**Javier Rodríguez Zaurin**

*The star formation histories and evolution of local LIRGs and ULIRGs*

Luminous and Ultraluminous infrared galaxies (LIRGs and ULIRGs) are much more numerous at higher redshifts than locally, dominating the star formation rate density at redshifts ~2. Therefore, they are important objects in order to understand how galaxies form and evolve through cosmic time. Local samples provide a unique opportunity to study these objects in detail. With that in mind, we have undertaken a programme of spectroscopic observations of over 40 objects involving both, long-slit and integral field spectroscopic datasets. Our aim is to investigate the distributions of the parameters associated with the stellar populations (i.e. age, reddening and percentage contribution), and also, whether the properties of the stellar populations correlate with other properties of (U)LIRGs (such as the spectral classification, infrared luminosity, etc...). We find that the star formation histories of ULIRGs are complex, with at least two epochs of star formation activity and that the characteristic timescale of the star formation acivity is <100 Myr. These results are consistent with models that predict an epoch of enhanced star formation coinciding with the first pass of the merging nuclei, along with a further, more intense, episode of star formation occurring as the nuclei finally merge together. It is also found that the young stellar populations (YSPs) tend to be younger and more reddened in the nuclear regions of the galaxies. This is in good agreement with the merger simulations, which predict that the bulk of the star formation activity in the final stages of mergers will occur in the nuclear regions of the merging galaxies. In addition, our results show that ULIRGs have total stellar masses that are similar to, or smaller than, the break of the galaxy mass function ($m_* = 1.4 \times 10^{11}$ Msol). The mass estimates increase by a factor or ~2 when accounting for old (10 Gyr) stellar populations. Finally, we find no significant differences between the ages of the YSP in ULIRGs with and without optically detected Seyfert nuclei, nor between those with warm and cool mid- to far-IR colours. While this results do not entirely rule out the idea that cool ULIRGs with HII/LINER spectra evolve into warm ULIRGs with Seyfert-like spectra, it is clear that the AGN activity in local Seyfert-like ULIRGs has not been triggered a substantial period (>~100 Myr) after the major merger-induced starbursts in the nuclear regions.

# THE STAR FORMATION HISTORIES AND EVOLUTION OF ULIRGS


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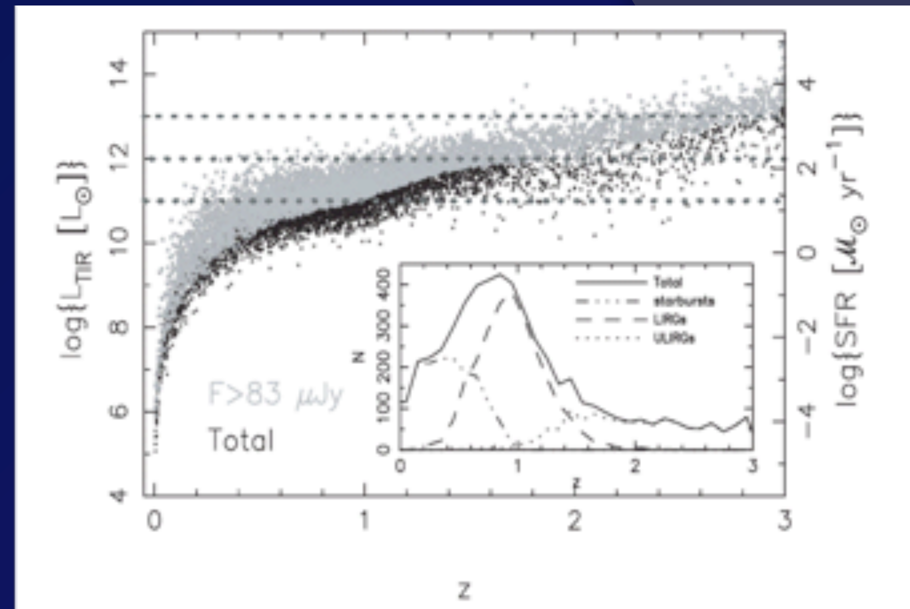
# Spectroscopy of LIRGs and ULIRGs:

- Optical long-slit spectroscopy of ULIRGs (ISIS-WHT)
(Rodríguez Zaurín et al., 2007,2008, 2009, 2010a)

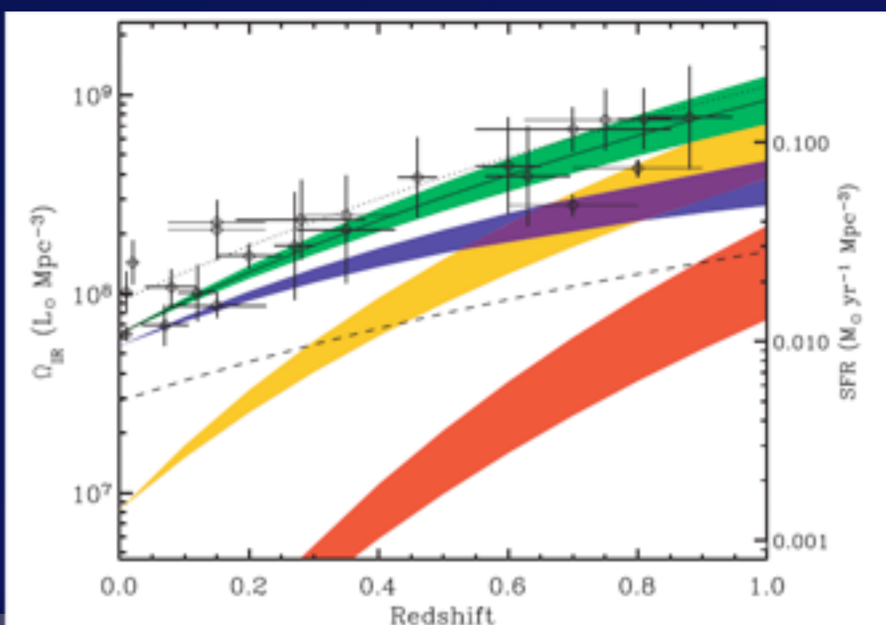
- VIMOS, SINFONI and PMAS integral field spectroscopy of local LIRGS and ULIRGs.
(Arribas et al., 2008, Monreal Ibero., et al 2010, Alonso Herrero., 2010, Rodríguez Zaurín., 2010b, submitted)

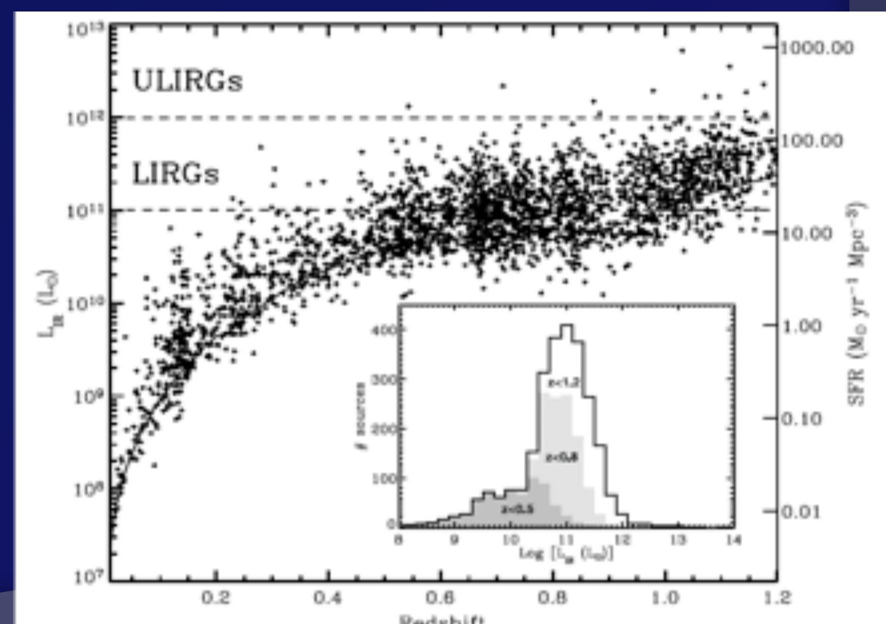
# Spitzer MIPS 24 μm results:

Pérez González et al., 2005




LIRGs and ULIRGs dominate the star formation rate density at z ~1-2. Therefore they are crucial to understand how galaxies form and evolve trhough cosmic time

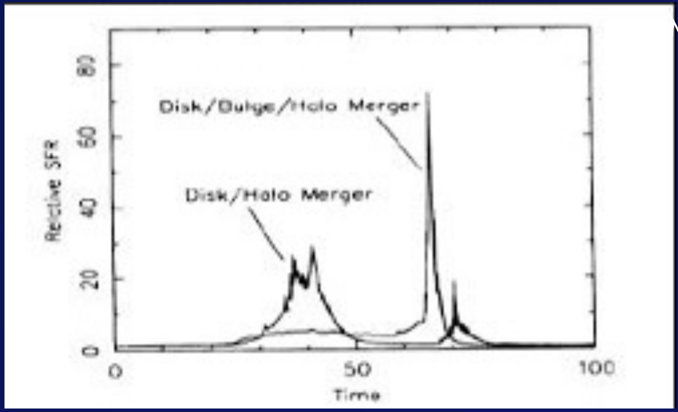



Le Floc'h et al., 2005

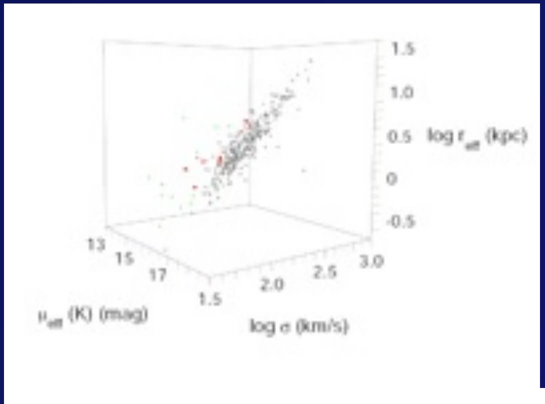
# We try to answer the following key questions:

- Do the merger simulations adequately describe the observed properties of ULIRGs?



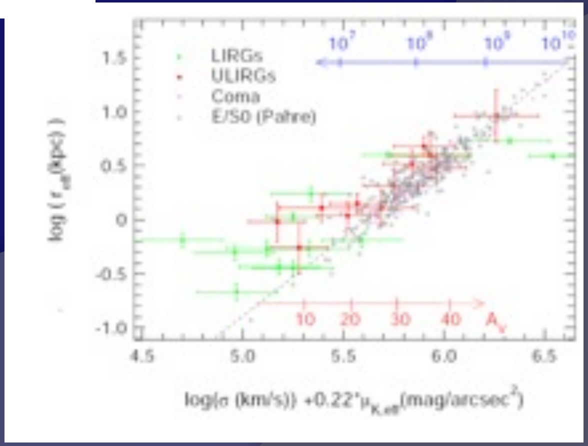

Mihos and Hernquist 1998

- Do the properties of the stellar populations in ULIRGs correlate with other properties of ULIRGs such as IR-luminosity of interaction class?



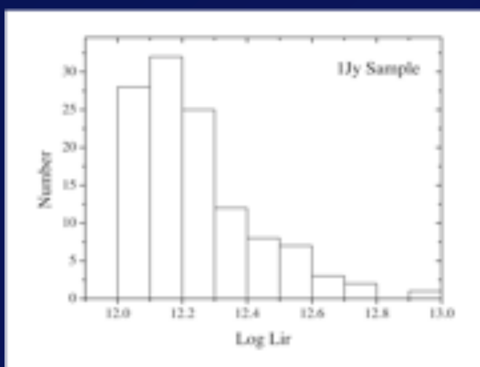

Genzel et al 2001

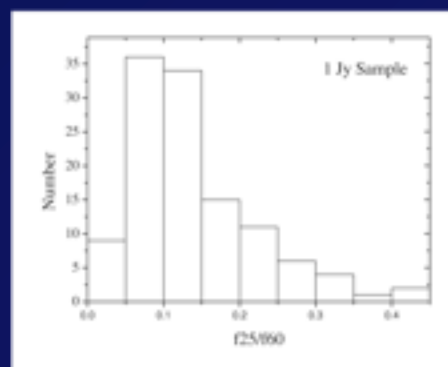
- What is the nature of the link between ULIRGs and other type of objects in the local universe such as QSOs, radio galaxies or ellipticals?

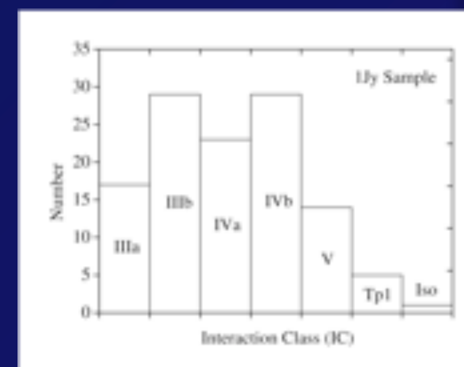


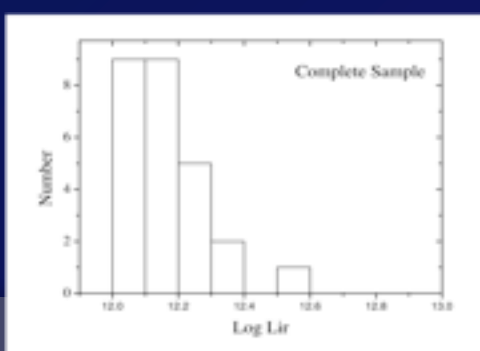
# Long slit spectroscopy of ULIRGs: 1. The sample

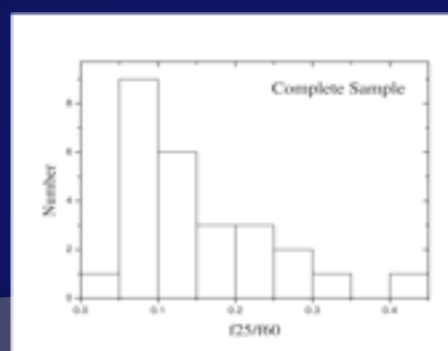
We used ISIS on the WHT to obtain optical (~3200 – 7200 Å long-slit spectra of a sample of 36 local ULIRGs with z < 0.18, extracted from the Kim & Sanders 1998 1Jy sample. This sample includes a ***complete*** RA- and δ-limited sub-sample of 26 objects.

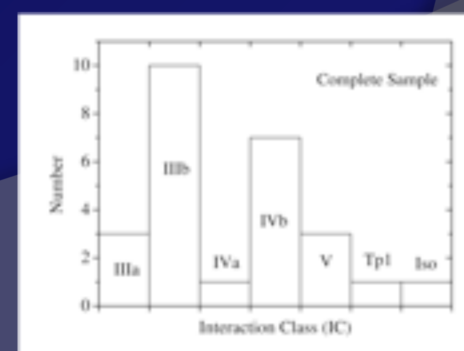


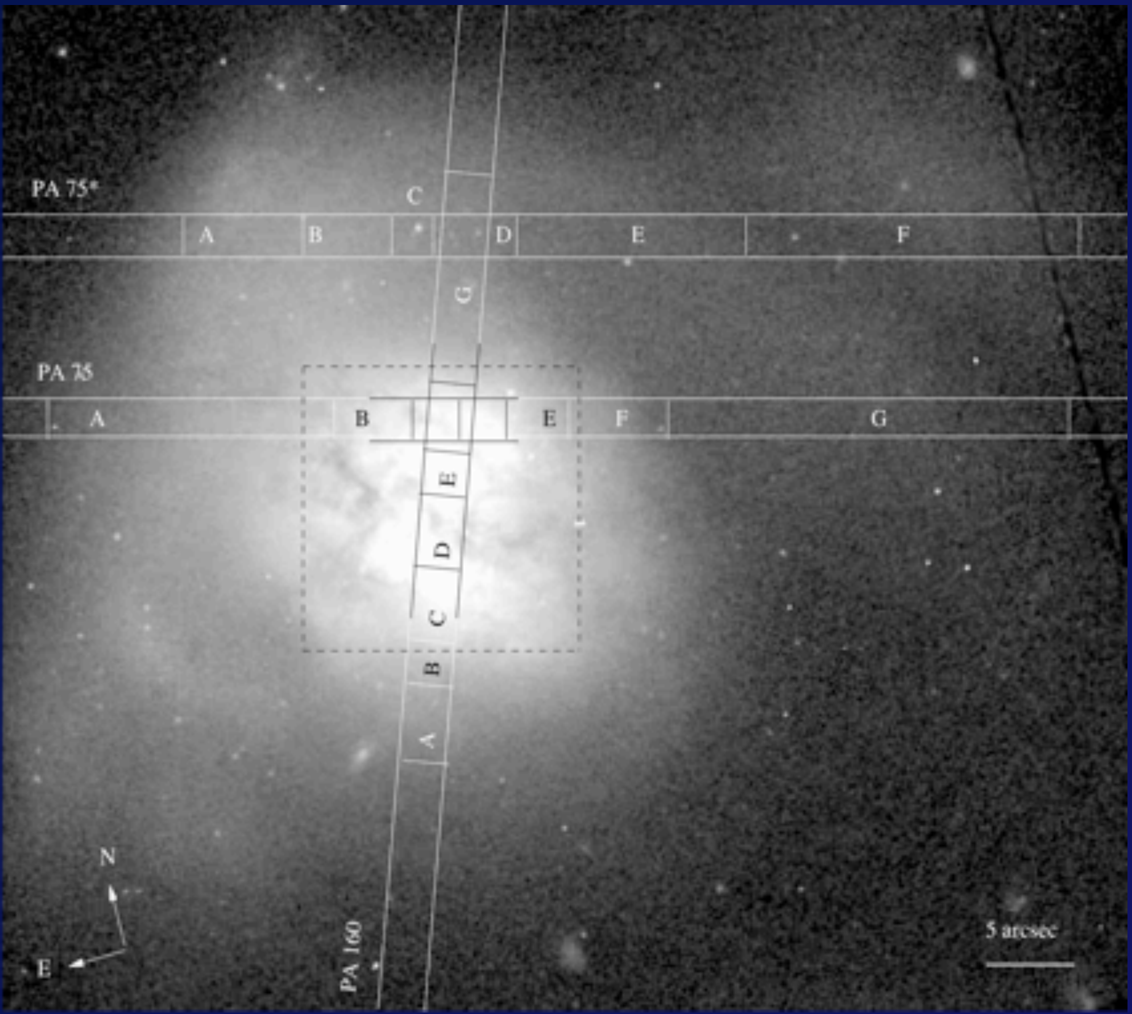



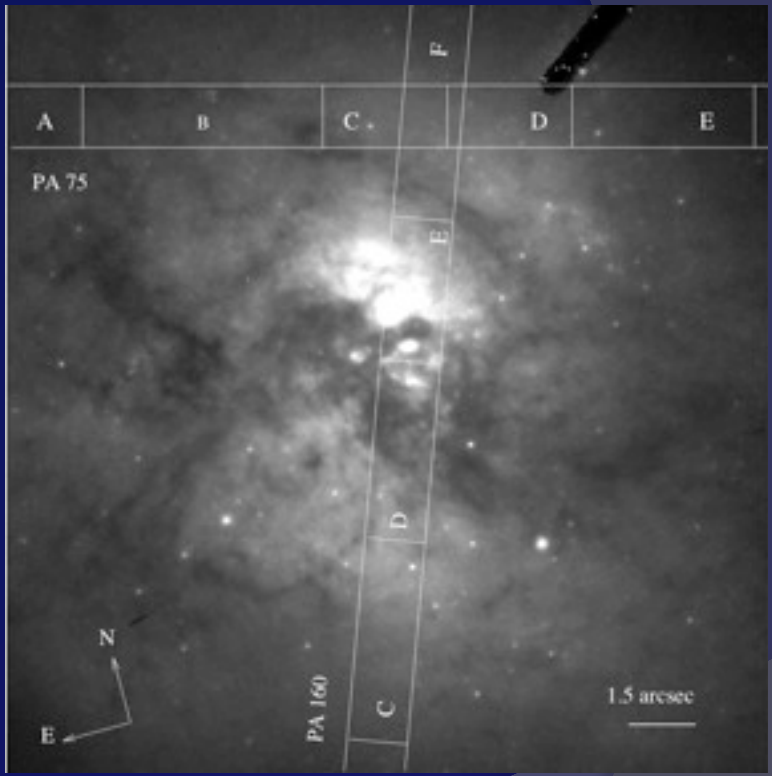



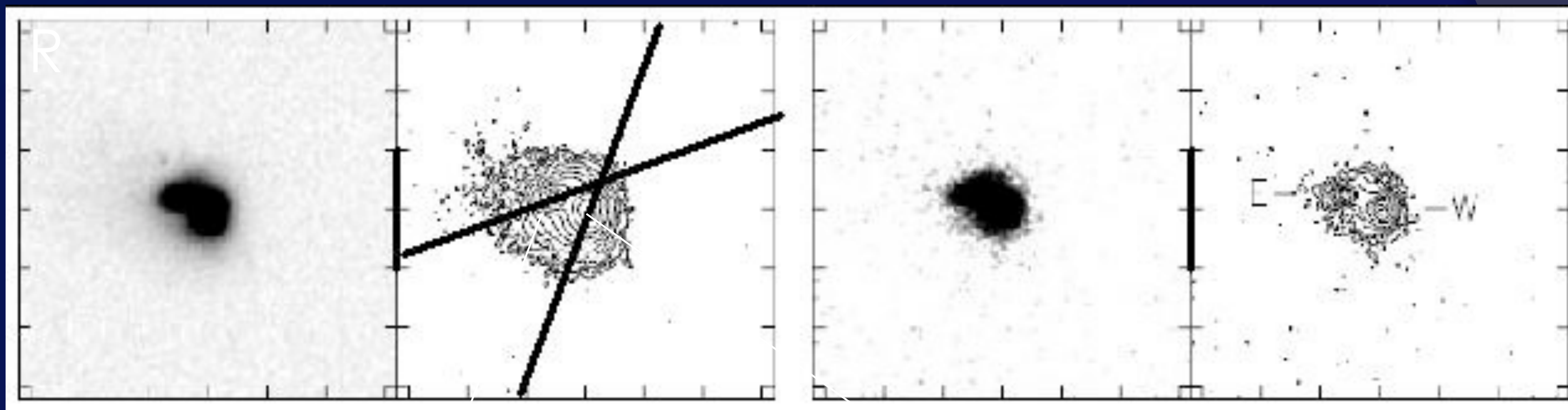
Examples

# Arp 220

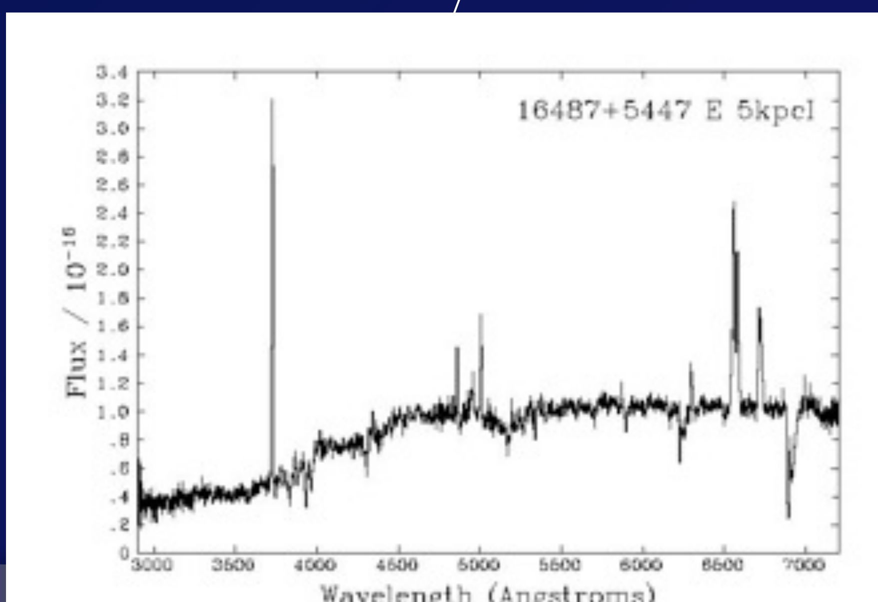


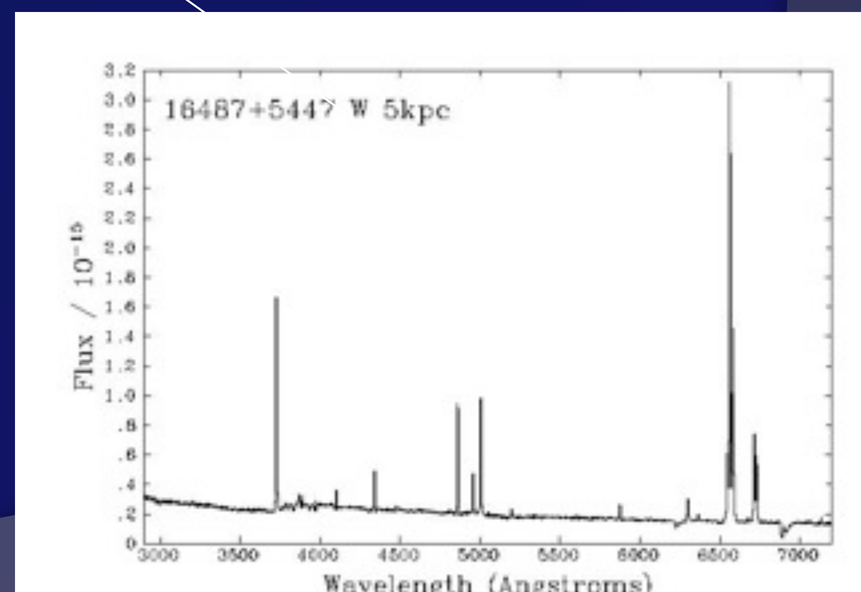



# Examples



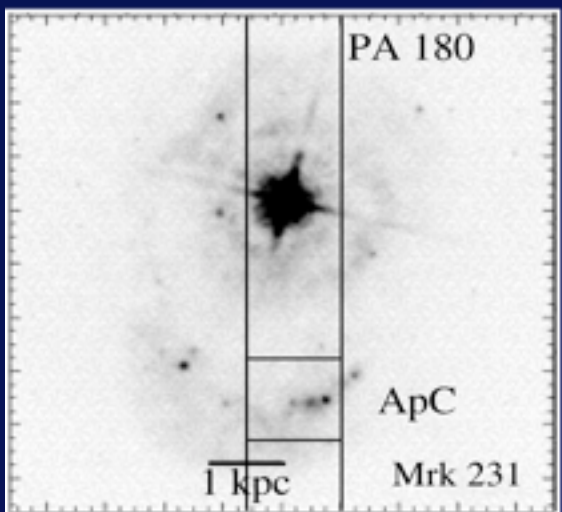

Kim et al., 2002



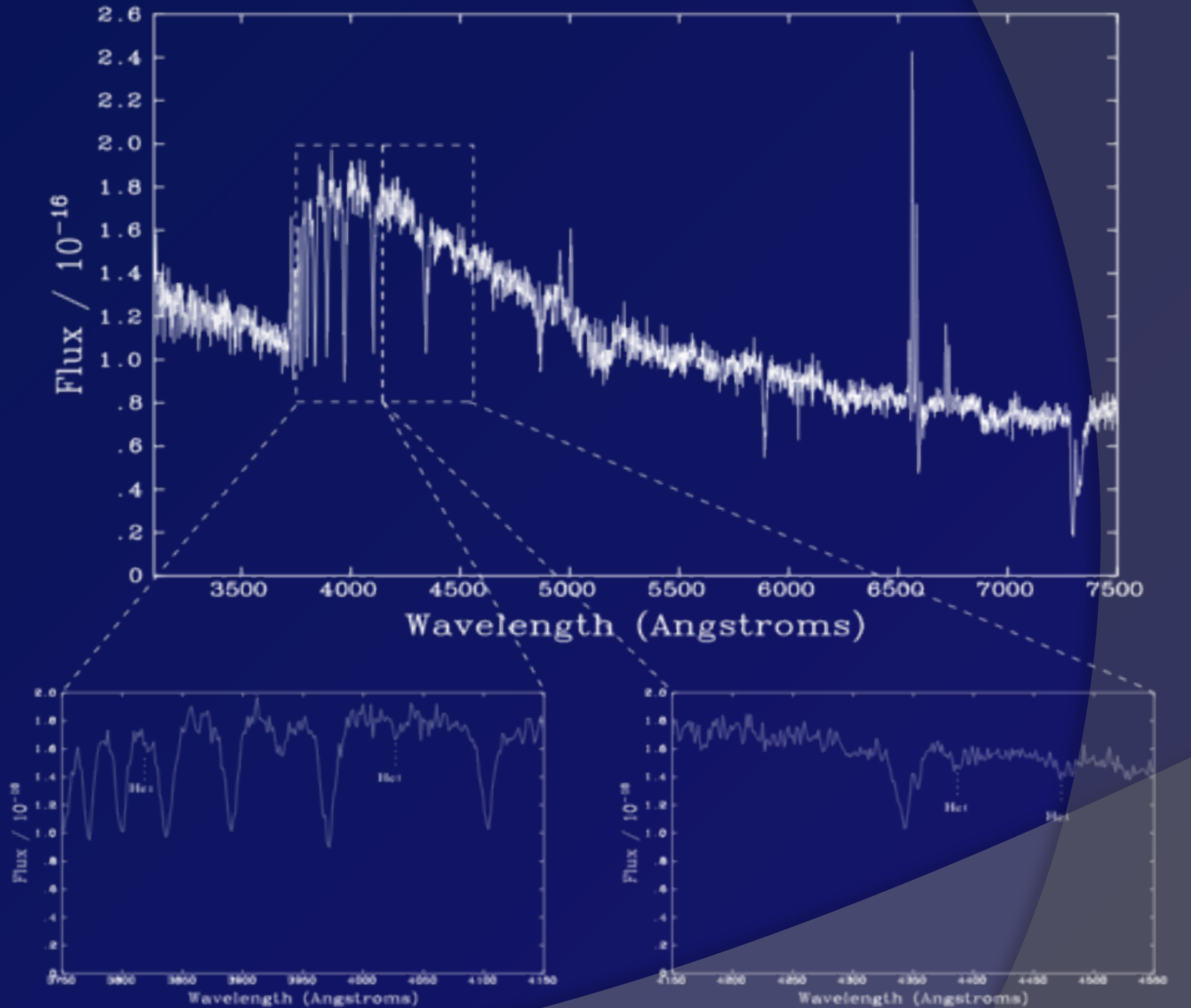



# Examples

Mrk 231




WFPC2 F439W
Surace et al., 1998



# 2. Modelling the stellar continuum

There have recently been many studies based on the modeling of the stellar, optical continuum for different types of galaxies, including (U)LIRGs, e.g.:

- MacArthur et al., 2009 → Spiral bulges and disks
- Zhong et al., 2010 → blue and red low surface brightness disk galaxies
- Cheng et al., 2010 →local infrared selected galaxies.
- …and others

These studies use the STARLIGHT code (Cid Fernandes, www.starlight.ufsc.br):

Input: 15 single stellar populations (SSP) of various ages and metallicities.
Output: % contribution to the light and Av for each SSP, for the best fitting model.

We use a "simple" IDL code (CONFIT) to perform a direct $\chi^2$ fit using a large number of combinations of two stellar templates (Bruzual & Charlot 2003).

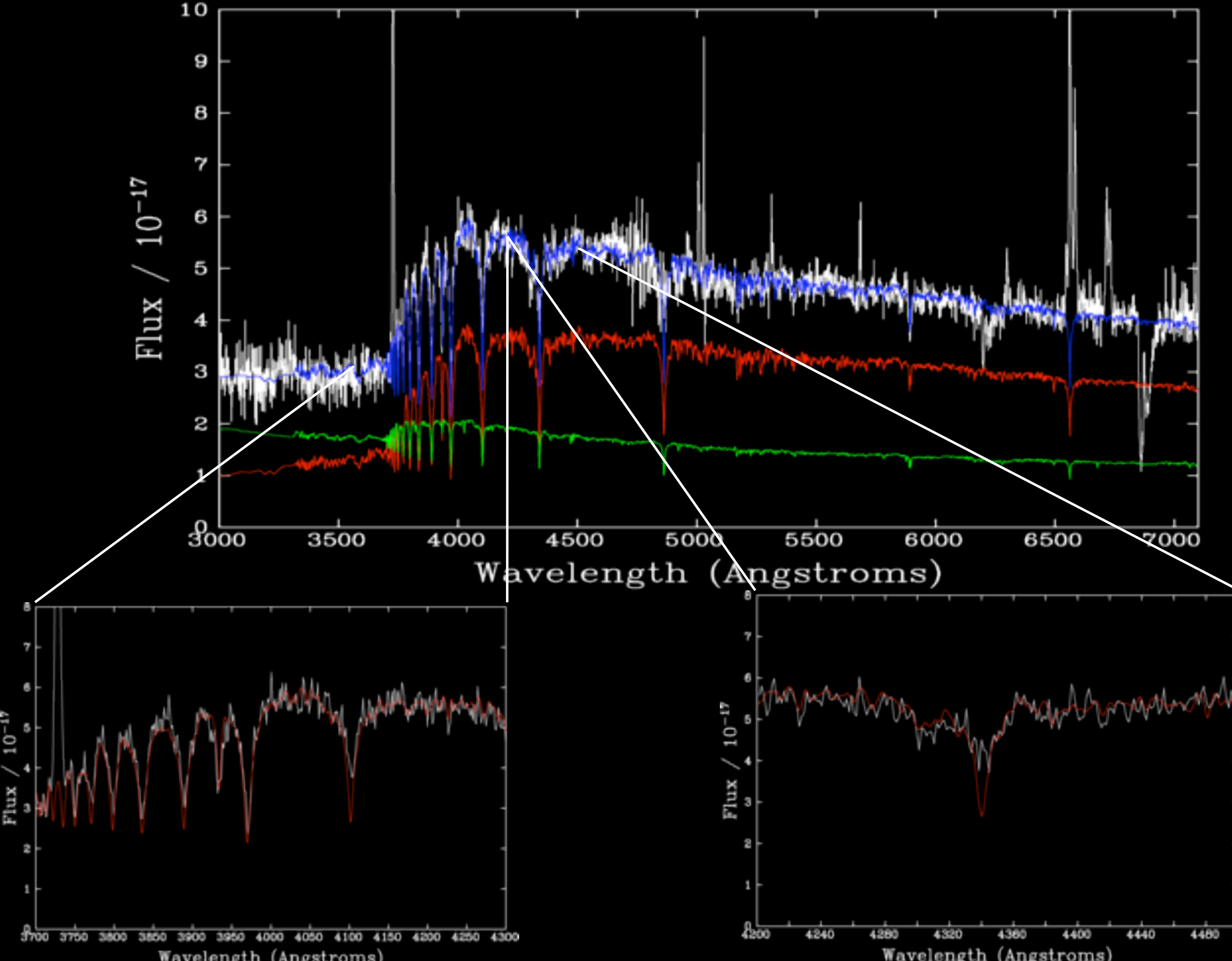
- **Input**: two grids of stellar templates.
  - Very young stellar populations (*VYSP*, $t_{VYSP} \leq 100$ *Myr*) with varying reddening.
  - "Intermediate-age" young stellar populations (*IYSP*, $100 < t_{IYSP} \leq 2.0$ *Gyr*), with varying reddening.

- **Output**: a range of ages, percentage contributions to the light and reddenings for the combinations providing adequate fits (those with reduced $\chi^2 < 1.0$ plus visually inspection! of the fit to the detailed absorption features).

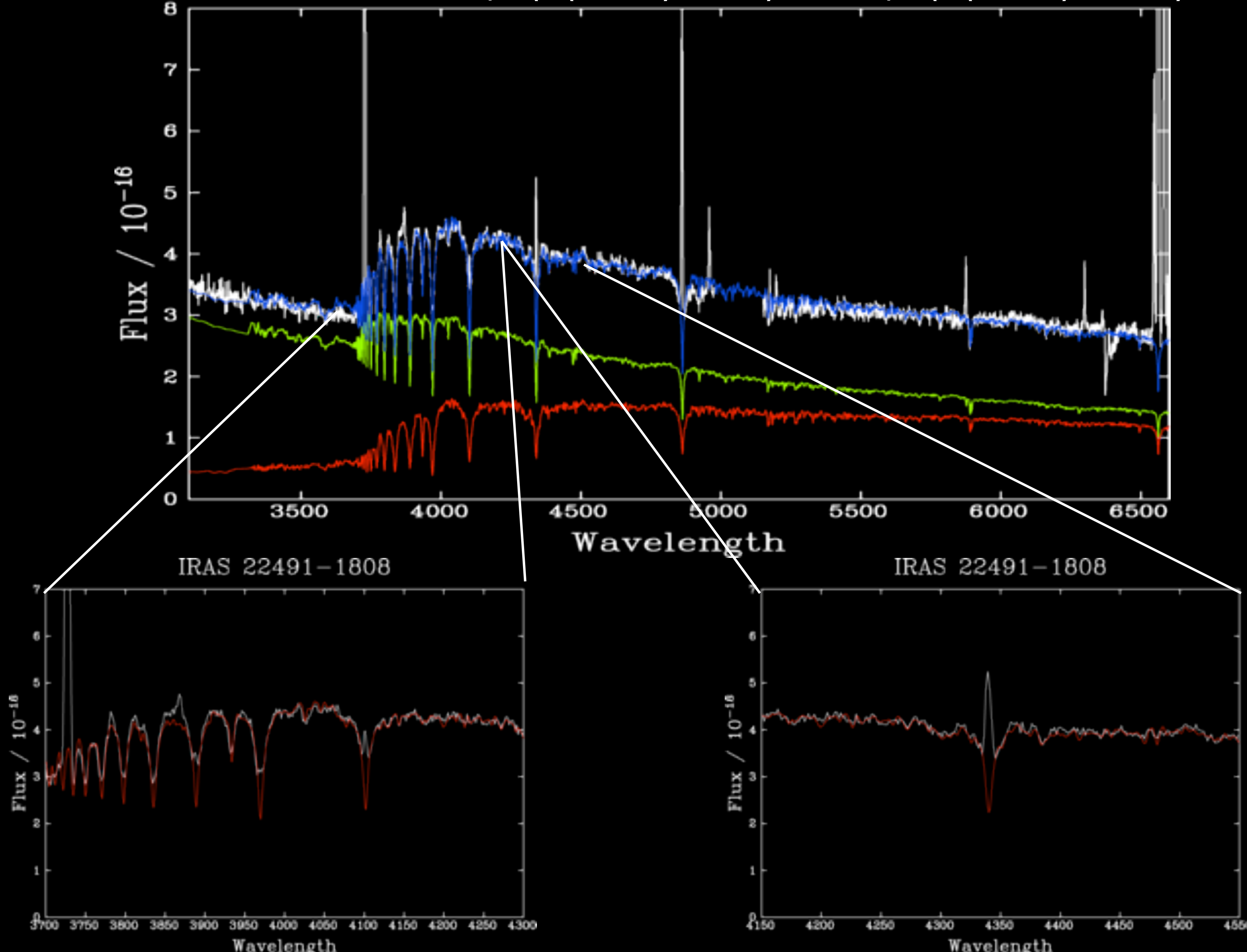
Two additional combinations were also used:

- The importance of the OSP: A 12.5 Gyr + $t_{SP} \leq 2.0$ Gyr + a power law
- Luminosity weighted YSP: A 12.5 Gyr plus SPs of ages $t_{SP} \leq 2.0$ Gyr and varying reddenings

# IRAS 13539+2920: 500 Myr (E(B - V)= 0.2)+ 6 Myr (E(B - V) = 0.5)



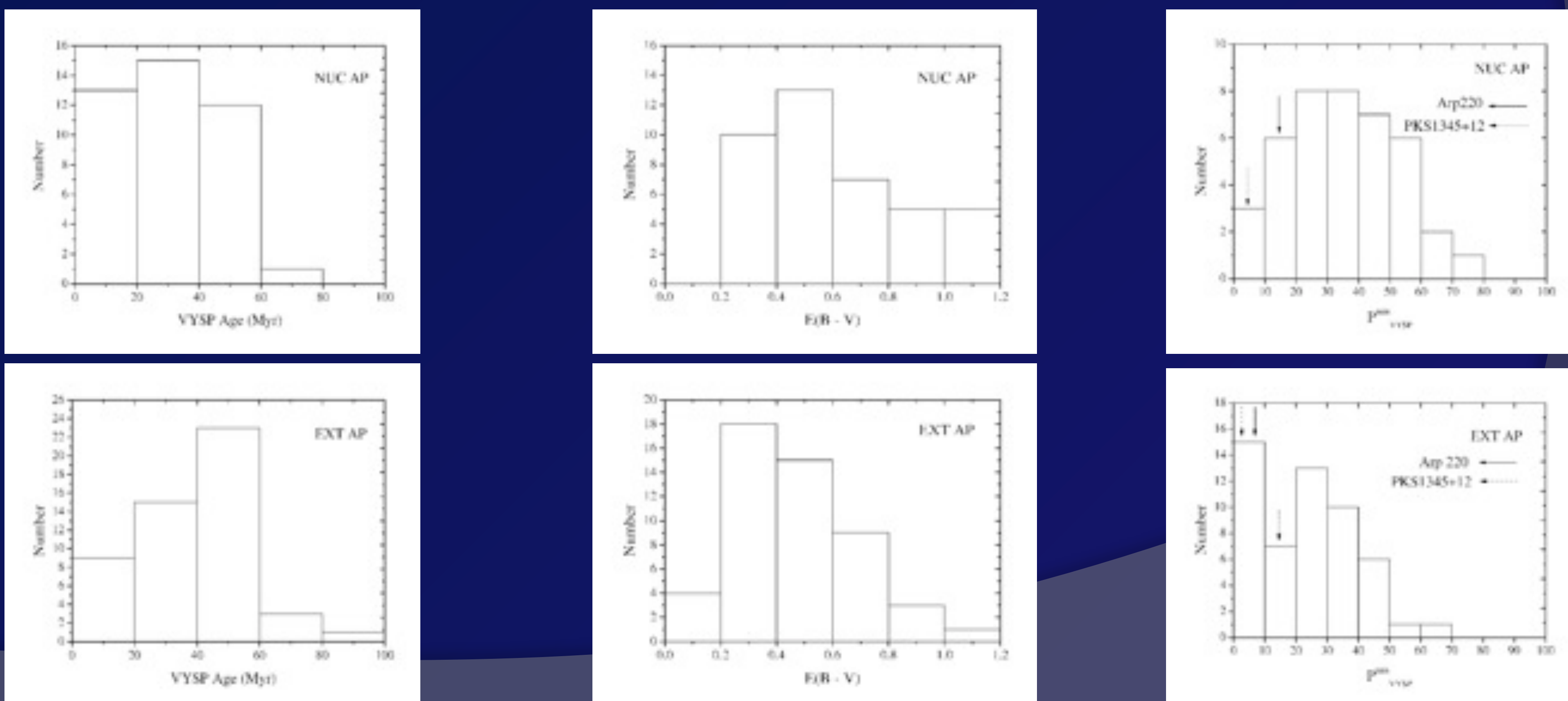
# IRAS 22491-1808: 500 Myr (E(B - V)= 0.2)+ 6 Myr (E(B - V) = 0.3)



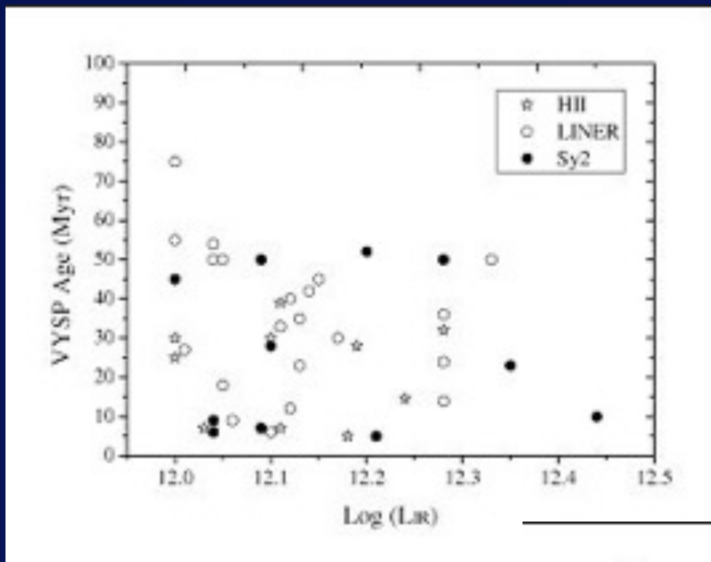
# 3 Results

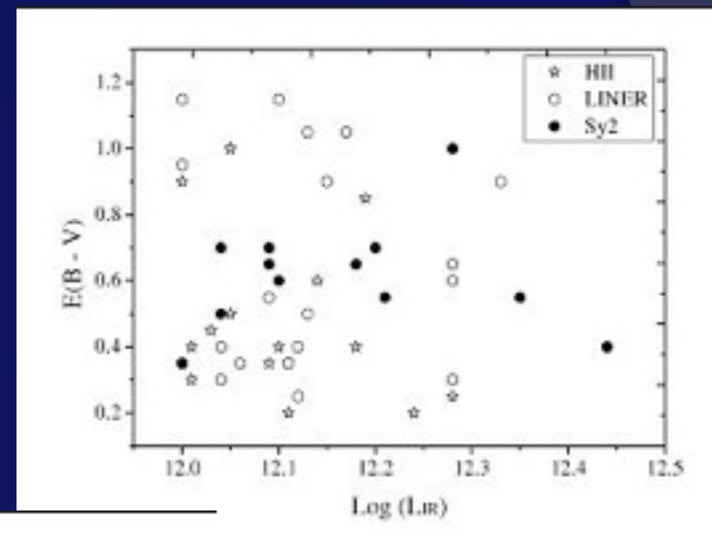
i) The modelling technique:  adequate fits are obtained using a combinations of VYSP + IYSP with ages typically in the range 0.3 – 2 Gyr.  OSP (older than ~10 Gyr), if present, do not make an important contribution to the optical emission from ULIRGs.

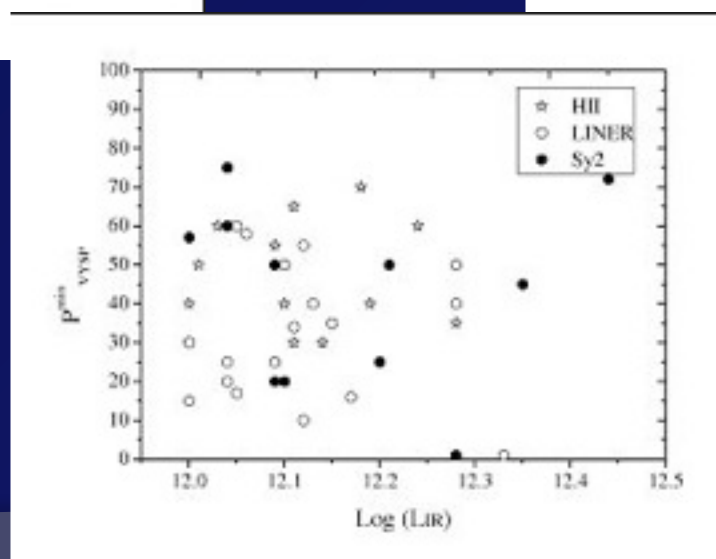
ii) Age, reddening and percentage contributions: our statistical analysis shows that the YSPs are more important in the nuclear



iii) Presence of correlations: We investigate whether the properties of the YSPs correlate with other properties of ULIRGs such as spectral classification (Sy, LINER and HII), morphological type (III, IV, V, Iso, Tpl),...etc.



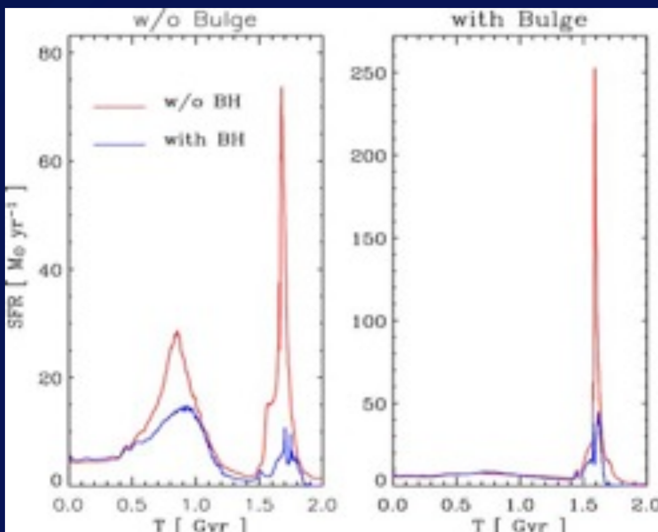



NO TRENDS or correlations are found:

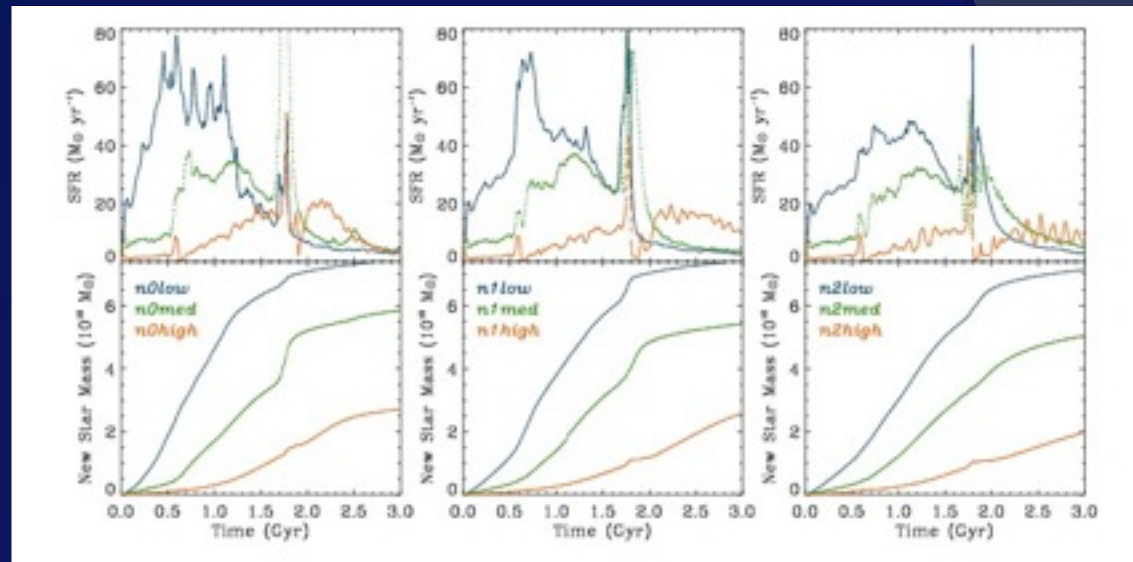
- Selection effect: since the objects in our sample are ULIRGs, it is likely that we are observing them close to one of the peaks of star formations and therefore, it is not strange that the properties of the YSPs are similar.
- Modelling technique: part of the scatter of the YSPs properties could be due to uncertainties inherent to the modelling technique.
- Other variables: there are other variables (gas content, geometry of the merger...etc) that could have a more important impact on the properties of the stellar populations than the ones examined here.

# iV) Merger simulations

Springel et al., 2005




Cox et al., 2005




In general, merger simulations predict two epochs of enhanced star formation: one close to the first encounter and other towards the end of the event, when the nuclei Coalesce (e.g. Mihos & Hernquist 1996, Barnes & Hernquist 1996, Springel et al2005, Cox et al 2006). However, the time lag and the relative intensity of the peaks depends mainly on:

-Presence of bulges (e.g. Hopkins et al 2009)

-Feedback effect (e.g. . Springel et al 2005, Cox et al., 2006)

-Gas content and mass ratio of the merging galaxies (e.g Johansson et al 2009)

-Geometry (e.g. Naab & Burket 2003, di Mateo et al 2007)

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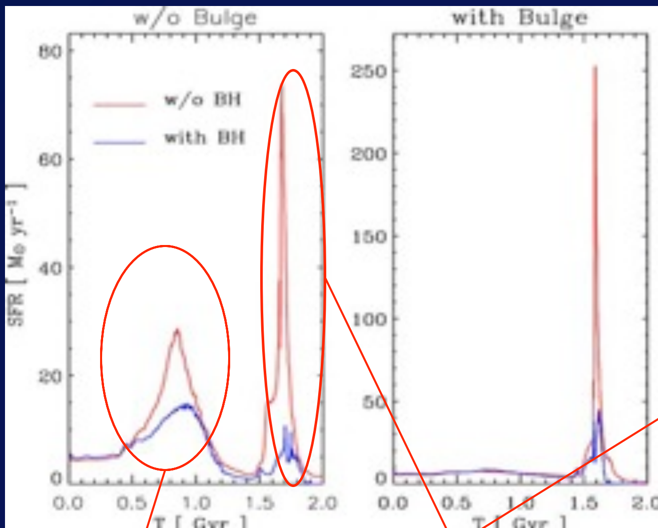
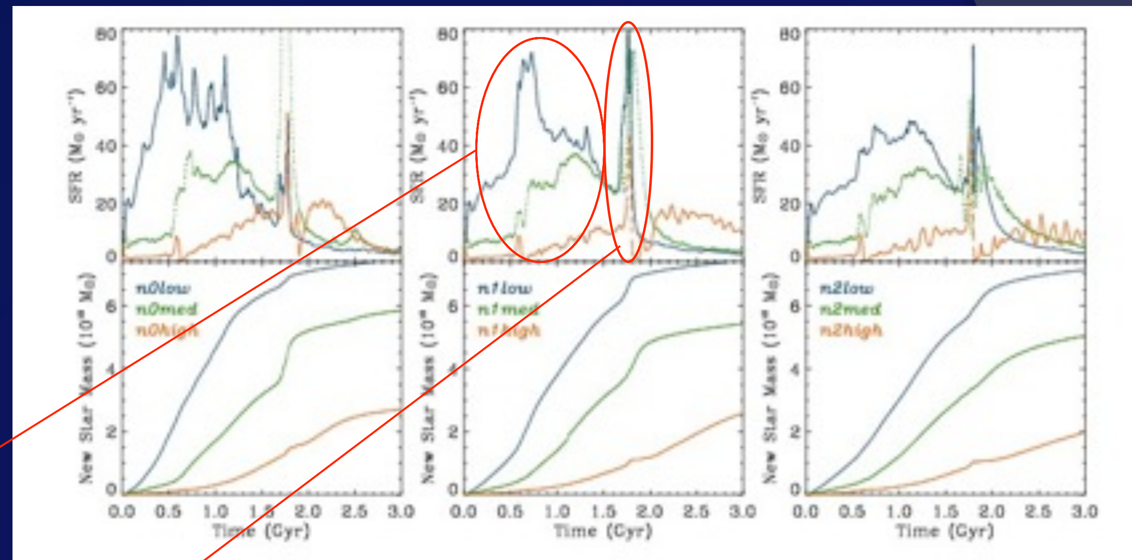



Cox et al., 2005




?

A SP of: <~ 1 Gyr + A SP of: <~ 100 Myr

In general, merger simulations predict two epochs of enhanced star formation: one close to the first encounter and other towards the end of the event, when the nuclei Coalesce (e.g. Mihos & Hernquist 1996, Barnes & Hernquist 1996, Springel et al2005, Cox et al 2006). However, the time lag and the relative intensity of the peaks depends mainly on:

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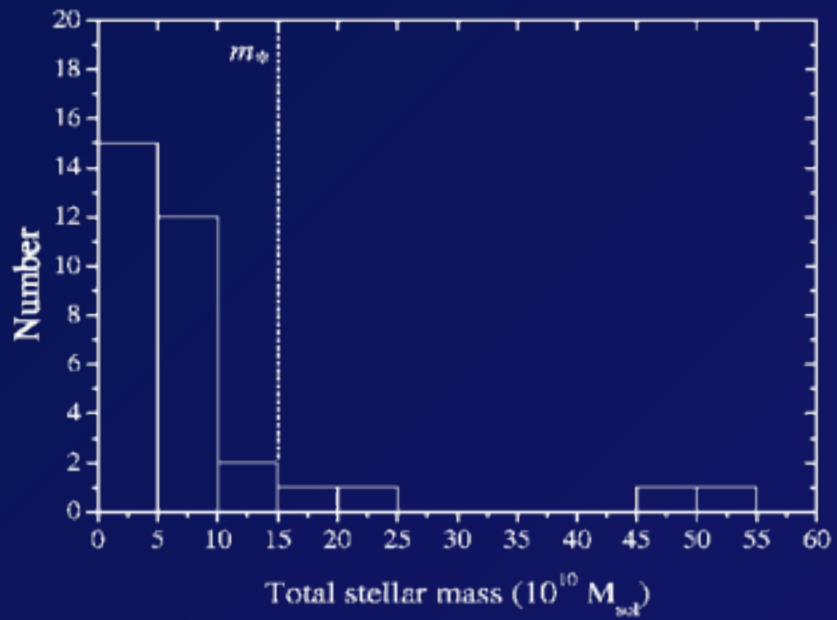
- In general, the modelling results are consistent with the merger simulations, with the VYSPs associated to the last enhancement of the starburst activity and the IYSPs likely related with the first peak at the beginning of the interaction.

- For those ULIRGs with wide nuclear separations the VYSPs are likely related with the first enhancement. Based on the merger simulations, the parent galaxies must have small bulges.

- There are 3 cases in our sample (PKS1345+12, IRAS 21208-0519 and IRAS 23327+2913) for which at least one of the parent galaxies is an early type galaxy.

v) Stellar mass content.




$m^* = 1.4 \times 10^{11} M_\odot$

- We find total stellar masses in the range of $0.18 \times 10^{10} \leq M_{YSP} \leq 50 \times 10^{10}$ $M_\odot$(PKS1345+12).
- Only 6 objects in our sample have total stellar masses > $1 \times 10^{11}$ $M_{sol}$
- In terms of stellar masses, our results are consistent with the idea that ULIRGs are $m_*$ or sub-$m_*$ (see also Rothberg & Fischer 2010)

vi) The origin of the YSPs

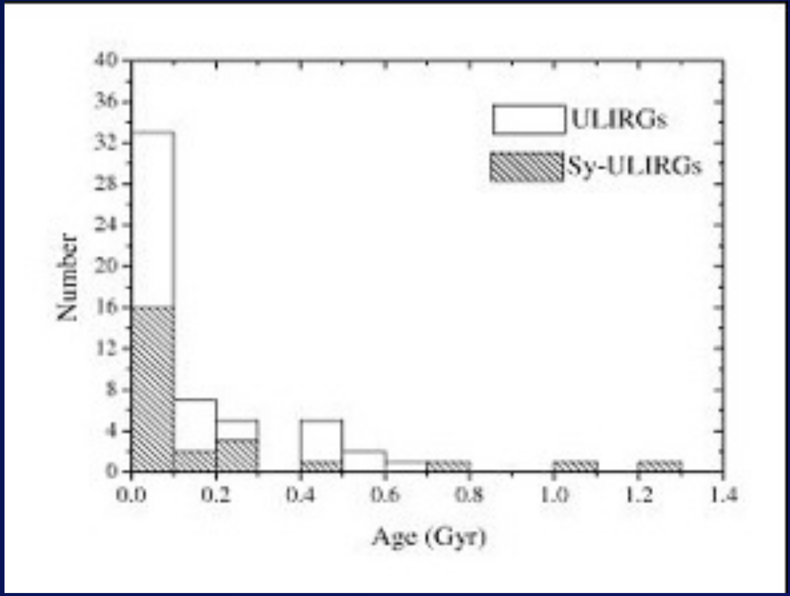
- We model the ULIRG spectra using combinations of Sa, Sb and Sc templates (Kinney et al., 1996) + YSPs:
No good fits are found with this combination without a significant, additional combination of YSPs.

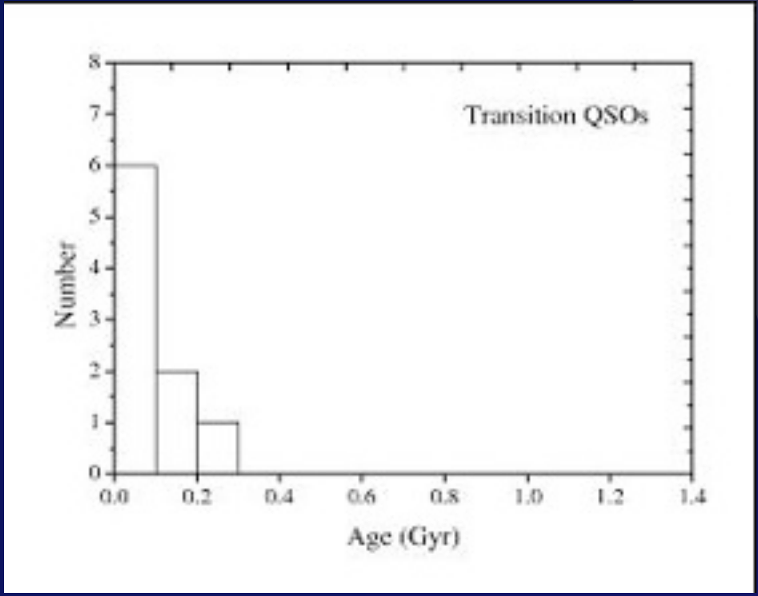
- ULIRGs : $M_{IYSP} = 0.5 - 50 \times 10^{10}\ M_{sol}$
$M\ (H2 + HI) \sim$ few times $10^{10}\ M_{sol}$ (Solomon et al, 1997, Evans et al 2002)

Sc : $M_{VYSP} = 1.2 – 8.5 \times 10^{9}\ M_{sol}$
$M\ (H2 + HI) \sim 1.4 \times 10^{10}\ M_{sol}$ (Roberts & Haynes 1994, Young and Knezek 1989)

10 of the objects in our sample have $M_{IYSP} > 5\ 10^{10}\ M_{\odot}$ and another 7 objects have $M_{VYSP} >\sim 10^{10}\ M_{\odot}$ our results suggest that if the parent galaxies are late-type spirals, only the merger between massive spirals can trigger the ULIRG phenomenon

## vii) Evolution of ULIRGs

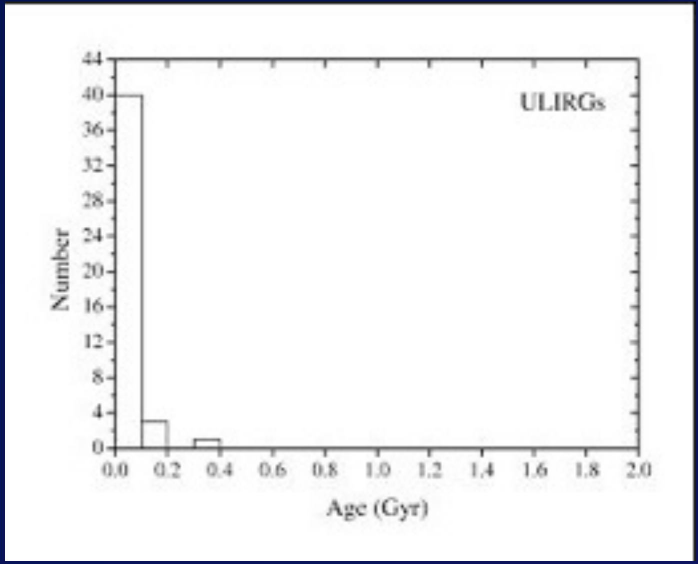


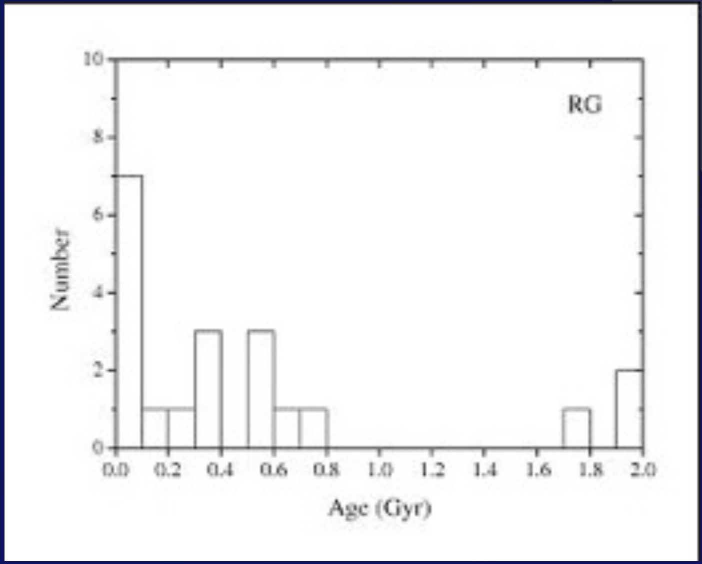




We find no difference between the YSPs properties of the ULIRGs and the so called Transition QSOs (Canalizo et al 1997, 2000, 2001).

Although this result suggests that there is no evolutionary link between these two type of objects, we cannot rule out the idea that such a link actually exist.

Tadhunter et al., 201?, in prep




- The radio galaxies (data compiled from several studies) cover a wider range of ages than ULIRGs. Interestingly, 5 of the 20 RG used for the plot are also ULIRGs and fall in the first bin. In those cases it is likely that the accretion during the merger event has triggered both, the starburst and the radio activity.

- 12 of the 20 RG galaxies have YSPs ages between 0.1 – 2 Gyr. In these cases there is a time lag between the main merger-induced starburst and the radio activity. It is possible that these are the evolved product of ULIRGs.

In order to explain the time lag (see Tadhunter et al 2005):

- Time required for the gas to lose its momentum and to be accreted into the vicinity of the black hole.
- Time required for the two black holes of the merging galaxies to coalesce and form a spinning black hole
- Late accretion. Multiple phases of radio activity.

Don´t forget that the ULIRGs are $m_*$ or sub-$m_*$ systems and RG are frequently more massive than ULIRGs.

Therefore, the conclusion is that not all RG have evolved from ULIRGs, although is possible that some ULIRGs evolve in RG.

## viii) Comparison with high-z studies.

We can compare the stellar mass in ULIRGs with the results found for high-z galaxies:

LBGs: 0.2 - 6 x $10^{10}$ $M_{\odot}$ (and up to 3 – 8 times higher) (Papovich et al.,2001)

DRGs: 0.29 – 46 x $10^{10}$ $M_{\odot}$ (Papovich et a 2006)

SMGs: >~7 x $10^{10}$ $M_{\odot}$ (Hainline et al., 2010)

Spitzer 24μm: 0.1 – 100 x $10^{10}$ $M_{\odot}$ (Caputi et al., 2006)

Local ULIRGs: 0.2 – 50 x $10^{10}$ $M_{\odot}$ (This work)

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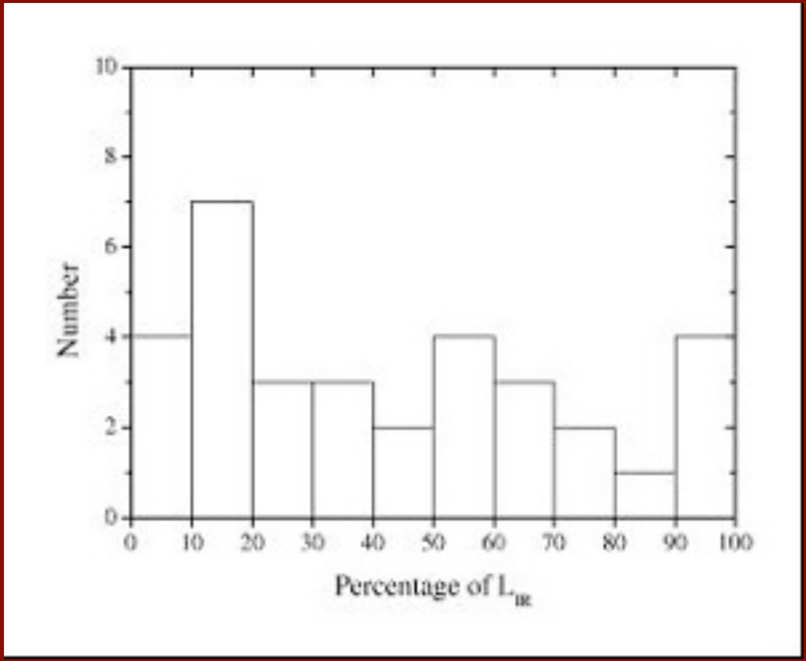
PKS 1345+12

ix) The "bolometric luminosities




- ➢Assuming that most of the optical light is absorbed and reprocessed by dust we can compare the estimated bolometric luminosity with the mid- to far-IR luminosity of the source.
- ➢For 48% of the objects the bolometric luminosities of the stellar populations detected in the optical represents a large fraction of the mid- to far-IR luminosity of the sources.
- ➢A priori, this results suggest that the main source of power MAY! not always be hidden in ULIRGs (wait until the end!).

# 4. Summary.

1-The optical spectra of the ULIRGs can be modelled using a combinations of two stellar populations, a VYSP (< 100 Myr) + IYSP (0.1 – 2 Gyr)

2- The younger stellar populations in the nuclear regions of the galaxies make a more important contribution to the optical light that those of the extended. Our suggest that are younger and redder.

3- We do not find any evidence to support/refute the evolutionary scenario cool ULIRG → warm ULIRG → QSO/RG.

4- In general, our results are consistent with the merger simulations.

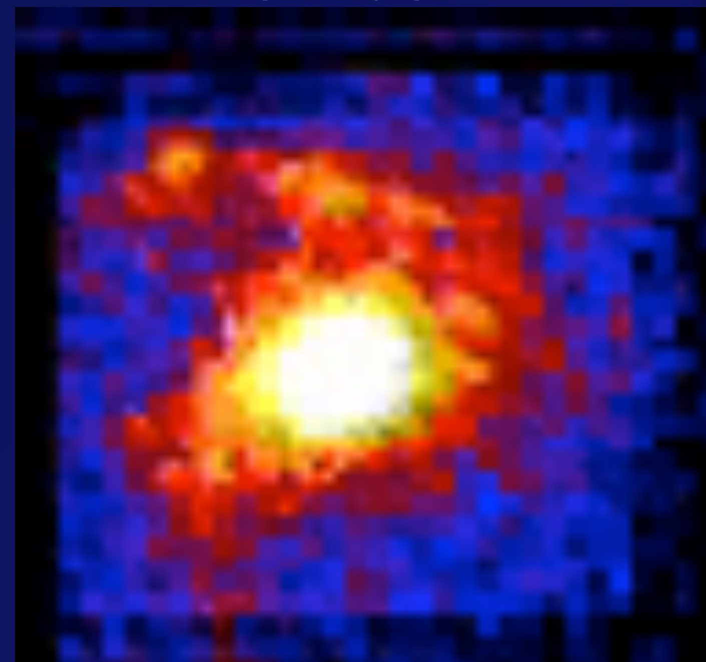
5- If the parent galaxies are spirals they must be among the most massive late-type spirals (upper 25% mass range)

6- ULIRGs have stellar masses that are similar to or smaller than high-z star forming galaxies such as DRGs, SMGs or Spitzer 24 μm galaxies.

# VIMOS, SINFONI and PMAS IFS of local LIRGs and ULIRGs

IC 5179

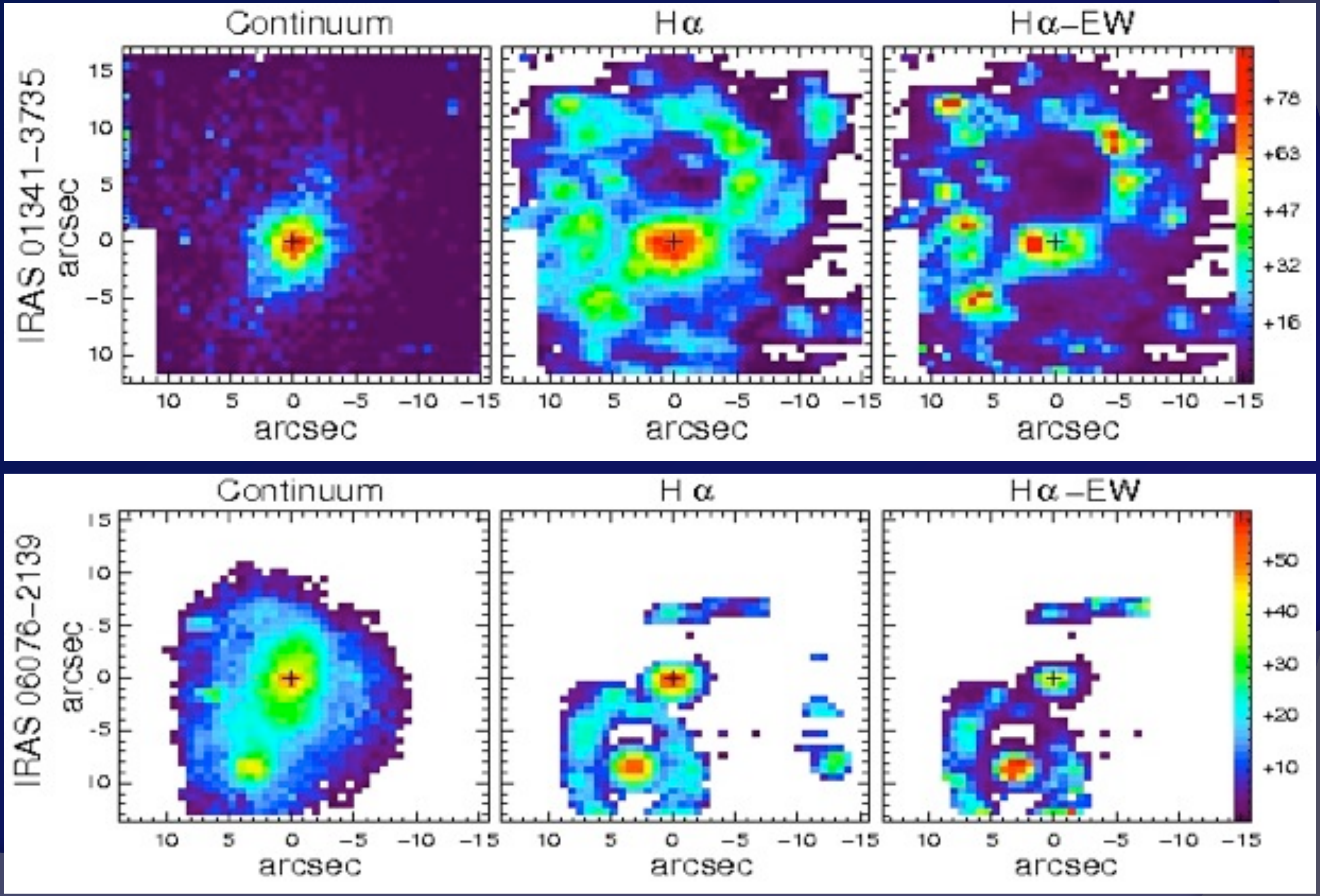
IC 4687

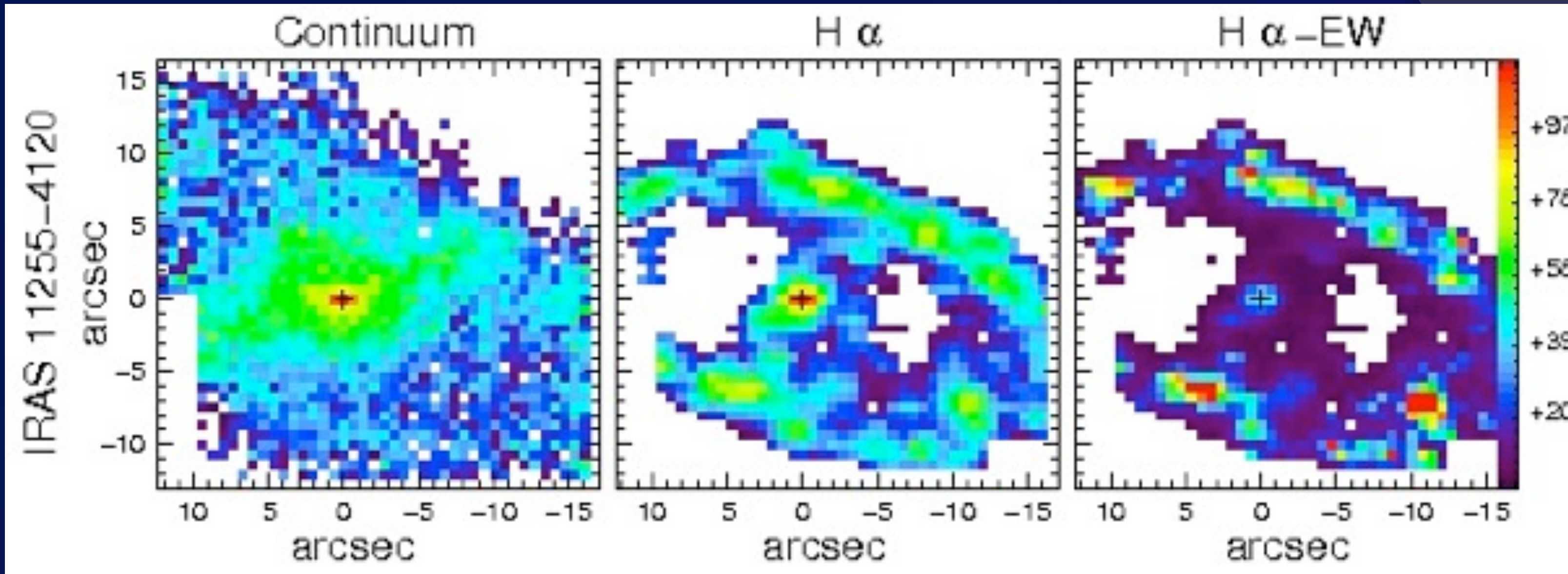


Optical (5200 – 7400 Å) IFS: structure and kinematics of the ionized gas (see E. Bellocchi´s short talk and poster).

Near-IR (H- and K-band IFS: structure and kinematics of the ionized gas, dust distribution and the different ionization mechanisms (see J. Piqueras short talk and poster) .

# The structure of the ionized gas




Continuum
H α
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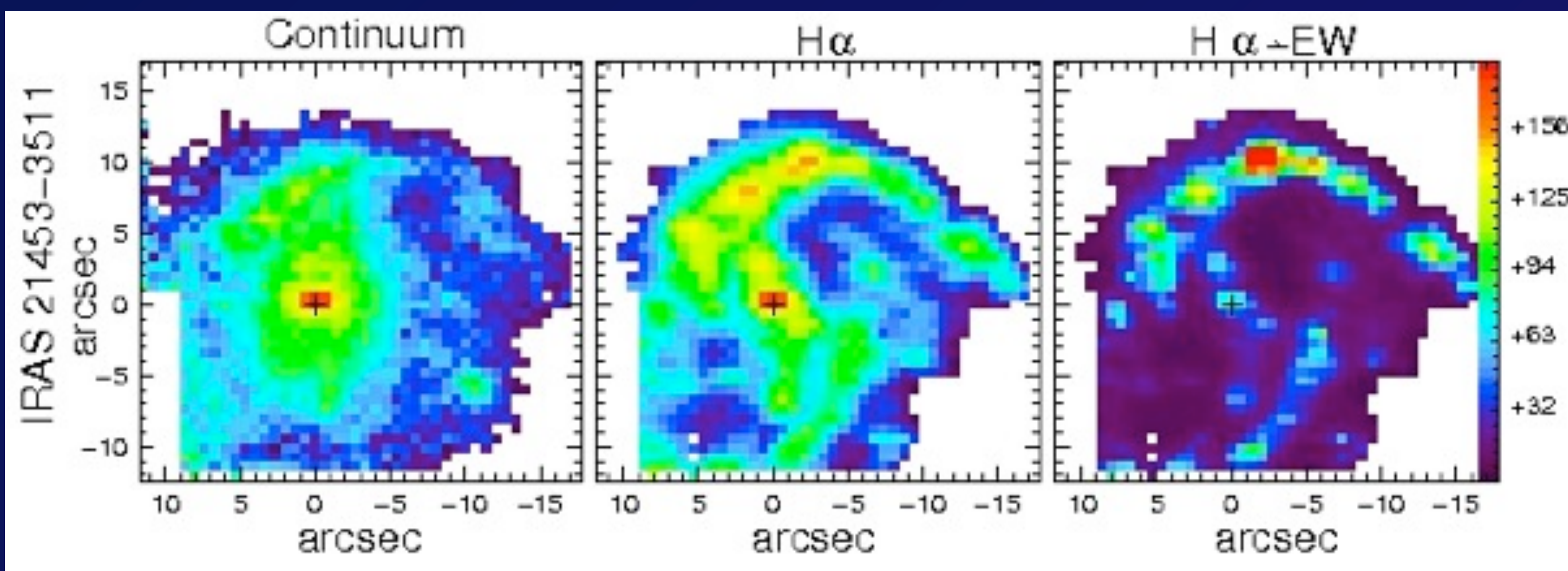
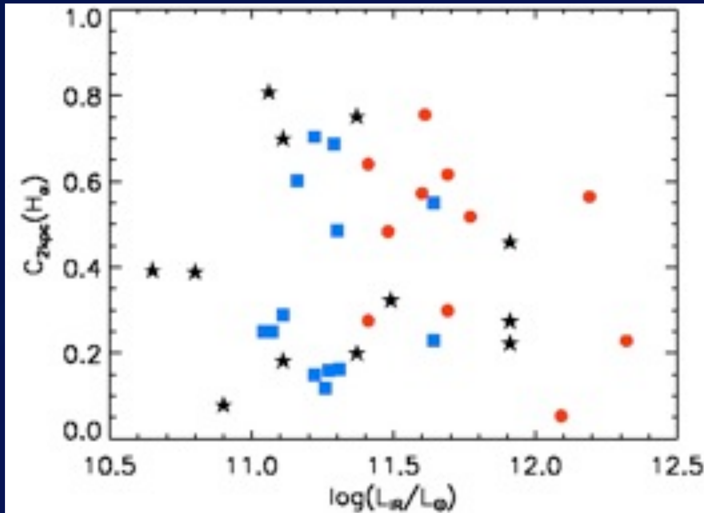
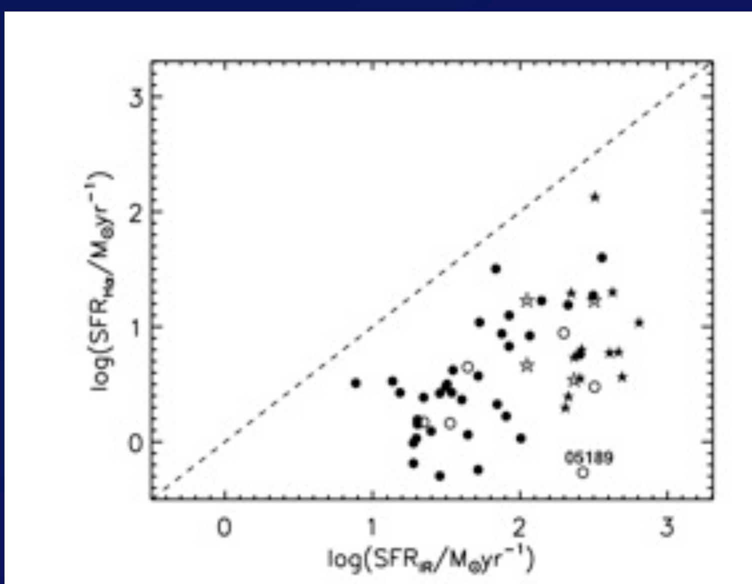
IRAS 11255–4120
arcsec
15
10
5
0
−5
−10
−15
arcsec
+97
+78
+58
+39
+20


Continuum
Hα
H α –EW
IRAS 21453–3511
arcsec
15
10
5
0
−5
−10
−15
arcsec
+156
+125
+94
+63
+32



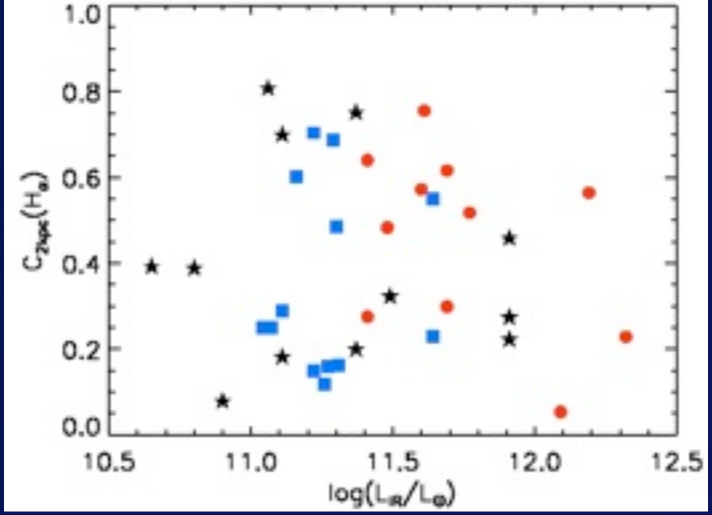

We have divided the objects in our sample into three morphological classes: isolated, early interactions and late mergers. We have investigated whether the distribution of the ionized gas is correlated with the infrared luminosities of the sources ($L_{IR}$) or their morphological class. *We find that the concentration of the Hα emission is not correlated with $L_{IR}$*. A possible explanation for this lack of correlations is higher concentrations of dust towards the nuclear regions of objects with higher $L_{IR}$.

Rodríguez Zaurín et al., 2010b, submitted




The SFR derived using Hα underpredict those obtained using LIR even after correcting for reddening effects.

However, if the reddening in the extended regions is still important in the values in the figure will represent underestimates of the real vales of $SFR_{H\alpha}$.

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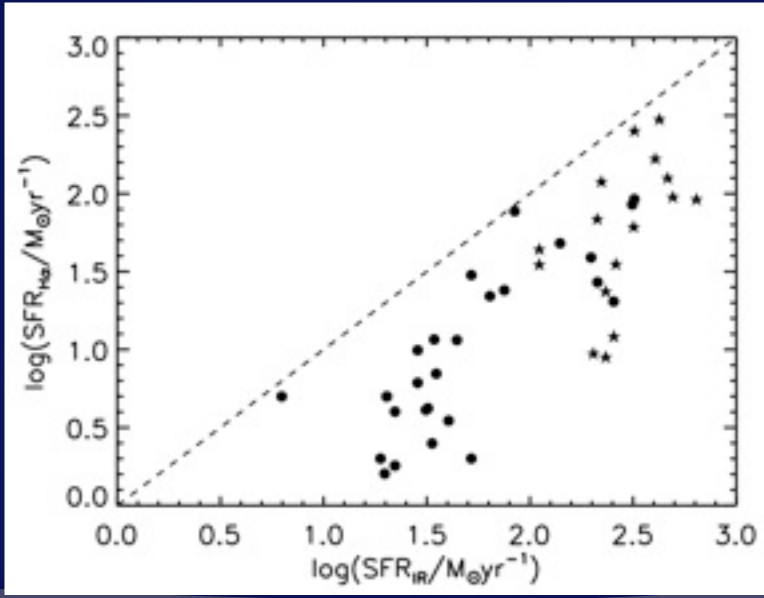


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