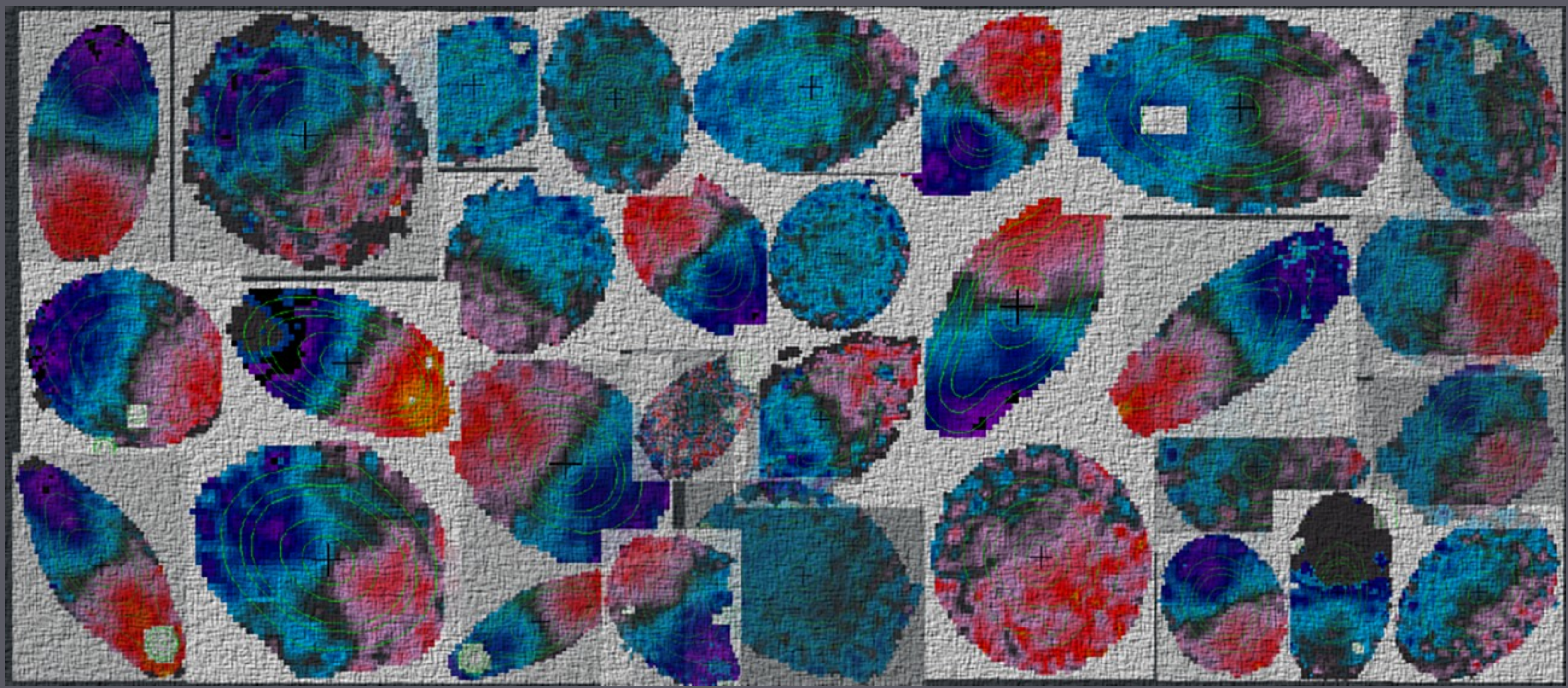
Extended nebular emission in CALIFA early-type galaxies

P. Papaderos
Centro de Astrofísica da Universidade do Porto (CAUP) &
Instituto de Astrofísica e Ciências do Espaço

Team
J.M. Gomes
J.M. Vílchez
C. Kehrig
M. Lehnert
B. Ziegler
S.F. Sánchez
B. Husemann
A. Monreal-Ibero
I. Perez
R. García-Benito
G. van de Ven
L. Wisotzki
. . .
and the CALIFA collaboration



IAU Symposium 309 • Vienna, 8.7.2014

Outline

- Automated processing of integral field spectroscopy (IFS) data from CALIFA (low-resolution V500 setup) with **Porto3D** (Papaderos & Gomes)

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

- Analysis of 32 ETGs from the CALIFA survey & tentative classification in two main types

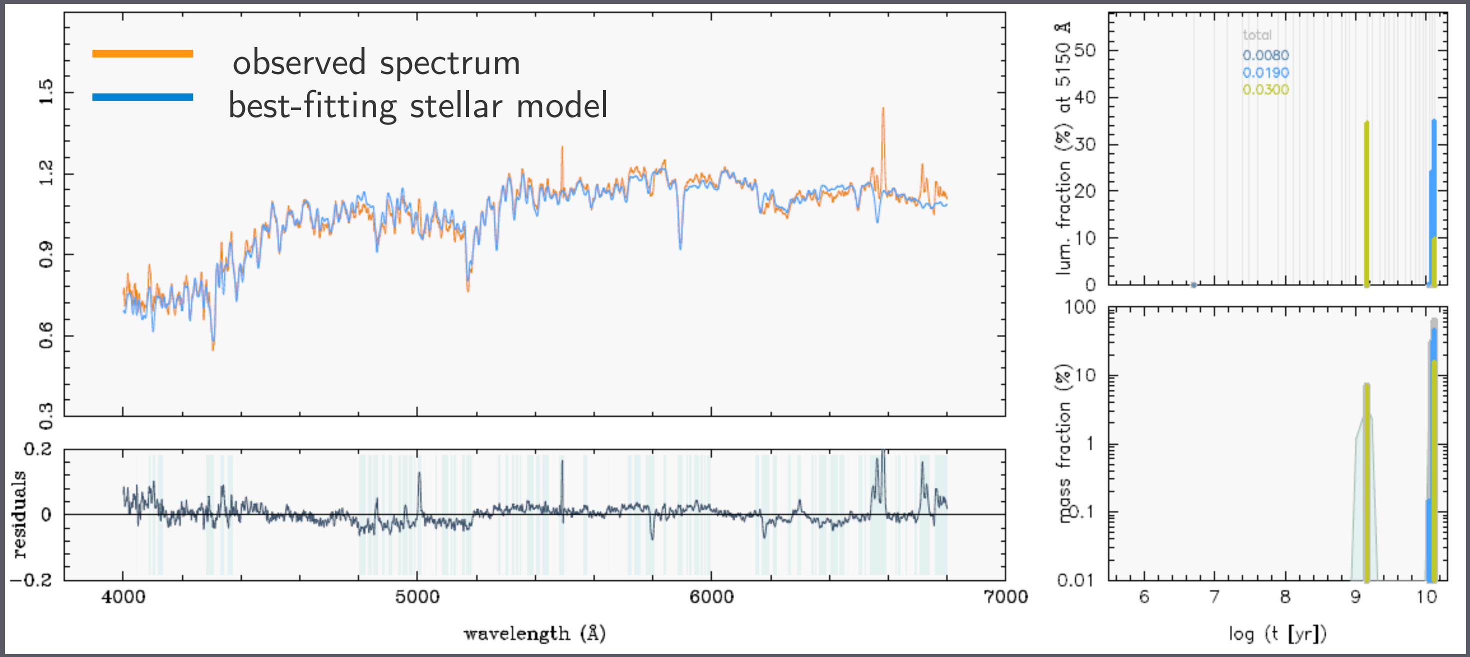
- Evidence for low-level star-forming activity in the periphery of ($\simeq$10% of) ETGs

- Evidence for Lyman continuum photon escape from ETGs
  ... and its implications for our understanding of AGN/LINER activity in ETGs

IFS data procesing with Porto3

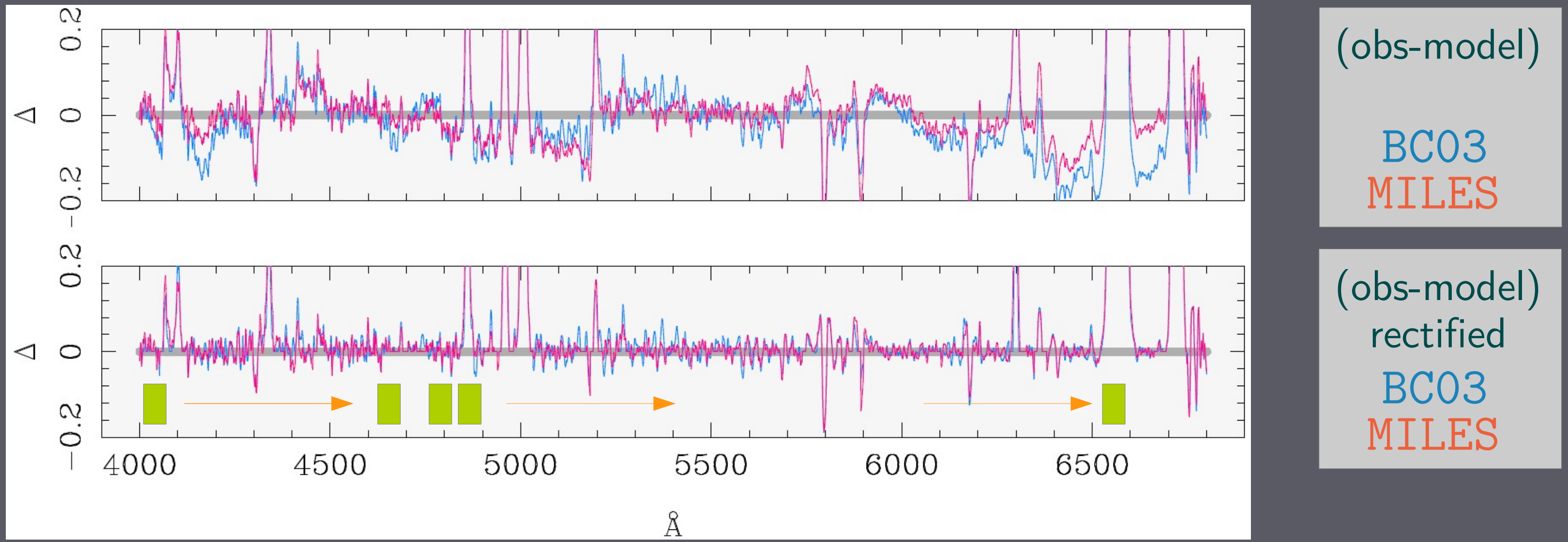
- Spaxel-by-spaxel fitting with **Porto3D** (1600 .. 3200 spaxels per galaxy) & fitting with STARLIGHT (Cid Fernandes et al. 2005) using both Bruzual & Charlot (BC03) and MILES Simple Stellar Population (SSP) spectra;

- Extraction of the **net** (observed – stellar model) spectrum and subsequent determination of emission-line fluxes, equivalent widths (EWs) and ionized gas kinematics.



Determination of emission-line fluxes and EWs

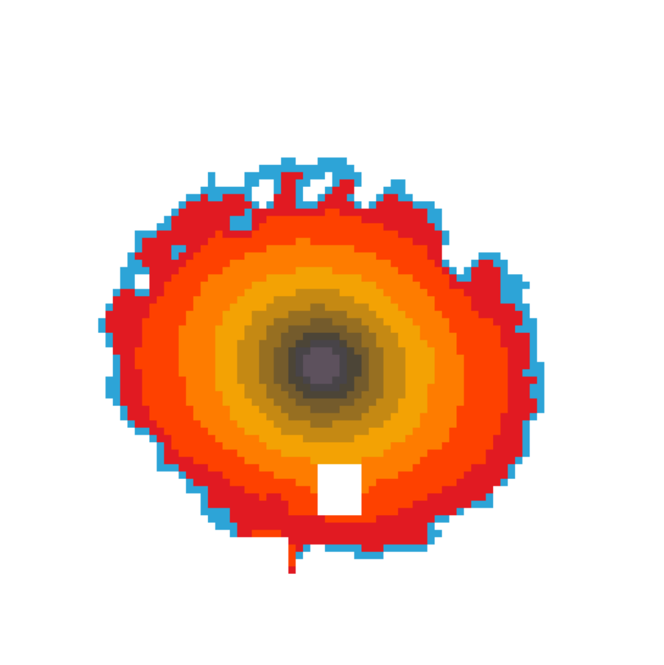
- Emission line flux measurements:
  - i) Gaussian fitting/deblending;
  - ii) flux summation within $\{\lambda_{min,i} : \lambda_{max,i}\}$ continuum-rectified pure emission-line spectra



- Quality check through a decision tree algorithm;
- Combination of results from models with BC03 and MILES
- Estimated uncertainties include:
  - formal errors in Gaussian fitting/deblending ↓
  - $\sigma_{line} = \sigma_{cont} N^{1/2} \left(1 + \frac{EW}{N\Delta\lambda}\right)^{1/2}$ ↗ (cf Gonzalez Delgado et al. 1995; Castellanos et al. 2002)
  - local residuals after fitting and their impact on the determined emission-line fluxes ↑
  - (optionally) difference between fluxes based on BC and MILES models →

Derivation of radial profiles

- single-spaxel (sisp) determinations for higher S/N spaxels
- average of all sisp determinations within irregular isophotal annuli (isan) adapted to the morphology of the (emission-line free) stellar continuum @ 6390-6490 Å (adaptation of a surface photometry technique in Papaderos et al. 2002, see also Noeske et al. 2003/06)
- as a check: processing of binned spectra extracted within azimuthally segmented isan to a minimum S/N of typically $\geqslant$ 50 @ 6390-6490 Å ; 200-800 segments)



Irregular isophotal annuli
Adapted to the morphology
of the emission-line free continuum
(typically $\simeq$ 12 .. 16)

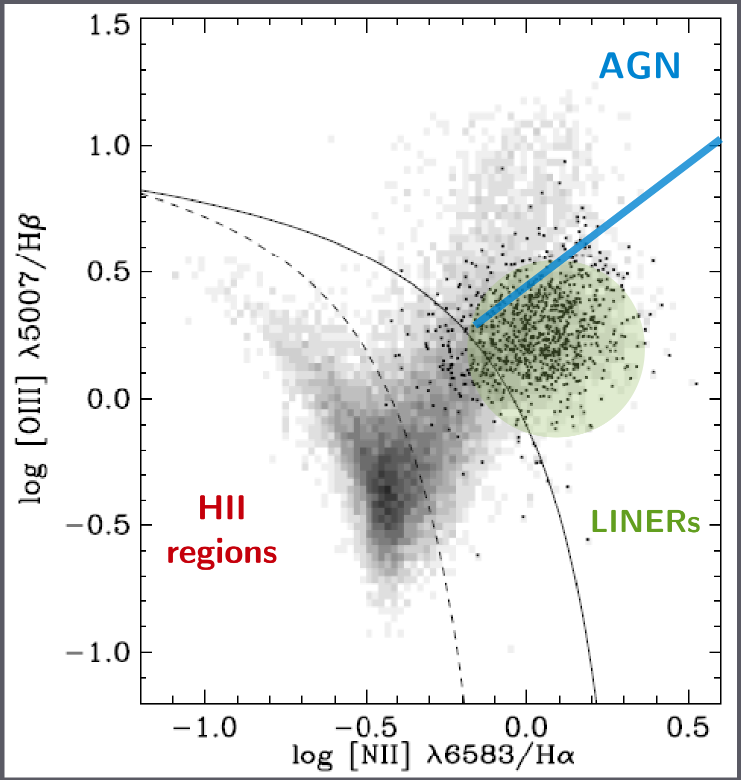
Azimuthally segmented
isophotal annuli to
a constant S/N ratio

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).

- The majority of ETGs with detected nebular emission are spectroscopically classified as LINERs (low-ionization nuclear emission-line regions)

- Nebular emission in ETG/LINERs is typically very faint (nuclear EW(Hα) between $\lesssim$0.5 Å ... 15 Å, median $\simeq$ 2.4 Å)



●: 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)

Excitation mechanism(s) of the WIM in ETGs

- Proposed gas excitation mechanisms in ETG/LINERs include

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) 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;
see also recent discussion by Coziol et al. (2014; arXiv:1405.4159v1)
and Stasinska (2014;arXiv:1406.0469))

WIM excitation by the pAGB stellar component

Hot post-AGB stars (age ≥ 100 Myr)

Bruzual & Charlot (2003) models for an instantaneous burst

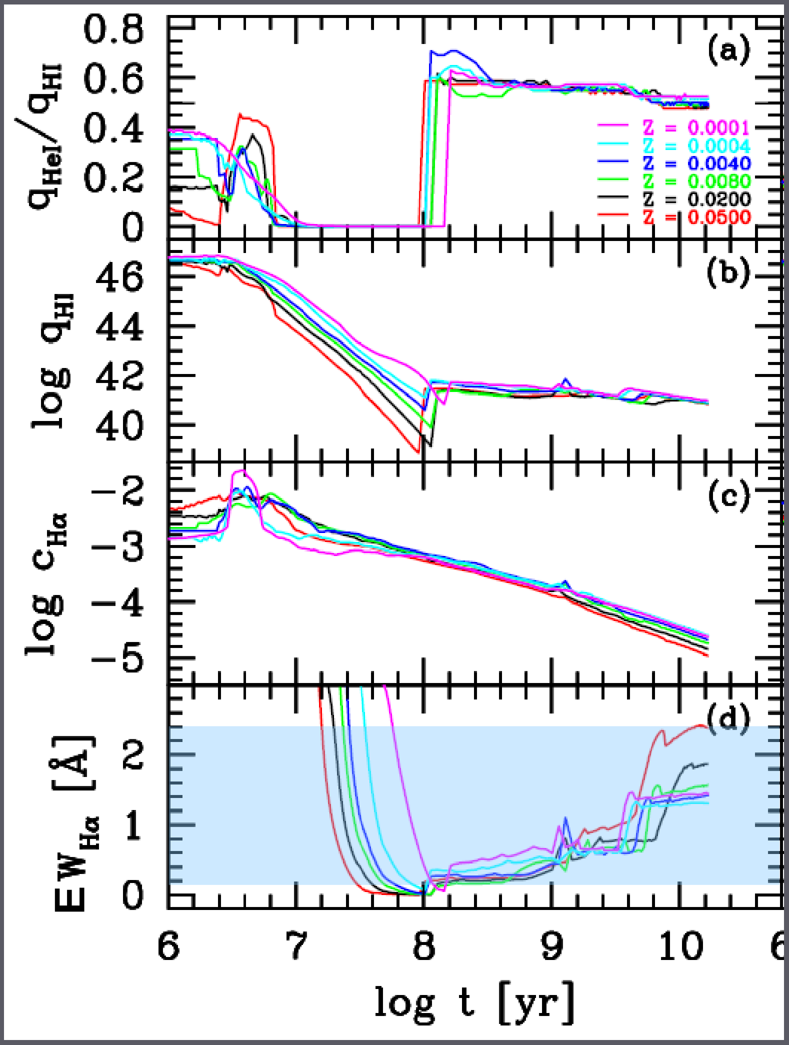
Hardness of the ionizing spectrum, as measured by the ratio of HeI to HI ionizing photons

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

Continuum level around the Hα line

Hα equivalent width

EW(Hα) : 1-2 Å for t≳3-10 Gyr



qHI (pAGB): No significant dependence on metallicity and age after 100 Myr

Cid Fernandes et al. (2011)

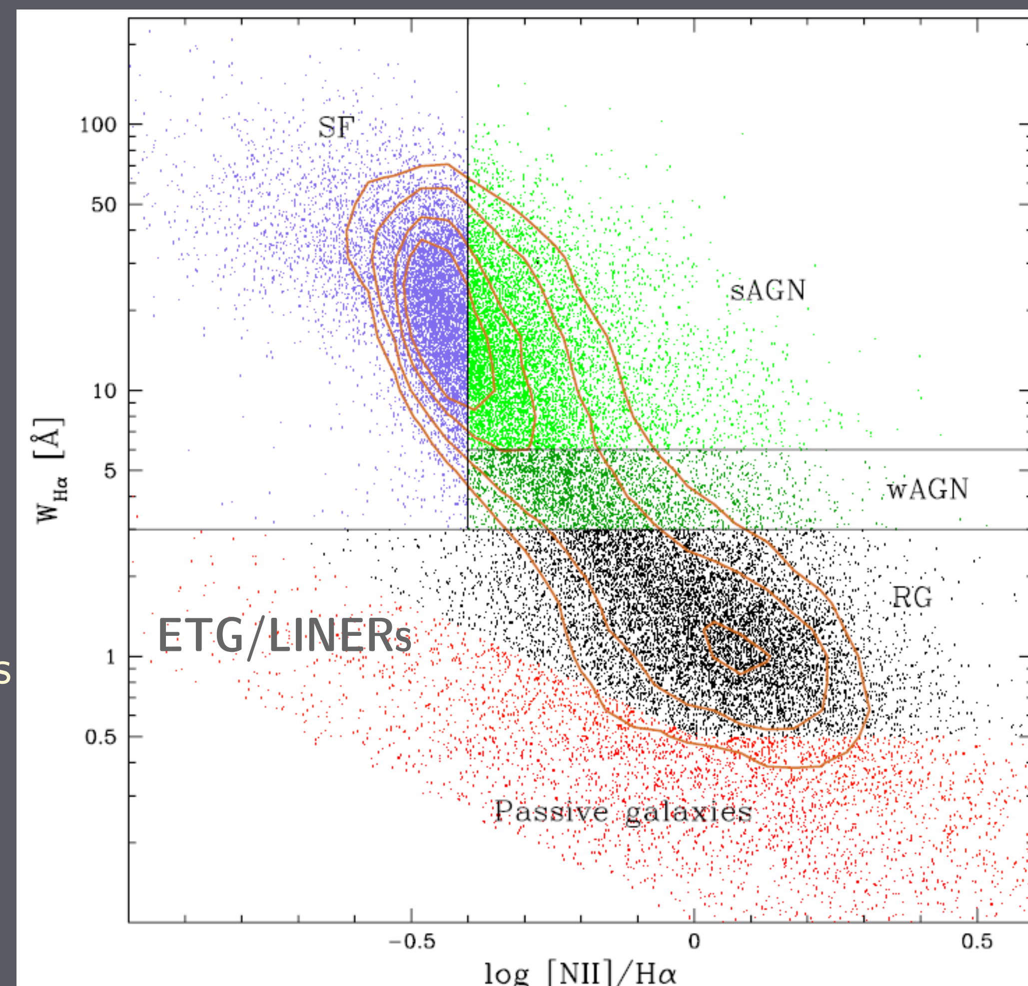
Several recent studies favor pAGB stars as the dominant WIM excitation source in ETG/LINERs

(e.g. Sarzi et al. 2006,2010, 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 ~ 1 and EW(Hα) Å ≥ 6
- Weak AGN (wAGN): EW: 3 ⩽ EW(Hα) Å ⩽ 6
- Retired galaxies (RGs): LINER-typical nuclear [NII]/Hα ratios (≳1) and 0.5 ⩽ EW(Hα) Å ⩽ 3
- Passive galaxies: in their majority, [NII]/Hα ratios typical of ETG/LINERs and AGNs, but very faint (EW(Hα) ⩽ 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 ➔ pAGB photoionization is an alternative to to the low-luminosity (accretion rate) AGN hypothesis ➔

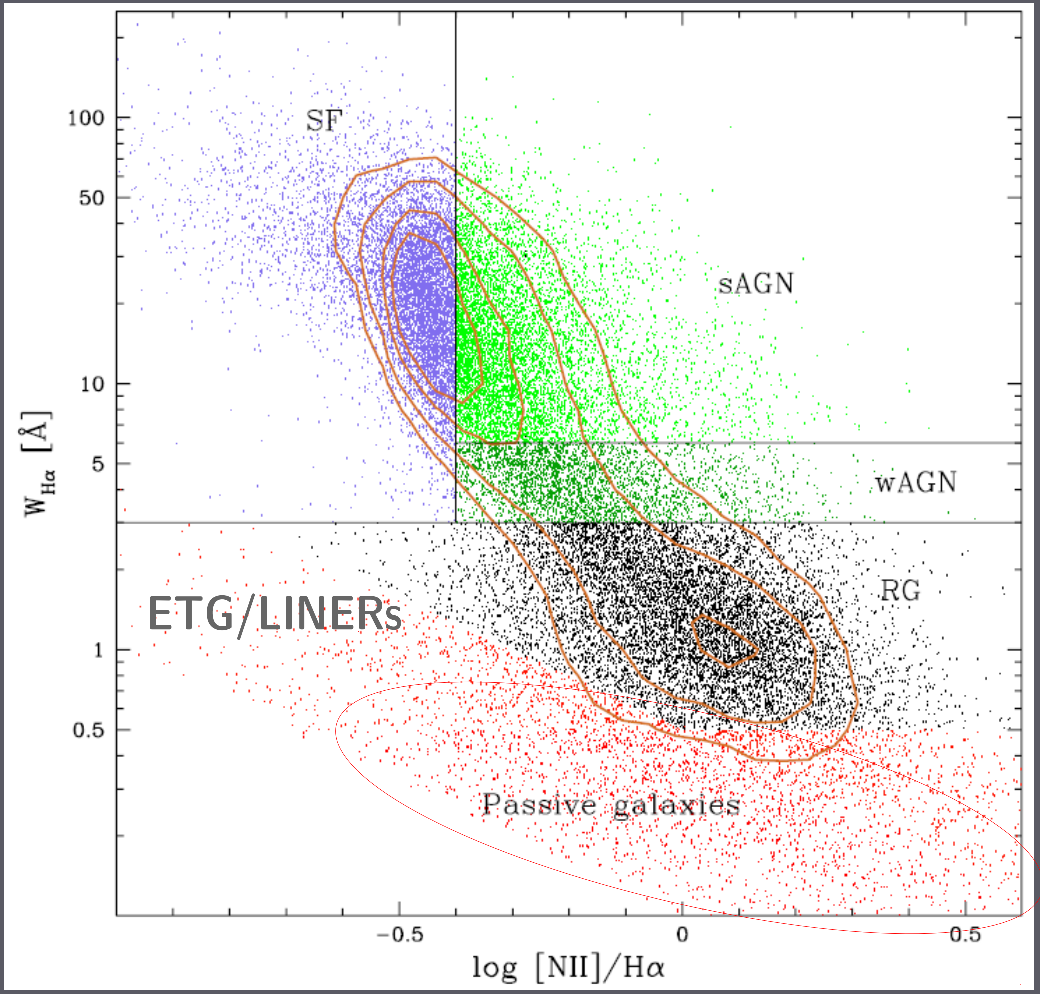
no "… *dichotomy in the AGN population (two states of black hole accretion)*"



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

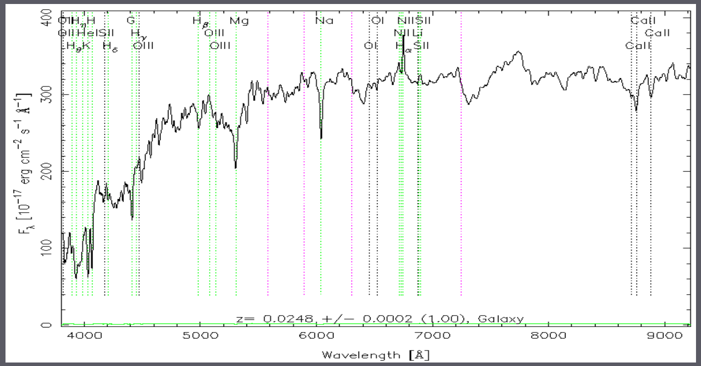
Questions ...

- Why nebular emission is virtually absent in "passive" ETGs? Since they also contain pAGB stars, they should also show some diffuse low-level (EW(Hα): 1-2 Å) nebular emission, similar to "retired" galaxies.

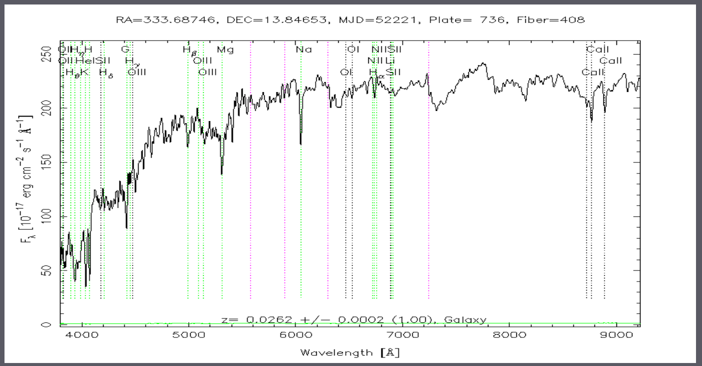


Questions ...

- Is the <u>line faintness</u> (consequently also the spectroscopic classification of ETGs as retired, or passive), unambiguous proof for the absence of an (at least weak) AGN?
Or, conversely, a proof for the predominance of pAGB photoionization, in the case of RGs (?)



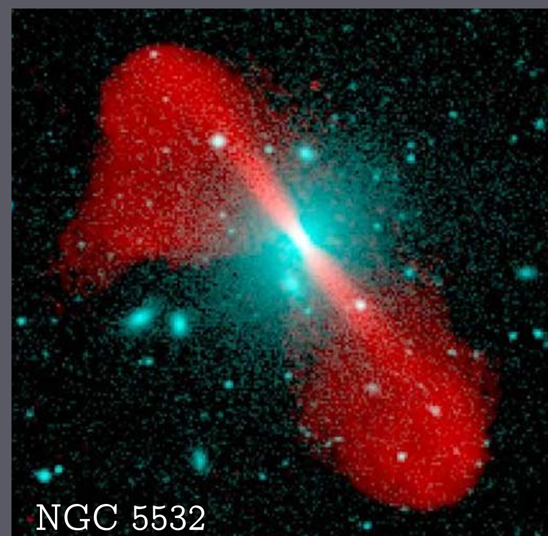
"Retired"
(no AGN)

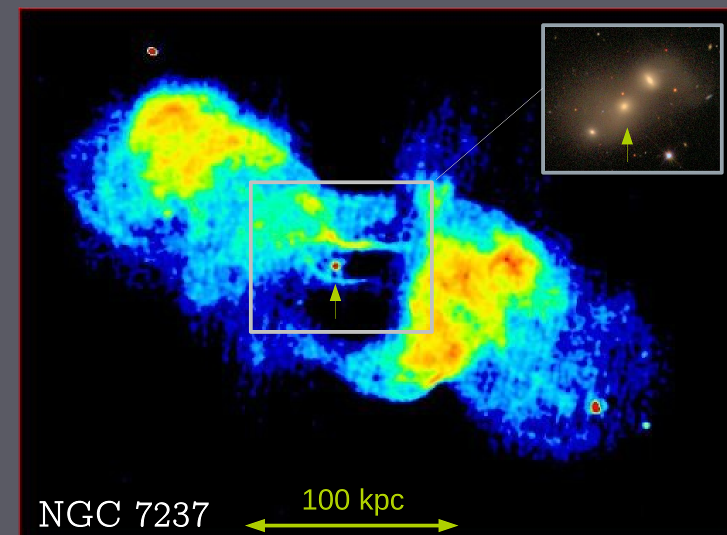


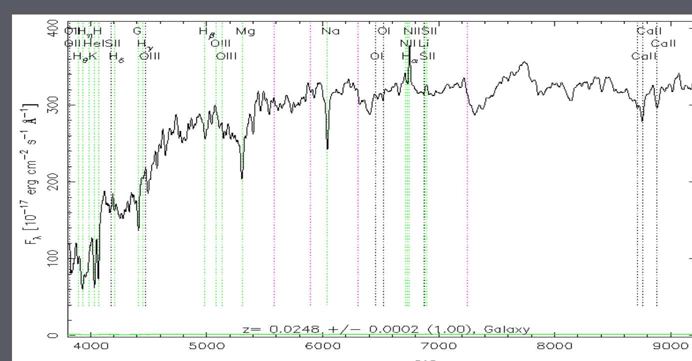
"Passive"
(no AGN?)

Questions ...

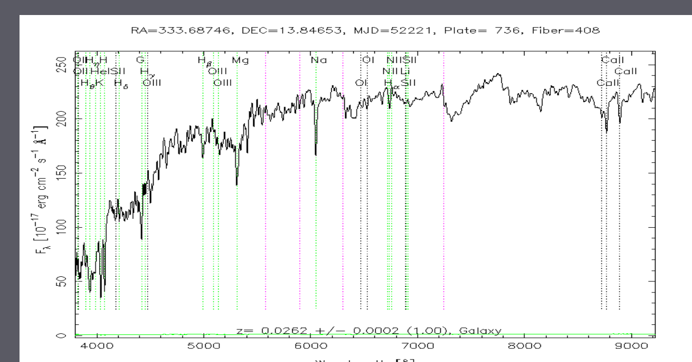
- Is the <u>line faintness</u> (consequently also the spectroscopic classification of ETGs as retired, or passive), unambiguous proof for the absence of an (at least weak) AGN?
Or, conversely, a proof for the predominance of pAGB photoionization, in the case of RGs (?)





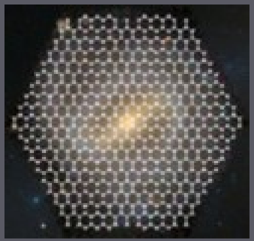


“Retired”
(no AGN)



“Passive”
(no AGN?)

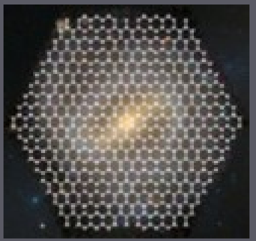
Studies of the WIM in CALIFA ETGs



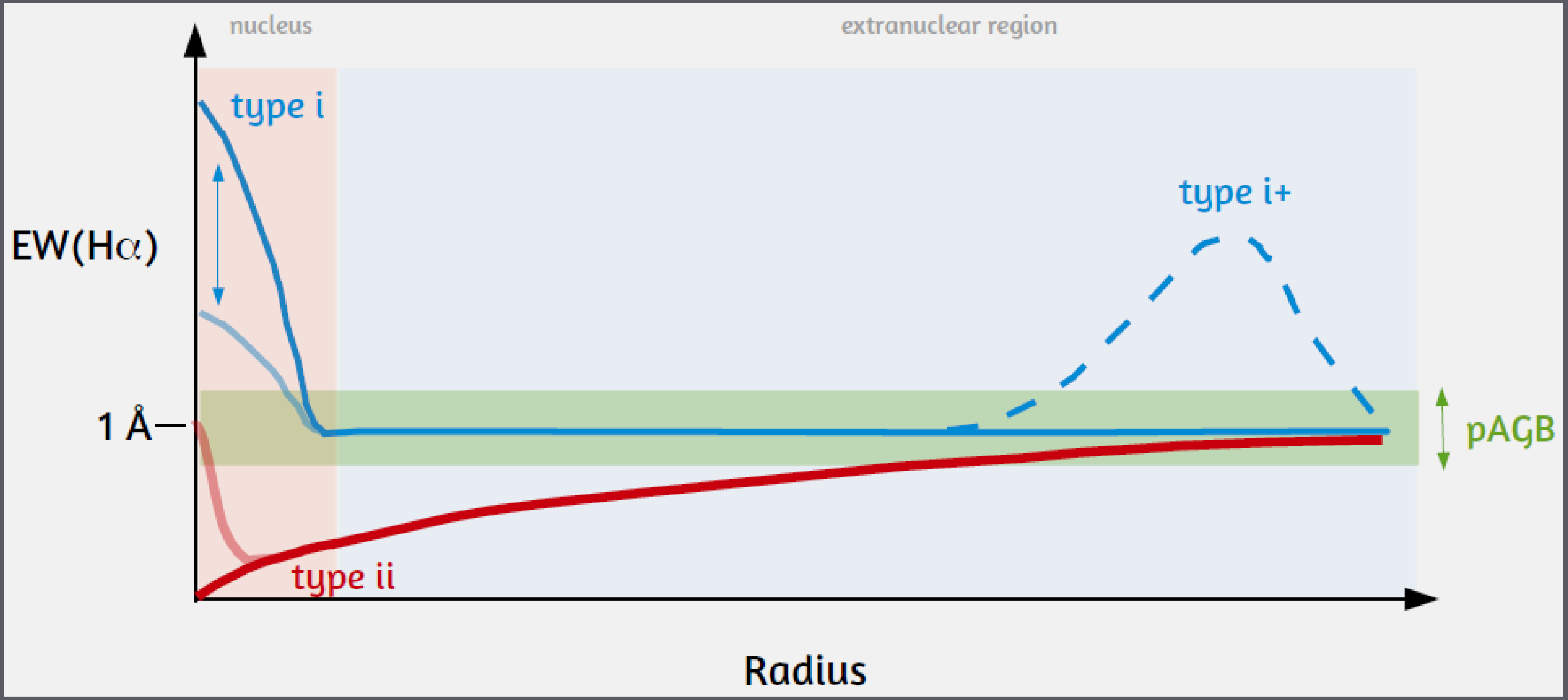
Spatially resolved studies of the WIM in ETG/LINERs (retired or passive galaxies in the WHAN classification) with *integral field spectroscopy* (IFS) could provide further constraints on the nature of the dominant excitation source (AGN, star formation, shocks, pAGB stars)

- Pilot study of 2 ETGs in Kehrig et al. (2012; A&A, 540, A11)
- 1D investigation of the nebular emission and the Lyman continuum escape fraction in 32 ETGs (20 E + 12 S0) in Papaderos et al. (2013; A&A Let., 555, L1)
- Detailed 2D analysis & discussion of the galaxy sample in Gomes et al. (2014, in prep.)

Tentative classification in two main classes



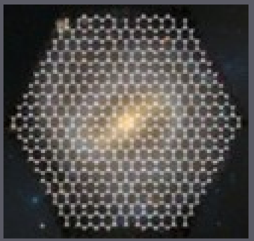
... based on the radial distribution of the EW(Hα)



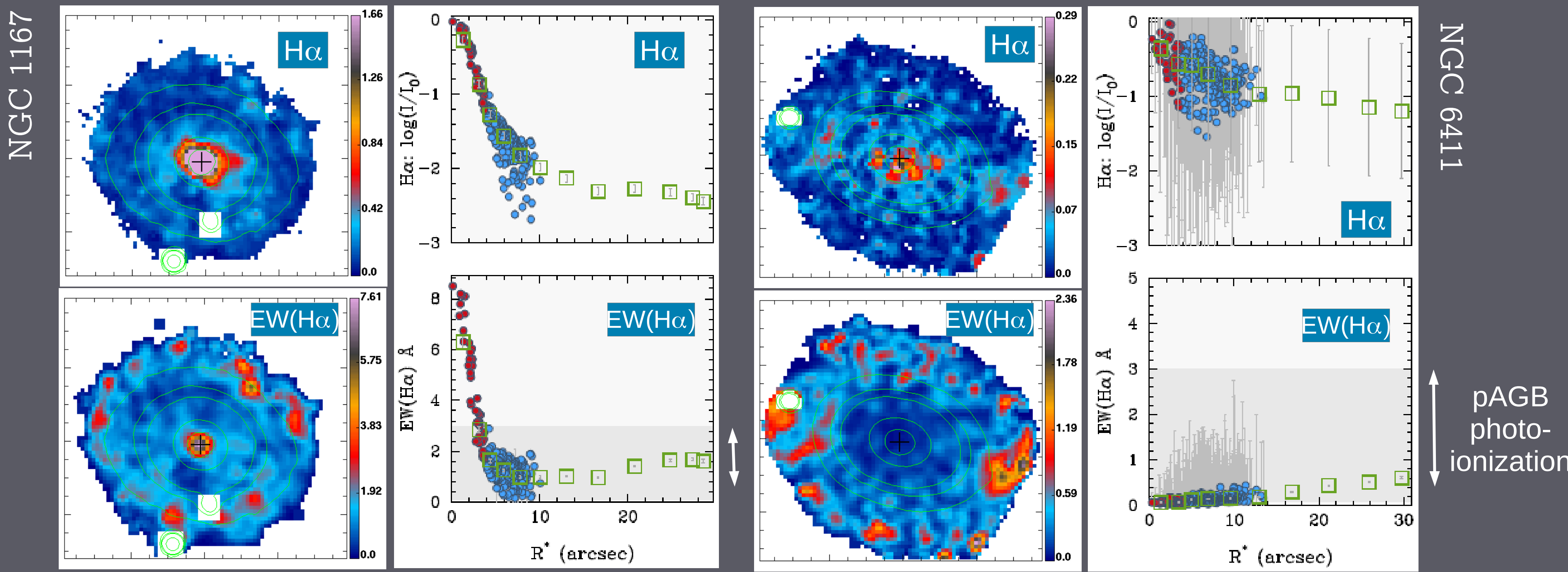
Papaderos et al. (2013), Gomes et al. (2014, in prep.)

- Type i/i+ (64% of S0's): comparatively large, radially constant EW(Hα) ~1 Å
- Type ii (78% of E's): very low (<0.5 Å) EW(Hα) with positive radial gradients

Studies of the WIM in early-type galaxies



Gomes et al. (2014, in prep.)



type i

type ii

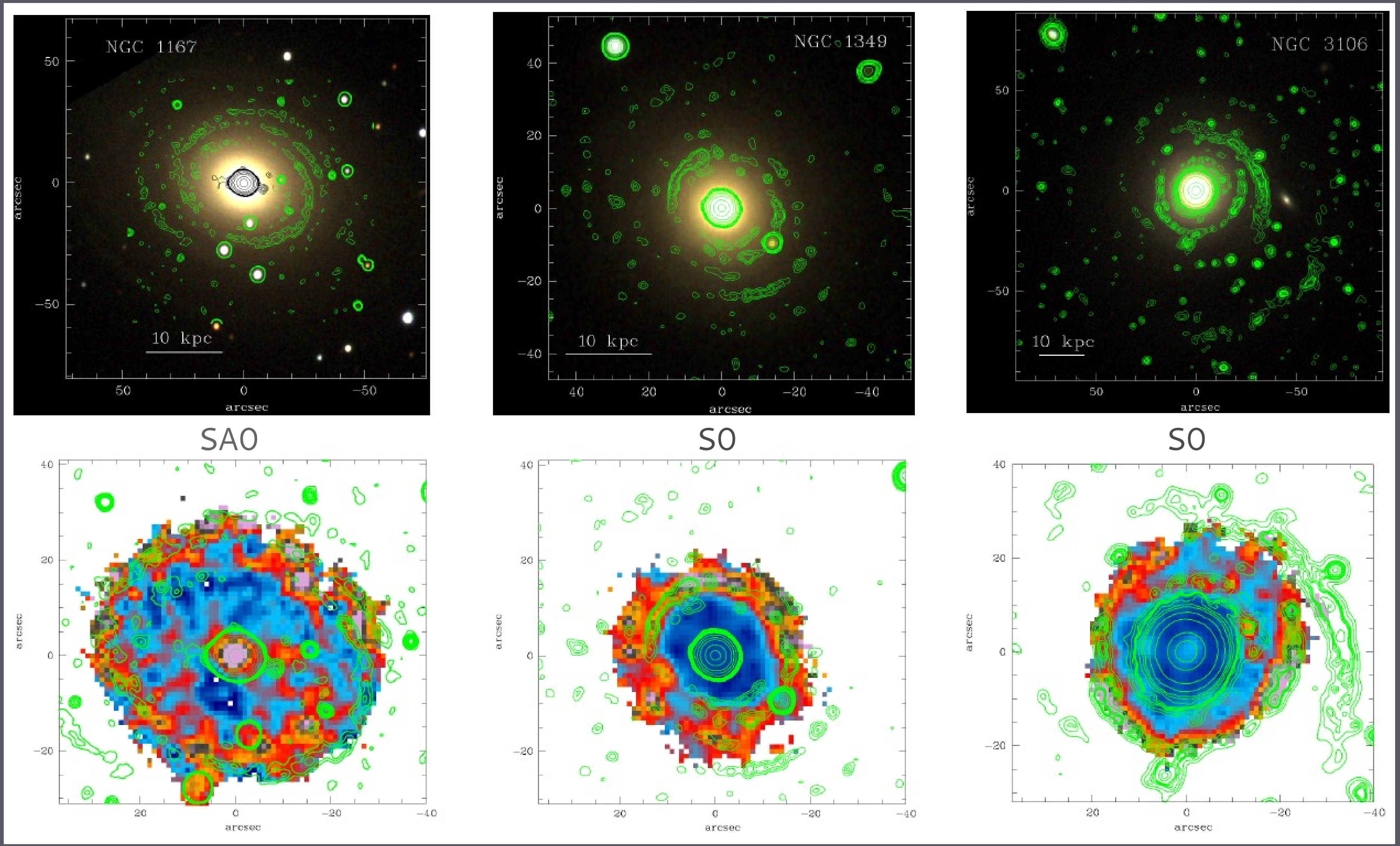
SISP: Single-spaxel determinations (nucleus; ⩽3.8 arcsec/periphery)

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

type i+ : low-level star-forming activity in the periphery of ETGs

Gomes et al. (2014, in prep.)



- SDSS r (upper panel) & EW(Hα) (lower panel) + contours from unsharp masking (Papaderos et al. 1998)
- estimated SFR: 0.08 – 0.3 M⊙/yr ; very low sSFR (10^{-12})
- almost WIM evacuated cores EW(Hα) ≃ 1 Å (retired/LINER ETGs) but star formation in the outskirts
- *... beware of aperture effects on spectroscopic classification of ETGs based on small-FoV data*

Radial distribution of the τ ratio

(see Binette et al. 1994 and Cid Fernandes et al. 2011 for similar ratios derived from longslit or single-fiber spectra)

τ ratio := $\underbrace{\text{H}\alpha}$ `predicted from pAGB photoionization`/Hα `observed`

For each spaxel

a) Summation of the Lyman continuum photon output corresponding to 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 for the gas. Optionally, correction for extinction, as inferred for the stellar component from Starlight models.

→

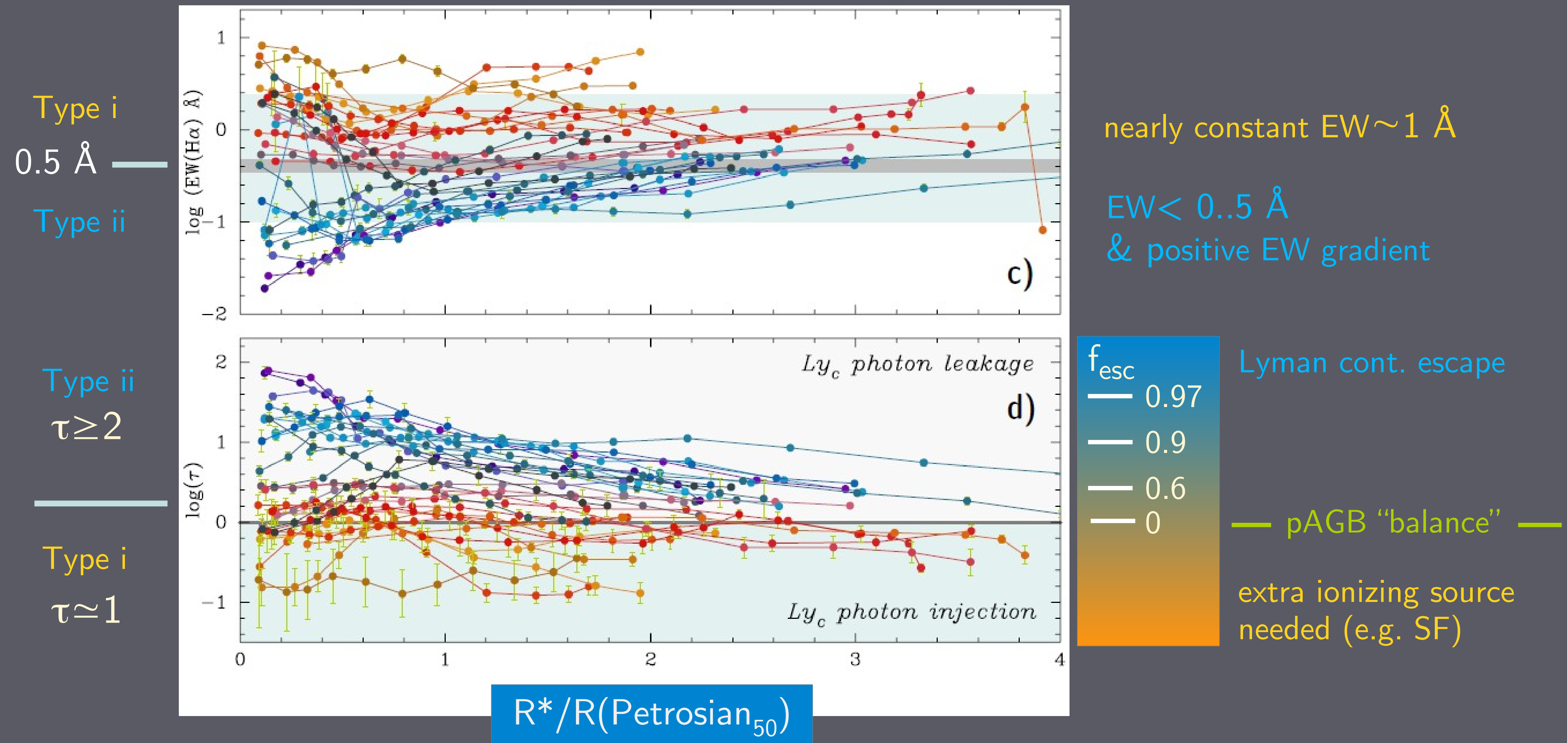
- $\tau=1$: pAGB* can account for the observed Hα luminosity
- $\tau<1$: extra ionizing source (e.g. star formation, AGN)
- $\tau>1$: Lyman continuum photon escape

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

Papaderos et al. (2013)

Radial distribution of EW(Ha) and the τ ratio in CALIFA ETG/LINERs

determinations within irregular annuli



- Type i : data consistent with $f_{esc} \simeq 0$ (consequently pure pAGB photoionization)
- Type ii: $f_{esc} \gtrsim 0.7$ (exceeding 0.9 in the nuclear region)

Implications of Lyman continuum escape for our understanding of AGN/LINER activity in early-type galaxies

- If $\geq$90% of the Lyman continuum output from pAGB stars in ETG nuclei escapes without being locally reprocessed into Balmer (and Lyα) emission, then this is obviously the case for any other discrete or extended nuclear energy source (e.g. an AGN)

- 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 a merely "weak" AGN (or absence of 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.

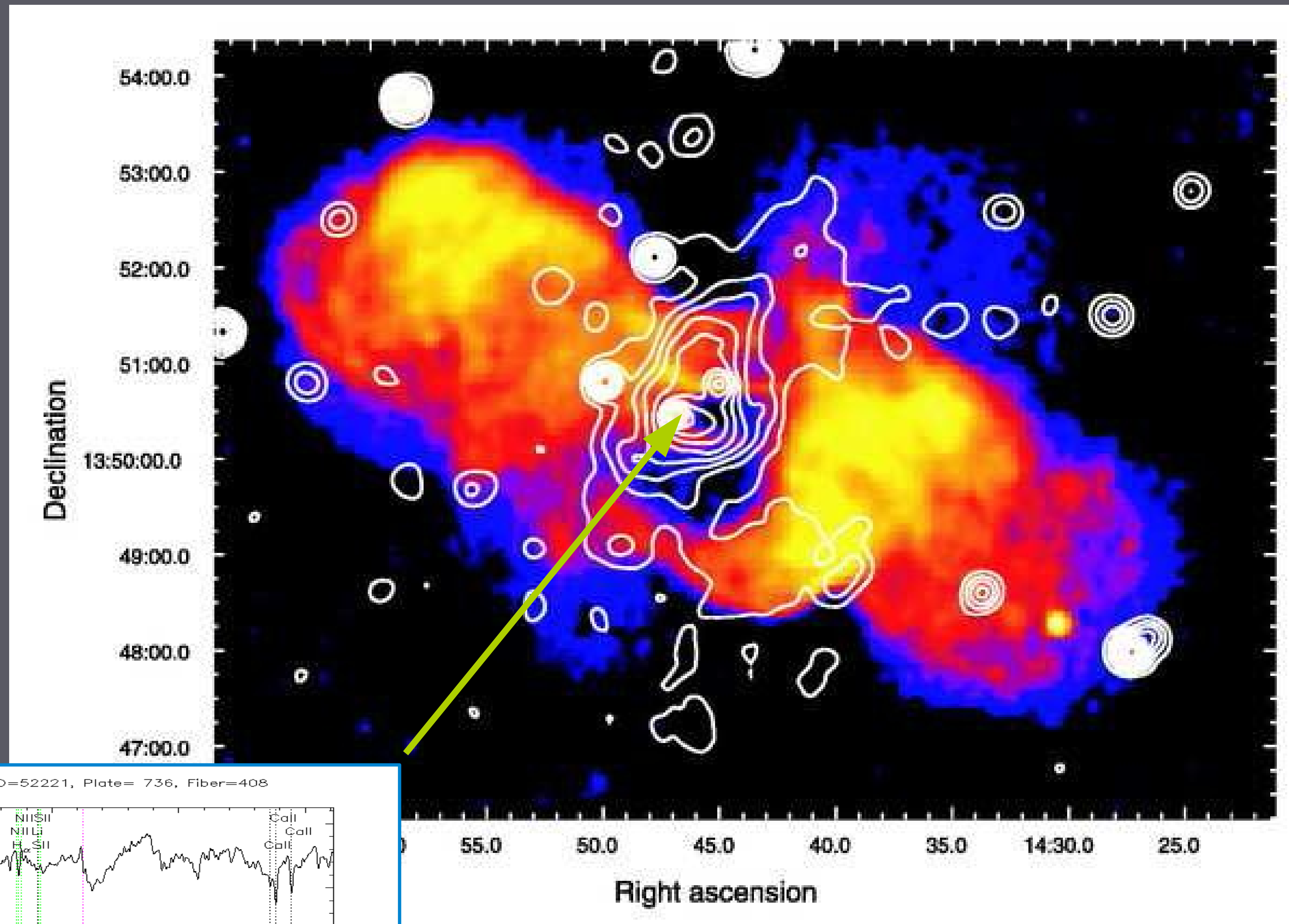
Summary

- The studied CALIFA ETGs show a significant heterogeneity with regard to their 1D/2D EW(Hα) and τ ratio distribution.
- Most probably, the excitation of the extended WIM component in these systems is driven by the superposition of different mechanisms (AGN, photoionization by pAGB stars and star formation, shocks) each having a different importance in different radial zones.
- In ~40% of ETGs **(type i)** the properties of extranuclear WIM emission are consistent with pAGB photoionization and a Lyman continuum photon escape fraction $f_{esc} \simeq 0$.
- The nuclei of ~60% of ETGs **(type ii)** are almost WIM evacuated and show a $f_{esc} \simeq 0.7 - 0.9$.
- Because of extensive Lyman continuum escape, nuclear line luminosities and equivalent widths in type ii ETGs are reduced by at least 1 dex $\rightarrow$ their line weakness is not in itself compelling evidence for their containing merely "weak" (sub-Eddington accreting) AGN

Lyman continuum escape 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.

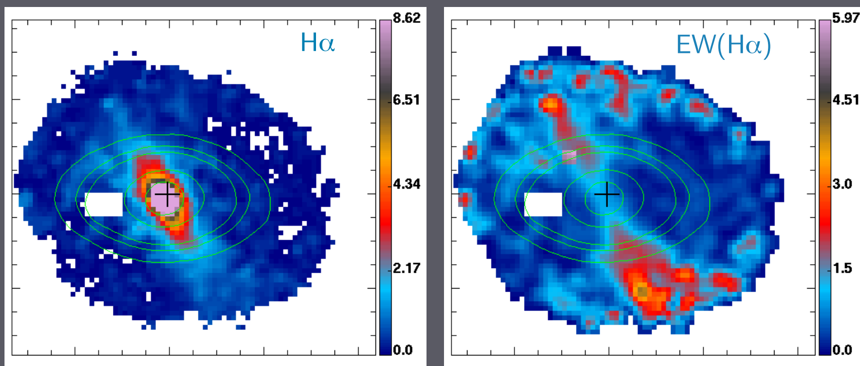
- more work to be done (as usually ... ☺)

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



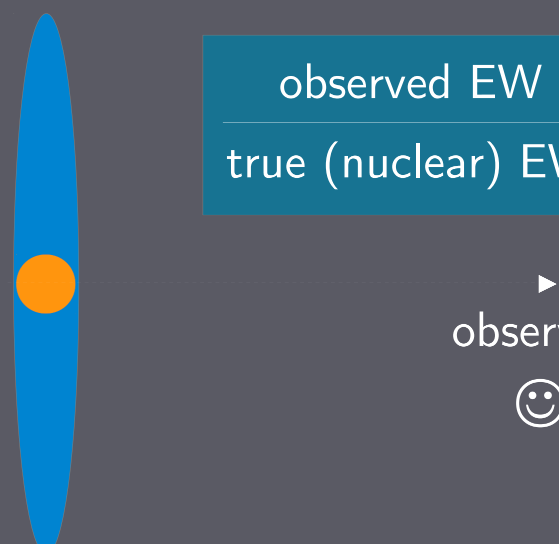
(Worrall et al. 2007)

The geometric EW dilution effect (Papaderos et al. 2013)



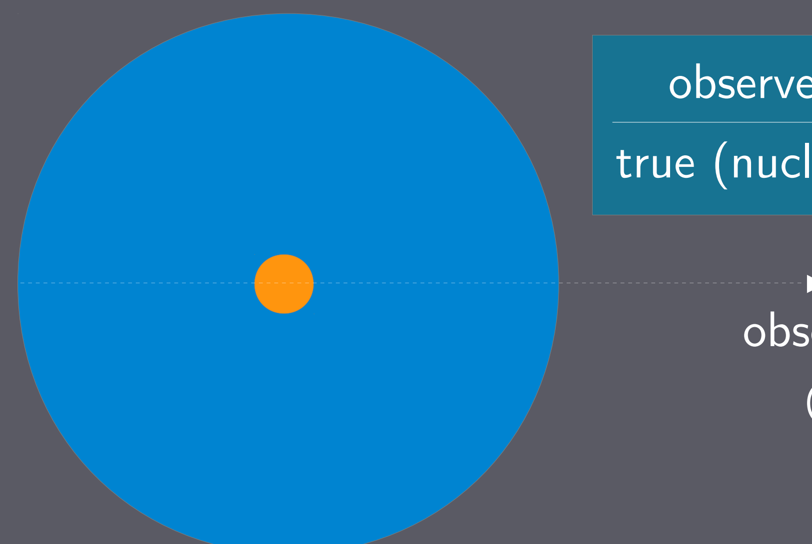
The observed equivalent width (EW) is not diluted only by the <u>local</u> stellar background, but also by the integrated <u>line-of-sight</u> emission of all stars along the optical path.

The EW depends on the relative 3D distribution of the emitting and diluting component (geometry matters)



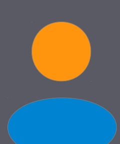
$$\frac{\text{observed EW}}{\text{true (nuclear) EW}} \simeq 1$$

observer ☺



$$\frac{\text{observed EW}}{\text{true (nuclear) EW}} \ll 1$$

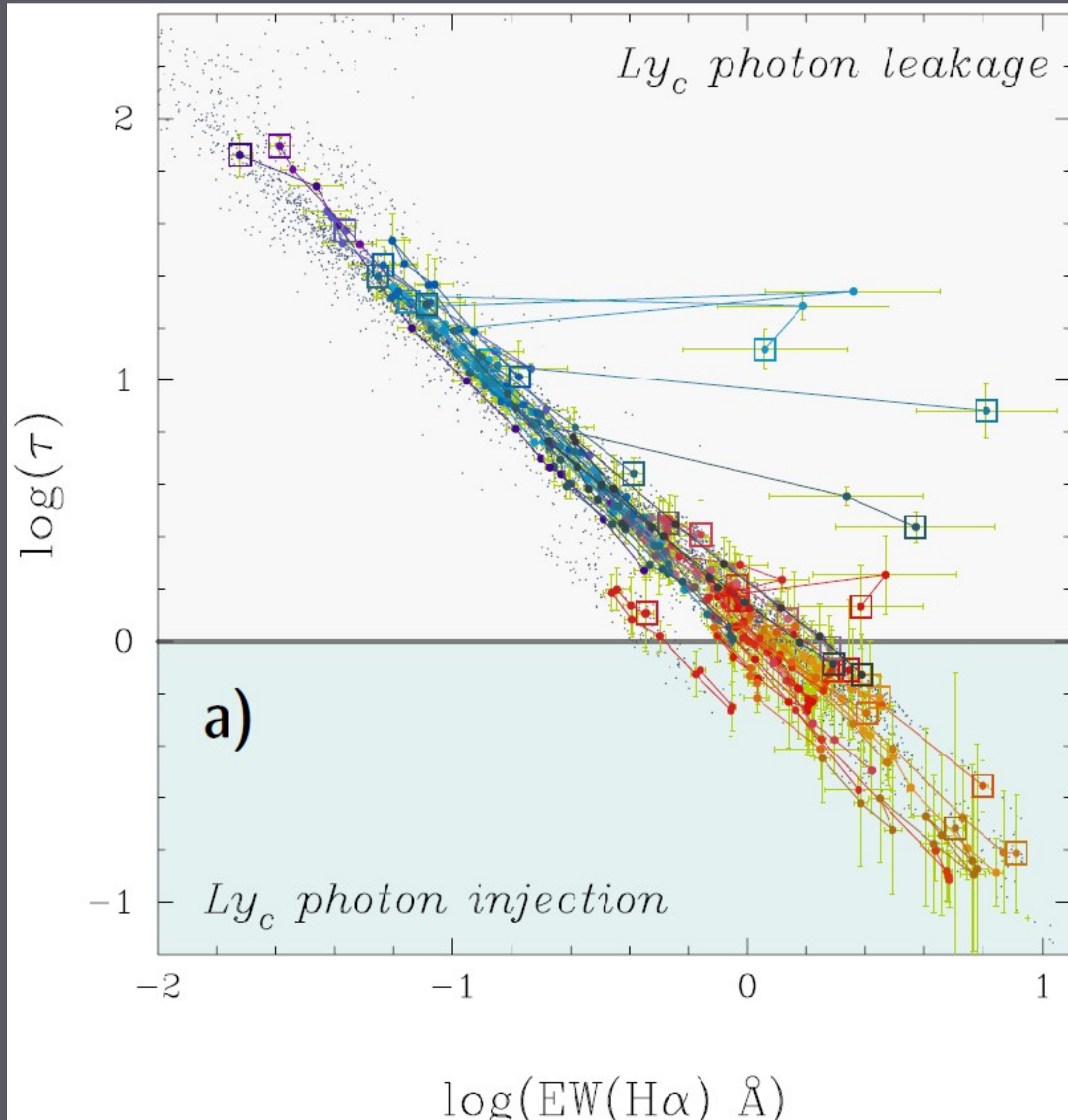
observer ☹



AGN

stars

Result: Malmquist-like selection effect, disfavoring the detection of nuclear AGN activity in galaxy spheroids (i.e. ETGs)

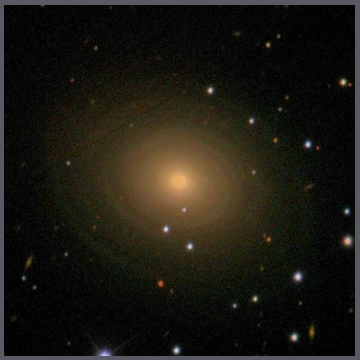


Determinations in ETG nuclei

Connected symbols: determinations within irregular annuli (isan method)

- Relation between EW(Hα) and τ
- EW(Hα) ~1 Å corresponds to $\tau \simeq 1$ (and $f_{esc} \simeq 0$)

Studies of the WIM in early-type galaxies



Gomes et al. (2014, in prep.)