Probing Starburst Feedback and Circumgalactic OVI in Emission

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Stockholm University

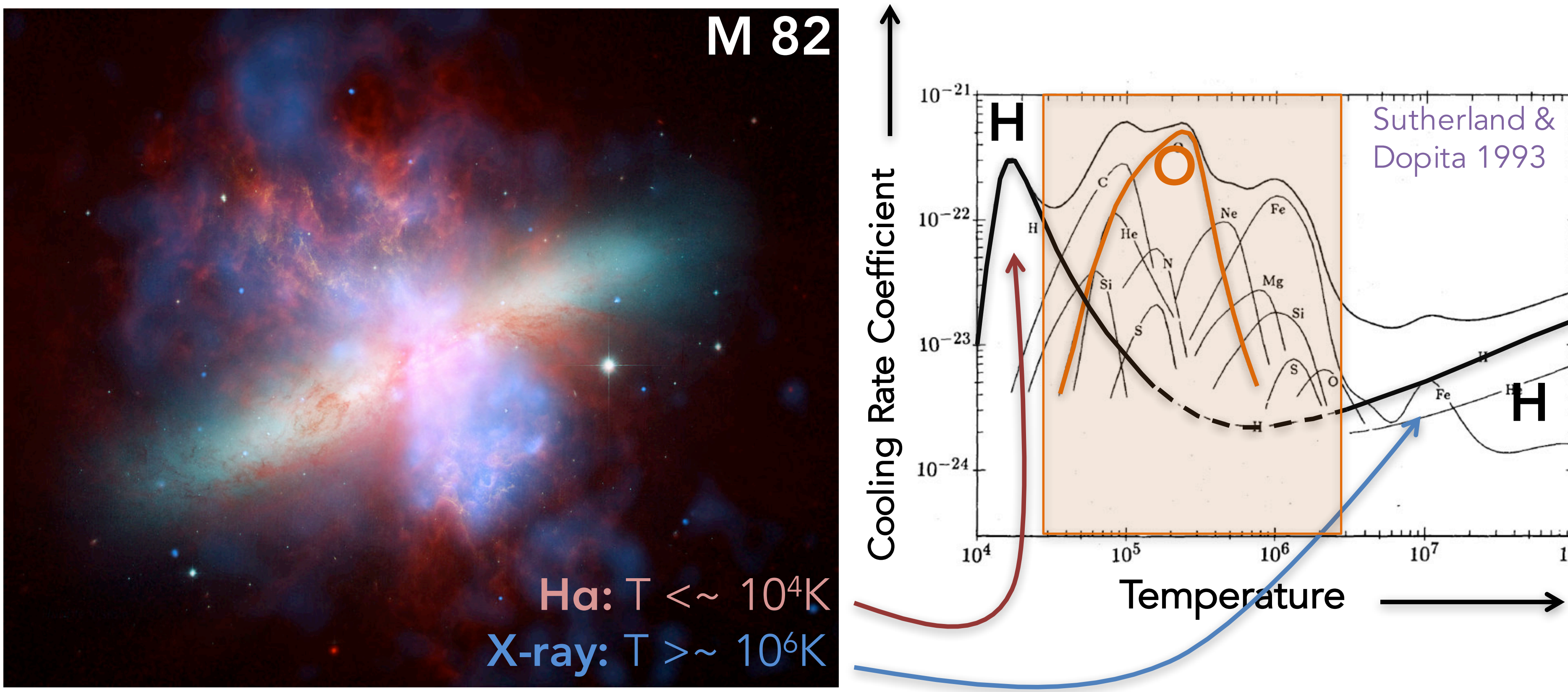
Oskar Klein centre

SNSB

Vetenskapsrådet

Knut och Alice Wallenbergs Stiftelse

Galaxy Superwinds



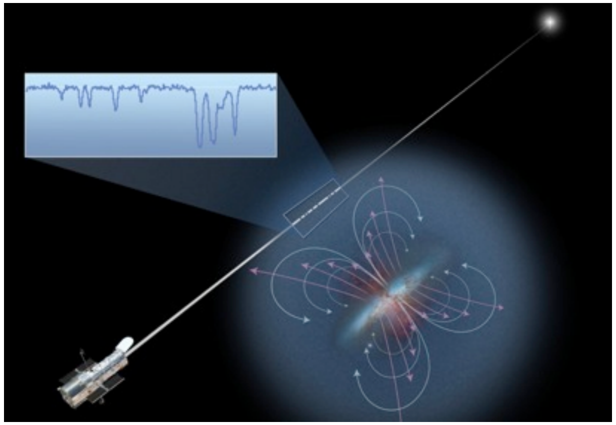
Galaxy outflows ubiquitous, but lose energy through radiation

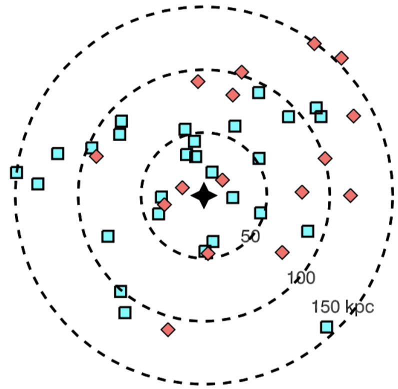
2 order of magnitude gap in temperature probed by recomb. lines & X-ray

Hard to simulate the collisional gas – interfaces too small

T ~ few x 10^5 K → metal resonance lines in UV. O VI (1032,1038Å) is very good!

O VI in absorption





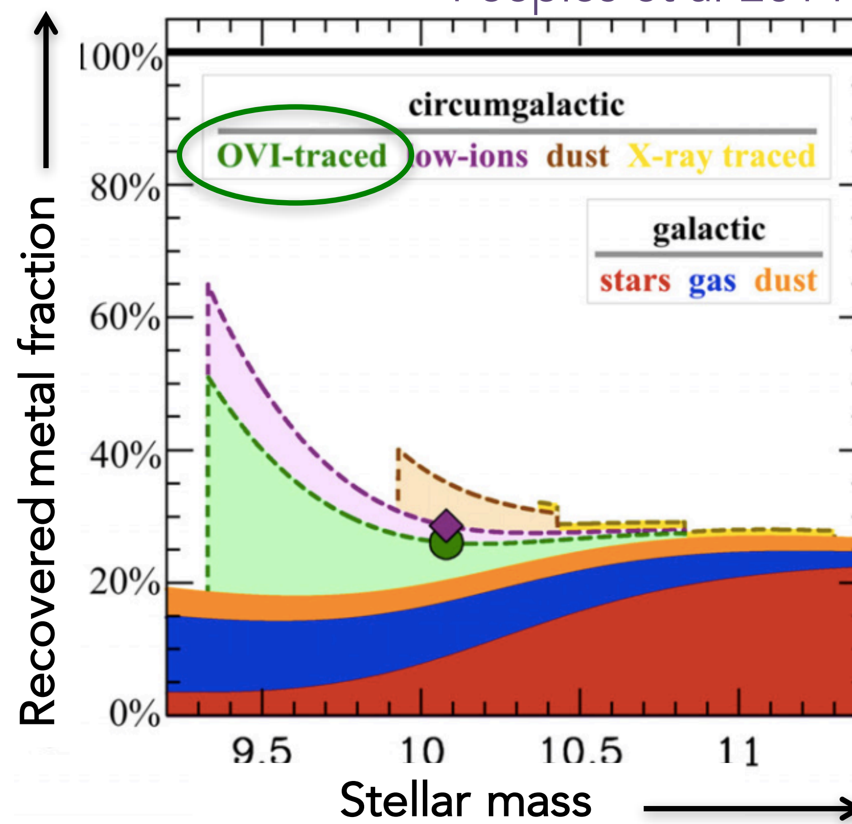
Tumlinson et al 2011,2013

Target galaxy-QSO pairs

QSO bright → very large radii

Robustly measure $N_{\mathrm{O\,VI}}$

Peeples et al 2014

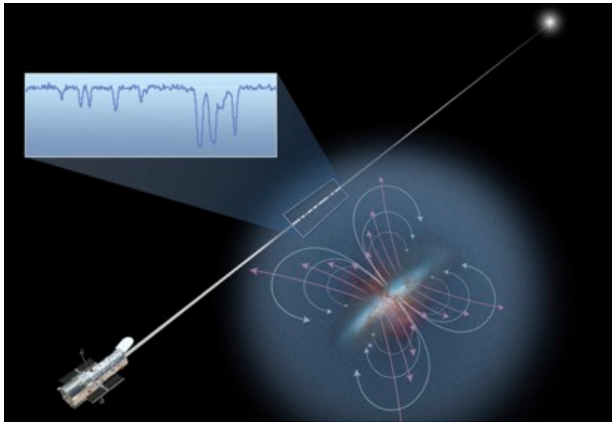


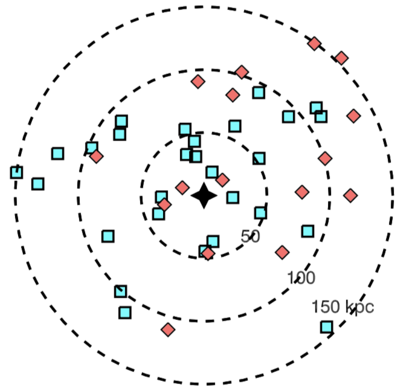
At low-z: ~70 % of oxygen is missing

O VI reservoir could be large especially at low M_{stell}

QSOs are rare (1, or 0 per galaxy) and most exciting starbursts cannot be studied

O VI in absorption





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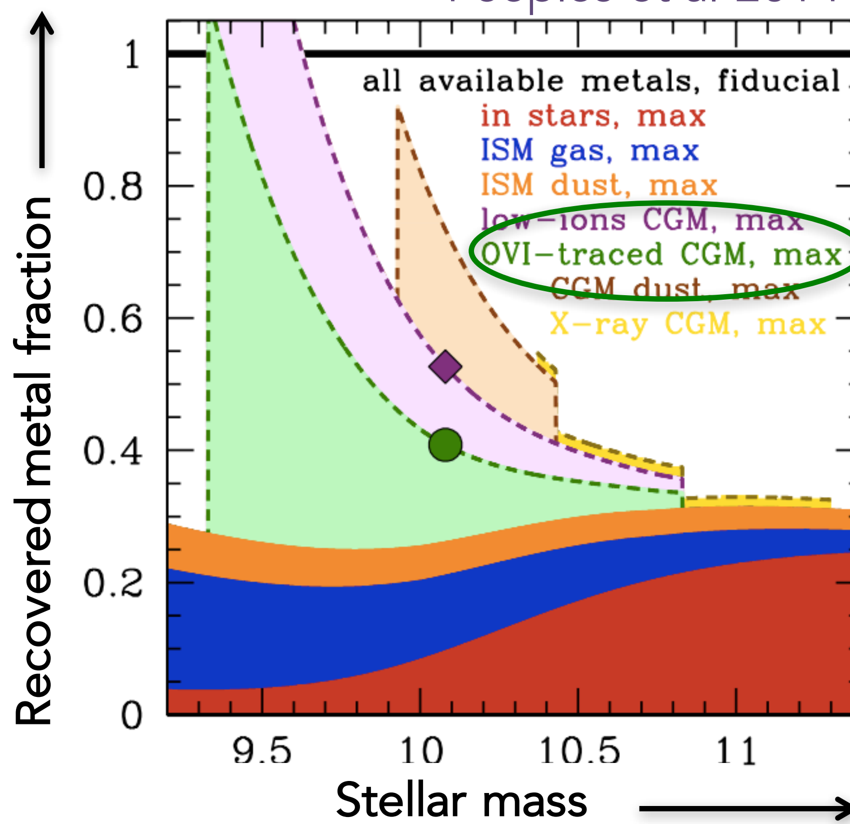

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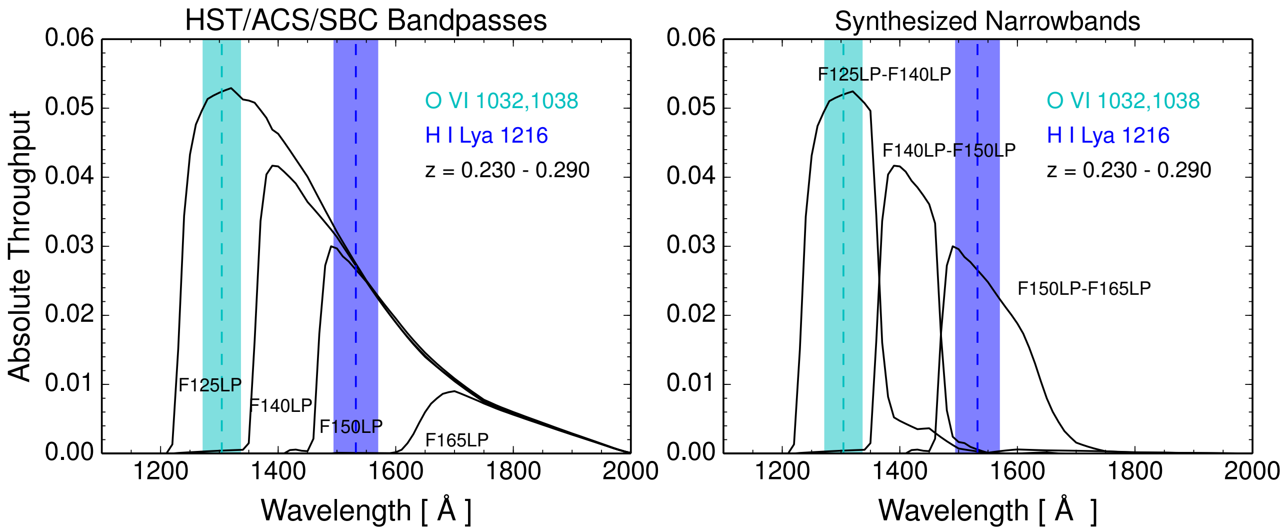
Oxygen missing from galaxies

Galaxies at Apache Point Observatory (MaNGA) program with SDSS-IV, combined with resolved gas maps could also reduce the need to make strong assumptions about how well the ISM is mixed.

With regards to the UV-traced CGM, until we can resolve this gas in emission and accurately map its morphology and extent for individual galaxy halos, absorption line studies are the only way to detect and characterize this massive reservoir. Given the apparent patchiness of the low-ionization CGM, with only ∼40 sightlines, the COS-Halos sample is not large

Peeples et al 2014

How to image O VI in emission



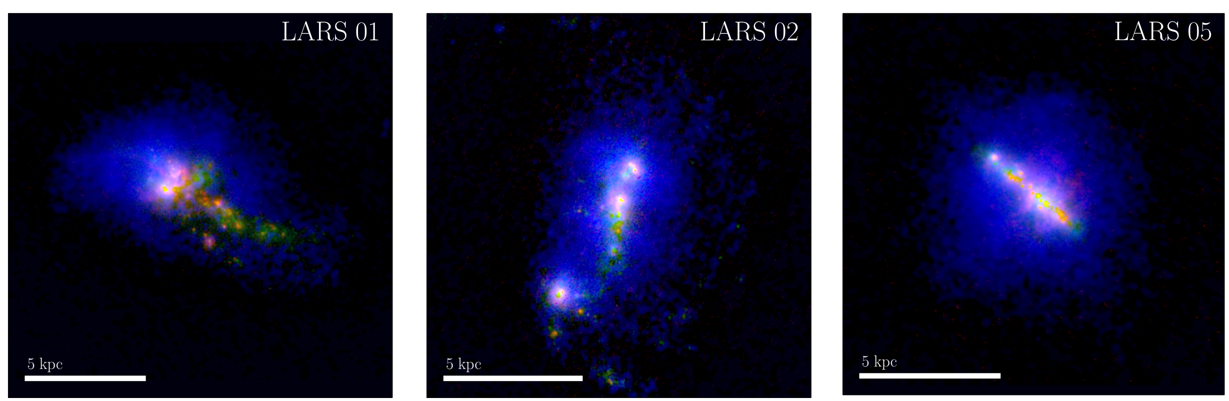
ACS/SBC LP filters: steep blue cut-on and extended red wing

Subtract pairs → well-defined, synthetic narrowbands (Hayes+2009)

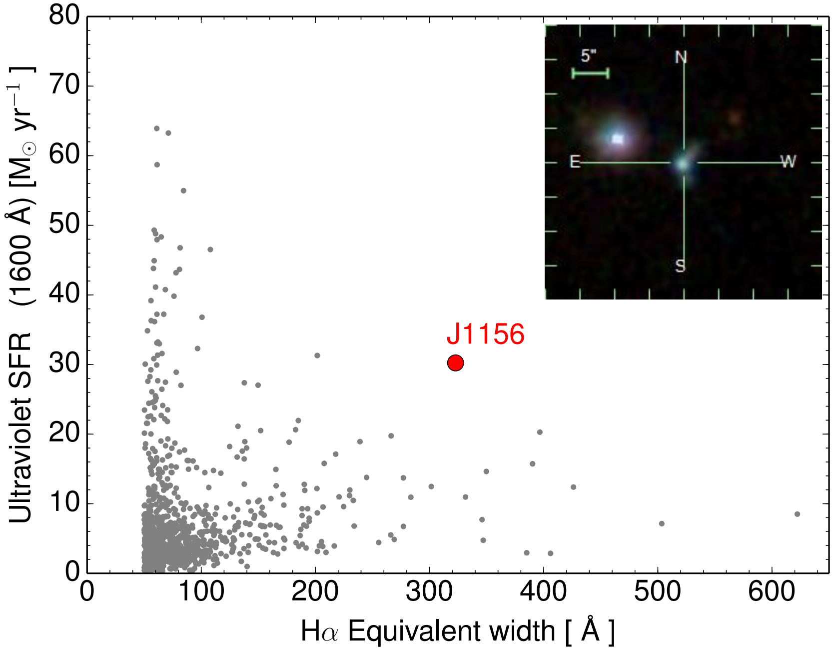
Pick (1+z) for Lyα (1216Å). ~60 starbursts imaged in LARS +extensions

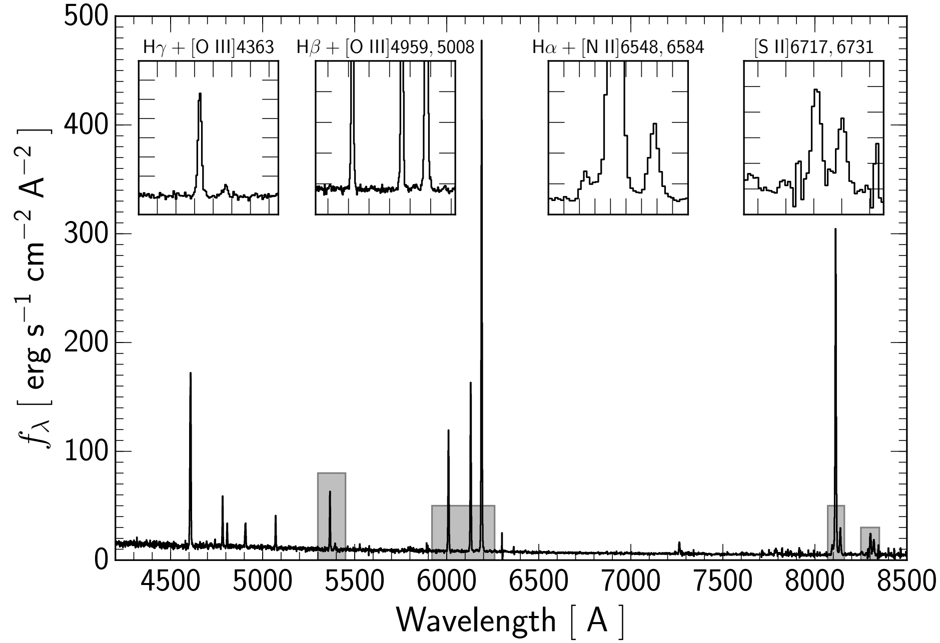
Same method for O VI (1032,1038Å) at z=0.23 – 0.29

Lyα at z~0.035
(Hayes+2013,2014)

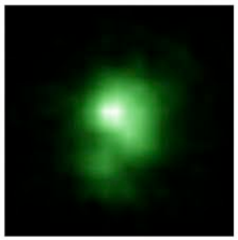


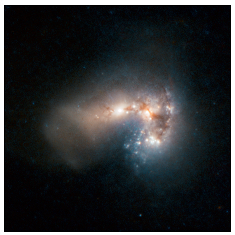
SDSS J115630.63+500822.1



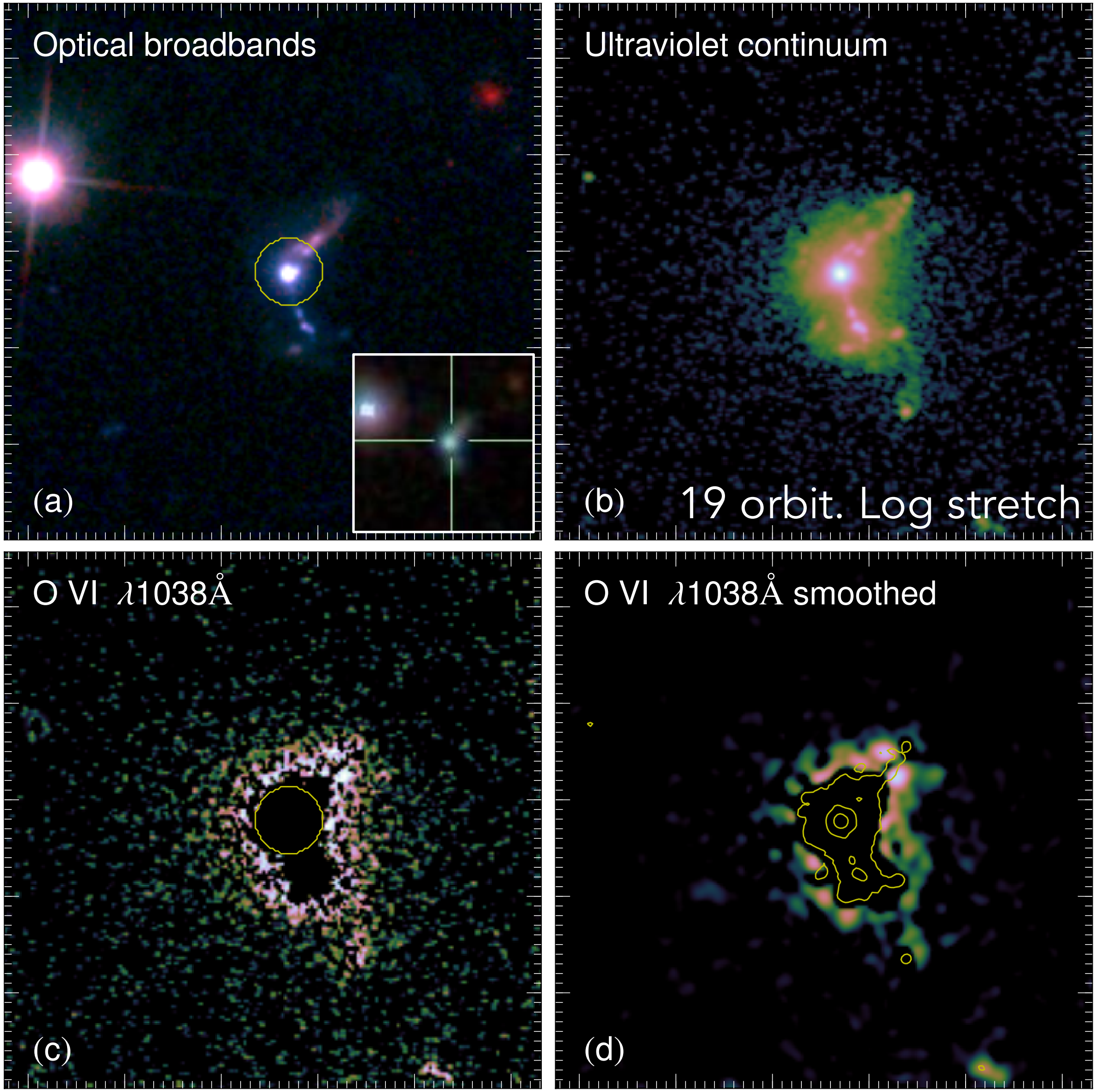


- GALEX + SDSS (UV luminous + high Hα EW)
- SFR ~40 $M_{\odot}$ yr^{-1} within 1 kpc (very compact)
- Blue optical spectra, strong optical emission lines
- SFH is 'burst like' with age ~12 Myr
- 12 + log(O/H) = 7.9 (T_e method)
- *A few x more luminous green pea, a more distant LBA, or 2 x Haro 11 @ 10x the distance*





ACS+UVIS Imaging



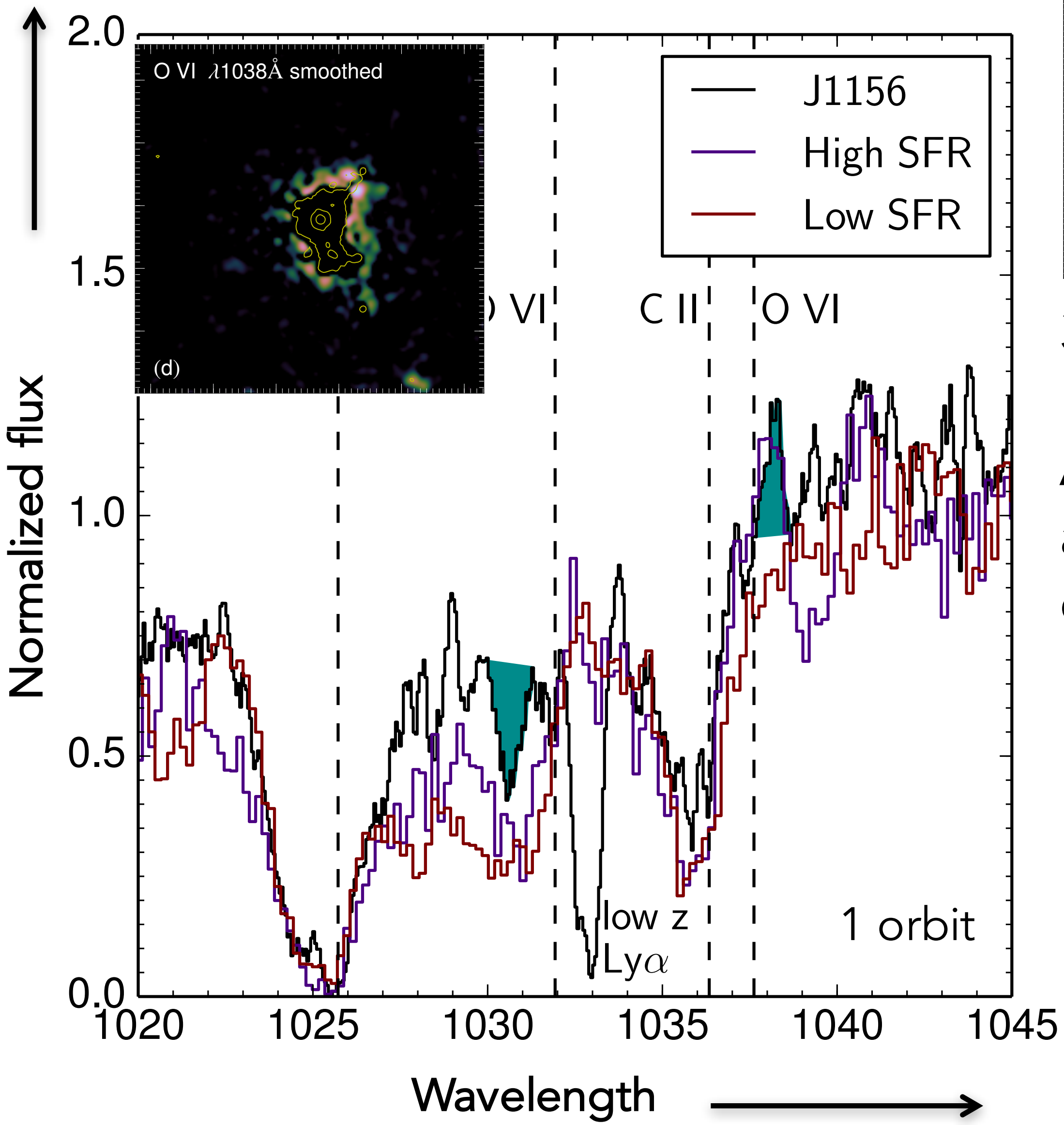
Very compact stellar population (UV/optical)

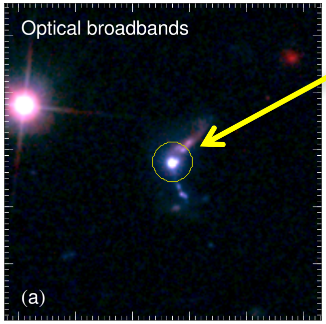
Flux deficit (absorption) where continuum is bright

A halo of O VI emission?

At least a significant flux excess in the O VI-transmitting filter.

COS Spectroscopy





3 σ emission at λ=1038Å

Absorption in Lyβ, C II 1036, and O VI 1032. Dominates over emitted flux in centre.

1032 Å absoption:

$N_{OVI} = 10^{14.7}$ cm^{-2}

$V_{OVI} = 380$ km s^{-1} (fast!)

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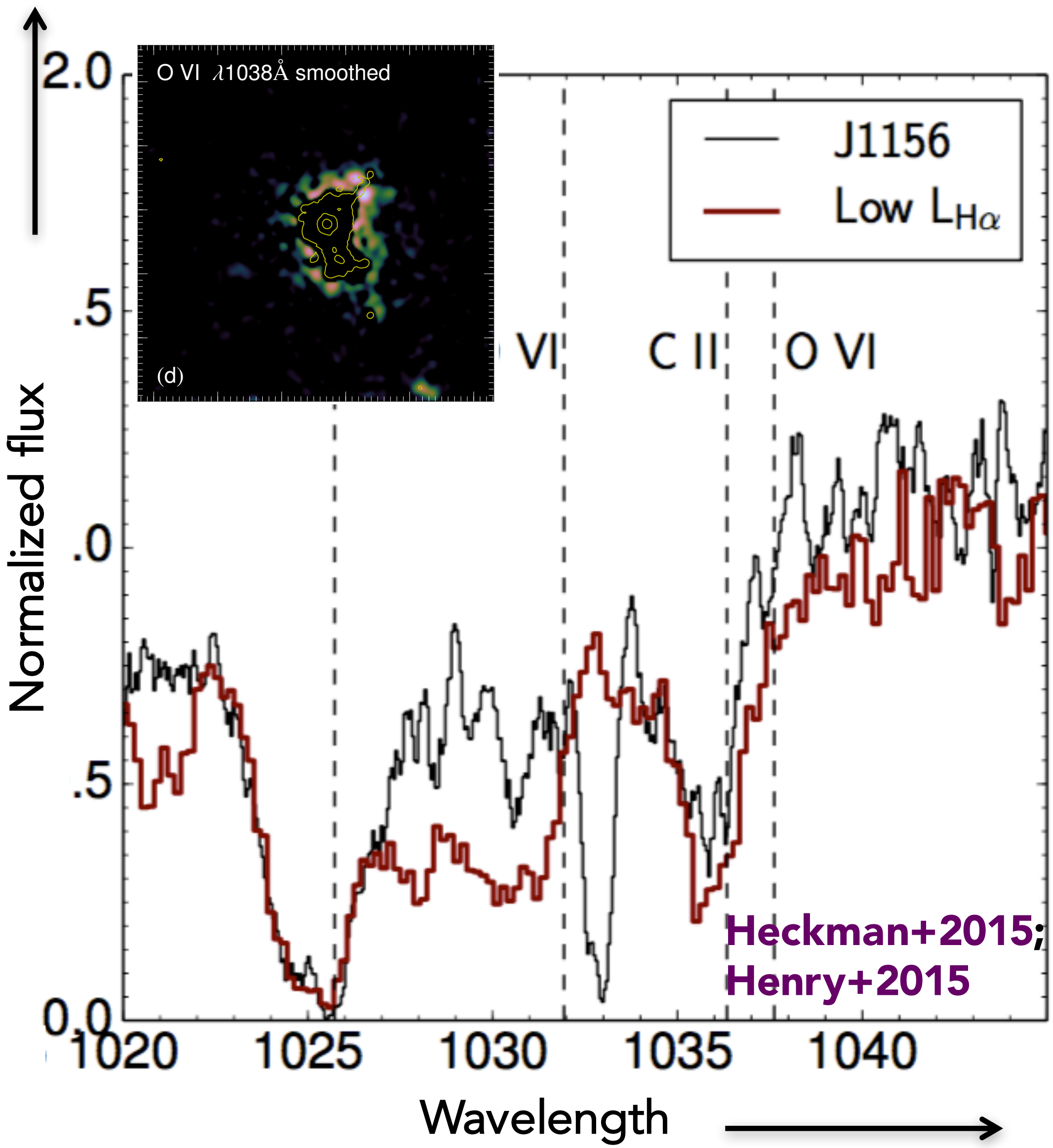

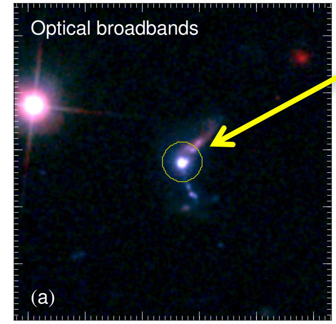

2.5″ aperture

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Stacked archive spectra agree at high L_{Ha} but not low

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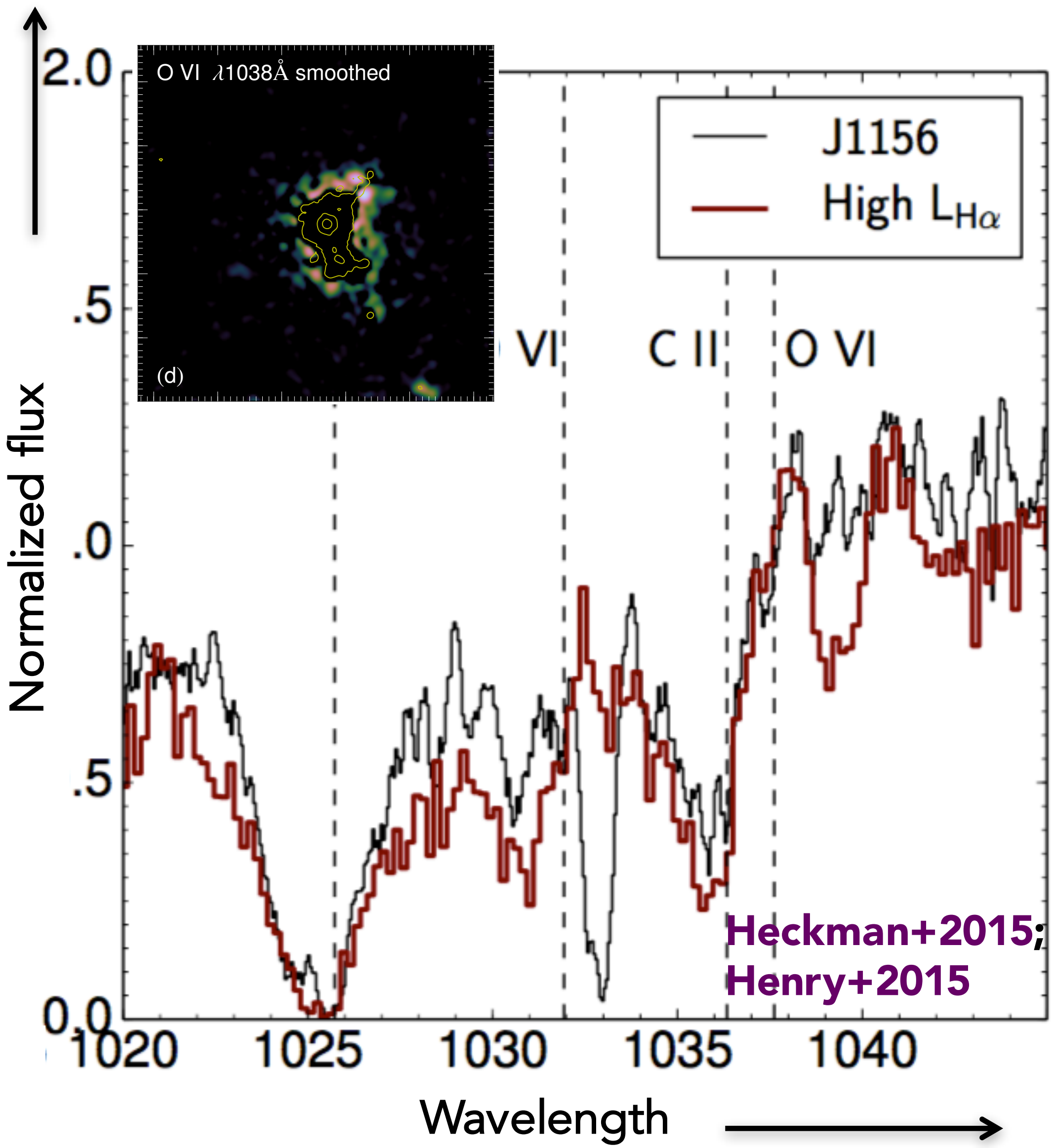

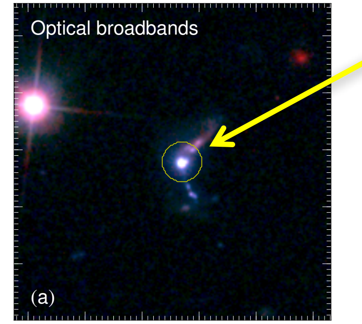

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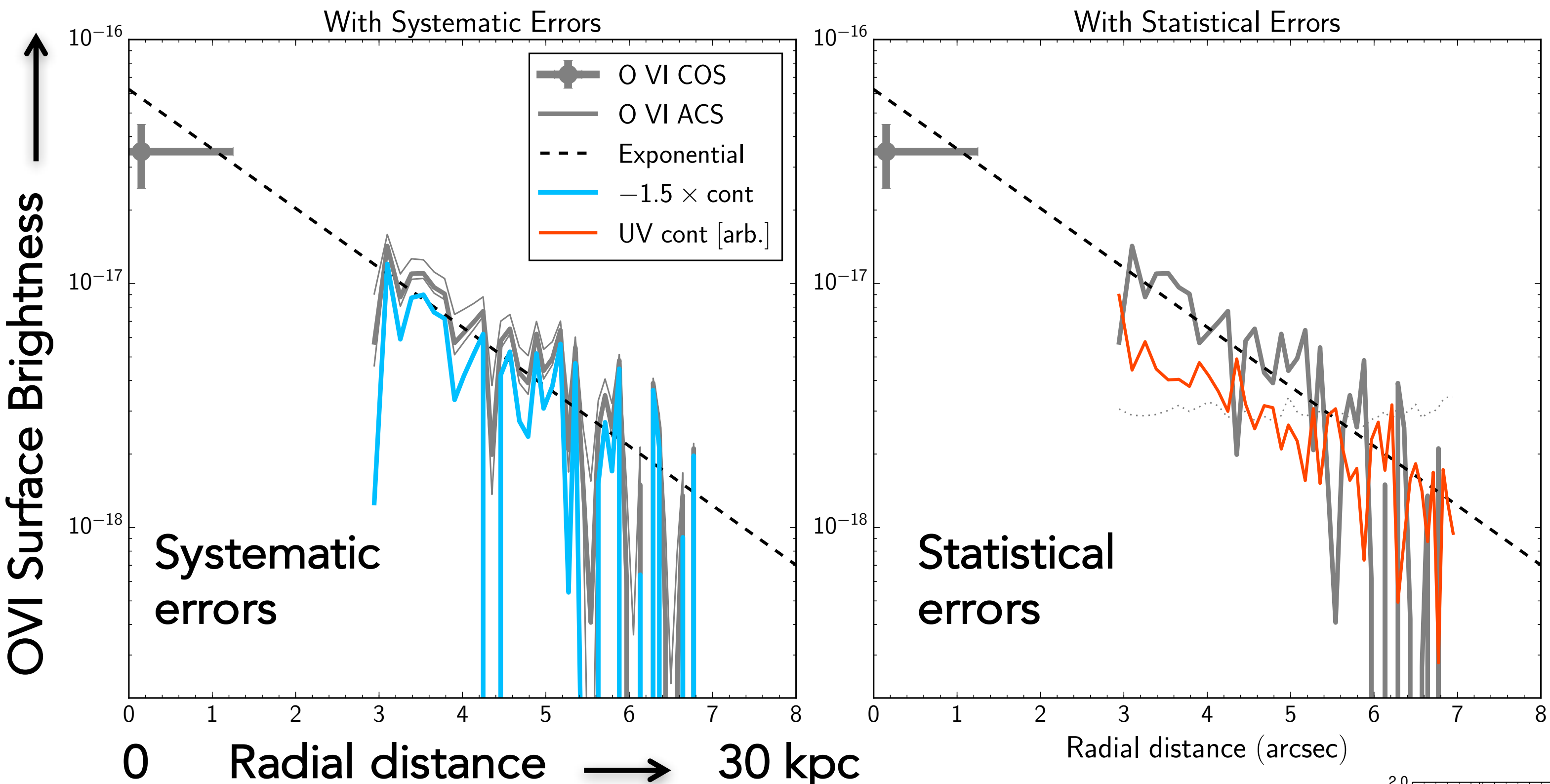
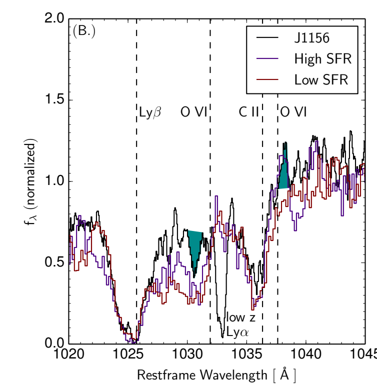
O VI Surface Brightness Profile





Combine ACS and COS to get SB

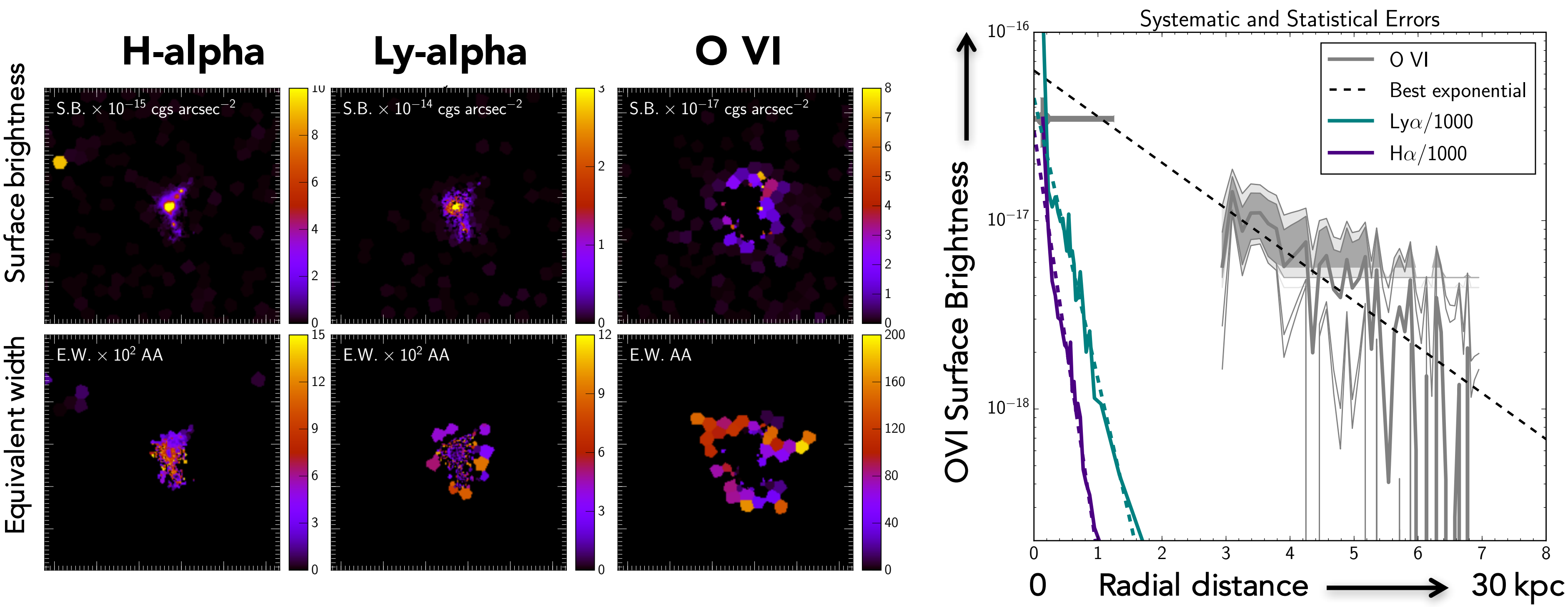
Result survives 2 and 3 times over-subtraction

Fit by exponential: scale = 7.5 kpc (< 1kpc in optical)

→ Total O VI luminosity : L_{OVI} = 2×10^{41} erg/s

Absorbed L_{OVI} is 6 x lower (resonance scattering not dominant)

O VI and other lines



Hα (recombination) Lyα (recomb.+scattering)

No signal (Lyα or Hα) at radius of O VI (HST 20x less efficient for Lyα)

Exponential scales: 0.75 kpc (Hα) and 1.1 kpc (Lyα) – 7.5 kpc (O VI)

O VI profile does not resemble the photoionized gas

Hubble can image $T \sim 10^{5.5}$ K gas now

Galaxies at Apache Point Observatory (MaNGA) program with SDSS-IV, combined with resolved gas maps could also reduce the need to make strong assumptions about how well the ISM is mixed.

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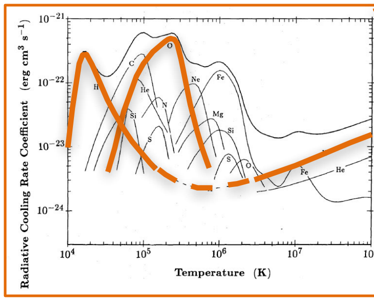
Peeples+2014

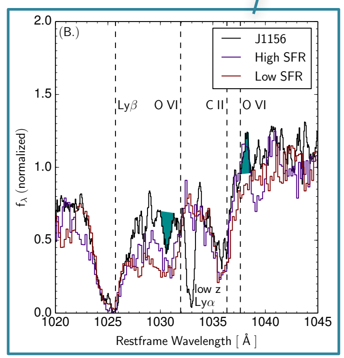
Conditions in the OVI-bearing gas

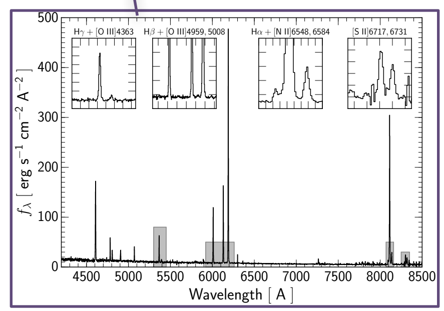
Surface brightness $$\mu_{OVI} = \Lambda_n n_e^2 \left(\frac{Z}{Z_{sun}}\right) D_{OVI}$$

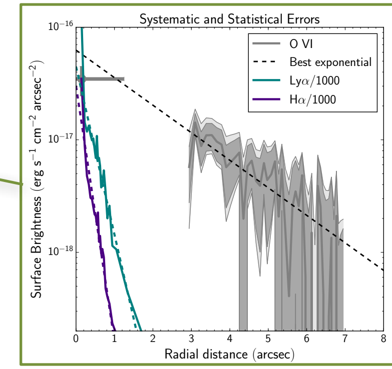
Density & size $$n_e = \frac{N_{OVI}}{D_{OVI}} \left(\frac{O}{H}\right)^{-1}$$

Solve for cloud diameter $$D_{OVI} = 2\Lambda_n \left(\frac{N_{OVI}}{O/H}\right)^2 \left(\frac{Z}{Z_{sun}}\right) \frac{1}{\mu_{OVI}}$$









Diameter of clouds D_{OVI} = 10 pc Very thin!

Exponential scale length 7.5 kpc

Fills ~1/1000 of the column

Electron density in clouds $n_e = 0.5$ cm^{-3}

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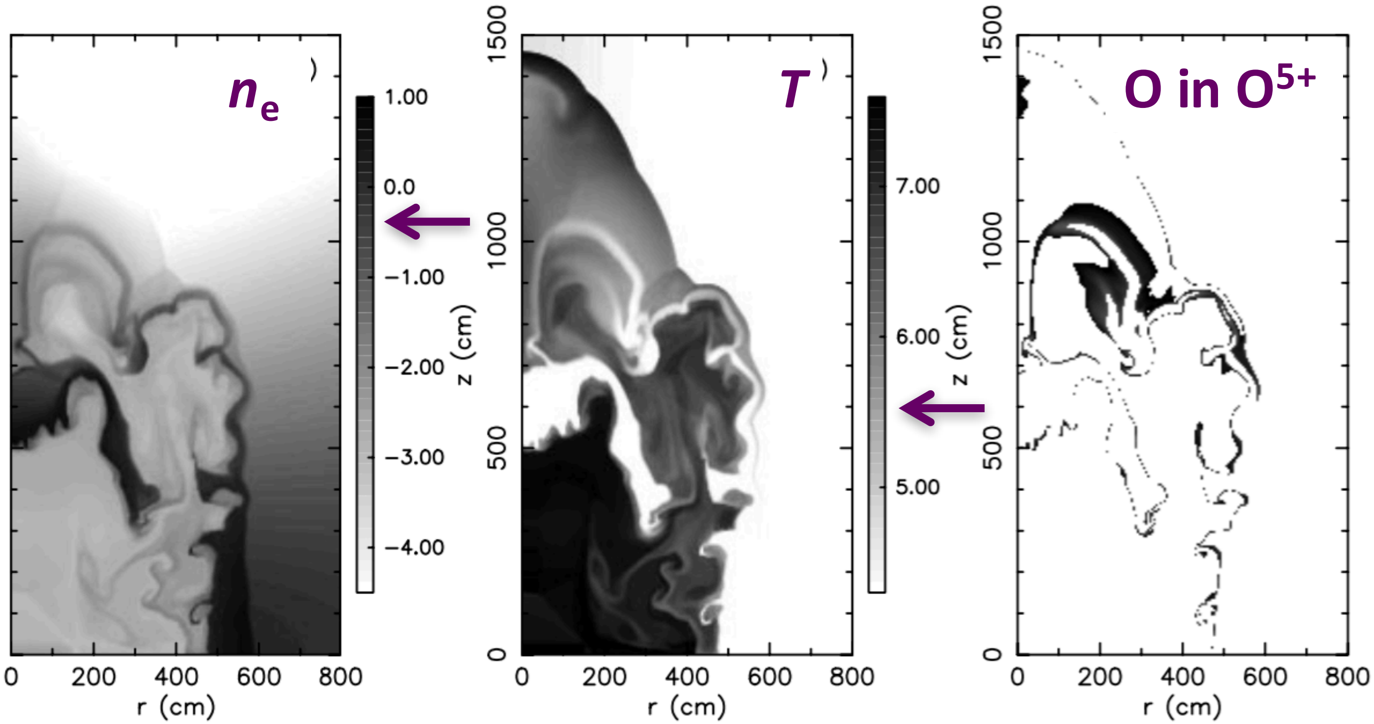

OVI-bearing gas **expected to be thin**

Hot gas collides with cold material

Hydro simulation of NGC 1705

Heckman+2001

Diameter of clouds D_{OVI} = 10 pc Very thin!

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Electron density in clouds $n_e = 0.5\ cm^{-3}$

Pressure in the gas phases

$$P / k_B = n_e T$$

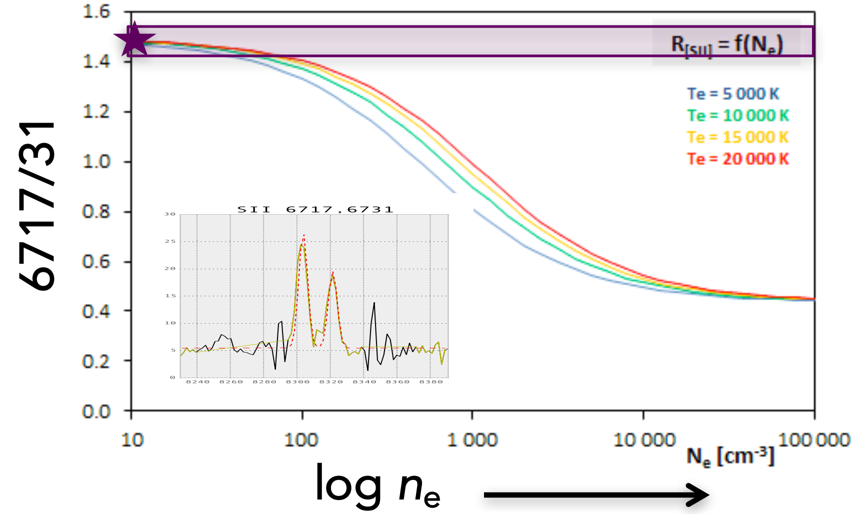
- Coronal O VI phase: $P/k_B \sim 1.6 \times 10^5$ K cm^{-3}
- Nebular HII phase:

  n_e : [S II] 6717,6731 Å doublet

  4.65 (< 44 at 1σ) cm^{-3}

  T_e : [O III] 5007 / 4363 Å auroral line

  1.5×10^4 K



$P/k_B \sim 0.69 \times 10^5$ K cm^{-3} (formal)

$< 6.5 \times 10^5$ K cm^{-3} (1σ)

Pressures in coronal phase (O VI) and nebular phase (optical emission lines) agree to within measurements

Coincidence or causal (pressure equilibrium)?

Some timescales

- Cooling Rate: $\Lambda = \Lambda_n n_e^2$ Internal energy: $U = \frac{3}{2} n_e k_B T$

  → Cooling time: $t_{cool} = U / \Lambda =$ 1.3 Myr

- Sound crossing time: $t_{SC} = \frac{d_{OVI}}{c_s} = \frac{10\text{pc}}{\sqrt{\gamma k T_e / m_i}} \approx \frac{10\text{pc}}{100\text{km/s}} = 10^5$ yr

- Time to reach exponential scale height at V_{out}

  7.5 kpc / 380 km s^{-1} = 20 Myr

Gas would cool long before it could be lifted to scale height
→ coronal gas is cooling *in situ* through the few x 10^5 K regime

Clouds would disrupt on a few t_{sc} which is << t_{cool}
→ pressure confinement may be necessary to see the O VI glow

Gas will recombine before it escapes

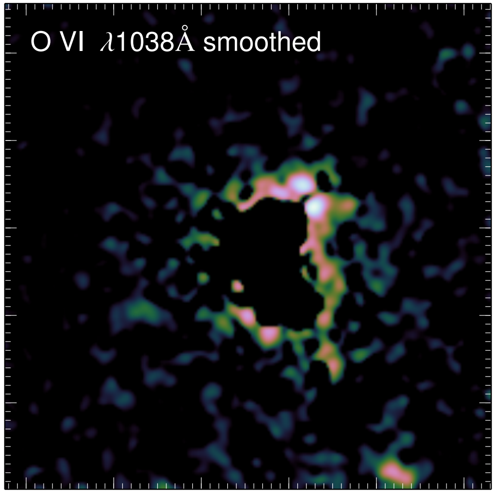
Mass, Momentum, & Energy

- **MASS.** Assume SB profile decreasing D_{OVI}, at constant $\{n_{OVI}, n_e\}$
  Integrate N_{OVI} profile: $M_{OVI} = 3 \times 10^4\ M_\odot$; $M_{cor} = 6 \times 10^7\ M_\odot$
  HII regions: $M_{HII} = 2.5 \times 10^9\ M_\odot$ **Coronal mass 2.5% HII**

- **ENERGY.** $E_{OVI} = 3 \times 10^{52}$ erg ; $E_{cor} = 6 \times 10^{55}$ erg
  Budget (winds+SN): $E_{FB} = 8 \times 10^{57}$ erg. **1% budget AT PRESENT**
  E_{cor} instantaneous, but E_{FB} is integrated over 12 Myr
  → $L_{OVI} \times t_{SF} = 7 \times 10^{55}$ erg → 1% of total budget; minor energy loss

All fractions increase by 1/ε (~10%? – thermalization efficiency of SN+O-star winds)

Future of the OVI



- cooling rate: Λ_{OVI} [erg/s/cm^3]
- Internal Energy $U = 3/2\, n_e\, k\, T$ [erg/cm^3]
- Cooling time $t_{cool} = U / \Lambda_{OVI} = 30$ Myr

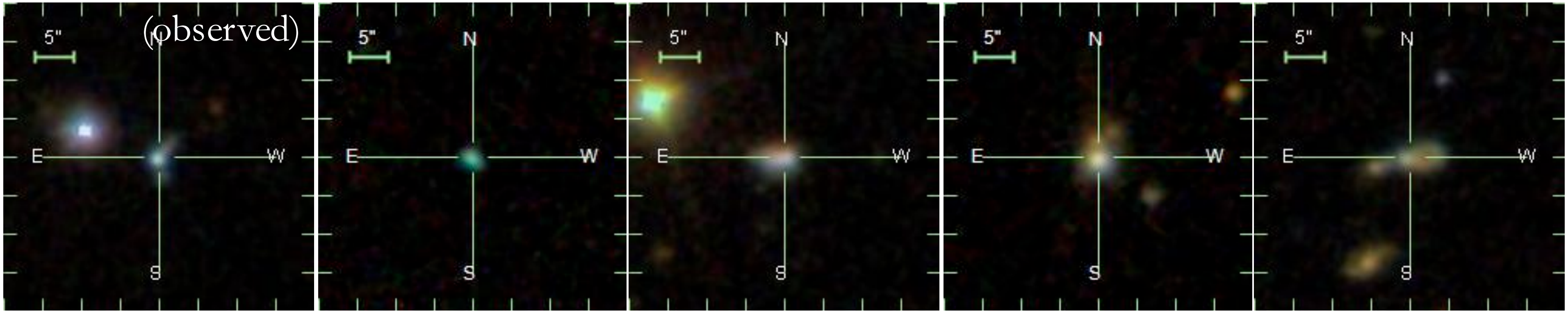
  → Gas is passing through a coronal phase

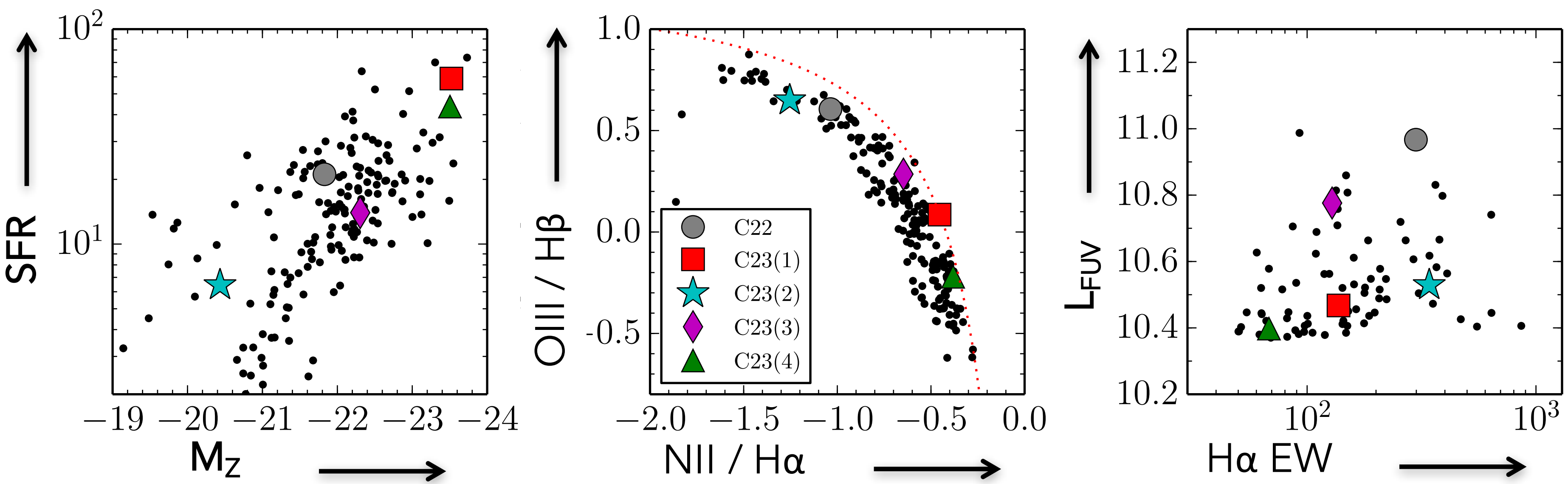
- $V_{OVI} = 380$ km/s. Escape velocity $v_{esc} = \sqrt{\frac{2GM}{r}}$
- For M=1.5×10^9 Msun (stellar), r = 7.5 kpc : $v_{esc} = 35$ [km/s]
- Need M_{DM} 100 × Mstell for DM to confine the gas

  → V_{OVI} exceeds V_{esc} but is also radiating KE from the wind
  [May | may not] escape…

- Will become neutral, re-enter Lyα forest, and become visible

Improving upon 1 galaxy: HST Cycle 23





Four more galaxies observing under cycle 23

First Sample will be complete by end 2016.

Improving upon 1 galaxy: HST Cycle 23

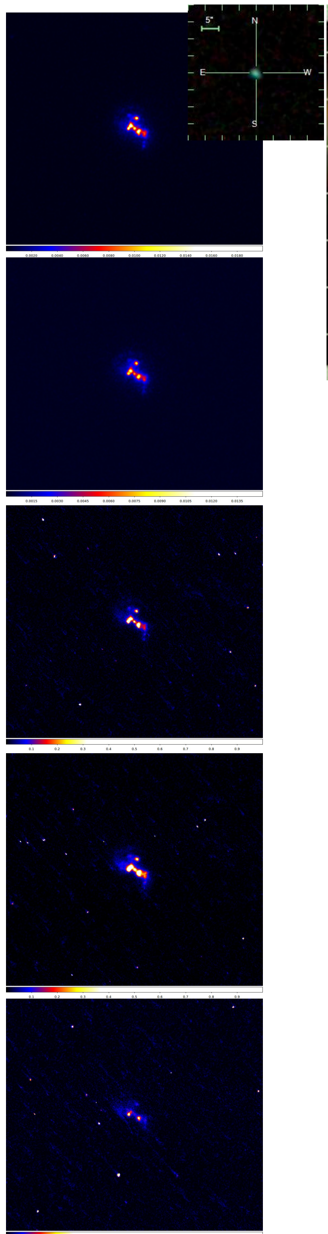
SBC/F125LP

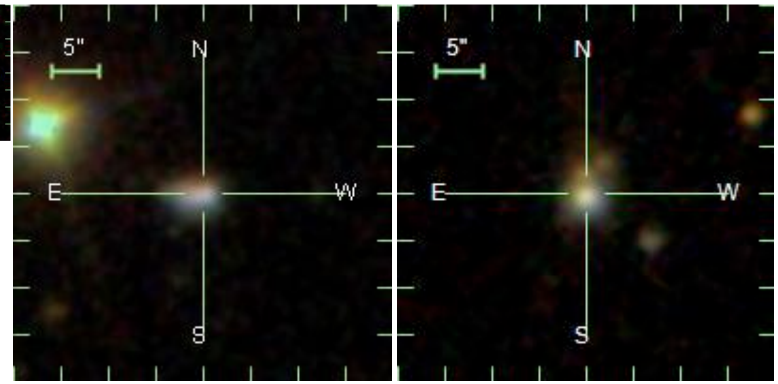
SBC/F140LP

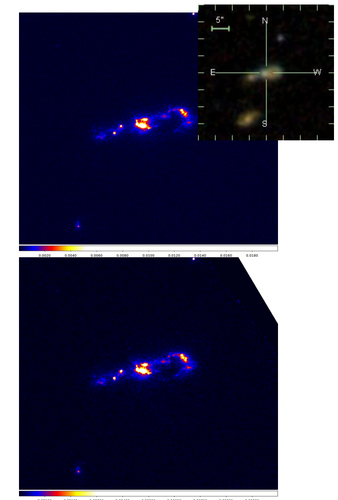
UVIS/F390W

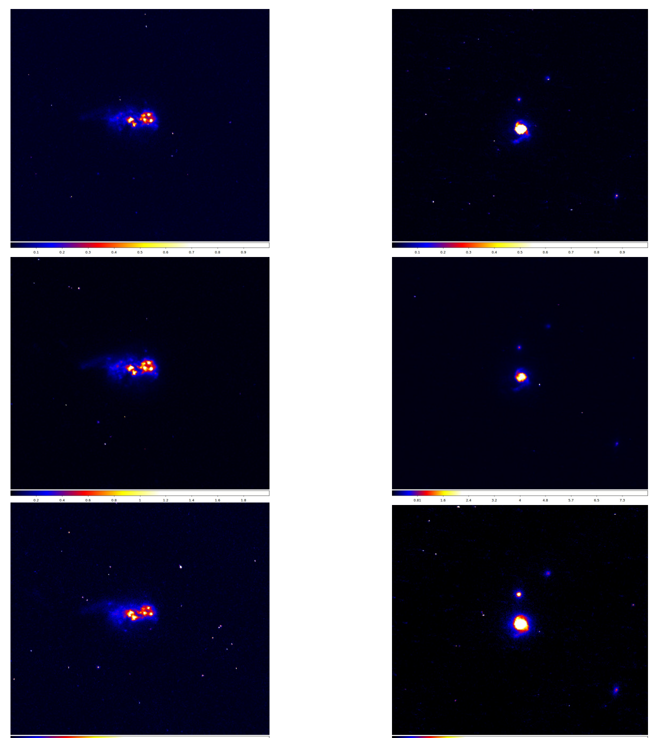
UVIS/F475W

UVIS/F850LP









Imaging 60% complete

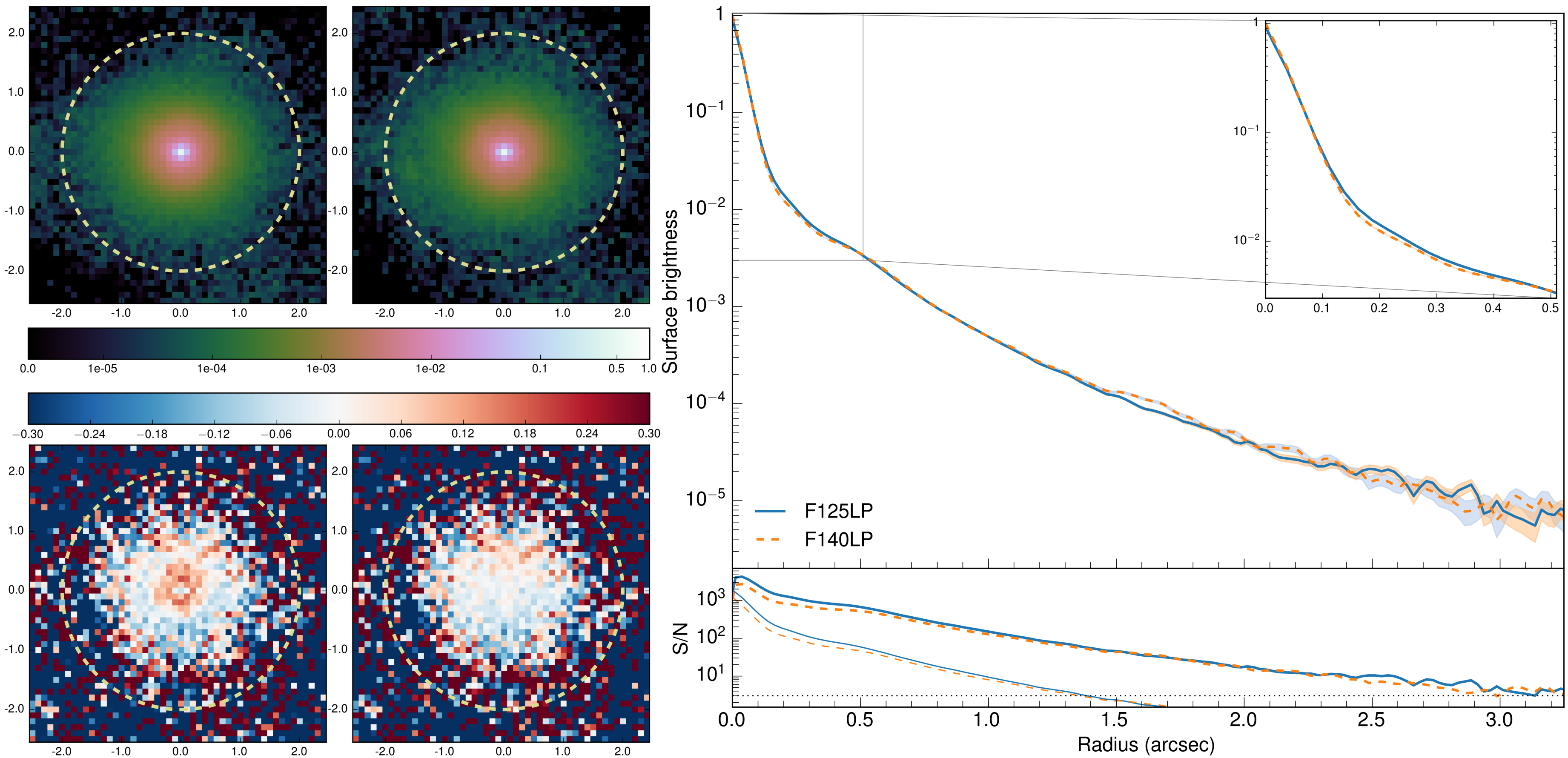
+1 orbit COS (not started)

Conclusions

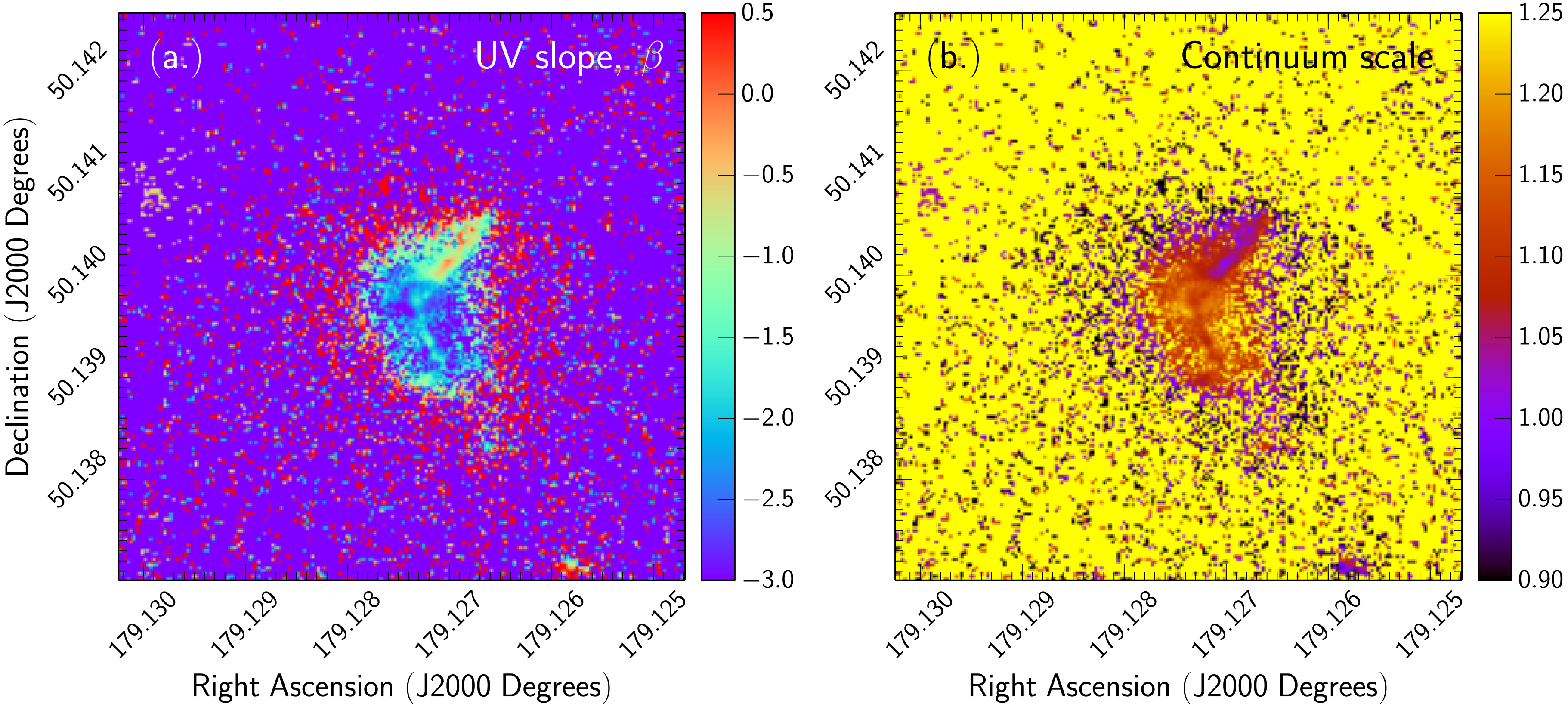
- HST can isolate O VI emission and image $T \sim 10^{5.5}$ K gas
- **measure** luminosity, column density, outflow velocity
  → **derive** mass, clumping, density, cloud size, cooling time, sound speed. Fate of the gas in T and space
- Cycle 23 HST programme will provide the first sample
- May hold implications for:
  → energetics of starbursts, gas cooling, regulation of star formation and galaxy growth
  → mass-metallicity relation, enrichment of IGM, …
- Guide future satellites?

Bonus Slides Follow

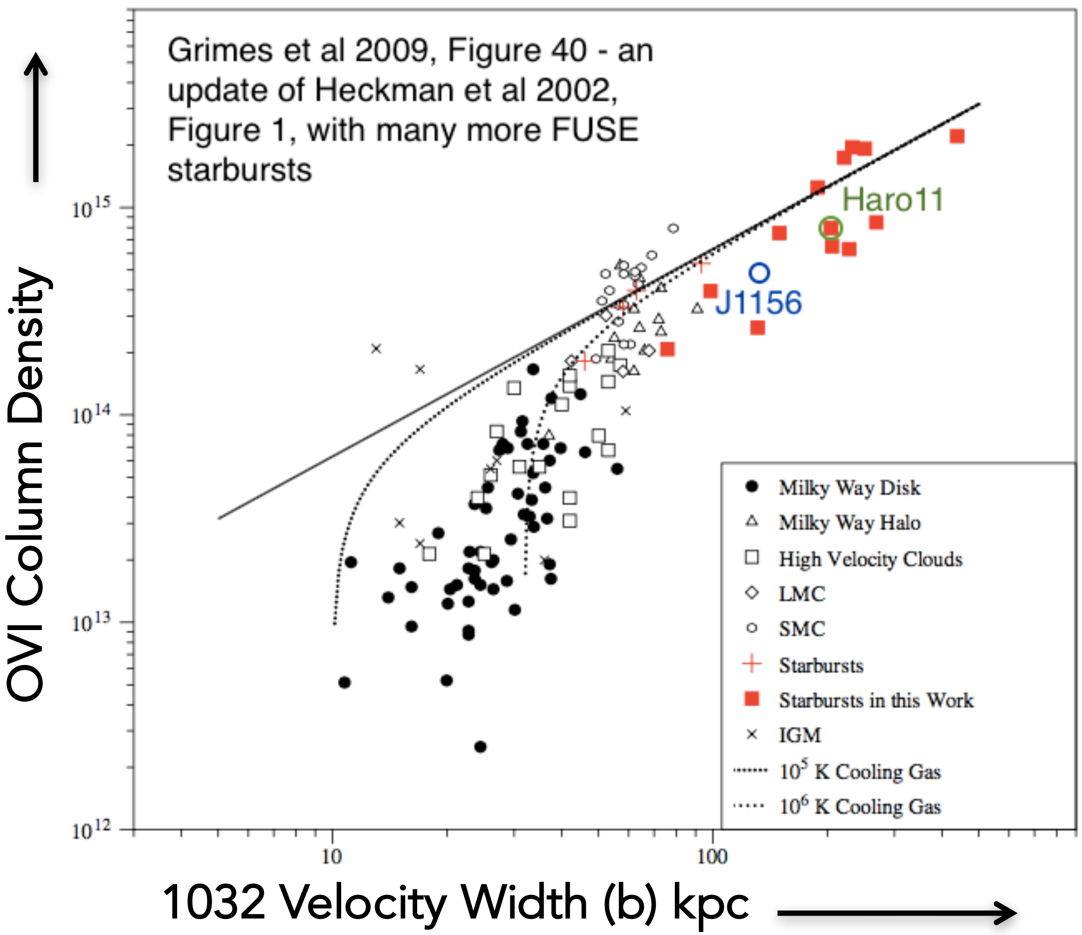
PSF matching



UV colours


(a.)
UV slope, β
Declination (J2000 Degrees)
50.142
50.141
50.140
50.139
50.138
Right Ascension (J2000 Degrees)
179.130
179.129
179.128
179.127
179.126
179.125
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
(b.)
Continuum scale
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90

COS Spectroscopy



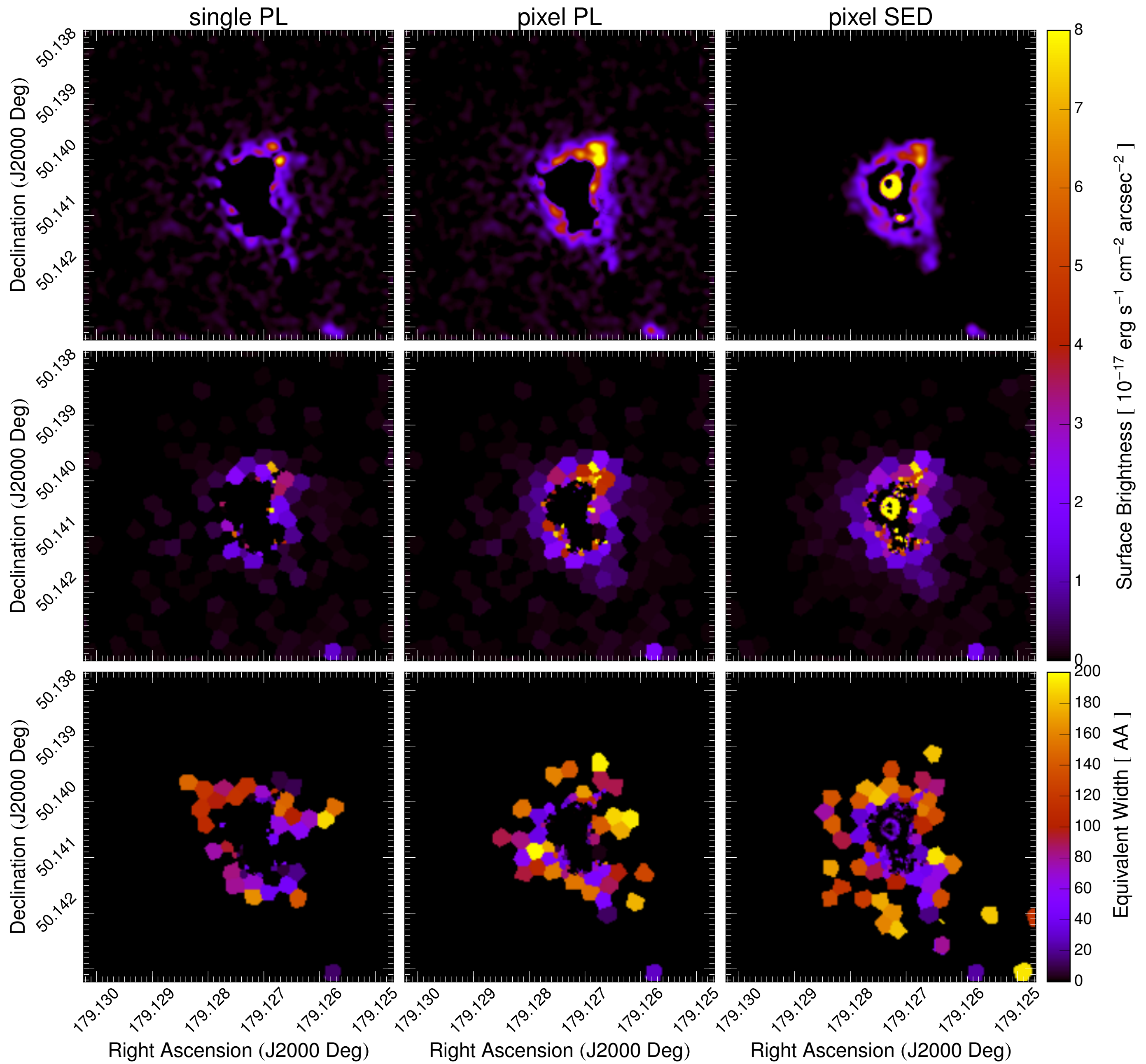
J1156 overlaid upon Grimes et al (2009) Figure 40; Heckman et al 2002 Figure 1. (See also Tripp et al 2008) Figure 16)

Expected relation between N_{OVI} and velocity width (b) for radiatively cooling collisional gas at T= {10^5, 10^6} K

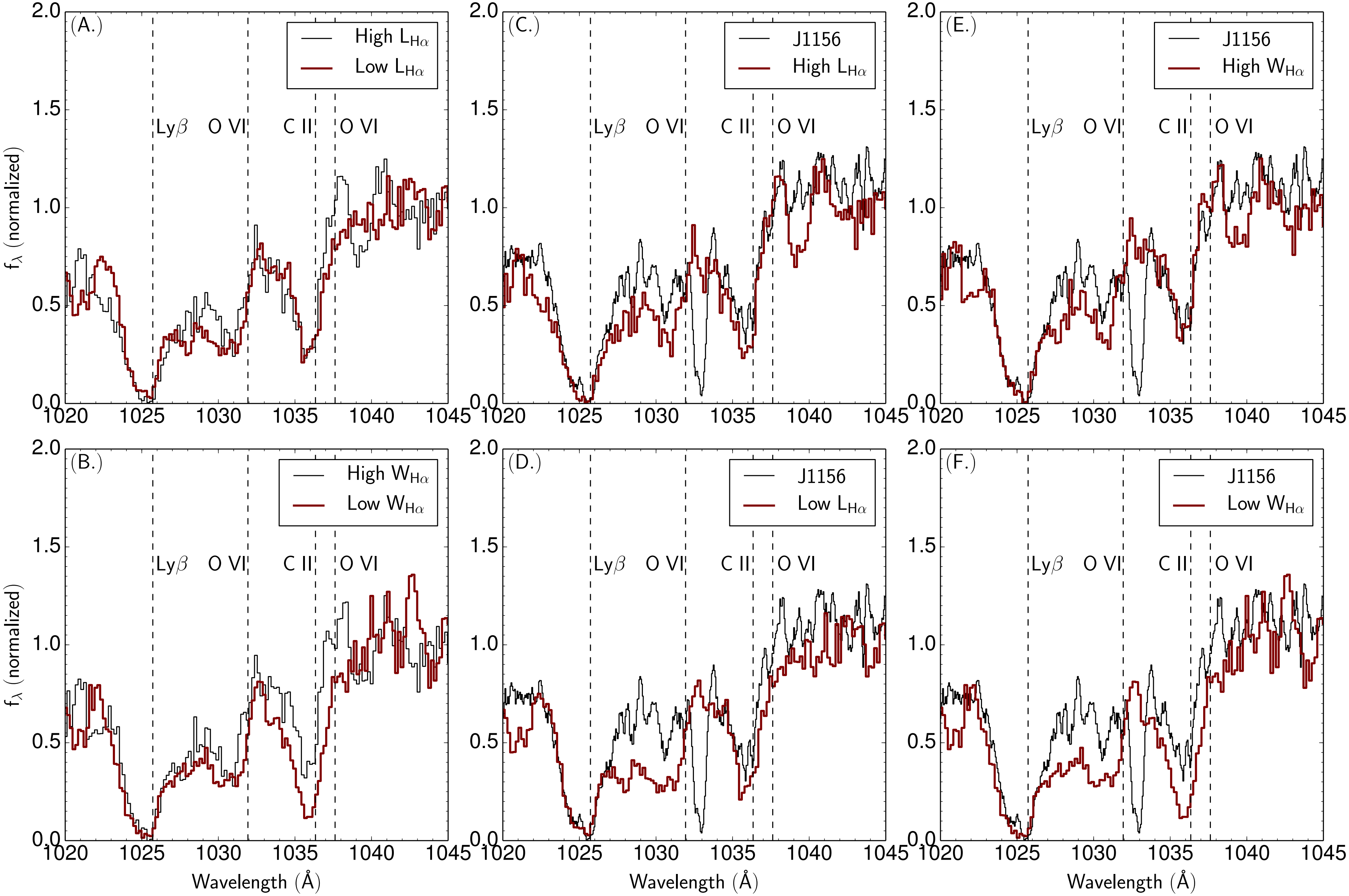
J1156 lies in among the FUSE starbursts (red square)

→ Consistent with collisional excitation

Different Continuum Subtractions



Archival Spectra



The Two Other Detections

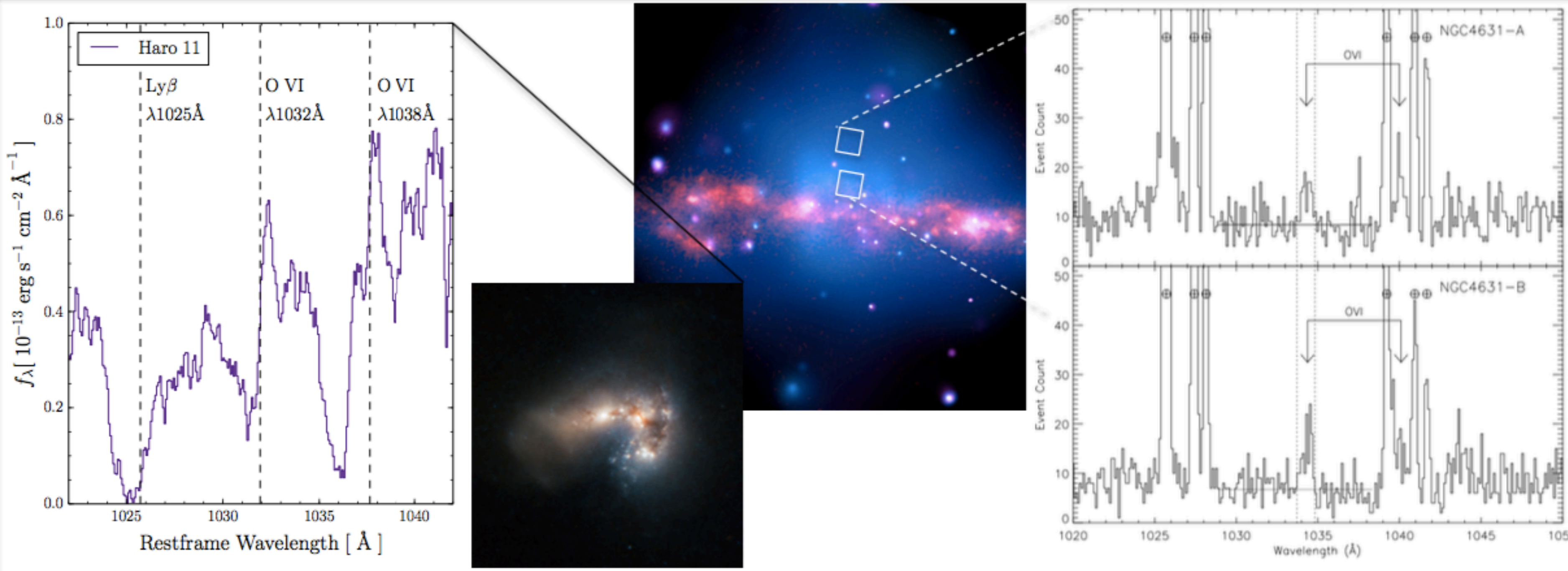
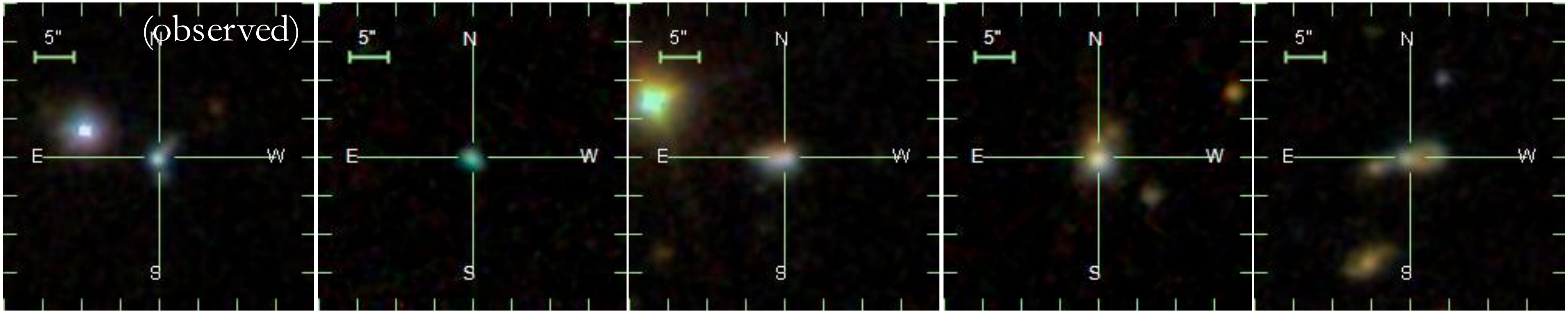


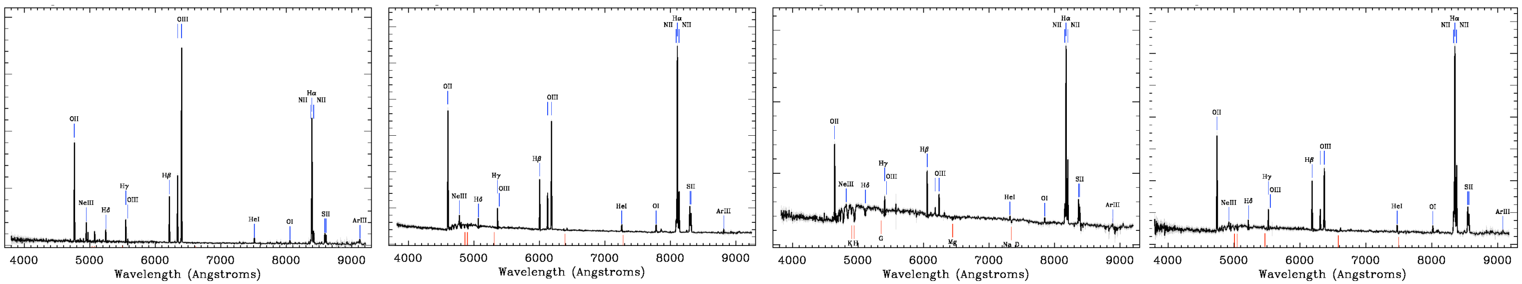
Figure 2. FUSE OVI spectra | *Left* panels show Haro 11 (d = 86 Mpc) for which the FUSE aperture encompasses the entire galaxy. Both absorption (bluehsifted) and emission are visible in OVI, but absorption more than exceeds emission. *Right* panels, however, show NGC 4631, which lies at just 8 Mpc. The FUSE aperture was positioned away from the stellar disk by Otte et al (2003) and as described, no continuum is visible here leaving high-contrast OVI emission lines that are easily isolated.

Grimes et al 2007,2009
Haro 11 – luminosity ½ that of J1156 in same physical aperture

Otte et al 2003
NGC 4631 – very much less. Less star-forming, much small physical scale. X-ray coincident

Improving upon 1 galaxy: HST Cycle 23





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