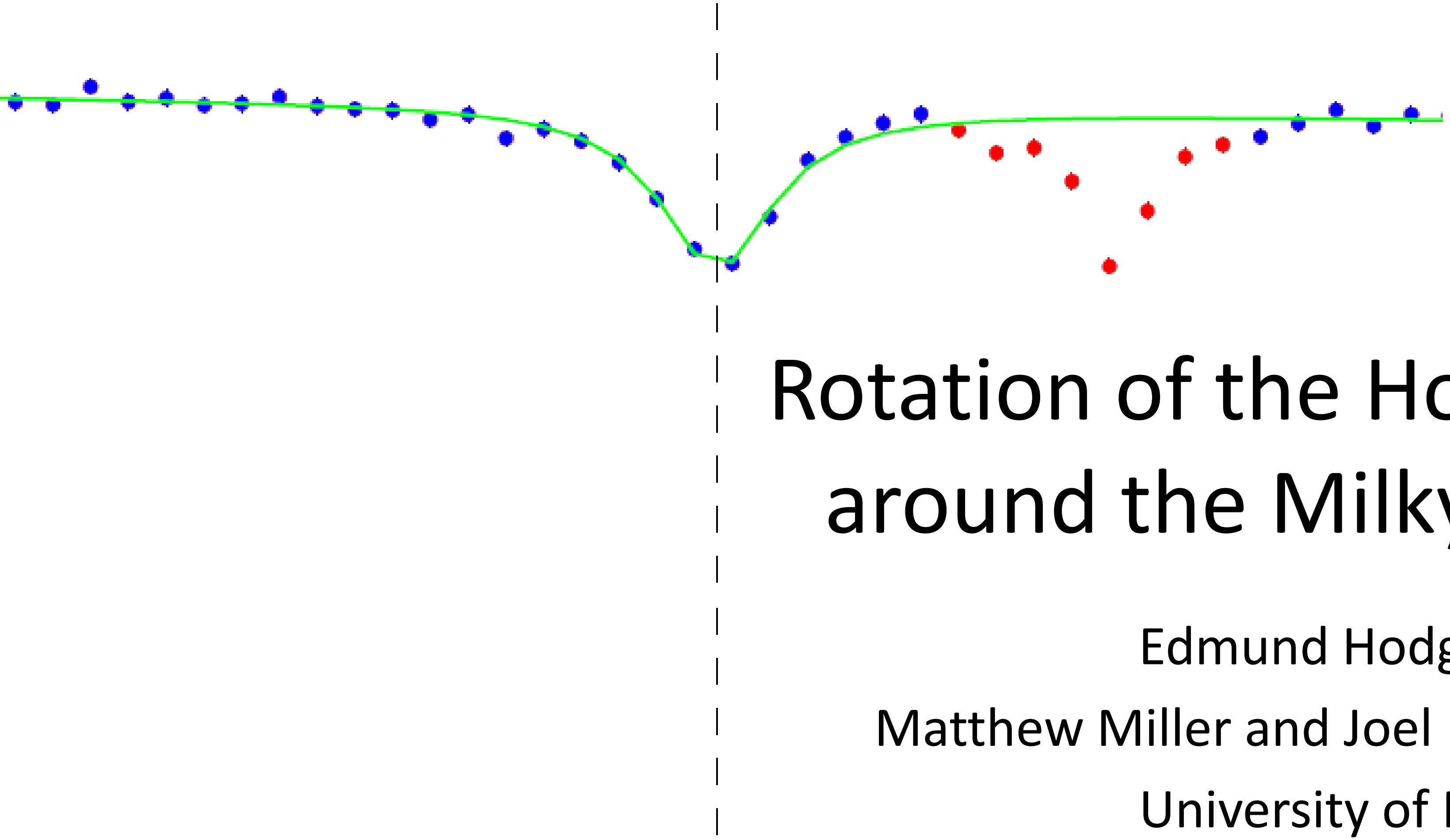

Rotation of the Hot Gas around the Milky Way

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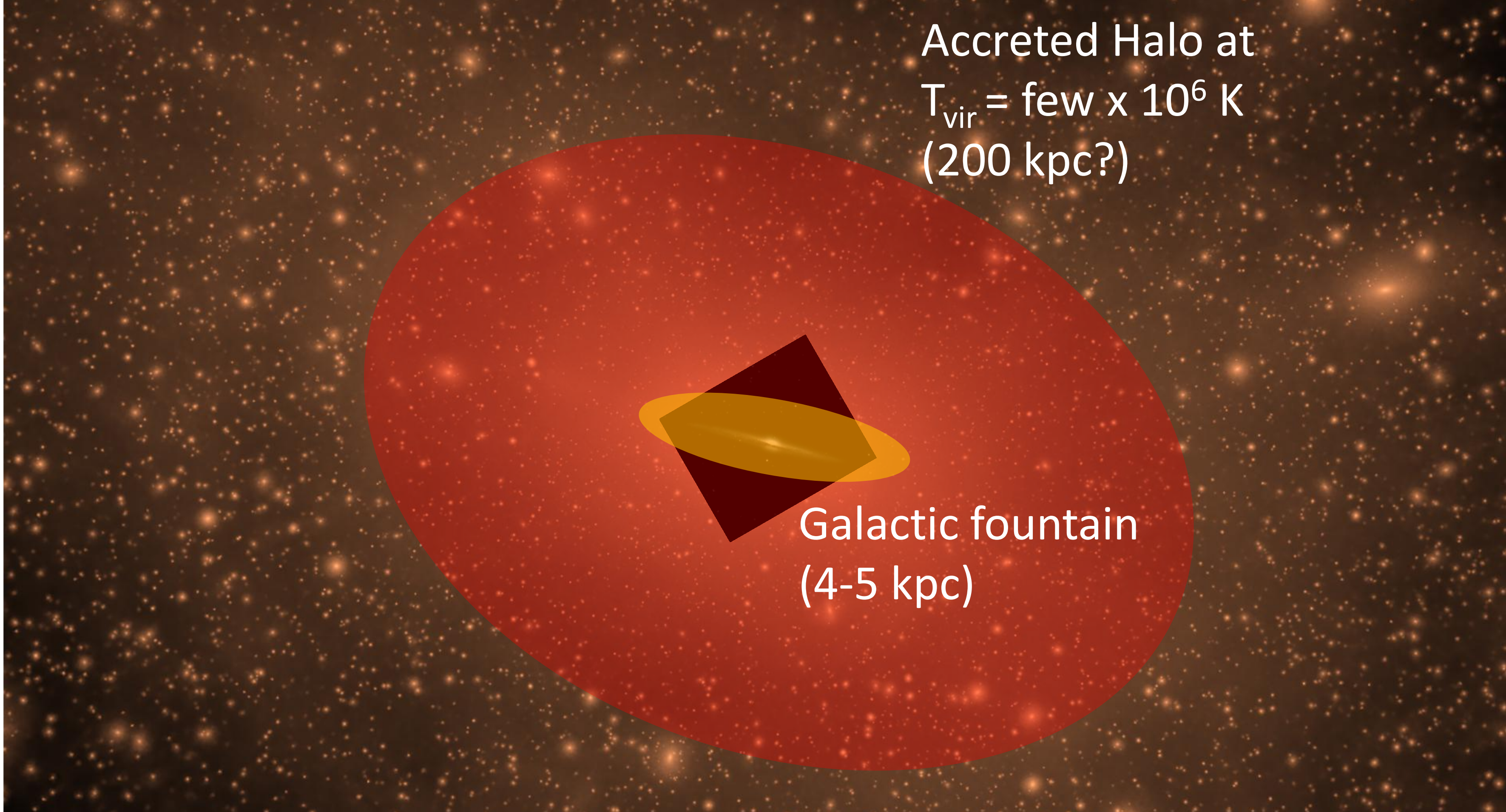
Agenda

- Galaxy Halos
- OVII Absorption Lines in the RGS Archive
- Halo Model
- Halo Rotation?
- Remaining Issues

- Please see Matt Miller's poster for more on halo kinematics with OVII lines!

Galactic Hot Halos



Mass, distribution, and kinematics of each component are important to understanding galaxy evolution

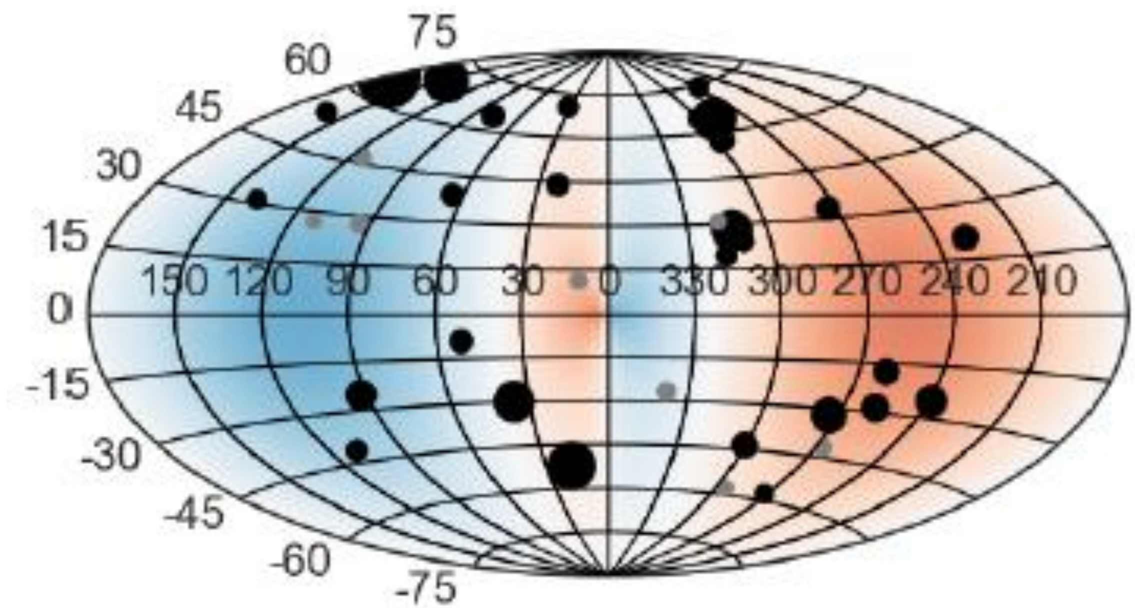
Galaxy halos have T ~ $10^{6.1}$-$10^{6.4}$ K (and sometimes low metallicity), so the dominant lines are OVII and OVIII (0.57, 0.65 keV)

Instrument	Resolving Power at OVII(r)	Effective Area (cm^2)
XMM MOS	10	300
XMM RGS	320	45
Chandra LETG	400	15
Astro-H SXS	140	100
Arcus	2000	400

The Milky Way is the only *galaxy* halo where we can measure kinematics, but SXB is faint so we need absorption lines

Sample

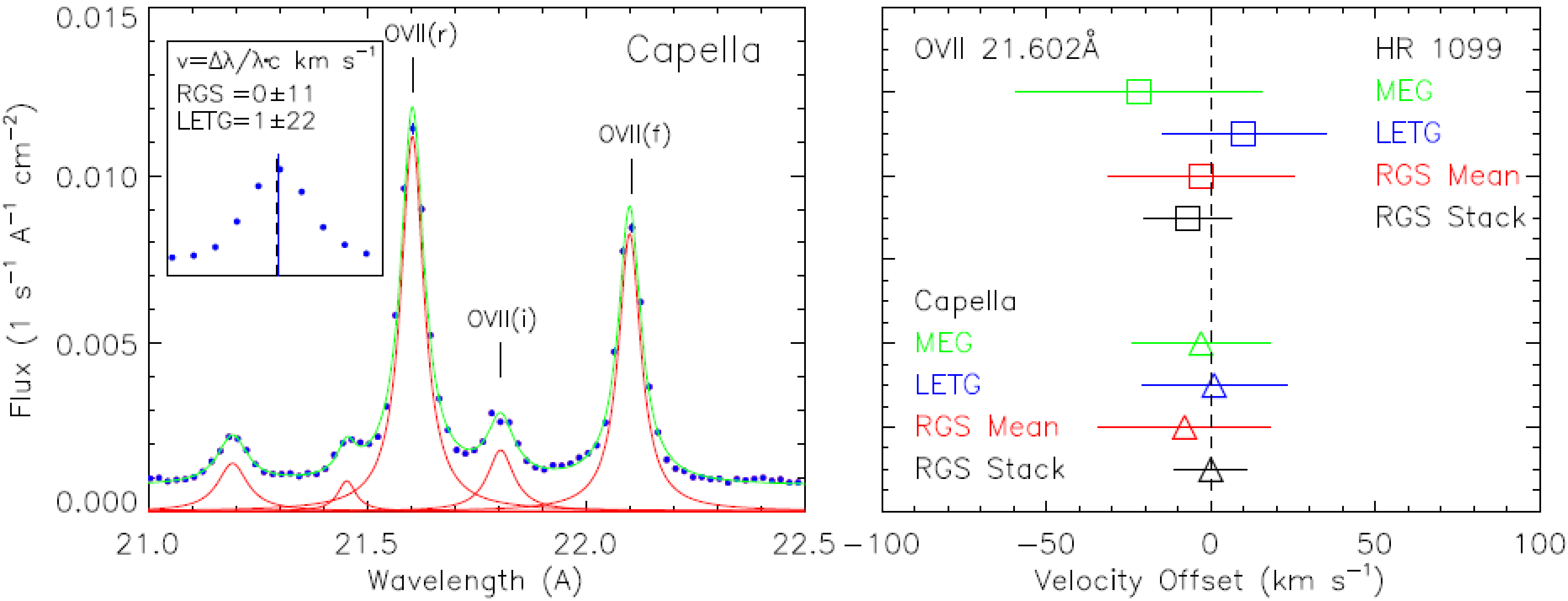
- ~40 OVII absorption lines detected at *z*=0 towards background AGNs or halo/Magellanic Cloud XRBs (Nicastro+02, Fang+02, McKernan+04, Yao & Wang05, Fang+06, Bregman & Lloyd-Davies07, Yao+09, Fang+15)
- RGS data (more targets with high S/N)



Reduction/Fitting Protocols

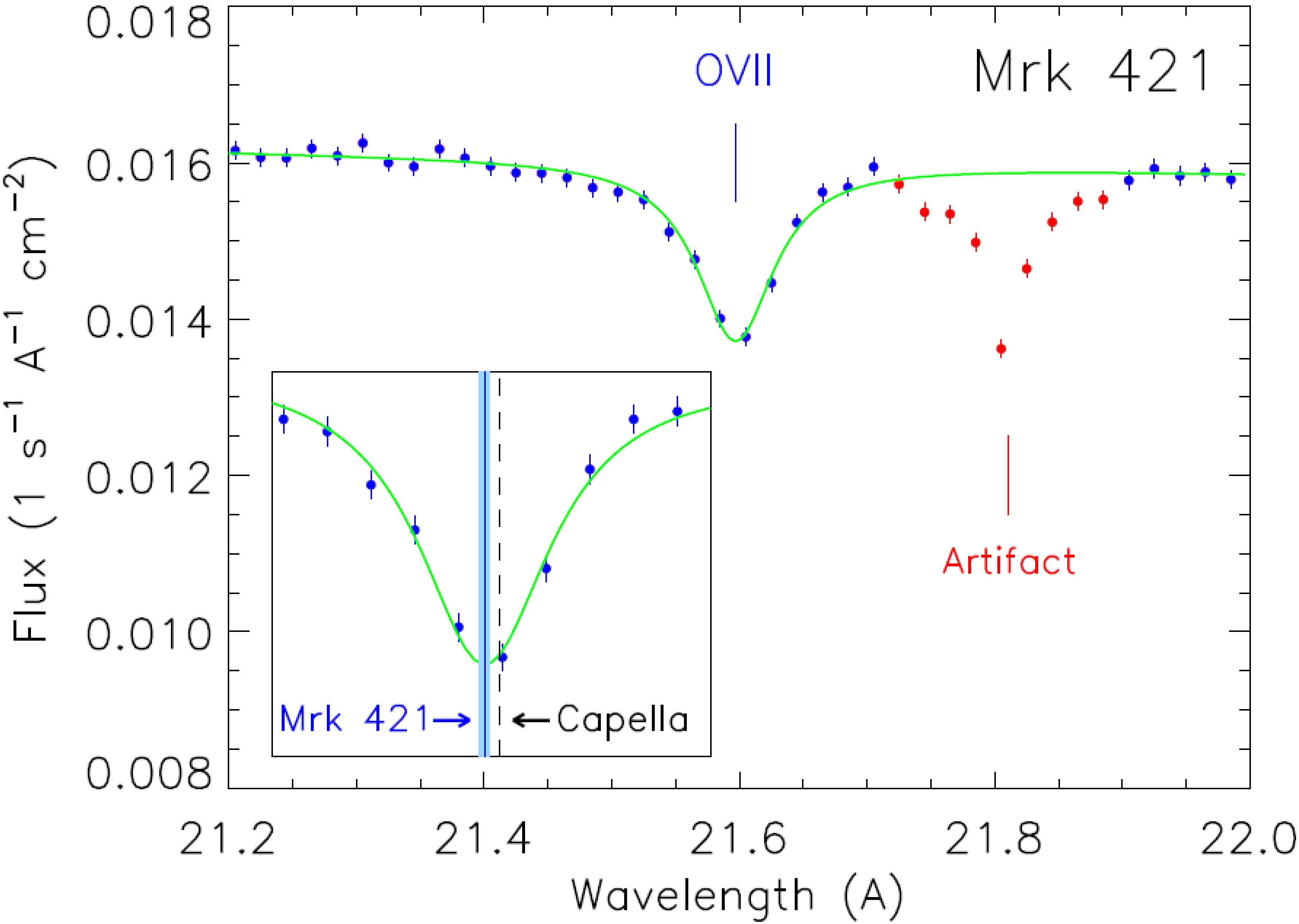
Systematic shifts: <10-15 km/s <15-30 km/s >30 km/s

1. Process every exposure with *rgsproc* from SAS v14.0.0 with KEEPCOOL=no, LAMBDABINWIDTH=0.02 Å, WITHDIAGOFFSET=YES, **HELIOCENTRICCORR=YES**, **SUNANGLECORR=YES**, USERSOURCE=YES (with SIMBAD RA/Dec). Do this 10 times to account for bin resampling.
2. Combine RGS1 spectra and responses with *rgscomb* and fit the stacked spectrum in XSPEC v12.9.0.
3. Fit in the 21.0-22.0 A bandpass, ignoring an instrumental feature at 21.75 Å, with a power law + Gaussian or Lorentzian absorption line model **fixed at the instrumental width**.
4. Measure the Doppler shift of the line referenced to the best-fit Capella line centroid (accounting for radial velocity) for OVII.
5. We include a 15 km/s error term for the systematic error, which is dominated by asymmetry in the line-spread function near OVII.

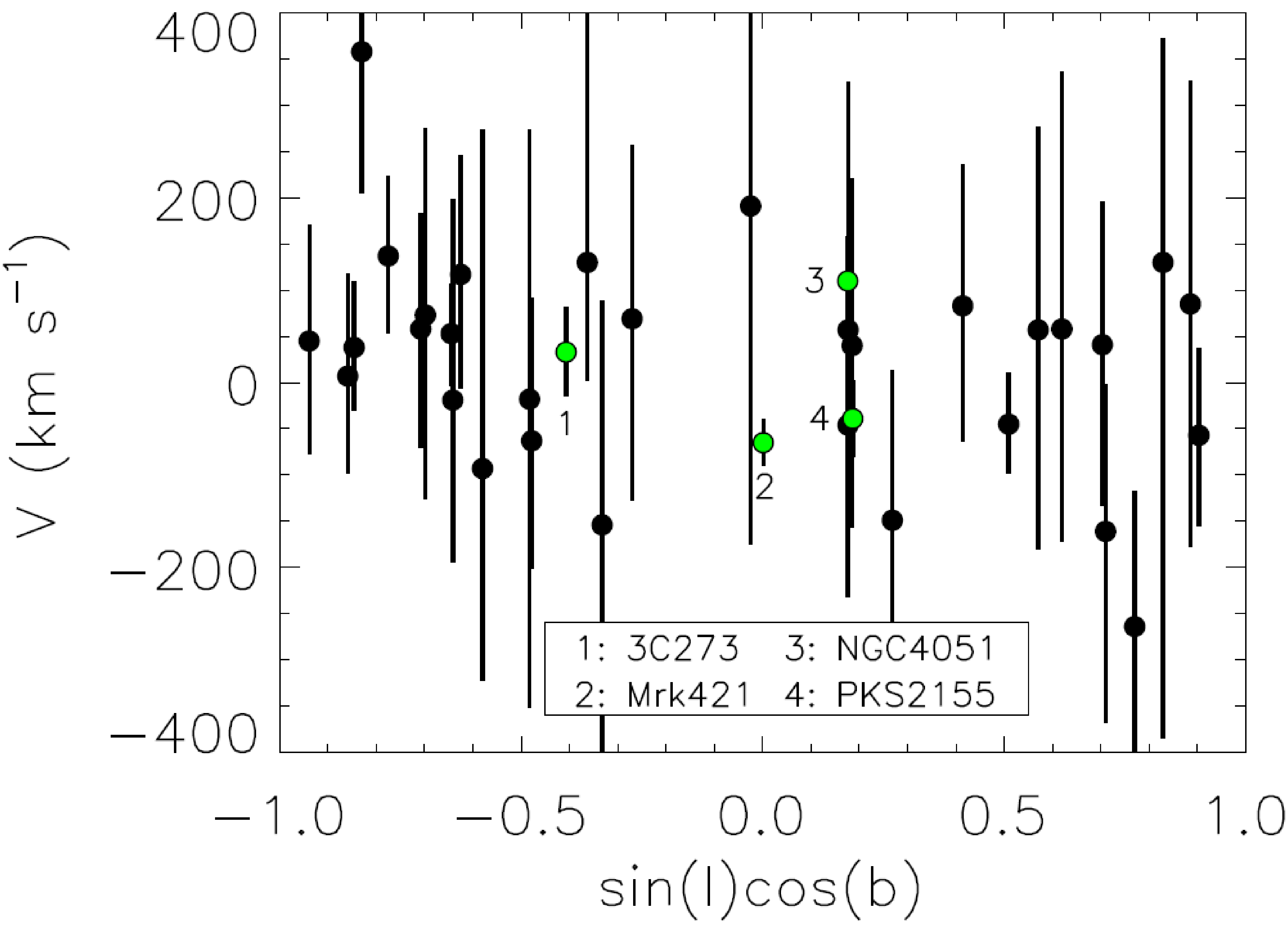


Wavelength solution in Capella and HR 1099 agrees with laboratory wavelengths (21.602Å for OVII) and LETG/HETG after subtracting stellar radial velocities.

Scatter in wavelength scale (~6 mÅ) is **strongly mitigated** by lots of exposures, which is also true for most quasar data.



Mrk 421
OVII
Artifact
Mrk 421→
←Capella
Flux (1 s^{-1} A^{-1} cm^{-2})
Wavelength (A)
0.018
0.016
0.014
0.012
0.010
0.008
21.2
21.4
21.6
21.8
22.0



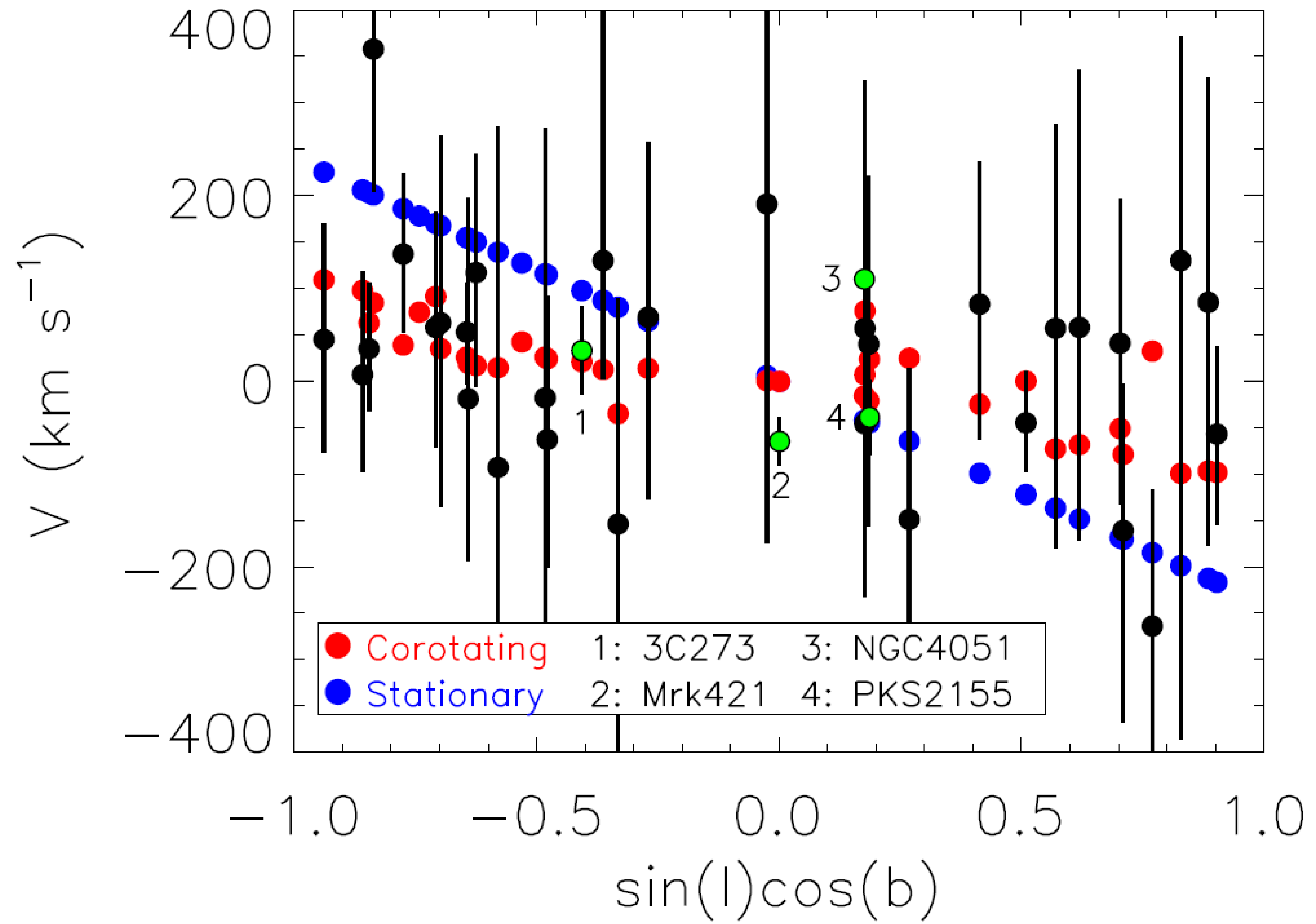
400
200
0
−200
−400
V (km s^{-1})
−1.0
−0.5
0.0
0.5
1.0
sin(l)cos(b)
1
2
3
4
1: 3C273
3: NGC4051
2: Mrk421
4: PKS2155

Halo Model

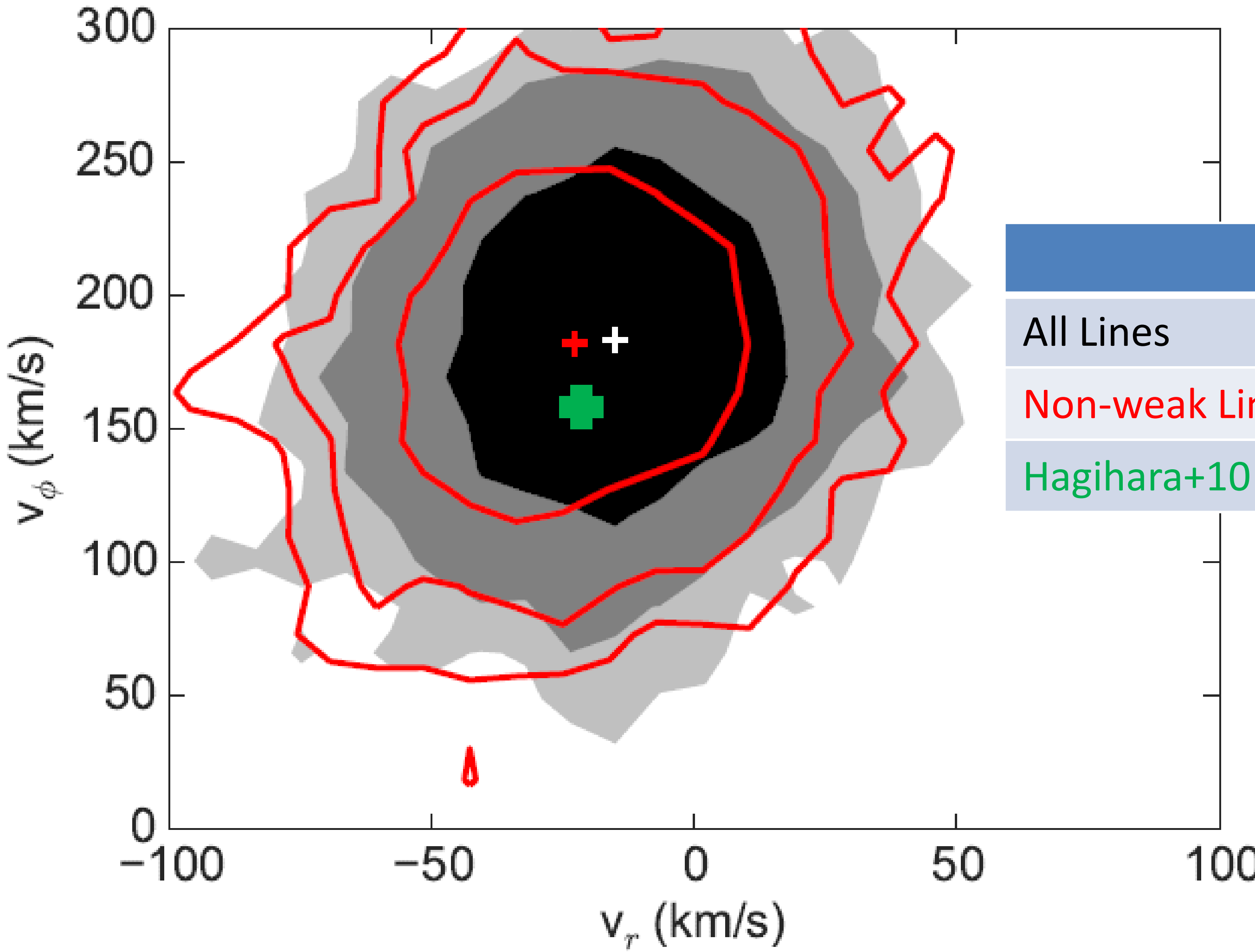
- Miller & Bregman 2015 found that a spherical halo is consistent with the Henley & Shelton XMM OVII/OVIII catalog.
- We use their density model

$$n(r) = n_0(1+(r/r_c)^2)^{-3\beta/2} \qquad n_0 r_c^{3\beta} = 1.35 \pm 0.24$$

- We assume a Doppler *b* = 85 km/s of random motion in small cells (Cen 2012), and v_{LSR} = 240 km/s (Reid+2014)
- We impose constant v_r , v_ϕ (free parameters) and integrate along sightlines from the Sun to obtain model velocities

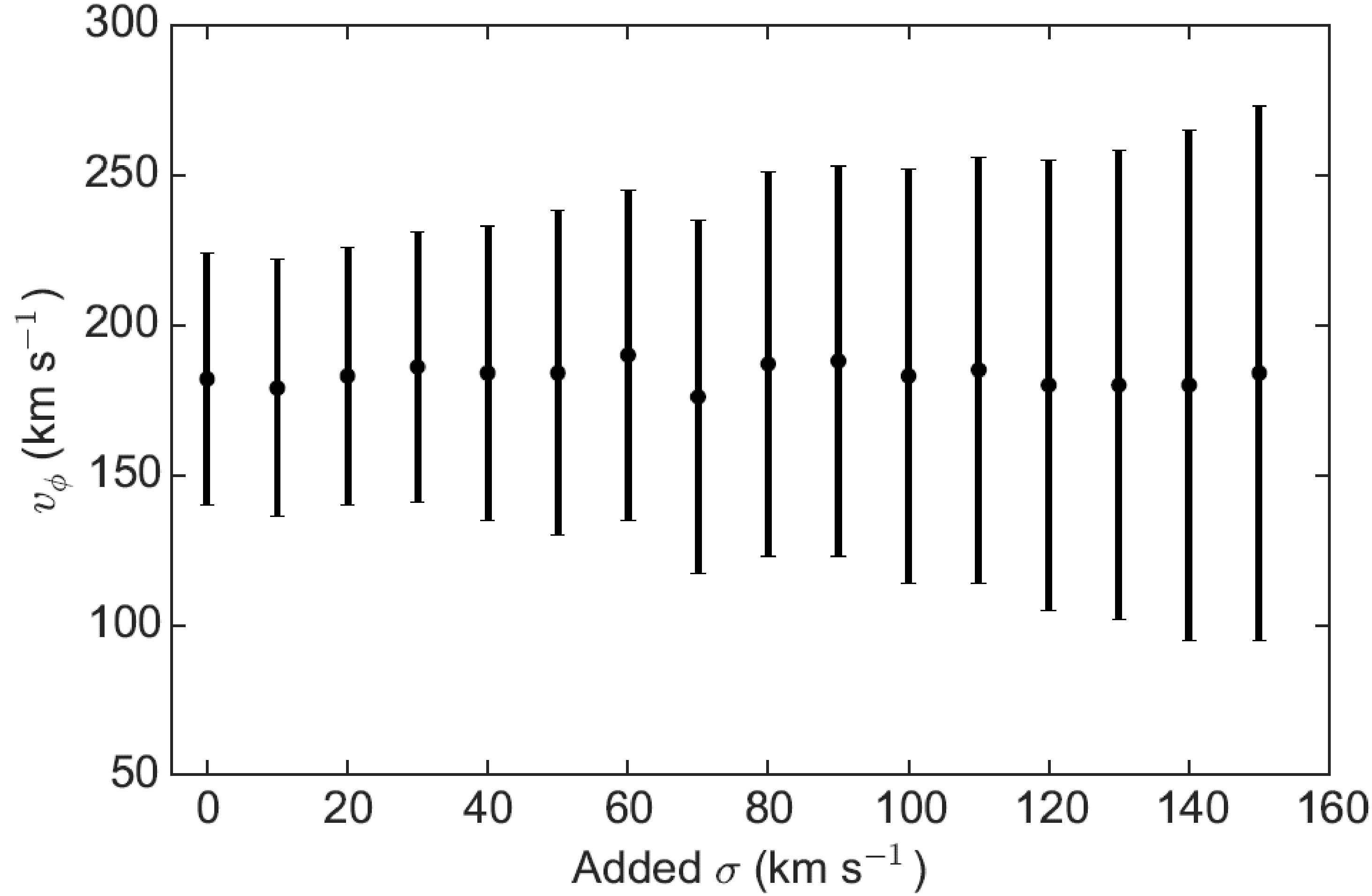


400
200
0
−200
−400
V (km s^{-1})
−1.0
−0.5
0.0
0.5
1.0
sin(l)cos(b)
Corotating
Stationary
1: 3C273
2: Mrk421
3: NGC4051
4: PKS2155
1
2
3
4

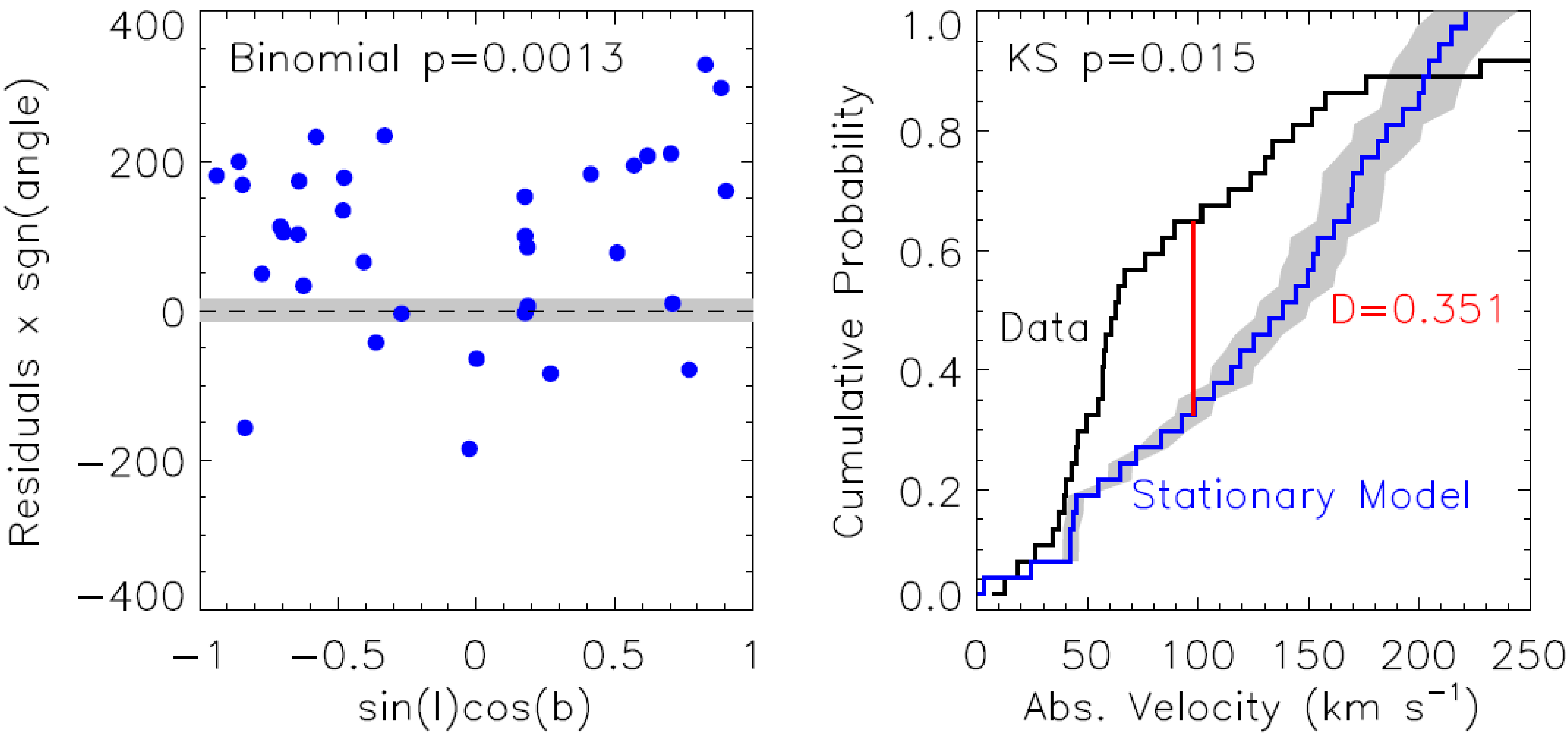


	Best-fit v_ϕ
All Lines	183±41
Non-weak Lines	181±40
Hagihara+10 Disk	151±32

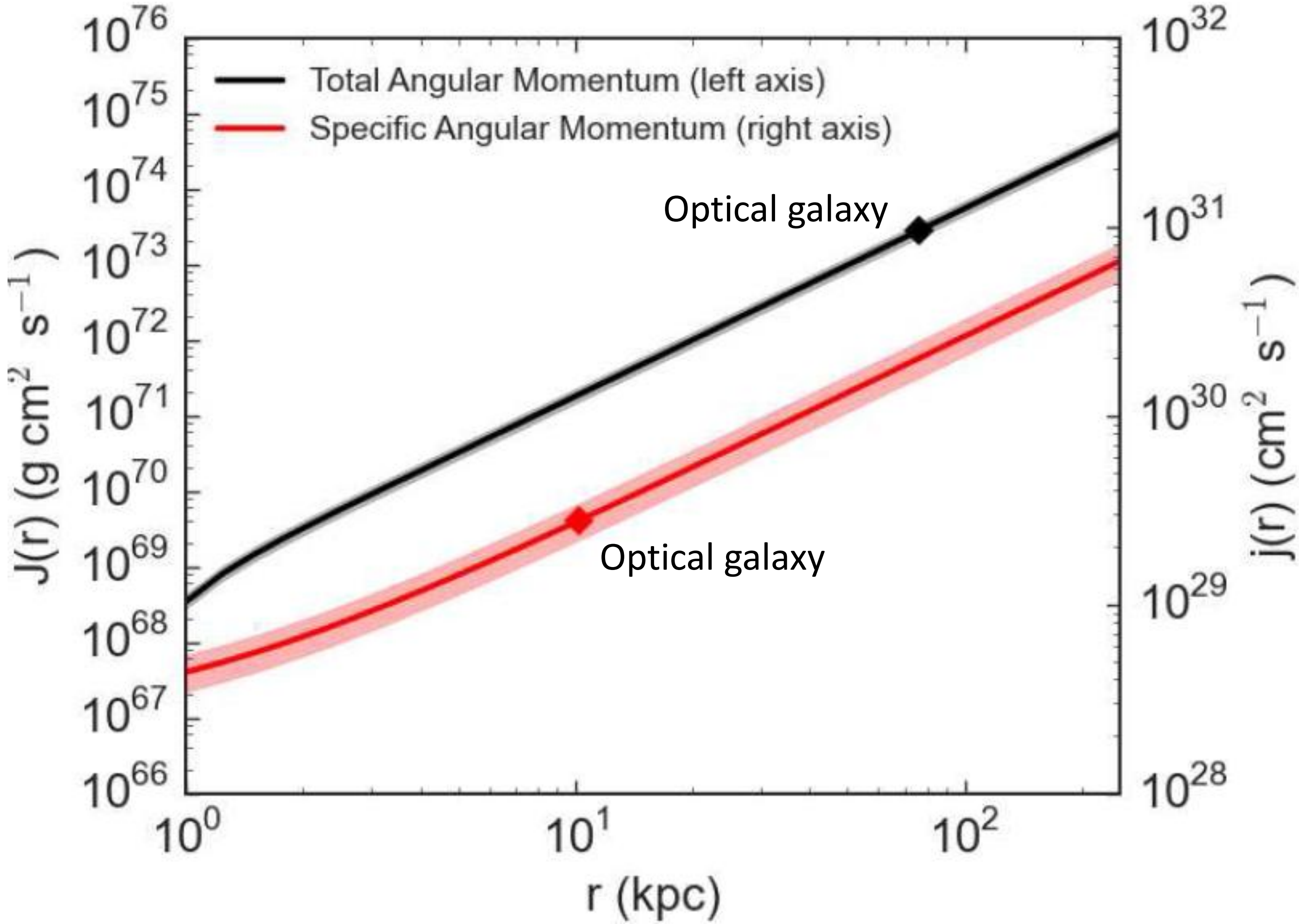
Best-fit parameters indicate prograde rotation and a lagging halo (but parametric fit is dominated by several points)



Accounting for intrinsic scatter (due to hydrodynamic flows) increases the uncertainty, but a rotating halo is preferred. Large dispersions lead to improbably low chi-square values.

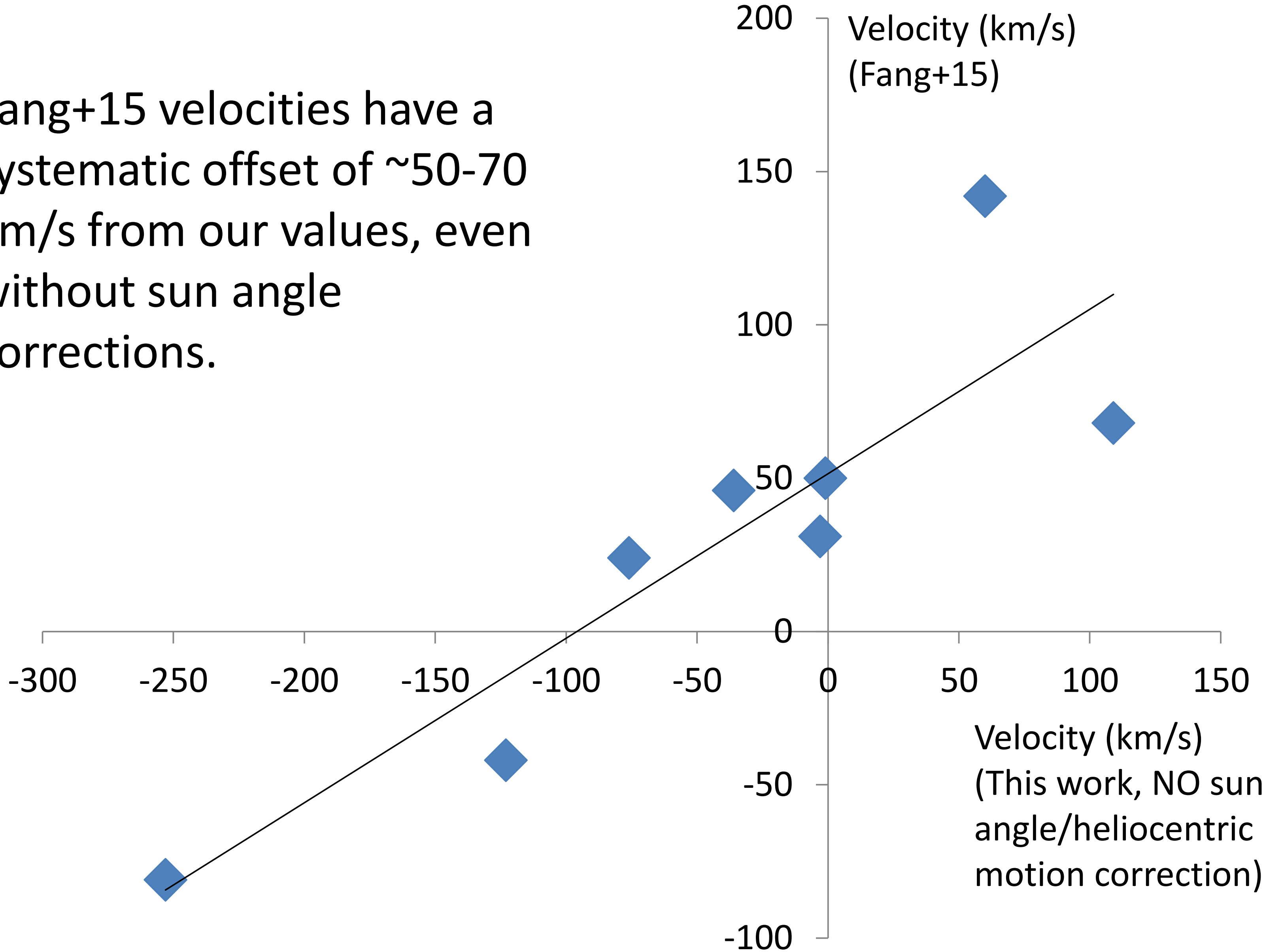


Nonparametric tests also disfavor a stationary halo



The halo (or thick disk) contains a comparable amount of angular momentum to the Galaxy.

Fang+15 velocities have a systematic offset of ~50-70 km/s from our values, even without sun angle corrections.



Systematic Offsets…

Mrk 509

Reduction/fit option	Shift (km/s)
Keep/reject cool pixels	4
~~Heliocentric/sun angle corr~~	~~35~~
Simbad/proposal coords	6
0.01/0.02 A bin width	1
Stacking/joint fit	8
Fixed/free width	14
Bandpass (+/-2 A)	3

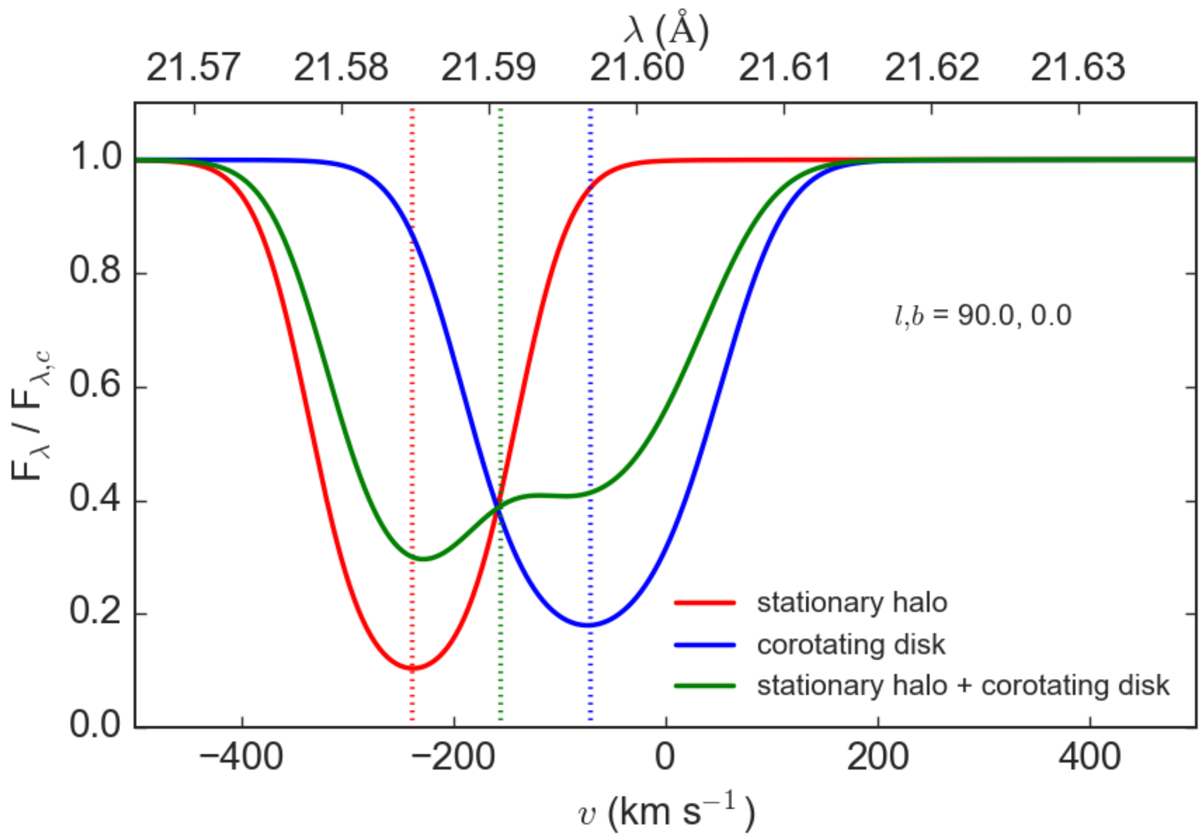
Changing various choices does not produce such offsets.

Probably a wavelength solution problem (only since SAS v13.0.0 is zero shift possible).

A constant offset only changes v_r (inflow/outflow).

Does the **extended** component rotate?

- Miller & Bregman 2015, Fang+2013, Henley & Shelton+2013, Gupta+13 favor an extended halo; Yoshino+09, Hagihara+10, Yao+09 favor a disky “halo”.
- If **both** components exist, do they both need to rotate?



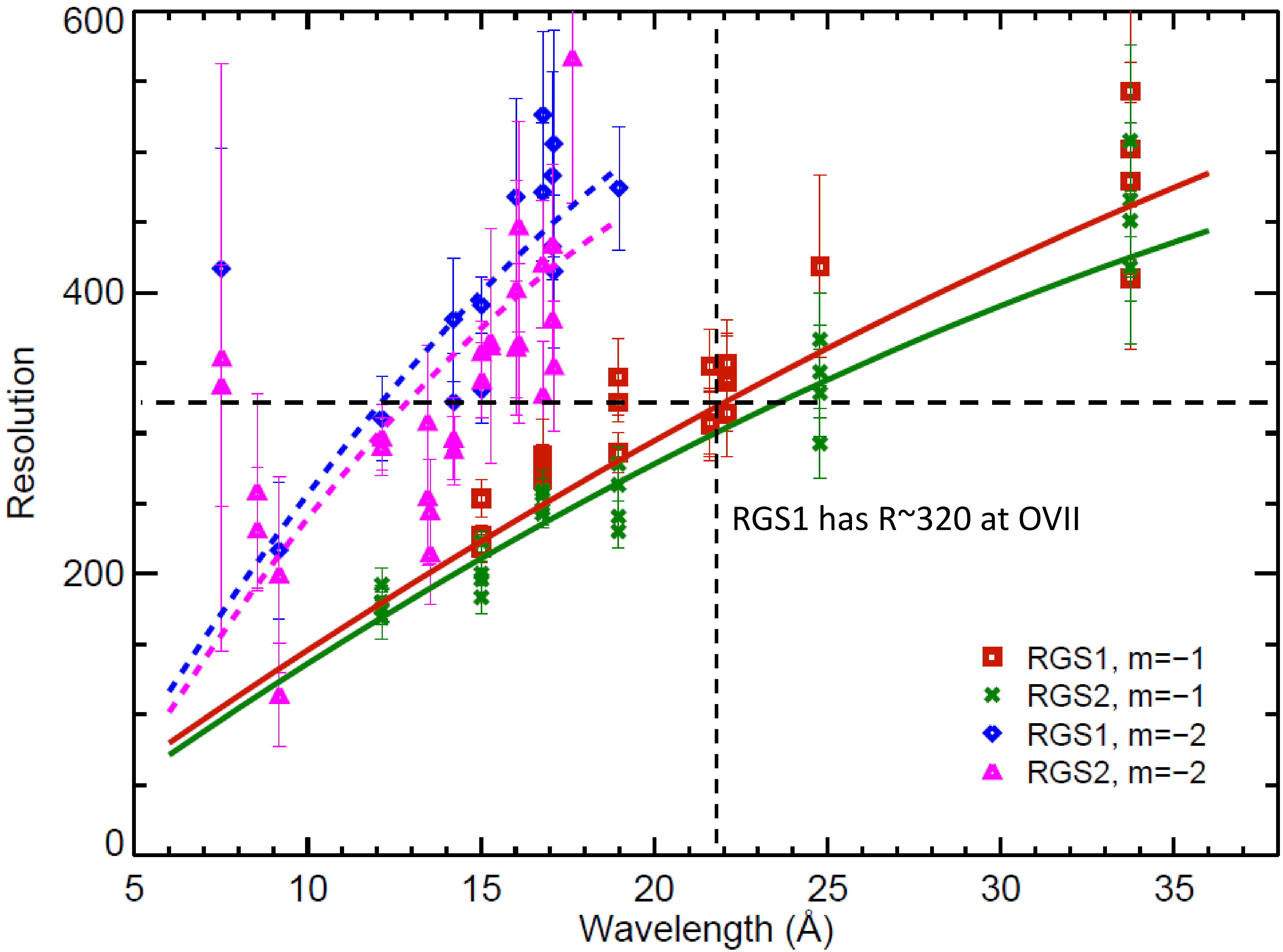
Summary

- The RGS wavelength calibration is now accurate to ~30 km/s when combining multiple observations of a single target

- We measured Doppler shifts in z=0 OVII absorption lines

- The absorbing material rotates, and has a lot of angular momentum.

- This is the first systematic kinematic measurement of the gas, but please see Matt Miller's poster for what we can do with a better instrument.



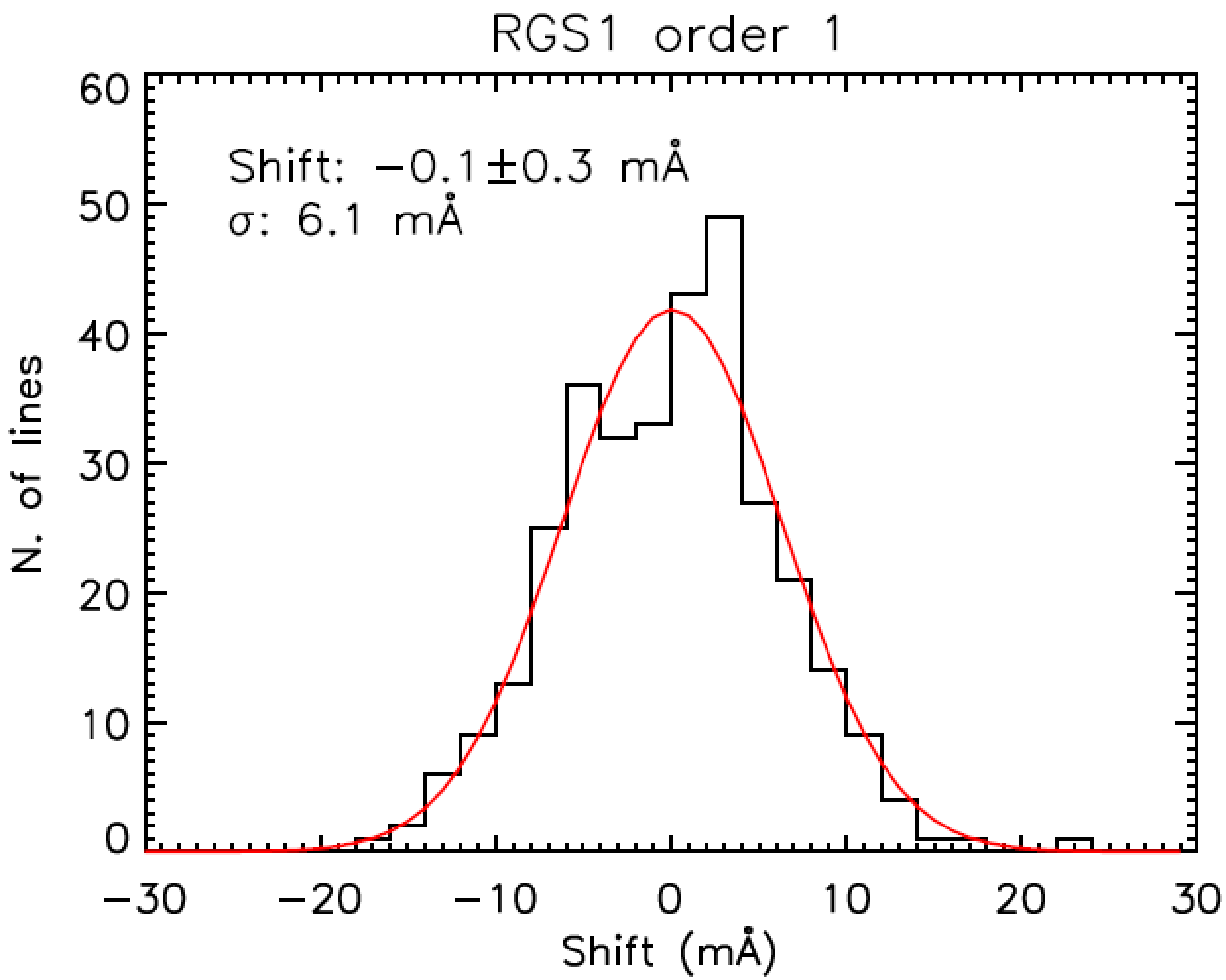
Gonzáles-Riestra (2015)
http://xmm2.esac.esa.int/docs/documents/CAL-TN-0030.pdf

Table 3: Summary

	GR08	GR08s	GR12	GR12v	GR12vs
RGS1 o1	6±8	-1±6	5±7	3±6	1±5
RGS2 o1	11±9	-2±7	10±7	8±7	1±5
RGS1 o2	2±6	0±6	4±4	3±4	1±3
RGS2 o2	5±7	0±6	5±4	4±4	1±3

Line shifts in mÅ, errors are standard deviations.
GR08: Data from CP07
GR08s: Data from CP07, with Solar Angle correction.
GR12: This work without velocity corrections.
GR12v: This work with system and barycentre velocity correction.
GR12vs:This work with star+barycentre velocity and Solar Angle correction.

Gonzáles-Riestra (2012)
http://xmm2.esac.esa.int/docs/documents/CAL-TN-0098-1-1.pdf



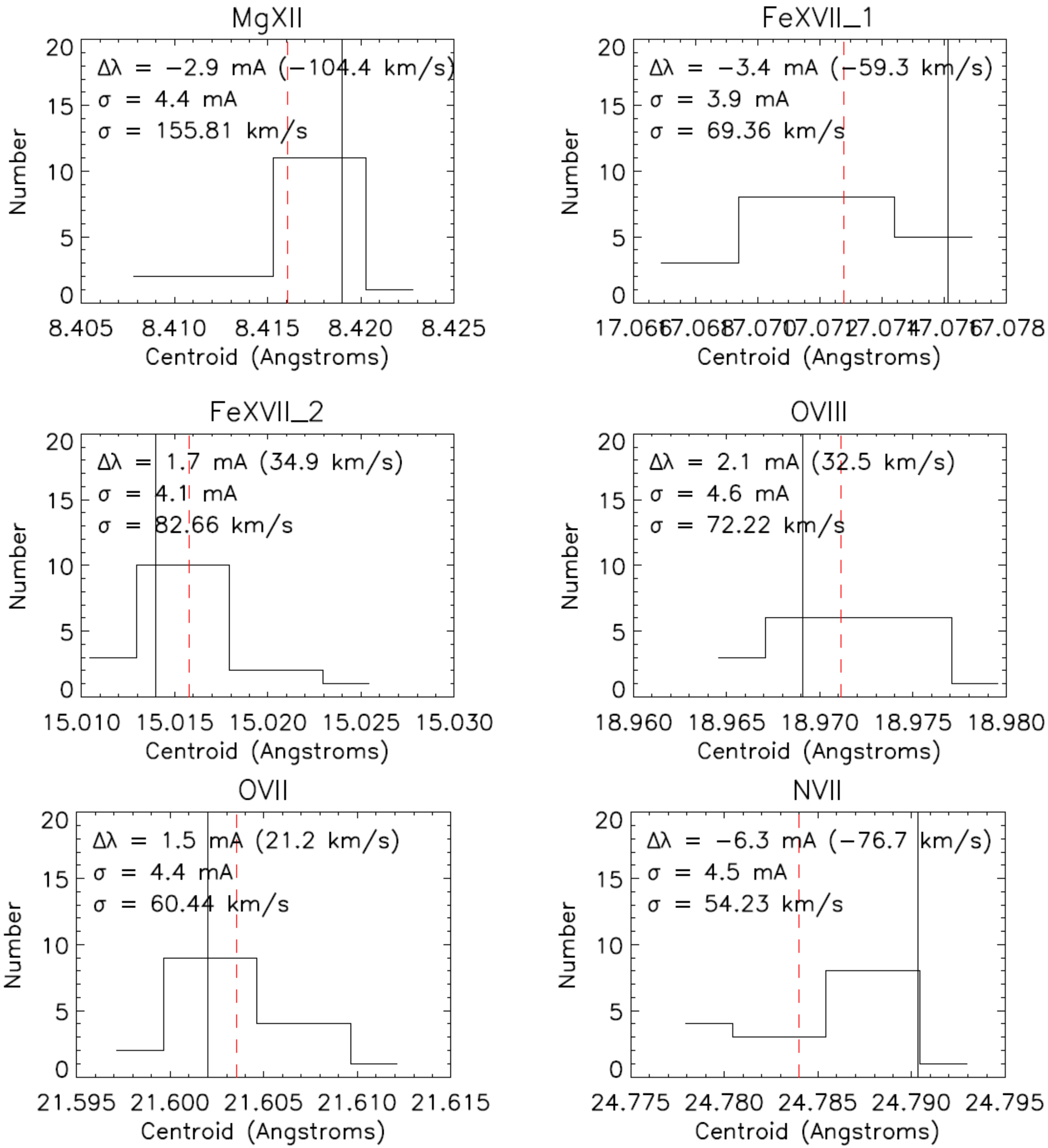
Gonzáles-Riestra (2015)
http://xmm2.esac.esa.int/docs/documents/CAL-TN-0030.pdf

Mrk 509 proposal coords vs. SIMBAD

ID	Angular Distance
30720	2 arcmin
30609	0 arcsec
60139	4.9 arcsec

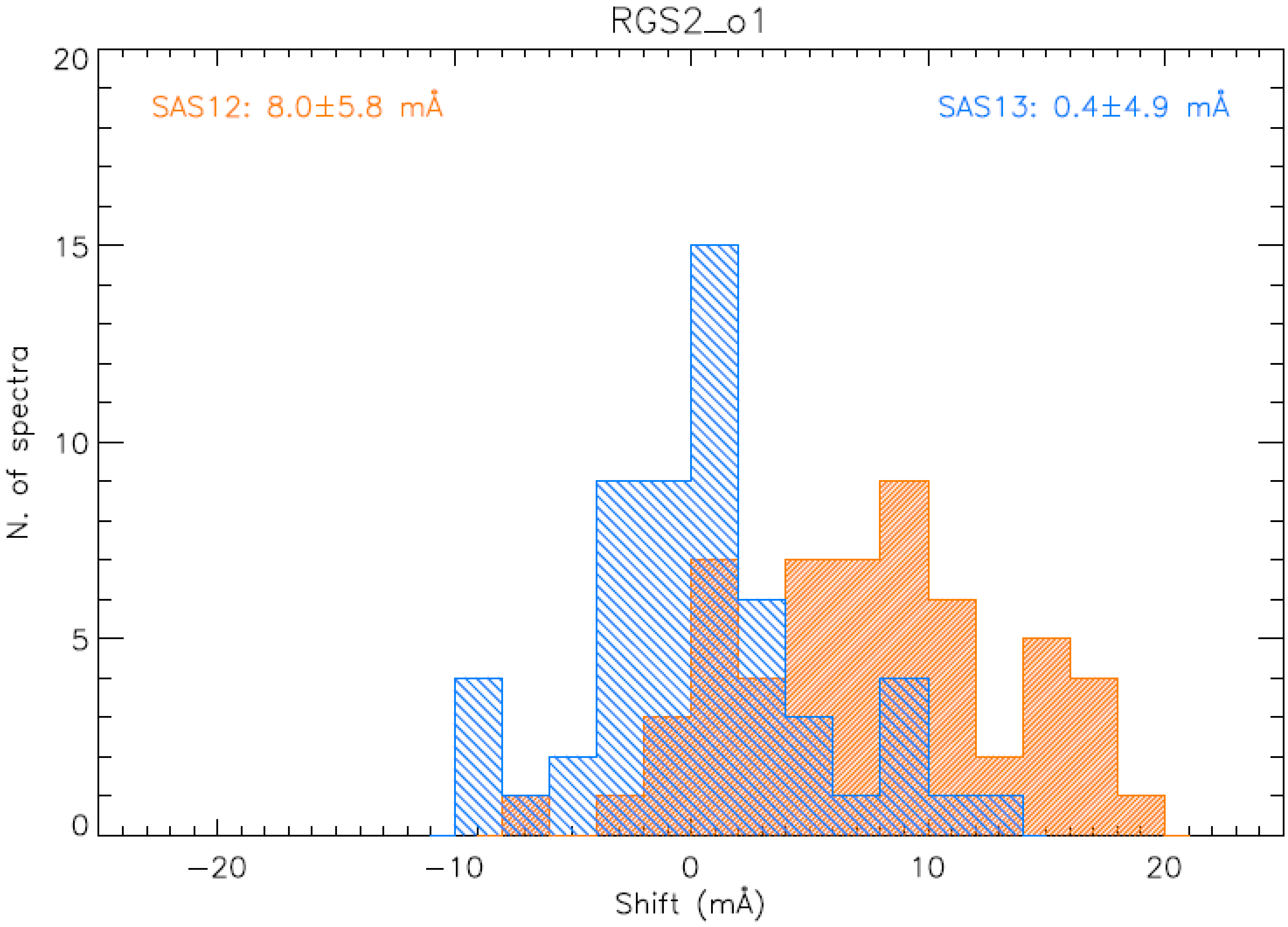
1 arcsec err ➔ 2.3 mA error (Gonzáles-Riestra 2015)

This is 32 km/s error per arcsec offset at 21.6 Angstroms!!

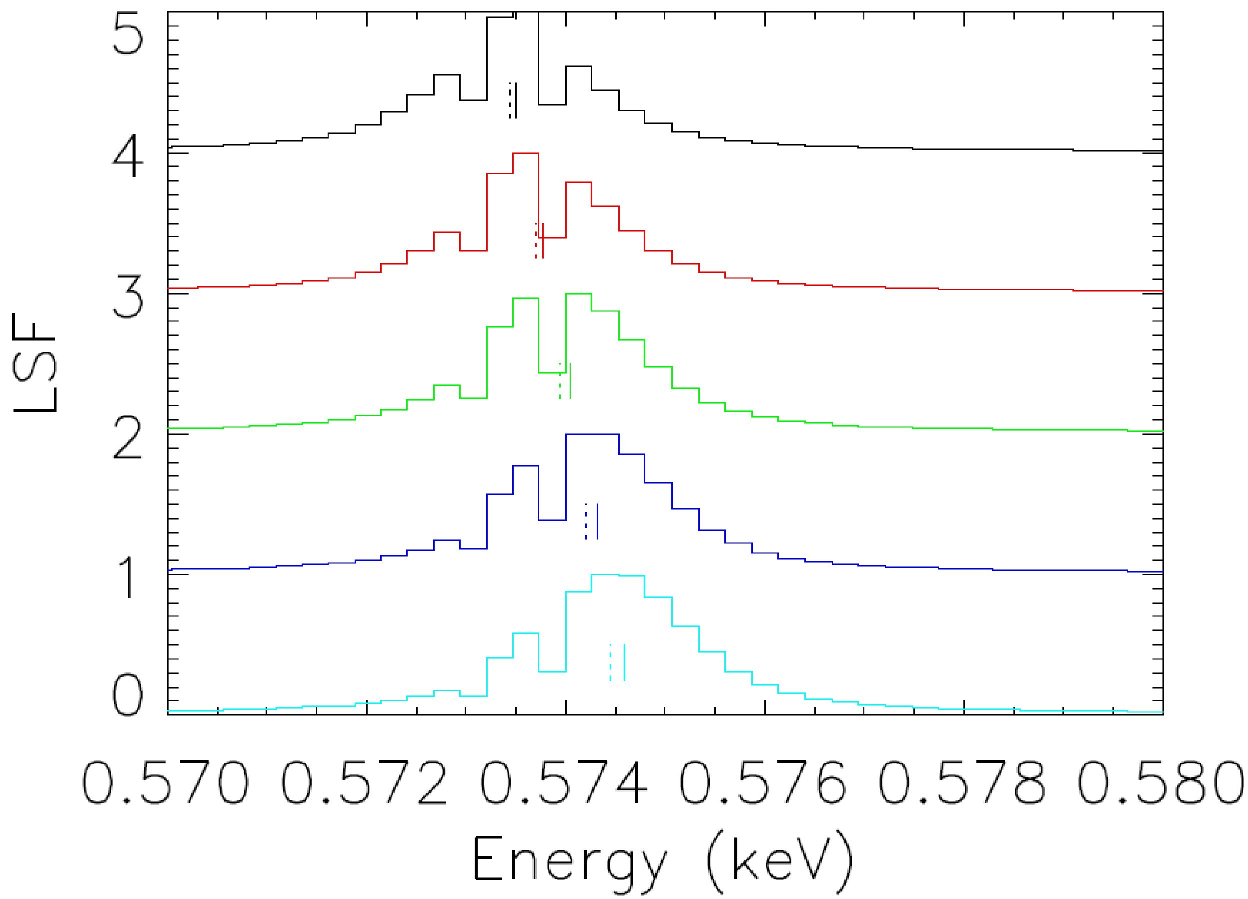


The uncertainty in the wavelength is 4-5 mA, so the spectrum is much more forgiving at OVII

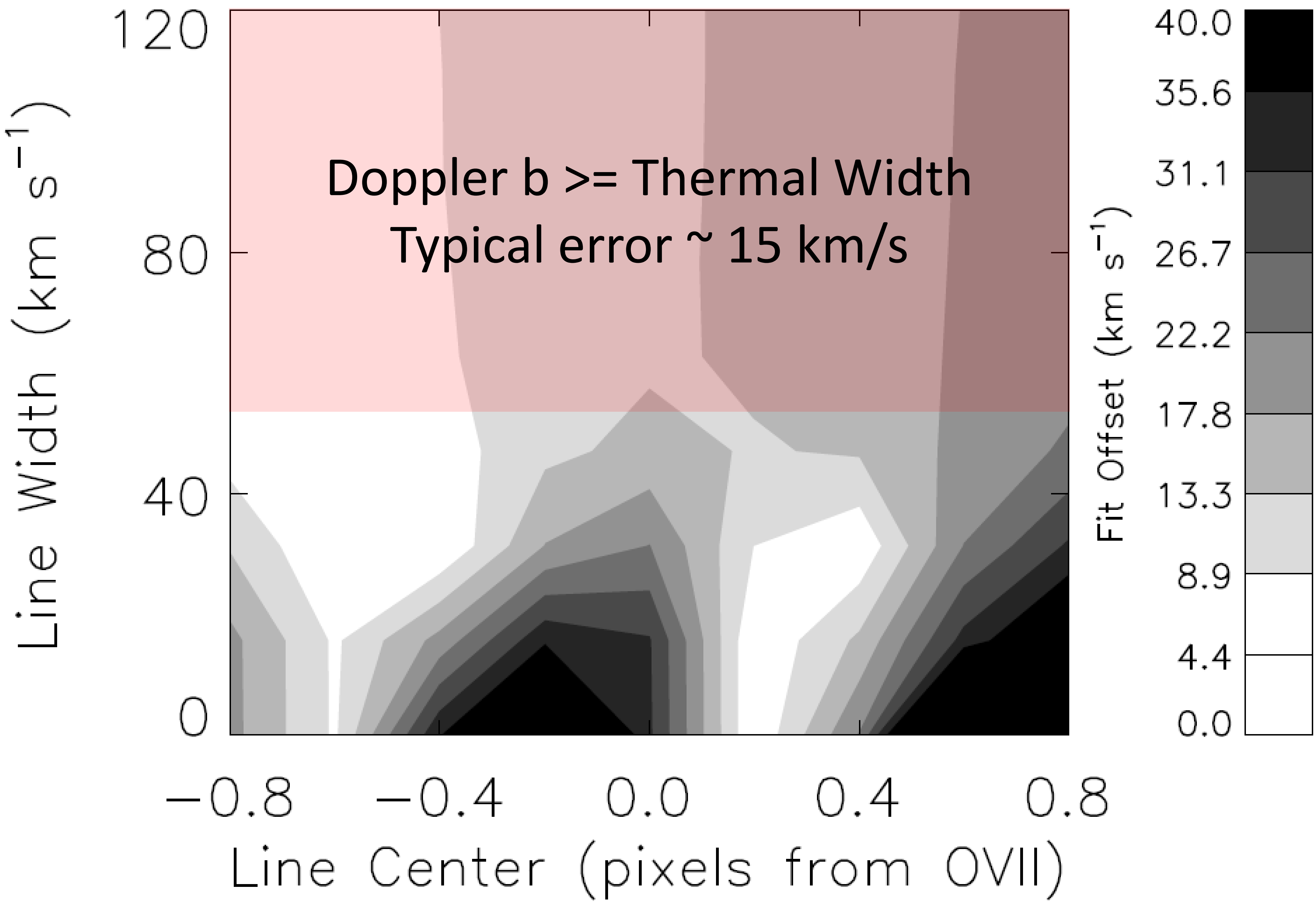
Name	Stacked RGS (km s^{-1})	Stacked LETG (km s^{-1})
Capella	0 ± 11	1 ± 22
HR 1099	-7 ± 22	10 ± 41
Mrk 421	-69 ± 19	-70 ± 55
PKS 2155-304	-44^{+42}_{-45}	-6^{+71}_{-65}
3C 273	33^{+41}_{-46}	66^{+93}_{-82}



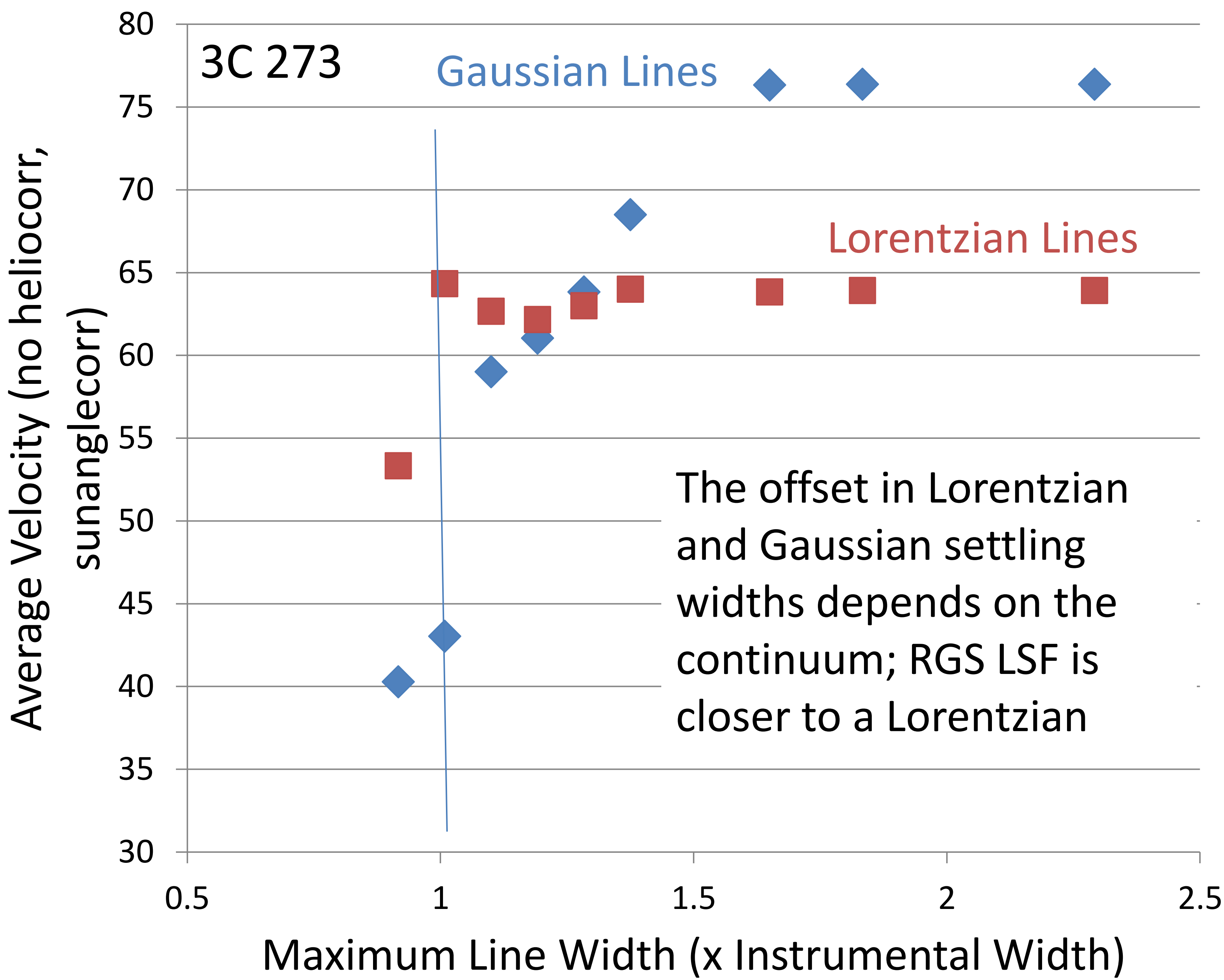
Projected heliocentric motion and sun angle corrections remove systematic wavelength shifts (Gonzáles-Riestra 2013)

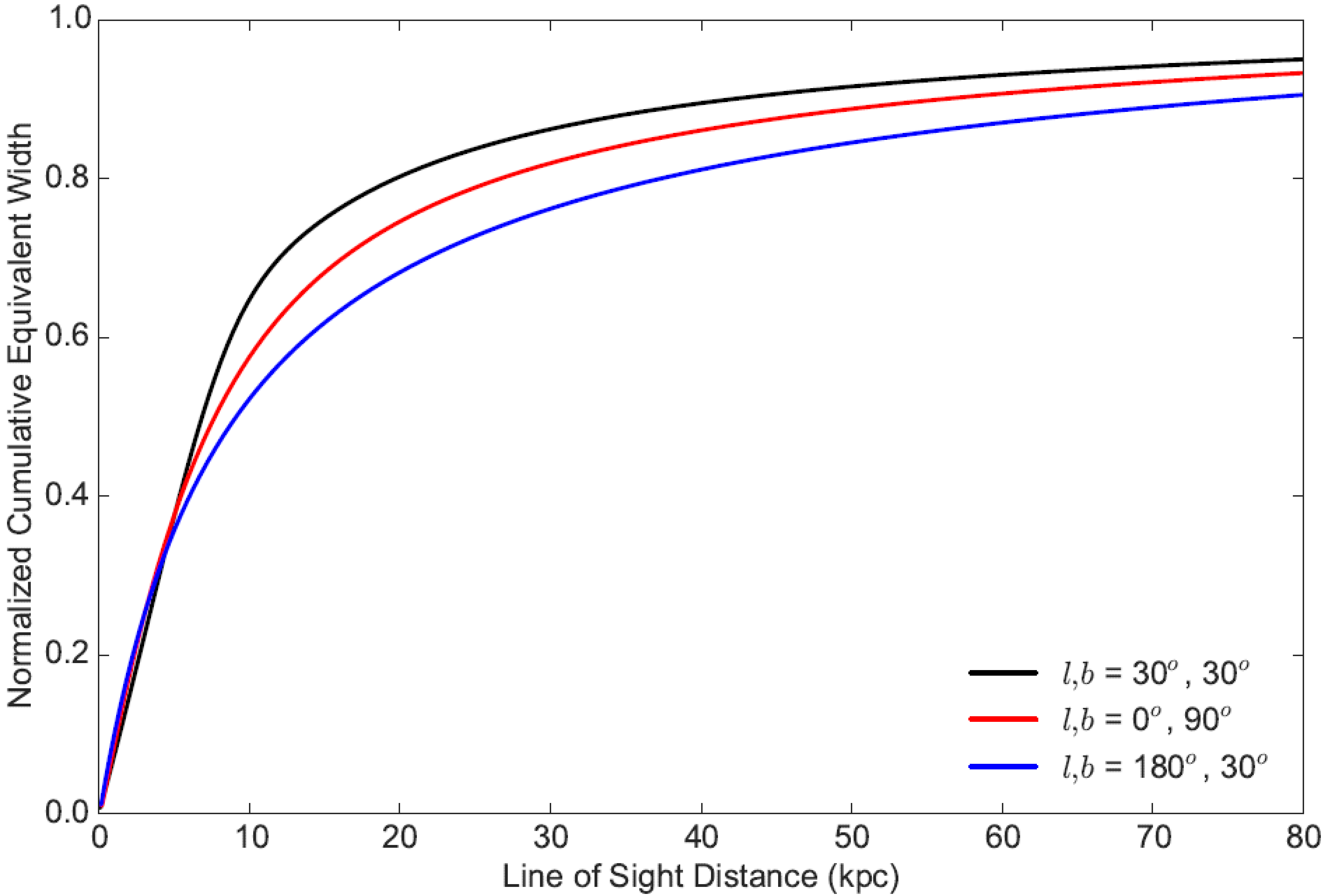


The largest source of systematic error appears to be asymmetry in the line-spread function (LSF), the instrumental response to a δ-function



Doppler b >= Thermal Width
Typical error ~ 15 km/s
120
80
40
0
Line Width (km s^{-1})
−0.8
−0.4
0.0
0.4
0.8
Line Center (pixels from OVII)
40.0
35.6
31.1
26.7
22.2
17.8
13.3
8.9
4.4
0.0
Fit Offset (km s^{-1})


3C 273
Gaussian Lines
Lorentzian Lines
The offset in Lorentzian and Gaussian settling widths depends on the continuum; RGS LSF is closer to a Lorentzian
Average Velocity (no heliocorr, sunanglecorr)
Maximum Line Width (x Instrumental Width)
80
75
70
65
60
55
50
45
40
35
30
0.5
1
1.5
2
2.5



1.0
0.8
0.6
0.4
0.2
0.0
Normalized Cumulative Equivalent Width
0
10
20
30
40
50
60
70
80
Line of Sight Distance (kpc)
l,b = 30^o , 30^o
l,b = 0^o , 90^o
l,b = 180^o , 30^o

Stationary Halo | Corotating Halo