Euclid Strong Lensing SWG

R. Gavazzi, (IAP)

Euclid France meeting, Paris, *7-8 jan. 2016*

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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

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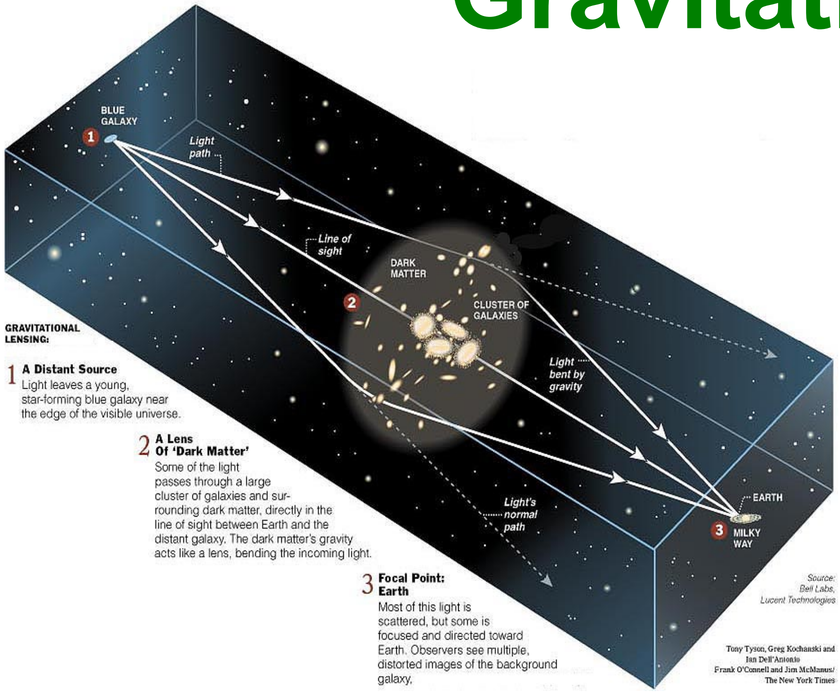
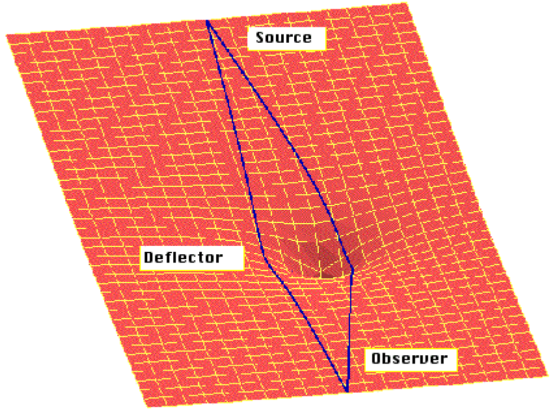
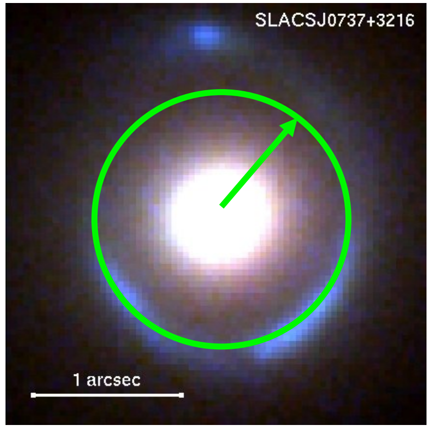
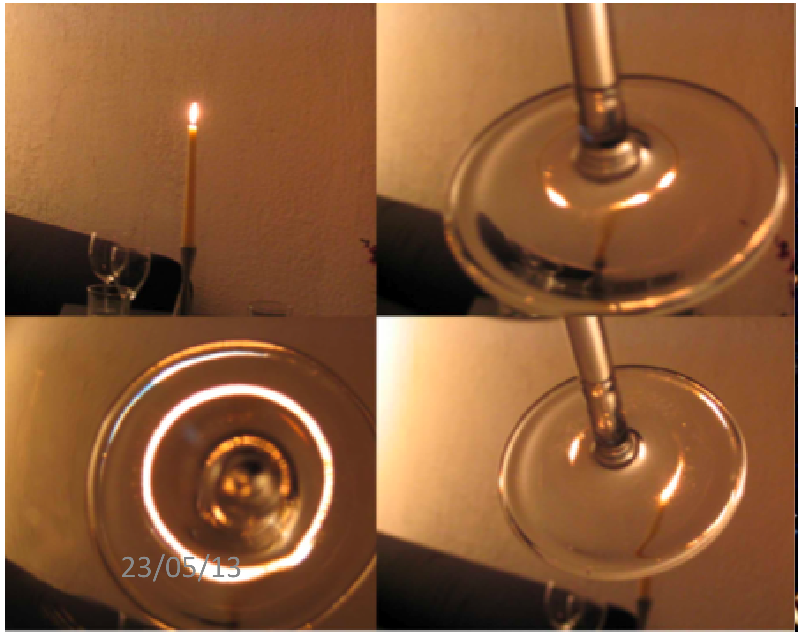
Gravitational Lensing

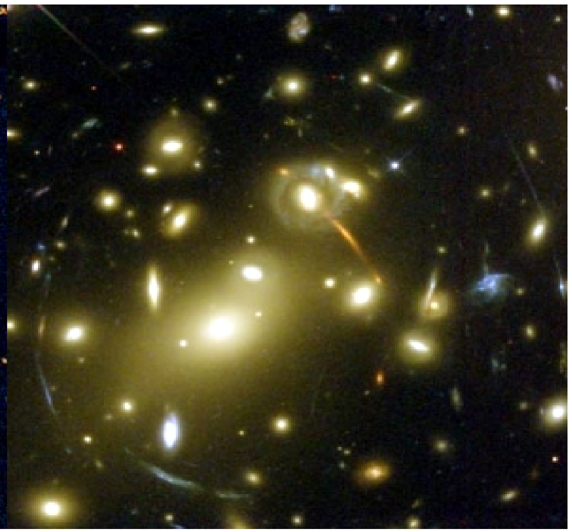








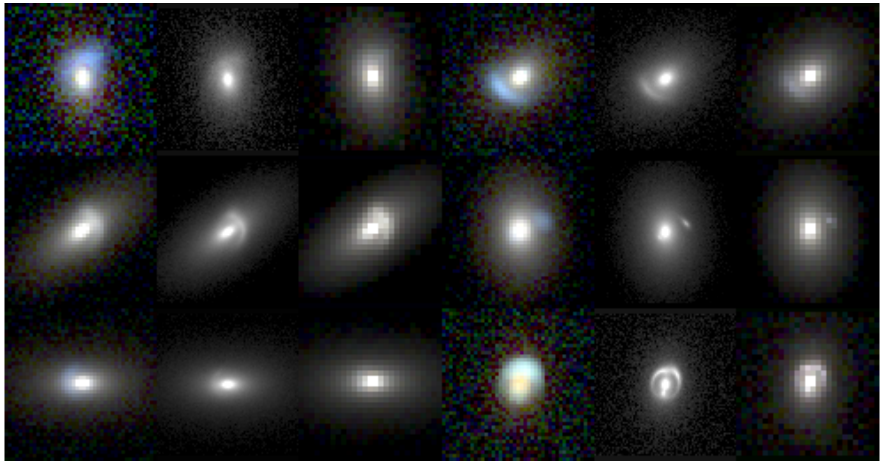
Strong lensing regime!



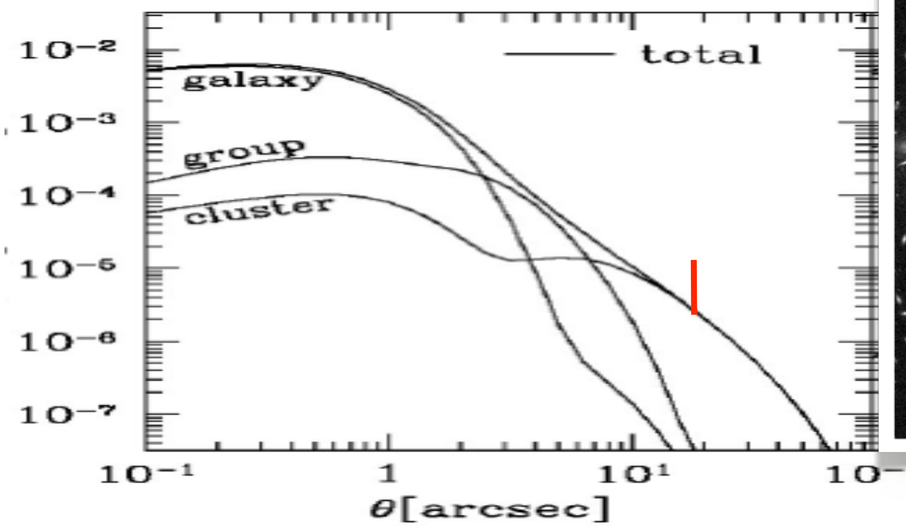
SL Expectations from Euclid

General Predictions:

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



CFHTLS-like / EuclidVIS and Euclid YJH idealized sims



Distribution of splitting angles (2x Einstein radius) Oguri 2006

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,NI*,…)**
    - Find galaxy-scale lenses
    - Find group/cluster-scale elongated arcs

    So far, sole aspects covered at the OU-SHE strong lensing WP level (SDC-CH)

- **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**

    Simplest instrumental signatures internally addressed (*sl_mock*, *BLF*)
    Eventually connection with OU-SIM?

Euclid Strong Lensing SWG activities

Work Package Definitions -- Draft - 04062014

- WP 1 -- Theory: produce forecasts and interface models with strong lensing observations [link to THWG] (Leonidas Moustakas, Carlo Giocoli)

- WP 2 -- Strong lensing by galaxies: define and develop the science cases for galaxy-galaxy and galaxy-QSO lensing [link to GEWG] (Neil Jackson, Stephen Serjant)

- WP 3 -- Strong lensing by galaxy clusters: define and develop the science cases for lensing by galaxy clusters [link to CGWG, WLWG, PEWG] (Jean-Paul Kneib, Raphael Gavazzi)

- WP 4 -- Likelihood: define methods for extracting cosmological information from strong lensing data and combine SL with other probes (Anais Rassat, Eric Jullo)

- WP 5 -- Exotic lenses: search and study exotic lenses (Phil Marshall, Giovanni Covone)

- WP 6 -- Image simulations: develop image simulations for supporting the activities of the group and of the ground segment [link to OU-SIM, WLWG] (Ben Metcalf, Massimo Meneghetti)

- WP 7 -- Modeling: develop methods for reconstructing strong lenses on galaxy and cluster scales (Ben Metcalf, Leon Koopmans)

- WP 8 -- Lens finders: search and classify strong gravitational lenses [with OU-SHE] (Gregor Seidel, Phil Marshall, Fred Courbin)

Lens Selection Pipeline (SGS)

• Automated selection pipeline based on multi-scale postage stamps of VIS-IR-EXT data and existing photo-z catalog (PHZ)

- ✓ 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 Hα 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!

Lens Modeling "Pipeline" (SWG)

Lens candidate (SGS)

Subtract lens galaxy
and create mask + PSF and
noise covariance model

Run grid-based modeling code
with *no mass model*.

Run grid-based modeling code
with parametric mass model.

Run grid-based modeling code
with grid-based mass model.

Determine full posterior PDF
and Bayesian Evidence.

Based on full grid-based
model evidence whether
substructure is needed.

Run grid-based modeling code
with parametric mass model
including substructure model.

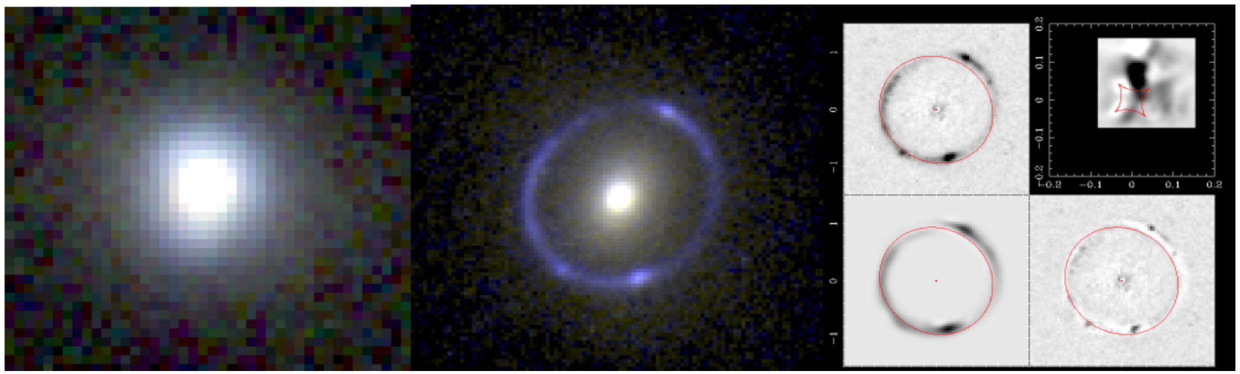
Determine full posterior PDF
and Bayesian Evidence.

Based on Bayesian Evidence
assess whether the candidate
is a genuine lens.

Mass model

- All mass model parameters
- Grid-based source model
- Grid-based mass model
- Substructure evaluation
- Full covariance matrix
- Full evidence evaluation

Science



Simulation needs

Bologna Lens Factory

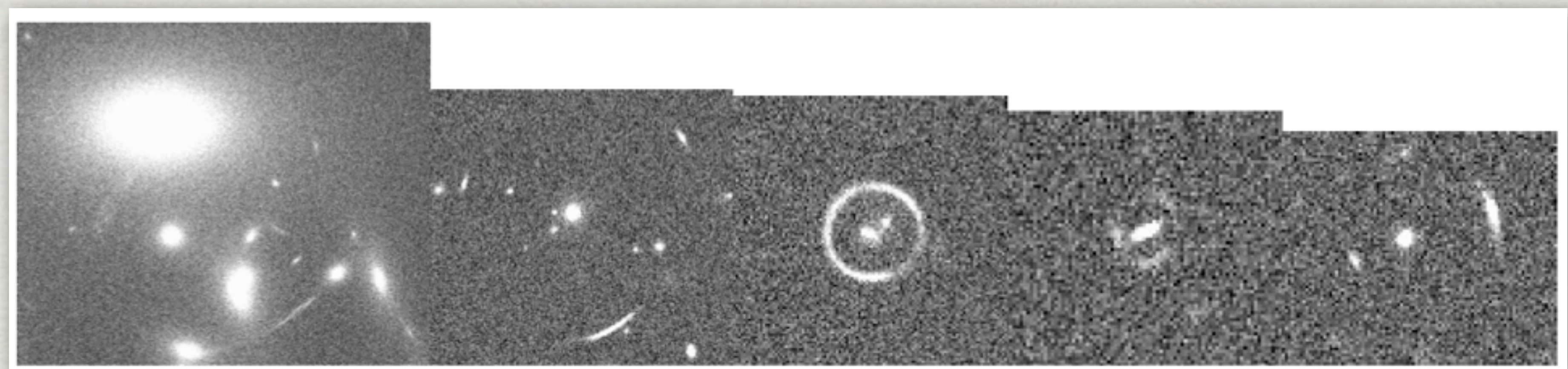
Metcalf, Meneghetti, Giocoli, Tessore,…

http://metcalf1.bo.astro.it/blf-portal/index.html

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

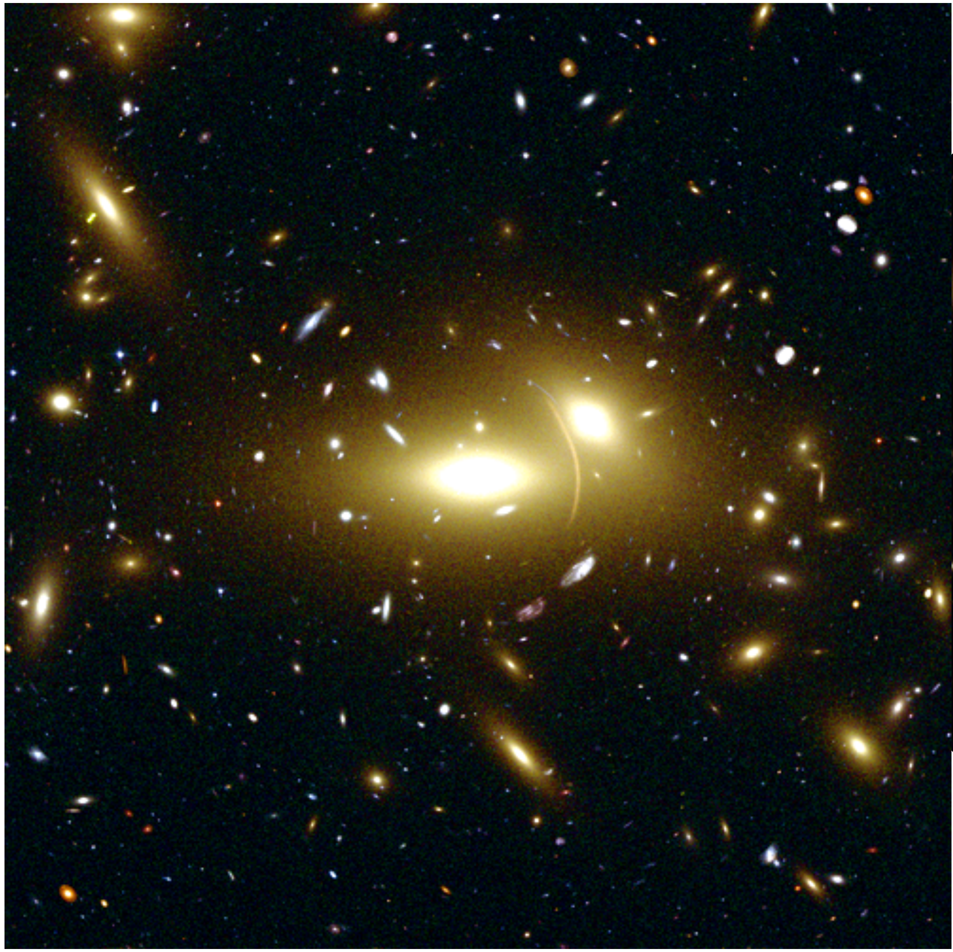
MOKA: produces realistic lenses

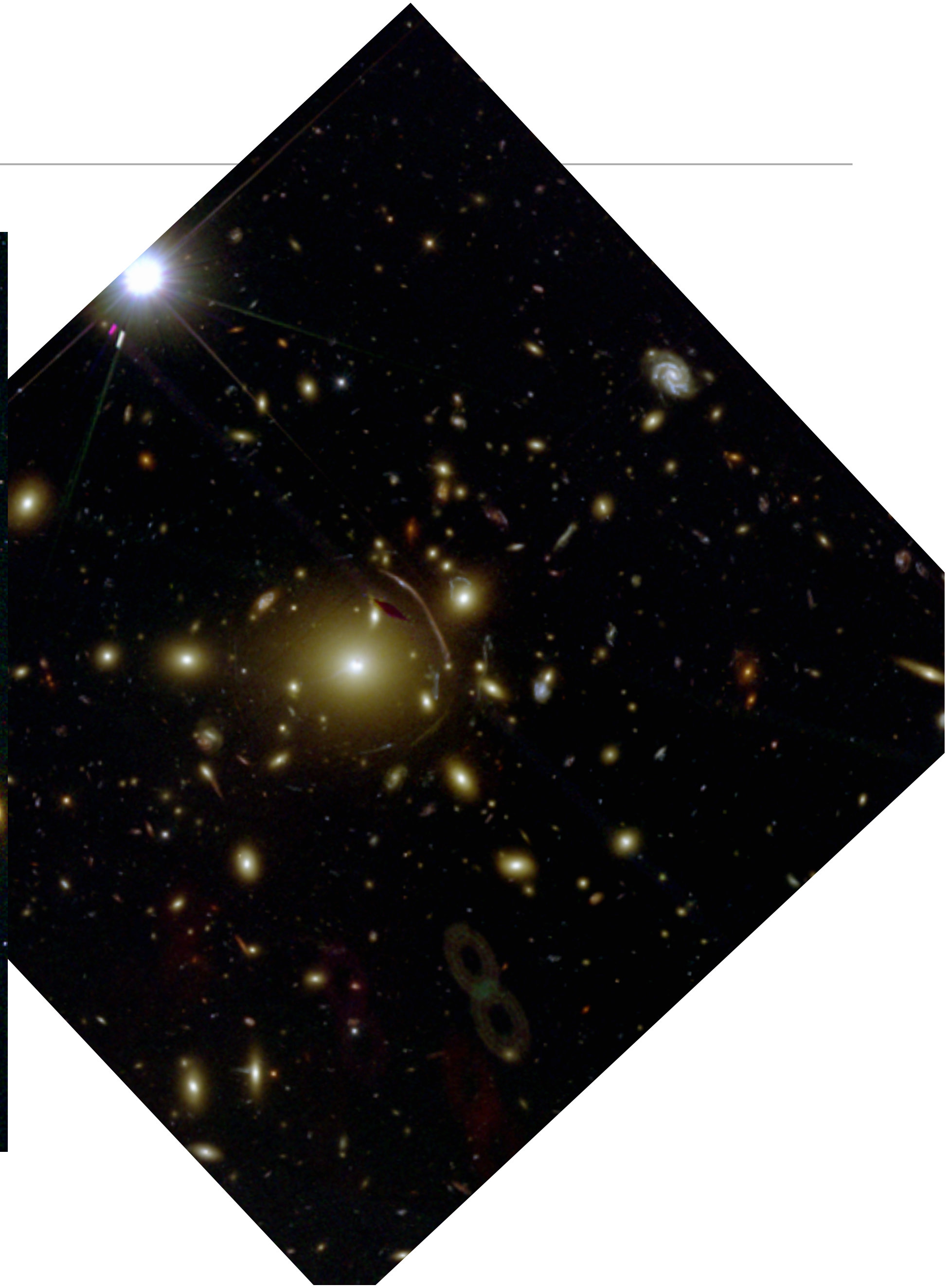
SkyLens: produces simulated observation using MOKA deflection angle maps, and info about host and galaxy populations

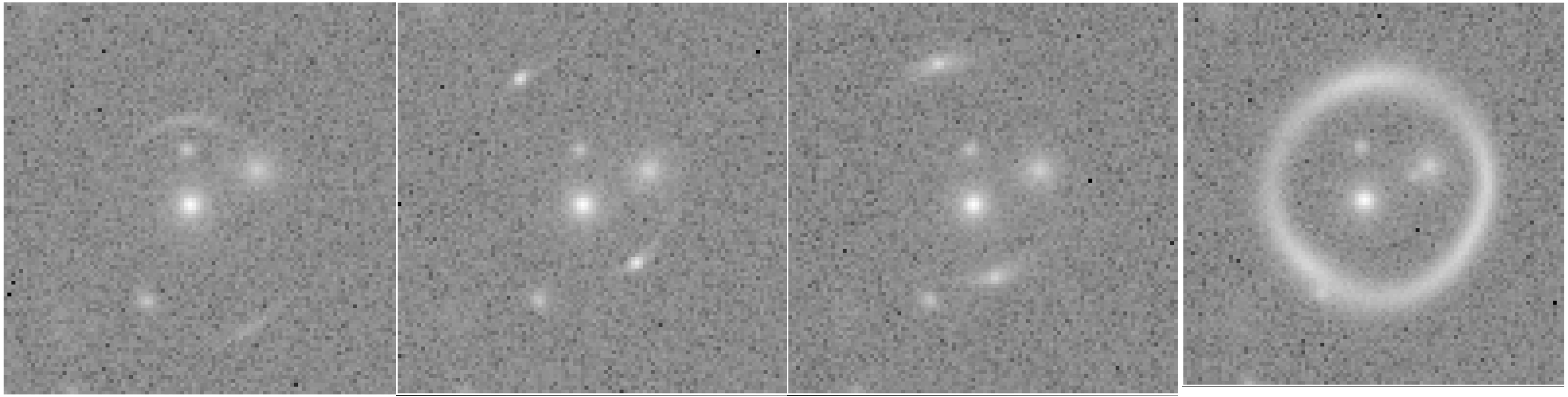
GLAMER: produces simulation of lenses and galaxy-galaxy lens simulated observations, and interloper effects

PSFing and noising: introduces "*noise*" to the simulated observations

Example: A383



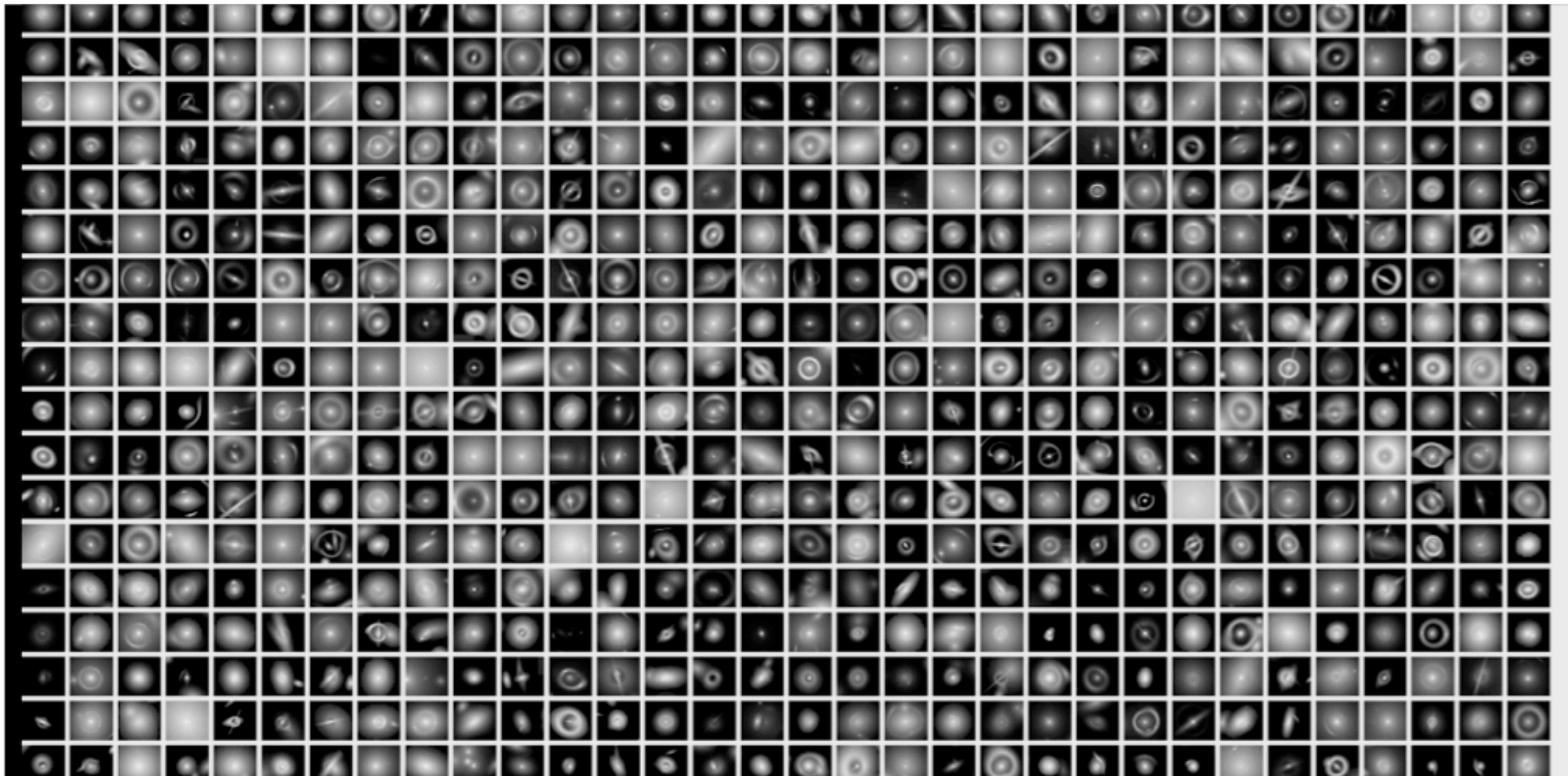




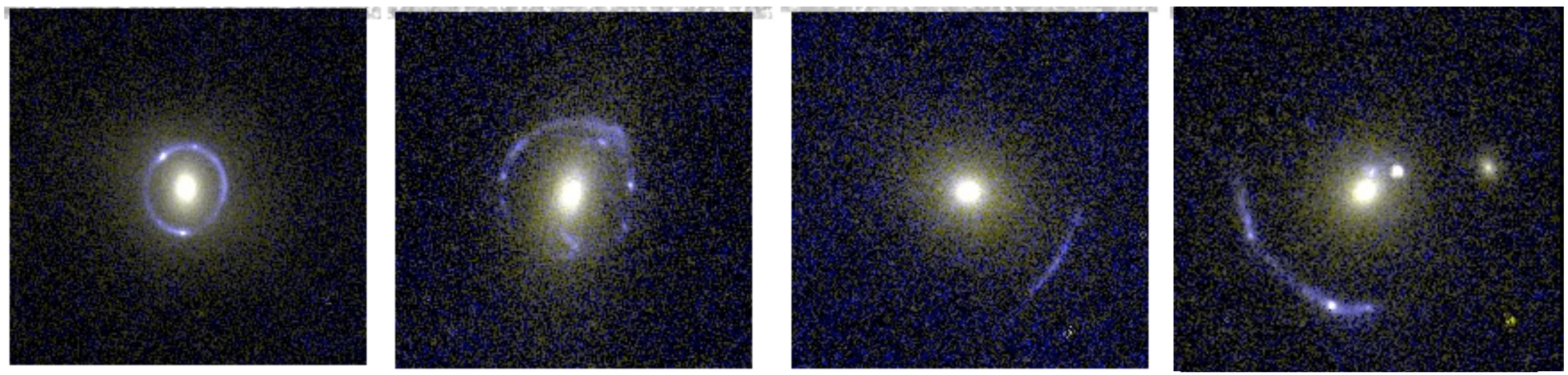
Same compound lens, different sources

Many different lens+source configurations

BLF, Metcalf



Galaxy Scale Strong Lenses

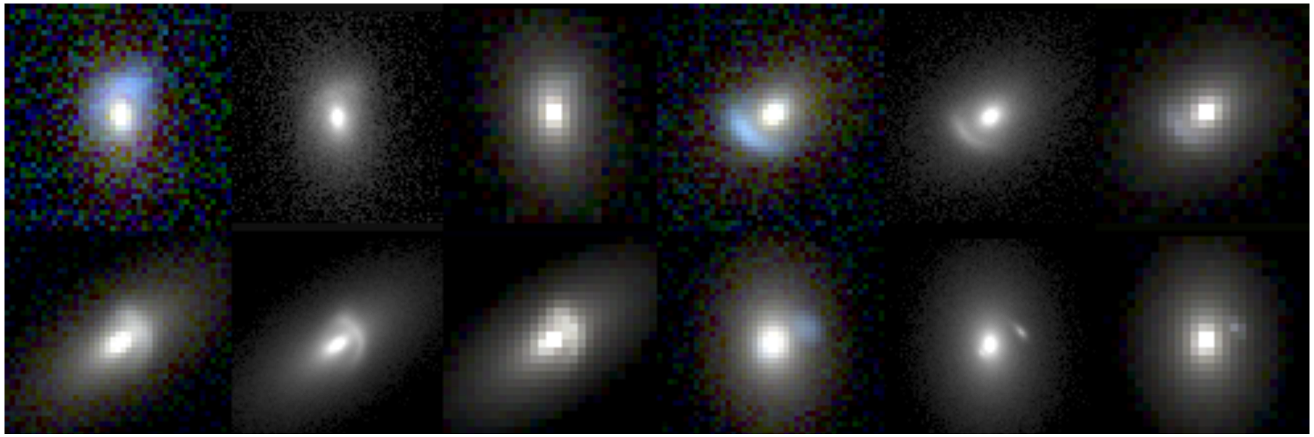


Galaxy-scale lens finders

goal:

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

- **4 flavors for ongoing method developments**
  - Model fitting : (Gavazzi) / "Lensed" (Metcalf) / (Koopmans)… single → multiband
  - Foreground subtraction + analysis of residuals… : RingFinder (Gavazzi) /PCA image subtraction (Courbin++), SVM (Jackson+)
  - Community classification (Marshall, Spacewarps in the vein of GalaxyZoo)



Short term Developments based on

- Improve algorithms
  - Multi-band analysis very likely to be the standard approach! (PCA, model fitting…)
  - Lens finders will probably work will VIS, NIR and EXT data.

- Application to more Wide-field imaging data:
  - KIDS (+VIKING to test benefits of NIR imaging) (Gijs Verdoes Kleijn, Leon Koopmans++)
  - Other ideas (CFHTLS, DES, …)

- Study of better simulations to prepare Lens Finding Challenge to assess performance of algorithms (completeness/purity) and help deciding which technics will go into OU/SDC implementation.

Metcalf/Meneghetti

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

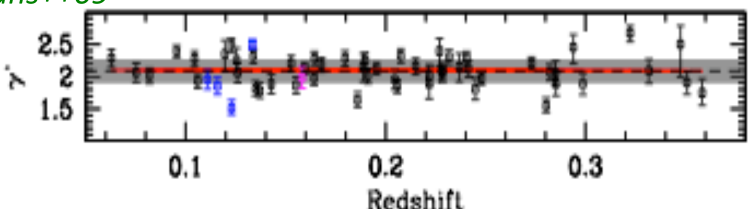
Galaxy Structure & Evolution

Total Density profile

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

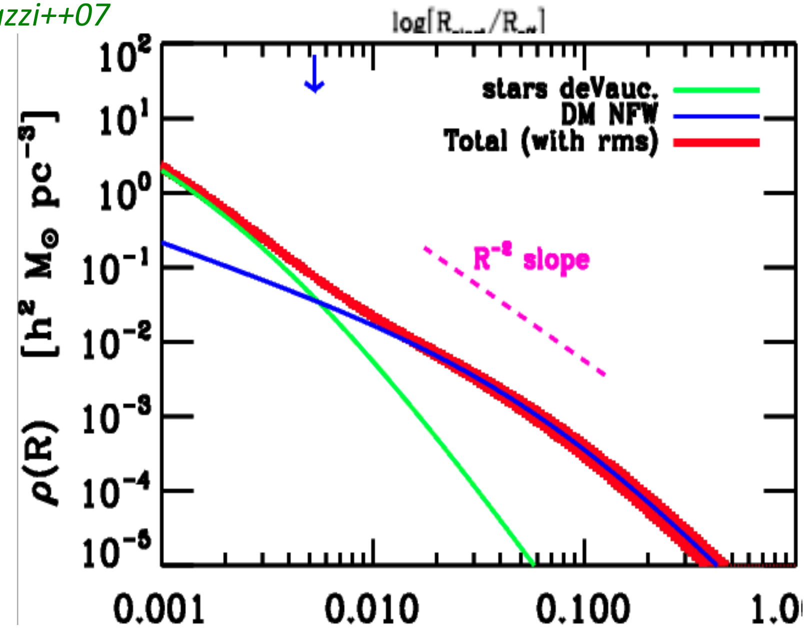
SLACS only

Koopmans++09



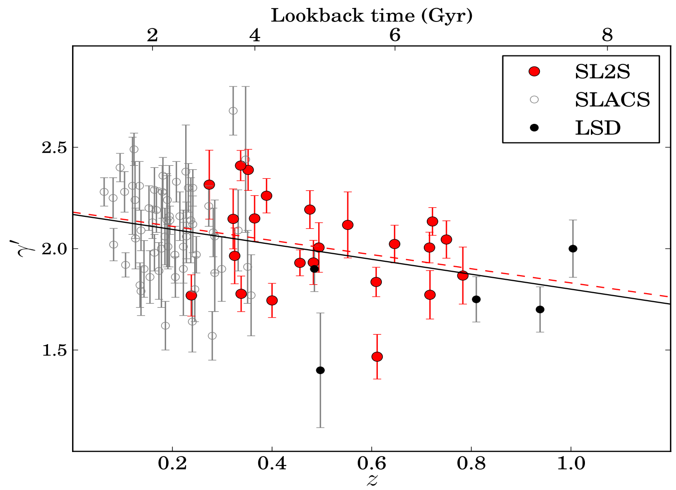
Isothermal behavior consistent with a mixture of stars and NFW dm halo

Gavazzi++07



SLACS+SL2S

Better handle on time evolution



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

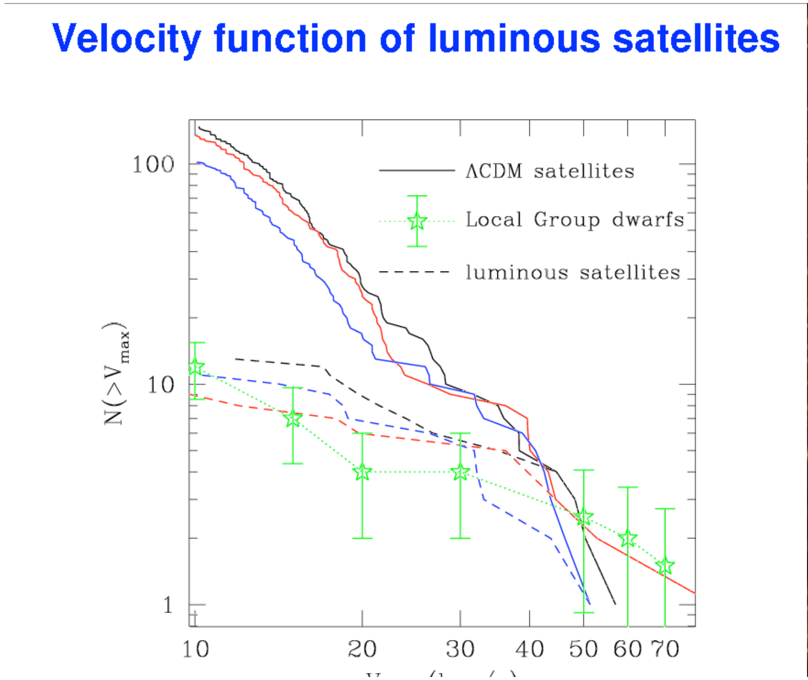
~3.5σ evidence for steepening of the total density profile with time with 33 SL2S lenses + SLACS+LSD. (See also Bolton++12)

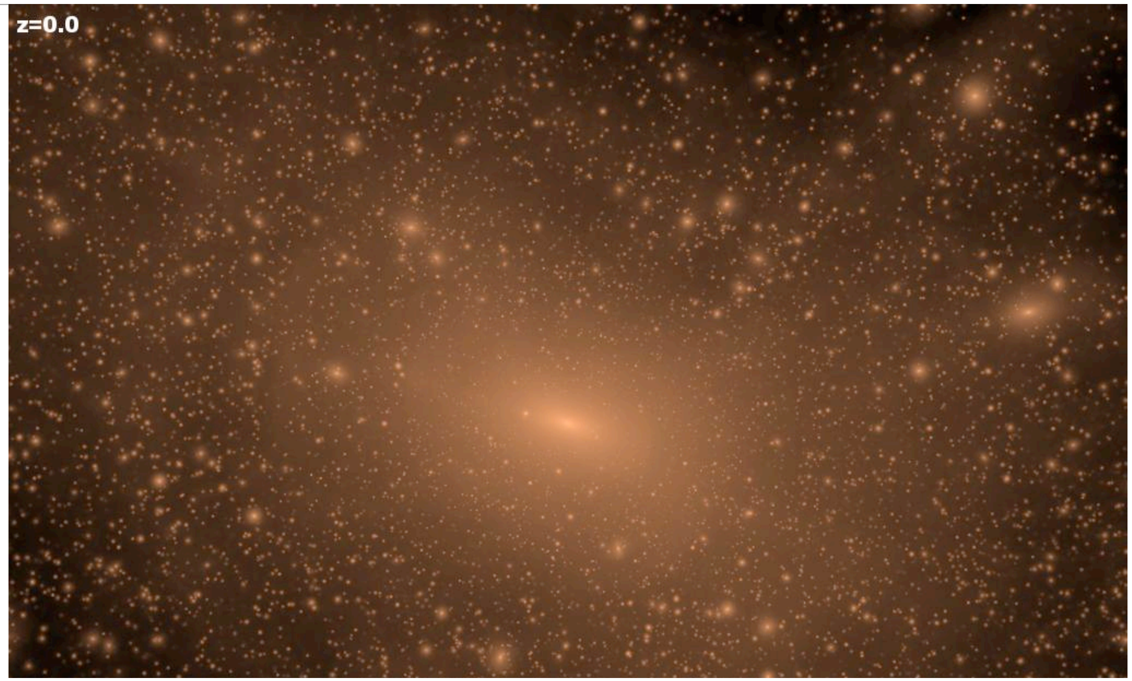
(CDM) Substructure

Some Science Goals:

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

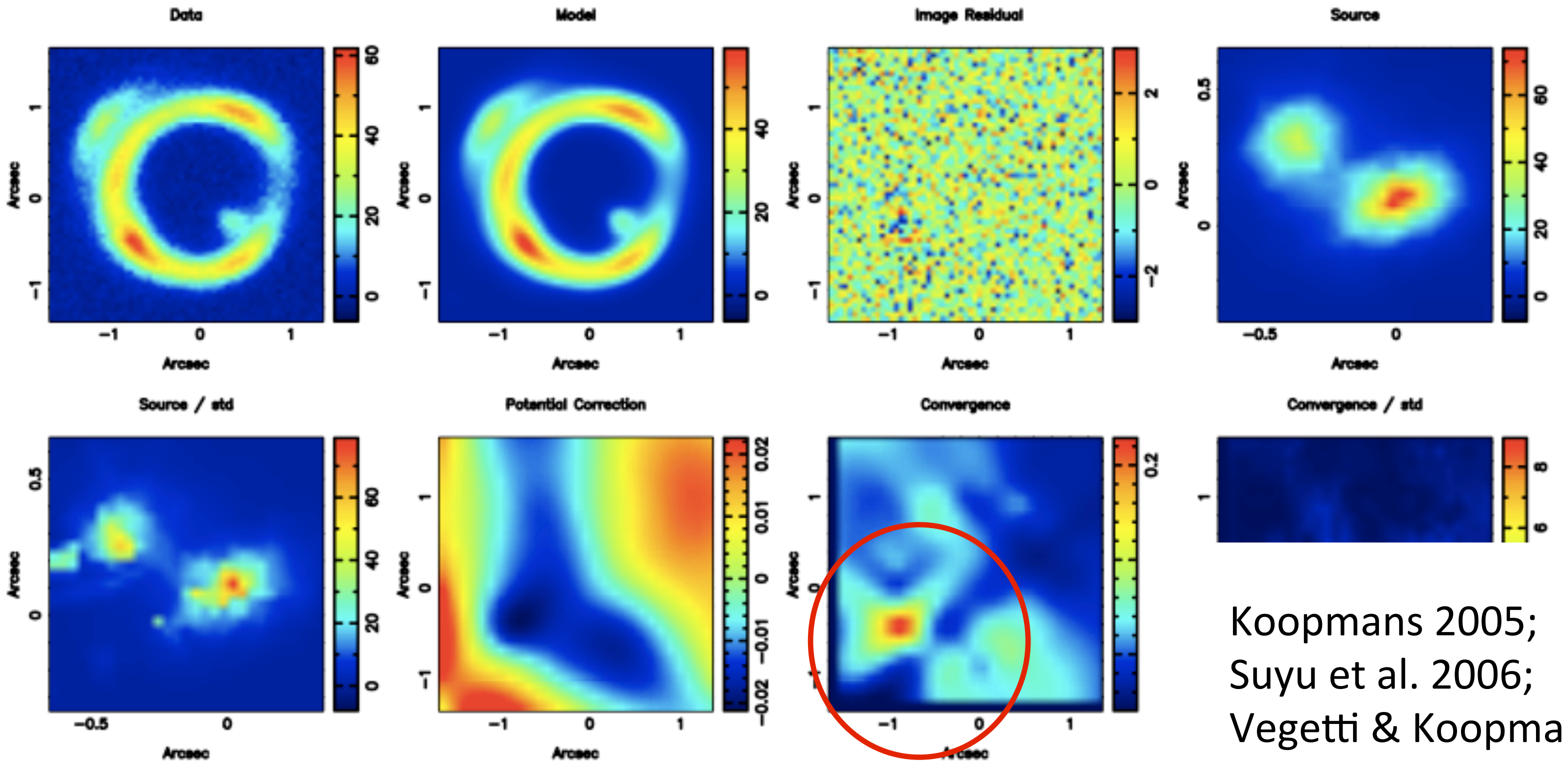
As a function of redshift, galaxy mass, type, etc.





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

Extended images provide complementary information



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

Vegetti et al. 2012, Nature

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

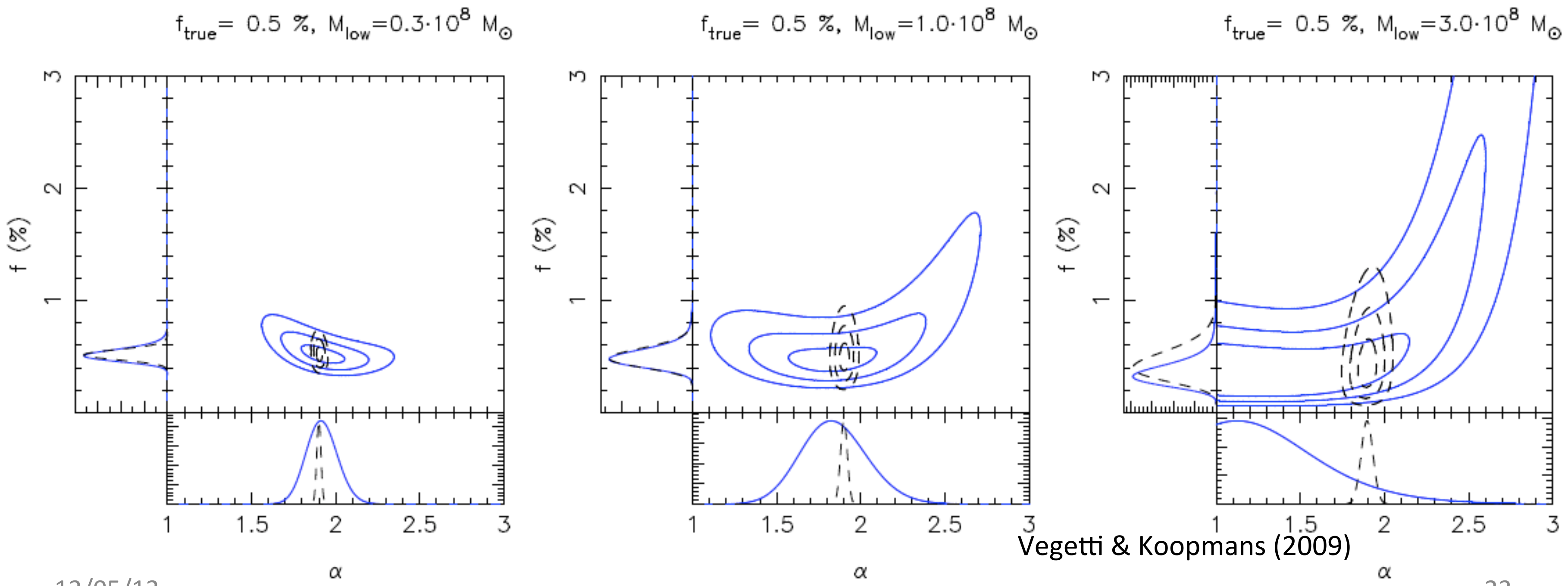
(CDM) Substructure

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

Already ~1000 EUCLID lenses of HST-like quality allow one to place limits

on the level of mass substructure in lens-galaxies beyond ~10^9 solar masses. (DEEP can provide!!).

Most of Euclid lenses would be more effective for Msub >~ 10^{10} Mo (below JWST, ALMA, SKA, VLBI, ELTs)



Vegetti & Koopmans (2009)

Cluster Scale Strong Lenses

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)
- **Toward the automation of Multiple images**
  - J Richard & G. Mahler @ CRAL

G. Seidel's Arcfinder

- Distribute cells
- Cell transport
- Ellipticities

  (1)initial objects

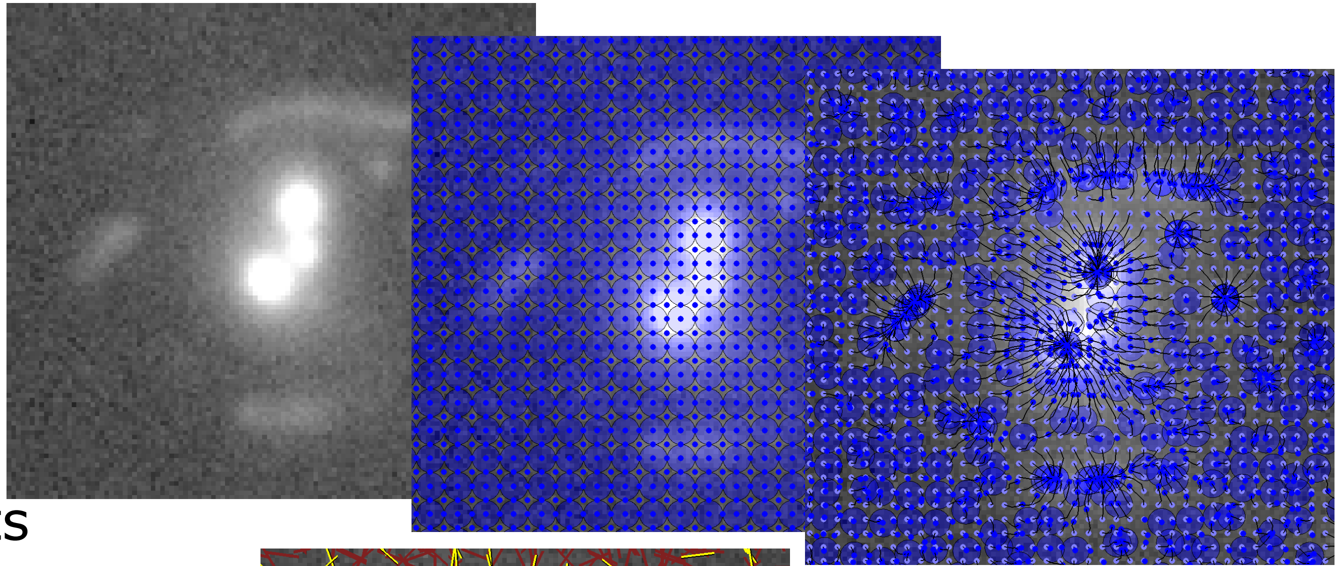
  (2)apply primary filters

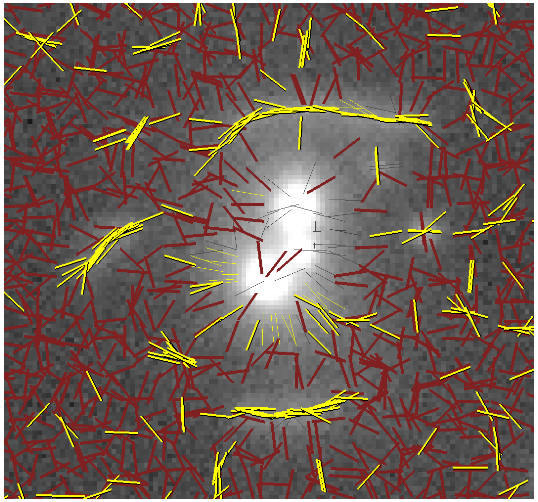
- Contour

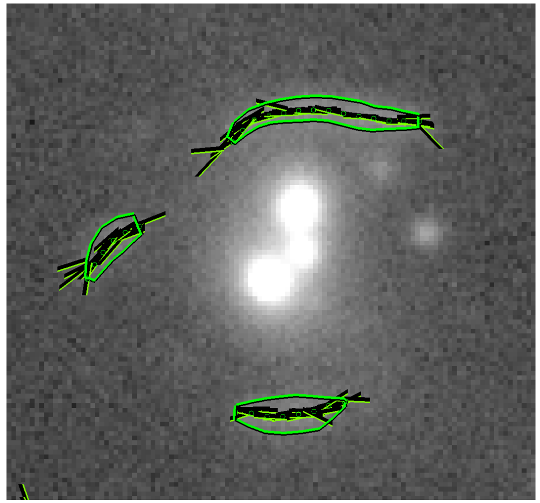
  (1)contour generation

  (2)photometry

  (3)apply secondary filters





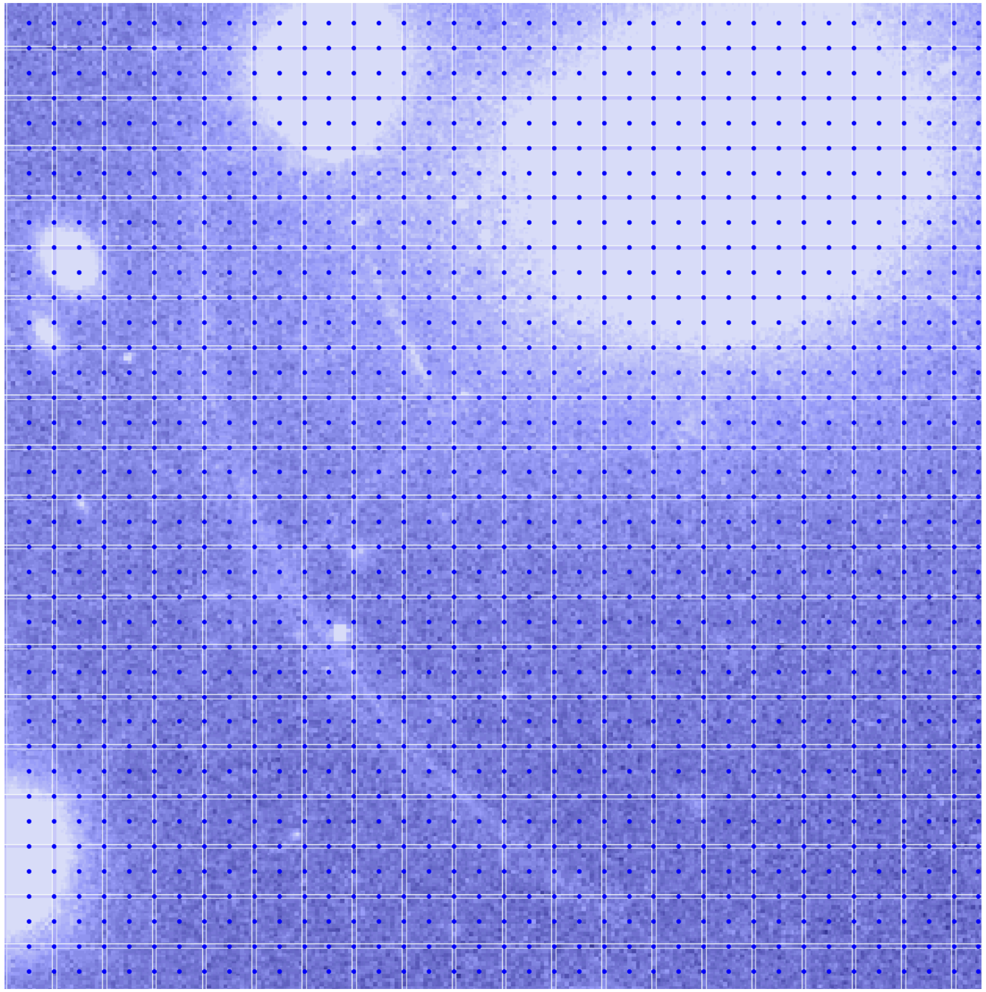


- **distribute cells on square grid**
- **shift to local centre of brightness**
- **compute ellipticities**

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

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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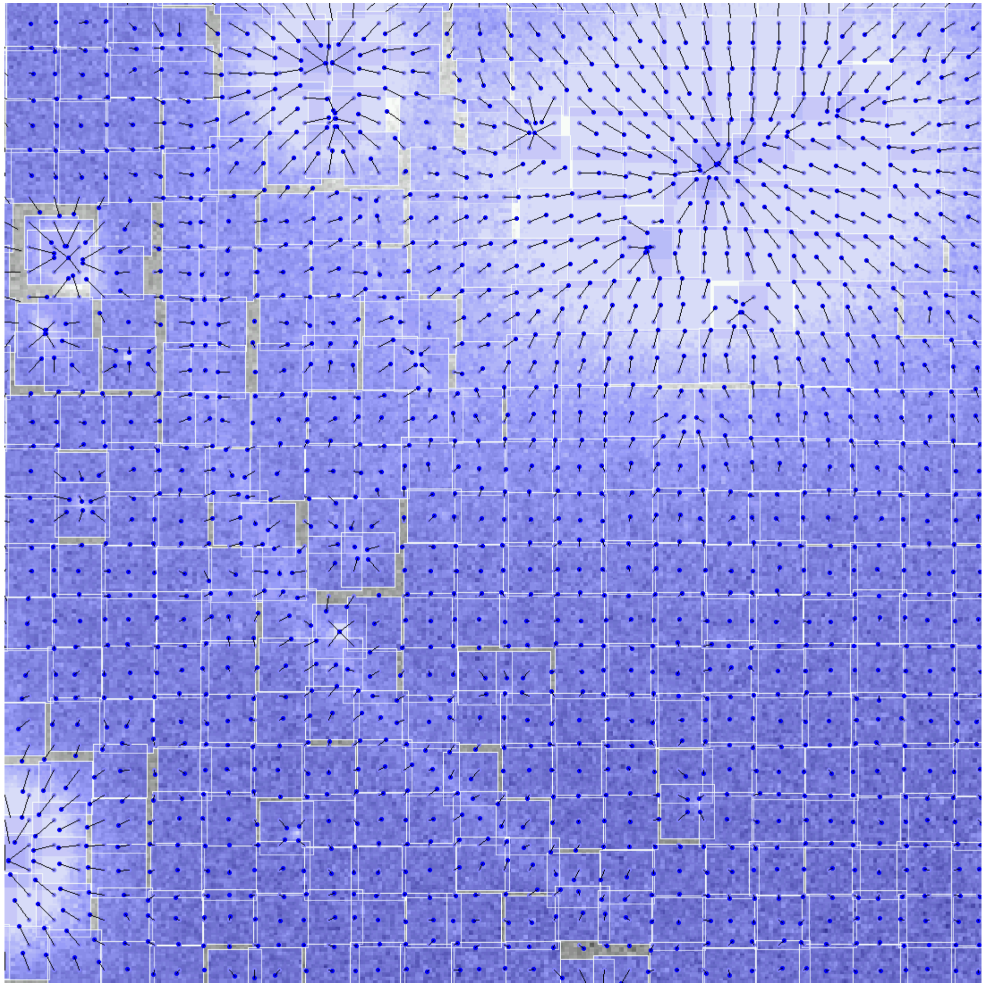

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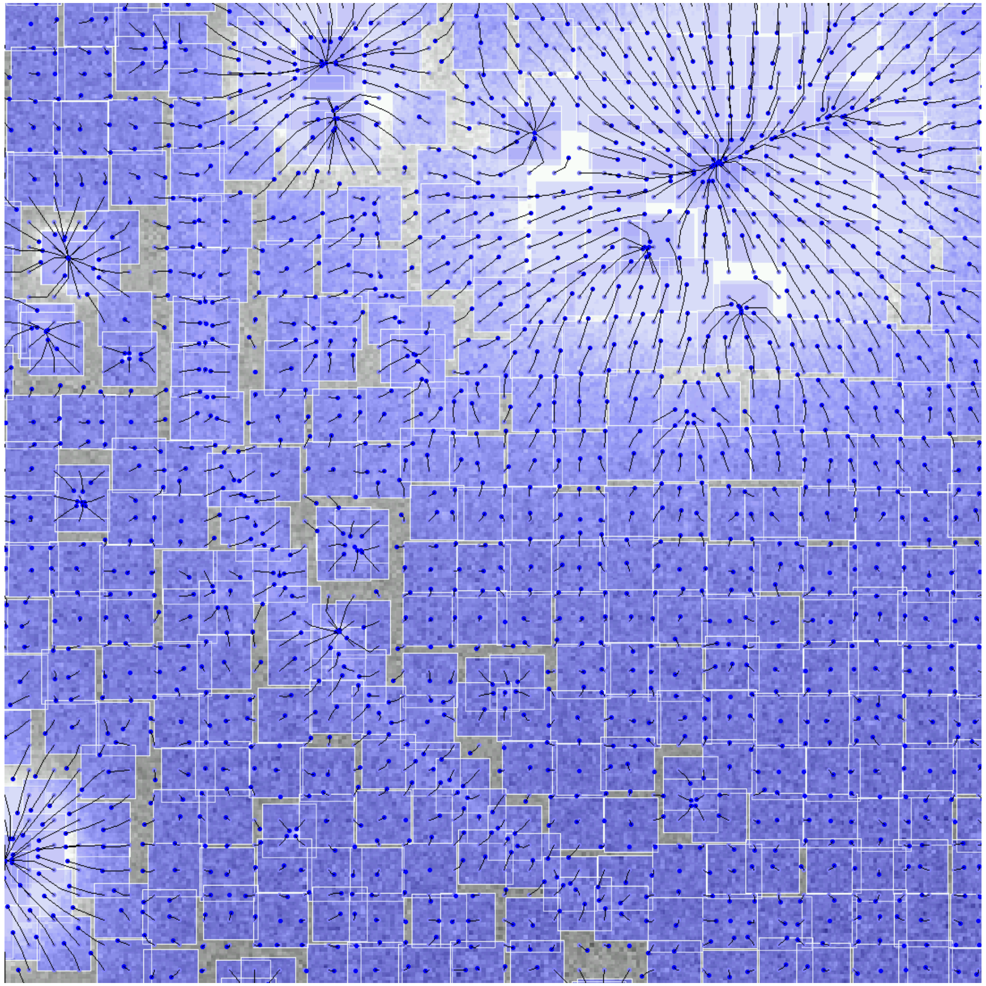

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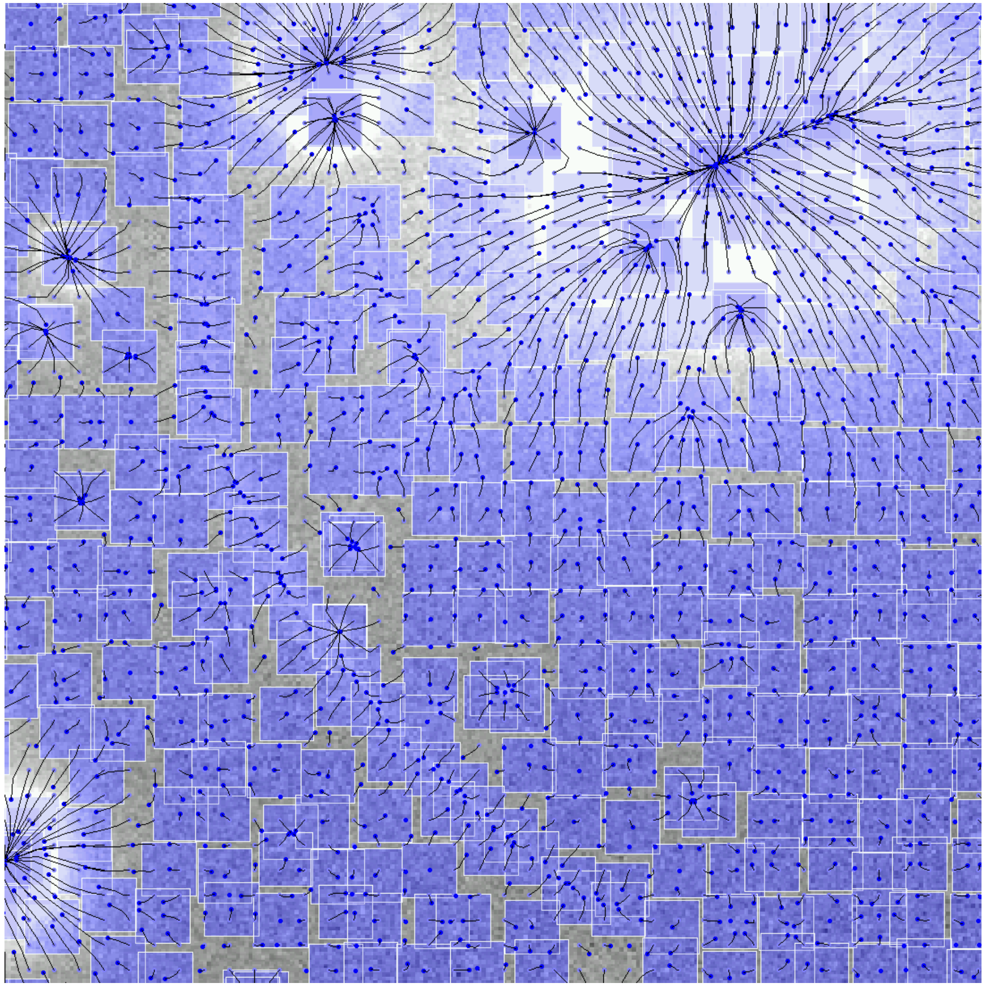

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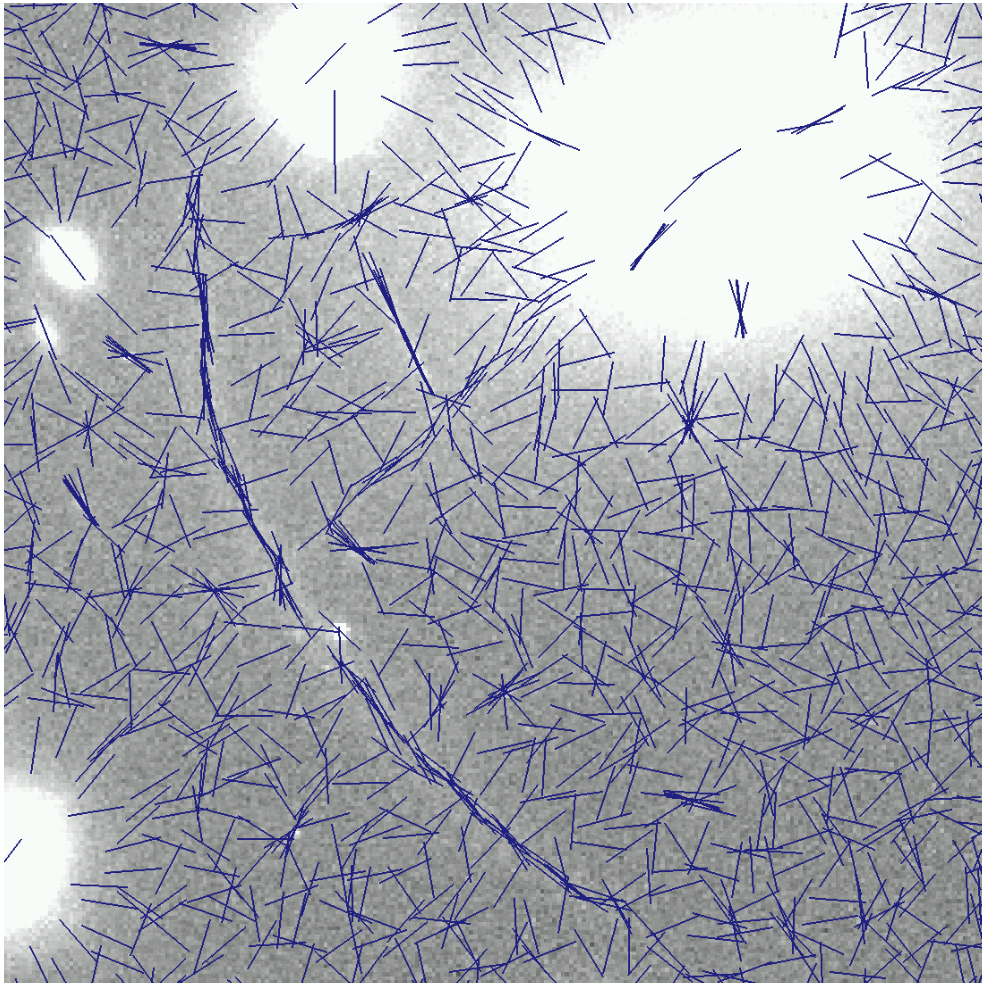


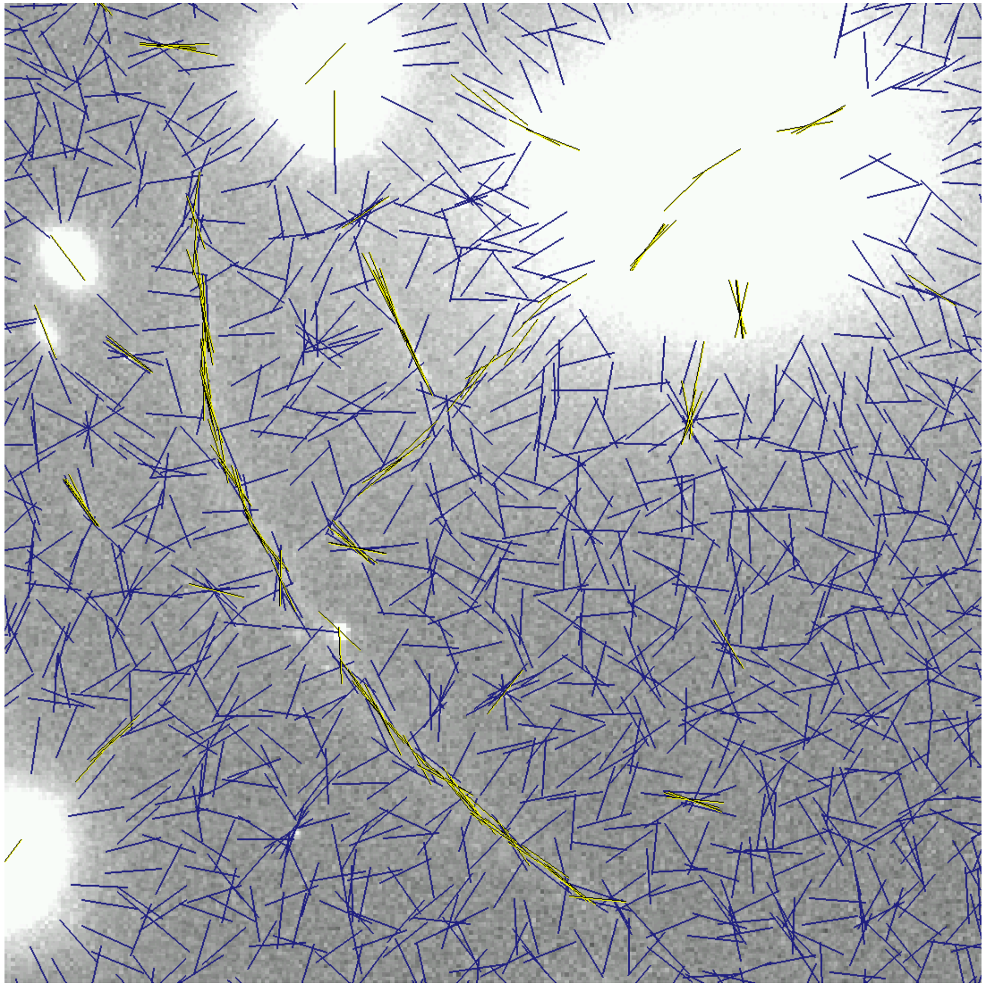
- **compute cell correlations**

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

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

for all cells

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



- initialise contours

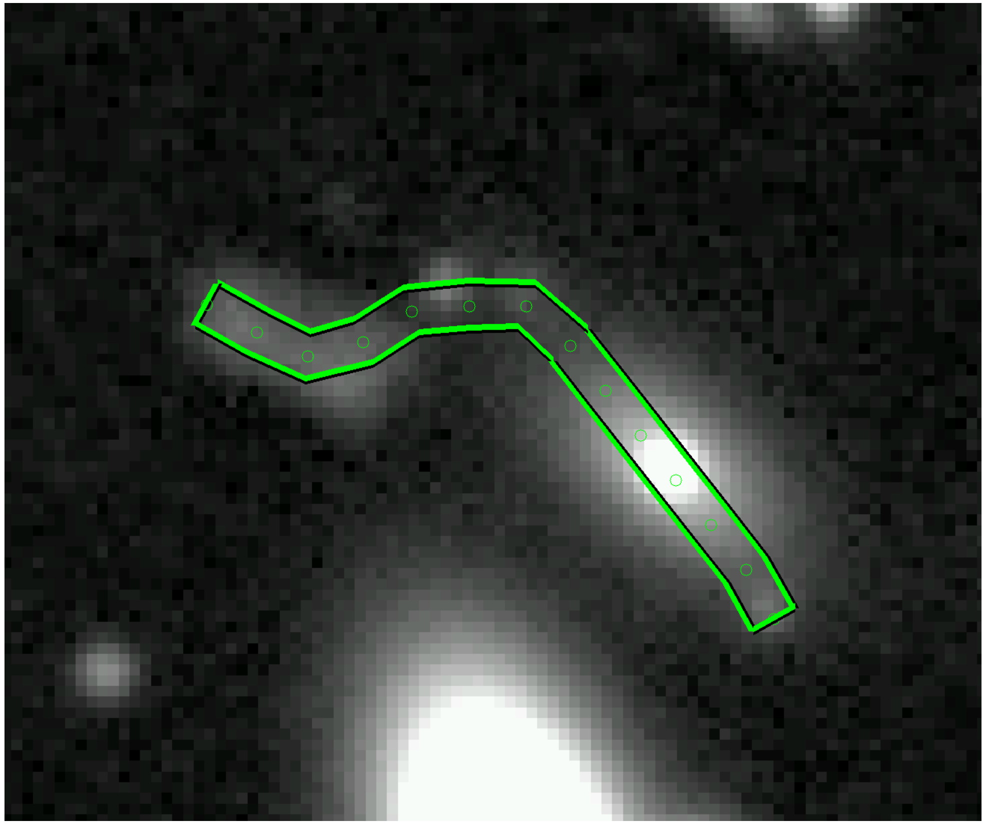
  (1) Delaunay triangulation on object cells

  (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



- **initialise contours**

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- **evolve basic contours into isophotes using active contour segmentation**

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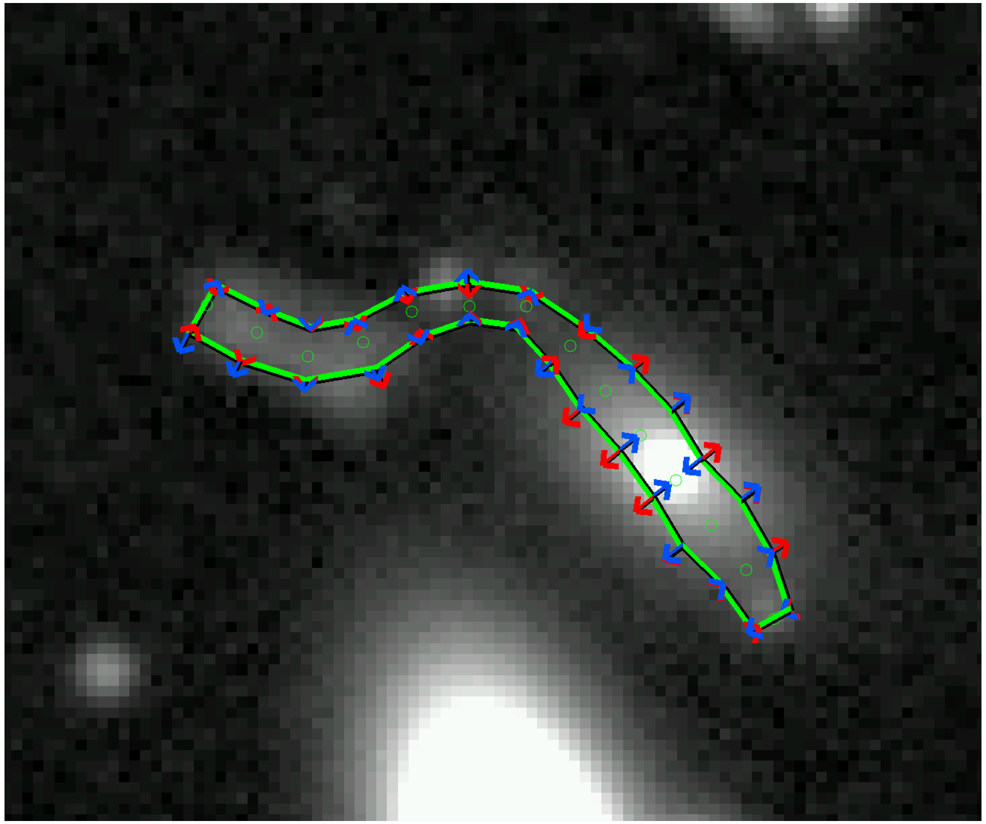

- **initialise contours**

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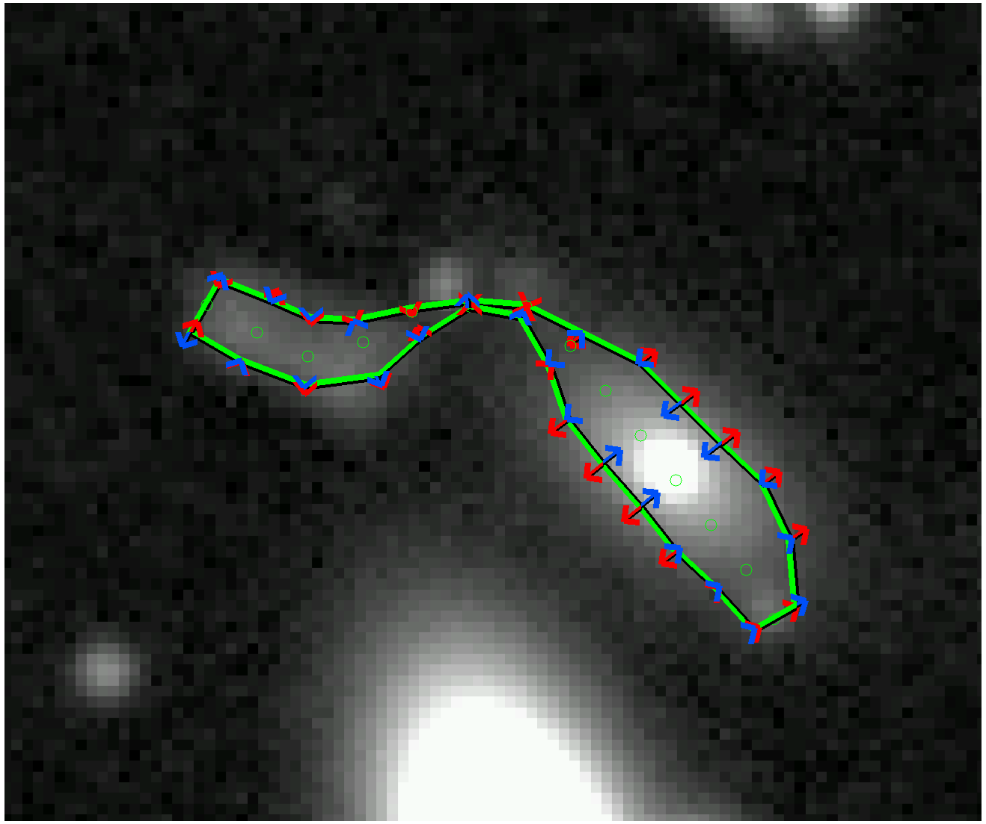
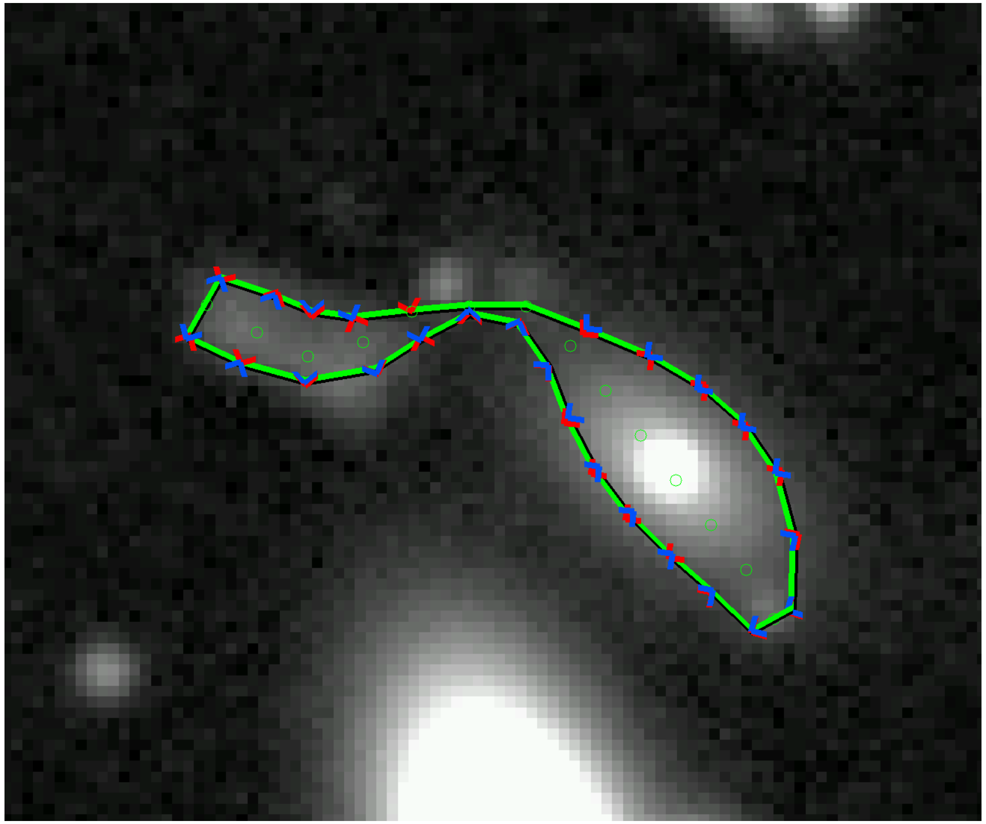


- **initialise contours**
  - **(1) Delaunay triangulation on object cells**
  - **(2) find minimal distance route with Dijkstra algorithm**
- **evolve basic contours into isophotes using active contour segmentation**
- **determine shape parameters, i.e. length, length to width ratio, curvature**
- **basic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



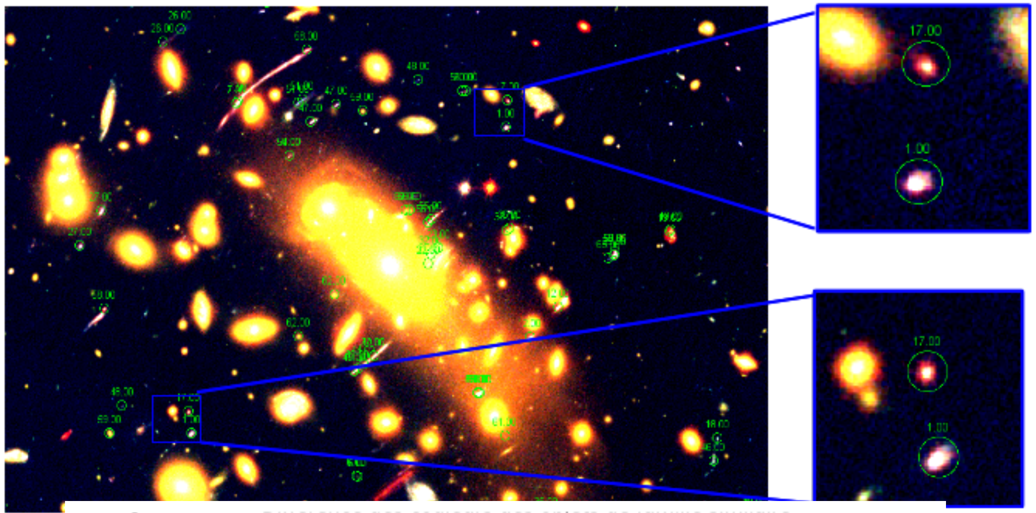
final contour (20 steps)

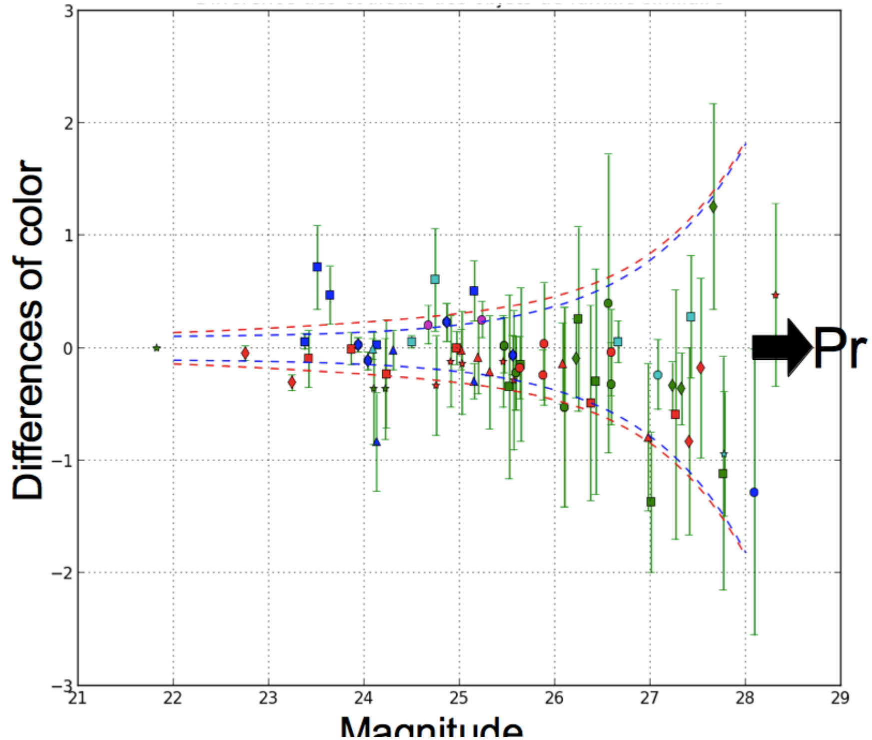
Multiple images in clusters

Mahler & Richard @ CRAL

Identification of candidate multiple images that could be tied by a SL model (lenstool)

Color Driven and (fully) automated…





Science with many Lensing Clusters

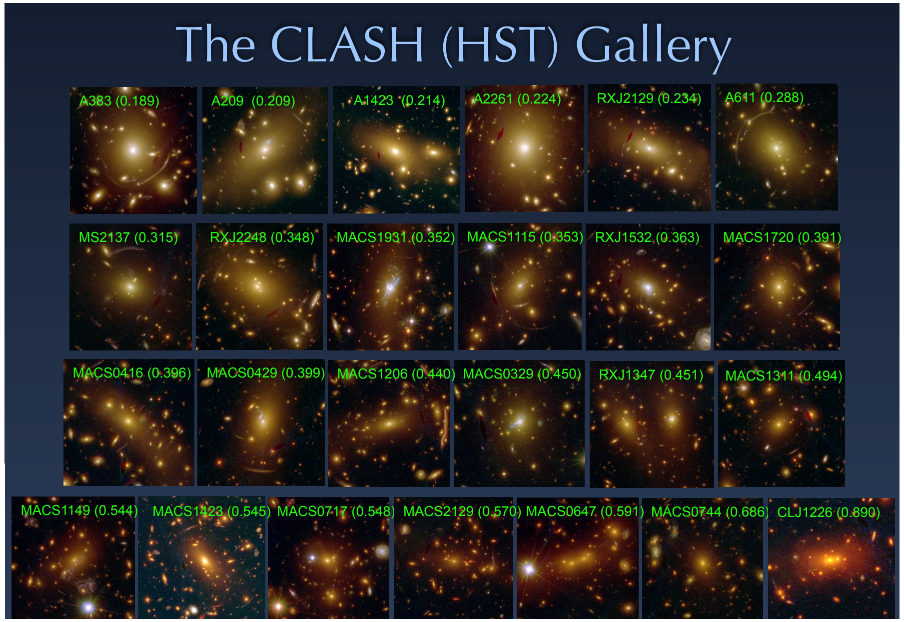
(in coordination with CGSWG,WLSWG…)

- Total-mass density profiles in the inner ~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.

Ongoing activities

Ideal benchmark for a better understanding of modeling systematics

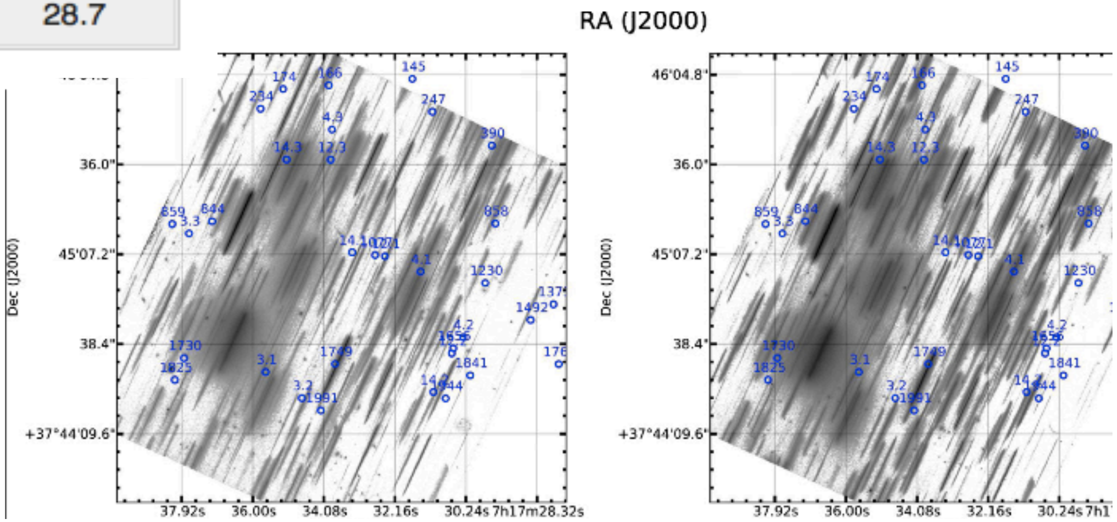


- CLASH : 25 clusters, 16 bands, ~ 1 orbit each (UV→NIR , with WFC3,ACS)

ACS: (70 orbits per position)			WFC3/IR: (70 orbits per position)		
Filter	Orbits	AB_mag	Filter	Orbits	AB_mag
F435W	18	28.8	F105W	24	28.9
F606W	10	28.8	F125W	12	28.6
F814W	42	29.1	F140W	10	28.6
			F160W	24	28.7

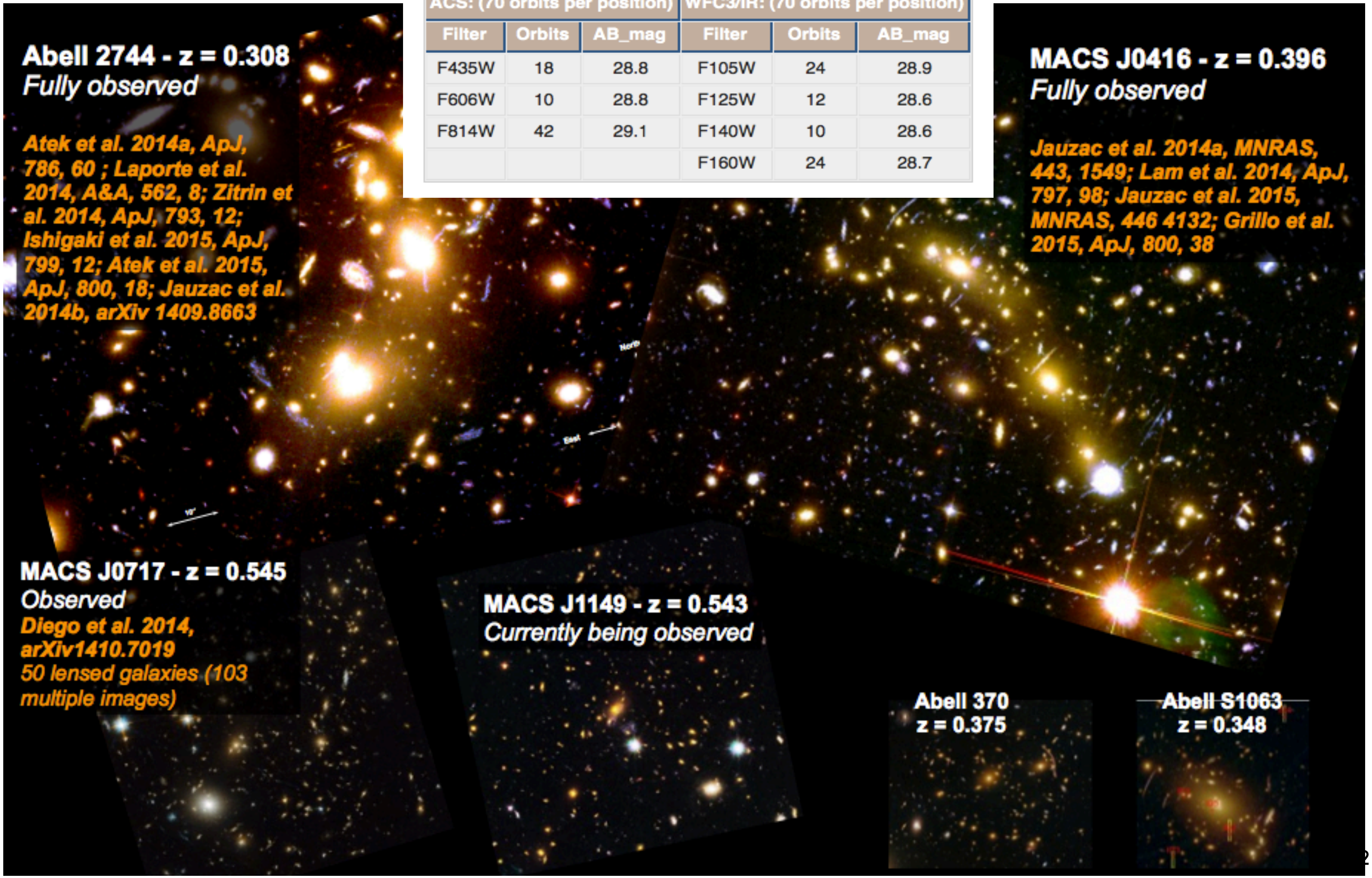
HFF, Frontier Fields 6 clusters : extremely deep!!!

- GLASS (Grism spectroscopy of 10 clusters, 140+140 orbits)

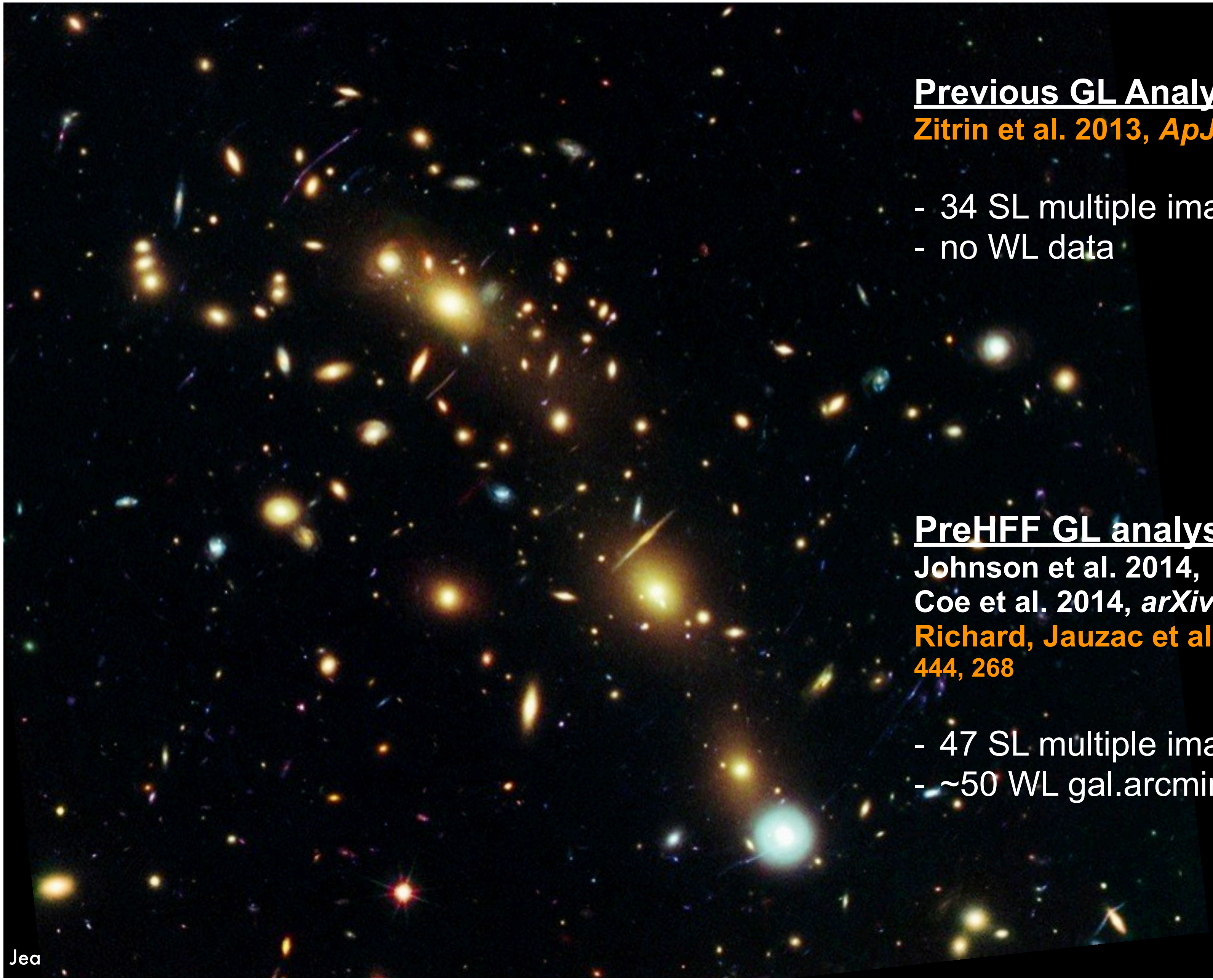


Hubble Frontier Fields

ACS: (70 orbits per position)			WFC3/IR: (70 orbits per position)		
Filter	Orbits	AB_mag	Filter	Orbits	AB_mag
F435W	18	28.8	F105W	24	28.9
F606W	10	28.8	F125W	12	28.6
F814W	42	29.1	F140W	10	28.6
			F160W	24	28.7



MACSJ0416 : Before HFF …



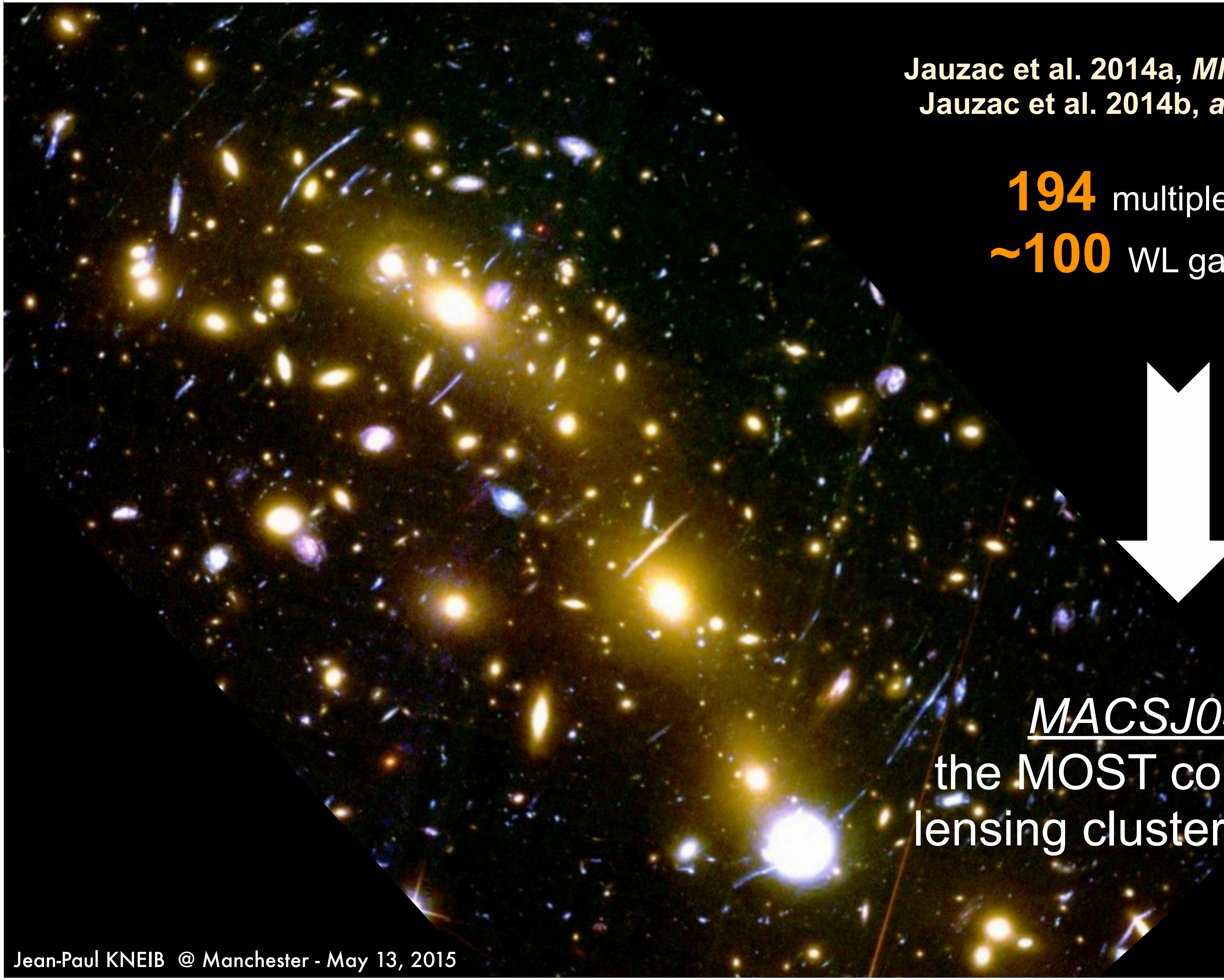
<u>Previous GL Analysis :</u>
Zitrin et al. 2013, *ApJ, 762, 30*

- 34 SL multiple images
- no WL data

<u>PreHFF GL analysis :</u>
Johnson et al. 2014, *arXiv 1405.0222*
Coe et al. 2014, *arXiv 1405.0011*
Richard, Jauzac et al. 2014, MNRAS, 444, 268

- 47 SL multiple images
- ~50 WL gal.arcmin^{-2}

MACSJ0416 : … After HFF !!!

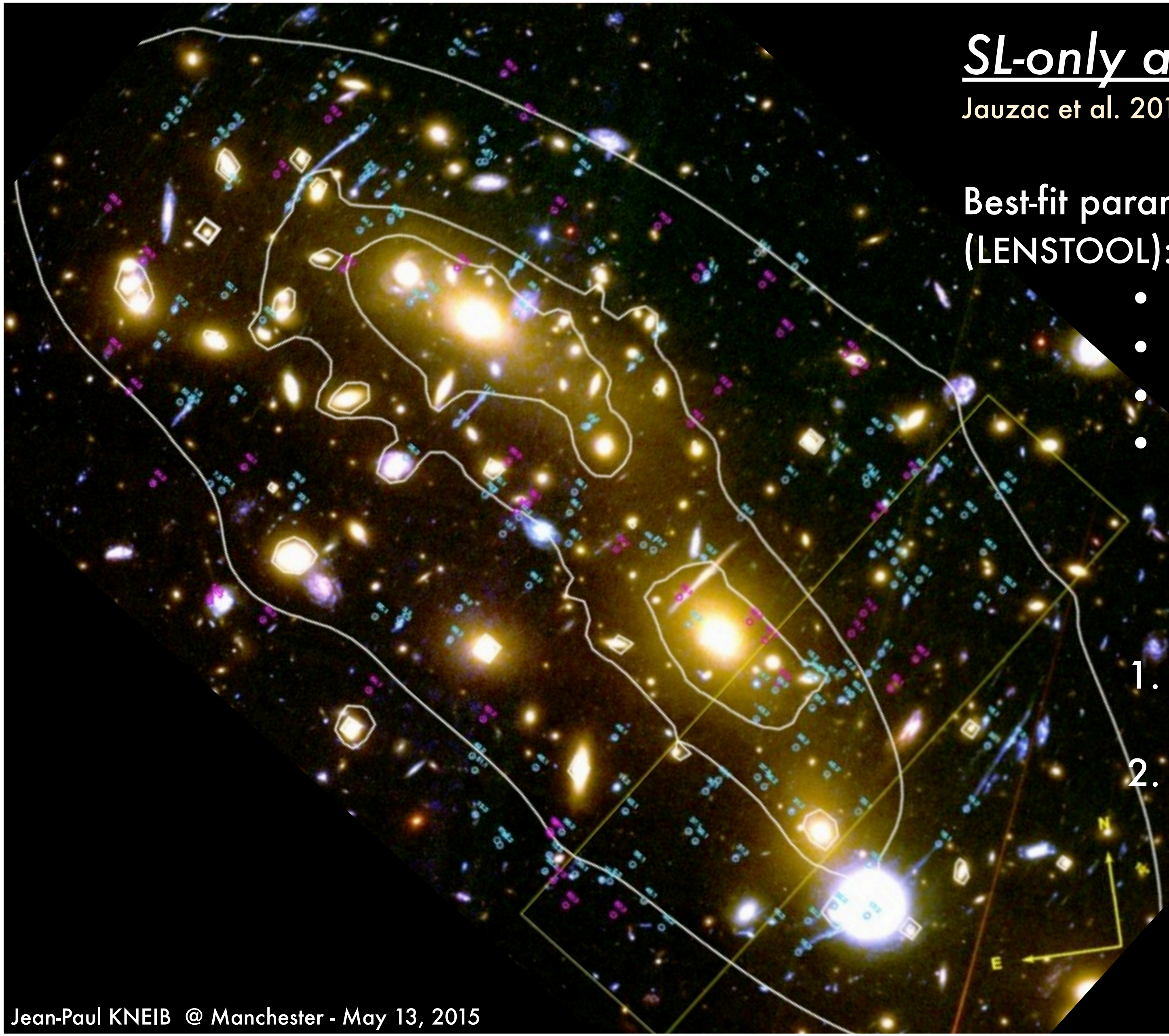


Jauzac et al. 2014a, *MNRAS, 443, 1549*
Jauzac et al. 2014b, *arXiv, 1406.3011*

194 multiple images
~100 WL gal.arcmin^{-2}

MACSJ0416 :
the MOST constrained lensing cluster to date !!!

Multiple Images in MACSJ0416



SL-only analysis

Jauzac et al. 2014, *MNRAS, 443, 1549*

Best-fit parametric mass model (LENSTOOL):

- 194 multiple images
- 2 DM clumps
- 98 cluster galaxies
- **RMS = 0.68''**

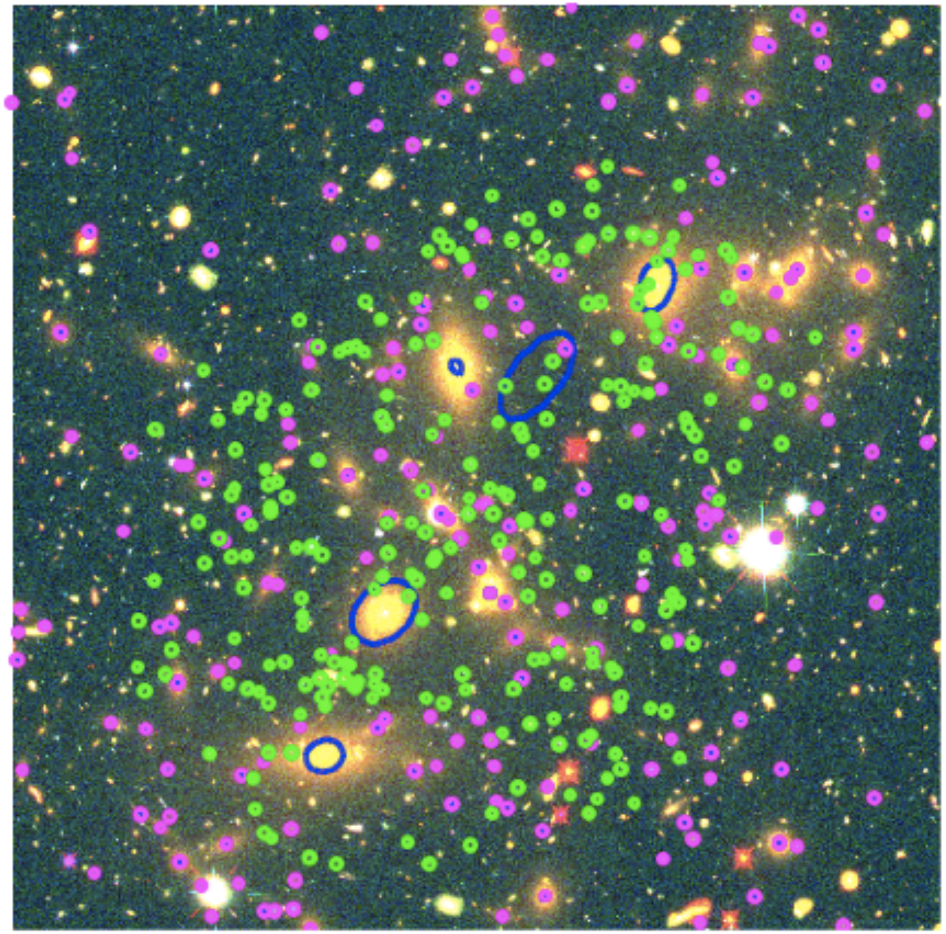
Elongated mass distribution NE-SW

1. Typical for galaxy mergers
2. Reason for so many multiple images

E Jullo & CATS team within HFF effort…. + Bologna (Meneghetti)Simulations

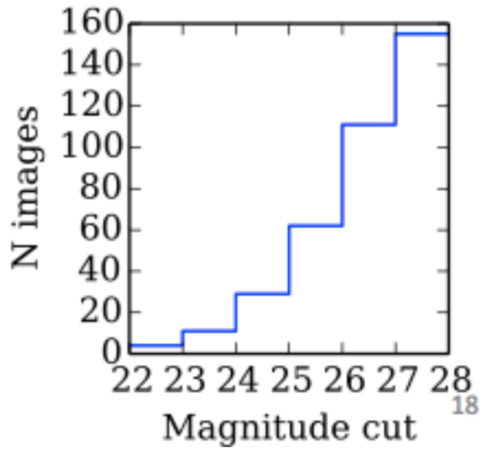
Simulated (DM+painted galaxies) cluster given to various team

Ares Cluster



- Image constraints
- Cluster Members
- Optimized potential

- 242 image constraints
- 122 systems
- 200 CM with magK<22

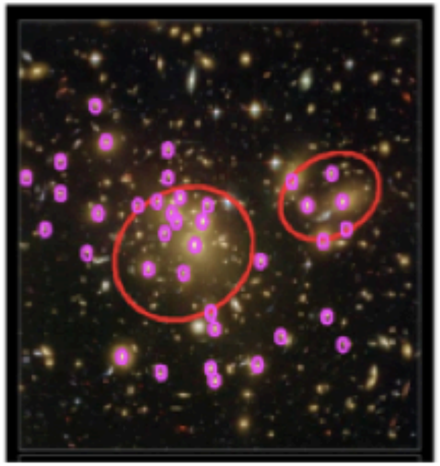


E Jullo & CATS team within HFF effort

Strong lensing modeling strategies

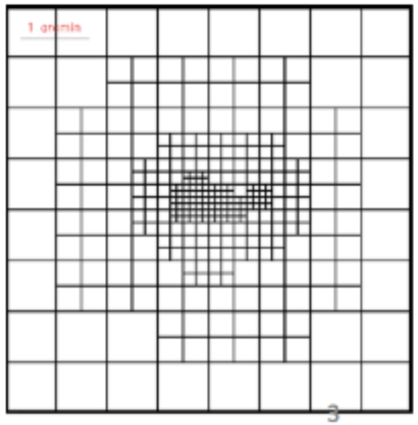
1) Observationally motivated models

- Decomposition into halos
- Good fit with few constraints
- Direct test of N-body derived models with evidence model ranking



2) Free-form models

- Decomposition into RBF *"pixels"*
- Better fit with lots of constraints
- Good at
  - Detecting substructures
  - Testing Light Traces Mass assumption



Errors due to galaxies modeling

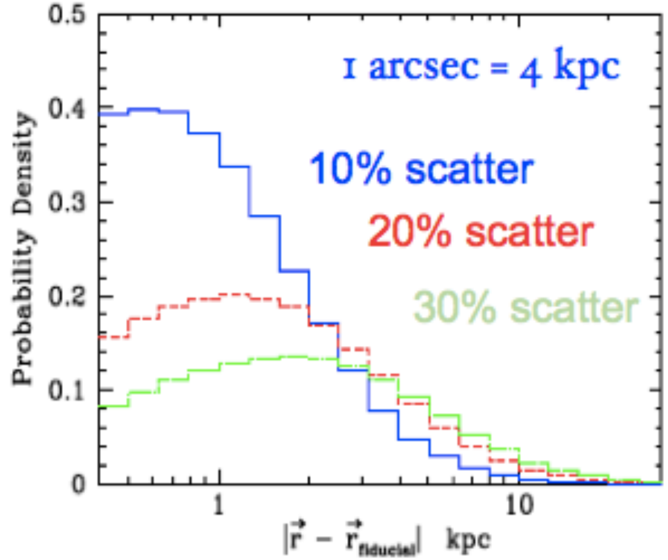
D'Aloisio & Natarajan 2010

PIEMD parameters
20% scatter

$$\begin{cases} \sigma_0 = \sigma_0^\star \left(\frac{L}{L^\star}\right)^{1/4}, \\ r_{\rm core} = r_{\rm core}^\star \left(\frac{L}{L^\star}\right)^{1/2}, \\ r_{\rm cut} = r_{\rm cut}^\star \left(\frac{L}{L^\star}\right)^{\alpha}. \end{cases}$$

The total mass of a subhalo scales then as:

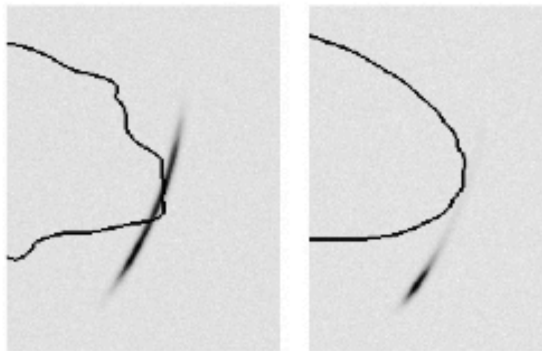
$$M = (\pi/G)(\sigma_0^\star)^2 r_{\rm cut}^\star (L/L^\star)^{1/2+\alpha},$$



- For A1689 Jullo+07
- Scatter in the scaling relations ~ 1"

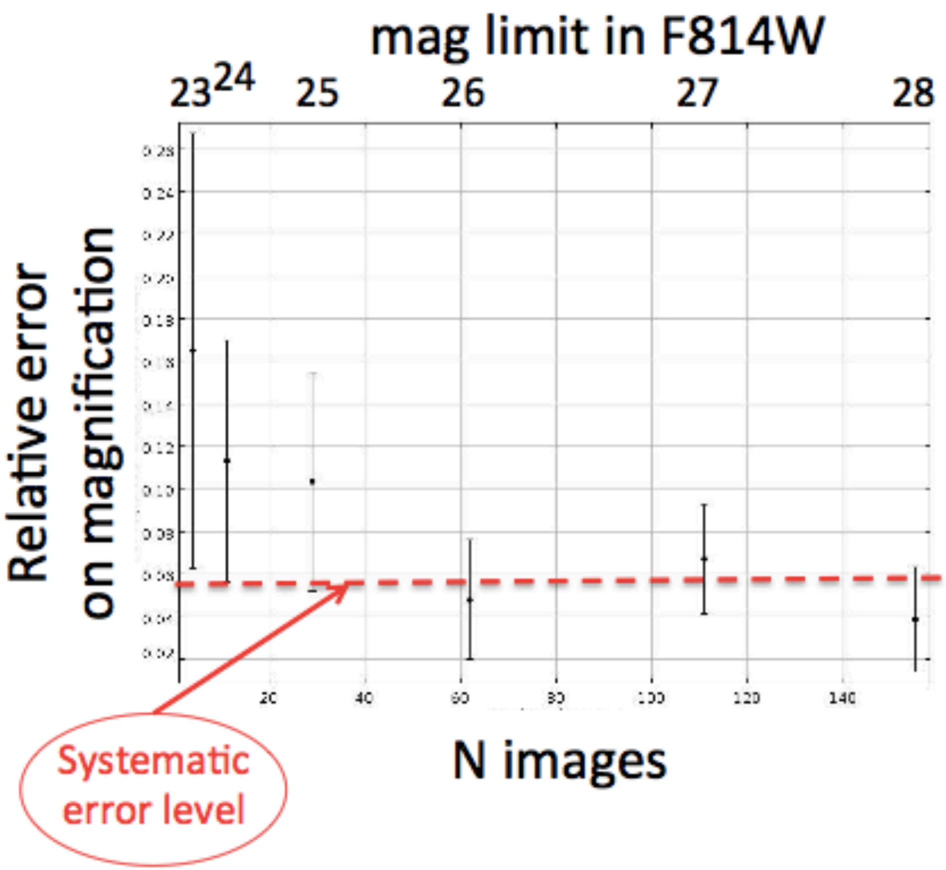
–> Scatter for each image

–> Images are weighted in χ^2 INDIVIDUALLY

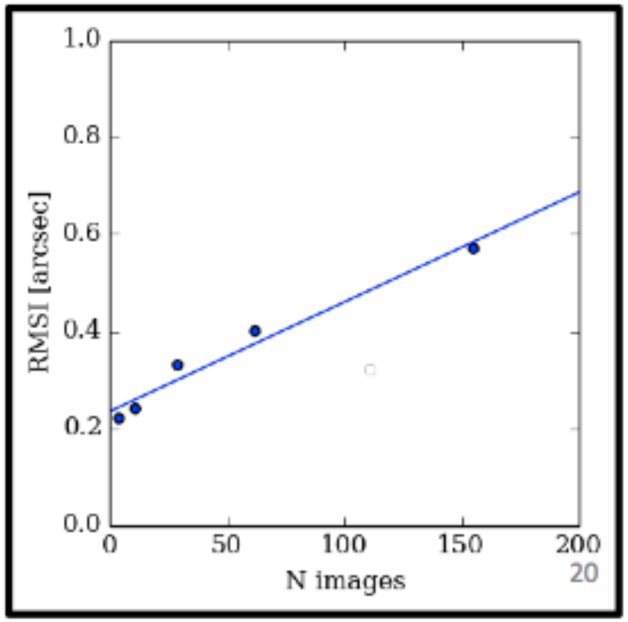


Meneghetti+07

Errors on magnification



- In our model of ARES, we improve on statistical errors until Nimg < 50
- Systematic errors dominate at Nimg > 50



E Jullo & CATS team within HFF effort…. + Bologna (Metcalf/Meneghetti) Simulations

Eric Jullo's preliminary conclusions on HFF effort

- We propose a new mixed "*parametric*" and free-form model to detect substructures in the outskirt of MACS0416
  - Good fit to the data but not justified in terms of Evidence
  - Not necessarily better in terms of RMSI
- Error bars saturate after Nimg > 50 → models get dominated by systematic errors
- There is a lot of room for modeling improvement
- We not necessarily need more simulated clusters, but more informations the existing ones (ex: v_disp of galaxies, 3D distribution, 3D cluster shape, etc)

Coordinate follow-up

- 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 ...

Conclusions

Number of strong lenses with rise by 2-3 orders of magnitude allowing

- *detailed evolution studies of massive galaxies (out to z~1) of various types*
- *to find thousands of lensing clusters with exquisite mass properties great natural telescope for the high-z quest!*

Until now main activities:

- *Galaxy scale lens finders*
- *Arc finders*
- *Simulations for finders benchmarking (BLF)*
- *Improve modeling accuracies, identify main systematics*

To be explored on a short time scale:

- *Finish the selection of finders.*
- *Synergies with WLSWG/ CGSWG*
- *More automation to initiate modeling (pick multiple images, foregrounds)*
- *Faster codes (more flexible models, linked to WL)*
- *How to properly exploit BIG samples of strong lenses.*