Title: Strong Gravitational Lensing by Clusters of Galaxies

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Abstract: The statistics of strong lensing by galaxy clusters are sensitive both to cosmology and the detailed physics that determines the structure of halos. To exploit these sensitivites requires large and well defined samples of lenses on these mass scales. I will report on efforts to provide such samples - we finally now have uniformly selected samples of several hundred lenses to work with.

Strong Gravitational Lensing by Clusters of Galaxies

Fundamental Physics and Large Scale Structure, Perimeter Institute

April 30, 2010

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and Astrophysics
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Kavli Institute
For Cosmological Physic
At The University of Chicago

Outline

- a (very) quick review
- new samples of lenses
  - SDSS
  - RCS-2
- multi-wavelength follow-up
  - optical and IR spectroscopy
  - SZA observations
- some initial statistics
  - BCG to arc alignments
  - optical properties of lensing clusters
  - the counts of arcs
  - cluster concentrations
- a quick diversion: sources, not lenses

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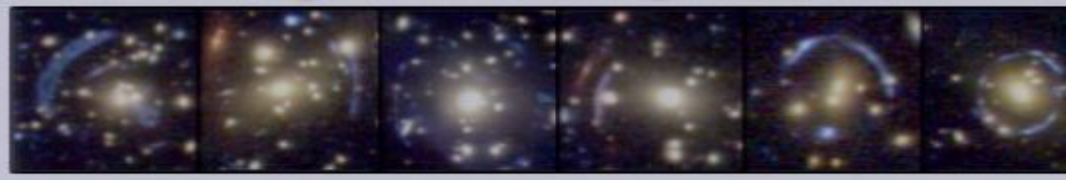

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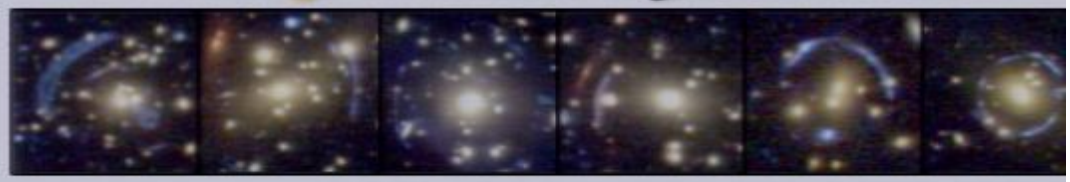

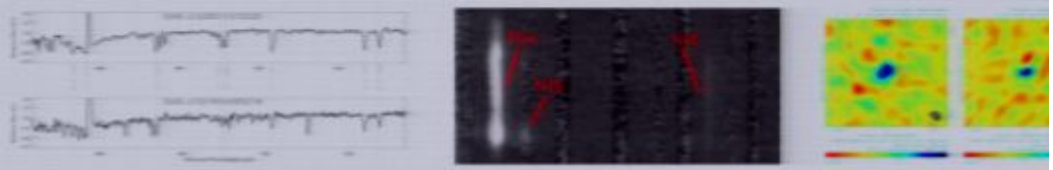

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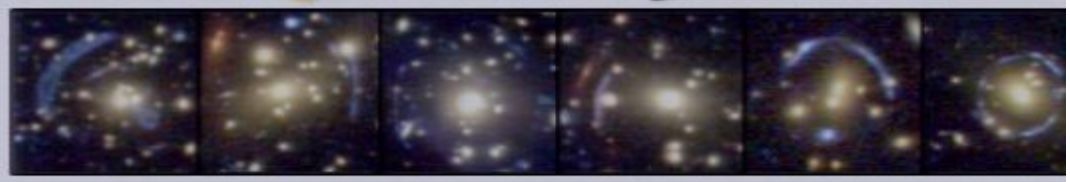

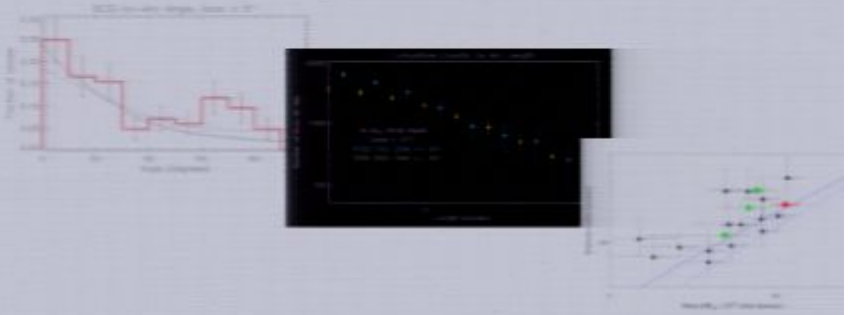

Principal Collaborators

SDSS Giant Arcs:

Joe Hennawi (MPIA)
Hakon Dahle (Oslo)
Keren Sharon (KICP)
Masamune Oguri (NAOJ)
Priya Natarajan (Yale)
Neal Dalal (CITA)
Stefanie Gallegos (NMSU)

RCS-2:

Matt Bayliss (Chicago)
Felipe Barrientos (Catolica)
Ben Koester (Chicago)
Howard Yee (Toronto)
Eva Wuyts (Chicago)
David Gilbank (Waterloo)
Molly Hicks (Michigan State)
Henk Hoekstra (Leiden)

SZA:

Megan Gralla (Chicago)
Dan Marrone (Chicago)
Marshall Joy (NASA-MSFC)
John Carlstrom (Chicago)
Max Bonamente (Alabama)

73 Years of Strong Lensing in 37 Seconds (abridged)*

*with apologies to the authors of "37 Plays in 97 Minutes
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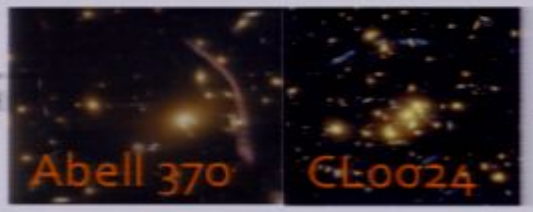
- finally discovered in clusters 

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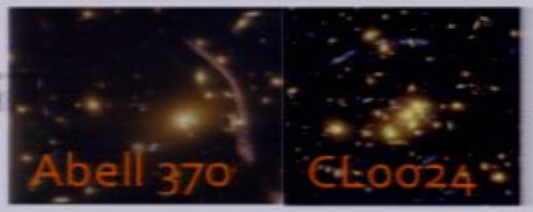
- finally discovered in clusters 

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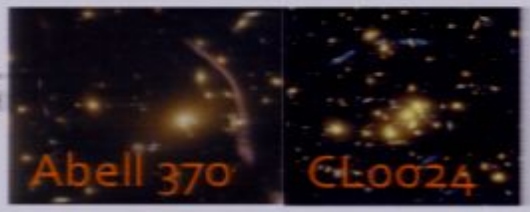
- finally discovered in clusters 

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- Bartelmann and other study arc statistics, and the advent of ΛCDM gives rise to the 'missing arcs' problem: many papers result
- Large imaging datasets finally yield large samples

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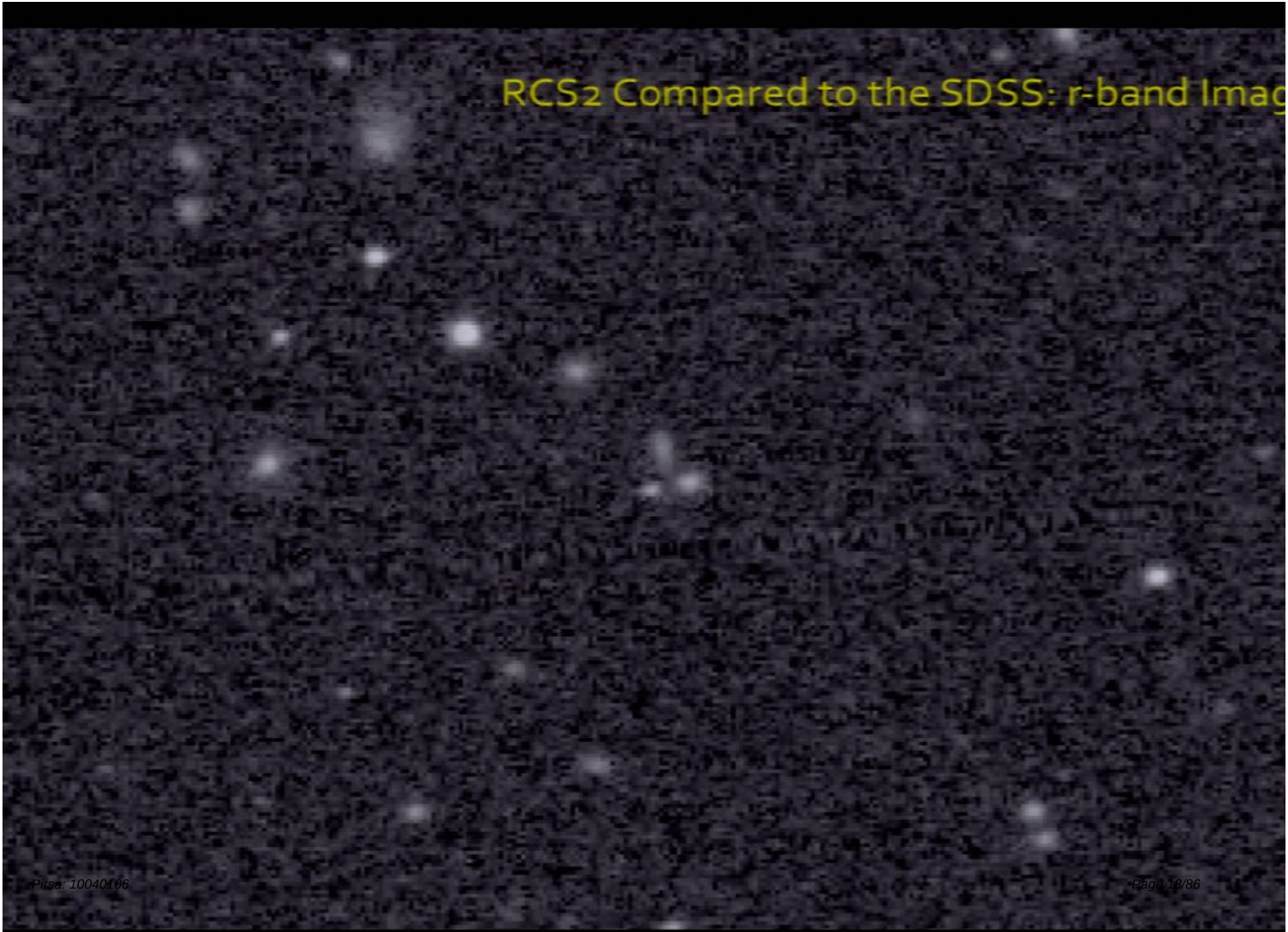
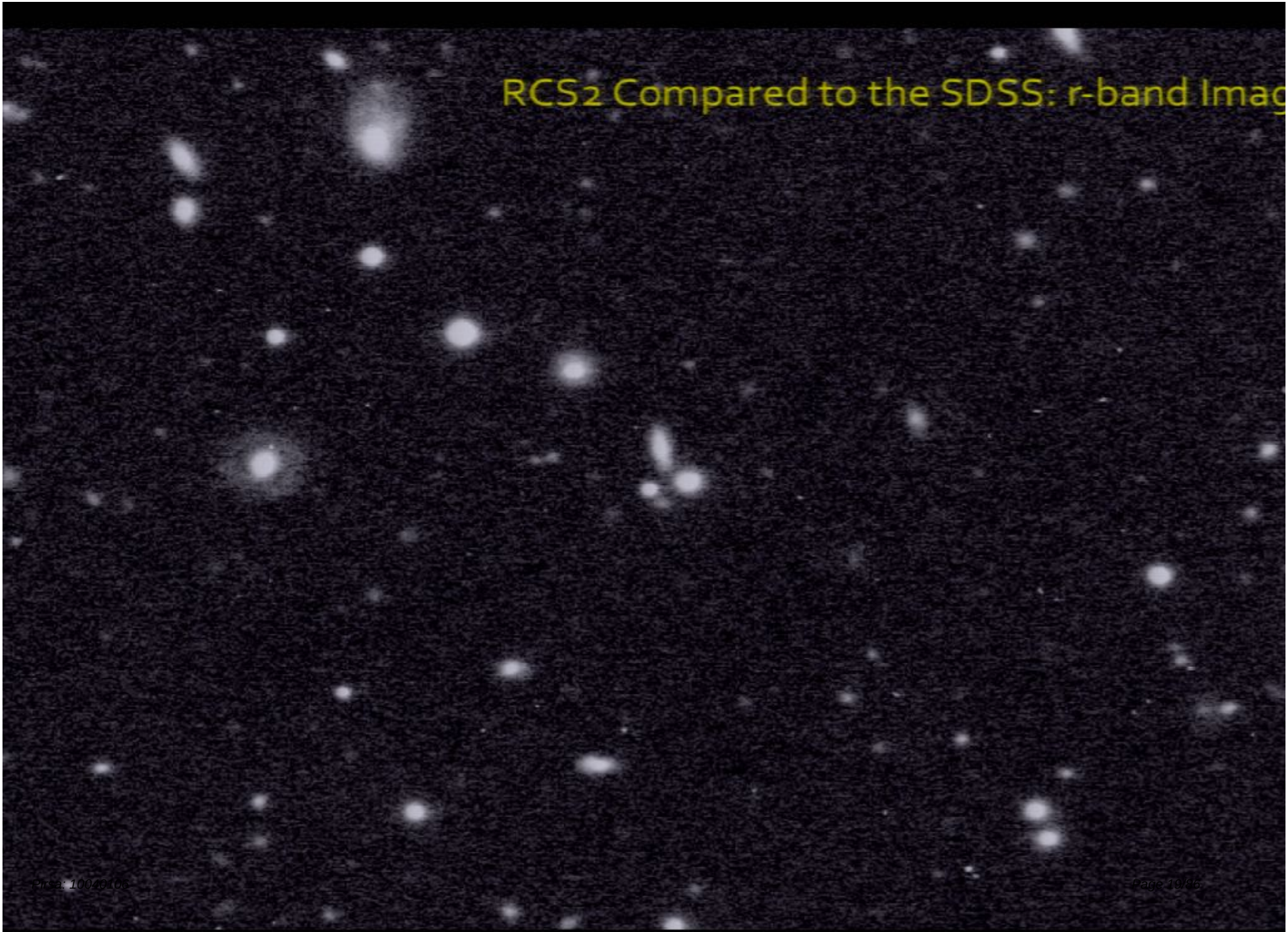
Finding Lenses 101

- from a cosmological / large-scale structure perspective, lensing at group to cluster scales (10^{13}-10^{15} M_{sun}) is arguably the most interesting
- to find all occurrences of strong lensing in a given imaging dataset one could in principal search the entire area imaged – but this is HARD!
- instead, define a sample of clusters and groups and search only on those lines of sight
- two ways to search – by eye or by computer. To learn how to do the latter you have to do the former first…

Two Optical Datasets: SDSS DR7 and RCS-2

	SDSS DR7 'Legacy'-	RCS-2
Area (square degrees)	~7800	~800 (1000)
Filters	(u)griz	gr(i)z
Depth (r-band, 5-sigma, P.S.)	22.9	24.8
Median r-band Seeing	1".40	0".70
Total # Objects	~2.5×10^8	~1.5×10^8
Cluster z Range (Coma-like)	0-0.45	0-1.0
Cluster Co-Moving Vol. (Gpc^3)	~5	~3.3
Status	Data acquisition complete, photometric cataloging complete, cluster catalog complete	Data acquisition complete, photometric catalog near-complete, cluster catalog preliminary/partial


RCS2 Compared to the SDSS: r-band Imag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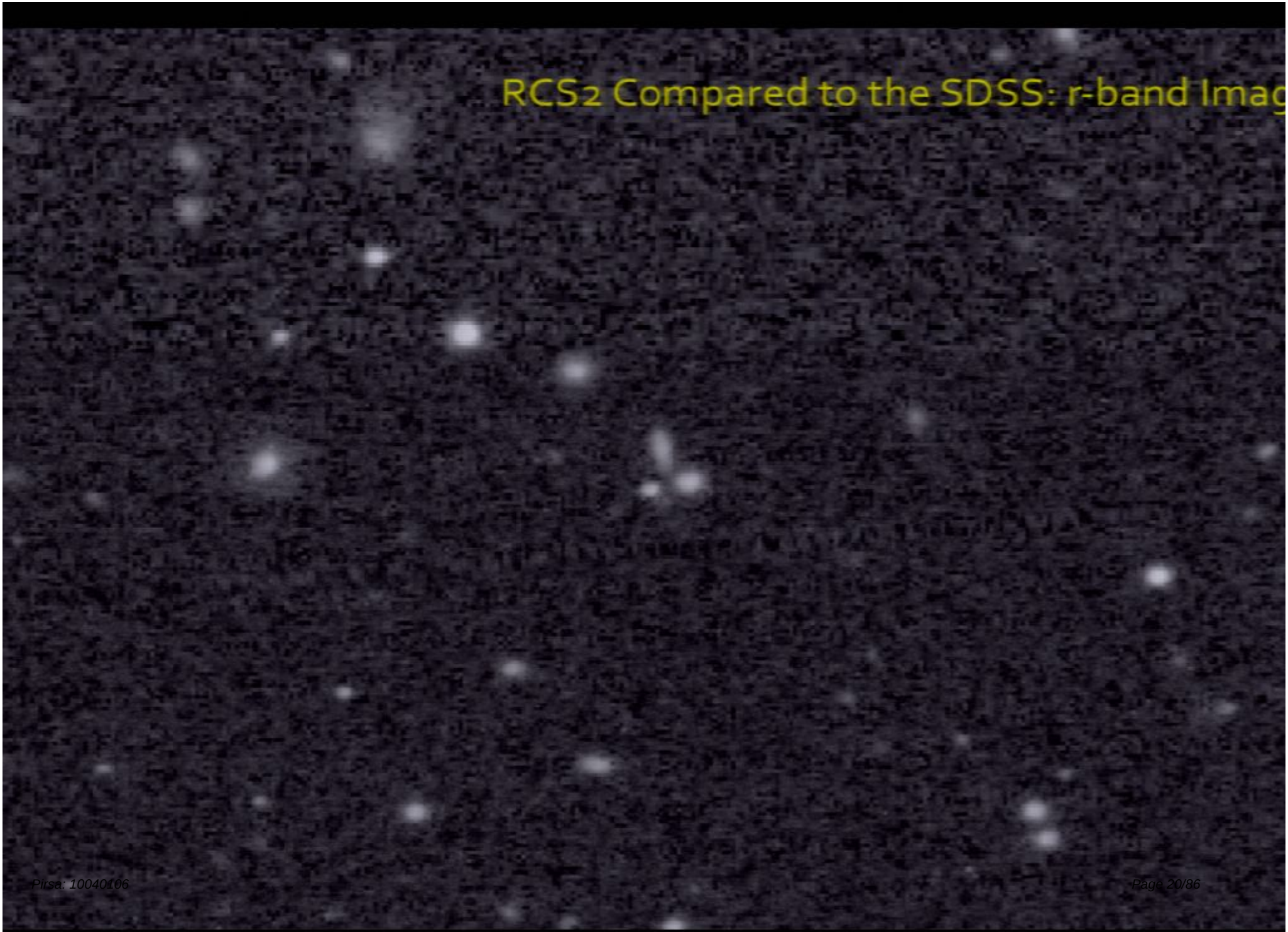
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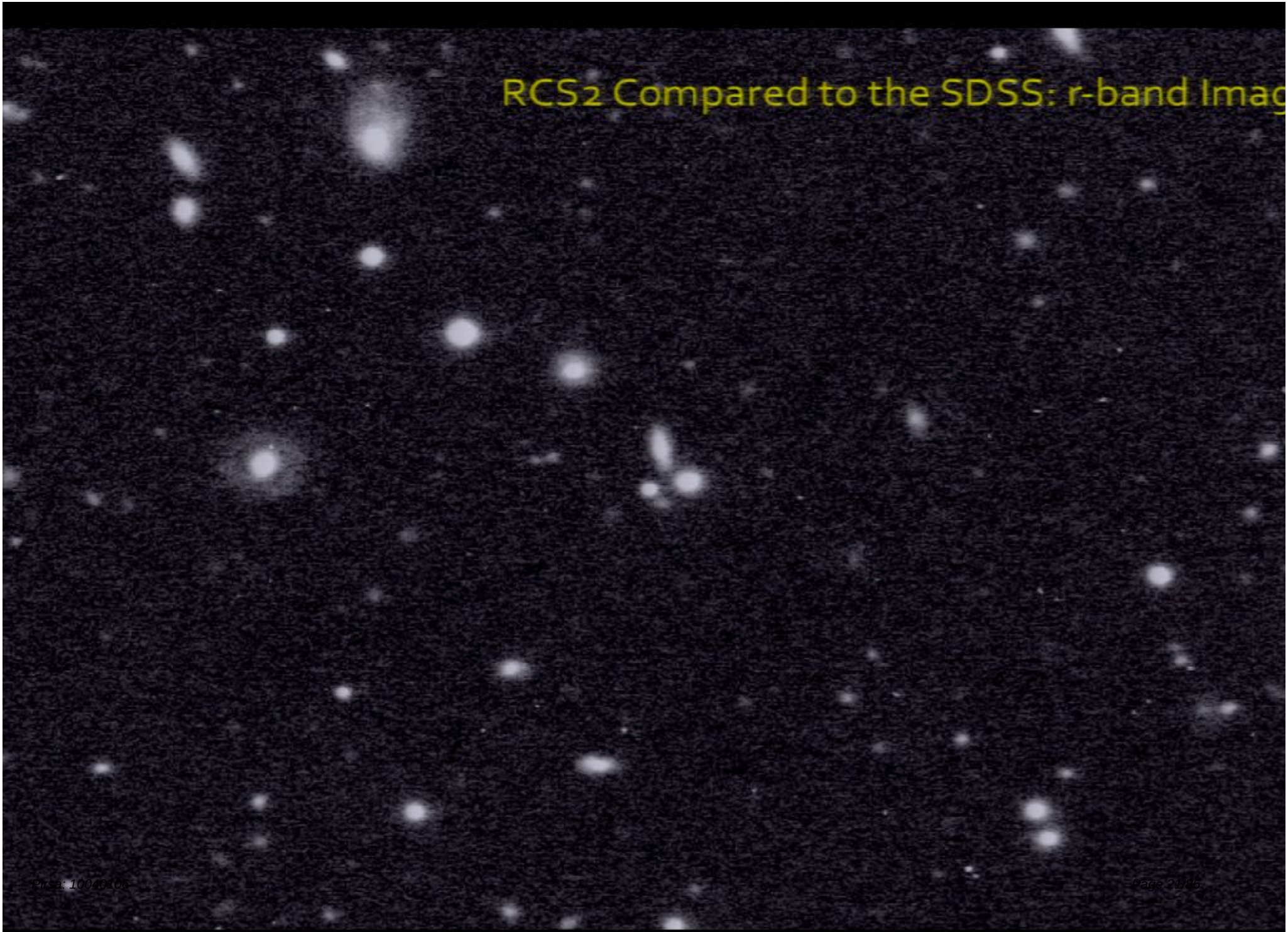
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The SDSS 'Visual' Sample

- Cluster and group catalog defined using red-sequence method applied to SDSS imaging: 40000 lines of sight
- Custom color image generator used to fabricate *griz* composite images, 4'x4' in size : multiple images used to tile "large" clusters: total number of images searched: 44210
- Each image examined by eye and scored from 0 (no evidence for lensing) to 3 (wow!)
- 10% re-examination rate, selected from a running window 1000 images wide, 1000 images back, with translation and rotation; 'circular' list to ensure all images can be re-sampled ; re-sampling probability as a function of 'current' score is adjusted to ensure all scores are well sampled
- 4 examiners, working independently

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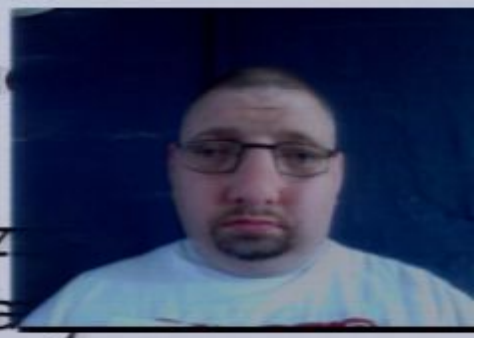

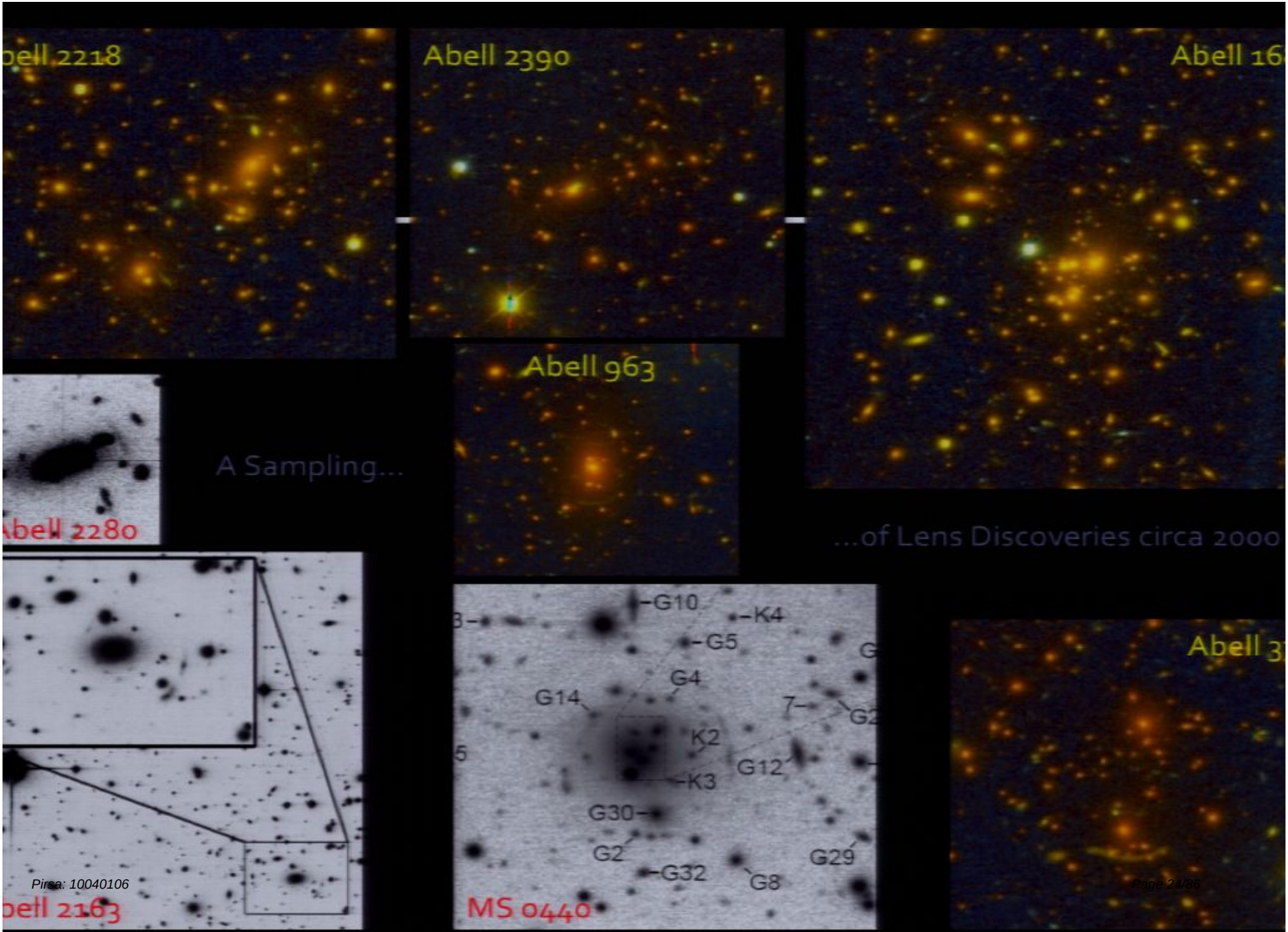
bell 2218
Abell 2390
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A Sampling...
bell 2280
...of Lens Discoveries circa 2000
G10
K4
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G14
K2
G12
K3
G30
G2
G32
G8
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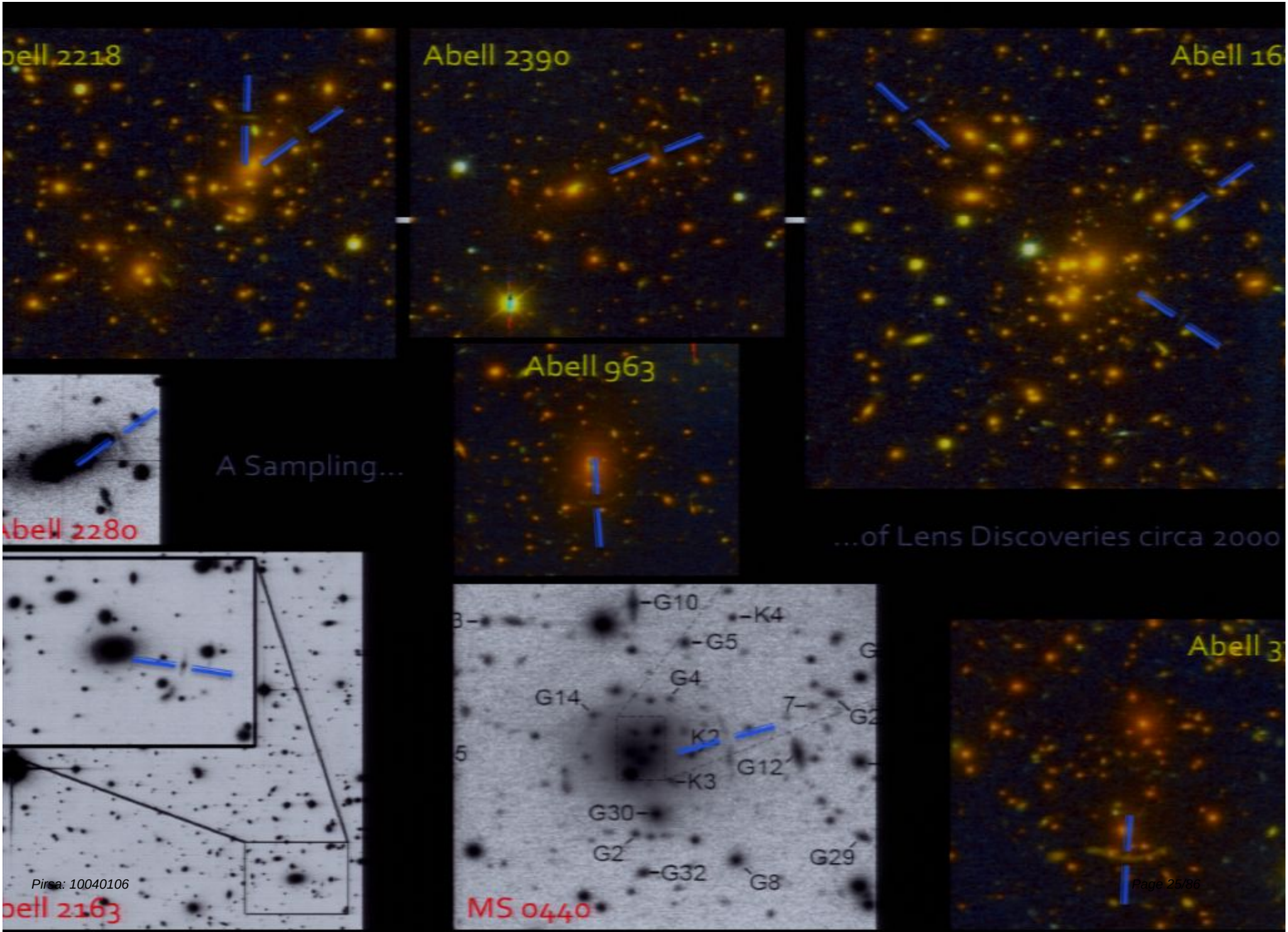
Abell 3
bell 2163
MS 0440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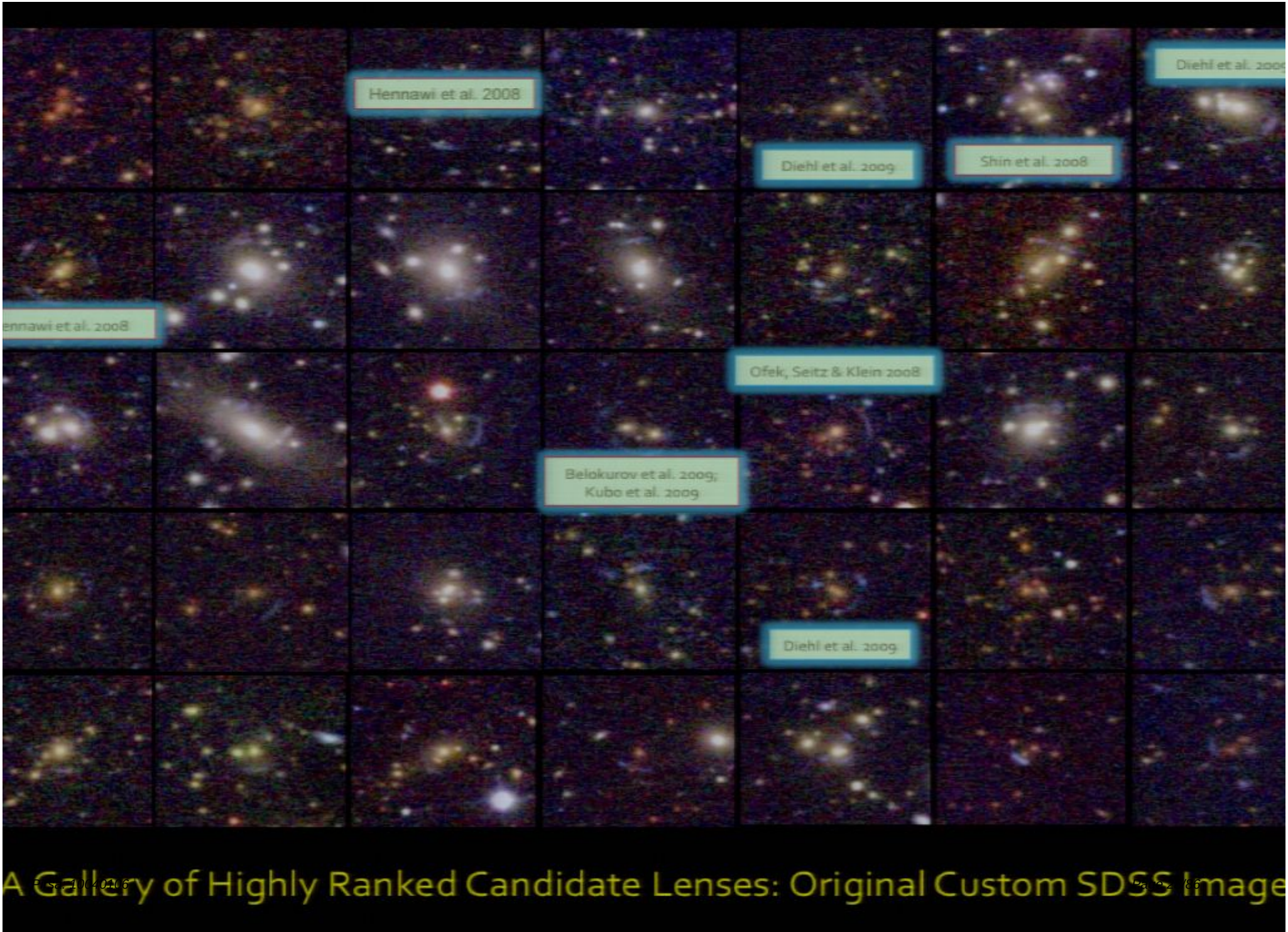
A Gallery of Highly Ranked Candidate Lenses: Original Custom SDSS Image


Hennawi et al. 2008
Diehl et al. 2009
Shin et al. 2008
Diehl et al. 200
ennawi et al. 2008
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Belokurov et al. 2009;
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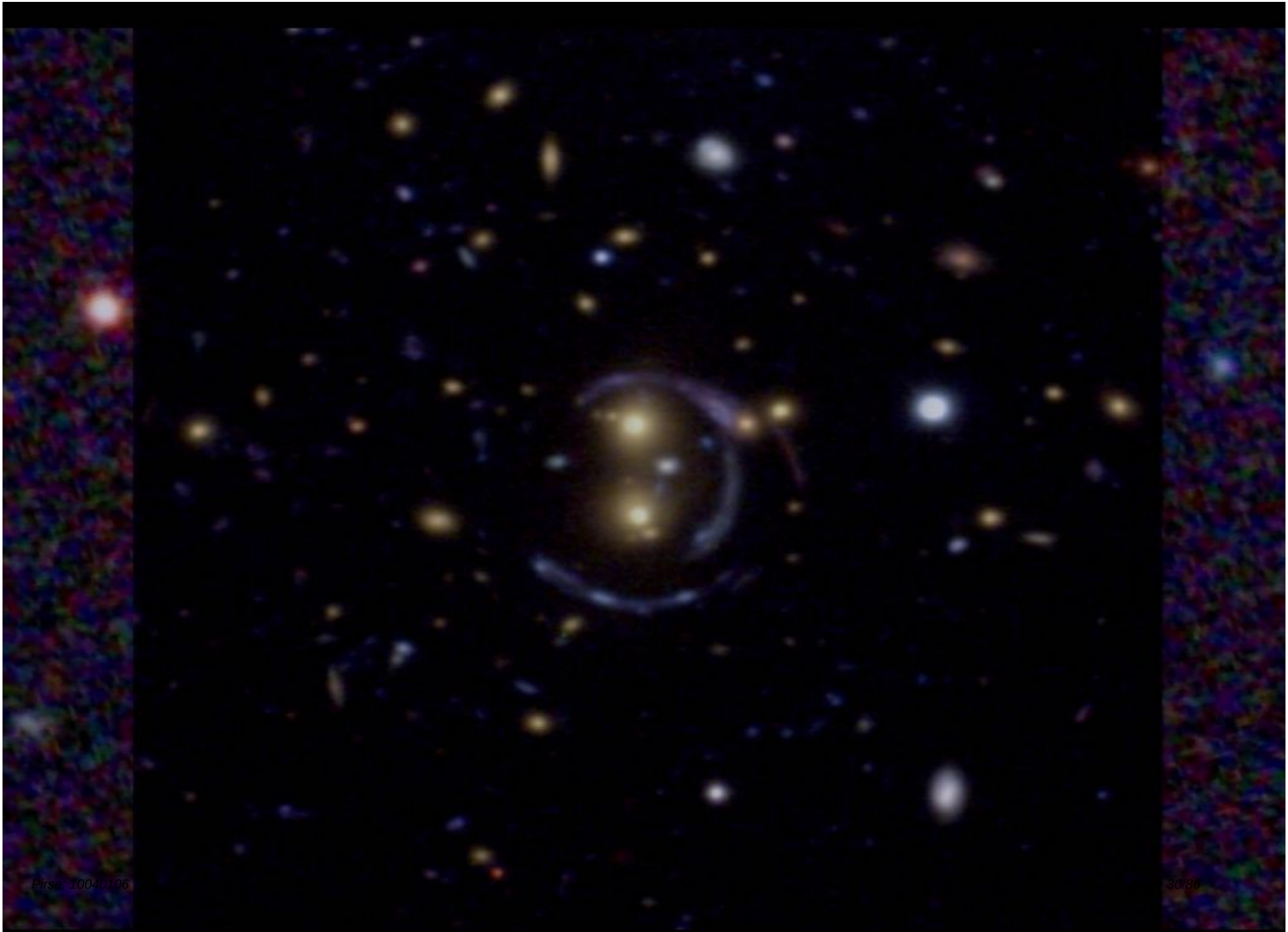
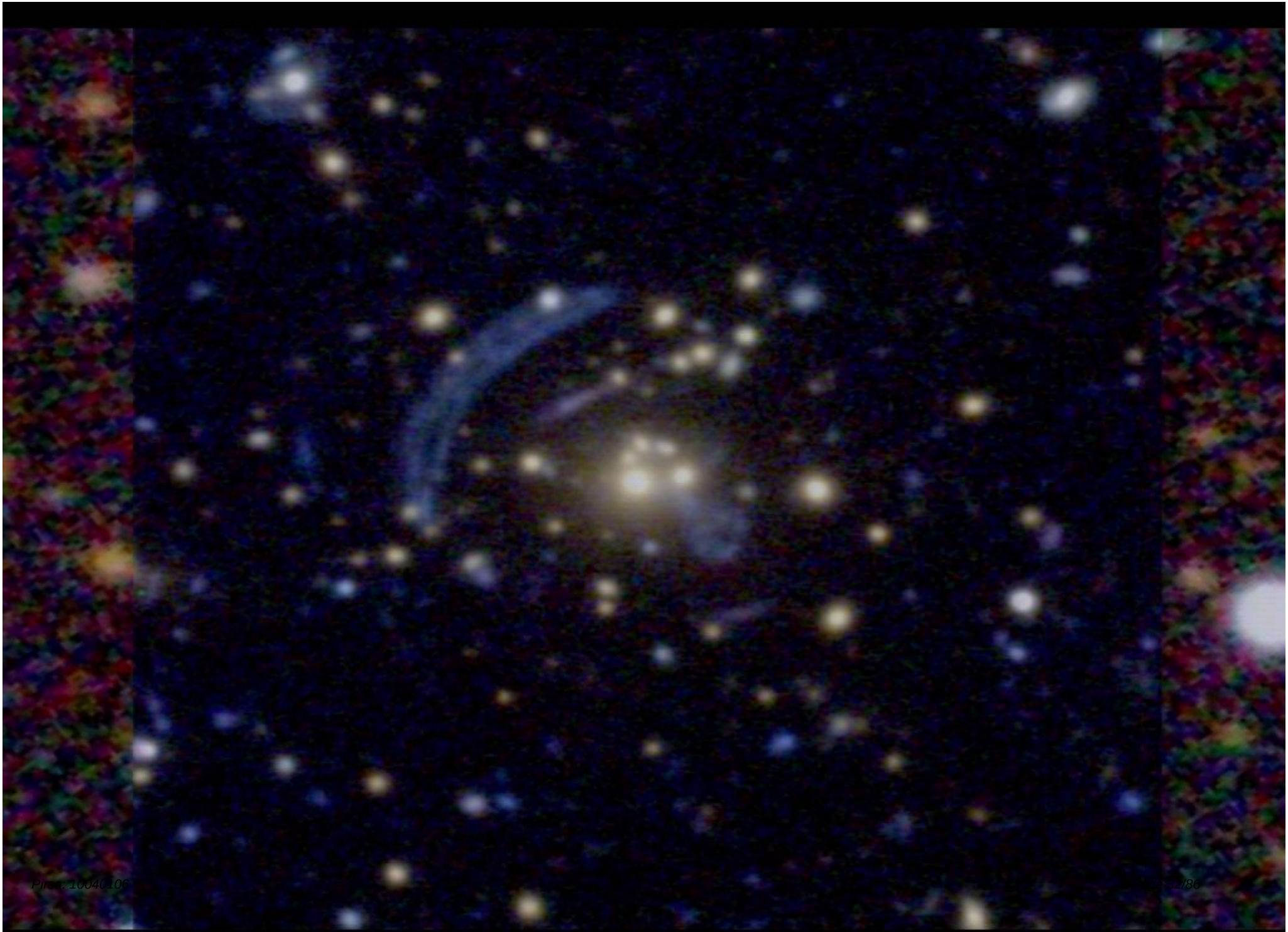
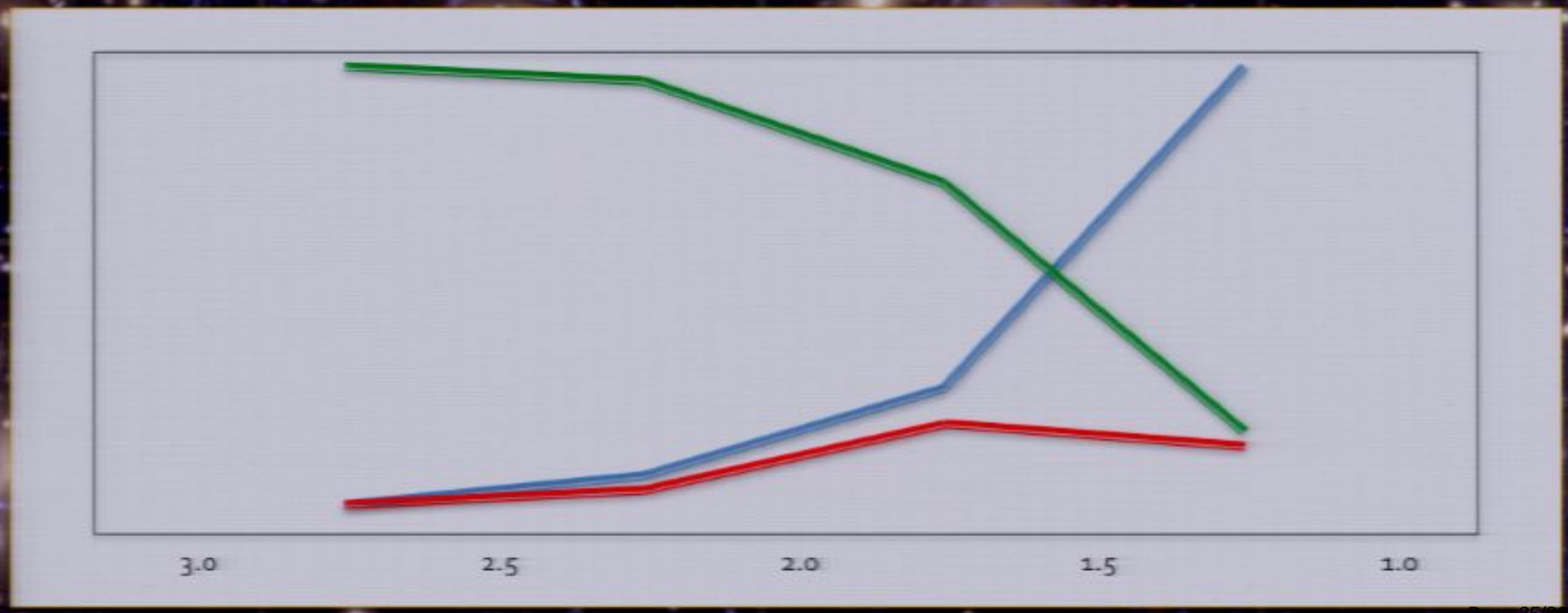




Mean Score	#	%Complete	%Confirmed	#Lenses
2.5-3.0	30	100	100	30
2.0-2.5	39	98	93	36
1.5-2.0	101	93	76	77
1.0-1.5	281	60	~25	(70)



Lenses From the RCS-2 Data

- Search of 330 square degrees yields several hundred candidates
- Cutting on r_E>5" and l/w > 10, yields 27 distinct cluster lenses; actual current number is 40 including prior partial search results
- Total expected number is ≈75 cluster lenses under the strict criteria above; total number of lenses, including many at 1"-5" r_E, is in the hundreds
- Timescale for completion is <6 months

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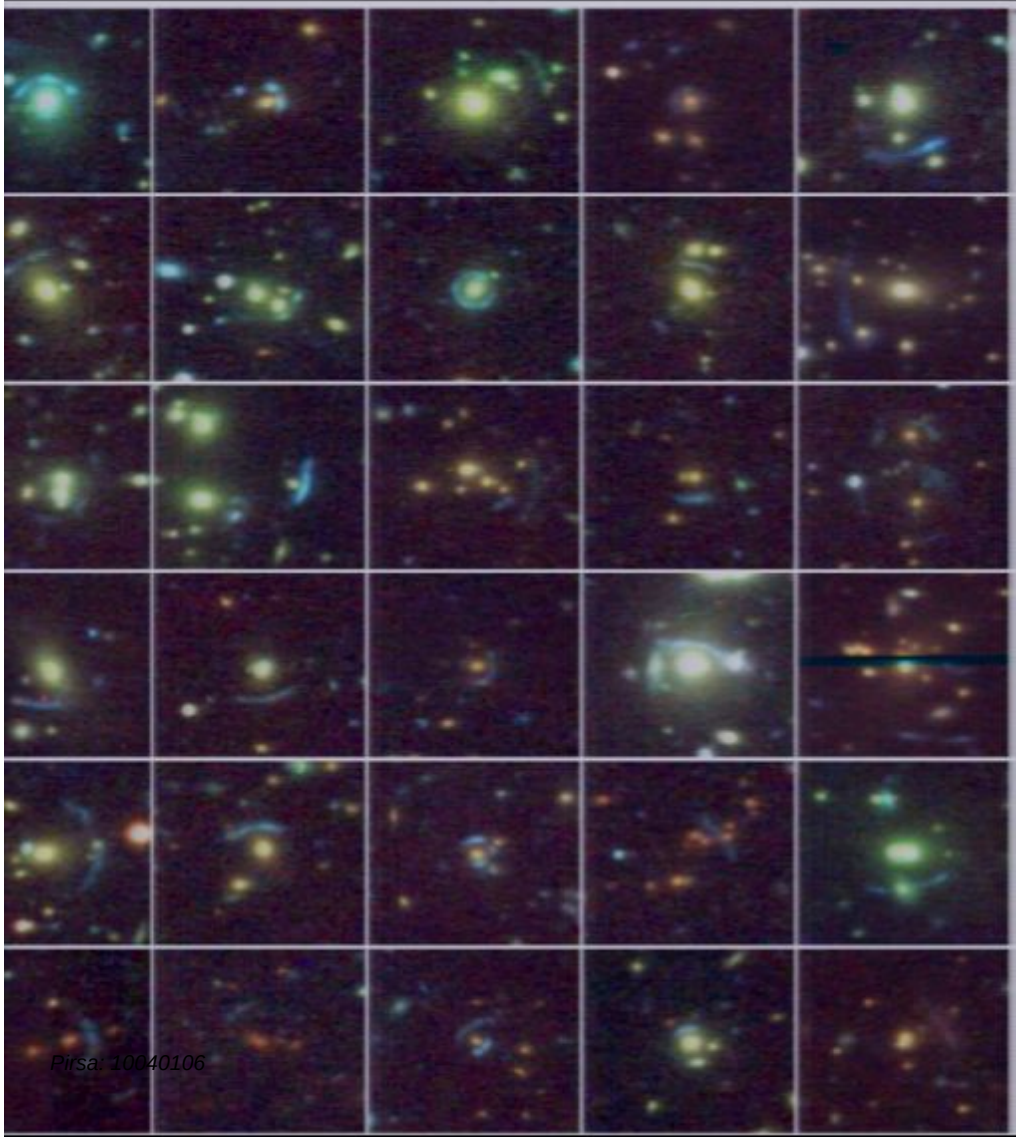

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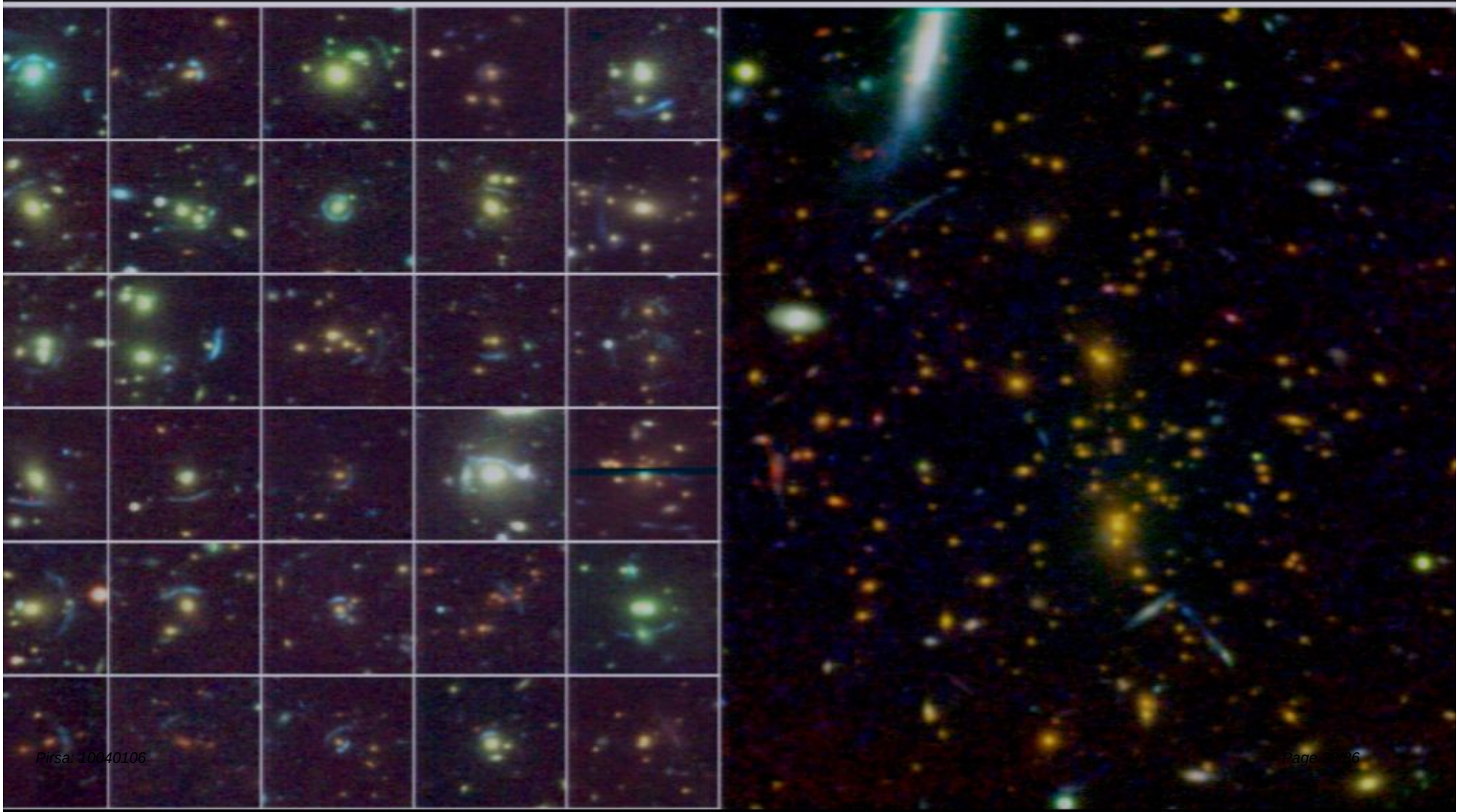

Optical and IR Spectroscopy

RCS-2 and SDSS samples are being targeted for spectroscopy (arcs, cluster dynamics), for purposes of confirmation, calibration, and detailed study

- Currently have ≈30 'main' arc redshifts, including near-IR spectroscopy in the optical 'redshift desert' Mean main arc redshift = 1.48 (median = 1.50): knowing this is important for efforts to model arc statistics!
- despite some IR data, some arcs (<10%) with attempted spectroscopy have no redshifts yet; likely are at $1.5<z<2.4$, so true mean may be slightly higher than $z=1.5$
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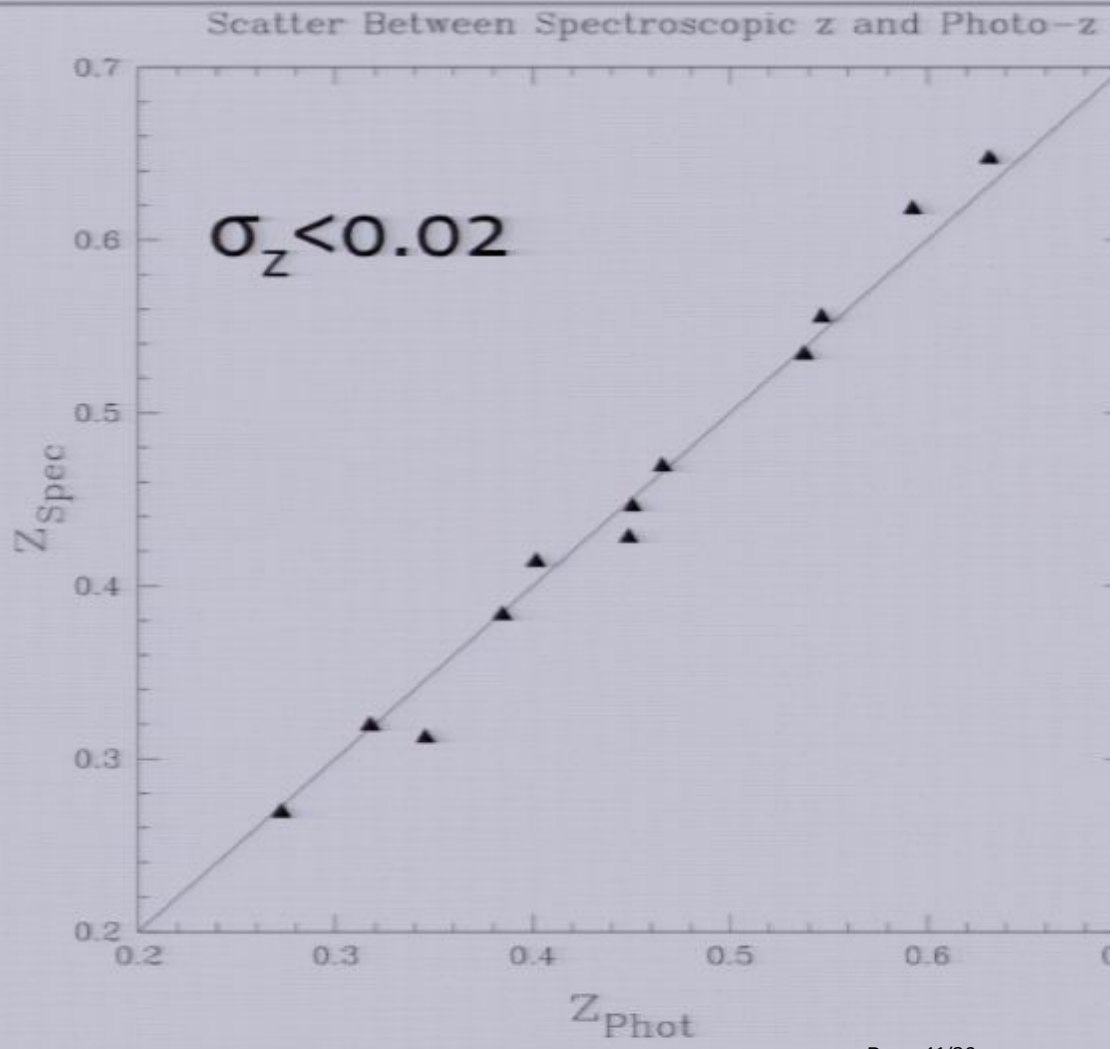
typical redshift ≈1.6

less than 10% at $z>3.2$

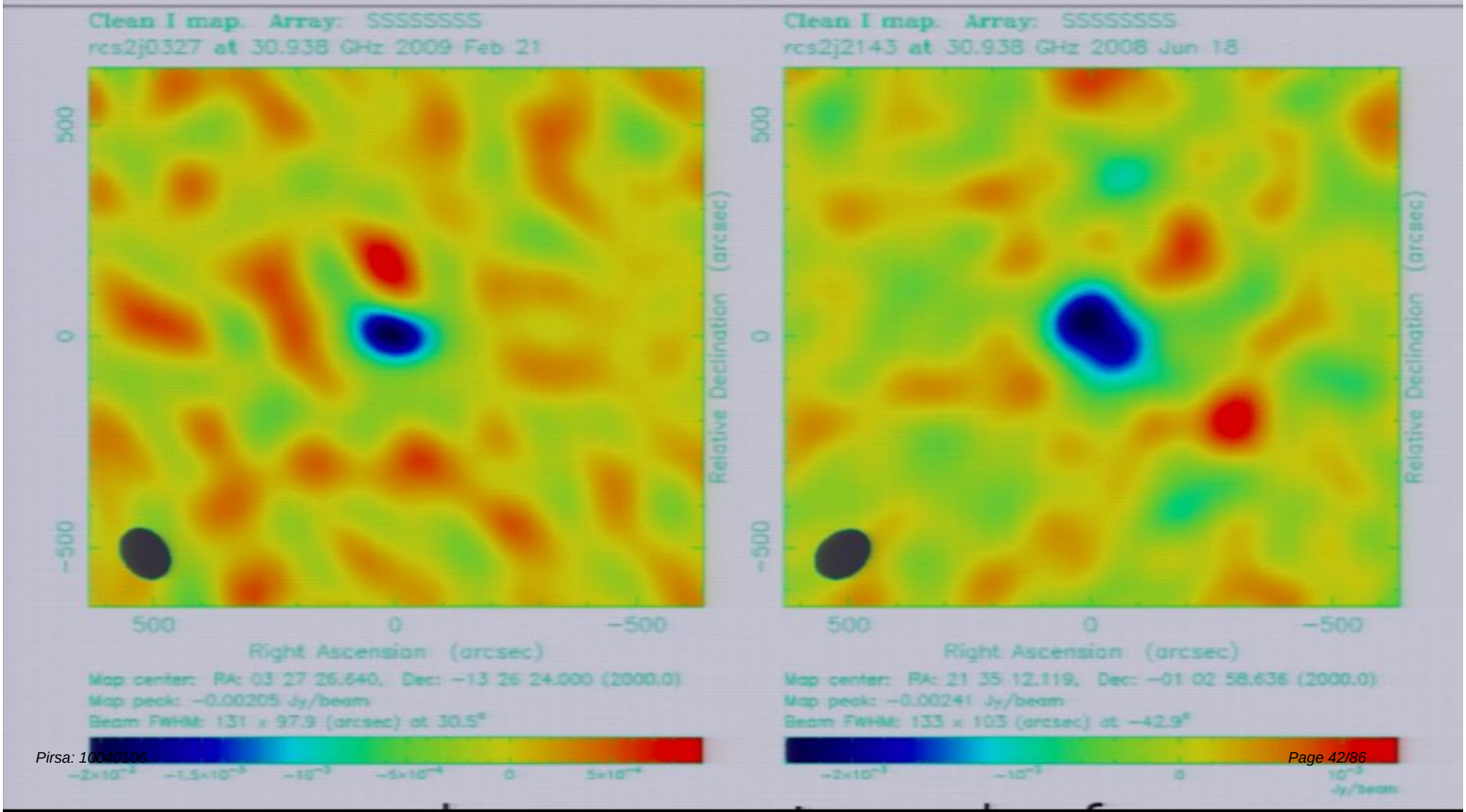
Optical and IR Spectroscopy

RCS-2 spectroscopy includes extensive coverage of clusters galaxies, principally using the GISMO instrument on Magellan. The initial result confirmation of the cluster photo-z, which are good to better than 0.02.

Eventually we shall have robust dynamical mass measurements (50+ members per cluster) for a planned 30 systems.



Sunyaev Zeldovich Array 30 Ghz Imaging



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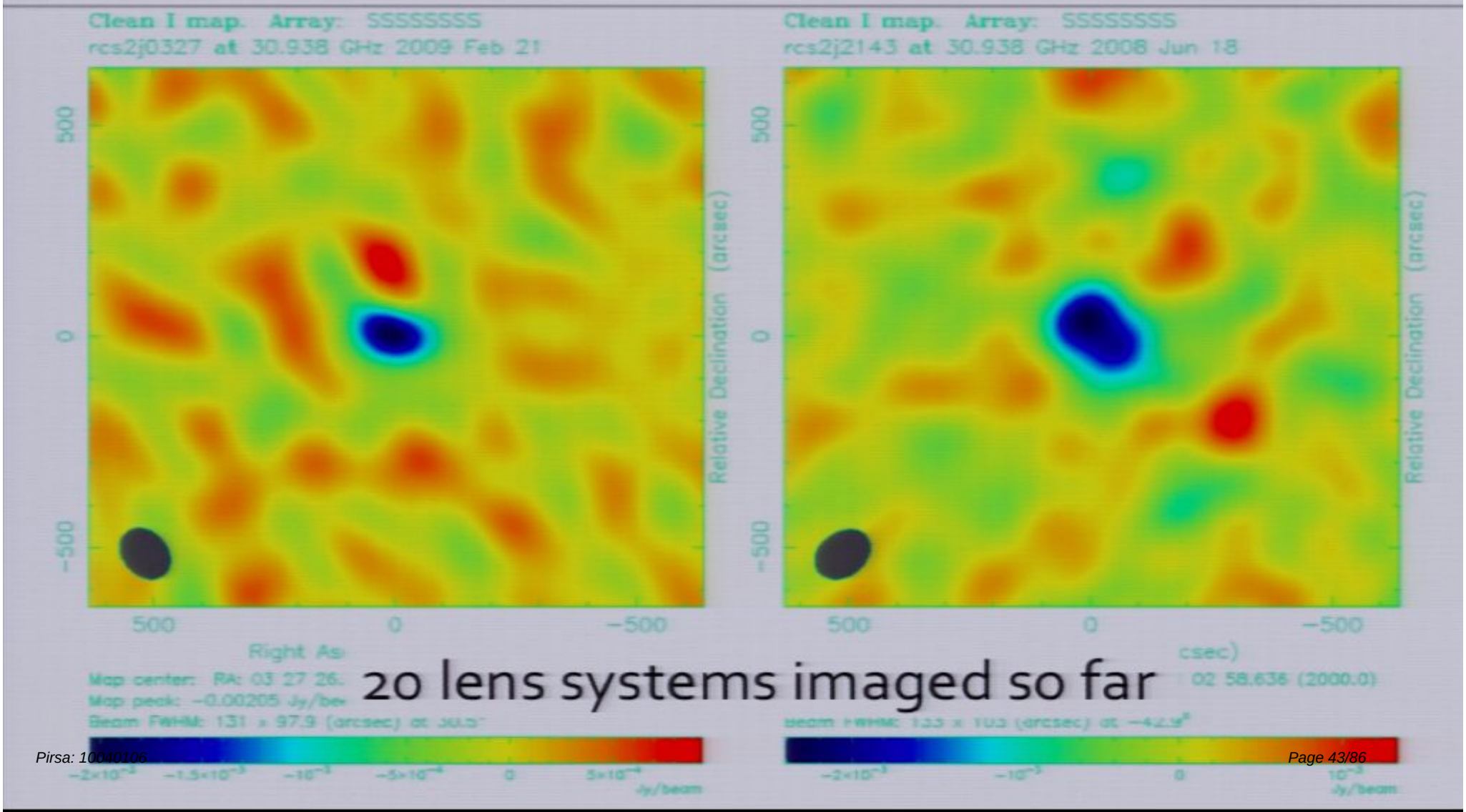
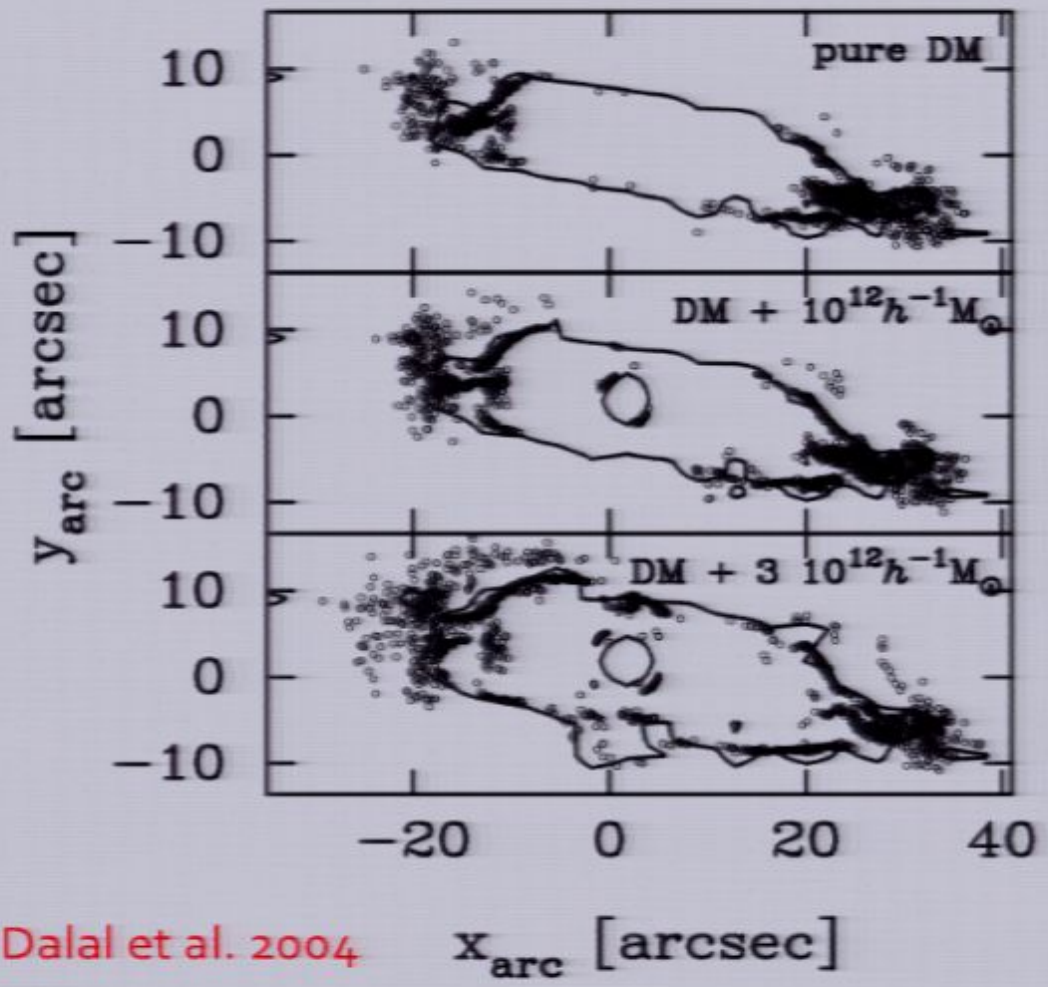


20 lens systems imaged so far

Alignment: Arcs to Halos



Dalal et al. 2004

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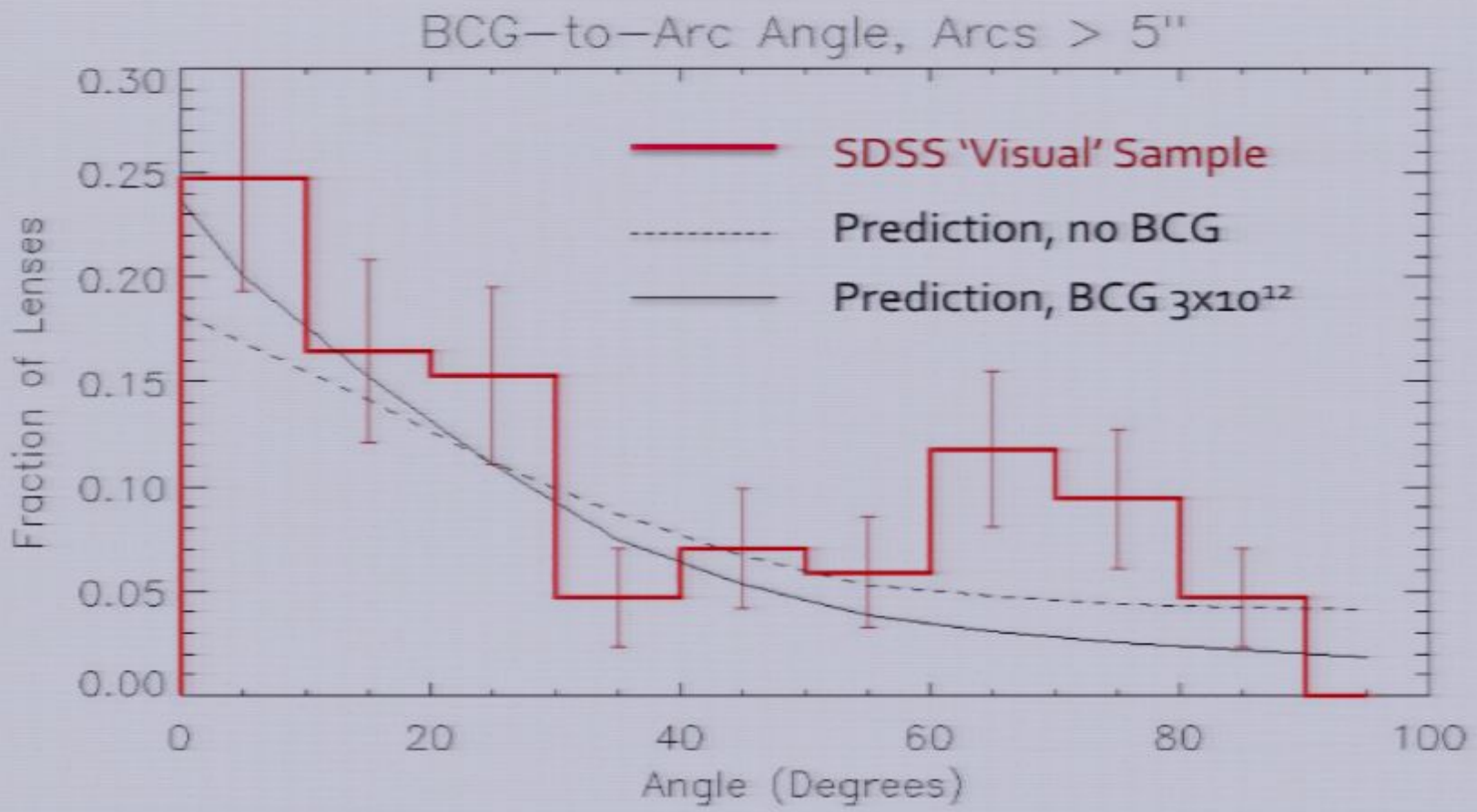
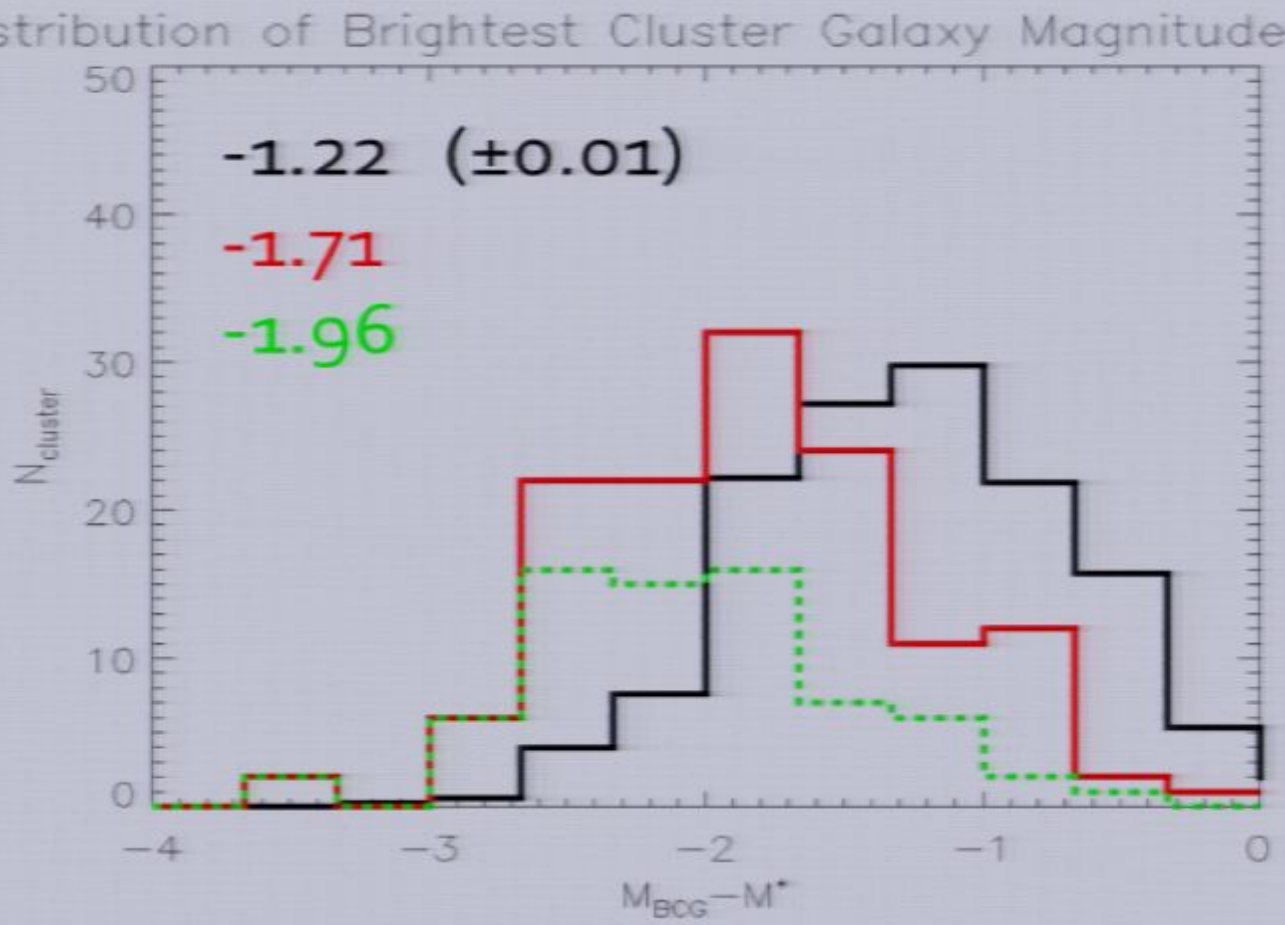


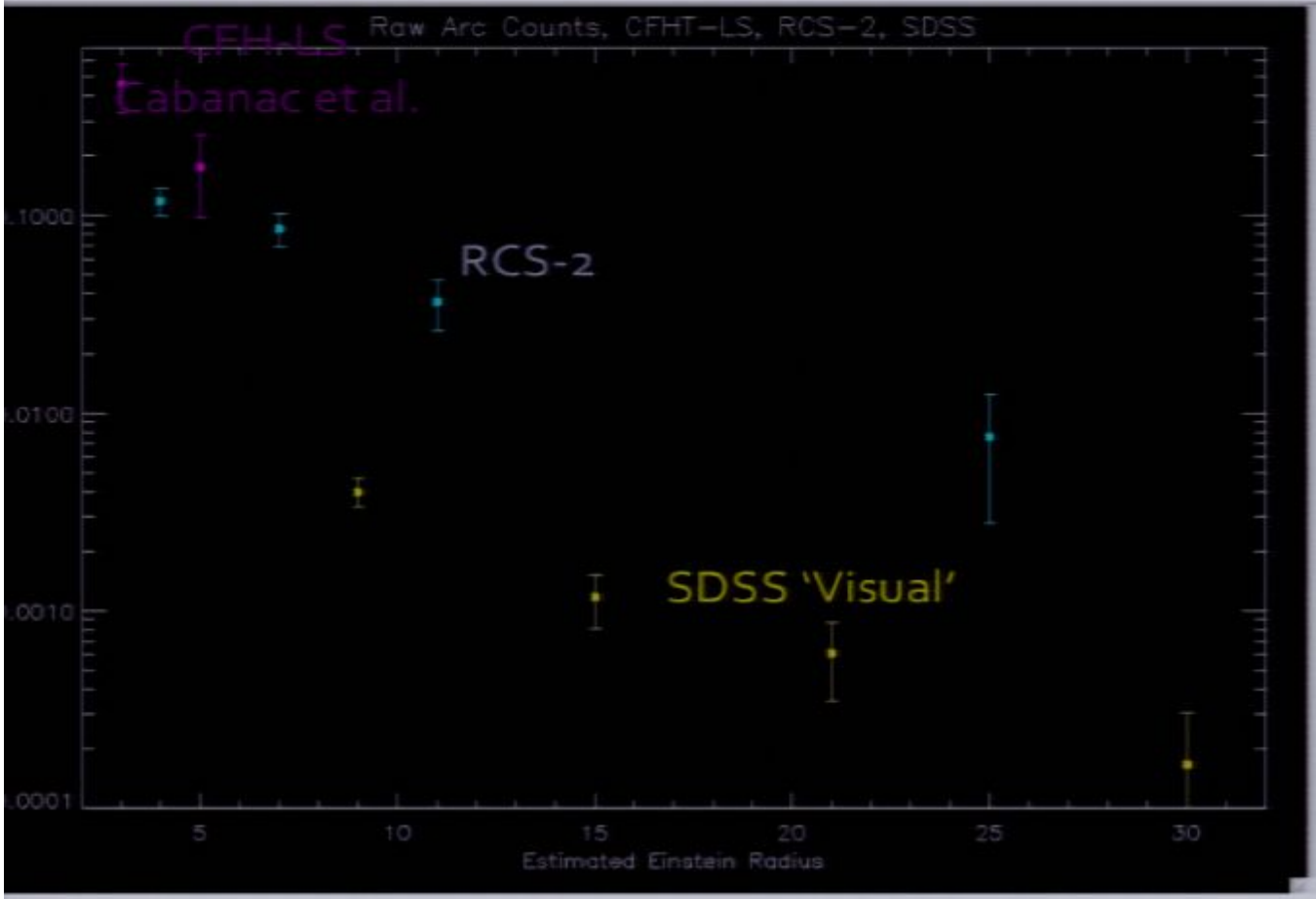
- most arcs are expected on the (projected) cluster major axis, though a large central galaxy will tend to circularize the distribution; current data are consistent with both predictions in Dalal et al. (2004), using BCG orientation as a surrogate for DM halo orientation...

BCG Magnitudes in Lensing Clusters

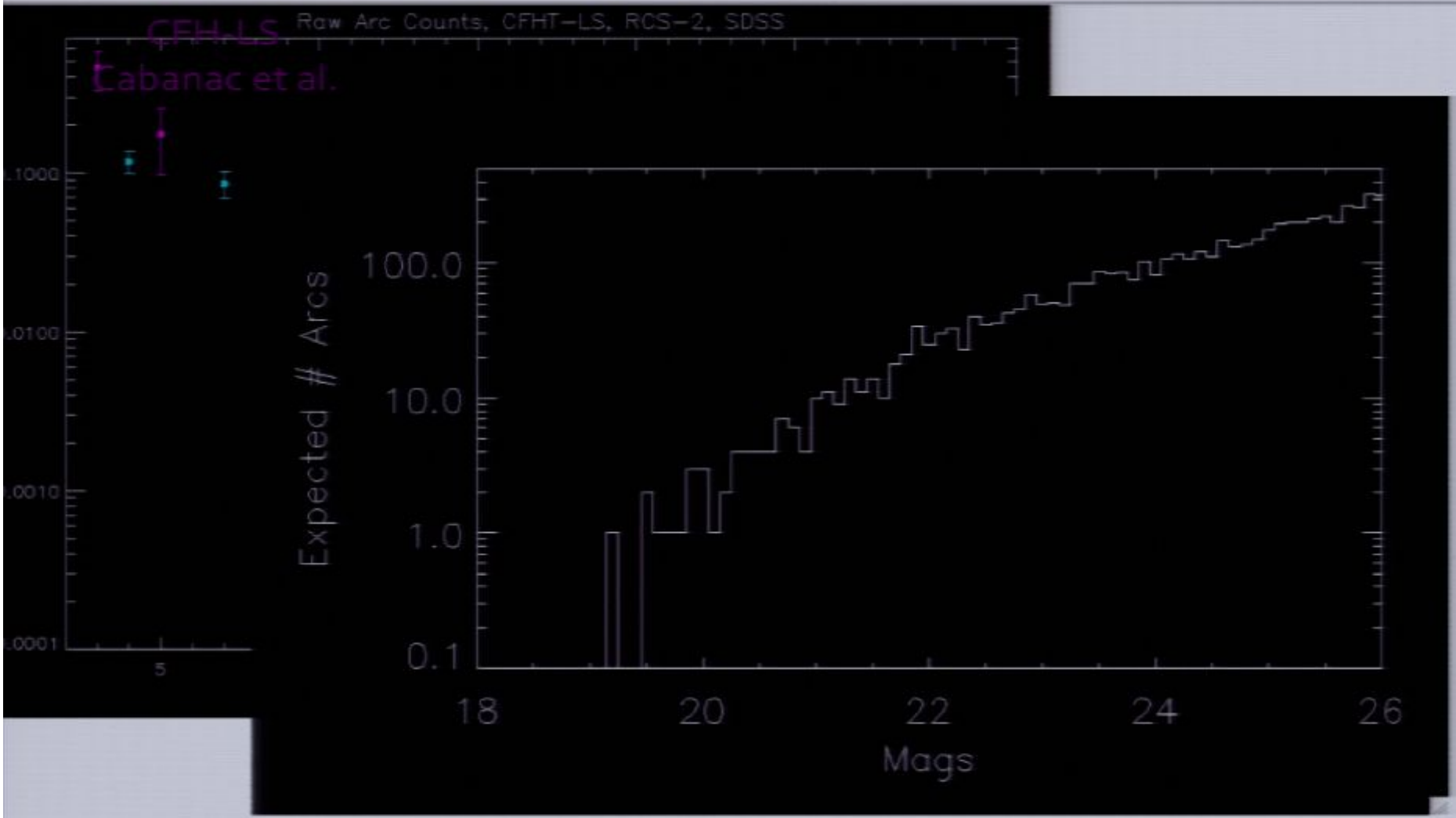


- the brightest cluster galaxies in lensing clusters (red) are ~60% brighter than BCGs in clusters matched in redshift and richness (black)- this effect is even more pronounced in larger r_E clusters

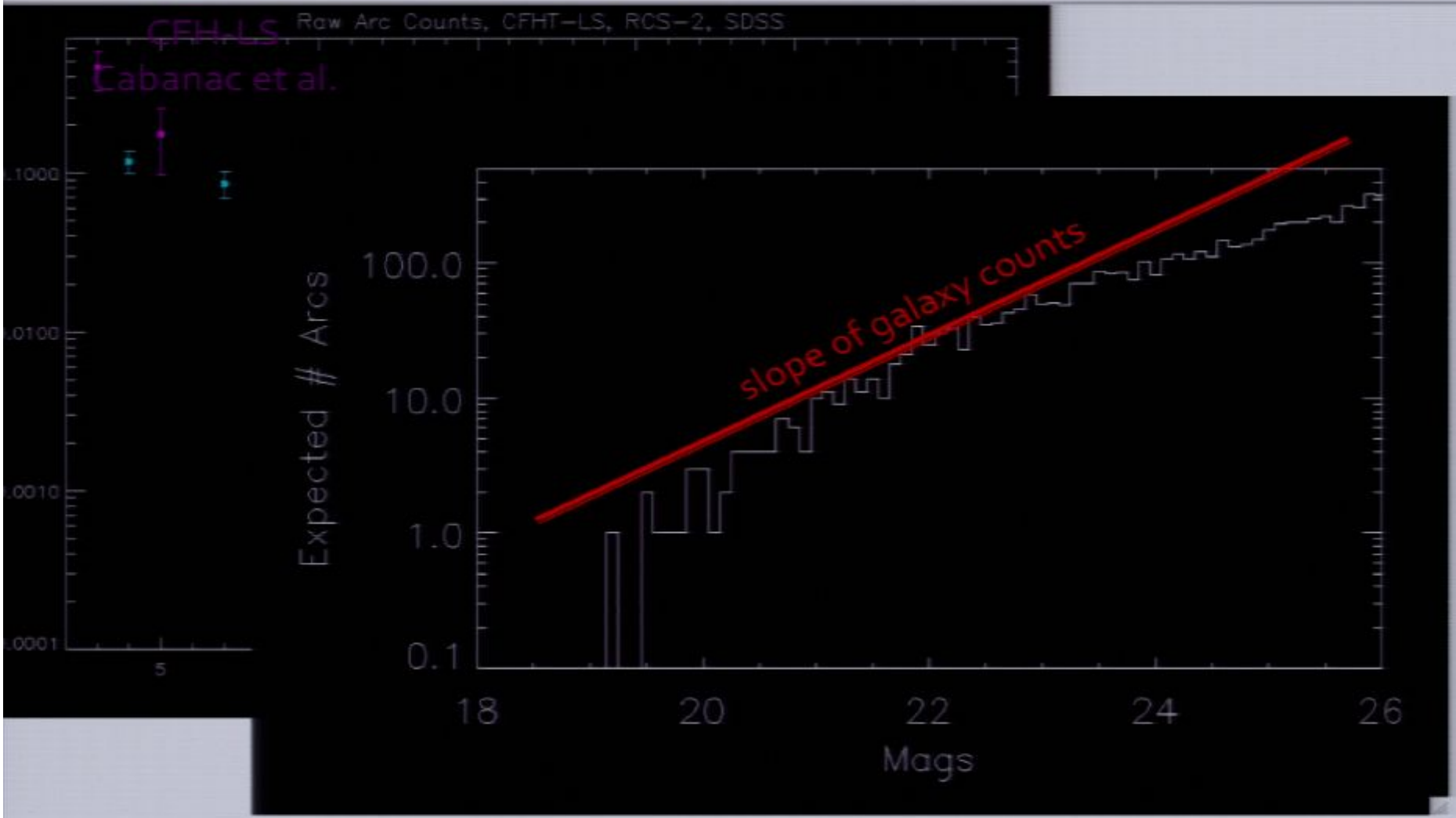
Arc Counts


Raw Arc Counts, CFHT-LS, RCS-2, SDSS
CFHTLS
Cabanac et al.
RCS-2
SDSS 'Visual'
.1000
.0100
.0010
.0001
5
10
15
20
25
30
Estimated Einstein Radius

Arc Counts


Raw Arc Counts, CFHT-LS, RCS-2, SDSS
CFHTLS
Cabanac et al.
Expected # Arcs
100.0
10.0
1.0
0.1
18
20
22
24
26
Mags

Arc Counts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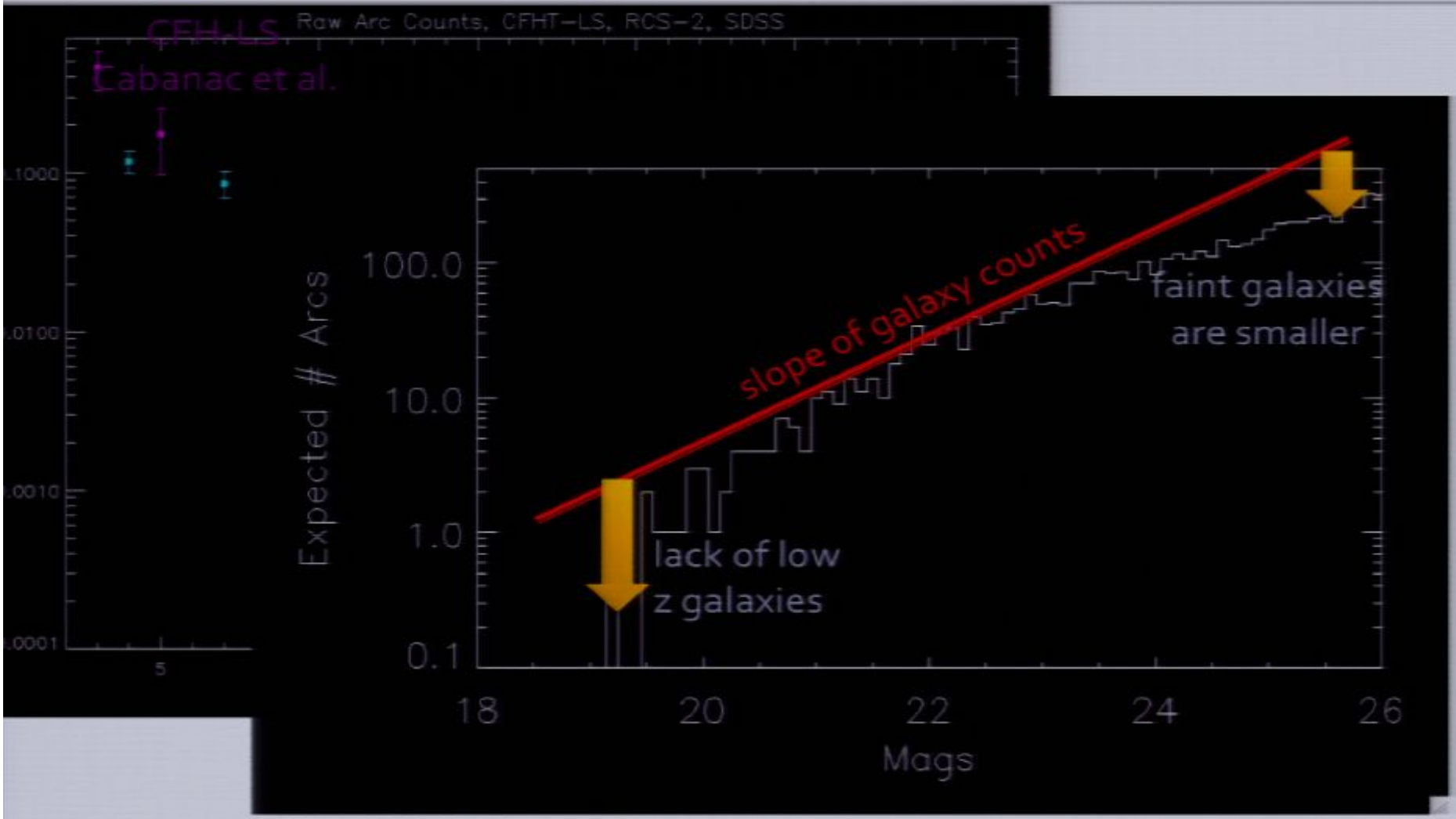
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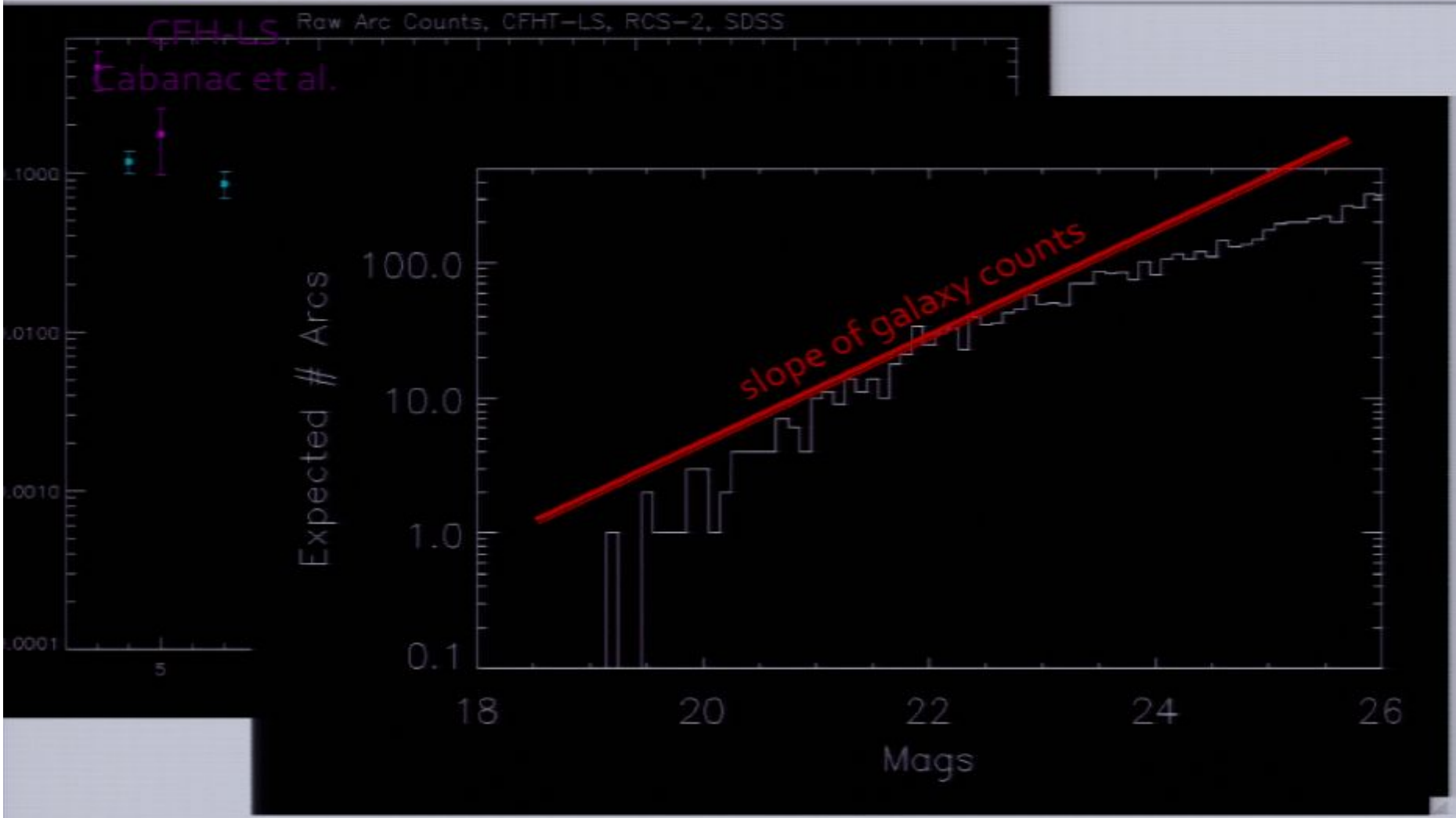
Mags
slope of galaxy counts
faint galaxies
are smaller
lack of low
z galaxies

Arc Counts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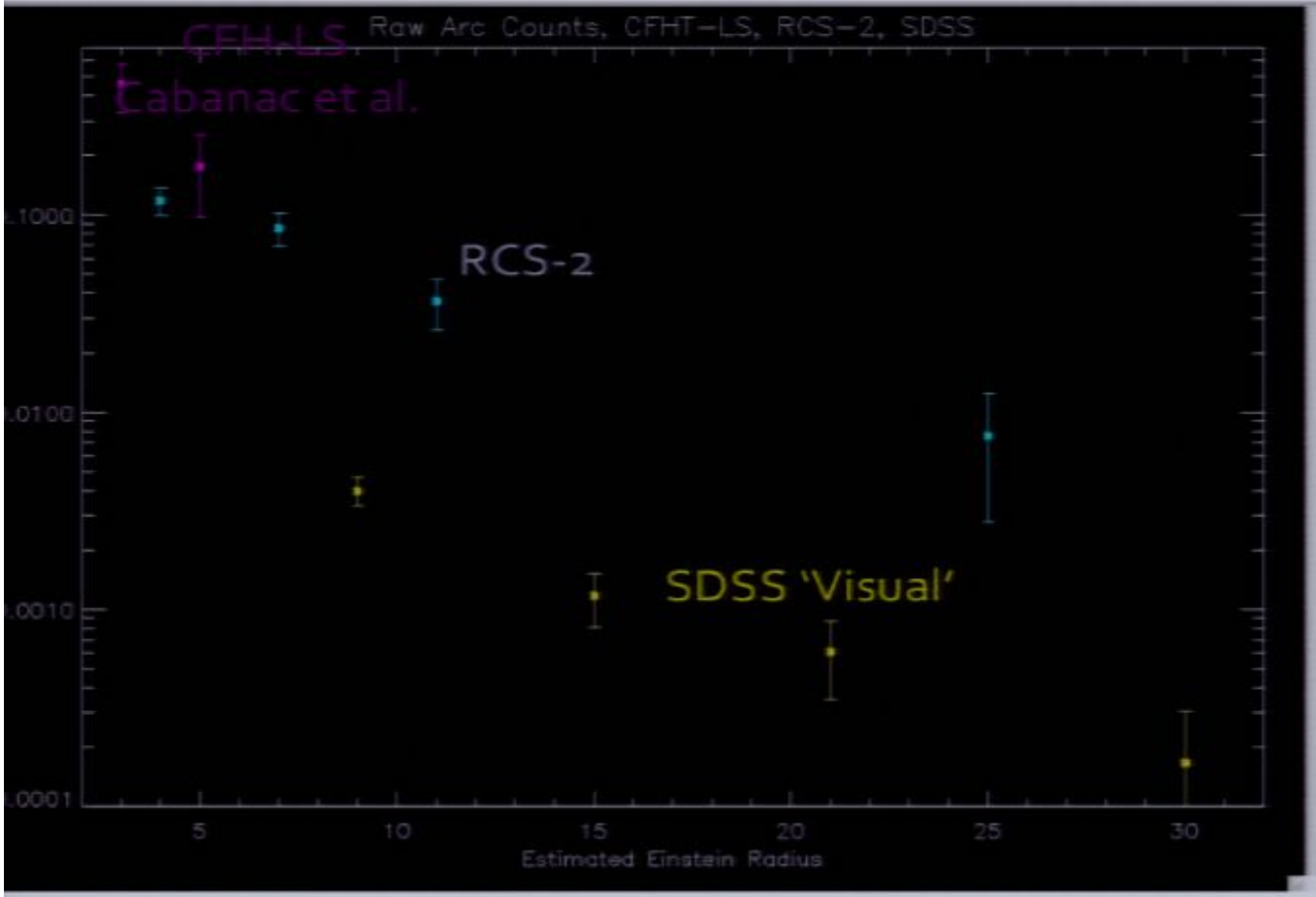
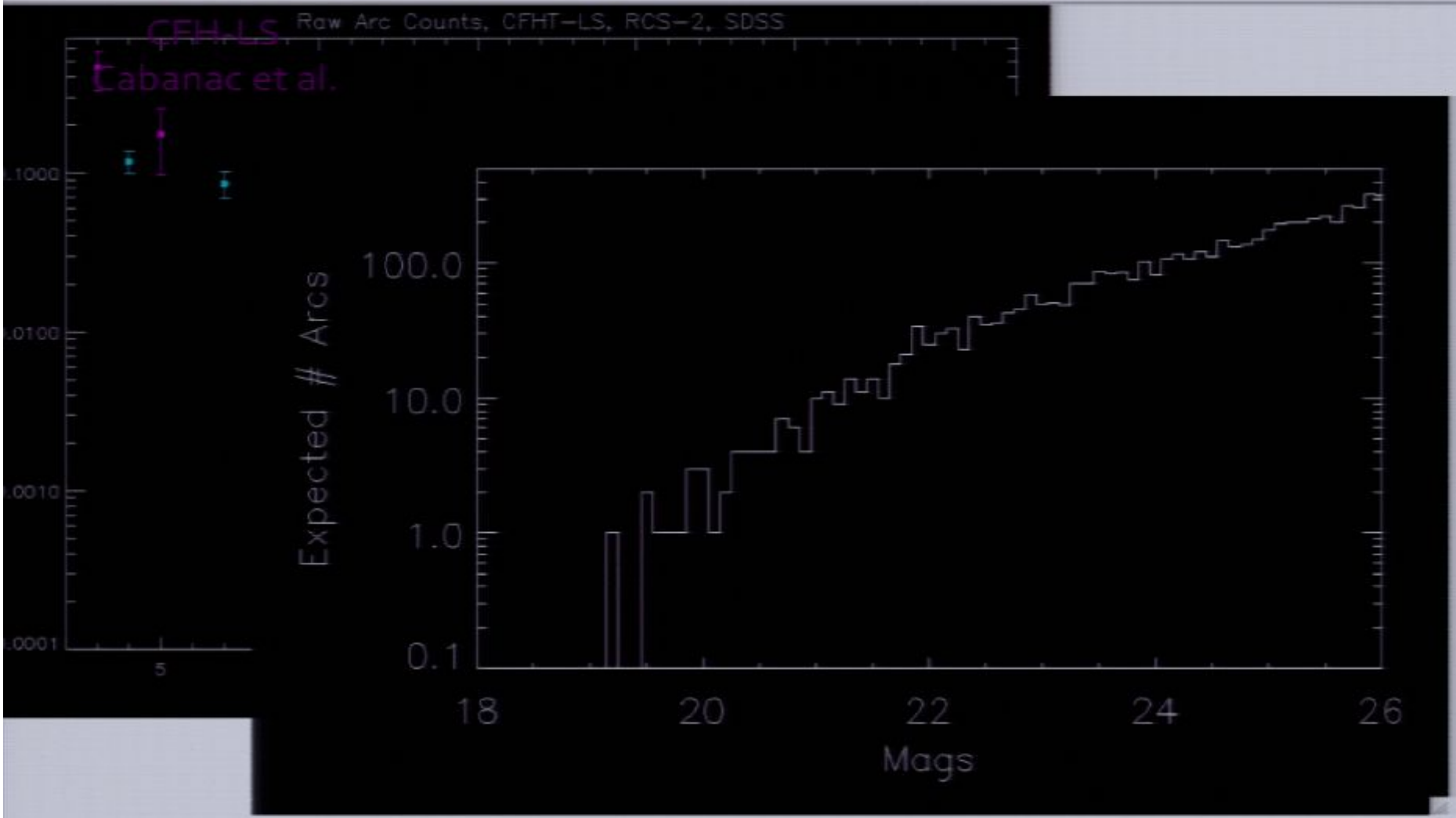
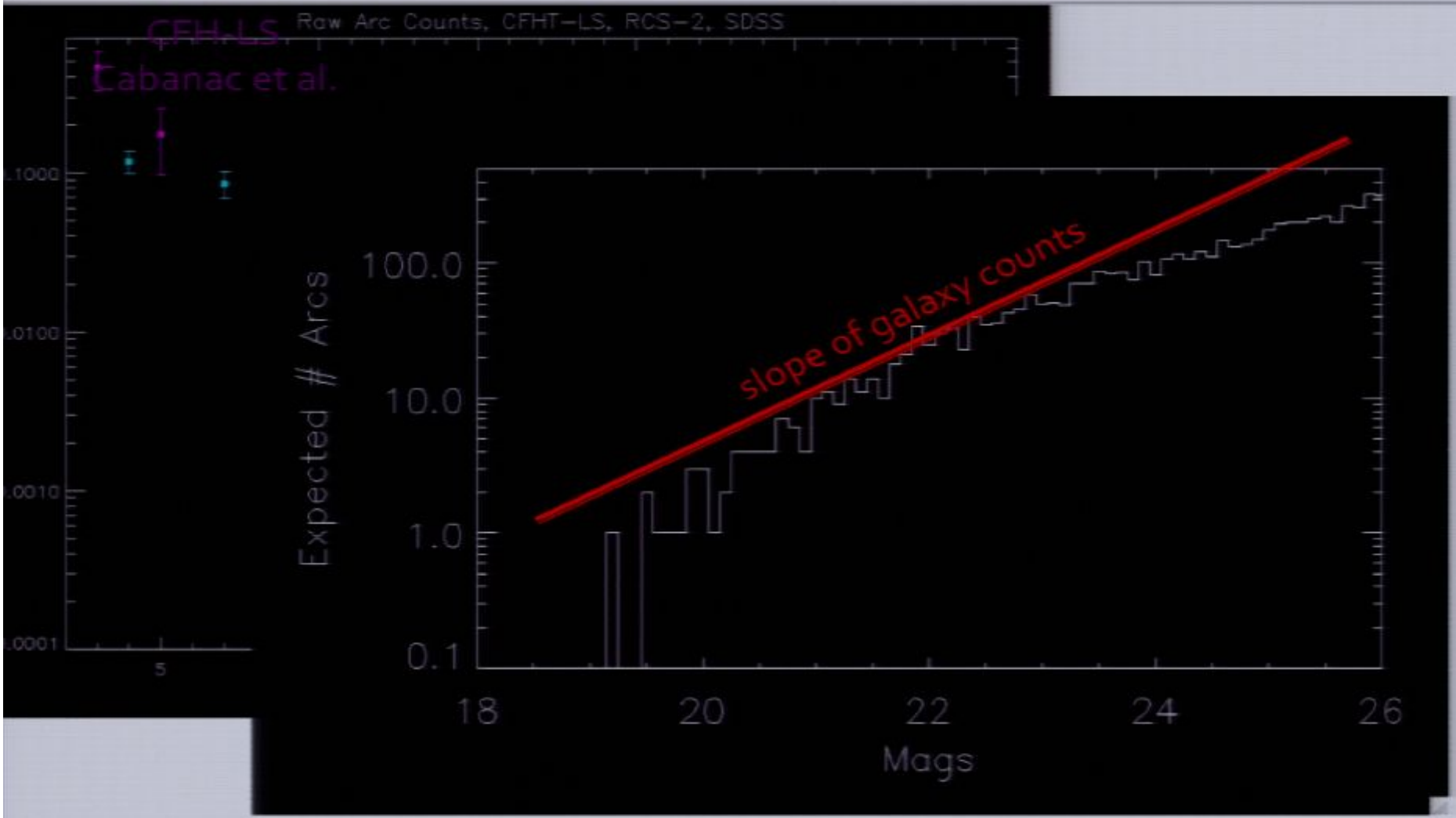

Raw Arc Counts, CFHT-LS, RCS-2, SDSS
CFHTLS
Cabanac et al.
RCS-2
SDSS 'Visual'
.1000
.0100
.0010
.0001
5
10
15
20
25
30
Estimated Einstein Radius

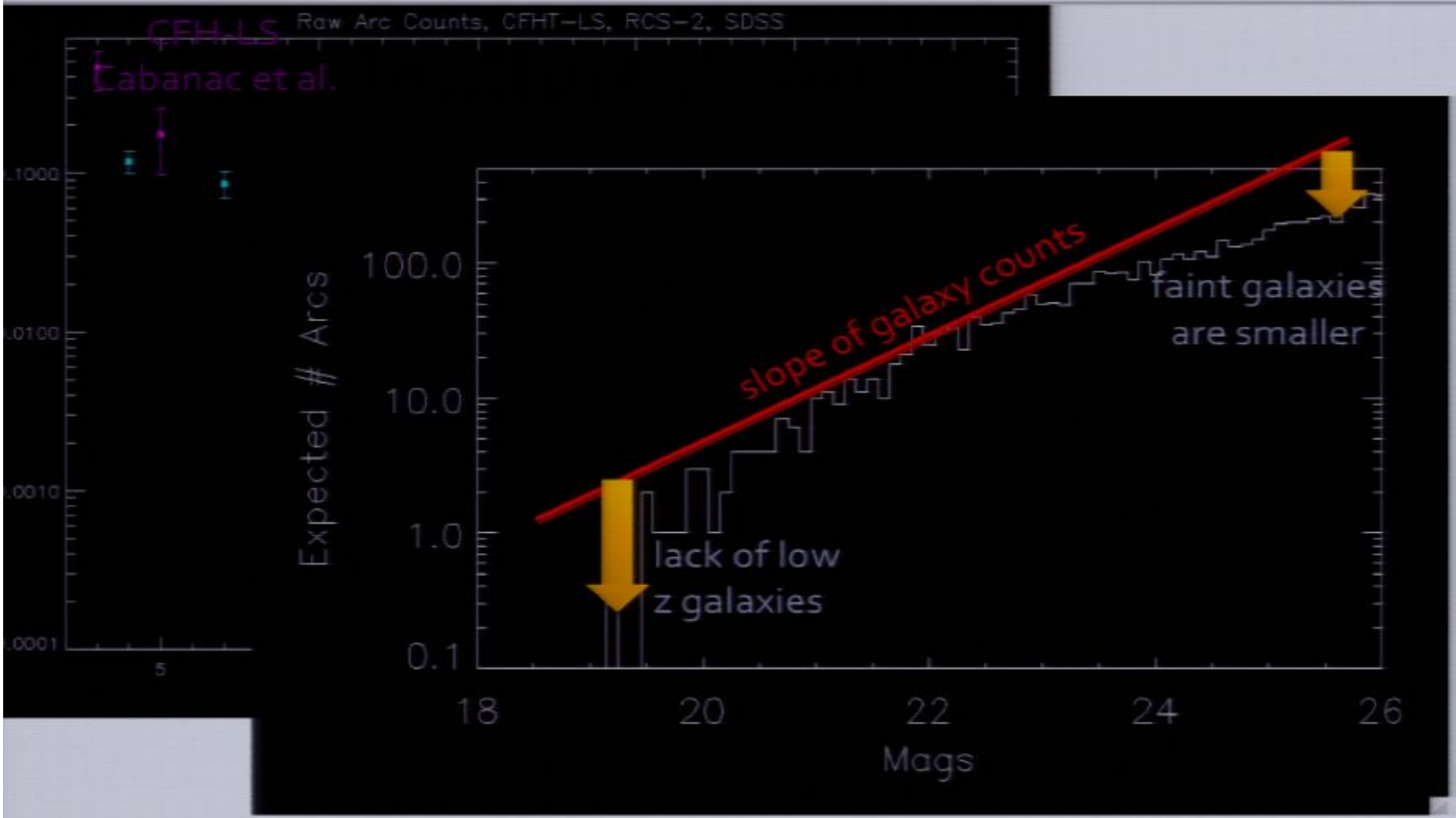
Arc Counts


Raw Arc Counts, CFHT-LS, RCS-2, SDSS
CFHTLS
Cabanac et al.
Expected # Arcs
100.0
10.0
1.0
0.1
18
20
22
24
26
Mags

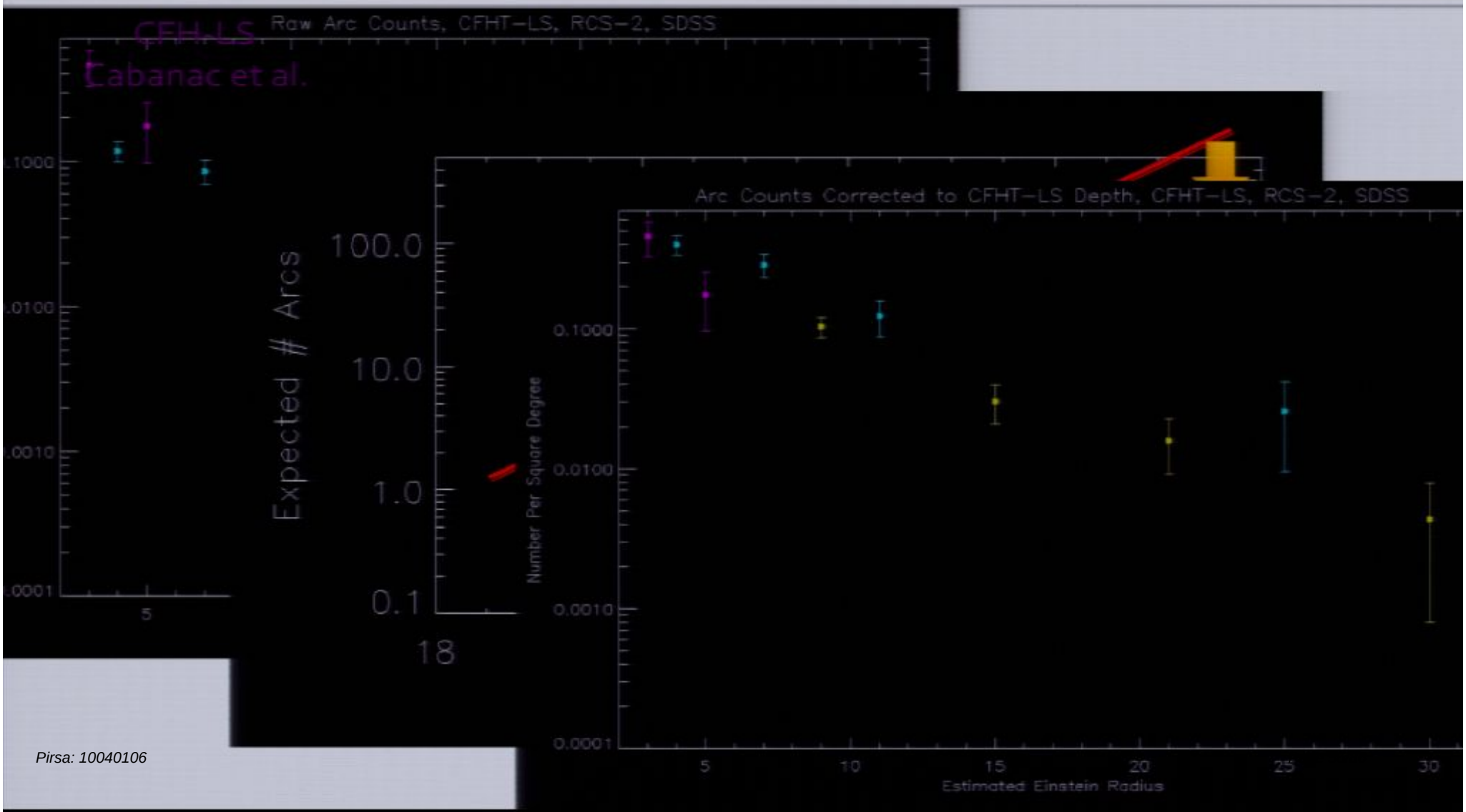
Arc Counts


Raw Arc Counts, CFHT-LS, RCS-2, SDSS
CFHTLS
Cabanac et al.
Expected # Arcs
100.0
10.0
1.0
0.1
slope of galaxy counts
18
20
22
24
26
Mags

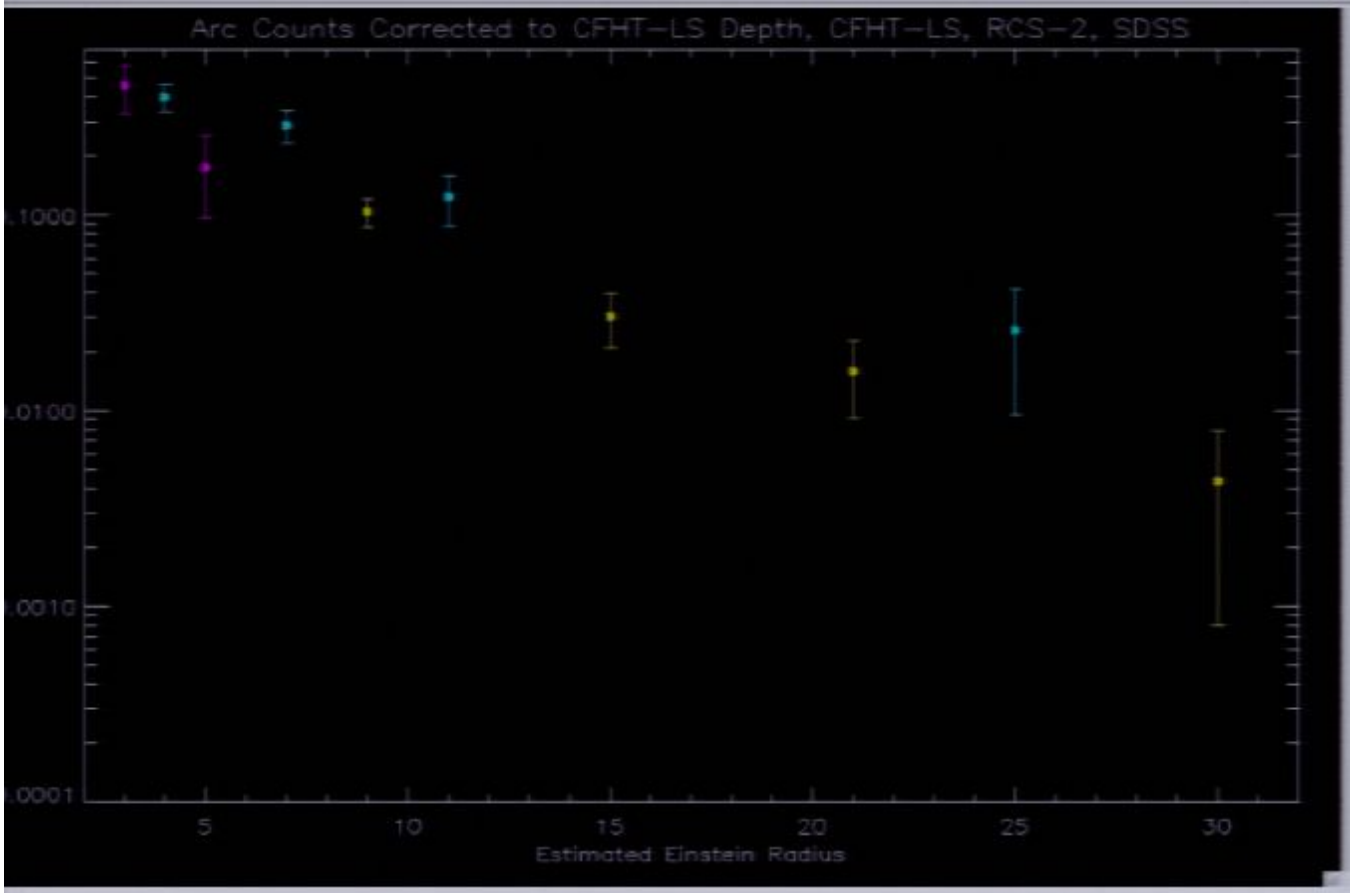
Arc Counts


Raw Arc Counts, CFHT-LS, RCS-2, SDSS
CFHTLS
Cabanac et al.
Expected # Arcs
100.0
10.0
1.0
0.1
18
20
22
24
26
Mags
slope of galaxy counts
faint galaxies
are smaller
lack of low
z galaxies

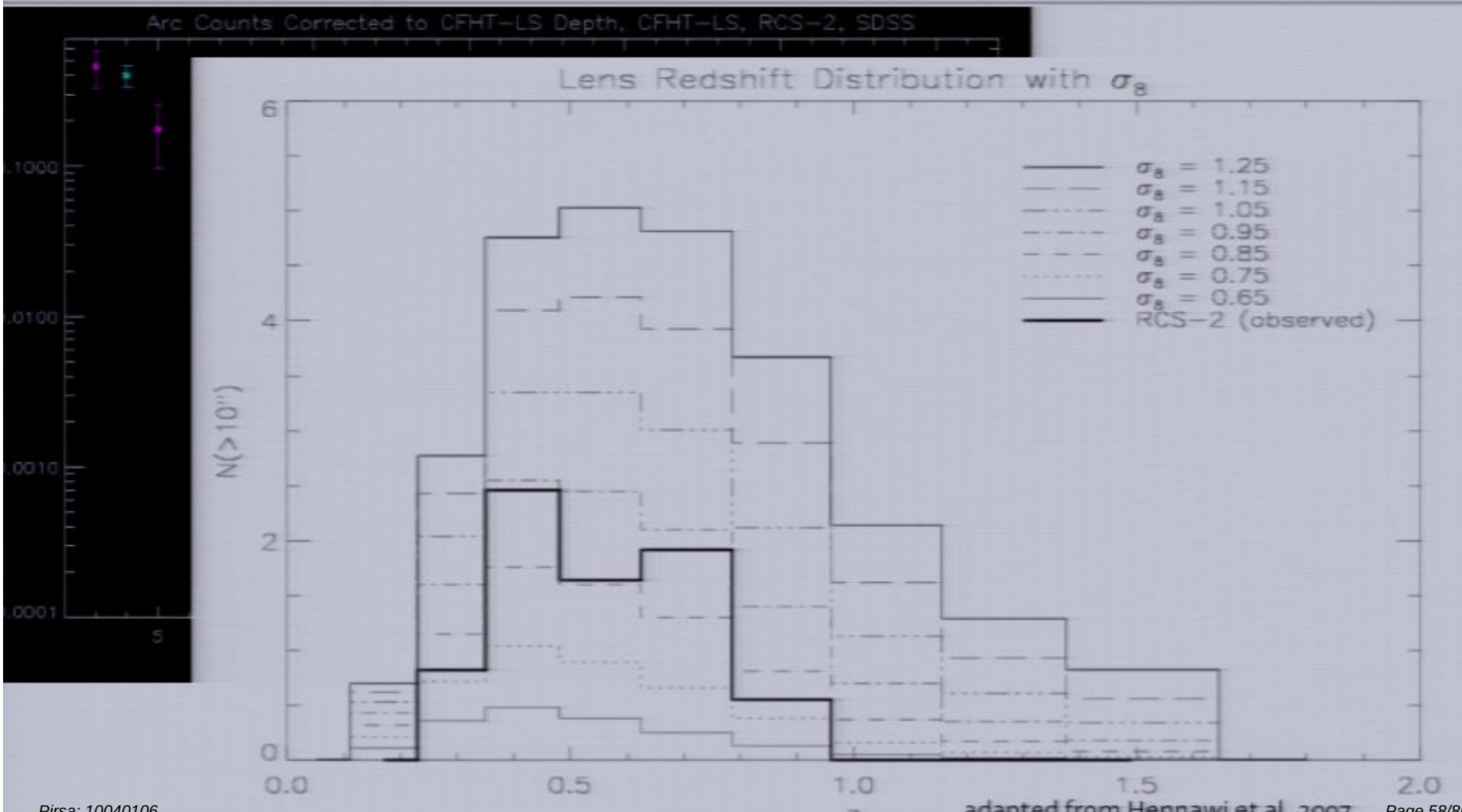
Arc Counts


Raw Arc Counts, CFHT-LS, RCS-2, SDSS
CFHTLS
Cabanac et al.
Arc Counts Corrected to CFHT-LS Depth, CFHT-LS, RCS-2, SDSS
Expected # Arcs
Number Per Square Degree
Estimated Einstein Radius
18

Arc Counts

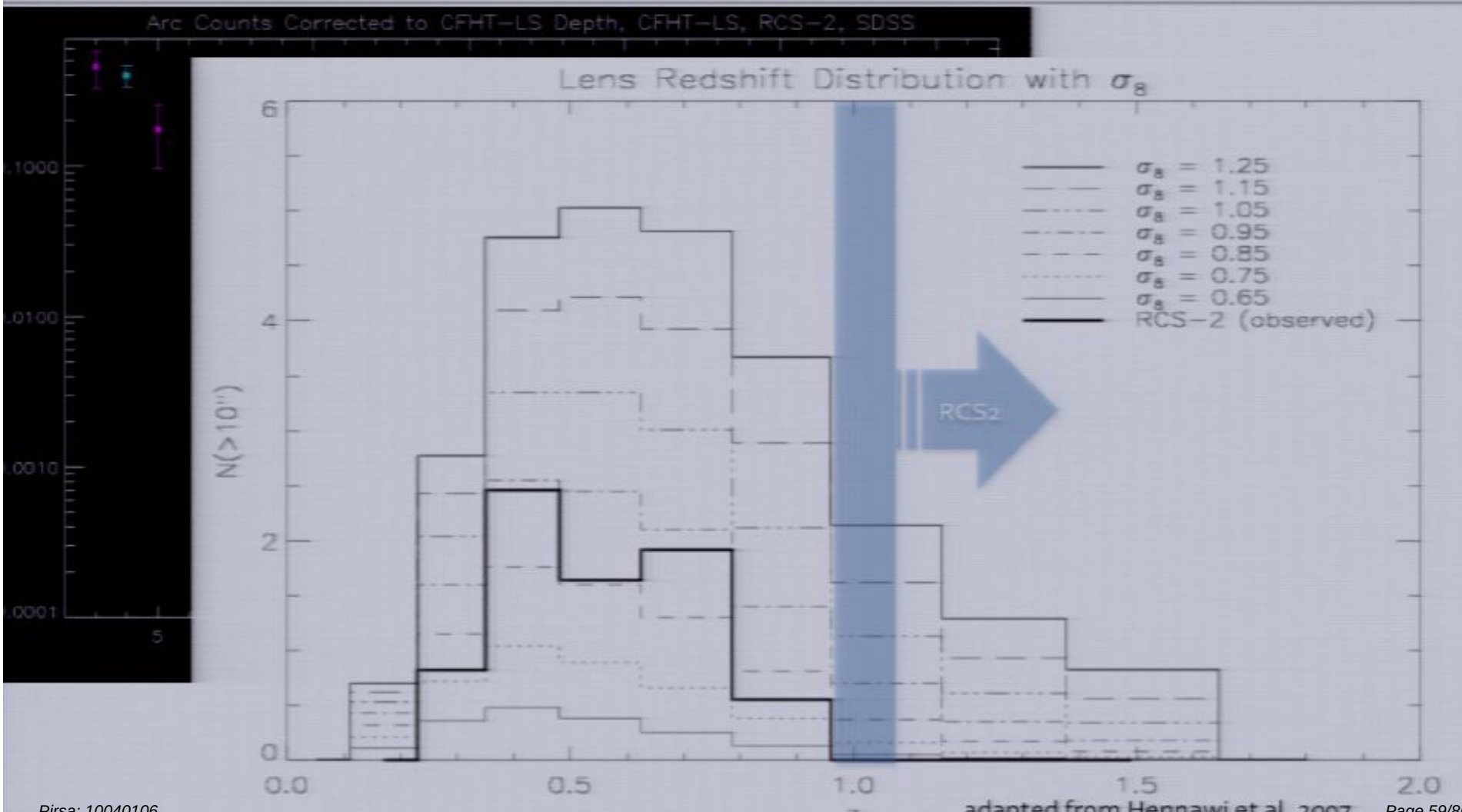

Arc Counts Corrected to CFHT-LS Depth, CFHT-LS, RCS-2, SDSS
.1000
.0100
.0010
.0001
5
10
15
20
25
30
Estimated Einstein Radius

Arc Counts



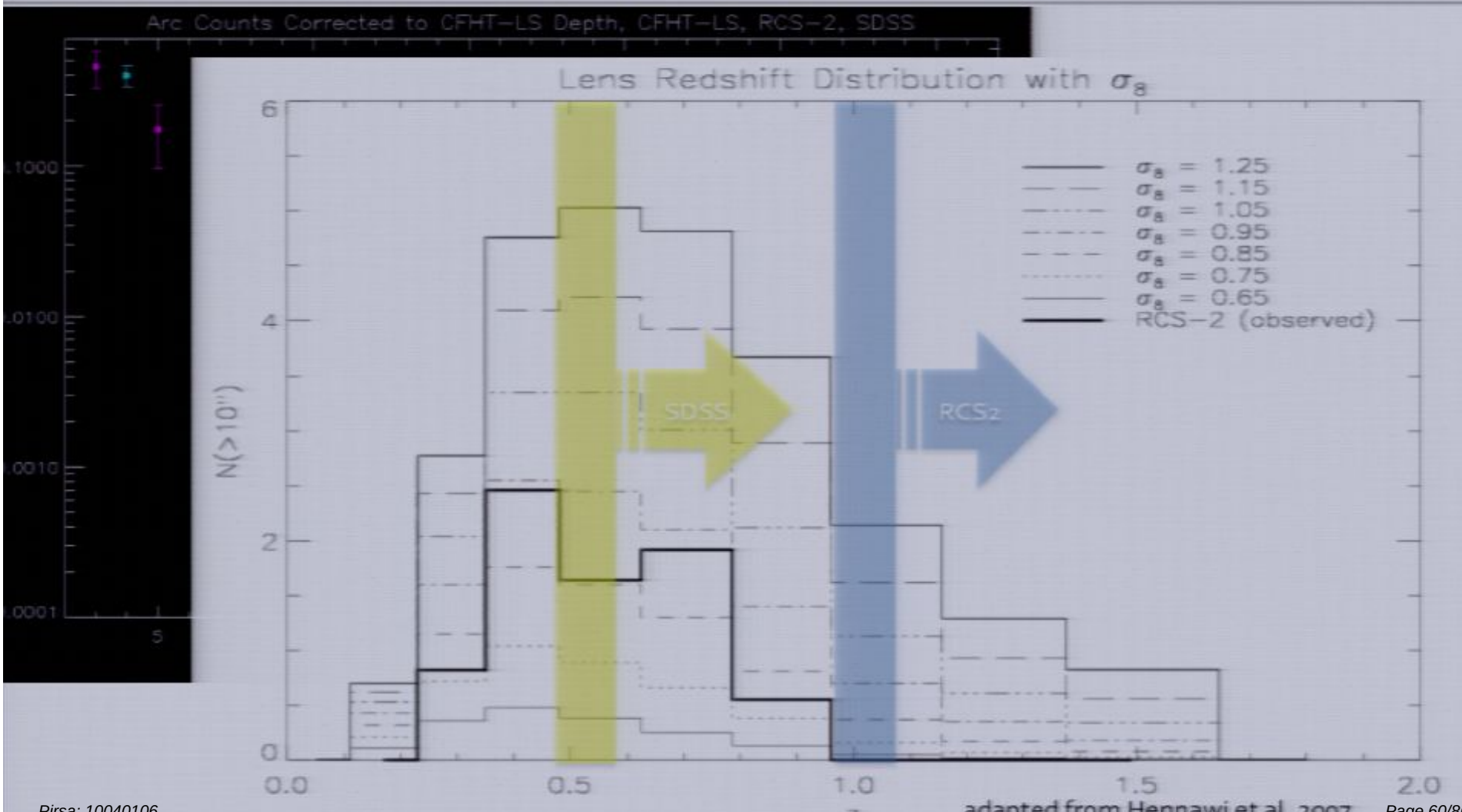
adapted from Hennawi et al. 2007

Arc Counts



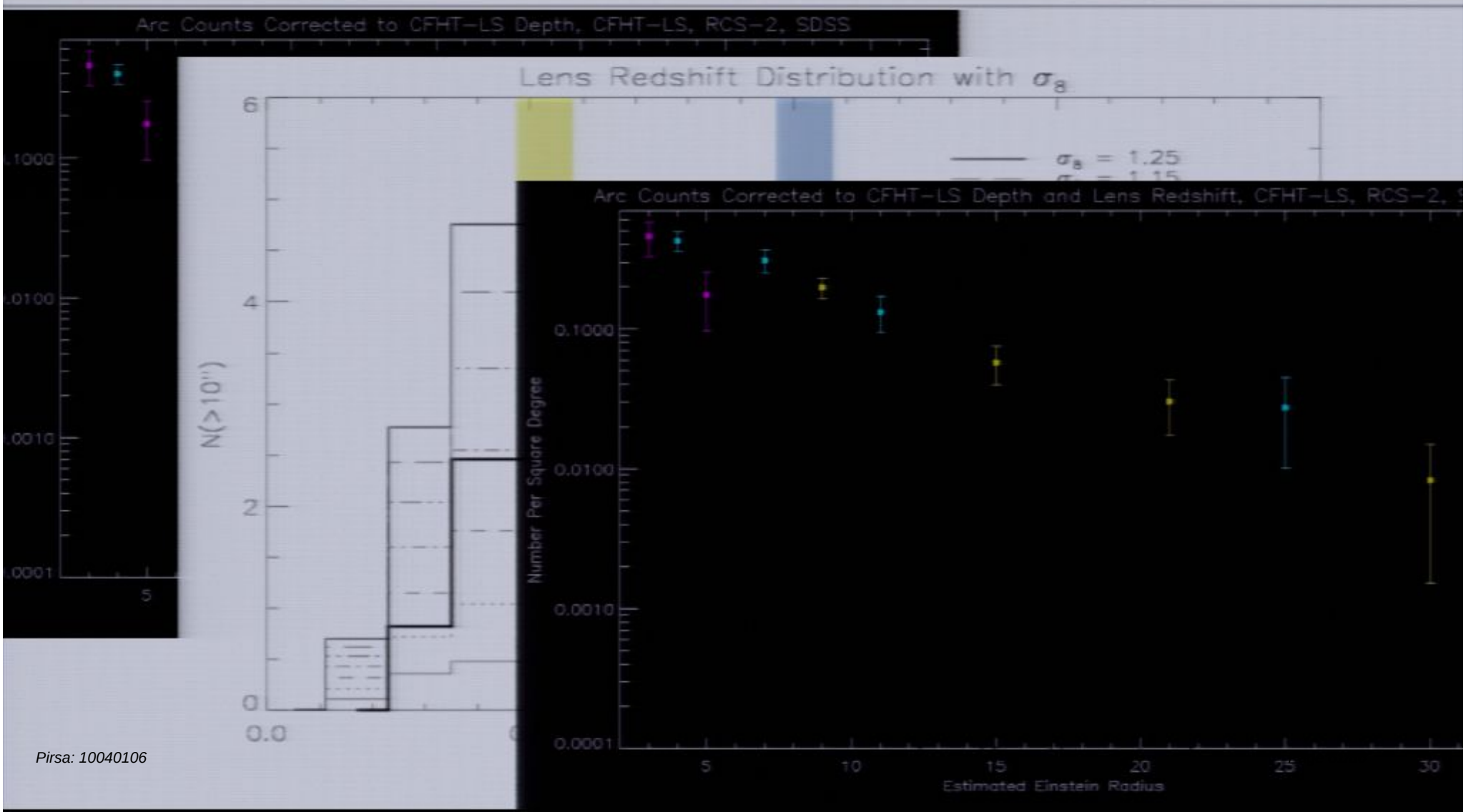
adapted from Hennawi et al. 2007

Arc Counts

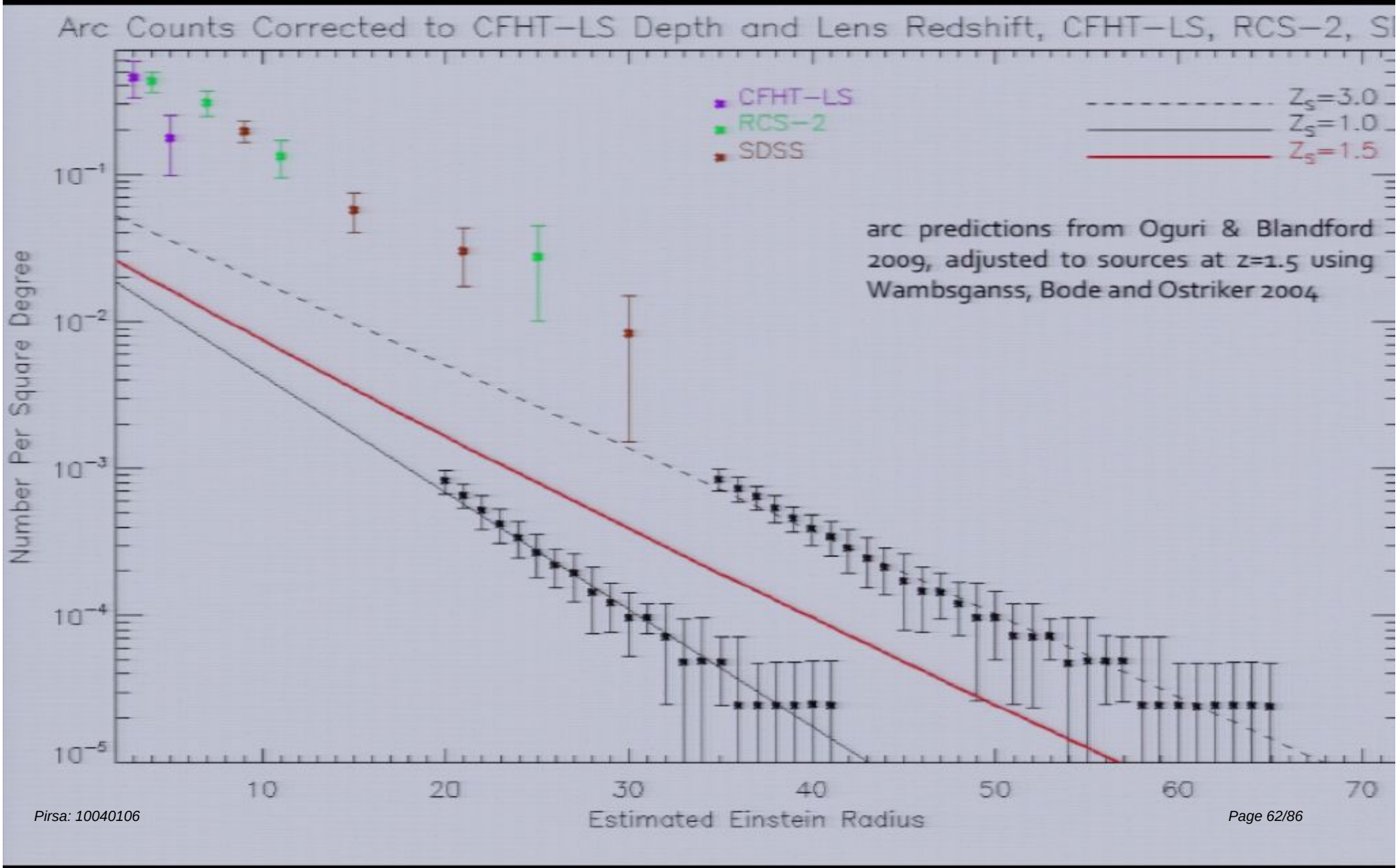


adapted from Hennawi et al. 2007

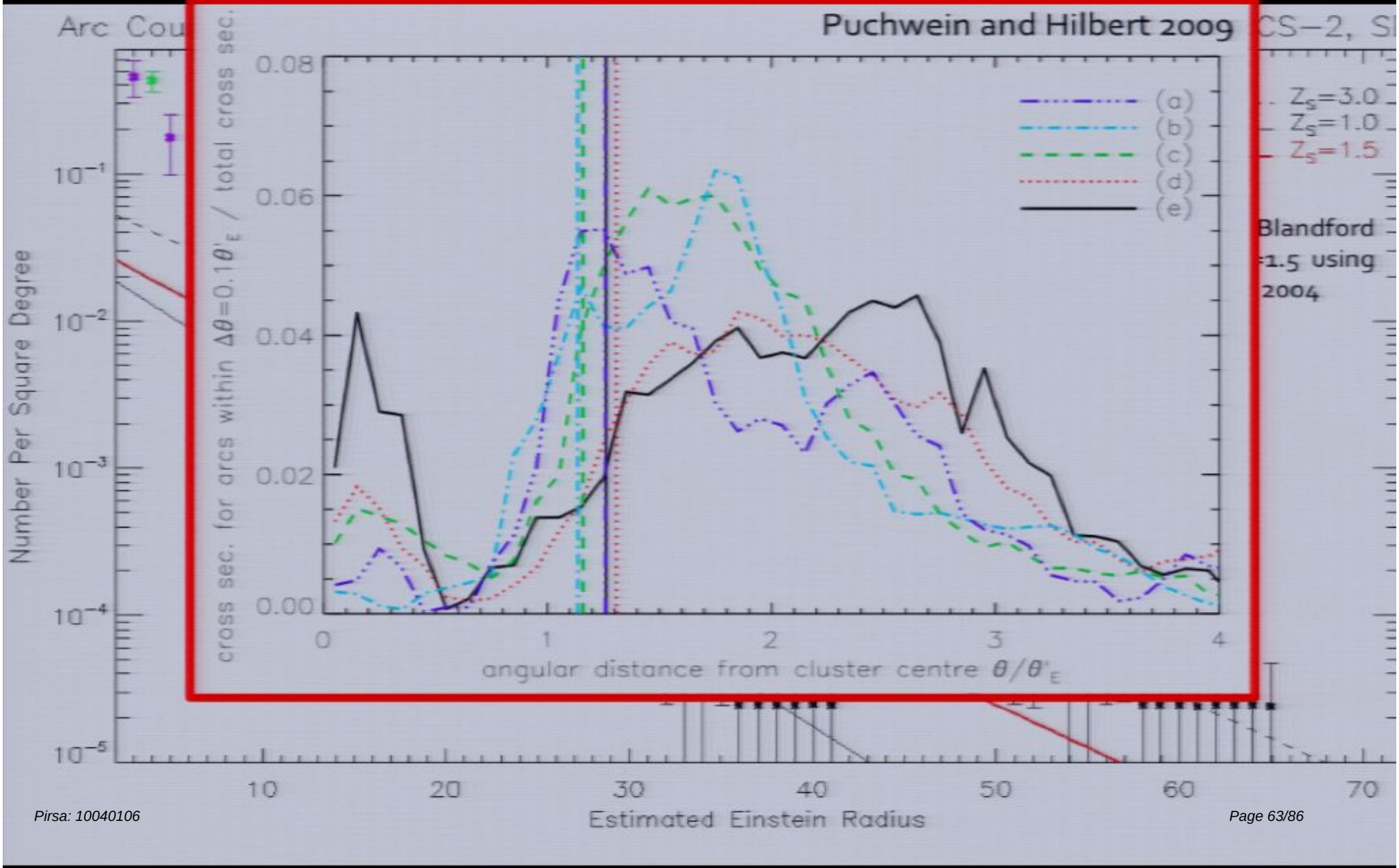
Arc Counts


Arc Counts Corrected to CFHT-LS Depth, CFHT-LS, RCS-2, SDSS
Lens Redshift Distribution with σ_8
σ_8 = 1.25
N(>10'')
Arc Counts Corrected to CFHT-LS Depth and Lens Redshift, CFHT-LS, RCS-2,
Number Per Square Degree
0.1000
0.0100
0.0010
0.0001
5
10
15
20
25
30
Estimated Einstein Radius

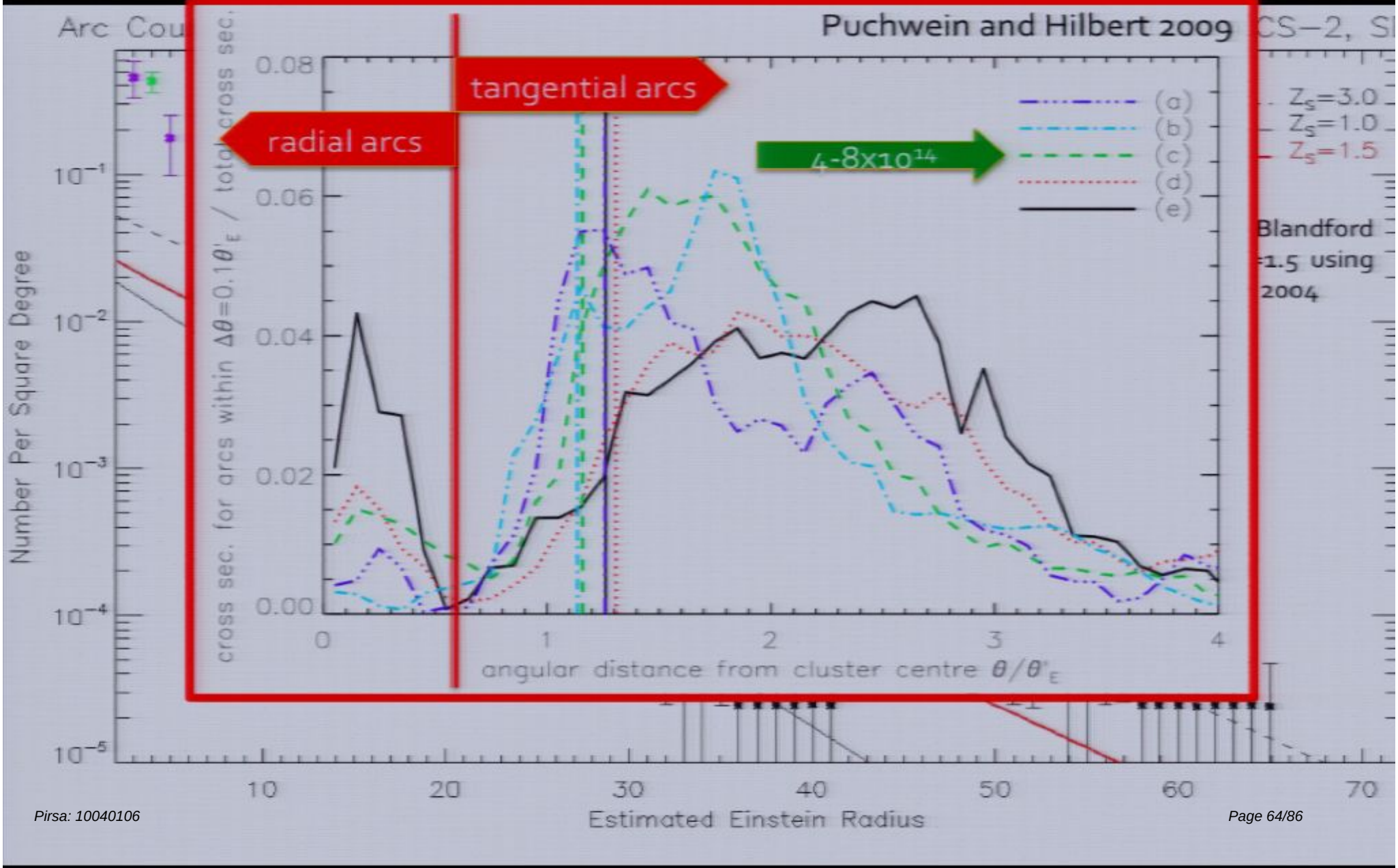
(Extremely) Rough Comparison to Theory



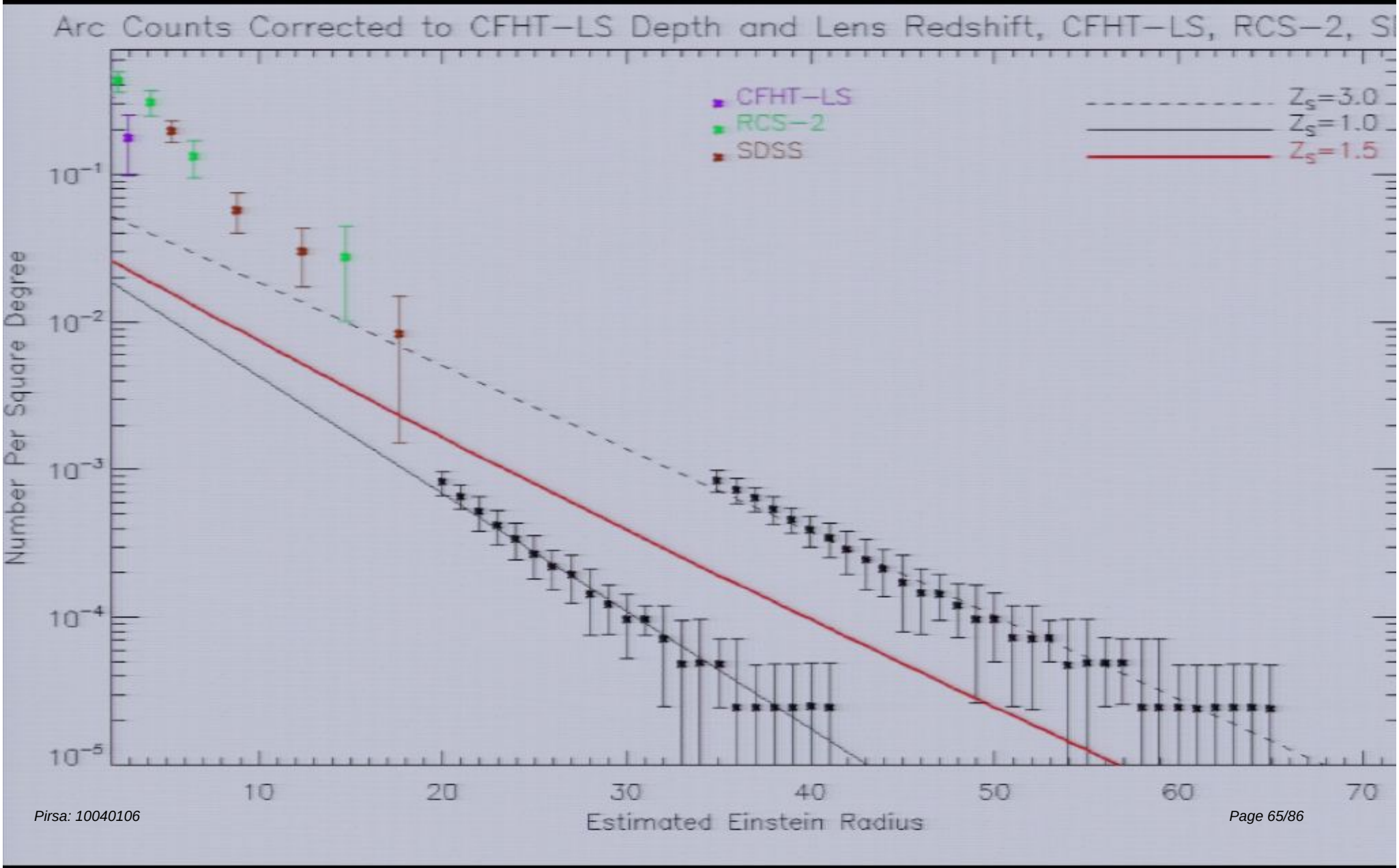
(Extremely) Rough Comparison to Theory



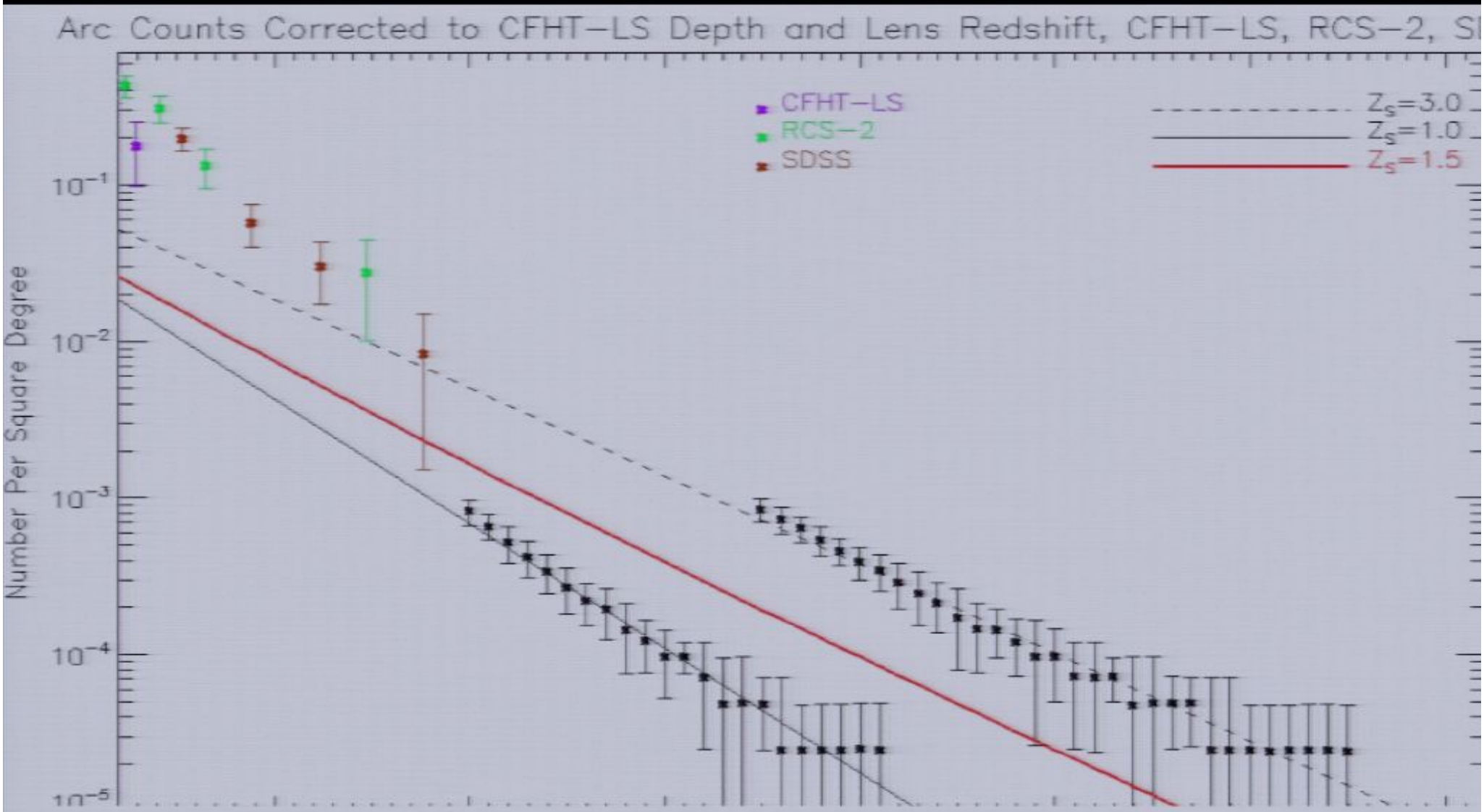
Extremely) Rough Comparison to Theory



(Extremely) Rough Comparison to Theory

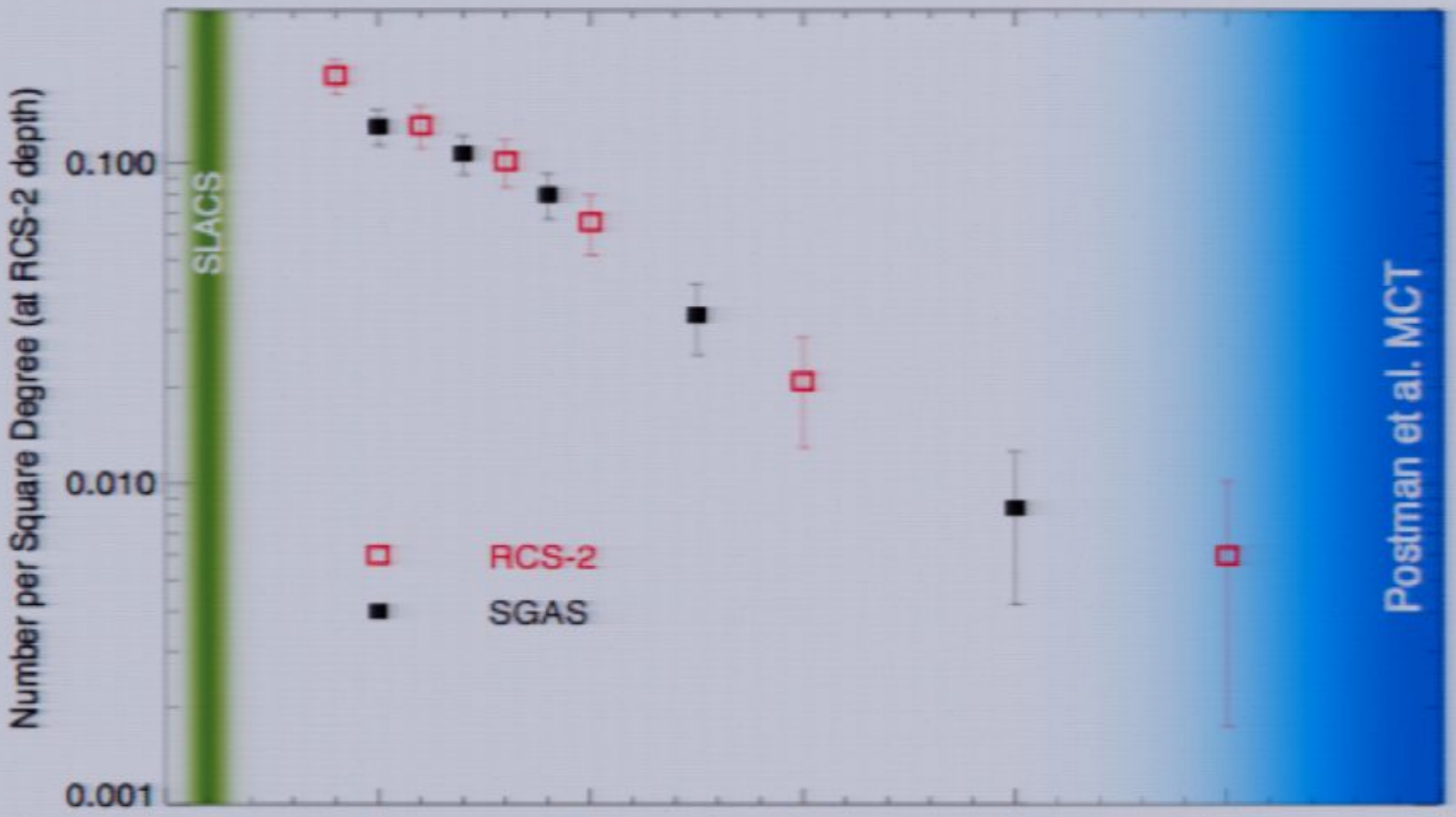


(Extremely) Rough Comparison to Theory

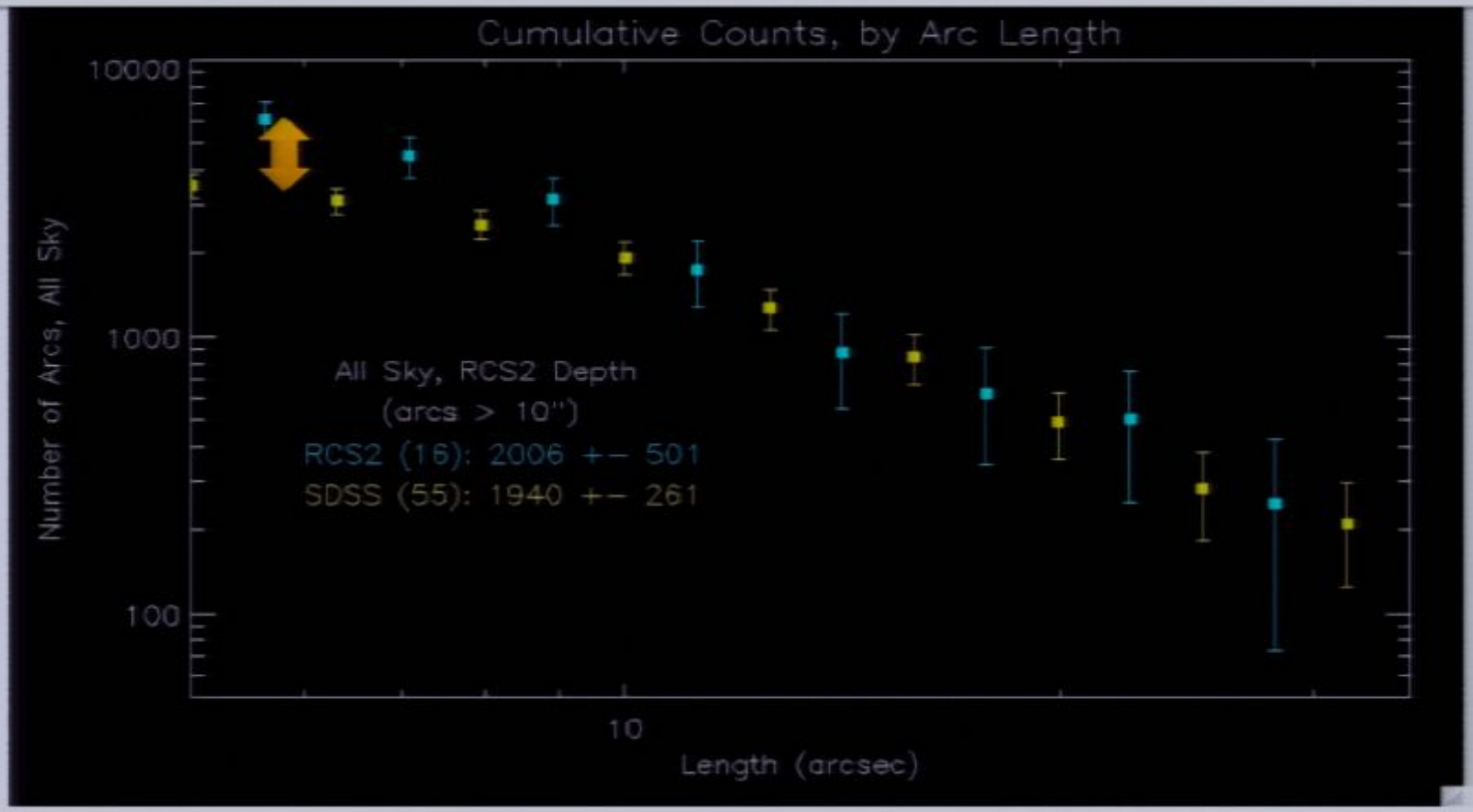


We conclude that, should $\sigma_8 \approx 0.8$ be confirmed, we would fail to understand the strong-lensing efficiency of the galaxy cluster population...by almost an order of magnitude." (Fedeli et al. 2008) – referencing comparison of latest predictions to data in Le Fevre et al. (1994) data on EMSS clusters (a handful of arcs)

Arc Counts, Context

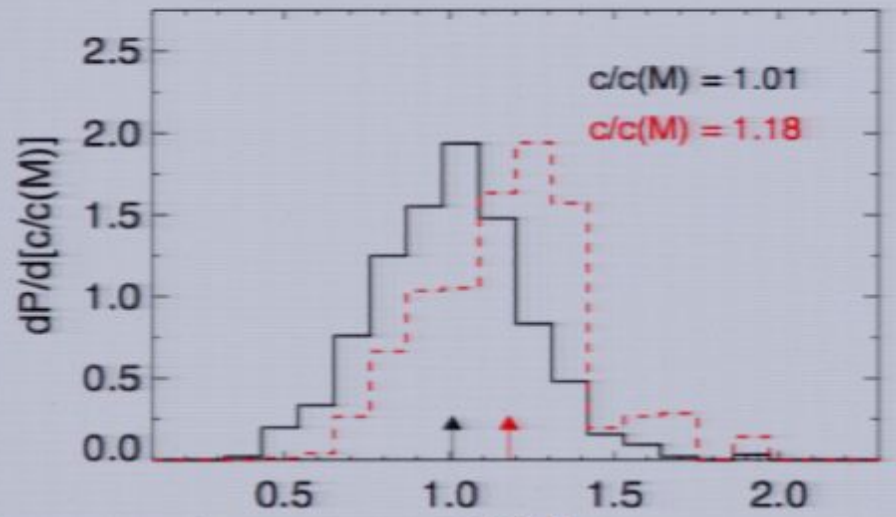


Arc Counts, by Length

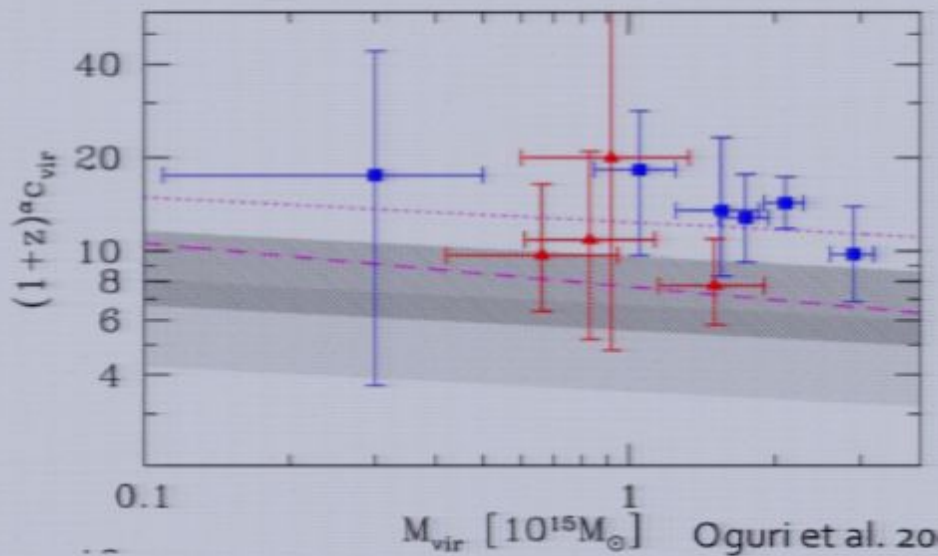


- counting arcs purely by length is a more direct measure, sacrificing a direct connection to lensing haloes for a more robust statistic; RCS-2 and SDSS results are in line with earlier work, with *much reduced uncertainties*. A oft-used measure in theoretical studies is length-to-width ratio; this is not readily accessed in real data in the absence of HST imaging...

Cluster Concentrations



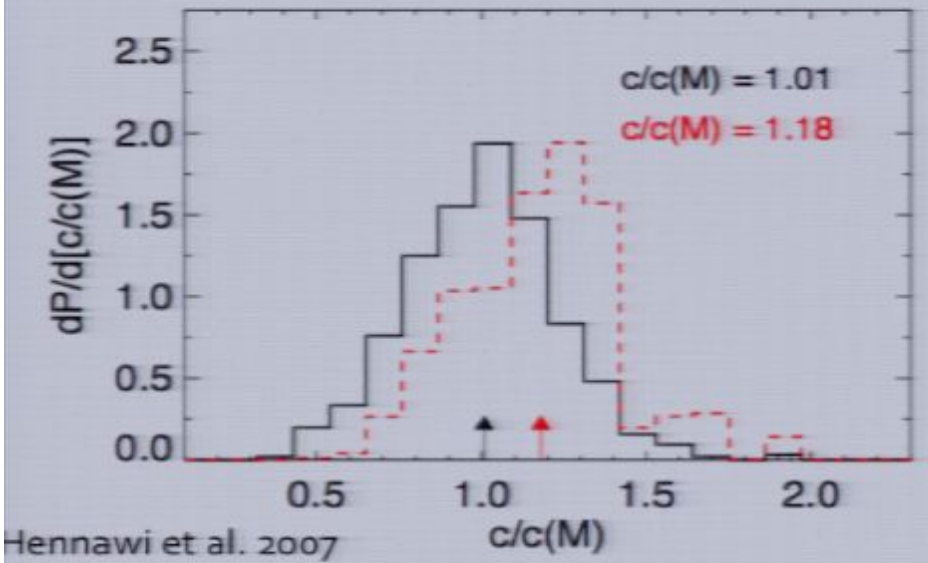
Hennawi et al. 2007



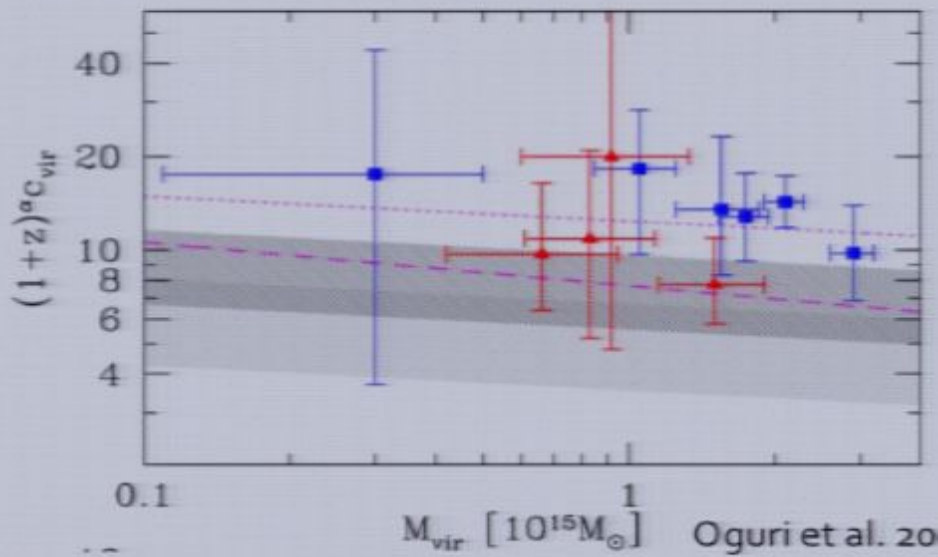
Oguri et al. 200

- lensing clusters are over-concentrated compared to expectations compared to weak+strong lensing constraints (shaded areas, with and without bias (e.g. Hennawi et al. 2007) from Oguri et al. 2009). Dashed line is x-ray selected clusters; dotted line shows fit to lensing selected clusters.

Cluster Concentrations



Hennawi et al. 2007



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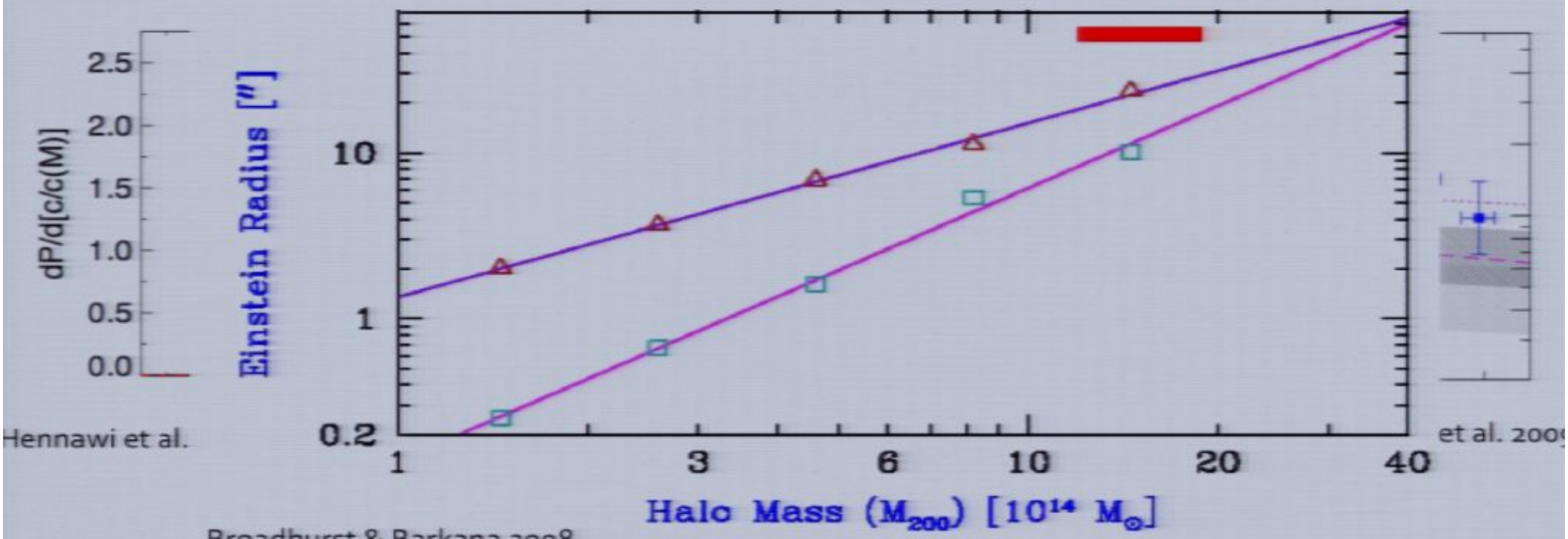
Cluster Concentrations



Broadhurst & Barkana 2008

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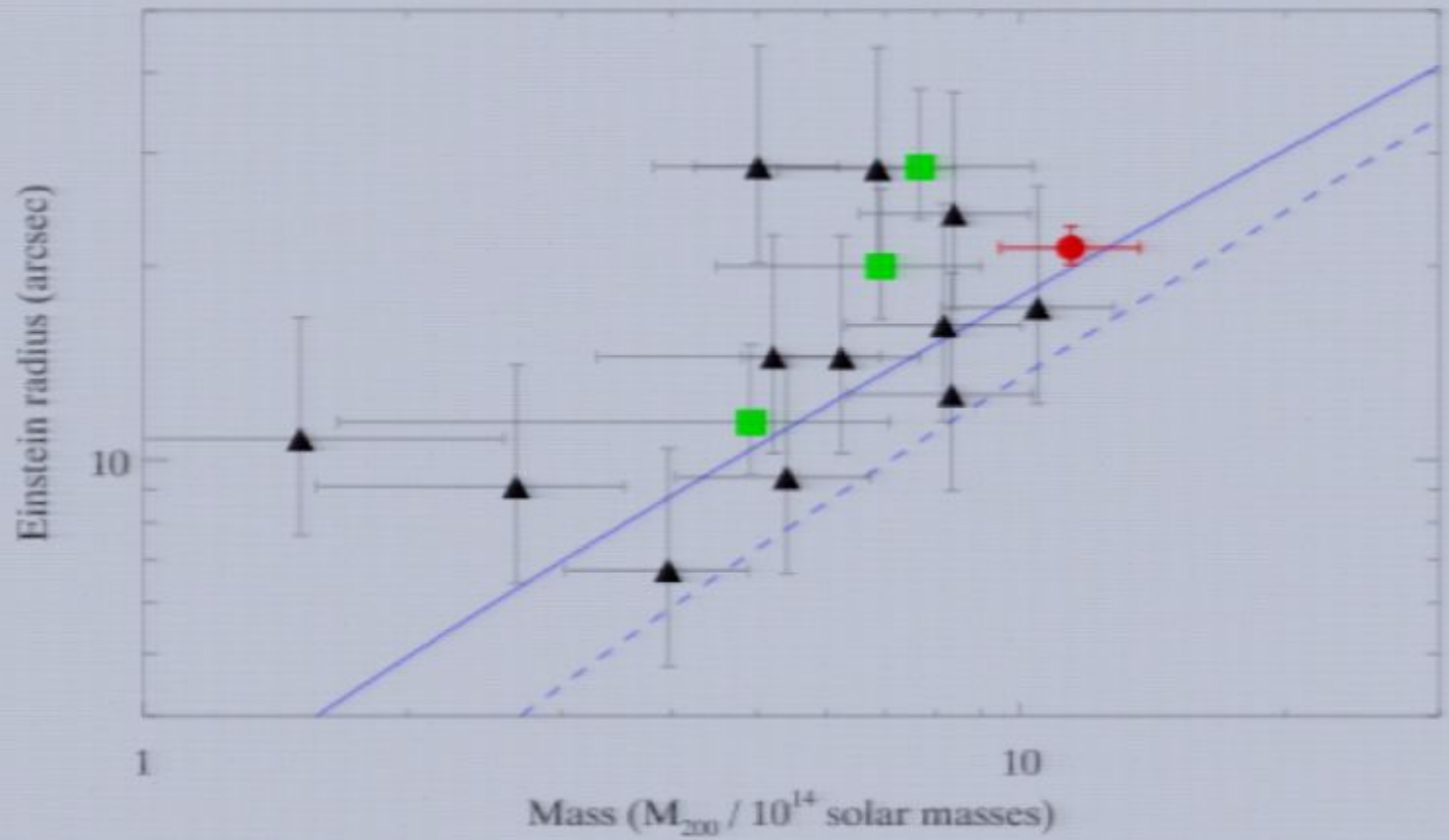
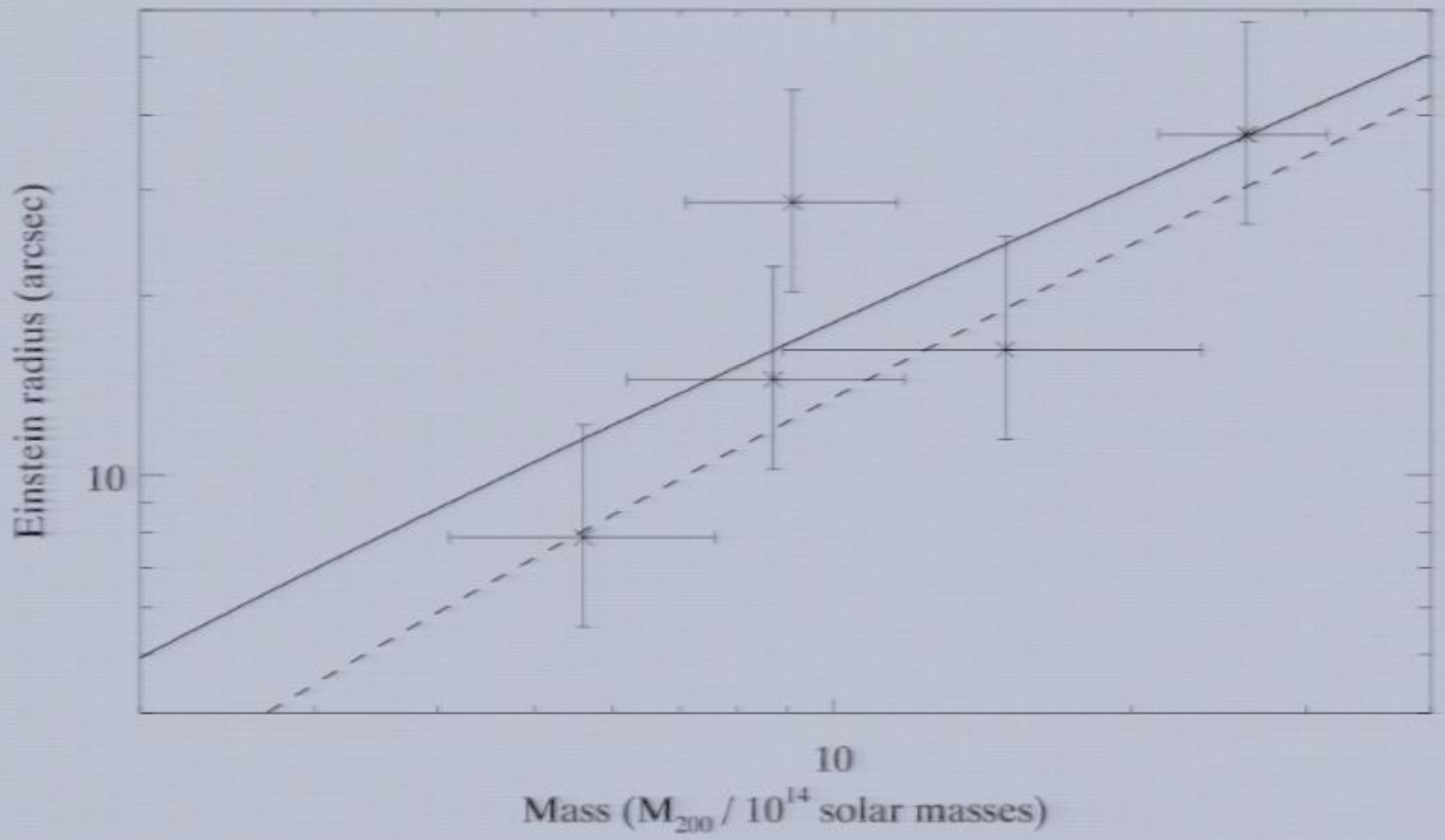
Cluster Concentrations



ralla et al. (2010, in prep): SZA-based total masses compared to estimated Einstein radii
orrected a la Puchwein & Hilbert 2009) (black) compared to weak lensing total masses (gree
averaged (red), compared to expectations from the halo model of Oguri and Blandford (20

Cluster Concentrations

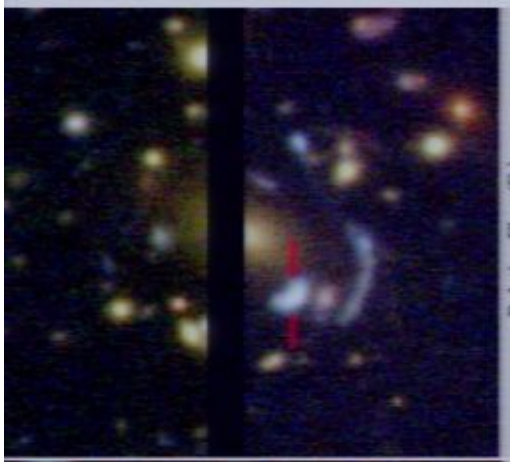


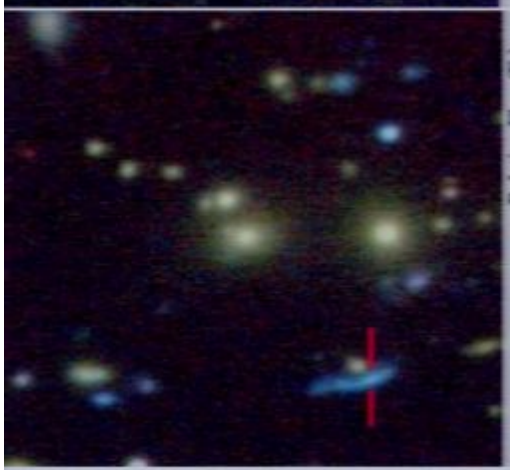
ayliss et al. (2010, in prep): Dynamical mass measurements give a similar picture - no strong
vidence for a concentration problem w.r.t. to theoretical expectations (even after
ccounting for a possible velocity bias)

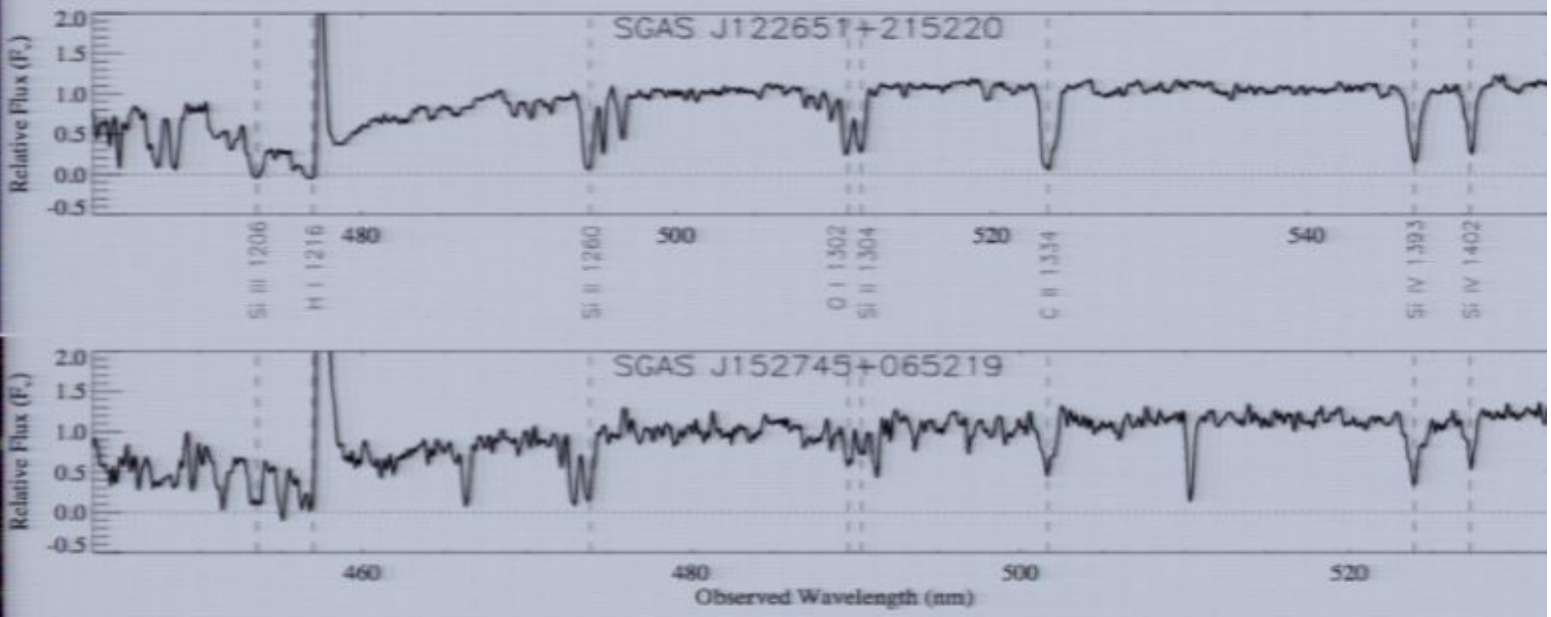
"Let me explain. No, there is too much, let me sum up…"

- we now have large and well-defined (2x~150) samples of cluster-scale strong lenses in hand, extending to z~1. The lensed sources are bright – complete spectroscopic coverage is possible.
- extensive multi-wavelength follow-up is ongoing
- comprehensive statistics (e.g., arc/halo alignments, galaxies in lenses versus non-lenses etc.) accessible with decent S/N for the first time
- the arc counts problem remains a problem
- we see no strong evidence for a concentration problem
- and…

Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5

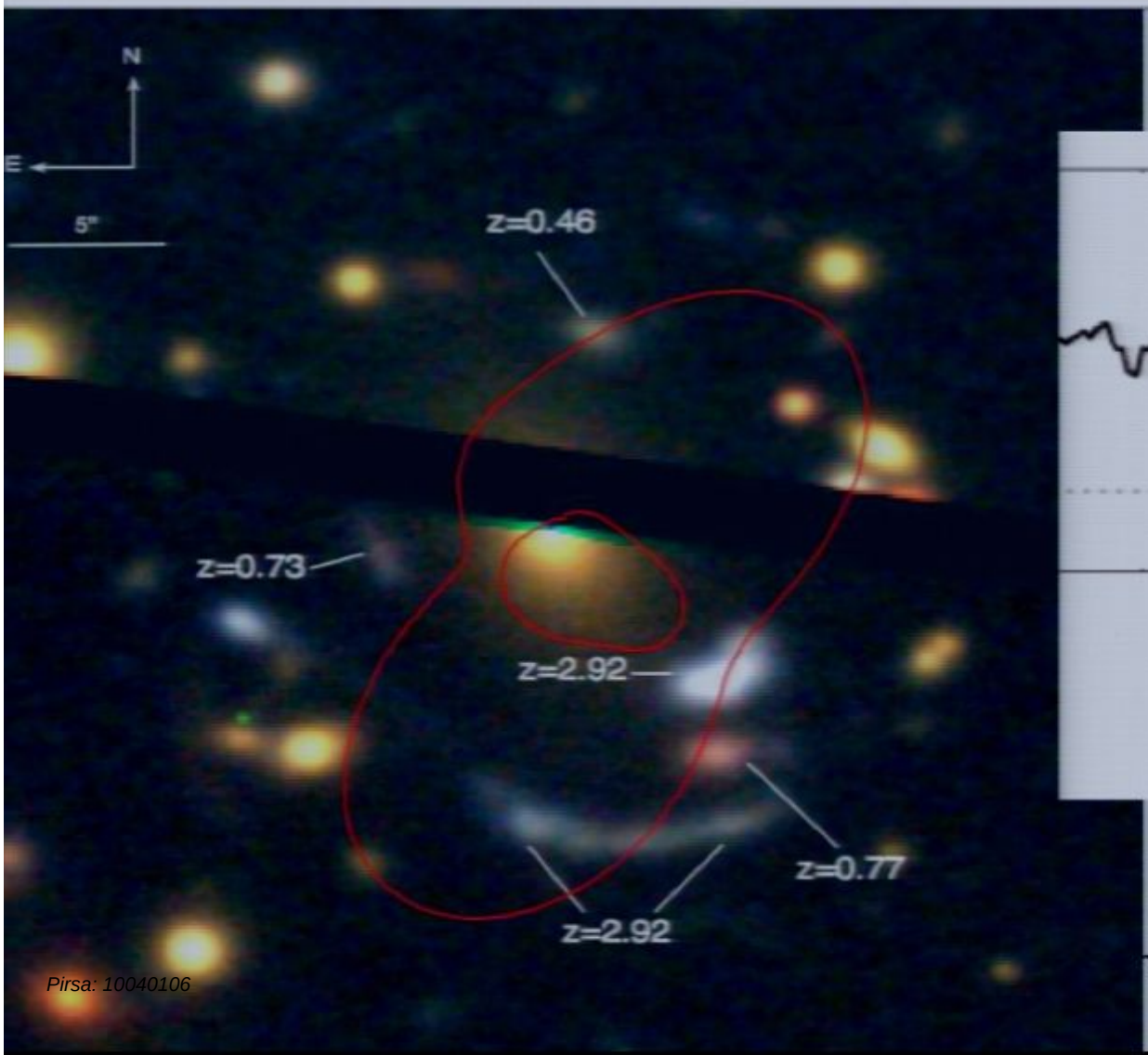


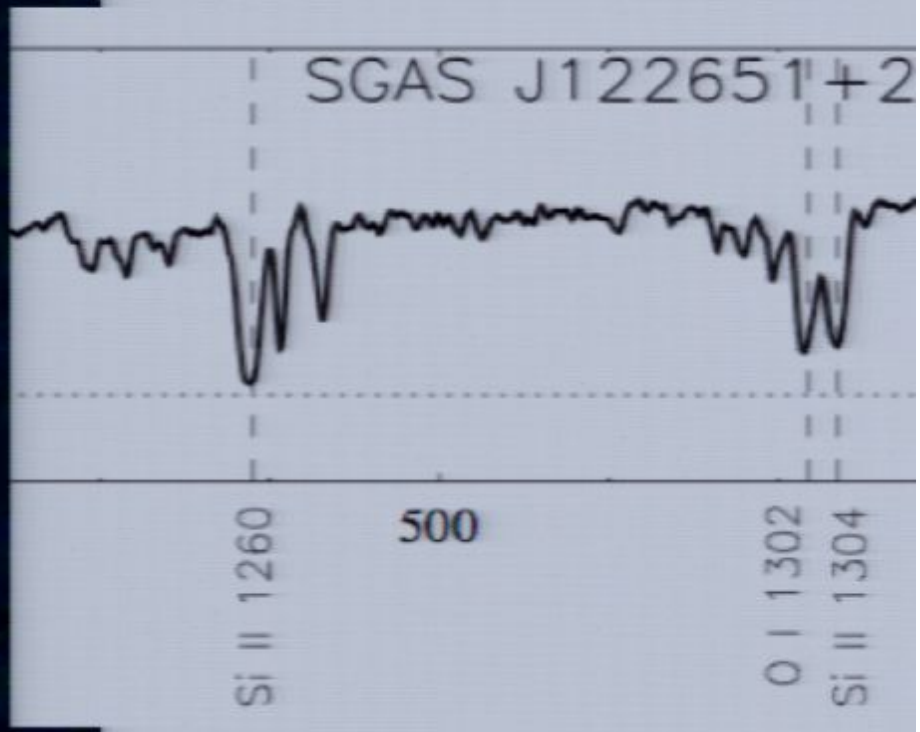




- Koester et al. (2010) : Ultra-bright lensed Lyman-break galaxies (LBGs) offer the opportunity t observe individual and typical high-z galaxies at unprecedented S/N. The large new lens samples w are finding include some spectacular examples...

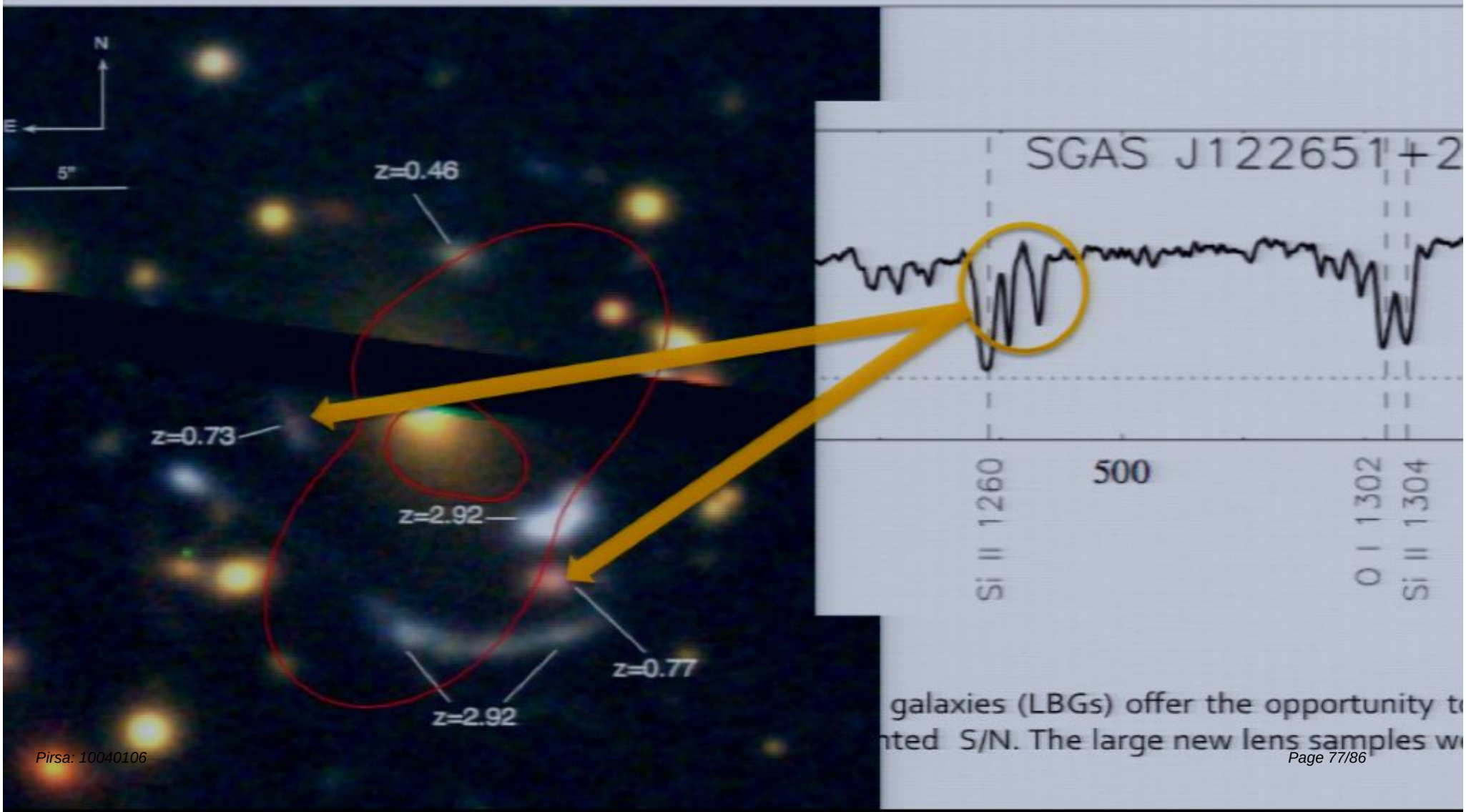
Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5



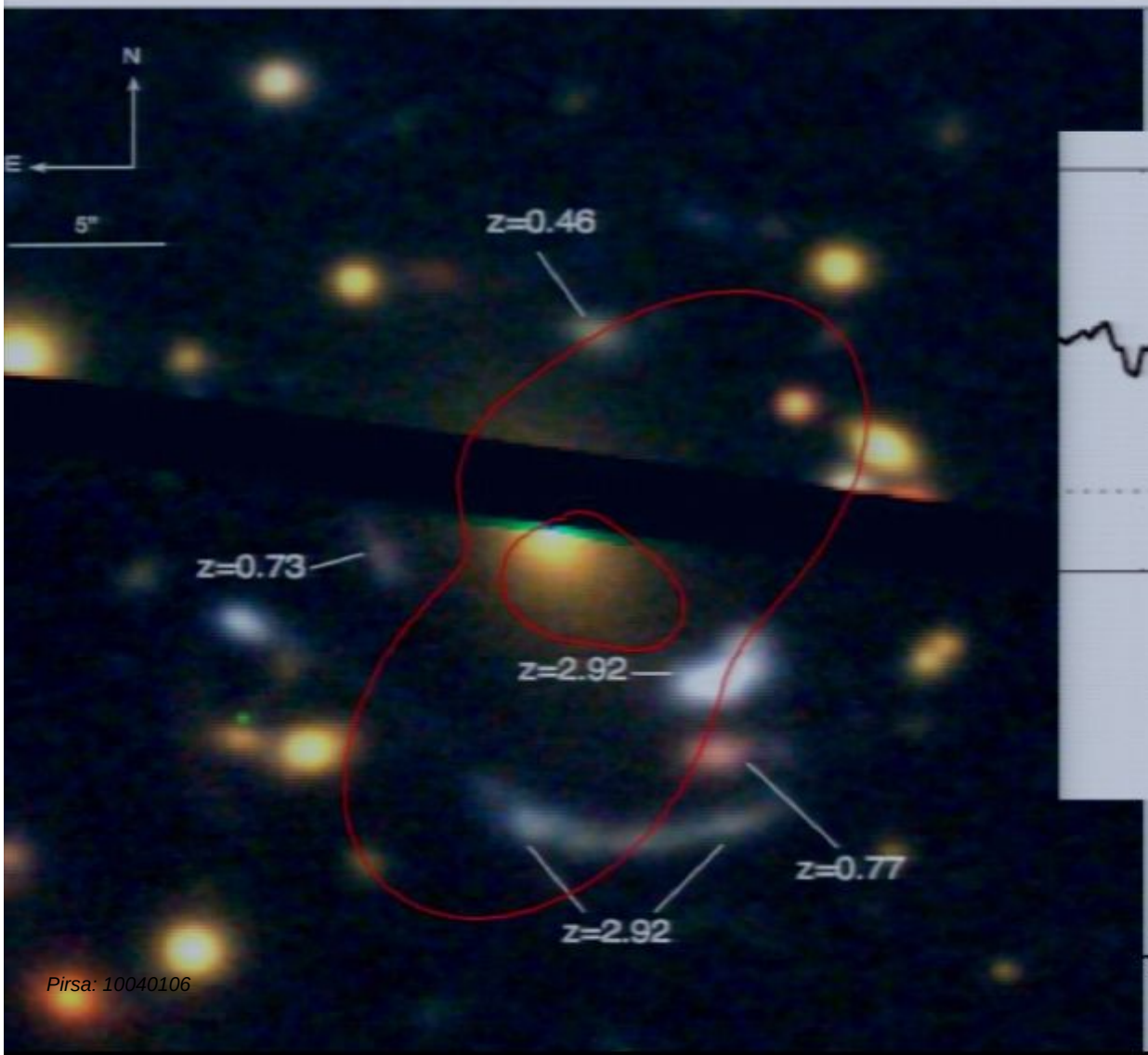


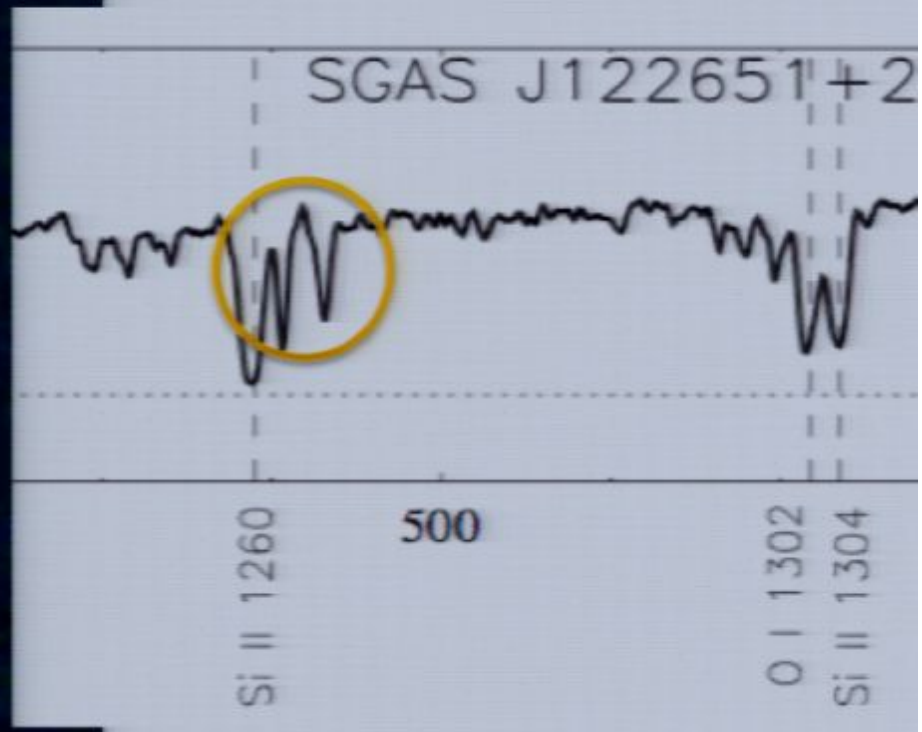
galaxies (LBGs) offer the opportunity t
nted S/N. The large new lens samples w

Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5



Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5





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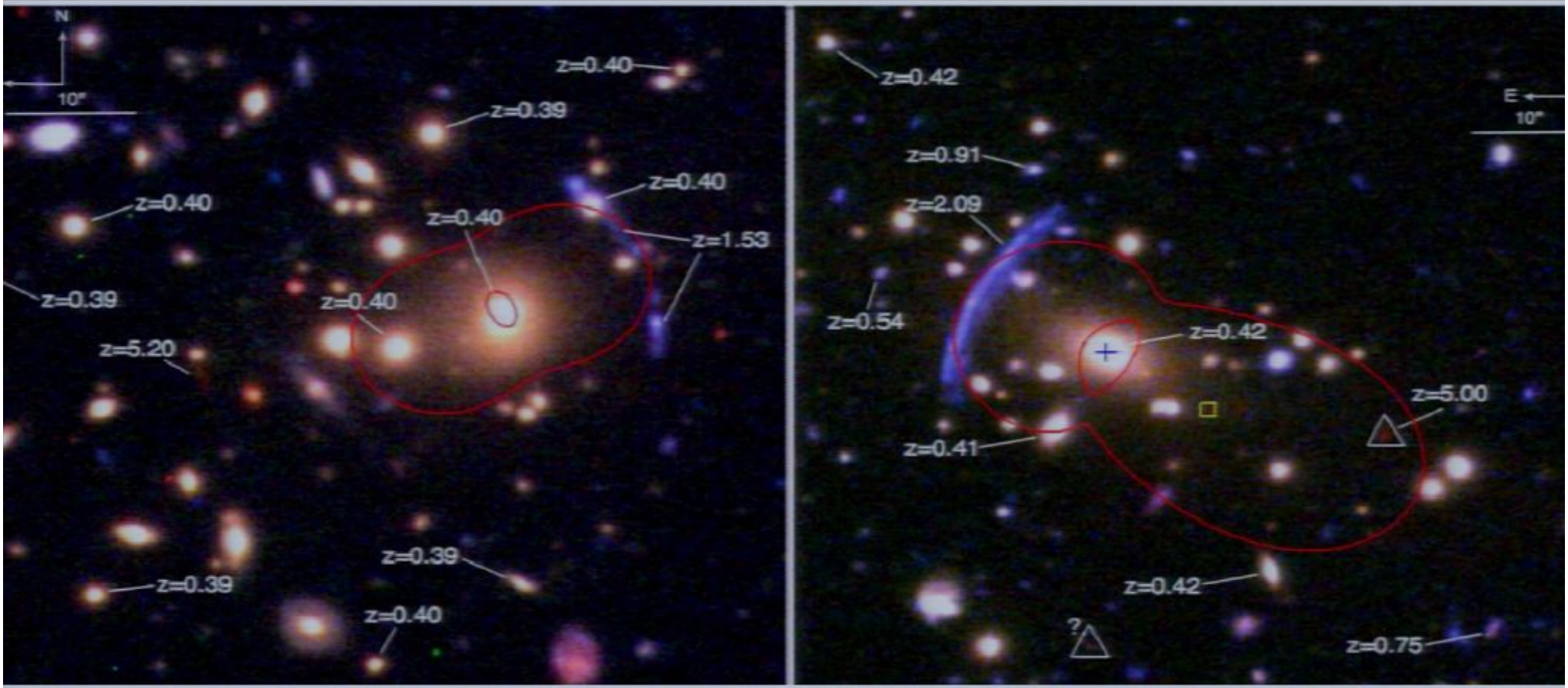
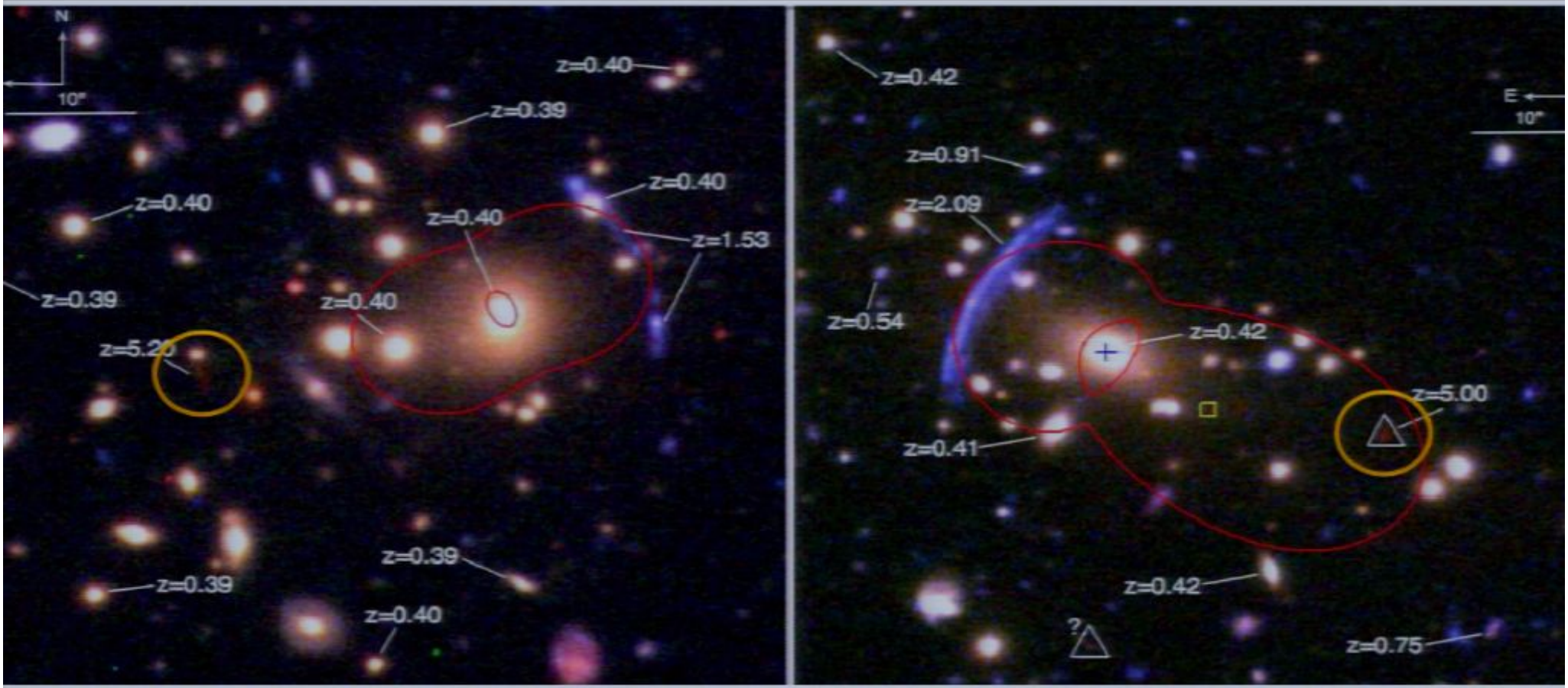
Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5



- Bayliss et al. (2010) : Lyman-alpha emitters (LAEs) at z~5 are poorly understood low mass galaxies

Our initial spectroscopy found several examples – the brightest known, but intrinsically faint – which allow some new insights. Both have hints of older stars: are these the sources of reionization?

Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5



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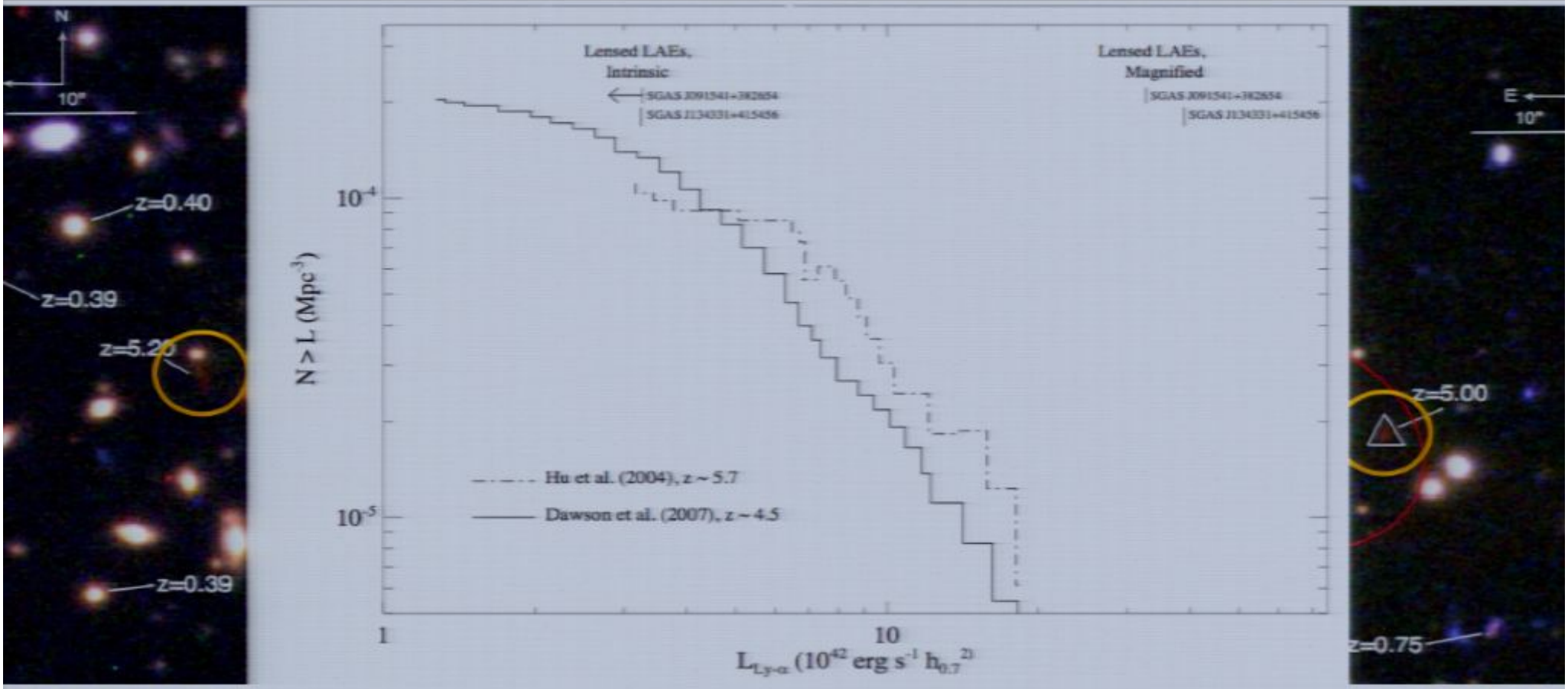

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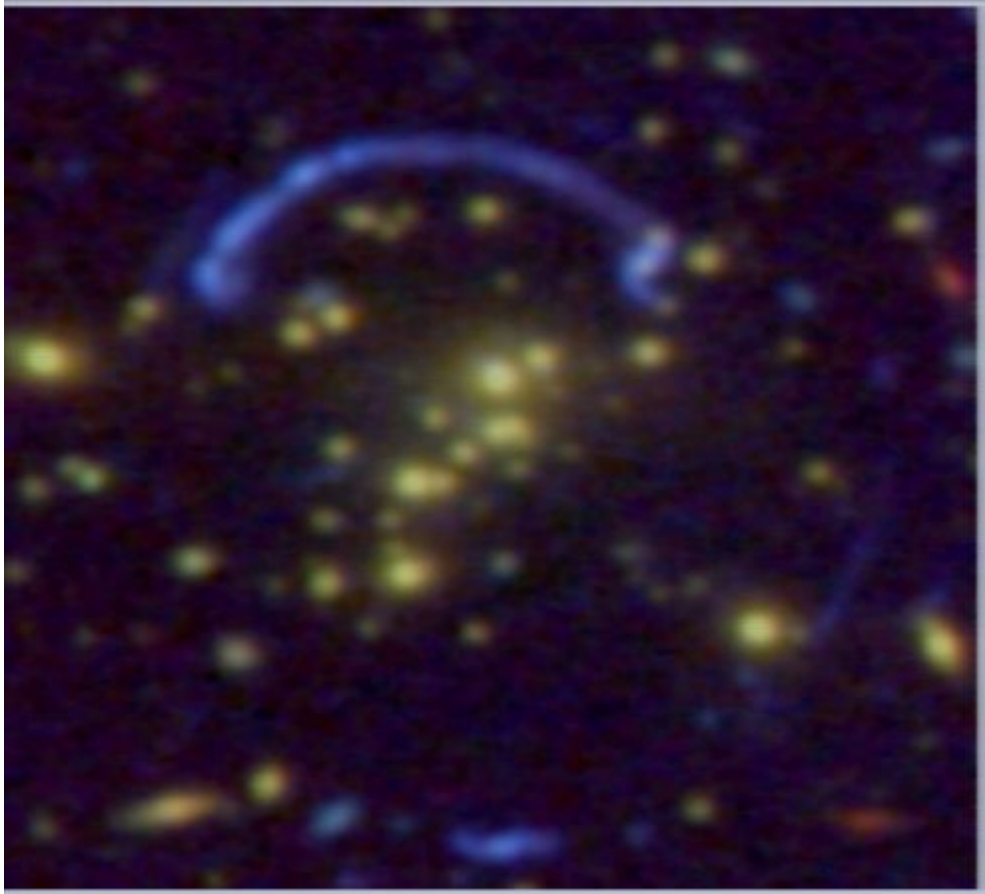
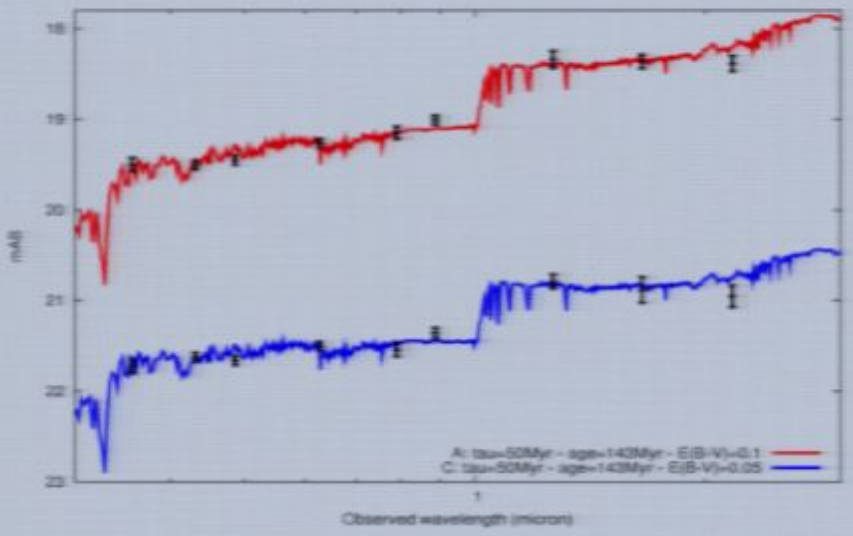
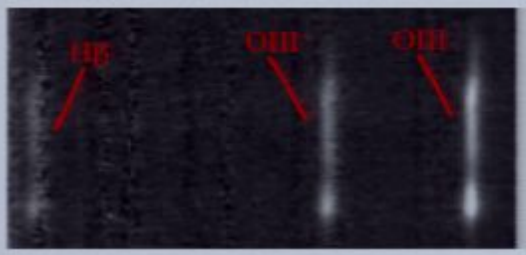
Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5

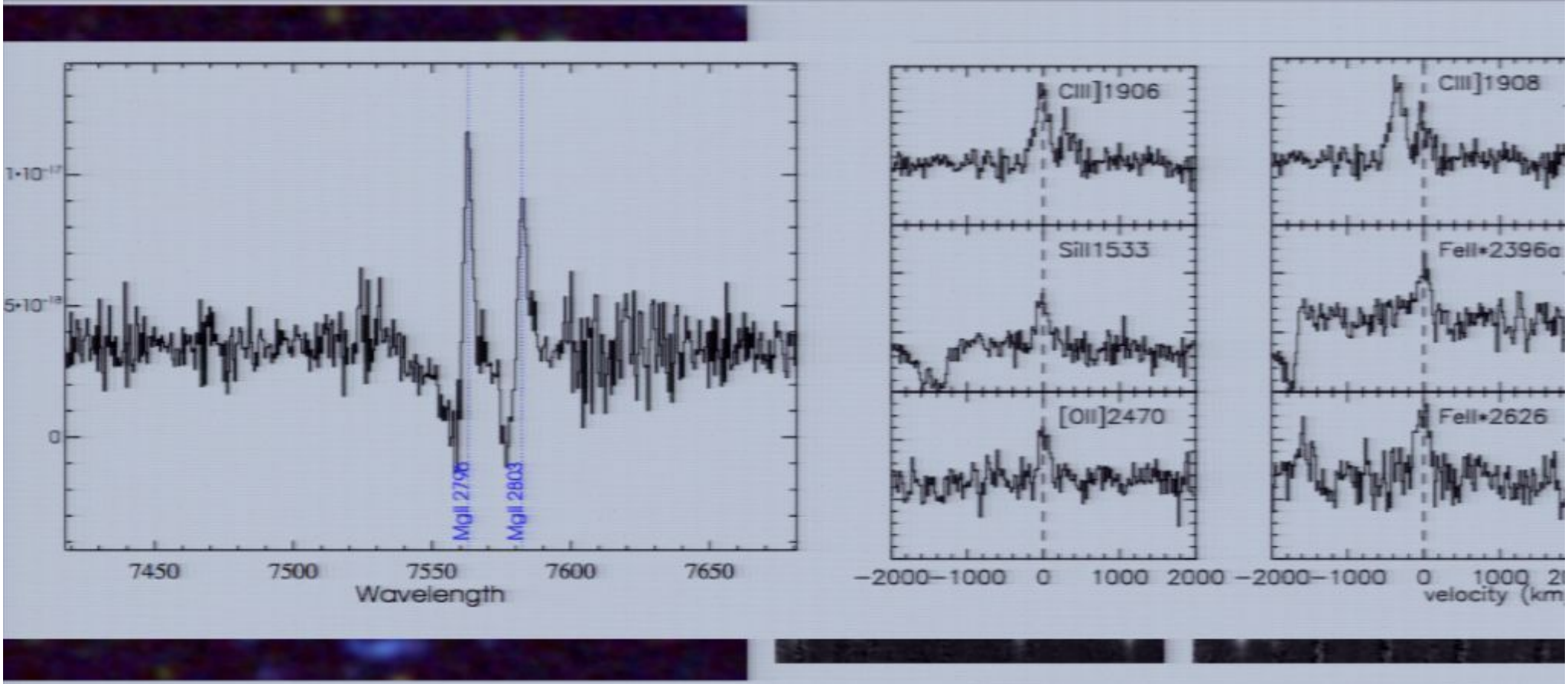






- Wuyts et al. (2010, in prep.) : The brightest lensed galaxy known: 3x brighter than the prototypical cB AND 20x larger on the sky. z=1.7 – in the redshift desert at the peak of the star formation in the Universe
- Rigby et al. (2010, in prep.) : This object has spectral features never before or only rarely seen – includi remarkable MgII 2800 P-Cygni-like emission and low ionization lines of various species.

Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5



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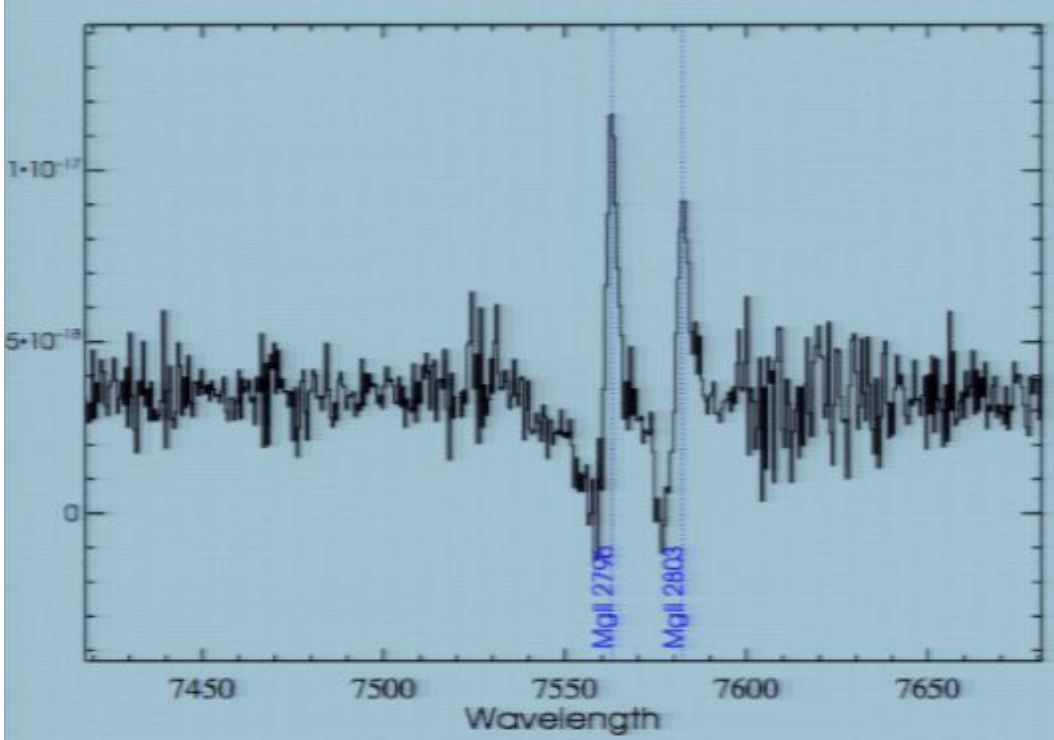
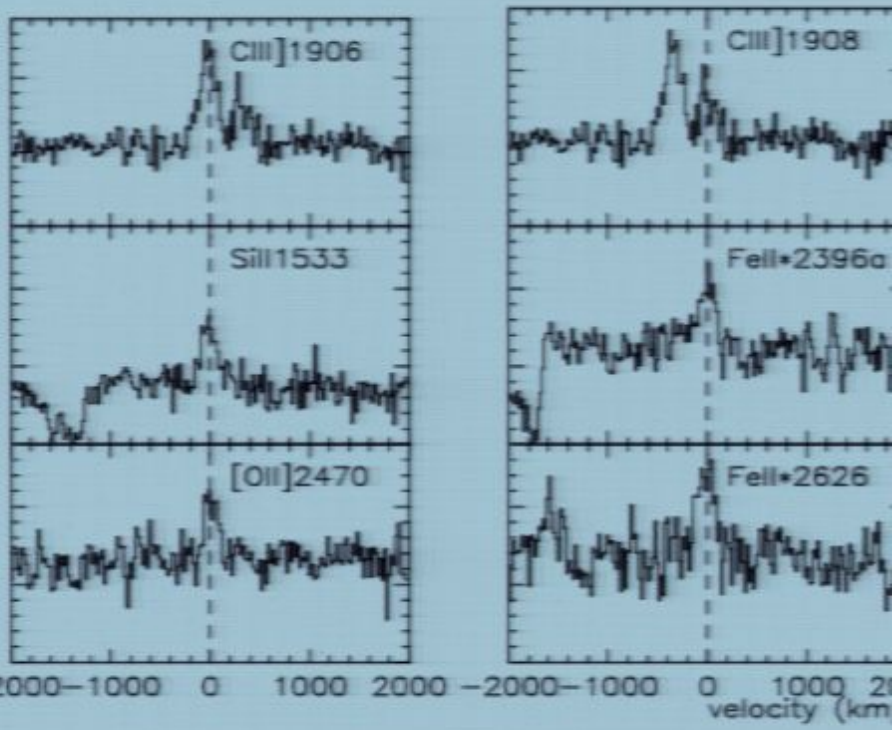
Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5





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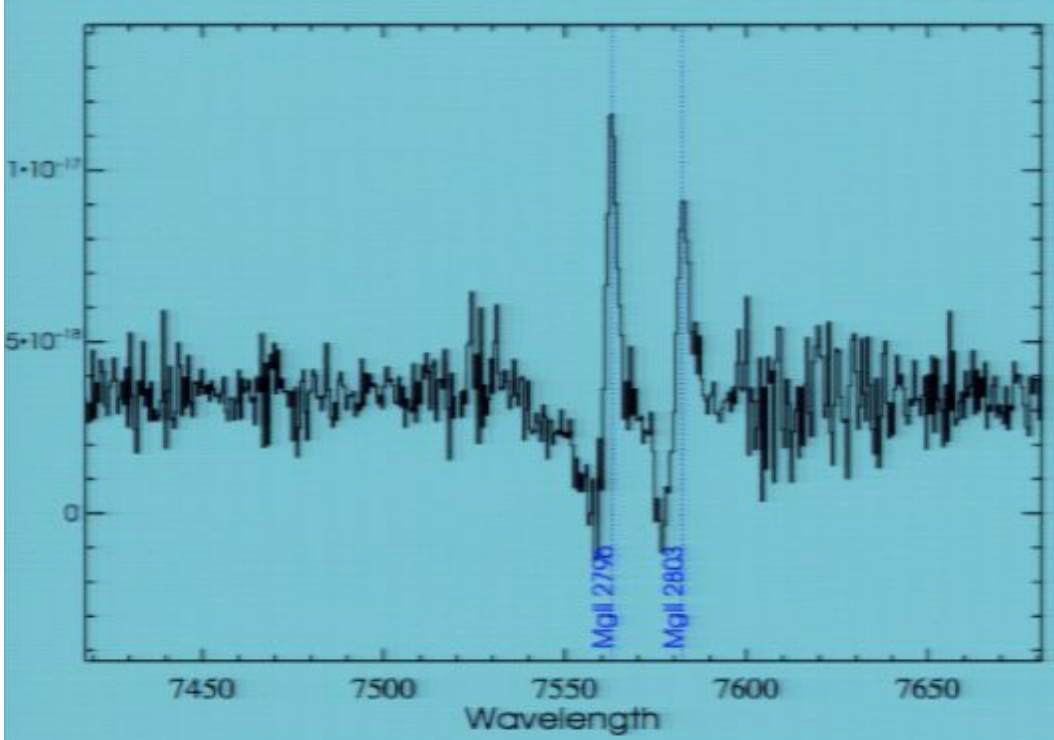
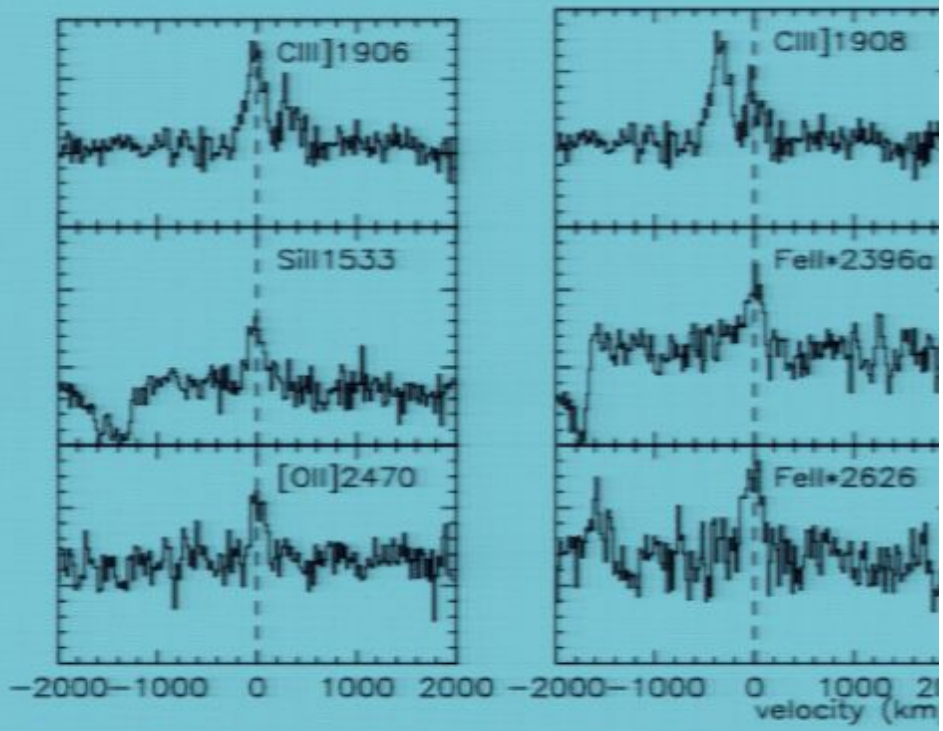
Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5





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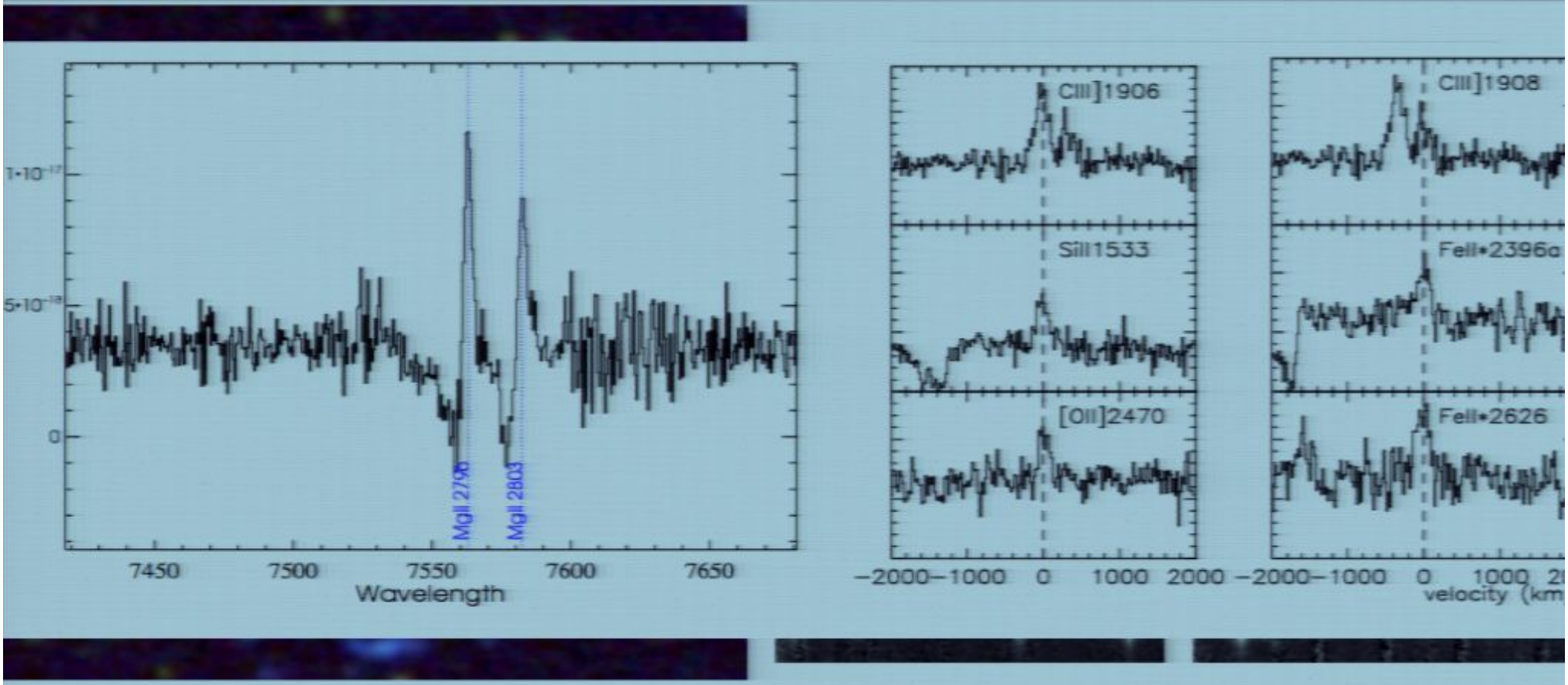
Lensed Sources: The Brightest LBGs at z~3 and LAEs at z~5



- Wuyts et al. (2010, in prep.) : The brightest lensed galaxy known: 3x brighter than the prototypical cB AND 20x larger on the sky. z=1.7 – in the redshift desert at the peak of the star formation in the Universe
- Rigby et al. (2010, in prep.) : This object has spectral features never before or only rarely seen – includi remarkable MgII 2800 P-Cygni-like emission and low ionization lines of various species.