A Spatially Resolved Mass Outflow Rate for Markarian 573

Mitchell Revalski

AGN Winds

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Physics & Astronomy

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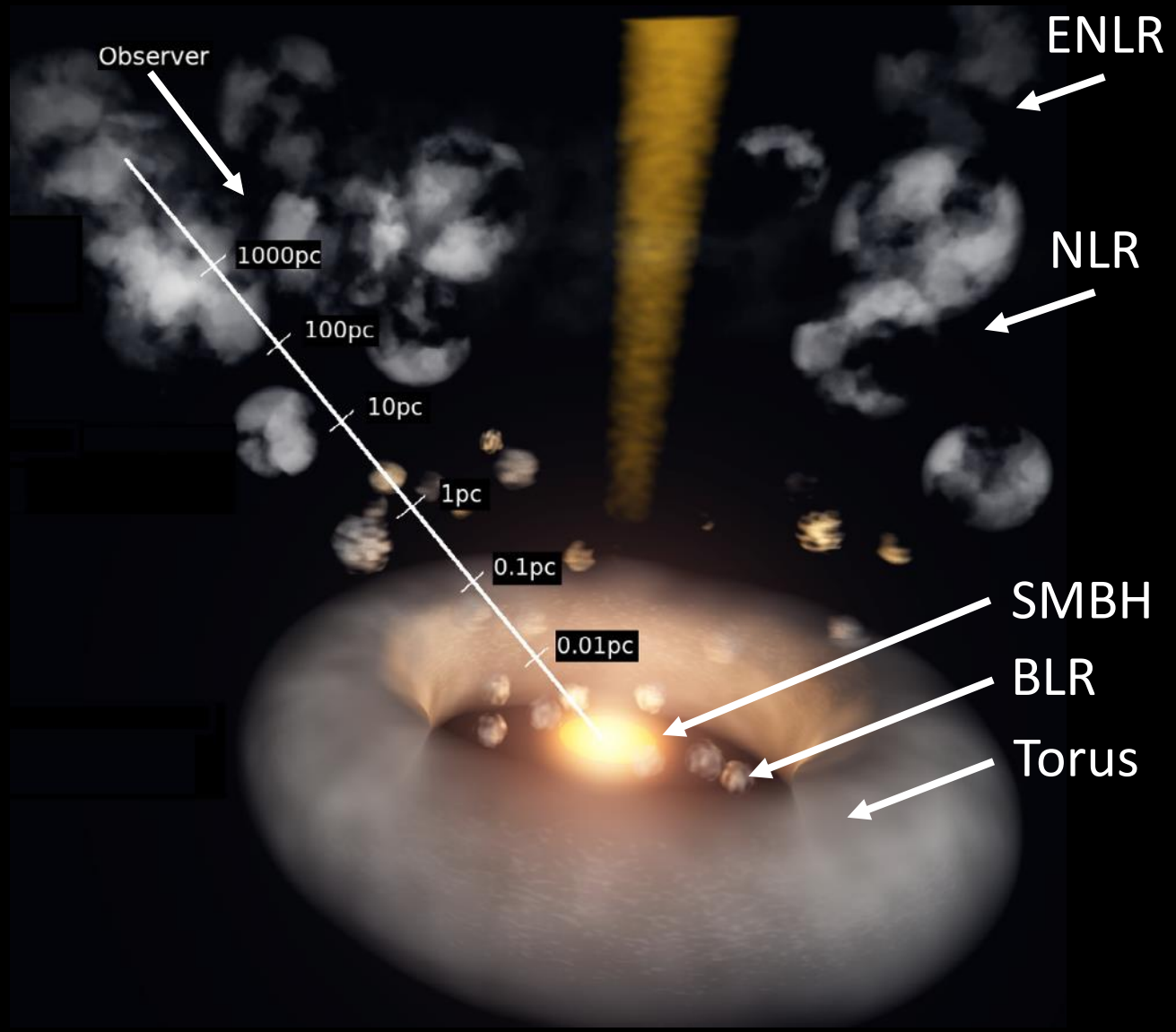
Narrow Line Region Outflows

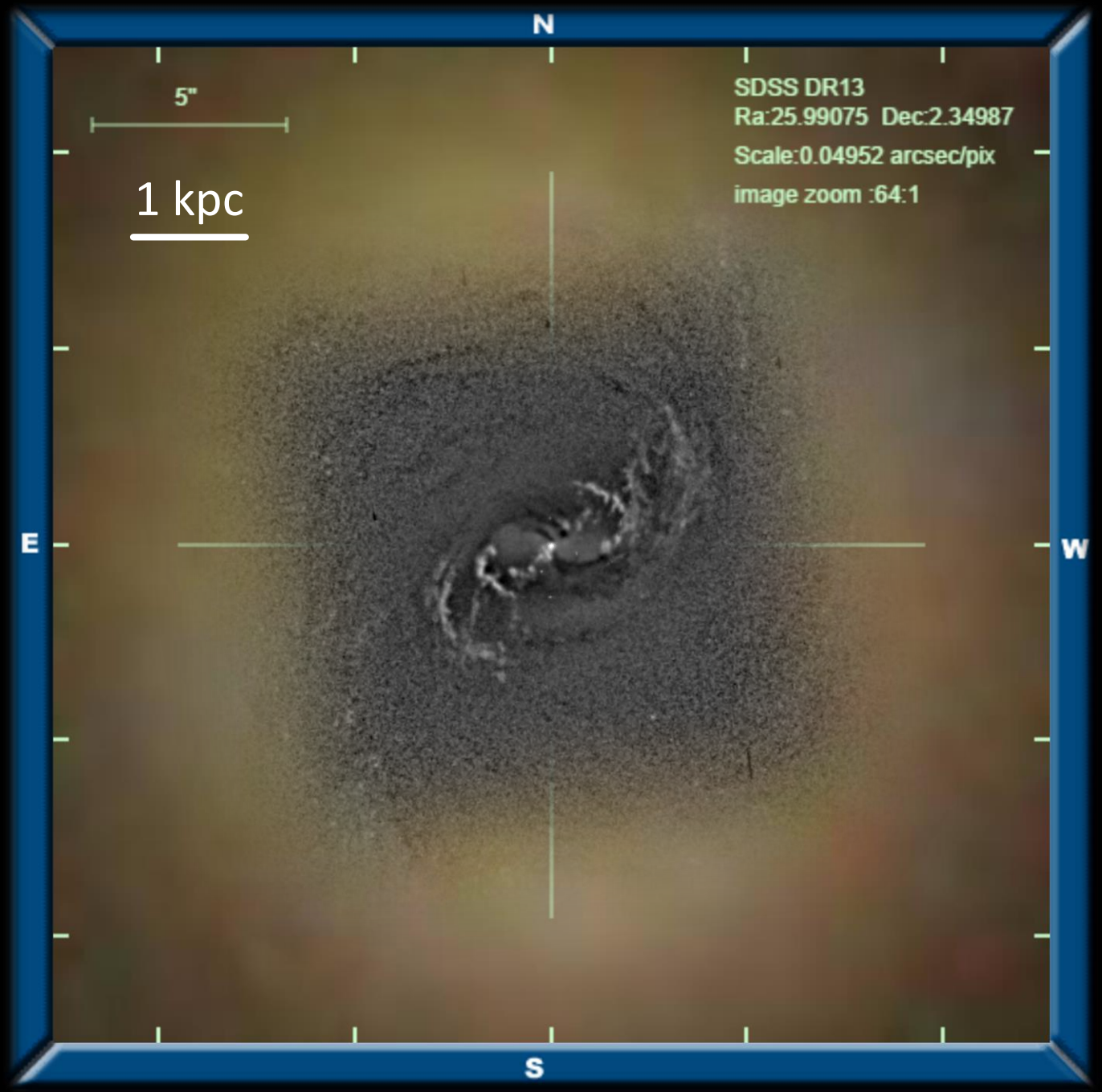
- Do NLR mass outflows:
- Provide significant bulge feedback?
- Scale with host AGN properties?
- Need *spatially-resolved* outflow rates (Crenshaw+ 2015)

➢ Quantify NLR mass outflow rates



Modified from Smith et al. 2008, A&A, 490, 103

Active Galaxy Markarian 573

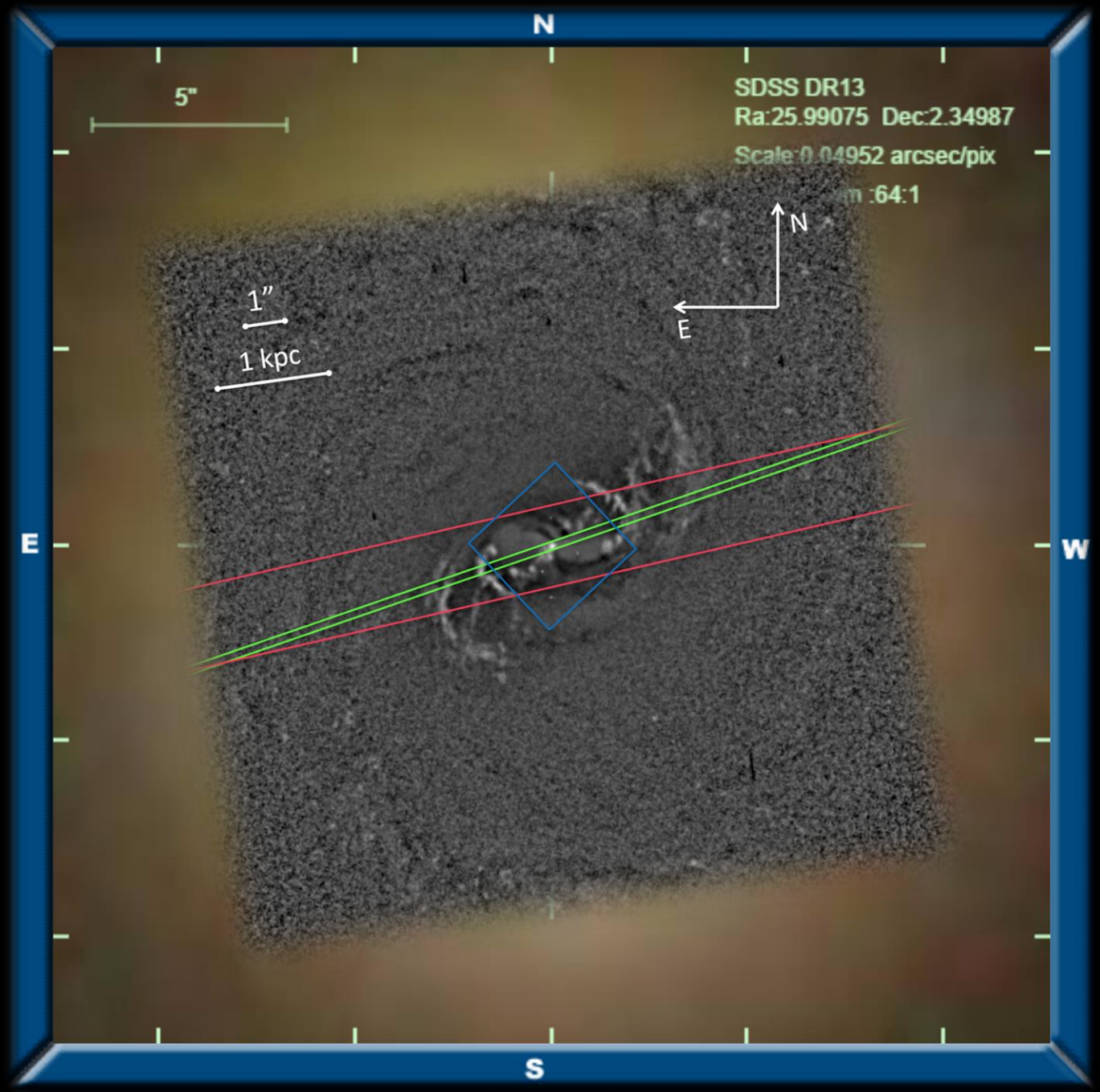

N
E
W
S
5"
1 kpc
SDSS DR13
Ra:25.99075 Dec:2.34987
Scale:0.04952 arcsec/pix
image zoom :64:1

Overview of Methodology

- Determine $\dot{\mathrm{M}}$ and $\mathrm{L_{KE}}$ at each position
- Velocity → Doppler motions corrected for orientation effects
- Mass → model spectra and derive conversion factor from luminosity and density to mass
- $\dot{\mathrm{M}}$ → account for total NLR mass with [O III] imaging and conversion factor

$$\dot{\mathrm{M}} = \left(\frac{\mathrm{M}v}{\delta r}\right)$$

$$\mathrm{L_{KE}} = \left(\frac{\dot{\mathrm{M}}v^2}{2}\right)$$

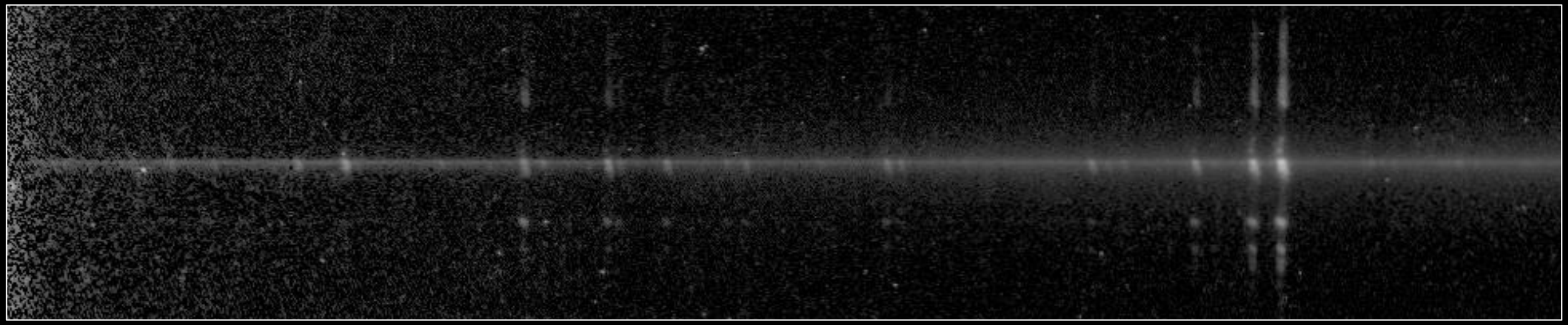


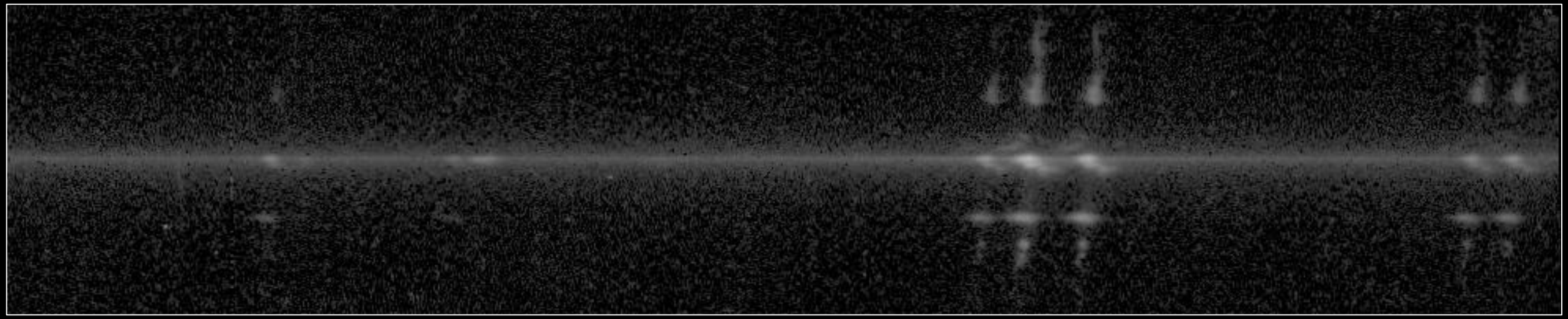
HST STIS

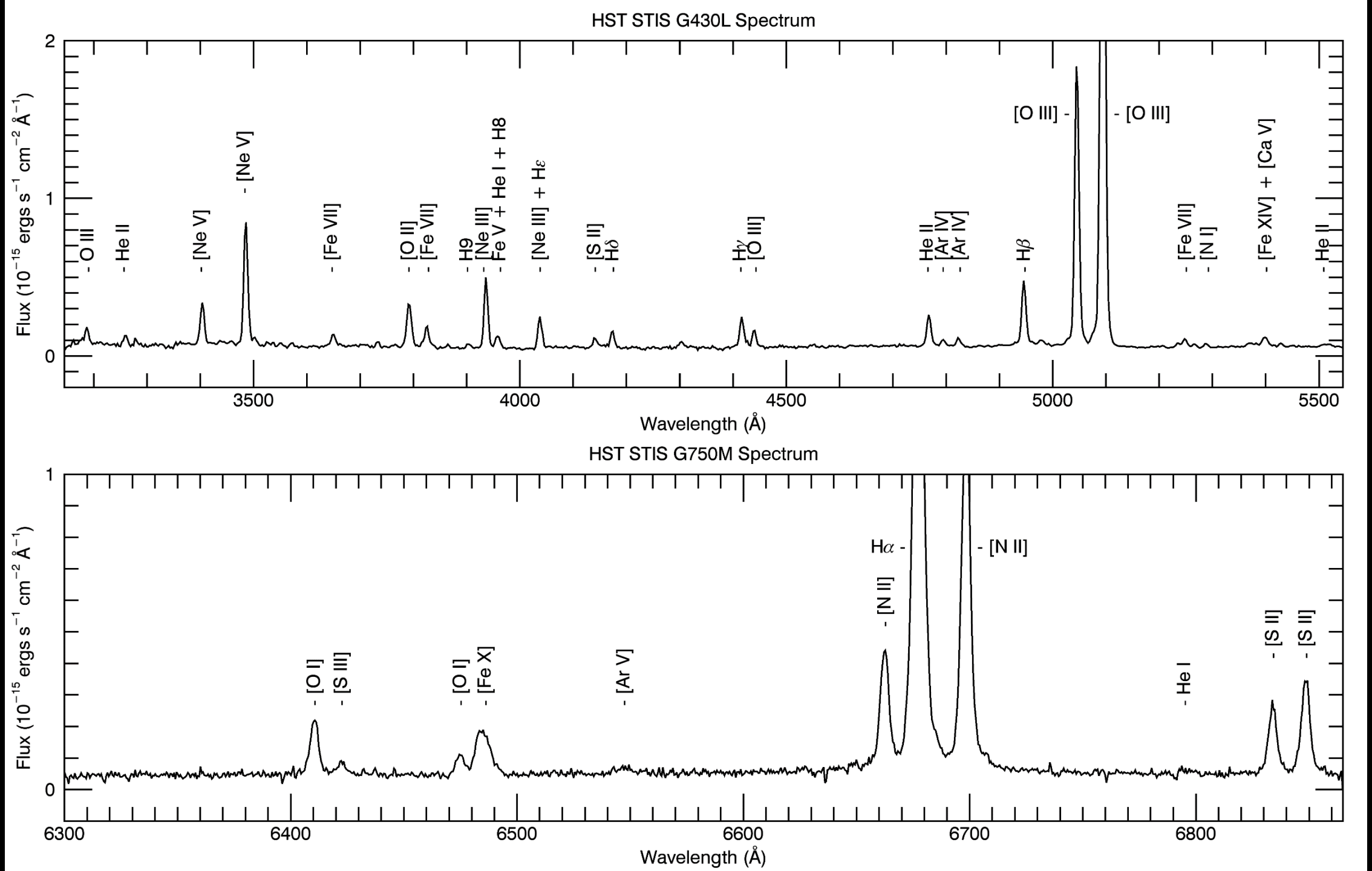
APO DIS

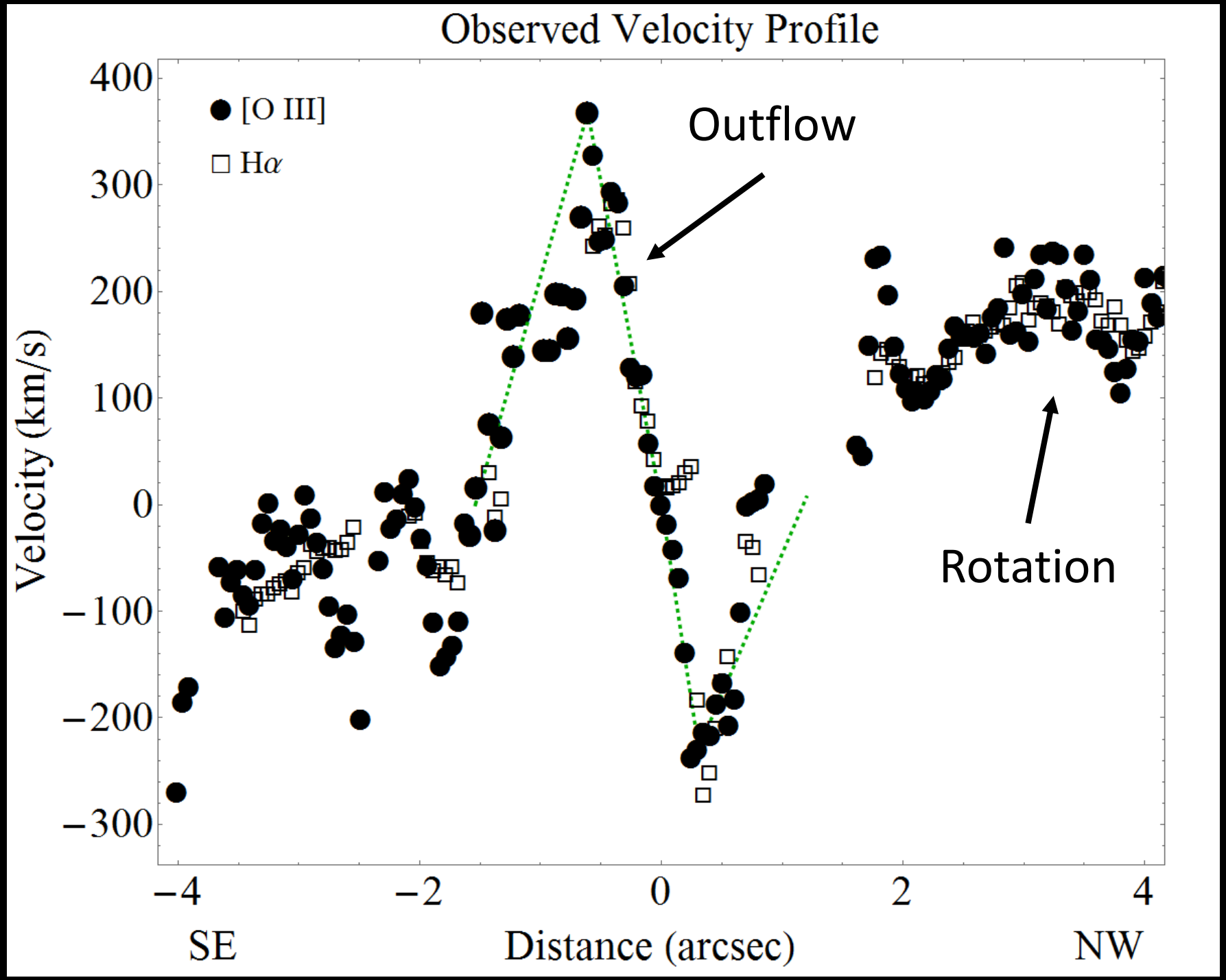
Gemini NIFS

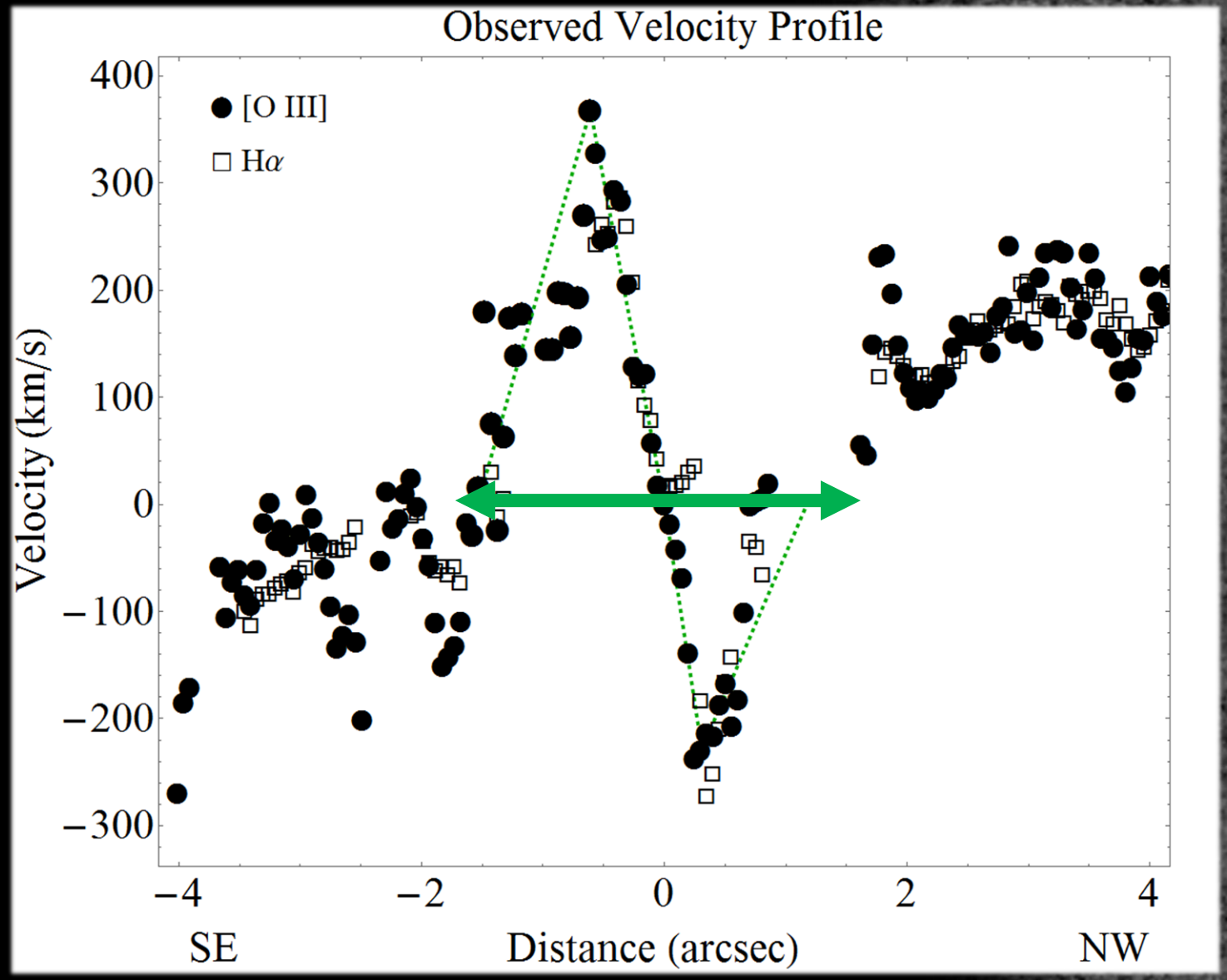
Extract Spectra at each Spatial Location



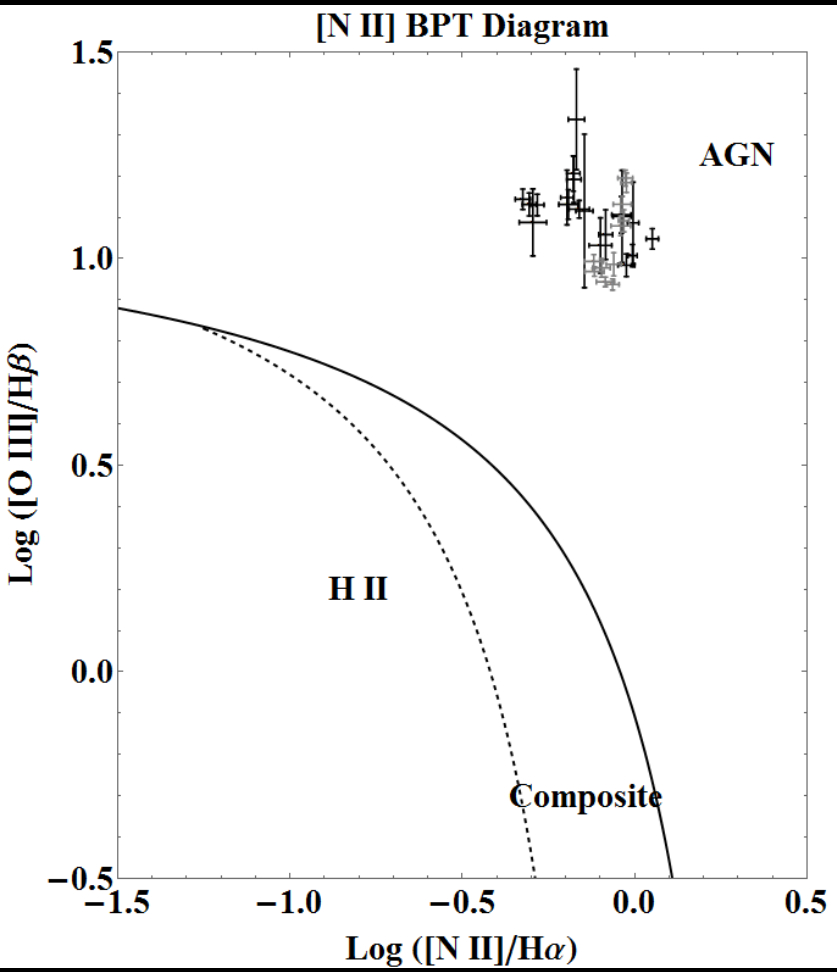


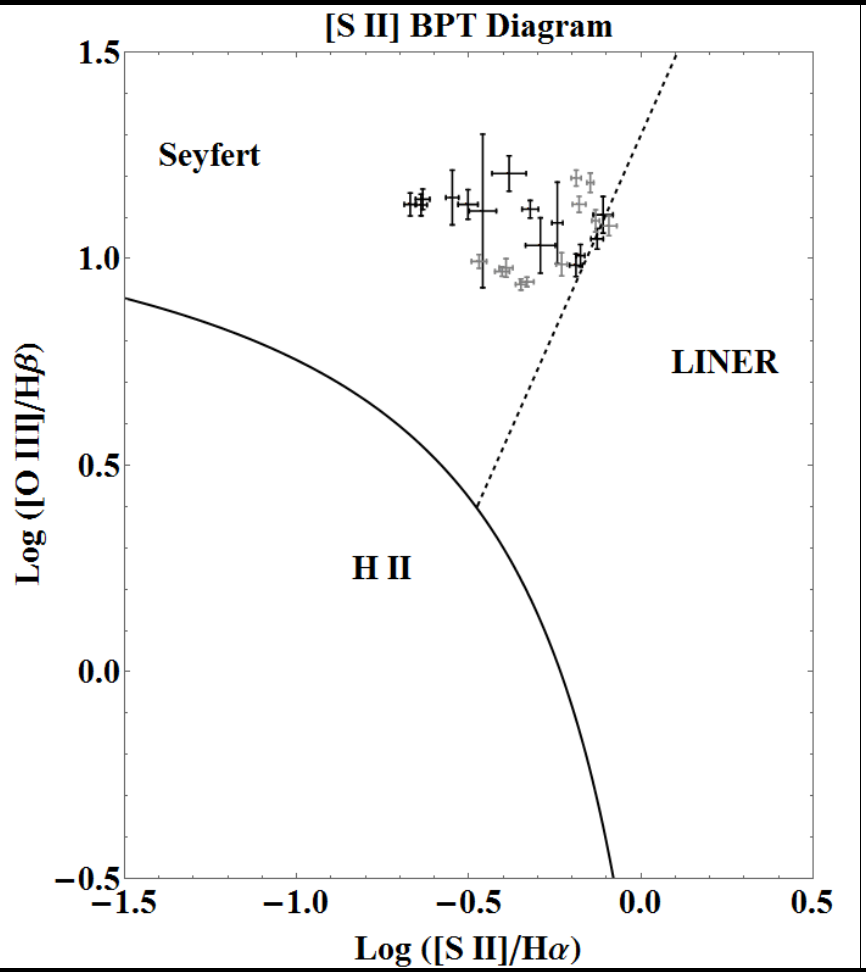

HST STIS G430L Spectrum
Flux (10^{-15} ergs s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
- O III
- He II
- [Ne V]
- [Ne V]
- [Fe VII]
- [O II]
- [Fe VII]
- H9
- [Ne III]
- Fe V + He I + H8
- [Ne III] + Hε
- [S II]
- Hδ
- Hγ
- [O III]
- He II
- [Ar IV]
- [Ar IV]
- Hβ
[O III] -
- [O III]
- [Fe VII]
- [N I]
- [Fe XIV] + [Ca V]
- He II
HST STIS G750M Spectrum
Flux (10^{-15} ergs s^{-1} cm^{-2} Å^{-1})
Wavelength (Å)
- [O I]
- [S III]
- [O I]
- [Fe X]
- [Ar V]
Hα -
- [N II]
- [N II]
- He I
- [S II]
- [S II]

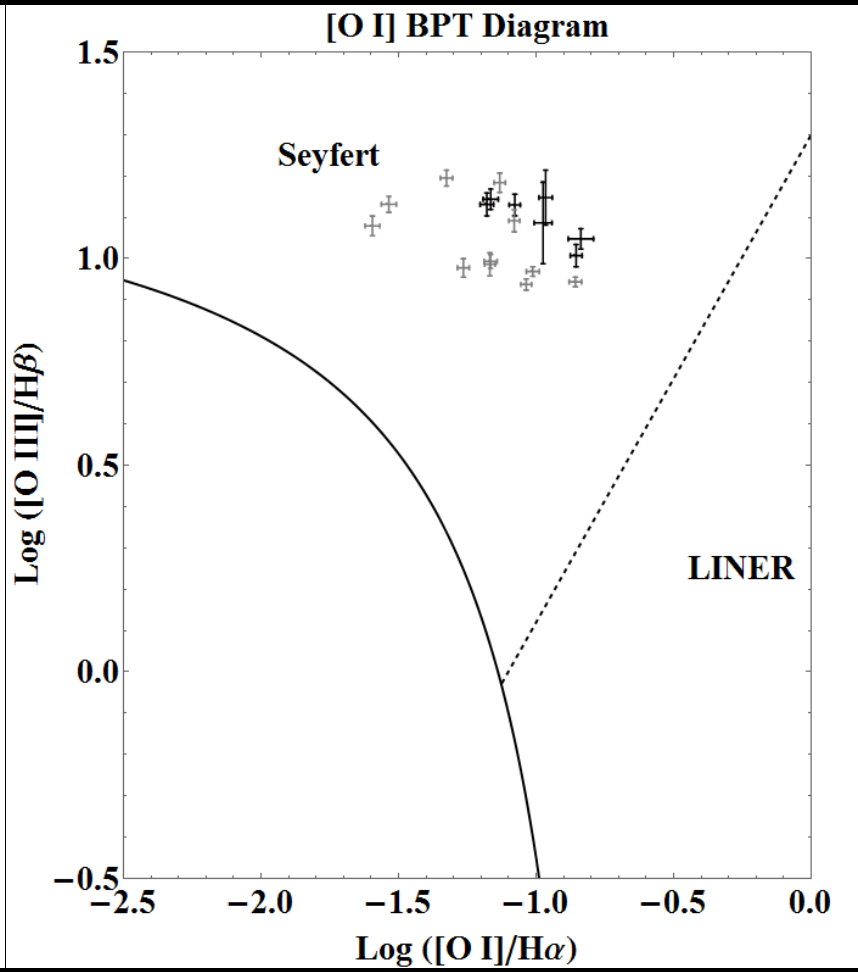

Observed Velocity Profile
[O III]
Hα
Outflow
Rotation
Velocity (km/s)
400
300
200
100
0
−100
−200
−300
−4
−2
0
2
4
SE
Distance (arcsec)
NW


Observed Velocity Profile
[O III]
Hα
400
300
200
100
0
−100
−200
−300
Velocity (km/s)
−4
−2
0
2
4
SE
Distance (arcsec)
NW

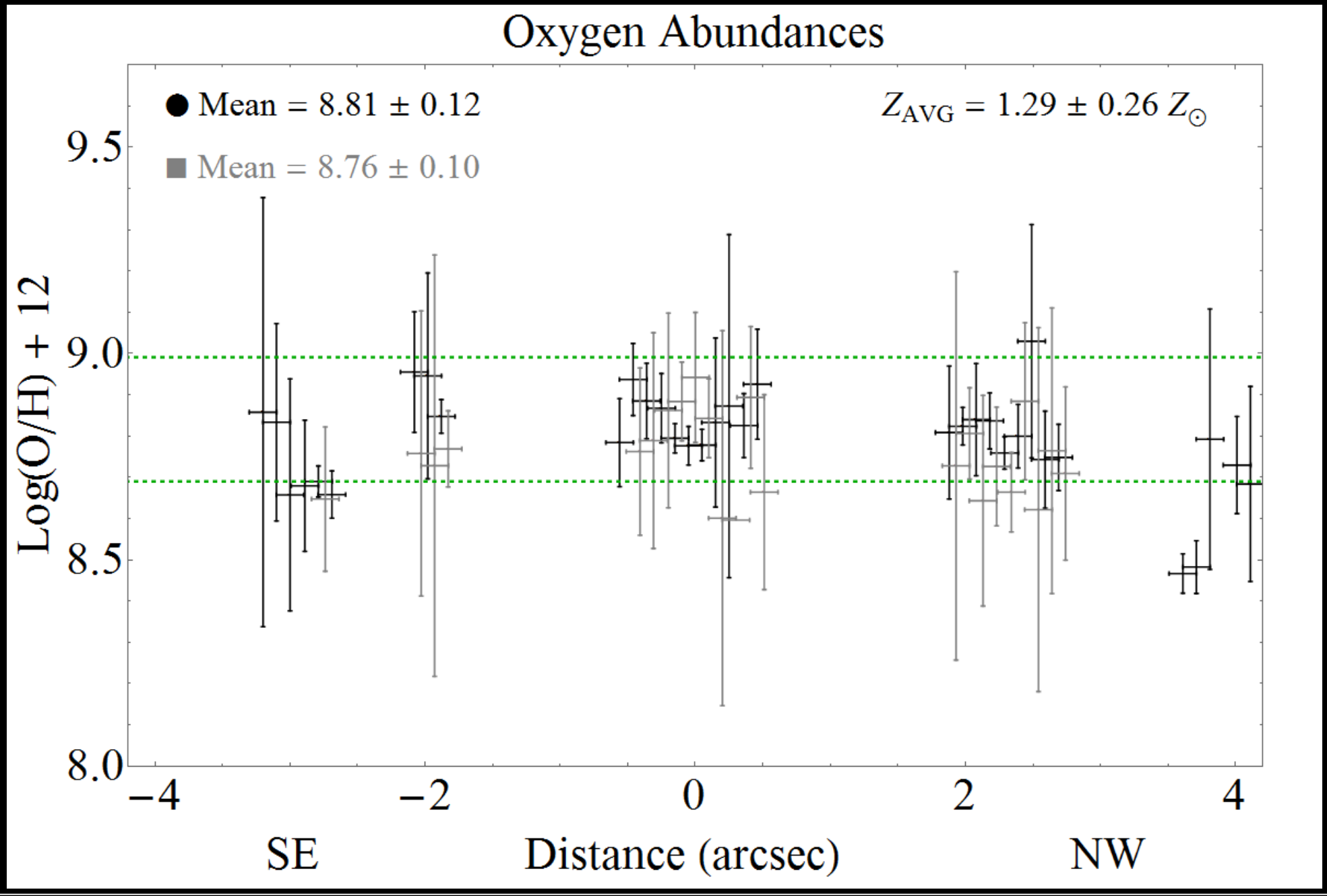
Diagnostics: Ionization



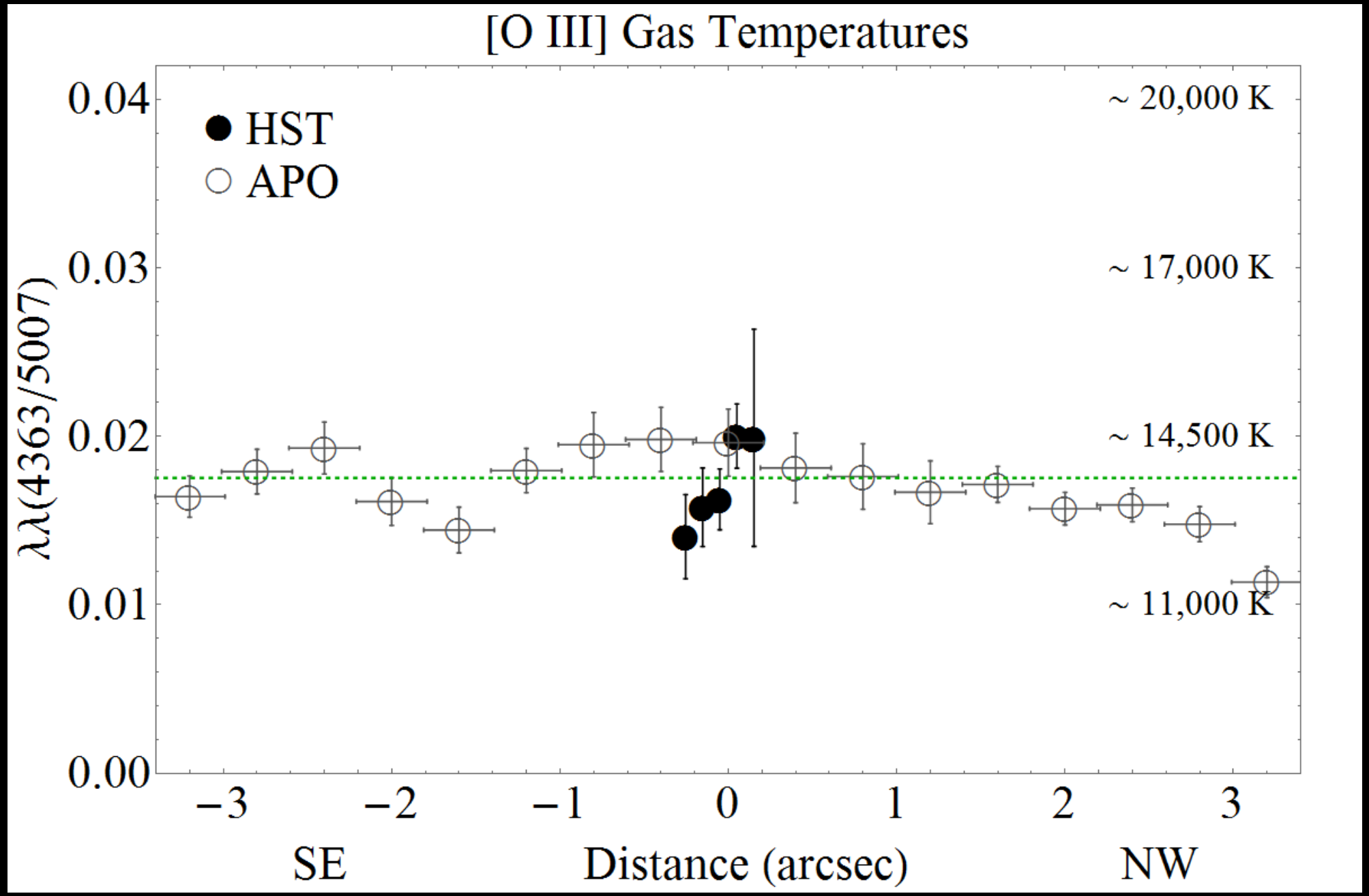




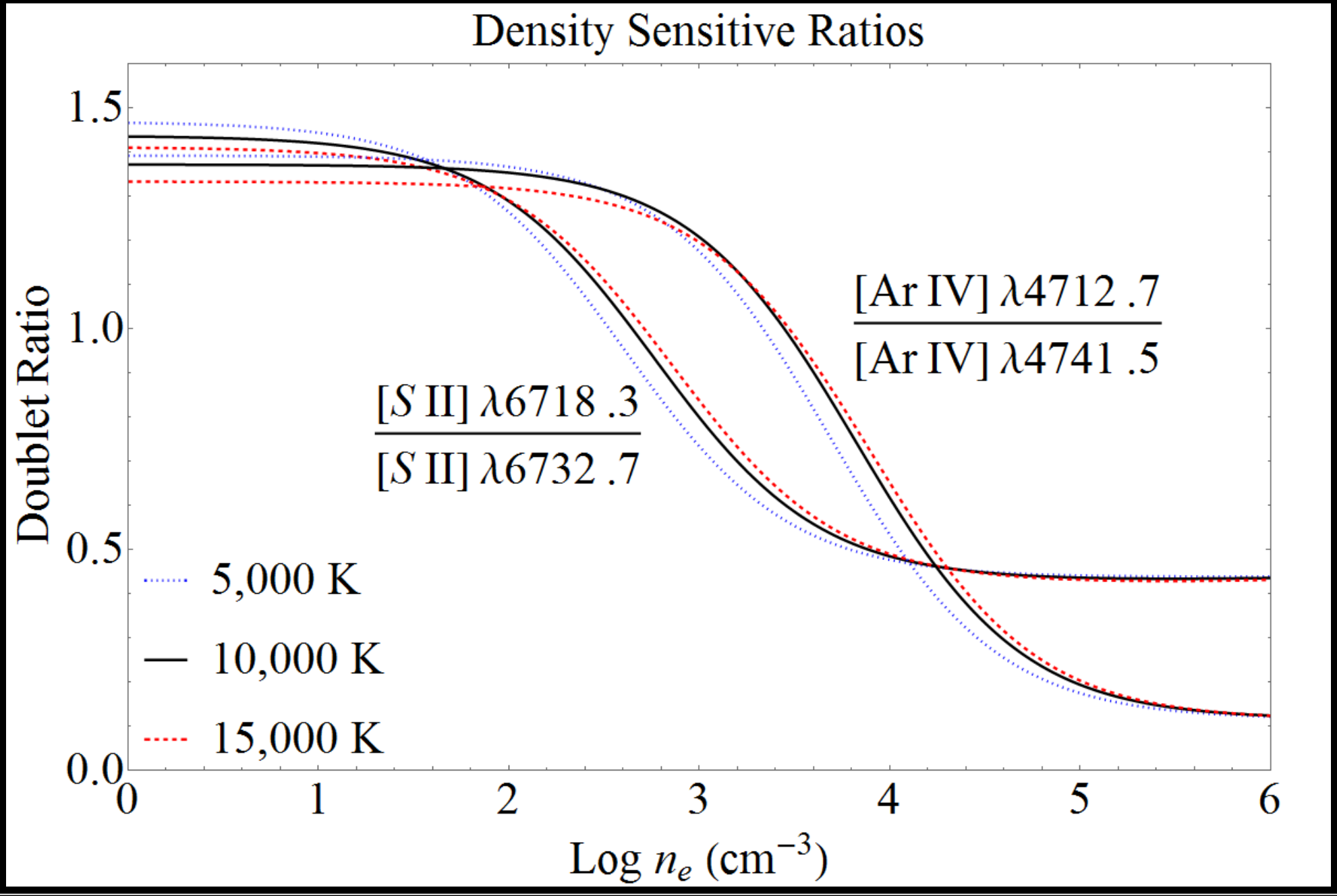
Baldwin+ 1981, Veilleux+ 1987, Kewley+ 2001;2006, Kauffmann+ 2003, Stasińska+ 2006, Meléndez+ 2014



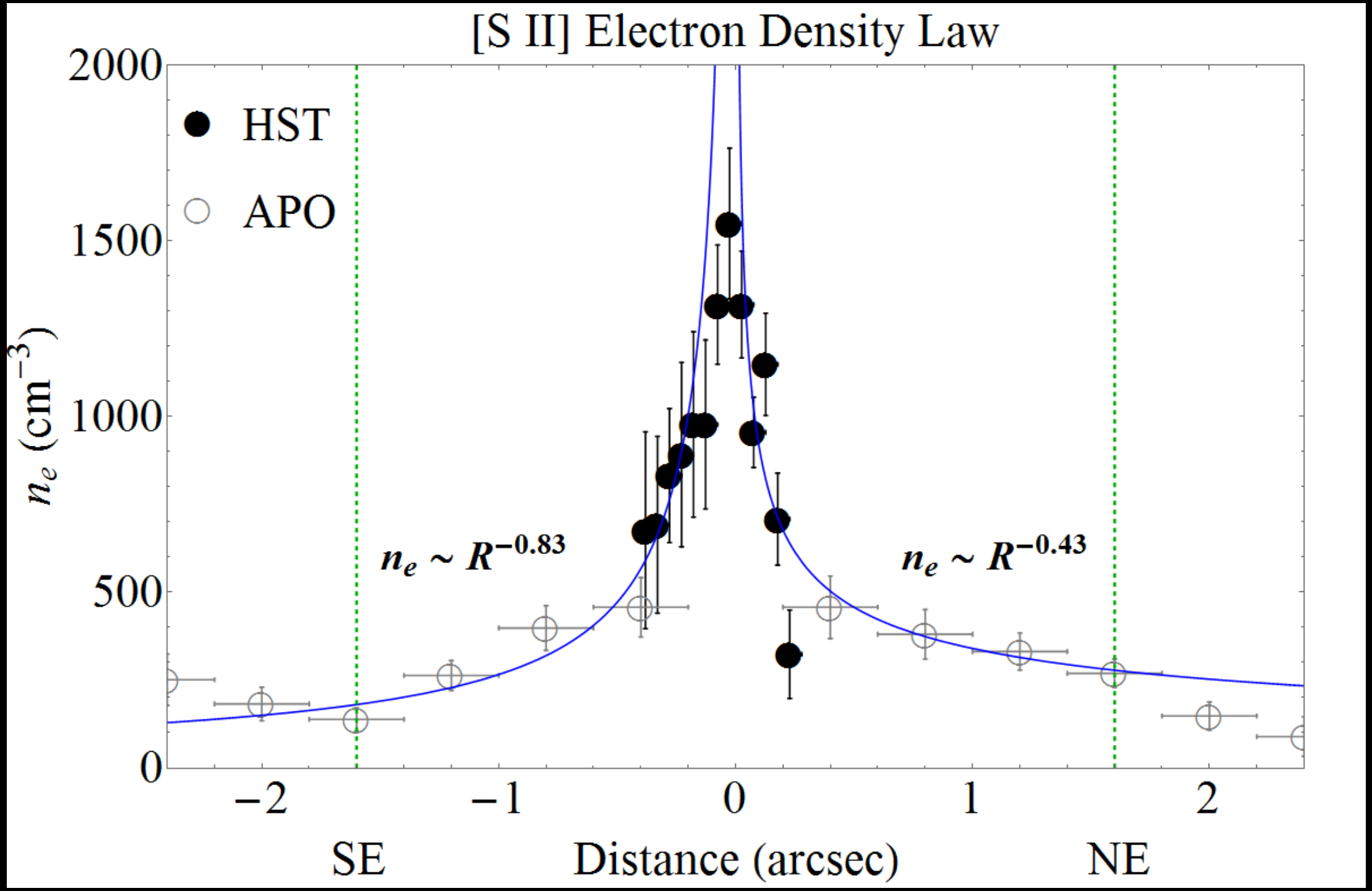
Storchi-Bergmann+ 1998, Asplund+ 2009, Dors+ 2015, Castro+ 2017



Osterbrock+ 2006, Draine 2011



Osterbrock+ 2006, Draine 2011, Ferland+ 2013


[S II] Electron Density Law
HST
APO
n_e (cm^{-3})
2000
1500
1000
500
0
$n_e \sim R^{-0.83}$
$n_e \sim R^{-0.43}$
−2
−1
0
1
2
SE
Distance (arcsec)
NE

Photoionization Modeling

- Inputs → luminosity, spectral energy distribution, abundances, dust, distance, density…

$$U = \left(\frac{Q(H)}{4\pi r^2 n_H c} \right)$$

- Outputs → emission line fluxes and ratios, column densities

- Create multicomponent models and select best fit

Osterbrock+ 2006, Collins+ 2009, Kraemer+ 2009

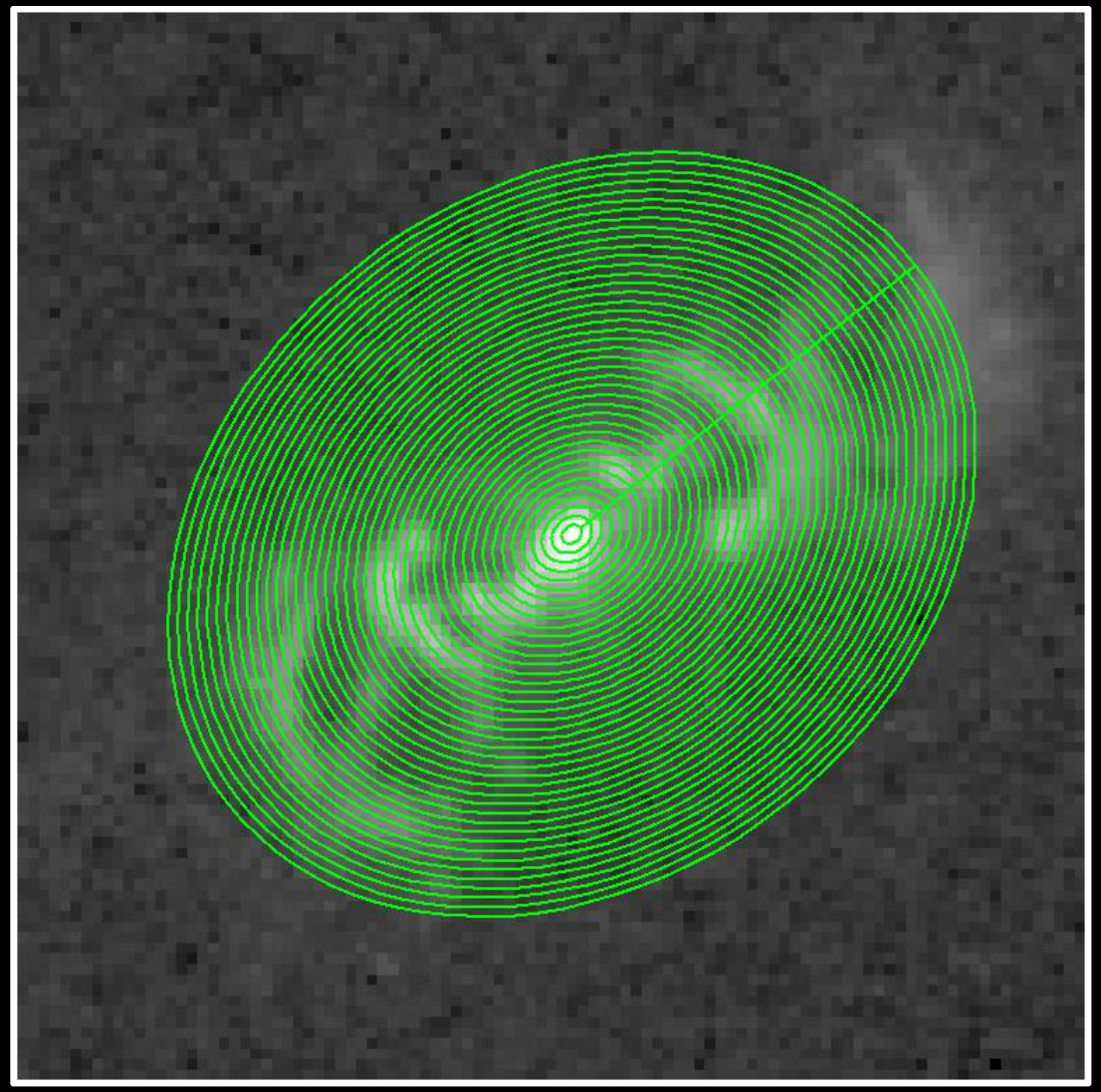
Determining the NLR Mass

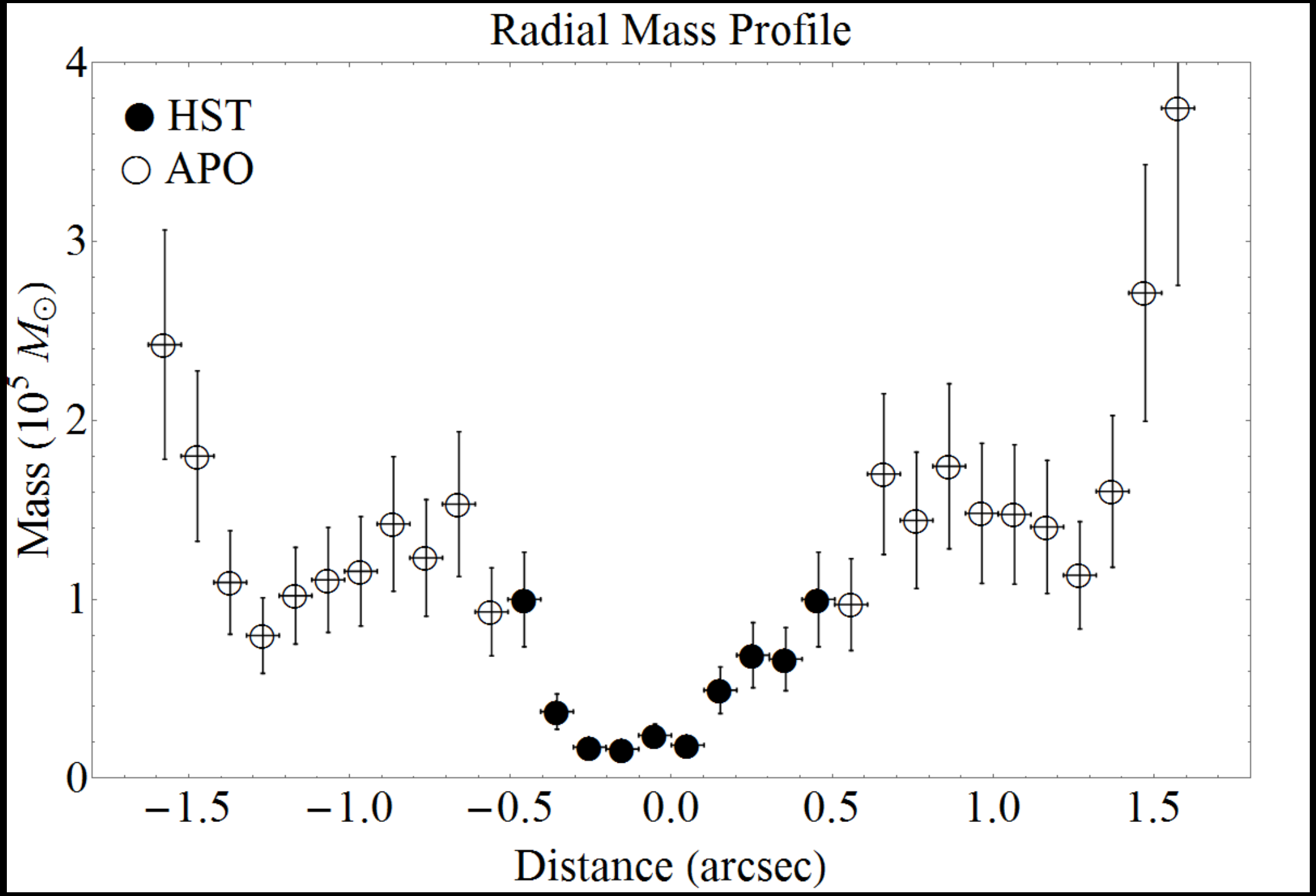
- $\mathrm{M} = \mathrm{N_H} \mu \mathrm{m_p} \left(\frac{\mathrm{L(H\beta)}}{\mathrm{F(H\beta)_{mod}}} \right) \rightarrow$ slit

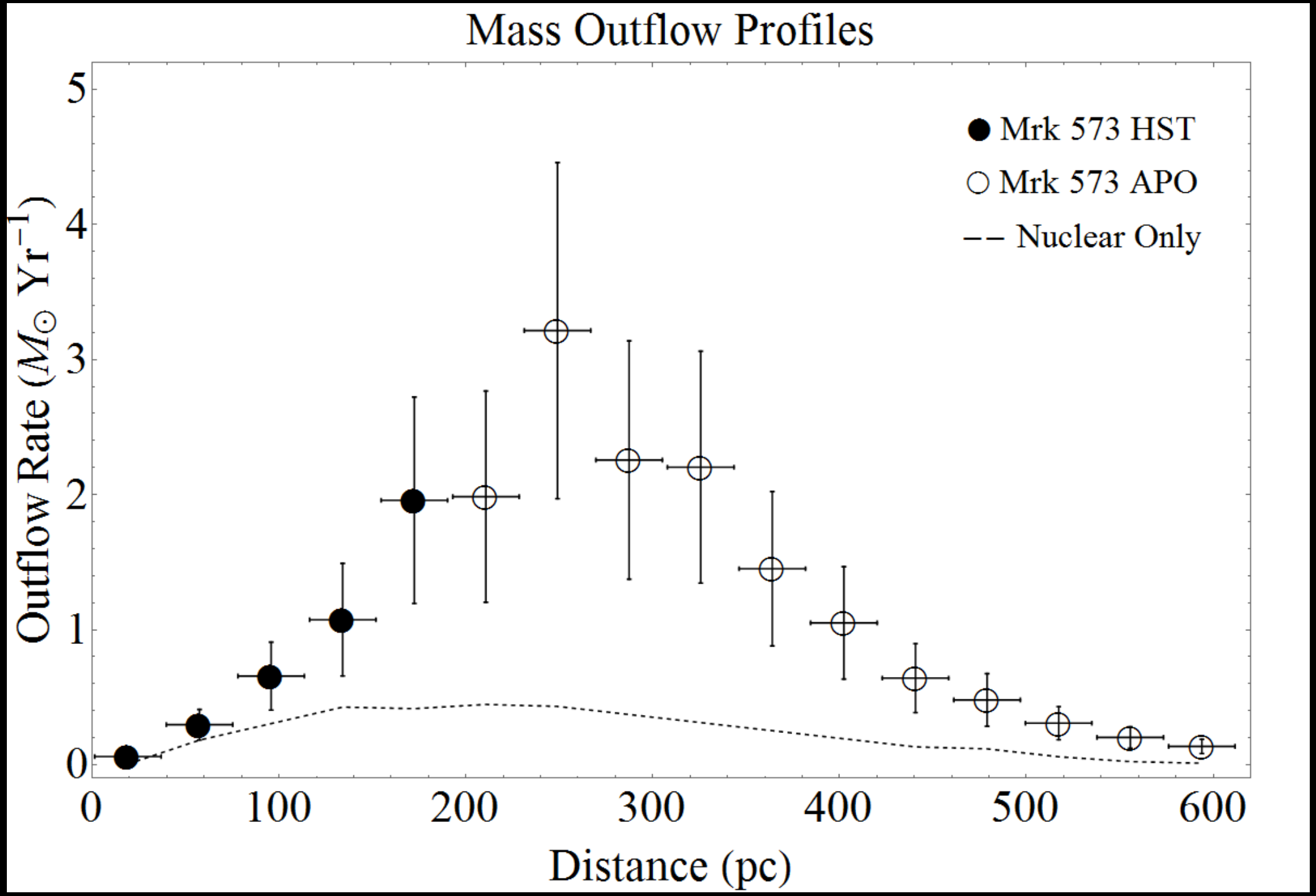
- $\mathrm{M} \rightarrow$ ionized gas mass
- $\mathrm{N_H} \rightarrow$ column density ($\mathrm{cm^{-2}}$)
- $\mu \rightarrow$ mean mass per particle (1.36)
- $\mathrm{m_p} \rightarrow$ proton mass
- $\mathrm{L(H\beta)} \rightarrow$ observed Hβ luminosity
- $\mathrm{F(H\beta)_{mod}} \rightarrow$ model Hβ flux

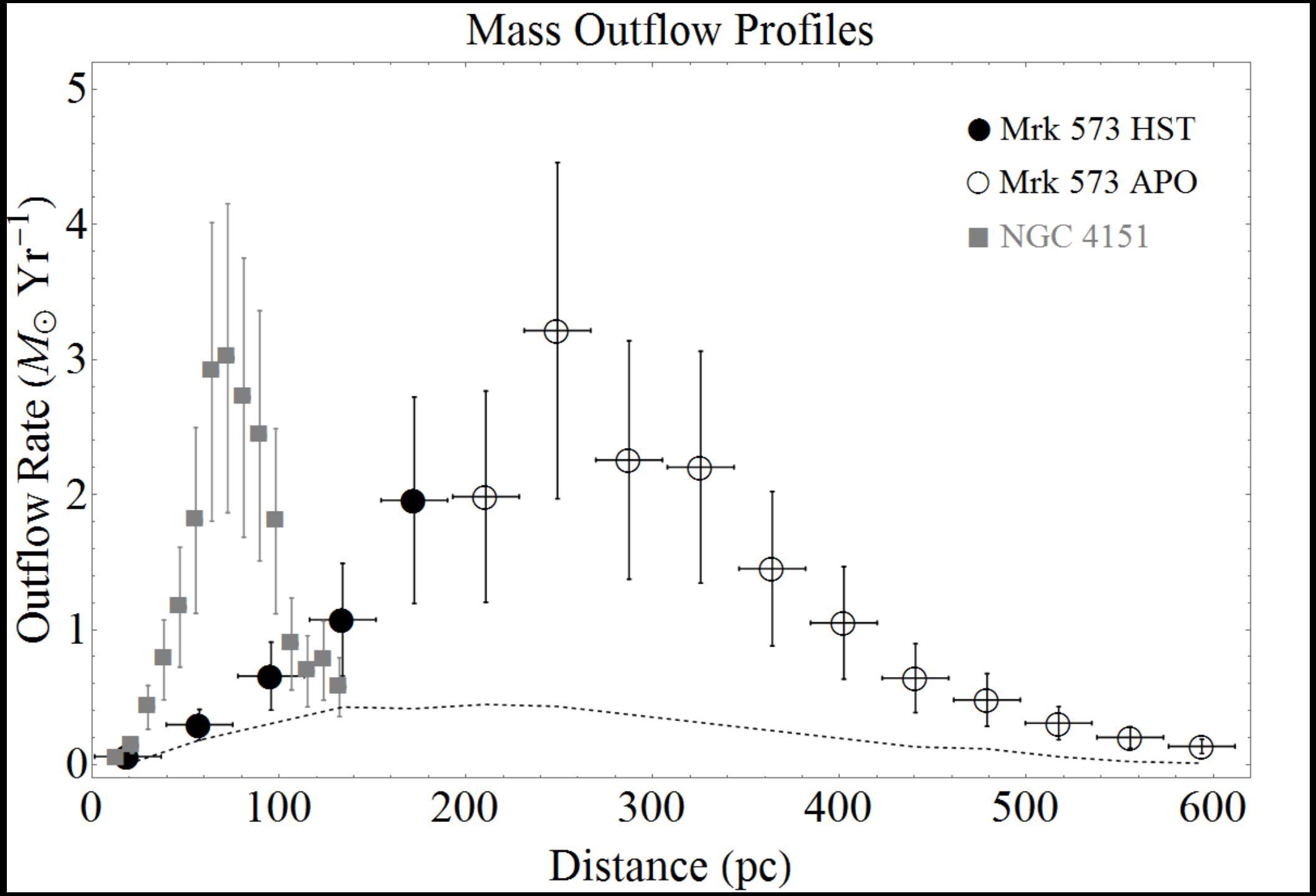
- $\mathrm{M} \propto \left(\frac{\mathrm{L(H\beta)}}{\mathrm{n_e}} \right) = \mathrm{s} \left(\frac{\mathrm{F_{[OIII]}}}{\mathrm{n_H}} \right) \rightarrow$ image

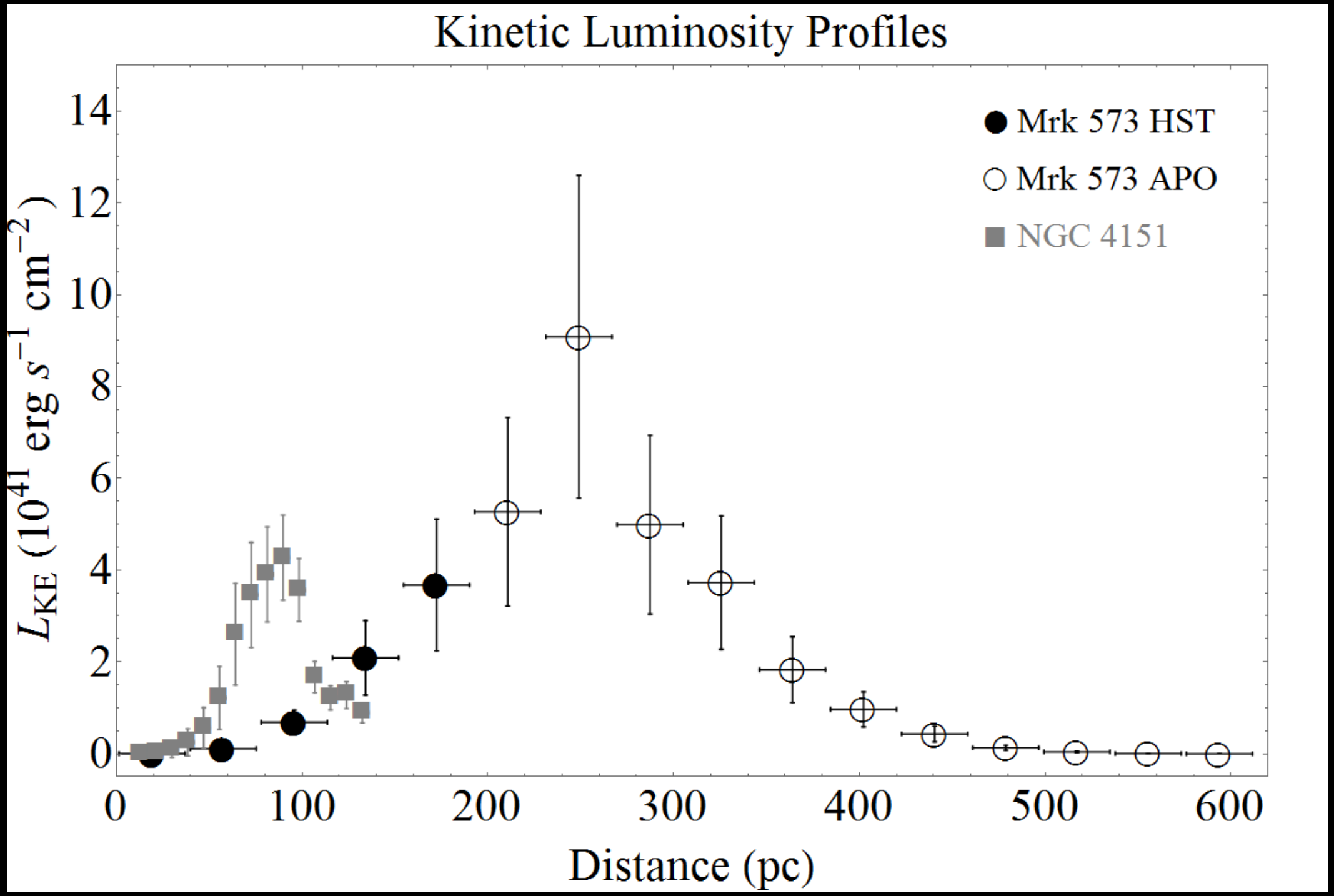
HST [O III] Image




Radial Mass Profile
HST
APO
Mass (10^5 $M_\odot$)
Distance (arcsec)
4
3
2
1
0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5


Mass Outflow Profiles
Mrk 573 HST
Mrk 573 APO
Nuclear Only
Outflow Rate ($M_\odot$ Yr^{-1})
Distance (pc)
0
1
2
3
4
5
0
100
200
300
400
500
600


Mass Outflow Profiles
Mrk 573 HST
Mrk 573 APO
NGC 4151
Outflow Rate ($M_\odot$ Yr^{-1})
Distance (pc)
0
1
2
3
4
5
0
100
200
300
400
500
600


Kinetic Luminosity Profiles
Mrk 573 HST
Mrk 573 APO
NGC 4151
L_{KE} (10^{41} erg s^{-1} cm^{-2})
Distance (pc)
0
2
4
6
8
10
12
14
0
100
200
300
400
500
600

Discussion

- Similar outflow rates, Mrk 573 $\sim$ 5-10x more energetic than NGC 4151.
- Comparison with global outflow estimates:
- Sum of spatially resolved curve $\sim 20\ M_{\odot}/yr$
- $\dot{M} \propto n_e v_{out} A f$: $\sim 30\ (6-600)\ M_{\odot}/yr$. (e.g. Muller-Sanchez+ 2011)
- $\dot{M} \propto L_{H\alpha}\, n_e^{-1} \bar{v}_{out} \sim 5\ (2-30)\ M_{\odot}/yr$. (e.g. Bae+ 2017)
- Take away: estimate densities from emission lines when possible. Employ a mean or weighted mean velocity for “global” outflow rates.

Conclusions

- Different spatial extents, similar peak outflow rates
- Outflow rates comparable to global estimates
  (e.g. Barbosa+ 2009, Storchi-Bergmann+ 2010, Müller-Sánchez+ 2011, Riffel+ 2013, Schnorr-Müller+2014, Bae+ 2017, Schönell+ 2017)
- Profile indicates in-situ acceleration not nuclear outflow
- Kinetic luminosities ~ 0.2-0.8% of bolometric
- Likely missing X-ray and molecular components
- Need more targets to search for correlations