A New Window of Exploration in the Mass Spectrum
Strong Lensing by Galaxy Groups in the SL2S

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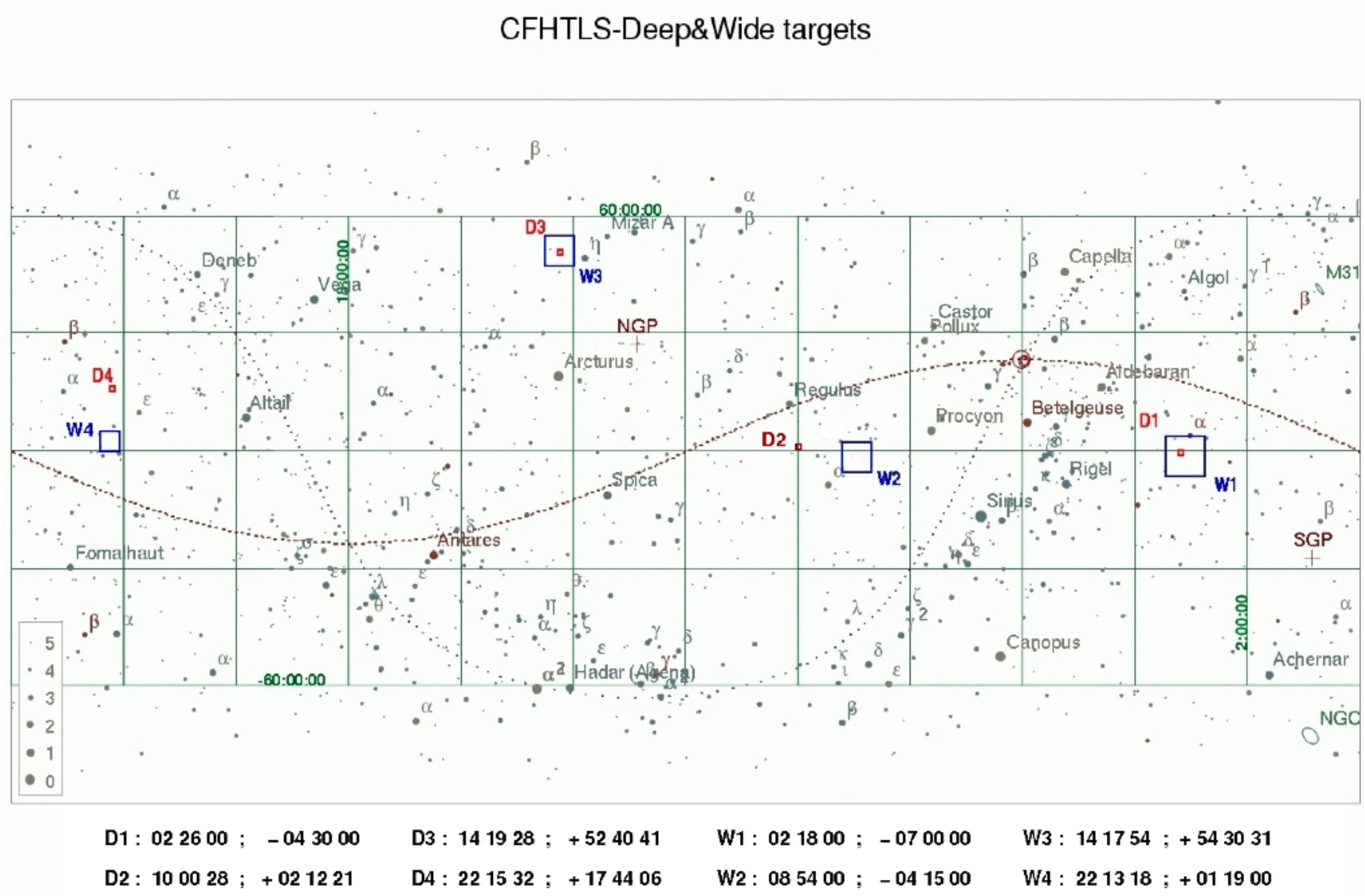
PLAN

- The Canada France Hawaii Telescope Legacy Survey (CFHTLS)
- The Strong Lensing Legacy Survey (SL2S) – talk by Rémi Cabanac
  - A Big reservoir of Strong Lenses ($\sim$ 100) Covering the Full Mass Spectrum: Galaxies, Cluster and Groups
- Strong Lensing *by* Galaxy Groups: Opening a New Window of Exploration in the Mass Spectrum
  - Probe an Intermediate Mass Regime
  - Global Analysis of a Sample of 13 Strong Lensing Groups ($+$ 7 new ones)
- Strong Lensing as a Probe of the Mass Distribution Beyond the Einstein Radius
  - The Dark Matter Distribution in SL2S J08544-0121, A Galaxy Group at z=0.35

The Canada France Hawaii Telescope Legacy Survey



MegaCam

1deg^2 0.186"/pix

Wide Survey

170 deg^2

IAB ~ 24

Deep Survey

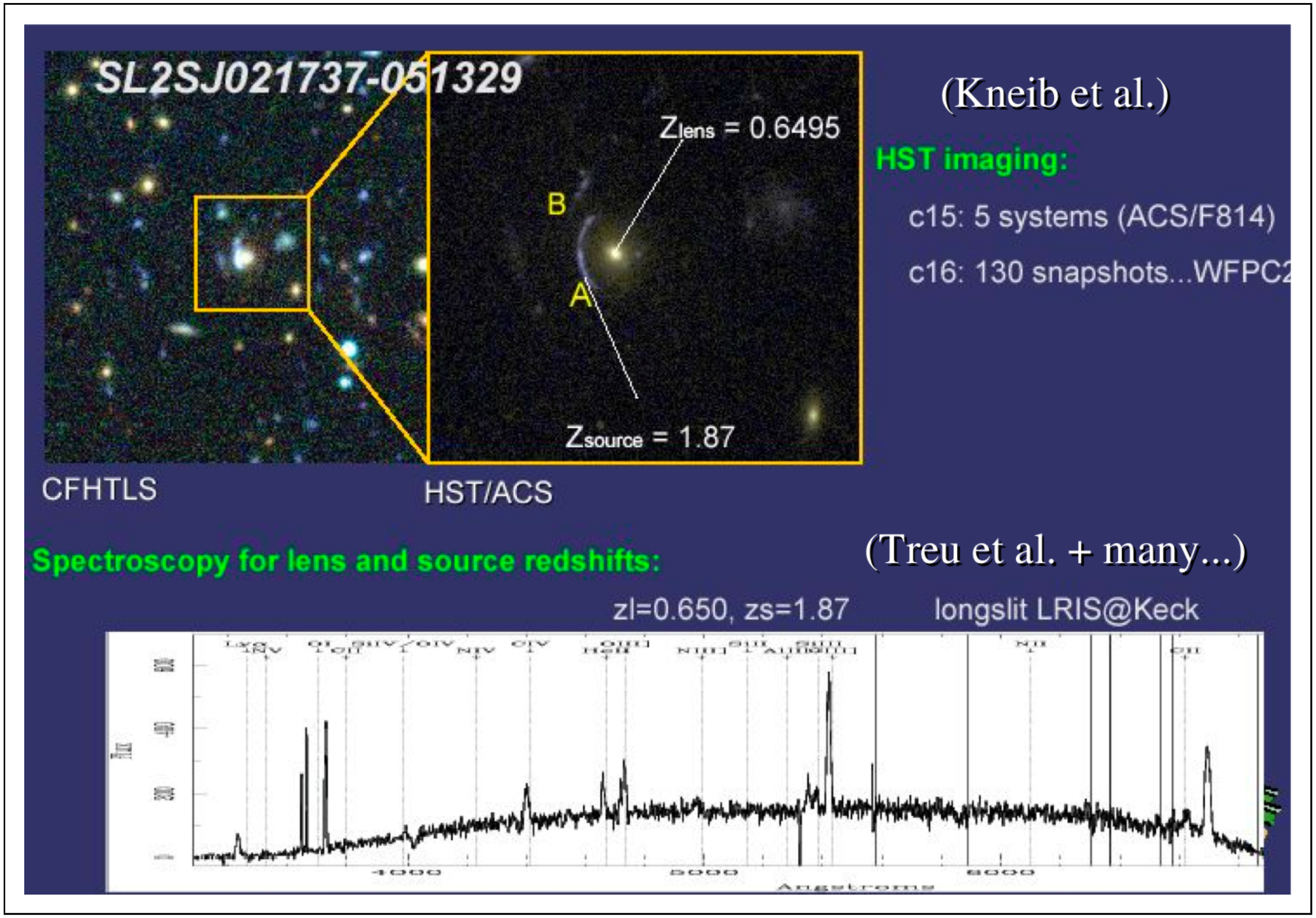
IAB ~ 27

Look for Strong Lenses Automatically:

Arc Finder (Alard et al., 2007) & Ring Finder (Gavazzi et al.)

⇒ Strong Lensing Legacy Survey (SL2S) (Cabanac et al., 2007)

Follow-up: Space Imaging + Spectroscopy (LRIS-Keck - FORS-VLT)

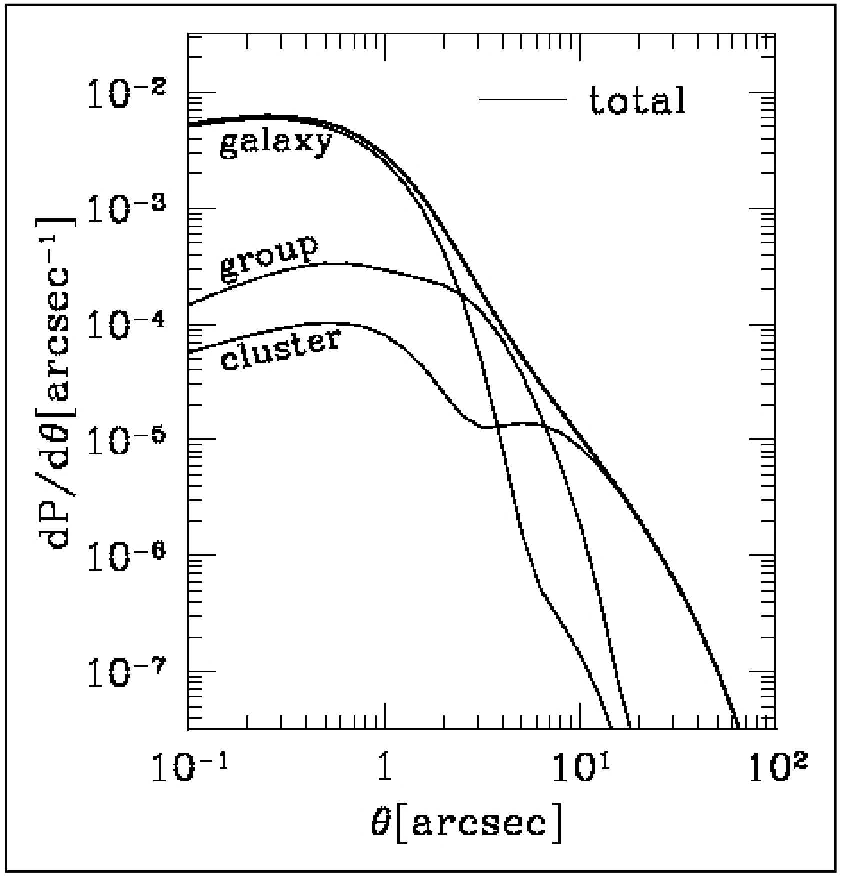


⇒ Confirm Lensing Hypothesis, Better Resolve the Arcs
Sometimes Inconclusive . . . Ongoing Work . . .

Strong Lenses over the Full Mass Spectrum

The Contributions of Different Types of Haloes
on the Image Separation Distribution ($\theta \sim 2$ R_E) (Oguri et al., 2006)

- Galaxies: $\theta < 3''$
- Clusters: $\theta > 15''$
- Intermediate Mass Range: ($10^{13} < M < 10^{14}$ $M_\odot$)
- $3'' < \theta < 15''$
- $\Rightarrow$ *Group Scale* Dark Matter Haloes

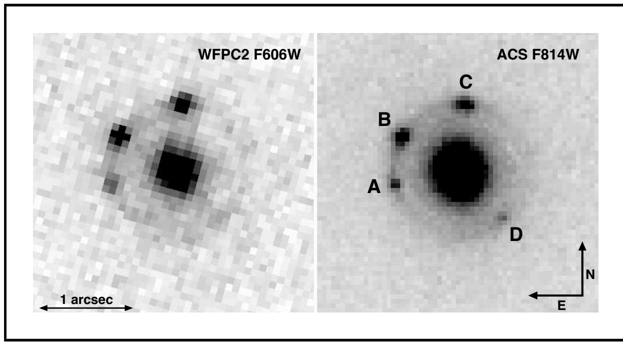


Intermediate Mass Range Lenses Should Exist in a ΛCDM Universe ?
All Scales are found in the SL2S

Strong Lensing *IN* and *BY* Galaxy Groups

IN Groups: A Galaxy Scale Lens ($R_E < 2''$) around a Galaxy living *within* a Group

- High Density environment likely to enhance the SL cross section
  (Kovner 1987; Oguri et al., 2005; Fassnacht et al., 2006; King 2007)
- Groups Contains Preferentially Elliptical Galaxies
- ⇒ Many Strong Lenses in Groups Reported:
  e.g. Kundic et al., 1997; Fassnacht & Lubin, 2002; Morgan et al., 2005; Williams et al., 2006; Momcheva et al., 2006; Auger et al., 2007, 2008; Tu et al., 2008, 2009; Grillo et al., 2008; Faure et al., 2008, Treu et al., 2008 ...



Cosmos 5921
(Anguita et al., 2009, A&A)

IN Groups: Strong Lensing Generated by a Galaxy Scale Dark Matter Halo

Strong Lensing *IN* and *BY* Galaxy Groups

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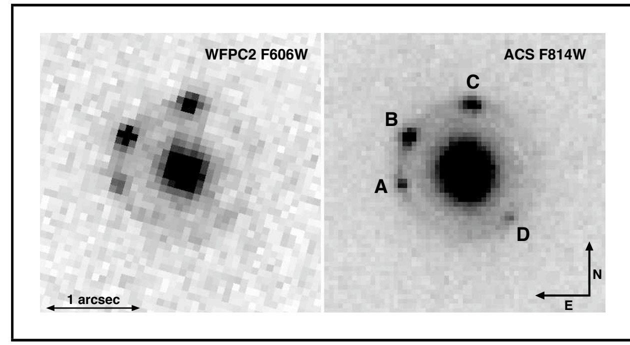


Cosmos 5921

(Anguita et al., 2009, A&A)

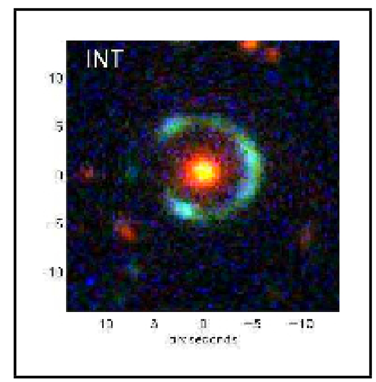
IN Groups: Strong Lensing Generated by a Galaxy Scale Dark Matter Halo

BY Groups: $3'' < R_E < 8'' \rightarrow M(R_E) \sim 10^{13}\, M_\odot$

⇒ *Group Scale Dark Matter Haloes*

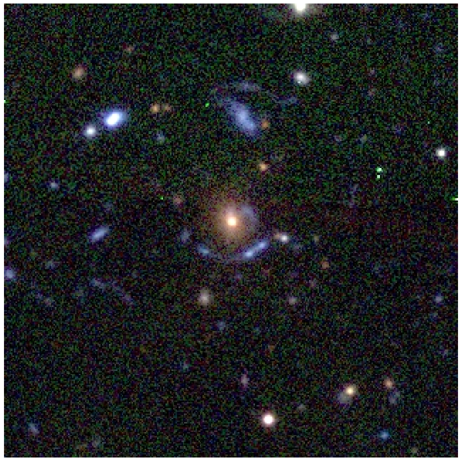
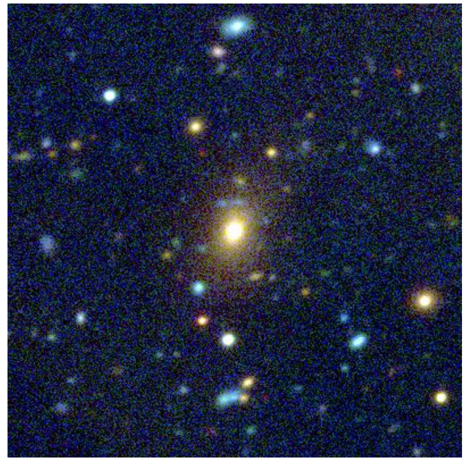
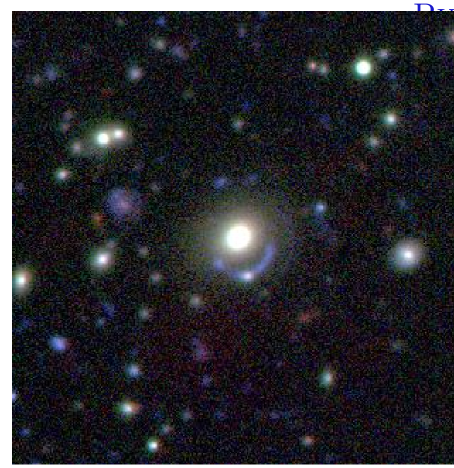
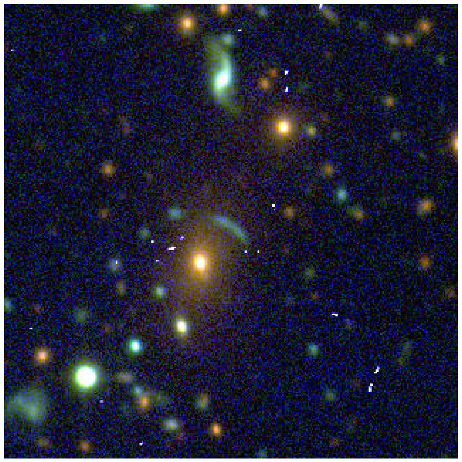
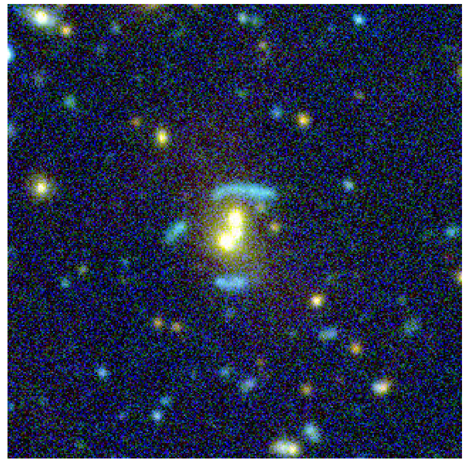
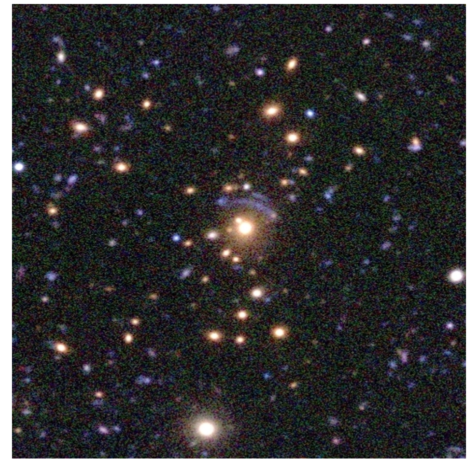
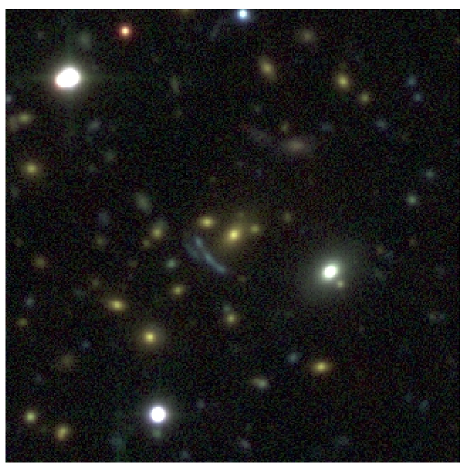
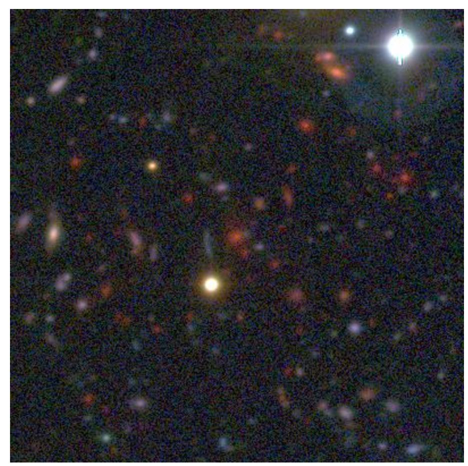
SL2S: 13 Strong Lensing Groups (from $z = 0.3$ to $z = 0.8$)

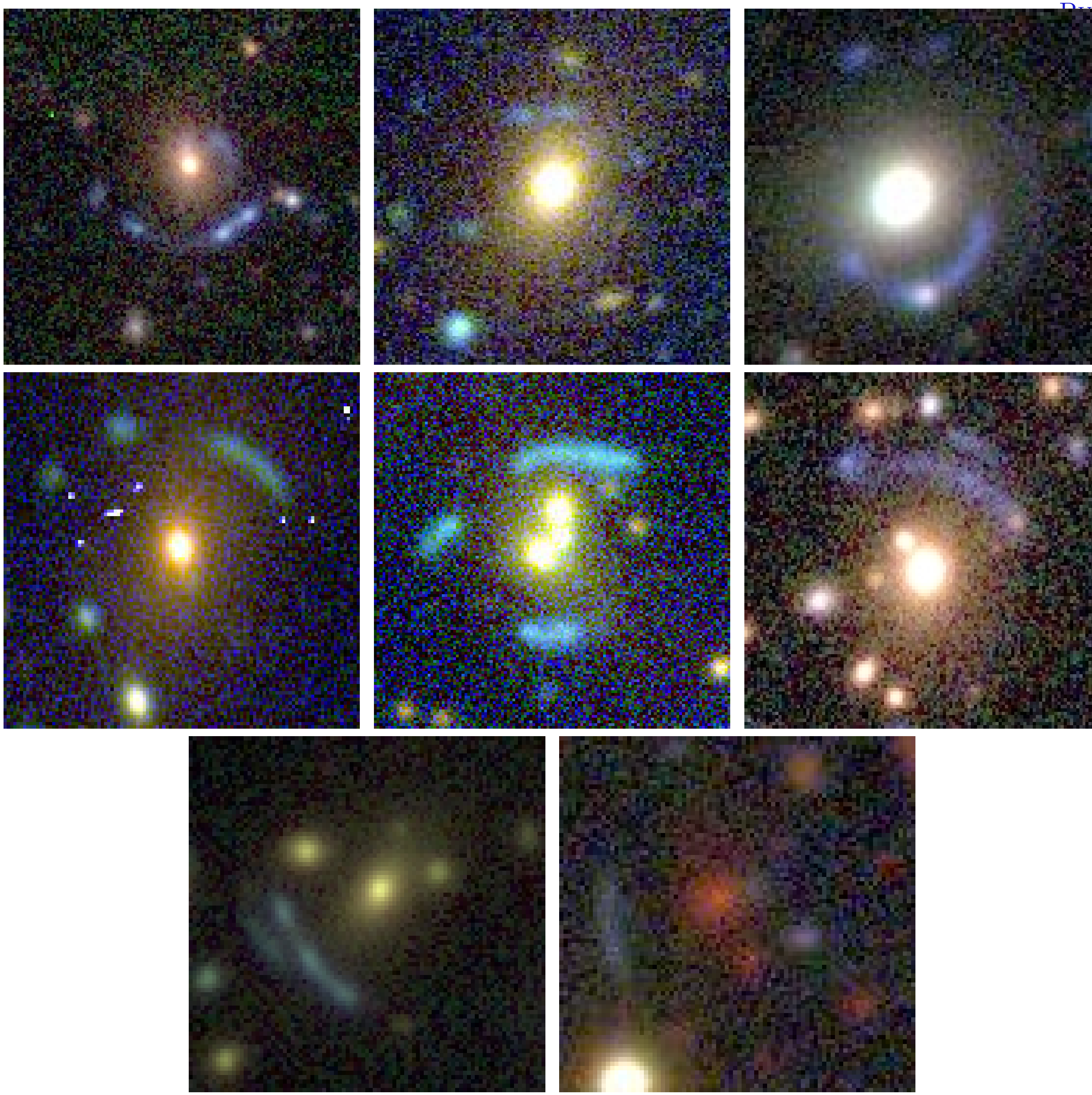
(Limousin, Cabanac, Gavazzi, Kneib, Motta et al., 2009, A&A) (+ 7 new ones)



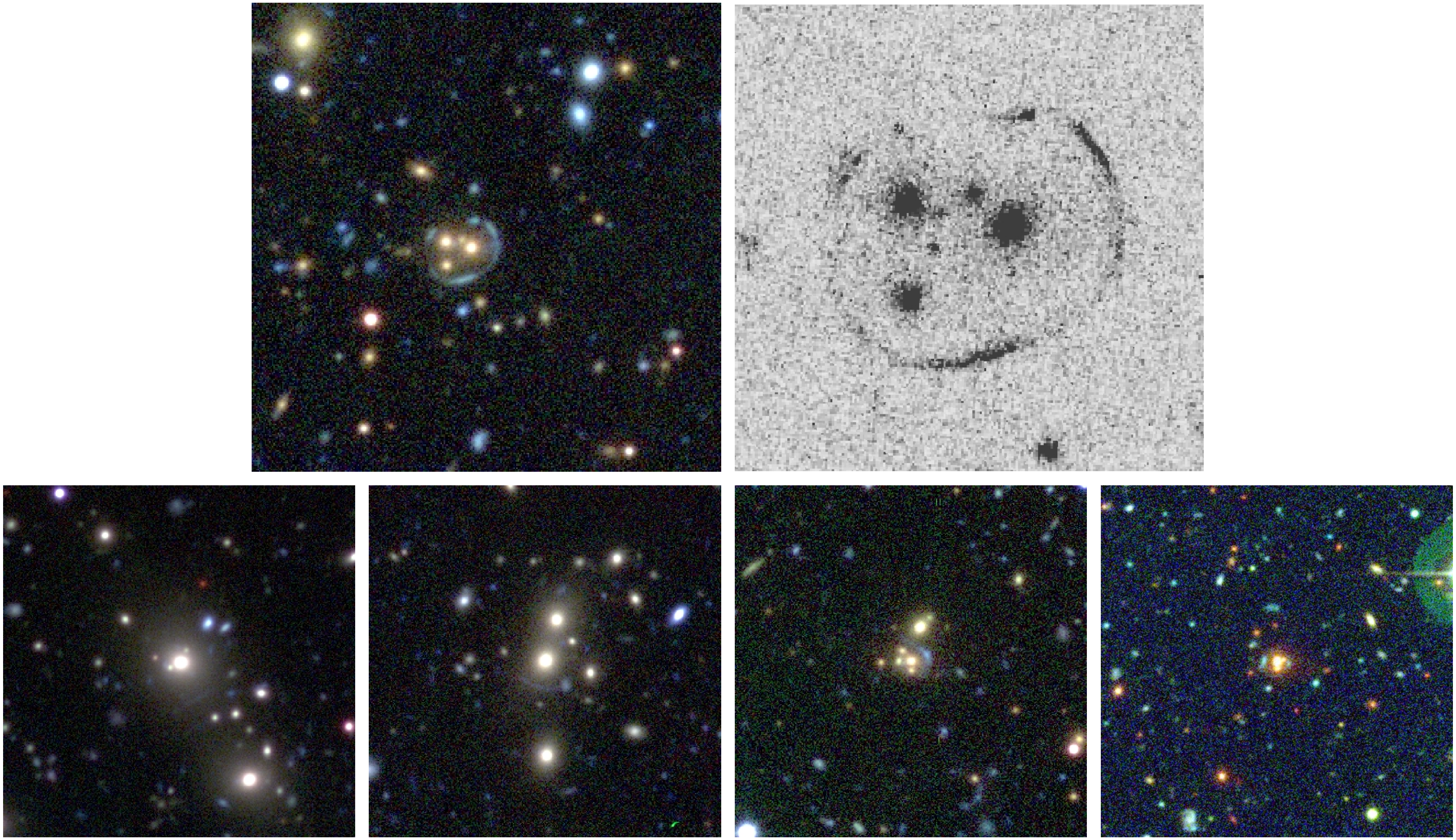
Cosmic Horse Shoe

(Belokourov et al., 2009, A&A)

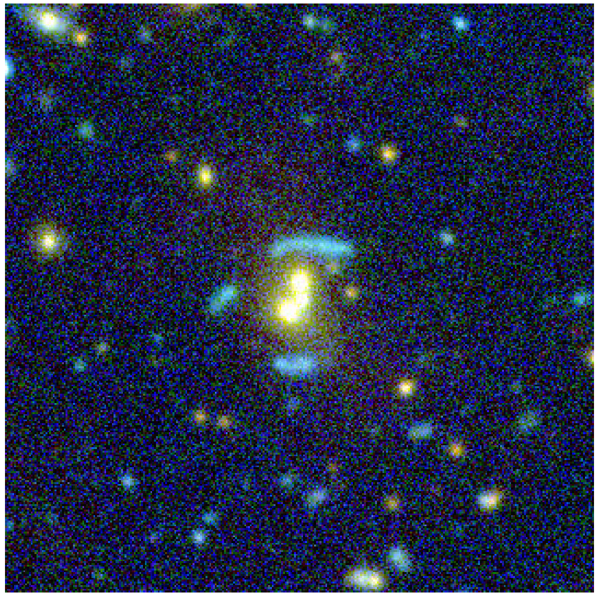


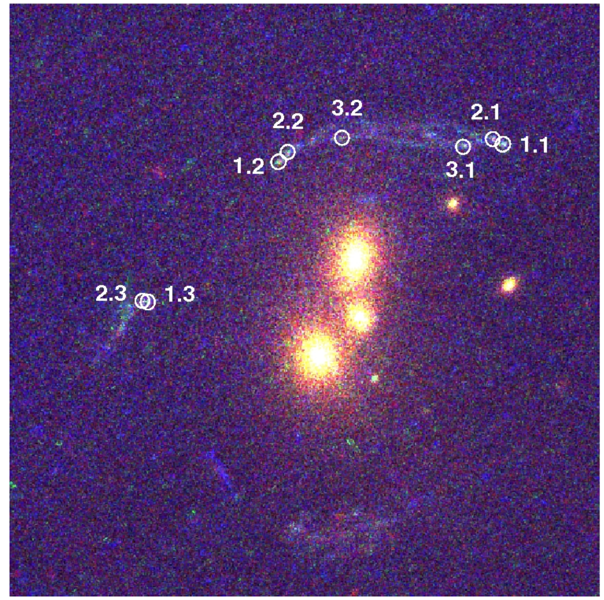
Non Cusp Groups

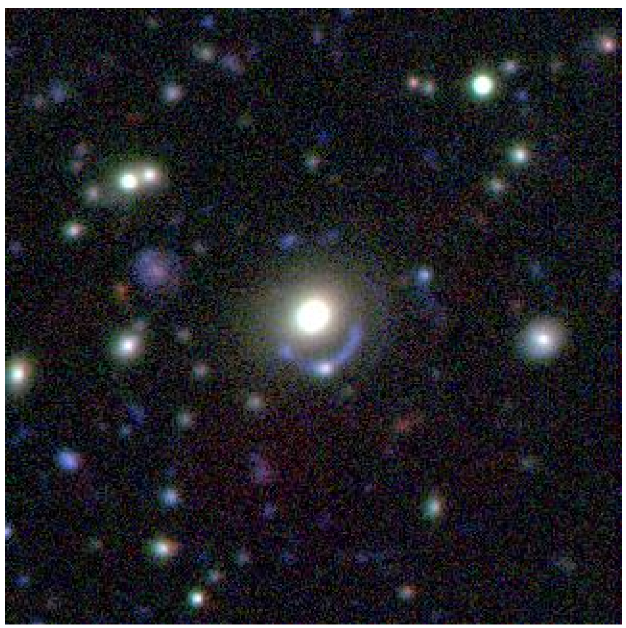


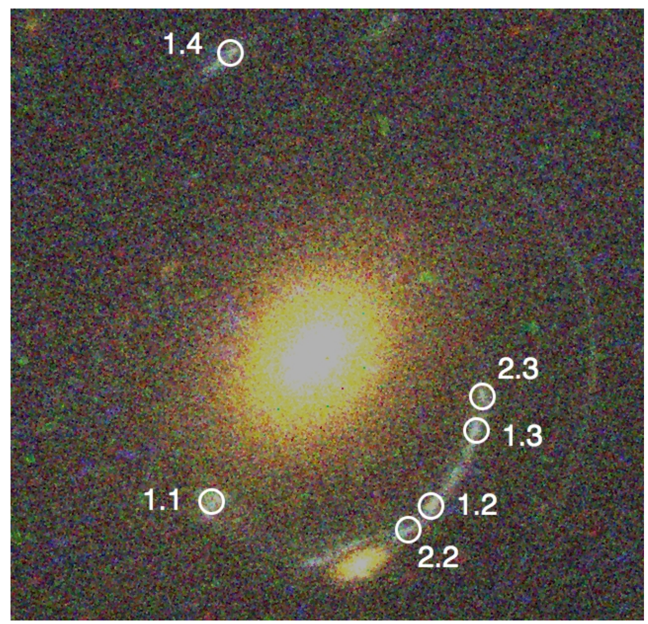
Identify Systems ? → No Strong Lensing Modelling

Space Based Follow-up: Strong Lensing Analysis









Analysis

HST Imaging $\Rightarrow$ Small Scales Properties: Strong Lensing Modelling $\longrightarrow$ R_E

CFHTLS Imaging $\Rightarrow$ Large Scales Properties

LIGHT:

- (g, r, i) Photometry
- Red Sequence Techniques
  $\longrightarrow$ Group Members
- $\Rightarrow$ Luminosity Contours

HOW IS THE LIGHT DISTRIBUTED ?

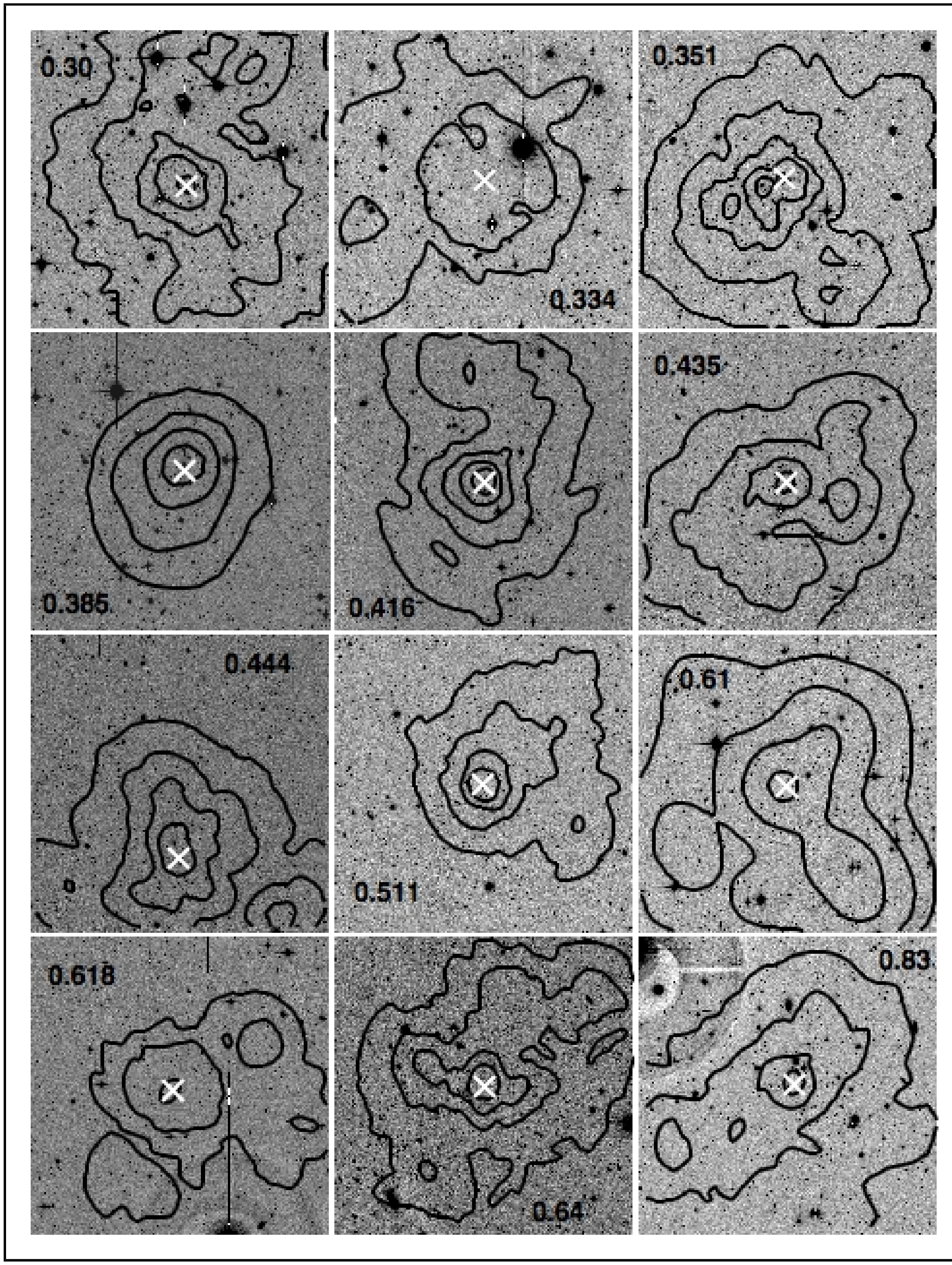
WEAK LENSING:
(TALK BY GAËL FOËX)

- Background Galaxies:
  $21.5 < i < 24 \sim \text{mag}_{\text{COMP}}$
- PSF Subtraction & Shape Parameters:
  IM2SHAPE (Bridle et al., 2002)
- Mean D_{LS}/D_S
  $\Rightarrow$ CFHTLS Deep Field Photometric Redshift Catalogue
  (Roser Pellò, 2008)
- Fit Shear Profile (γ) using SIS
  $\Rightarrow$ σ_{SIS}

HOW MUCH MASS IT CONTAINS ?

Results (Limousin et al., 2009, A&A)

- Einstein Radii: $2.5'' < \mathrm{R_E} < 8''$
- Weak Lensing: ($\sigma \sim 500$ km s^{-1})
- Lens (white cross):
  Dominates the Luminosity Distribution
  (except J08544-0121, see later)
- ⇒ Mass Light Correlated
- M/L$_i$ ∼ 250: Comparable
  - Poor Groups ($\sigma \sim 300$ km s^{-1})
  - Clusters ($\sigma > 1\,000$ km s^{-1})
- ⇒ Bridges the Gap



Combining Complementary Probes

Relevant to get a better understanding of the limitations and advantages of each tool

- Spectroscopy of Group Members: FORS 2 on VLT (Poster by Veronica Motta)
  Dynamical Mass, Structures along the Line of Sight
- Near Infra Red Imaging from WIRCAM on CFHT (P.I. G. Soucail)
  Stellar Mass, improved Photometric Redshift
- X-ray (proposal XMM/Chandra)

Investigating some Groups in More Details:

- Inner Density Profile of SL2S J02140-0532 (Talk by Tomás Verdugo)
- SL2S J02176-0513: The Mass Profile of an Early-Type Galaxy in a Group Environment (Talk by Rémi Cabanac)
- SL2S J08544-0121

Strong Lensing as a Probe of the Mass Distribution *Beyond* the Einstein Radius

Strong Lensing (SL) is well established to provide accurate mass measurements at the location of the Einstein Radius (location of the arcs)

However, precise modelling can be "bothered" by some External Mass Distribution (*e.g.* the Group/Cluster within which the Lens is embedded)

(Kochanek & Blandford, 1991; Keeton et al., 1997; Keeton et al., 2000; Kochanek et al., 2001; Oguri et al., 2005)

Example: derive H_0 from SL + time delays: $\Delta(h)/h \sim 0.22$ (Keeton & Zabludoff, 2004)

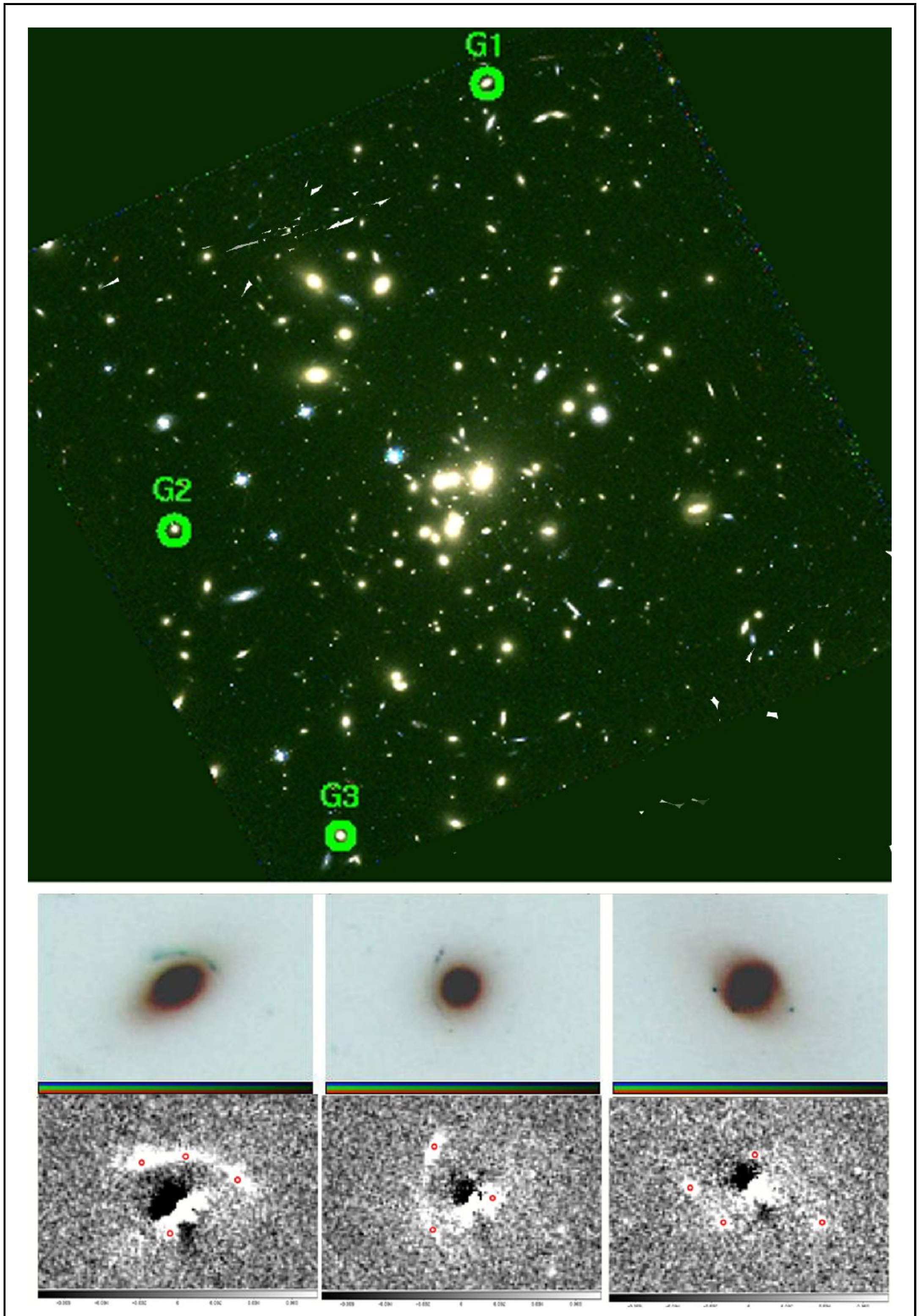
Turn this "bother" to our advantage ⇒

Use precise SL modelling to Probe the External Mass Distribution: "Ring Technique"

Simulations & Application on Abell 1689

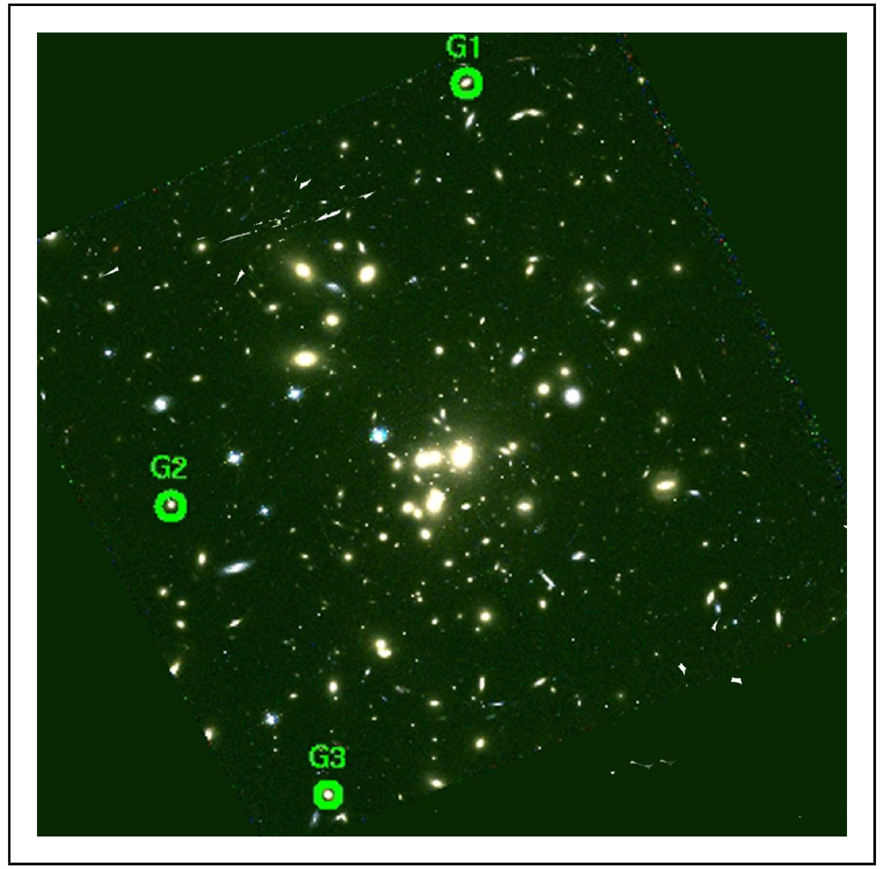
(Tu, Limousin et al., 2008, MNRAS)

Application on SL2S J08544-0121 (Limousin et al., submitted)


G1
G2
G3

Ring Technique on Abell 1689 (Tu, Limousin et al., 2008 - MNRAS)

Fitting the Images around the Three Galaxies ONLY
($>$ 100 multiple images in the Cluster Core NOT considered)



- Model: 3 Isothermal Potential (G1, G2, G3)
  + Cluster (One Clump, free position)
  $\Rightarrow \chi^2 > 100$ – Clump Between Lights Clumps

- Model: 3 Isothermal Potential
  + Two Clumps associated with Each Light Clump
  $\Rightarrow \chi^2 < 4$

Rings ONLY: Strong Evidence for BIMODALITY of the Cluster Core

(Miralda-Escude & Babul, 1995; Broadhurst et al., 2005; Zekser et al., 2006; Halkola et al., 2006; Limousin et al., 2007; Leonard et al., 2007; Saha et al., 2007; Umetsu et al., 2007)

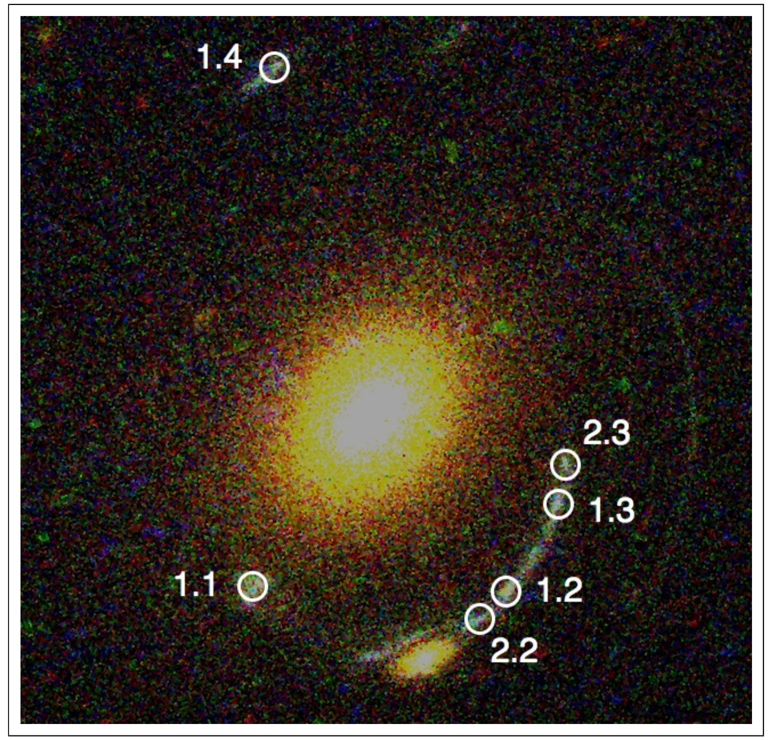
SL2S J08544-0121 at $z = 0.35$: Modelling the Lens

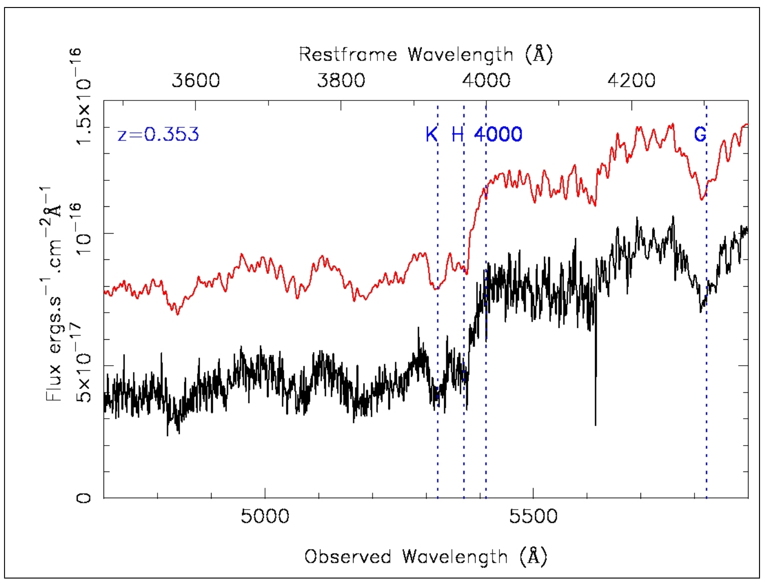
- Bright Arc: $z_{\rm spec} = 1.268$
  (Johan Richard, LRIS, KECK)

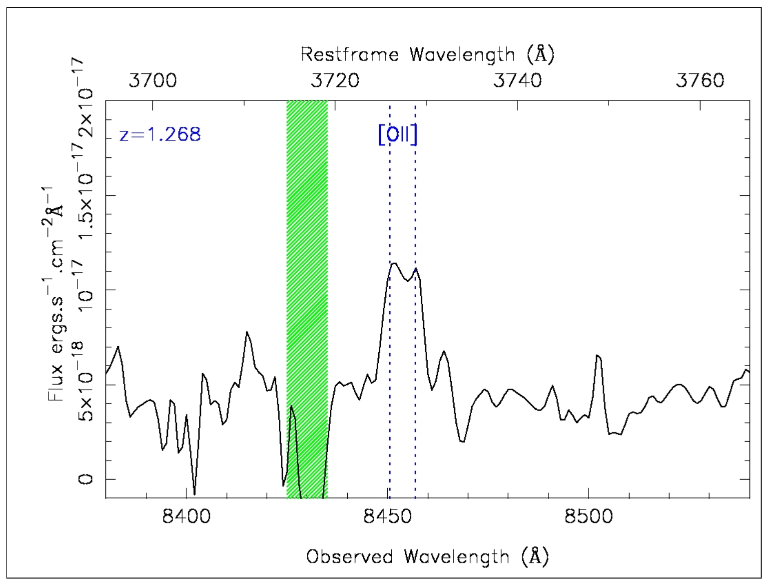
- Faint Arc ?

- Strong Lensing Model:
  An Elliptical Isothermal Potential
  Centred on the Main Galaxy ?

- $e = a^2 - b^2/a^2 + b^2 < 0.6$
  (Jing & Suto, 2001)







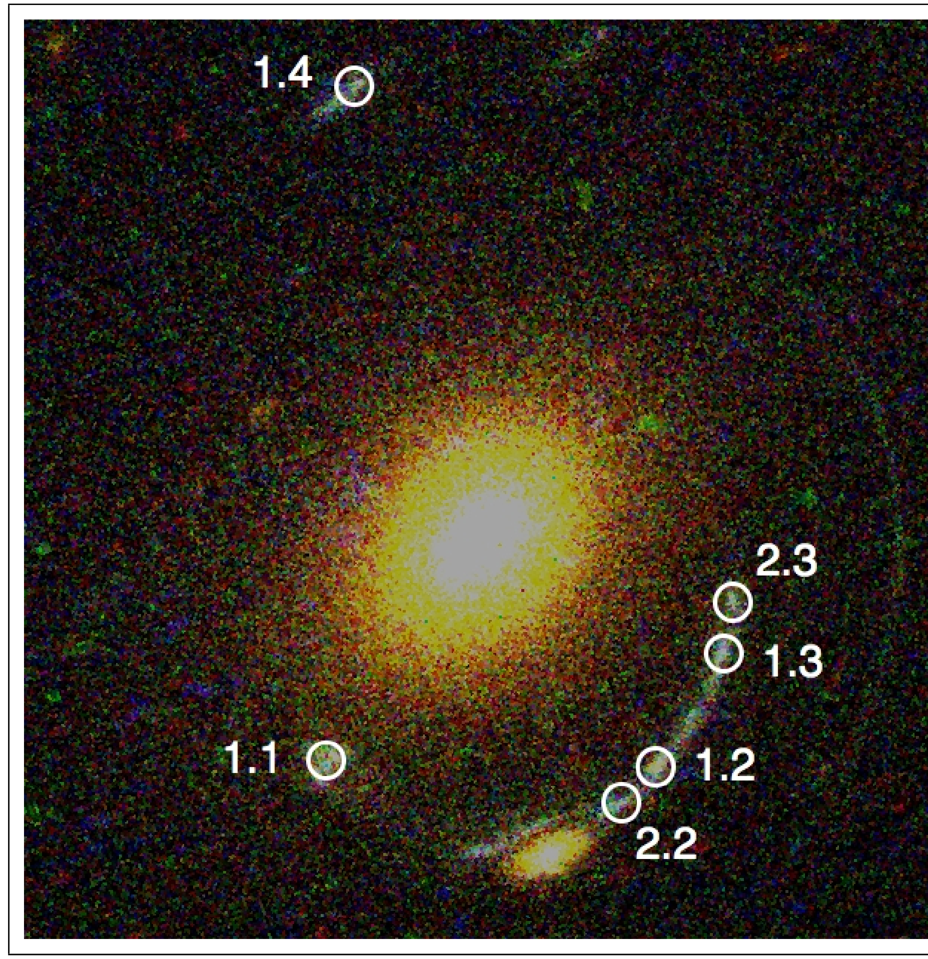
SL2S J08544-0121 at $z = 0.35$: Failed Modelling

- Bright Arc: $z_{\rm spec} = 1.268$
  (Johan Richard, LRIS, KECK)

- Strong Lensing Model:
  An Elliptical Isothermal Potential
  Centred on the Main Galaxy ?

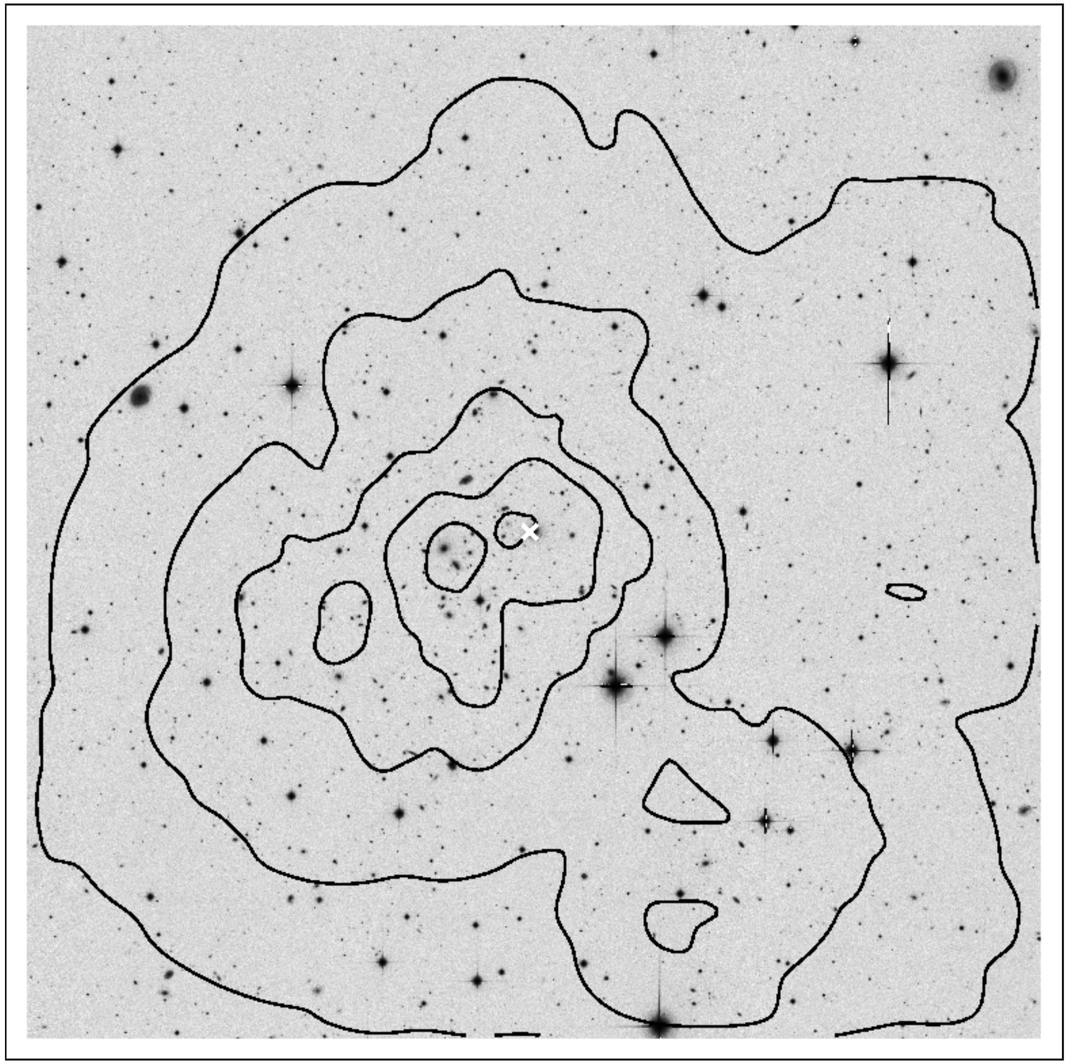
- $e = a^2 - b^2/a^2 + b^2 < 0.6$
  (Jing & Suto, 2001)

- $\Rightarrow$ BAD fit :
  RMS=0.4″, $\chi^2_{\rm red}$=29, $e > 0.6$



$\Rightarrow$ Need to Account for
External Mass Perturbation ?

Environment



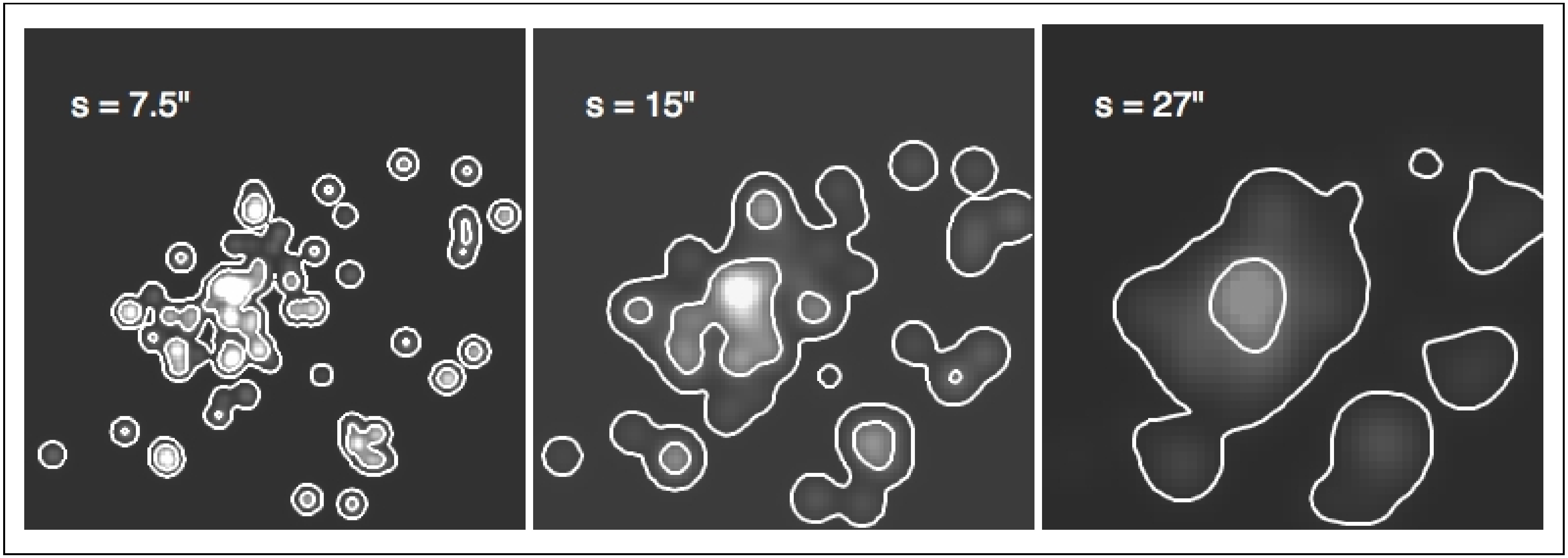
Lens (X) not Found at the Centre of the Light Distribution (Bimodal)

External Mass Perturbation based on the Light Distribution ?

⇒ Is Mass Traced by Light ?

Introducing an External Mass Perturbation: (s, M_{EXT})

Group Members [- LENS]: Total Light $\longrightarrow$ Luminosity Map (smoothing, s)



$L = 10^7, 10^8\ L_{\odot}$ arcsec^{-2}

Luminosity Map $\longrightarrow$ Mass Map (M_{EXT}) (Jullo & Kneib, 2009)

$\longrightarrow$ External Perturbation (s, M_{EXT})

Remodelling the Lens
Accounting for External Mass Perturbation (s, $M_{\rm EXT}$)

Good Fits are Found for a Range of s and $M_{\rm EXT}$
(best fit: rms=0.05$''$, $\chi^2 \sim 1$)

s and $M_{\rm EXT}$ do Characterize the Galaxy Group Properties

From a LOCAL ($\sim$10$''$) Strong Lensing Analysis ...

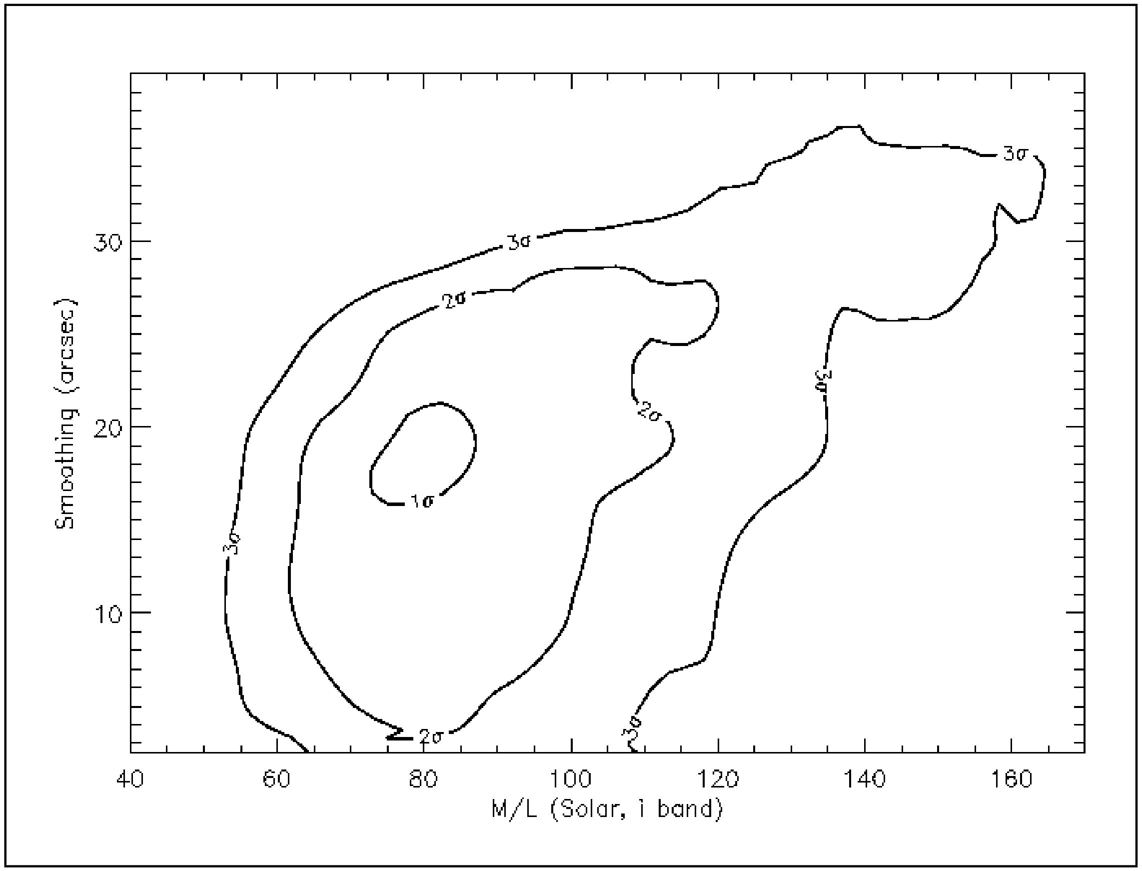
$\Rightarrow$ Global ($\sim$100$''$) Constraints on the Group as a Whole !

$\Rightarrow$ Strong Lensing *only* is Sensitive to the Mass Distribution on Large Scales

Constraints on the Group (Strong Lensing Only)

for (s, M_{TOT}) [Lens Modelling] $\rightarrow \Delta(\chi 2) \rightarrow$ Confidence Levels

($M_{TOT} = M_{EXT} + M_{LENS}$ ($\sim$ KST) & $L = L_{TOT}$)

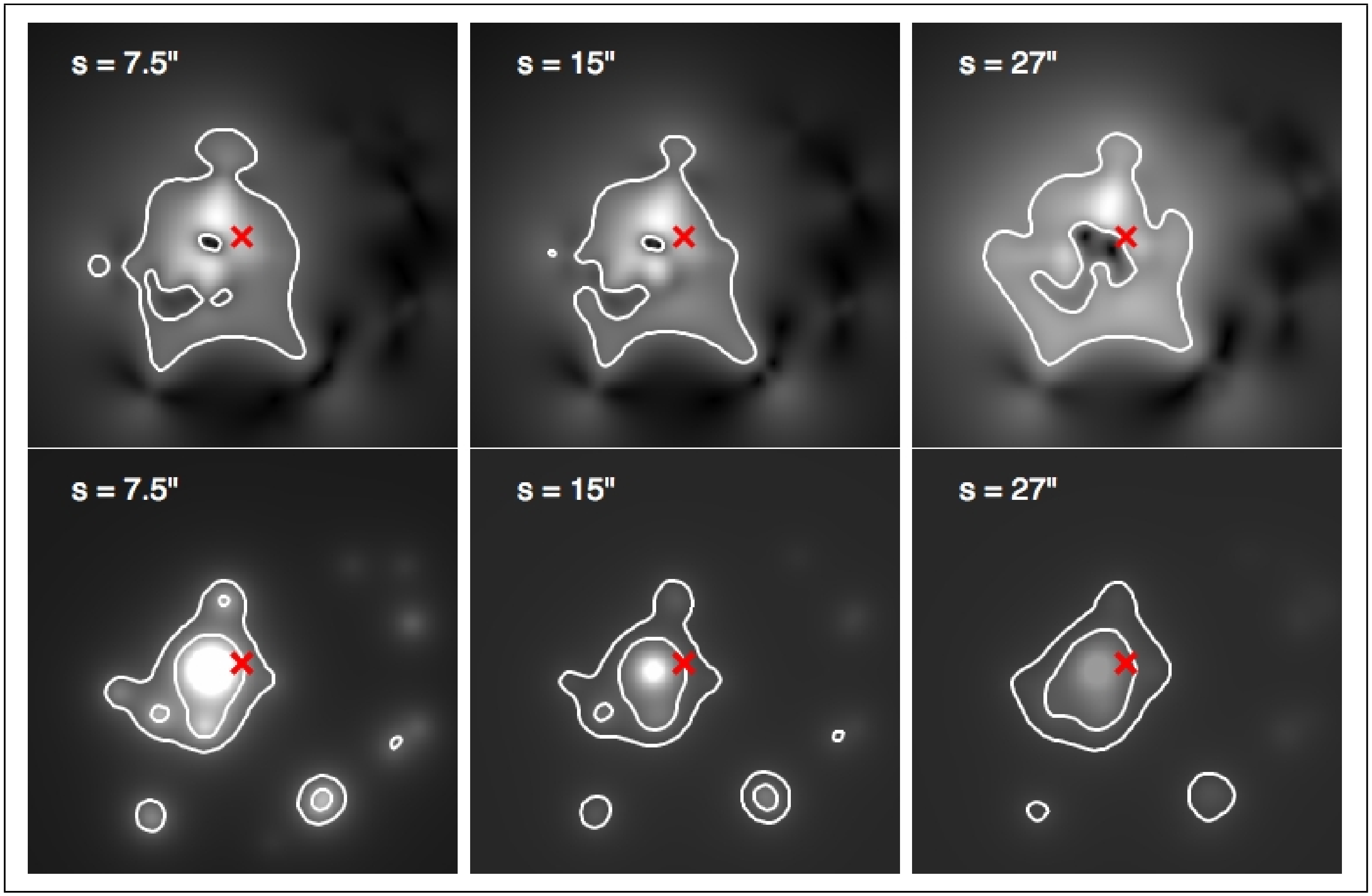


$s < 40''$ & $52 < M_{TOT}/L < 165$ (3σ)

EFFECT OF THE LARGE SCALE PERTURBATION

EXPERIENCED LOCALLY BY THE LENS ?

External Mass Perturbation [First Order]: $\kappa_{\rm ext}$ & $\gamma_{\rm ext}$



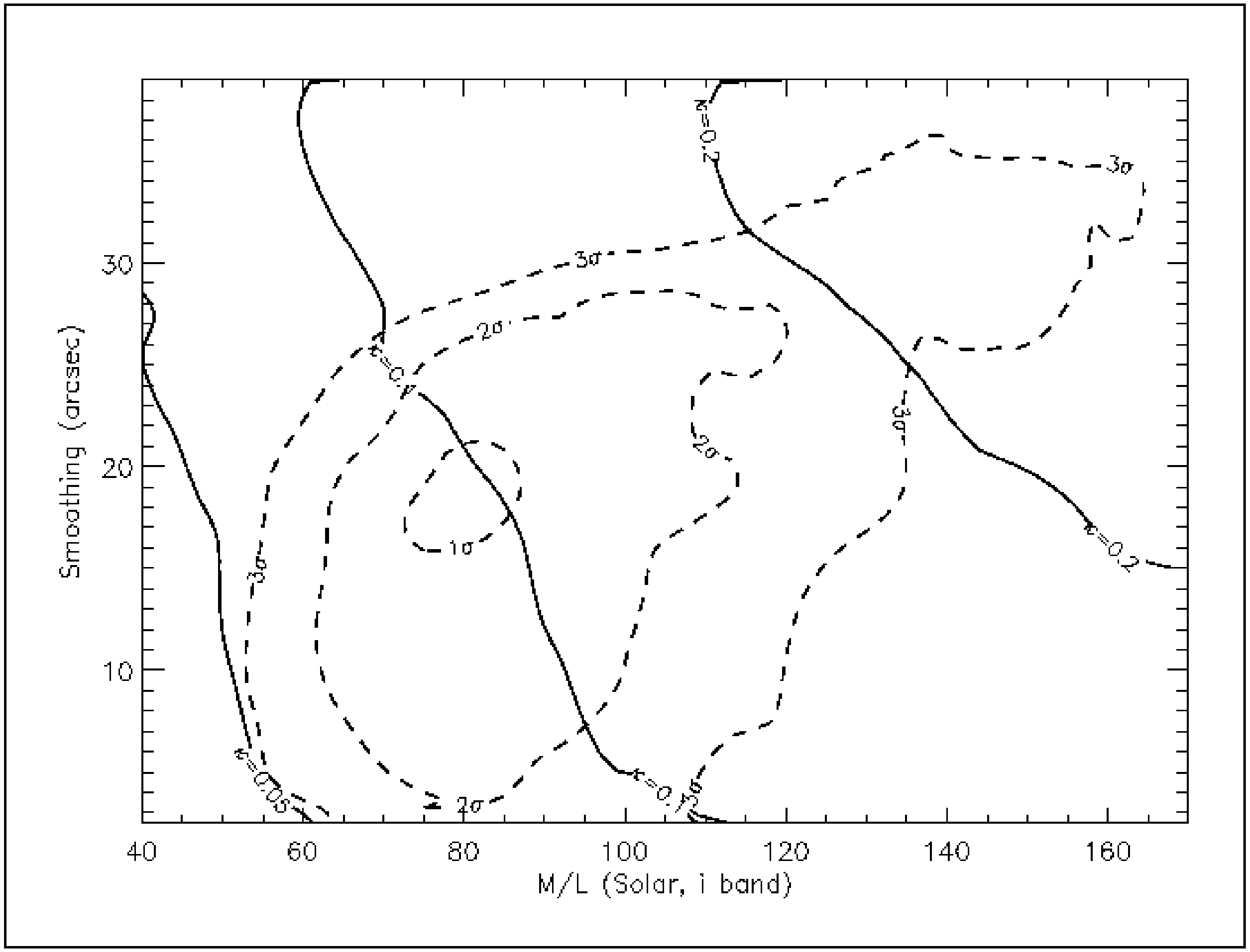
$\mathrm{M_{EXT}}$ Fixed $(5.7\,10^{14}\ \mathrm{M_\odot})$: $\gamma_{\rm ext} = 0.1$ – $\kappa_{\rm ext} = 0.1, 0.2$

$$\gamma_{\rm ext} = \gamma_{\rm ext}(s) \ \& \ \kappa_{\rm ext} = \kappa_{\rm ext}(s)$$

What does the Lens Feel ? [First order]

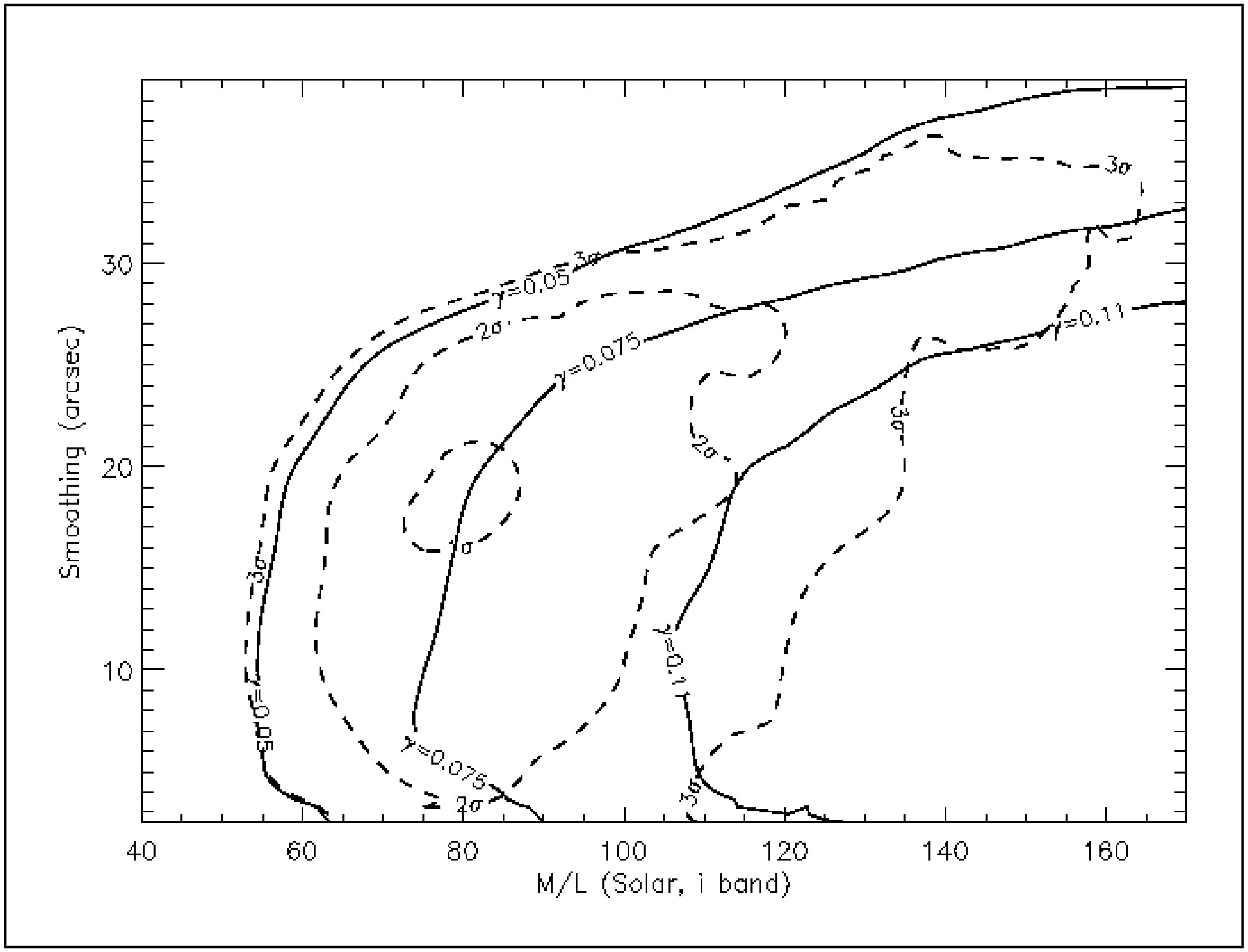
$\Rightarrow$ Average $\gamma_{\rm ext}$ & $\kappa_{\rm ext}$ Around the Lens

κ_{ext} Experienced by the Lens



κ lines do NOT FOLLOW Degeneracies

$\gamma_{\rm ext}$ Experienced by the Lens



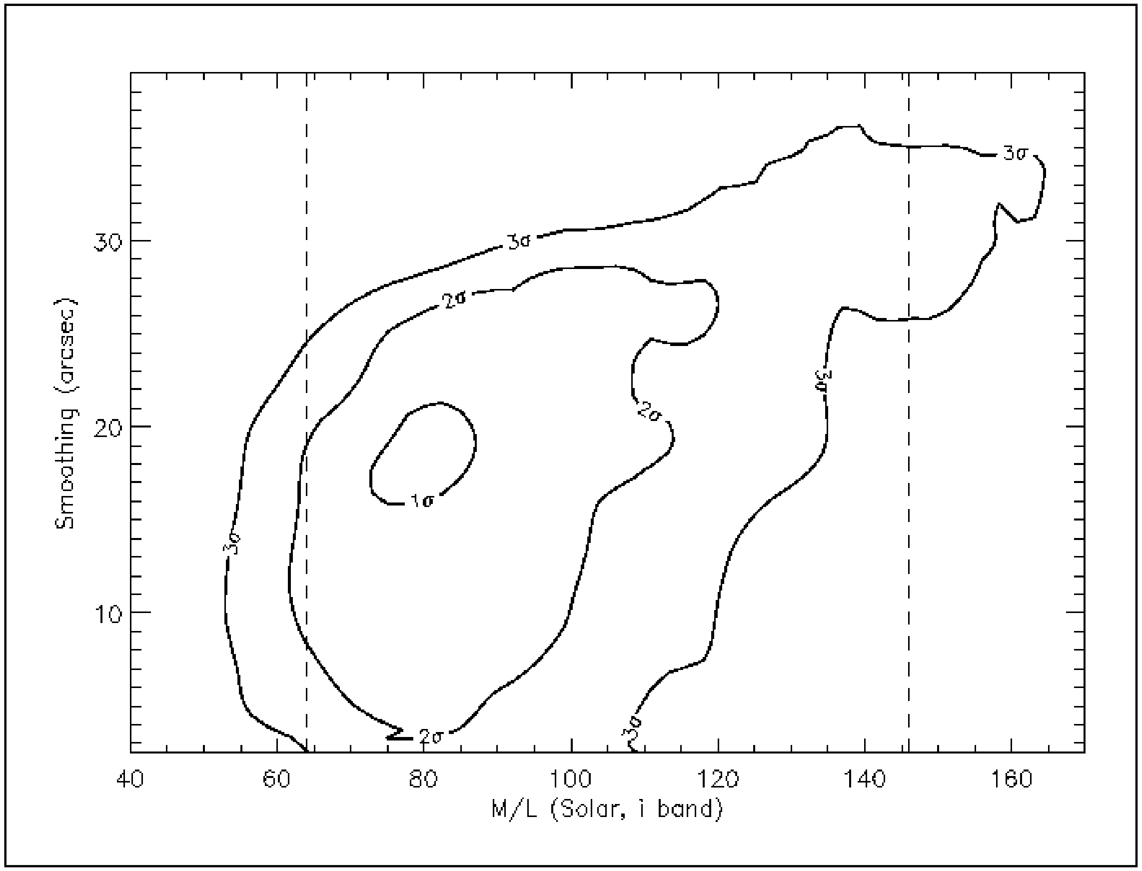
γ lines DO FOLLOW Degeneracies:

Multiple Images NEED LOCALLY a Shear Value of $\sim$ 0.075

Degeneracies Understood: large s compensated by larger Mass [FIRST ORDER]
CONTOURS DO CLOSE: HIGHER ORDER TERMS BEYOND SHEAR

Complementary Mass Probes: Weak Lensing

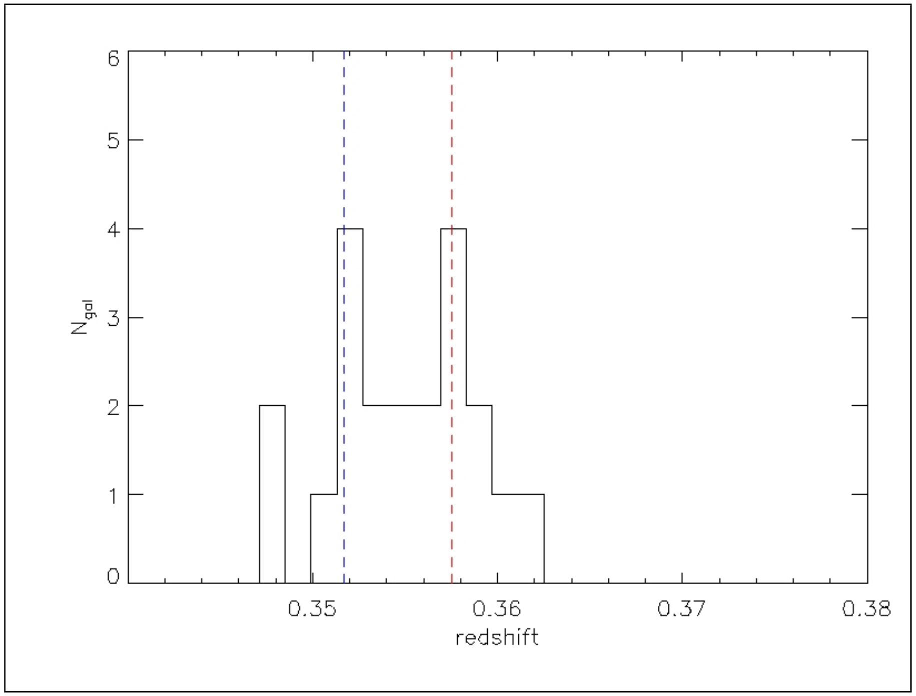
$$\sigma_{\rm SIS} = 658^{+119}_{-146}\ \mathsf{km\,s^{-1}} \Rightarrow \mathsf{M/L} = 106 \pm 40\ (1\sigma)$$



Good Agreement with the Strong Lensing only Constraints

Complementary Mass Probes: Dynamics (losvdisp)

Group Members Dynamics (FORS 2@VLT)



(Valparaiso Team, poster by Veronica Motta)

A Bimodal Structure in Velocity Space as Well
(Light Distribution was Found Bimodal and
Motivated the Lensing Scenario Presented)

Complementary Mass Probes: X-Ray ?

X-Ray Counterpart ? (XMM - Chandra)
(P.I. Fabio Gastaldello)

- Check the lensing based scenario
  (in particular the light traces mass Hypothesis)

- catch an interesting snapshot of the structure formation process

Can Strong Lensing Compete over Weak Lensing ?

In SL2S J08544-0121, SL seems to compete over WL !

Cheaper in terms of Telescope Time ?

- High Quality Data (CFHTLS + Terapix)
- Deep Enough + good seeing (0.5$''$)

- Shallow Snapshot HST Imaging
- BUT STILL EXPENSIVE

Easier ?

- Model and Subtract the PSF
- Measure Shape Parameters of Faint Objects
- Removal of Faint Group/Cluster Members

- Only Conjugating a Few Images !
- Arc Brightness Distribution (Suyu et al., 2006)

More Accurate ?

- WL: $66 < M/L < 146$ (1σ)

- SL: $52 < M/L < 165$ (3σ)

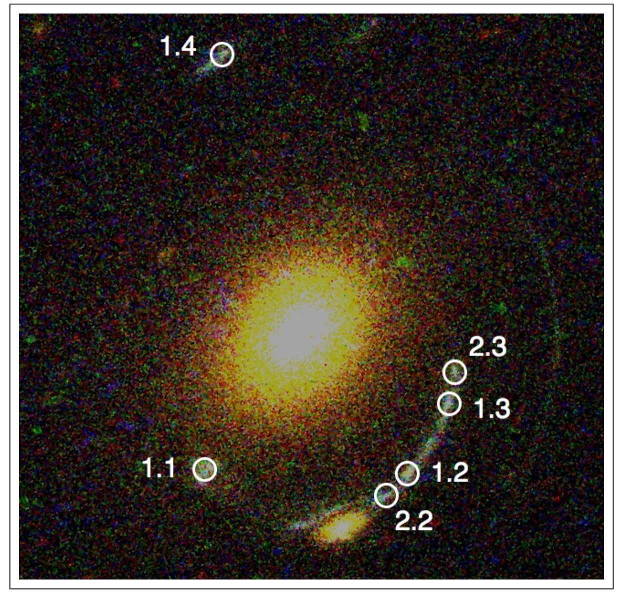
Extendable to Higher Redshift ?

- WL signal Decreases Quickly with Lens Redshift
- SL2S J08544-0121 at $z = 1$: NO WL

- HST Imaging of $z = 1$ Lens Feasible

Where do Constraints are Coming From ?

A Highly Perturbed SL System
d(1.1 - 1.2 - 1.3) $\sim 5''$
d(1.4) $\sim 8''$



Removing Image 1.4:

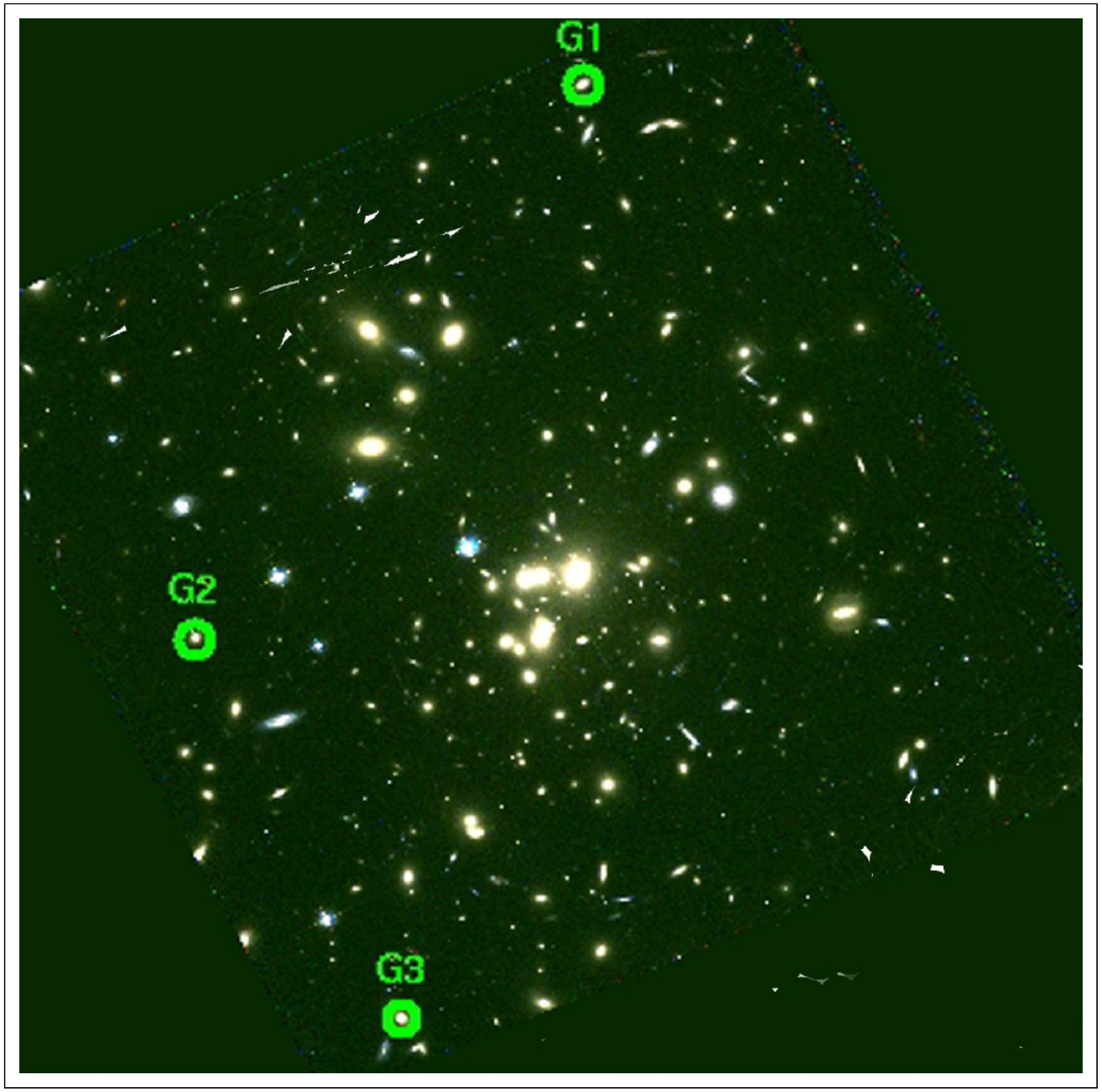
- Lens Modelling (No Ext. Perturb.): Good Fit RMS=$0.04''$, χ^2=0.06
- Lens Modelling (+ Ext. Perturb.): Equally Good Fit for a Large Range of s, M/L

$\Rightarrow$ No Need for an External Mass Perturbation

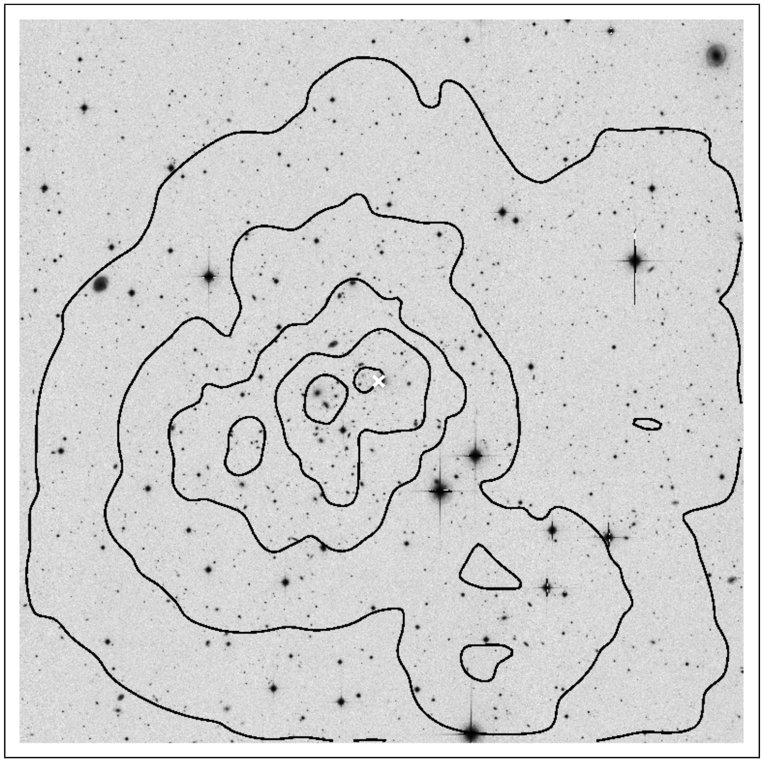
Looking for Perturbed Strong Lensing Systems ?

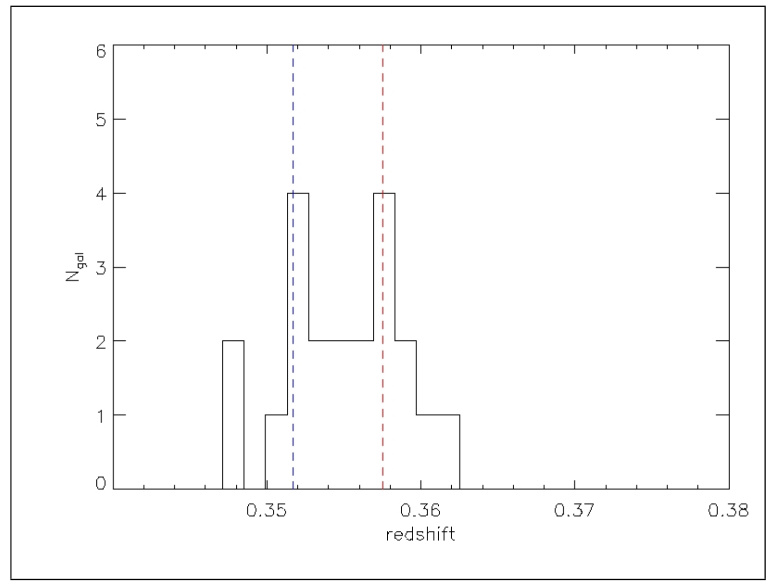
A Non Dominant SL System
as a Particule Test Probing the Main Potential

A Non Dominant SL System as a Particule Test Probing the Main Potential



A Non Dominant SL System as a Particule Test Probing the Main Potential

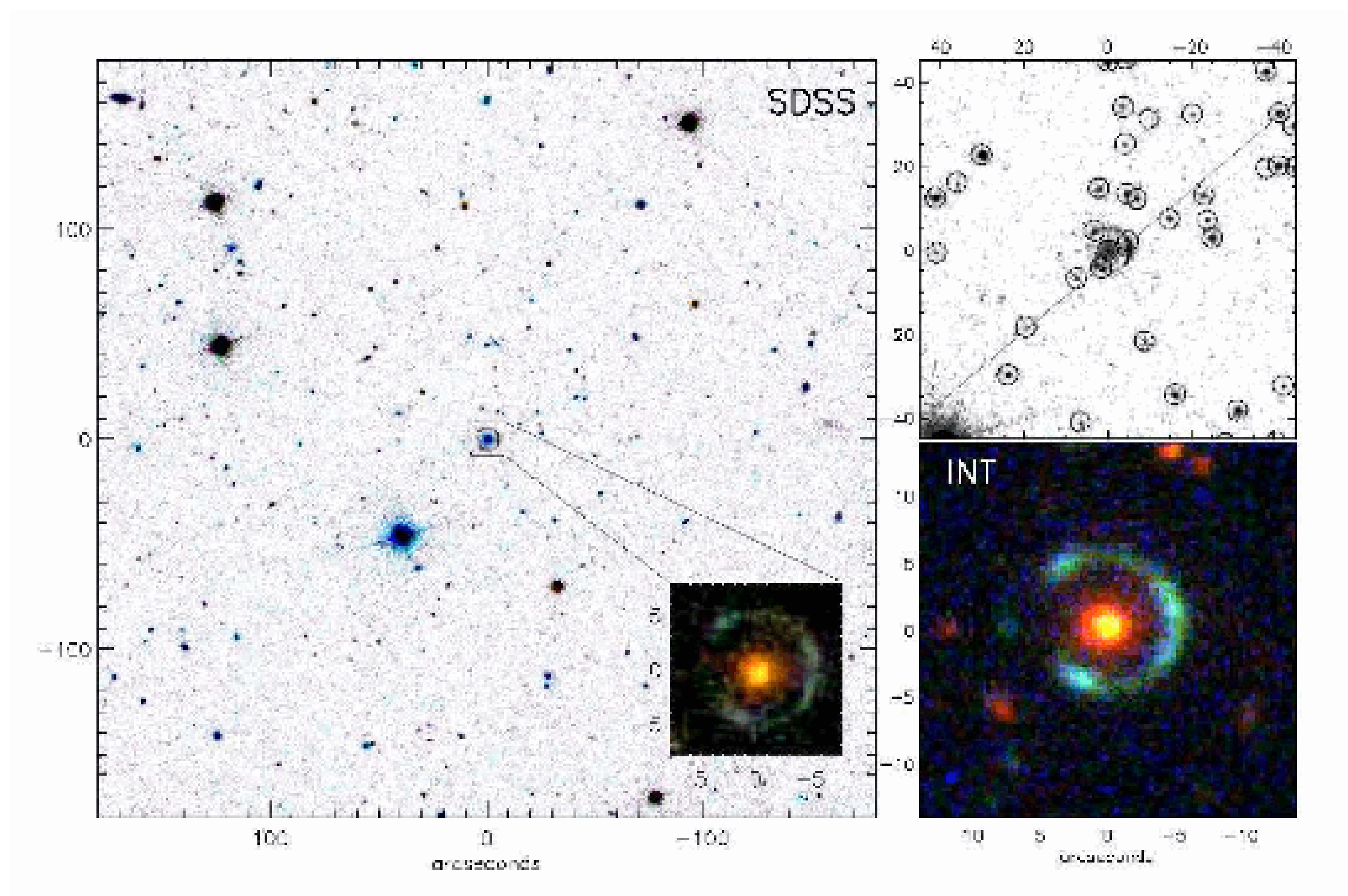




Bimodality ! (In its Light Distribution and in Velocity Space)

A Non Dominant SL System as a Particule Test Probing the Main Potential

Cosmic HorsheShoe
(Belokurov et al., 2007;
Dye et al., 2008)
Almost Complete Einstein Ring of Radius $5''$
from a LRG ($z = 0.44$)
$\Rightarrow$ A Non Perturbed SL System:
Dominates the Group Light Distribution



No External Shear Required by the SL Model

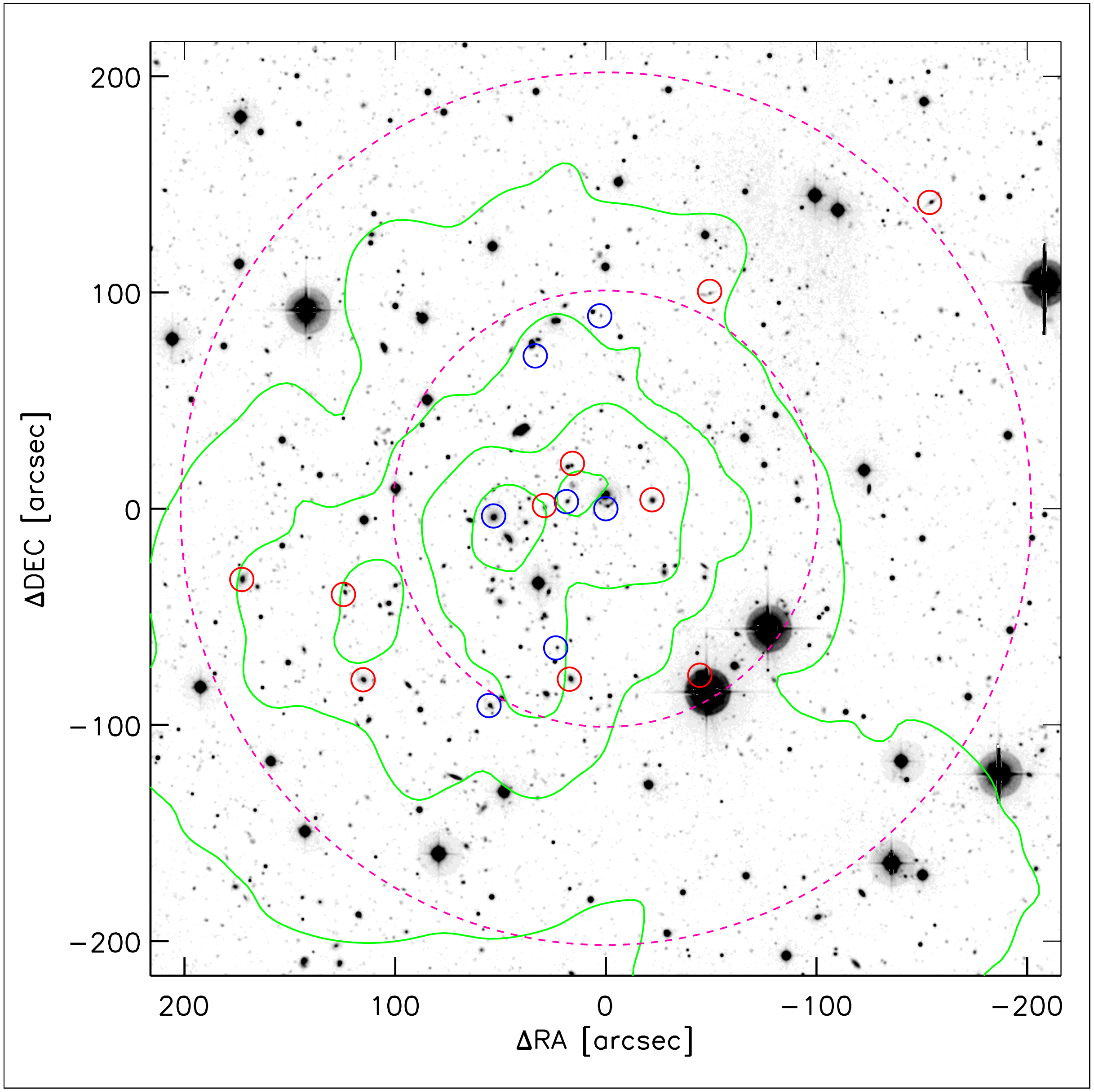
Conclusions

Strong Lensing BY Galaxy Groups

- Intermediate Mass Scale Strong Lenses DO Exist: $\sim$ 20 in the SL2S
- This Finding Opens a New Window of Exploration in the Mass Spectrum
- From SDSS $\sim$10 groups
- Bridges the Gap Between Galaxies and Clusters
- From SDSS $\sim$10 groups Sample Being Built !
  see, *e.g.* The CAmbridge Sloan Survey Of Wide ARcs in the skY (CASSOWARY) + FermiLab Team

Strong Lensing Can be Used (sometimes) to Probe Mass Distributions
Far Beyond the Einstein Radius
$\Rightarrow$ a Non Dominant Strong Lensing System as a
Particule Test of the Main Potential

Look For Highly Perturbed SL Systems:
ARCHIVE – FUTURE = LSST - JDEM ...



Red: Members Associated to the most massive structure
Blue: Members Associated to the less massive structure (and less extended ?)

Shear Ellipticity Degeneracies

Ellipticity-shear degeneracy is quite complicated, and depending on the situation the values can either correlate or anti-correlate. See, e.g., Keeton, Kochaneck, Seljak 1997, in which both examples were shown.

In most situations the ellipticity of the galaxy, rather than external shear, mainly determines the ellipticity of the lens potential. The fact that the lens potential want to be elliptical does not say anything about the external shear.

Misalignment of the position angle is a good indicator of the external shear.

1 PLAN
2 The Canada France Hawaii Telescope Legacy Survey
3 Follow-up: Space Imaging + Spectroscopy
(LRIS-Keck - FORS-VLT)
4 Strong Lenses over the Full Mass Spectrum
5 Strong Lensing *IN* and *BY* Galaxy Groups
6
7
8 Non Cusp Groups
9 Space Based Follow-up: Strong Lensing Analysis
10 Analysis
11 Results (Limousin et al., 2009, A&A)
12 Combining Complementary Probes
13 Strong Lensing as a Probe of the Mass Distribution
Beyond the Einstein Radius
15 Ring Technique on Abell 1689 (Tu, Limousin et al., 2008 - MNRAS)
16 SL2S J08544-0121 at $z = 0.35$: Modelling the Lens
17 SL2S J08544-0121 at $z = 0.35$: Failed Modelling
18 Environment
19 Introducing an External Mass Perturbation: (s, $\mathrm{M_{EXT}}$)
20 Remodelling the Lens
Accounting for External Mass Perturbation (s, $\mathrm{M_{EXT}}$)
21 Constraints on the Group (Strong Lensing Only)
22 External Mass Perturbation [First Order]: $\kappa_{\rm ext}$ & $\gamma_{\rm ext}$
23 $\kappa_{\rm ext}$ Experienced by the Lens
24 $\gamma_{\rm ext}$ Experienced by the Lens
25 Complementary Mass Probes: Weak Lensing
26 Complementary Mass Probes: Dynamics (losvdisp)
27 Complementary Mass Probes: X-Ray ?
28 Can Strong Lensing Compete over Weak Lensing ?
29 Where do Constraints are Coming From ?
30 A Non Dominant SL System as a
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