LI(N)ERs and Lyman continuum photon escape

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Outline

- Warm Interstellar Medium (WIM) in early-type galaxies (ETGs) & proposed mechanisms for its excitation

- Analysis of integral field spectroscopy data for 32 ETGs from the CALIFA survey (Papaderos+13, Gomes+16)

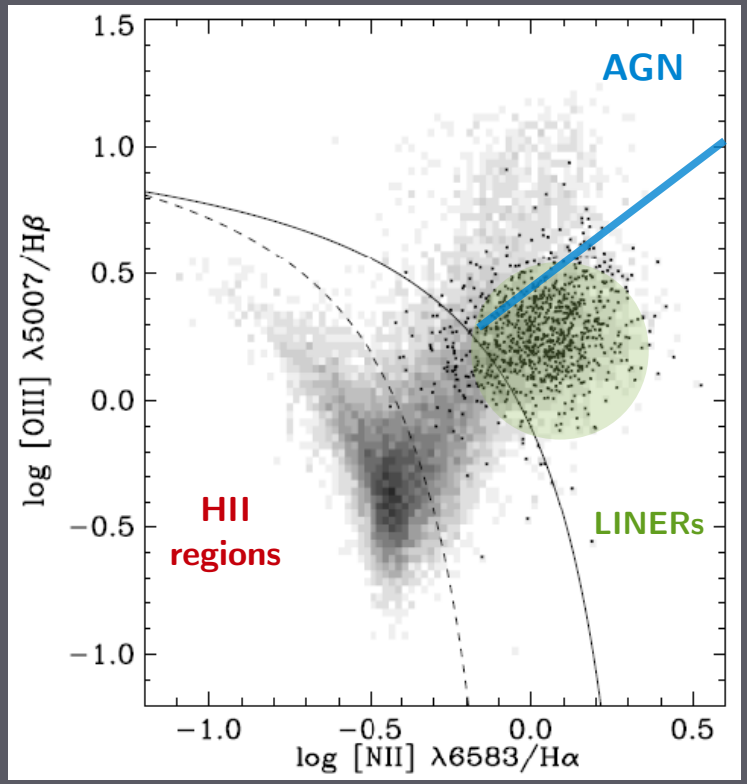
- Evidence for Lyman continuum photon escape from ETGs ... and its implications for our understanding of accretion-powered nuclear activity in ETG/LINERs

Warm interstellar medium in early-type galaxies (ETGs)

- ~3/4 of early-type galaxies (ETGs) contain a warm ISM (WIM) component (e.g., Demoulin-Ulrich et al. 1984, Kim 1989, Trinchieri & di Serego Alighieri 1991, Sarzi et al. 2006,2010, Finkelman et al. 2010, Annibali et al. 2010, Kehrig et al. 2012, Yan & Blanton 2012).

- Nebular emission in LINER/ETGs is typically very faint (nuclear EW(Hα) ranges from $\lesssim$0.5 Å to ~15 Å, median $\simeq$ 2.4 Å).

- The majority of ETGs with detected nebular emission are spectroscopically classified as **LINER** (low-ionization nuclear emission-line regions; Heckman 1980)



●: Photometrically selected (red) LINER/ETGs $0.09 \leqslant z \leqslant 0.1$ (Yan & Blanton 2012)

Kewley et al. (2001)

Kauffmann et al. (2003)

Stasińska et al. (2008)

Gas excitation mechanisms in ETGs

- Proposed gas excitation mechanisms in ETG/LINERs:

a) "weak" (low-luminosity) AGN (e.g., Ferland & Netzer 1983, Ho 2008): geometrically thick, radiatively inefficient accretion flow at low luminosities and accretion rates.

b) low-level star formation
(e.g., Trager et al. 2000, Schawinski et al. 2007, Kaviraj et al. 2008)

c) fast shocks (Dopita & Sutherland 1995, Allen et al. 2008)

d) hot post-AGB ($\geq$100 Myr) stars (HOLMES: hot low-mass evolved stars)
(e.g., Trinchieri & di Serego Alighieri 1991, Binette et al. 1994,
Stasińska et al. 2008, Cid Fernandes et al. 2010/11; Eracleus et al. 2013)

Gas excitation by the pAGB component

Hot post-AGB stars (age ≥ 100 Myr)

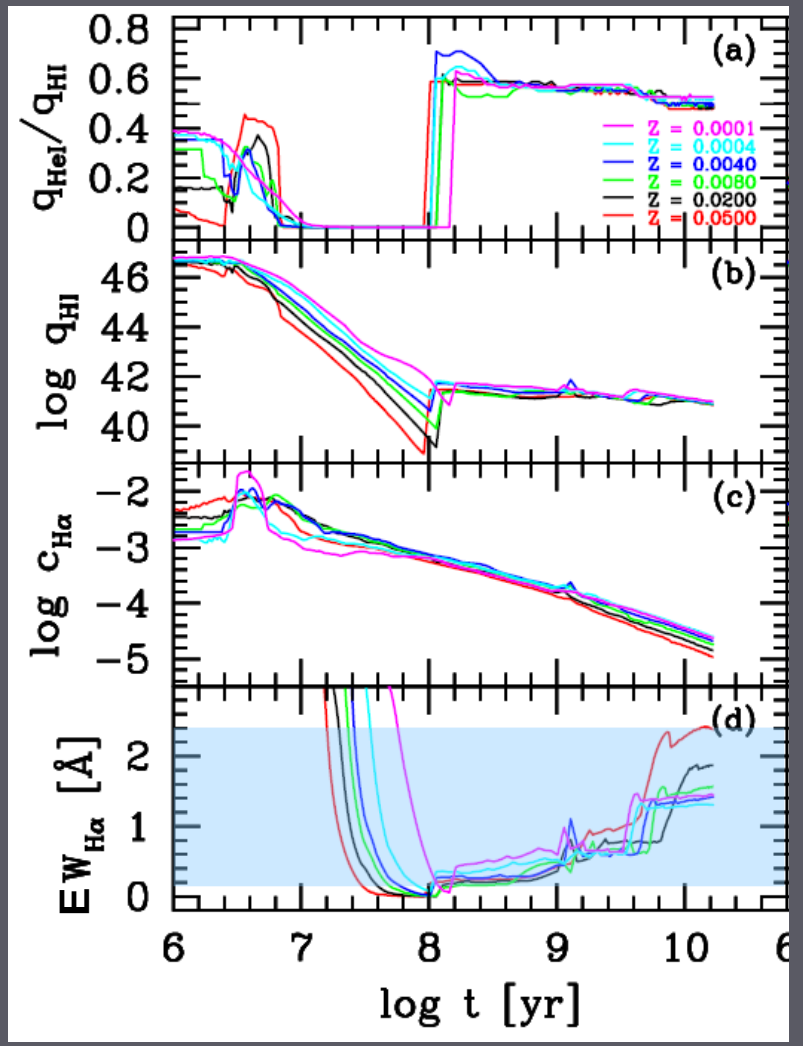
Bruzual & Charlot (2003) models
for an instantaneous burst

Hardness of the ionizing spectrum, as measured by the ratio of HeI to HI ionizing photons

After ~100 Myr, the rate of HI ionizing photons settles to $\sim 10^{41}$ s^{-1} $M_{\odot}^{-1}$

Continuum level around the Hα line

Hα equivalent width
EW(Hα) : 1-2 Å for t≳1 Gyr



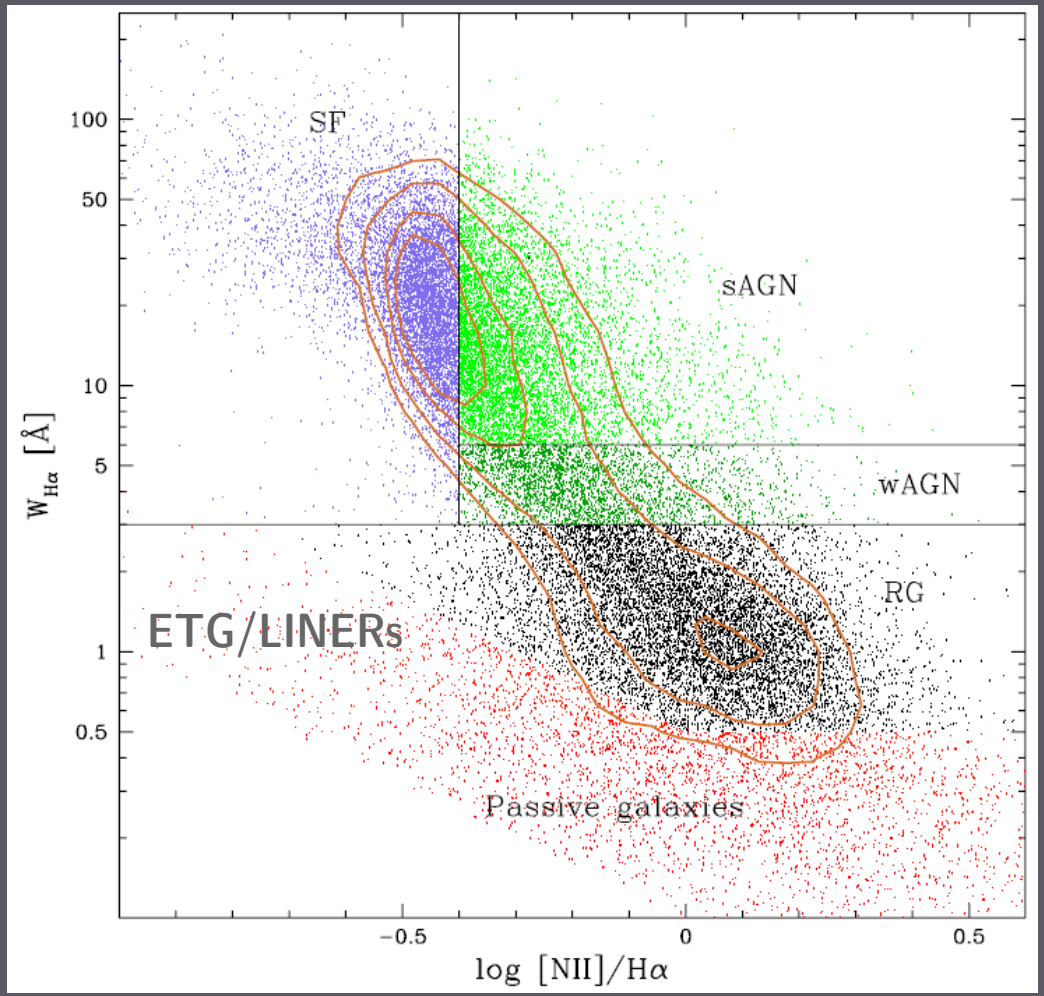
qHI (pAGB): very weak dependence on age and metallicity

Cid Fernandes et al. (2011)

Several recent studies favor pAGB stars as the dominant WIM excitation source in ETG/LINERs
(e.g. Sarzi et al. 2010, Yan & Blanton 2012, Kehrig et al. 2012, Cid Fernandes et al. 2010/11, Singh et al. 2013)

Alternative spectroscopic classification of weak-line galaxies
WHAN: EW (Hα) versus [NII]/Hα

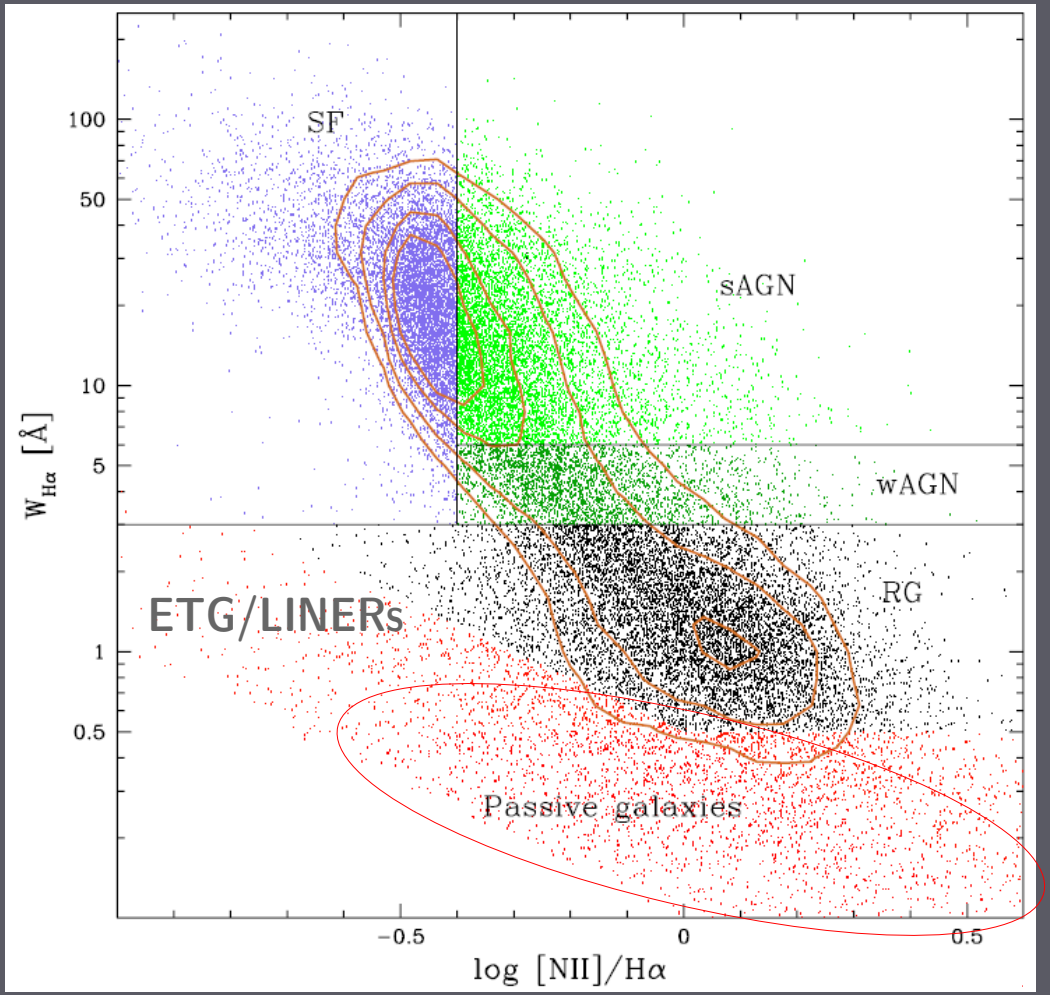
- Strong AGN (sAGN): nuclear [NII]/Hα ratio $\sim$ 1 and EW(Hα) Å $\geq$ 6
- Weak AGN (wAGN): EW: 3 $\leqslant$ EW(Hα) Å $\leqslant$ 6
- Retired galaxies (RGs): LINER-typical nuclear [NII]/Hα ratios ($\gtrsim$1) and 0.5 $\leqslant$ EW(Hα) Å $\leqslant$ 3
- Passive galaxies: in their majority, [NII]/Hα ratios typical of ETG/LINERs and AGNs, but very faint (EW(Hα) $\leqslant$ 0.5 Å) nebular emission
- Cid Fernandes et al. 2011: The WIM excitation in RGs (i.e. ETG/LINERs and weak-line galaxies in general) is due to pAGB stars ➜
  RGs are actually fake AGN.



WHAN classification diagram
Cid Fernandes et al. (2010/11)

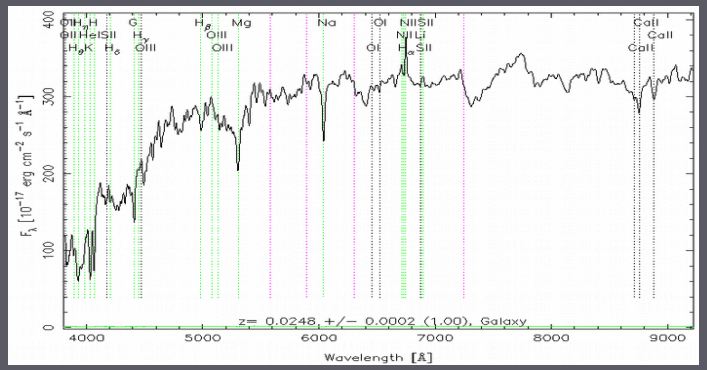
Questions ...

- Why nebular emission is absent in "passive" ETGs? Since they contain some gas and pAGB stars, they should also show diffuse (EW(Hα): 2-3 Å) nebular emission, similar to "retired" galaxies.

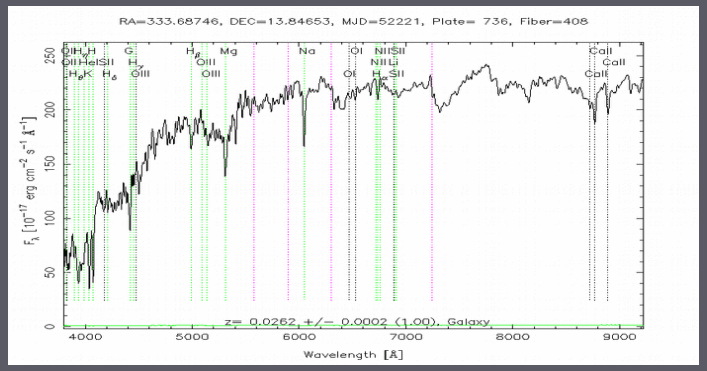


Questions ...

- Is the line faintness (consequently also the spectroscopic classification of ETGs as retired, or passive), unambiguous proof for the absence of an AGN (or a LLAGN)?



"Retired"
(no AGN)



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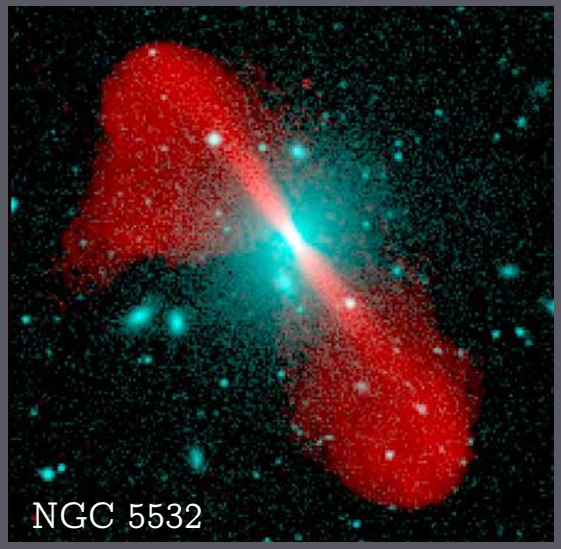
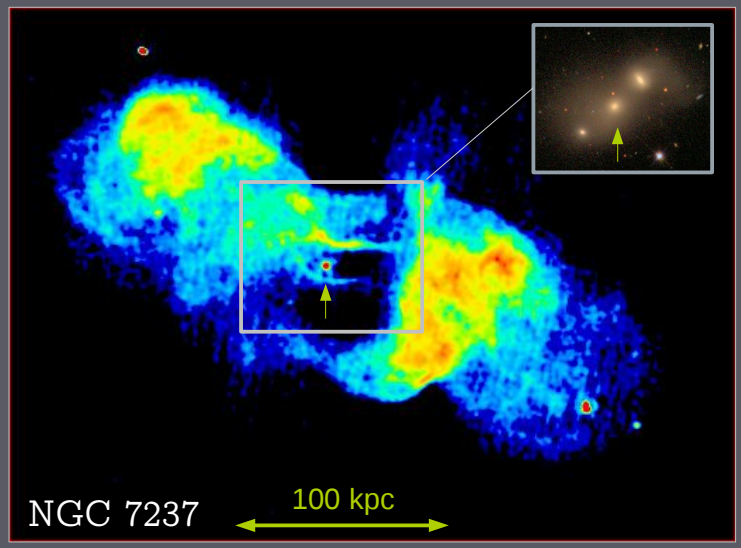
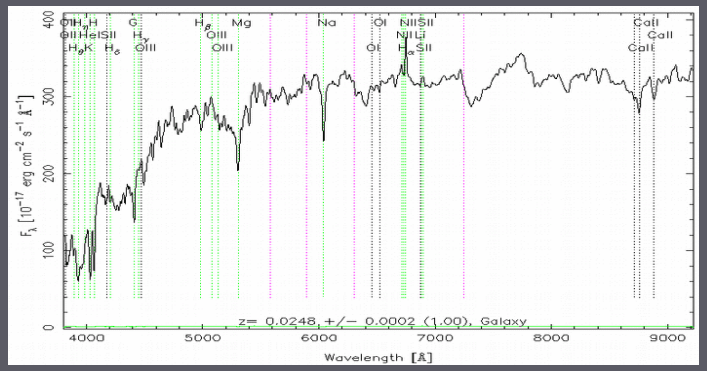
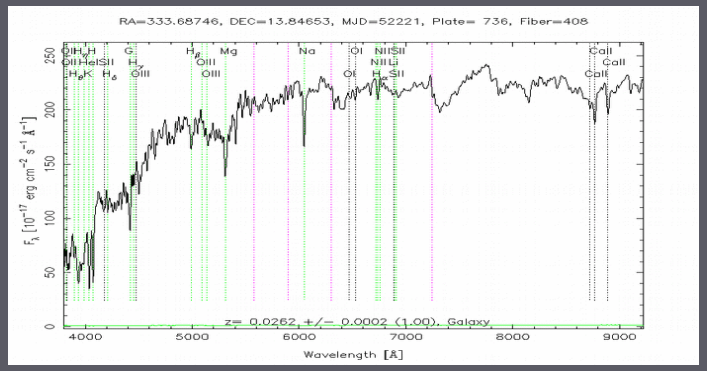




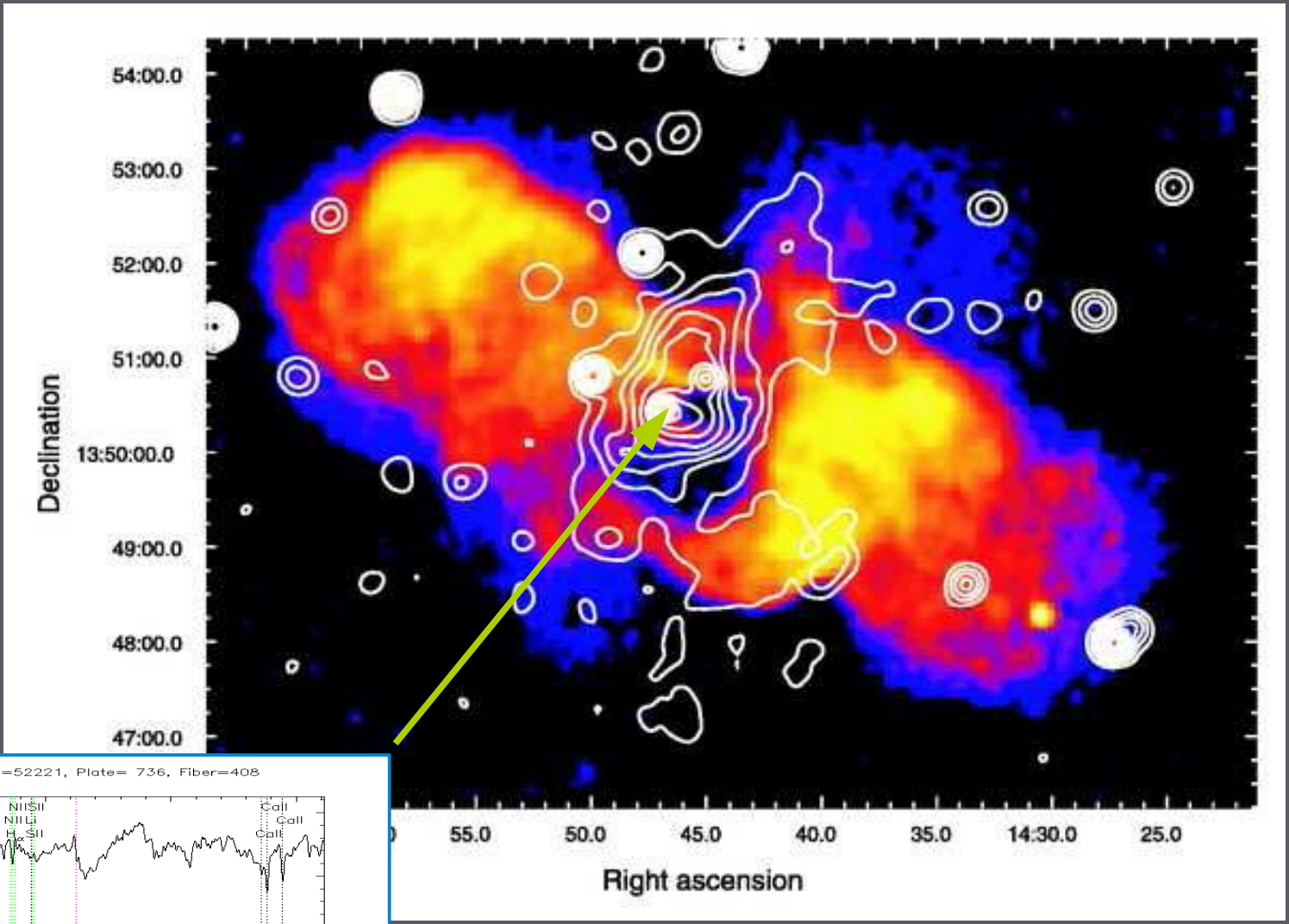


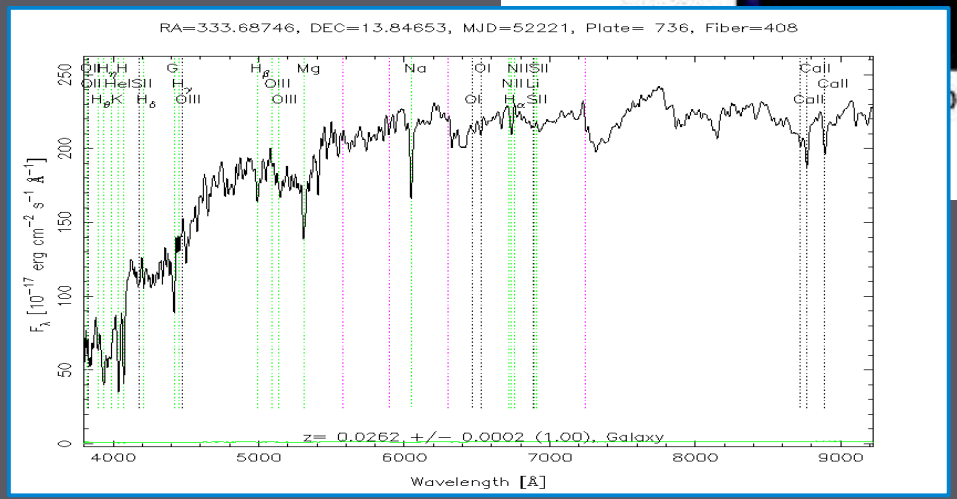
"Retired"
(fake AGN)



"Passive"
(no AGN)

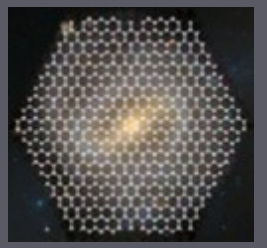
NGC 7237: X-ray (contours) & radio continuum map





(Worrall et al. 2007)

Studies of the WIM in early-type galaxies



- **CALIFA** (Calar Alto Integral Field Area survey)

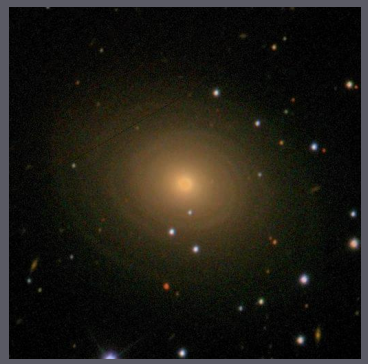
  Sanchez et al. (2011); Husemann et al. (2012)
- Pilot study of 2 ETGs in Kehrig et al. (2012)
- Investigation of the Lyman continuum photon escape fraction in 32 ETGs (20 E + 12 S0) in Papaderos et al. (2013) and Gomes et al. (2016)

Method

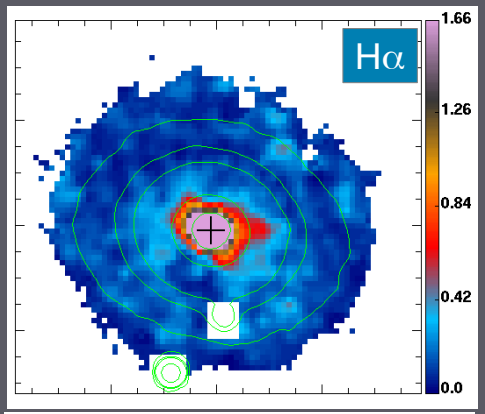
- Automated spaxel-by-spaxel spectral fitting with STARLIGHT (Cid Fernandes et al. 2005) and the **Porto3D** pipeline; Bruzual & Charlot (BC03) and MILES Simple Stellar Population (SSP) spectra for 34 ages $\times$ 3 metallicities.

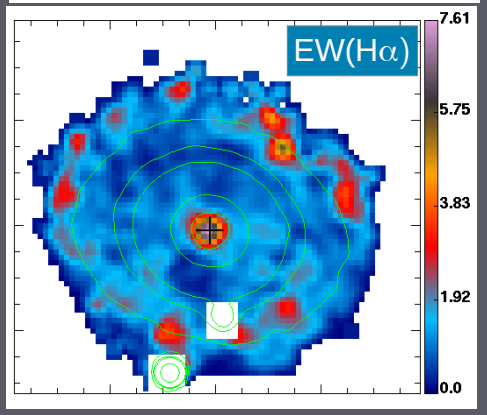
- Emission line flux determination after subtraction of the best-fitting stellar SED

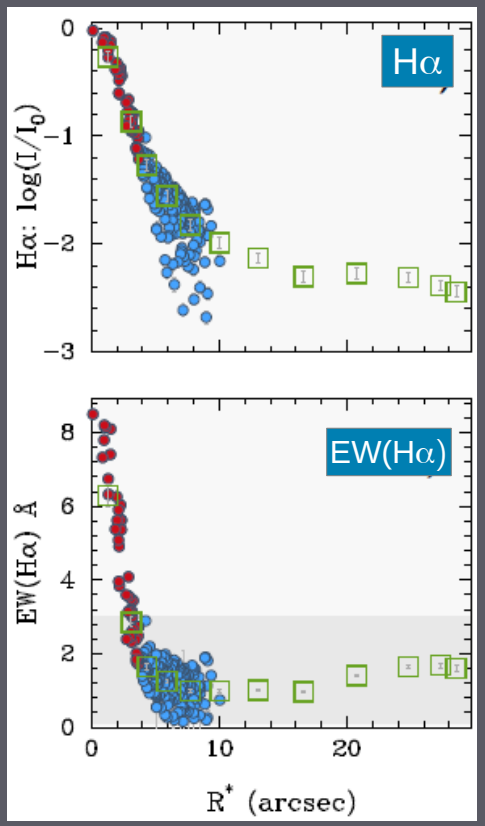
Studies of the WIM in early-type galaxies

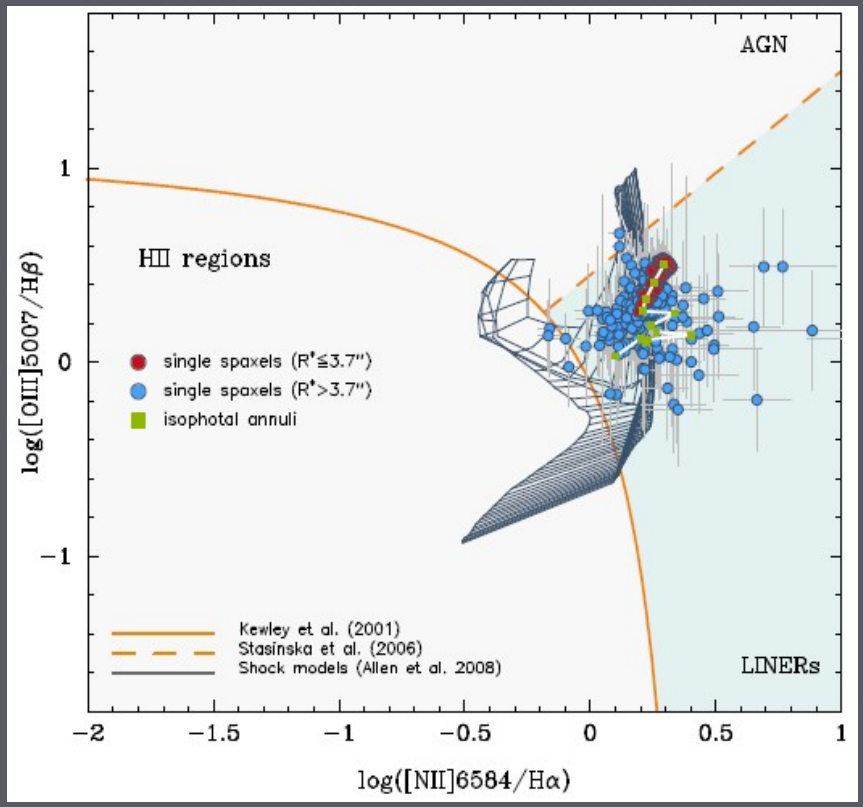


Gomes et al. (2016)









- **SISP**: Single-spaxel determinations (nucleus/periphery)
- **ISAN**: Average of SISP determinations within irregular isophotal annuli, adapted to the morphology of the (line-free) stellar continuum
- EW(Hα) range predicted for pure pAGB photoionization

τ ratio

τ ratio := Hα predicted from pAGB photoionization/Hα observed

For each spaxel

a) Summation of the Lyman continuum photon output from the best-fitting population vector (linear combination of SSPs) for $t \geqslant 10^8$ yr

b) Computation of the expected Hα luminosity, assuming case B recombination and standard conditions.

- τ=1 : pAGB* can account for the observed Hα luminosity
- τ<1 : extra ionizing source (e.g. star formation, AGN)
- τ>1 : Lyman continuum photon escape

$$f_{esc} = (1 - \tau^{-1})$$

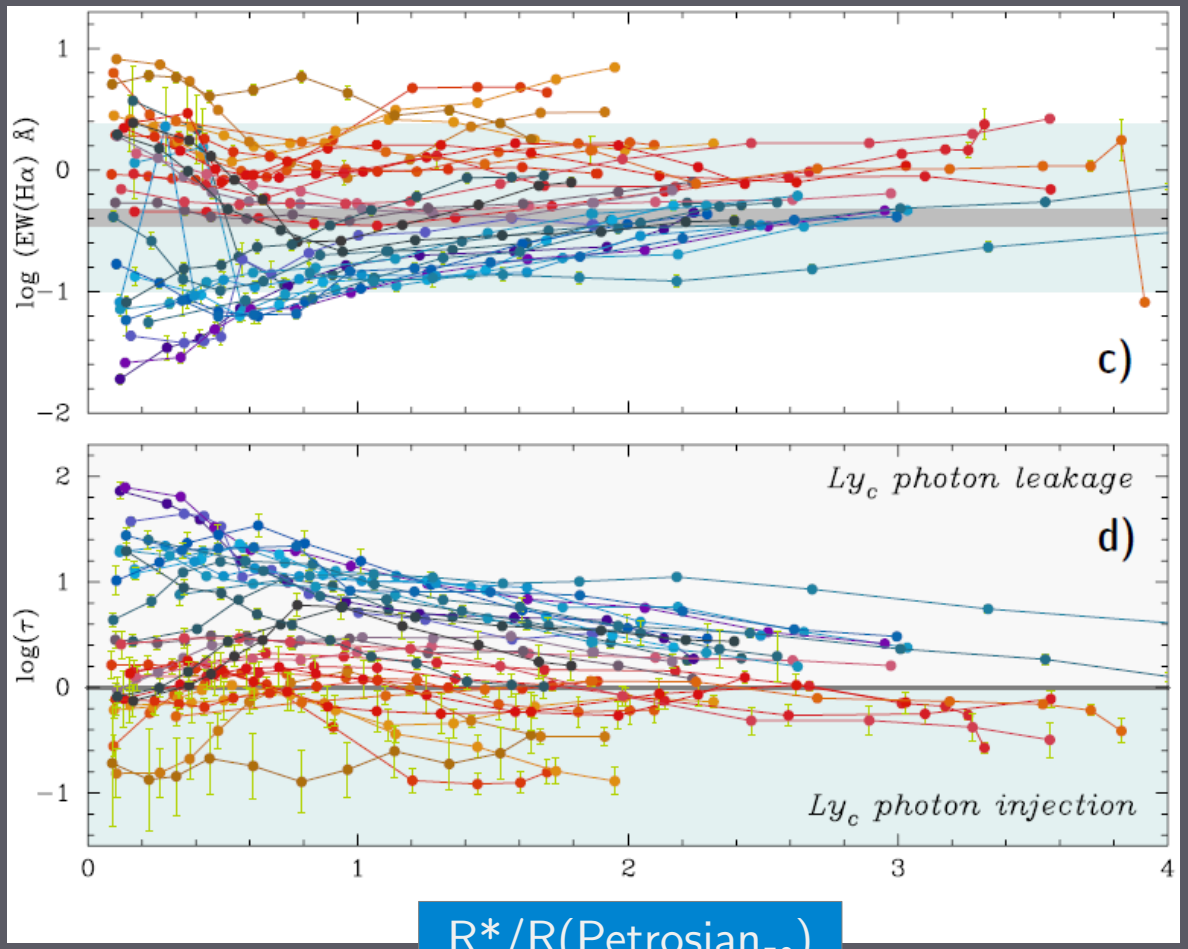
Radial EW(Ha) and τ ratio profiles in CALIFA ETG/LINERs

determinations within irregular isophotal annuli (ISAN)

Type i

0.5 Å

Type ii



nearly constant EW∼1 Å

EW< 0..5 Å
& positive EW gradient

Type ii

τ≥2

Type i

τ≃1

0.97
0.9
0.6
0

Lyman cont. escape

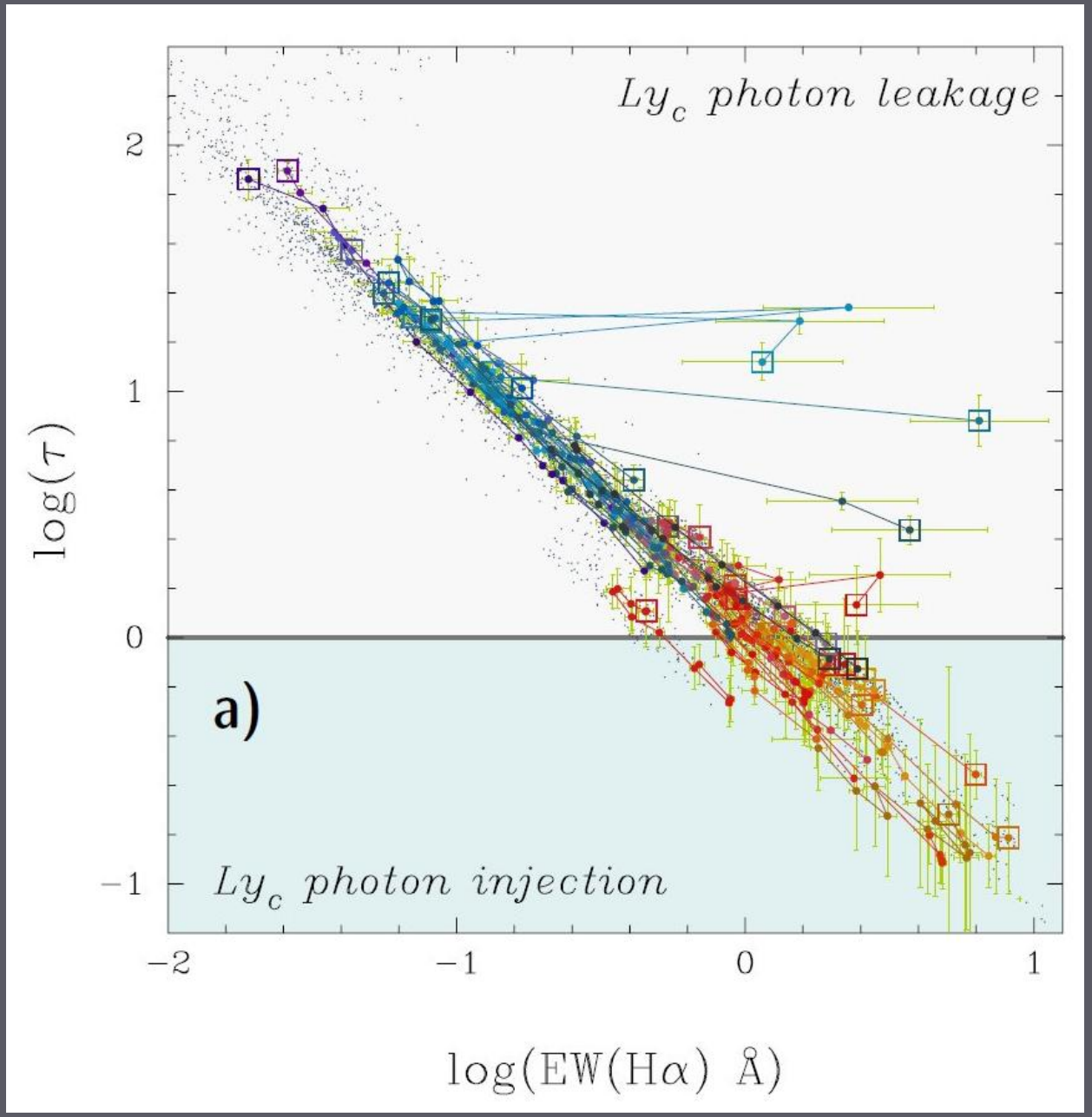
pAGB "balance"

extra ionizing source needed (e.g. SF)

Tentantive classification of ETG/LINERs (Papaderos et al. 2013)

- Type i (64% of S0's): comparatively large, radially constant EW(Hα) ∼1 Å and $f_{esc} \simeq 0$
- Type ii (78% of E's): very low (<0.5 Å) EW(Hα) with positive radial gradients and a mean $f_{esc} \gtrsim 0.7$ (exceeding 0.9 in the nuclear region)

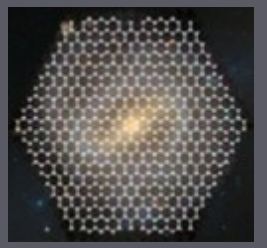
EW(Hα) vs log(τ)



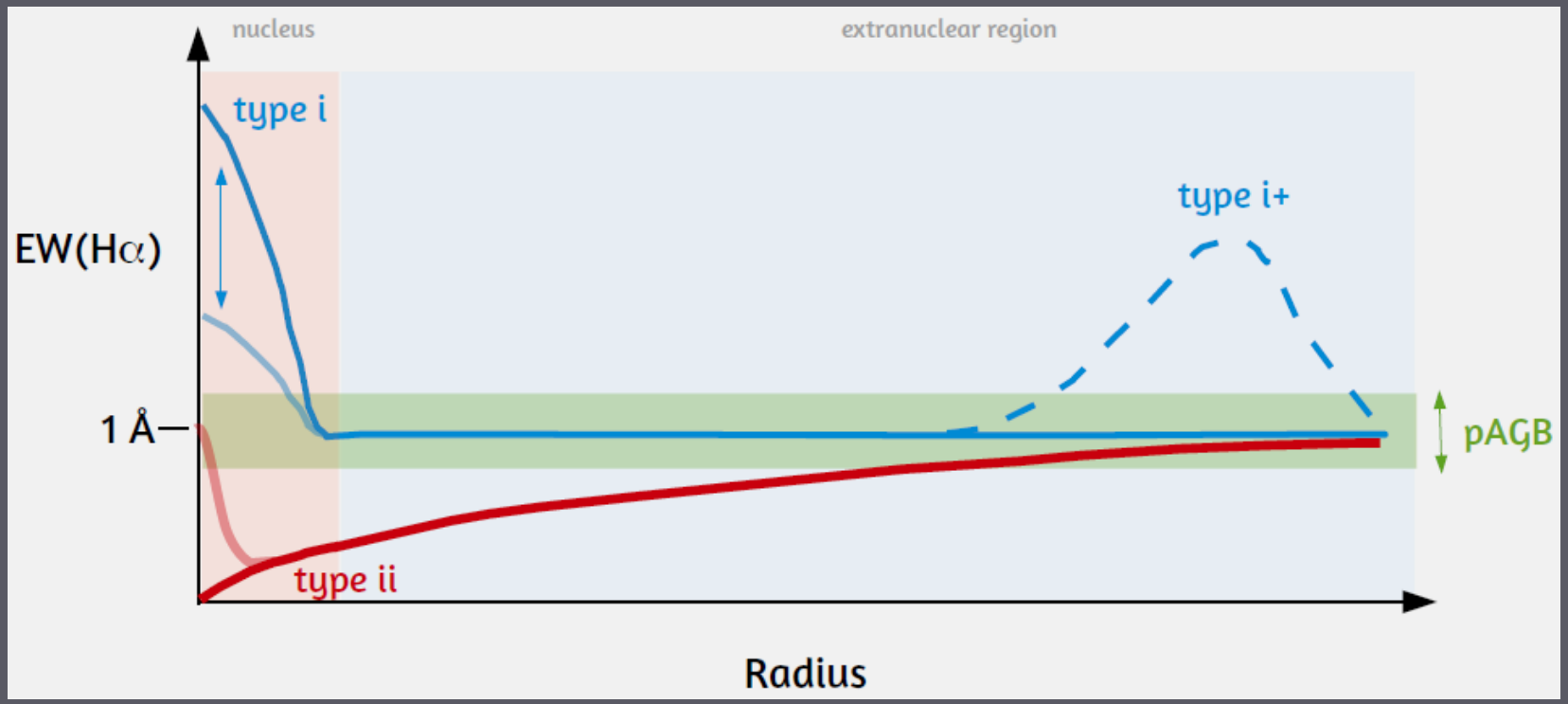
Papaderos et al. (2013)

Open squares: central value for each ISAN profile (interconnected symbols)
Dots: single-spaxel determinations

Tentative classification in two main classes



based on the radial distribution of the EW(Hα)



Papaderos et al. (2013), Gomes et al. (2016c)

- Type i/i+ (64% of S0's): comparatively large, radially constant EW(Hα) ∼1 Å
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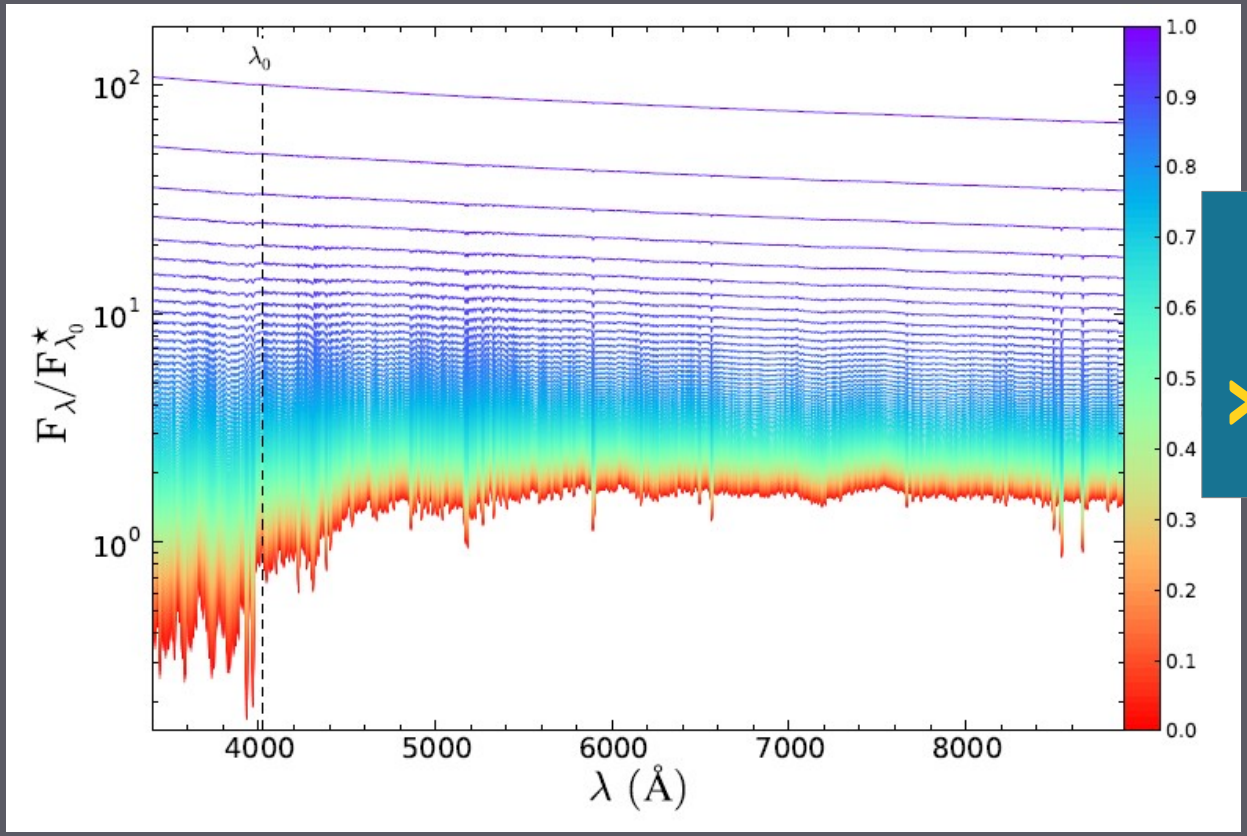
Detectability of an AGN power law component in LyC-leaking ETGs (and "passive" galaxies in general)



Cardoso et al. (2016)

X_{AGN}: fractional flux contribution of a single power law component (spl) with $F\nu \propto \nu^{-1.5}$ at 4020 Å, for a stellar SED of age 10 Gyr. Additionally, models with a library of power law components with different spectral indices (mpl).

Detectability of an AGN power law component in LyC-leaking ETGs (and "passive" galaxies in general)

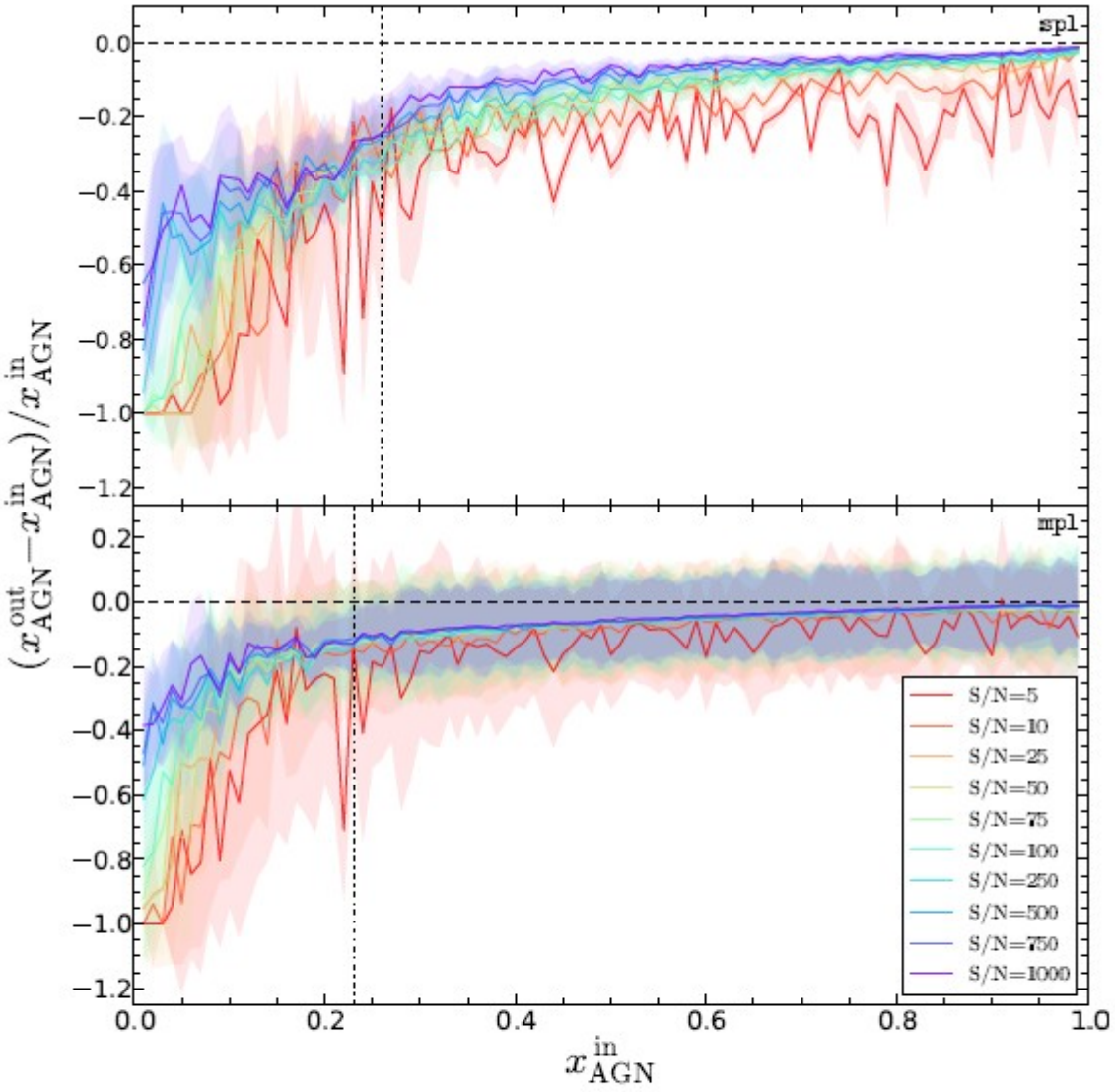


Fig. 3. Relative error of the fractional flux contribution of the AGN $(x^{out}_{AGN} - x^{in}_{AGN})/x^{in}_{AGN}$ as a function of x^{in}_{AGN} for `spl` and `mpl` fits (*upper and lower panels*, respectively). The vertical dash-dotted lines mark the

1) Modelling of synthetic stellar+powl SEDs with Starlight

2) Comparison between output and input $\mathbf{X_{AGN}}$

Our analysis indicates an effective $\mathbf{X_{AGN} \sim 0.26}$

Cardoso et al. (2016)
(see also Cardoso et al. 2017)

Summary

- $\gtrsim$60% of ETG/LINERs in our CALIFA galaxy sample fall into the **type ii** class
- Their radial τ and EW(Hα) profiles point to a low, inwardly decreasing gas density and/or volume filling factor
- In type II ETGs $\gtrsim$70-95% of the Lyman continuum output from pAGB stars (consequently, from any other ionizing source, e.g. an AGN) escape into the galaxy halo or the intergalactic space without being locally reprocessed into nebular emission
- Because of extensive Lyman continuum escape, nuclear line luminosities and equivalent widths are reduced by at least 1 dex $\rightarrow$ the line faintness of ETG/LINERs is not in itself compelling evidence for the absence of significant AGN activity.

Lyman continuum escape, which has heretofore not been considered, may constitute a key element in understanding why many ETG/LINERs with clear signatures of AGN activity in radio or X-ray wavelengths show merely faint optical line emission.