Spectroscopically Selected Gravitational Lenses

Adam S. Bolton
Harvard-Smithsonian CfA

with

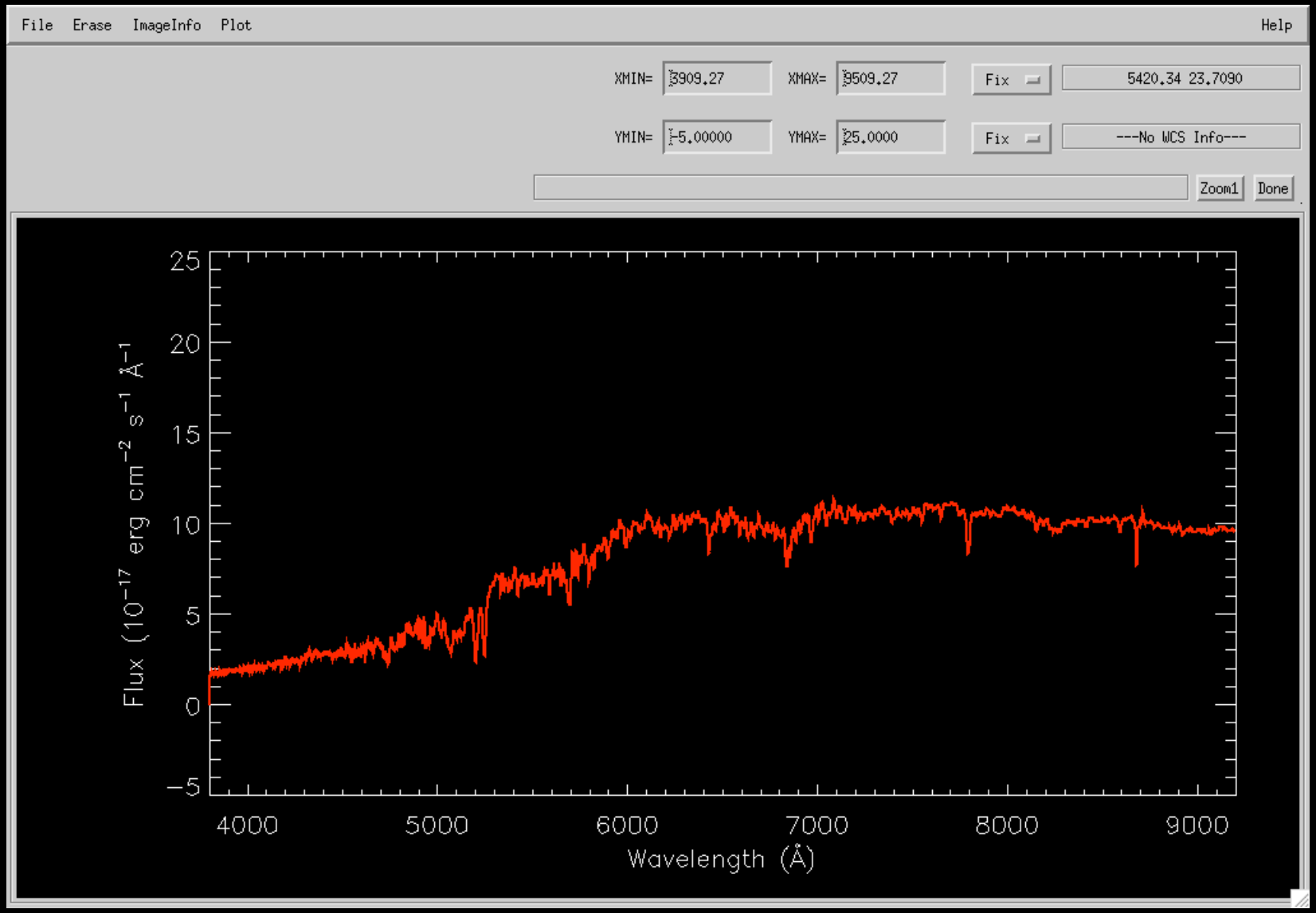
S. Burles, L. V. E. Koopmans, T. Treu, L. A. Moustakas

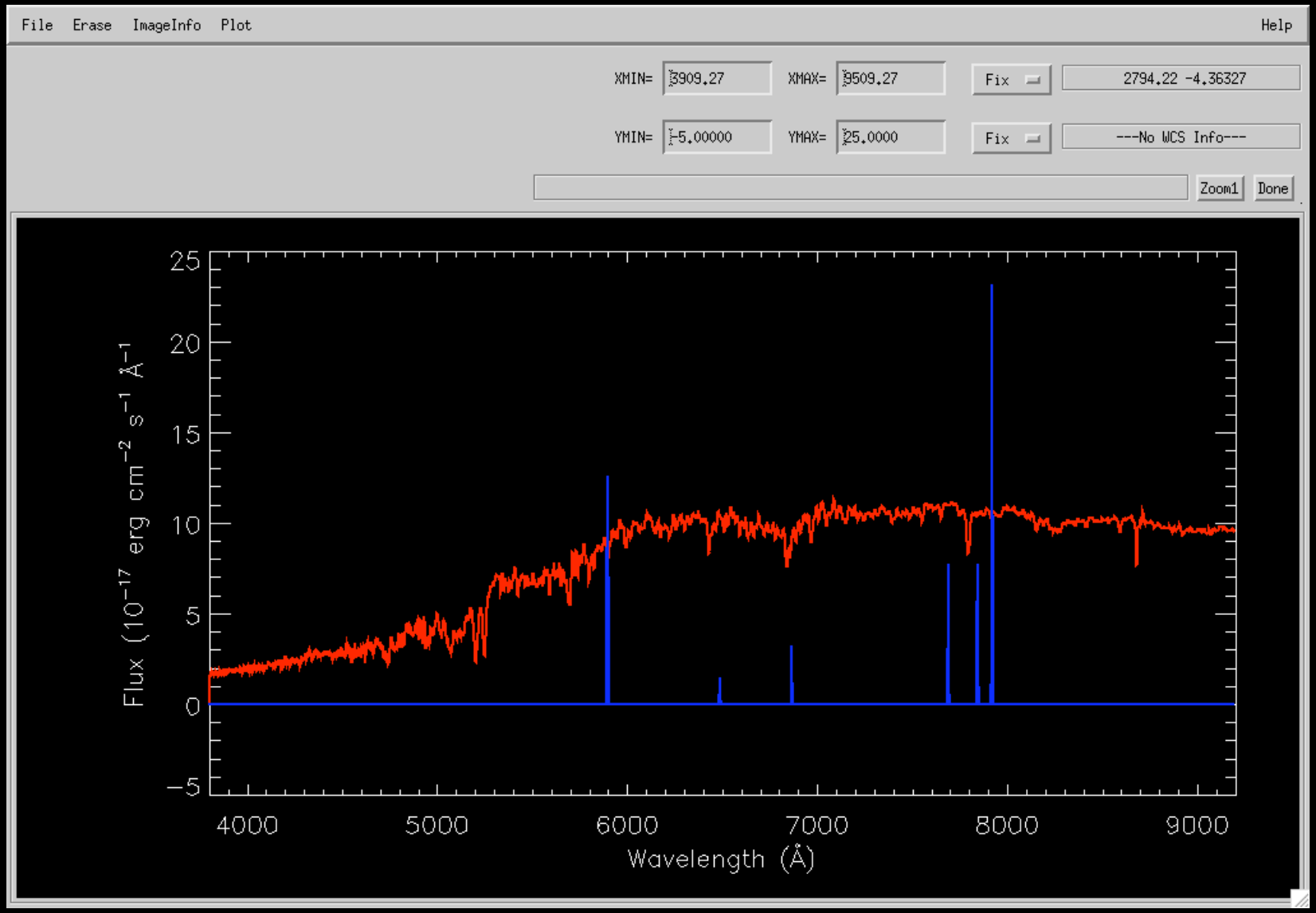
The basic idea (as currently conceived):

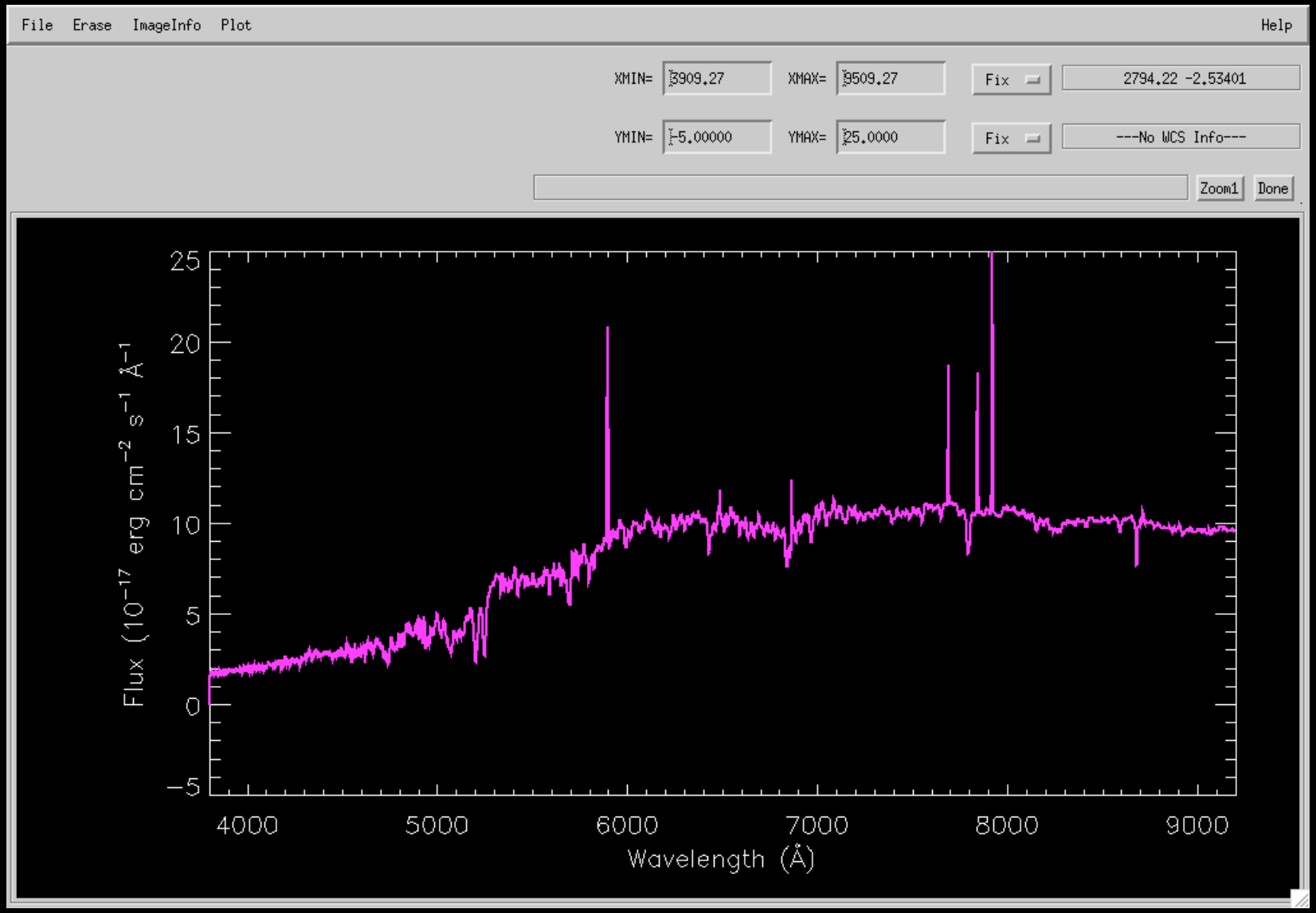
A survey of potentially lensING objects, rather than of potentially lensED objects.

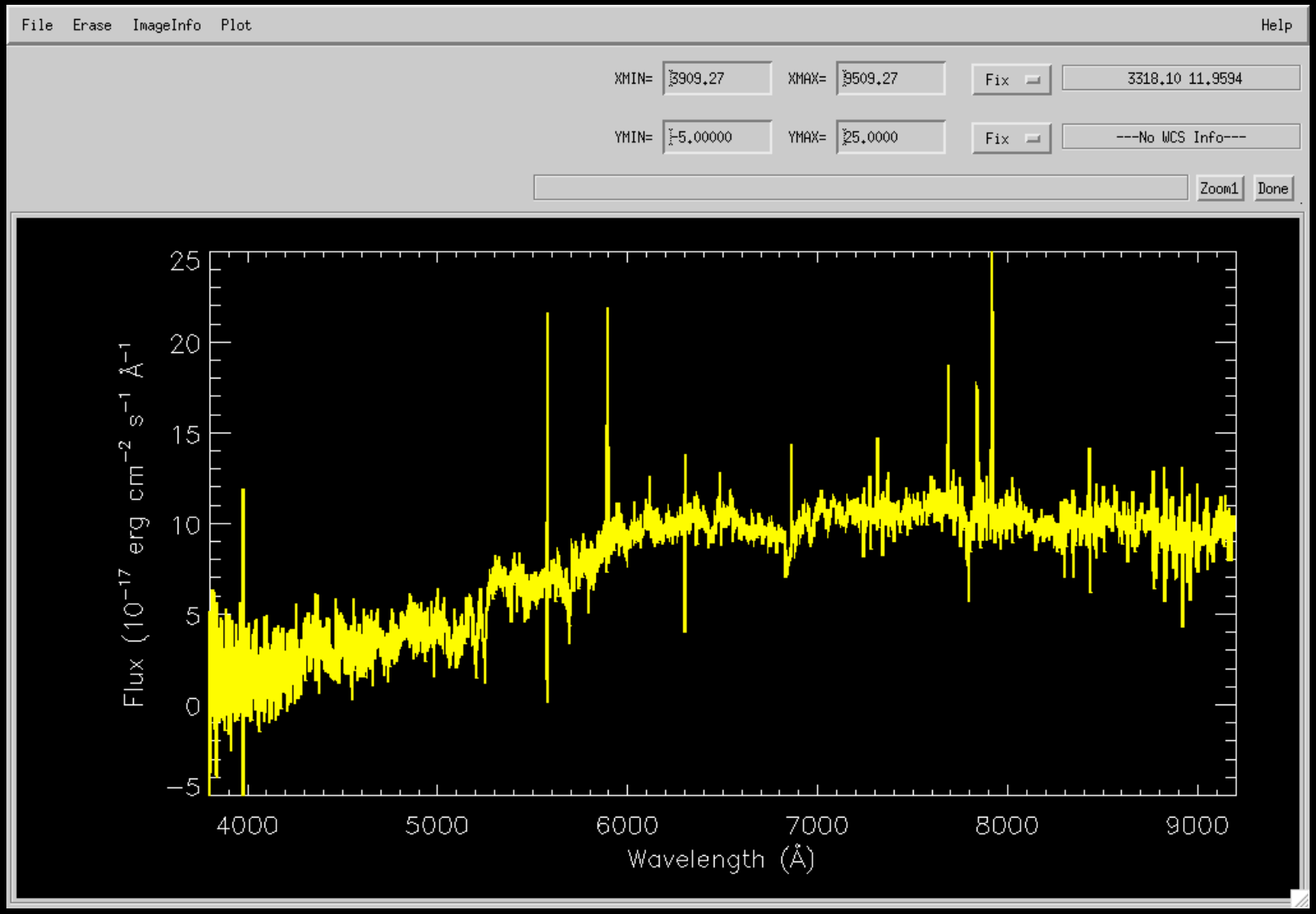
(SDSS Imaging)

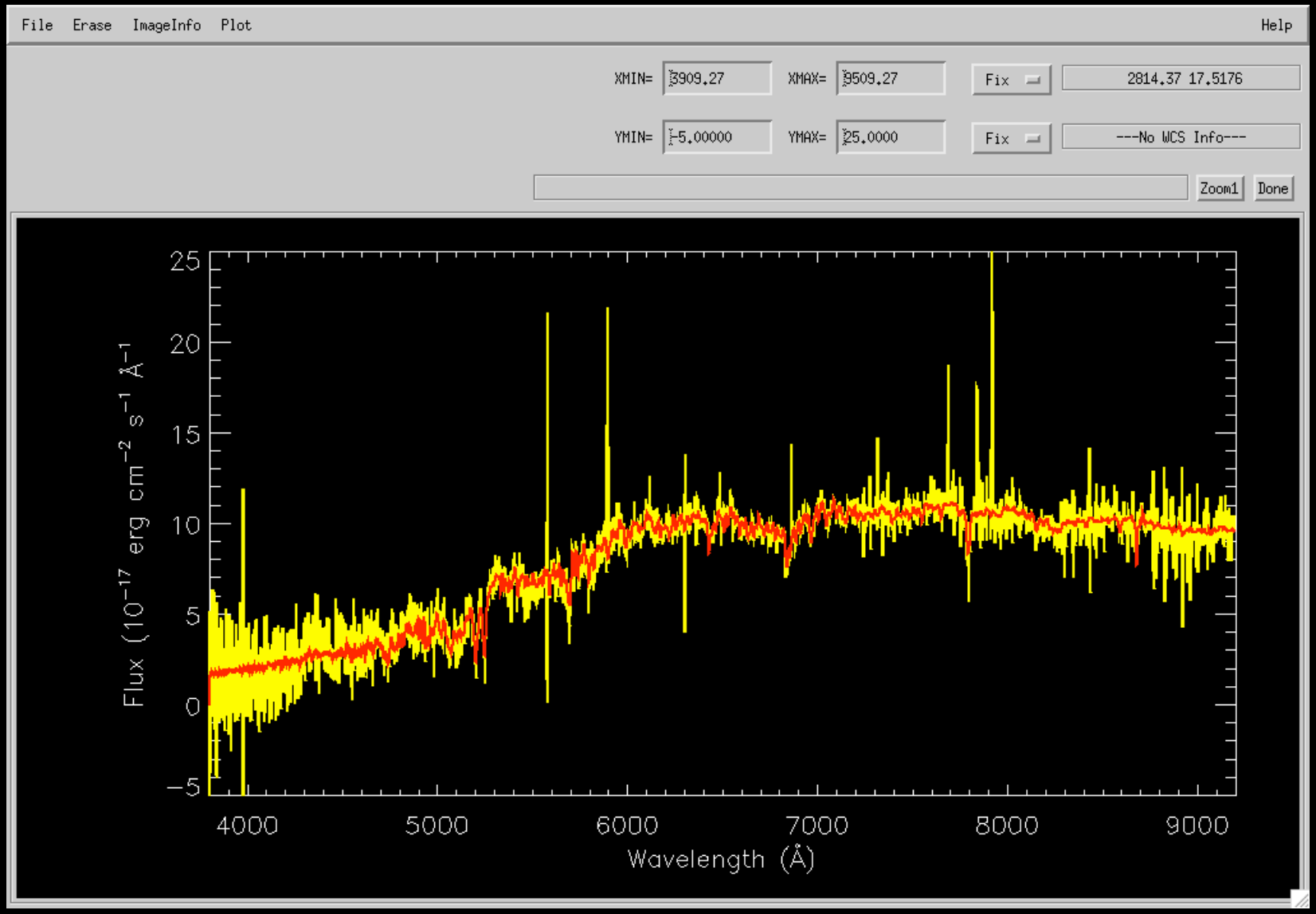
SDSS Spectroscopy

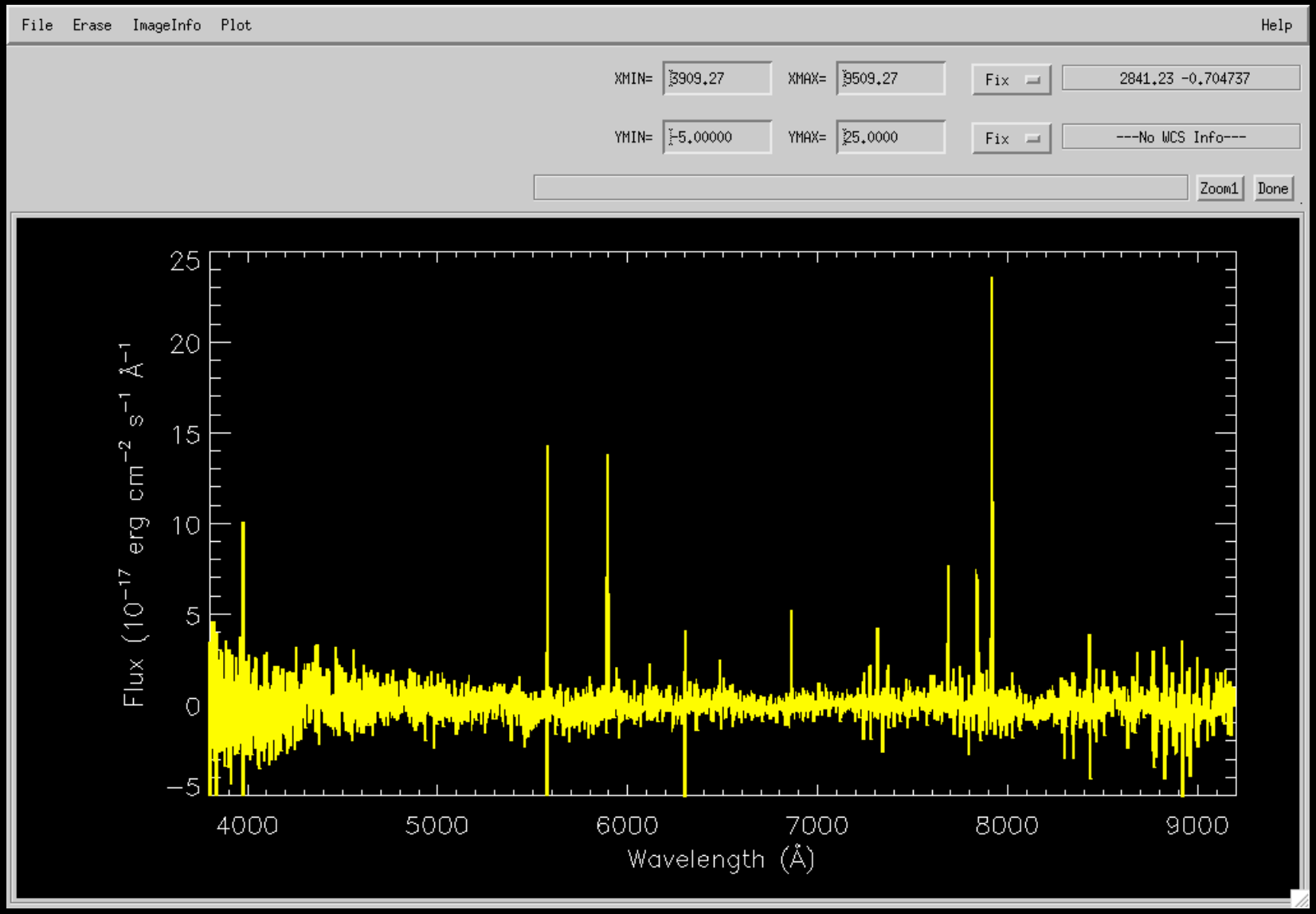


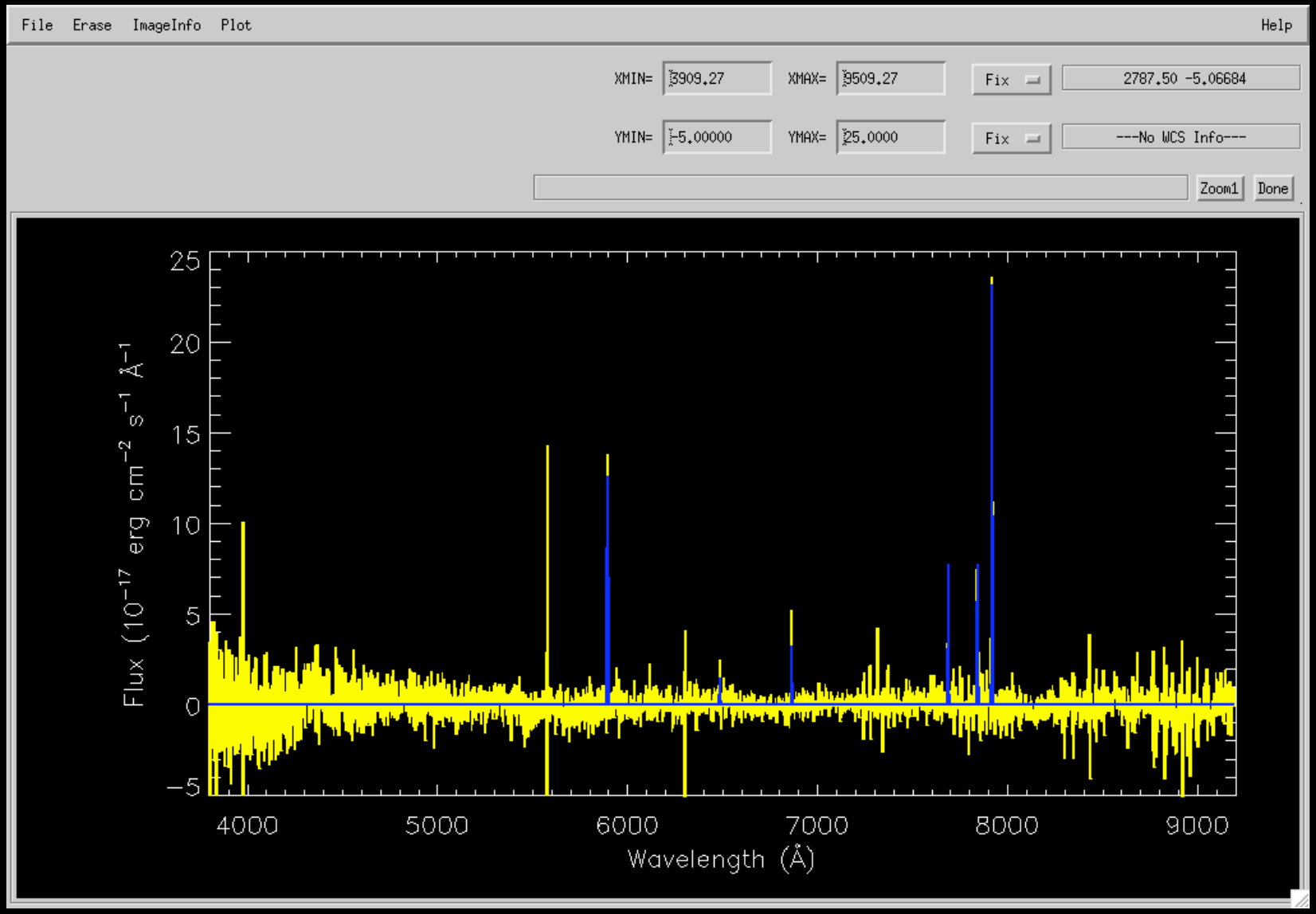

File
Erase
ImageInfo
Plot
Help
XMIN= 3909.27
XMAX= 9509.27
Fix
2794.22 -4.36327
YMIN= -5.00000
YMAX= 25.0000
Fix
---No WCS Info---
Zoom1
Done
25
20
15
10
5
0
−5
Flux (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
4000
5000
6000
7000
8000
9000
Wavelength (Å)


File
Erase
ImageInfo
Plot
Help
XMIN= 3909.27
XMAX= 9509.27
Fix
2794.22 -2.53401
YMIN= -5.00000
YMAX= 25.0000
Fix
---No WCS Info---
Zoom1
Done
25
20
15
10
5
0
−5
Flux (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
4000
5000
6000
7000
8000
9000
Wavelength (Å)


File
Erase
ImageInfo
Plot
Help
XMIN= 3909.27
XMAX= 9509.27
Fix
3318.10 11.9594
YMIN= -5.00000
YMAX= 25.0000
Fix
---No WCS Info---
Zoom1
Done
25
20
15
10
5
0
−5
Flux (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
4000
5000
6000
7000
8000
9000
Wavelength (Å)


File
Erase
ImageInfo
Plot
Help
XMIN=
3909.27
XMAX=
9509.27
Fix
2814.37 17.5176
YMIN=
-5.00000
YMAX=
25.0000
Fix
---No WCS Info---
Zoom1
Done
25
20
15
10
5
0
−5
Flux (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
4000
5000
6000
7000
8000
9000
Wavelength (Å)

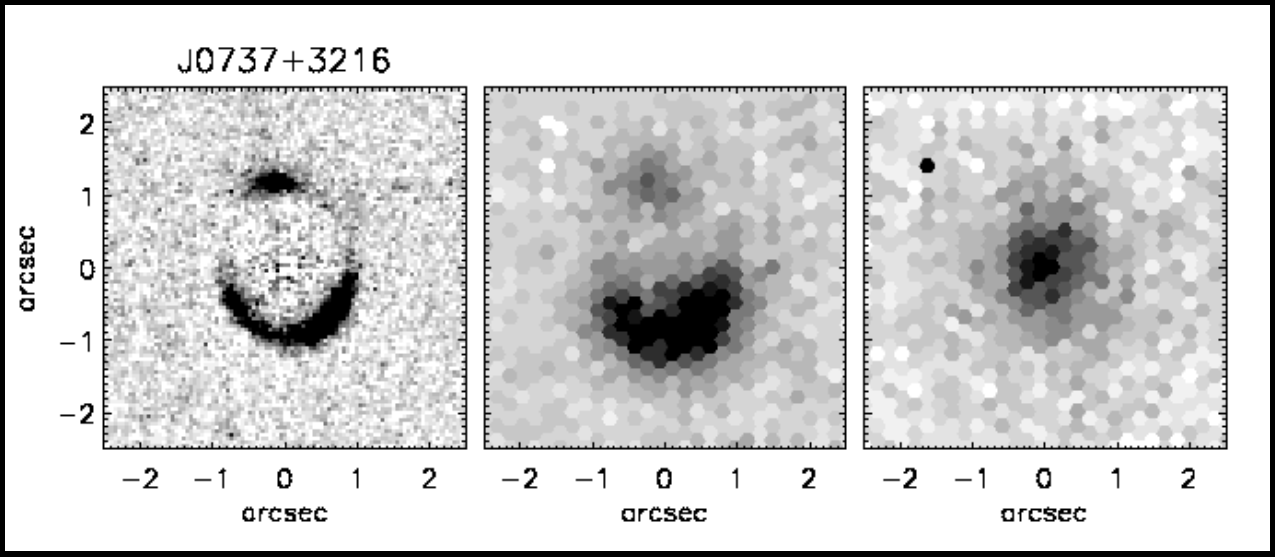

File
Erase
ImageInfo
Plot
Help
XMIN= 3909.27
XMAX= 9509.27
Fix
2841.23 -0.704737
YMIN= -5.00000
YMAX= 25.0000
Fix
---No WCS Info---
Zoom1
Done
Flux (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
25
20
15
10
5
0
−5
4000
5000
6000
7000
8000
9000
Wavelength (Å)


File
Erase
ImageInfo
Plot
Help
XMIN= 3909.27
XMAX= 9509.27
Fix
2787.50 -5.06684
YMIN= -5.00000
YMAX= 25.0000
Fix
---No WCS Info---
Zoom1
Done
25
20
15
10
5
0
−5
Flux (10^{-17} erg cm^{-2} s^{-1} Å^{-1})
4000
5000
6000
7000
8000
9000
Wavelength (Å)

HST-ACS WFC Imaging

Still skeptical?

Resort to spatially-resolved emission-line spectroscopy with ground-based IFUs.



A History of Spectroscopic Lens Discovery

Huchra et al. 1985 (Q2237+0305)

Warren et al. 1996, 1998, 1999 (0047-2808)

Willis 2000, Hewett et al. 2000

Mortlock et al. 2001

Johnston et al. 2003 (SDSS J0903+5028)

SDSS: Bolton et al. 2004

SLACS: Bolton et al. 2005,2006; Treu et al. 2006; Koopmans et al. 2006

OLS: Willis et al. 2005, 2006

Bolton's Selection Recipie

Select SDSS LRGs and MAIN galaxies w/o strong emission
- ~200,000 spectra in parent sample

Subtract D. J. Schlegel's best-fit PCA galaxy templates

Require at least 3 significant higher-z emission lines
- Model noise empirically
- Automated search for higher-z emission lines
- Human vetting of candidate spectra
- ~200 "good" lens candidates

Of note:
- Effectively limits z_lens <~0.4, z_source <~0.8
- Working in the F_source << F_lens limit
- Can also relax 3-line requirement

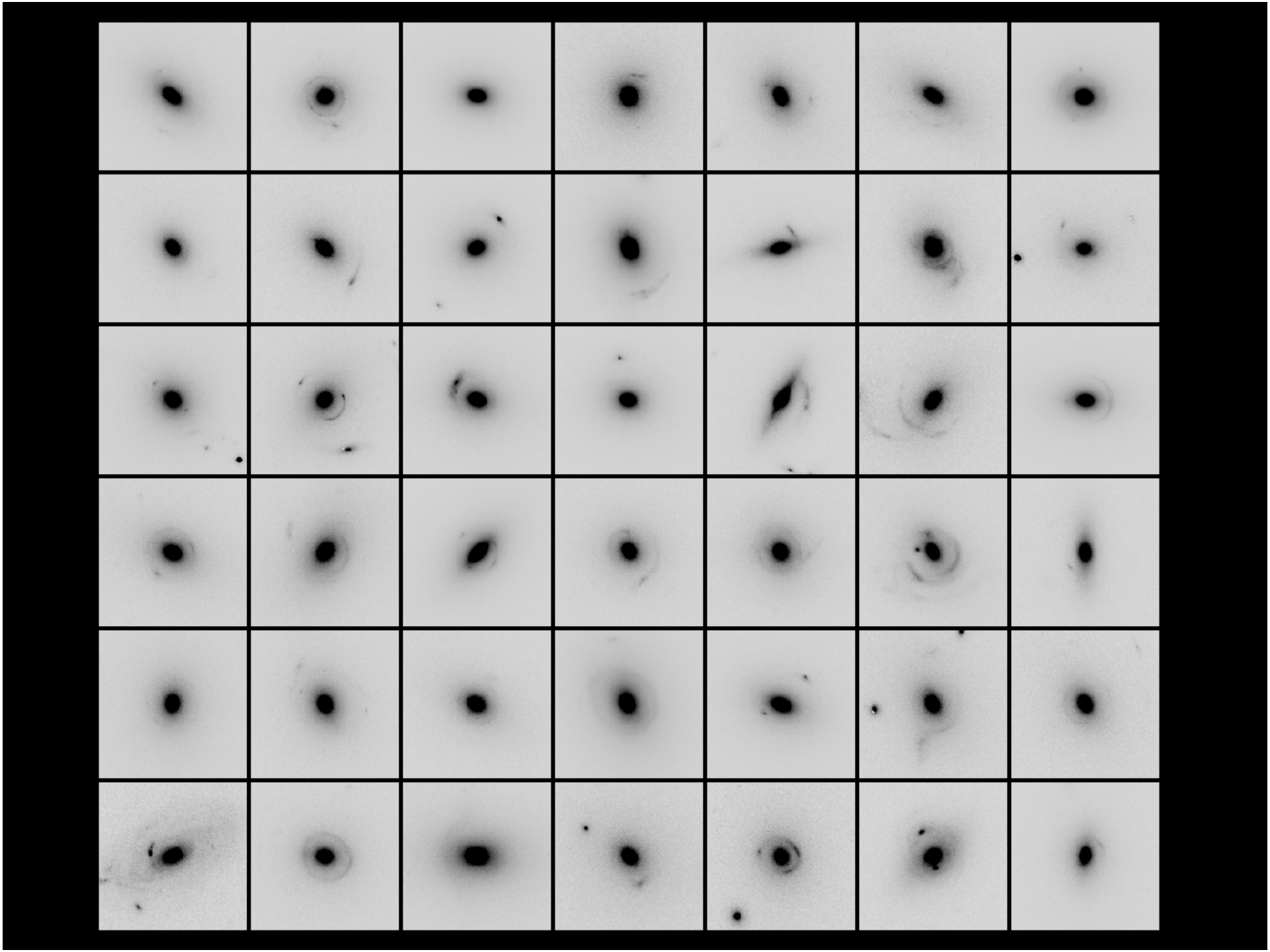
The SLACS Survey (SLACS = Sloan Lens ACS)

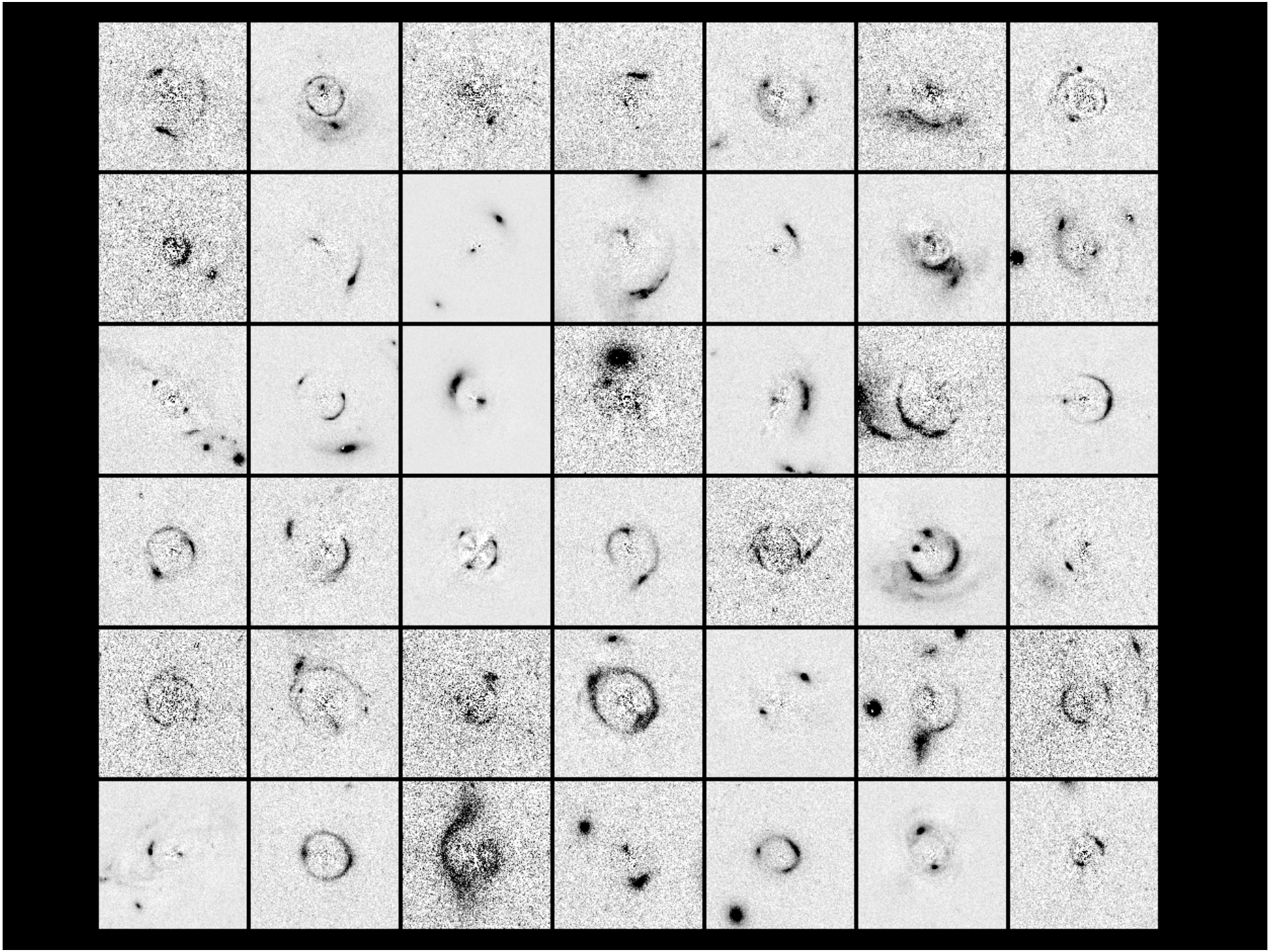
(Bolton+Burles) + (Koopmans+Treu) + Moustakas
+ Gavazzi, Czoske, Barnabe', Vegetti

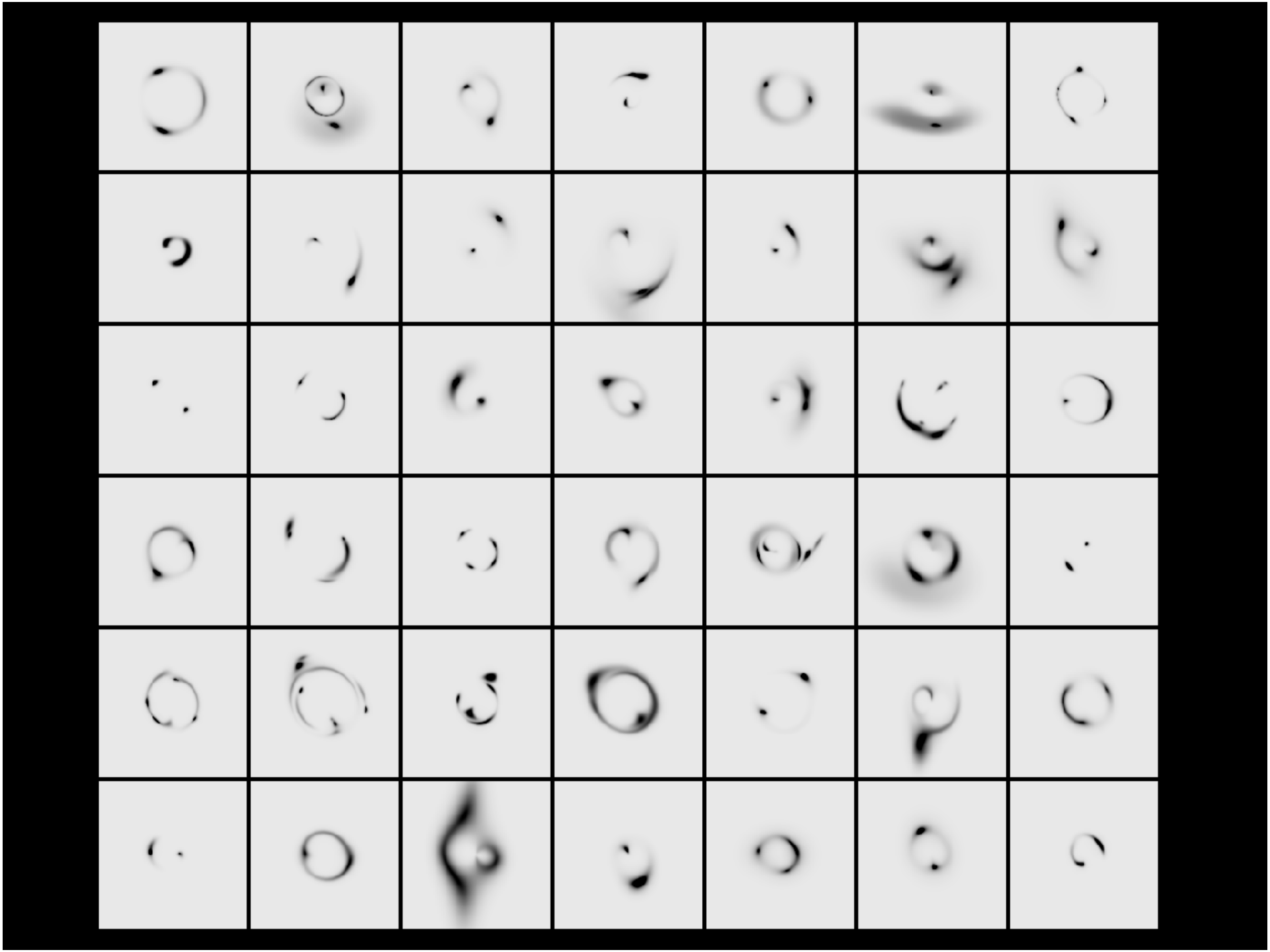
HST-ACS WFC: Imaging for discovery of new lenses:
Cycle 13: 49 Snapshot targets, 2x7min (39 observed)
Cycle 14: 118 Snapshot targets, 1x7min (53 observed)
Cycle 15: 50 GO targets, 1 orbit each (11 obs. so far…)

HST-ACS WFC: Deep follow-up imaging
Cycle 14: 15 GO targets (3 orbits each)
Cycle 15: 20 GO targets (3 orbits each)

50+ new strong lenses so far!



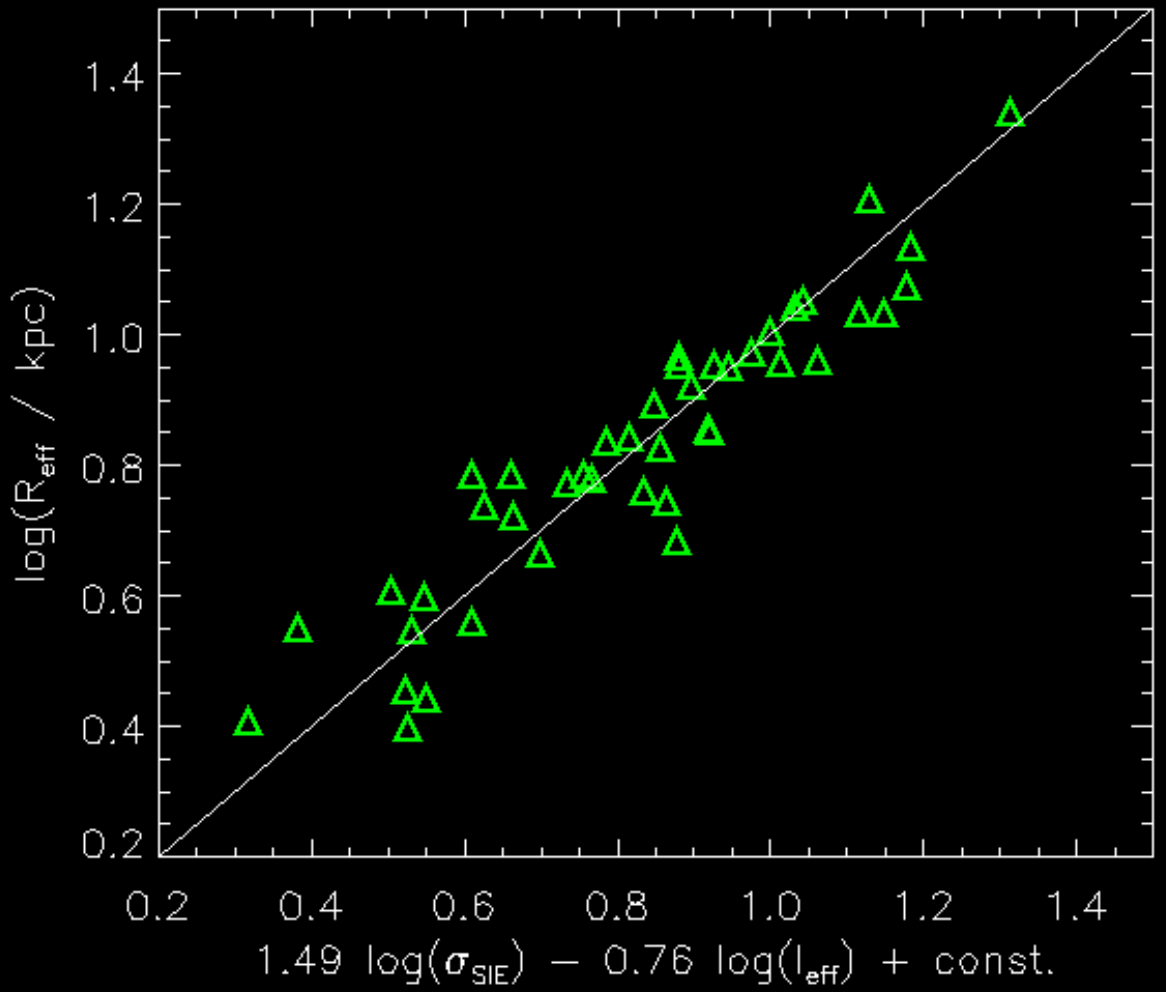




SLACS Sample Characteristics:

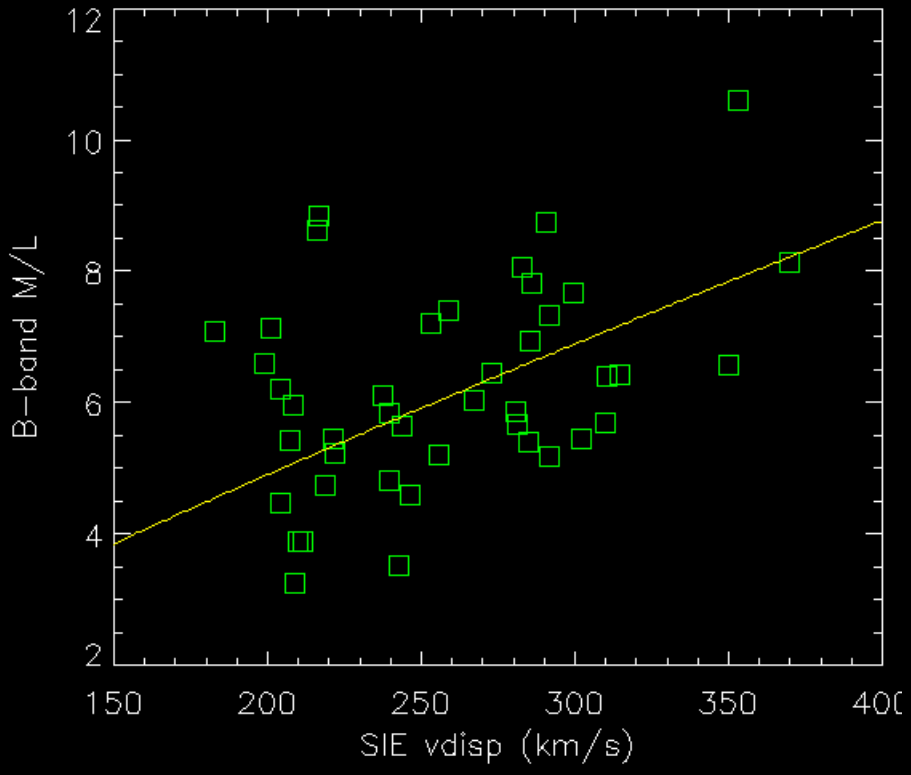
z_lens	=	0.16 +/- 0.08
z_source	=	0.52 +/- 0.17
sigma_v	=	253 +/- 46 km/s
R_eff	=	2”.2 +/- 0”.8
	=	6.2 +/- 3.0 kpc
R_Ein	=	1”.1 +/- 0”.3
	=	0.55 +/- 0.16 R_eff
M_Ein	=	3x10^10 -- 5x10^11 M_Sun
r_AbsMag	=	-20.5 to -24.5

Fundamental Plane of SLACS Lenses



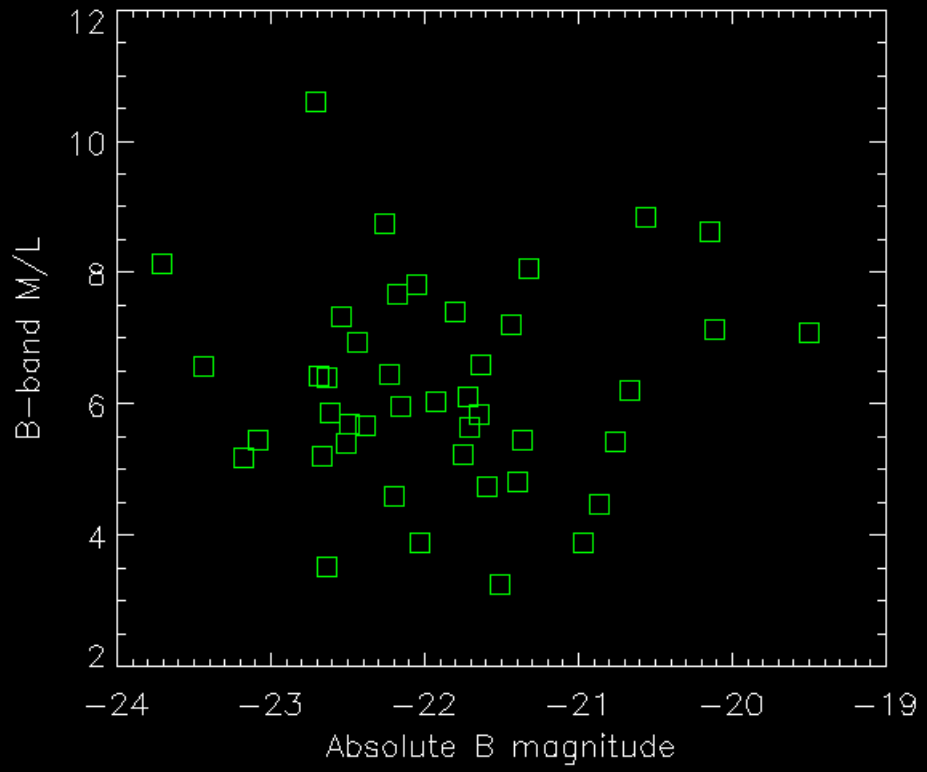
(Coefficients uncertain by 0.18 and 0.06 respectively.)

Other correlations (or lack thereof…)

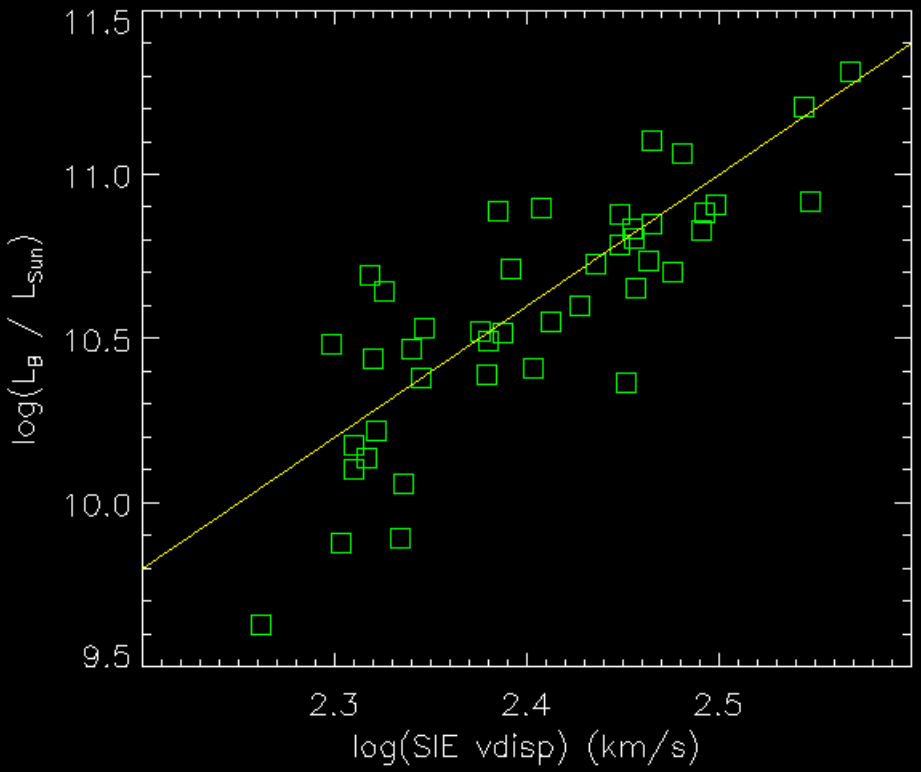


Mass-to-light vs. vdisp
(line is M/L ~ sigma^0.84, from Cappellari et al. 2006)

Mass-to-light vs. luminosity

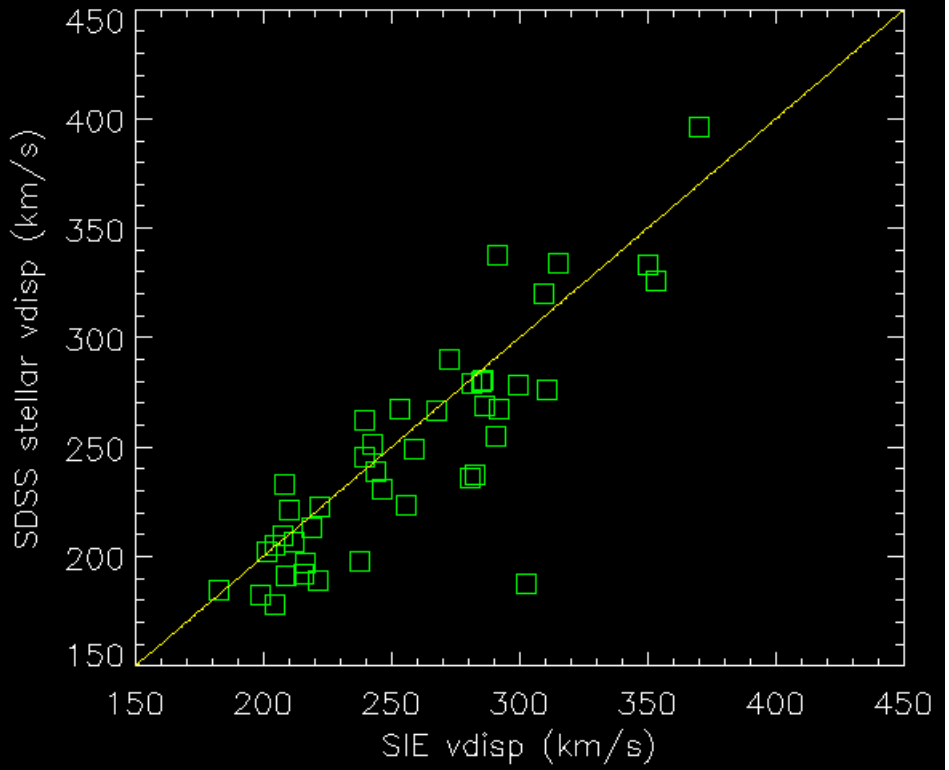


Other correlations (or lack thereof…)

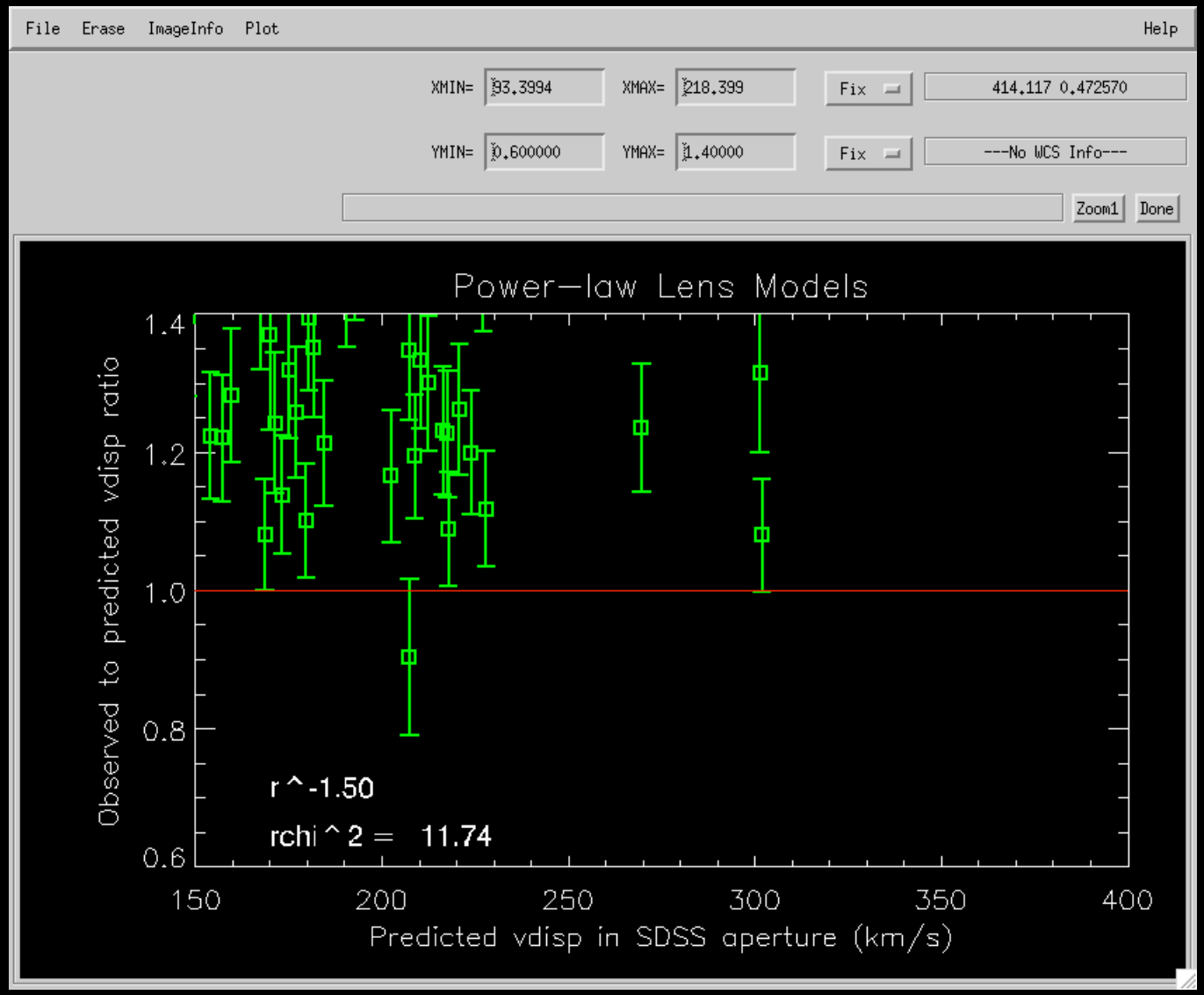


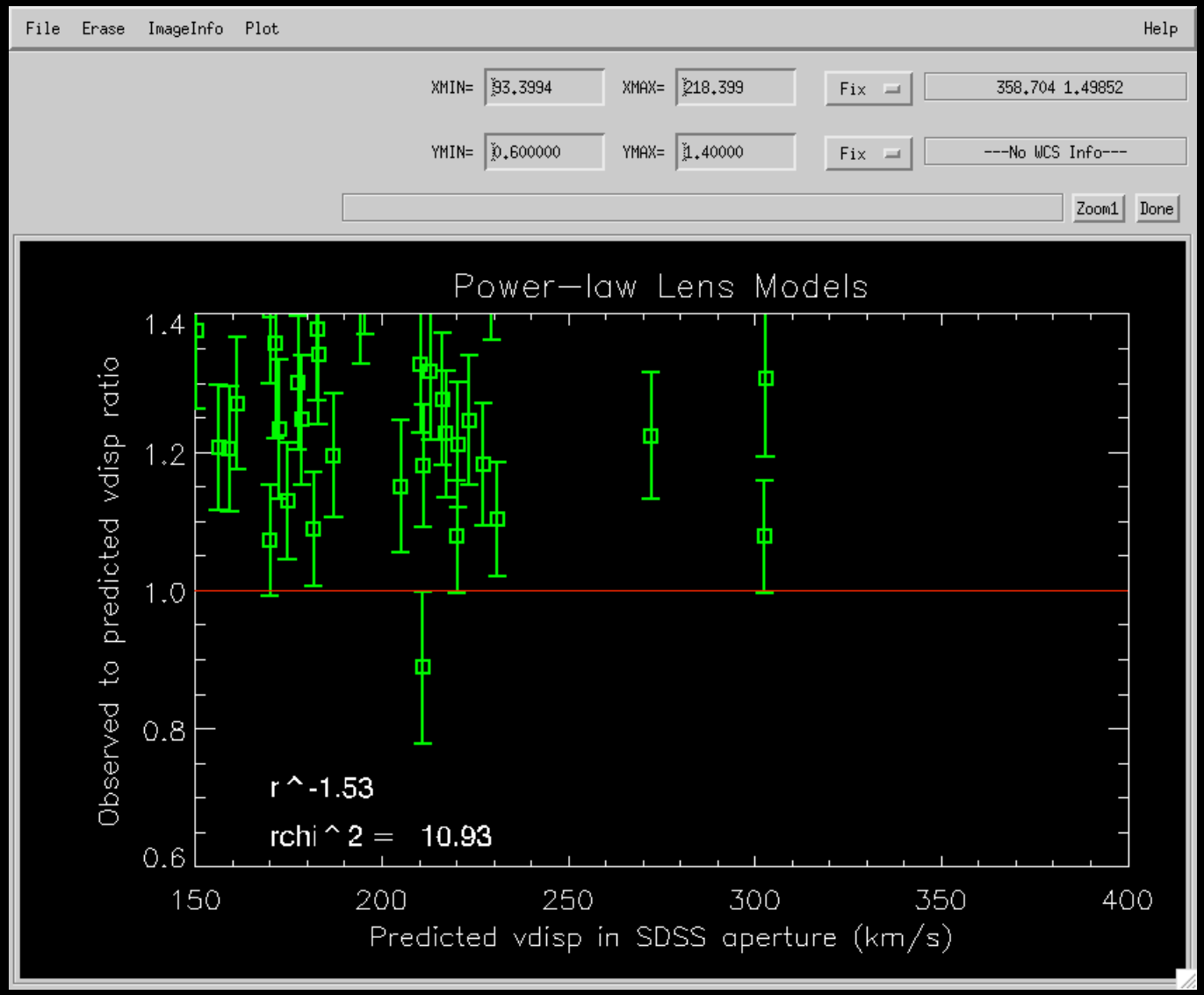
Faber-Jackson
(line is L ~ sigma^4)

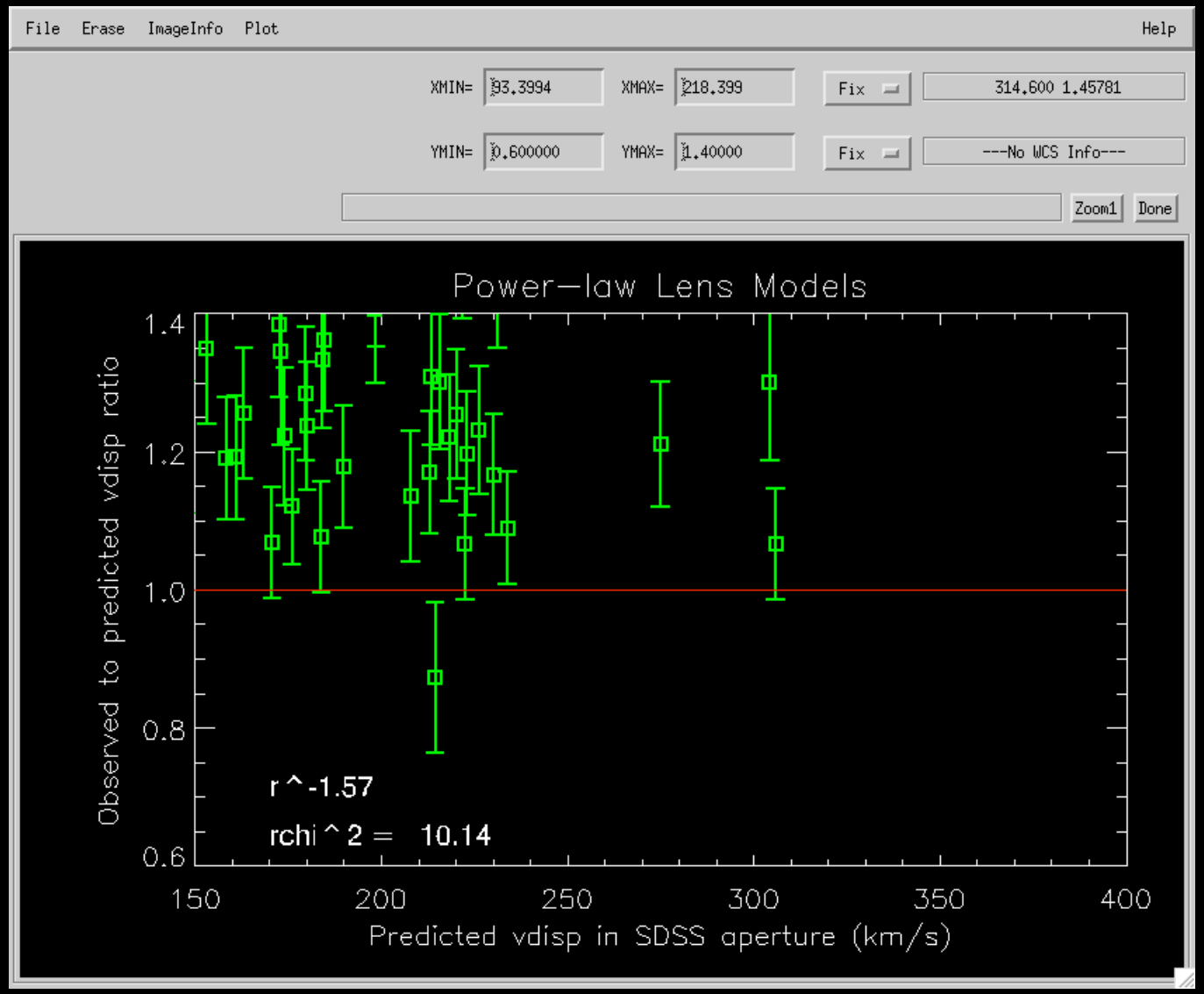
Lensing vs. stellar vdisp
(line is 1:1)

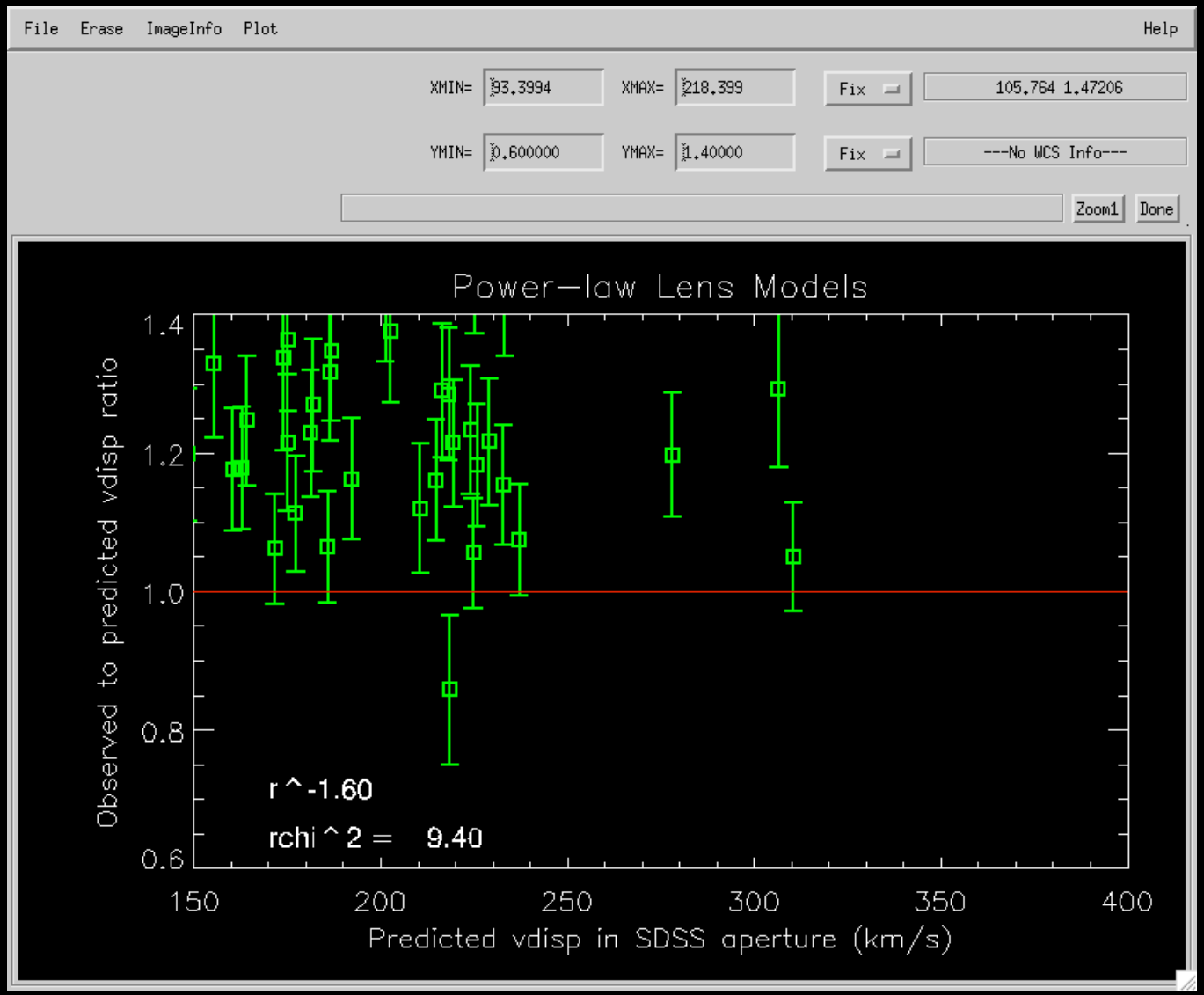


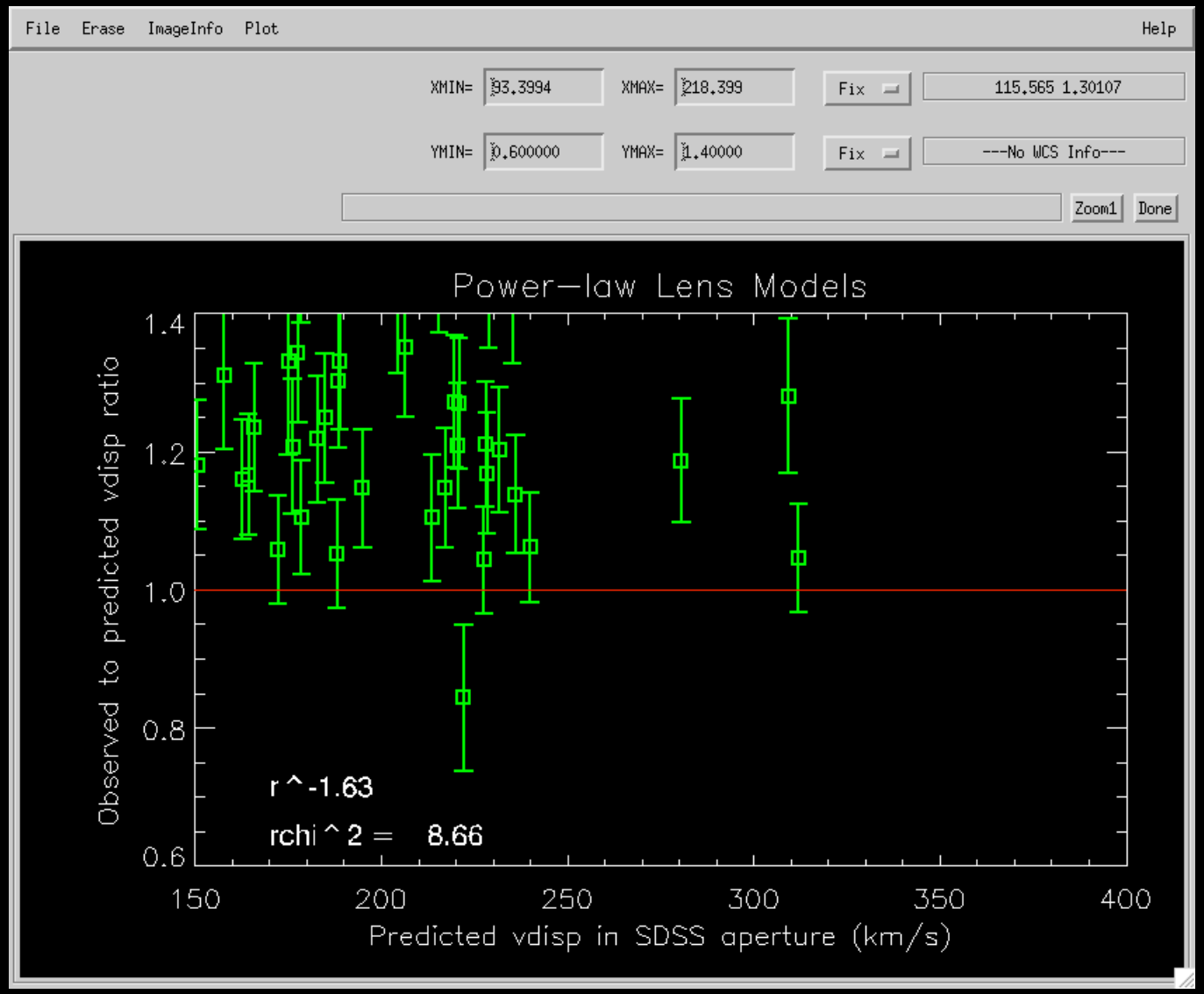
Constraint on mass profile

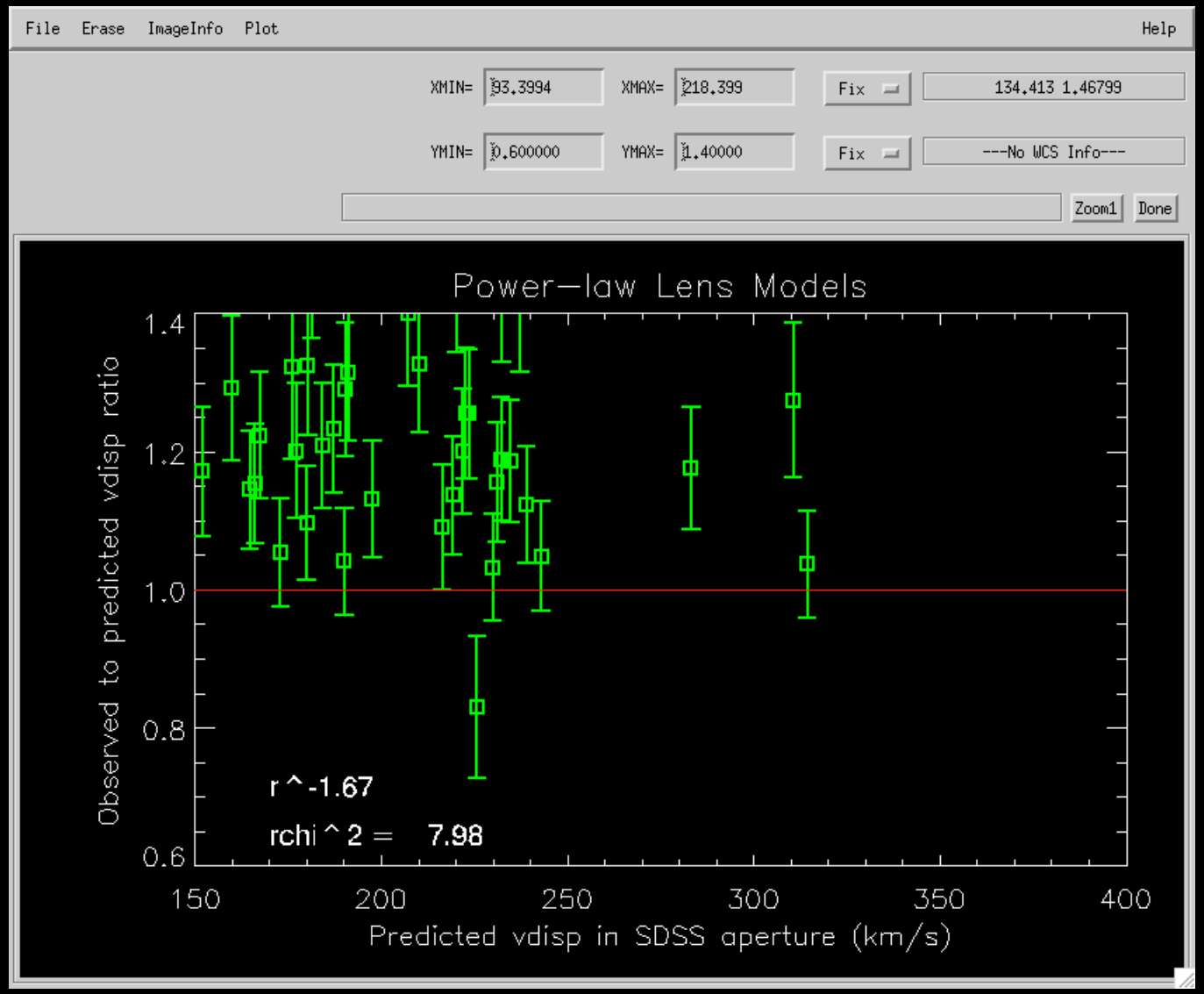


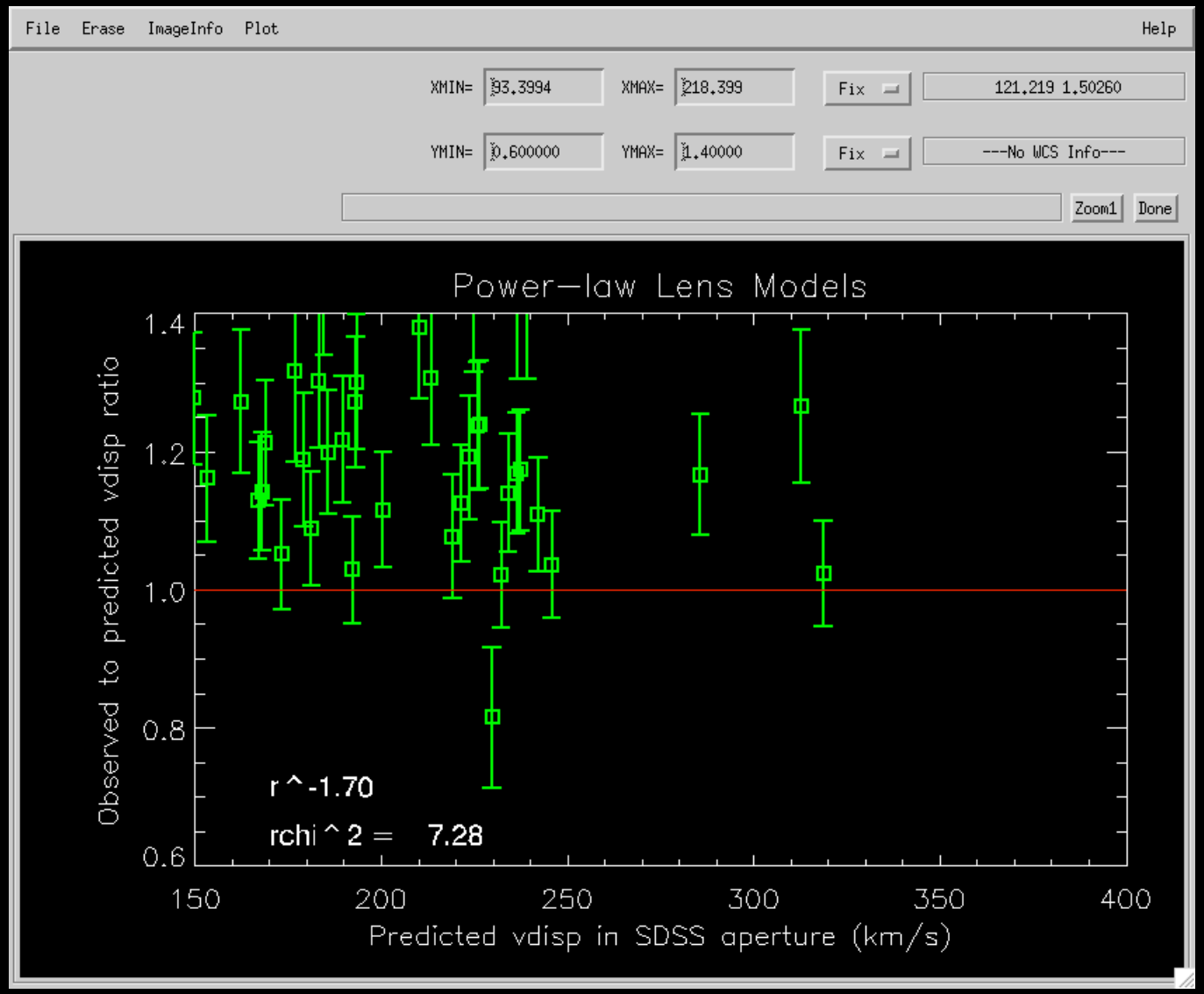

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
358.704 1.49852
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.53
rchi ^ 2 = 10.93
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

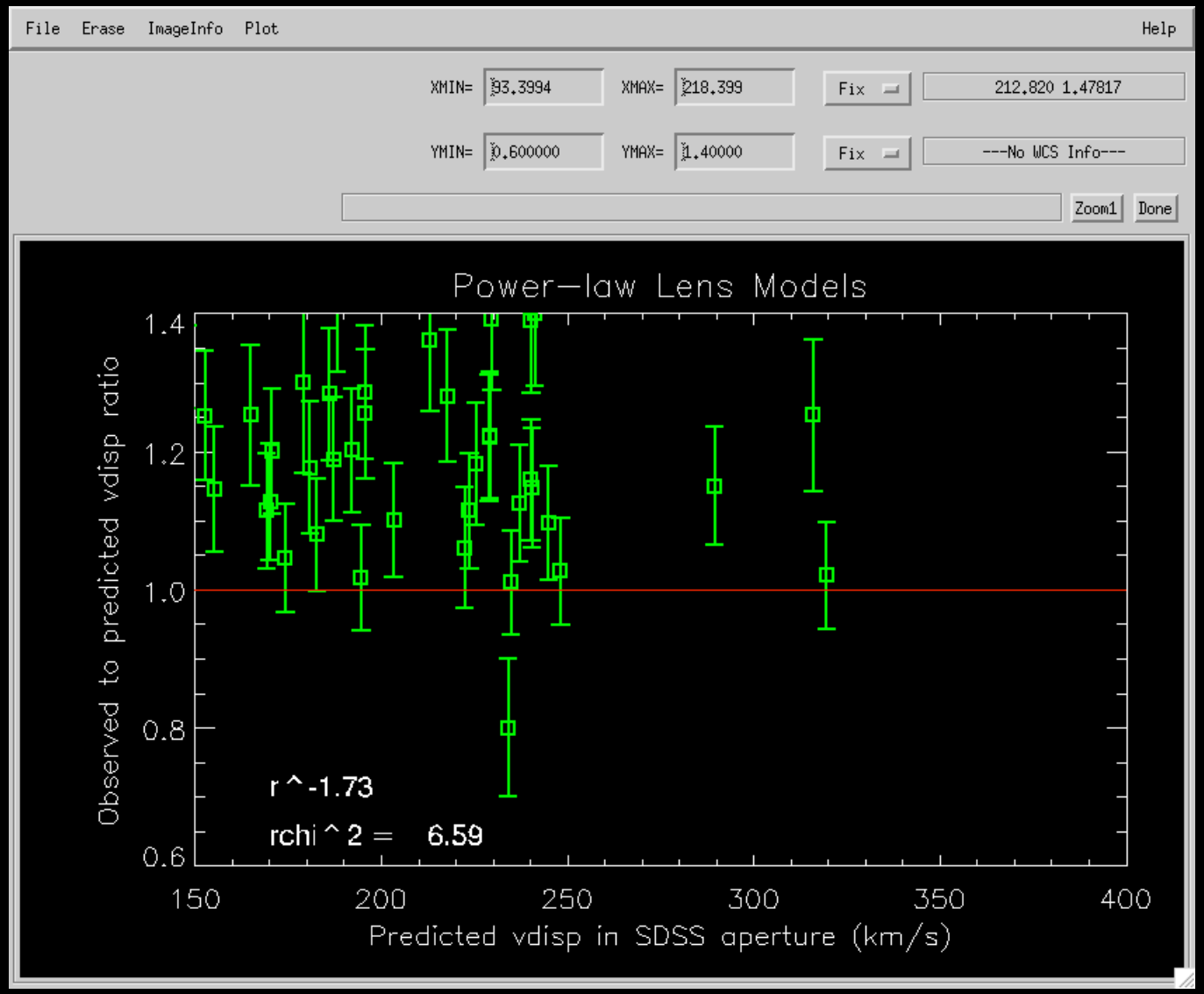

File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
314.600 1.45781
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r^-1.57
rchi^2 = 10.14
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

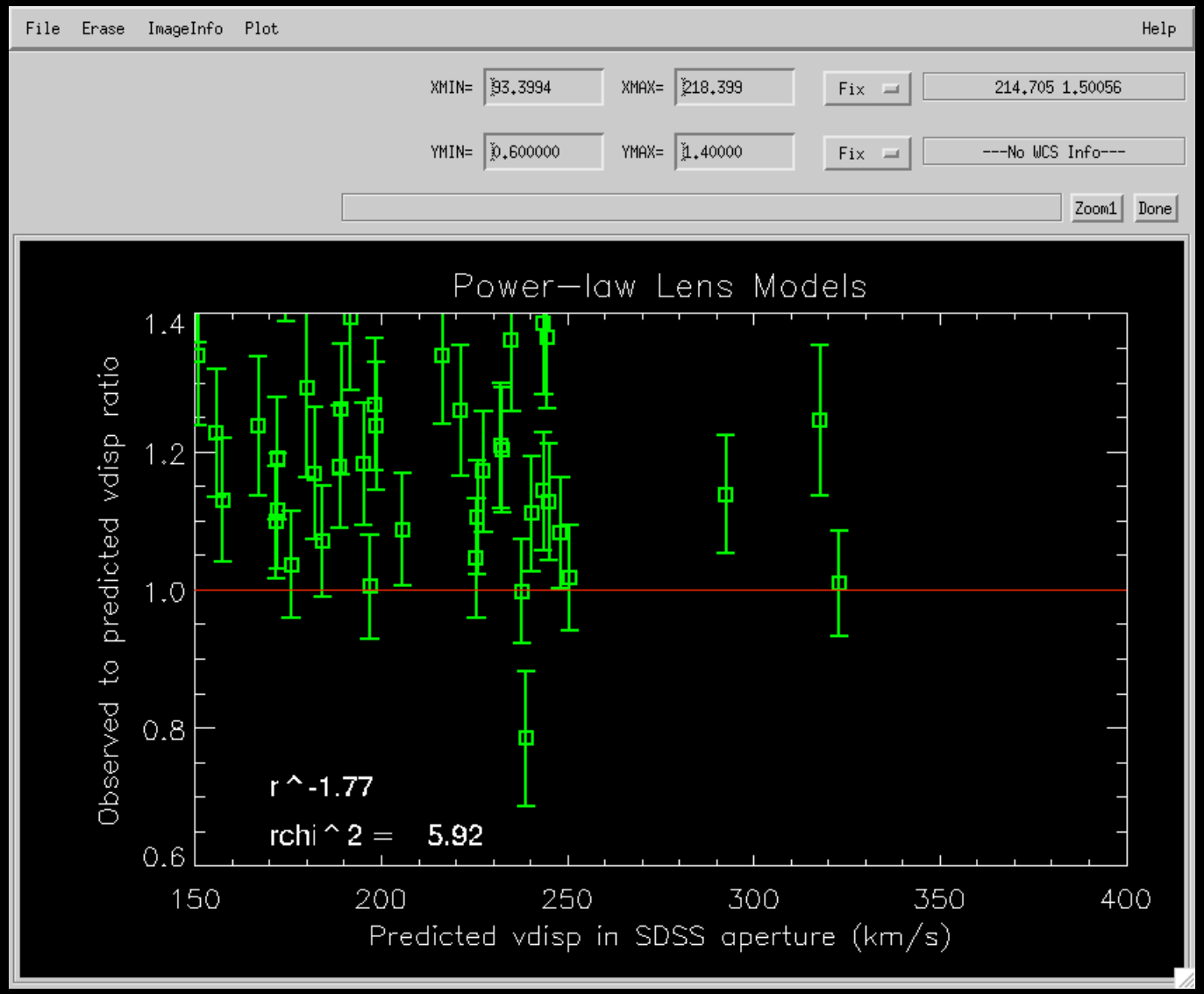

File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
105.764 1.47206
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.60
rchi ^ 2 = 9.40
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

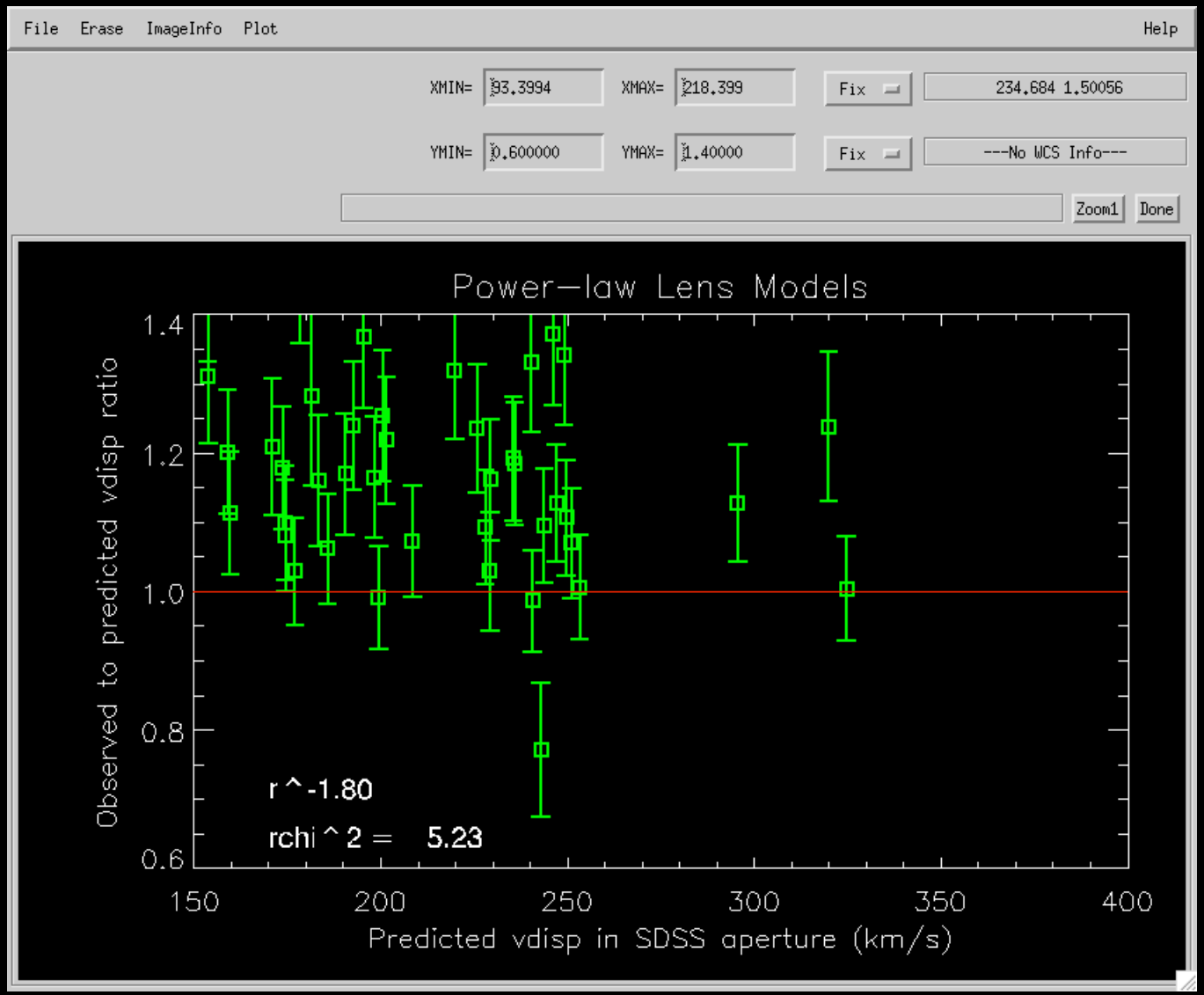

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
115.565 1.30107
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.63
rchi ^ 2 = 8.66
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

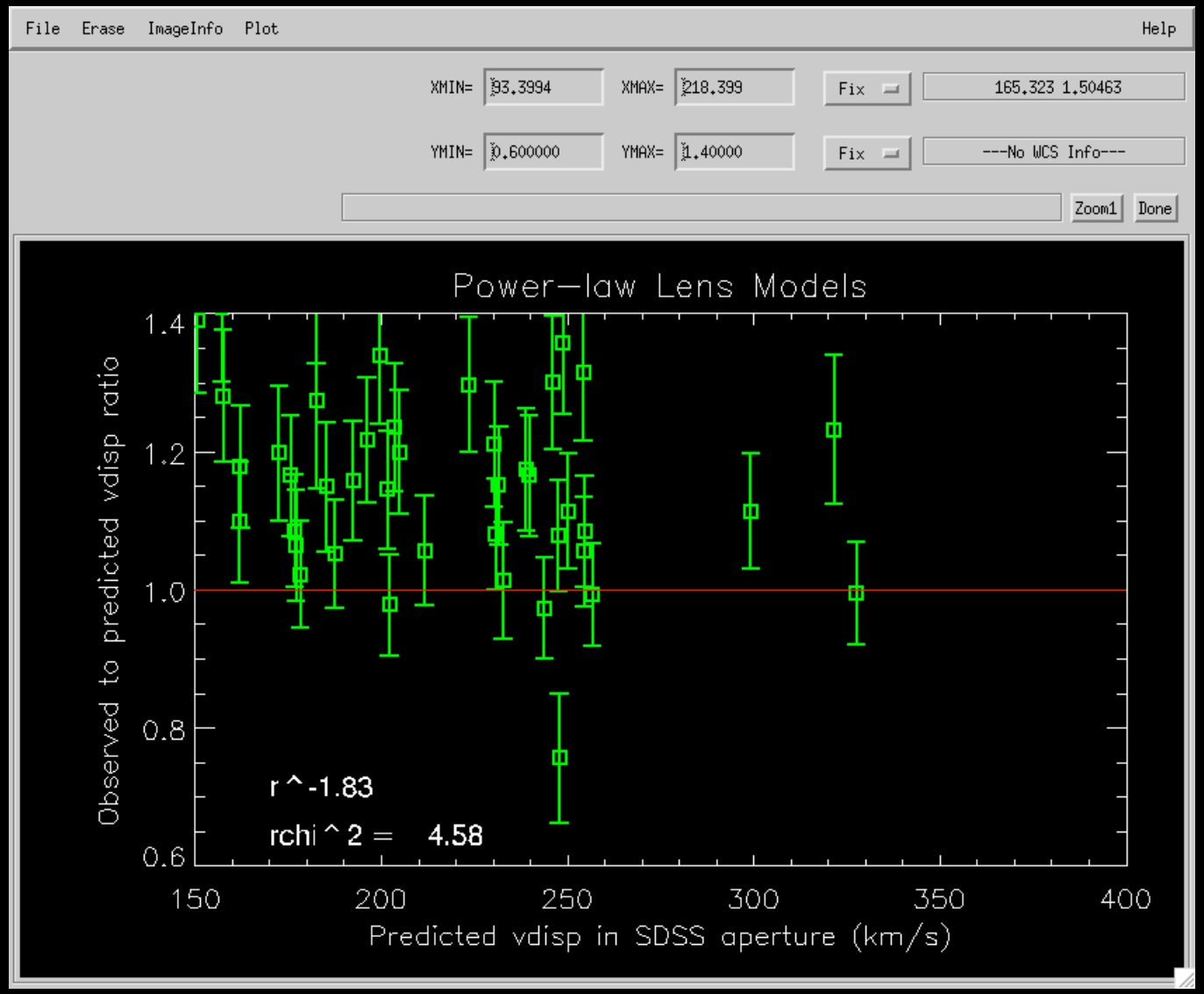

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
134.413 1.46799
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.67
rchi ^ 2 = 7.98
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

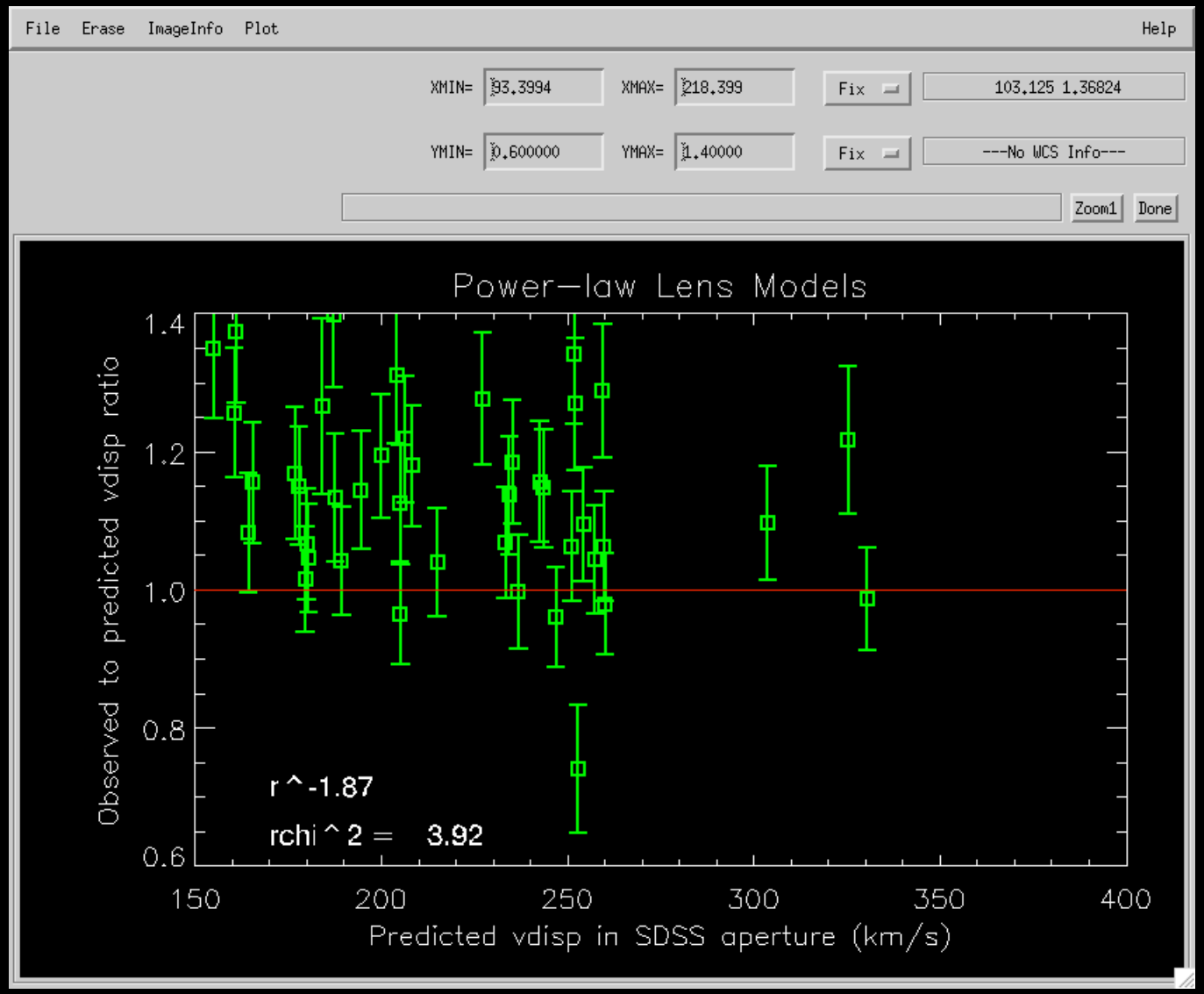

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
121.219 1.50260
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.70
rchi ^ 2 = 7.28
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

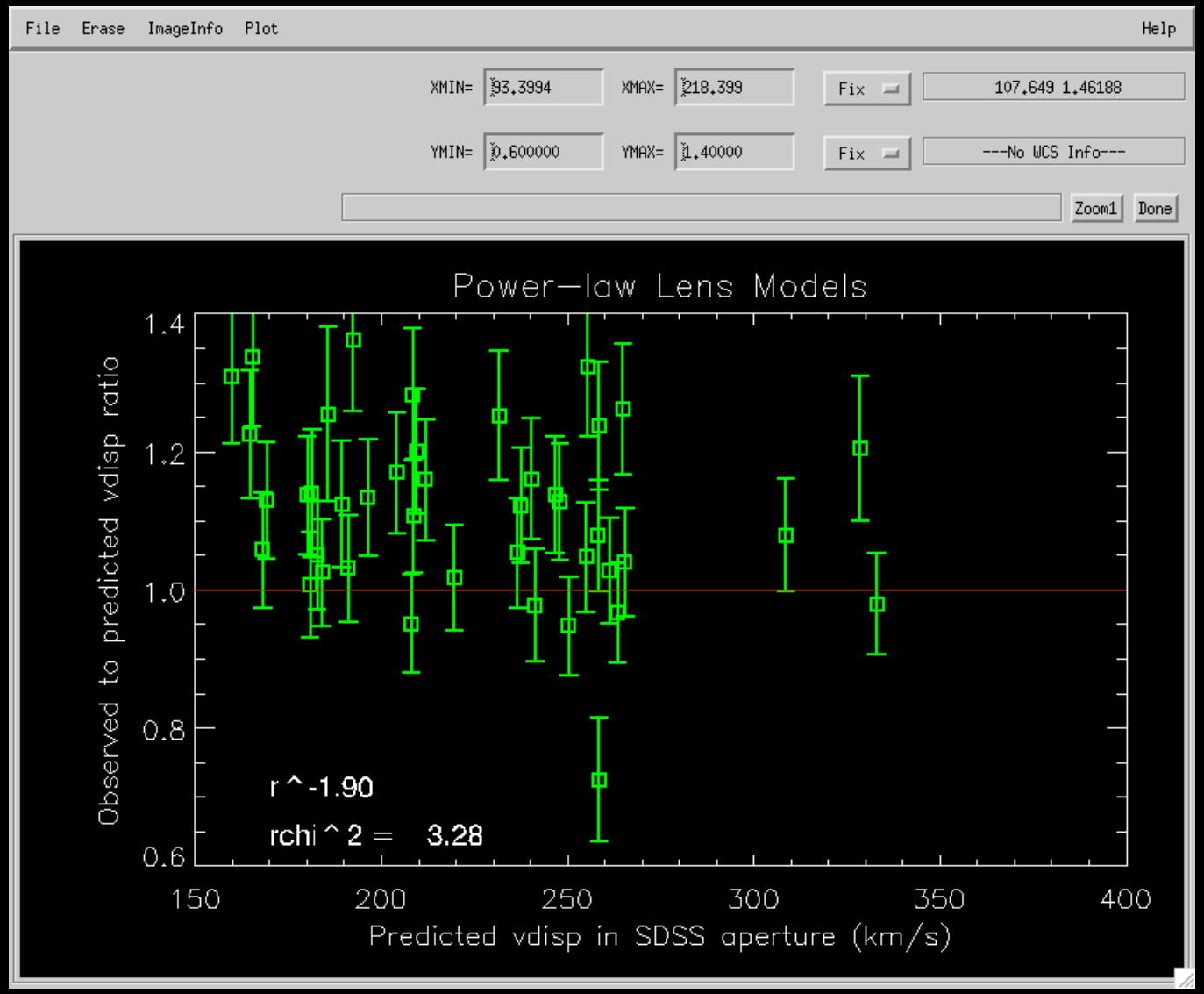

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
212.820 1.47817
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.73
rchi ^ 2 = 6.59
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

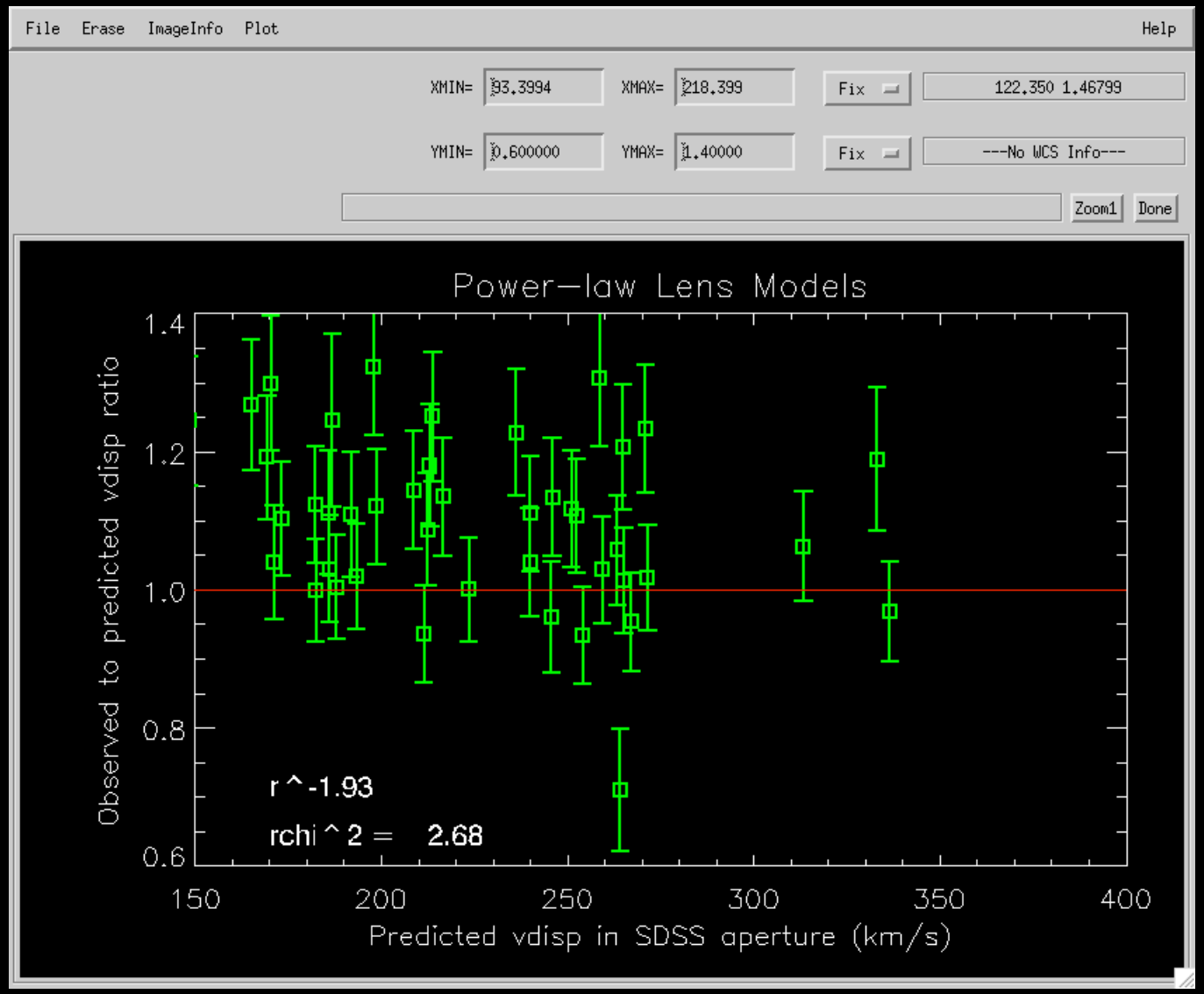

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
214.705 1.50056
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.77
rchi ^ 2 = 5.92
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

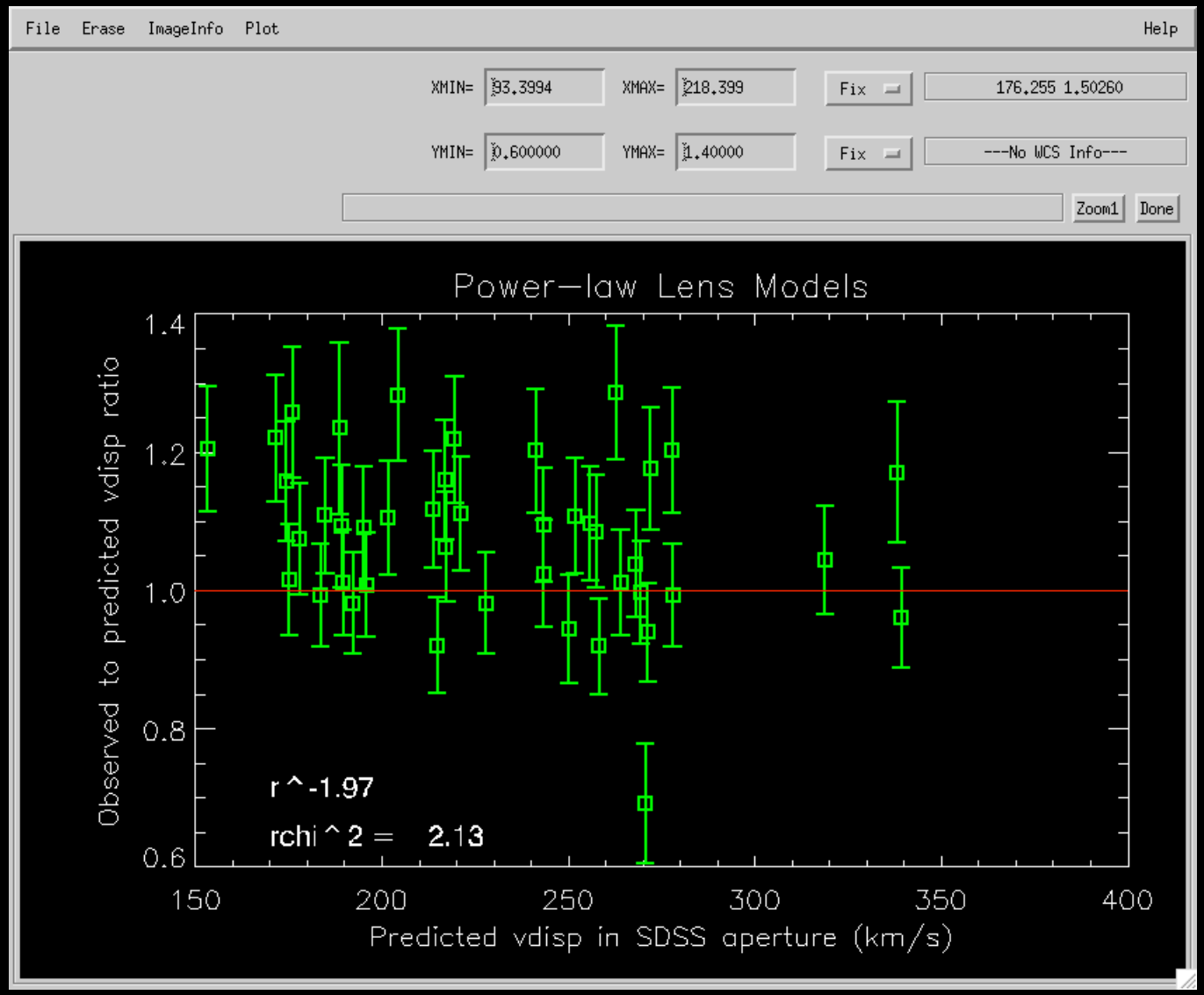

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
234.684 1.50056
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.80
rchi ^ 2 = 5.23
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

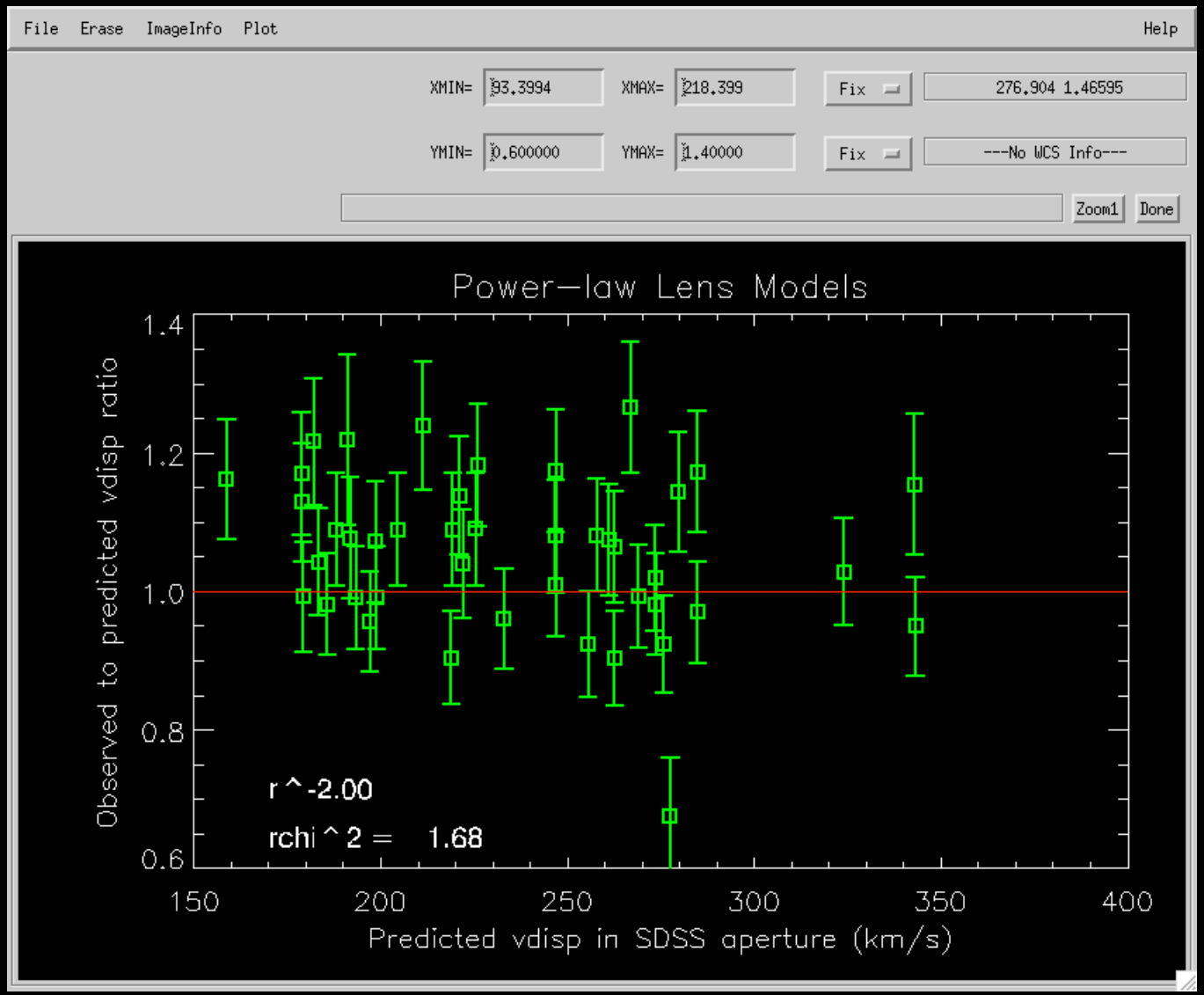

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
165.323 1.50463
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.83
rchi ^ 2 = 4.58
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

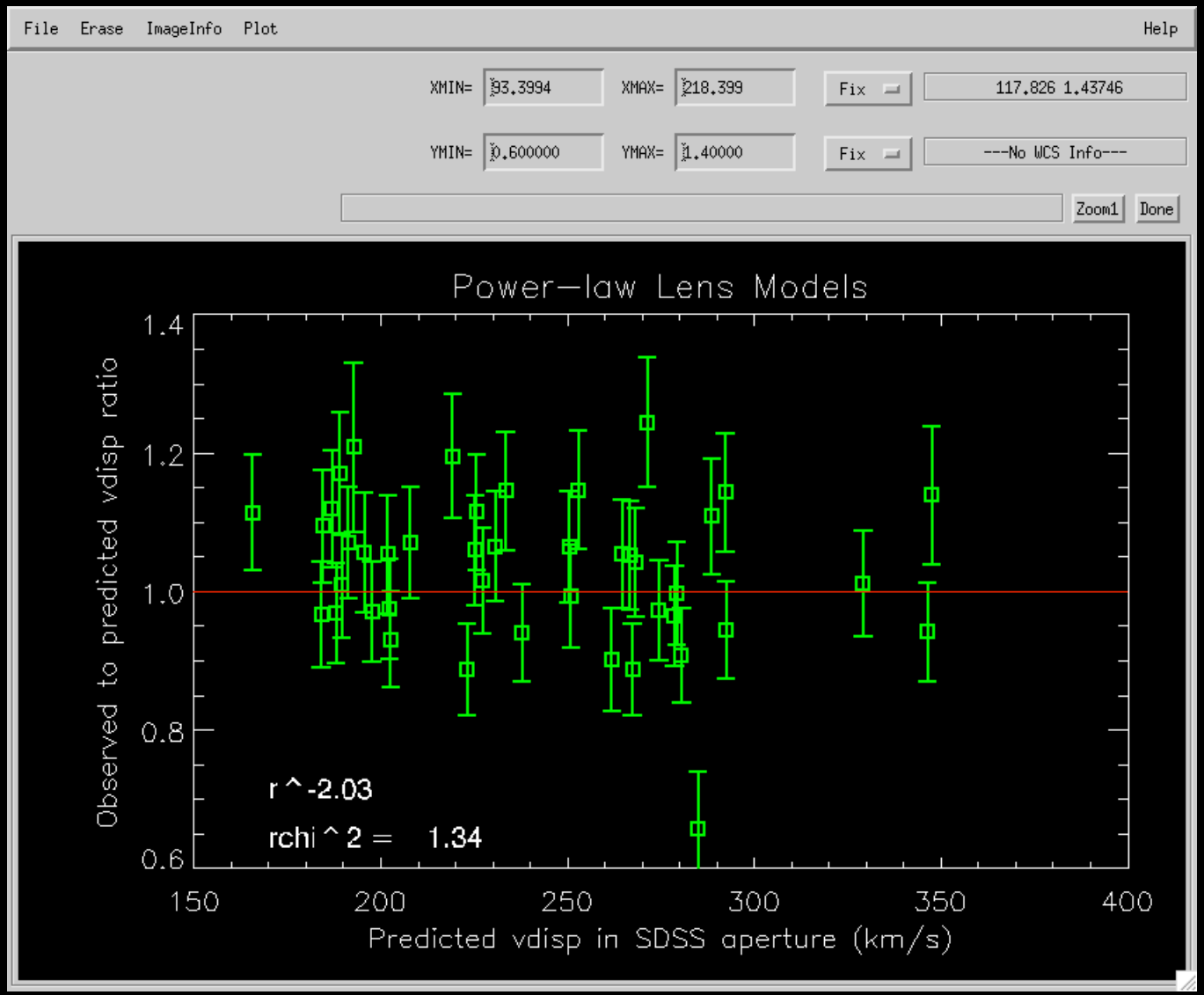

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
103.125 1.36824
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.87
rchi ^ 2 = 3.92
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

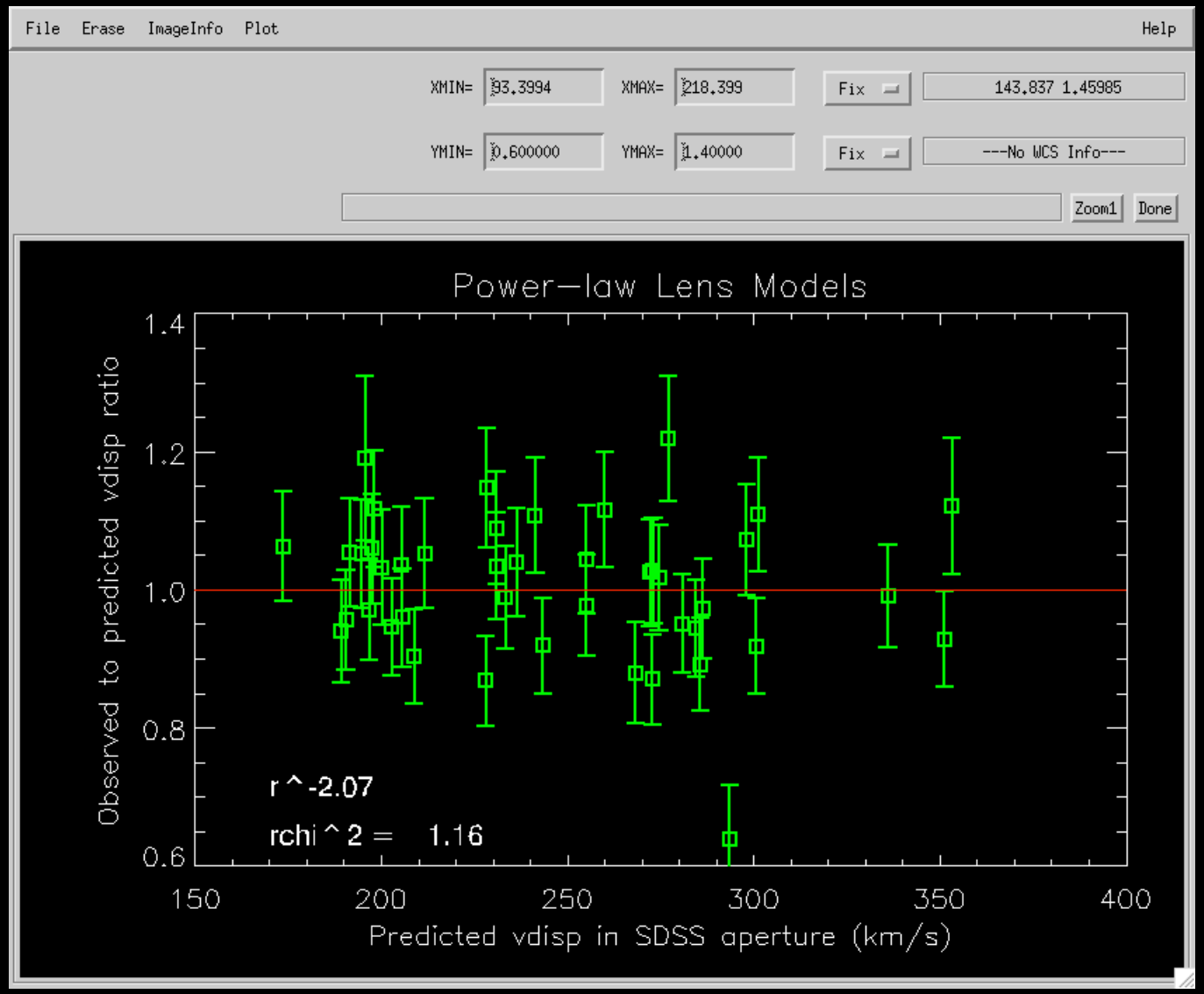

File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
107.649 1.46188
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.90
rchi ^ 2 = 3.28
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

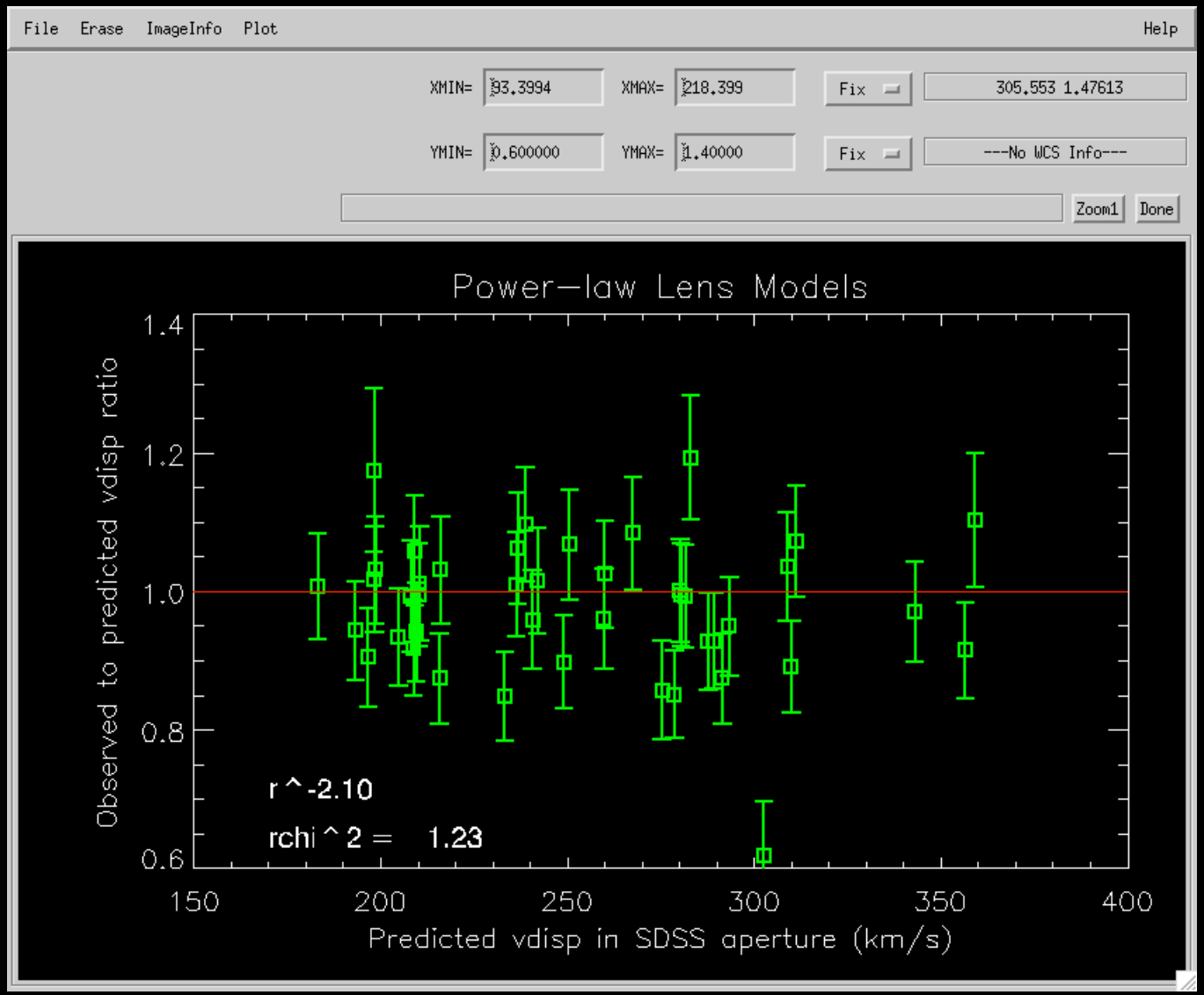

File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
122.350 1.46799
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -1.93
rchi ^ 2 = 2.68
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

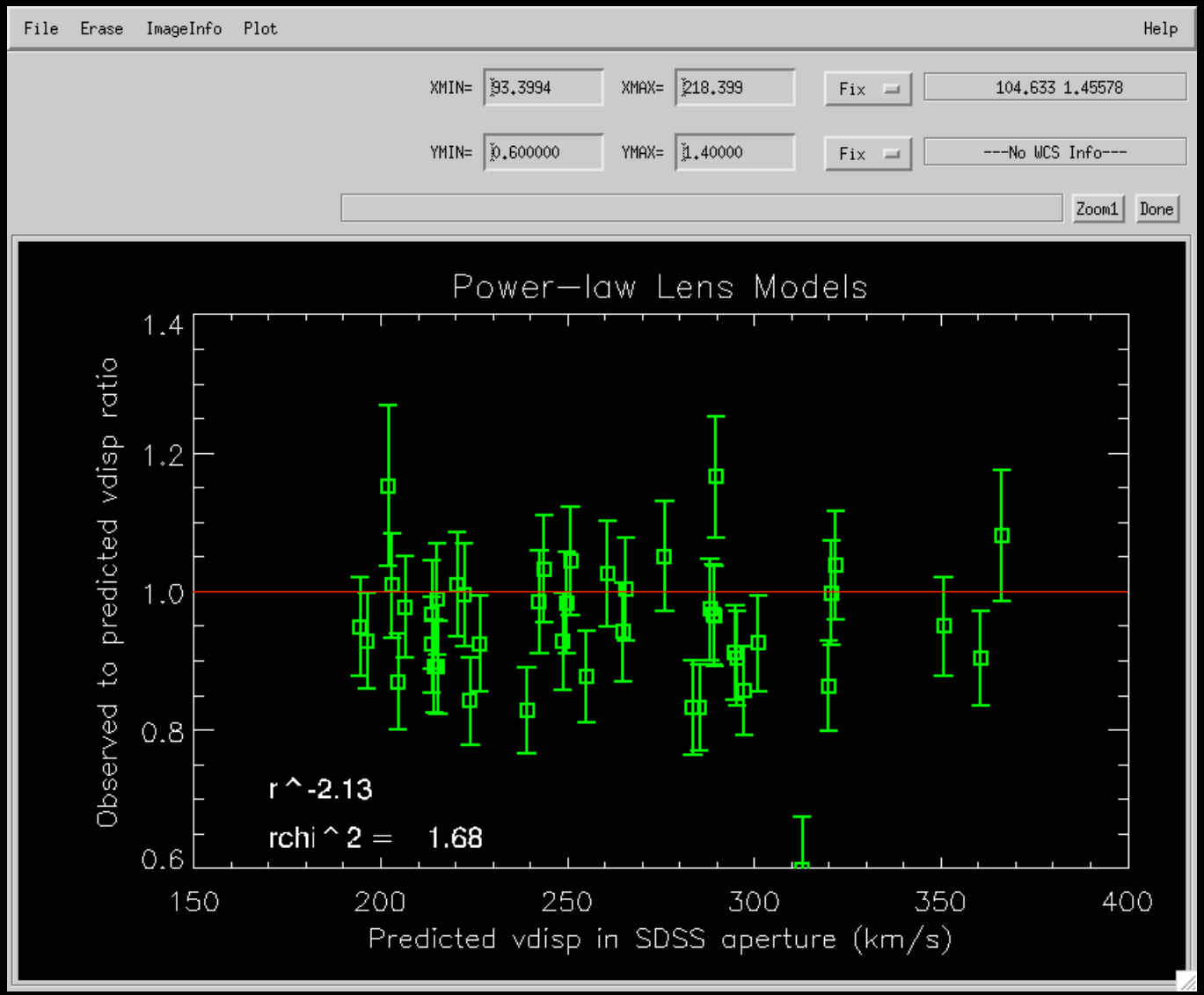

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
176.255 1.50260
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r^-1.97
rchi^2 = 2.13
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

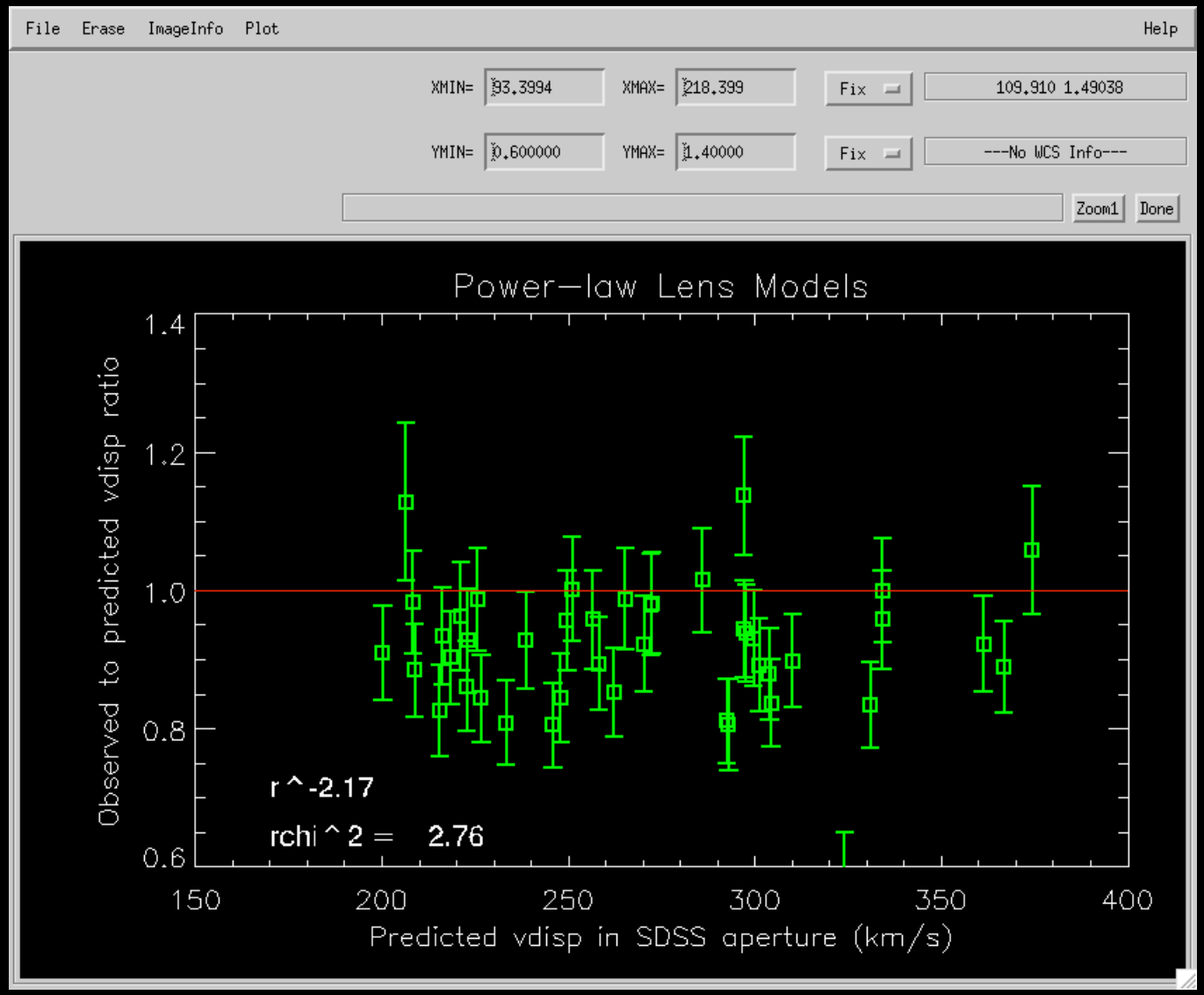

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
276.904 1.46595
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.00
rchi ^ 2 = 1.68
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

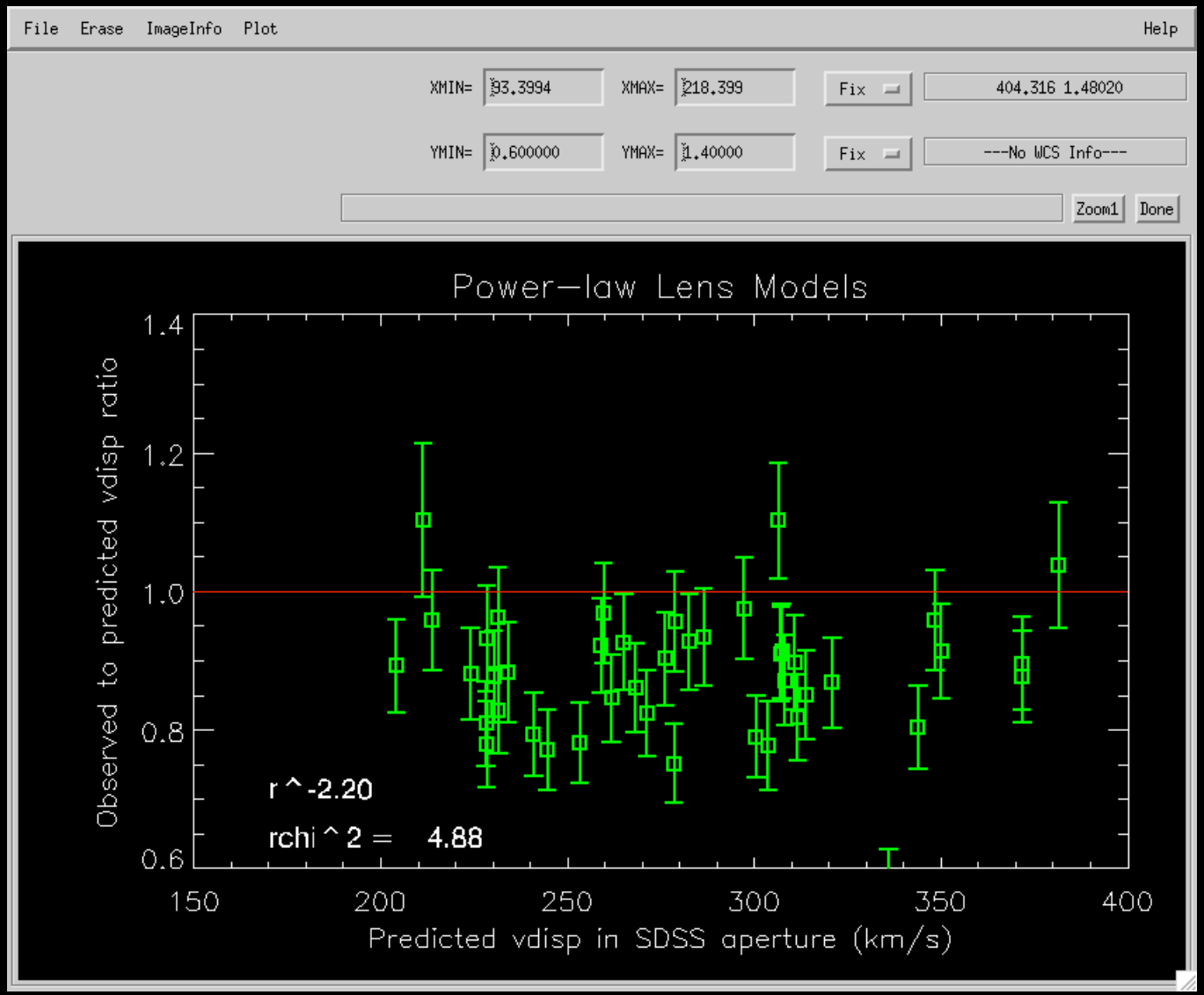

File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
117.826 1.43746
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.03
rchi ^ 2 = 1.34
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

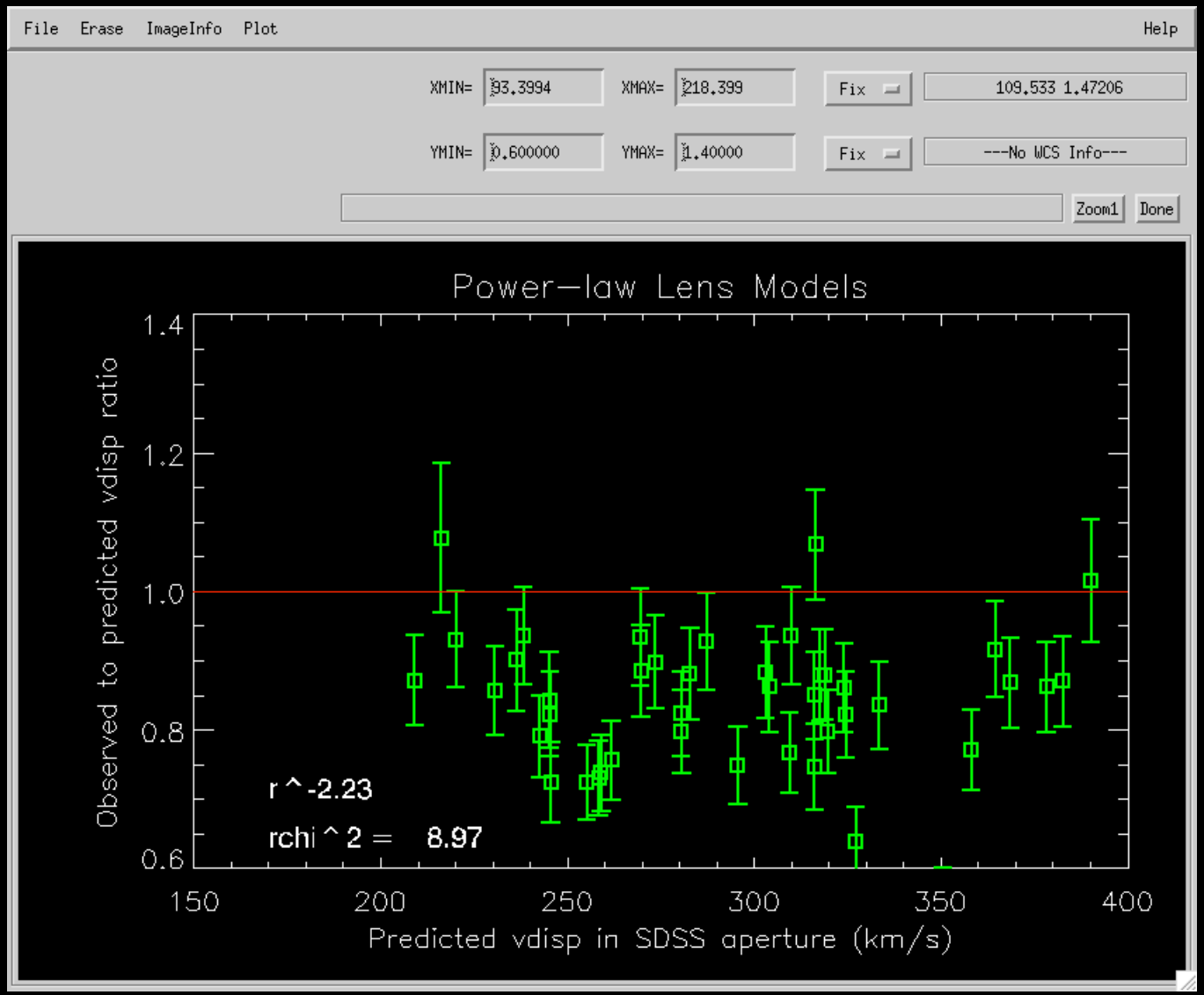

File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
143.837 1.45985
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.07
rchi ^ 2 = 1.16
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

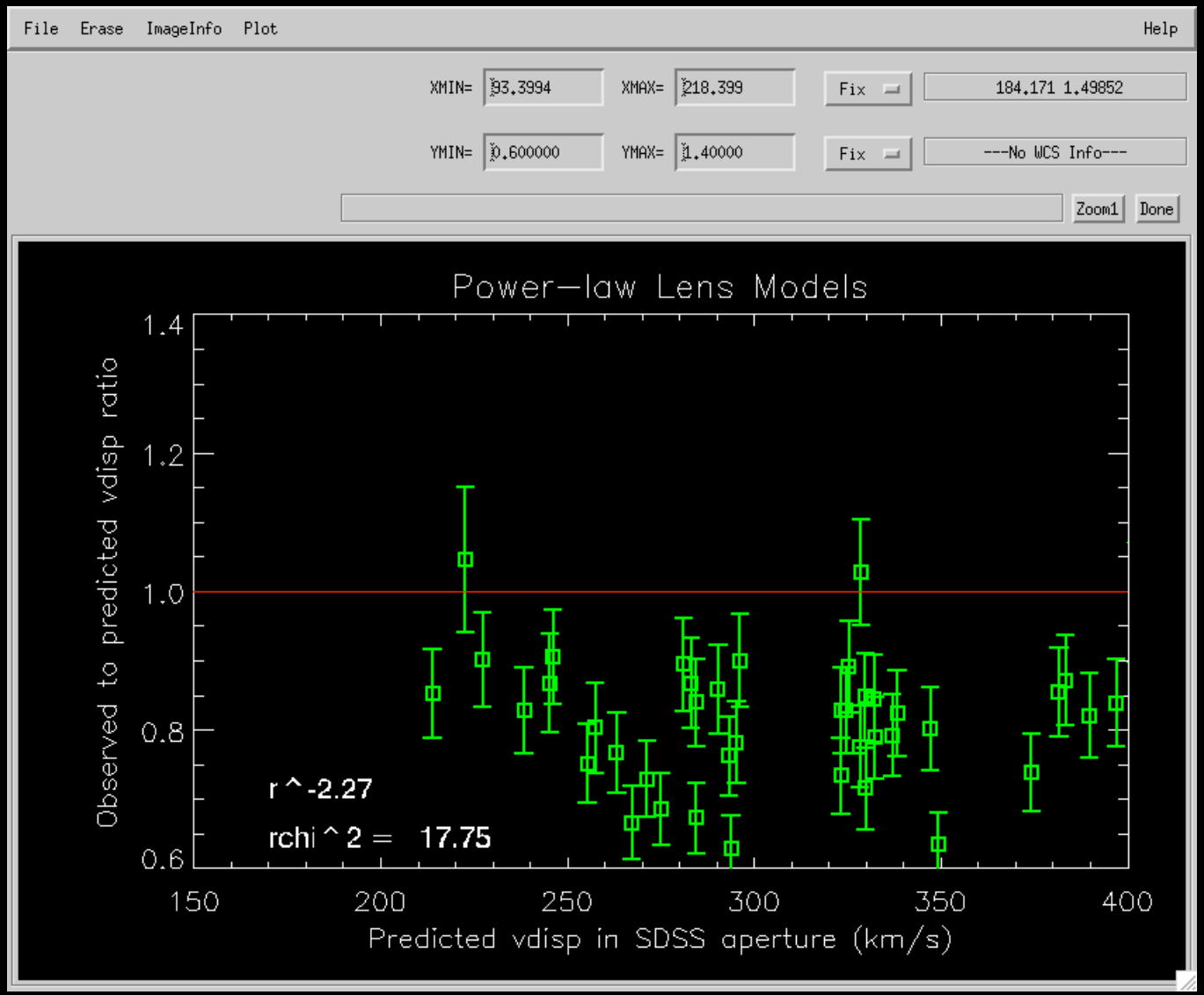

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
305.553 1.47613
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r^-2.10
rchi^2 = 1.23
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

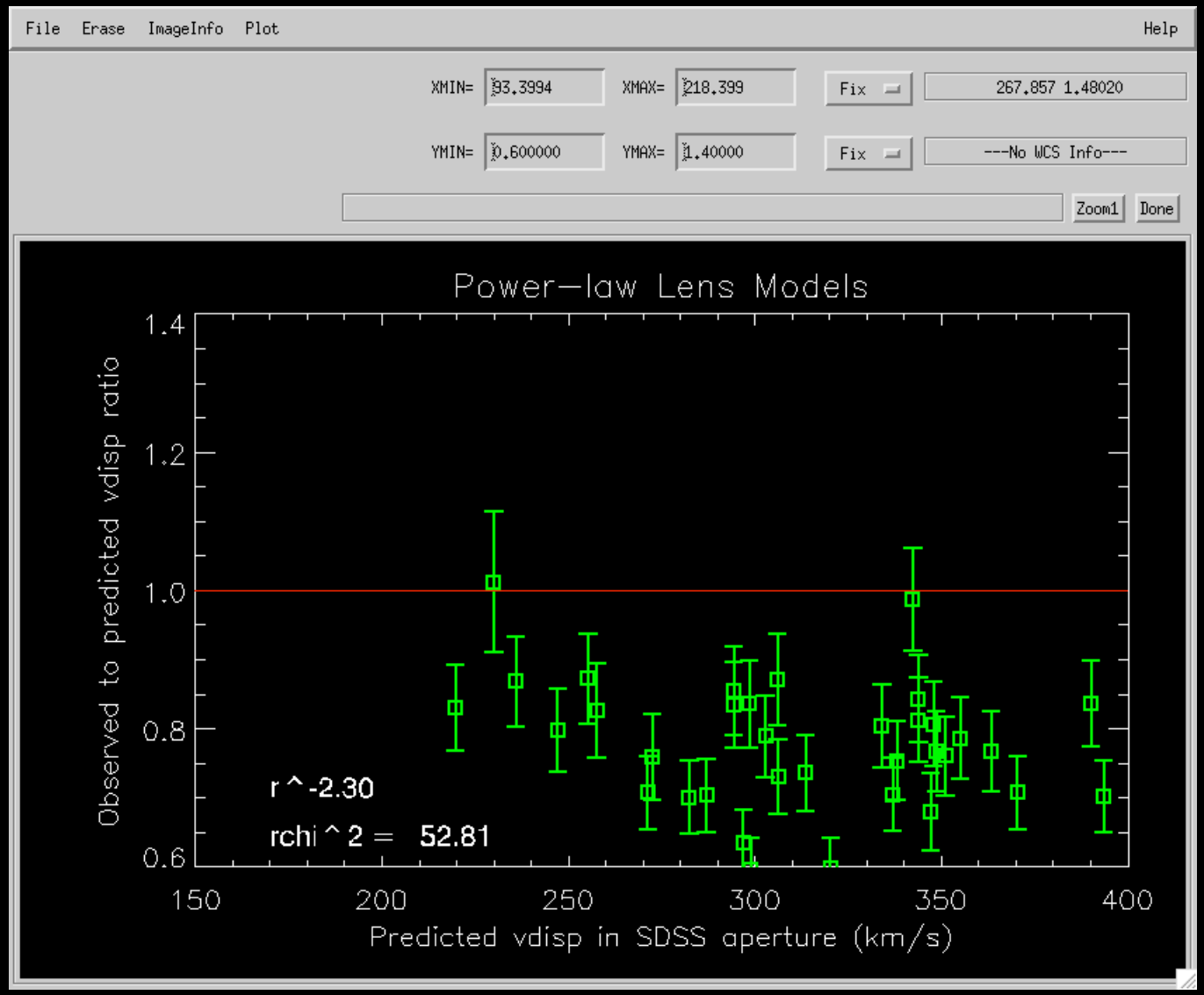

File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
104.633 1.45578
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r^-2.13
rchi^2 = 1.68
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

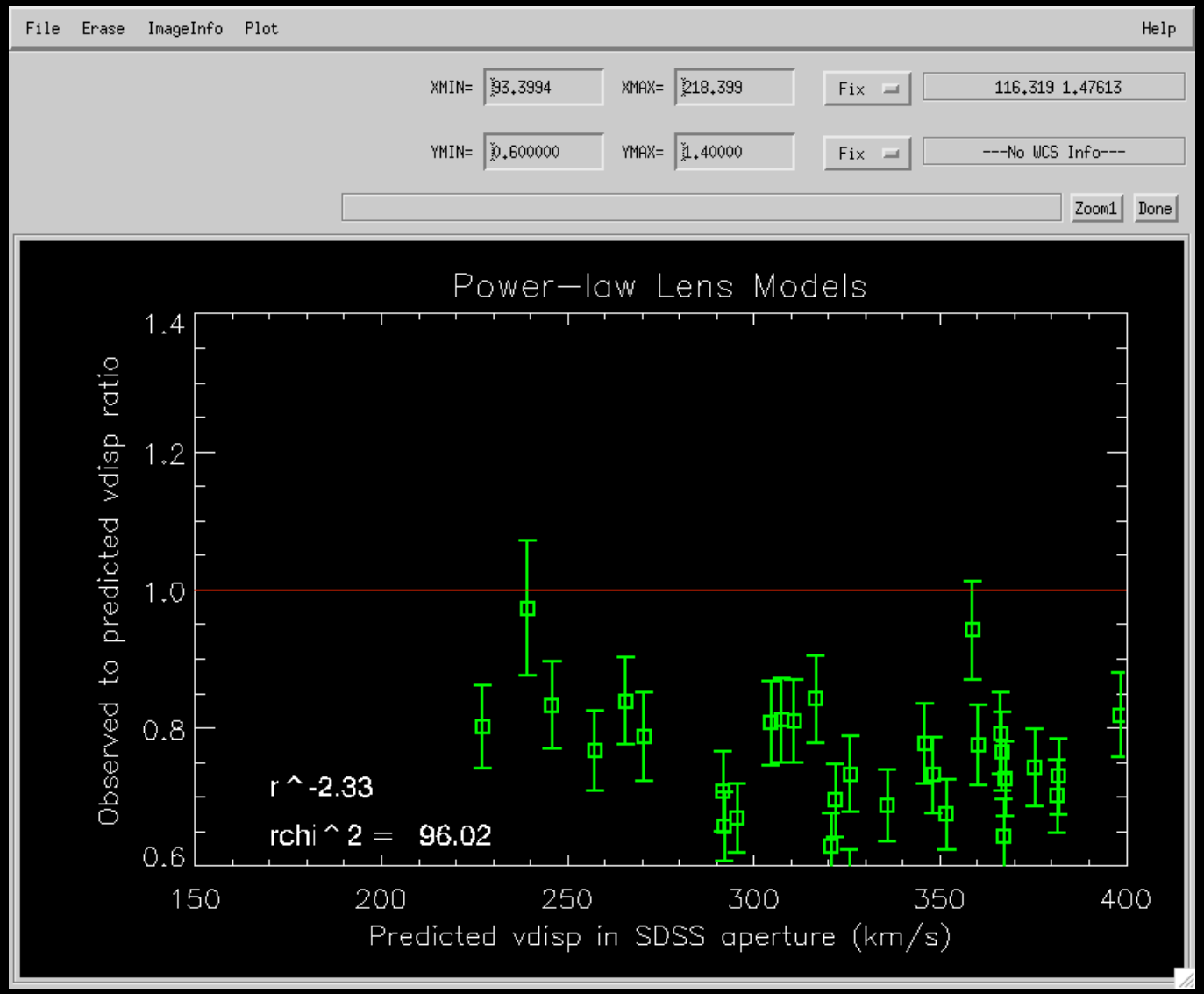

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
109.910 1.49038
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r^-2.17
rchi^2 = 2.76
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

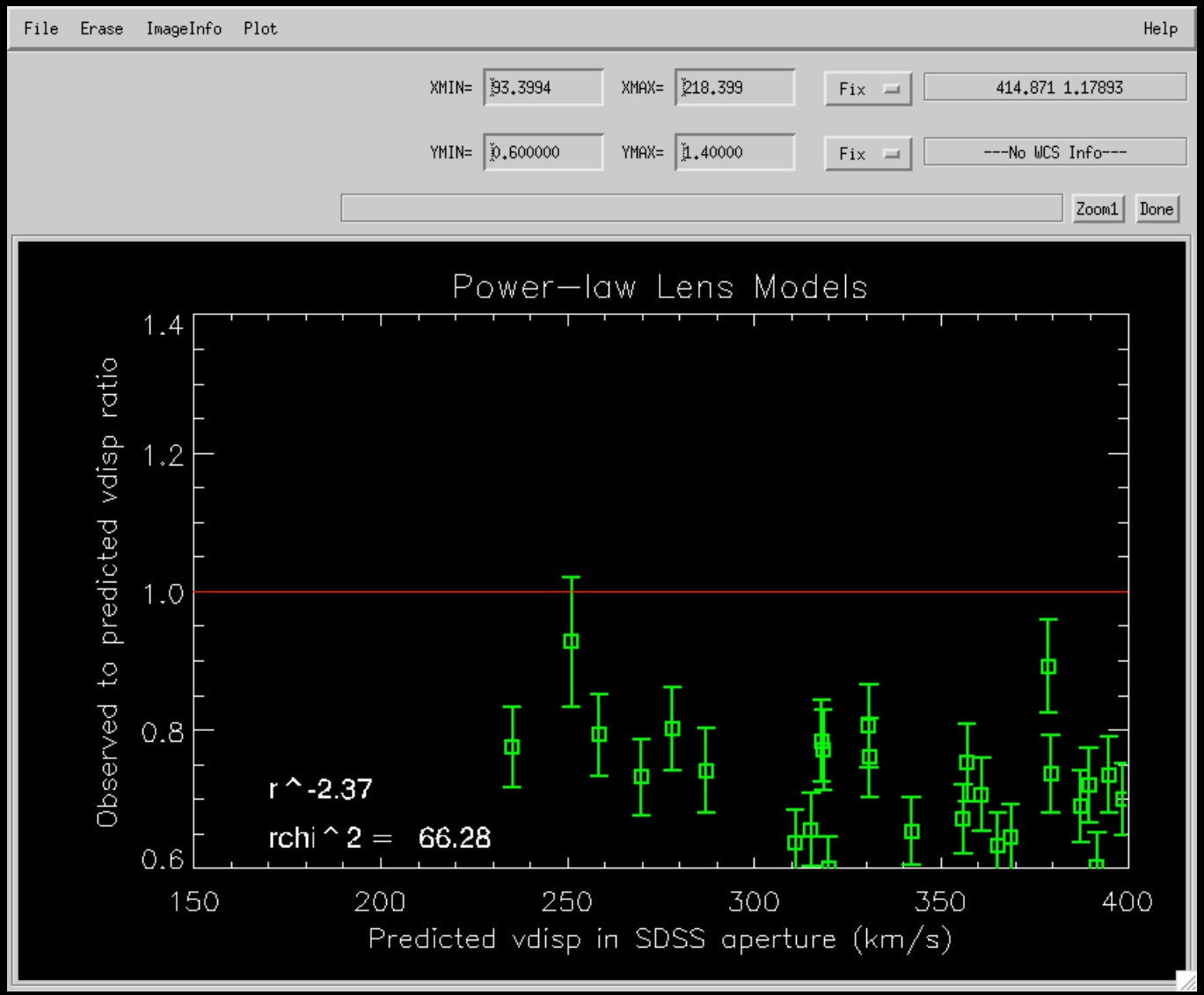

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
404.316 1.48020
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.20
rchi ^ 2 = 4.88
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

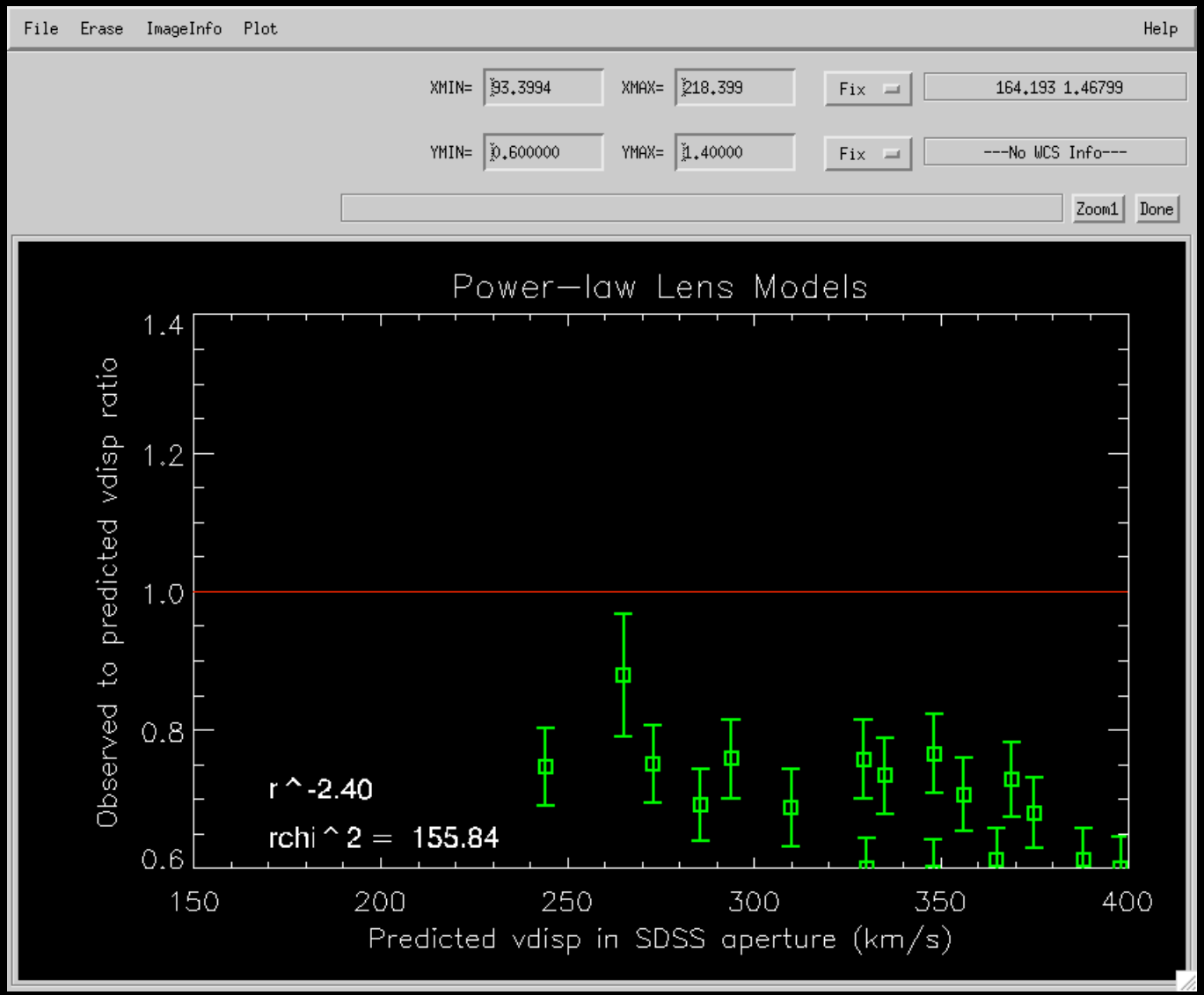

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
109.533 1.47206
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.23
rchi ^ 2 = 8.97
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)


File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
184.171 1.49852
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.27
rchi ^ 2 = 17.75
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

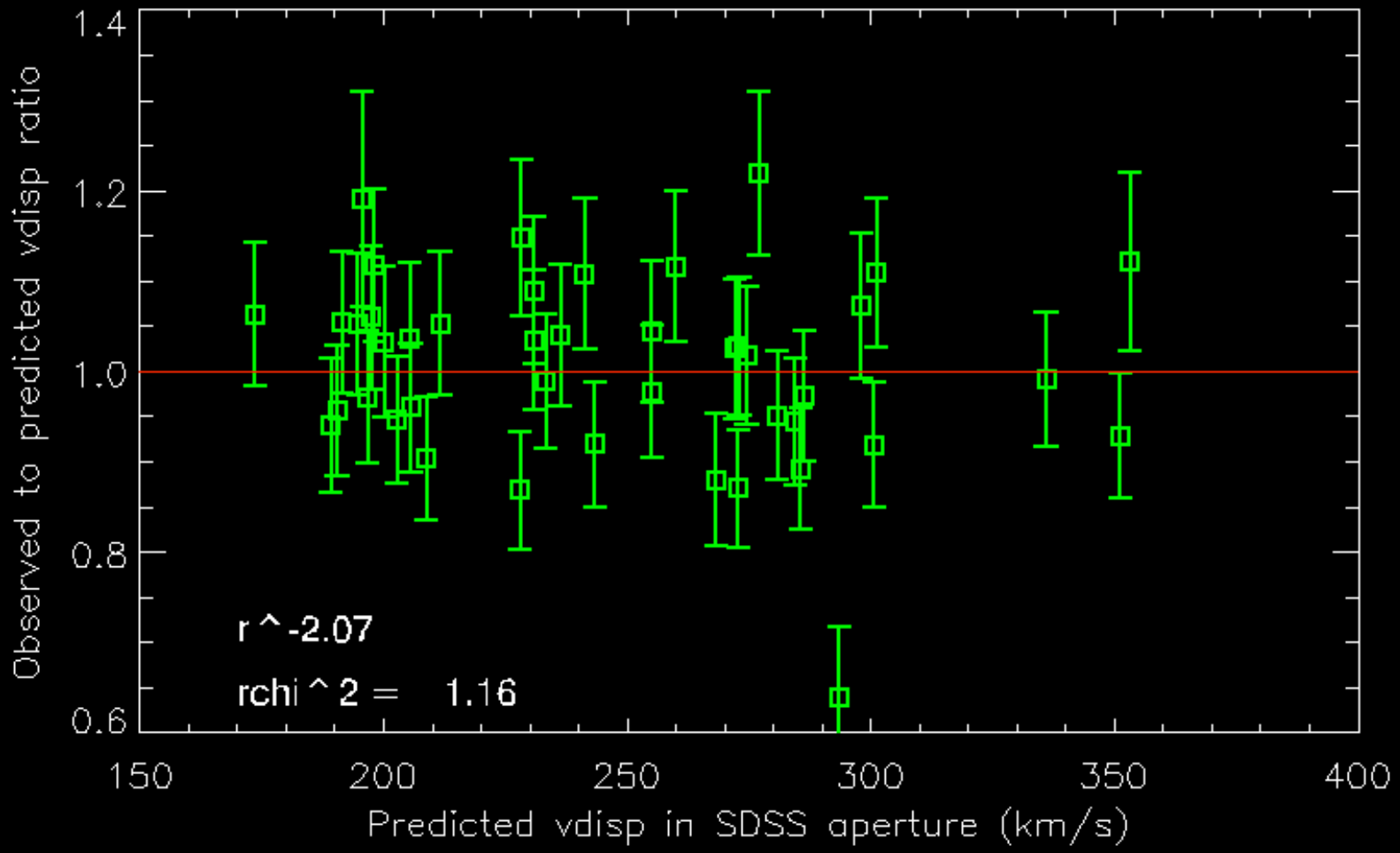

File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
267.857 1.48020
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.30
rchi ^ 2 = 52.81
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)


File
Erase
ImageInfo
Plot
Help
XMIN= 93.3994
XMAX= 218.399
Fix
116.319 1.47613
YMIN= 0.600000
YMAX= 1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.33
rchi ^ 2 = 96.02
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)


File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
414.871 1.17893
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.37
rchi ^ 2 = 66.28
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)


File
Erase
ImageInfo
Plot
Help
XMIN=
93.3994
XMAX=
218.399
Fix
164.193 1.46799
YMIN=
0.600000
YMAX=
1.40000
Fix
---No WCS Info---
Zoom1
Done
Power-law Lens Models
Observed to predicted vdisp ratio
1.4
1.2
1.0
0.8
0.6
r ^ -2.40
rchi ^ 2 = 155.84
150
200
250
300
350
400
Predicted vdisp in SDSS aperture (km/s)

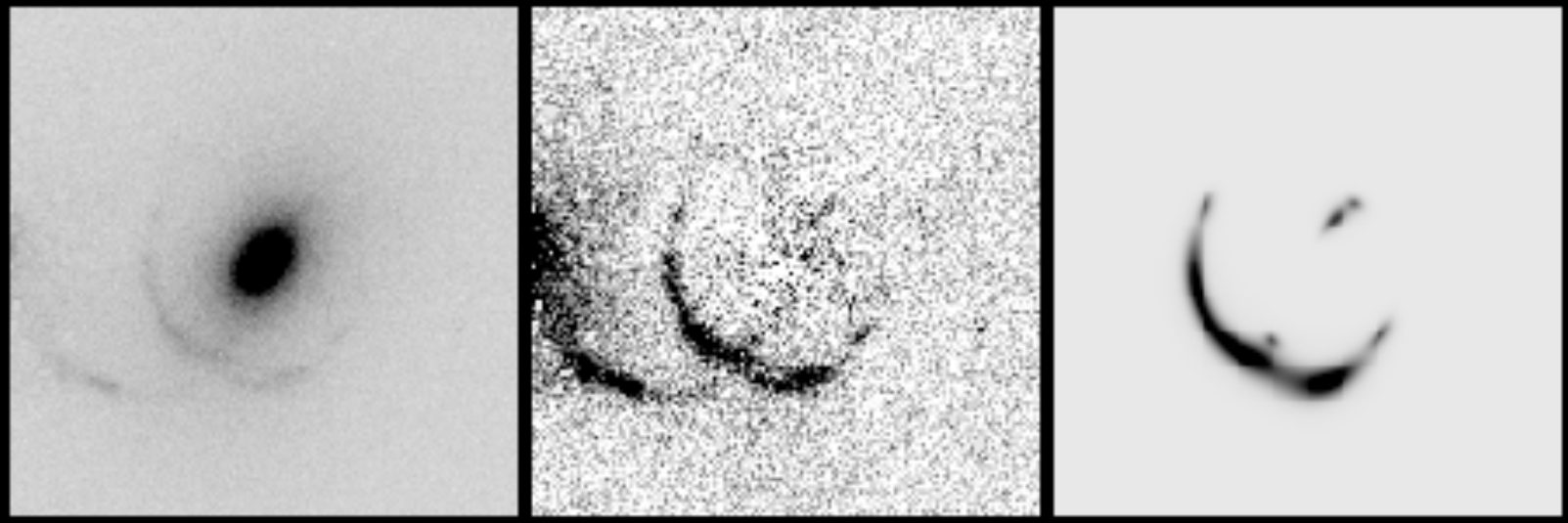
Best model is (still) isothermal or slightly steeper



SDSS J1100+5329: The exception that proves the rule

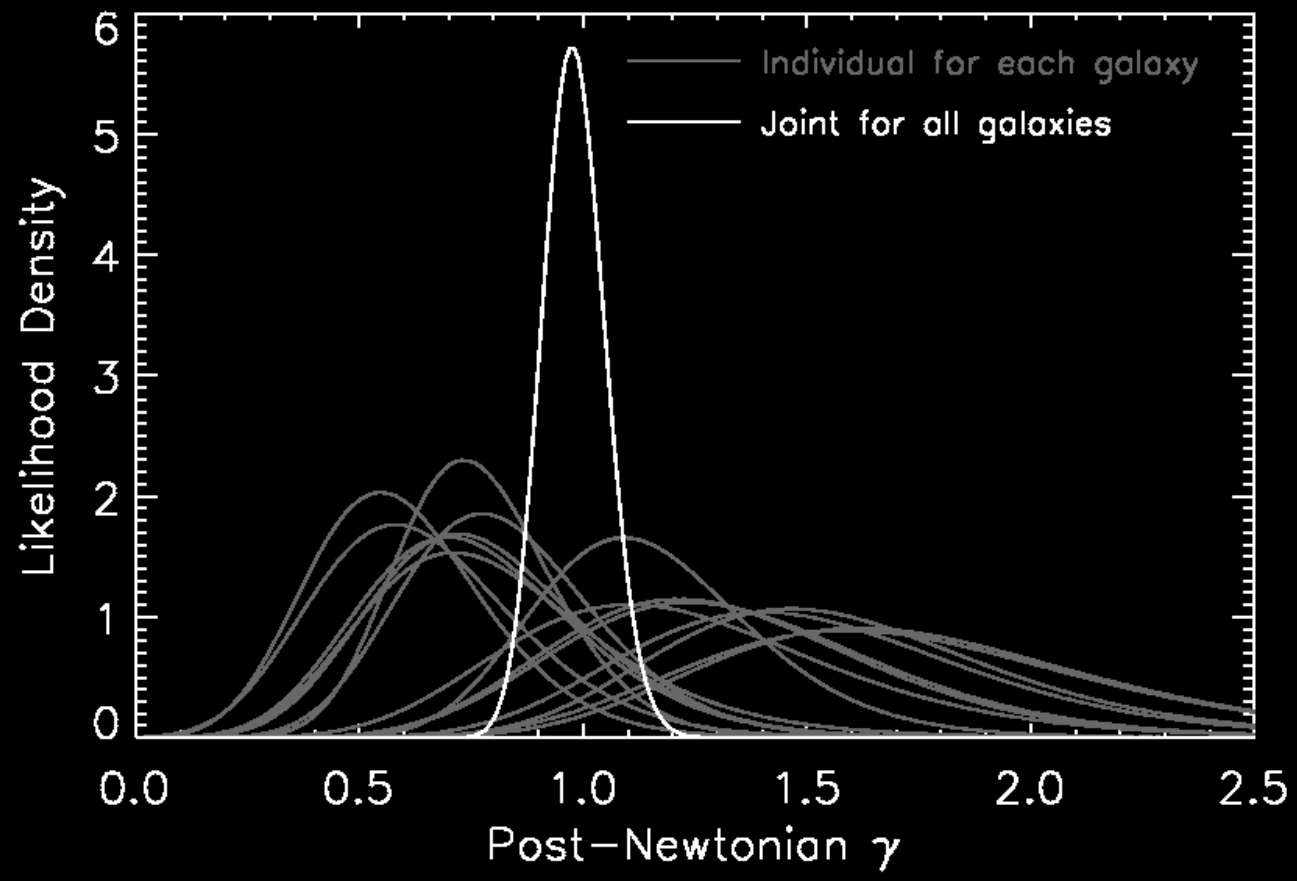
-Both lensing and lensing+dynamics indicate significantly shallower-than-isothermal mass profile.

-Selection technique doesn't really *care* about mass profile.



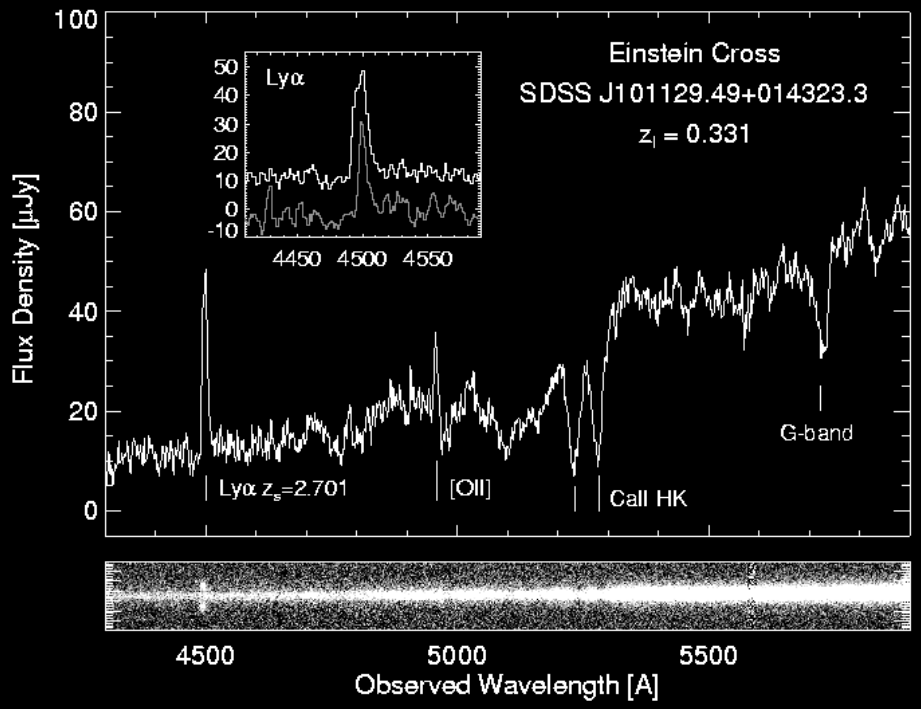
Did you already know that galaxies were isothermal? Then you can…

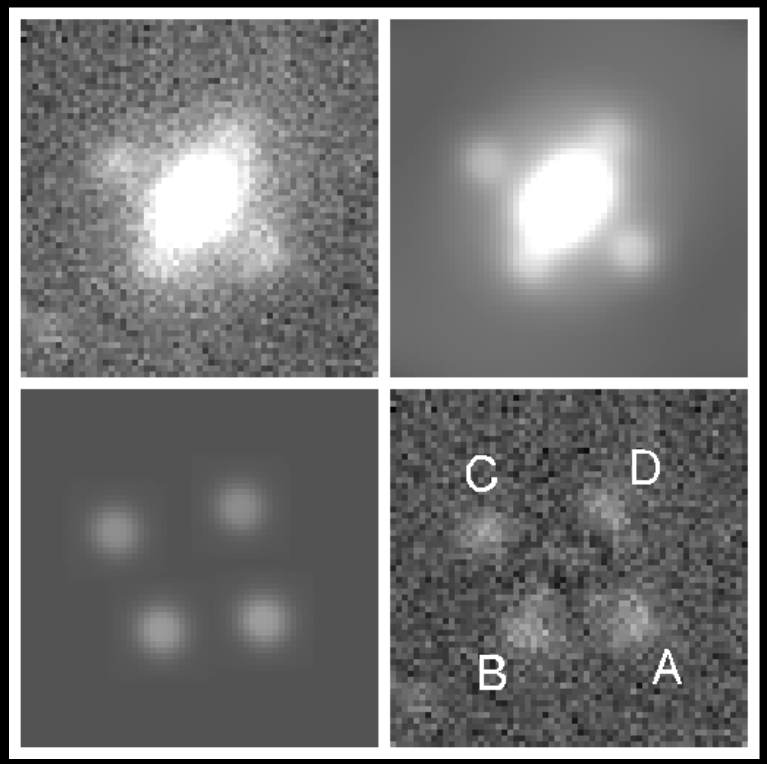
Test (and confirm) GR directly on galactic scales!



Bolton, Rappaport, & Burles 2006

To higher z: lensed Lyman-alpha emitters





Bolton et al. 2006b

Spectroscopic Lens Selection: DISADVANTAGES

-You need to take a lot of spectra (i.e. dedicated surveys are unlikely -- need redshift/QSO survey.)

-Traditional imaging pre-selection of spectroscopic targets can/will eliminate many of the interesting cases.

-Even more hopeless than source-based lens surveys when it comes to cosmology from lens statistics.

Spectroscopic Lens Selection: ADVANTAGES

-Seems to work really well: obvious way forward for generating large statistical samples of lenses.

-In princile, can target and study any lens population of interest.

-Can “piggyback” on larger spectro survey with little to no further technical considerations.

-Lens and source redshifts known from the outset.

-Can be less biased than source-based lens surveys w.r.t. lens population for comparison with non-lenses.

Spectroscopic Lens Selection: THE FUTURE

-Hard to beat SDSS; need next-generation spectroscopic survey (though other current surveys may fill niches).

-Higher-z lenses and sources would be particularly valuable.

-Future pipe dream: spatially-resolved spectroscopic survey, magnitude limited, with full O(N^2) redshift-finding analysis.

-With enough strongly lensed starforming galaxies, monitor programs for lensed supernovae become feasible.

Conclusions and future work

-Given a large spectroscopic database and a suitable means of imaging follow-up, spectroscopic lens detection is a powerful technique.

-The SLACS survey has confirmed 50+ galaxy-scale strong lenses in this manner.

-SLACS lens galaxies appear to be representative of the parent SDSS early-type galaxy population.

-SLACS lenses are ~isothermal in their inner few kpc.

-More lenses; better lens models; lensing+dynamics self-consistently; weak lensing signal; etc.