LINERs and Lyman continuum photon escape

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OAC, Kolymbari, Crete
Escape of Lyman radiation from galactic labyrinths
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Outline

- 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 (Papaderos+13, Gomes+16)

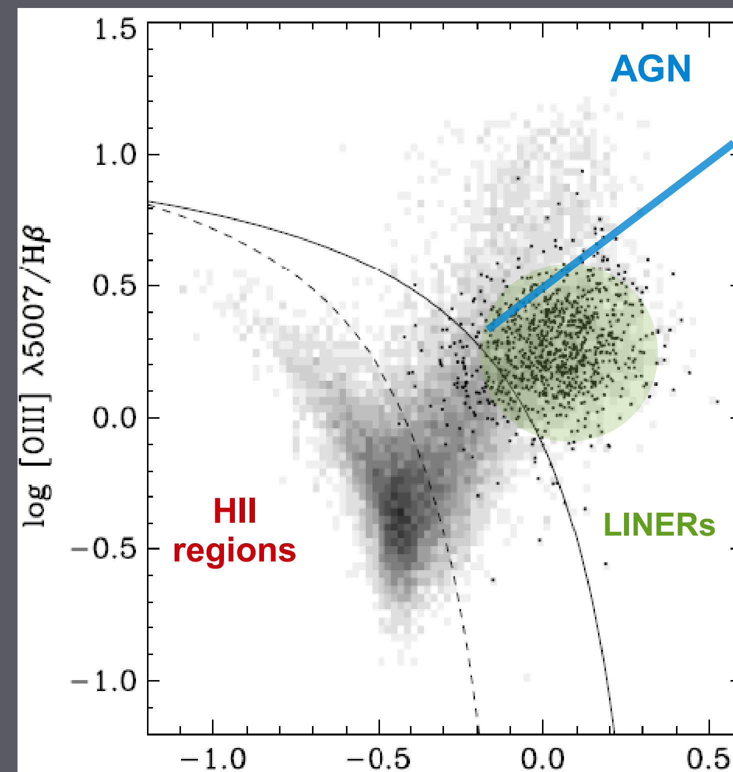
- Evidence for Lyman continuum photon escape from ETGs
  … and its implications for our understanding of AGN/LINER activity in ETGs

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



●: Photometrically selected (red) LINER/ETGs

0.09 ⩽ z ⩽ 0.1 (Yan & Blanton 2012)

———— Kewley et al. (2001)

— — — Kauffmann et al. (2003)

———— Stasińska et al. (2008)

Excitation mechanisms of the WIM 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)

WIM excitation by the pAGB component

Hot post-AGB stars (age ≥ 100 Myr)

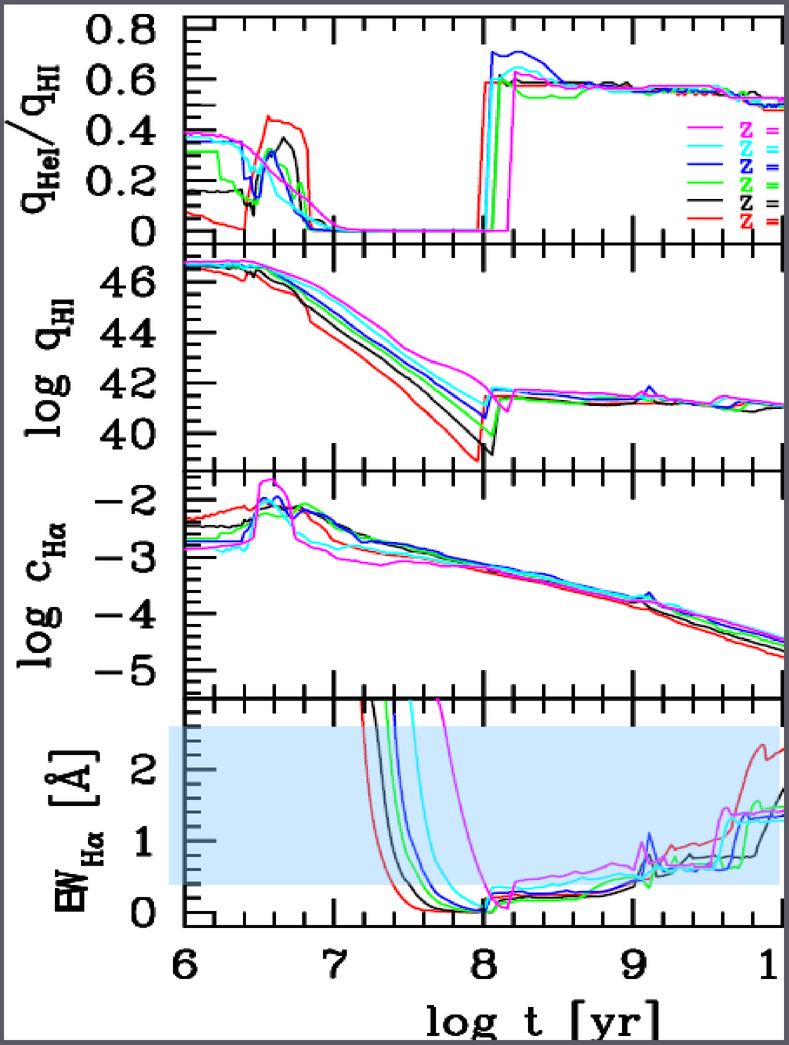
Bruzual & Charlot (2003) models
for an instantaneous burst

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

After ~100 Myr, the rate of 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≳1 Gyr



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

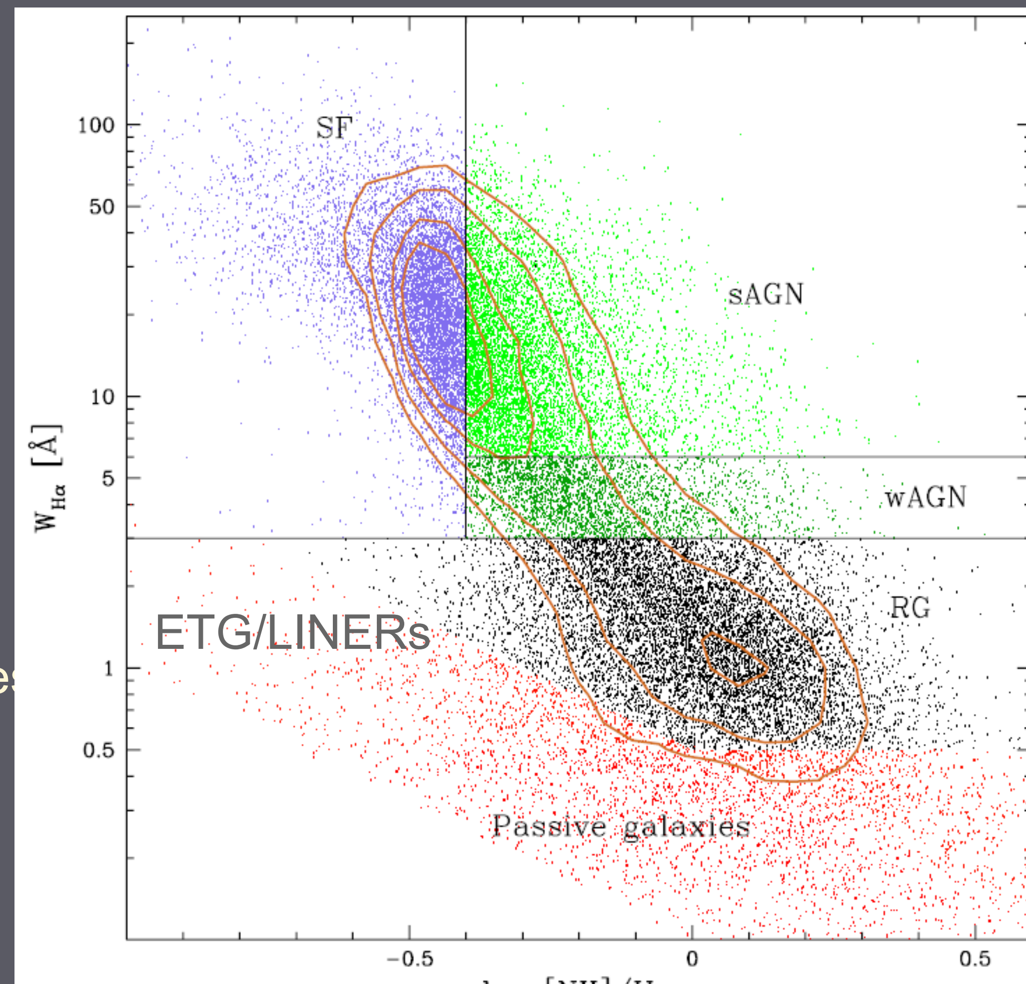
Cid Fernandes et al. (2011)

Several recent studies favor pAGB stars as the dominant WIM excitation source in ETG/LINERs
(e.g. Sarzi et al. 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 → RGs are actually fake AGN.

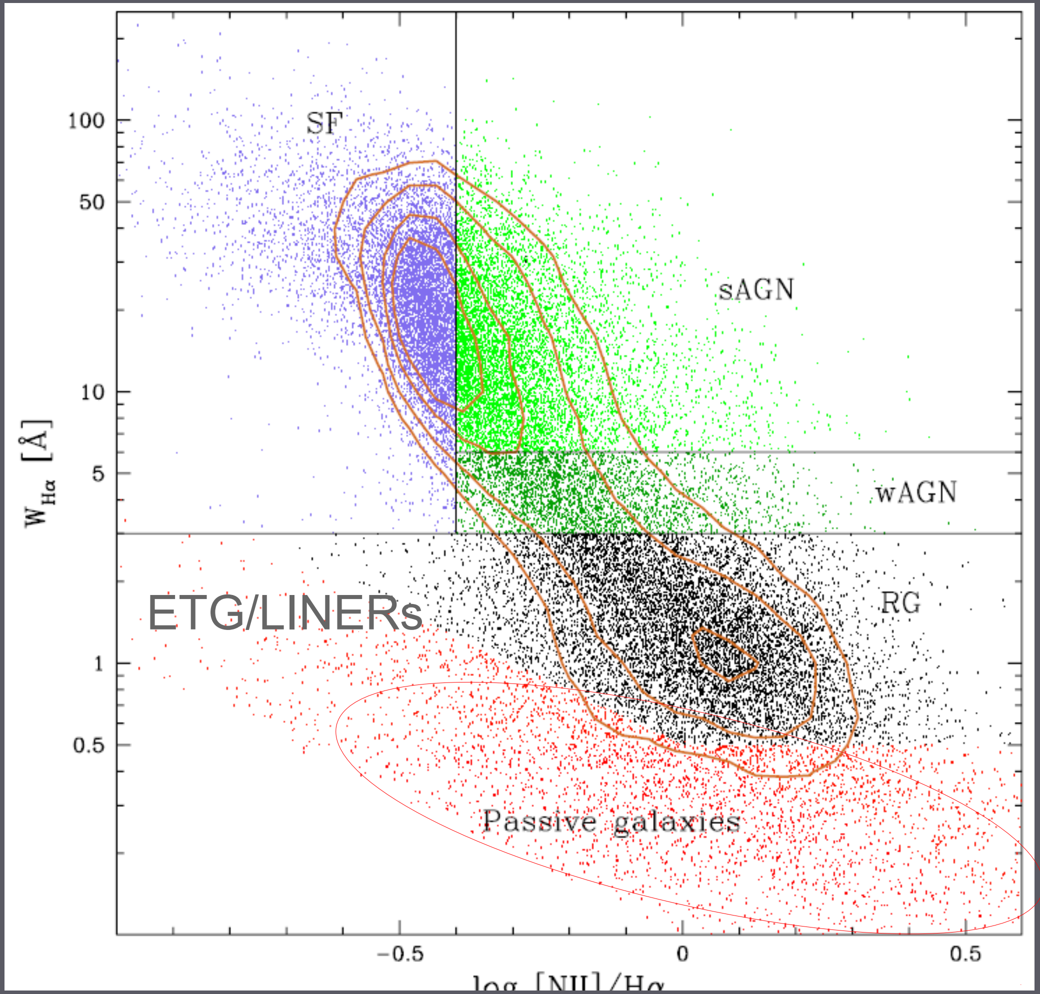
"They are erroneously counted as AGN, leading to the illusion of a dichotomy in the AGN population. It might therefore be that the real dichotomy is between AGN and retired galaxies, and not between two states of black hole accretion." Cid Fernandes et al. (2010)



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

Questions ...

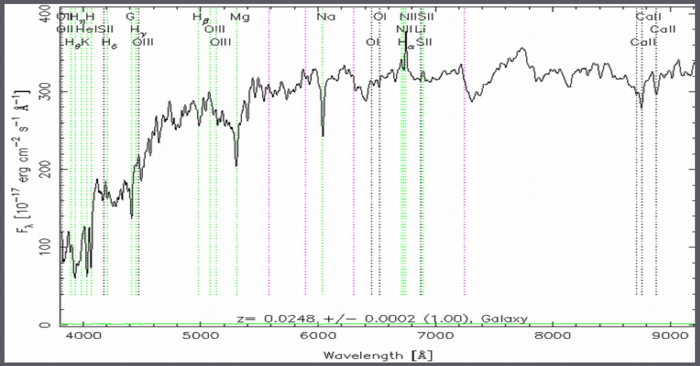
- Why nebular emission is absent in “passive” ETGs? Since they also contain pAGB stars (and gas returned into the ISM during their evolution), they should also show some diffuse low-level (EW(Hα): 1-2 Å) nebular emission, similar to “retired” galaxies.



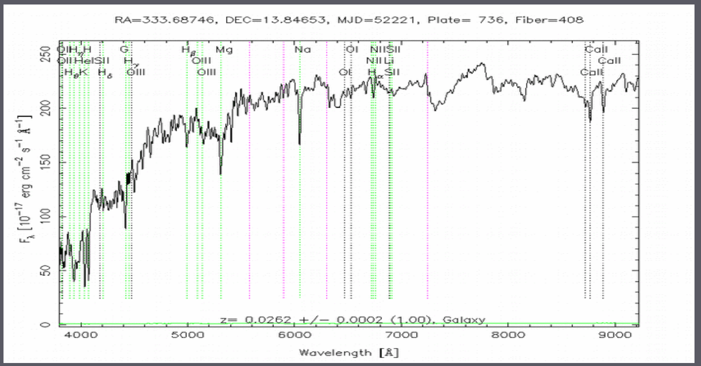
Questions ...

- Is the <u>line faintness</u> (consequently also the spectroscopic classification of ETGs as retired, or passive), unambiguous proof for a low AGN accretion state or the absence of an AGN?

… conversely, strong evidence for the predominance of pAGB photoionization, in the case of retired galaxies (?)



“Retired”
(no AGN)



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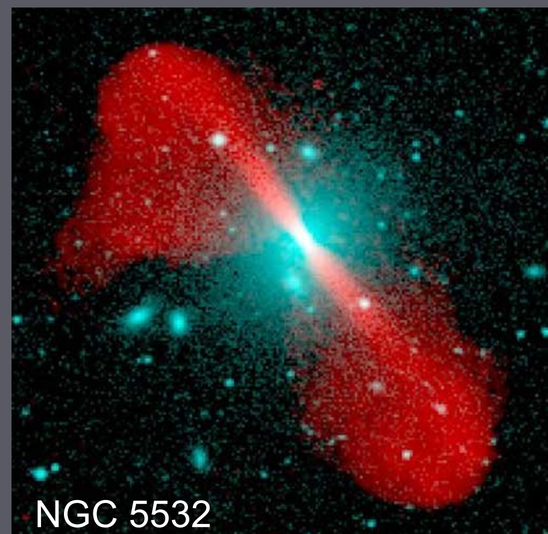
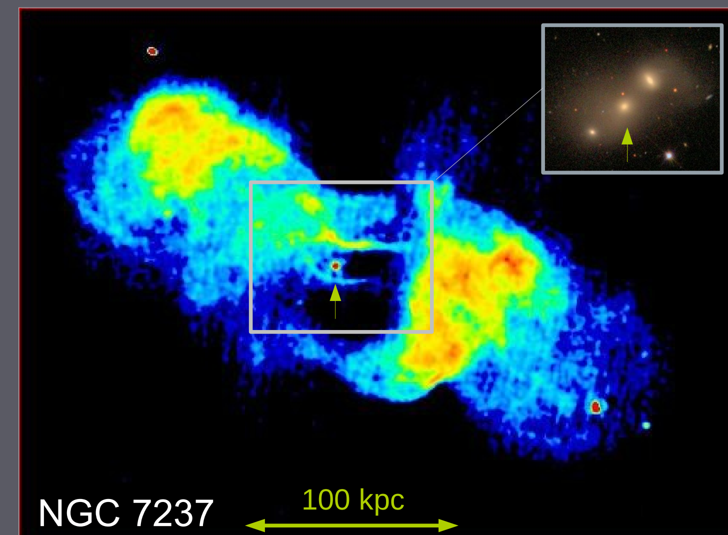
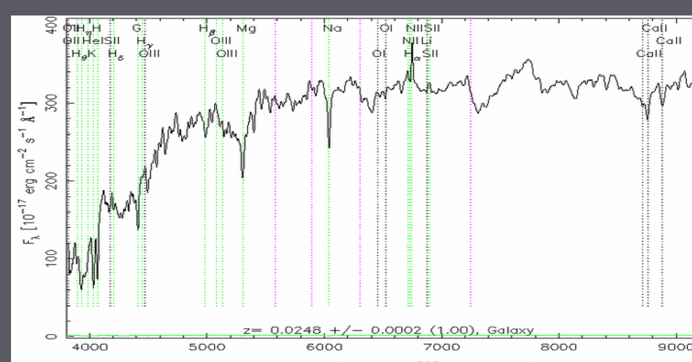
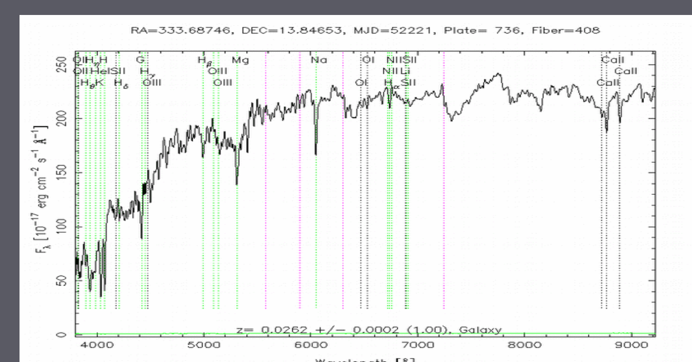




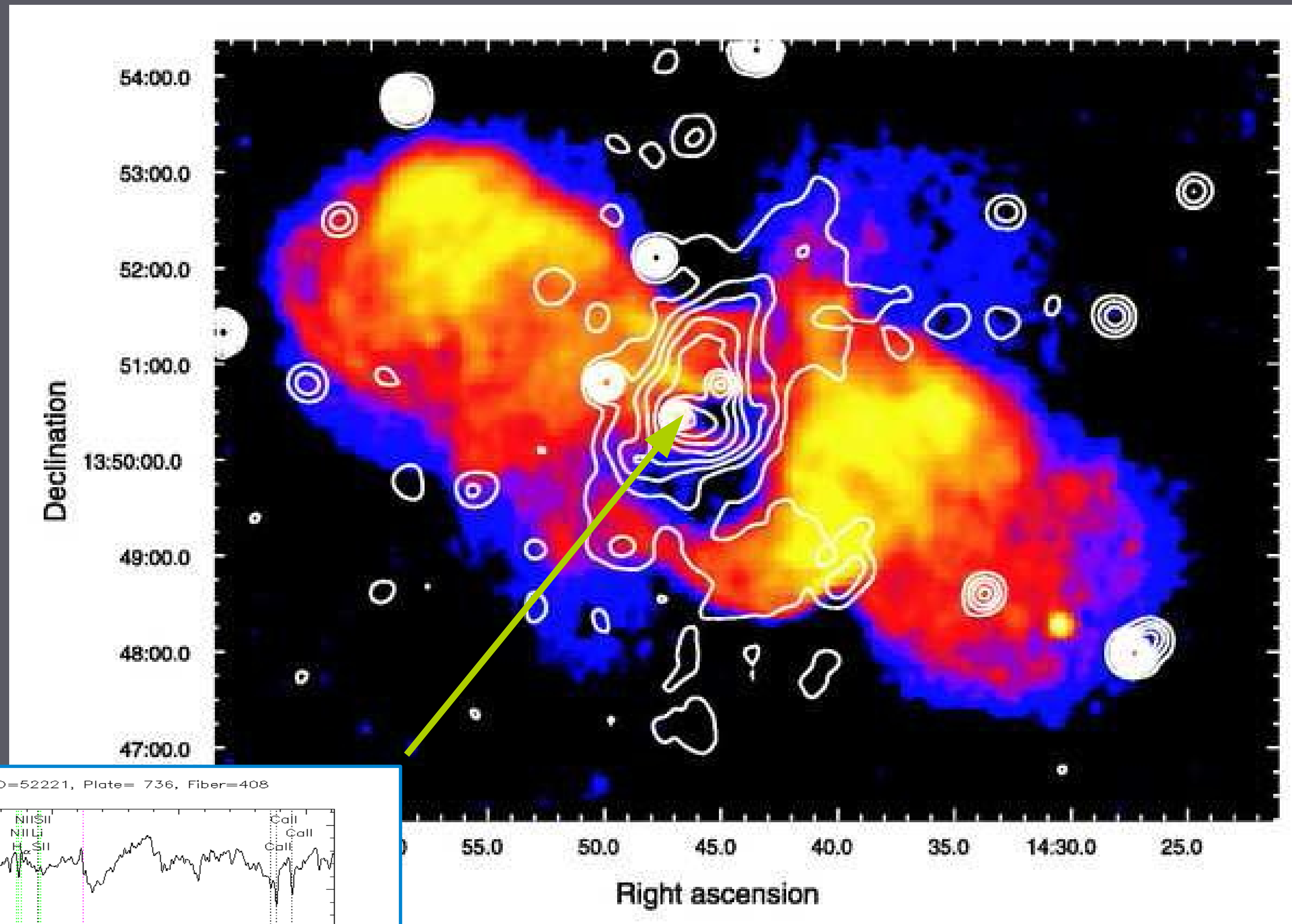


“Retired”
(fake AGN)



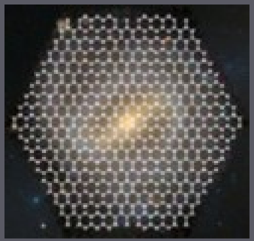
“Passive”
(no AGN)

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



(Worrall et al. 2007)

Studies of the WIM in early-type galaxies



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

CALIFA (Calar Alto Integral Field Area survey)

Sanchez et al. (2011; A&A, 538, A8); Husemann et al. (2012, A&A, 549, A87)

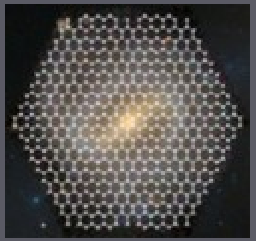
- nearly 600 galaxies in the local Universe observed so far
- Field of view ~ 1 arcmin^2
- 2 spectroscopic setups:

low-resolution (V500): 3745 – 7300 Å; R $\simeq$ 850 @ 5000 Å ; $\mu_{lim} \simeq$ 23.6 V mag/□”^{2}
high-resolution (V1200): 3400 – 4750 Å; R $\simeq$ 1650 @ 4500 Å ; $\mu_{lim} \simeq$ 23.4 V mag/□”^{2}

- flux detection limit ~ 10^{-17} erg s^{-1} cm^{-2}

http://califa.caha.es/ for further details and information on the **Data Release 3**

Studies of the WIM in early-type galaxies



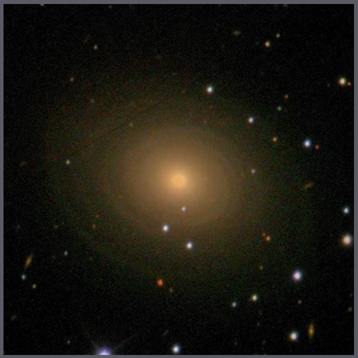
- Pilot study of 2 ETGs in Kehrig et al. (2012)
- Investigation of the Lyman continuum photon escape fraction in 32 ETGs (20 E + 12 S0) in Papaderos et al. (2013)
- Detailed discussion of the ETG sample in Gomes et al. (2016a-c)

Method

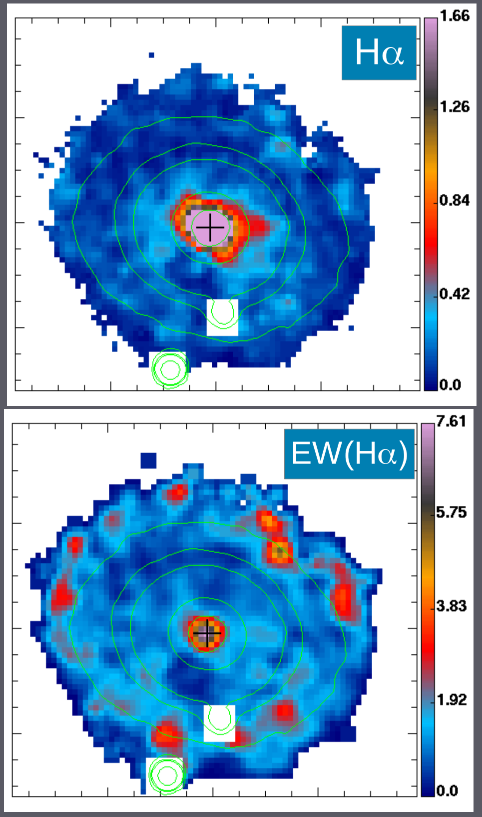
- Automated spaxel-by-spaxel spectral fitting with STARLIGHT (Cid Fernandes et al. 2005) and the **Porto3D** pipeline:
1600 .. 3200 spaxels per ETG modeled using both Bruzual & Charlot (BC03) and MILES Simple Stellar Population (SSP) spectra for 34 ages $\times$ 3 metallicities.

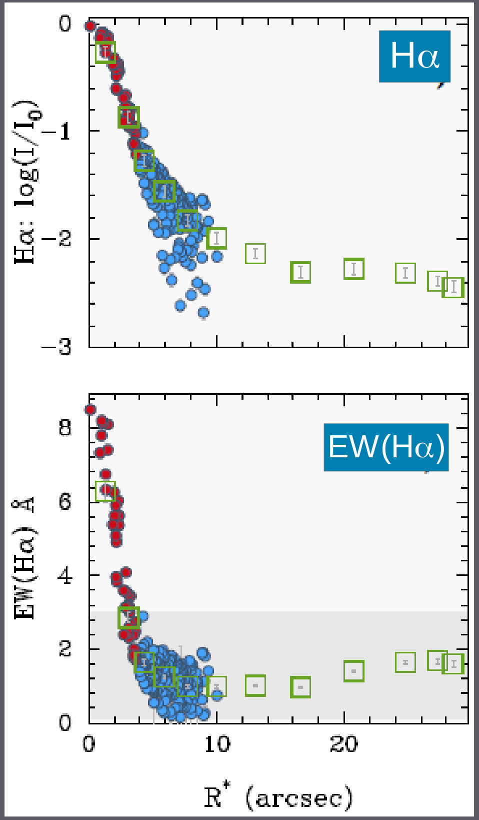
- Emission line flux determination after subtraction of the best-fitting stellar SED

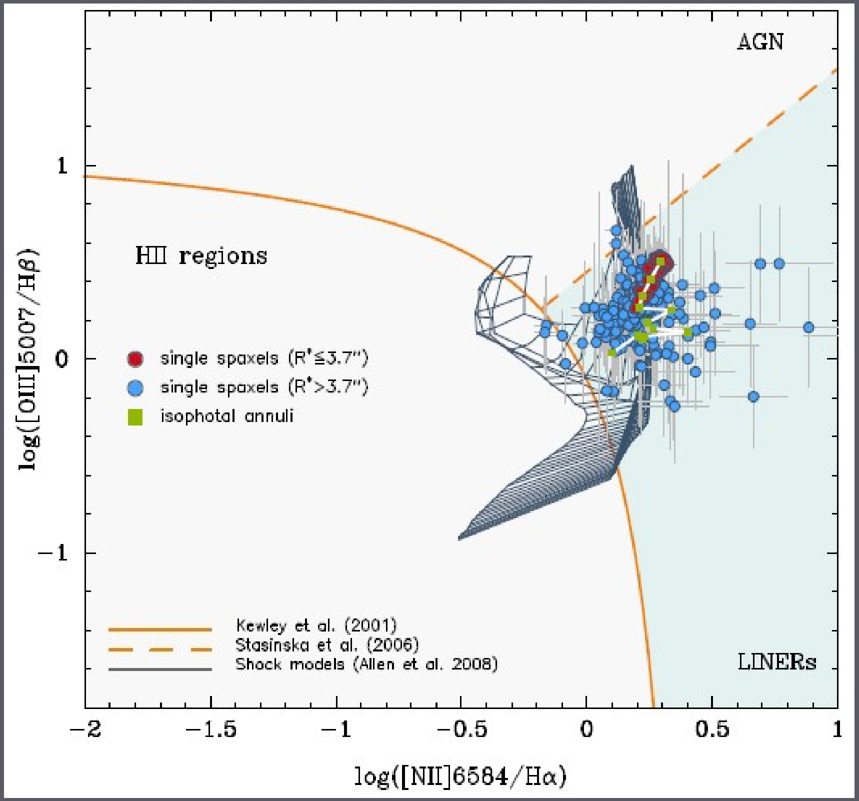
Studies of the WIM in early-type galaxies



Gomes et al. (2016c)







● ● 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

Determination of the 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

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

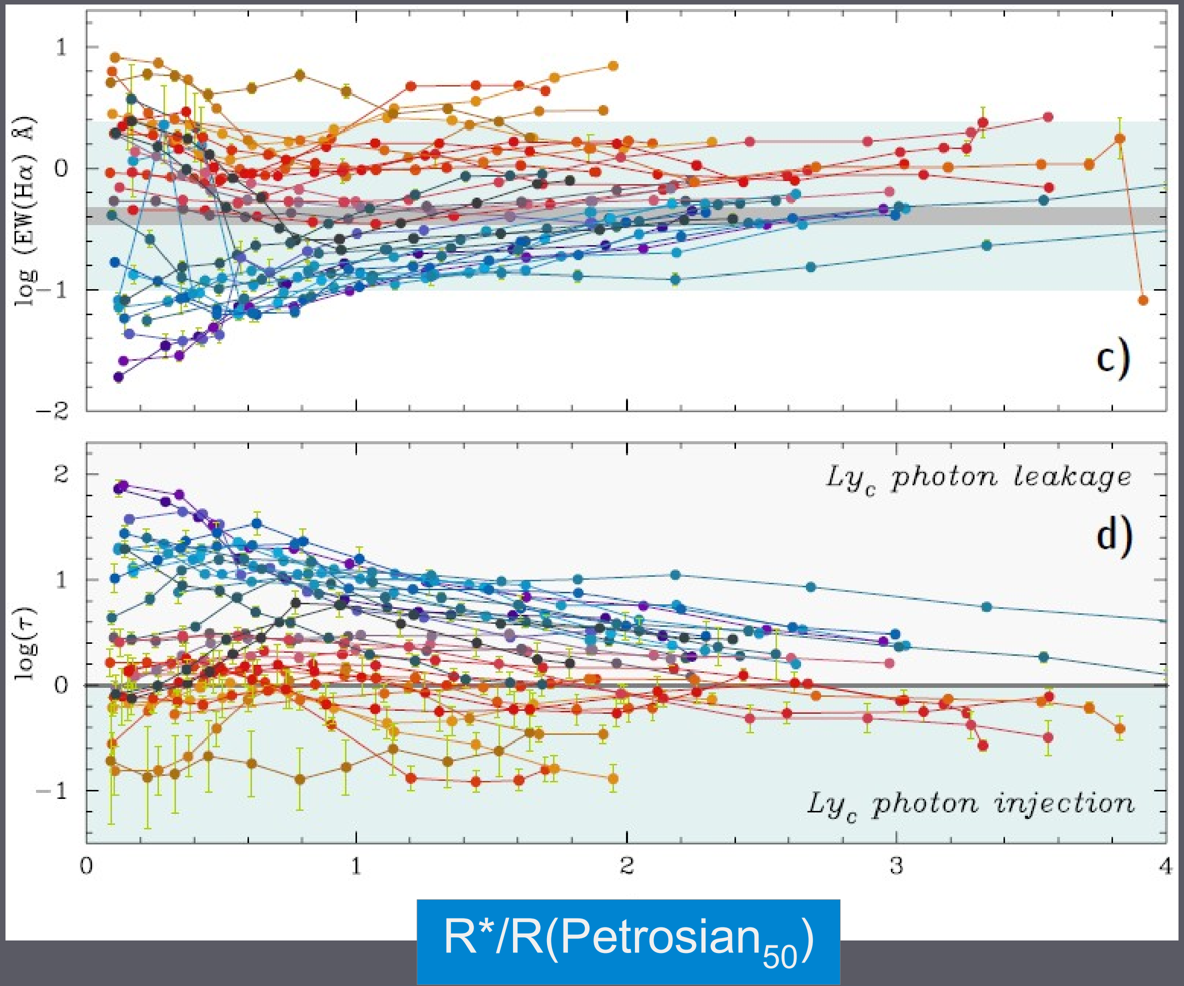
Radial distribution of EW(Ha) and the τ ratio in CALIFA ETG/LINERs

determinations within irregular annuli

Type i

0.5 Å

Type ii



nearly constant EW ~ 1 Å

EW< 0..5 Å
& positive EW gradient

Type ii
$\tau \geq 2$

Type i
$\tau \simeq 1$

0.97
0.9
0.6
0

Lyman cont. escape

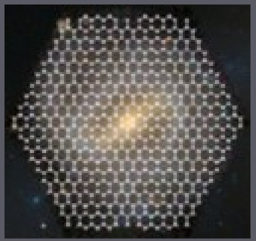
pAGB "balance"

extra ionizing source needed (e.g. SF)

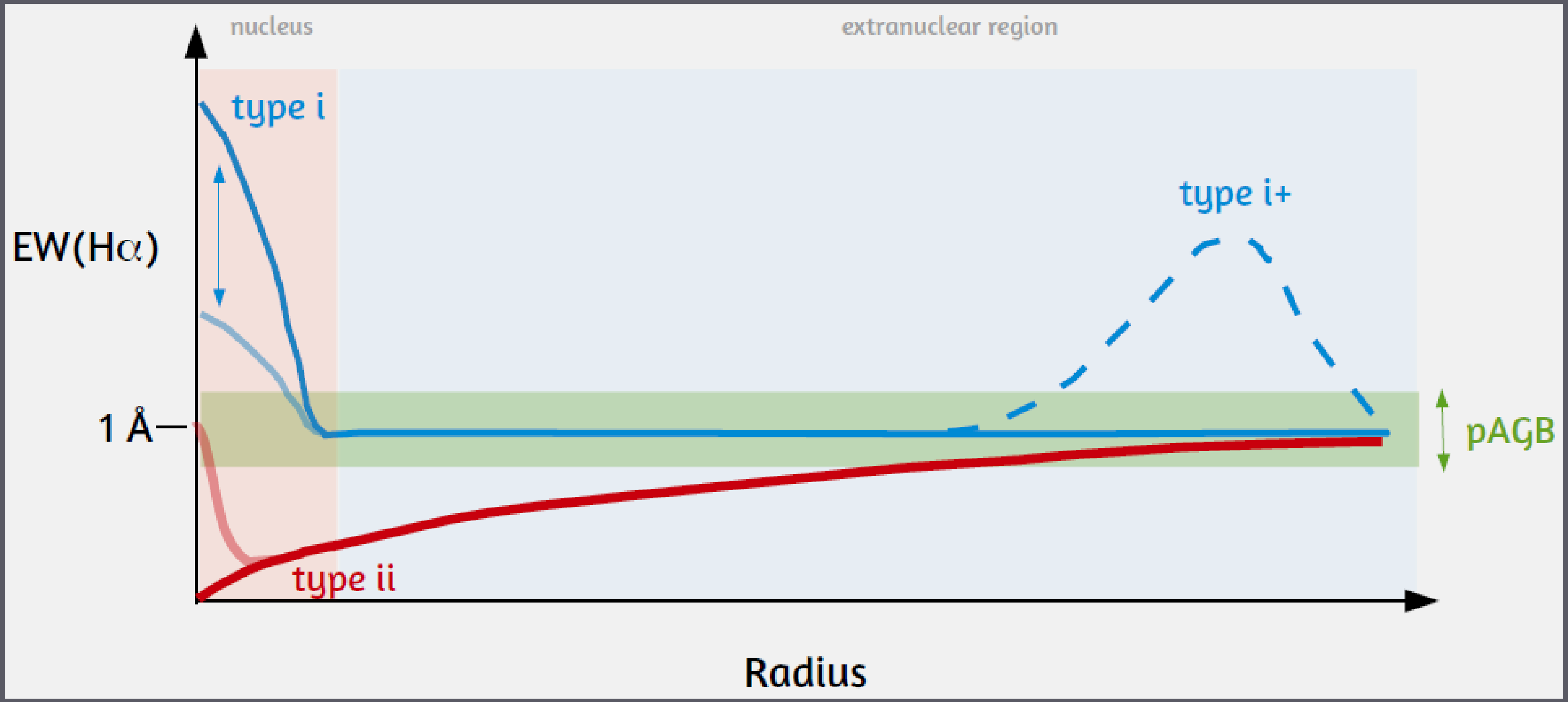
Tentantive classification of ETG/LINERs (Papaderos et al. 2013)

- 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)

Tentative classification in two main classes



based on the radial distribution of the EW(Hα)
(details in the presentation by J.M. Gomes)



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

- 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

Weakness of nuclear emission-line fluxes & EWs in ETG/LINERs

- LLAGN (sub-Eddington accreting SMBH): non-universally valid hypothesis

- dust extinction: non-universally valid hypothesis (inter alia, because of the EW(Hα) – τ anticorrelation; cf Papaderos et al. 2013)

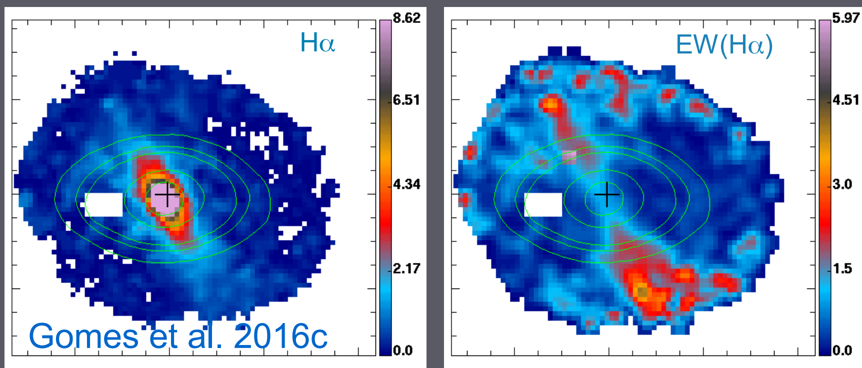
- high f_{esc} ($\simeq$0.7-0.95)

+

- dilution of nuclear emission-line equivalent by the line-of-sight stellar background

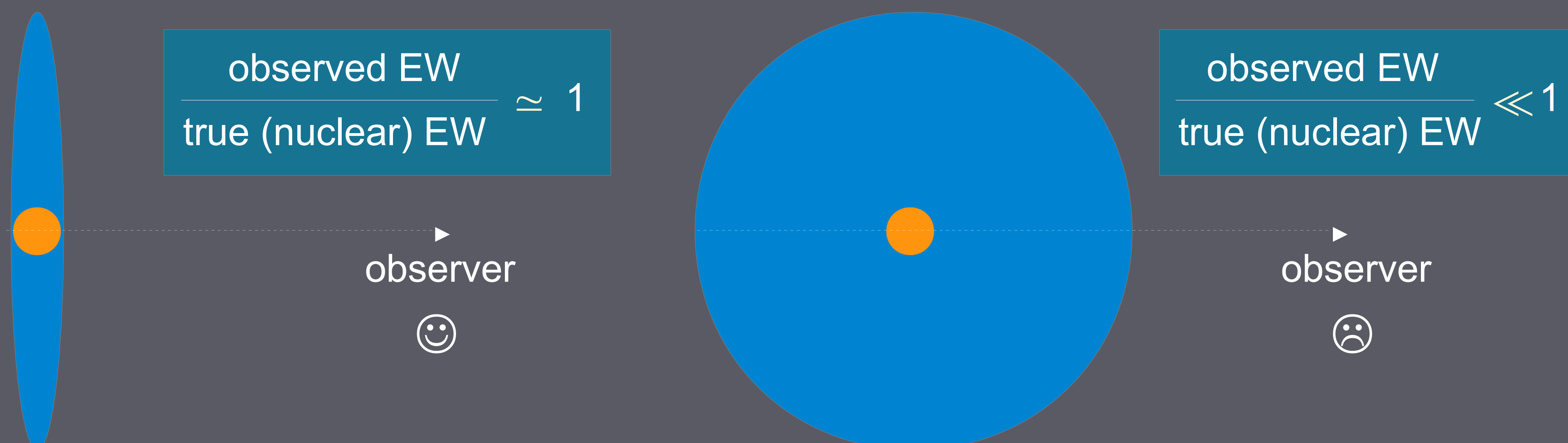
Geometric dilution of emission-line equivalent widths

(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)



Result: Malmquist-like selection effect, disfavoring detection of nuclear AGN activity in galaxy spheroids (i.e. ETGs).
Particularly relevant in the case of single-fiber spectroscopy (e.g., SDSS, GAMA)

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
- $\gtrsim$70-95% of the Lyman continuum output from pAGB stars (consequently, from any other ionizing source, e.g. an AGN) escape into the intergalactic space without being locally reprocessed into Balmer (and Lyα) emission
- Because of extensive Lyman continuum escape, nuclear line luminosities and equivalent widths are reduced by at least 1 dex → 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.