

# CHEMODYNAMICS OF GREEN PEA GALAXIES


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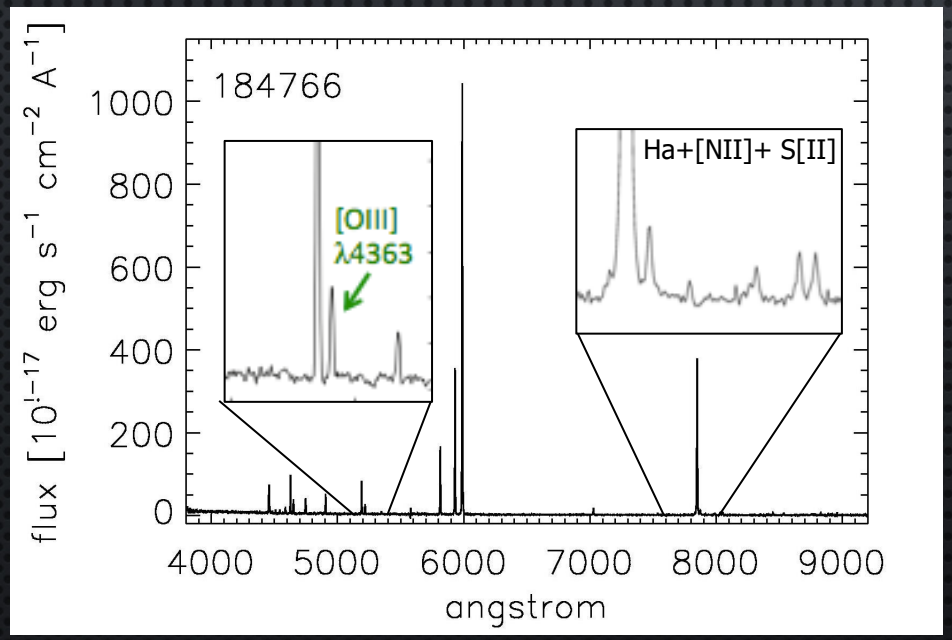

XI Estallidos Workshop @ CIEMAT-Madrid

19/01/2024

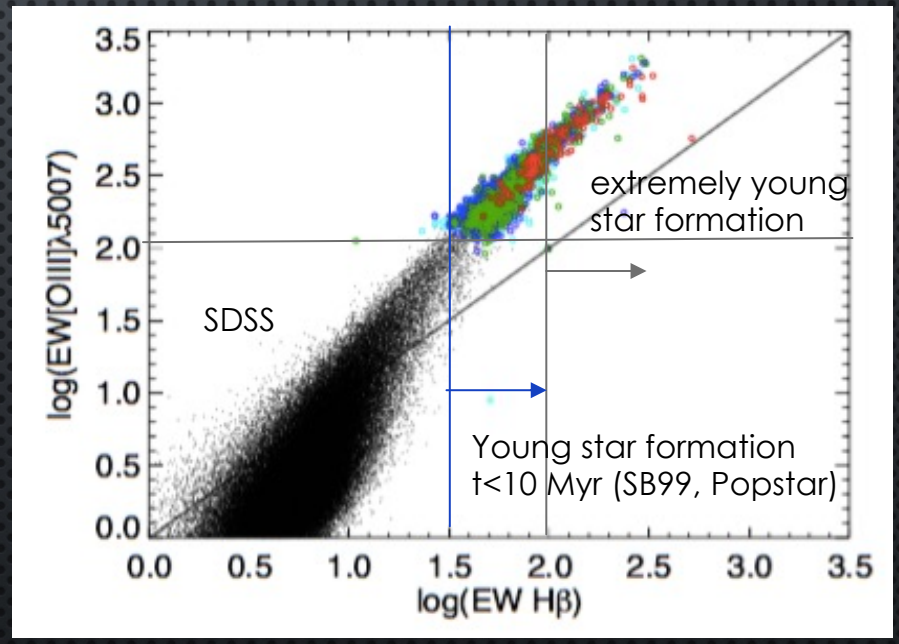
# GREEN PEAS ARE EXTREME EMISSION LINE GALAXIES

Compact luminous starbursts in a low-mass galaxy
Green colour due to unusually strong [OIII]5007 redshifted to r' band



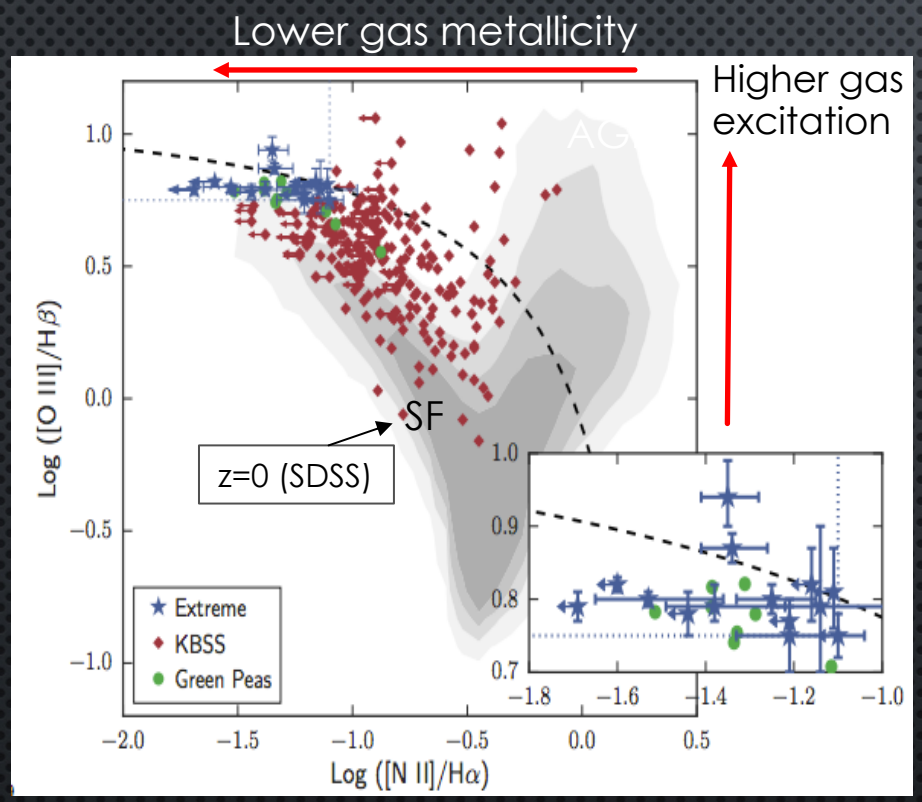

Spectra reflects the properties of a gas-rich, highly ionized, very young, metal-poor, galaxy-wide starburst



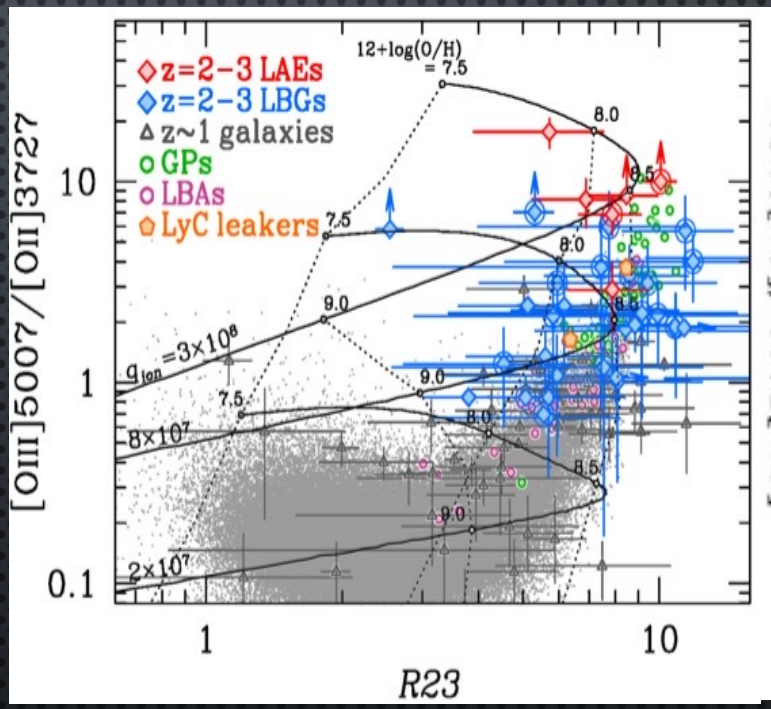

GPs are rare local galaxies with properties closely resembling those seen ubiquitous in high redshift galaxies

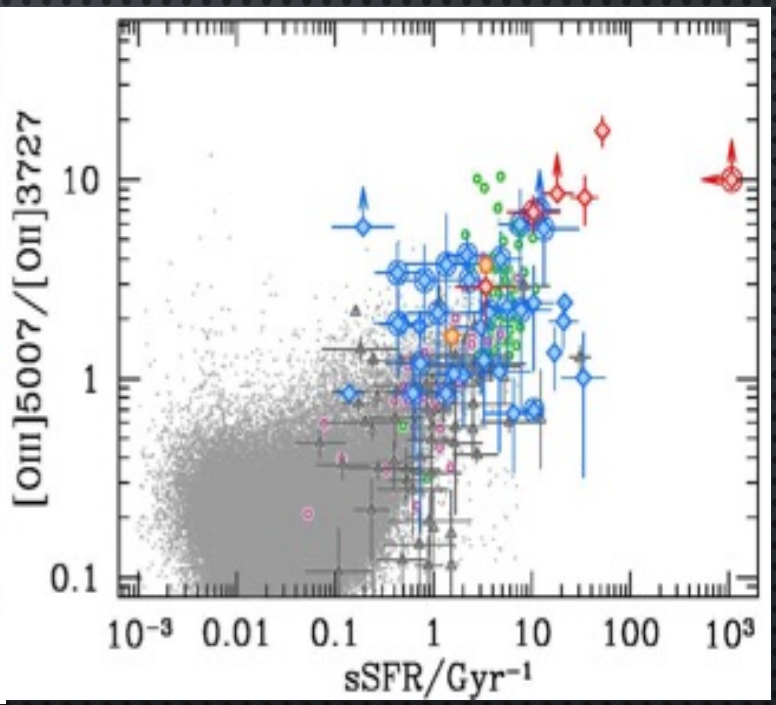
# GREEN PEAS

Similar position in emission line diagnostics compared to z~2-3 galaxies




*KBSS survey z=2-3*
*Erb+16, Steidel+14*



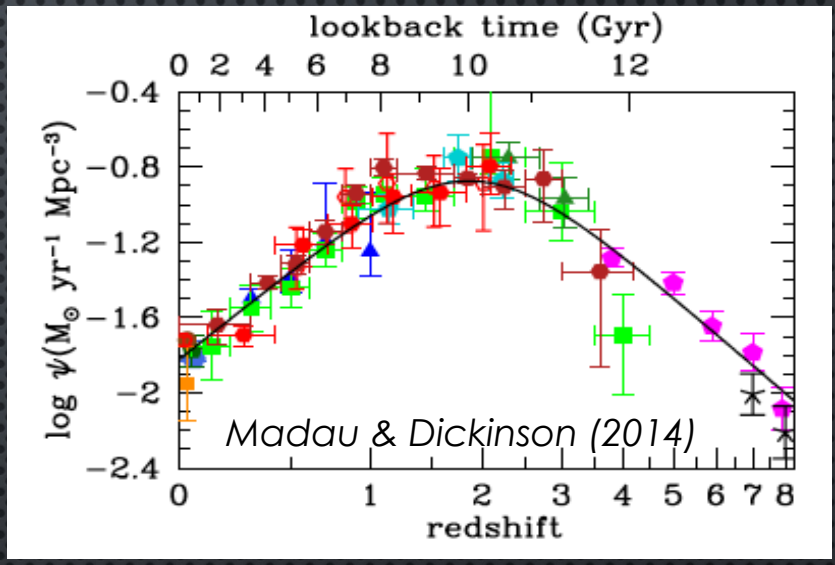

Nakajima+13,14

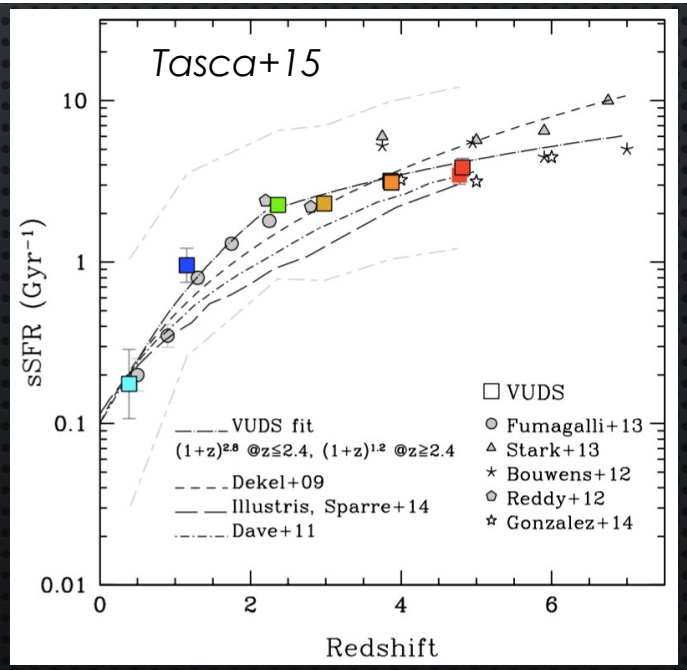
# GREEN PEAS ARE RELEVANT IN A WIDE CONTEXT

BIG QUESTIONS

- Galaxy assembly
  - Understand mechanisms driven and regulating galaxy growth: *massive star formation, accretion, mergers, feedback, chemical enrichment…*
- First galaxies & re-ionization
  - Understand early phases of galaxy formation and chemical evolution
  - Understand Lyman photon production and escape

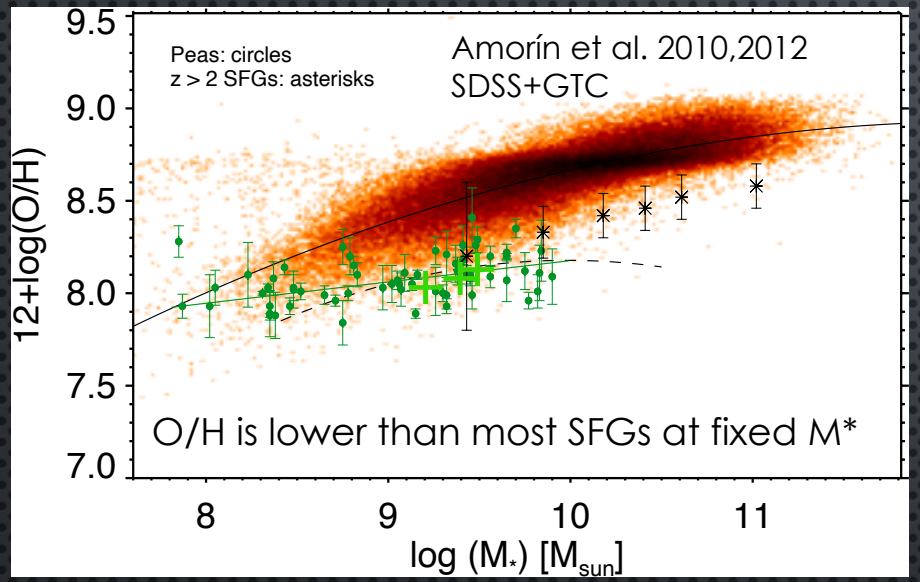
*Low-mass galaxies are key!*
*Need lower-z "analogs" of reionization galaxies to constrain Fesc and ξion*




<u>Need observational constraints from statistical samples:</u>
SFHs, chemical abundances, kinematics, structure, environment…

# GREEN PEAS ARE METAL POOR

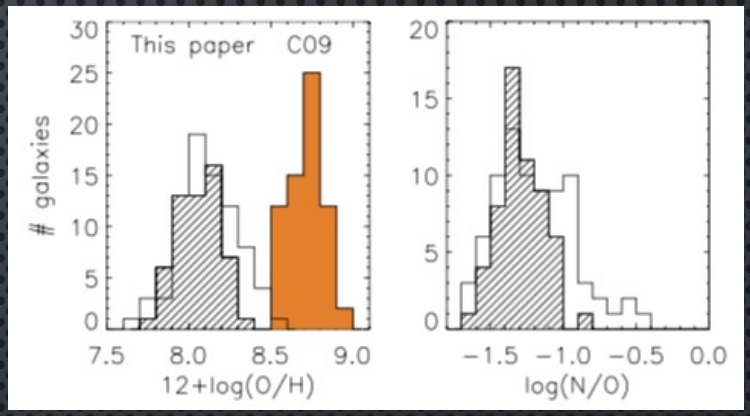


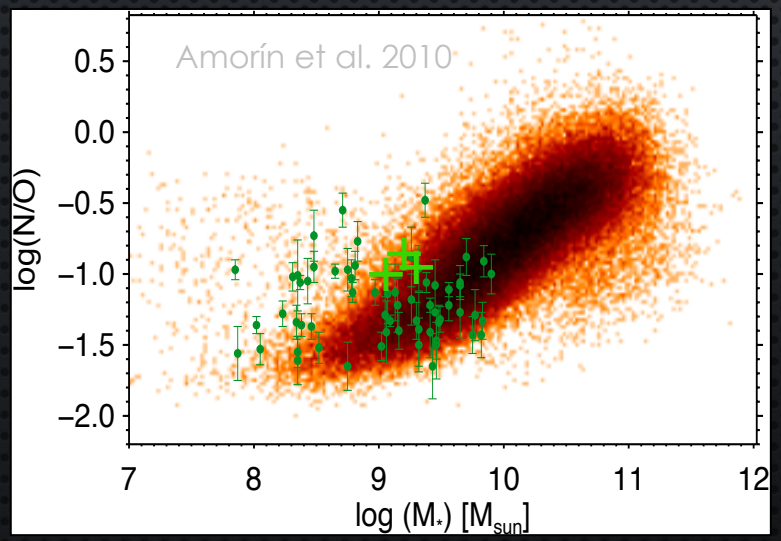

Low metallicity + high N/O + high SSFR = problems for N2-based strong-line methods…

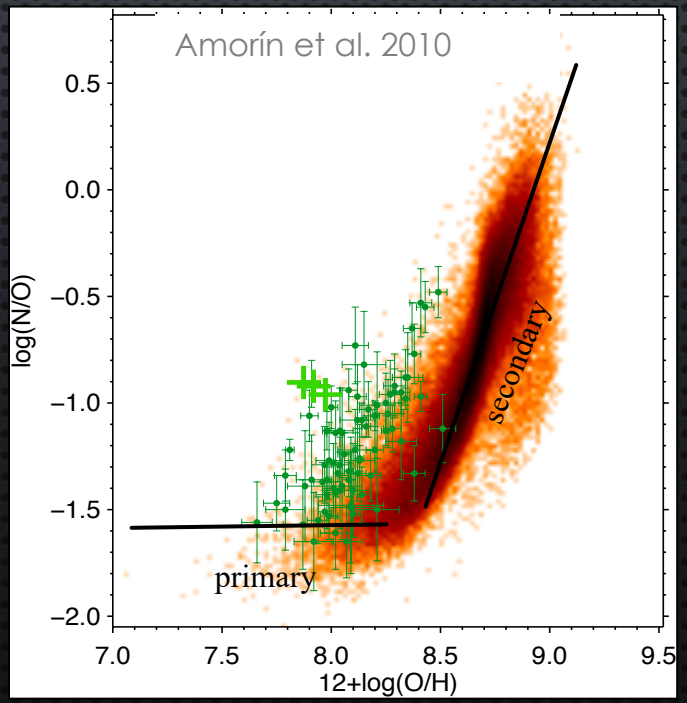
O3N2 may lead to strong overestimations of O/H (e.g. Cardamone+09)

→ Te-based methods are needed !!

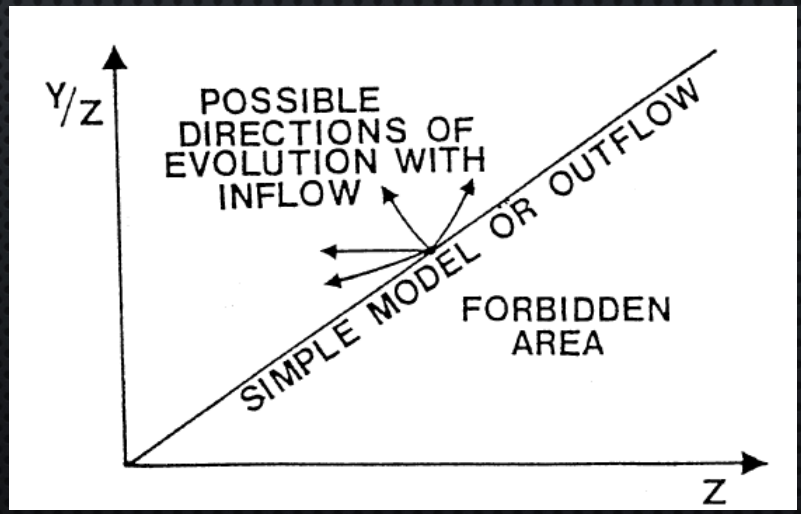
N/O is mostly "normal" for their M* BUT higher for their O/H



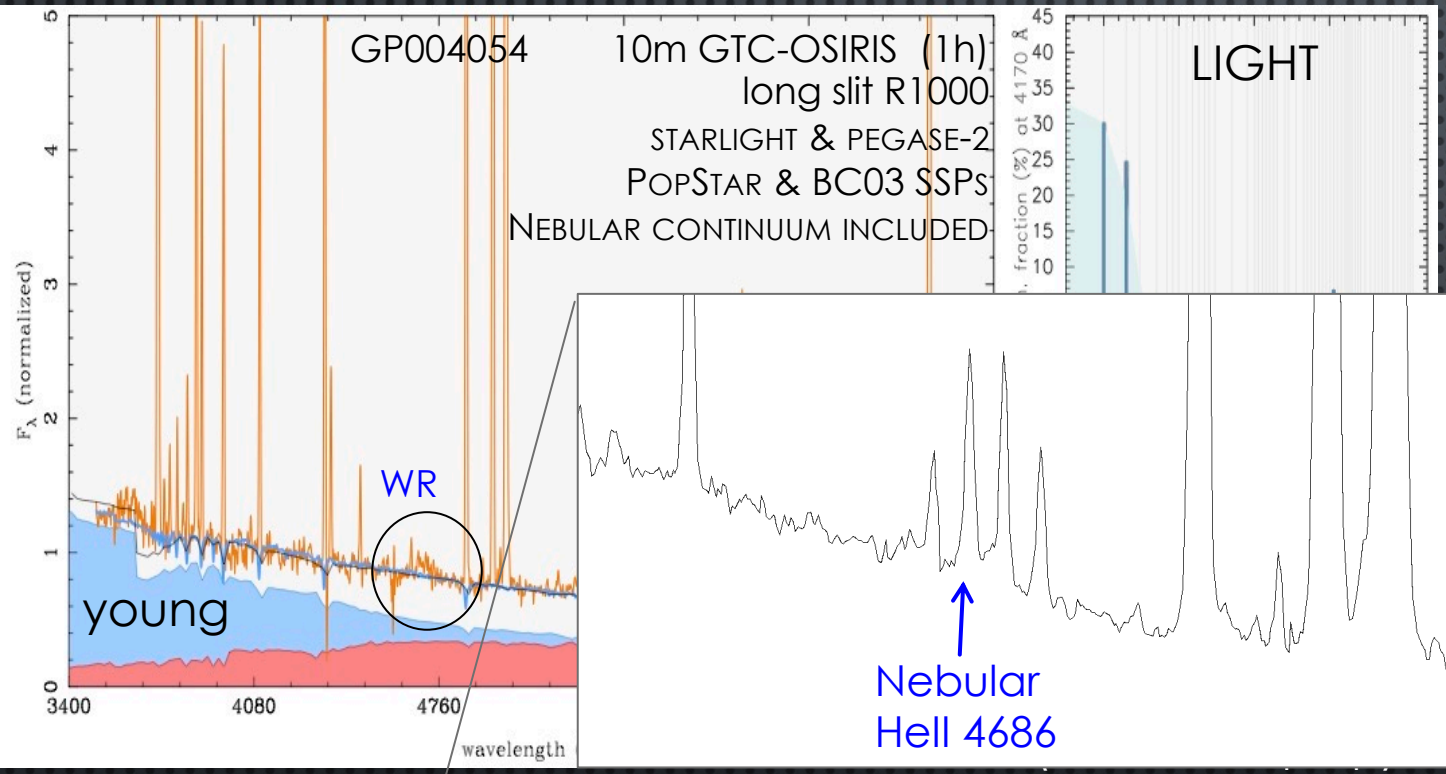



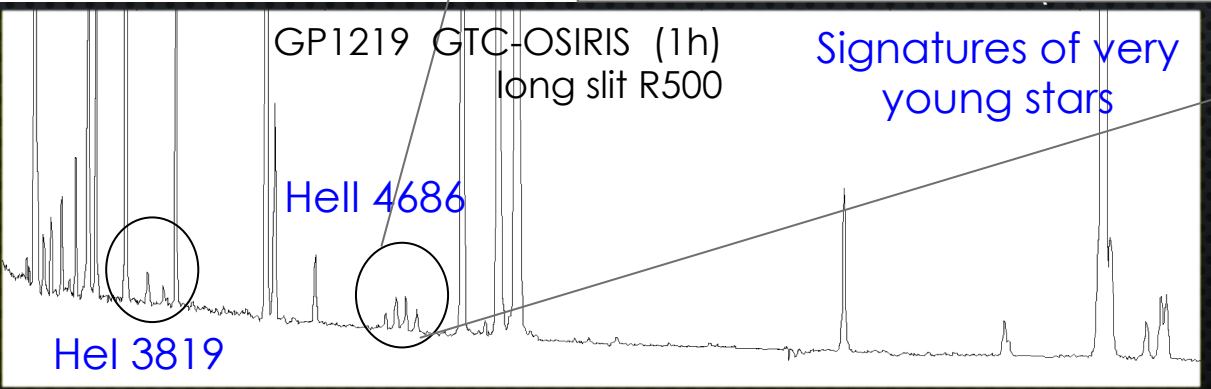

Sudden massive inflow of metal-poor gas ? Metal enriched outflows ?

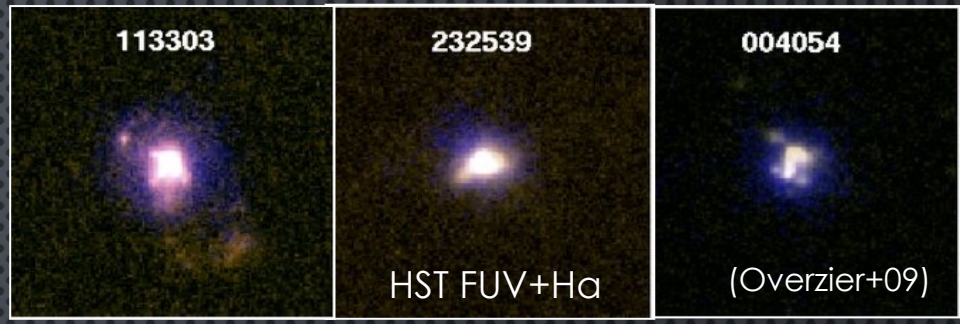


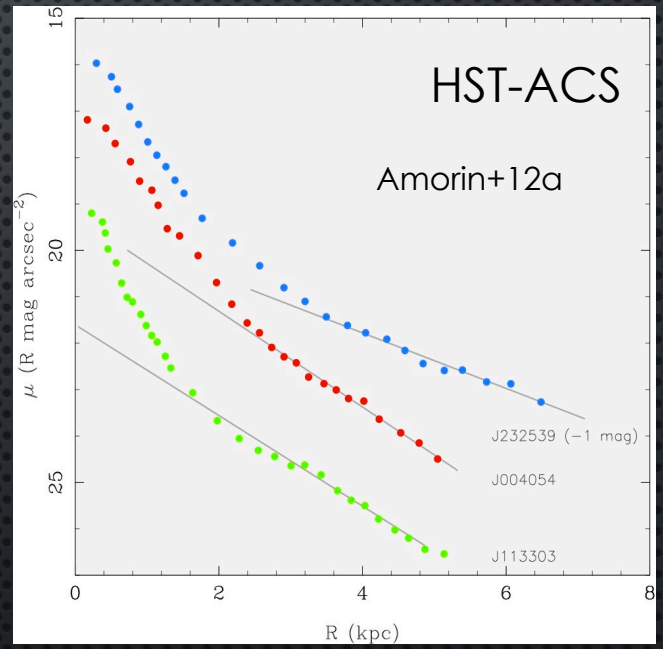
# GREEN PEAS IN MORE DETAIL: GTC AND HST

*(Amorín et al. 2012a, ApJ)*



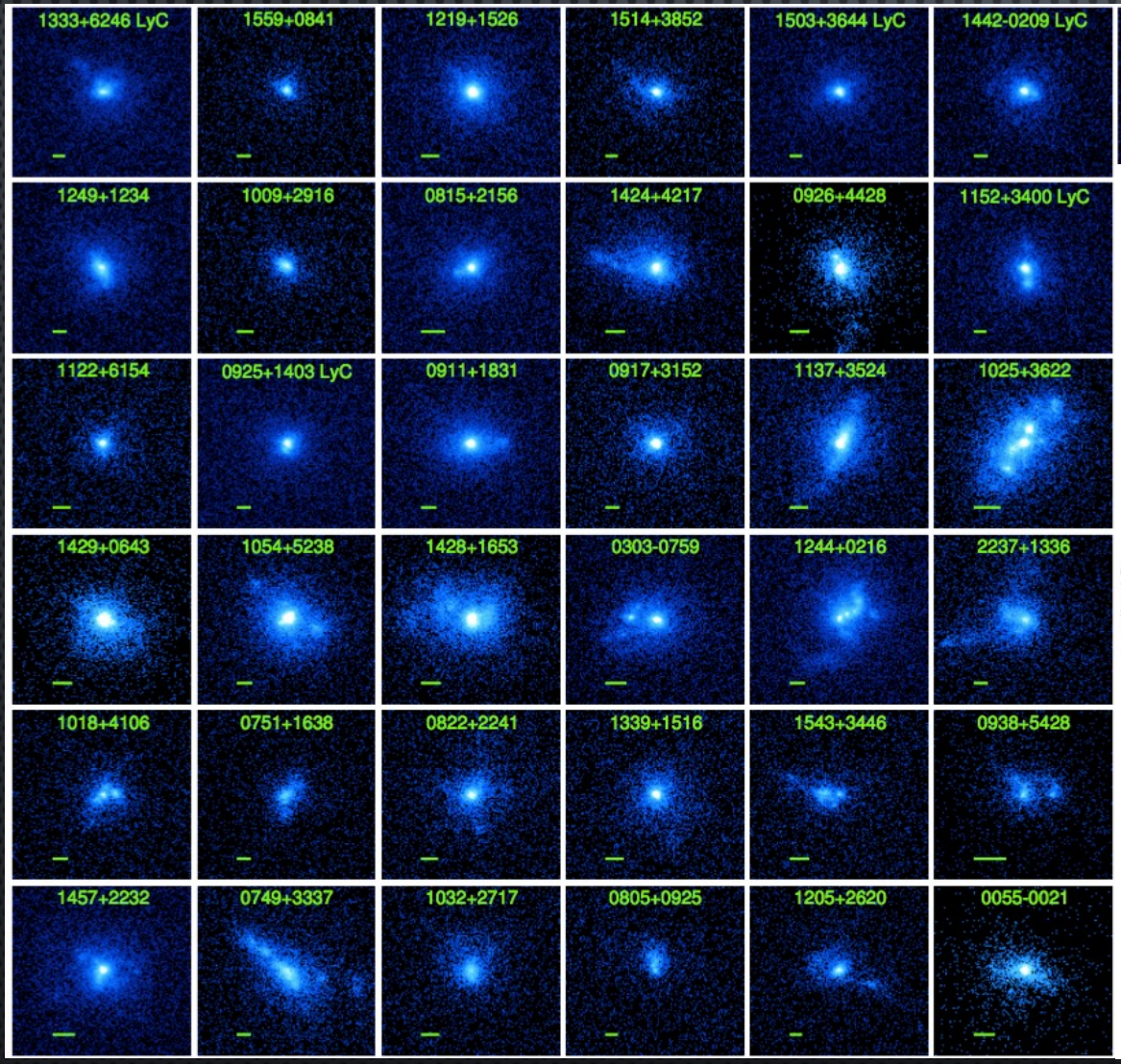




GPs are rapidly forming between 4-20% of their total mass (~$10^9$ $M_{sol}$). Starburst ages of few (1-5) Myr

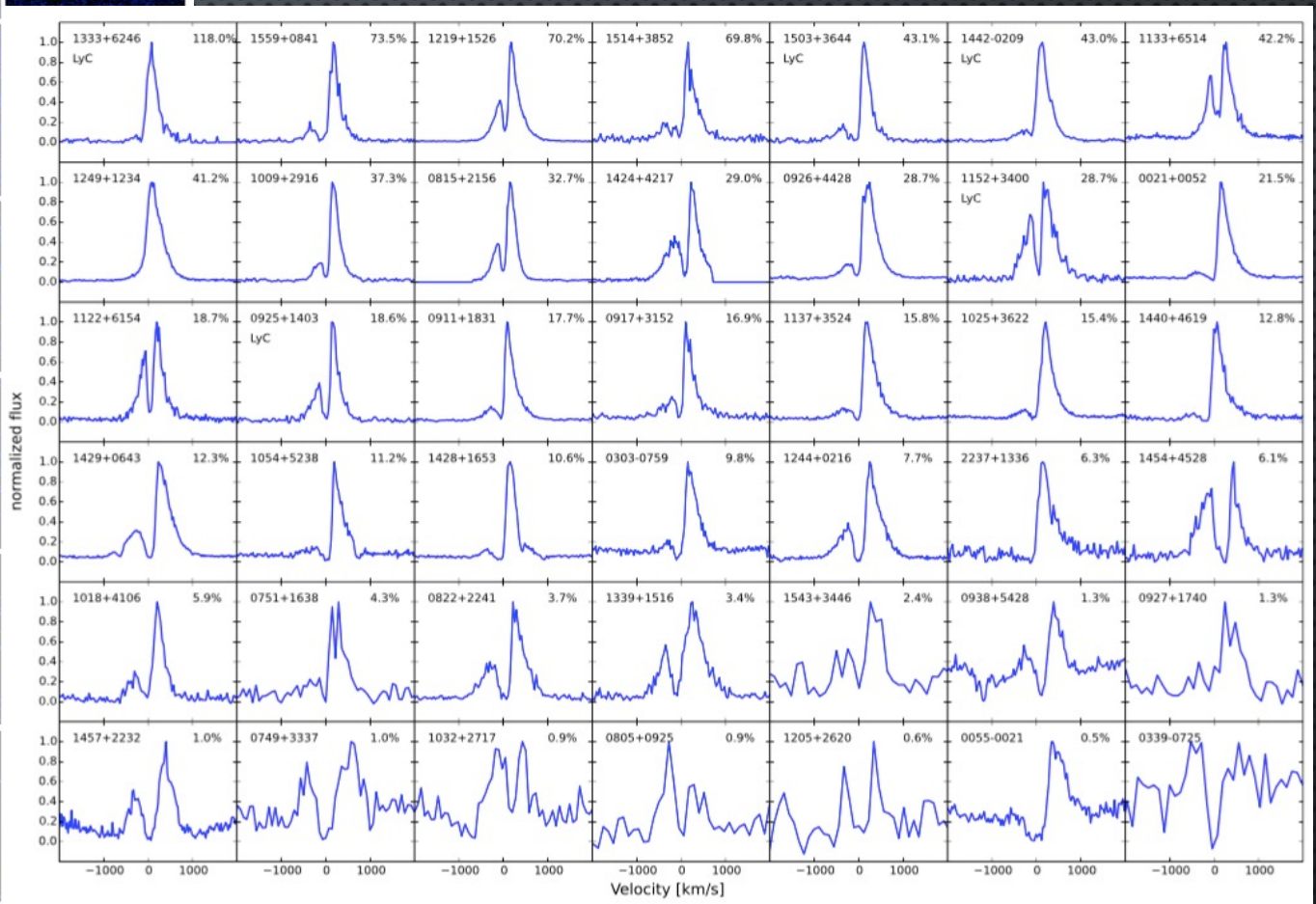
Spectral synthesis + surface photometry suggest an evolved stellar component (age>1Gyr)

# GREEN PEAS IN THE UV

Continuum + Lya



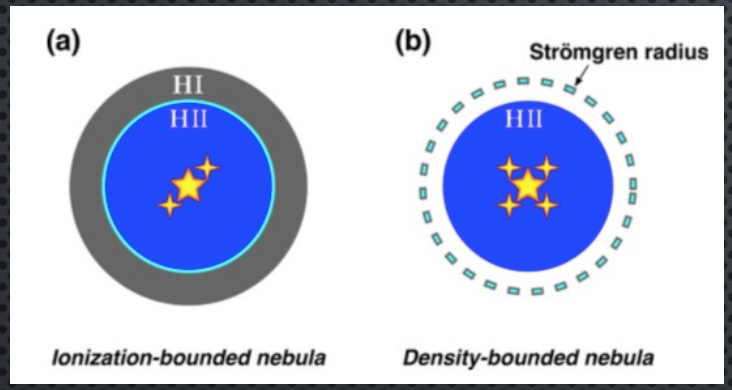

Complex Lya profiles
High Lya escape fractions



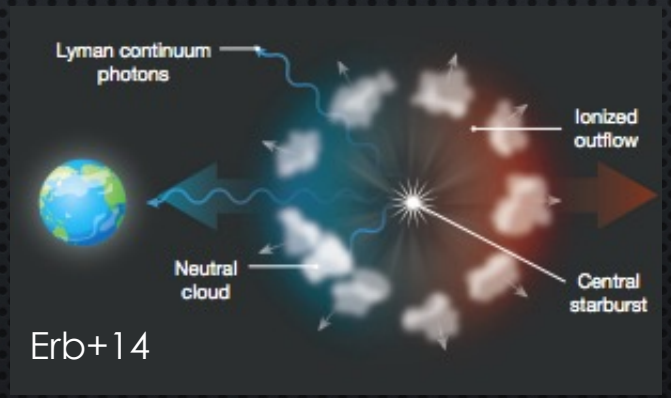

Yang+17a,b

# GREEN PEAS ARE LYC LEAKERS

*Kanajima & Ouchi14*




GPs contain massive HII regions approaching density bounded conditions?



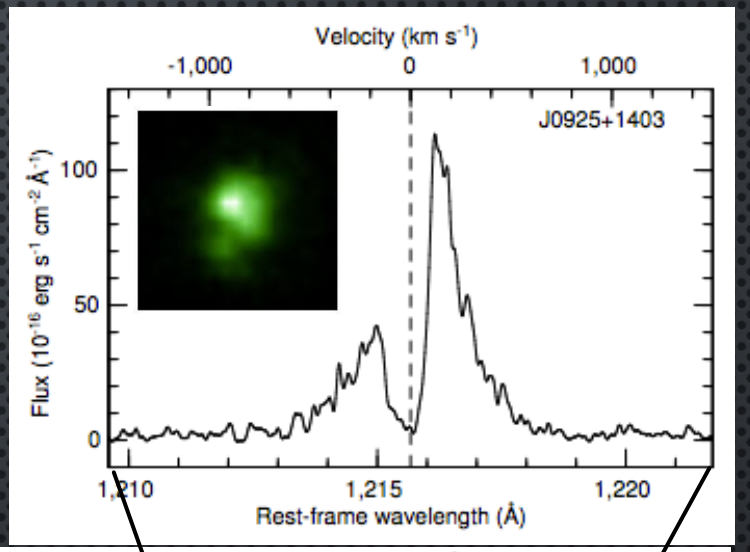

Erb+14

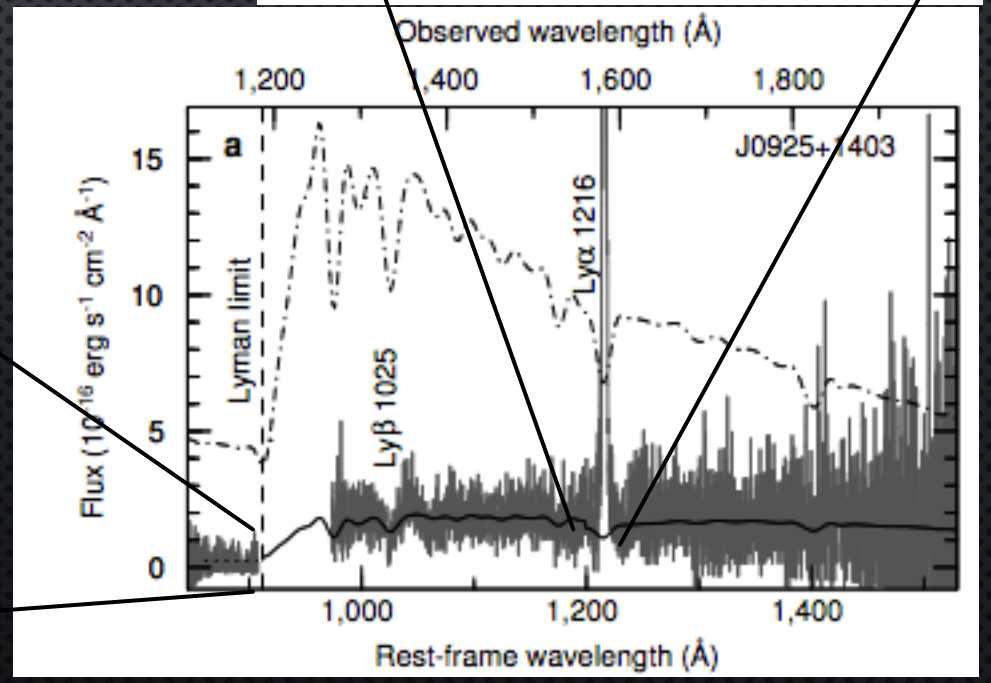
**100% success to date…**

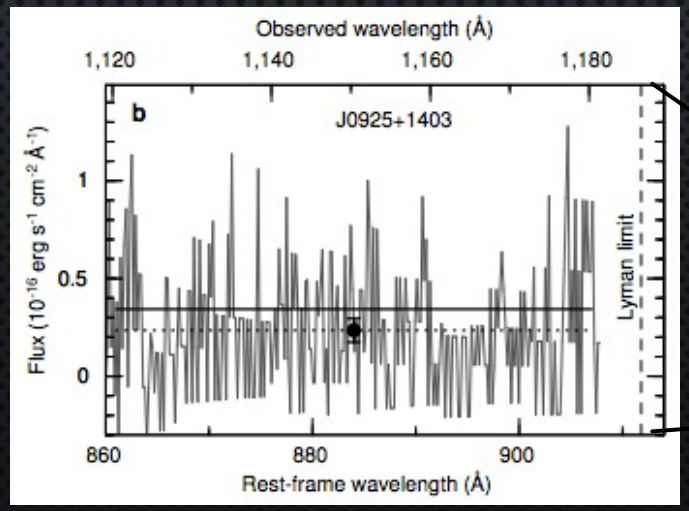
*Izotov+16a,b; Verhamme+16; Schaerer+17, Izotov+18a,b*

About 16 GPs at z~0.3-0.4 observed with HST/COS show strong Lya and LyC emission with *Fesc* ~ 5-75%

Similar values to the few detected at z~3



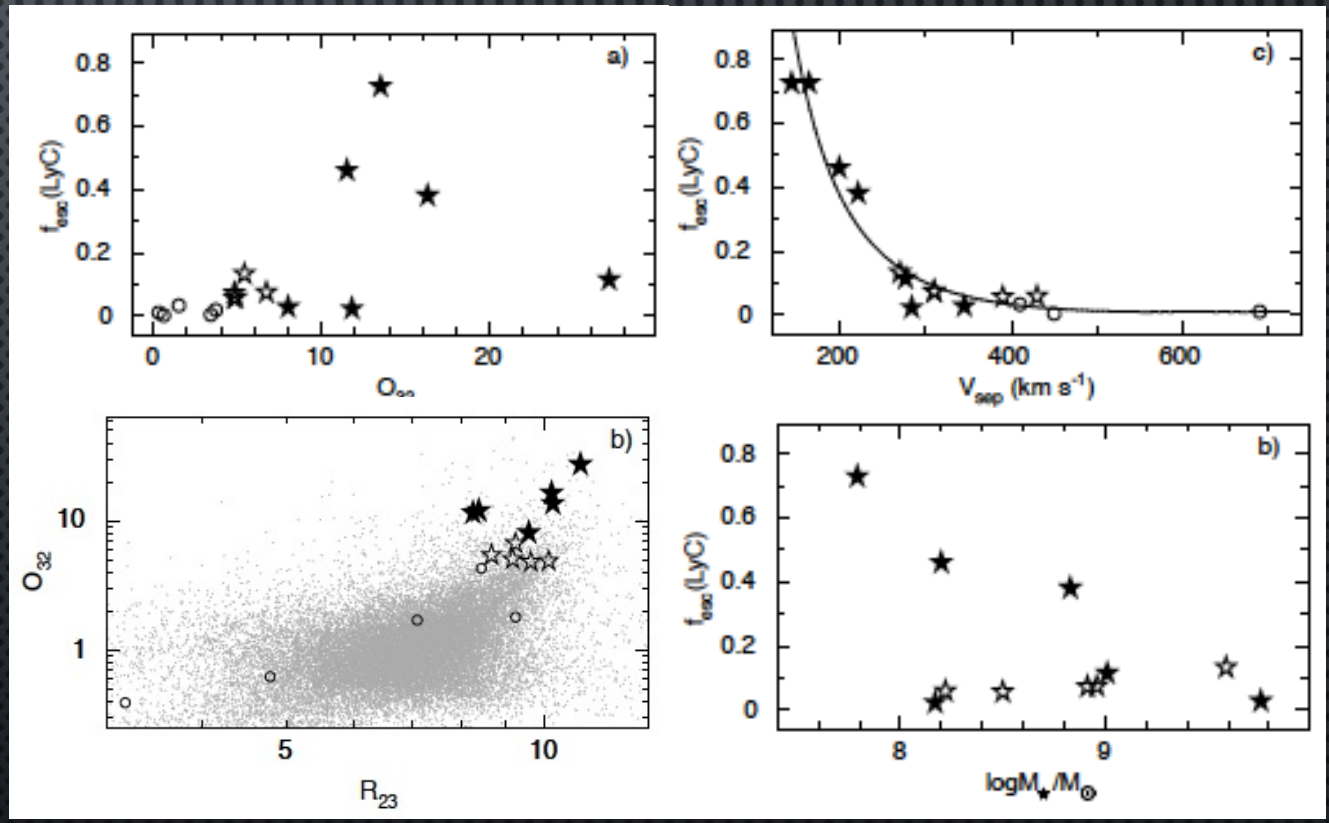
# WHAT PROPERTIES DEFINE A LYC LEAKER?

(Jaskot & Oey 2013; Nakajima & Ouchi 2013, Henry+2015,18 Verhamme+2017, Izotov+2016,18a,b, Schaerer+2017, Chisholm+2018)

Crucial since we need low-z analogs to study Fesc, which defines reionization at z>6

- High OIII/OII
- Weak low ionization absorptions
- High OIII+Hbeta EWs
- Lya EW>70;  EW MgII 2300 in emission
- Narrow double-peaked (small vel. separation)
- Strong ionized outflows ?

→ Vigorous, young and compact SF
→ Low HI column densities
→ High ionization parameter
→ Low metallicity (<20% solar) & Low mass (logM*<9)




Izotov+2018

Need more statistics over a wider range of properties (COS-HST)

# OUR PROJECT: CHEMODYNAMICS OF GREEN PEAS

Unveiling the kinematic structure of the GPs

- Physical properties and abundances for individual kinematic components
- Observational evidences of feedback
- Testing model predictions with observations



INSTRUMENTAL SETUP: HR2400, R1200B and R1200R
Spectral dispersion 0.18, 0.23 and 0.26 A/pixel (R~12000)
Slit width 0.9"; FWHM=0.5Å & Spatial resolution 0.22"/pixel
Long integration times (~1.5-3.5 hr per setup per galaxy)

Deep high dispersion long-slit spectroscopy
ISIS @ 4.2m William Herschel Telescope
Current status: 8.5 nights
Last run in Jan 2018

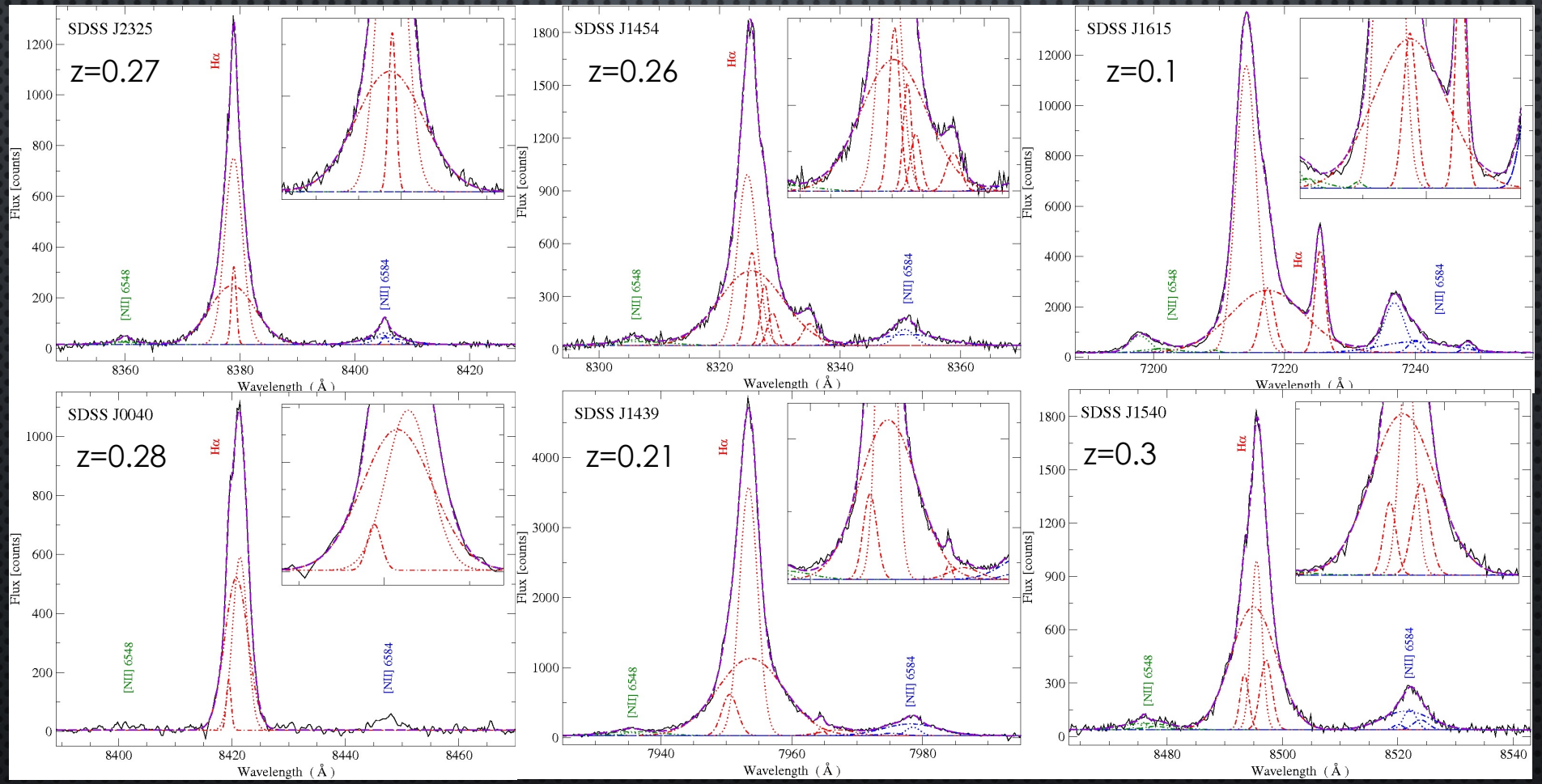
Currently observed sample: 24 GP galaxies at z~0.10-0.37 selected from our previous studies (SDSS) including:

- 2 confirmed LyC leakers and 16 strong Lya emitters
- 4 galaxies with coverage of [OII]3727 and [OIII]4363

6 objects published (Amorin+12b)
2+ papers prep. (Hogarth, Amorin)

# FIRST RESULTS: COMPLEX LINE PROFILES

Amorín et al. (2012b)




Iterative multicomponent fitting method based on *IRAF-NGAUSSFIT* (See e.g. Firpo+(10,11) Hägele+(07,09,10,12)

# SIGNATURES OF FEEDBACK AND TURBULENT ISM

*Amorín et al. (2012b)*

Multiple narrow components associated to SF clumps
Δv~50-500 km/s and σ =40-120 km/s

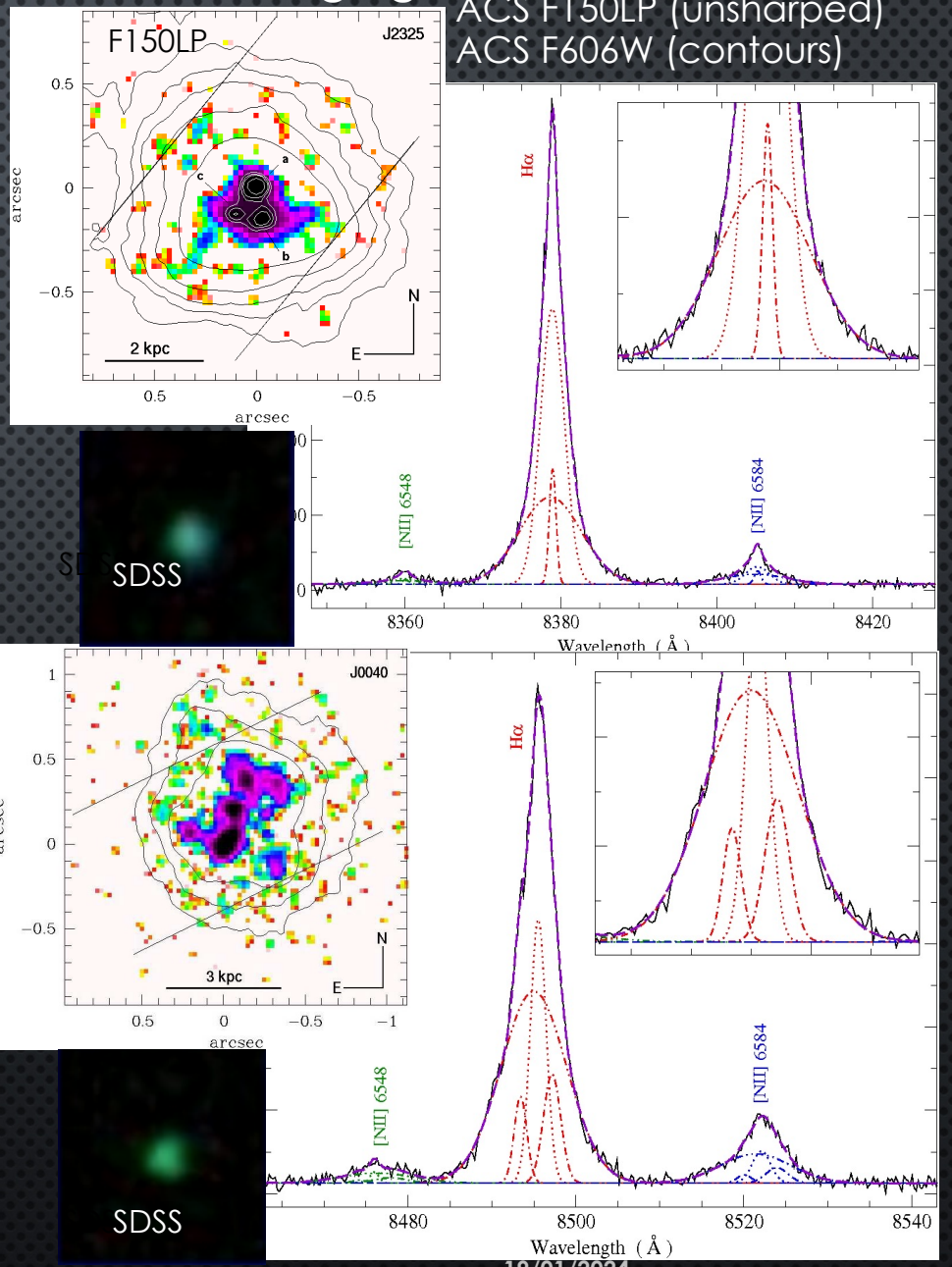
Turbulent ISM in thick/clumpy disks?
Coalescence of massive SF clumps ? Minor mergers ?

Broad emission associated to high velocity gas
σ =100-250 km/s  FWZI ~ 650-1750 km/s
$L_{Ha}$~$10^{41}$-$10^{42}$ erg/s (up to 40% of the total Ha)

Likely signature of strong winds and SNe remnants
Shocks? Metal-poor AGNs ? Turbulent mixing layers?

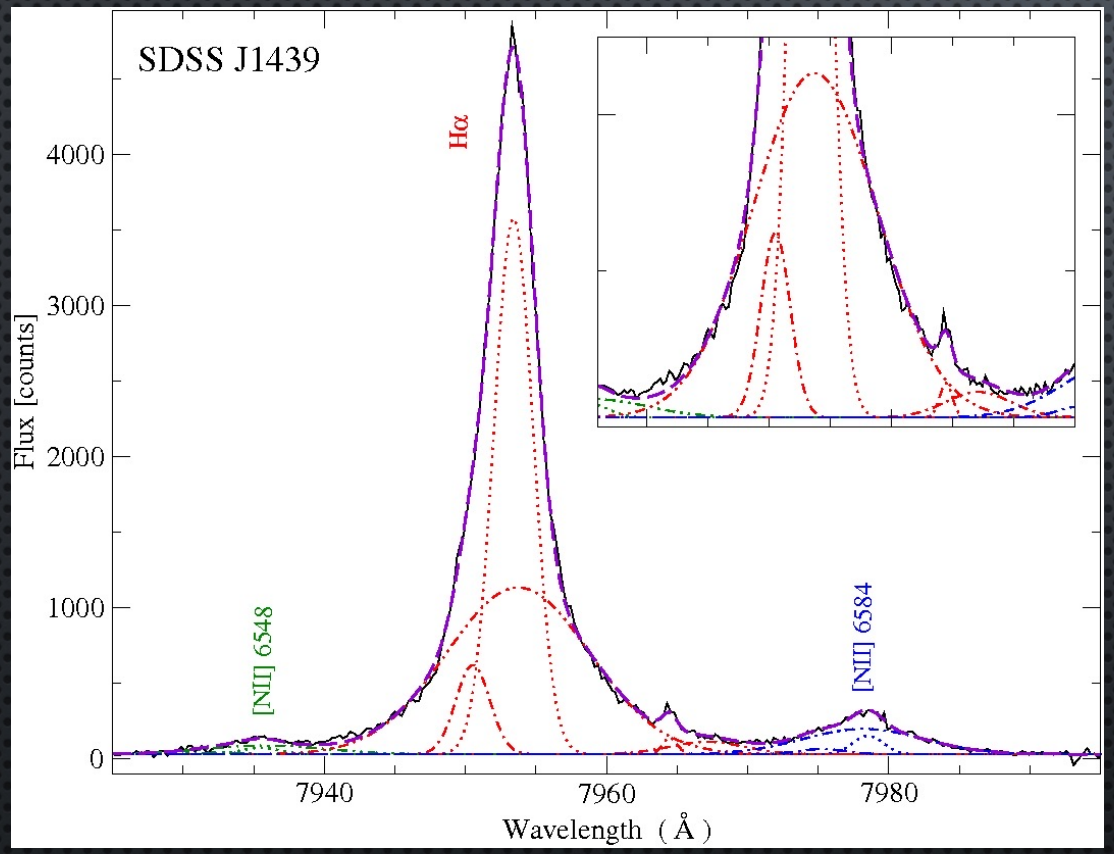
Rest FUV imaging

ACS F150LP (unsharped)
ACS F606W (contours)



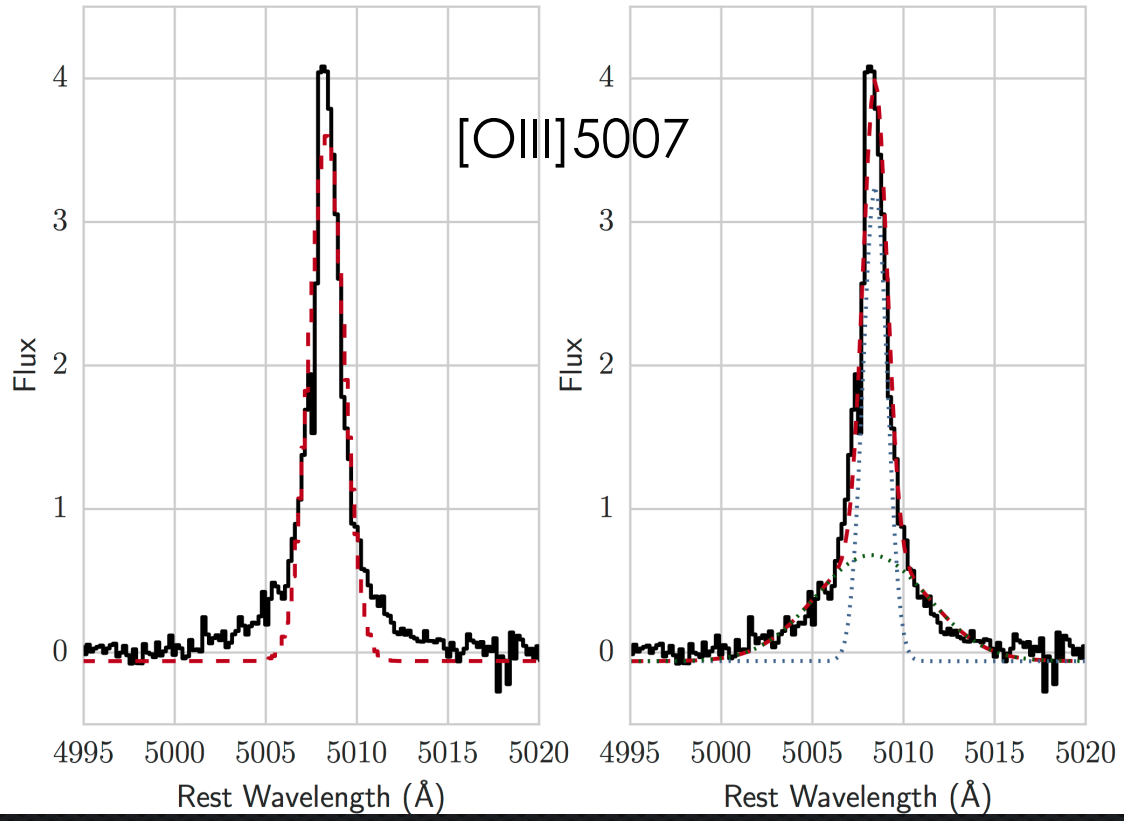
# SIMILARITIES FOUND AT HIGHER Z

*Amorín et al. (2012b)*




Bright GP @ z~0.3; log M*~9.5

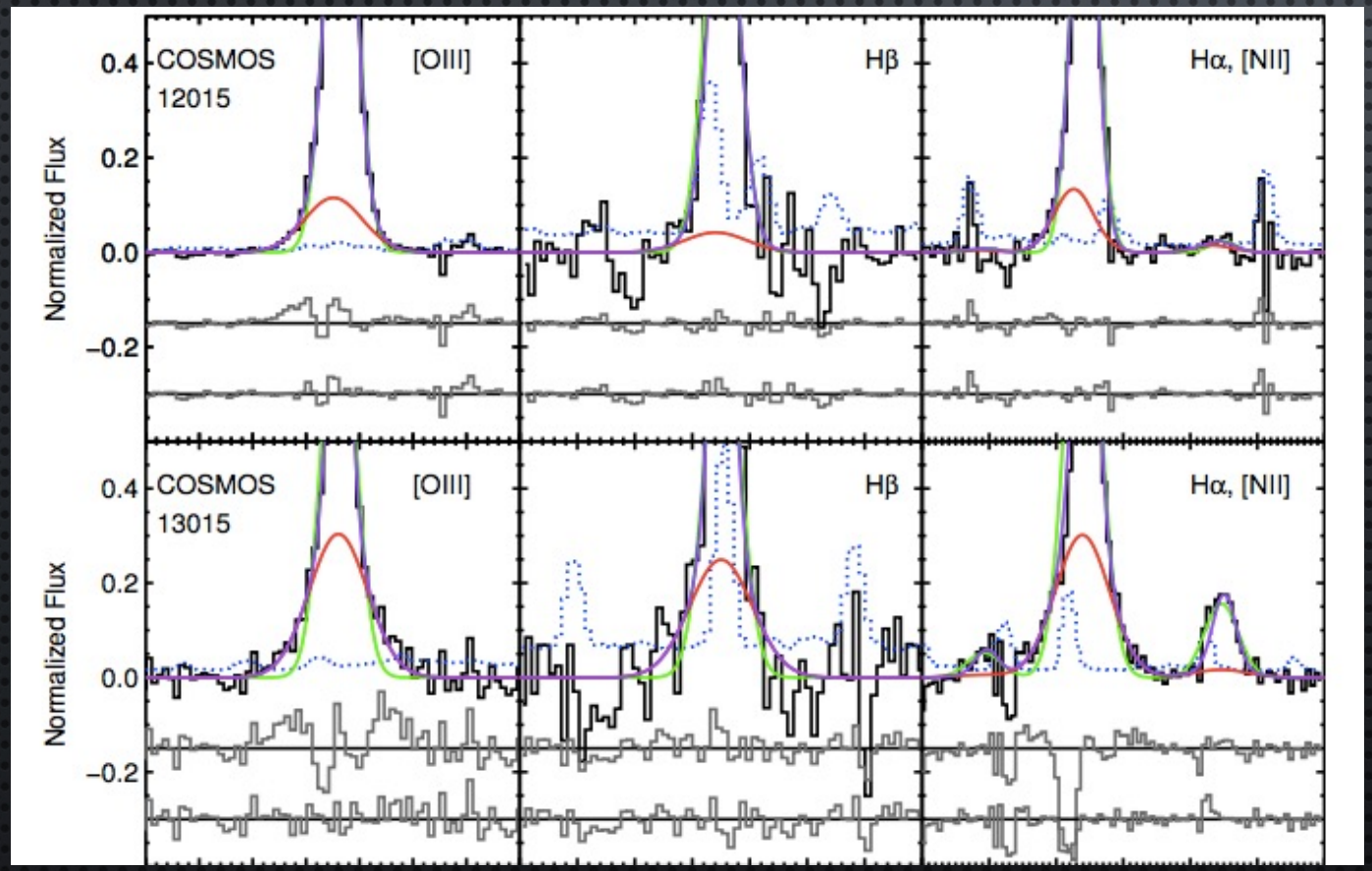
(Xshooter, Courtesy D. Erb)




LAE at z~2.3; BX418 Log $M_*$~9.4

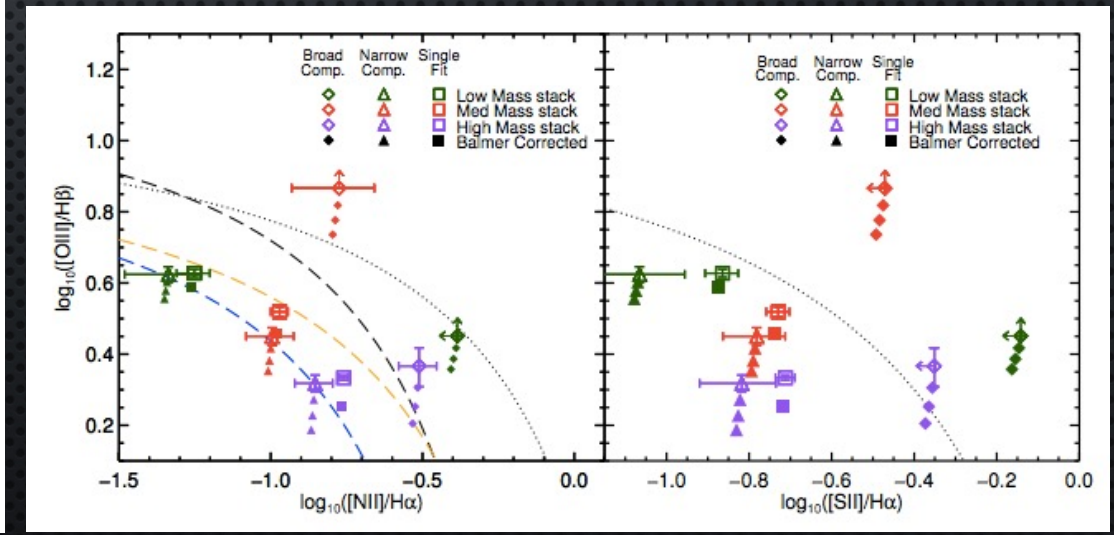
# POSSIBLE IMPACT OF BROAD EMISSION ON EMISSION LINE DIAGNOSTICS?

Can broad/multiple components (i.e. strong outflows, clumpiness) affect optical diagnostics in integrated spectra of high-z galaxies?




Freeman+17
MOSDEF z~2-3, logM*>9
Narrow < 275 km/s (FWHM)
Broad > 300 km/s

Requires very high SNR !!

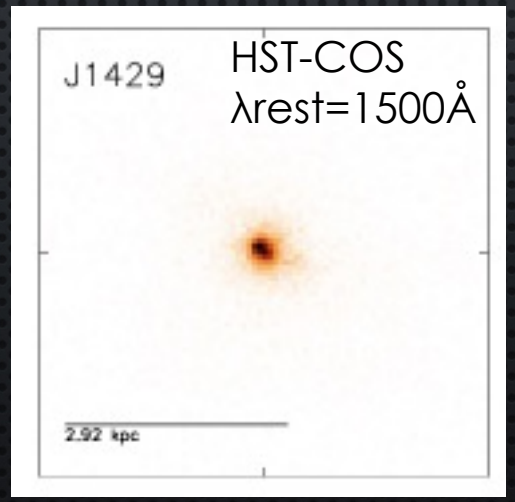


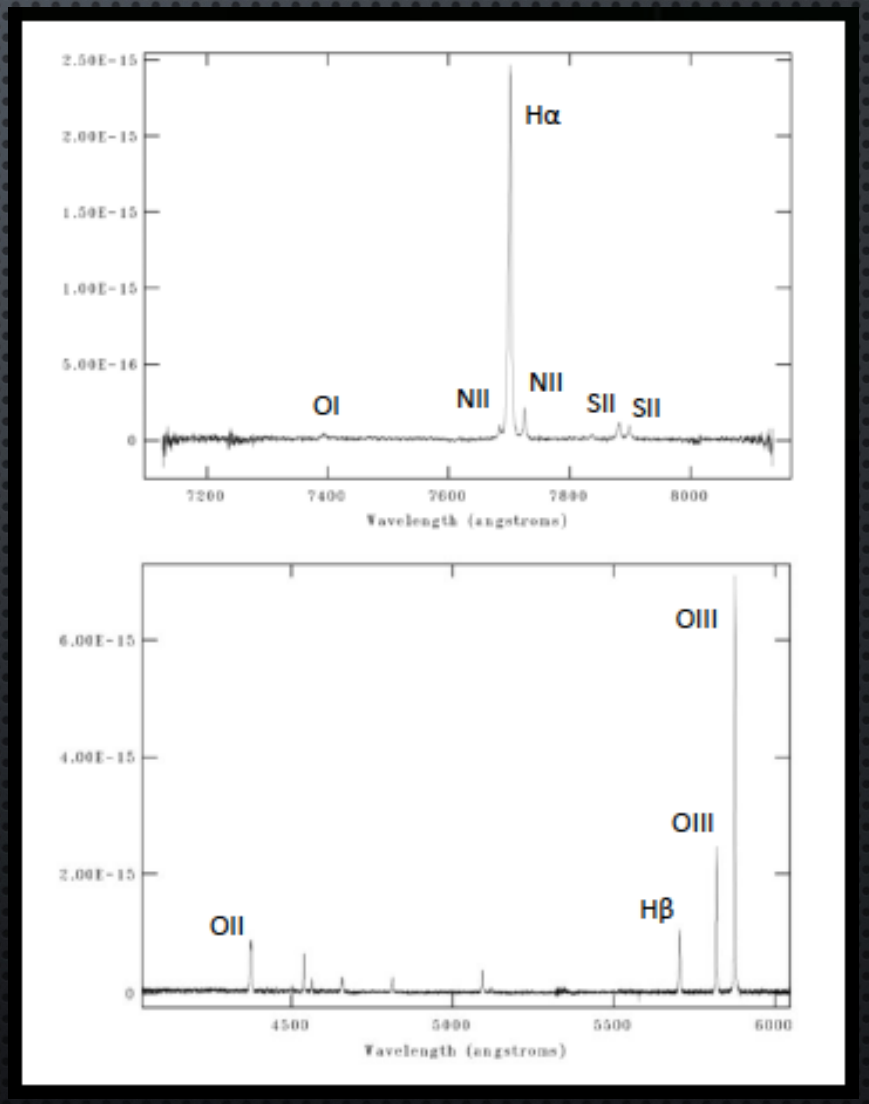
# FIRST CHEMODYNAMIC STUDY OF GREEN PEAS



Lucy Hogarth (UCL)
Fellow summer student at
Uni. of Cambridge



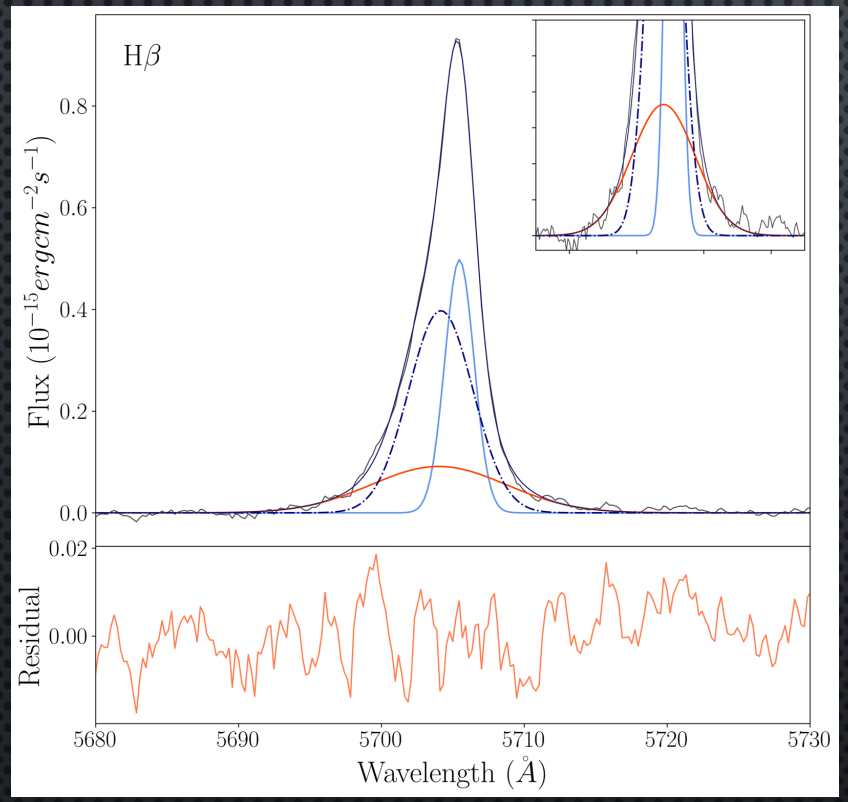



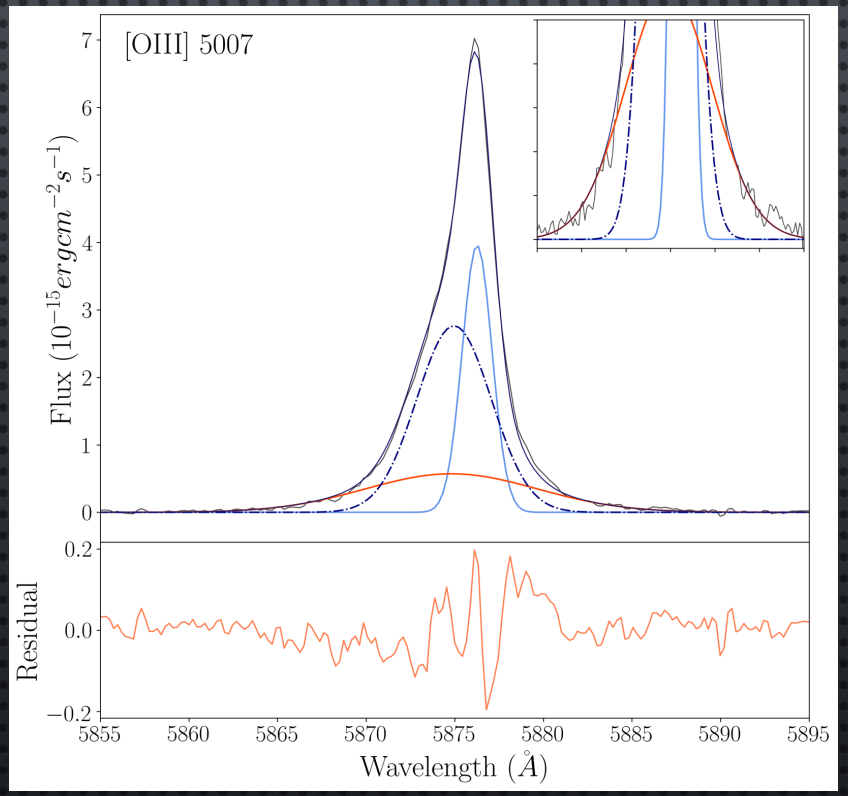

z=0.17
SFR(FUV)~30 M/yr
Log(M*)=9.4
EW(Ha)~900 A
$R_e$(FUV)~290pc

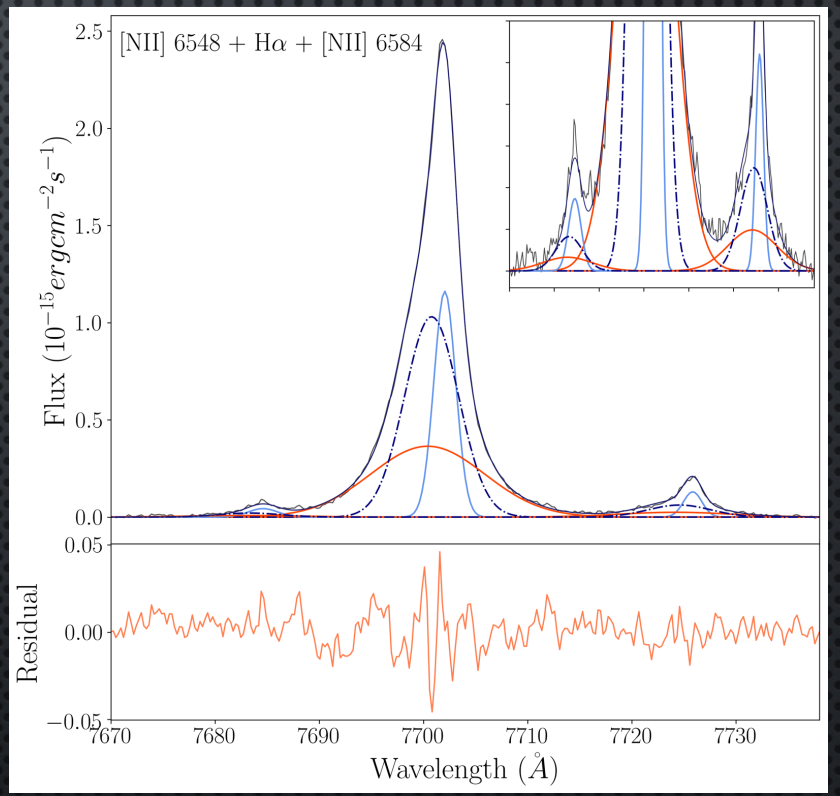
# EMISSION LINE MULTI-COMPONENT ANALYSIS OF GREEN PEAS

Bright lines

Velocity resolution ~25 km/s



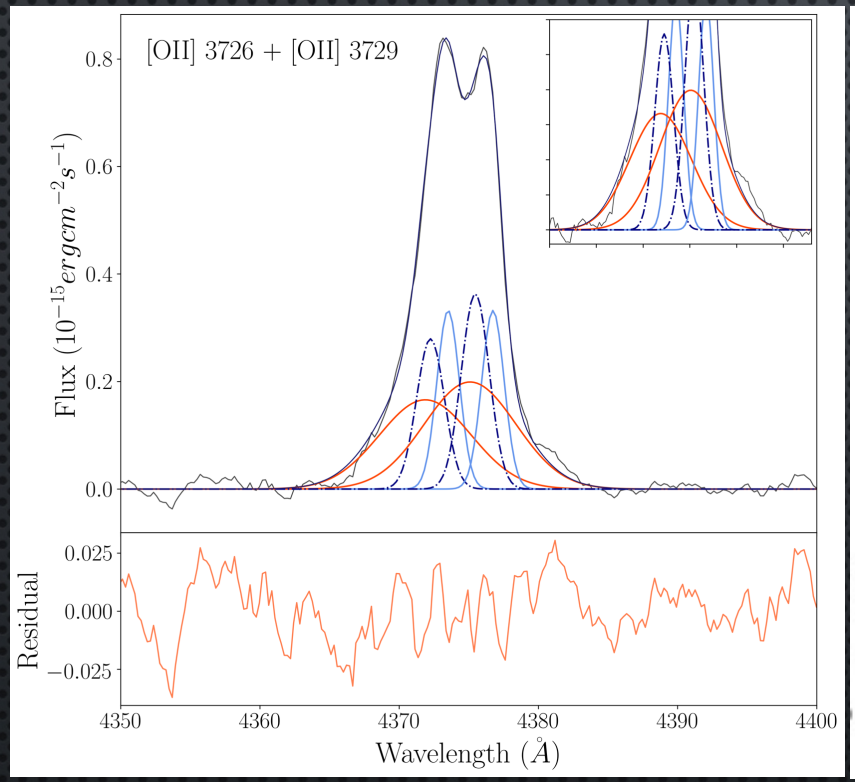



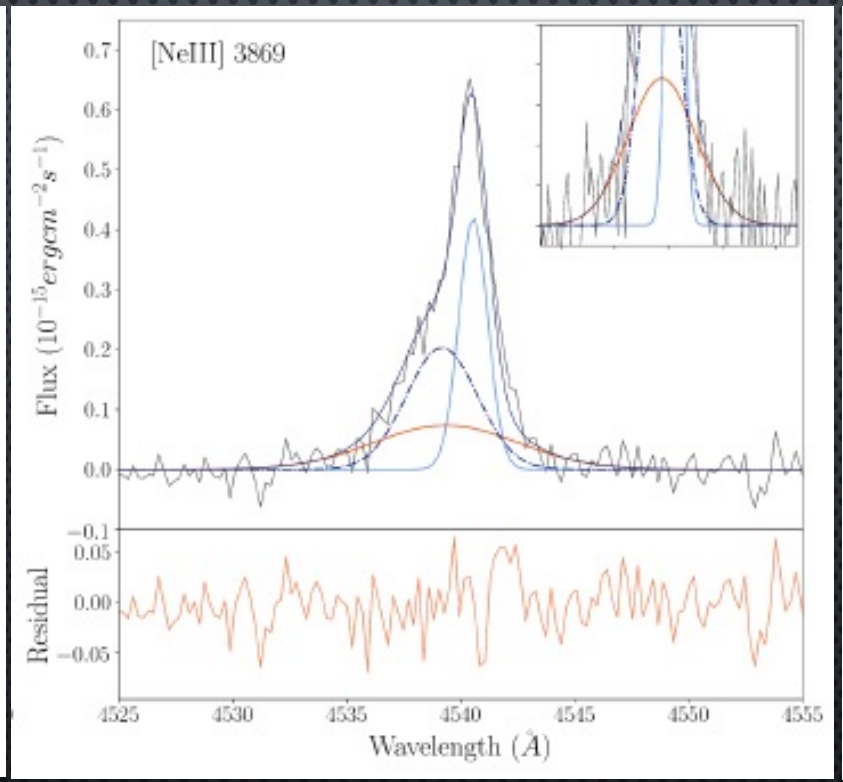

Hogarth, Amorín, et al. (in prep)

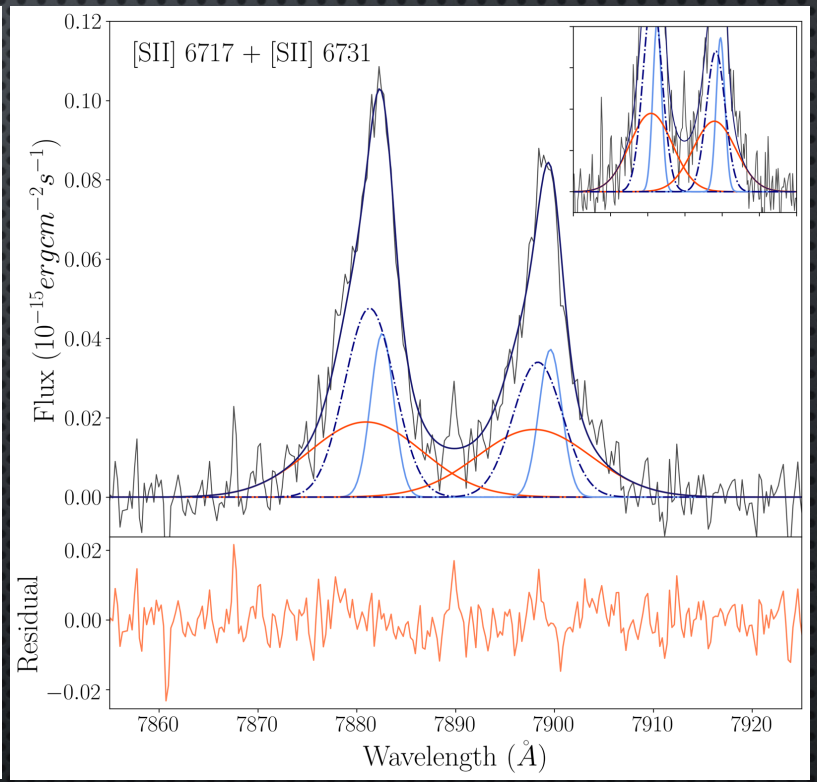
# EMISSION LINE MULTI-COMPONENT ANALYSIS OF GREEN PEAS

Tricky/Faint lines

Velocity resolution ~25 km/s



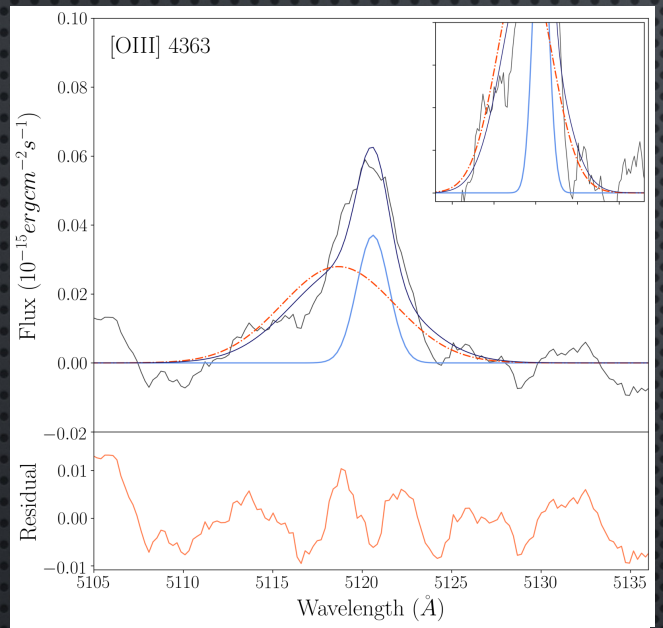



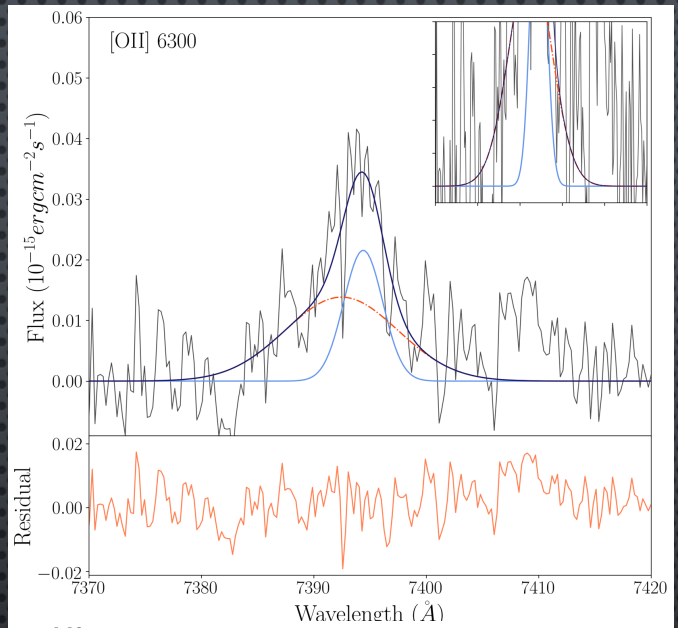



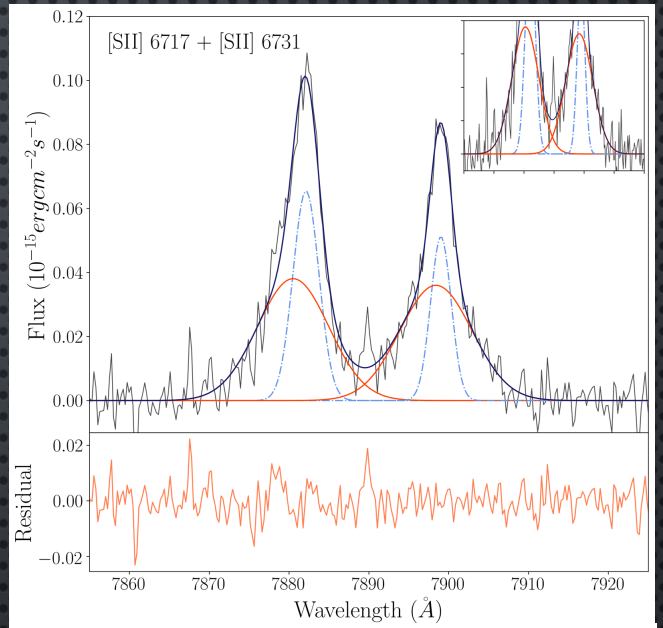

Hogarth, Amorín, et al. (in prep)

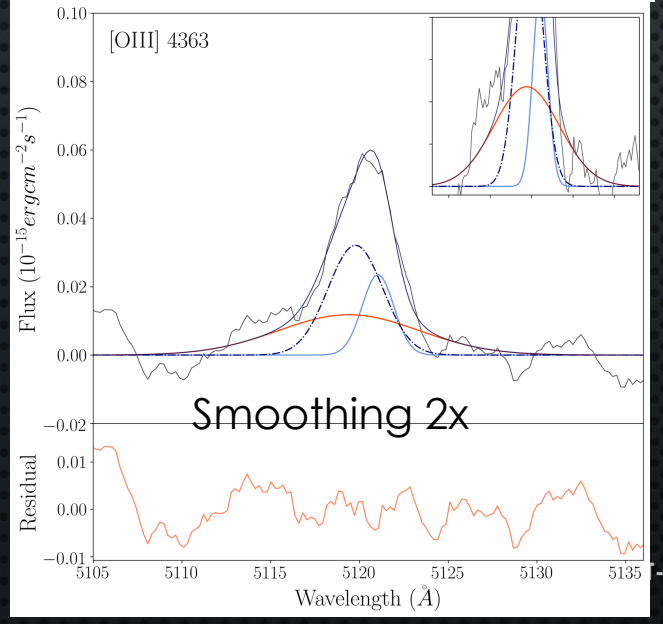
# PROBLEM AT LOW SNR: 2 OR 3 COMPONENTS?

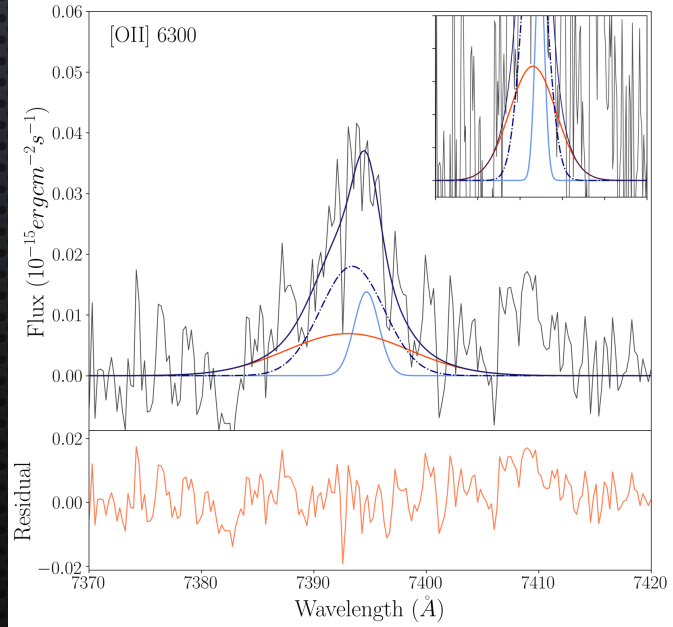
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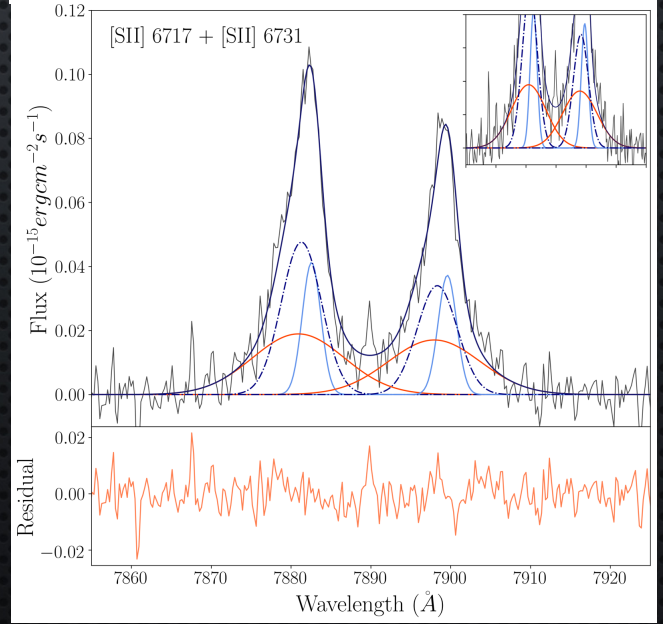


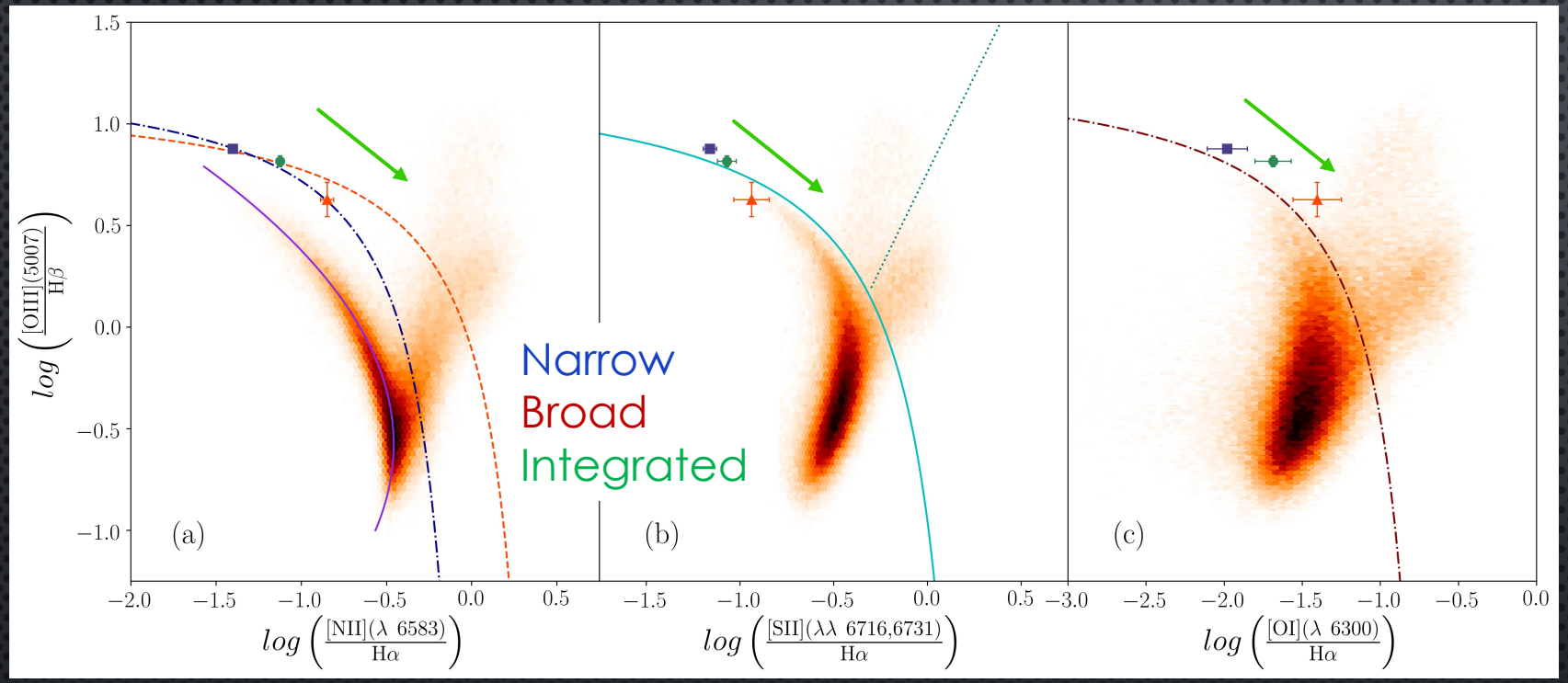



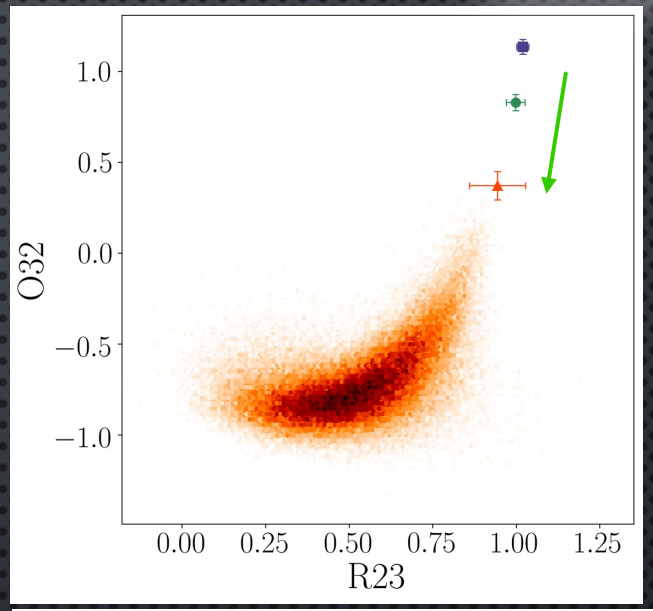



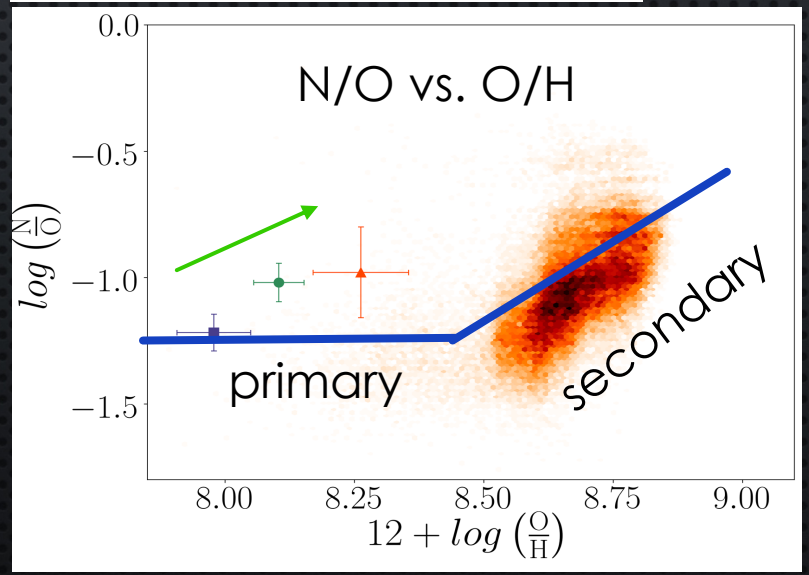



# IMPACT ON EMISSION LINE DIAGNOSTICS

PRELIMINARY




BPT trend consistent with Freeman+17, but need statistics !!

- Ideally better with spatially resolved studies
- May this have an impact on high-z studies?

(e.g. with JWST, MOONS, etc..)

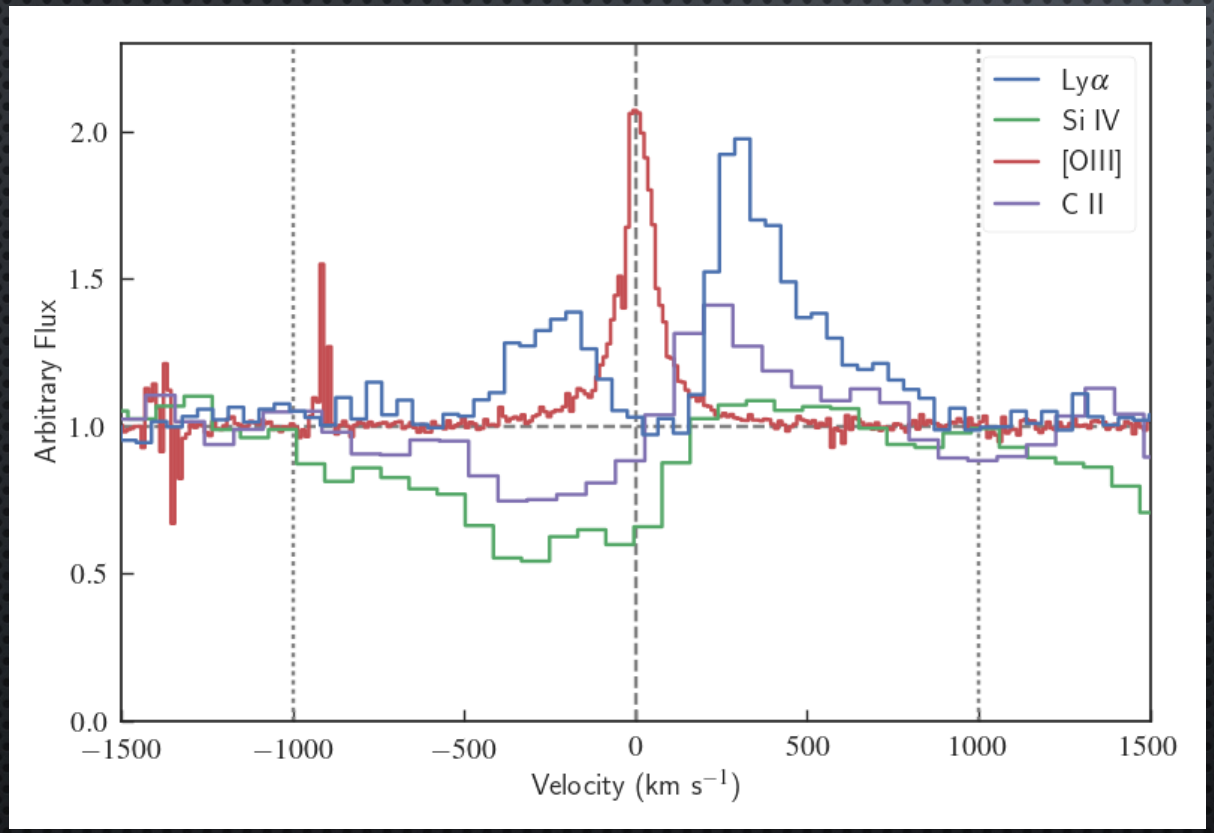


Hogarth, Amorín, et al. (in prep)

# KINEMATICS: COMPARISON UV-OPTICAL

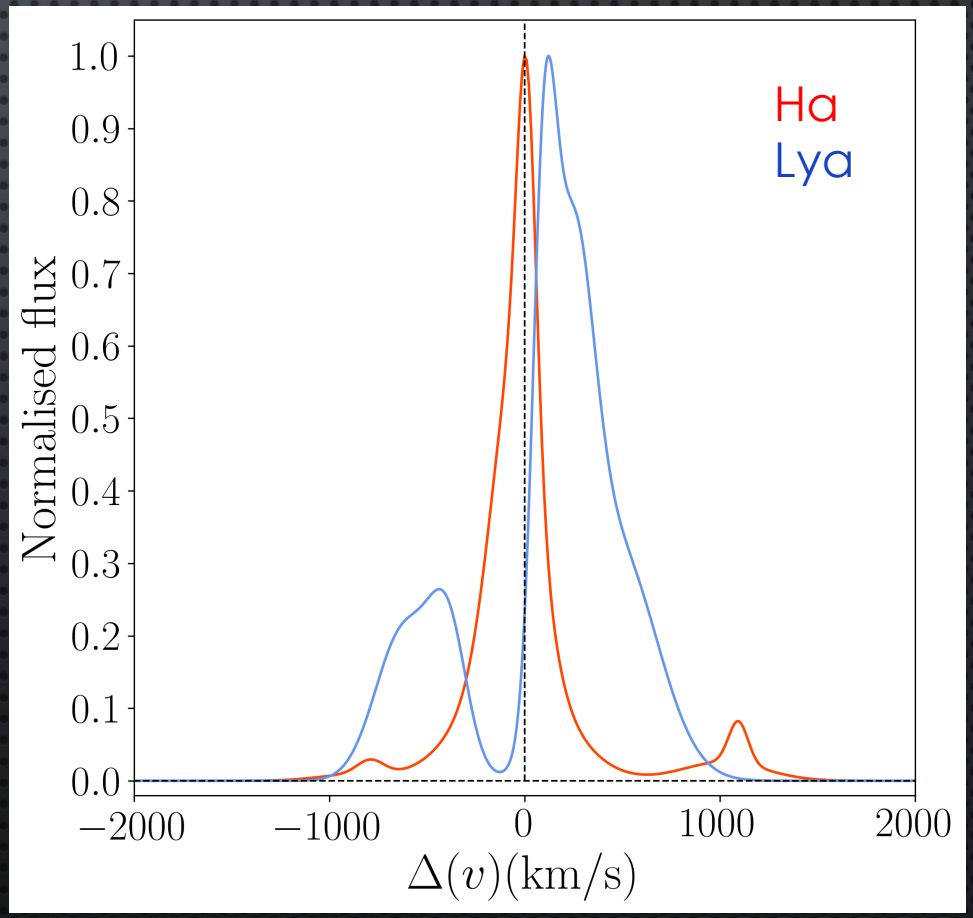
PRELIMINARY

BX418 (z~2.3) log $M_*$~9.4




(Courtesy D. Erb)

GP J1429 (z~0.17) log $M_*$~9.4




Hogarth, Amorín, et al. (in prep)

# 3D VIEW OF STARBURST ACTIVITY IN LOW-MASS GALAXIES

Example from the LARS survey (Hayes, Östlin et al.)

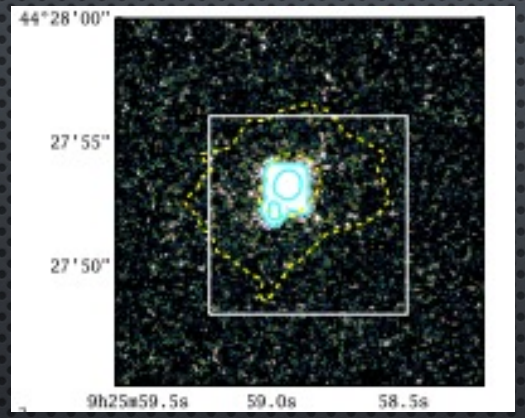
Dispersion dominated starbursts show higher Lya EW and escape fraction

Turbulence in local starbursts appear causally connected to ISM conditions that favor Lya escape

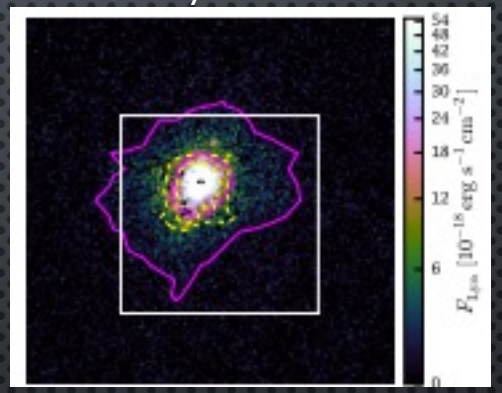
*(Herentz et al. 2015)*



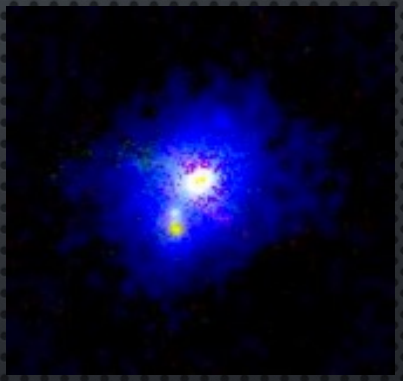
HST Ha

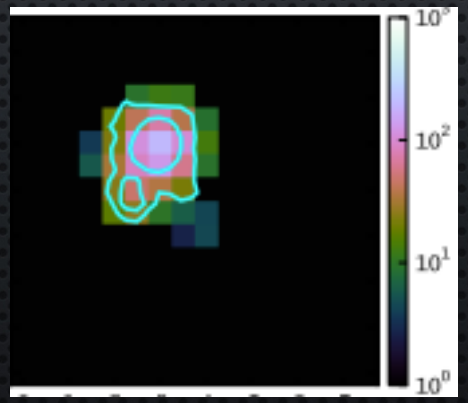



HST Lya

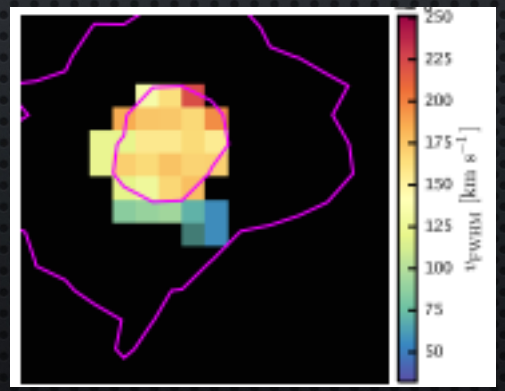


HST Lya+Ha+stars

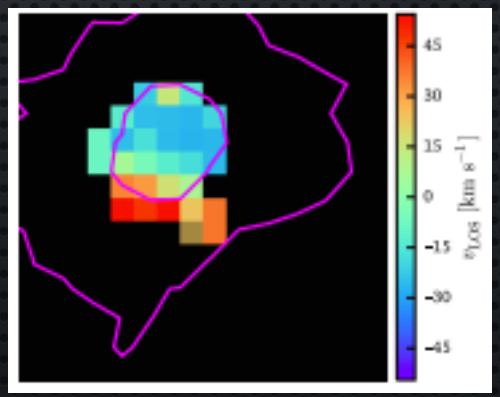




PMAS Ha



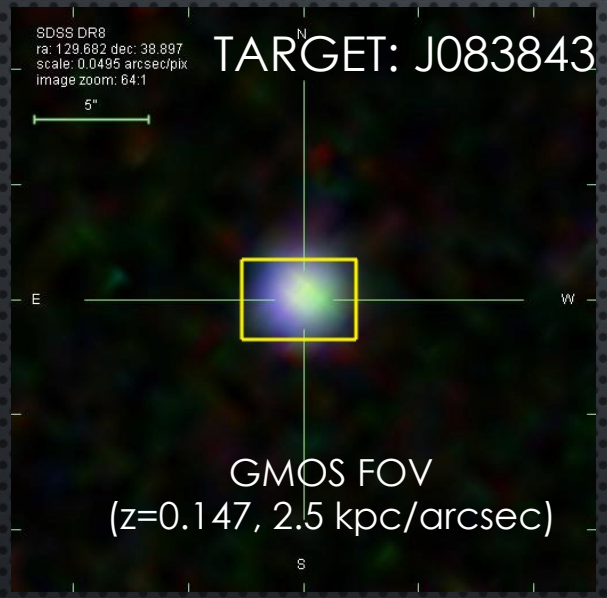
PMAS $V_{FWHM}$

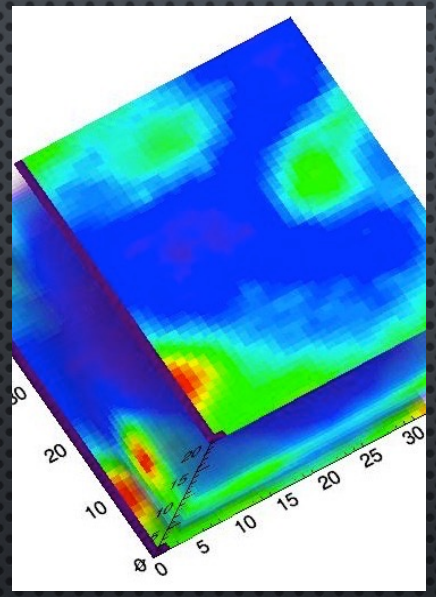


PMAS $V_{LOS}$

# AN IFS PILOT PROGRAM WITH GEMINI/GMOS

PI: G. Hagele



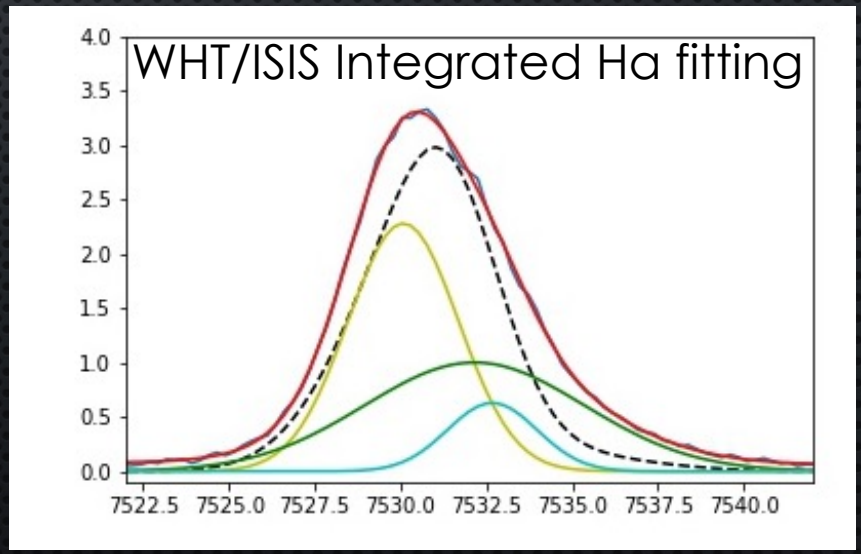



GMOS





Gemini North

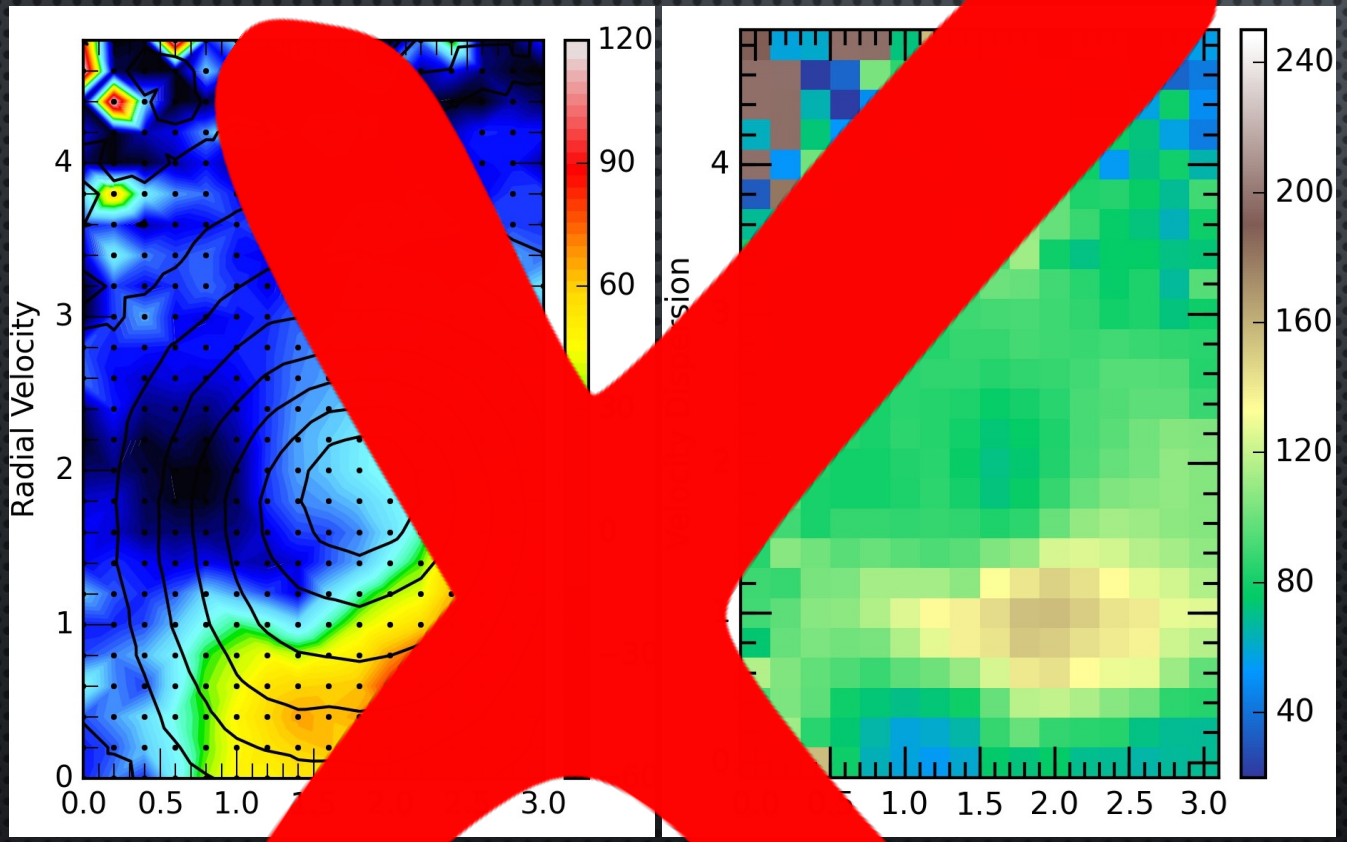



- A bright GP at z~0.147 selected from SDSS-DR7.
- Average properties for GPs: Compact, metallicity 20% solar, high SSFR~10^(-8) 1/yr
- WHT/ISIS reveal multiple kinematic components
- Observations taken with GMOS at Gemini North using R831 (R=4400) in 1-slit mode. From $\lambda_{rest}$=5700-7200Å; $\sigma_{int}$=25 km/s; Texp~3h in excellent weather conditions (average seeing ~0.5'')

# AN IFS PILOT PROGRAM WITH GEMINI/GMOS

Velocity field

Velocity dispersion




**Single Gaussian fitting**

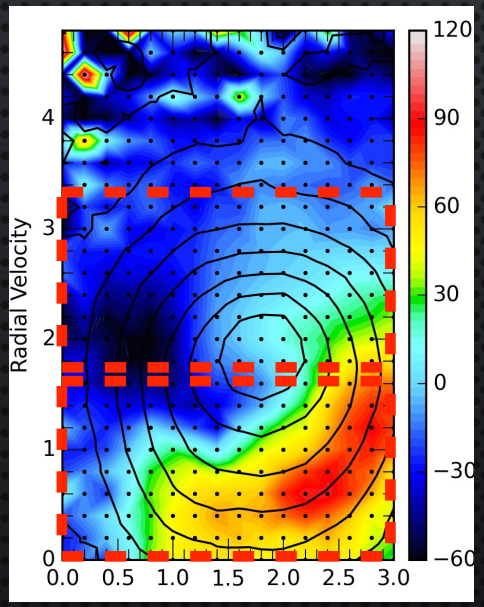
- Produce a sort of rotation velocity field with strong perturbations
- Nearly uniform velocity dispersion map, with a local increase towards the maximum velocity shift w.r.t systemic

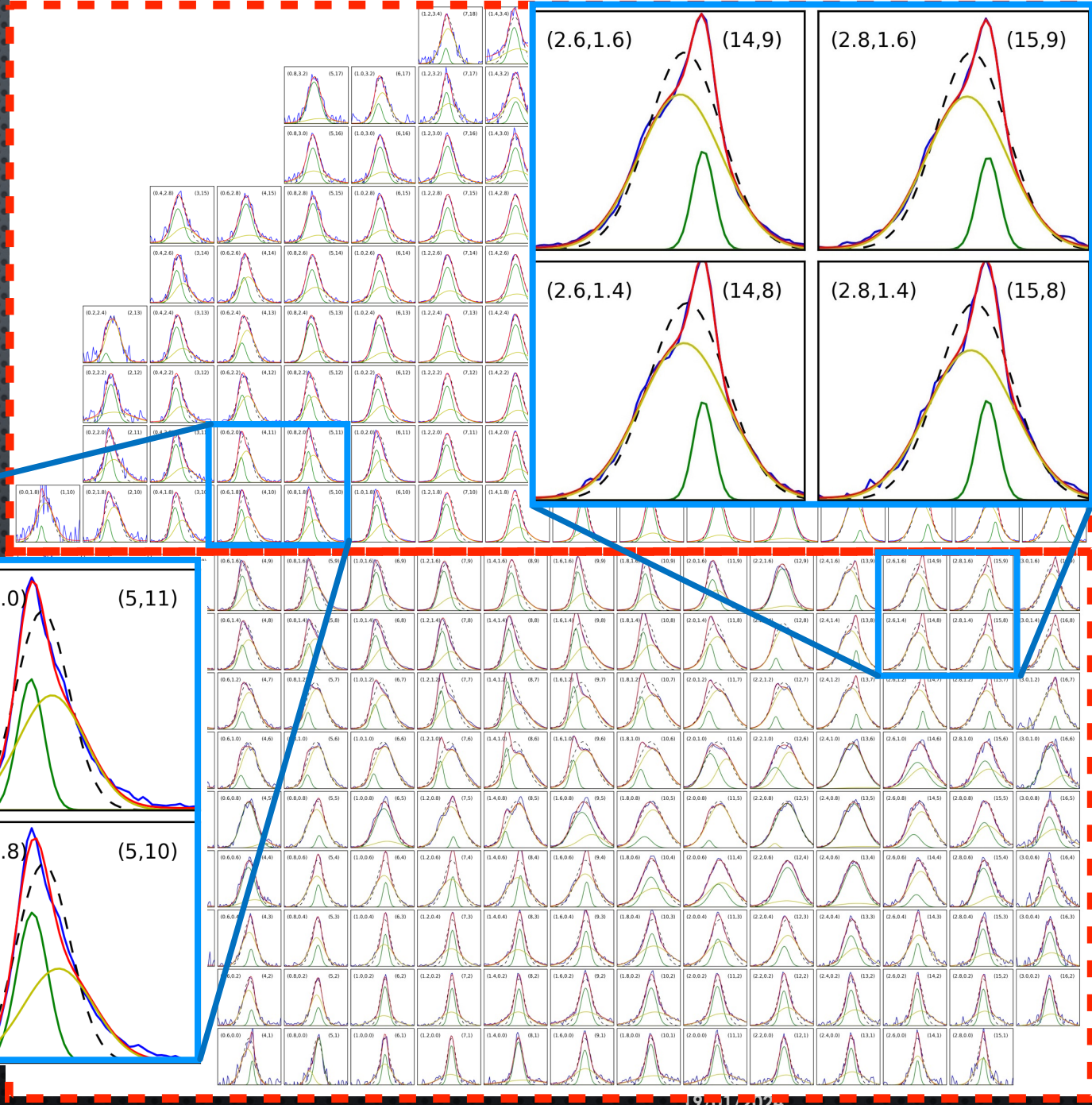
NOT SATISFACTORY

## Multiple kinematic components

- A closer look shows complex line profiles with strong spatial variations
- Need multicomponent analysis spaxel by spixel. How?

Bosch et al. (in prep)



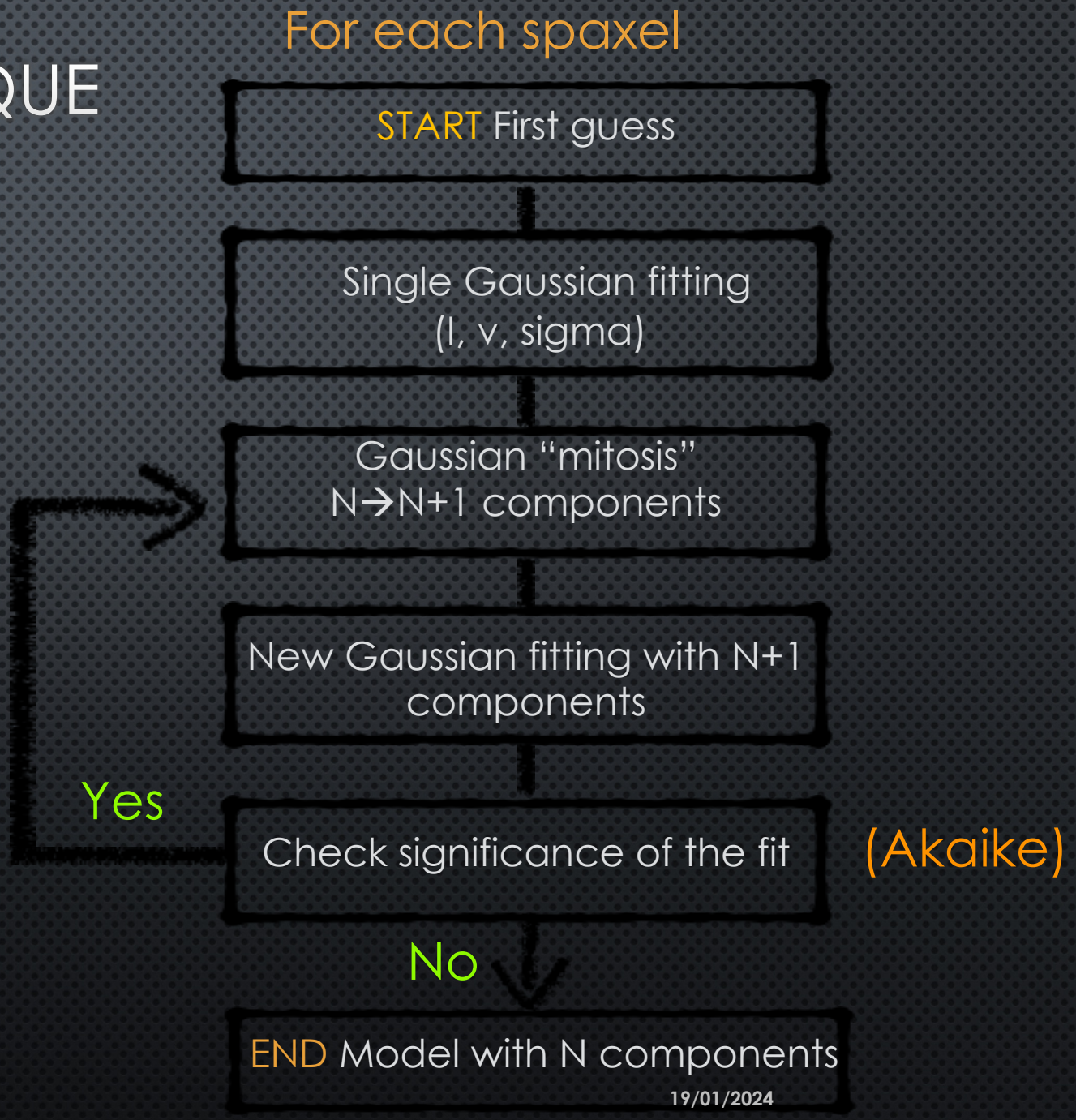



# MULTICOMPONENT TECHNIQUE

**Conditions**
- Chi2 techniques are efficient but highly dependent on initial conditions

**Problem**
- Initial conditions (intensity, velocity and FWHM) of a variable number of components may change strongly across the FOV

**Solution**
- Iterative multicomponent fitting with statistical significance check




Bosch et al. (in prep)

# Complex line profiles:
## Number of components?

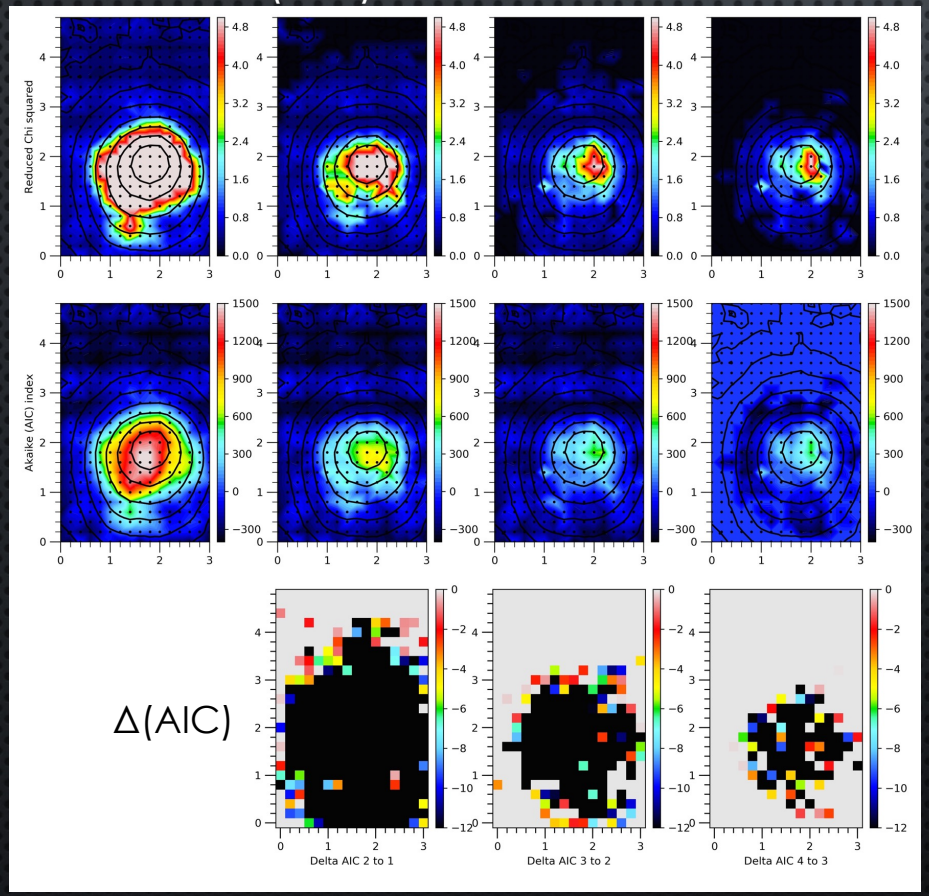
The AKAIKE index (AIC) compares different models for same data penalizing the increase of parameters when no significant change in Chi2 is obtained. Δ(AIC) is then related to the probability of a statistical improvement of the model

Rule of thumb: Δ(AIC)>10

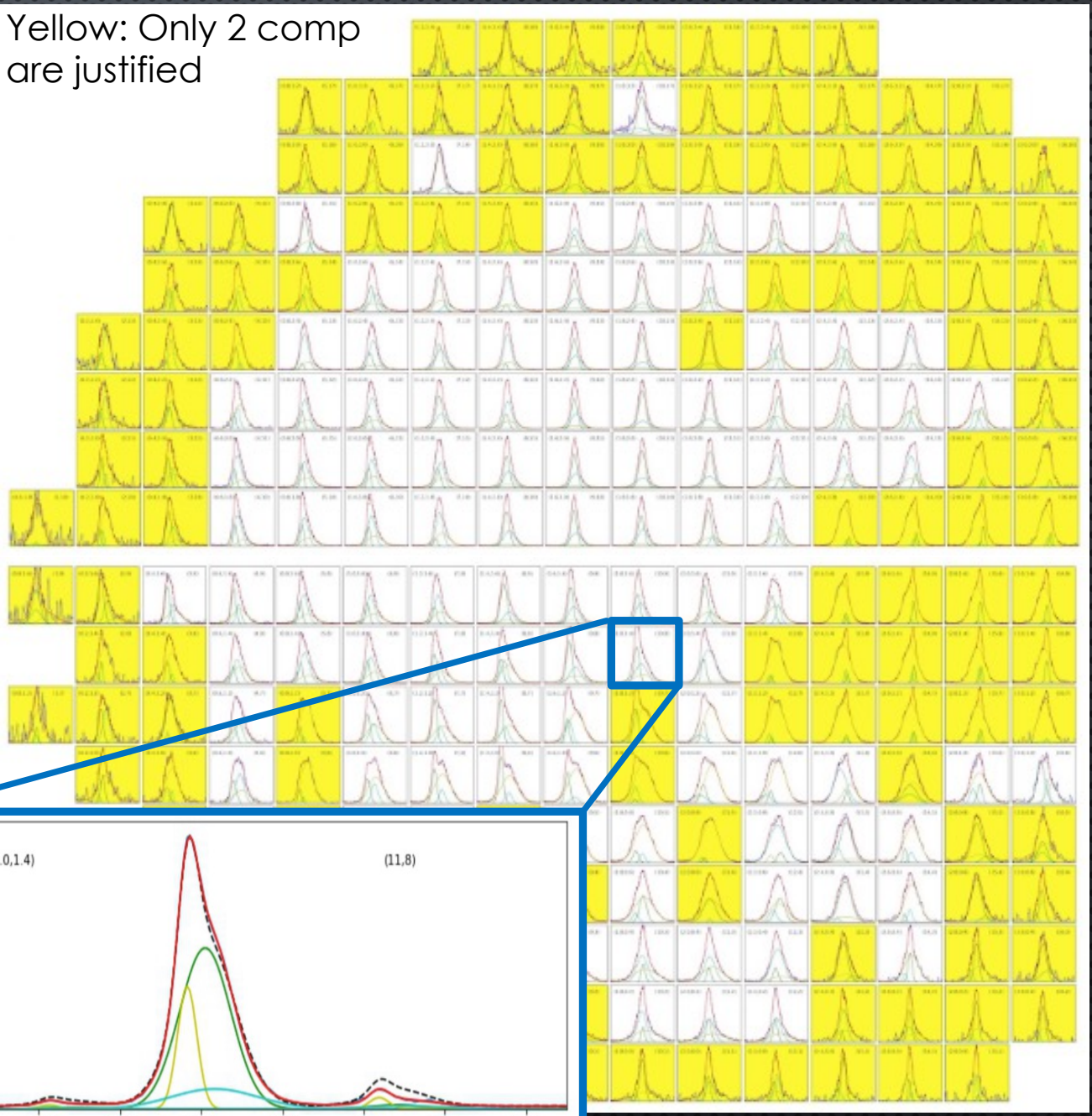
Chi2

AIC

Δ(AIC)




Yellow: Only 2 comp are justified



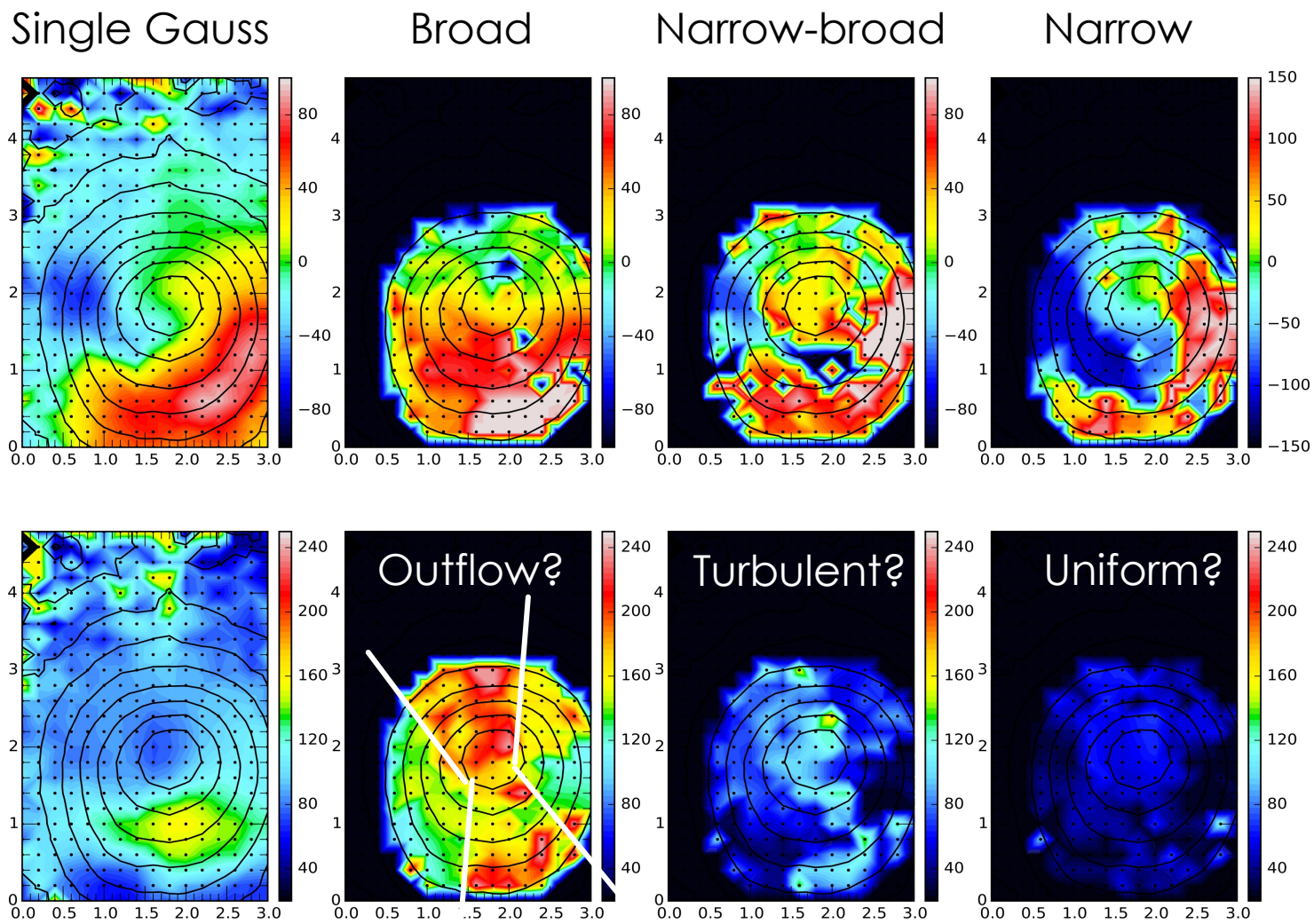
# HALPHA KINEMATICS WITH A 3-COMPONENT MODEL

Relative velocity map

Contours trace the continuum

velocity dispersion map

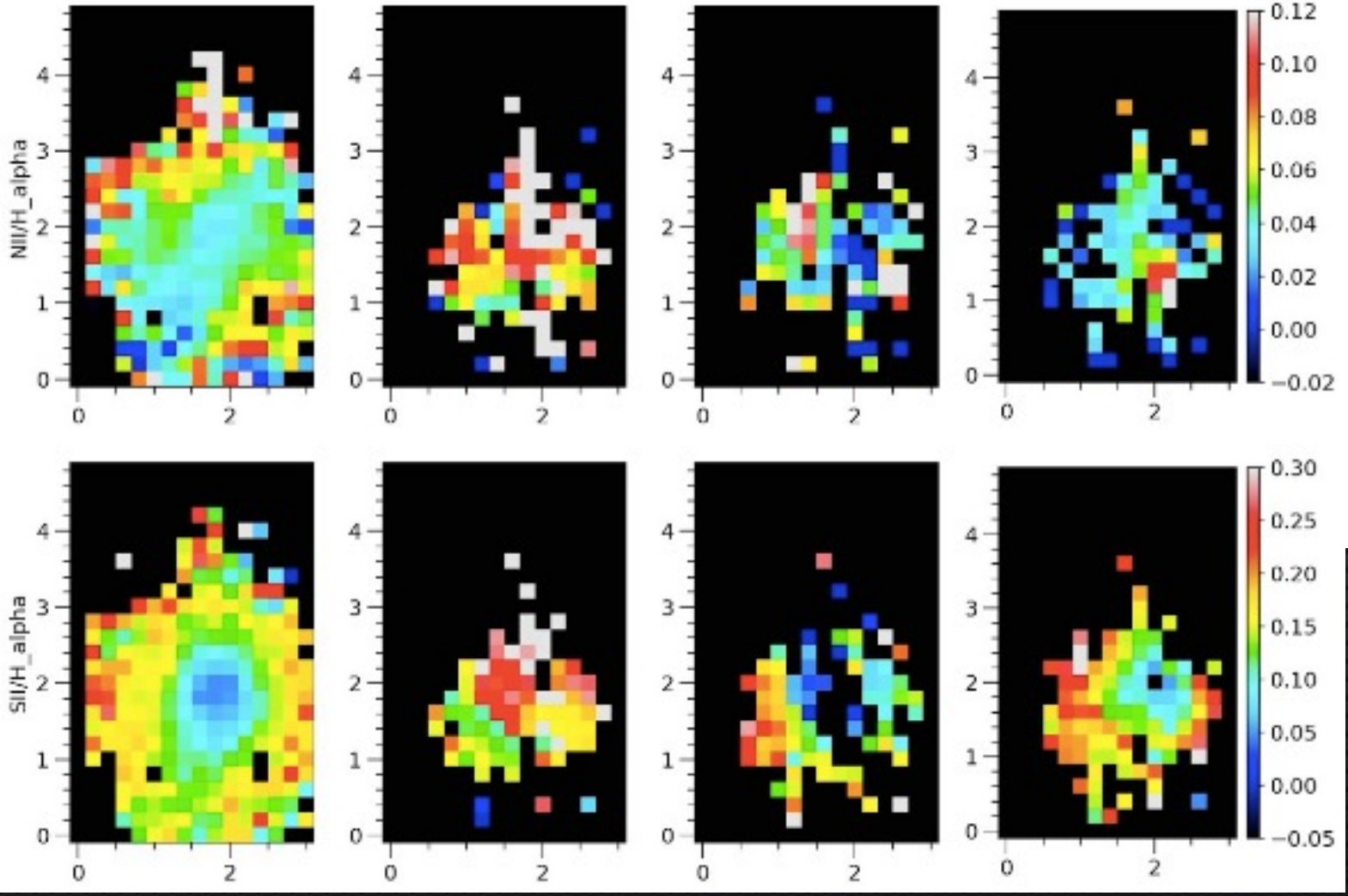
Bosch et al. (in prep)

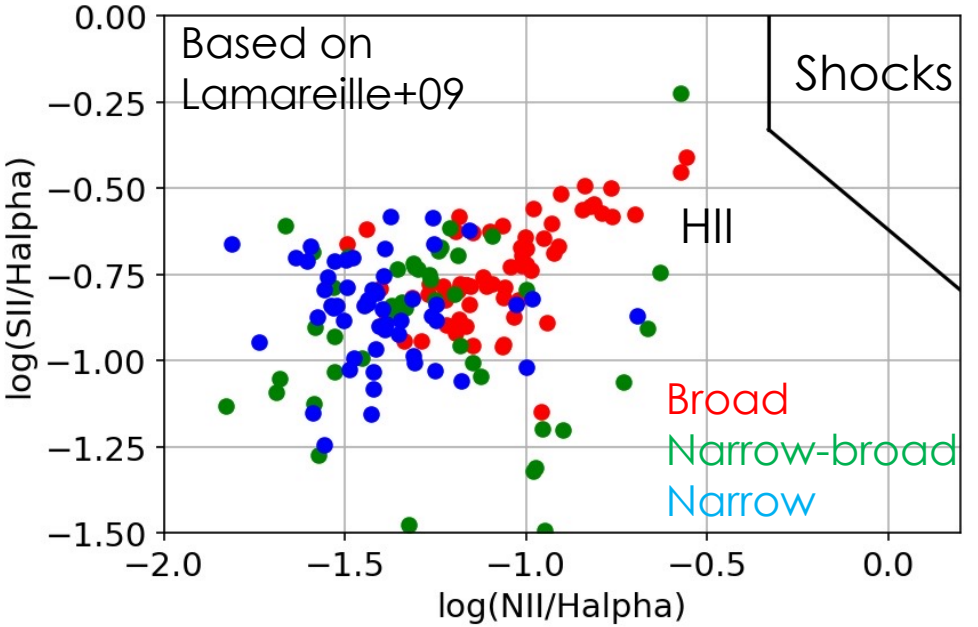


# EMISSION LINE DIAGNOSTICS

PRELIMINARY

Single Gauss | Broad | Narrow-broad | Narrow



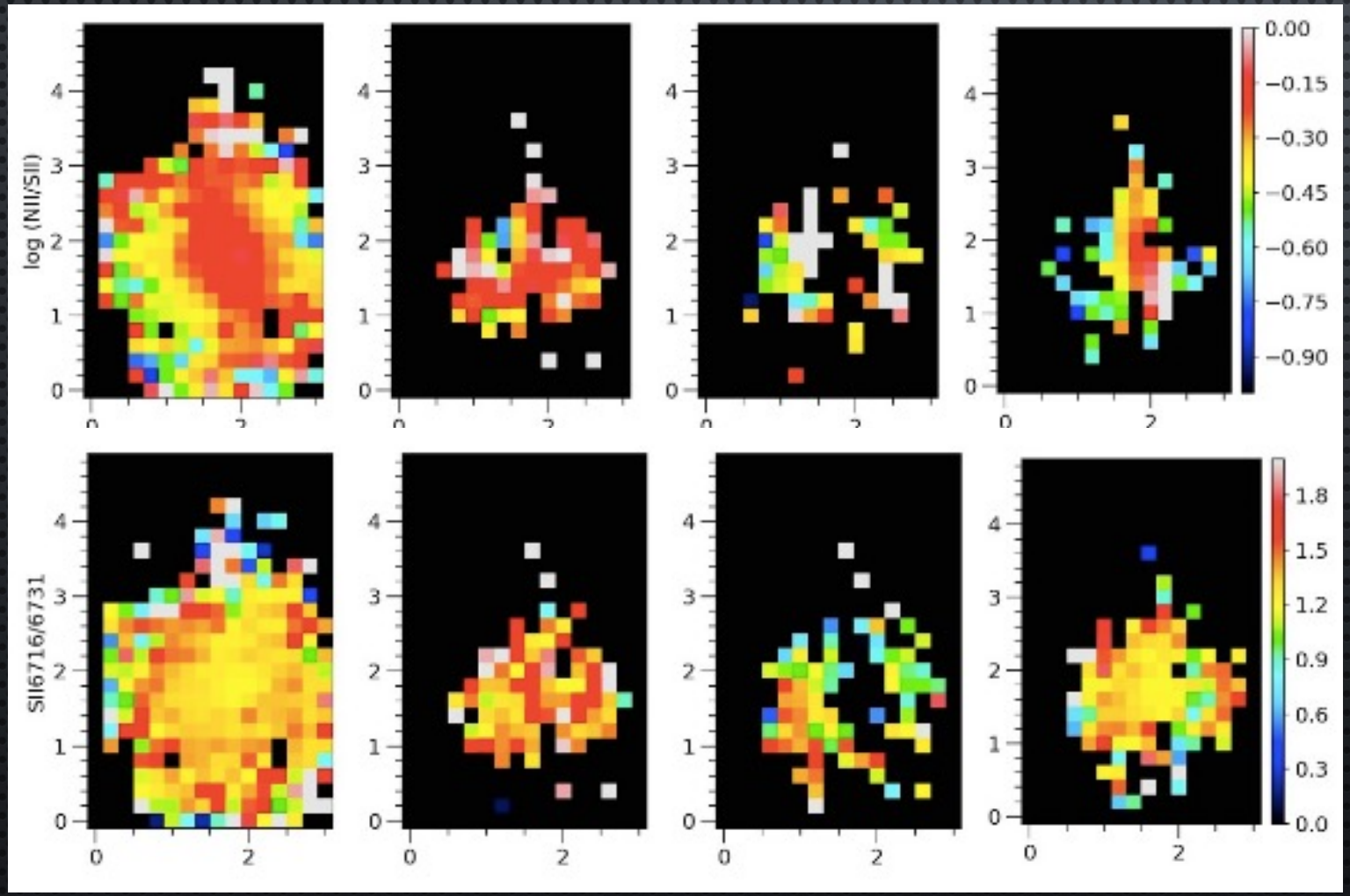

Broad emission tend to show higher S2 and N2. Shocks ?

Structure seen in single Gauss seem dominated by the narrower component

# EMISSION LINE DIAGNOSTICS

PRELIMINARY

Single Gauss | Broad | Narrow-broad | Narrow




Some structure is seen only in single Gaussian model in the direction of the higher vel dispersion spaxels

Broad emission tend to show higher N2S2. Higher N/O ?

No significant effect in Ne(SII) ?

Overall consistent with single slit results

# SUMMARY AND PROSPECTS

Deep high dispersion spectroscopy is a powerful tool for coupling gas kinematics and ISM properties
➡ Impact in galaxy evolution and high redshift studies

In compact starbursts single Gaussian line profile are not accurate enough. Multicomponent analysis required
Deep slit observations are OK for compact/distant objects, but IFS is the ideal tool for more extended targets

Results: We find evidence of high velocity dispersion on top of a rotation-like pattern

- Consistent with "hot/thick" disks with multiple "turbulent" massive young clumps of SF
- Evidence of spatially-resolved outflows
- Mild change in line ratios with broad component the most distinctive
- These ISM conditions together with a hard radiation field may favor the escape of ionizing photons

Our large representative sample of ~30 GPs with WHT/ISIS data will provide a more general picture
Two galaxies are confirmed LyC leakers and most of them are LAEs
Four galaxies with spectra in the entire optical range allows a thorough chemodynamic analysis

An extended GMOS proposal for a larger number of bright GPs is planned

STAY TUNED !!

VLT/X-Shooter and GTC/MEGARA are ideal instruments to extend this project to higher redshift
Two submitted proposals for confirmed LyC leakers (col. With D. Schaerer)

# THANK YOU FOR YOUR ATTENTION !!

# INTRODUCTION

**MOTIVATIONS**

The formation and evolution of dwarfs through cosmic times is still not fully understood

- How do low-mass galaxies assemble their stellar mass ?
- How massive star formation triggers and propagates in metal-poor environments ?
- How feedback and chemical evolution proceeds in these galaxies ?

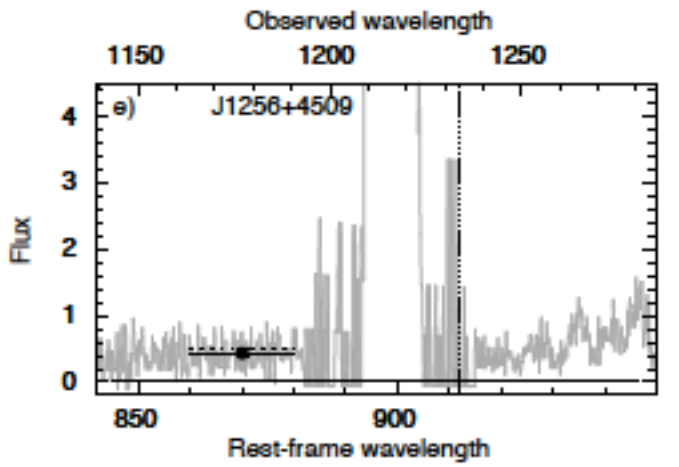
**OBSERVATIONAL CONSTRAINTS:**

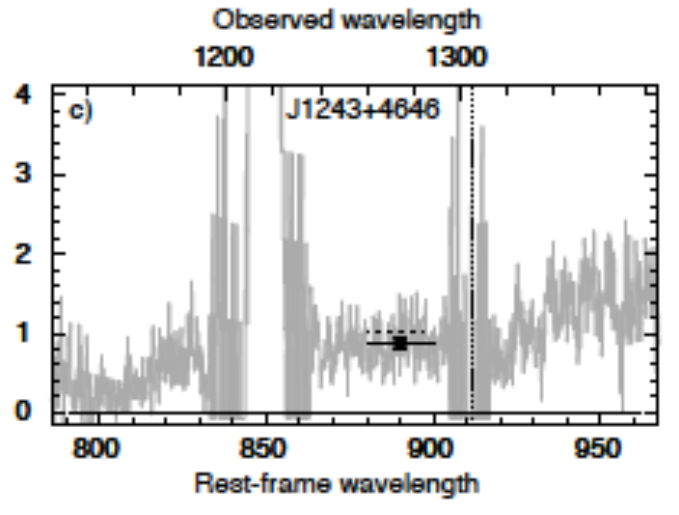
- SFH, SFE: Emission lines + stellar populations
- Gas-phase and stellar metallicity, relative chemical abundances (e.g. N/O, C/O, Fe/O…)
- Kinematics (e.g. outflows, turbulence)
- Morphology
- Environment

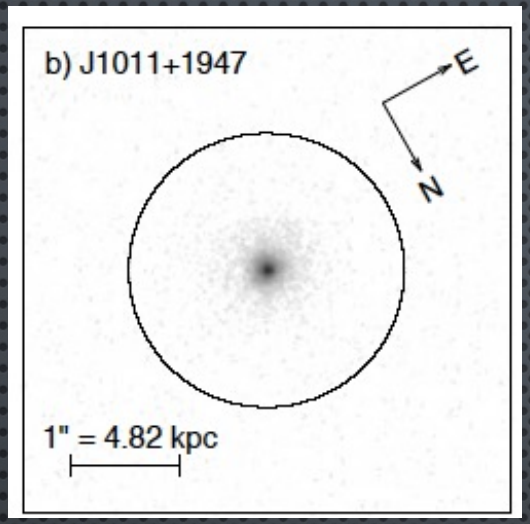
**KEY OBSERVATIONS**

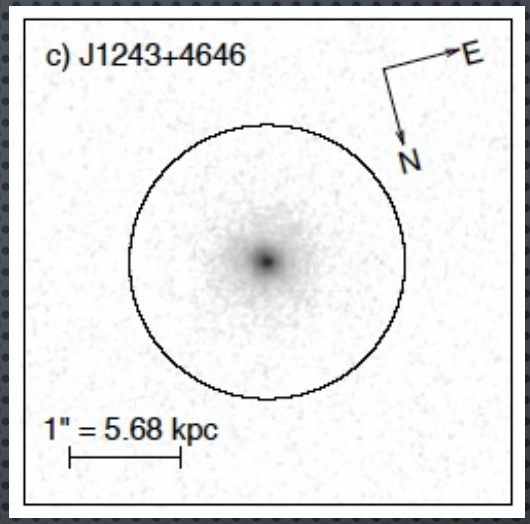
- Deep spectroscopy + imaging
- large statistical samples + detailed individual cases
- MOS and IFU spectroscopy
- Multiwavelength

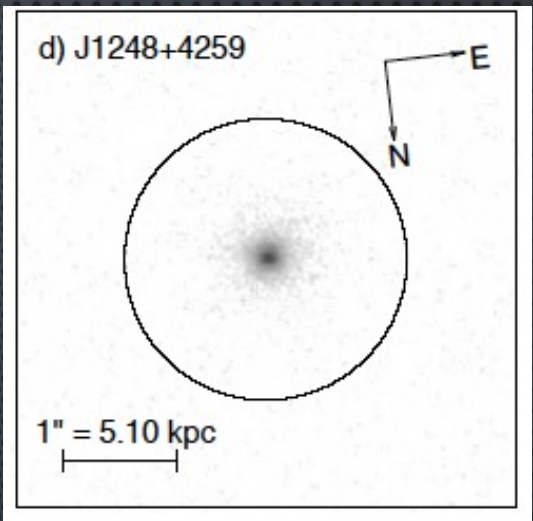
# Leakage of LyC photons <912A



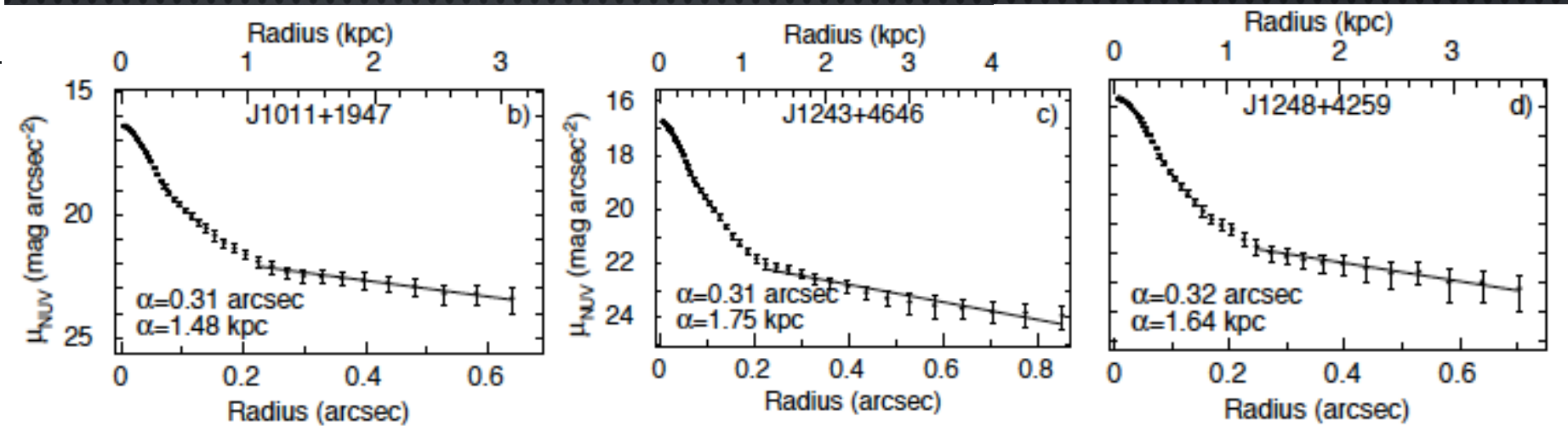




Leakers have compact disks in FUV ? Or due to Lya halo?




Izotov+18