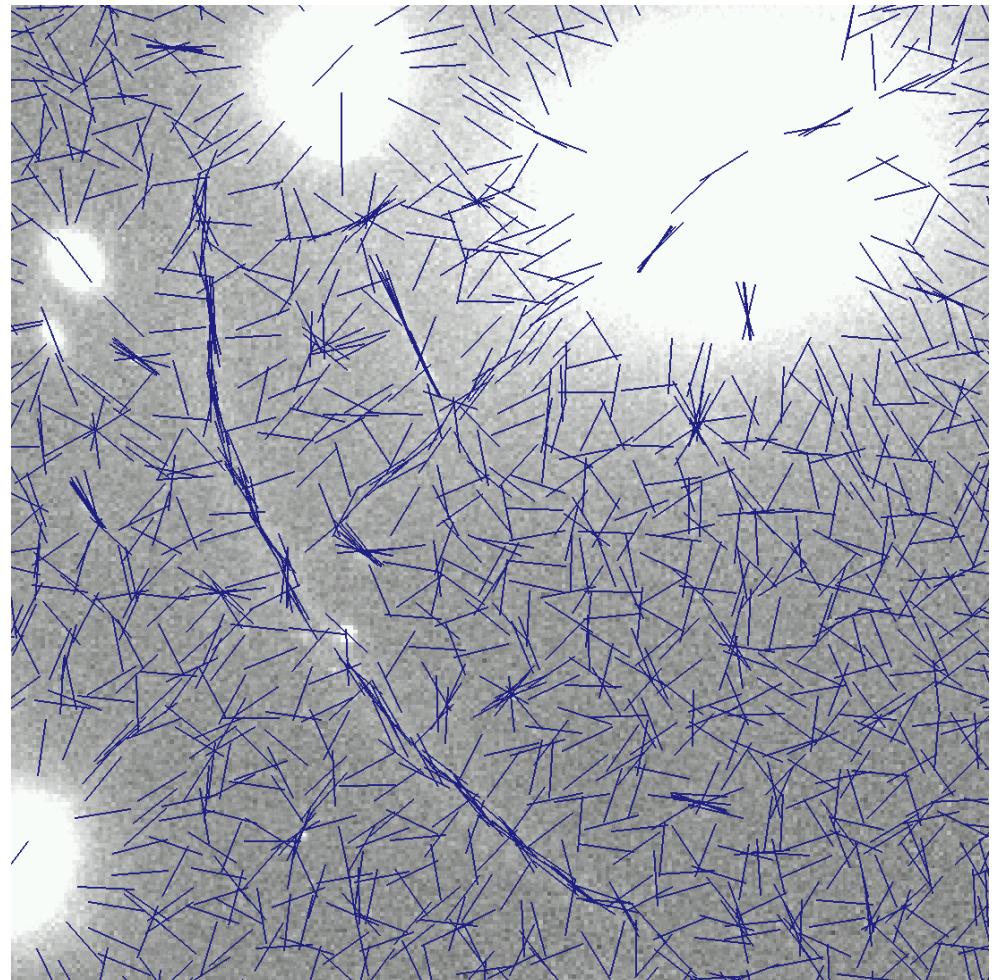


- **distribute cells on square grid**
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- **compute ellipticities**

$$\chi = \frac{Q_{11} - Q_{22} + 2iQ_{12}}{Q_{11} + Q_{22}}$$

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$$Q_{ij} = \frac{\int_A (\mathbf{x}_i - \bar{\mathbf{x}}_i)(\mathbf{x}_j - \bar{\mathbf{x}}_j) d^2x}{\int_A q(I(\mathbf{x})) d^2x}$$



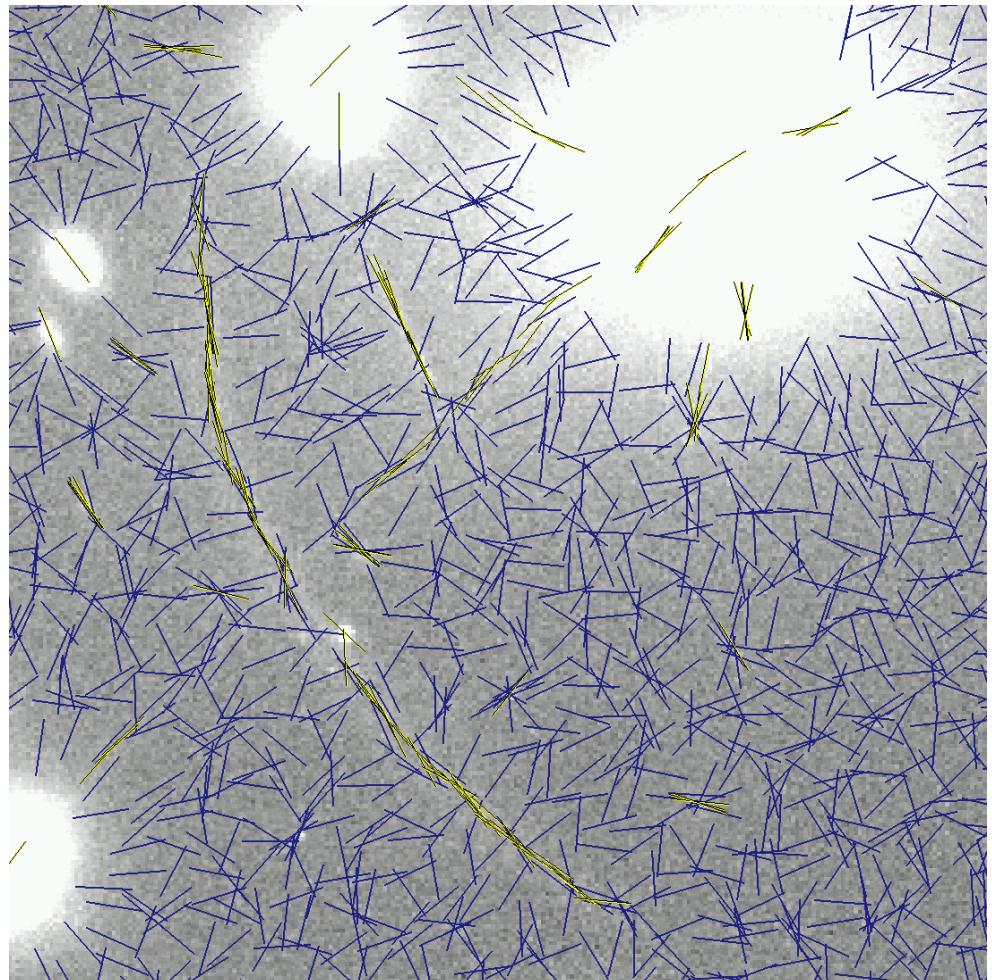
- **compute cell correlations**

$$c^{kl} = \mathbf{e}^k \cdot \mathbf{e}^l \cdot \max(0, 1 - \frac{(\mathbf{x}^k - \mathbf{x}^l) \times \mathbf{e}^k}{d})$$

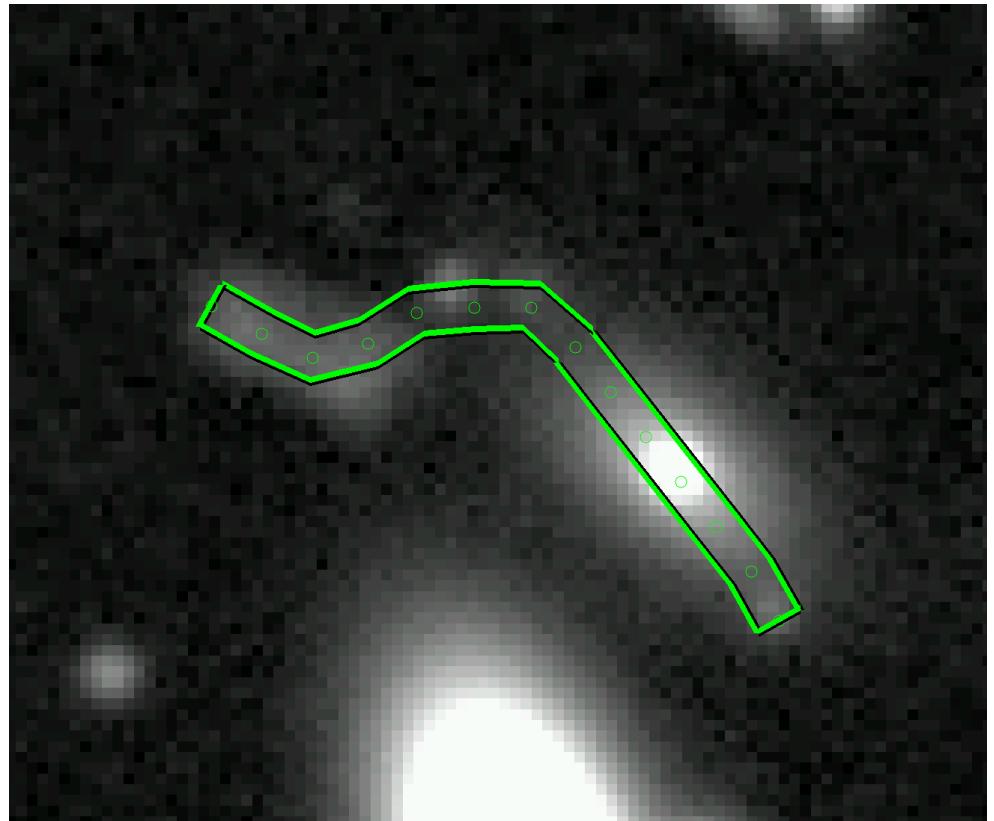
$$c^k = \frac{1}{N} \sum_{j \in N} c^{kj}$$

**for all cells**

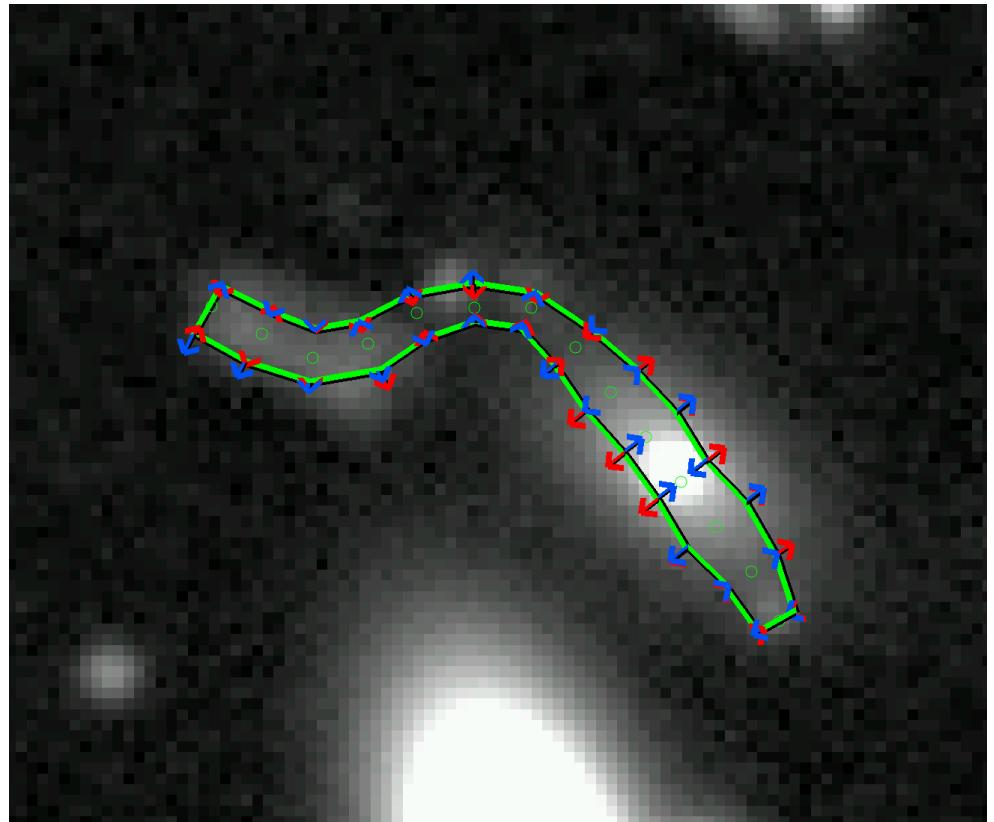
- **assemble objects using friend of friend method**



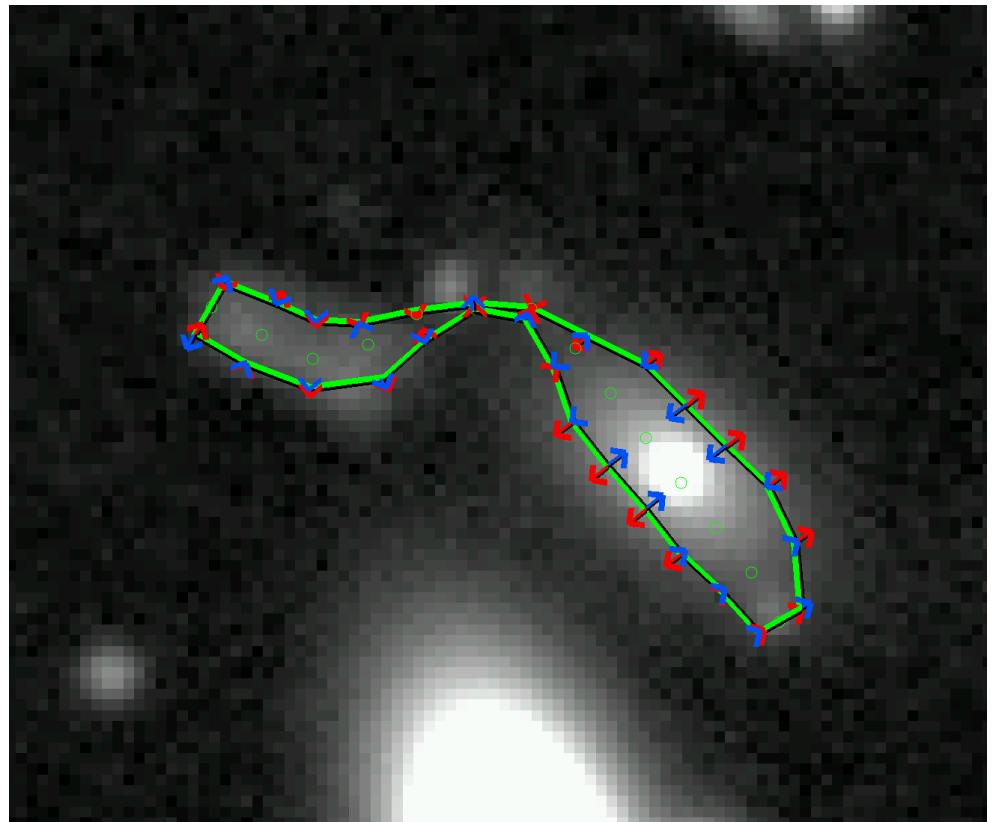
- initialise contours
  - (1) Delaunay triangulation on object cells
  - (2) find minimal distance route with Dijkstra algorithm
- evolve basic contours into isophotes using active contour segmentation
- determine shape parameters, i.e. length, length to width ratio, curvature
- basic photometry, i.e. integrated flux, signal



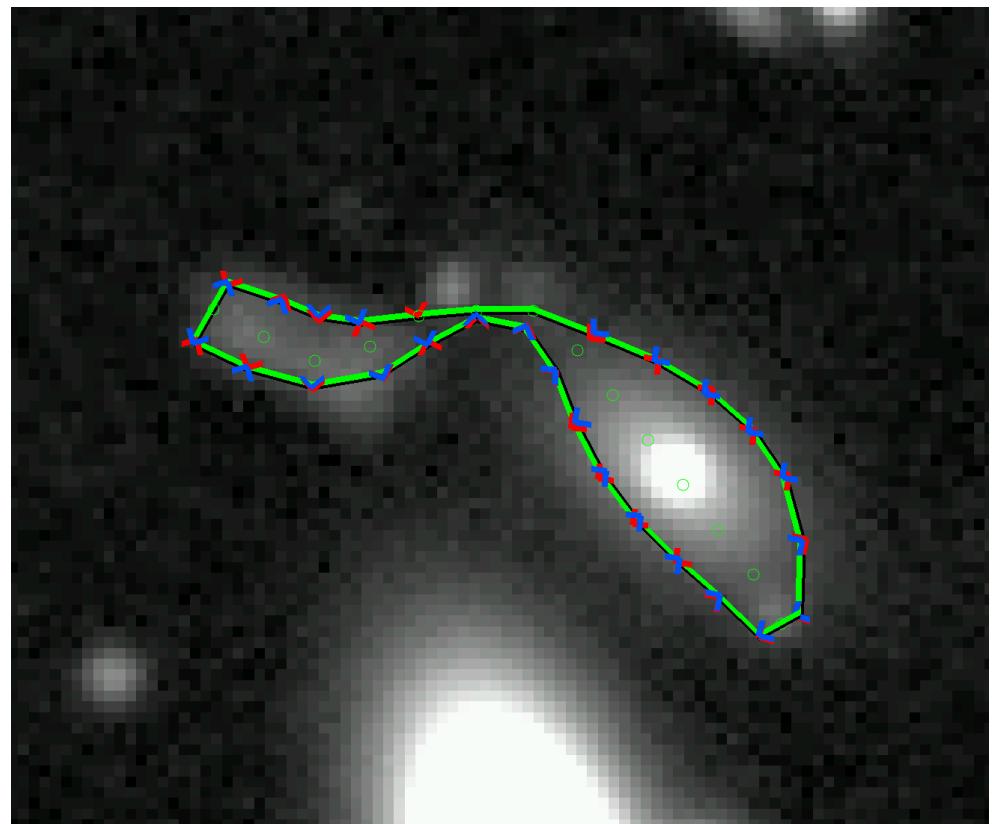
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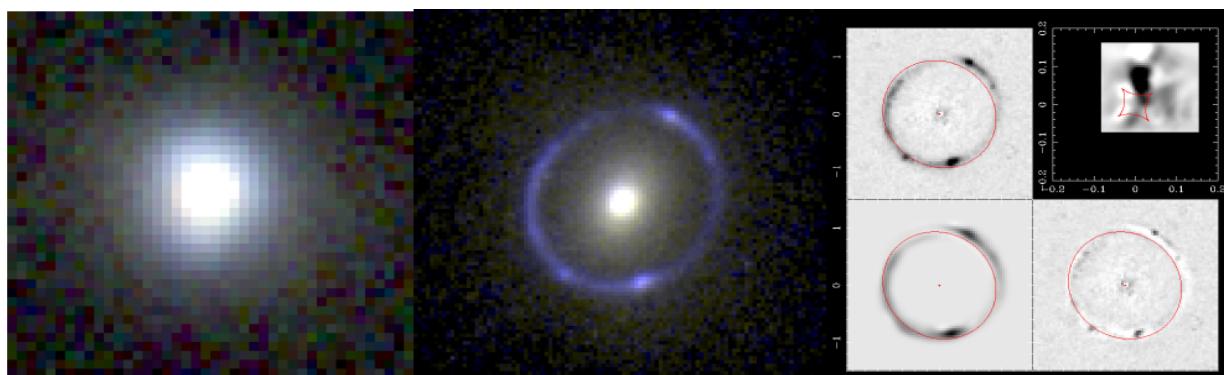
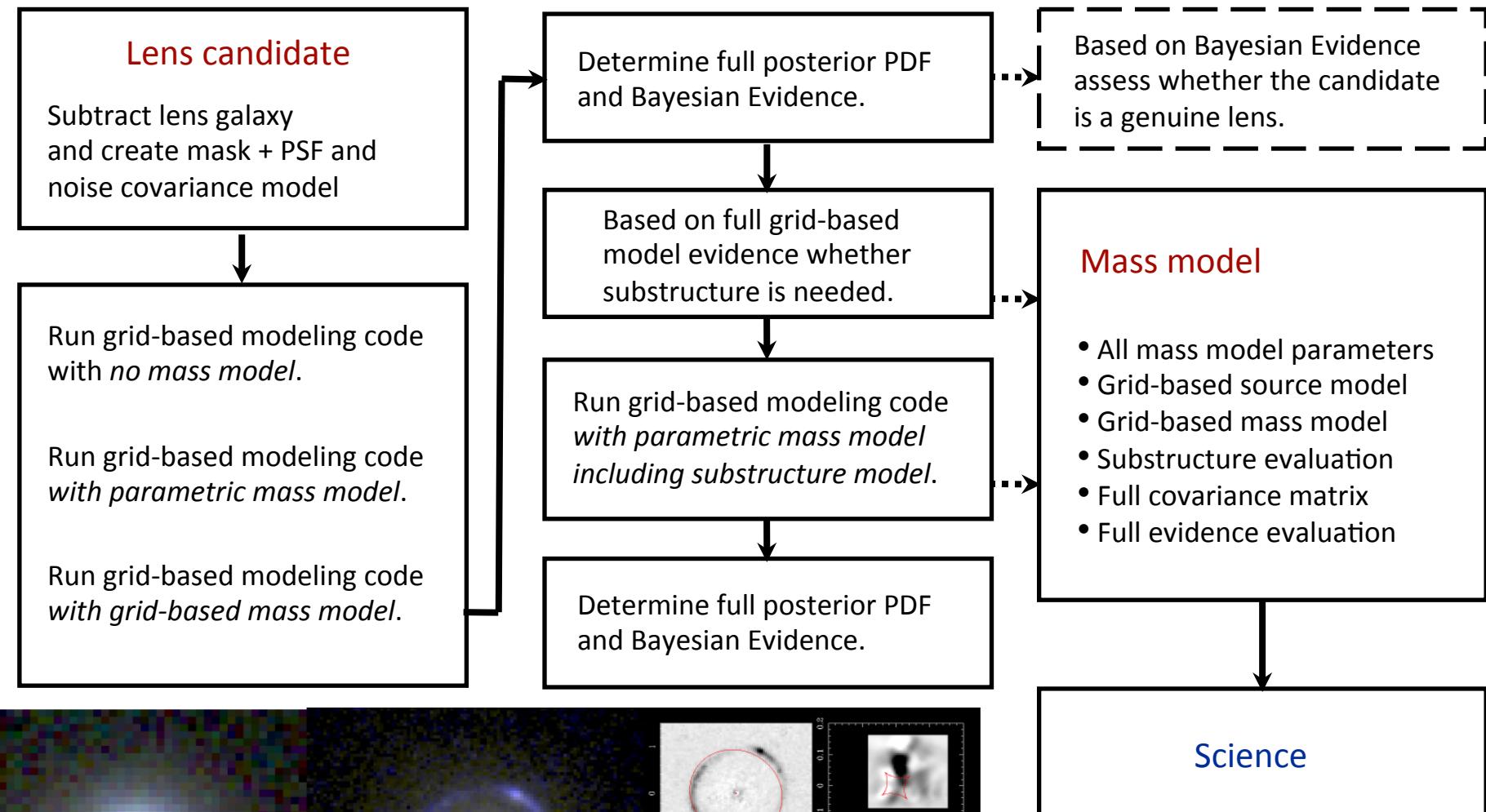


- initialise contours
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- determine shape parameters, i.e. length, length to width ratio, curvature
- basic photometry, i.e. integrated flux, signal



final contour (20 steps)

# Lens Modeling Pipeline



# Coordinated follow-up

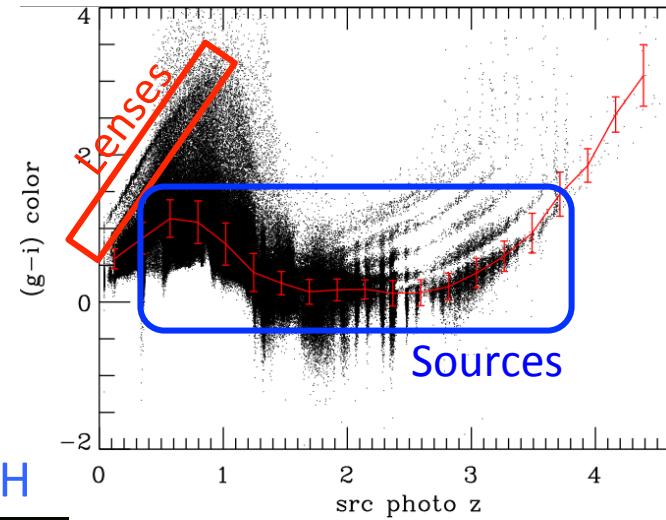
- Ground-based multi-color data (from OU-EXT)
  - ✓ Lens/Source SEDs and stellar masses/IMFs (via stellar-pop. analysis)
  - ✓ Improved photo-z's where needed.
- Ground-based spectroscopic follow-up (bottleneck -> photo-z, *golden samples*)
  - ✓ Slit/IFU Kinematics
  - ✓ Study of the stellar components of the lens and source
  - ✓ Redshifts
  - ✓ Study of lensed QSOs
- Ground-based AO
  - ✓ Higher spatial resolution for e.g. lens modeling & substructure studies
- Space-based follow-up: ....
- Radio/submm/FIR/....
- More ...

# *Simulation needs*

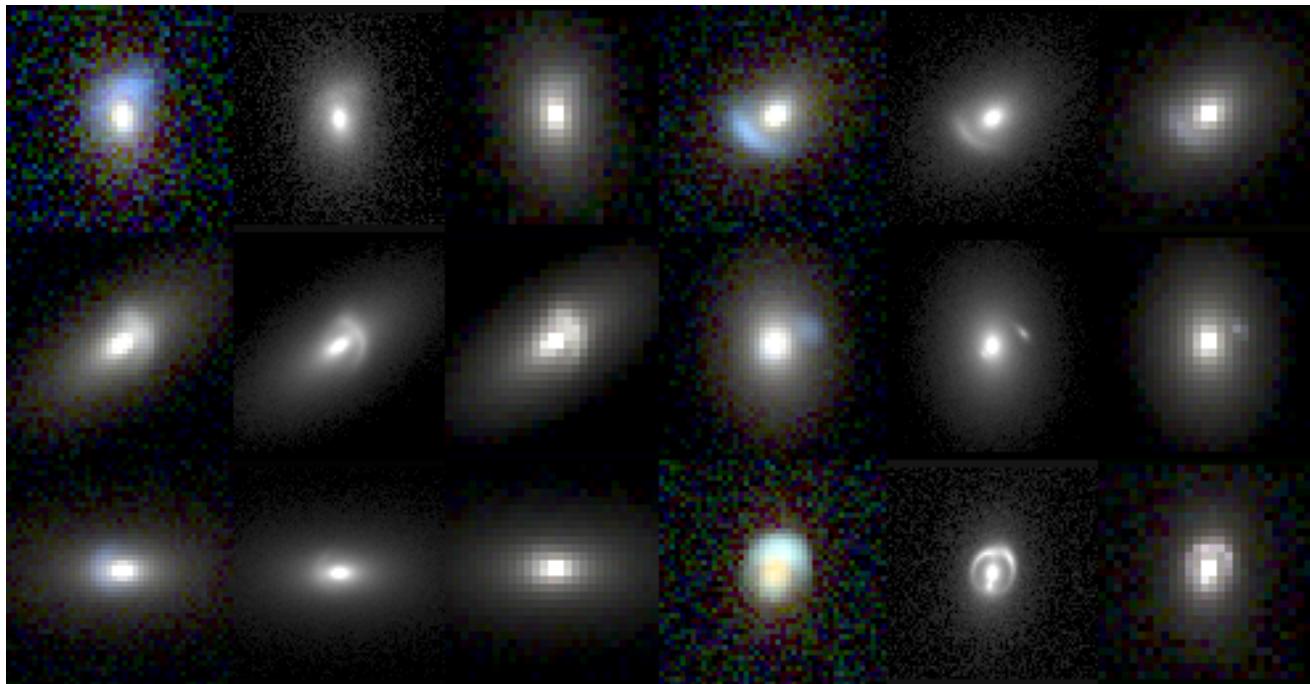
# Fast galaxy-scale SL sightlines constructor, sl\_mock

- Population of lenses and sources from catalogue
- Light-mass relation (eg, Fundamental Plane + SIE)
- Catalogue provides full covariance z, size, mag, color (COSMOS)
- As sources are extended, a strong lens obeys  $\mu_{\text{tot}} > 4$ .
- Can mimic Ground (CFHTLS) and space (HST, Euclid) observations.
- Can predict important statistics (magnification PDF, Rein PDF)
- Produces several such lines of sight per second !!

*Gavazzi et al (in prep)*

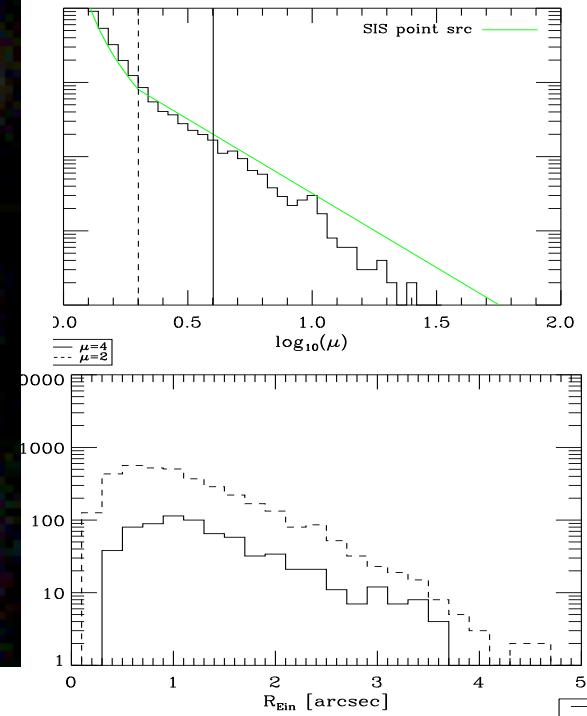


CFHTLS-w VIS YJH CFHTLS-w VIS YJH

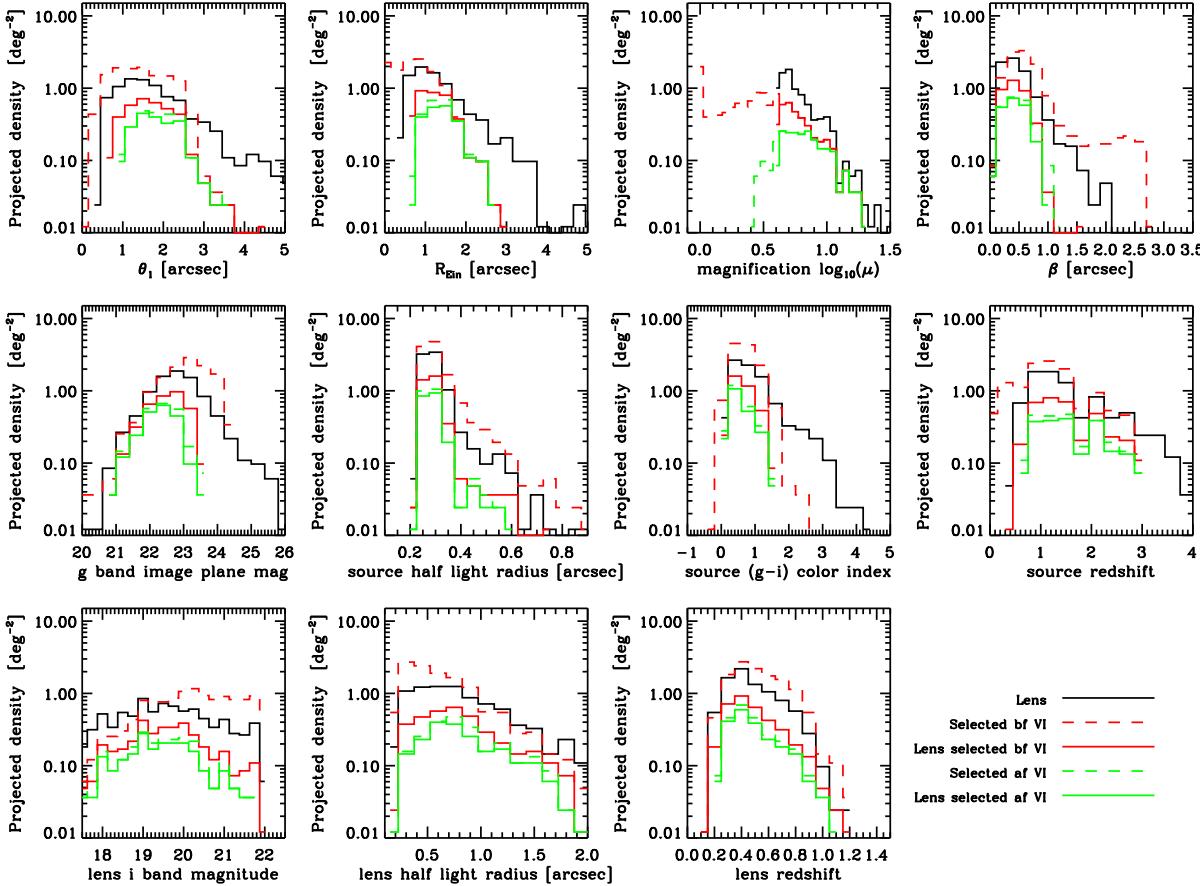


13/05/13

Euclid consortium meeting, Leiden



- Can test performance of a given lens finder
- Useful to control selection effects and improve detection methods.
- SI\_mock currently lacks
  - large scale environment of lenses
  - complex light distributions (both for the source and deflector)
  - Multiple deflectors -> and eventually groups/clusters



### Example:

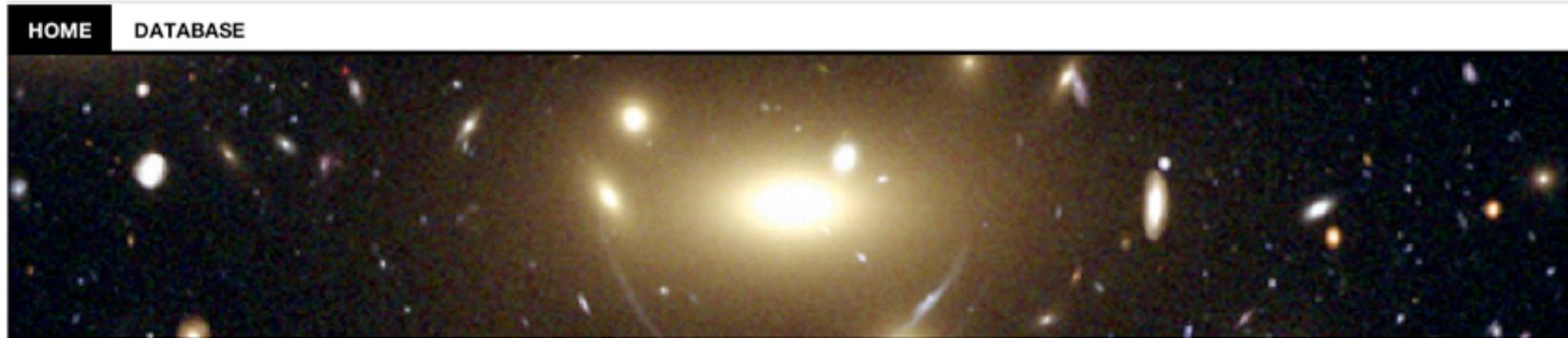
RingFinder: *Gavazzi et al (in prep)*, application to CFHTLS-wide

	$\mu > 4$
# of existing lenses	8.6
q_flag	$\geq 0$ $\geq 2$ $\geq 3$
# of selected candidates	12.5   6.4   2.5
# of selected lenses	3.6   3.4   2.1
completeness (%)	42   39   25
purity (%)	29   53   86

Purely automated      Visual inspection

# Bologna Lens Factory

## Bologna Lens Factory



### PAGES

- [Database](#)
  - [Fields](#)
  - [Galaxy Clusters](#)
  - [Millennium Tests](#)

### Home

The people mainly involved in this project (in alphabetical order) are:

- [Fabio Bellagamba](#)
- [Carlo Giocoli](#)
- [Massimo Meneghetti](#)
- [Robert Benton Metcalf](#)
- [Margarita Petkova](#)

### CODES

- [GLAMER \(Internal\)](#)
- [MOKA](#)
- [SKYLENS](#)

### USEFUL LINKS

- [EUCLID Consortium](#)
- [GLENCO Group](#)



INAF



OaBO



ERC  
Established by  
the European Commission



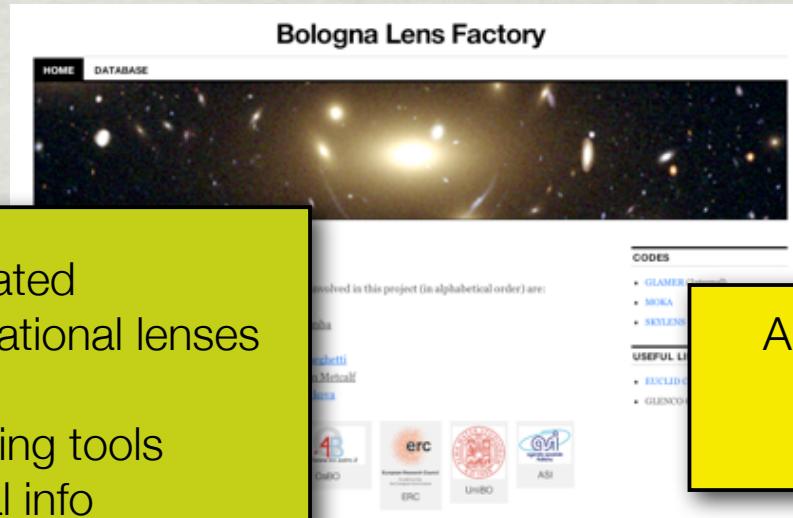
UniBO



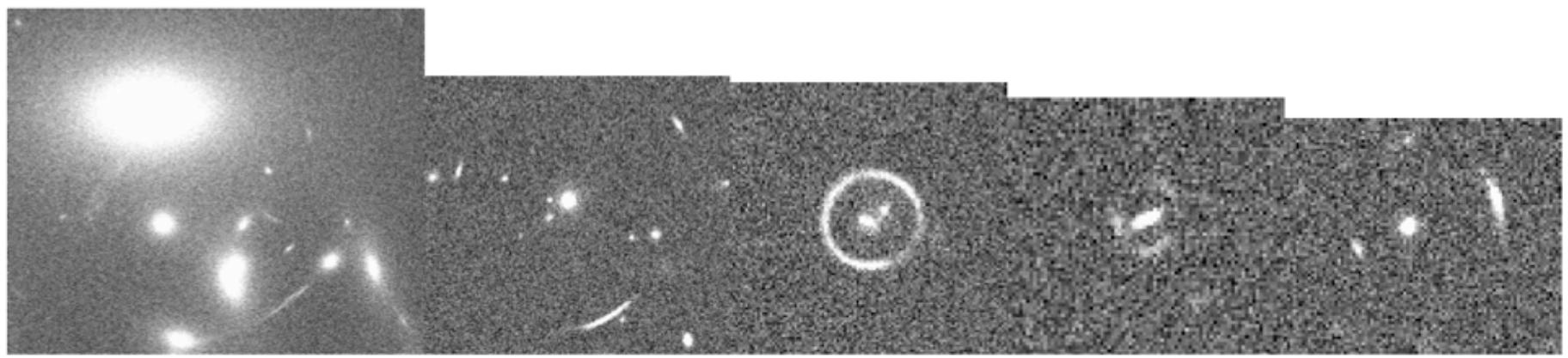
ASI

# BLF project

- a database of simulated observations of gravitational lenses
  - testing arc finders
  - testing mass modelling tools
  - extract cosmological info



A project part of the  
activities of the  
**Euclid SLWG**



# Bologna Factory Tools



**MOKA**: produces realistic lenses

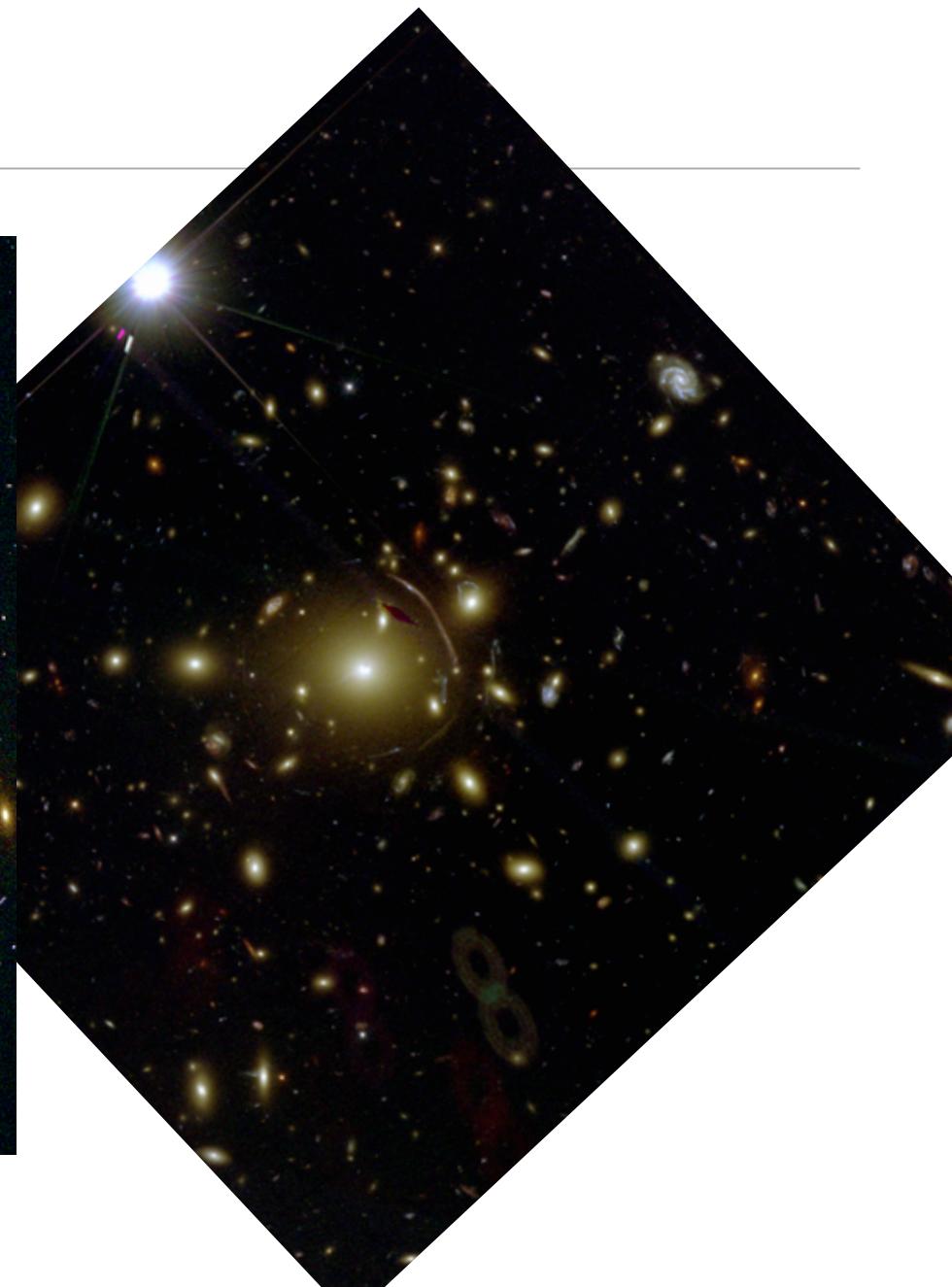
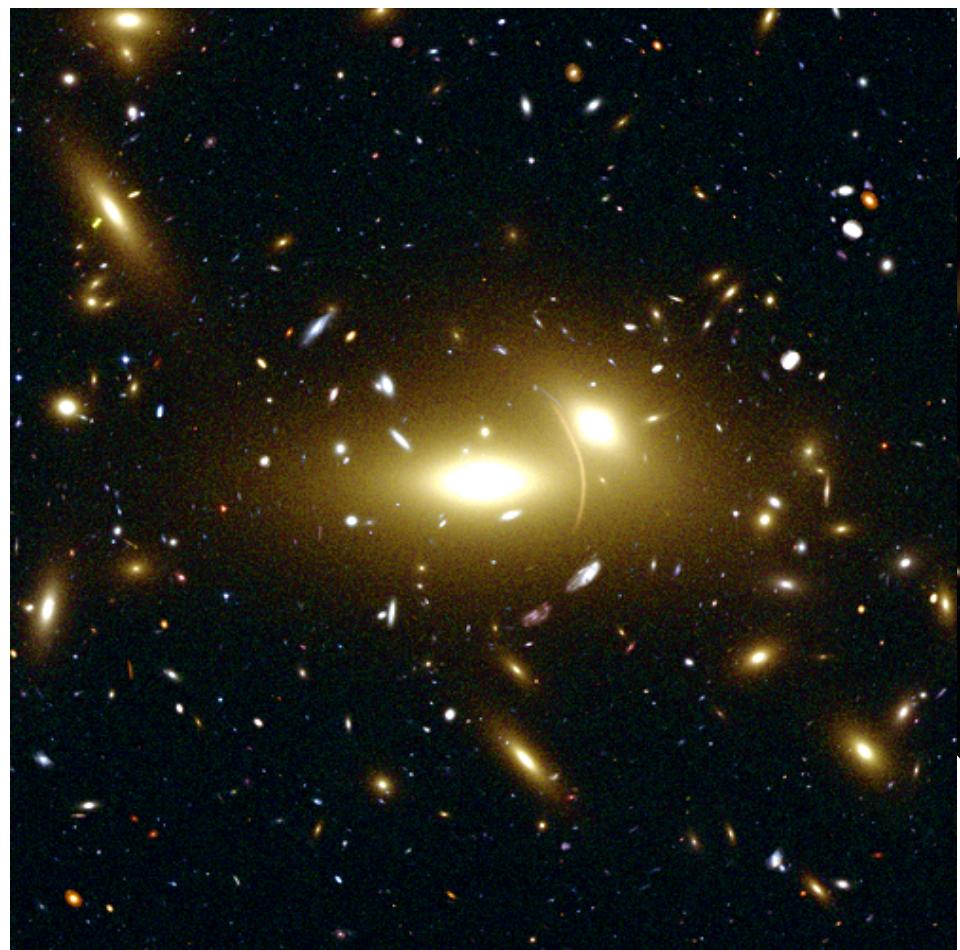
**SkyLens**: produces simulated observation using MOKA deflection angle maps, and info about host and galaxy populations

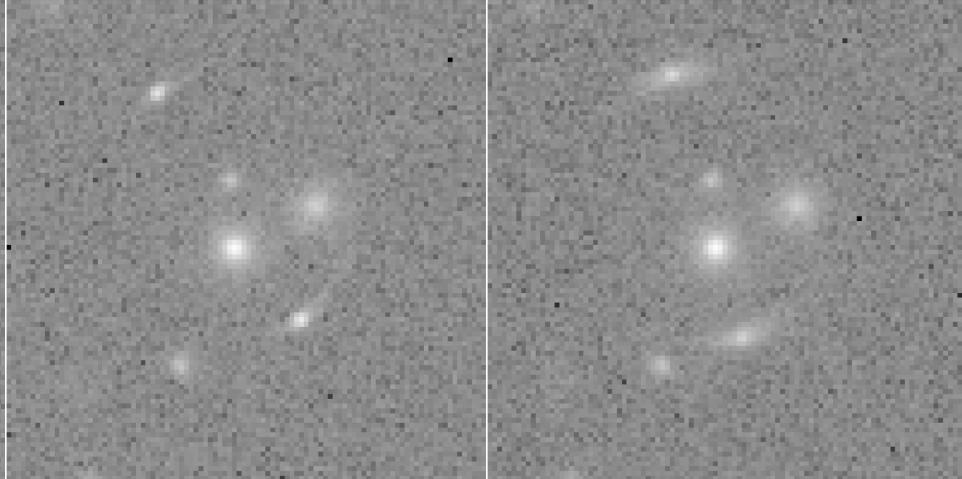
**GLAMER**: produces simulation of lenses and galaxy-galaxy lens simulated observations, and interloper effects

**PSFing and noising**: introduces “noise” to the simulated observations

# Example: A383

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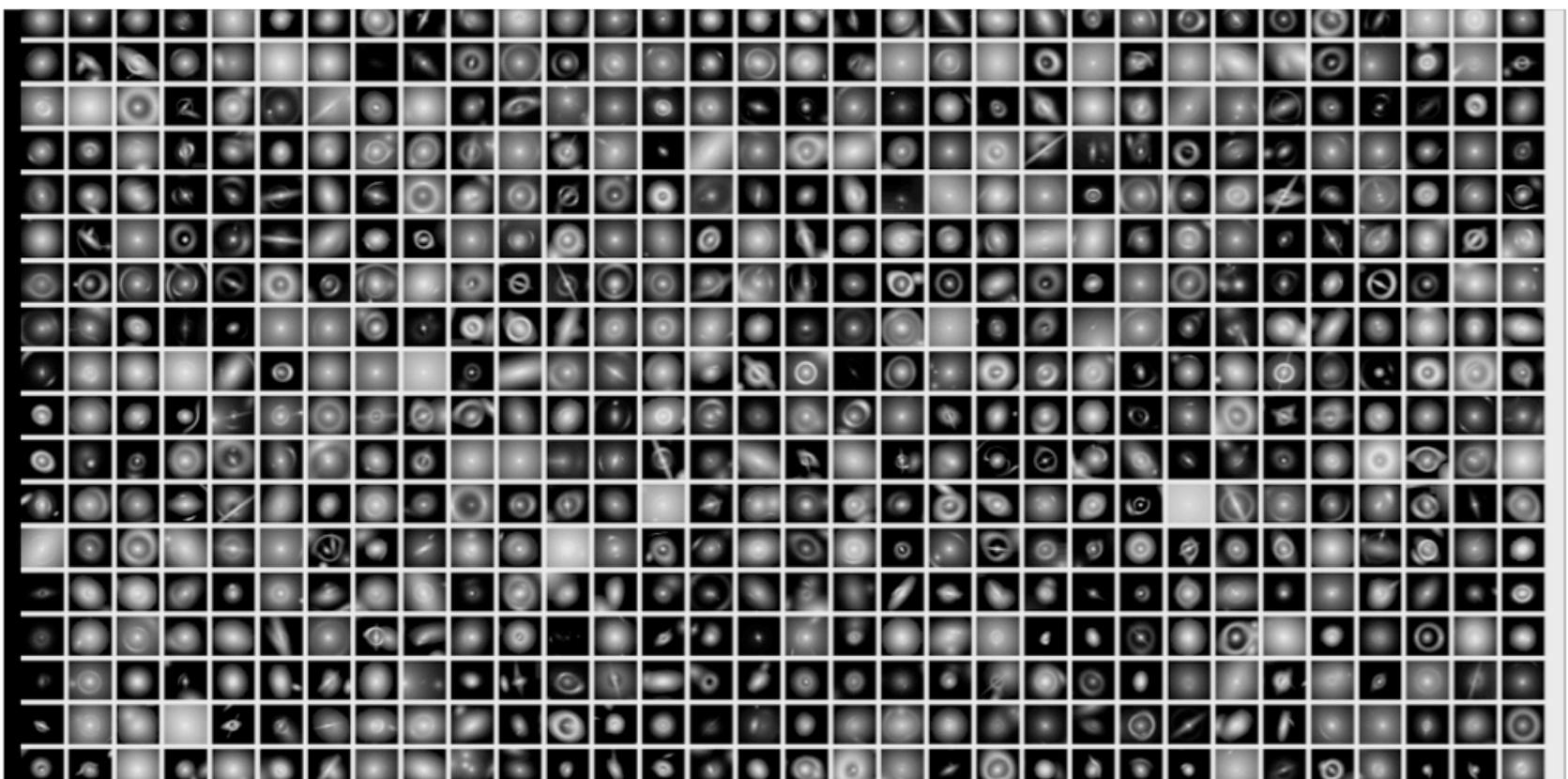




Same compound lens, different sources

Many different lens+source configurations

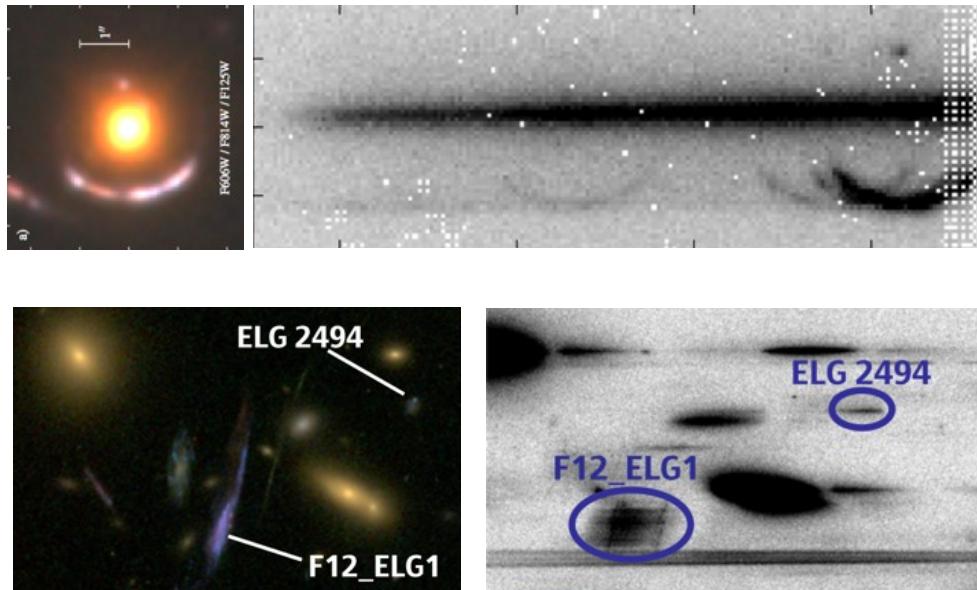
BLF, Metcalf



# NISP data

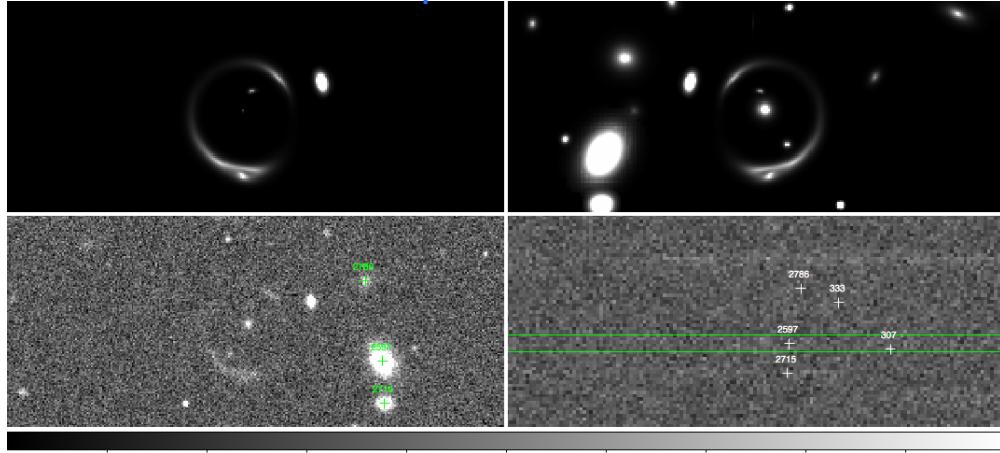
Brammer et al.

- Grism spectroscopy potentially useful
- If  $3000 \text{ z/deg}^2$ , about 1% of VIS lenses (ie  $\sim 2000$ ) will get redshift from Euclid alone
- Powerful for detection (a la SLACS) ??? TBD
- Simulations (Jullo, Zoubian, Atek) underway.



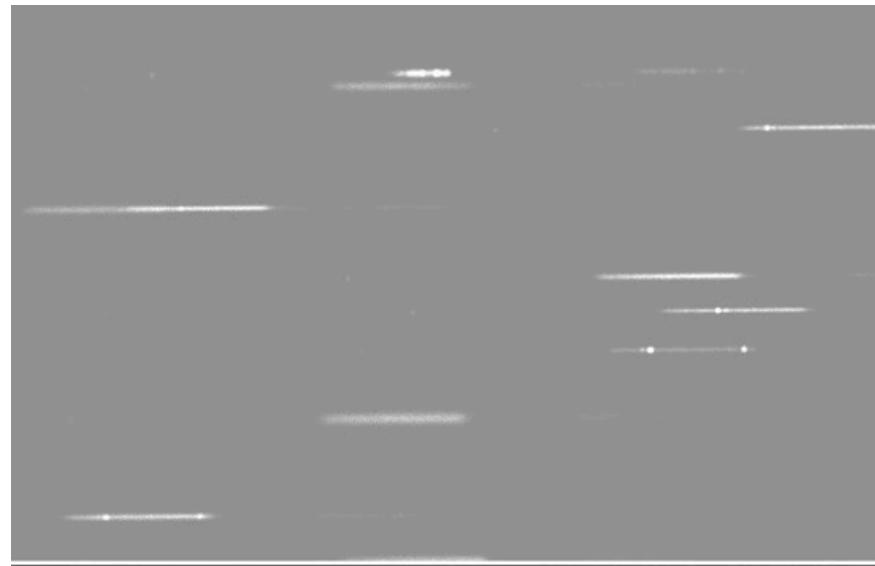
Frye et al. 2012

Crude dispersion of BLF simulations



Redshift #2597 : 0.3127, mag\_i = 21.9

Redshift source : 4.146, mag\_i=24.0



# Conclusions

*Number of strong lenses with rise by orders of magnitudes allowing*

- *detailed evolution studies of massive galaxies (out to  $z \sim 1$ ) of various types*
- *to find thousands of lensing clusters with exquisite mass properties  
great natural telescope for the high- $z$  quest!*
- *Still a lot to be done... We need you!*