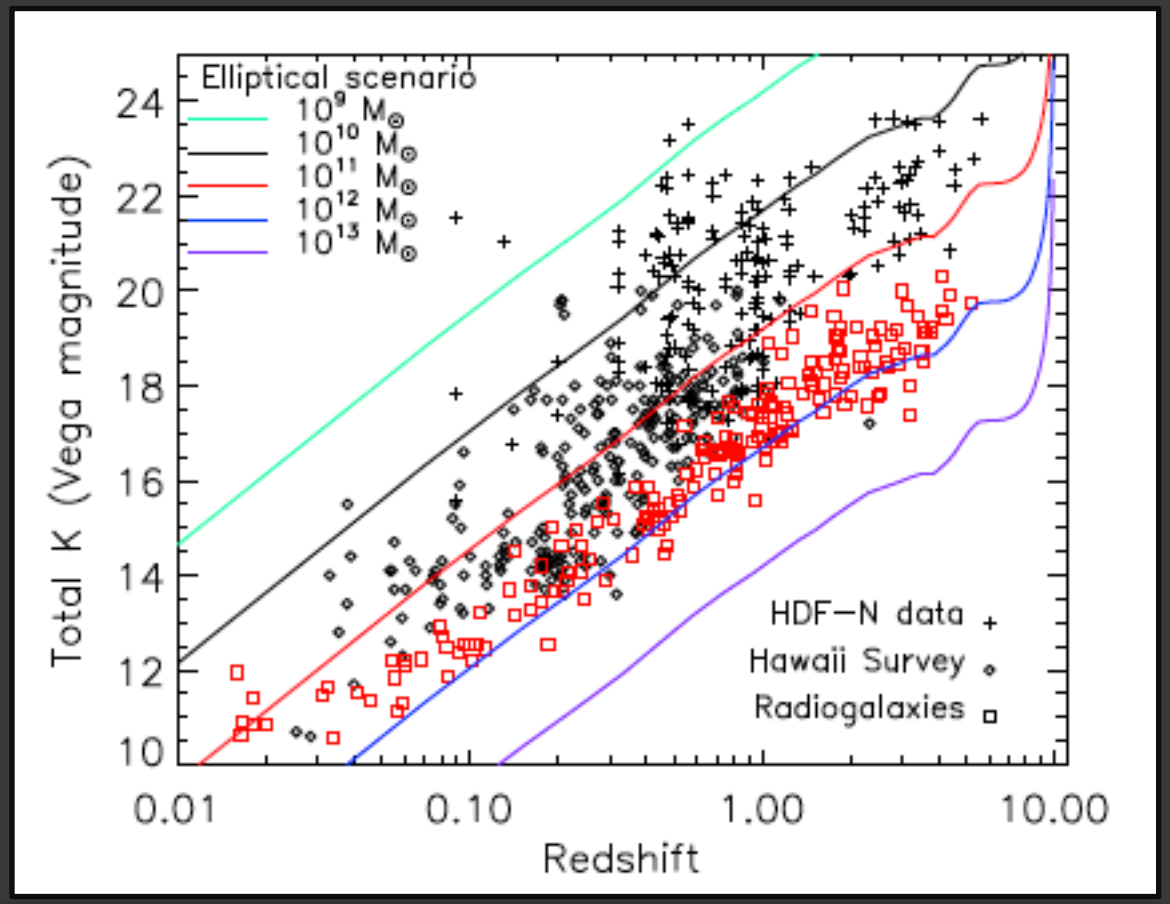
Speaker: Sthabile Kolwa

PhD Collaborators: Joël Vernet, Carlos De Breuck, Theresa Falkendal, Matthew Lehnert, Bitten Gullberg, Ian Smail and Mark Swinbank

Dissecting the multi-phase haloes of high redshift radio galaxies with ALMA and MUSE

Summary: High redshift radio galaxies

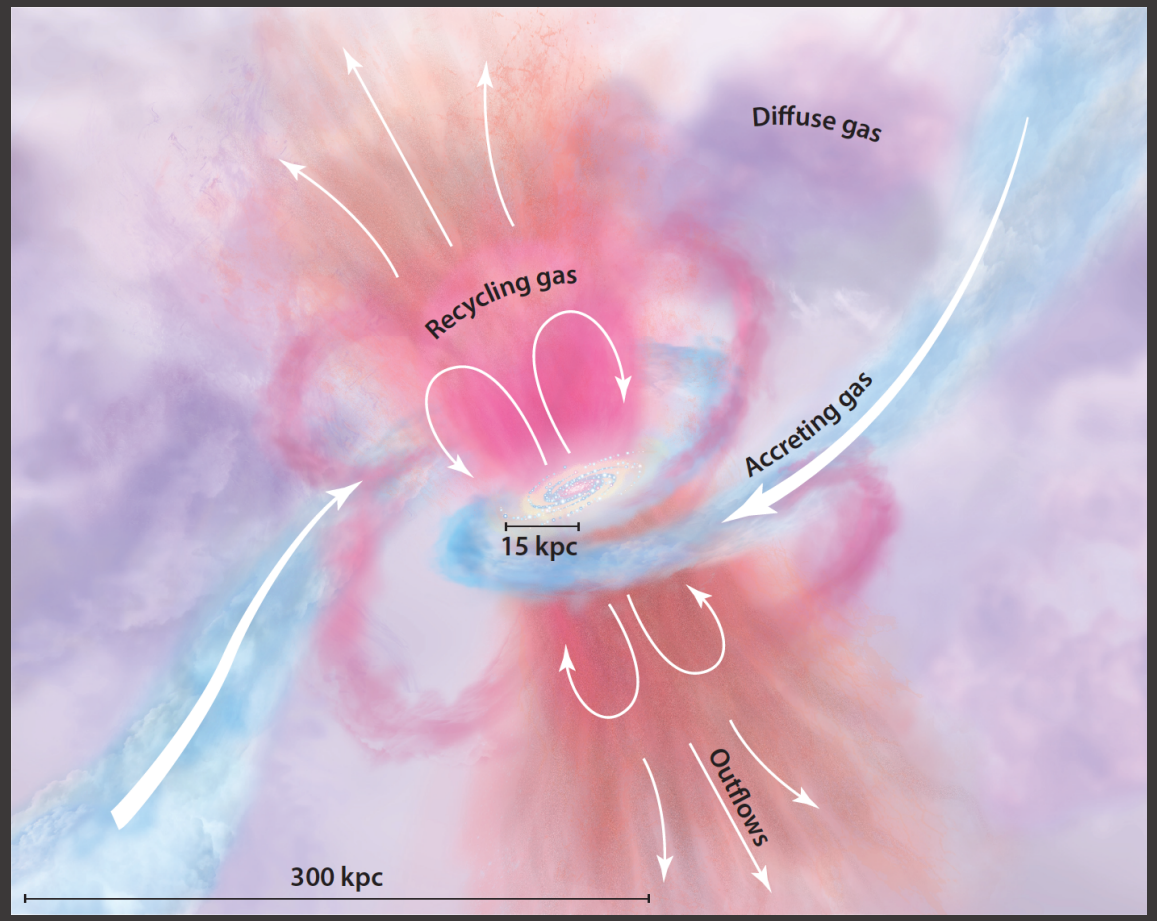
- Massive elliptical 10^{11} - $10^{12} M_{\odot}$ (NIR Hubble K-z diagram; IMF: Rana & Basu +1992)
- Ancestors of local cD and gE galaxies (Pentericci+1999)
- High SFR from mm/sub-mm i.e. dust (e.g. ALMA) 300 – 1000 $M_{\odot}$/yr (Falkendal+2017 in prep.)
- Environments: Lyα proto-clusters (Galametz+2010)
- Kinematically quiet Lyα haloes (Villar-Martin+2003) extending 80 – 250 kpc from galactic nucleus traced by ionisation region
- Steep non-thermal radio SED i.e. α = -1.44 (Emonts+2011)



Rocca-Volmerange+2004

Circumgalactic medium (CGM): by definition

> Gas gravitationally bound within the virial radius of a galaxy



Tumlinson, Peeples and Werk (2017)

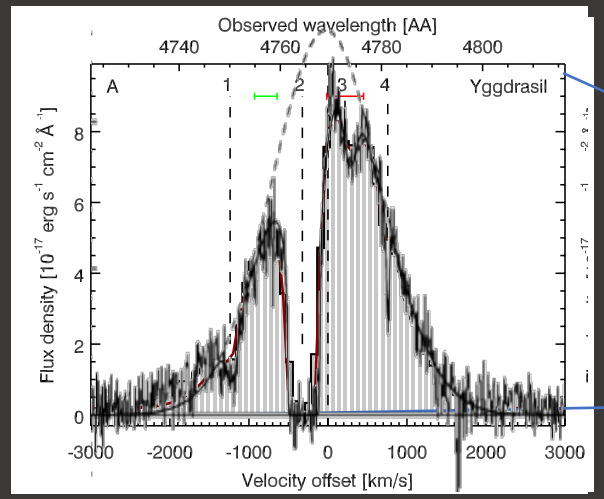
Phenomenological Study: MRC 0943-242

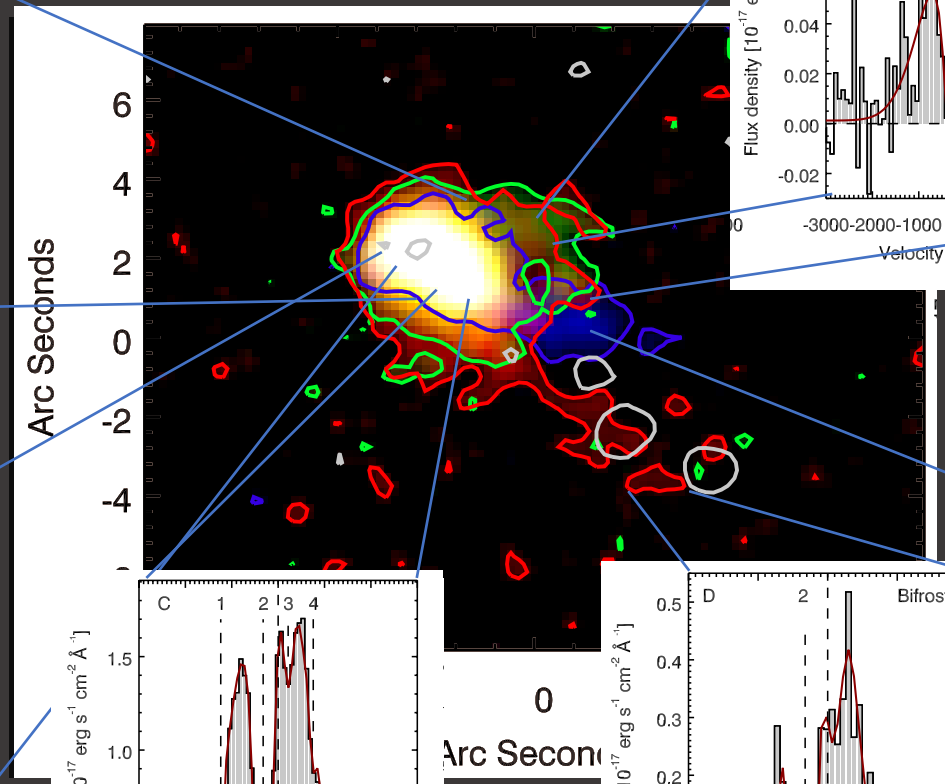
- z = 2.923 radio galaxy (Gullberg+2016)
- 1.1 Jy at 408 MHz (Large+1981)
- Embedded in low-surface brightness Lyα halo ~60 kpc (Villar-Martín+2003)
  - Kinematically quiet halo (FWHM: 400-600 km/s)
- Stellar-mass: $M_* \sim 10^{11}\ M_\odot$ (Seymour+2007)
- $M_{halo} \sim 7 - 44 \times 10^{11}\ M_\odot$ (Jarvis+2003)
- Surrounded by vast shells of absorbing HI gas (Binnette+2000)

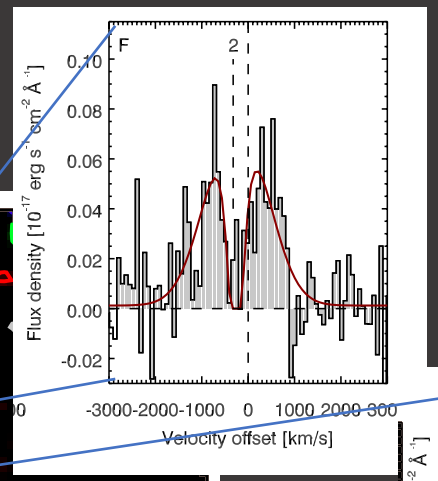
- VLT/MUSE IFS (spec. range: 4800 – 9300 Å; spec. res.: 2.8 – 2.7 Å)
- Study morphology, kinematics and metallicity of circumgalactic medium (CGM) gas
- Understand interplay between radio jets and AGN

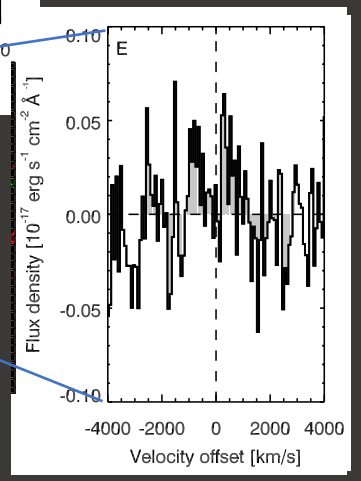
Varying Lyα line profiles in 0943 CGM

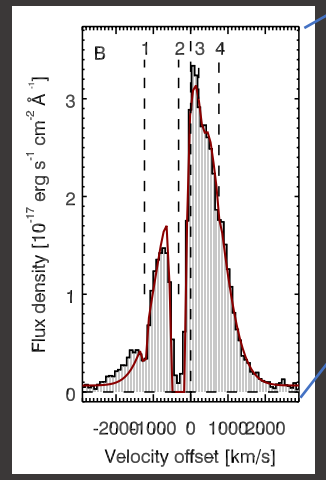
UVES data: Jarvis + 2003

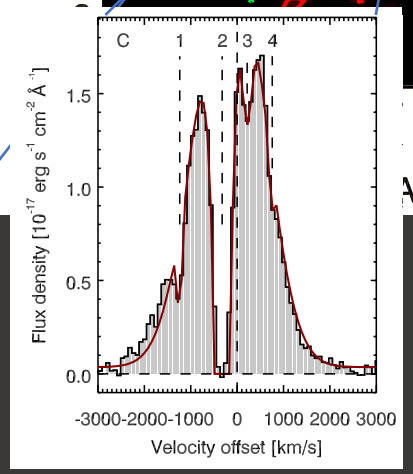


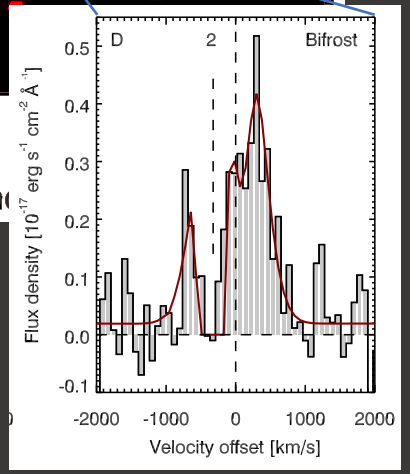












- HI medium non-homogenous
- Extends to r < 60 kpc from AGN

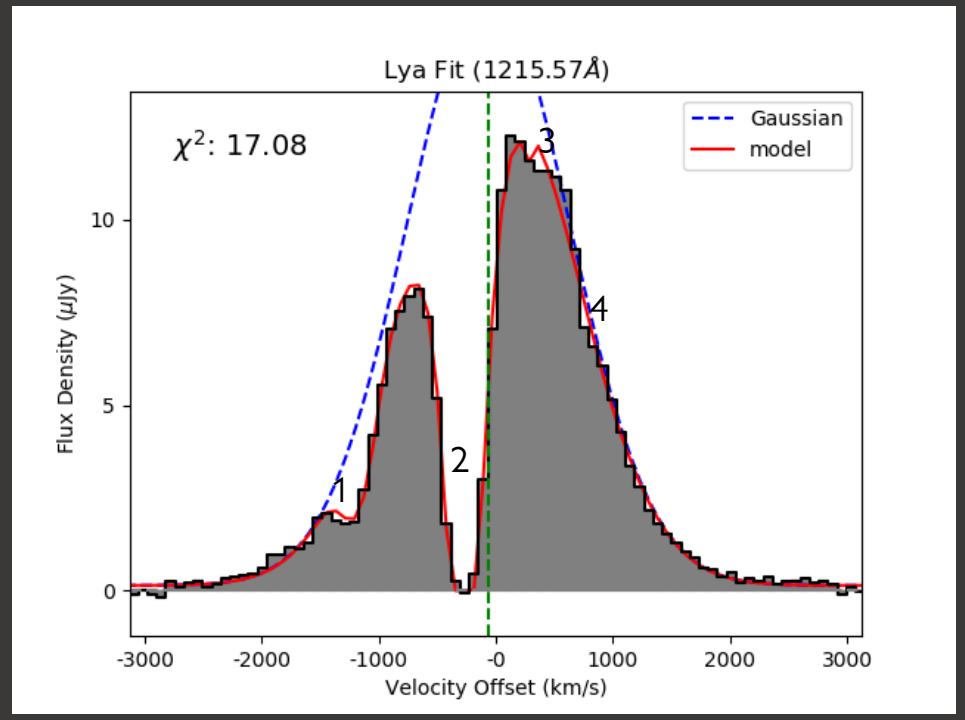
VLT/MUSE taken with 1h int. time (Gullberg+2016)
Lyα (green: 4754-4758 Å; red: 4768-4776 Å)
HeII (blue: 6422 – 6430 Å) (Gullberg+2016)

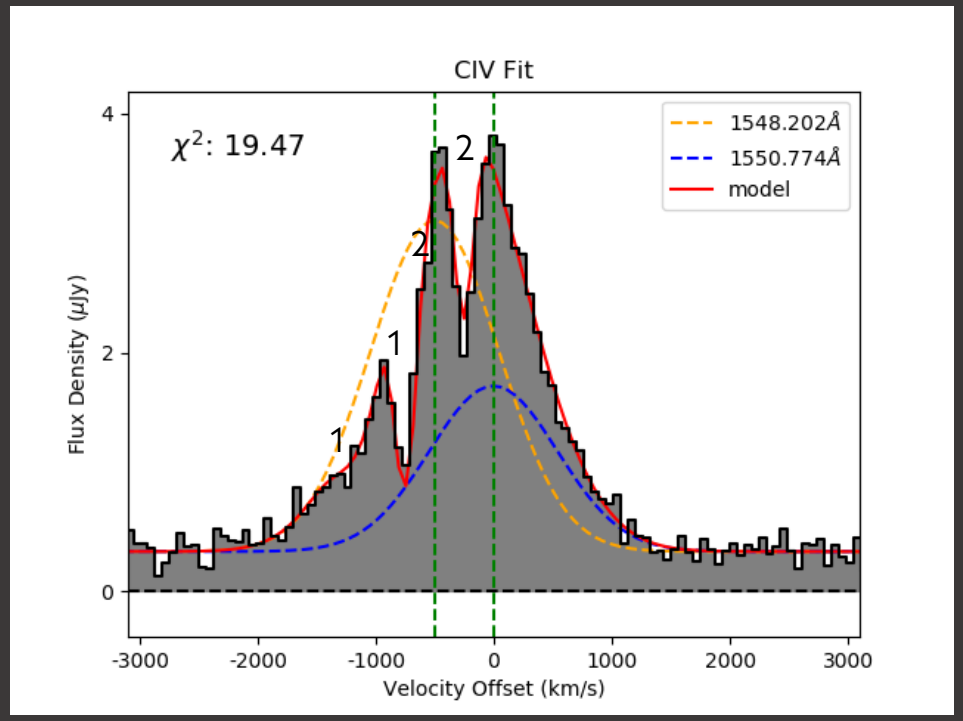
MAPPINGS emission and absorption lines in 0943

- MAPPINGS IE: photoionization model with (U = 0.018), a relatively hard ionizing SED ($\alpha = -1.0$) and a high gas metallicity ($Z/Z_{\odot} = 2.1$) provides the best overall fit to X-SHOOTER emission lines (Silva et al 2018)

- MAPPINGS IC: low metallicity ($Z/Z_{\odot} = 0.01$) gas cocoon is primary absorbing medium for gas (Binnette et al 2000)

HI and CIV absorption in 0943 CGM





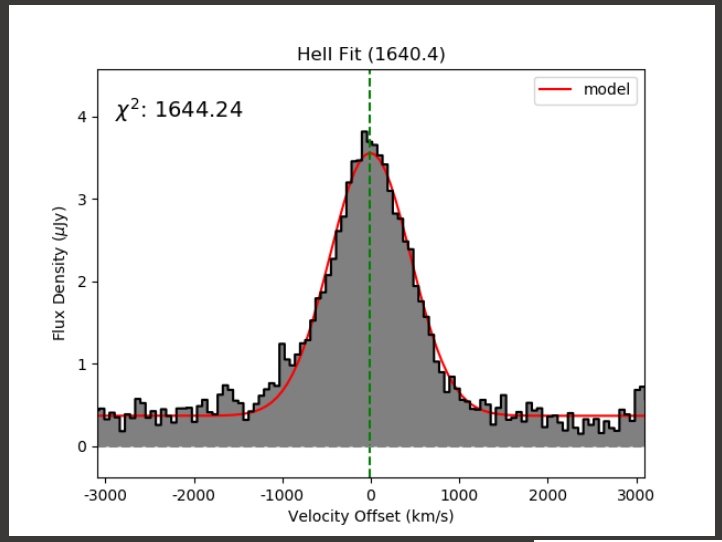
Gaussian and Voigt composite:
σ: 11.05 ± 0.17 Å
z1: 2.907 ± 0.000231
N1: (1.68 ± 0.276) x 10^{14} cm^{-2}
z2: 2.919 ± 0.0000418
N2: (1.80 ± 0.238) x 10^{19} cm^{-2}
z3: 2.926 ± 0.000214
N3: (1.66 ± 292) x 10^{15} cm^{-2}
z4: 2.936 ± 0.006702
N4: (4.32 ± 26.0) x 10^{12} cm^{-2}

VLT/MUSE: spatially integrated R=0.6''
(Centered on high flux density peak in nuclear region)

Gaussian and Voigt composite:
σ1: 11.02 ± 0.26 Å
σ2: 11.02 ± 0.26 Å
z1: 2.914 ± 0.000465
N1: (2.71 ± 0.24) x 10^{14} cm^{-2}
z2: 2.919 ± 0.000076
N2: (2.58 ± 0.69) x 10^{14} cm^{-2}

- Clear evidence for HI and CIV absorbers in CGM
- Lyα absorbers 1 and 2 coincides in velocity with CIV absorbers 1 and 2, resp.

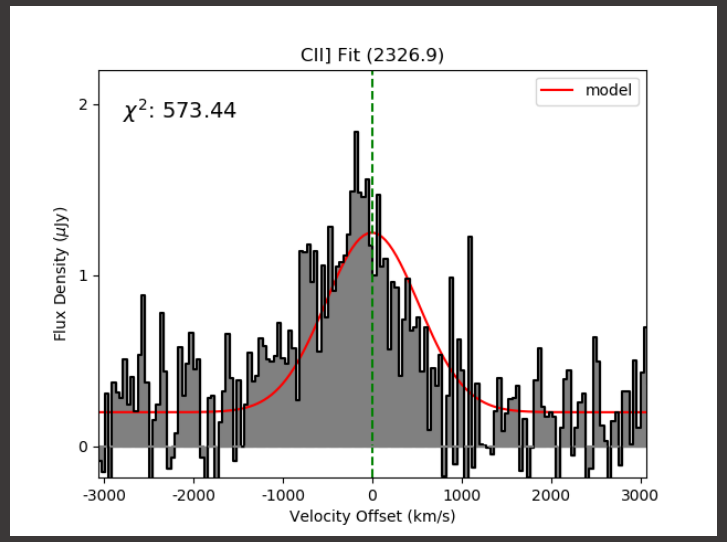
Emission Line Model Fits to Nuclear Region of MRC 0943-242



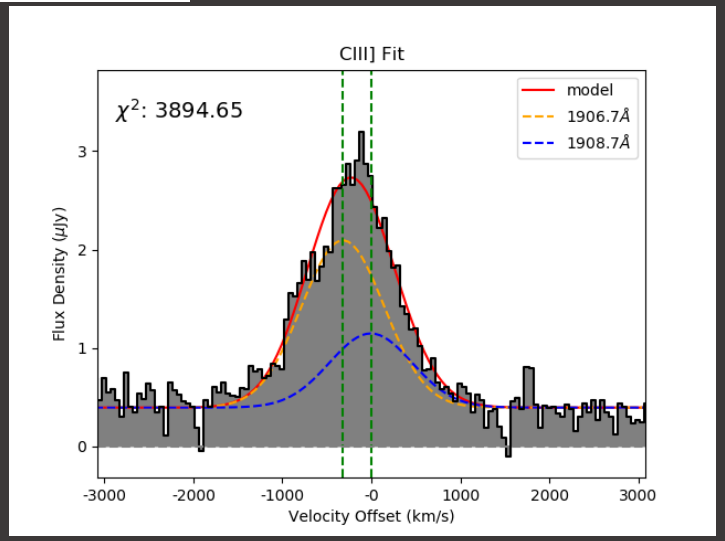
σ: 9.81 ± 0.17 Å
FWHM: 1076.37 ± 18.77 km/s

- Emission line gas in close proximity to central AGN
- Model: single component Gaussian fits
- Emission lines Reveals turbulent, kinematically perturbed gas: FWHM ~ 1000 km/s

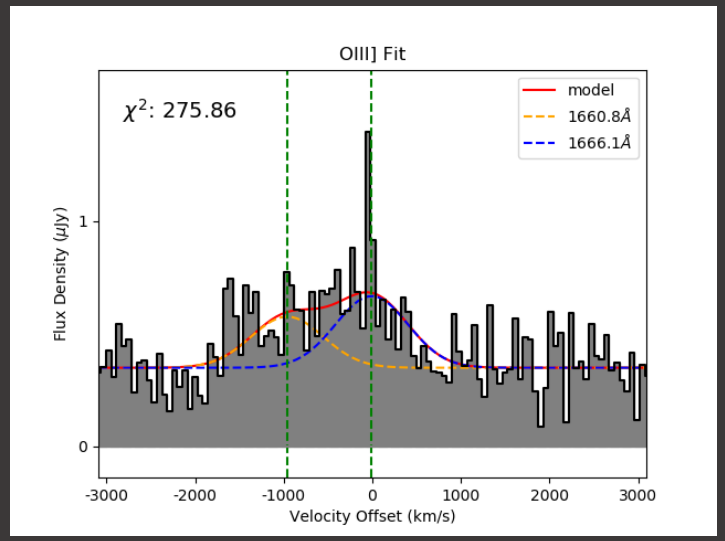
VLT/MUSE: spatially integrated R=0.6''
(Centered on high flux density peak in nuclear region)



σ: 15.85 ± 1.42 Å
FWHM: 1225.62 ± 110.01 km/s



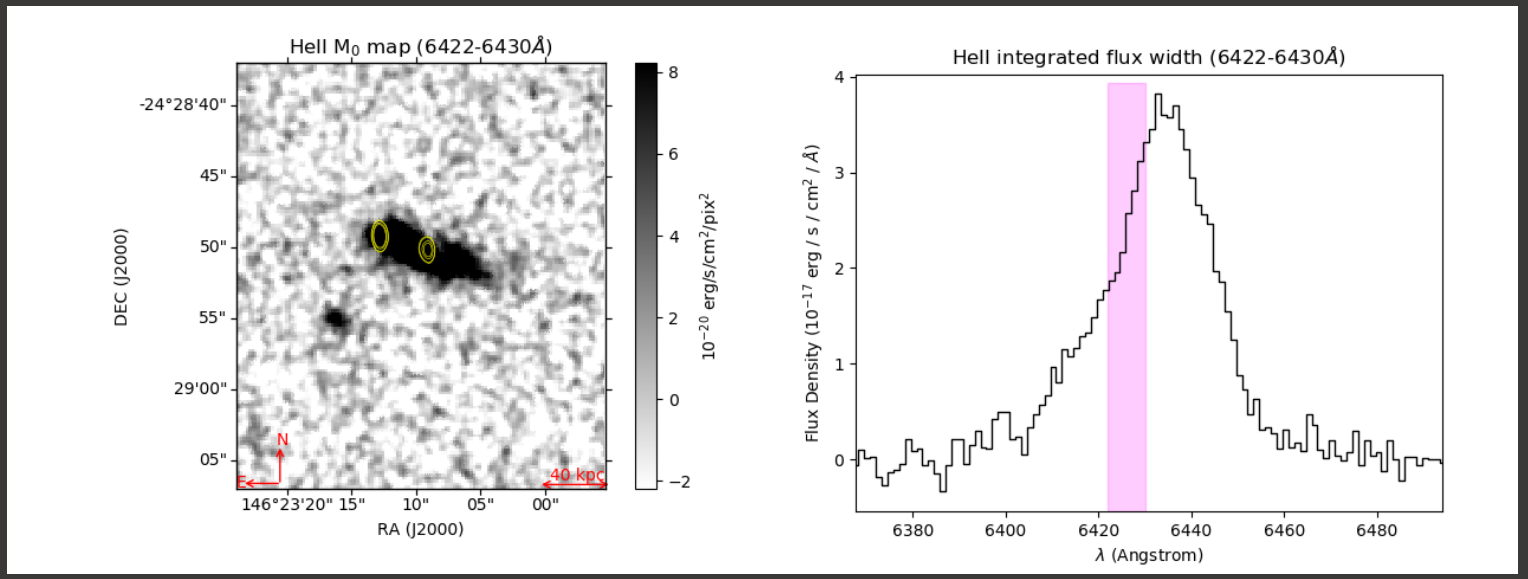
σ_1: 11.59 ± 1.54 Å
$FWHM_1$: 1093.62 ± 123.17 km/s
σ_2:11.59 ± 1.54 Å
$FWHM_2$: 1092.47 ± 123.04 km/s

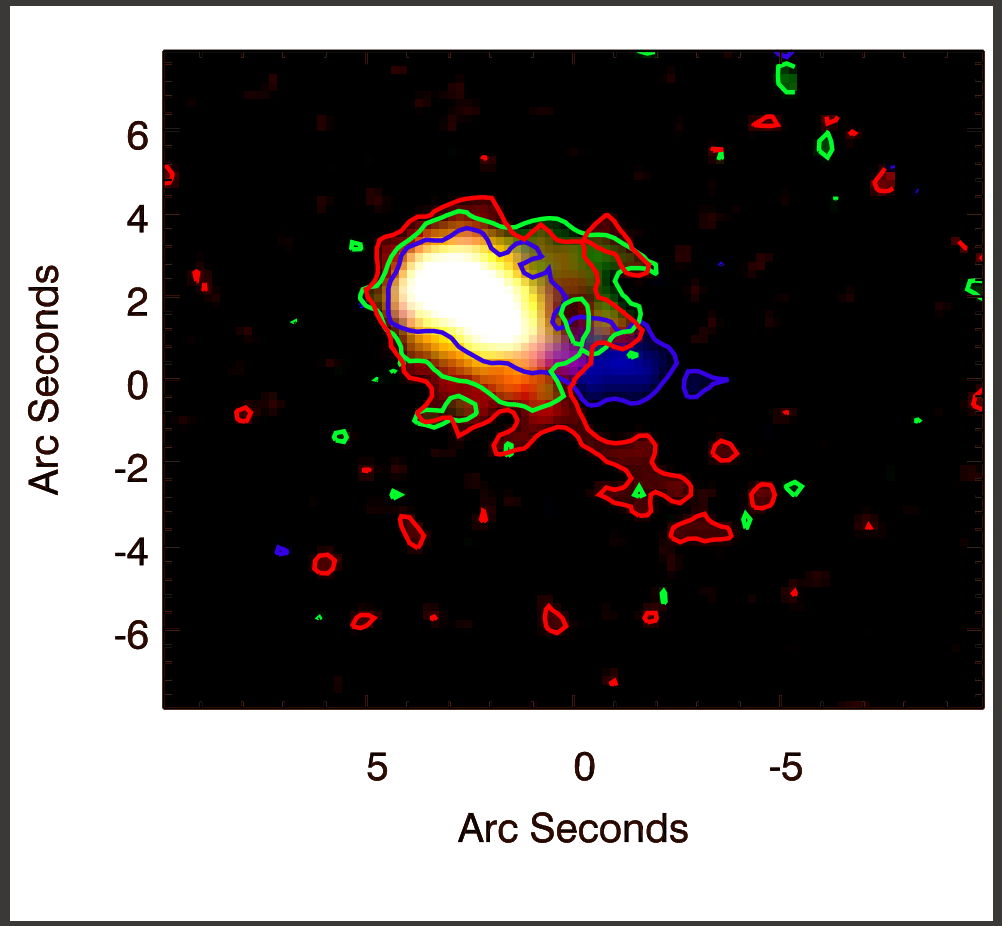


σ_1: 8.90 ± 1.58 Å
$FWHM_1$: 964.15 ± 188.58 km/s
σ_2: 8.90 ± 1.58 Å
$FWHM_2$: 961.08 ± 187.98 km/s

Tidally perturbed gas extending WSW: HeII and Lyα

- HeII extension in WSW
- Lyα absorbed out completely in WSW (aligned with radio jet)
- Lyα bridge in SW





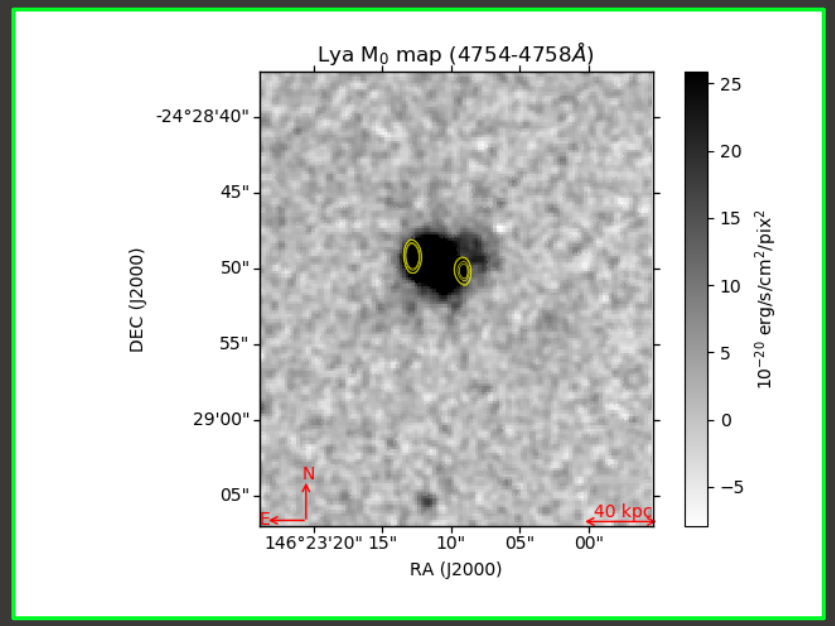
VLT/MUSE taken with 5h int. time (Kolwa+2016 in prep.): HeII (blue: 6422 – 6430 Å)

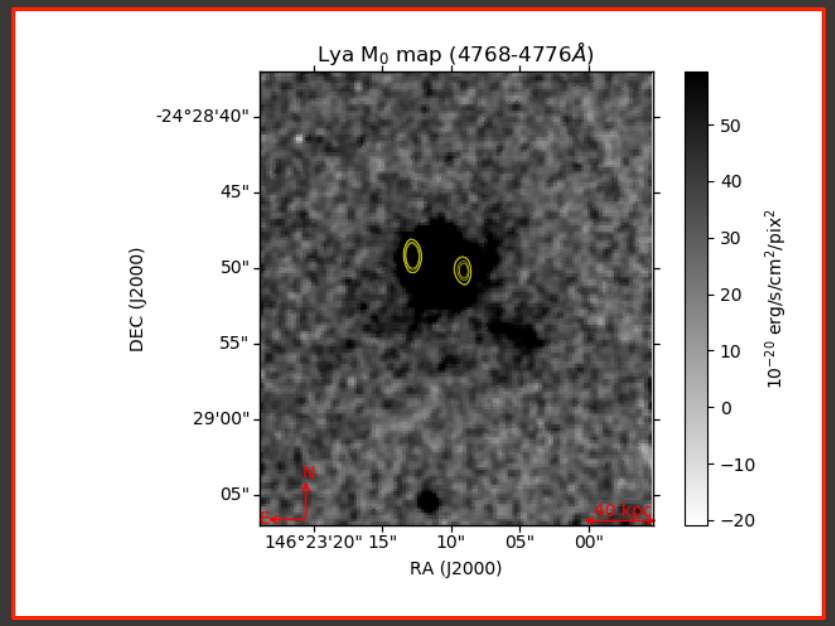
VLT/MUSE Lyα integrated spectrum aperture radius: 0.8''

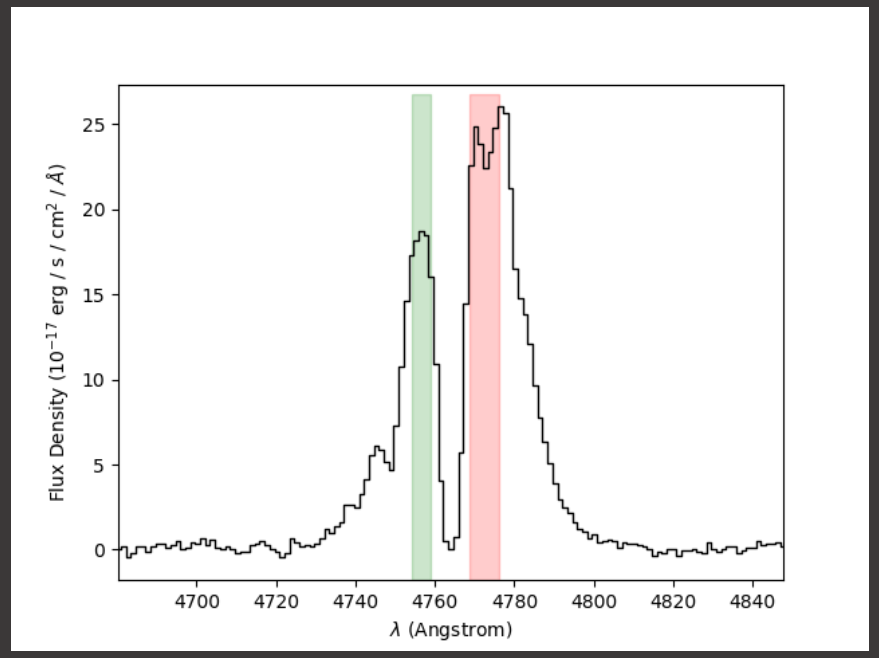
VLT/MUSE taken with 1h int. time (Gullberg+2016) Lyα (green: 4754-4758 Å; red: 4768-4776 Å)

Tidally perturbed gas extending SW: Lyα

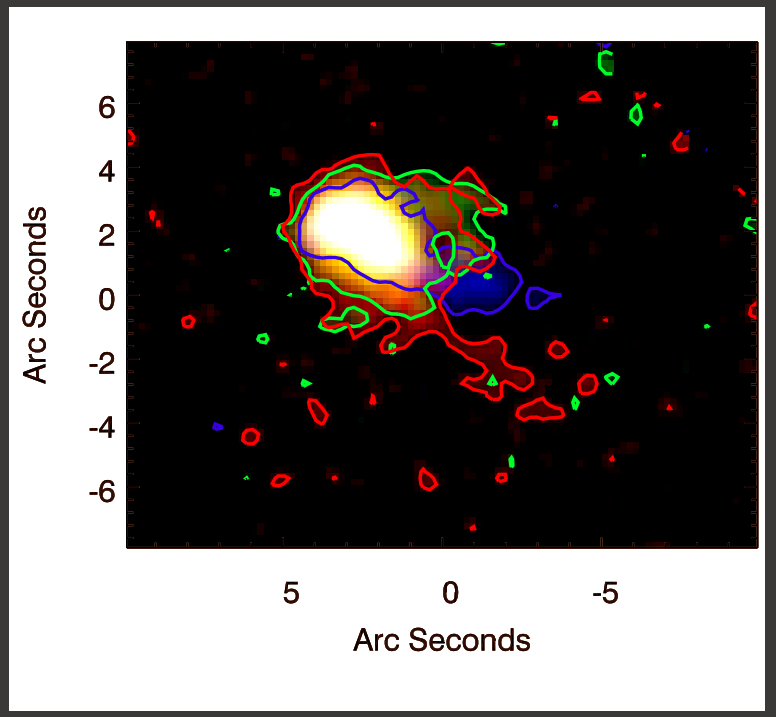
VLT/MUSE: Lyα (green: 4754-4758 Å; red: 4768-4776 Å)







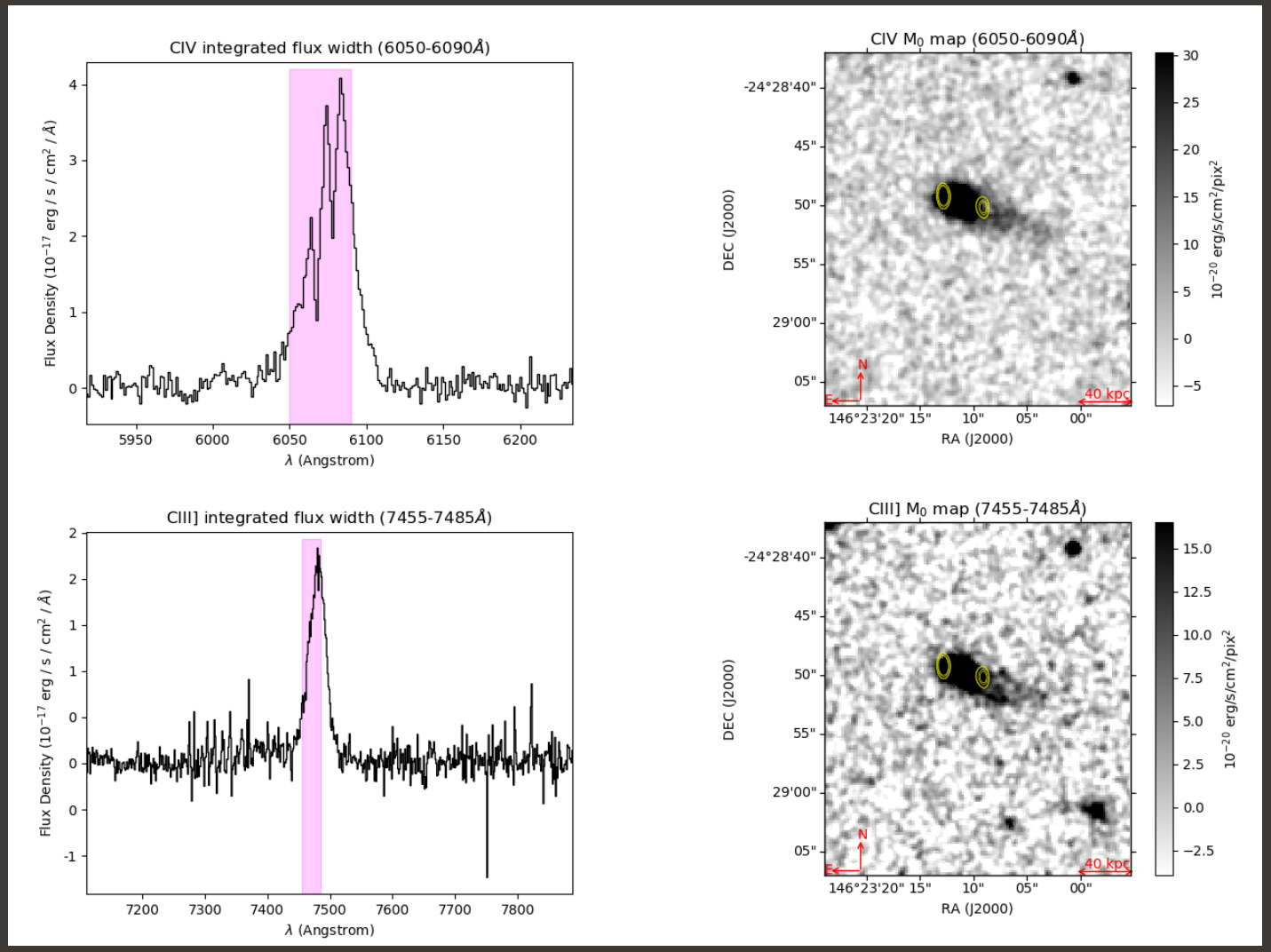
VLT/MUSE: Lyα integrated spectrum
aperture radius: 0.8''



VLT/MUSE including HeII (blue: 6422 – 6430 Å) (Gullberg+2016)

- Shell of diffuse Lyα extending
- Lyα bridge of gas extended ~60kpc from nucleuxs
- Observational merger-tracers in warm ($T \sim 10^4$ - 10^5 K) medium

Tidally perturbed gas extending WSW: CIV and CIII]



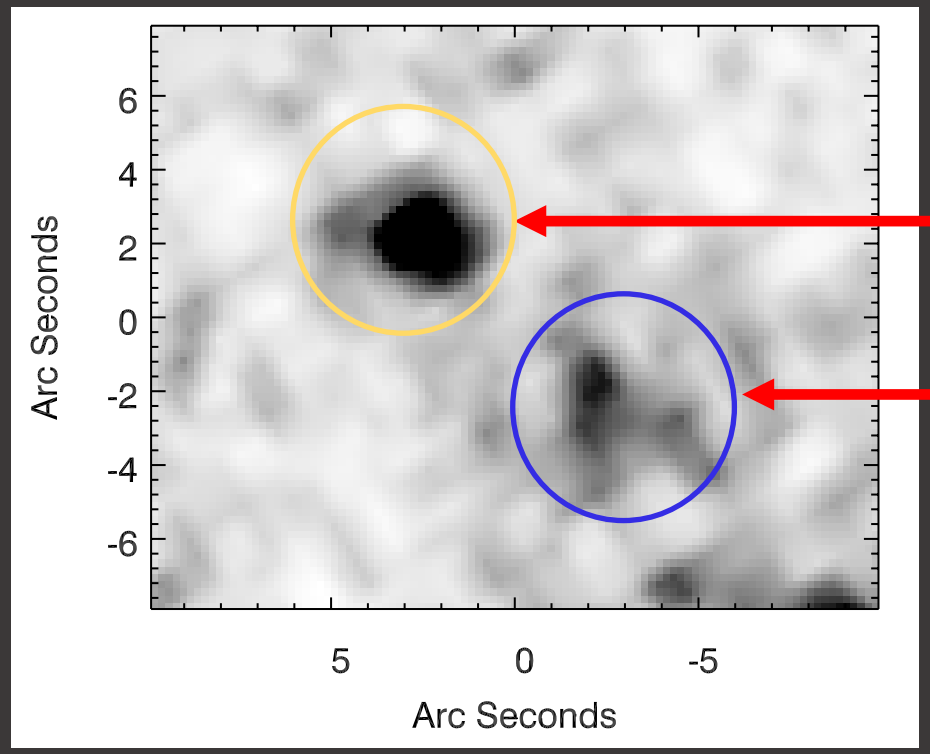
VLT/MUSE: CIV (6050– 6090 Å) and CIII] (7455 – 7485 Å); 4.5 GHz VLA contours (yellow)

- Diffuse, extended CIV and CIII] gas
- Simulations predict outflows of metal-rich gas from mergers
- Tidal tails in emission

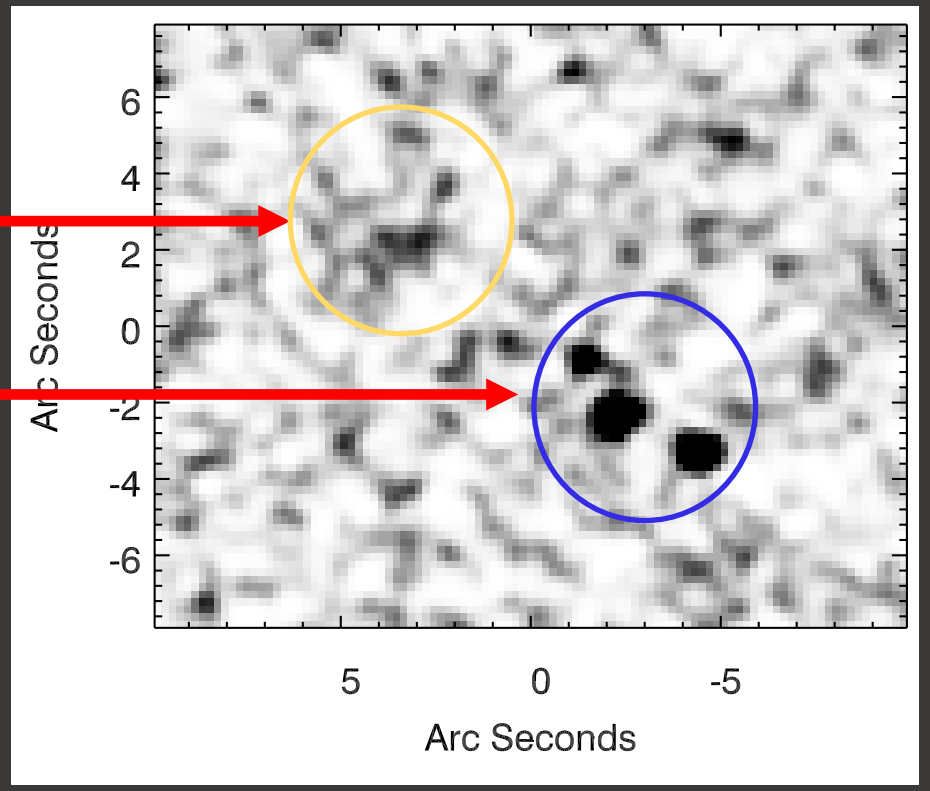
OR

- Alignment with radio jets (yellow contours)
- Also shock-heated of gas

Spitzer+ALMA archival



Spitzer 4.5 μm data



ALMA 235 GHz data

- Spitzer/4.5 μm data reveals stellar mass (M_*) distribution of MRC 0943-242 (Seymour+2007)
- ALMA 235 GHz imaging strong dust continuum ~40-70 kpc main galaxy AGN
- Spatially coincident M_* and three-component dust continuum prior evidence of dusty, star-forming galaxy

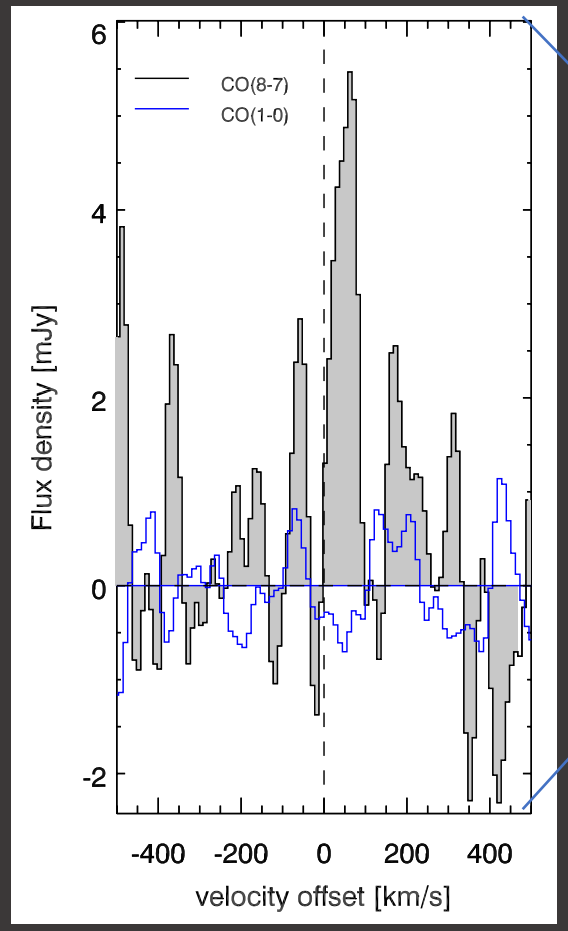
Molecular gas (H_2) traced by CO(1-0)

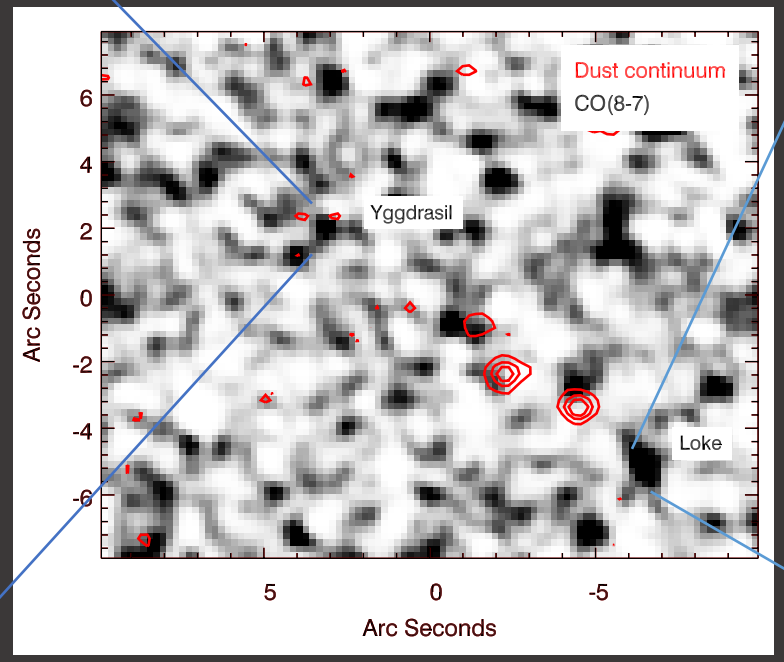
$\alpha_{CO} = 0.8\ M_\odot K\ km\ s^{-1}\ pc^{-2}$

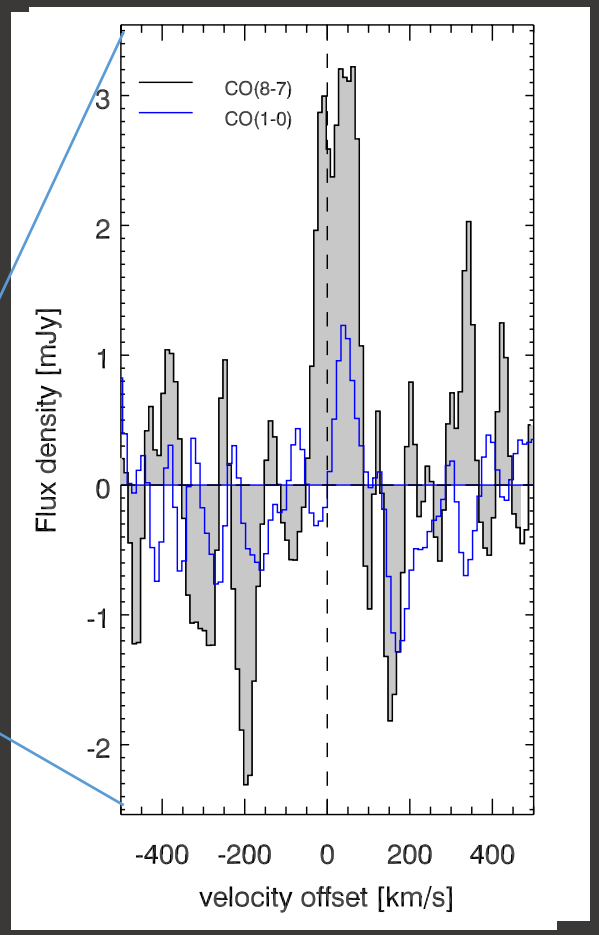
RG: $M_{H2} = 2.3 \times 10^{10}\ M_\odot$

Offset: $M_{H2} = 6 \times 10^{10}\ M_\odot$

Upcoming: ALMA band 3 CI(1-0) detections to better constrain M_{H2} (Kolwa et al in prep.)







Blue: ATCA CO(1-0) spectrum (Emonts et al 2011)

Summary

- MAPPINGS have revealed low metallicity absorber and high metallicity emission CGM
- Evidence of tidally stripped gas in a massive high-redshift galaxy
- Stellar mass and dust continuum (235 GHz) coincide perturbed gas
- Galaxy merger or jet-triggered star-formation
- Absorbing HI and CIV mediums also observed
- ALMA CO(1-0) has measured H_2 masses
- ALMA CI(1-0) detections will constrain further H_2 distribution and mass