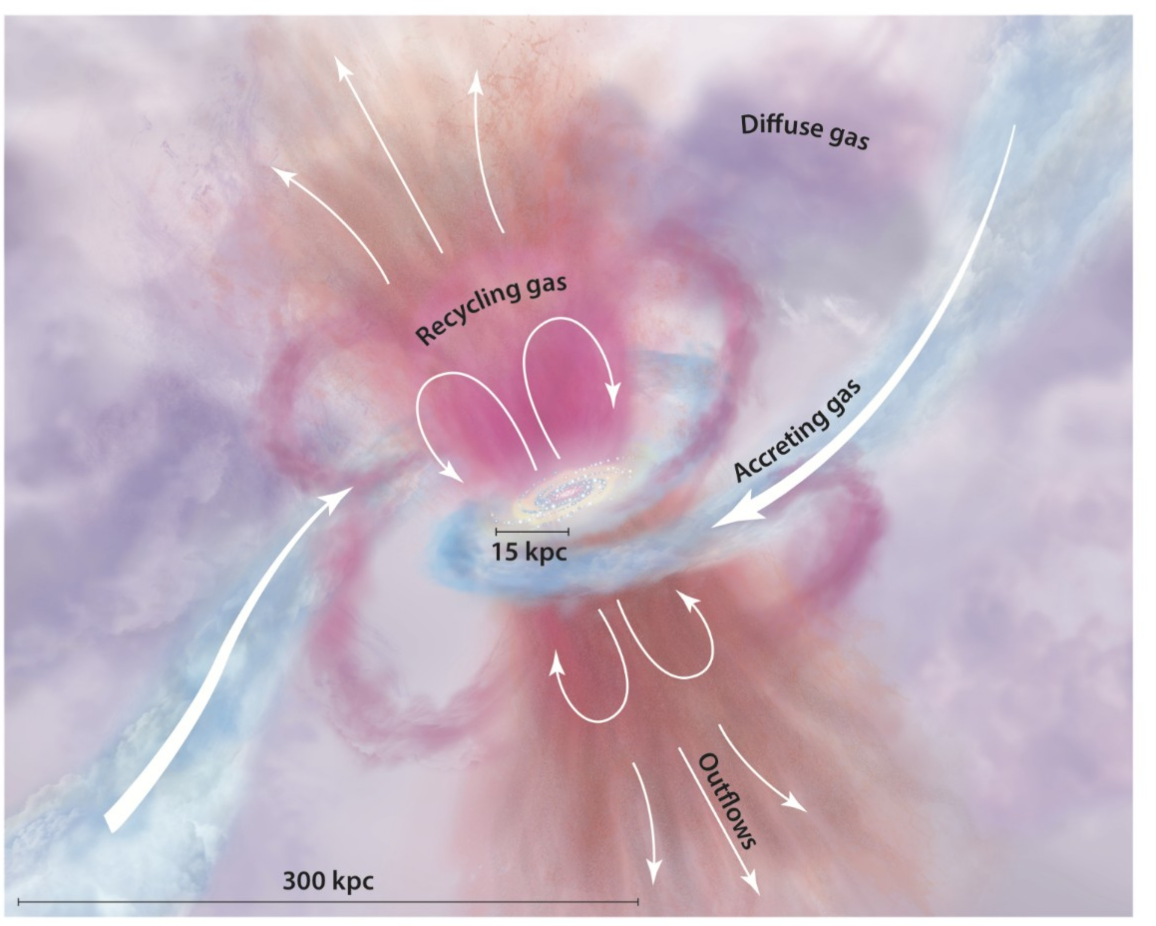
SPECMAP-CGM

Statistical constraints on galactic scale outflows properties traced by their extended Mg II emission with MUSE

Ismael Pessa, Lutz Wisotzki, Tanya Urrutia, John Pharo, Ramona Augustin, Daria Kozlova, Héctor Salas, Daniil Smirnov, et al.

18th Potsdam Thinkshop, 16/07/2025



Tumlinson et al. 2017

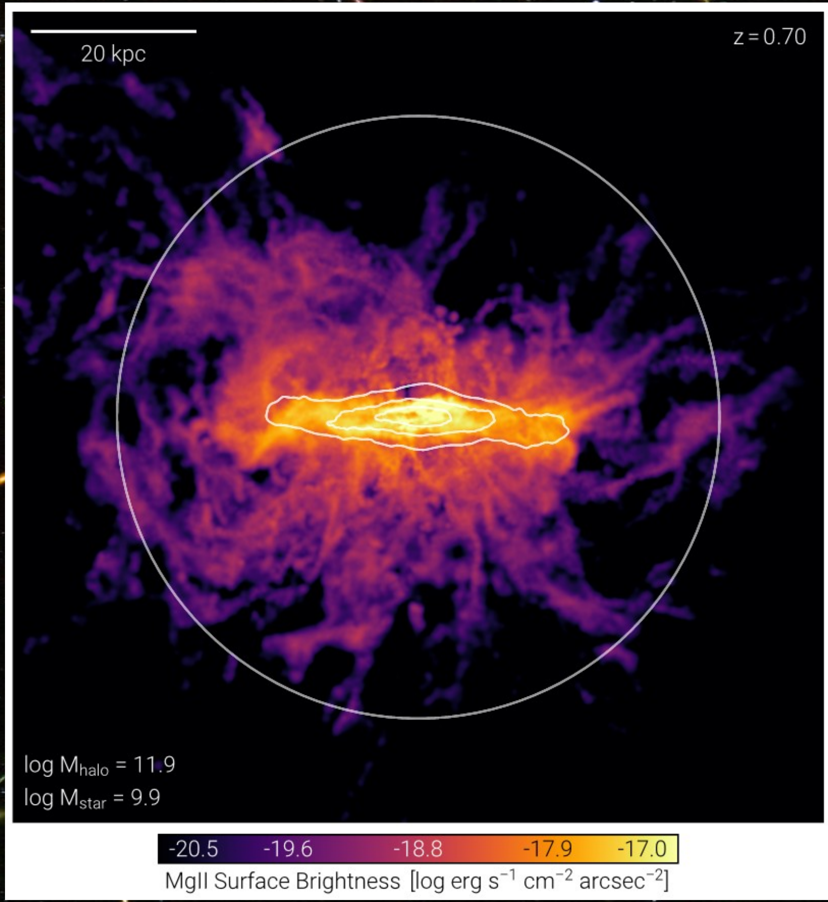
CGM: Circumgalactic medium

Diffuse gas surrounding galaxies

Interface between the galaxy and the intergalactic medium

Many physical processes that regulate galaxy evolution take place in the CGM!

Outflow are powerful drivers of galaxy evolution



Nelson et al. 2023, Mg II haloes in TNG50

Galactic scale outflows strongly impact their host galaxy properties:

- Metallicity of the ISM and CGM

- Regulation of star formation

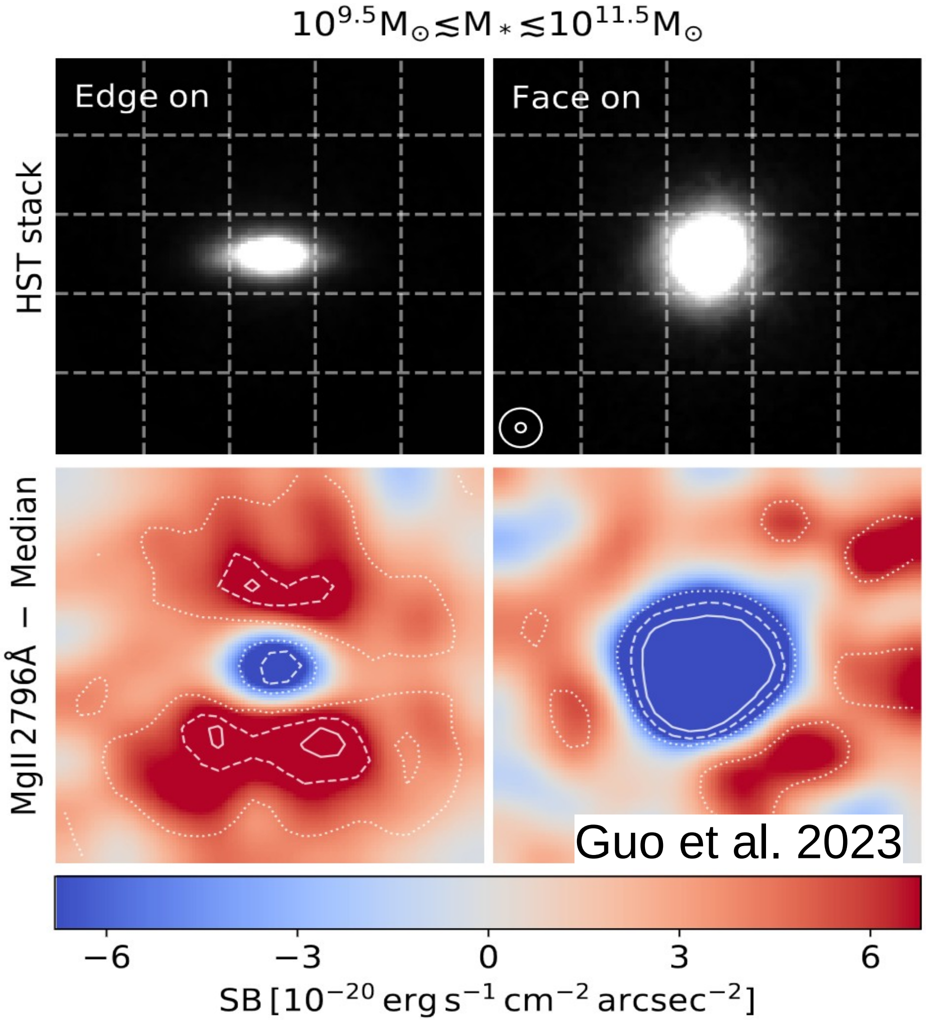
- Redistribution of gas on the galaxy

- Influence galaxy morphology

- Firstly probed in absorption

- Now we have the data to detect them in **emission** → more complete picture of the outflow properties

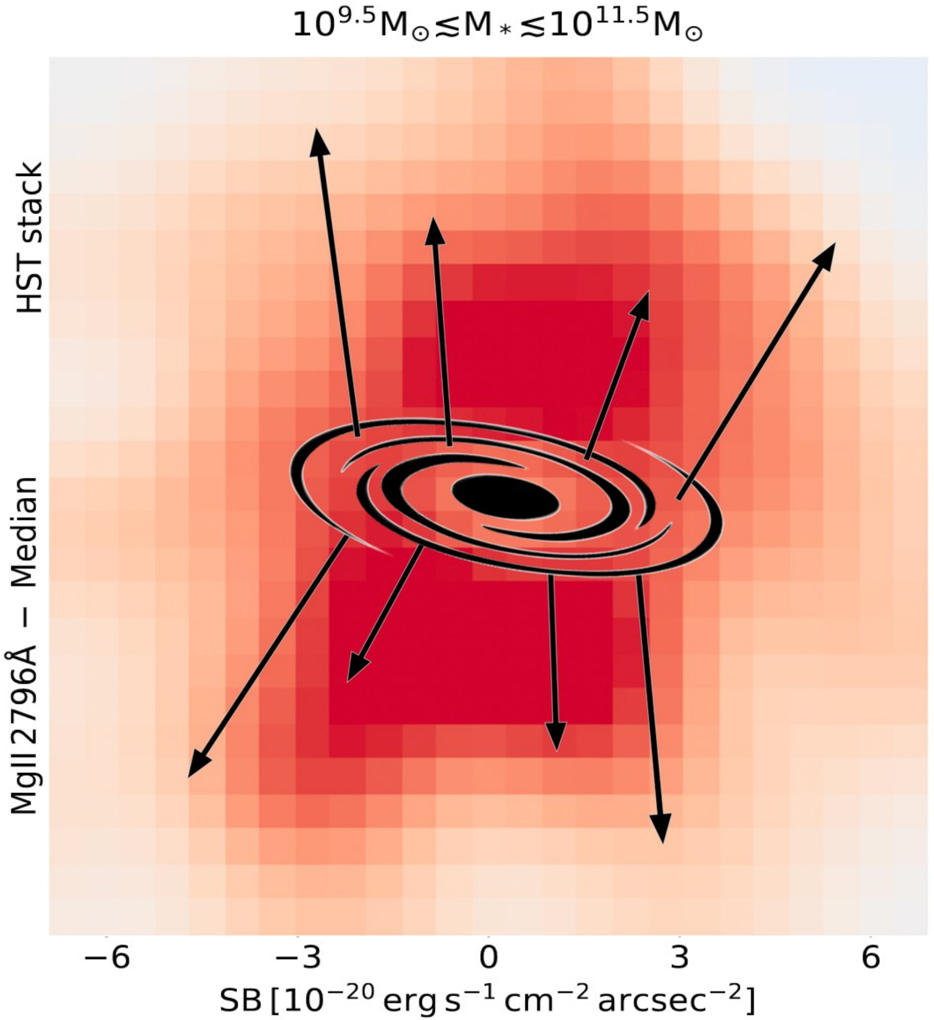
Extended emission on spatially resolved data of stacked samples



Guo et al. 2023: Stacking Mg II emission of 172 galaxies from the MUSE Hubble UDF

Spatially resolve halos → strong difference between edge-on and face-on samples

Extended emission on spatially resolved data of stacked samples



Guo et al. 2023: Stacking Mg II emission of 172 galaxies from the MUSE Hubble UDF

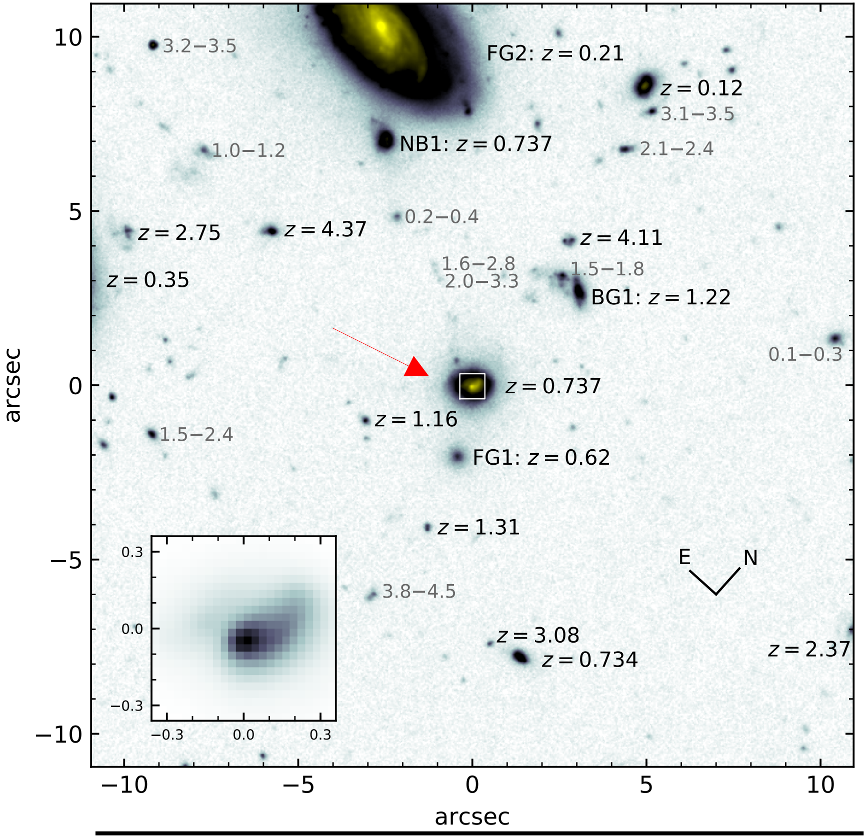
Spatially resolve halos → strong difference between edge-on and face-on samples

Consistent with **widespread** biconical outflows

Stacking large samples of galaxies loses peculiarities of individual objects

Can we resolve the MgII extended emission for individual galaxies?

Discovery of MUSE-HUDF #884 Mg II Halo



~80 kpc at z=0.737

- Search for emission lines using LSDCat software in the MUSE-HUDF Mosaic data → Extended emission around a galaxy at *z*~0.737

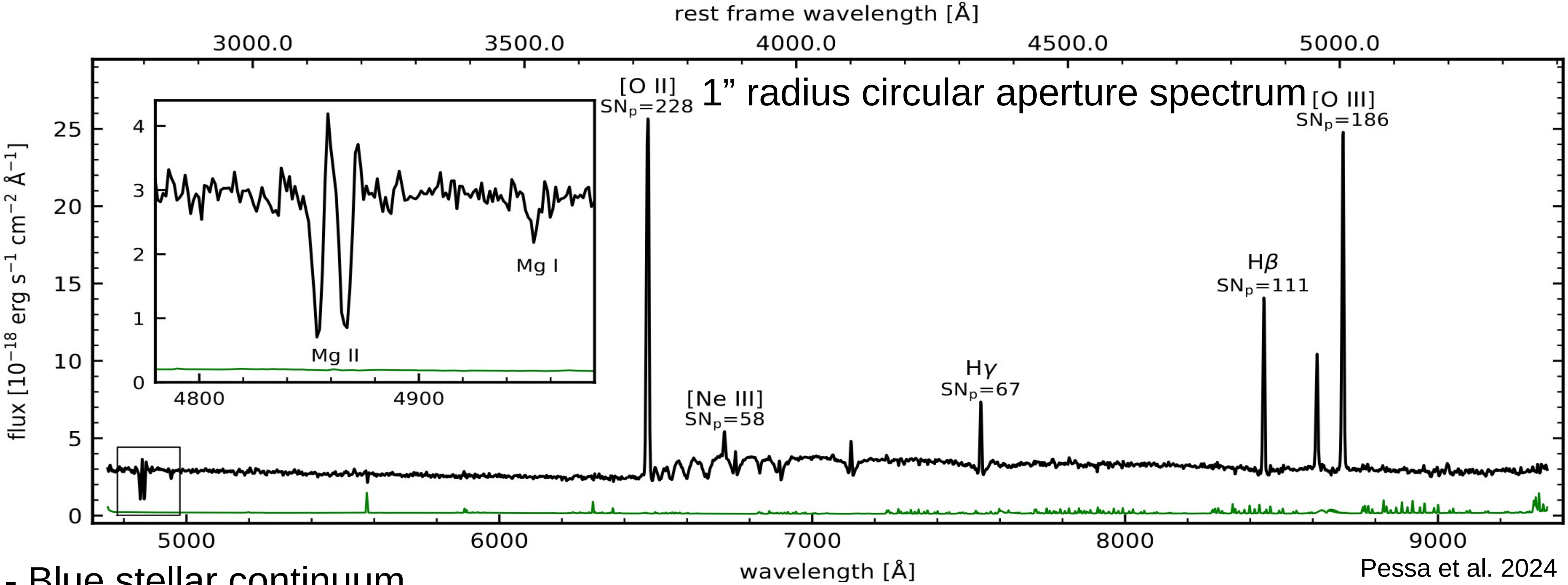
- ~10 hr depth data

- SFR and M_* values put this galaxy above the SFMS at z~0.7

Coordinates (J2000.0)	03:32:44.20, −27:47:33.5
Systemic redshift	$z = 0.73722 \pm 0.00003$
Absolute magnitude	$M_{AB} = -20.7$
Stellar mass	$\log(M_\star/M_\odot) = 10.3 \pm 0.3$
Star formation rate	$SFR \simeq 10 \pm 7\ M_\odot\ yr^{-1}$
Half-light radius (F125W) [a]	$r_e = (1.45 \pm 0.01)$ kpc
Sersic index (F125W) [a]	$n = 1.82 \pm 0.02$

Pessa et al. 2024

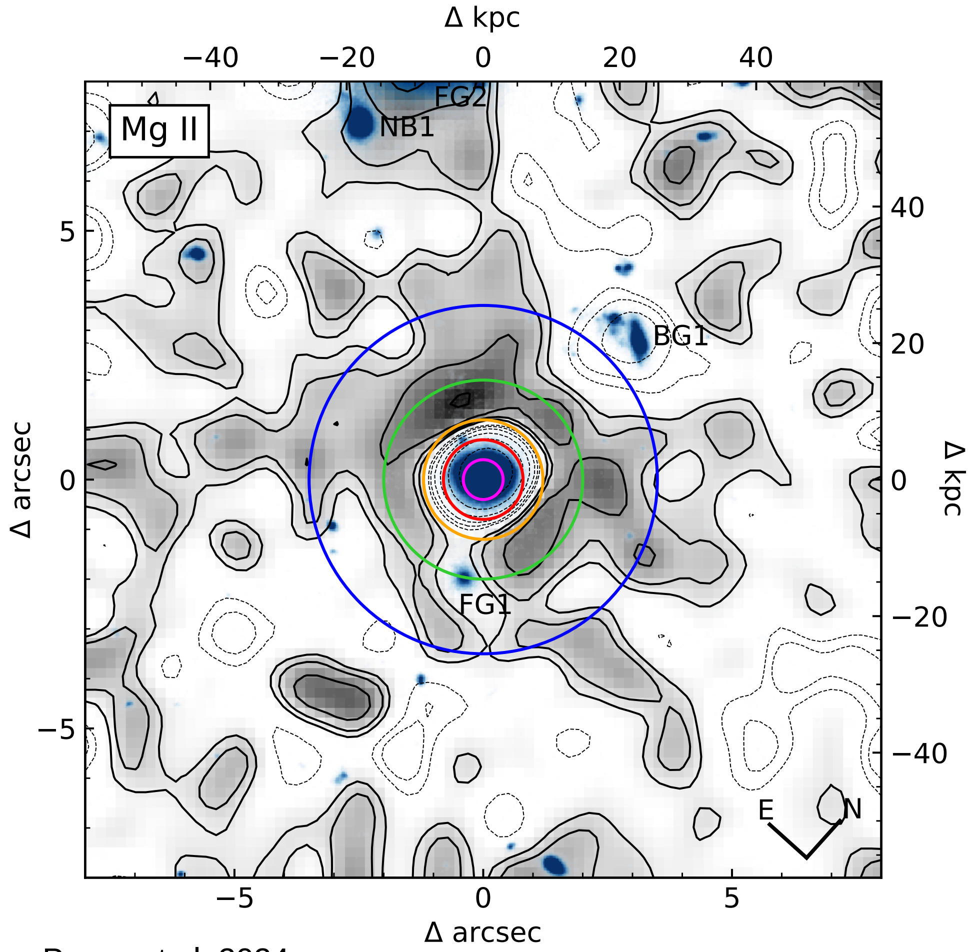
Discovery of MUSE-HUDF #884 Mg II Halo: Integrated spectrum



Pessa et al. 2024

- Blue stellar continuum
- Prominent Balmer absorption and nebular emission lines
- Clear P-Cygni profile in Mg II doublet
- Emission line ratios consistent with normal SF galaxy (no evidence for AGN)

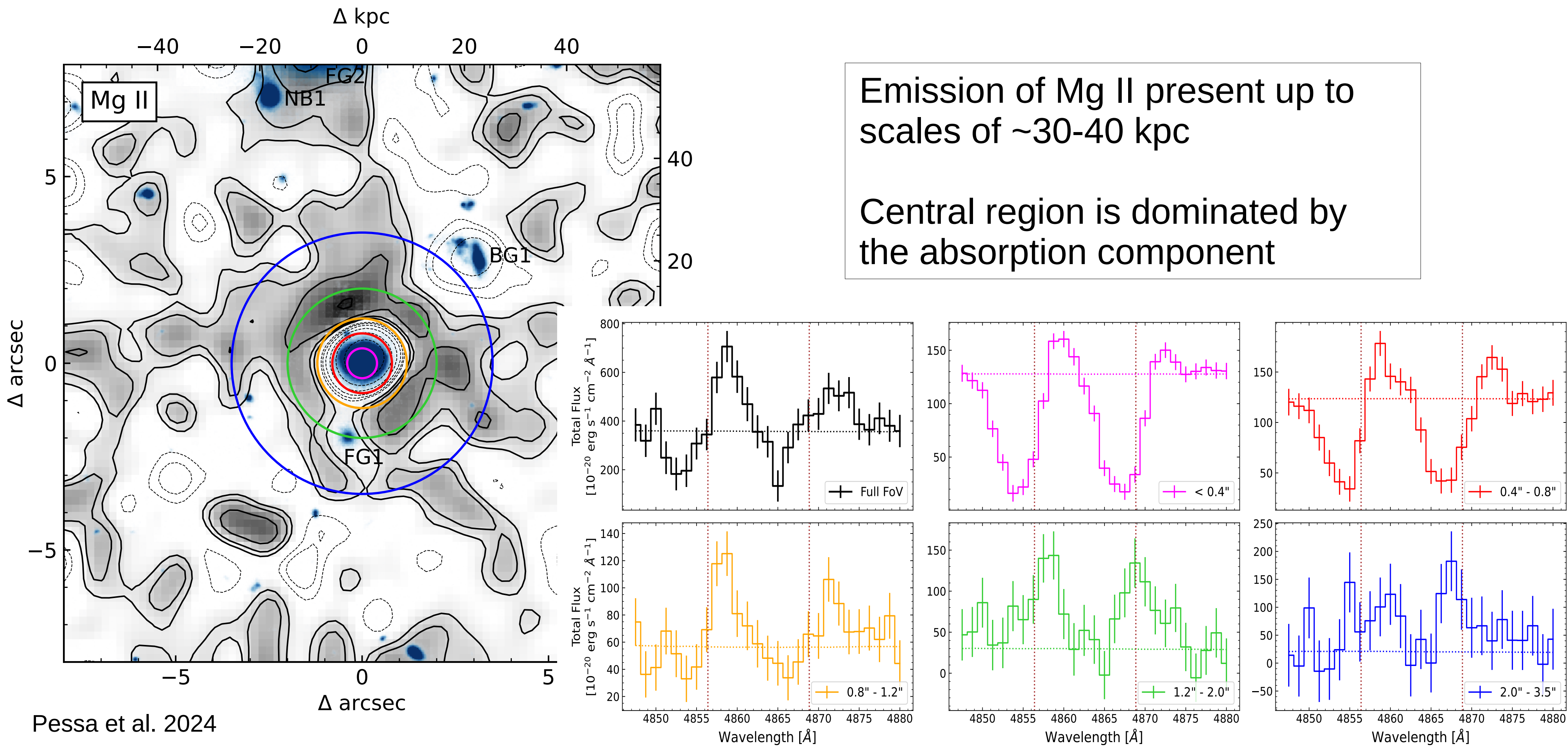
Discovery of MUSE-HUDF #884 Mg II Halo: Extended emission



Pessa et al. 2024

Emission of Mg II present up to scales of ~30-40 kpc

Discovery of MUSE-HUDF #884 Mg II Halo: Extended emission

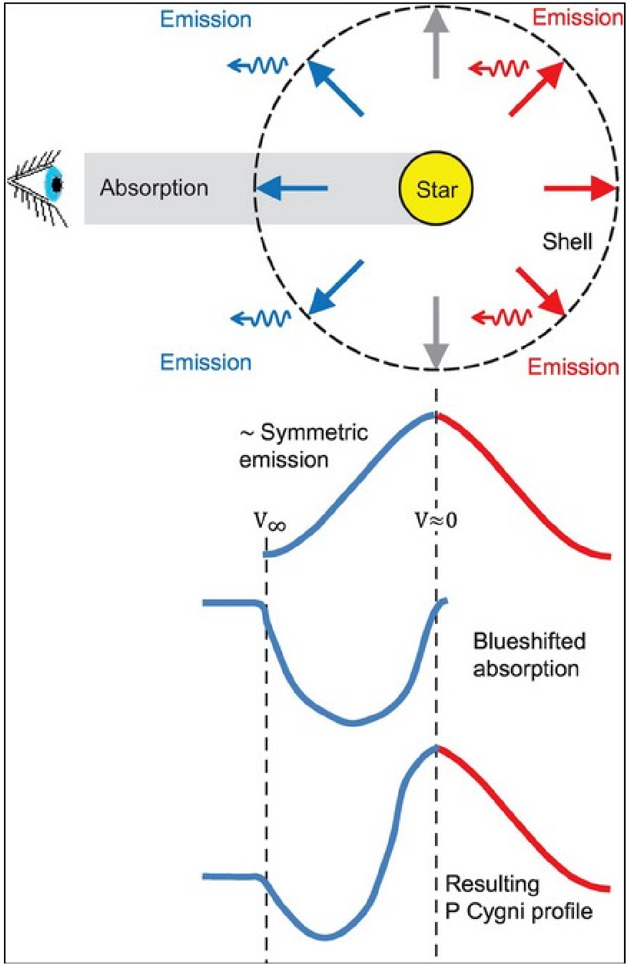


Pessa et al. 2024

Emission of Mg II present up to scales of ~30-40 kpc

Central region is dominated by the absorption component

Modeling the extended Mg II emission



- P-Cyg profile characteristic from outflows

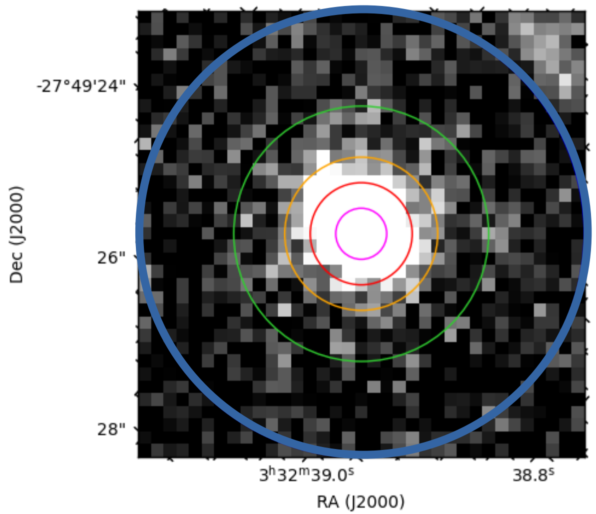
- Basic model from Scuderi et al. 1992, in the context of stellar winds

- Adapted to model resonant lines present in galactic winds by Scarlata et al. 2015, Carr et al. 2018

- We have modified the modeling scheme **from 1D spectra modeling to 3D (IFS) modeling**

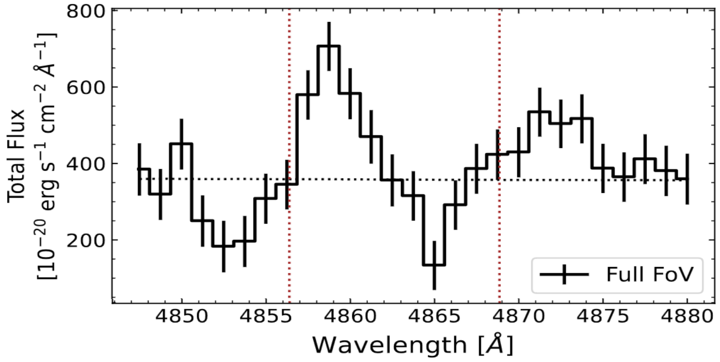
- Expanding velocity of outflows scales with radius as a power law **$v \sim r^{\gamma}$** → Density and optical depth vary radially, following the velocity field

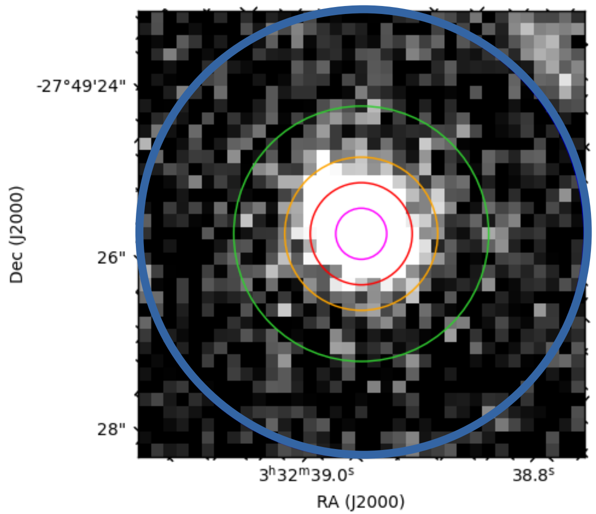
- Model a 3.5” radius around the central galaxy (~26 kpc)



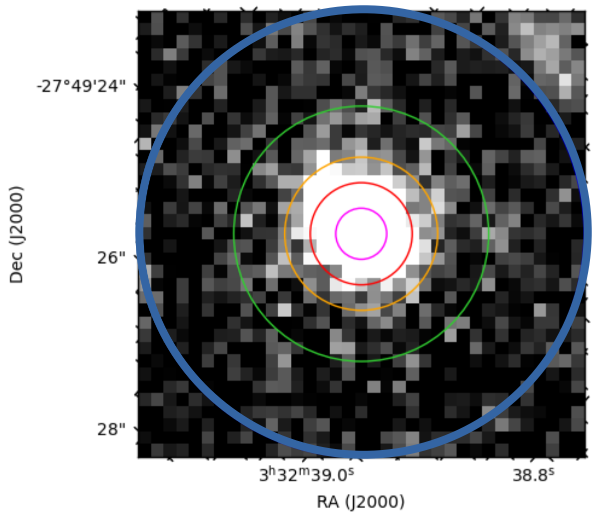
- Model a 3.5” radius around the central galaxy (~26 kpc)

- Modeled wavelength range: 2790 - 2809 Å (rest-frame)

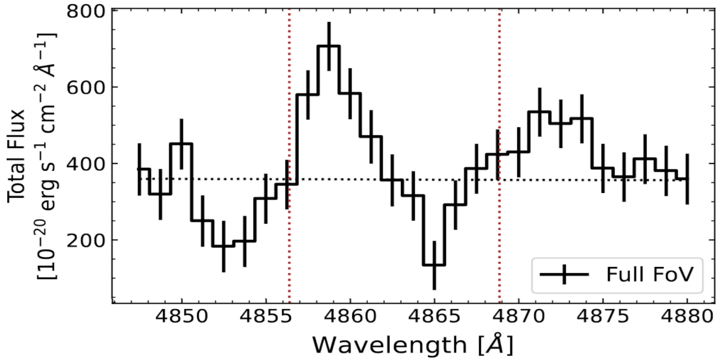




- Model a 3.5” radius around the central galaxy (~26 kpc)



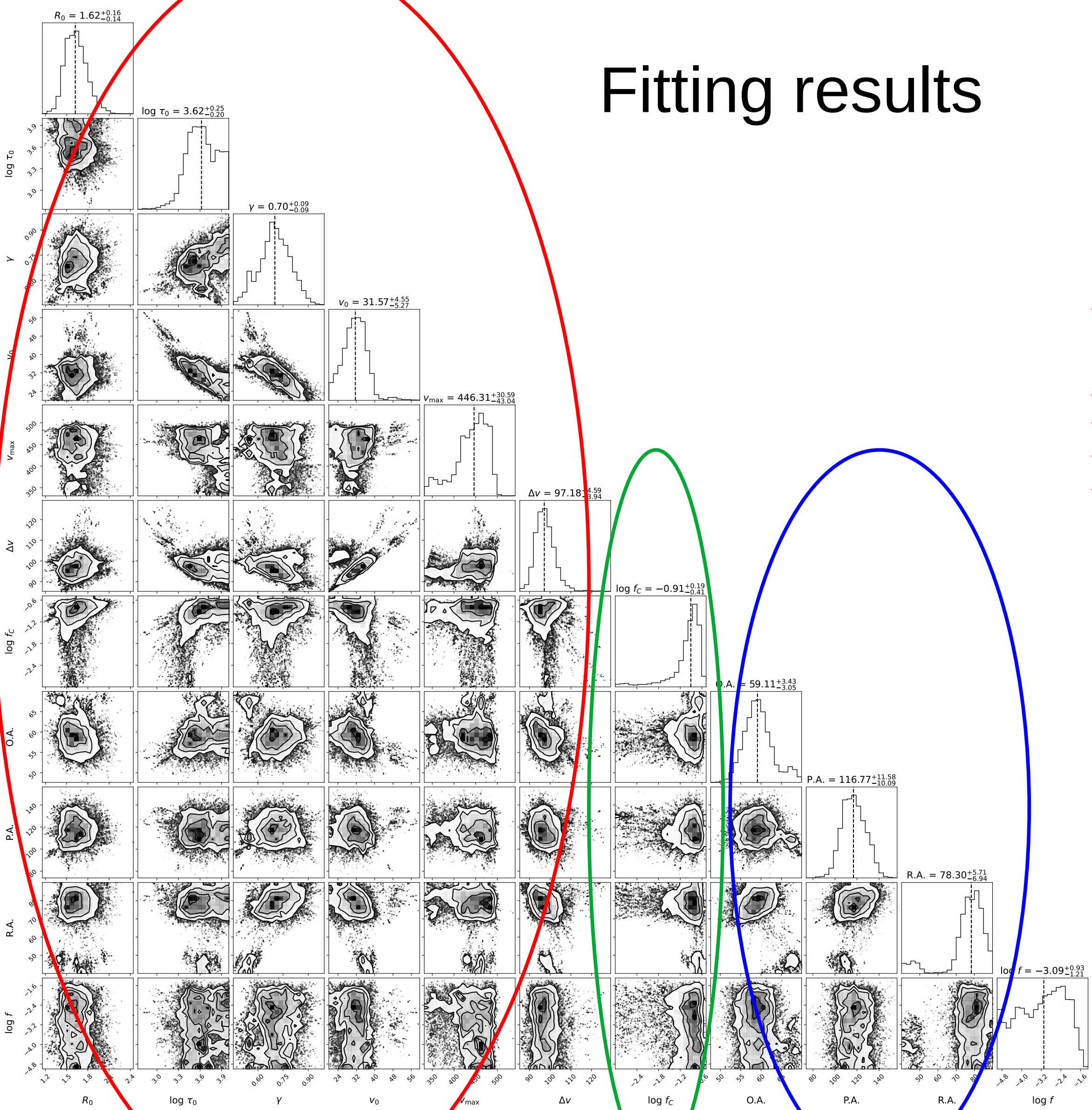
- Modeled wavelength range: 2790 - 2809 Å (rest-frame)



- Given a set of parameters, produce a model cubel, analog to the input data cube.

- Correct by instrumental LSF and PSF → MCMC fitting to find best fit parameters

Fitting results



Use of MCMC routines to find the best model parameters

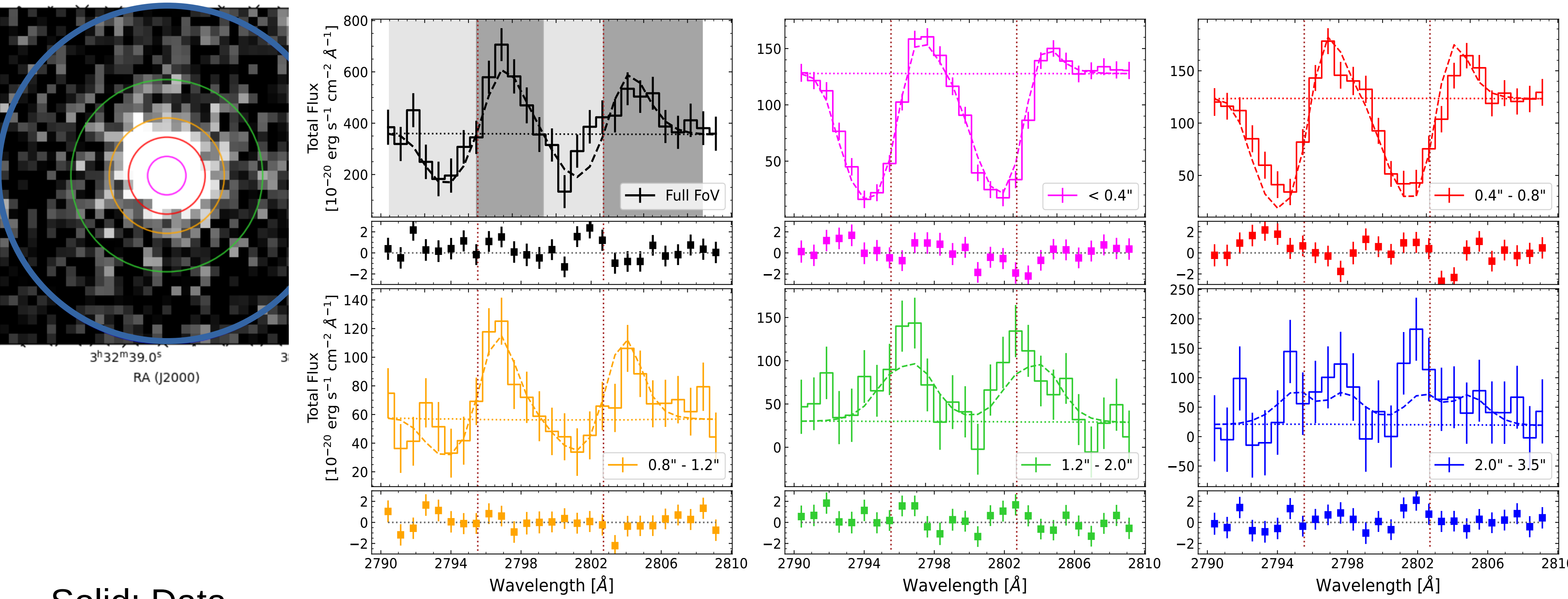
Wind properties: R_0, τ_0, γ, v_0, v_{max}

R_0: Launching radius
τ_0: Central optical depth
γ: Index of velocity power law **($v \sim r^{\gamma}$)**
V_0: Launching velocity
V_{max}: Maximum outflow velocity.

Nebular continuum contribution: fC (additional emission component proportional to local continuum)

Outflow biconical geometry: O.A., P.A., R.A.

Pessa et al. 2024



Solid: Data
Dashed: Model

Pessa et al. 2024

- Very good agreement when comparing ring-like aperture integrated spectra
- Differences between model and data increase towards outer apertures

What do we learn from our modeling?

- Biconic outflows play a relevant role in shaping the CGM of galaxies (well constrained geometry)

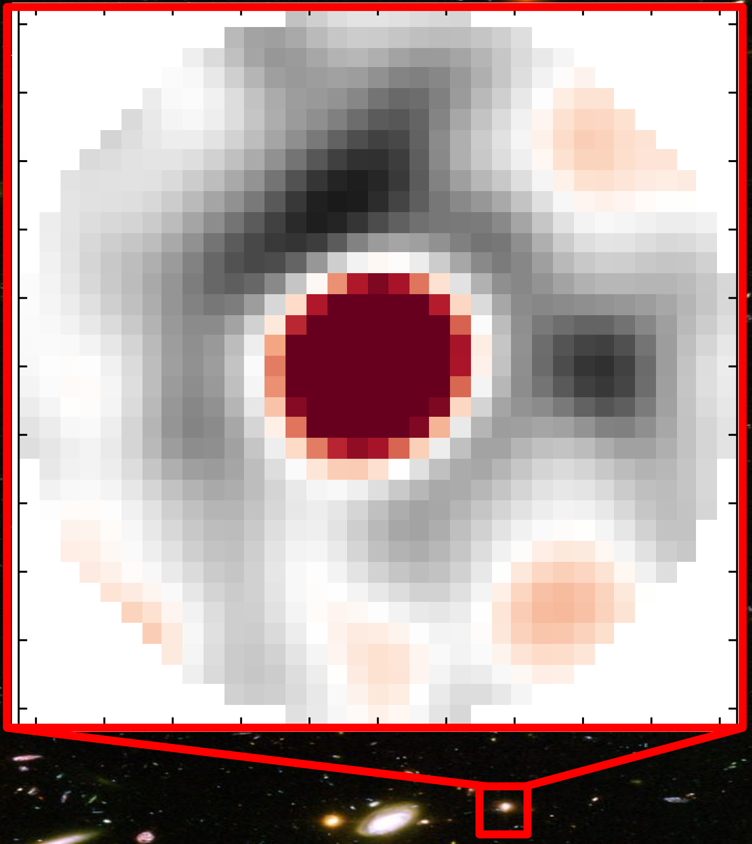
- Other mechanisms likely become progressively more dominants towards outer radii, where residuals become more relevant

- Our data is consistent with wind velocities that increase with radius

- Mass outflow rate inferred from our model: $12 \pm 7\ M_{\odot}\ yr^{-1} \rightarrow$ mass loading factor ~ 1 (these number subjects to large systematic errors induced by assumptions)

- Outflow velocity reach velocities higher than the escape velocity of the dark matter halo → outflow will be likely ejected into the IGM

What is next?



Despite the successful modeling of UDF #884, it is known that outflows and CGM properties depend on many host galaxy properties (e.g., **halo mass, SFR, redshift**, etc) → 1 galaxy is not enough!

For the first time, we can carry out a systematic spatially resolved modeling of outflows in a large sample of Mg II halos

→ Distribution of outflow properties vs. host galaxy properties.

The MUSE Cosmic Assembly survey Targeting Extragalactic Legacy fields (MUSCATEL)

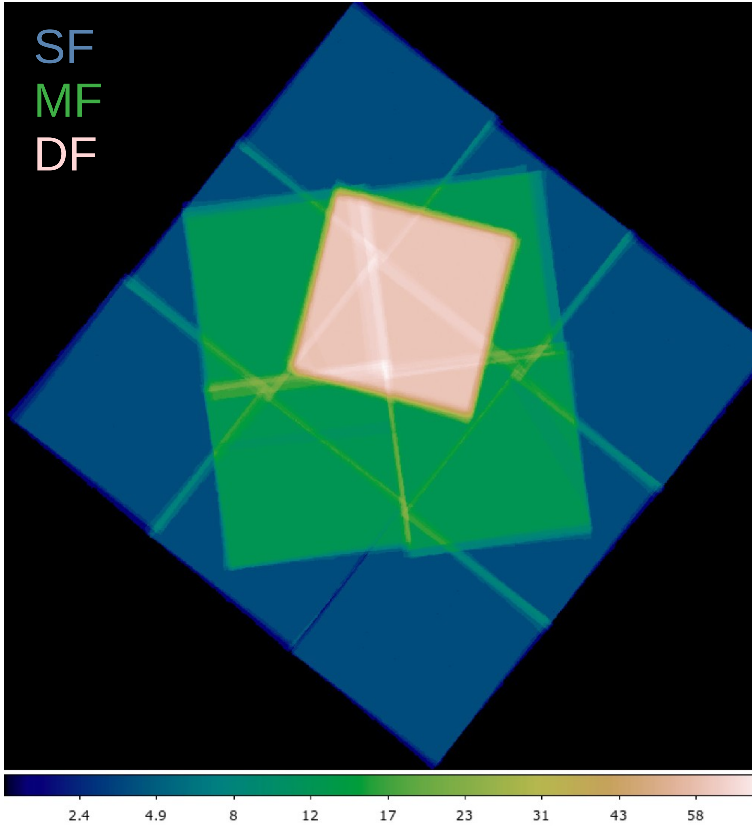
MUSE observations of parallel fields of the Hubble Frontier Fields (HFF), for 4 clusters accessible to the VLT (A2744, M0416, AS1063, A370)

- Wedding cake approach for observing:

- 3'x3' mosaic of 100 min
- 2'x2' mosaic of 5 hours
- A deep 1 arcmin^2 of 25 hour

- Deep imaging in 7 NIR + optical HST bands

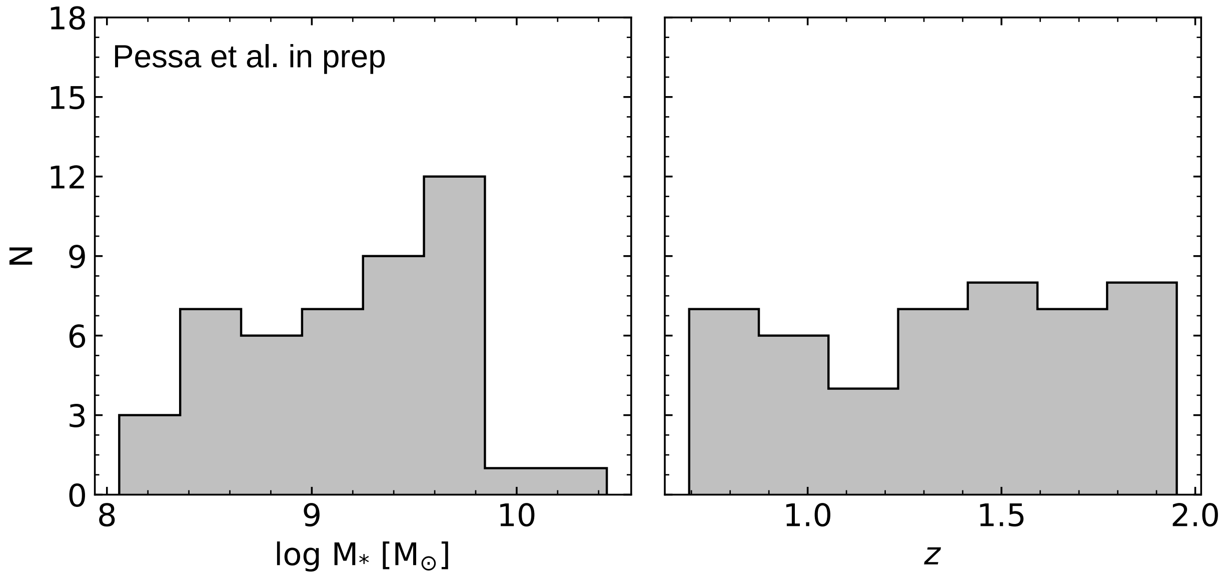
Some goals: Increase number of deep fields, reduce cosmic variance, better statistics (e.g., clustering studies)



Goal: Build a sample of Mg II halos from MUSCATEL galaxies, and look for outflowing galaxies with an extended Mg II halo, suitable to infer outflow properties

→ Galaxies in the redshift range where Mg II falls inside MUSE wavelength range ~ [0.7-1.9]
→ Significant extended Mg II emission
→ P-Cygni profile in Mg II

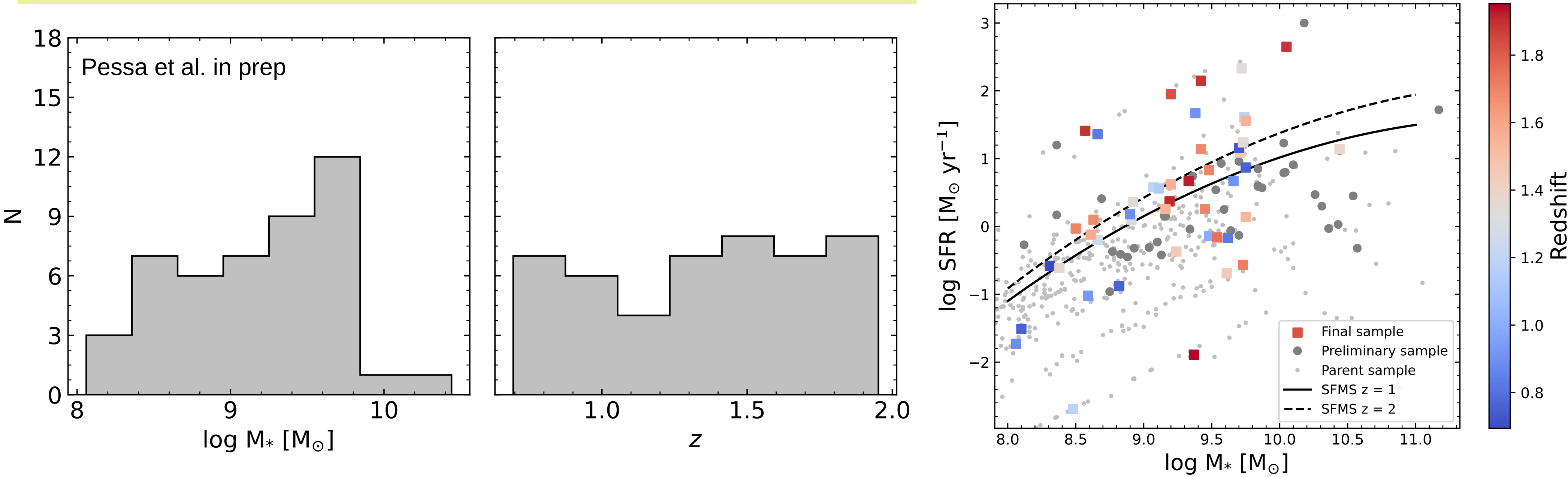
→ **Sample of 47 galaxies with extended Mg II halos in MUSCATEL**

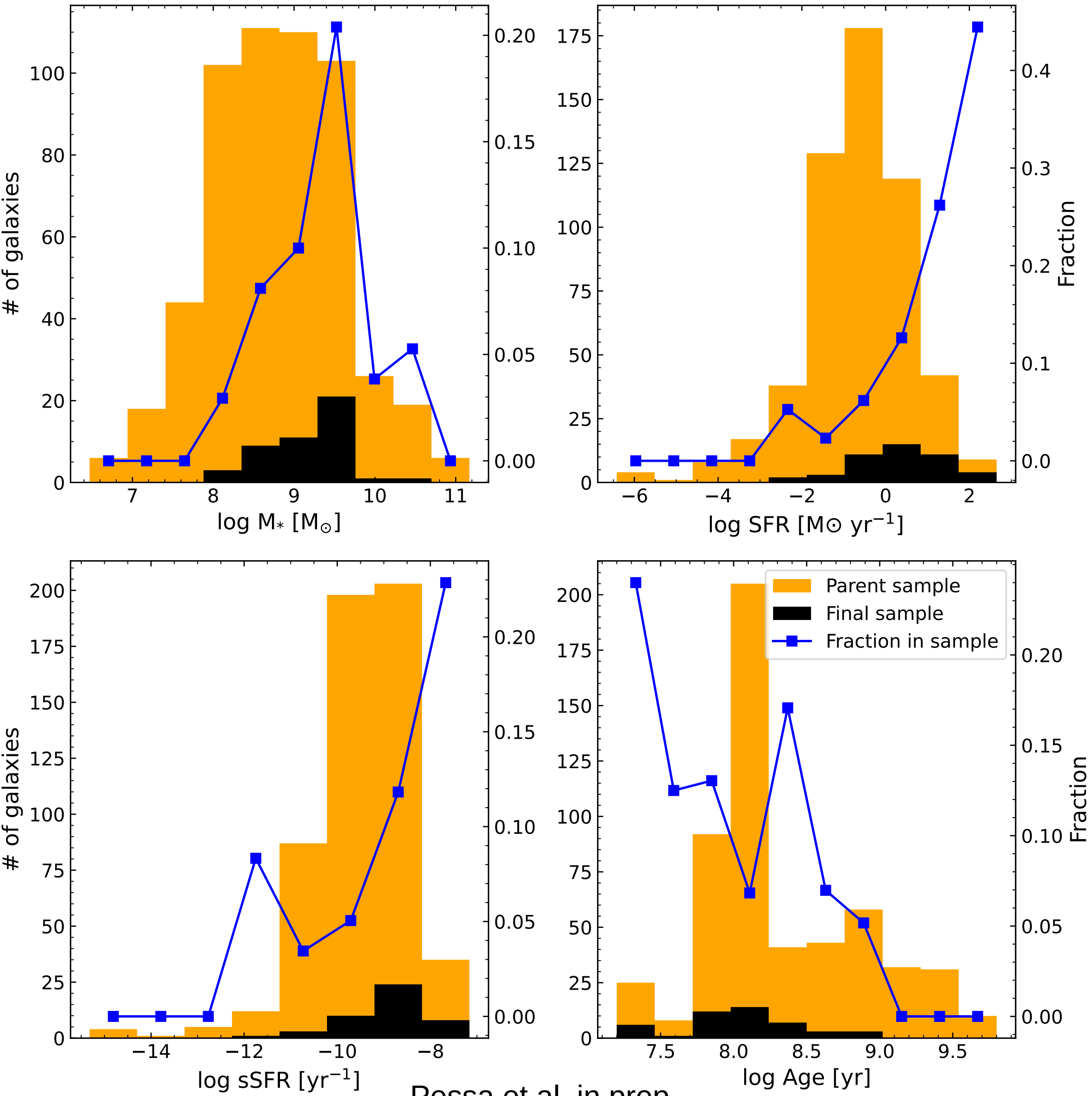


Goal: Build a sample of Mg II halos from MUSCATEL galaxies, and look for outflowing galaxies with an extended Mg II halo, suitable to infer outflow properties

→ Galaxies in the redshift range where Mg II falls inside MUSE wavelength range ~ [0.7-1.9]
→ Significant extended Mg II emission
→ P-Cygni profile in Mg II

→ **Sample of 47 galaxies with extended Mg II halos in MUSCATEL**





Pessa et al. in prep

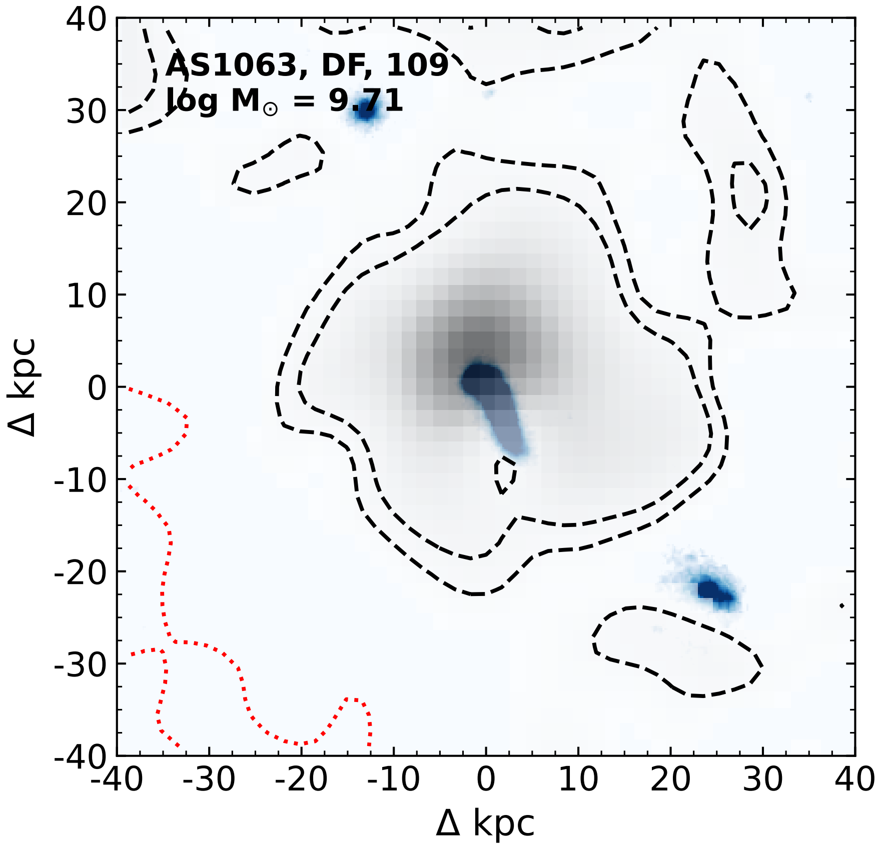
Fraction of galaxies from the parent MUSCATEL sample in our MgII halos sample

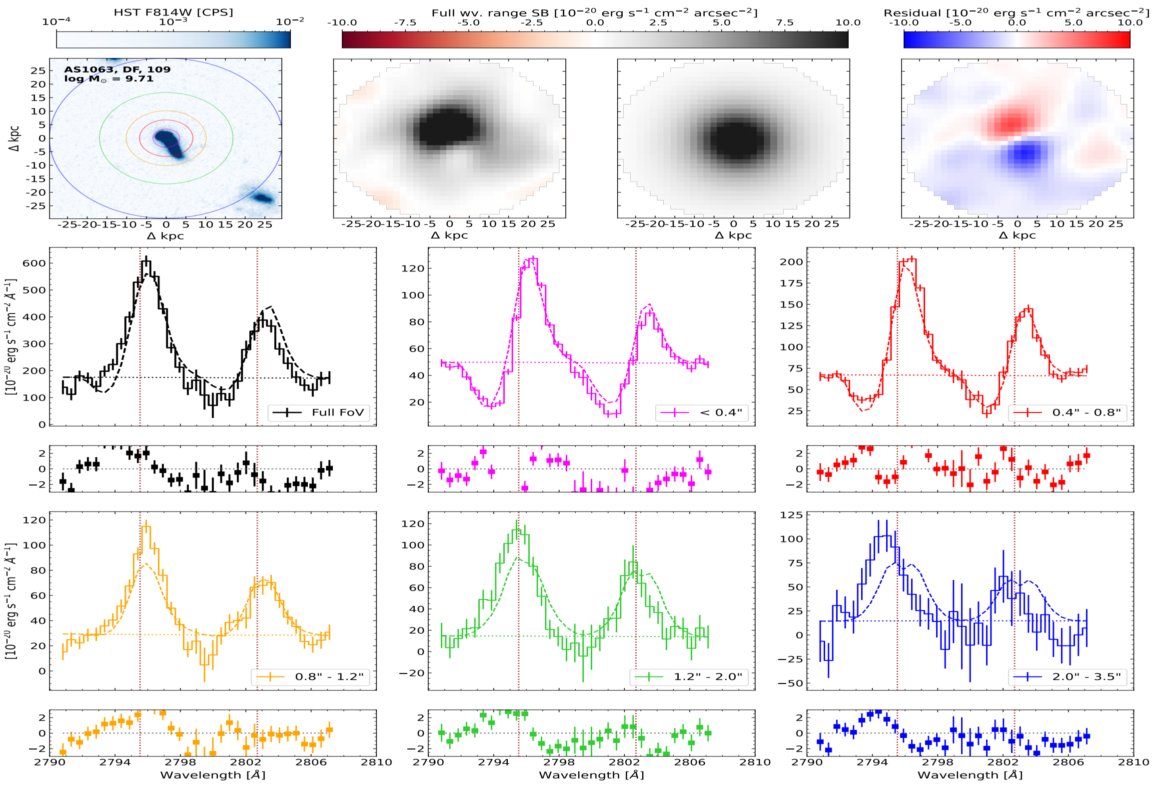
- per bin of mass, SFR, sSFR, age

→ Tentative preference towards higher SFR/sSFR and younger ages

Consistent with expectations for SF driven outflows

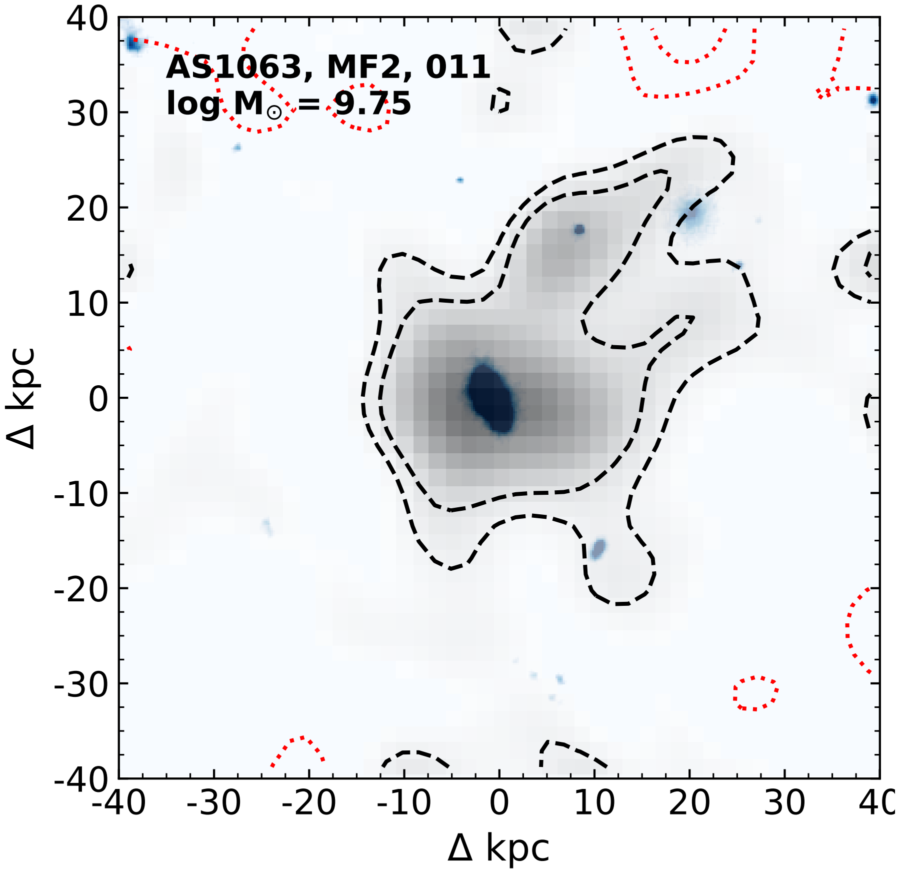
Quick look into our sample galaxies

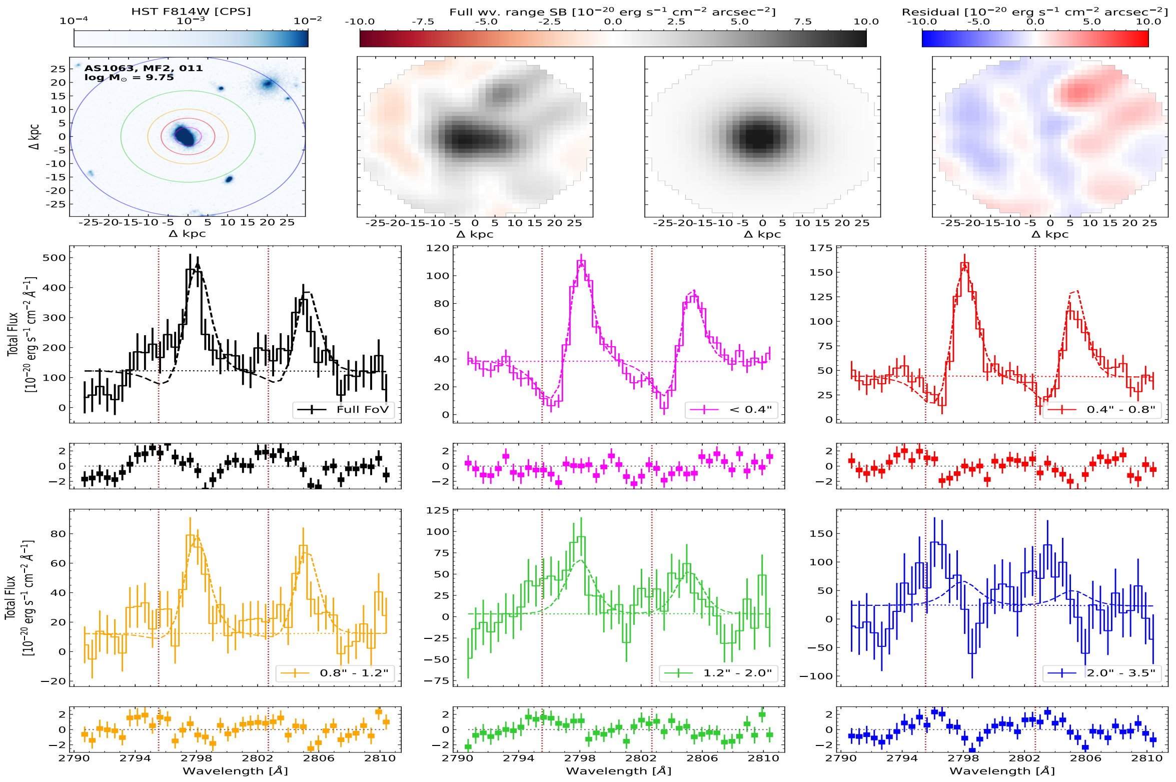




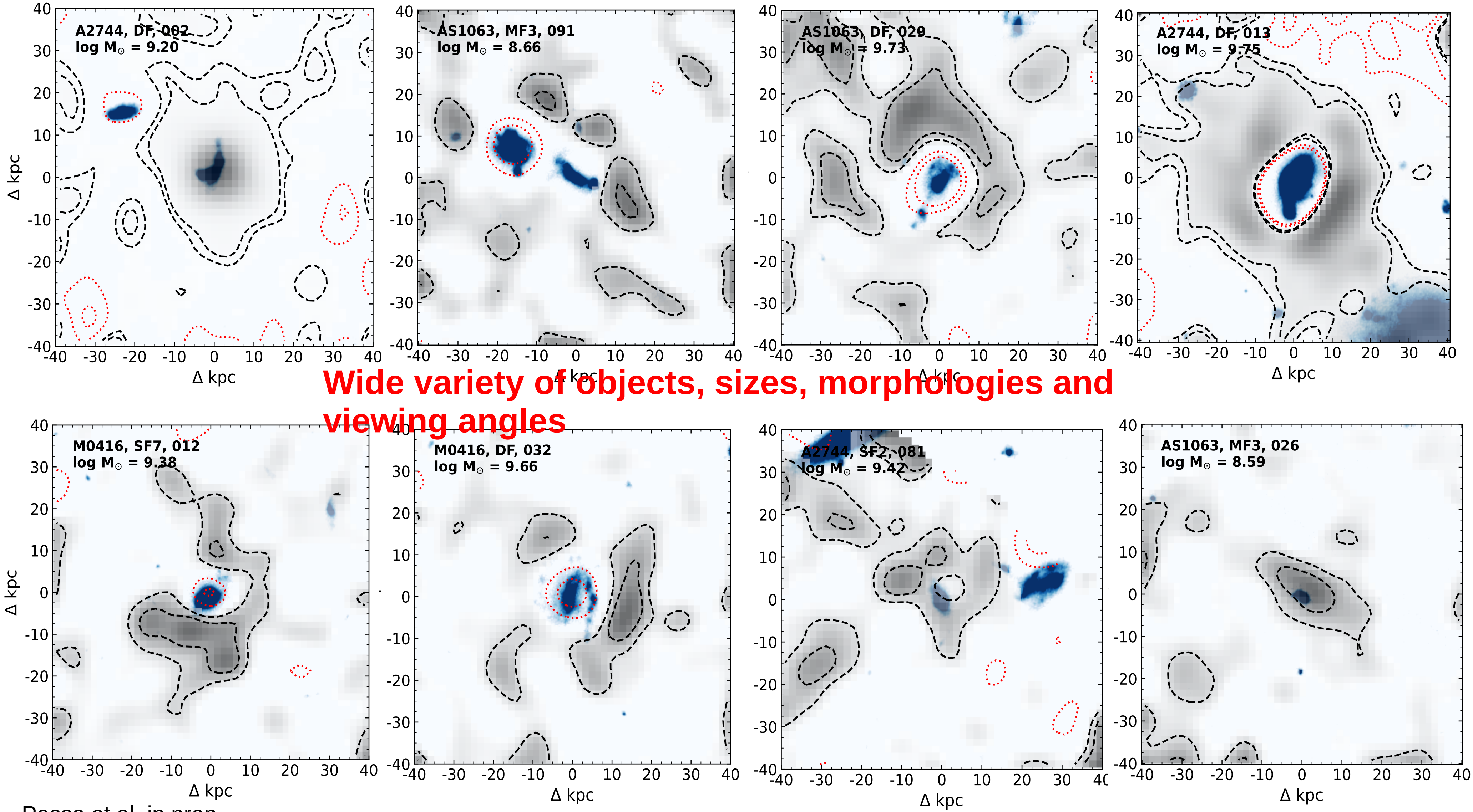
Pessa et al. in prep

Quick look into our sample galaxies



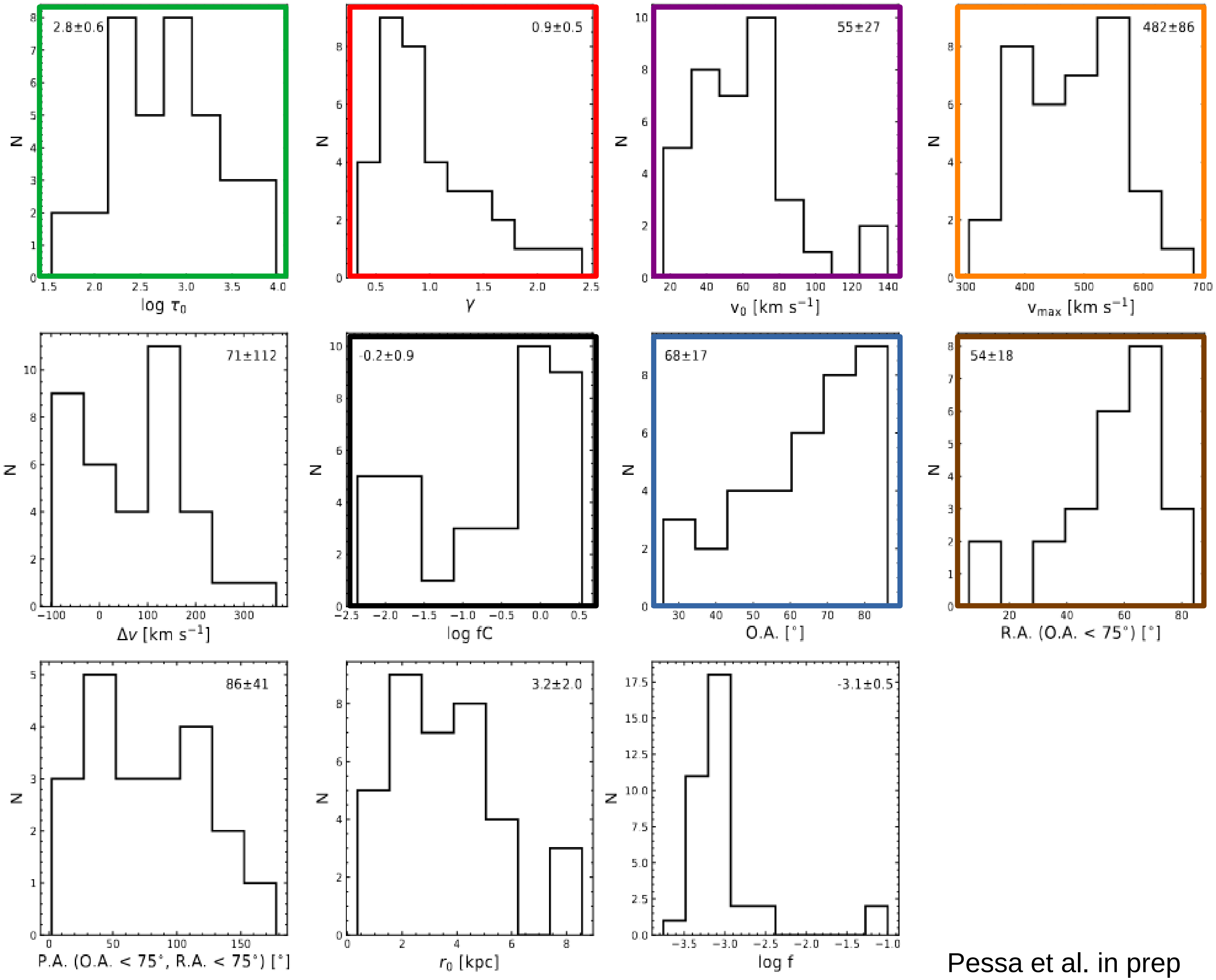


Pessa et al. in prep



Wide variety of objects, sizes, morphologies and viewing angles

Pessa et al. in prep



Pessa et al. in prep

High central optical dept τ_0

Acceleration rate γ ~ 1

Launching velocity v_0 ~ 50 km/s

Maximum velocity V_{max} ~480 km/s

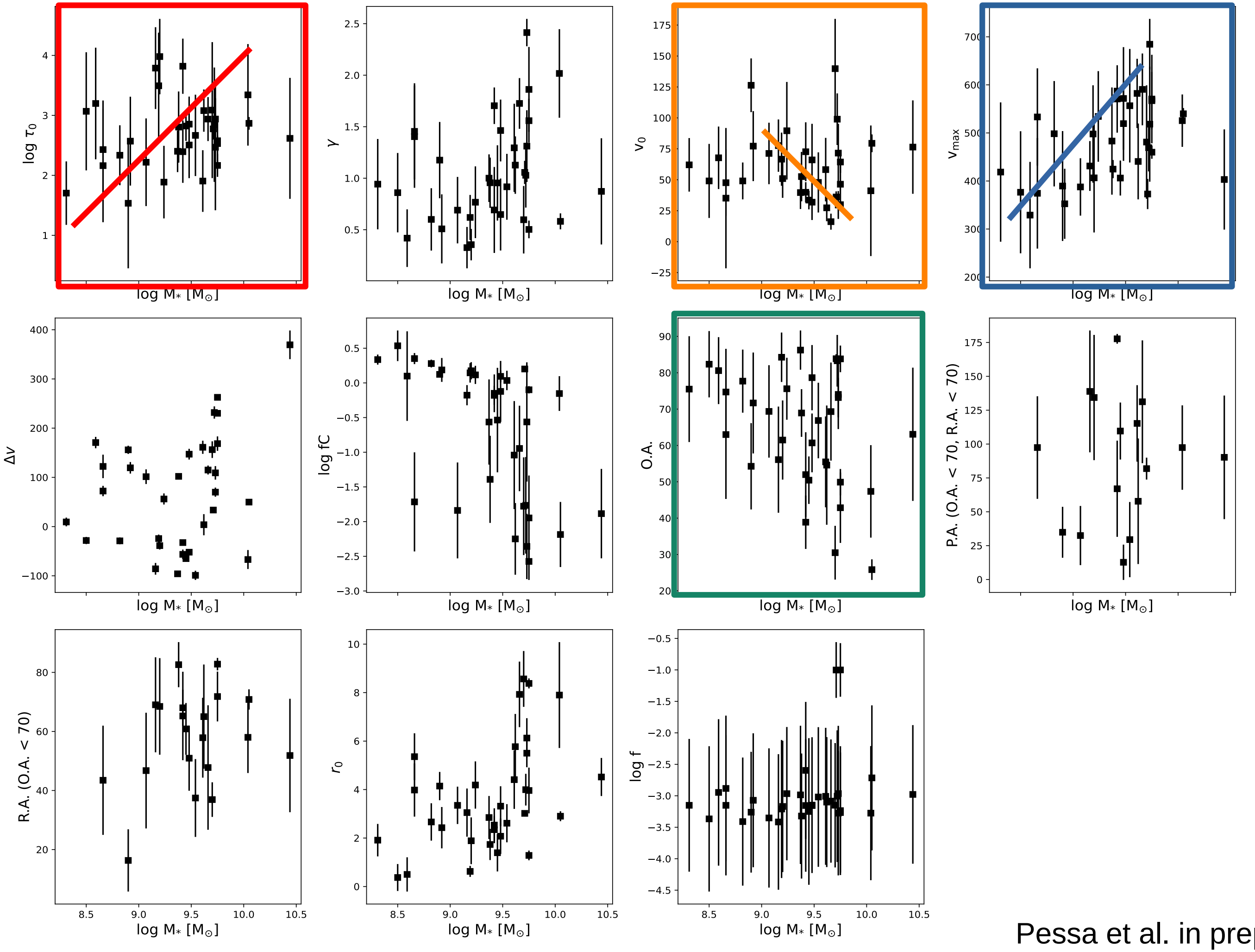
→ velocities in line with predictions from SN driven galactic winds sims.

Bimodality in nebular emission contribution fC

Generally wide OA

Preferentially ~face on outflows

Correlation of outflow parameters with stellar mass



Pessa et al. in prep

Tentative trends with stellar mass:

- Higher stellar mass galaxies exhibit higher central optical depths

- Higher stellar mass galaxies exhibit higher outflow maximum velocity

Wider OA for less masive galaxies

- (Possibly) Higher stellar mass galaxies exhibit lower launching velocity

High scatter → Mass is likely not the only mechanisms involved.

Summary and conclusions

- Discovery of extended MgII halo of UDF #884. Simple outflow modeling scheme is able to reproduce observations

- We use the model to infer outflow properties of UDF #884 such as central optical depth, expansion rate and geometry.

- Use of MUSCATEL data to expand our modeling to as many galaxies as possible. **For the first time, we are able to probe galactic wind properties in emission on a statistically significant sample, instead of individual objects.**

- Extended Mg II halos are more common in younger galaxies with high SFR/sSFR (although not exclusive)

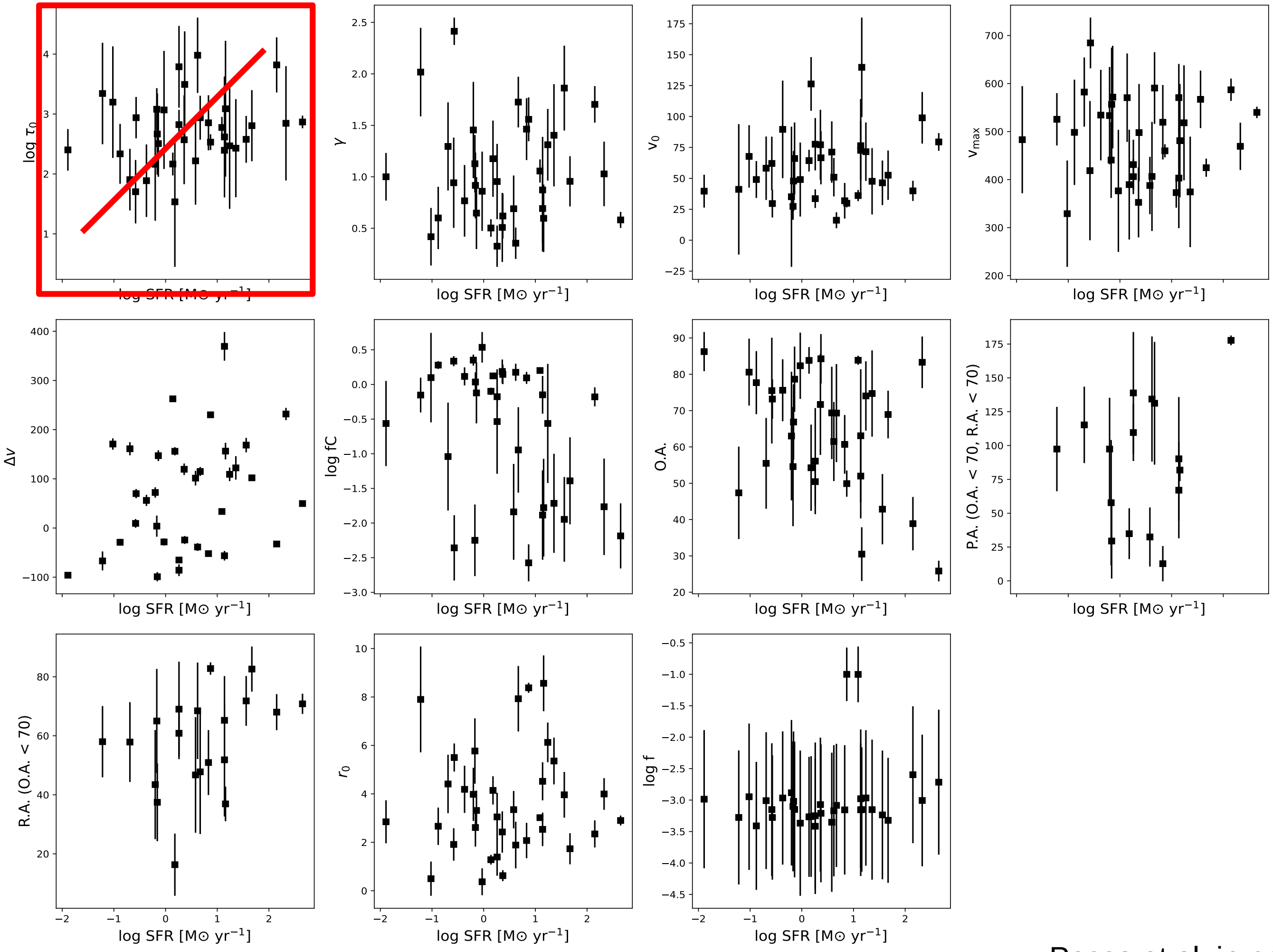
- Outflow model is able to reproduce a wide range of observations → Distribution of parameters that describe outflow properties.

- Use available photometric/spectroscopic data to measure galaxy properties and investigate the existence of correlations between outflow properties and host galaxy properties → Tentative correlations between τ_0, v_0 and v_{max} vs. M_*)

Future plans:

- Include additional deep MUSE data in our sample
- Compare our findings with the recent SFH of our sample galaxies → Link MgII halo properties to specific SF events
- Compare our results with other modeling approaches (e.g., RT simulations)

Correlation of outflow parameters with SFR for Pcygni halos



SFR measurements available from SED fitting →

Similar trends, increased scatter.

First time we are able to probe wind properties on a population level analysis.

Pessa et al. in prep

Why is scatter higher in trends with SFR? → Not intuitive (also, not any clear trend with sSFR), SFR and sSFR are more closely related to stellar feedback

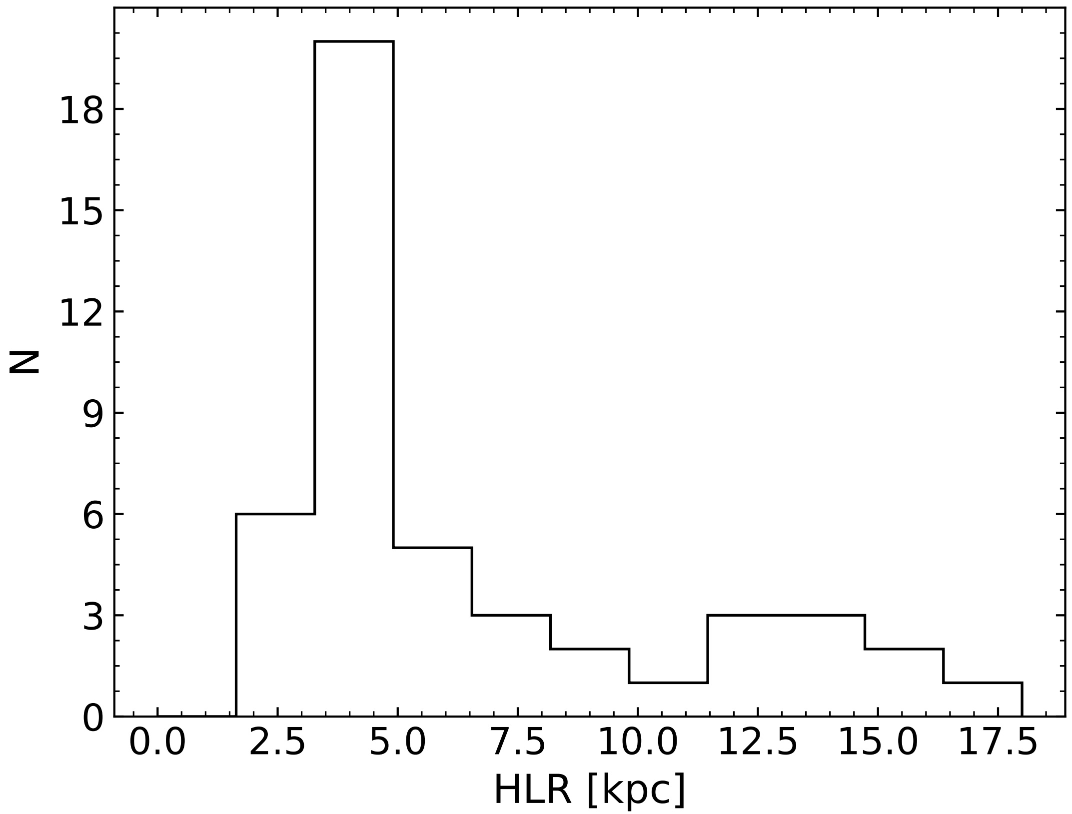
Possible reasons:

a) Large systematic uncertainties in the SFR determination

b) Timescales of SFR and travel times of gas: Present-day SFR of a galaxy might not be directly correlated with the outflow properties that we see today.

Encouraging to link the outflow properties to the recent SFH of galaxies, exploring if it is possible to connect features of the Mg II halos with a specific star formation event.

Size distribution of Mg II emission halos



Tentative bimodality in the size distribution of Mg II halos

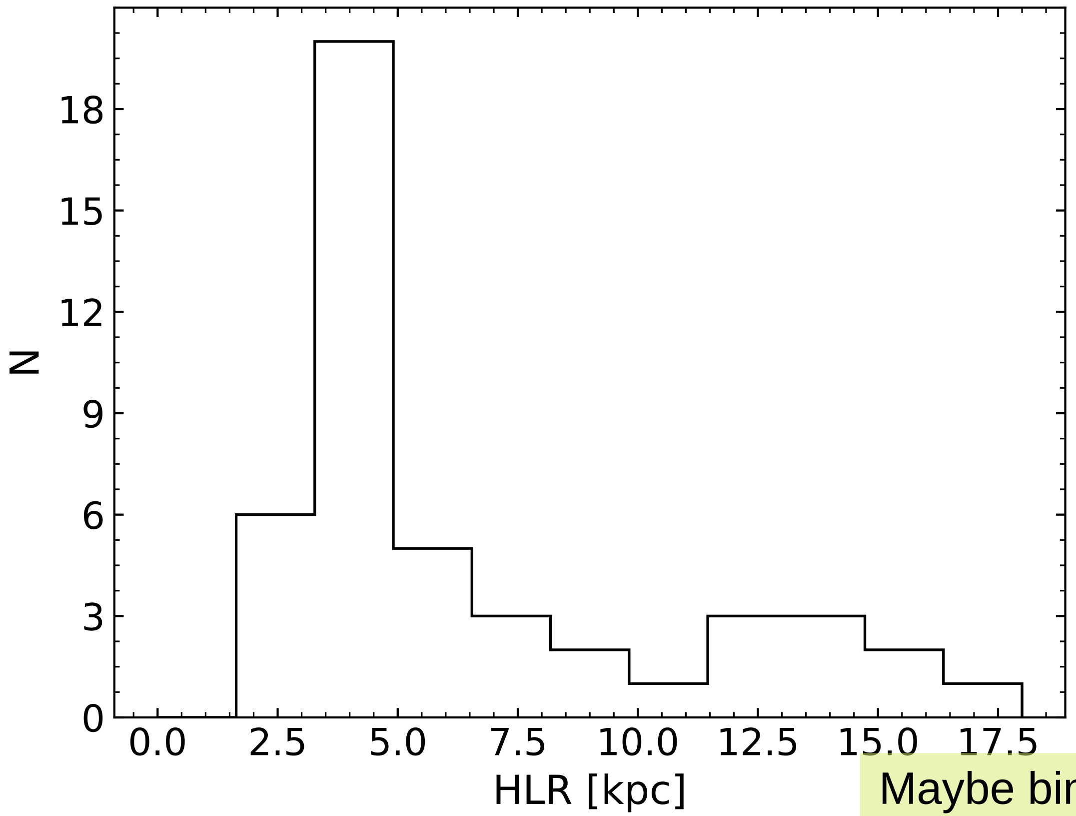
- Main peak at ~4 kpc

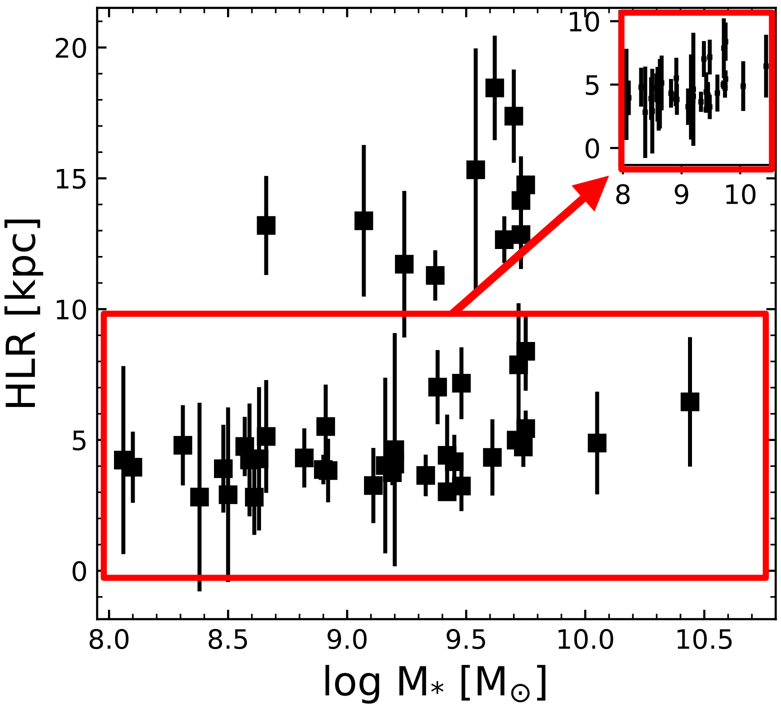
- Possibly secondary peak at ~13 kpc

Any dependency of size with host galaxy properties?

Pessa et al. in prep

Size distribution of Mg II emission halos

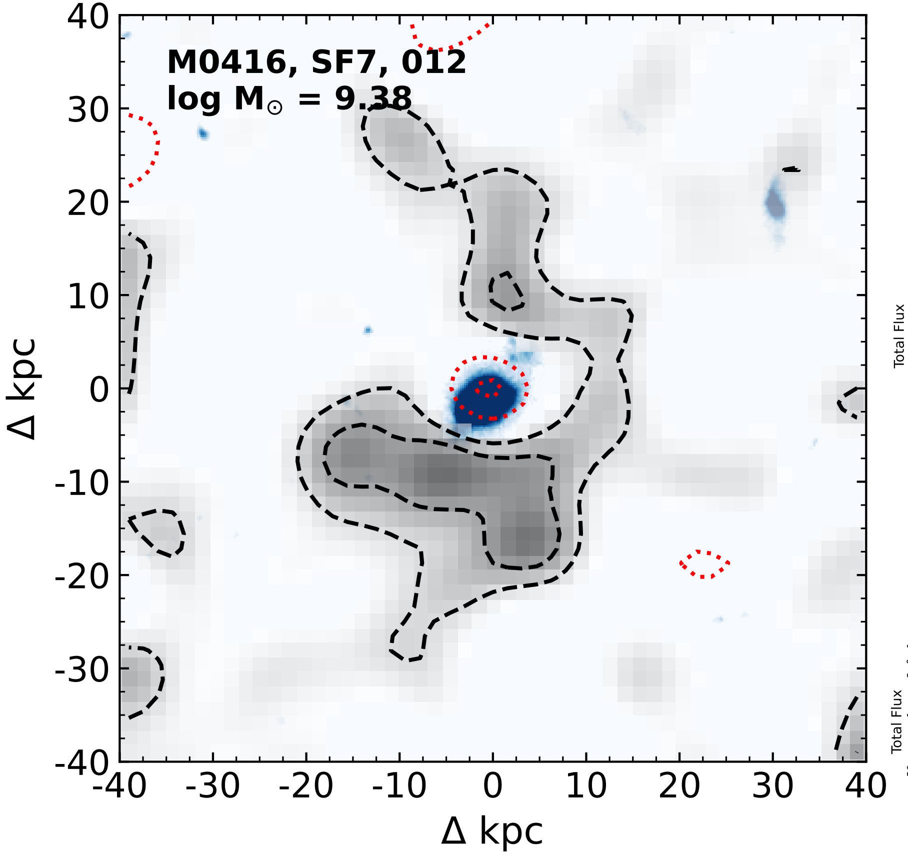


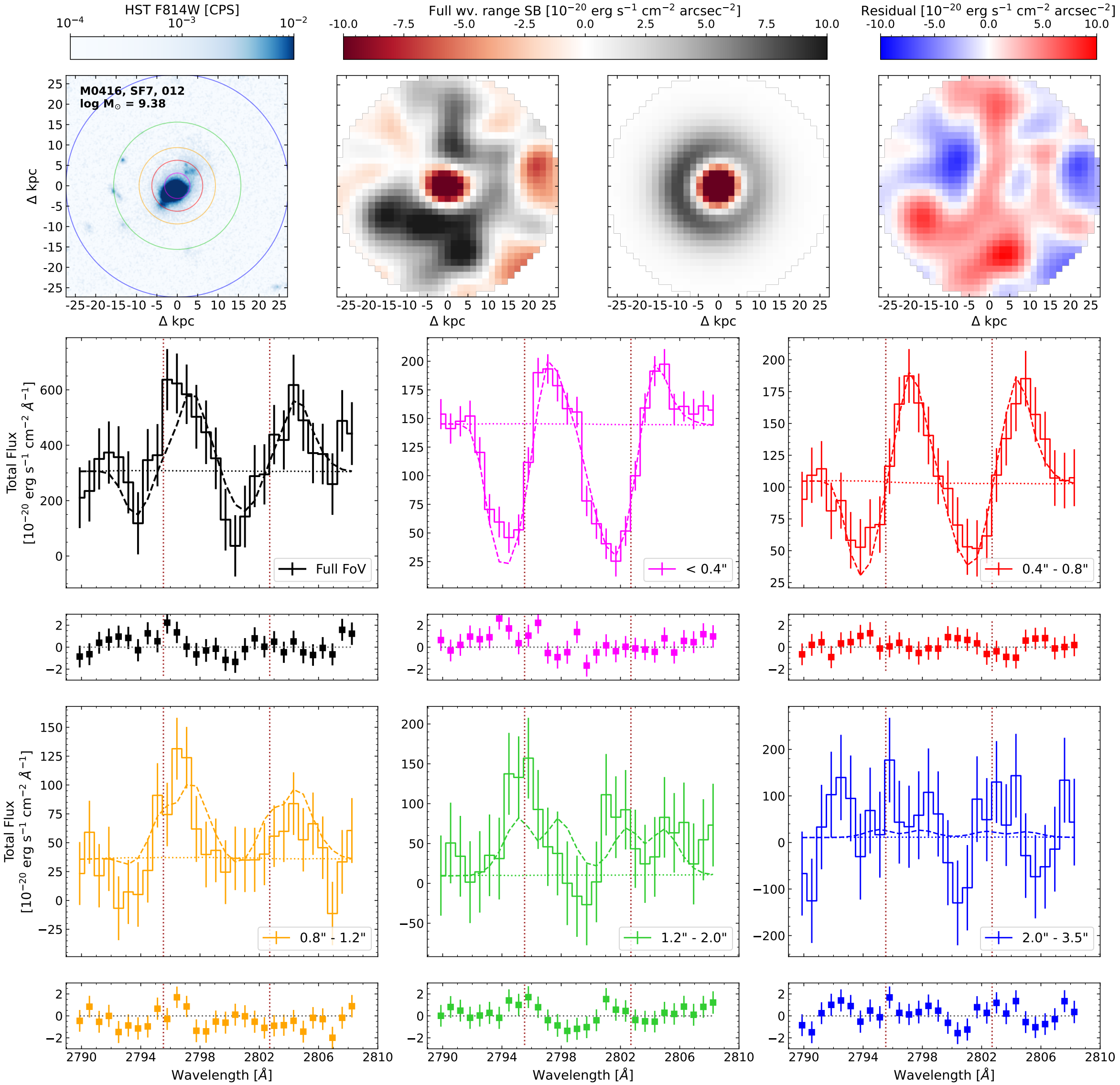


Pessa et al. in prep

Maybe bimodality is hinting to a different origin?
→ More compact object could be more closely connected to a mechanism that depends on stellar mass

Quick look into our sample galaxies





Pessa et al. in prep

Modeling the extended Mg II emission: Main assumptions

1) Sobolev approximation:

Consider the outflow as an ensemble of thin spherical shells of a given radius, velocity, and optical depth.

If the velocity gradient is large, the photons produced by the central source will interact with the outflowing material **only at the specific radius where the absorbing ions are at resonance (due to their Doppler shift)**

Modeling the extended Mg II emission: Main assumptions

1) Sobolev approximation:

$$v = v_0 \left(\frac{r}{R_0}\right)^{\gamma} \quad \text{for } r < R_{\max}$$

$$v = v_\infty \quad \text{for } r \geq R_{\max}$$

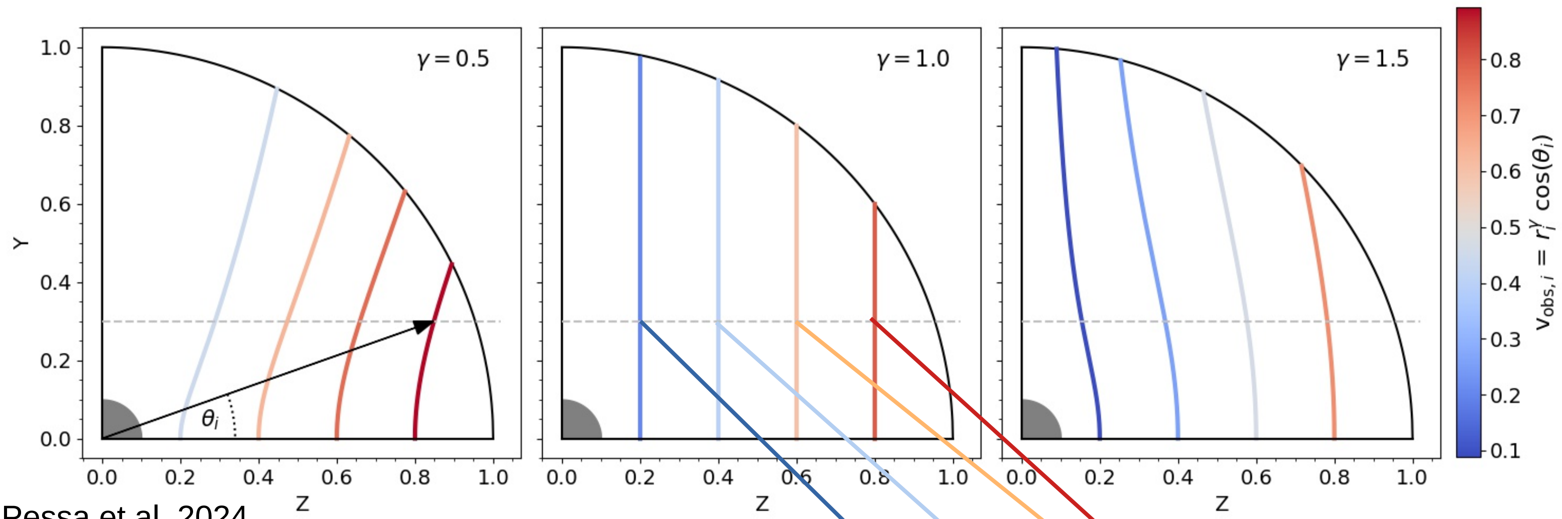
Alternative velocity laws are possible (monotonic)

2) Mass conservation: The flux of ions remains constant through the outflow:

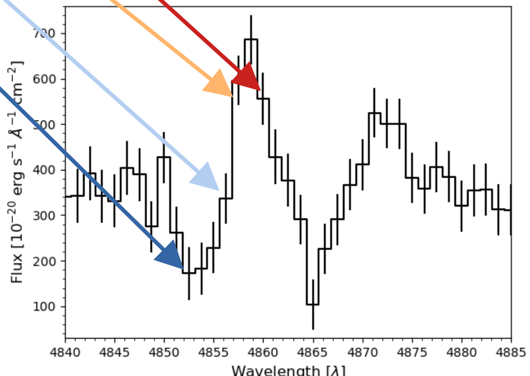
$$n(r) = n_0 \left(\frac{R_0}{r}\right)^{\gamma+2} \longrightarrow \tau(r)$$

Modeling the extended Mg II emission: Main assumptions

1) **Sobolev approximation**: Isovelocity surfaces



Pessa et al. 2024

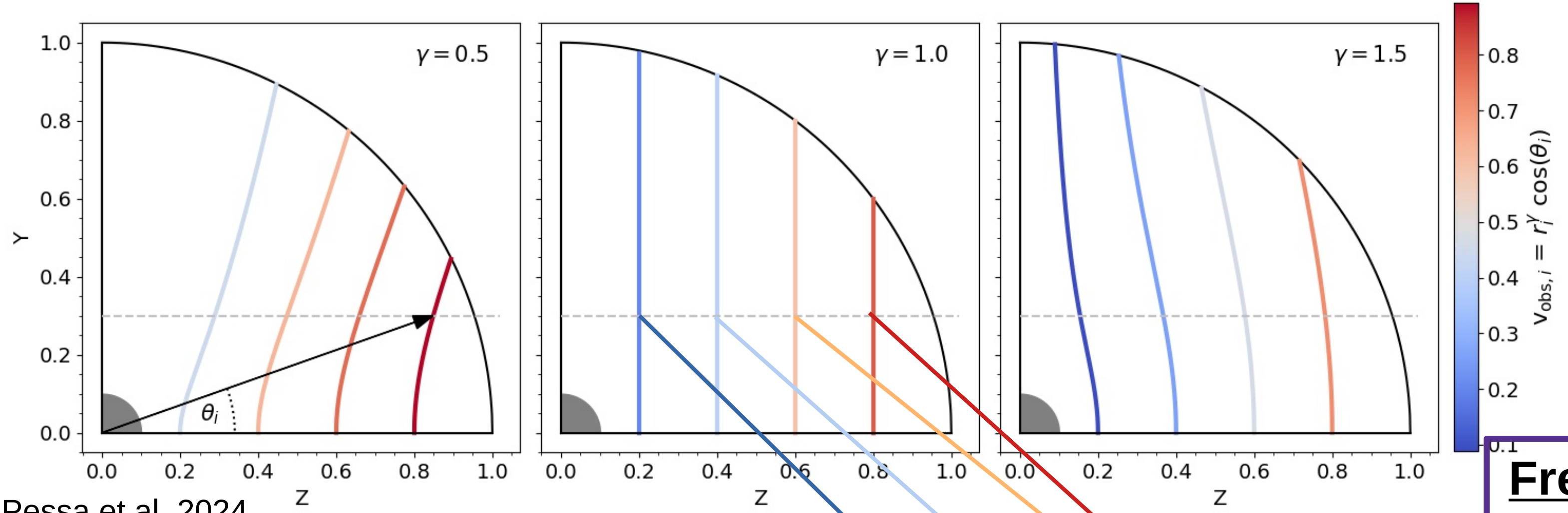


Any given sightline will cross each velocity surface once at an specific location → Bijective relation between velocity and location.

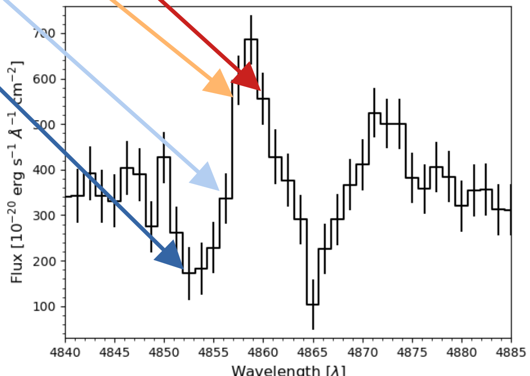
$$\tau = \tau(r) \leftrightarrows \tau(v)$$

Modeling the extended Mg II emission: Main assumptions

1) **Sobolev approximation**: Isovelocity surfaces



Pessa et al. 2024



Any given sightline will cross each velocity surface once at an specific location → Bijective relation between velocity and location.

Free parameters:

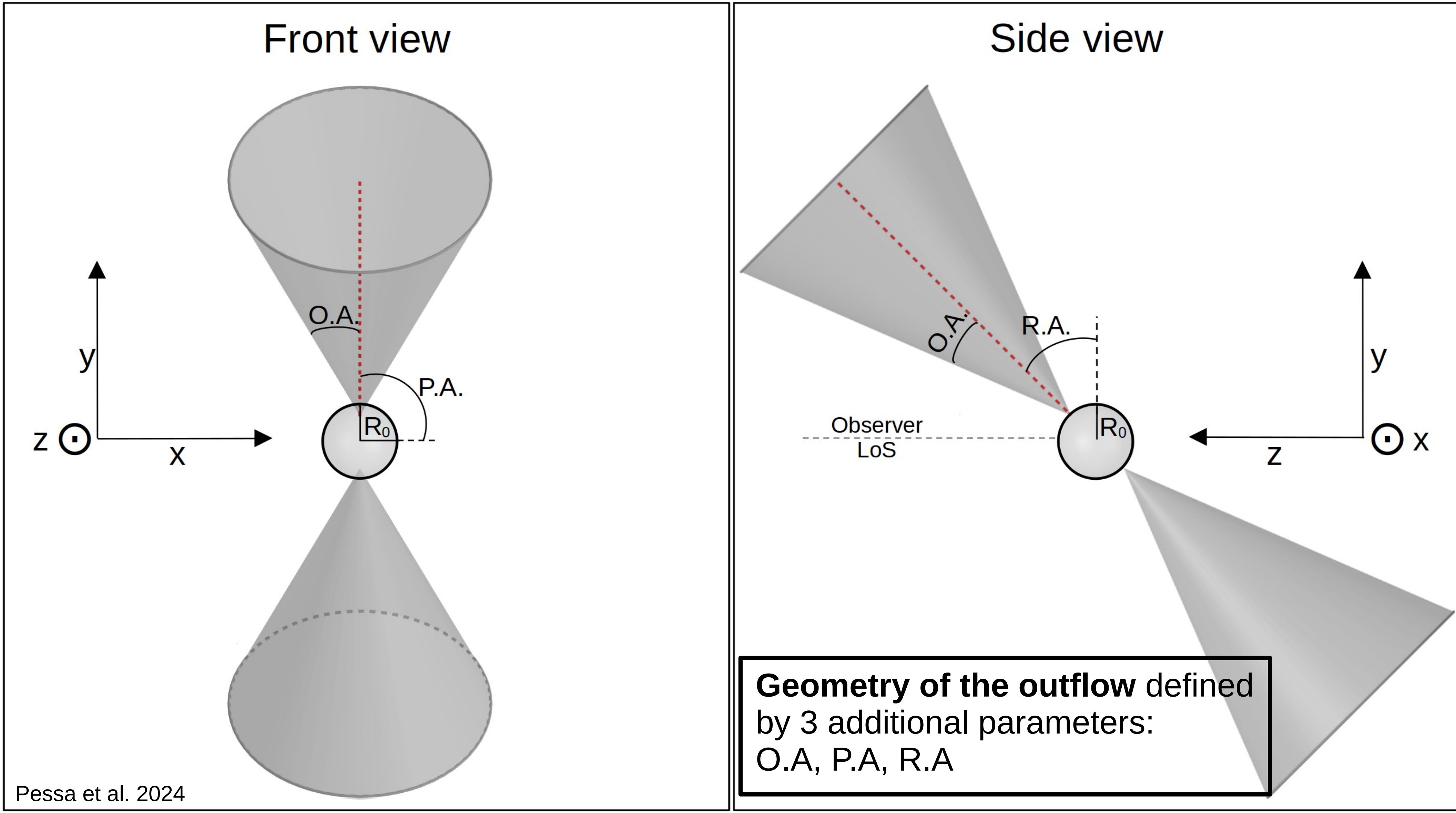
R_0: Radius of central source

τ_0: Central optical depth

γ: Index of velocity law

V_0: Launching velocity

V_{max}: Maximum velocity reached


Front view
O.A.
P.A.
y
z
x
R0
Pessa et al. 2024
Side view
O.A.
R.A.
Observer
LoS
R0
y
z
x
Geometry of the outflow defined by 3 additional parameters:
O.A, P.A, R.A