Lyman alpha imaging of starbursts in the local universe

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Why do Lyman alpha imaging? Background

YES

- Lyman alpha in theory strongest recombination line, up to one third of inosining photons may be reprocessed to Lya
- Young galaxies should hence be bright in Lyα
- Lyman alpha can be observed from ground for $z > 2$
- Hence a potentially powerful tool to study galaxy formation

BUT

- Early studies with IUE of local galaxies showed Lyα to be unexpectedly weak – Why?
- Lyα/Hβ values incompatible with observed reddening
- Early blind high-z surveys did not, until late 90'ies, yield much
- Lyα is a resonant line and resonant scattering would make line radiative transfer sensitive to even small amounts of dust

Why do Lyman alpha imaging? Background…

PROGRESS

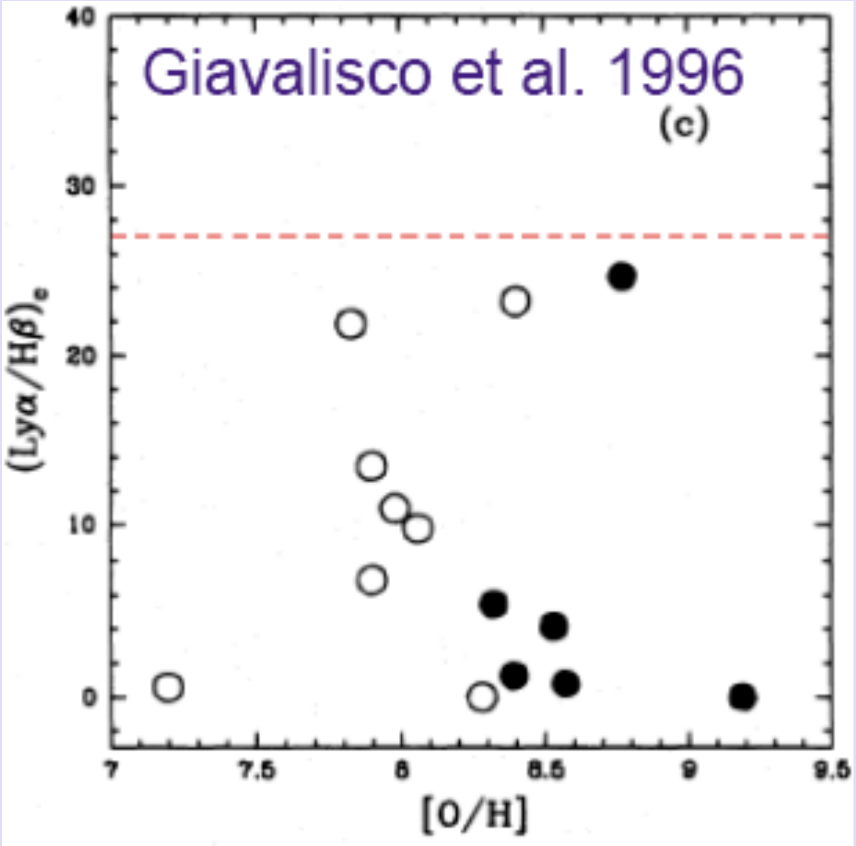
- High resolution spectroscopic studies with HST/GHRS revealed importance of ISM kinematics (Kunth et al 1994, Lequeux et al. 1995, Mas-Hesse et al. 2003):
  - P-Cyg profiles
  - Neutral ISM absorption lines

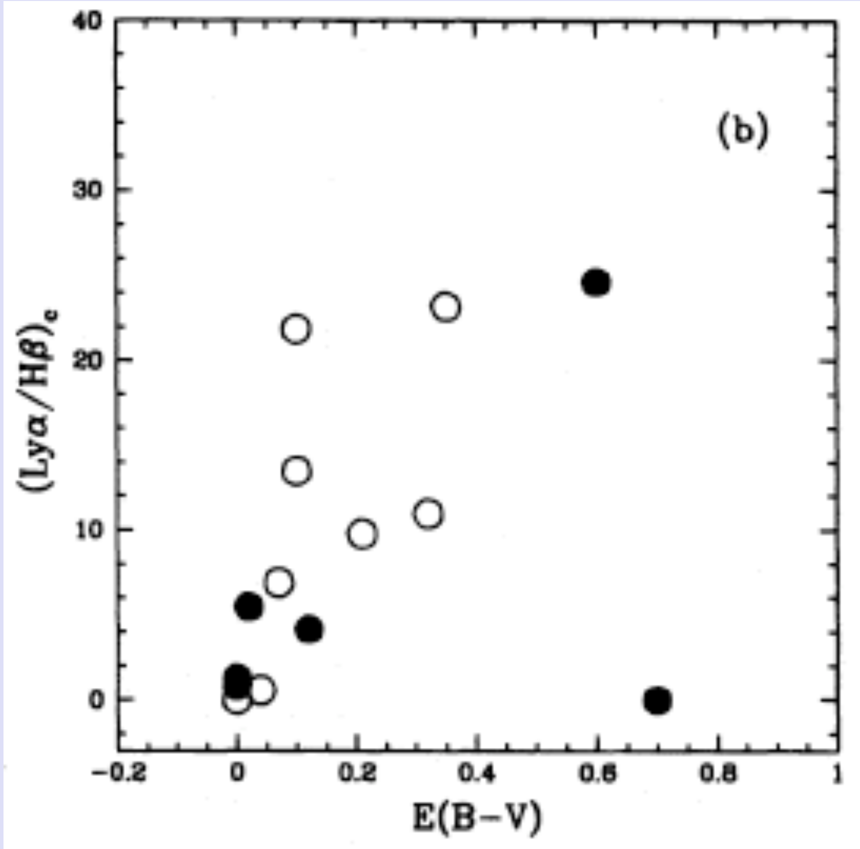
- High-z surveys targeting fainter levels and larger fields have during the last decade been very successful

See review talk by Miguel Mas-Hesse…

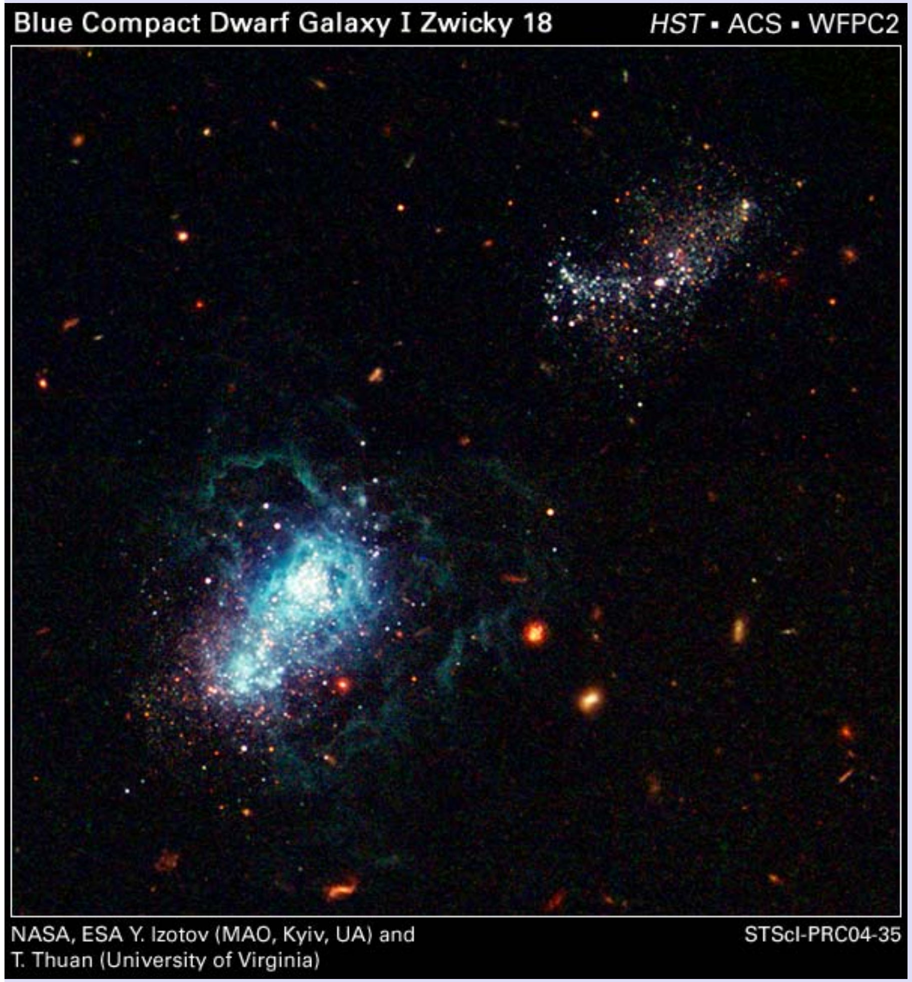
Why do Lyman alpha imaging? Examples

Local star forming galaxies (IUE):
Lyα is weak and cannot be corrected for extinction



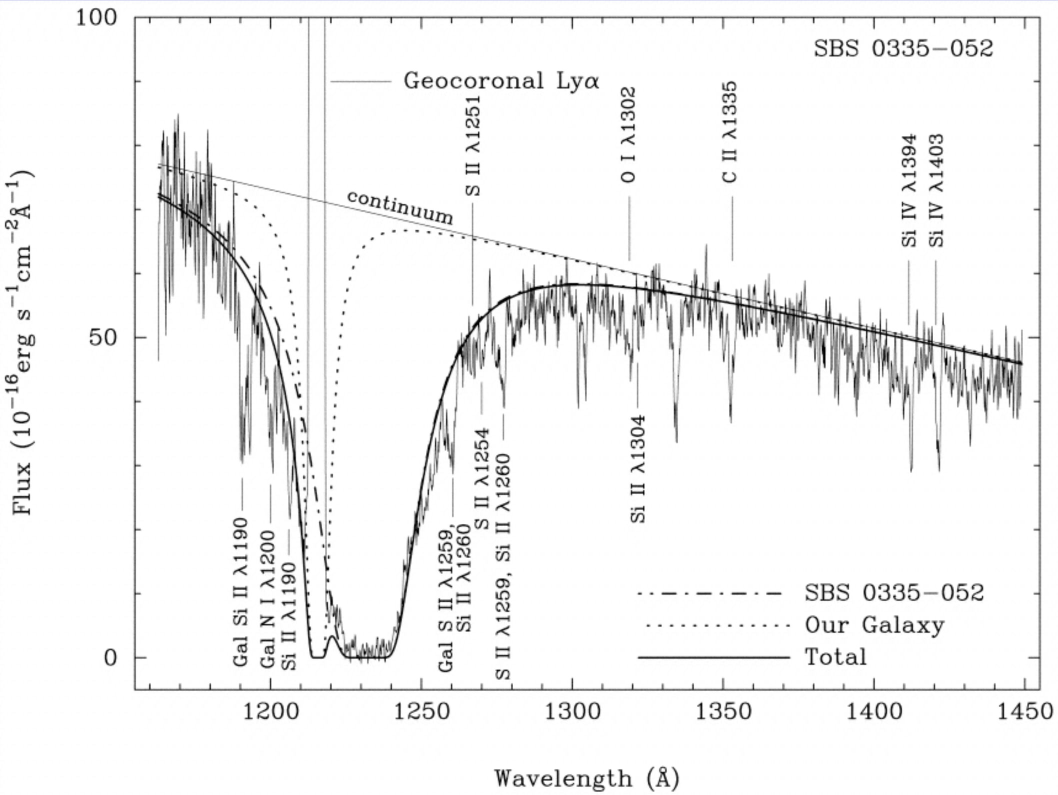


Why do Lyman alpha imaging? Examples…



IZw18, the galaxy with the most Metal-poor and dust-poor ISM Known is a damped absorber !

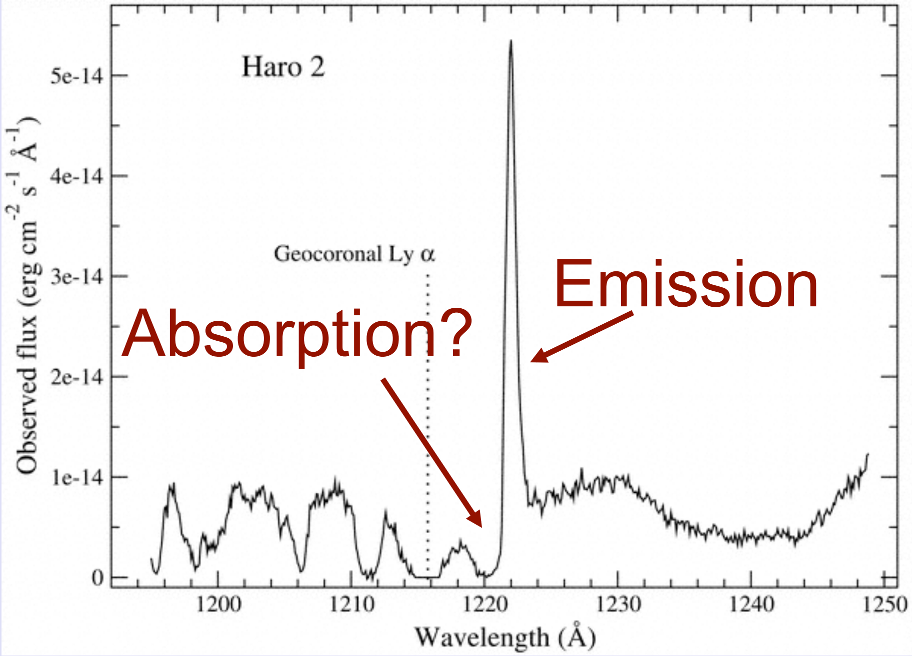
Also SBS0335-052 (below)

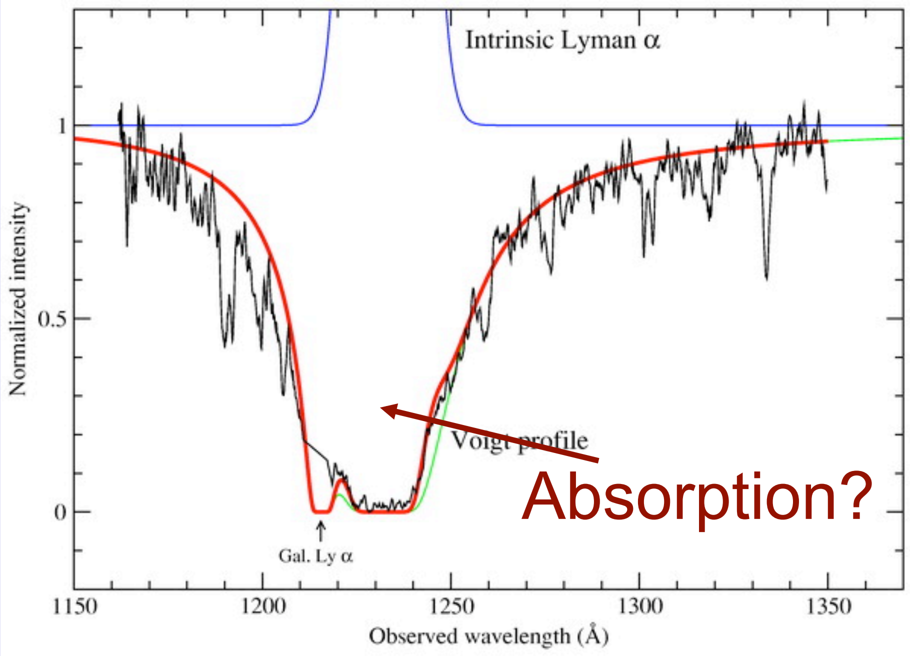


Can the Lyα photons scatter out of the spectroscopic aperture?

Why do Lyman alpha imaging? Examples...

After production (in HII region)





Haro 2 (STIS)

SBS 0335-052 (STIS)

Mas-Hesse et al. 2003

Resonance scattering

➠ emission & absorption need not be local!

Why do Lyman alpha imaging? Examples...

A (dusty) multiphase medium can in fact also enhance Lyα (Neufeld 1991)

Where do Lyα come out?

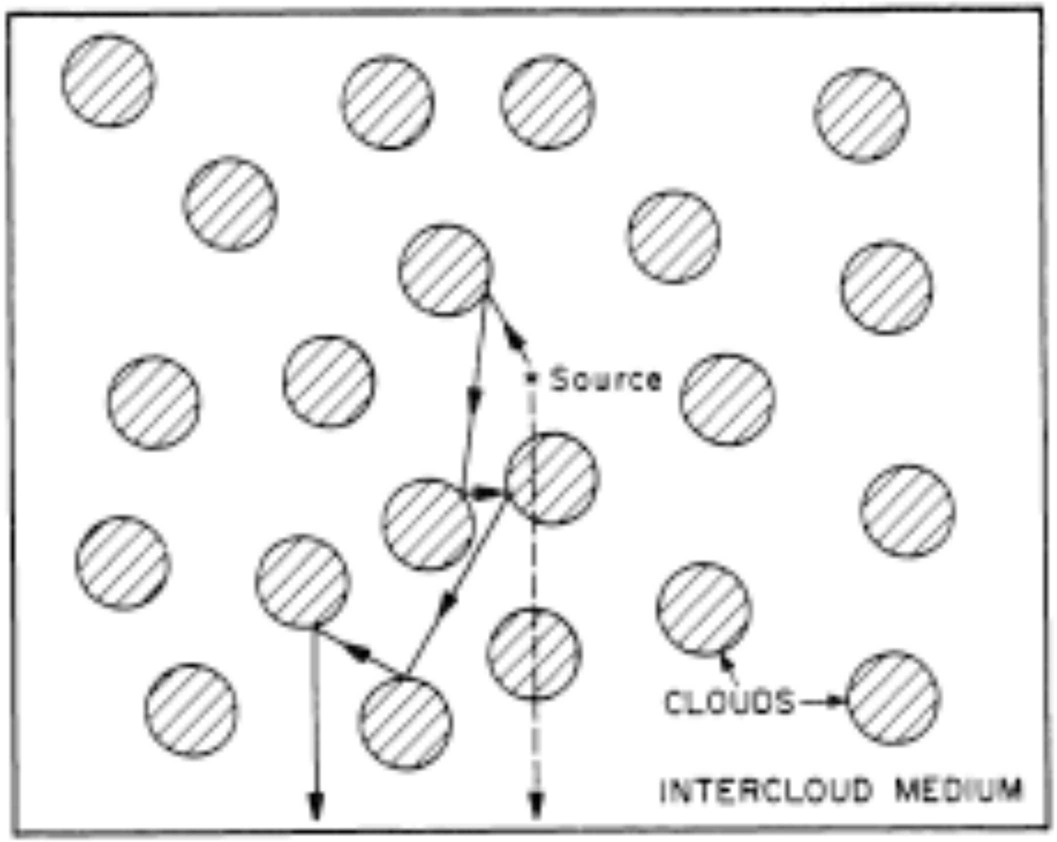


FIG. 1.—Escape of radiation from a two-phase medium. *Solid line*: typical path of a Lyα photon; *dashed line*: path of an unscattered photon.

Can boost EW
Similar case: edge on starburst
Think M82

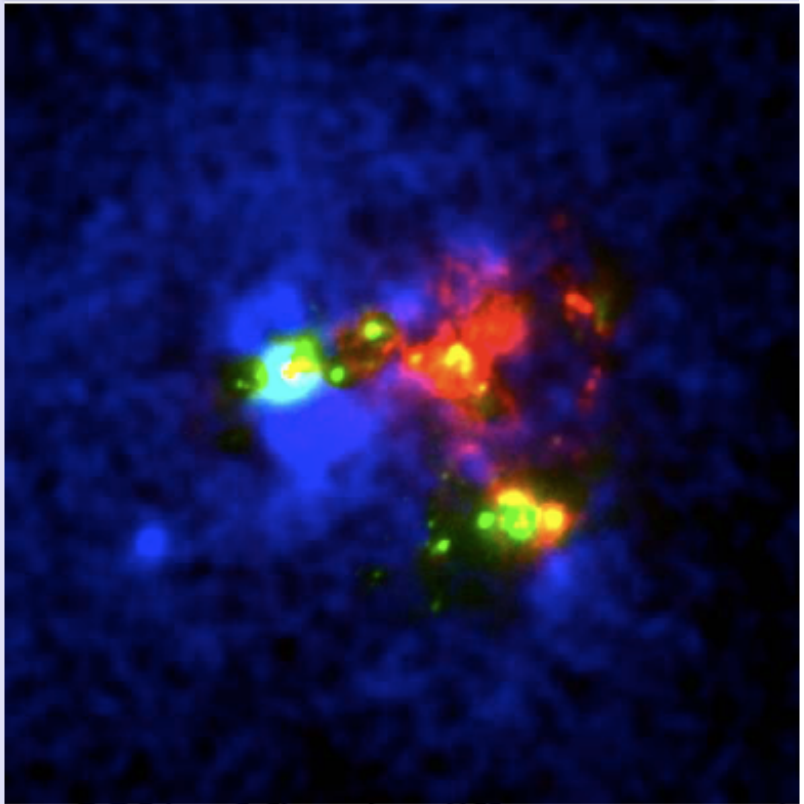
Why do Lyman alpha imaging?

Imaging of Lyα in the local universe can be done with HST ACS/SBC (narrowband Lyα and long pass filters) and STIS

While Imaging cannot reveal ISM effects, it allows to:

- Study the spatial distribution of Lyα
- Indentify large scale diffuse Lyα emission from resonant scattering
- Study Lyα as a vs local conditions:
  - Ionising stellar population age
  - UV luminosity
  - Dust
  - etc

Haro11: Lyα, Hα, UV, 8x8 kpc



• 90% of flux in diffuse compnt.

Lyα Regulation and observation

Physical properties
- Dust
- HI (distribution & kinematics)
  - Vary on small (<< kpc) scales
  - Coupled to the star-formation process
- viewing geometry

How do the Lya photons that do escape escape?

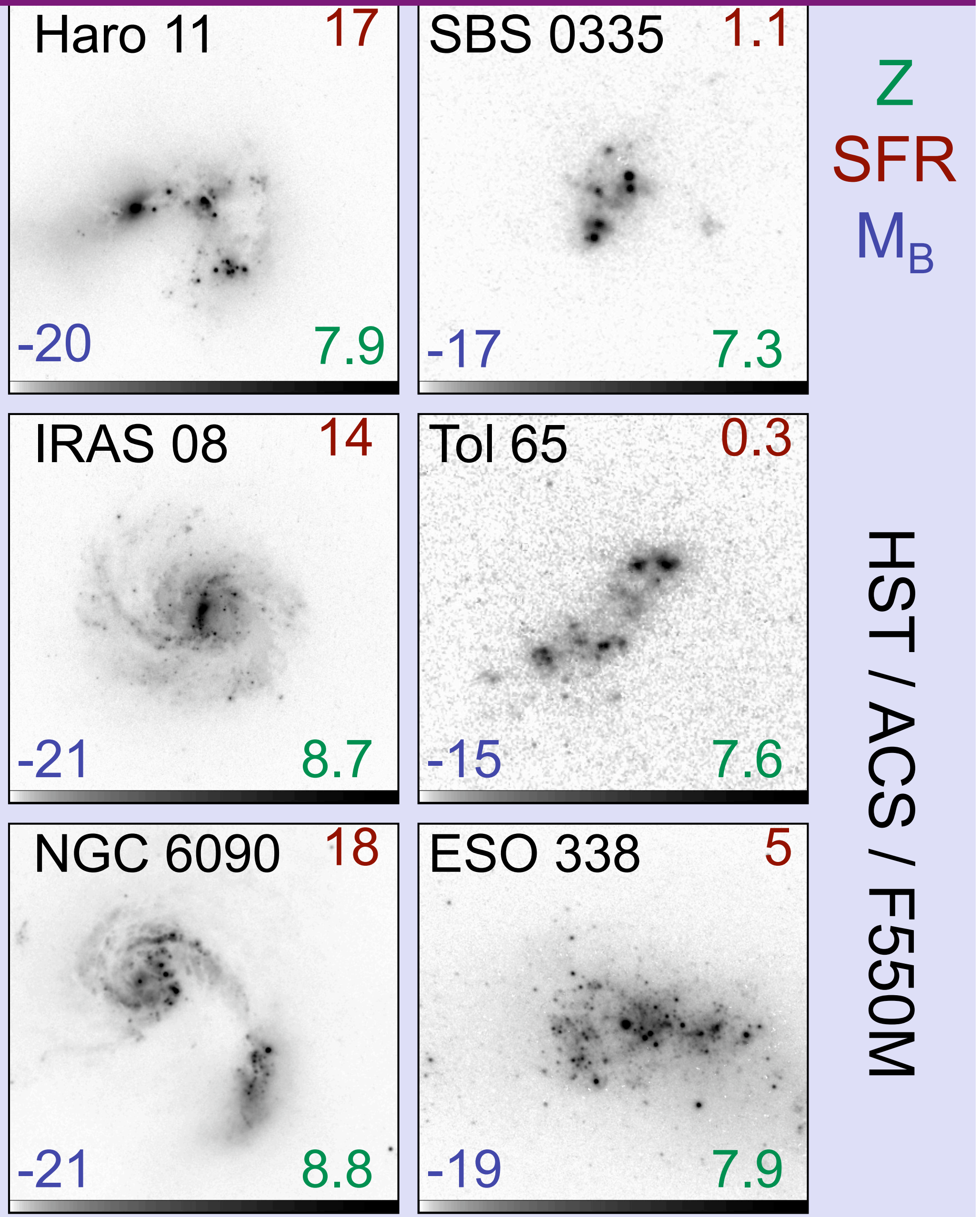
Observations
- High-z img. global flux & EW
  spec. global line profiles + F & EW
- Low-z spec. IUE ~global line profile
  HST localised studies

No HI rec. lines

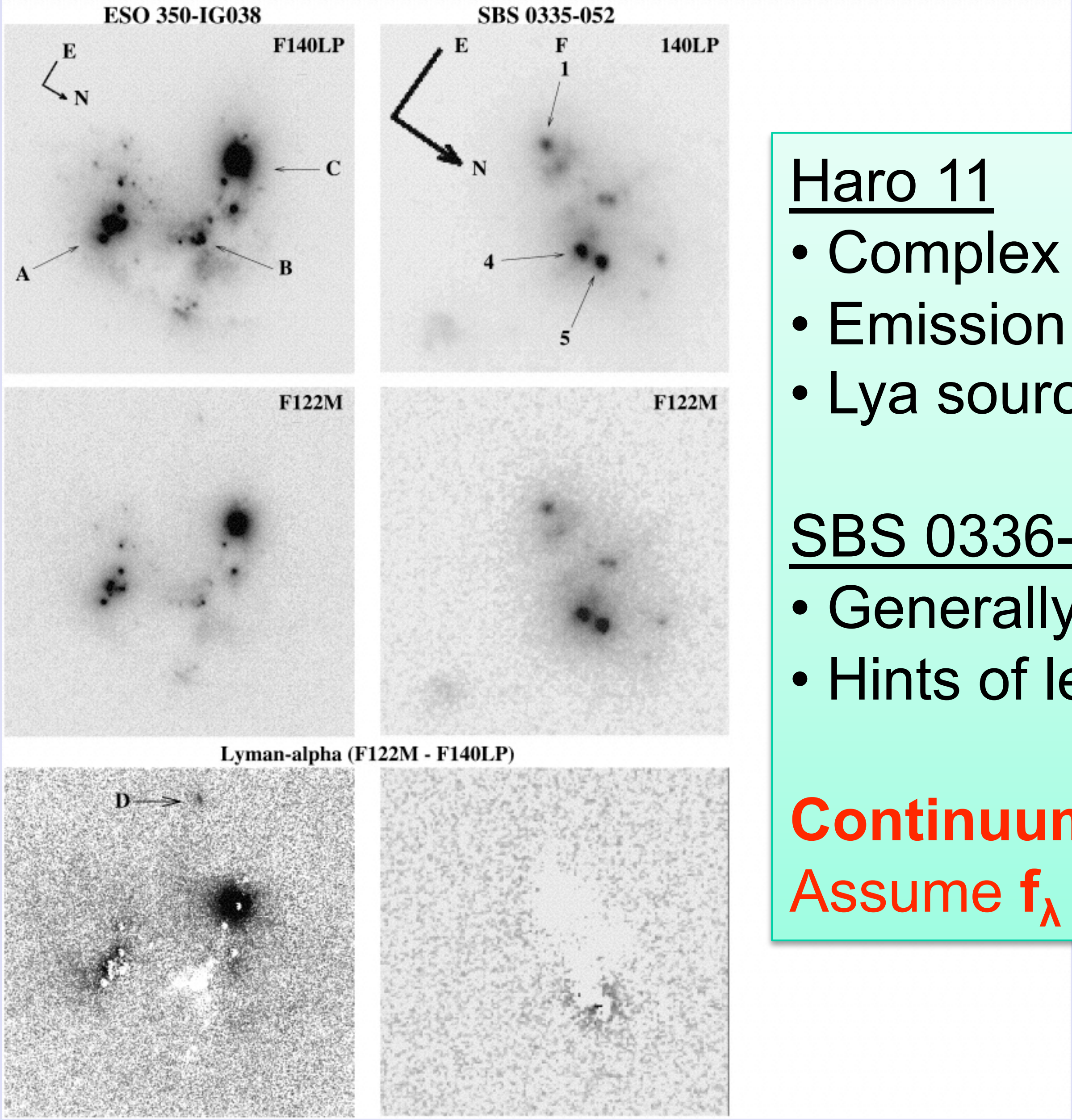
HI Rec. lines

HST/ACS Lyα Imaging - a pilot study

- 6 galaxies
- 40 orbits 30 with ACS/SBC
  10 with HRC & WFC
- 0.03” sampling
- Span a range of
  - morphology
  - metallicity
  - dust
  - Luminosity
- Emitters AND absorbers
- Emitters with range of Lyα profiles (evolutionary stages)



Preliminary results (Kunth et al 2003)



<u>Haro 11</u>

- Complex emission + absorption
- Emission from dusty regions
- Lya source with no continuum

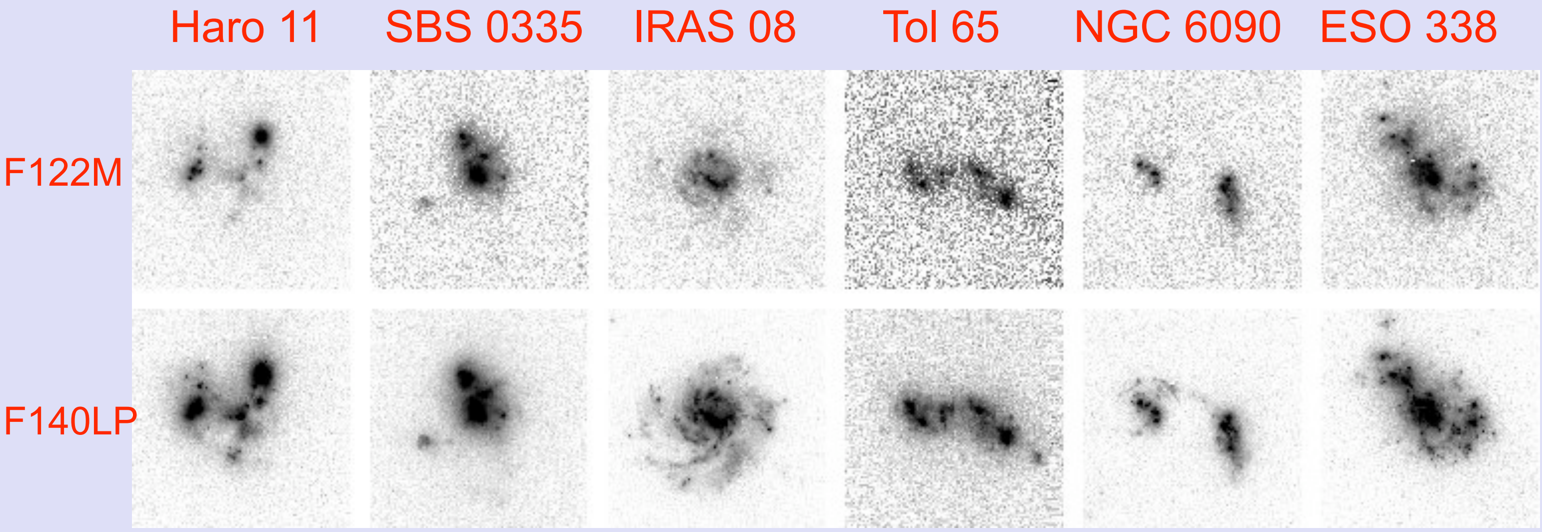
<u>SBS 0336-052</u>

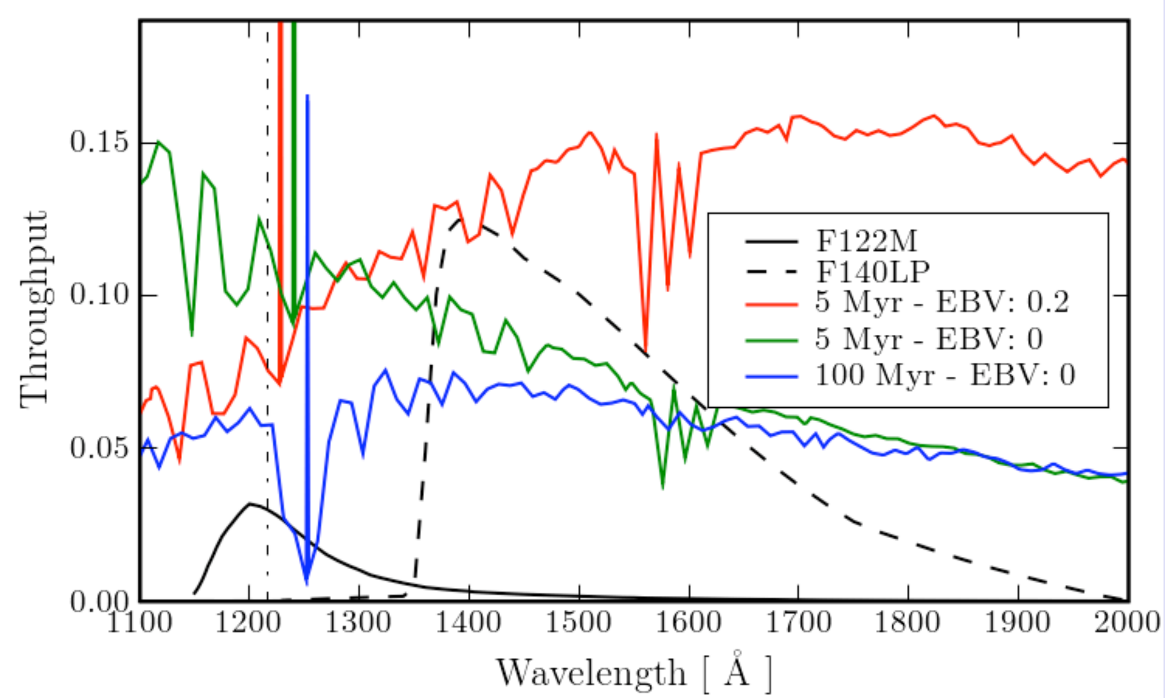
- Generally damped absorption
- Hints of leakage from N edge

Continuum subtraction issues

Assume $\mathbf{f_\lambda}$ proportional to $\boldsymbol{\lambda^\beta}$

SBC observations: F122M and F140LP - the cursed

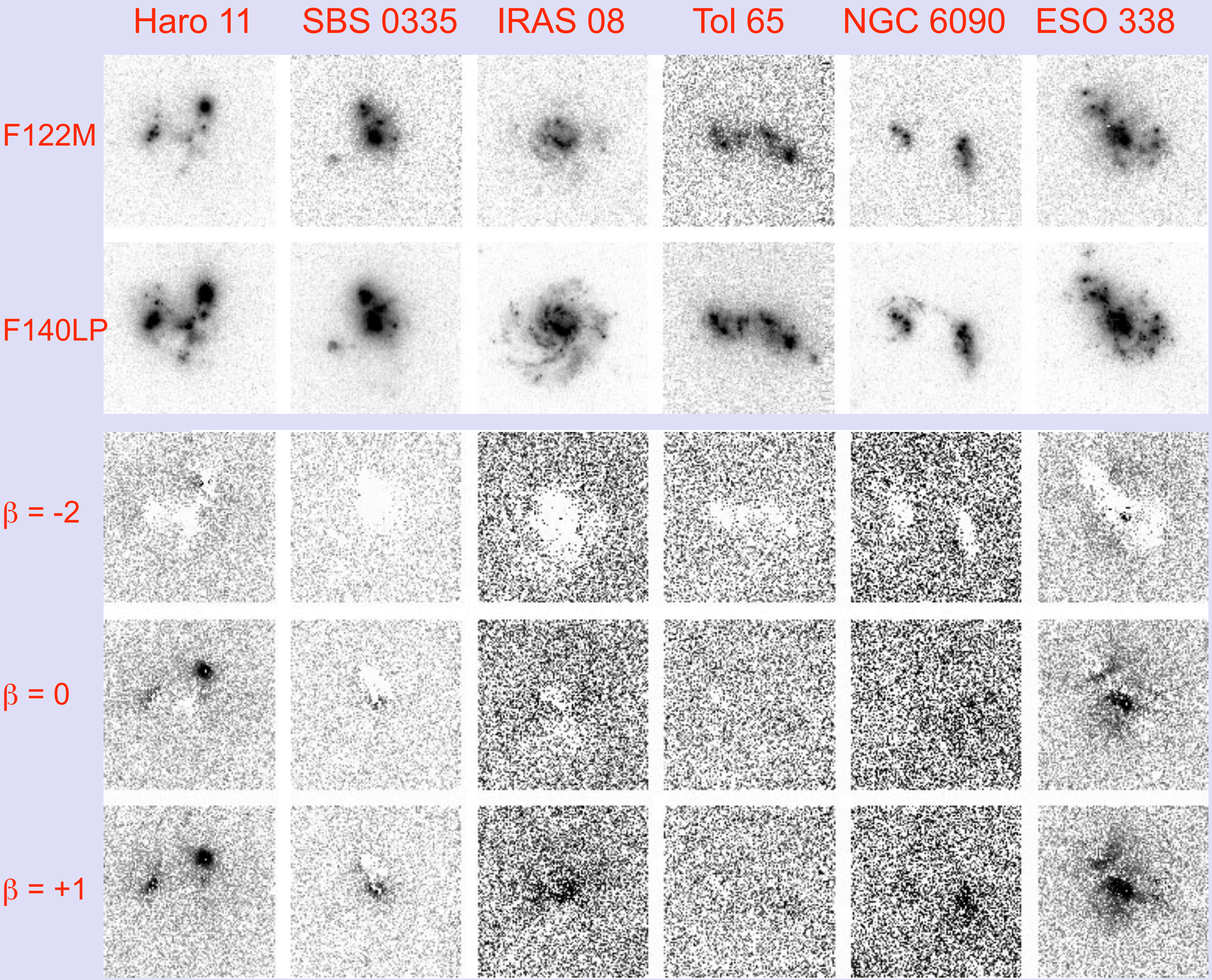




Continuum subtraction difficult since 1500Å flux do not uniquely predict continuum at Lyman alpha.

Moreover, Milky Way HI absorption falls in F122M bandpass

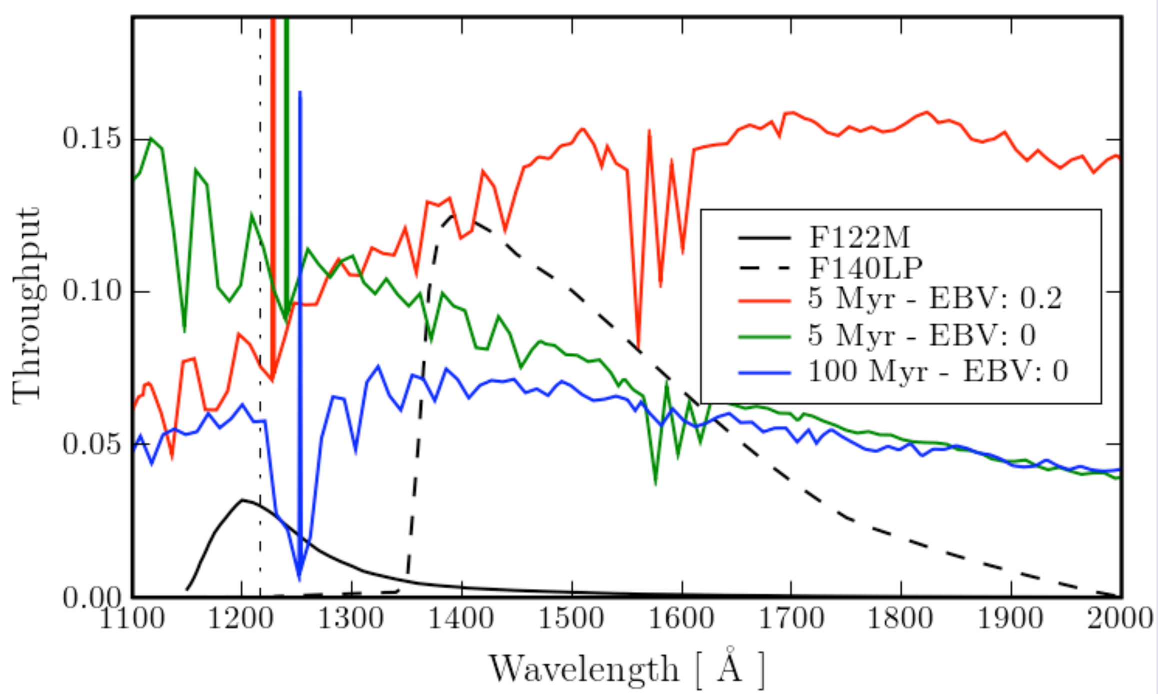
SBC observations: F122M and F140LP - the cursed



Catastrophic result when assuming simple power-law in the UV ←

Continuum subtraction - the issue

Strong continuum evolution
between F140LP and F122M



Galactic E(B-V)

Galactic HI

Stellar age

E(B-V)

★ Lya absorption

CTN -- Continuum throughput normalisaton

factor that scales F140LP to F122M

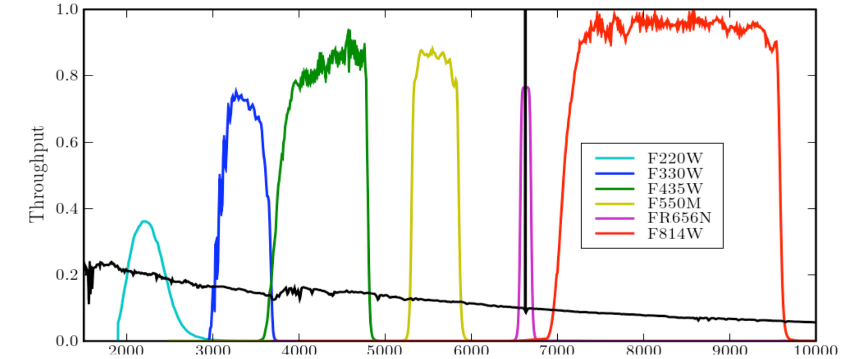
Look up

Figure out

Continuum subtraction – the solution

Additional observations:

- ACS Broadband 2000 Å to 8000Å (avoiding strongest emission lines)
- Narrowband Ha

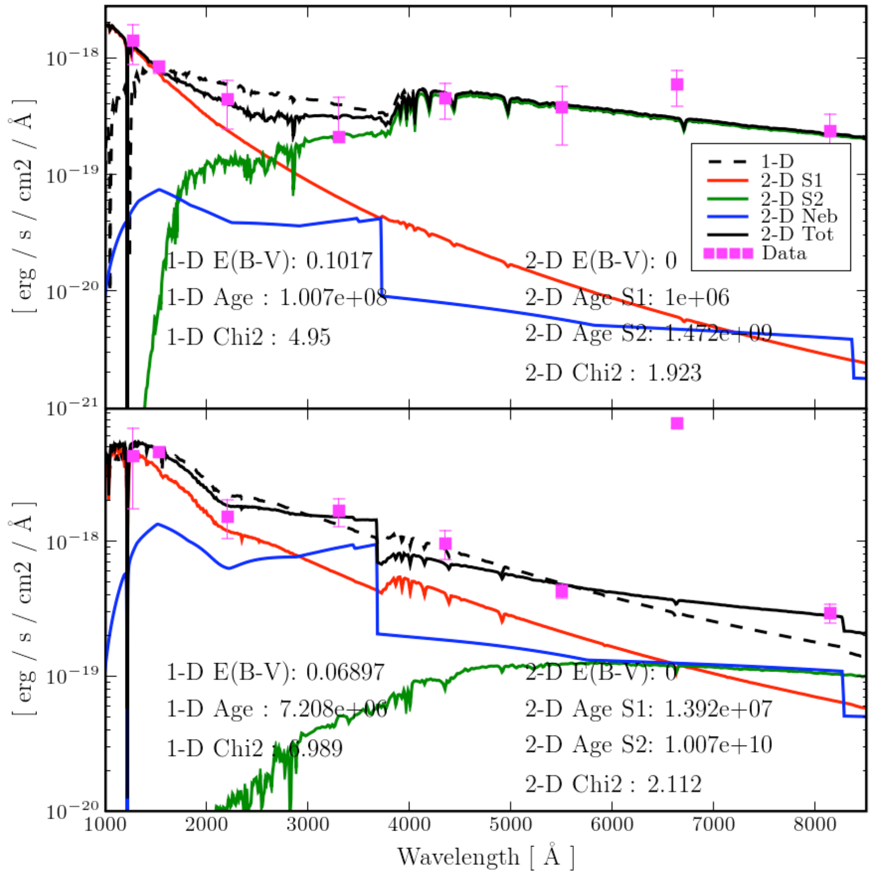


Model stellar continuum using SB99 (Leitherer et al 1999) Fit:

- Stellar age
- E(B-V)

} β and 4000 Å break

2 stellar + nebular gas spectra



Maps:

- Stellar age
- Photometric mass
- E(B-V)

- Ha
- CTN
- Lya

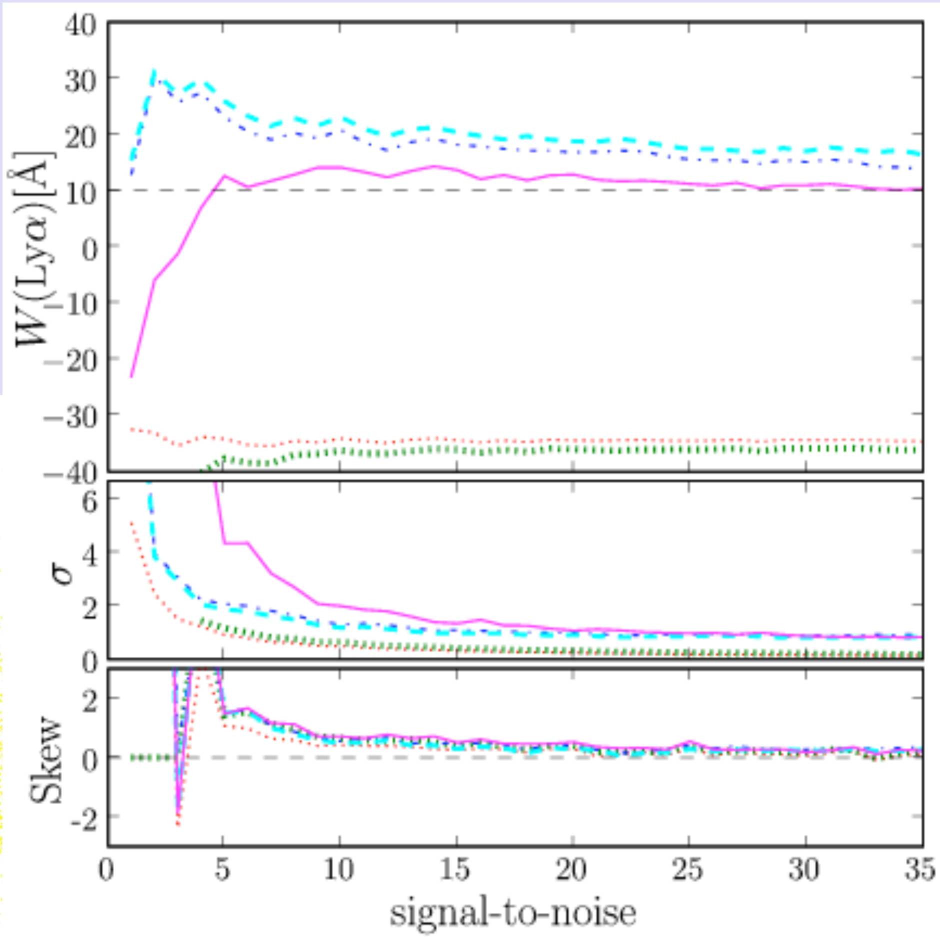
Hayes et al 2009, AJ in press (arXiv0803.1176)

Continuum subtraction - accuracy

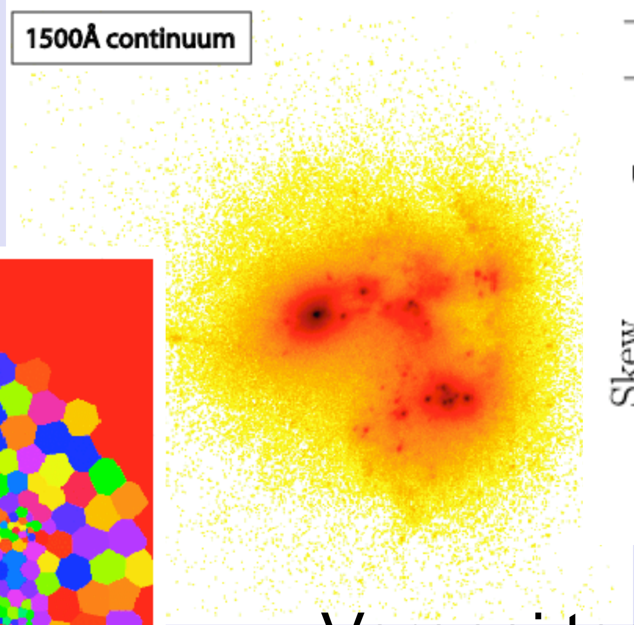
How accurate is that?

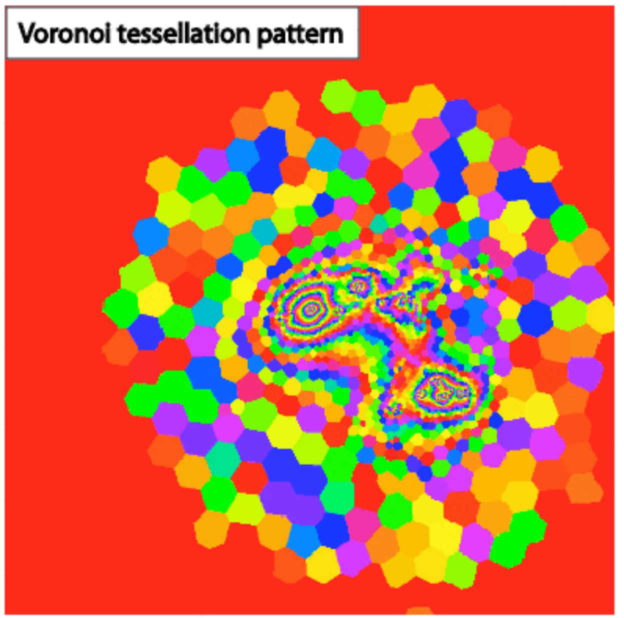
Monte-Carlo sim says need:

- *Z* to within 50%
- *SN* > 5-10 in every "spaxel"



Hayes et al 2009

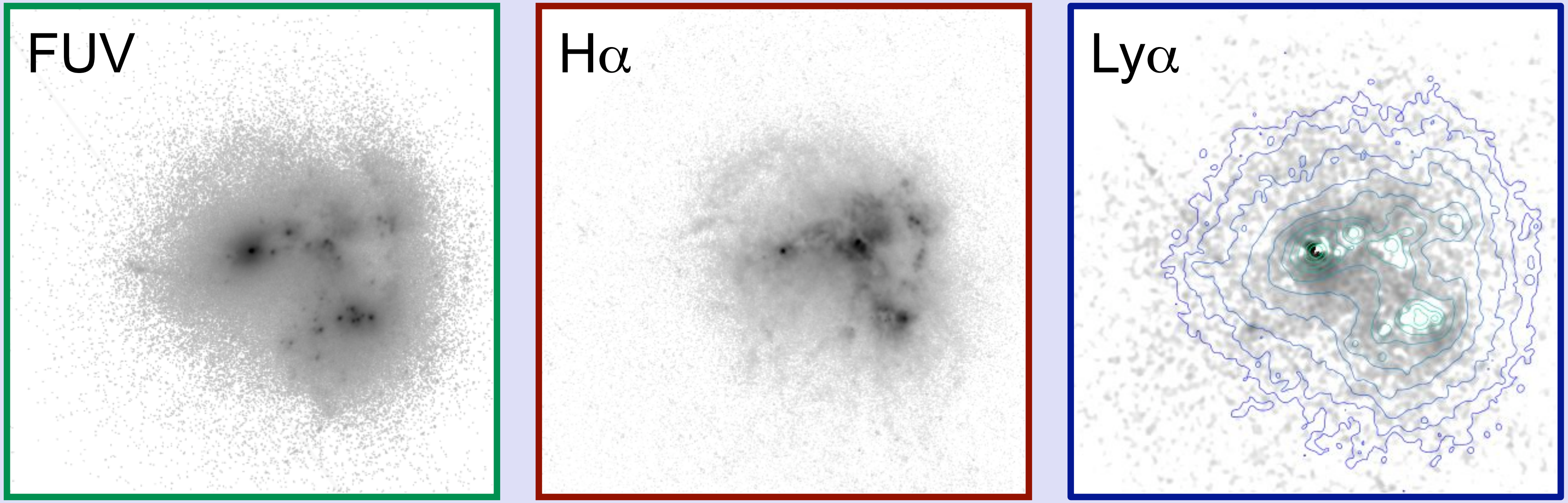




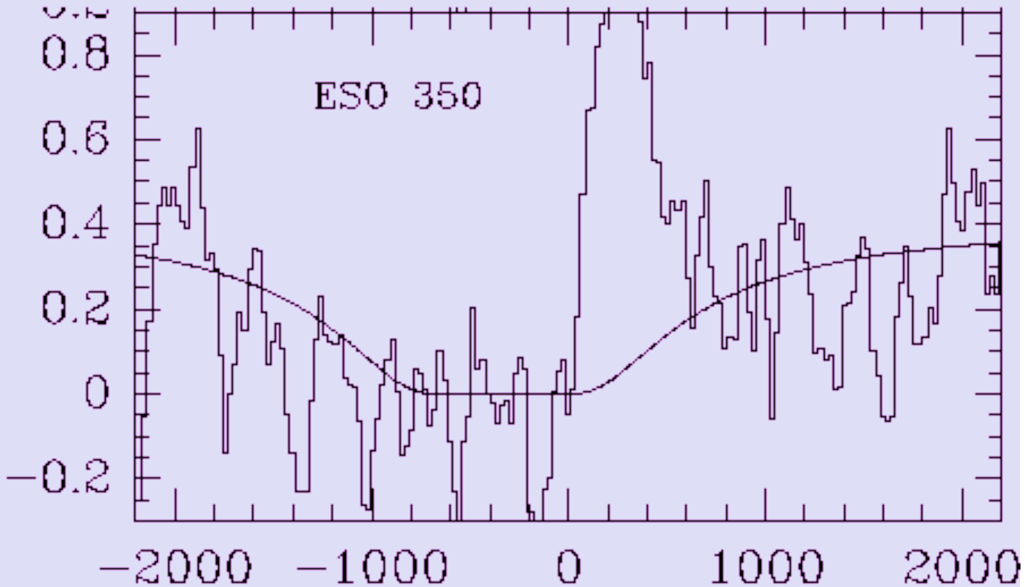
Voronoi tessellate to S/N=10
Apply pattern to all bands

NB effects may show up at high z as well (Hayes and Ostlin 2006)

Results: Individual: Haro 11

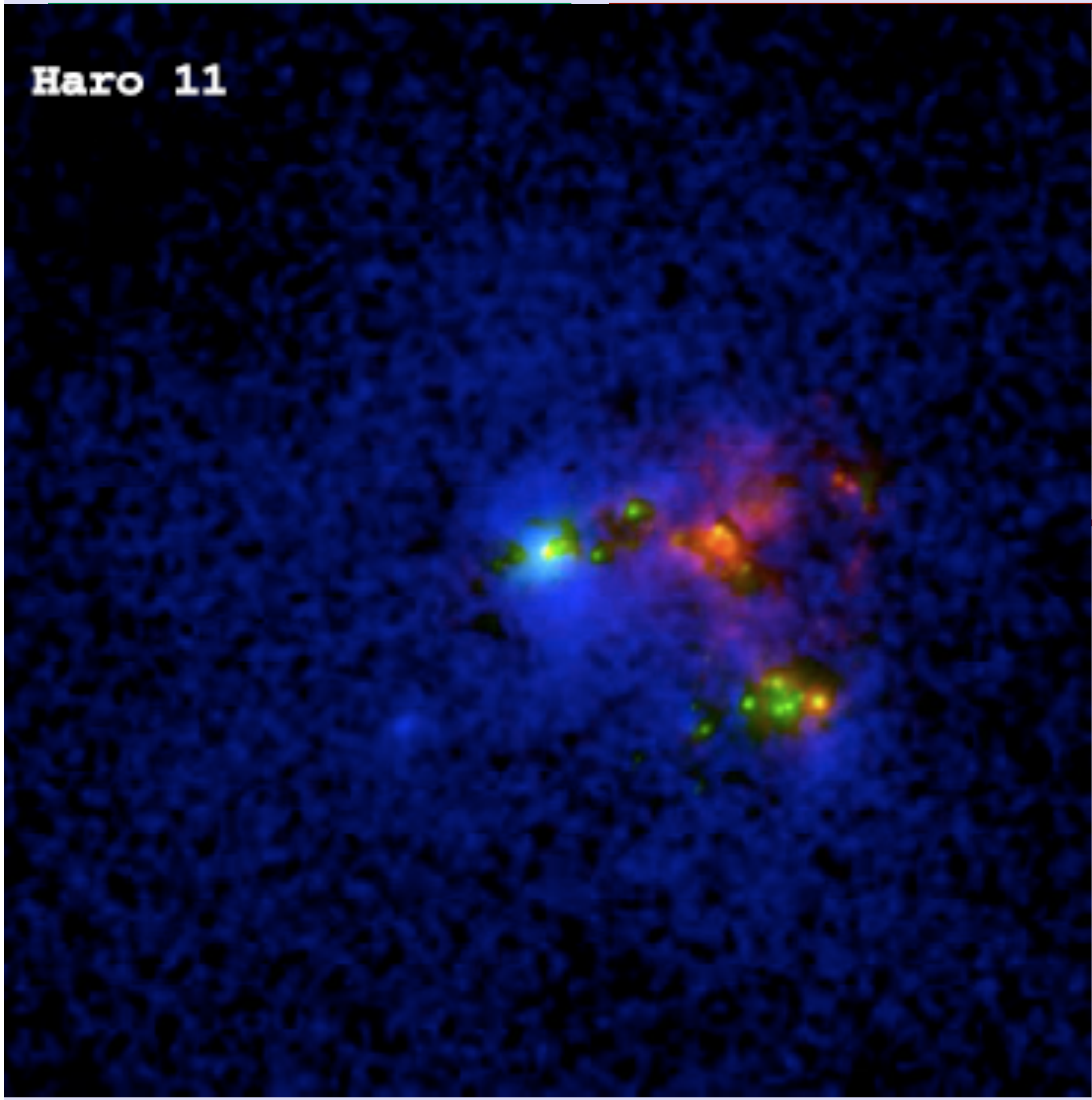


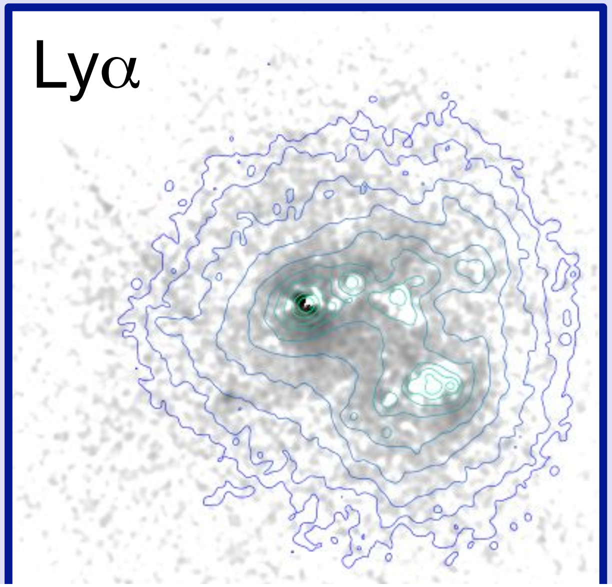
- Net Lyα emitter
- Lyα does NOT resemble FUV
- Lyα does NOT resemble Hα
- 90% of flux in diffuse compnt.

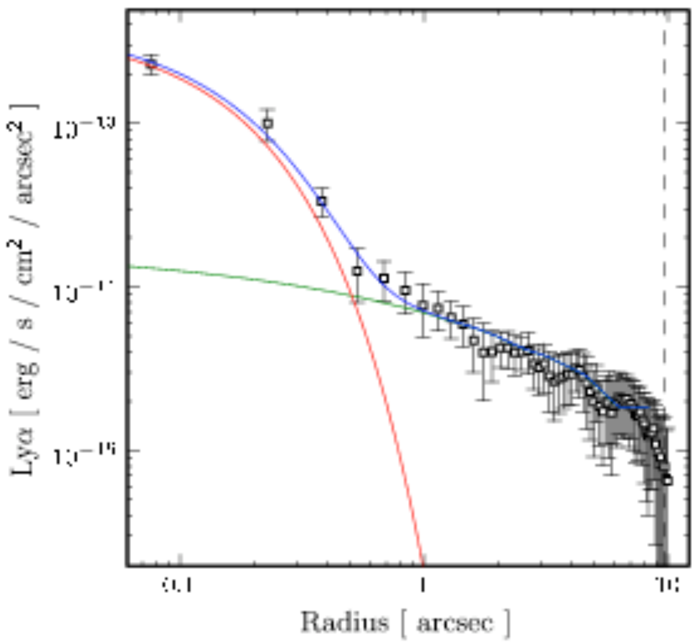


(Hayes et al. 2007;
Östlin et al. 2009 AJ in press, arXiv0803.1174)

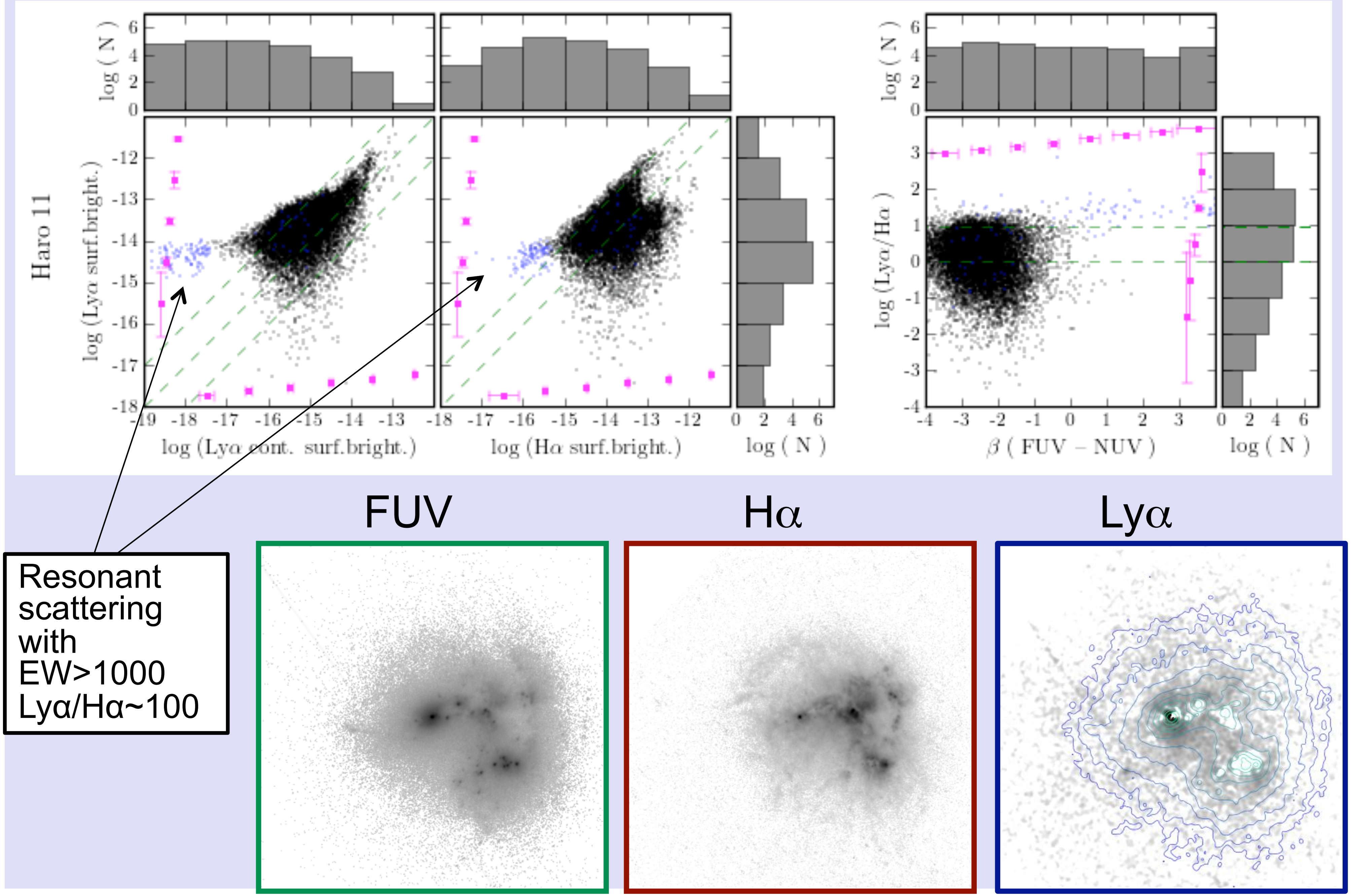
Results: Individual: Haro 11





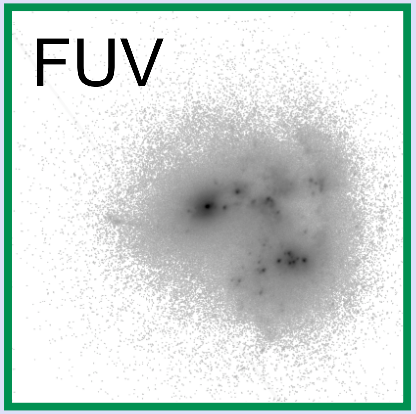


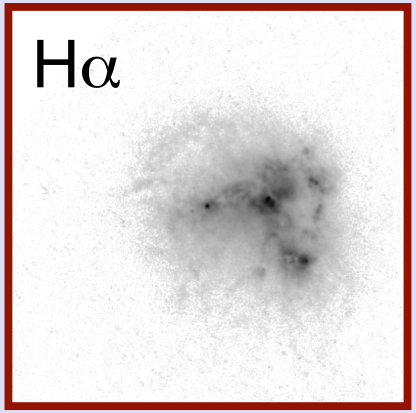
Results: Individual: Haro 11

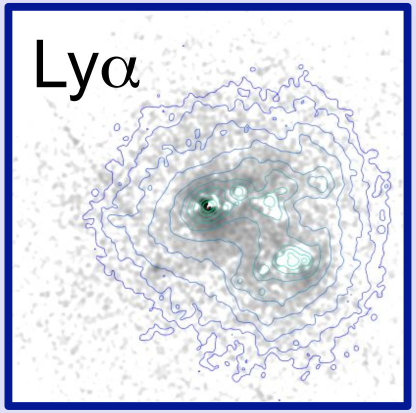


Resonant scattering with EW>1000 Lyα/Hα~100

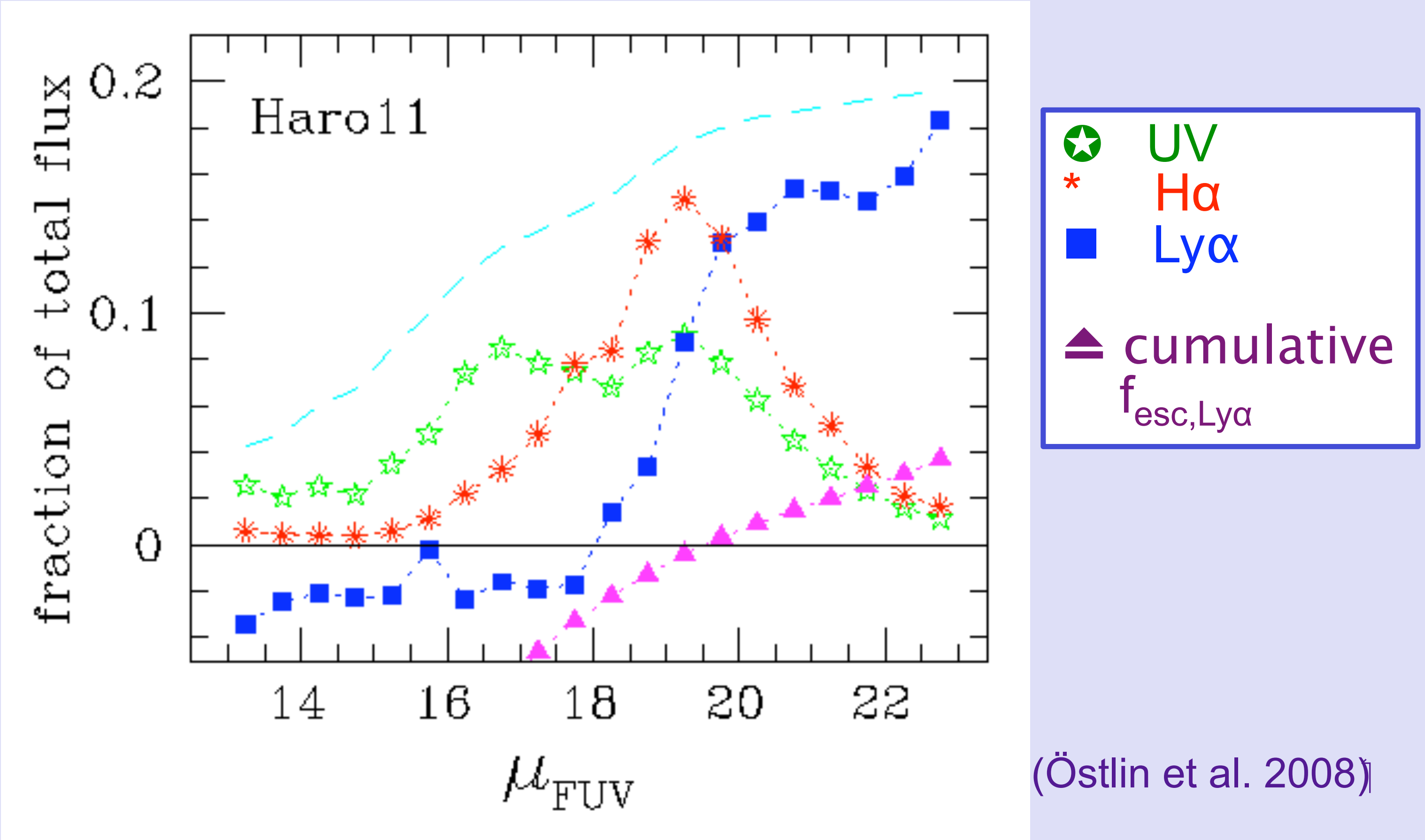
Results: Individual: Haro 11







Fraction of emitted flux vs. SB (FUV =1500Å), AB-mag

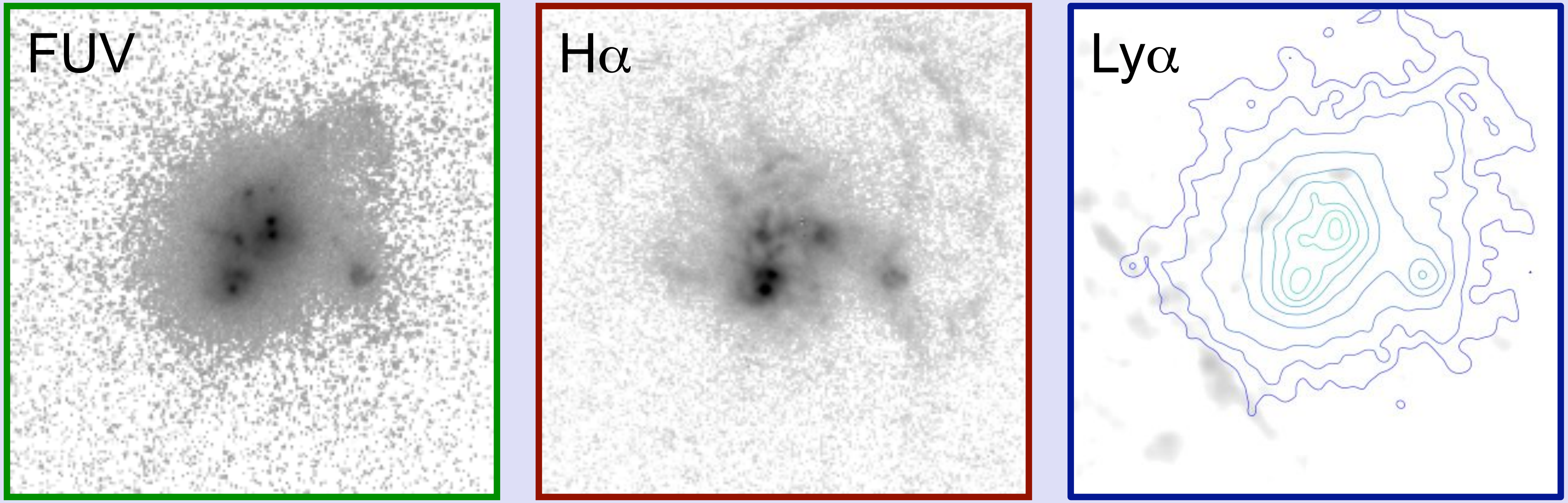


(Östlin et al. 2008)

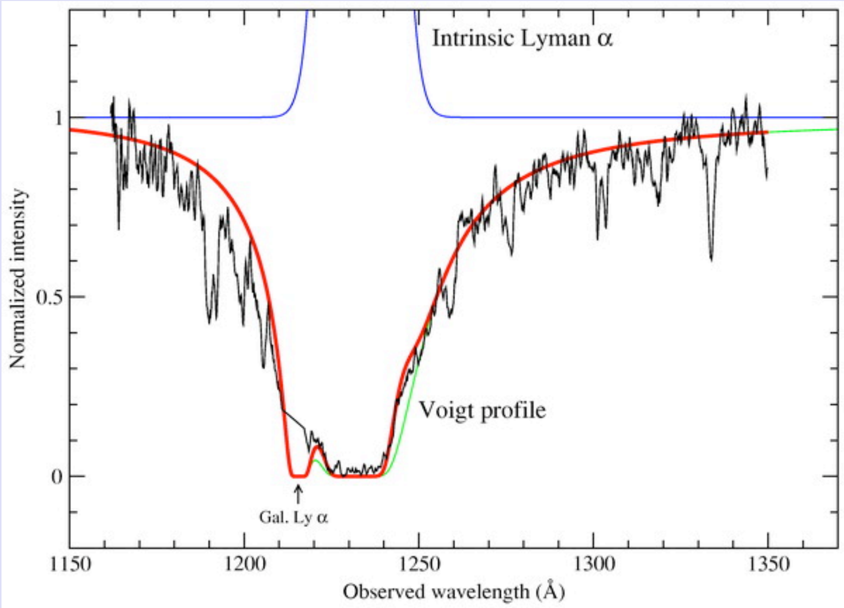
Ha peak offset from FUV to low SB

Lya peak further offset => scattering

Results: individual: SBS 0335-052

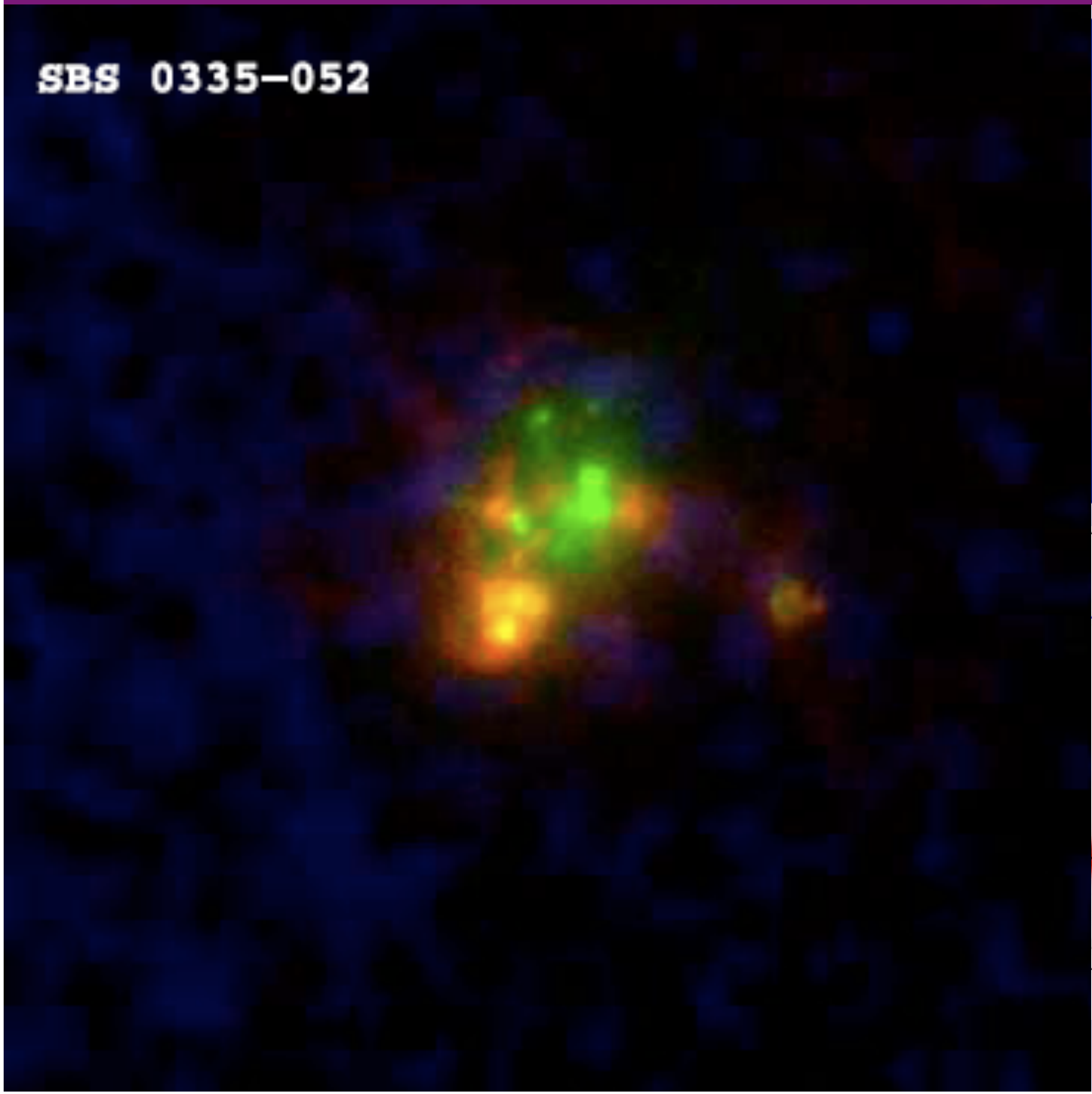


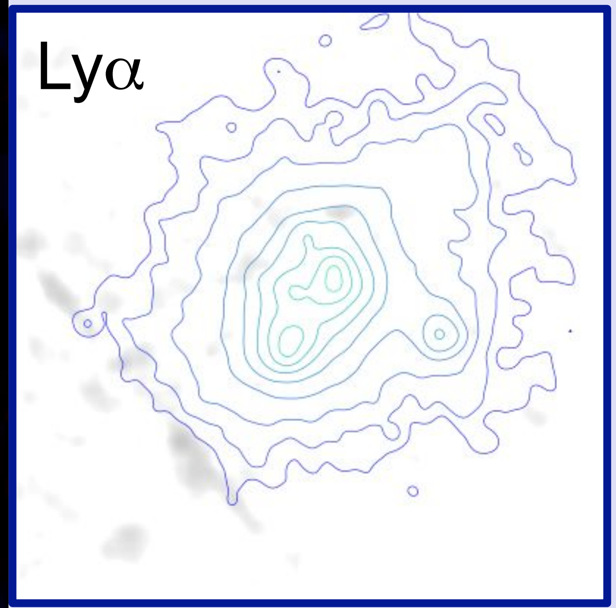
- Net Lyα absorber

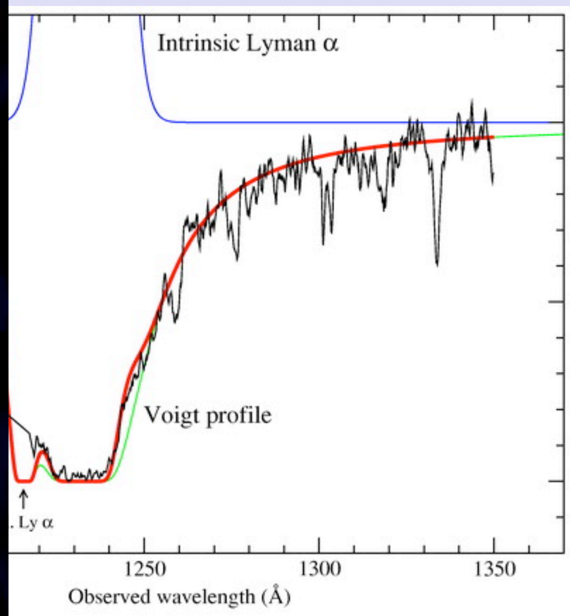


(Östlin et al. 2008)

Results: individual: SBS 0335-052







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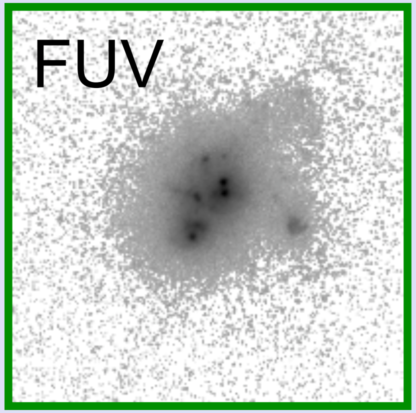
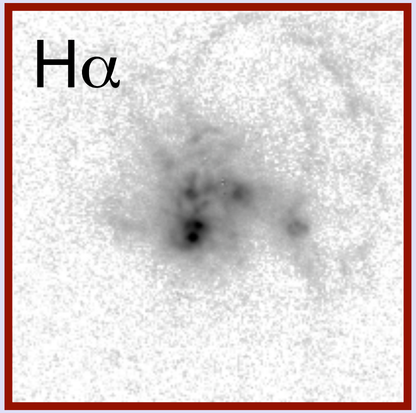
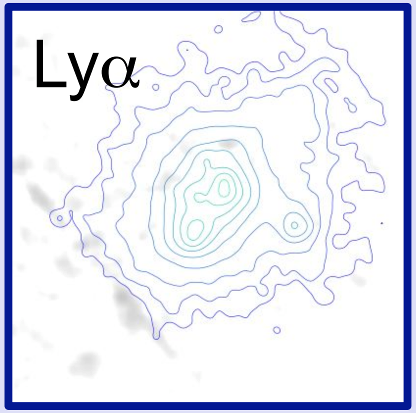
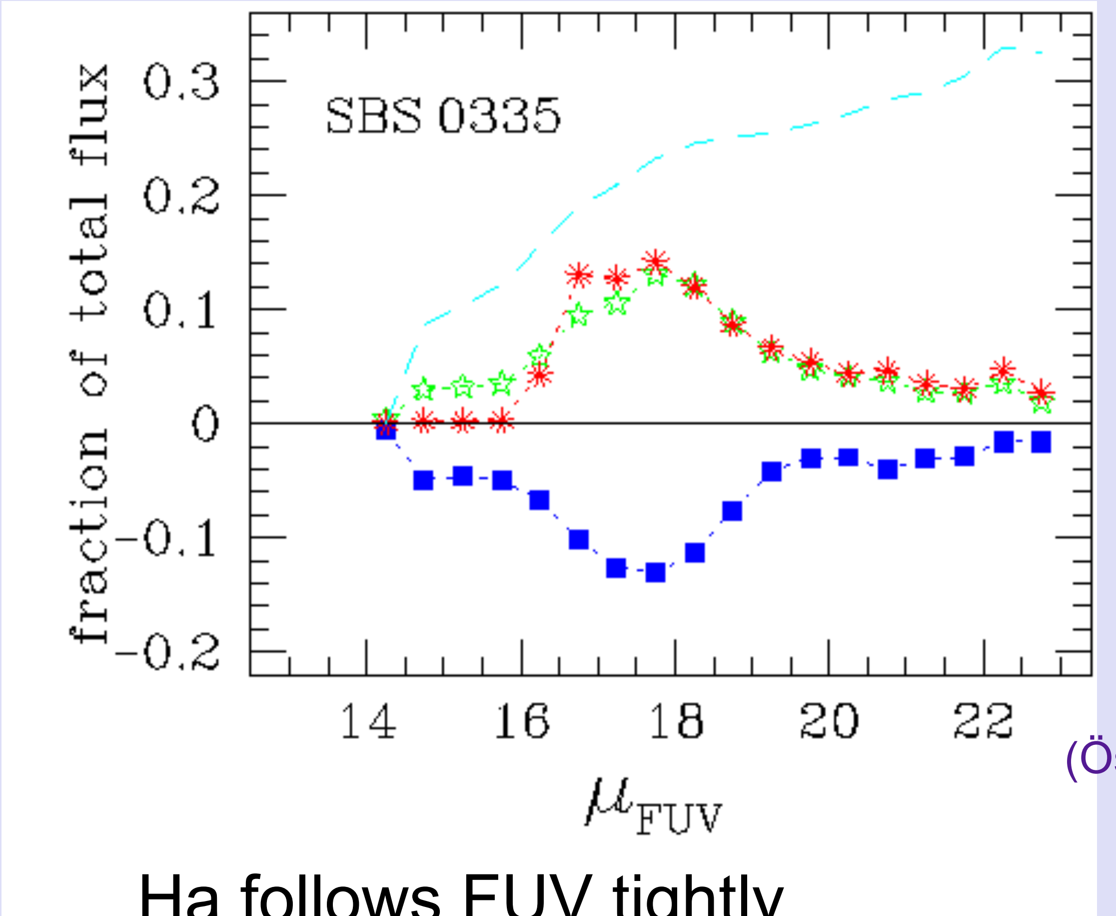






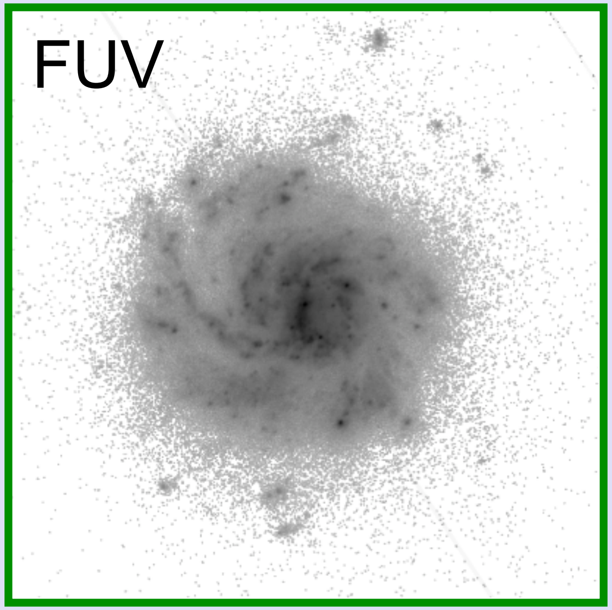
Fraction of emitted flux vs. SB (FUV)

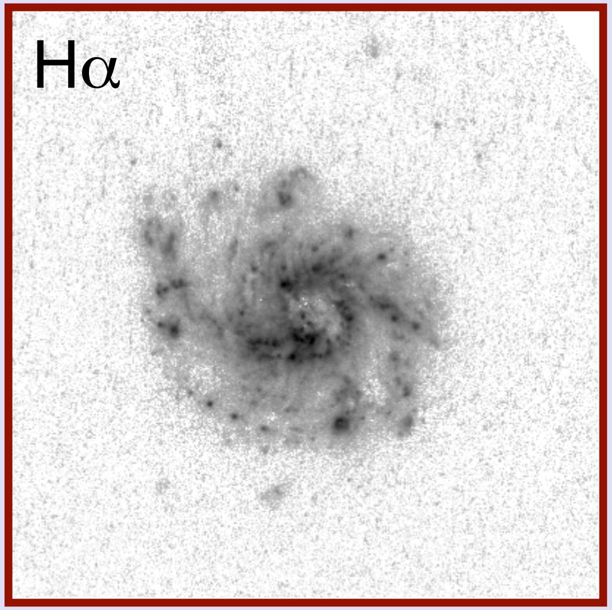


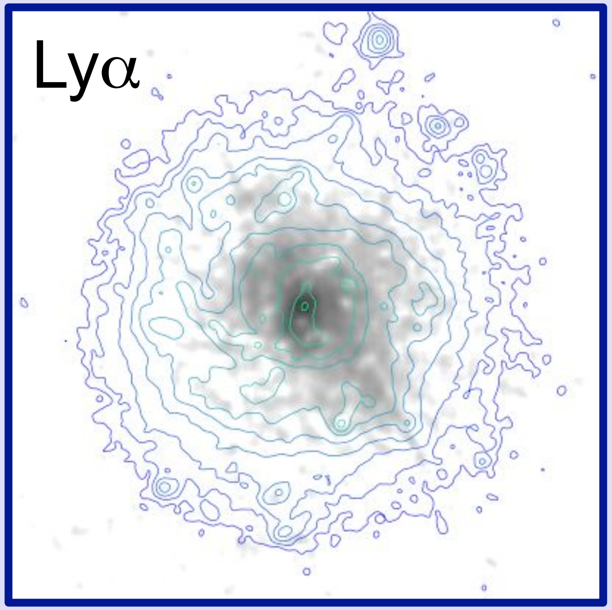
(Östlin et al. 2008)

Ha follows FUV tightly
Lya almost exact mirror

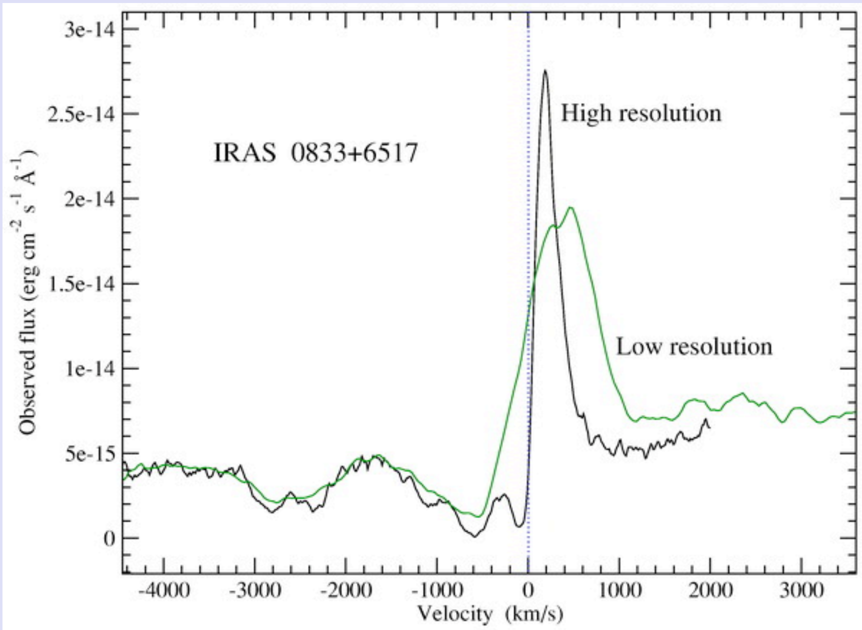
Results: individual: IRAS 08339+65







- Strong nuclear emission
- Diffuse component



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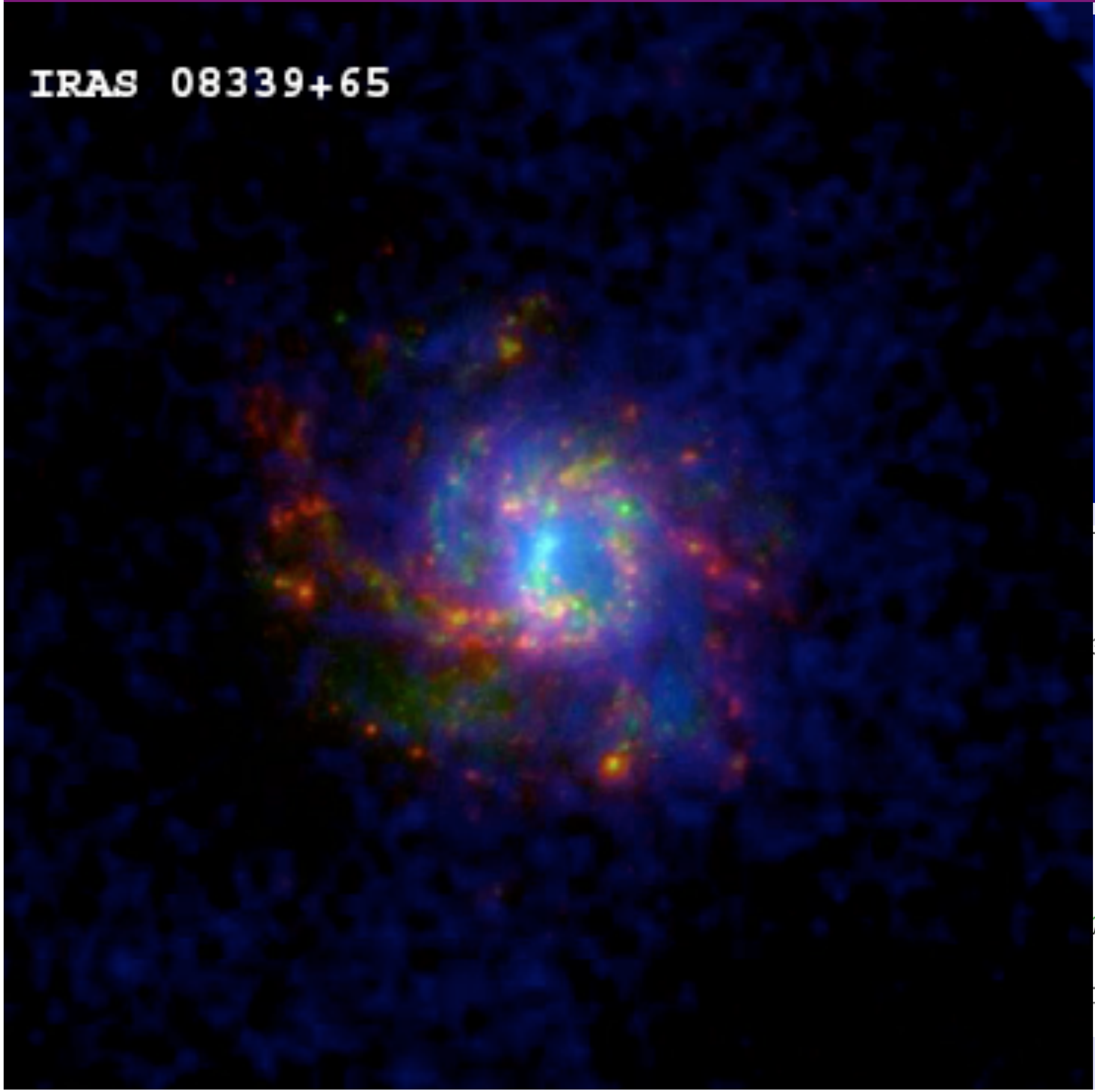

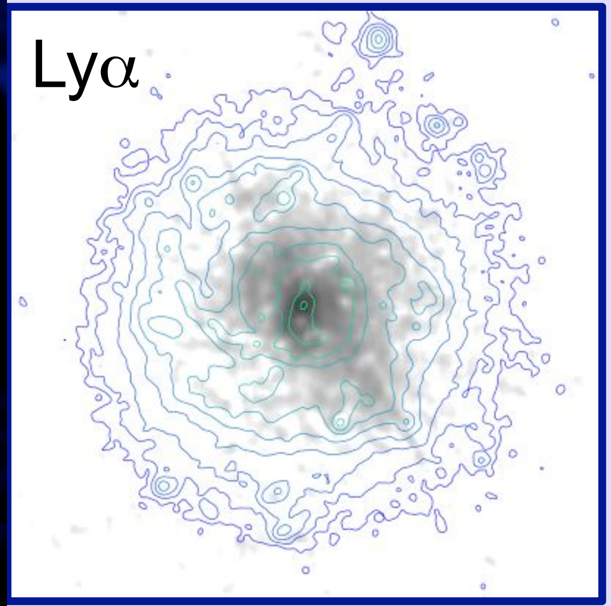

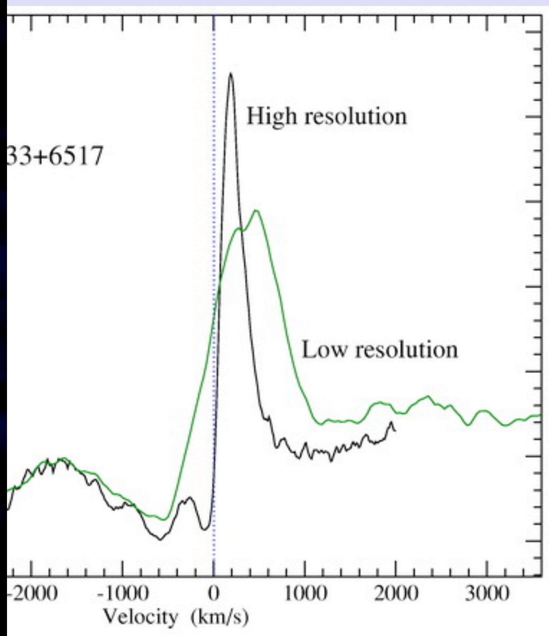

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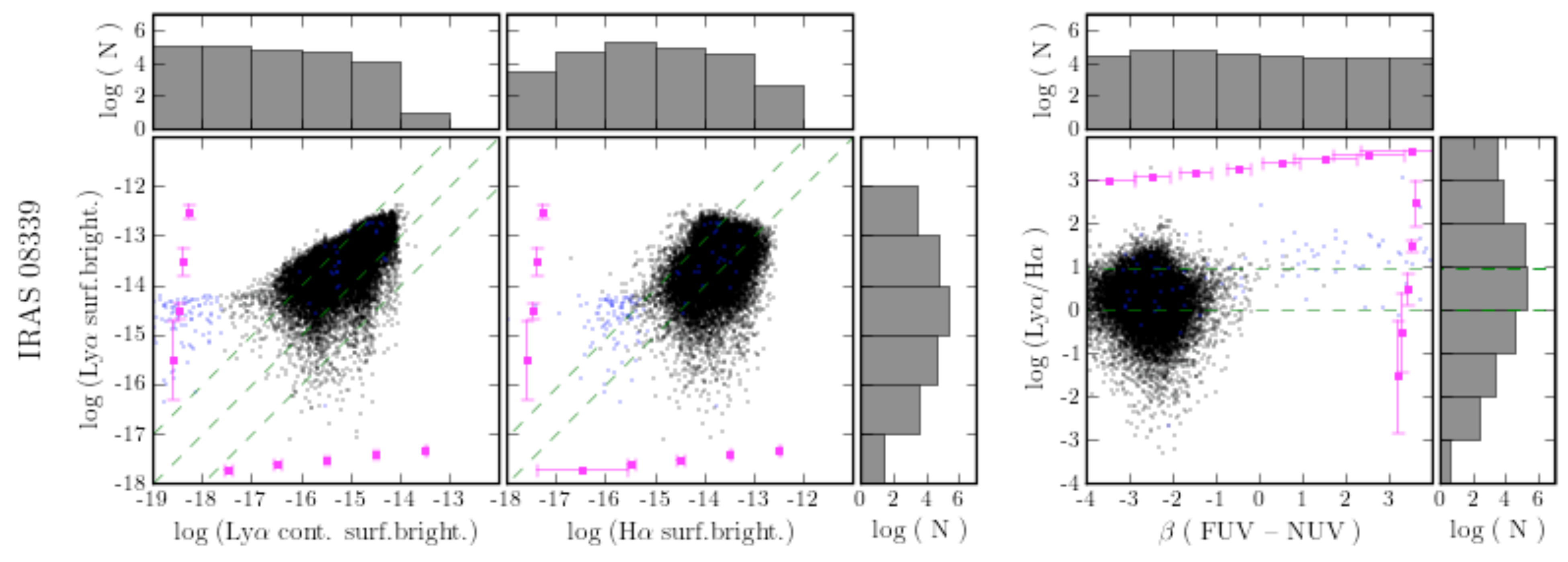

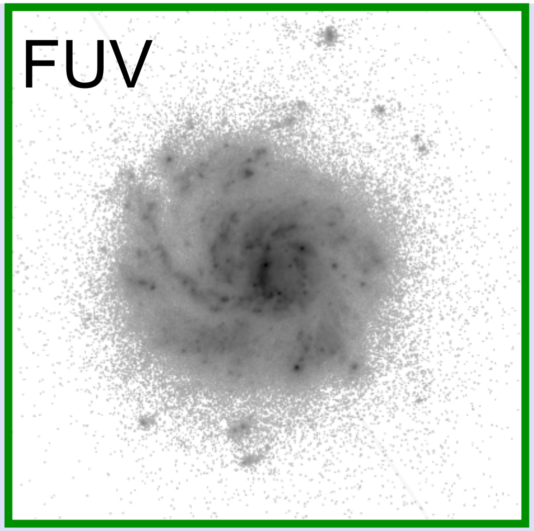

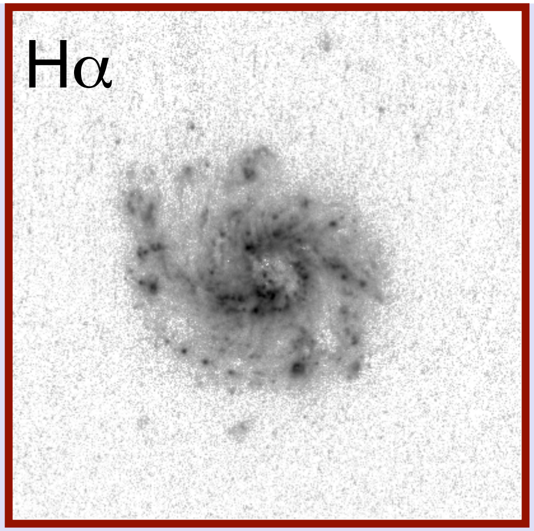

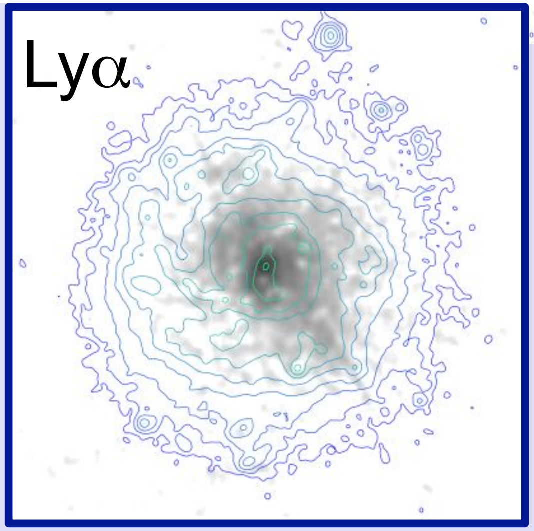

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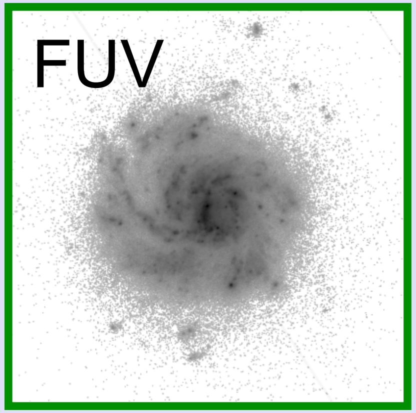
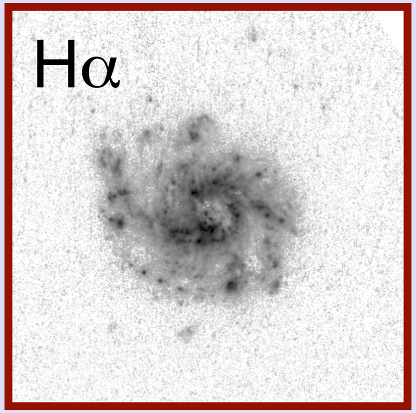
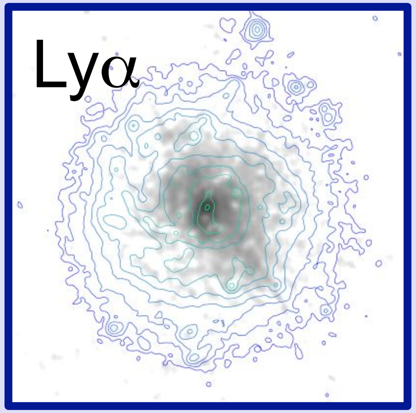
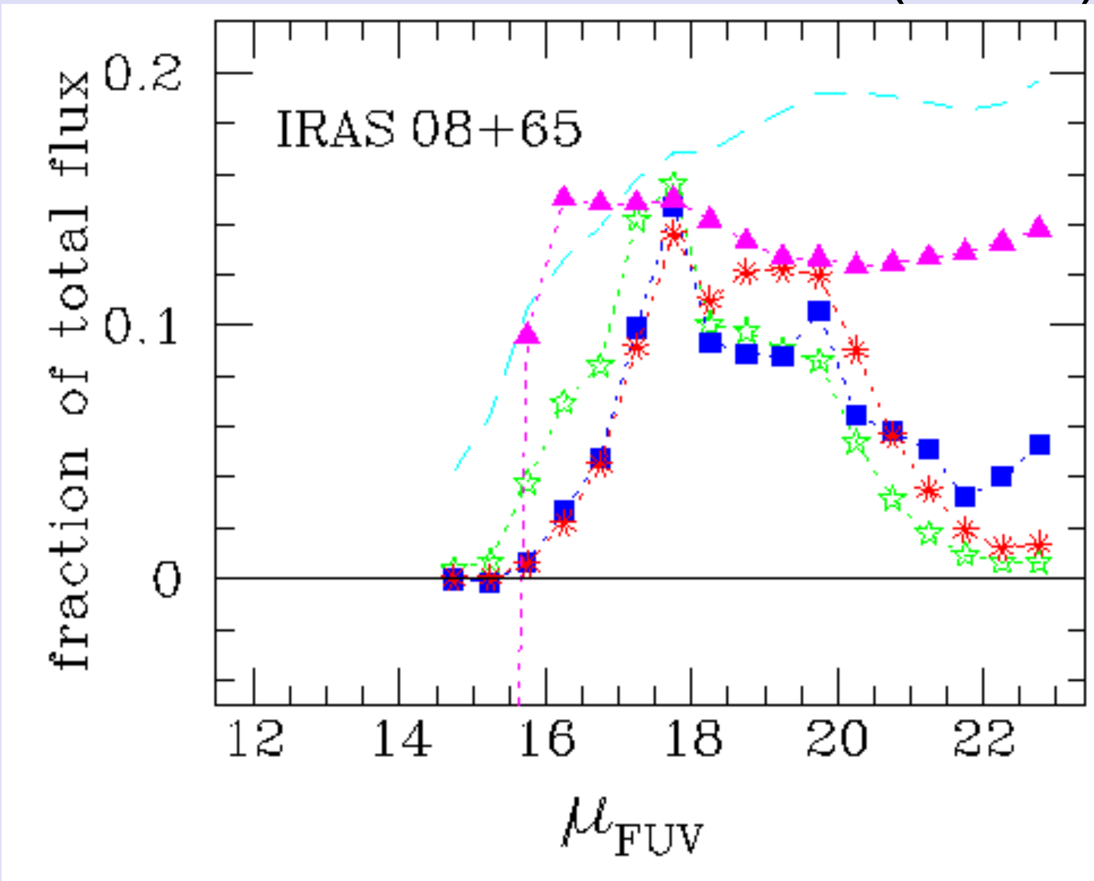


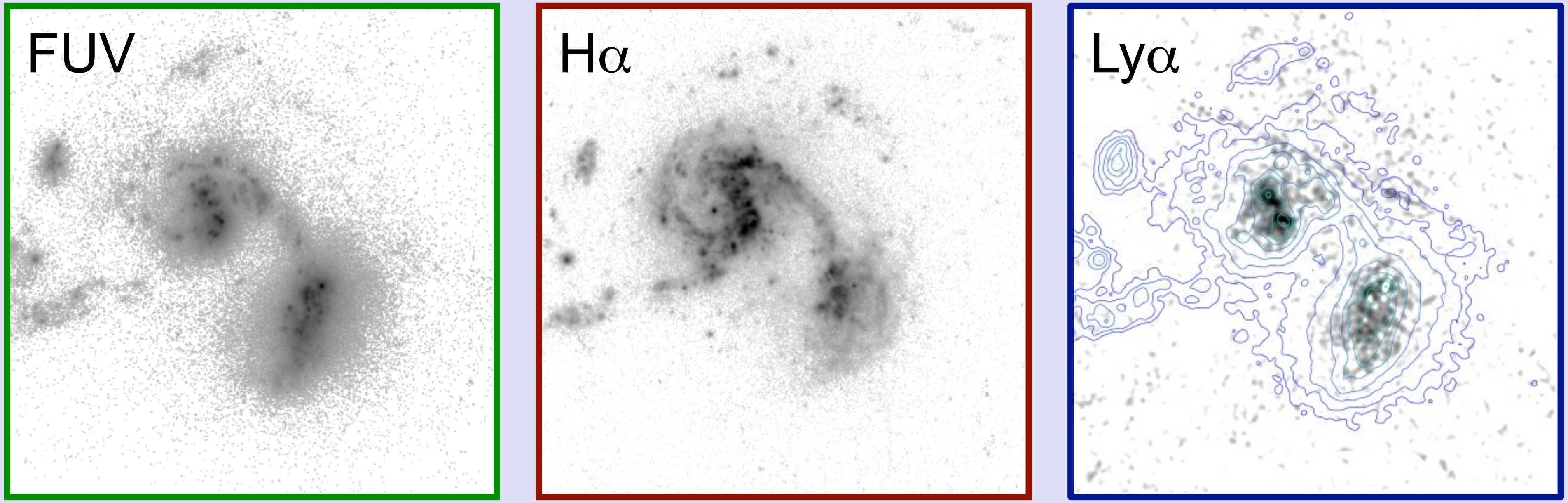




Fraction of emitted flux vs. SB (FUV)

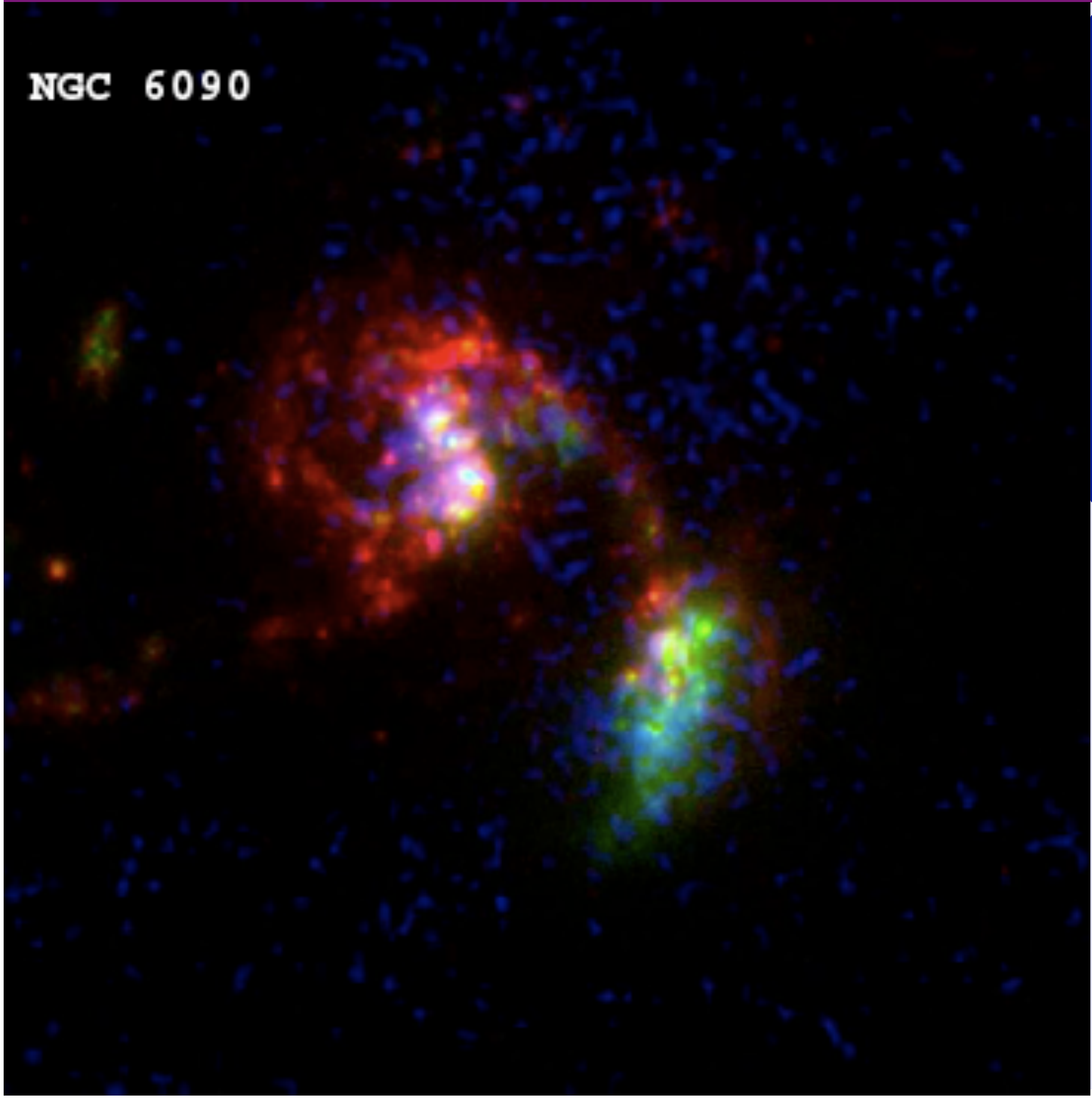


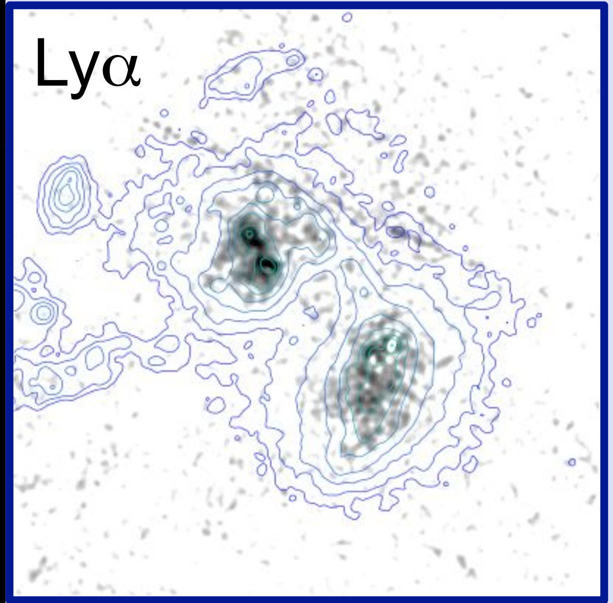
Results: individual: NGC 6090



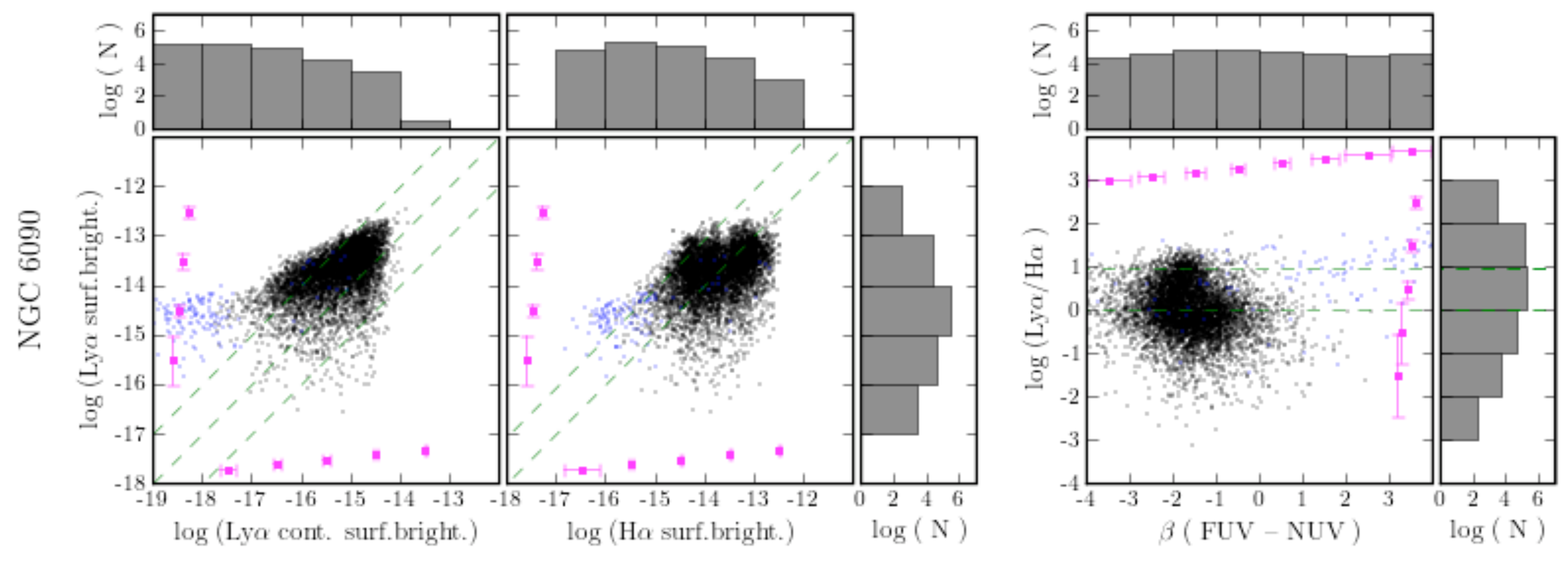
- Strong + diffuse Lya from NE core
- Weak diffuse surrounding SW

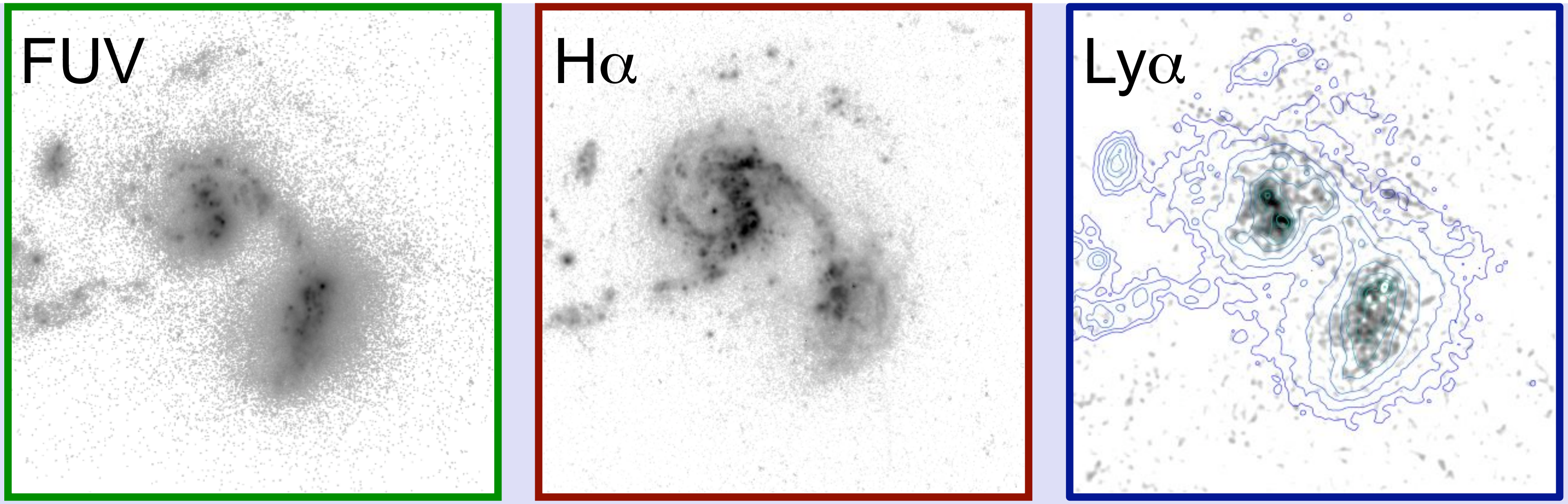
Results: individual: NGC 6090



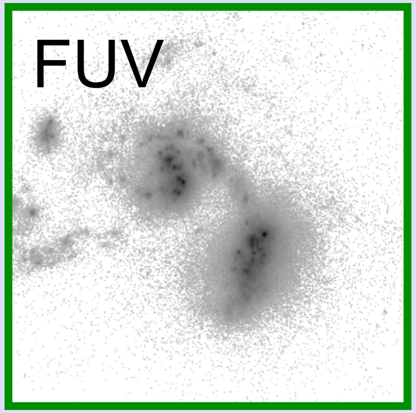


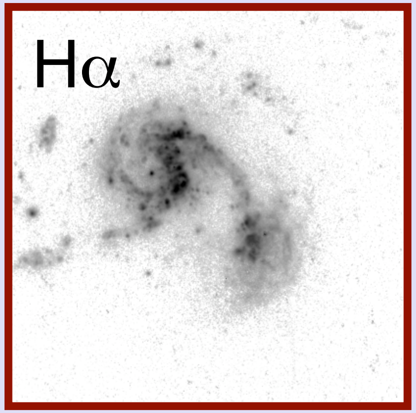
Results: individual: NGC 6090

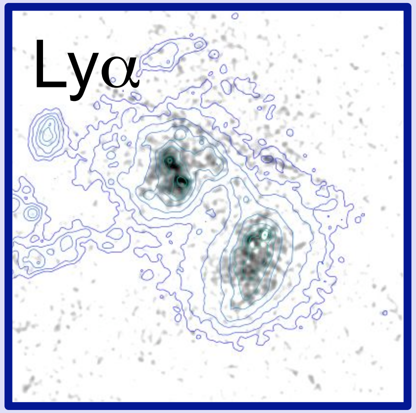




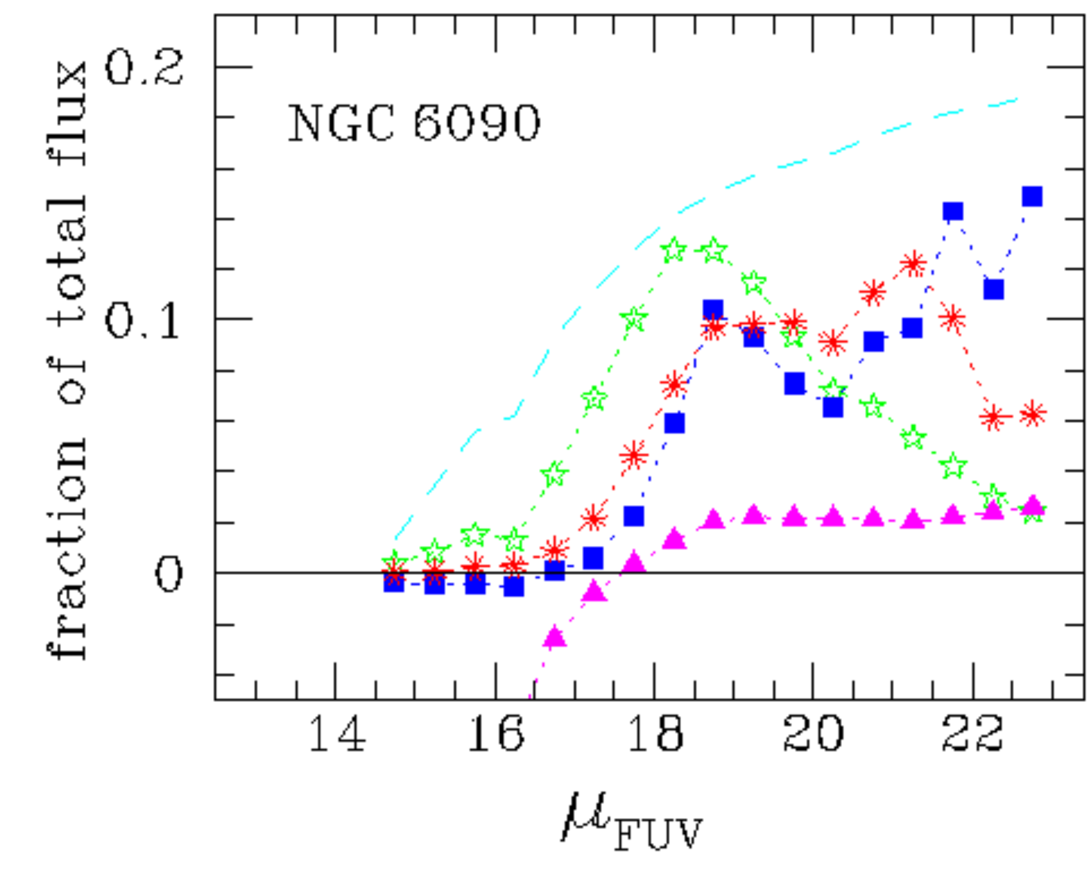
Results: individual: NGC 6090



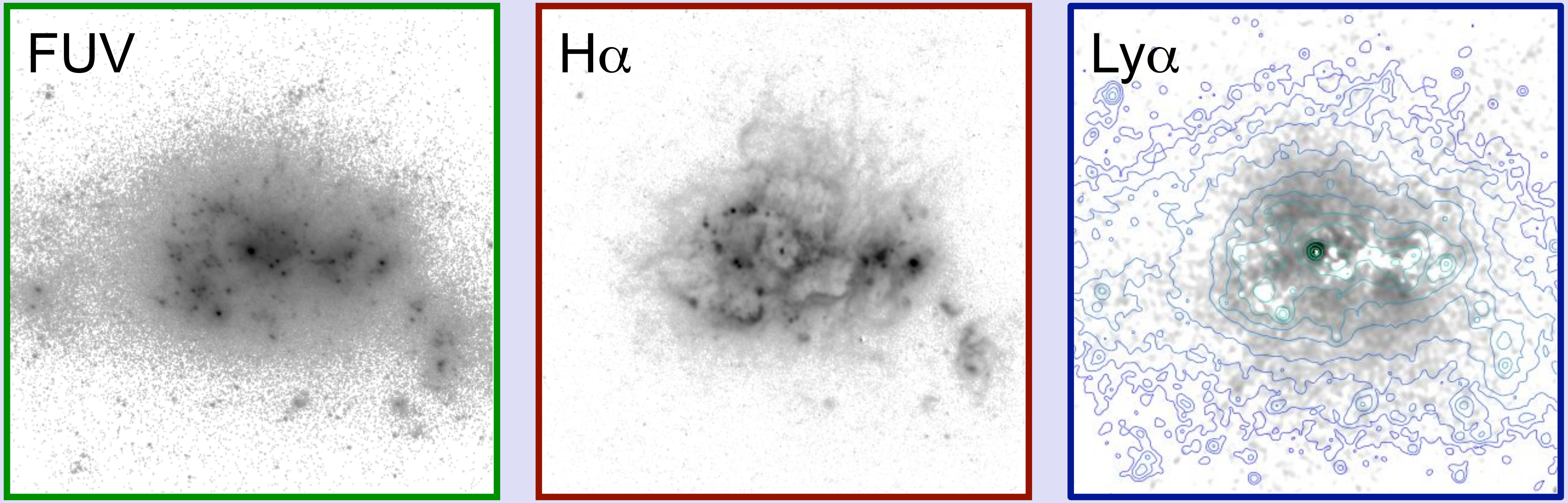




Fraction of emitted flux vs. SB (FUV)

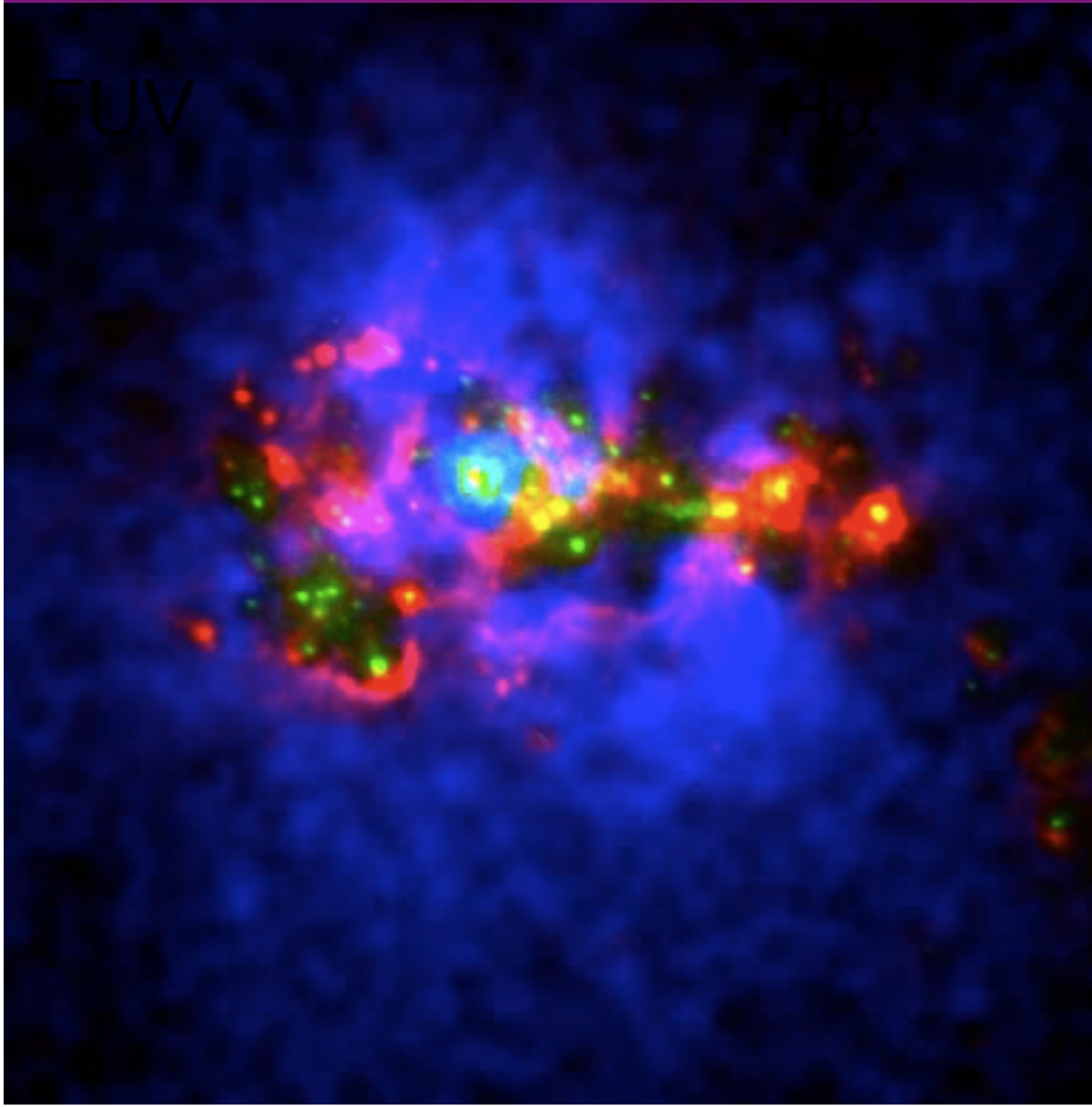


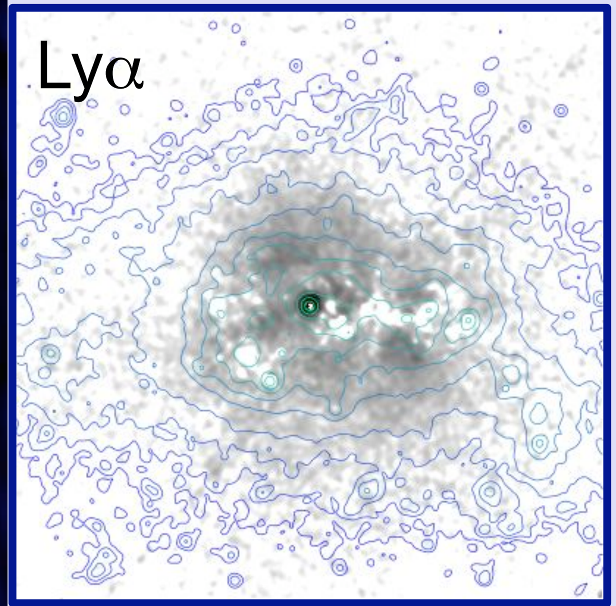
Results: individual: ESO 338-IG04



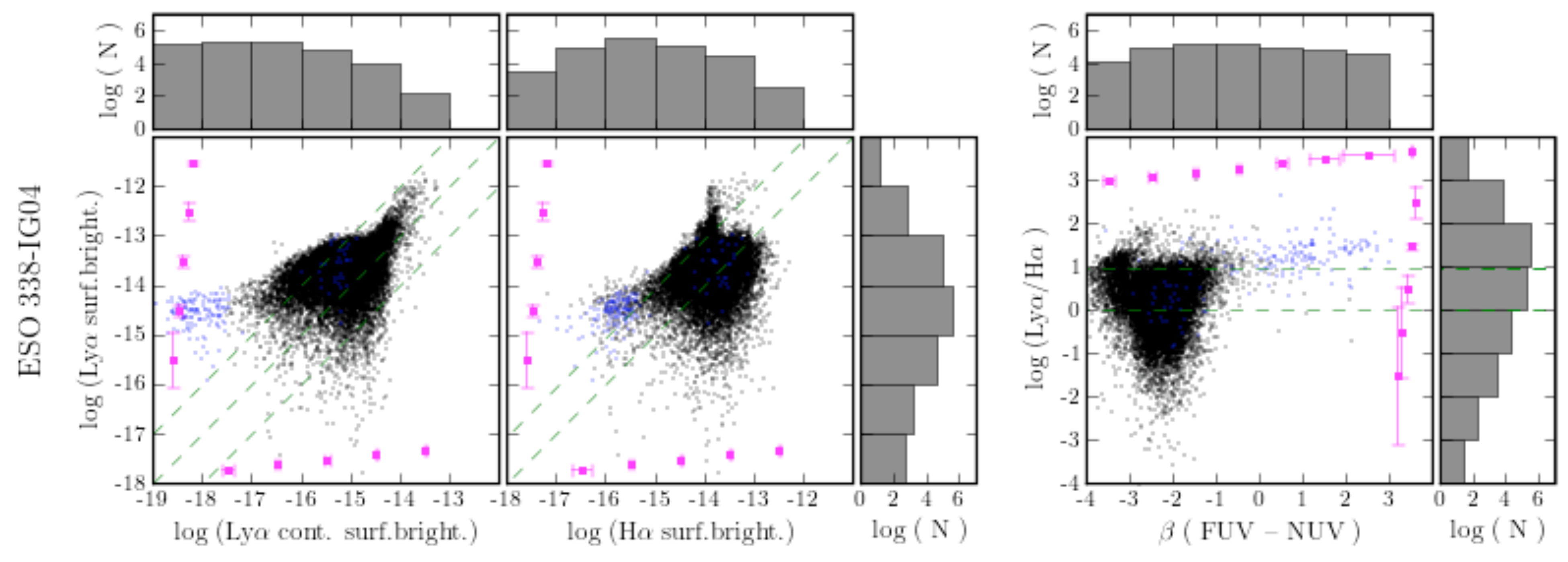
- Net Lyα emitter
- Lyα largely symmetric around one knot

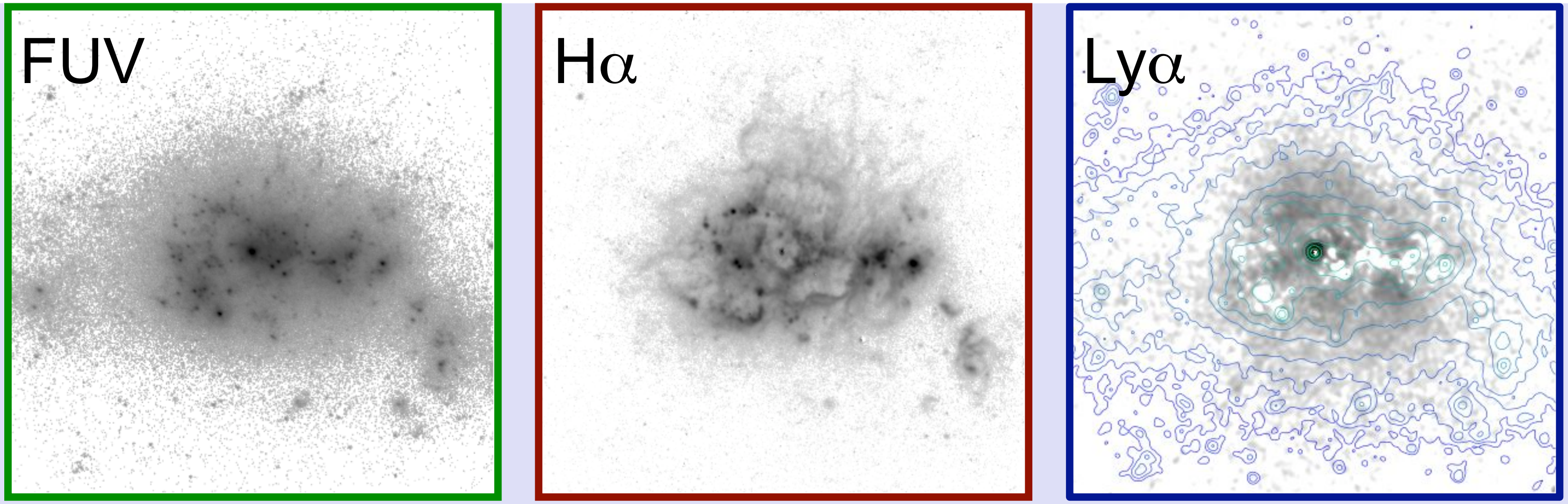
Results: individual: ESO 338-IG04



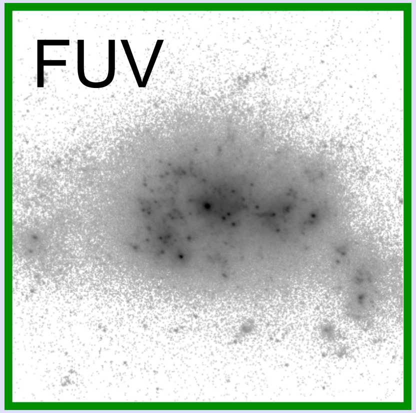


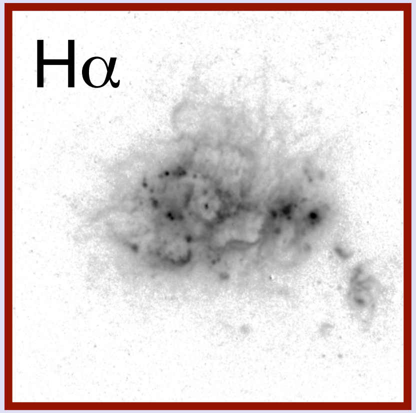
Results: individual: ESO 338-IG04

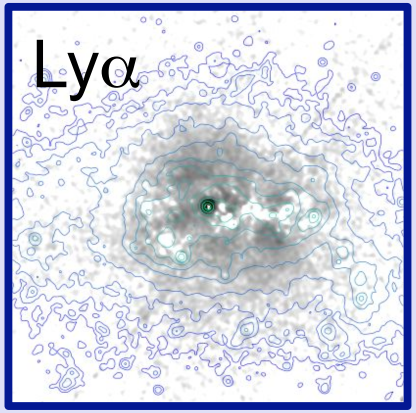




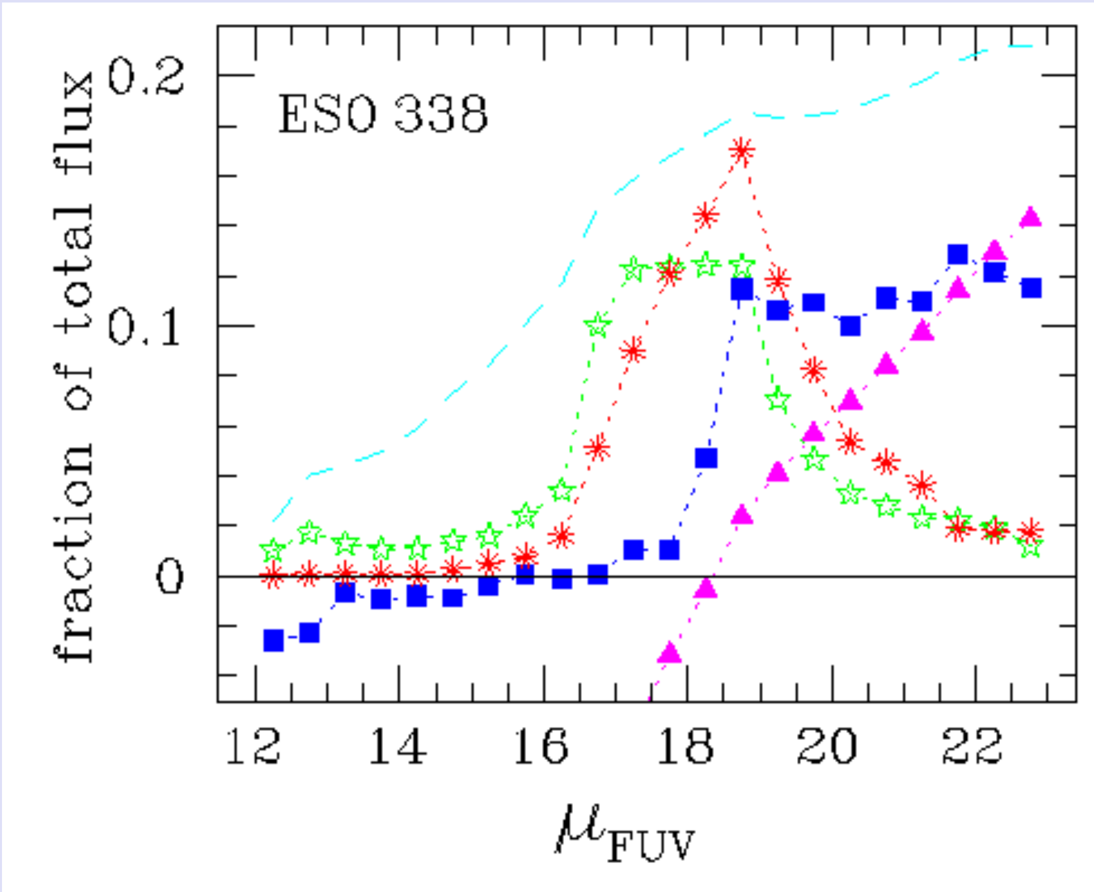
Results: individual: ESO 338-IG04



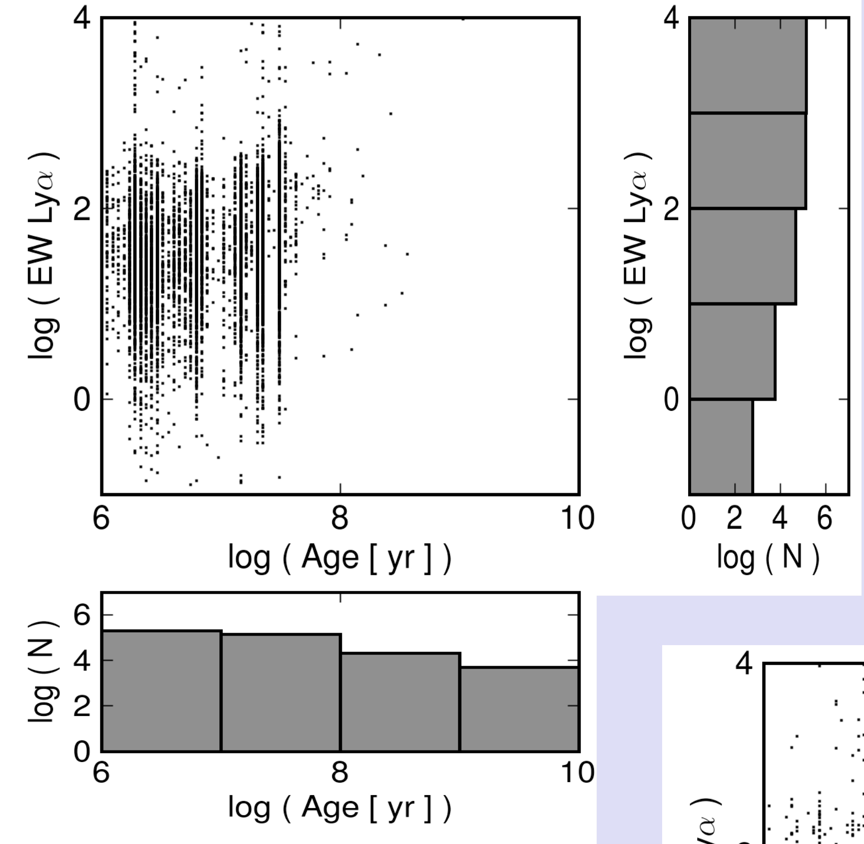




Fraction of emitted flux vs. SB (FUV)



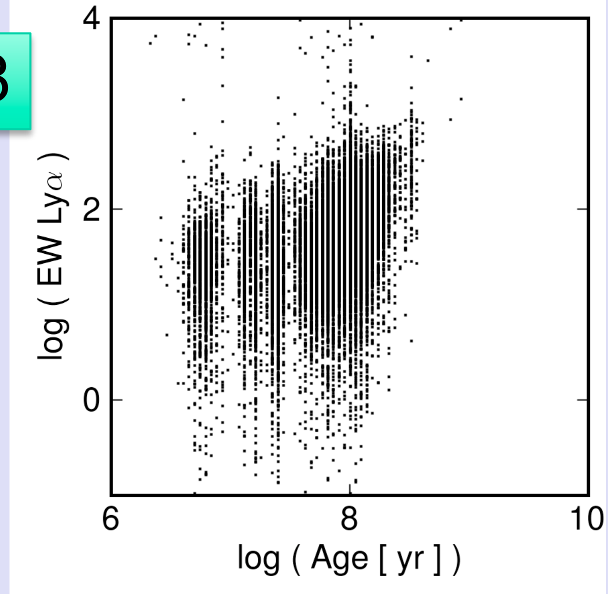
Results: local age correlations?

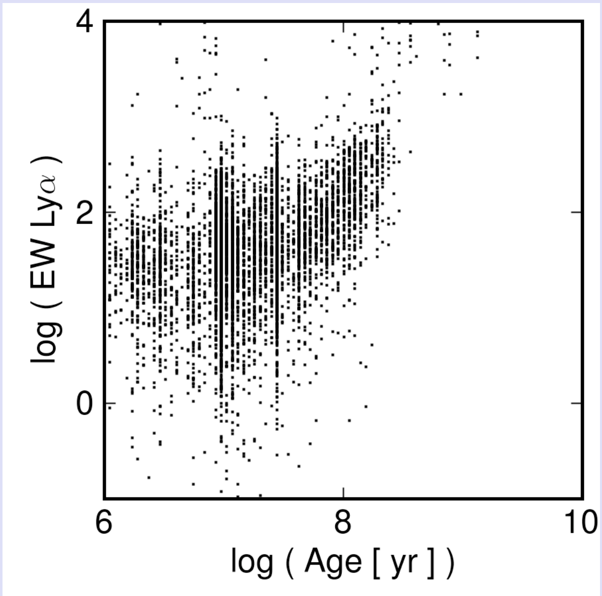


Haro 11

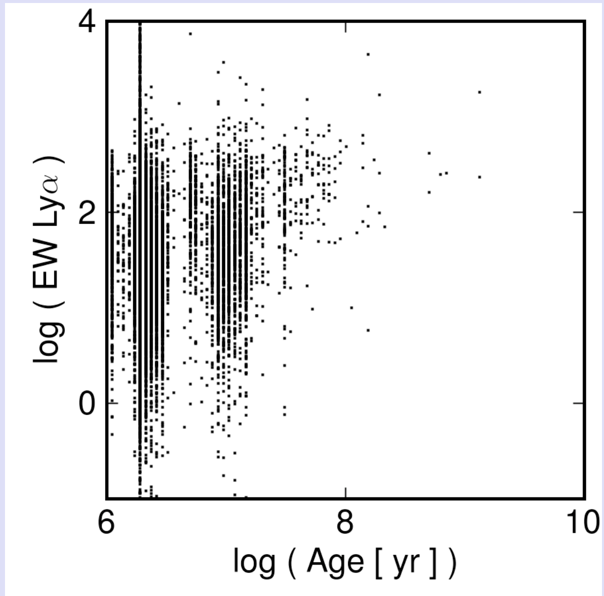
Spaxel level values

IRAS 08



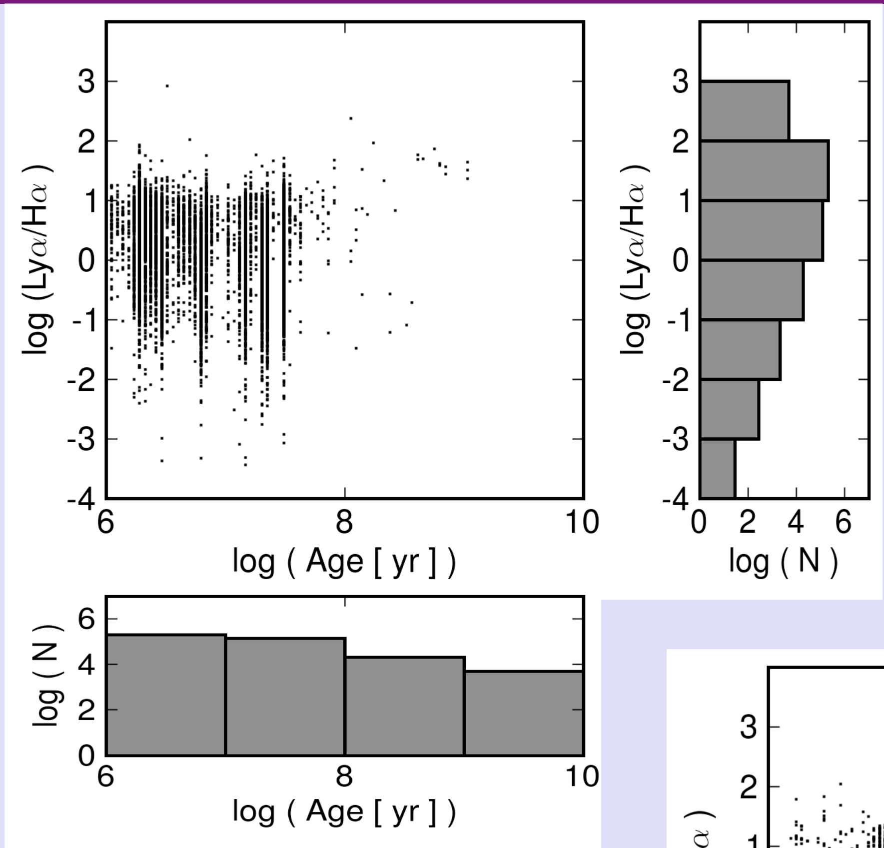


NGC 6090



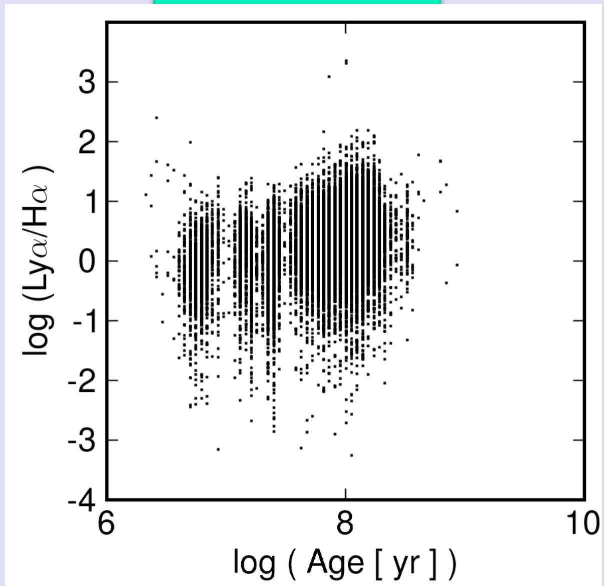
ESO 338

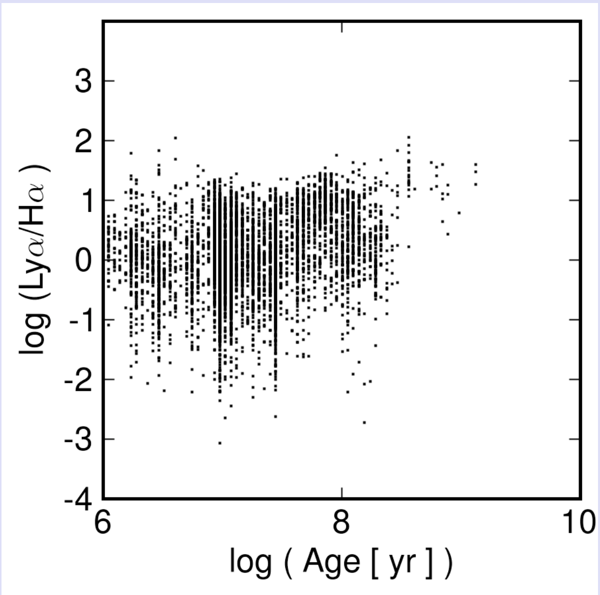
Results: local age correlations?



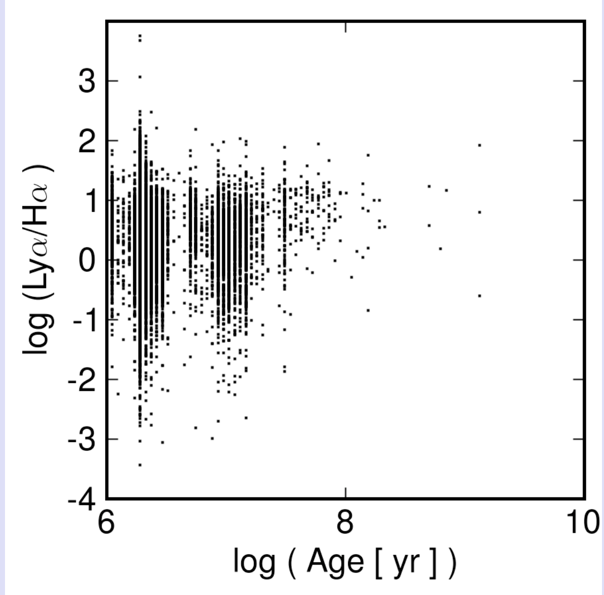
Haro 11

IRAS 08



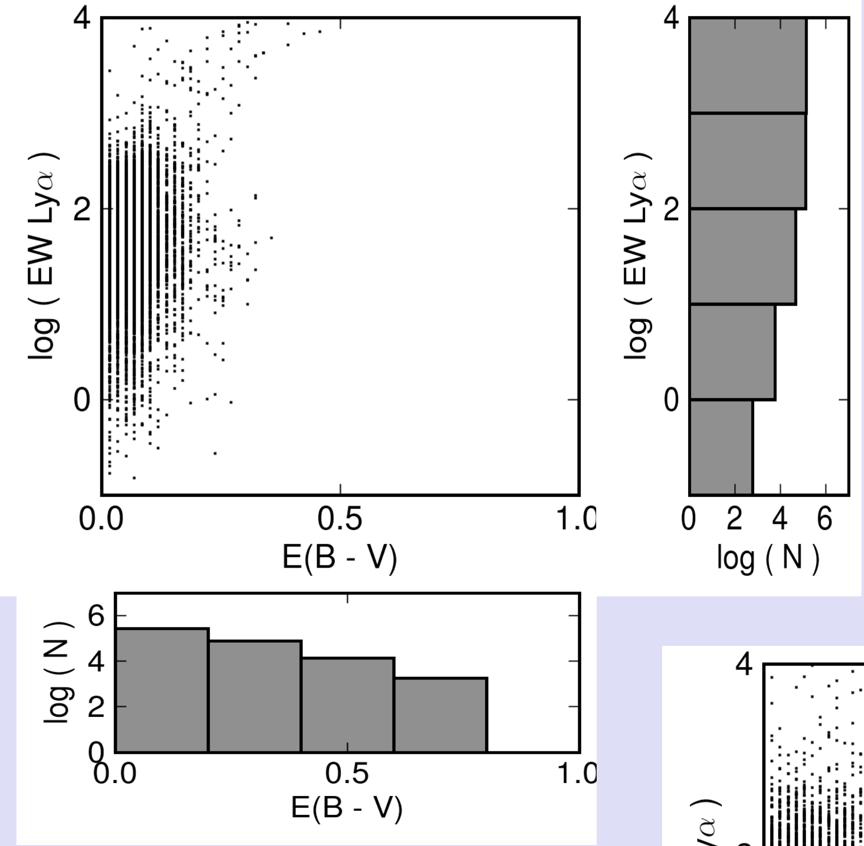


NGC 6090



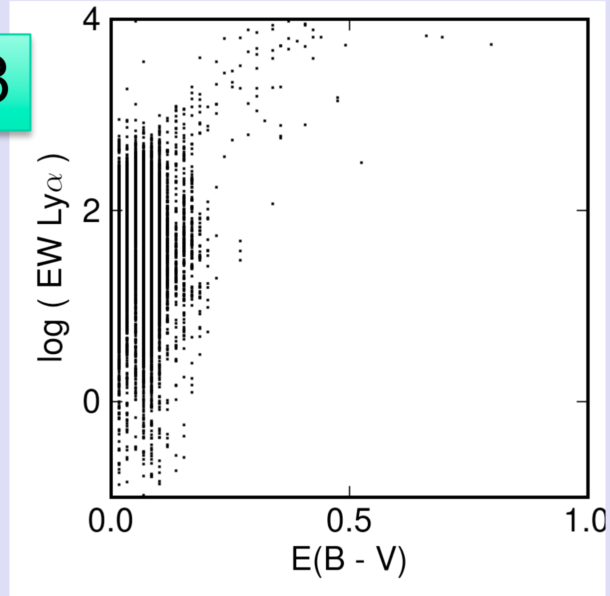
ESO 338

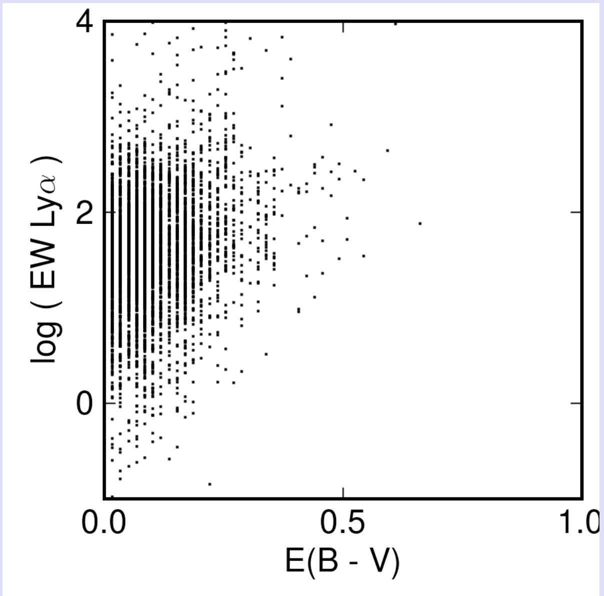
Results: local dust correlations?



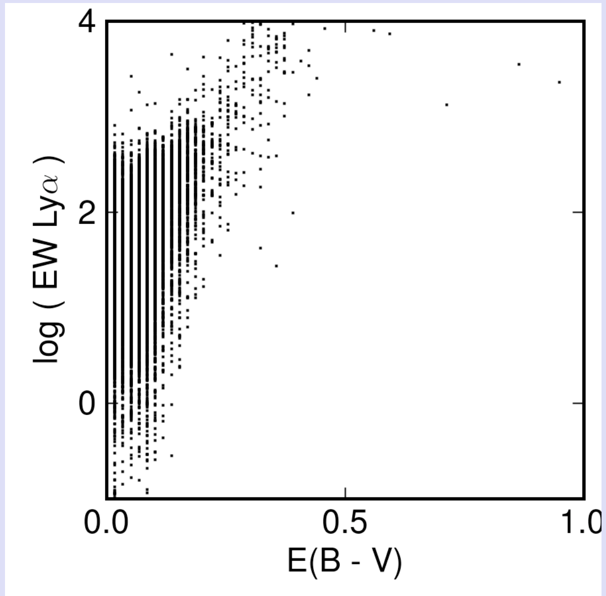
Haro 11

IRAS 08





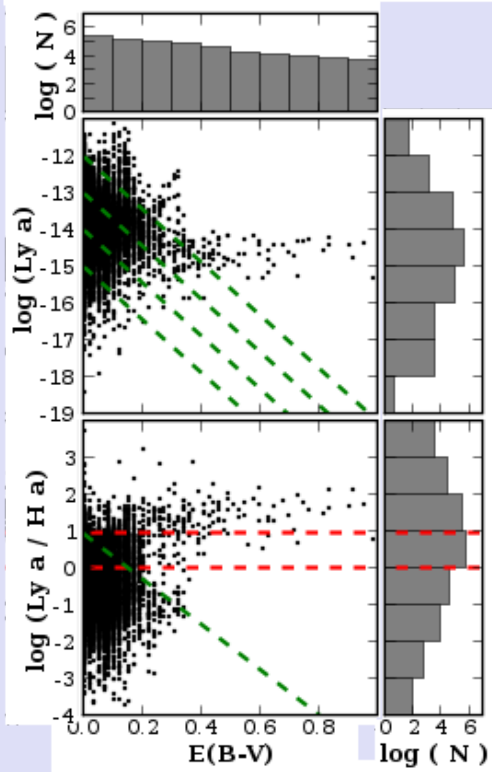
NGC 6090

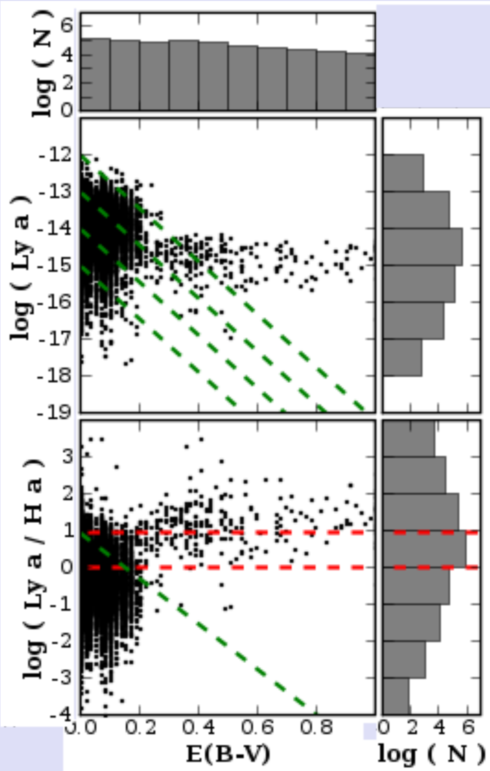


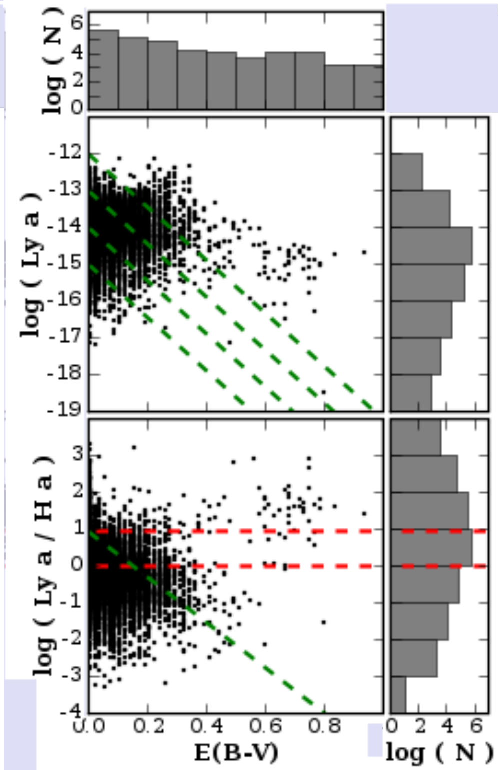
ESO 338

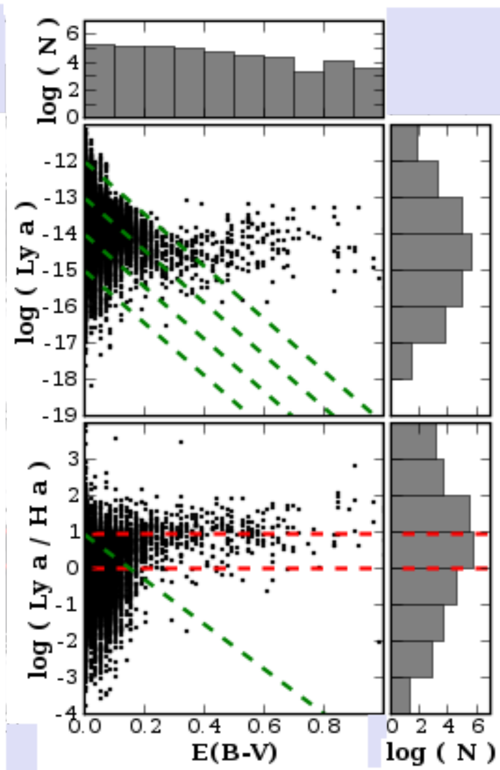
Results: local E(B-V) correlations?

Haro 11 | IRAS 08 | NGC 6090 | ESO 338



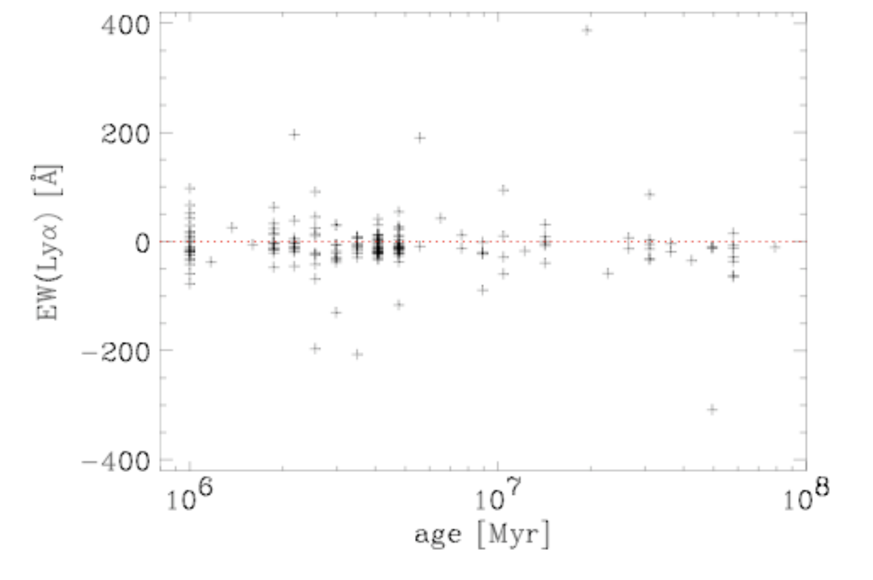


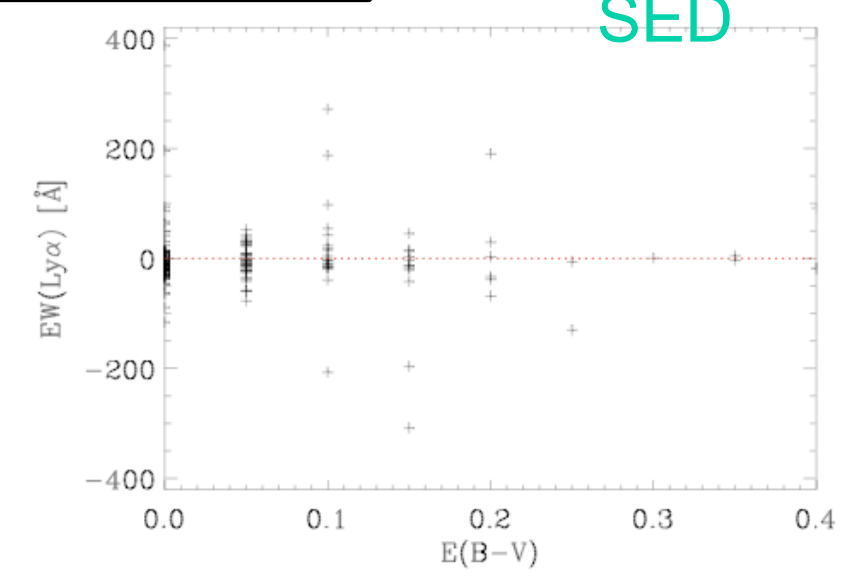


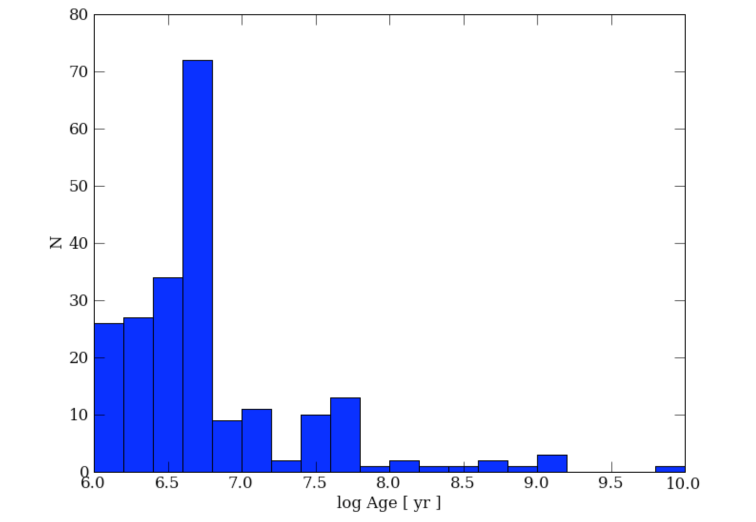


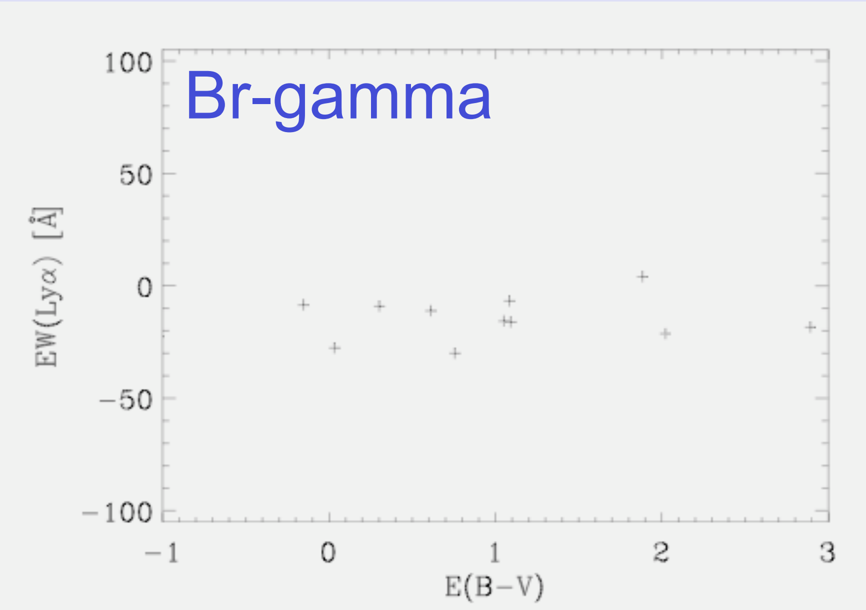
Super Star Clusters (SSCs) in ESO 338-04

Young SSCs provide the ionising luminosity, so…



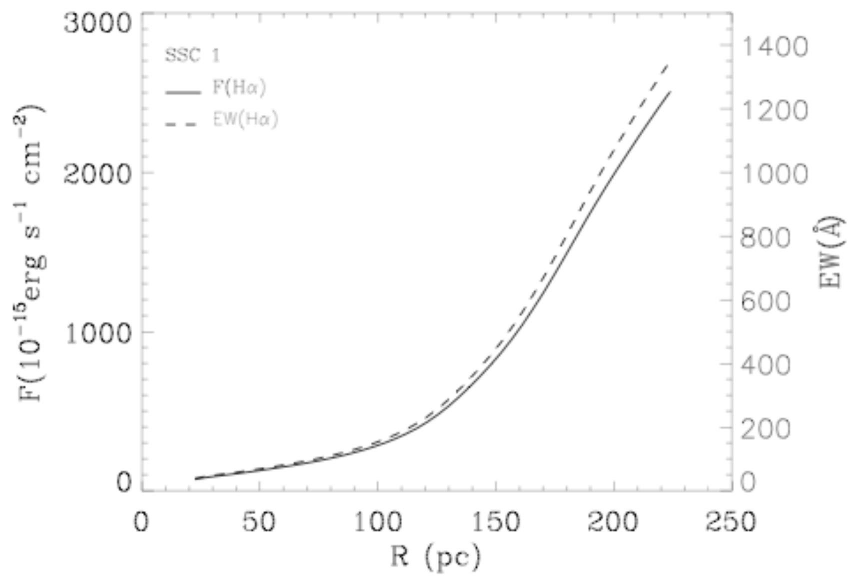


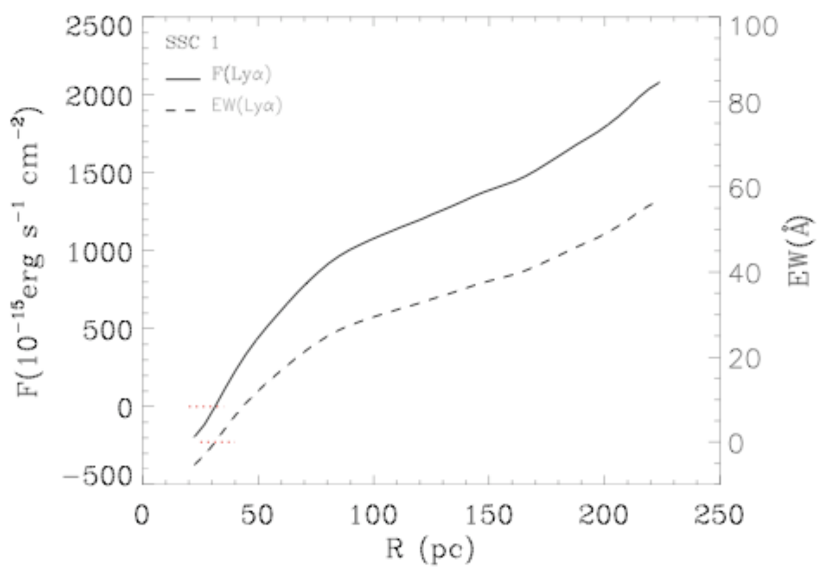




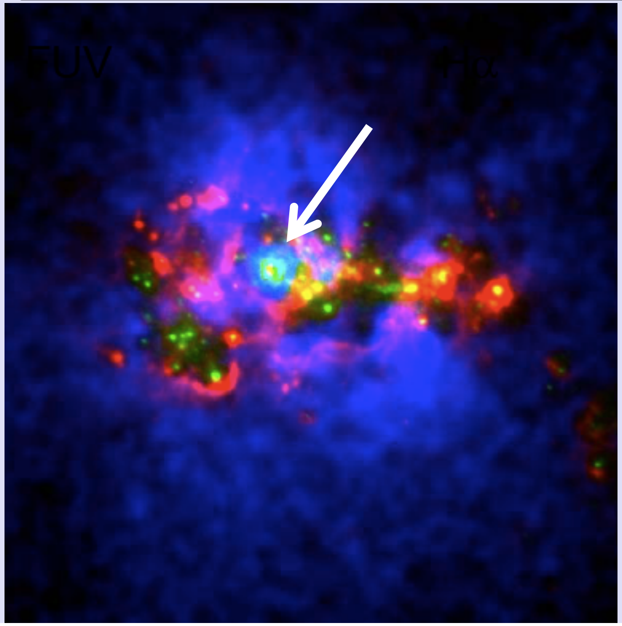
Adamo, Hayes, Östlin et al in prep

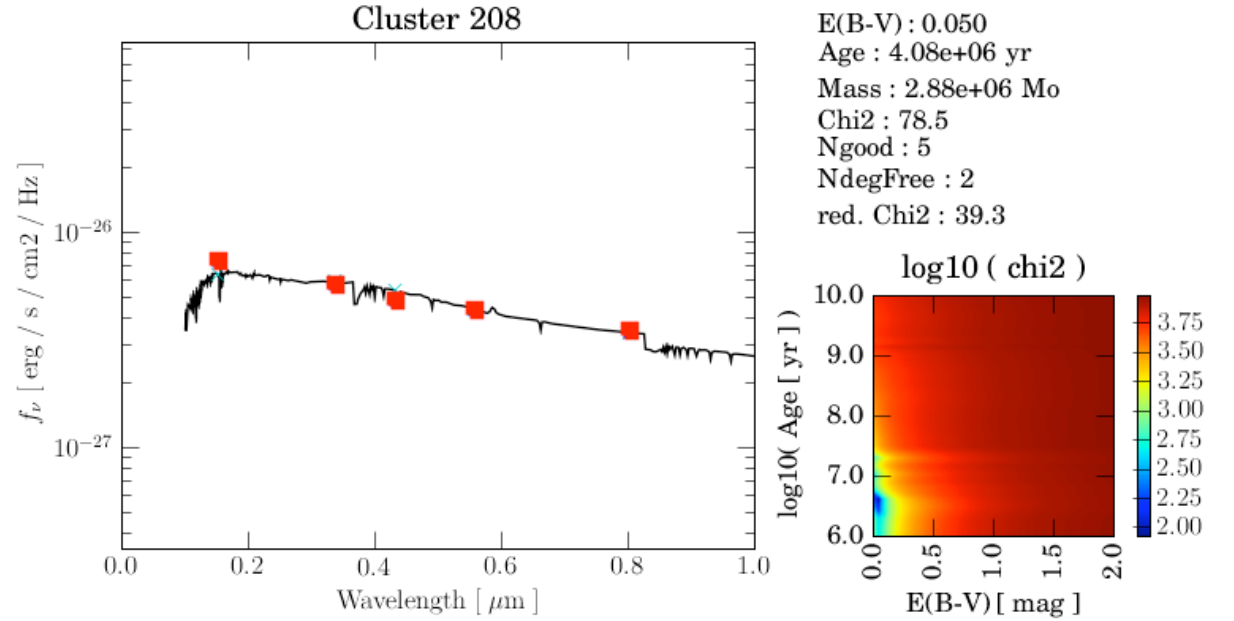
SSCs in ESO 338-04 - whats going on?



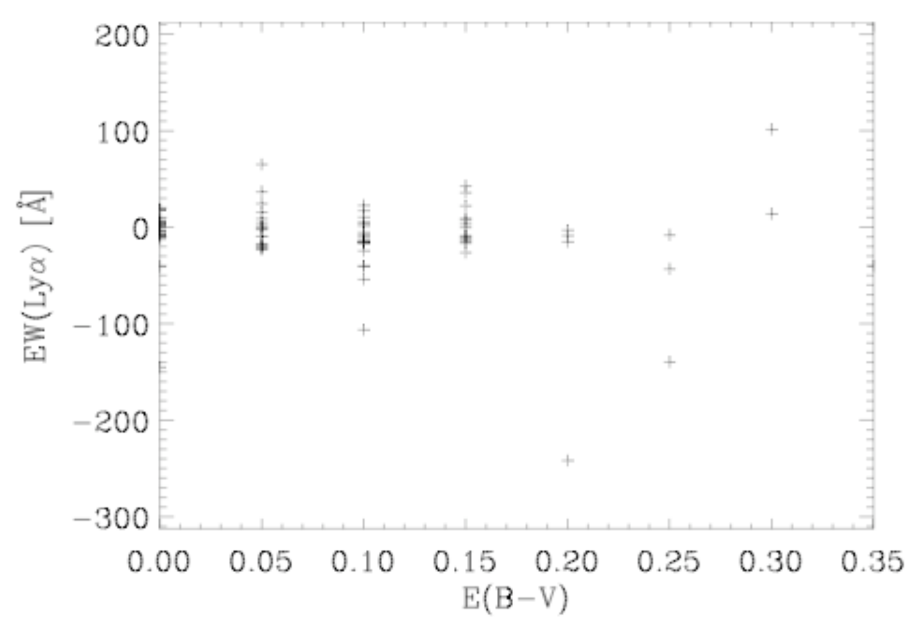


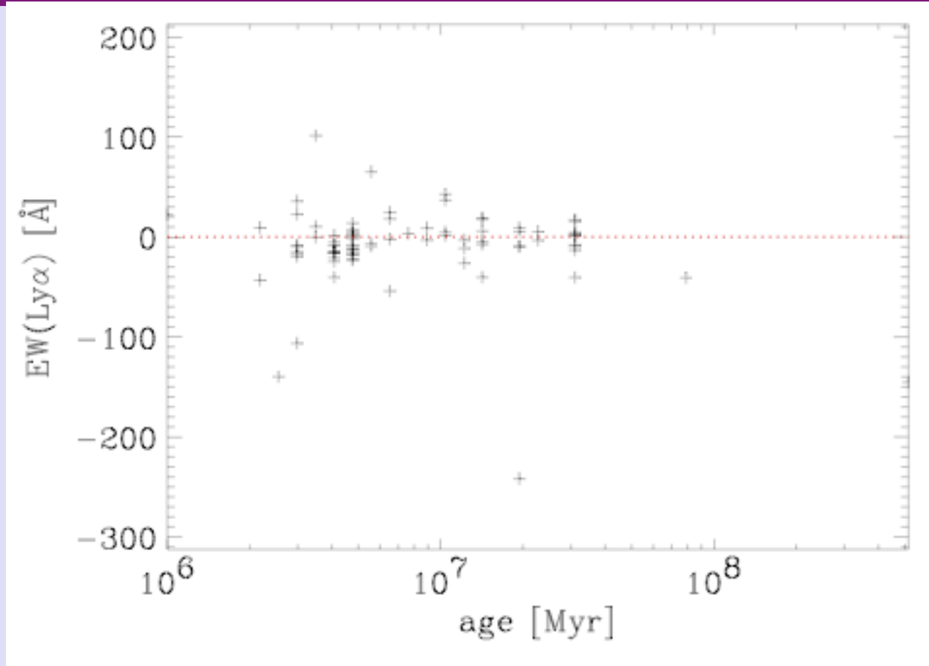
Lya rises faster than Ha producing Lya/Ha>10 at high surface brightness!
Scattering in the wind cone along the line of sight (see Verhamme's talk)





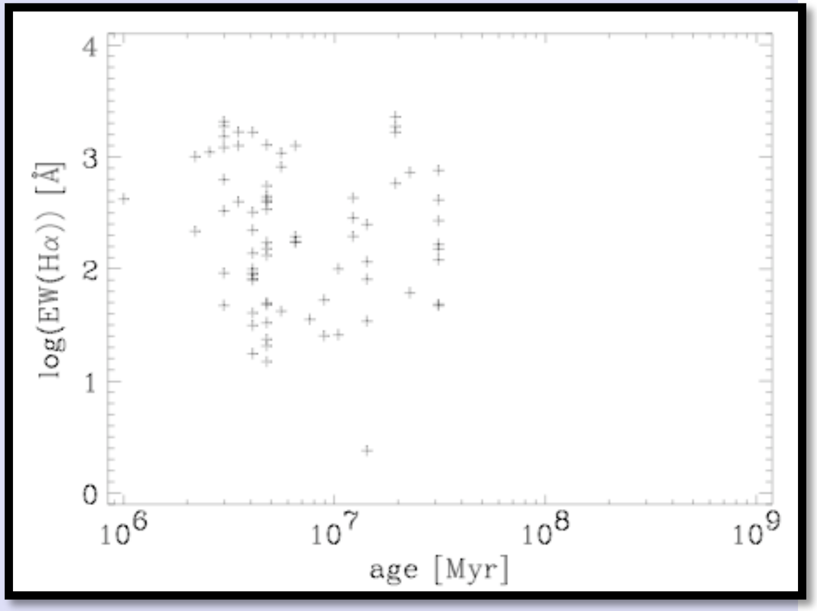
SSCs in Haro11



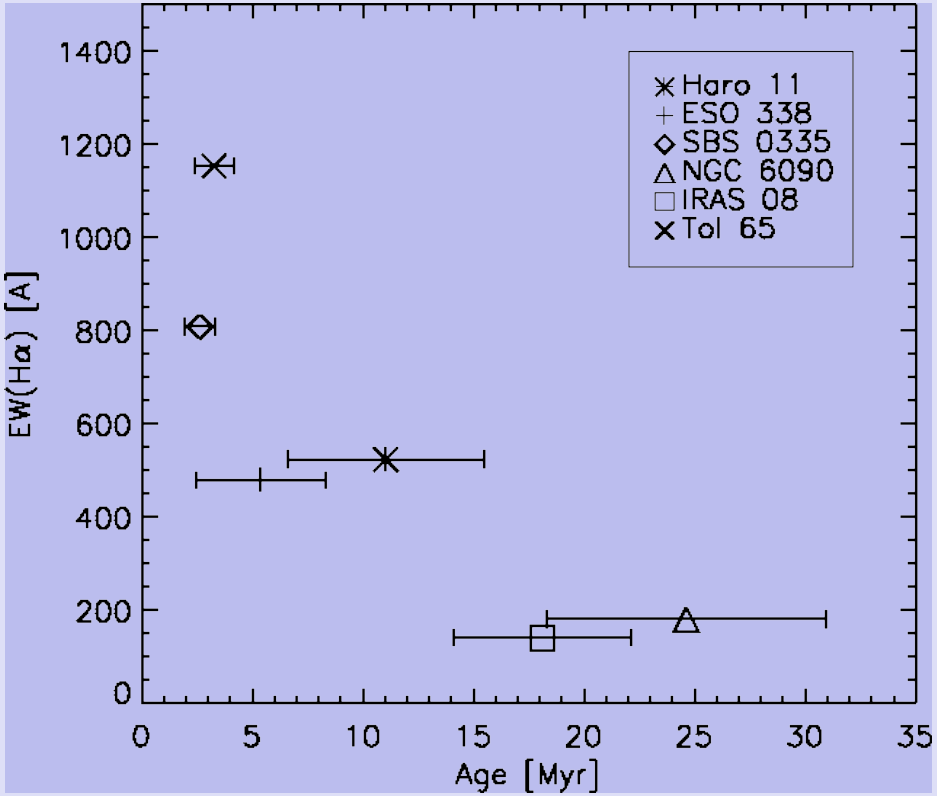


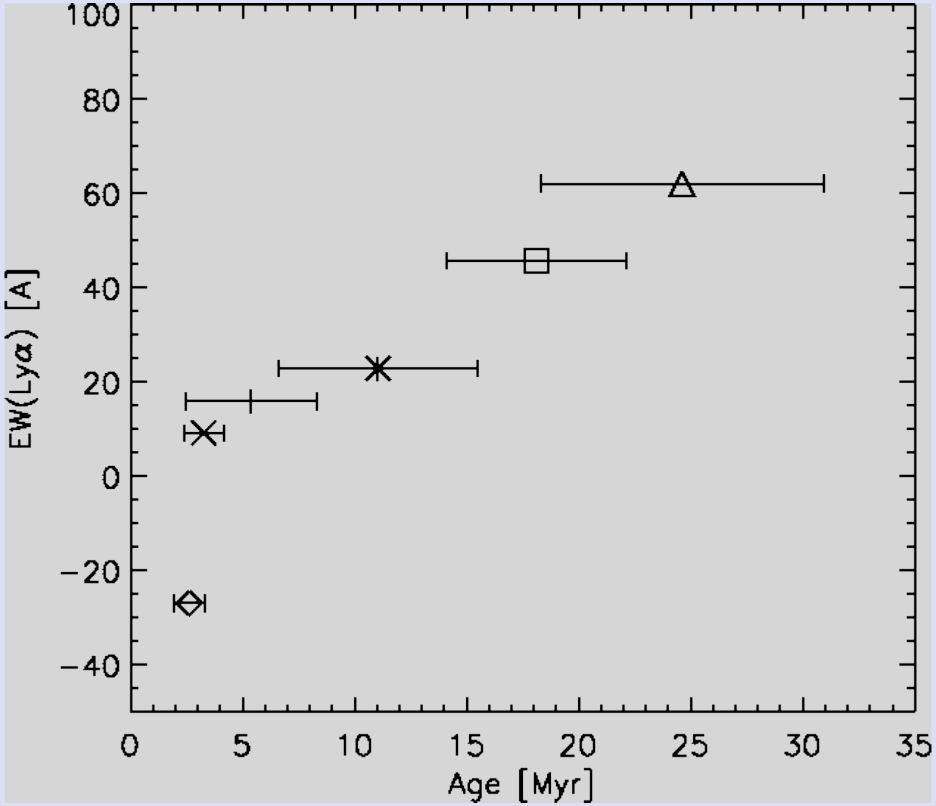
Again, no obvious correlations.
Most Lya photons have no idea of the local E(B-V) in the gas.

At low ages we see high positive and negative EW(Lya)
-some strongly emitting, some strongly absorbing



Lyman alpha escape an evolutionary process?





Global luminosity weighted ages of starburst young pop from 2pop fit (Atek et al. 2008)
Young sources have a hard time getting Lyα out

A further look at nebular dust though HI-lines

HI-recombination line images:

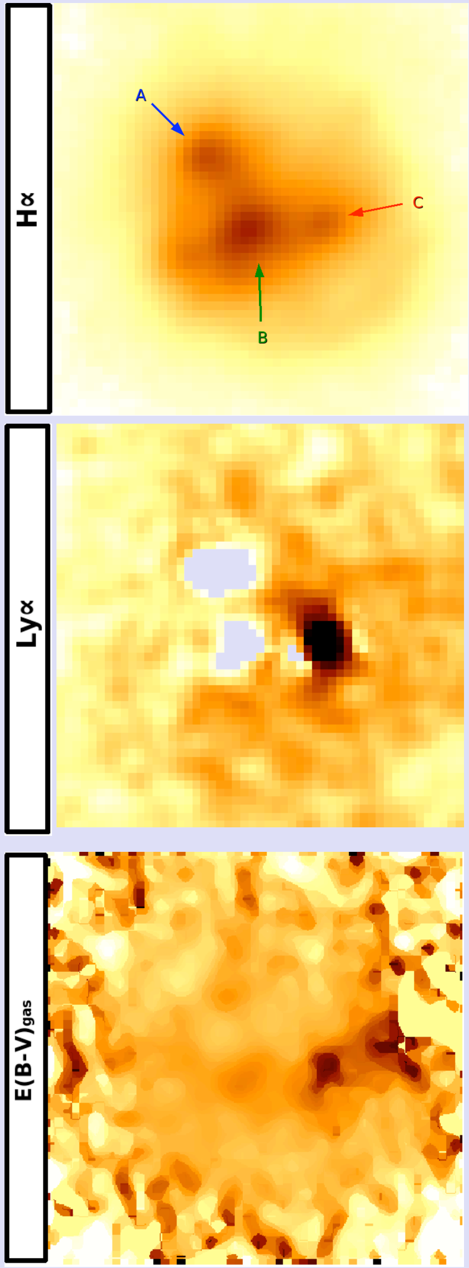
HST/ACS: Lyα and Hα

ESO/NTT: Hα and Hβ, full sample, 1” resolution (Atek et al. 2008)

For ESO 338-04 and Haro11: VLT/NACO Brγ
Resolution ≈ HST

For SBS 0335-052 archival HST/NICMOS Paα (Thompson et al 2006, Reines et al. 2008)

Results ESO/NTT Hα/Hβ: Haro 11 (Atek et al 2008)



Lya and Ha *vs.* dust distribution :

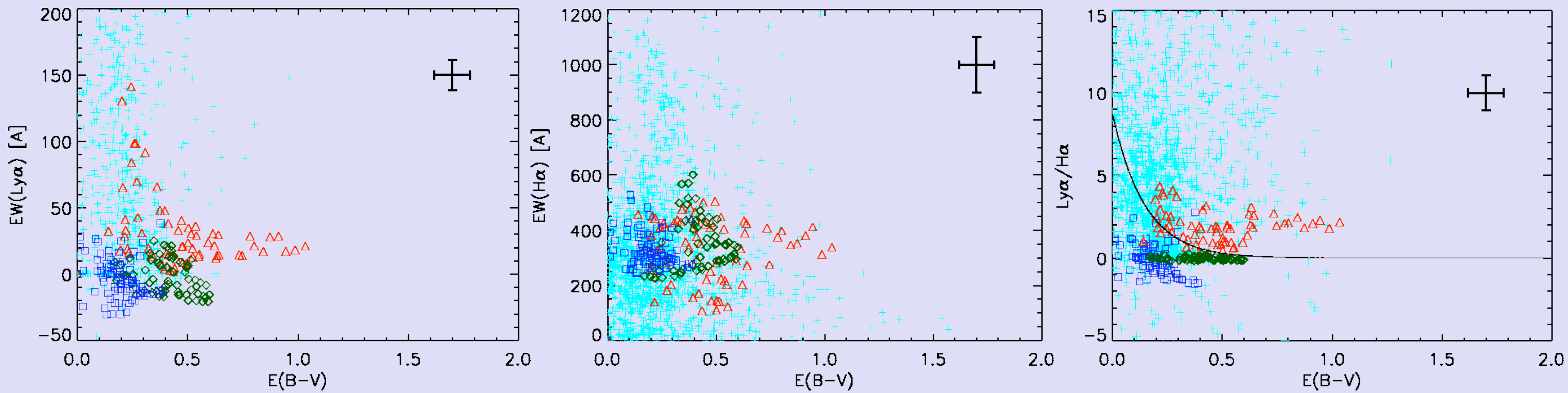
- Lya does not resemble Ha nor FUV image
- Blended emission and absorption

Lya seen only in knot C

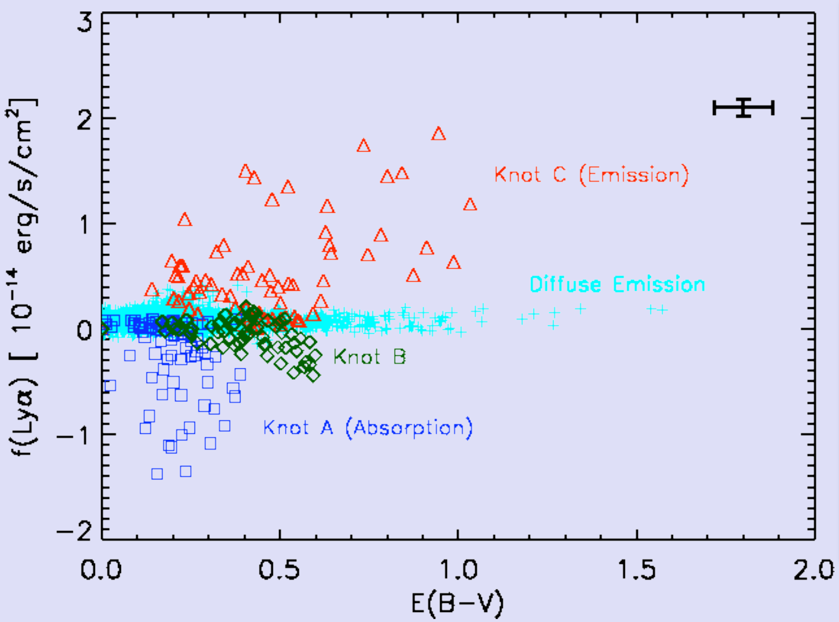
- Lya radiation escapes from the dustiest region

Why dust is not the main regulatory factor ?

Results Hα/Hβ, Haro 11 Regulation factors



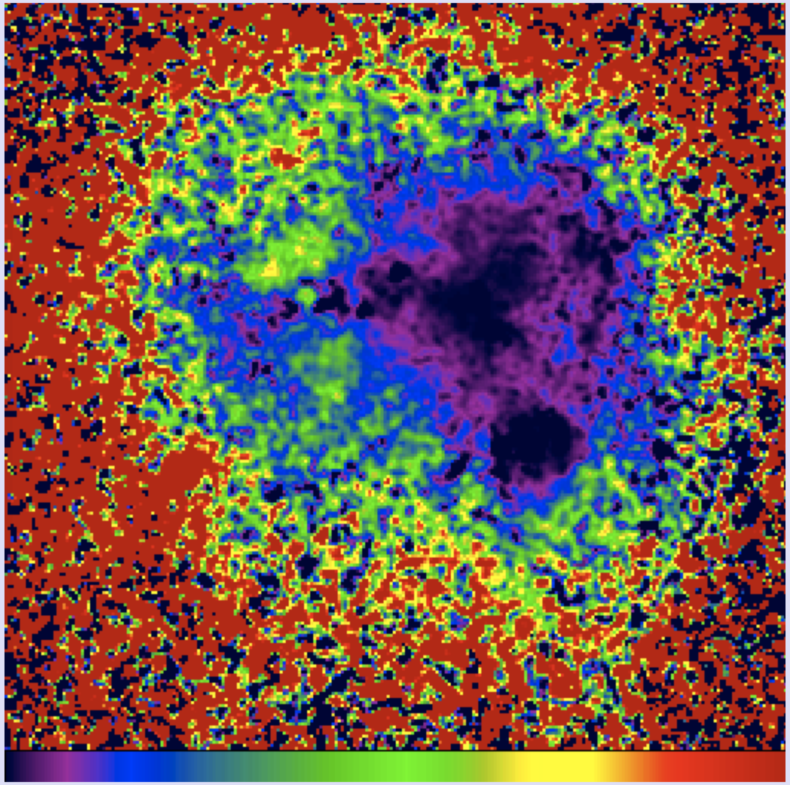
Atek et al. 2008



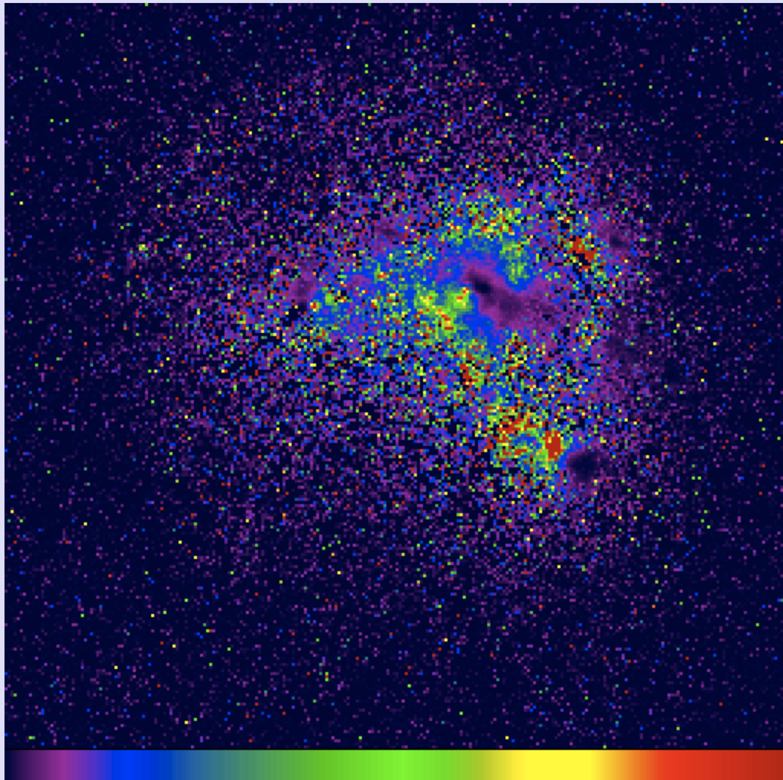
- Diffuse emission component independent of the dust
- Emission from knot C with E(B-V) ~ 0.4
- Absorption from knot A with E(B-V) ~ 0.2
- EW(Lyα) *vs* EW(Hα)
- Lyα/Hα above the theoretical value (8.7 case B extinction corrected)

→ Enhanced Lyα/Hα ratio !!

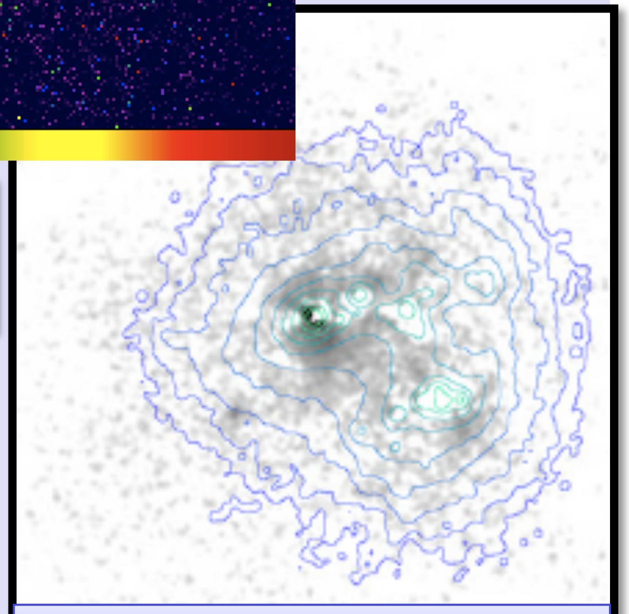
Preliminary results VLT/NACO Brγ, Haro 11



Lyα/Hα, range [0,10]



Hα/Brγ [0,100]
10➔ E(B-V)=1

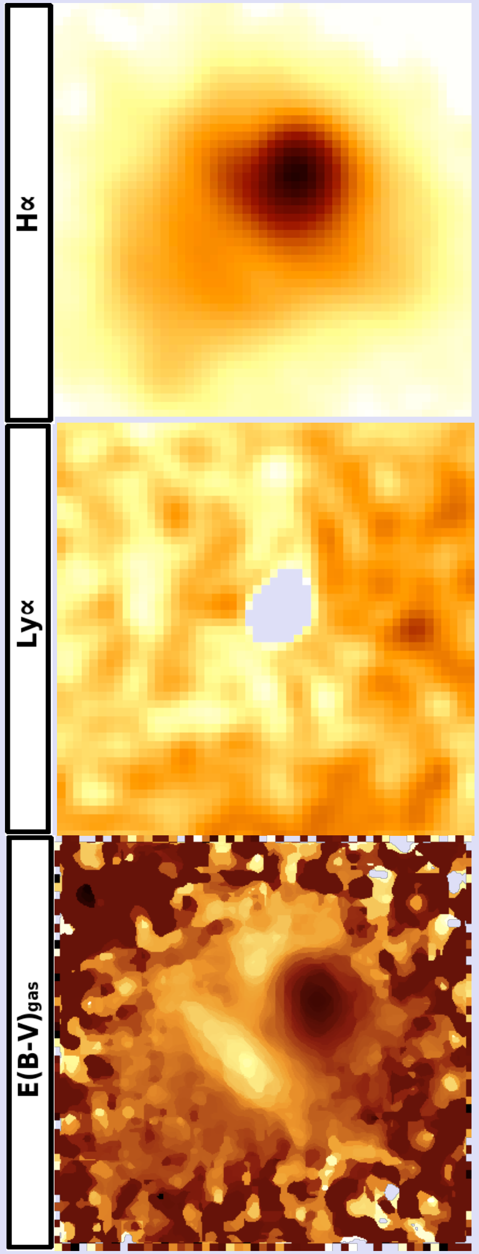


Lyα + UV contour

Effective resolution 0.1”
Combining with HST Lyα & Hα

No clear correlation of Lyα/Hα with E(B-V)

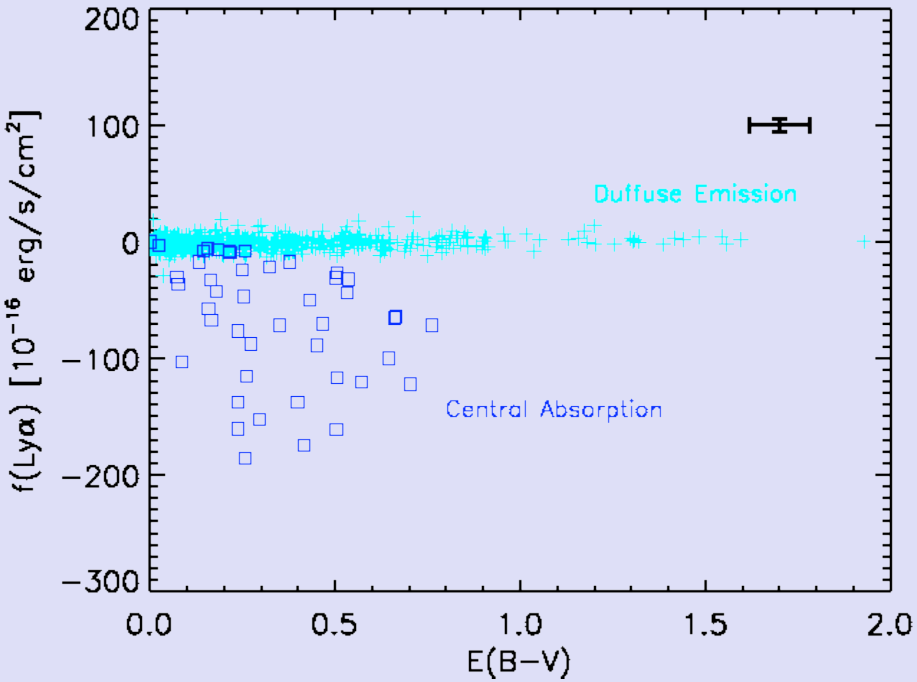
Results ESO/NTT Hα/Hβ: SBS 0335-052



Lya and Ha *vs.* dust distribution :

- ✦ Lyα absorption associated with Hα emission
- ✦ Lyα absorption coincident with dusty region

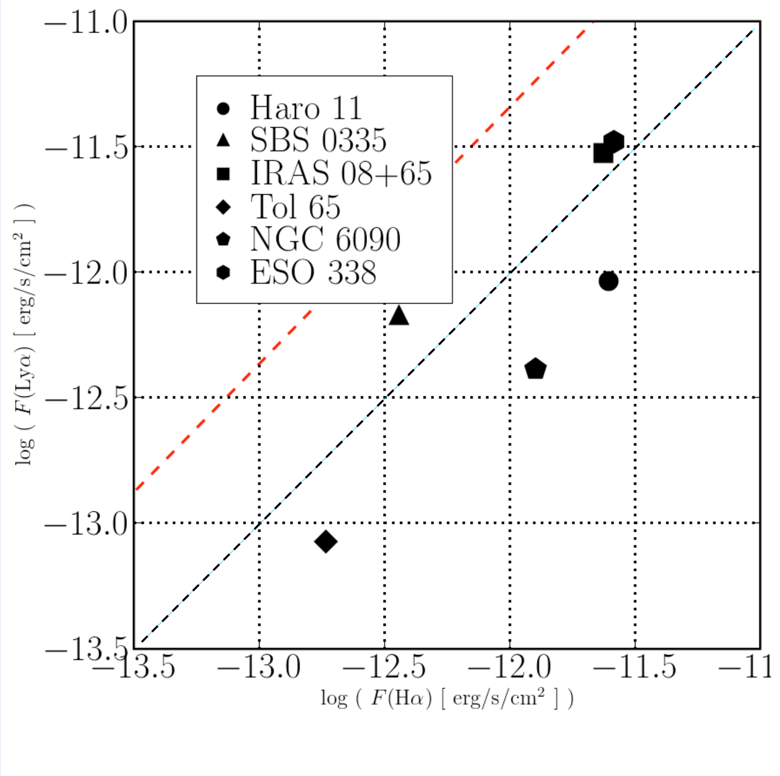
Why dust is now important for Lya obscuration ?



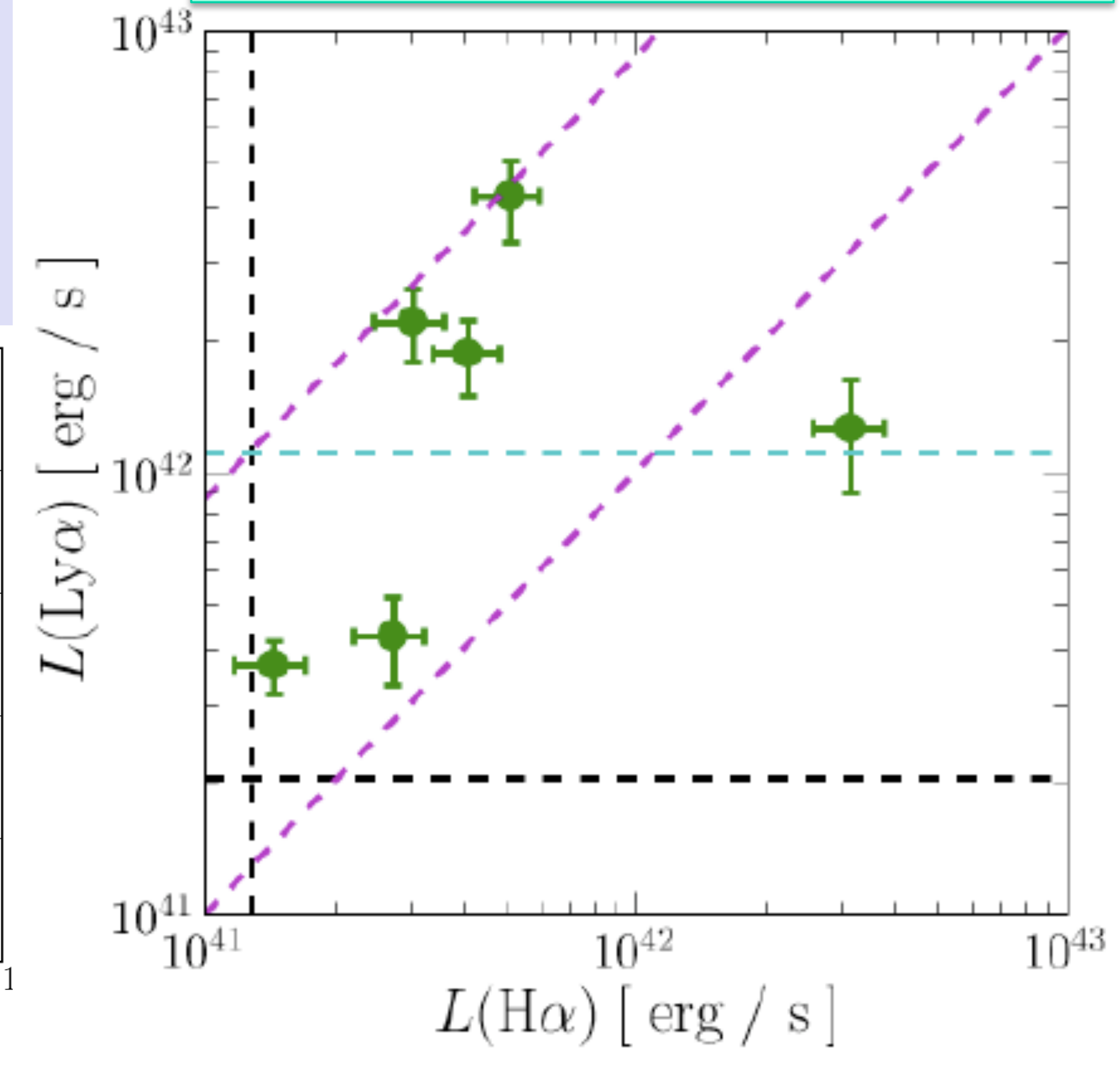
NB Hα/Paα in the dusty region fairly normal; Reines et al (2008)

Results: global

Name	F(Ha)	F(Lya)
	10^{-13} erg/s/cm^2	
Haro 11	24	9.0
SBS 0335	3.4	-4.3
IRAS 08	23	31
Tol 65	1.8	1.3
NGC 6090	13	5.1
ESO 338	25	46

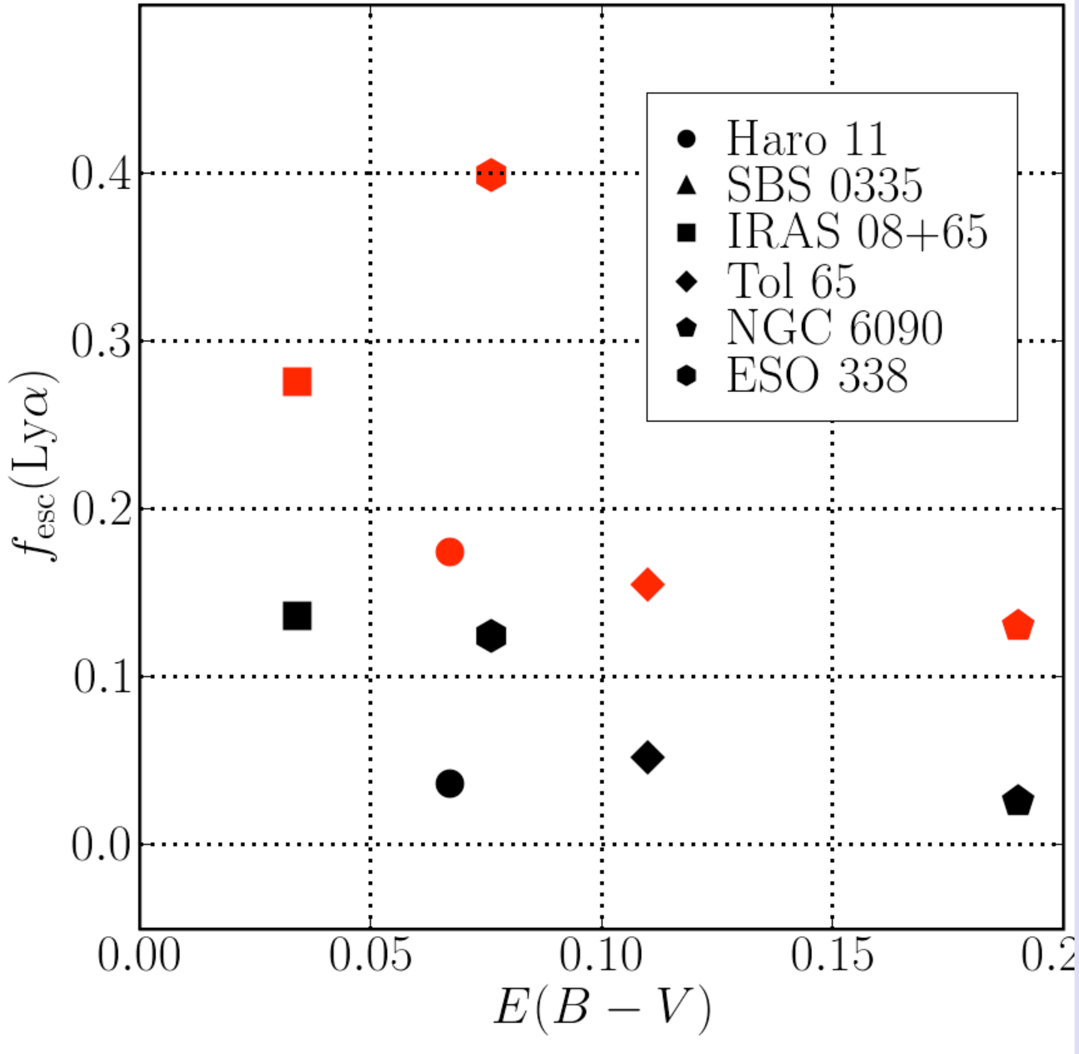


Results from z=2, DoubleBlind
See Hayes' talk



Results: global

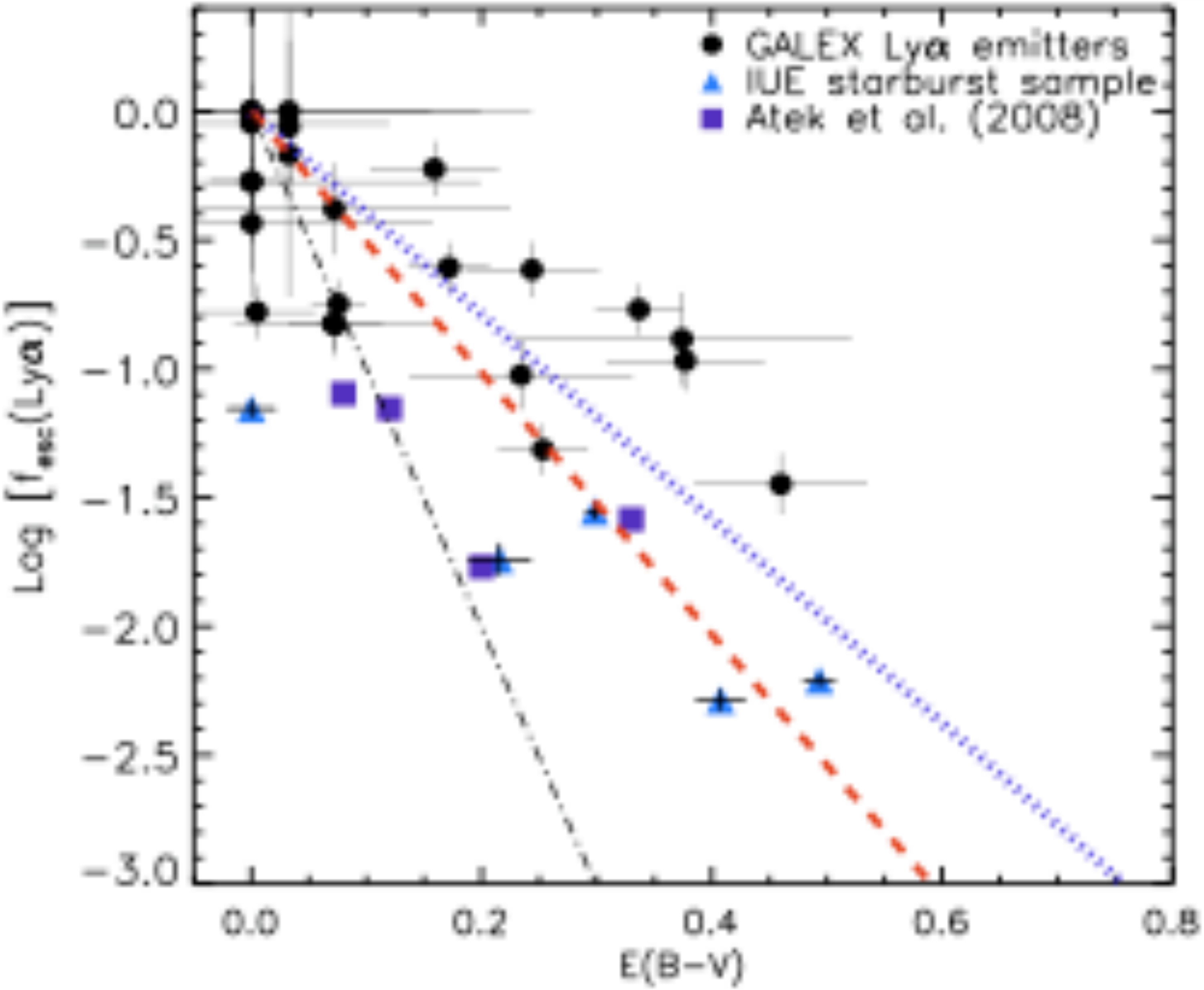
Name	E(B-V)	f_{esc}	$f_{esc,c}$
Haro 11	0.07	0.037	0.18
SBS 0335	0.04	-0.20	0.28
IRAS 08	0.03	0.14	0.28
Tol 65	0.11	0.053	0.16
NGC 6090	0.19	0.027	0.13
ESO 338	0.08	0.13	0.40



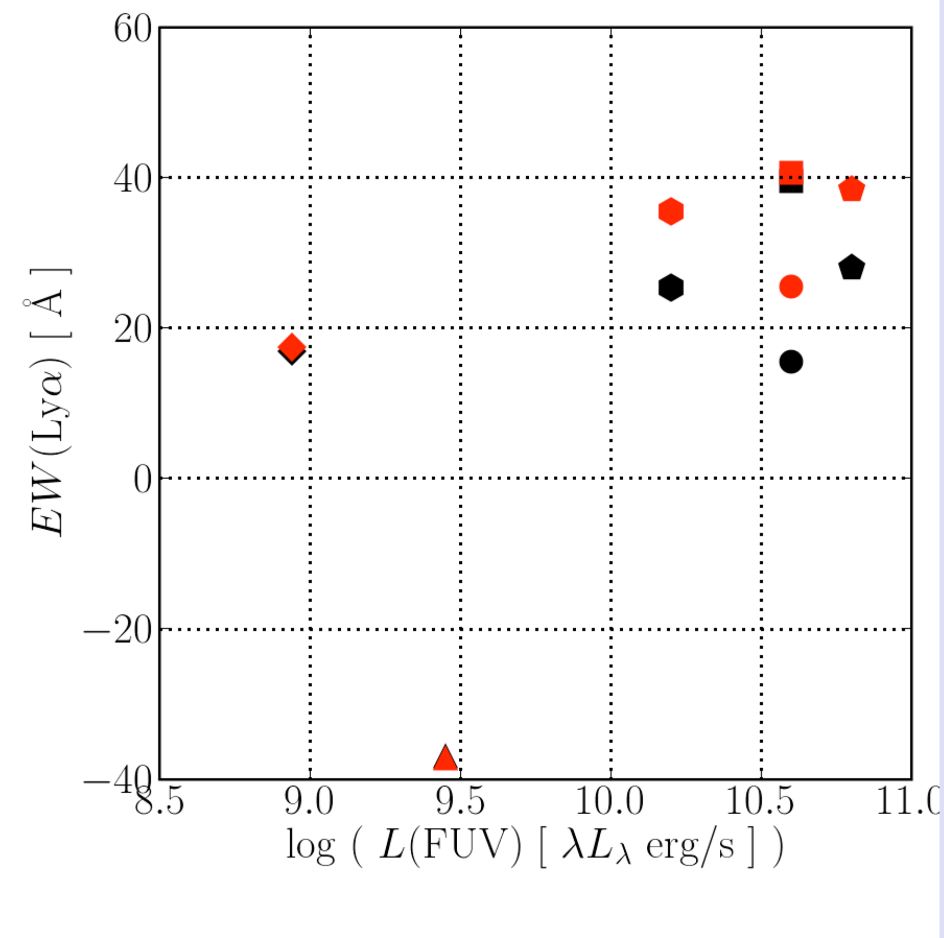
Results: global

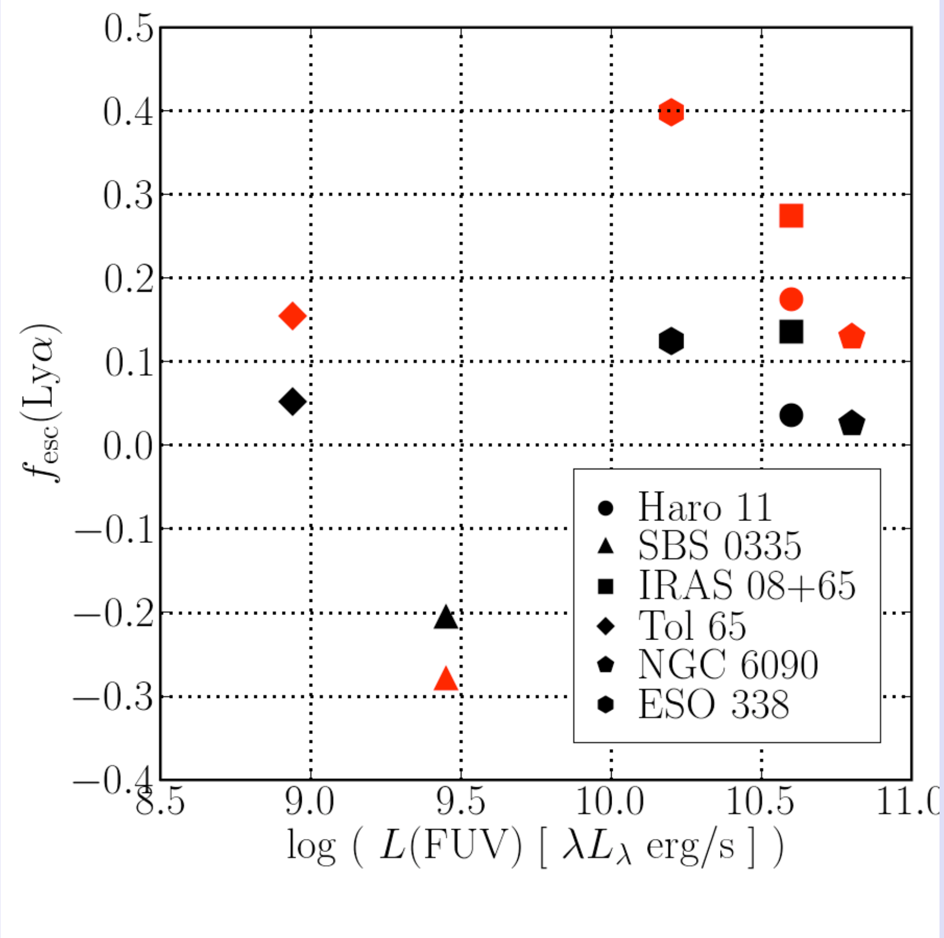
Comparison with Galex z~0.3 sample
See poster by Atek (poster number 1)
arXiv:0906.5349

Name	E(B-V)
Haro 11	0.07
SBS 0335	0.04
IRAS 08	0.03
Tol 65	0.11
NGC 6090	0.19
ESO 338	0.08



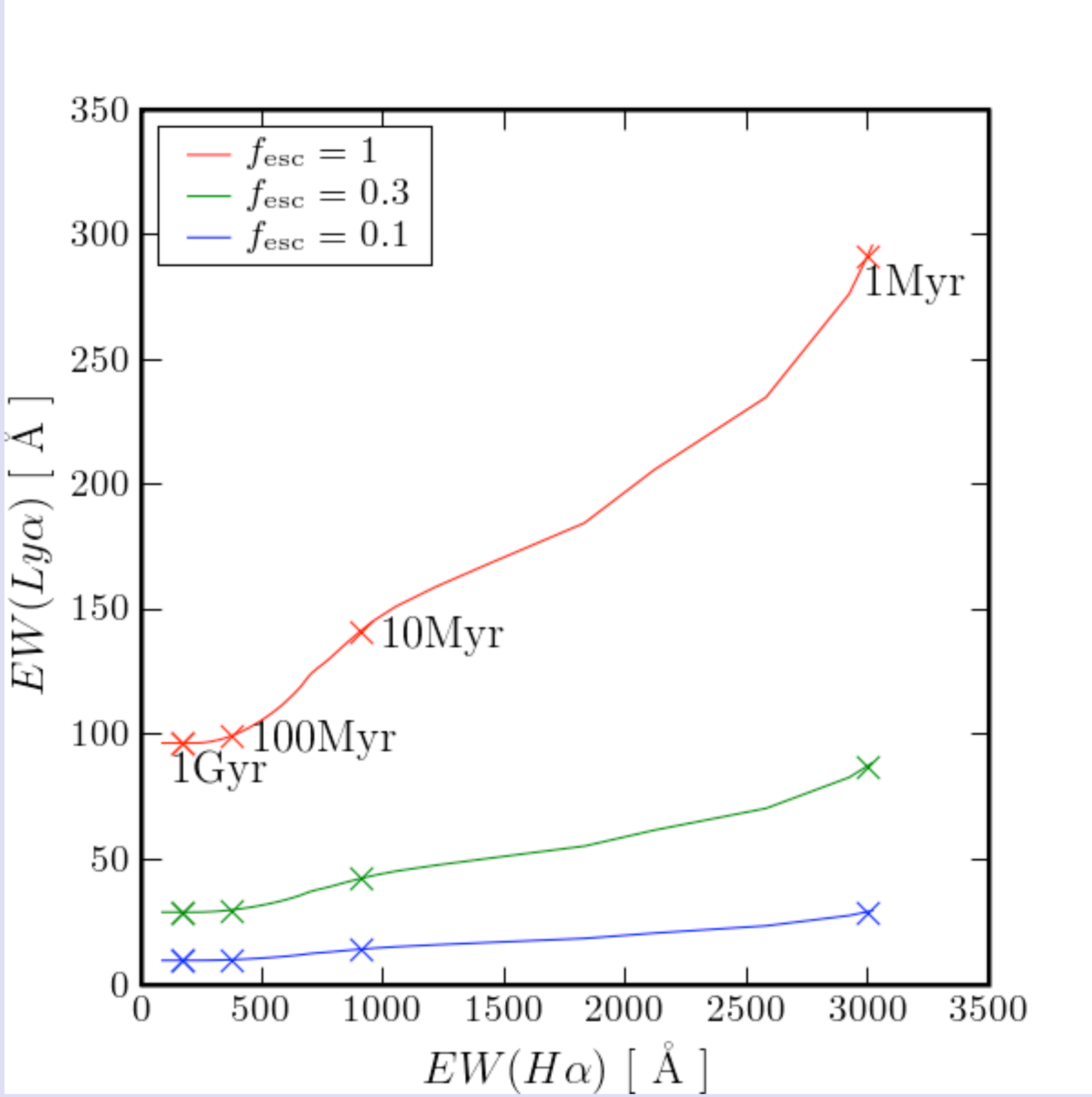
Results: global





Results: global

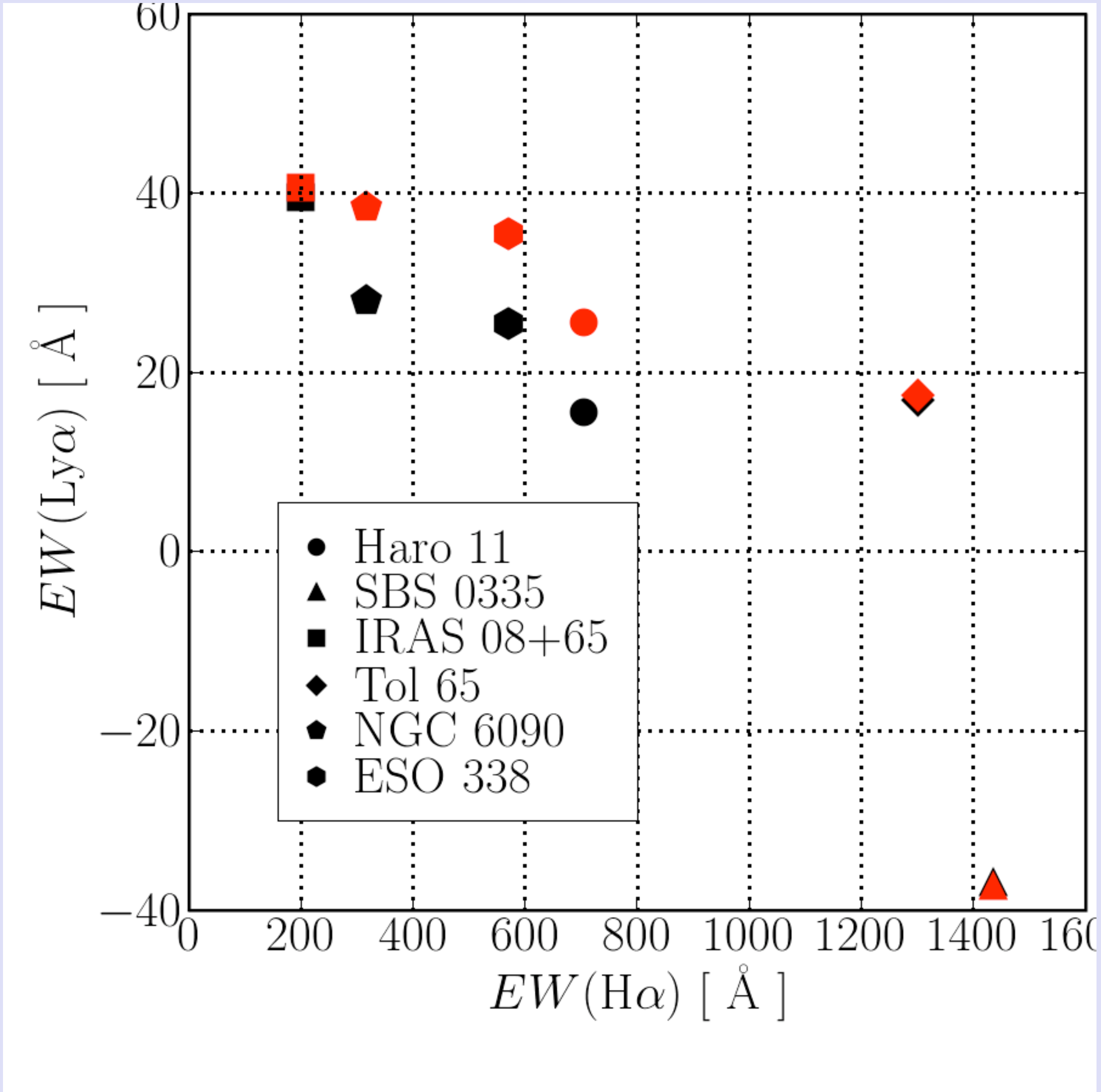
Name	W(Hα) [Å]	W(Lyα) [Å]
Haro 11	705	15.6
SBS 0335	1434	-36.8
IRAS 08	195	39.2
Tol 65	1300	15.5
NGC 6090	314	28.3
ESO 338	570	28.1



SB99 (Leitherer et al.) prediction

Results: global

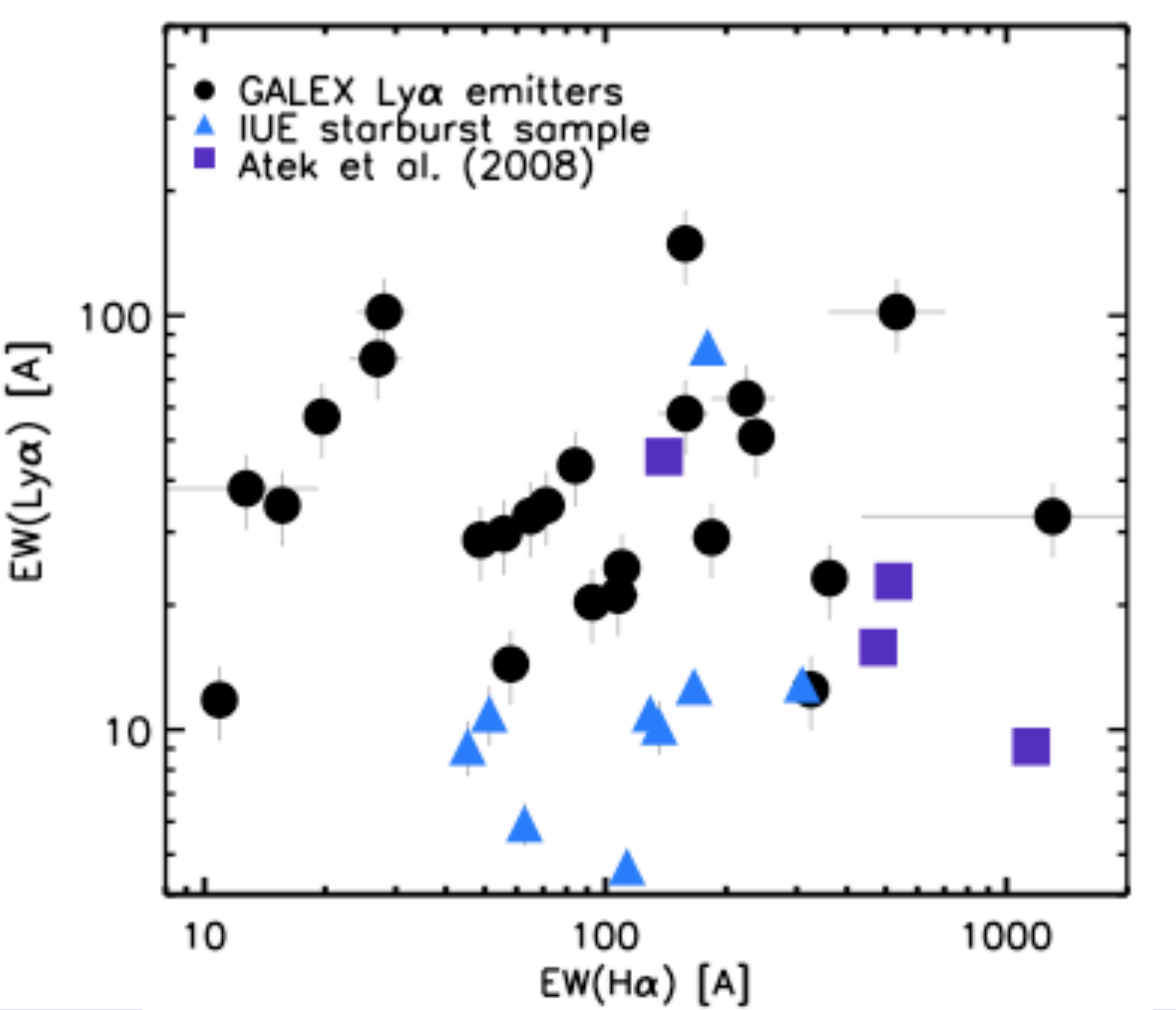
Name	W(Hα) [Å]	W(Lyα) [Å]
Haro 11	705	15.6
SBS 0335	1434	-36.8
IRAS 08	195	39.2
Tol 65	1300	15.5
NGC 6090	314	28.3
ESO 338	570	28.1



But EWs anticorrelated!

Results: global

Name	W(Hα) [Å]	W(Ly [Å]
Haro 11	705	15.6
SBS 0335	1434	-36.8
IRAS 08	195	39.2
Tol 65	1300	15.5
NGC 6090	314	28.3
ESO 338	570	28.1



Comparison with Galex z~0.3 sample
Atek et al 2009 in prep

Summary of observational results

- First calibrated Lyα maps produced
  - spatial resolution ~10 - 20 pc
  - available at: http://ttt.astro.su.se/projects/Lyman-alpha/
  - Östlin et al 2009, AJ in press (arXiv0803.1174)

- Substantial evidence for Lyα resonant scattering presented:
  - morphologies, scattering halos, extended emission
  - Local super-recombination values
  - Lyα spatially offset from Hα and UV
  - Lyα emission from old and/or dusty regions
  - No direct correlation with nebular dust parameters
  - Close to ionising sources, EW(Lyα) scatter between +/- 200Å

- Low escape fractions (< 20%) -- dust corrections fail (<50%)

- Anti-correlation between Hα and Lyα equivalent width???

- Demonstrates the need for a detailed, statistically significant investigation of local well resolved galaxies

Reionization with Multifrequency Datasets, Stockholm, August 17-21, 2009

Meeting on combining information of different datasets for studying reionization: 21cm, Ly-a, QSOs, CMB, backgrounds.

Invited speakers: Ger de Bruijn, Gil Holder, Ilian Iliev, Matt Jarvis, Nobunari Kashikawa, Antony Lewis, Adam Lidz, Miguel Morales, Jochen Weller

Organizers: Garrelt Mellema, Göran Östlin, Saleem Zaroubi, Axel Brandenburg

Venue: AlbaNova University Center, Stockholm, Sweden

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