Where does the stripped gas go?

Formation of multiple structural components in galaxies from recycled gas

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Scientific Context

- Galaxies interact with each other or with the surrounding environment (merging, ram pressure stripping...). During these processes, gas can be stripped and feed the intra-cluster medium.

- Where does the gas go? Can it be accreted by other galaxies in an amount large enough to generate new stars and new stellar components?

- **Exploiting another project:** Study galaxies with counter-rotating stellar components by separating these components from the total observed spectrum.
  - Counter-rotating stellar components are easier to separate than other components (e.g., bulge, disk);
  - They are most likely associated to an *accretion* event (gas and/or stars).

Scientific Context

- **One step forward**. In the case of gas accretion, we can get clues on the origin of gas: primordial, from filaments, already-processed gas.

- *Can a stellar component in a galaxy A be originated from gas stripped from another galaxy B?*

- Steps to follow:
  - Separate the contribution of individual components (stars and gas) from the observed galaxy spectrum (at each position in the sky).
  - Study each component independently (kinematics, morphology, age, [Z/H], [α/Fe]) – stars and gas.
  - Infer the origin of the decoupled stellar component.
  - Infer the origin of the accreted gas (*w.i.p.*).

Scientific Context

Two main scenarios for counter-rotating galaxies:

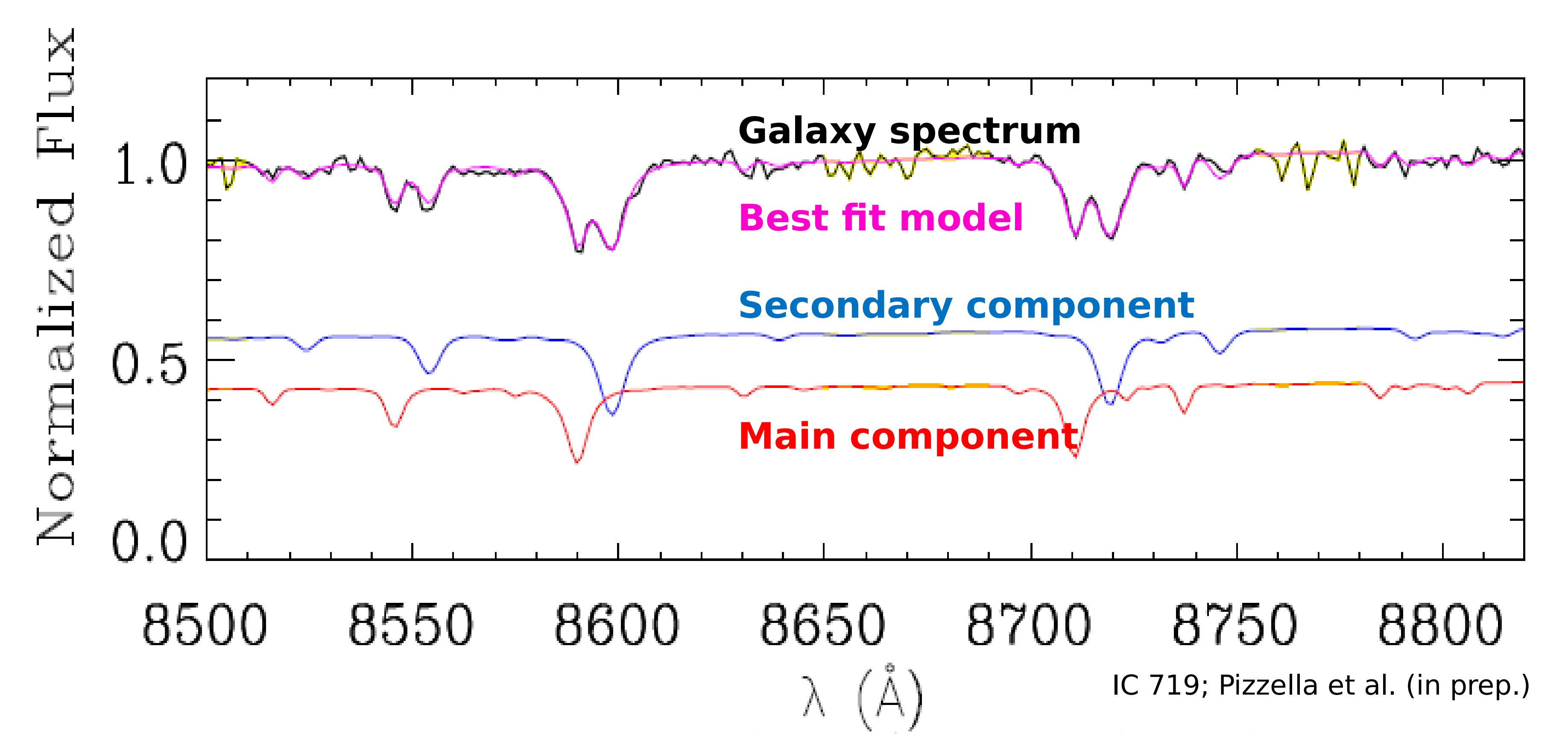
- Gas accretion followed by star formation: only gas (e.g., Thakar et al. 1997, Algorry et al. 2014) or minor mergers with gas-rich companion (Bassett et al. 2017).
  - The stellar component co-rotating with the gas is always younger, thinner, kinematically cold, and less massive (→ **secondary component**).
  - If gas-only accretion from filaments, the secondary component has larger scale radius.
  - The properties ([Z/H], [α/Fe]) of the secondary component depend on the properties of the acquired gas: low [Z/H] and high [α/Fe] if from poorly pre-processed gas (cosmic filaments); high [Z/H] and low [α/Fe] if highly pre-processed gas (e.g. stripped from other galaxies).

- Galaxy binary mergers (minor/or major; dry/wet); e.g. Puerari & Pfenniger (2001), Crocker et al. (2009).
  - The age of the secondary component depends on the relative age of the progenitors and the star formation history after the merger.
  - If major merger, the gas (if present) rotates as the thicker, most massive, and kinematically hotter stellar component.

SPECTRAL DECOMPOSITION:

Disentangling kinematics *and* stellar populations of two components

We construct *2 independent stellar components* as linear combinations of stellar templates from a spectral library (→stellar populations). Convolution with *2 Gaussian LOSVDs* (→kinematics). Iterative procedure (χ^2 minimization).

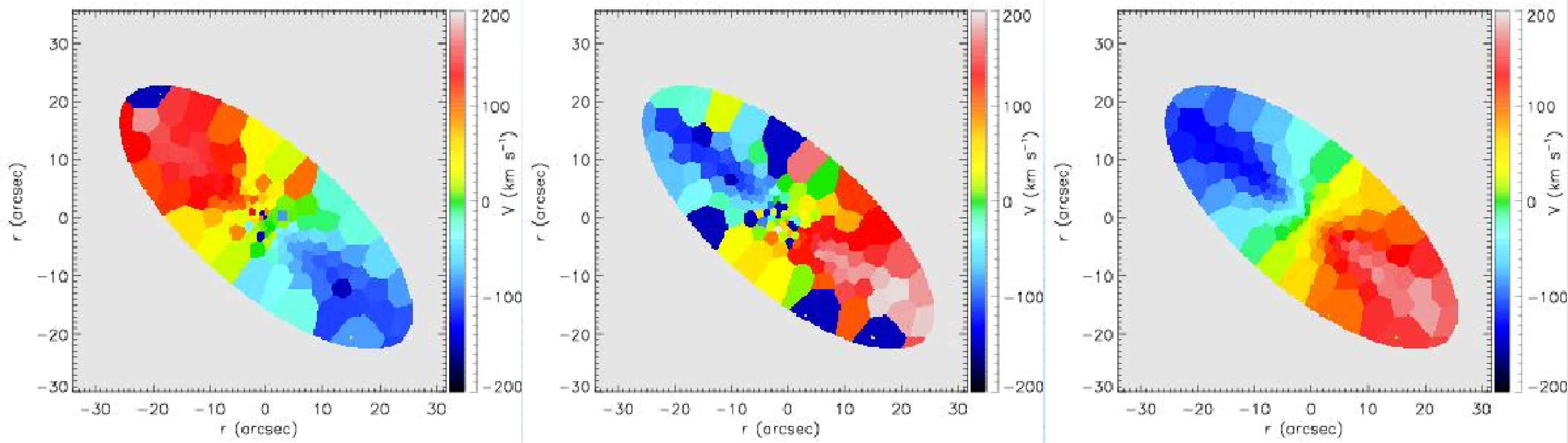


IC 719; Pizzella et al. (in prep.)

Differences in the position and width of absorption line features (**→different kinematics**), and in the equivalent width of the absorption lines (**→ different stellar populations**).

IC 719 – rotation

Main component | Secondary component | Ionized gas

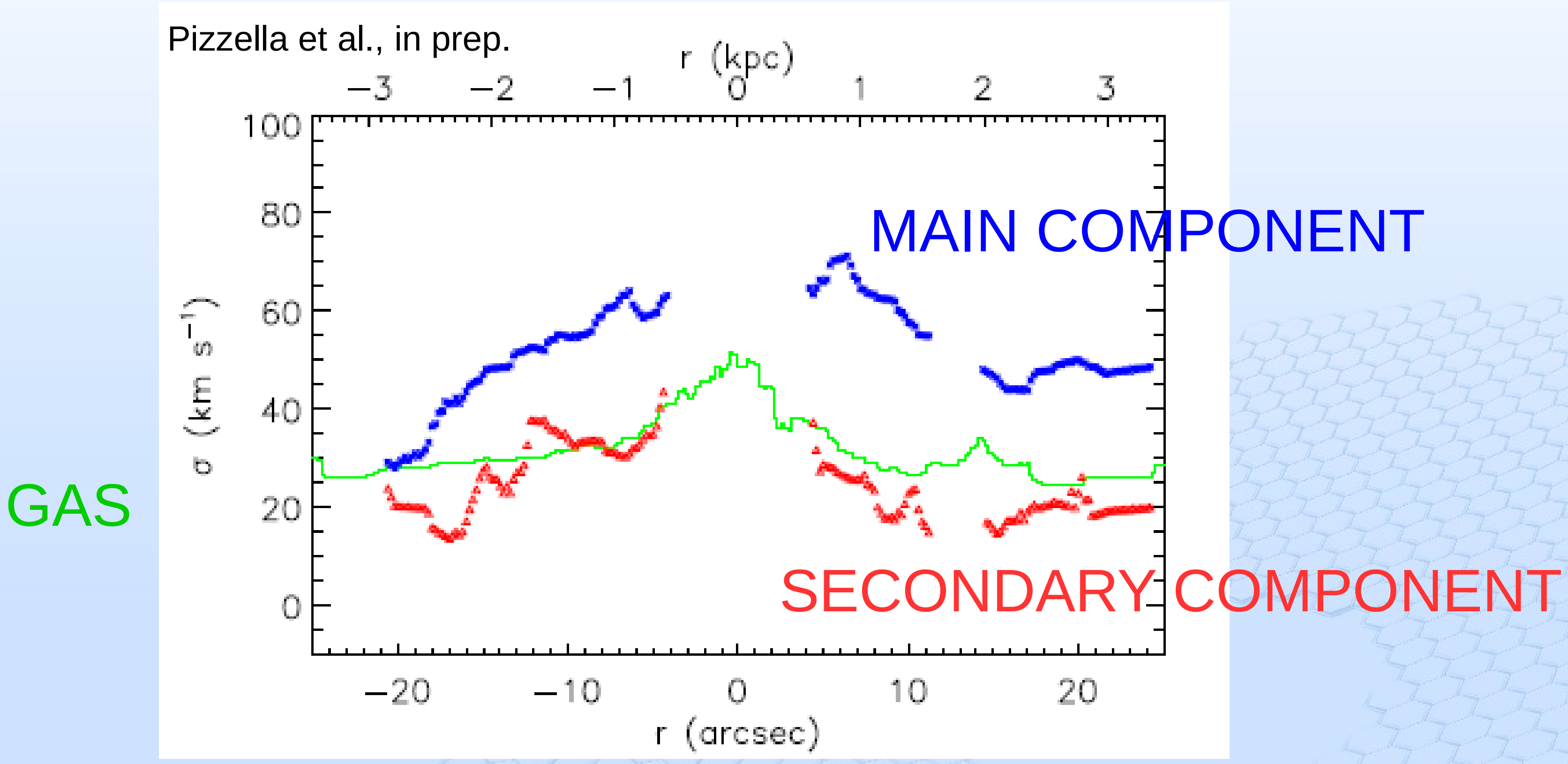


1. The main stellar component and the secondary stellar components counter-rotate with respect to each other. The secondary component rotate faster than the first component.
2. The ionized gas rotate in the same direction of the secondary component.

THE GAS IS KINEMATICALLY ASSOCIATED WITH THE SO-CALLED "SECONDARY COMPONENT".

Pizzella et al., in prep.

IC 719 – velocity dispersion

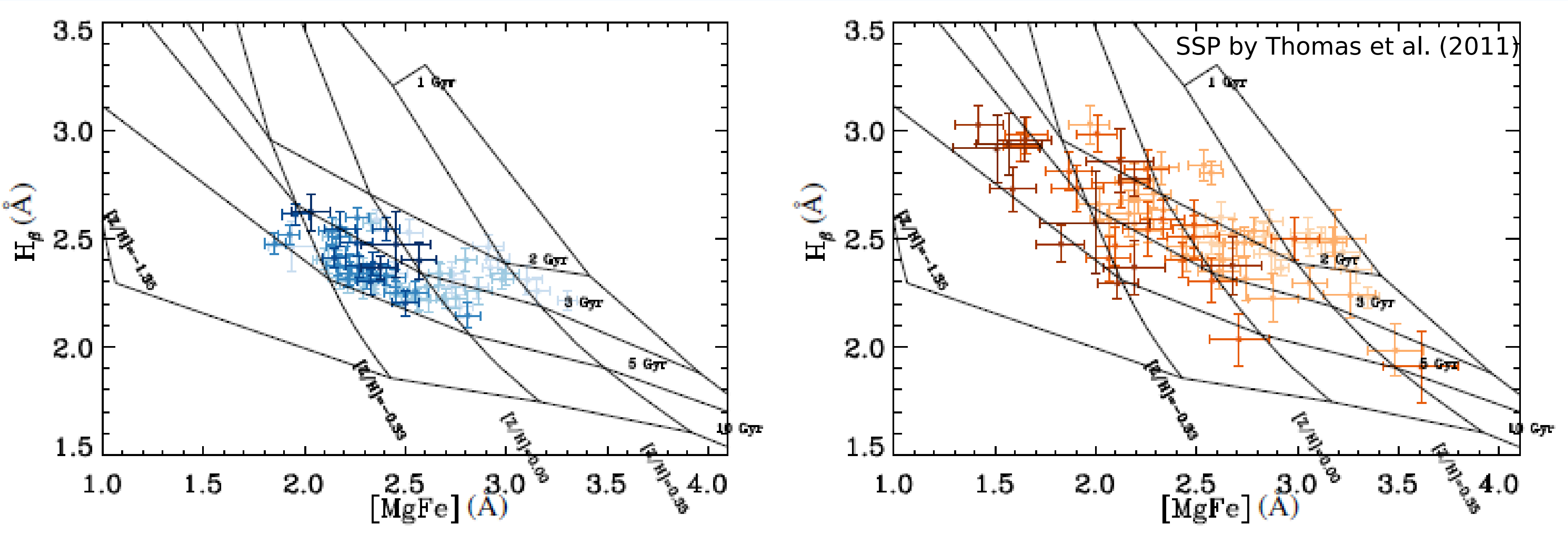


The secondary component is dynamically colder

The gas is associated with the dynamically colder stellar component

IC 719 – stellar populations

MAIN COMPONENT SECONDARY COMPONENT

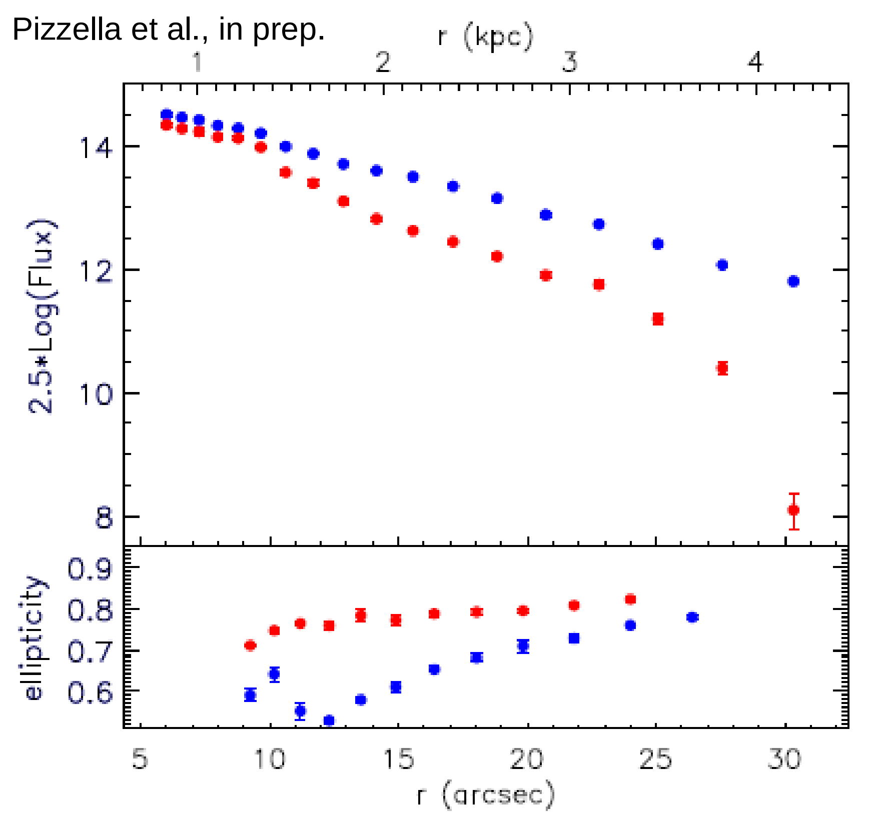


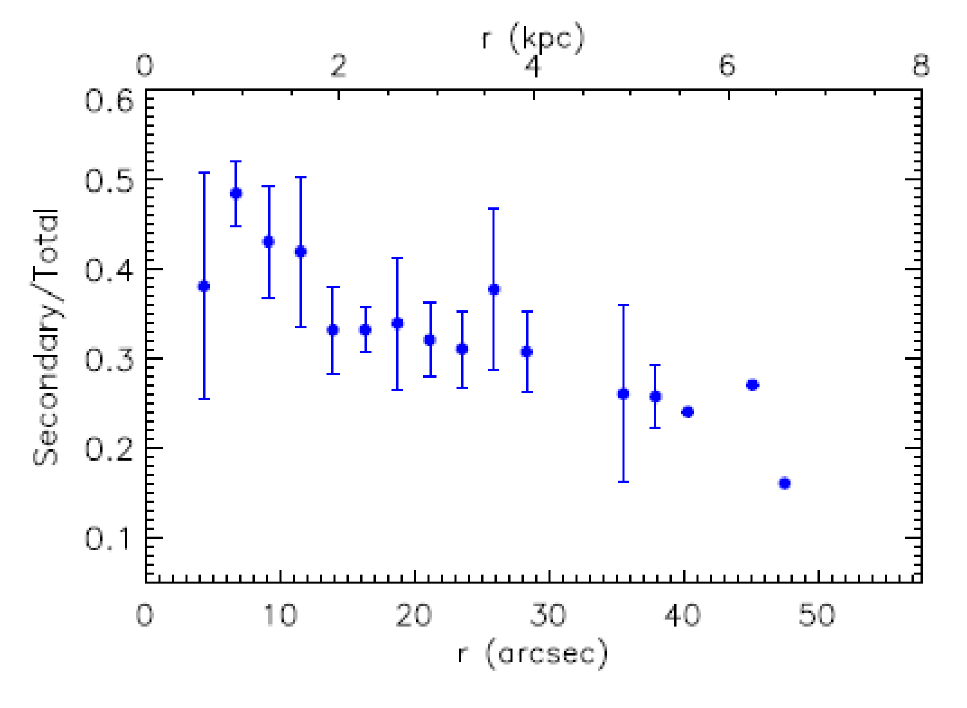
Stars in the secondary component are younger, with a shallow positive age gradient. Similar metallicity.

The gas is associated with the kinematically colder and younger stellar component

Pizzella et al., in prep.

IC 719 – surface brightness and morphology



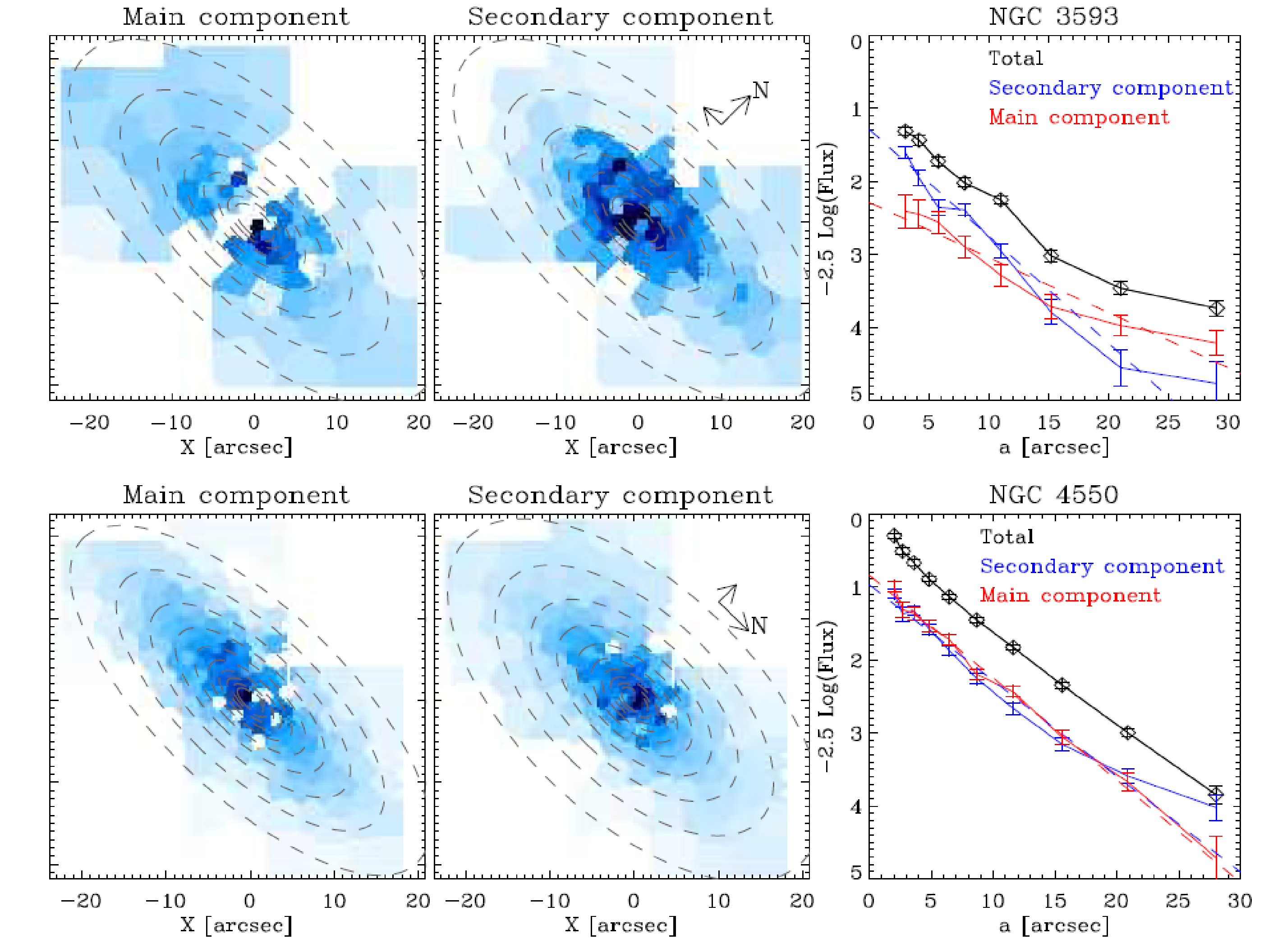


- The main stellar component is morphologically thicker (0.3<q<0.4) and more extended (Rh=1.5 kpc) than the counter-rotating disk (0.2<q<0.25, Rh=1 kpc).
- The secondary counter-rotating disk contributes from nearly 50% (center) down to 20% (edges) of the galaxy surface brightness.
- The gas is associated to the younger, less massive, dynamically colder and morphologically thinner stellar component → **In agreement with the gas accretion scenario / in contrast with the major merger scenario**

Other examples

NGC 3593

NGC 4550

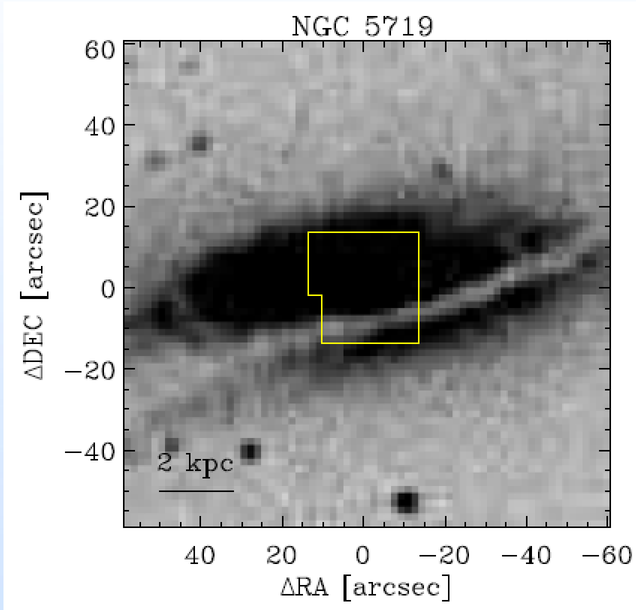


The 2 disks have different scale lengths

The 2 disks have different ellipticity

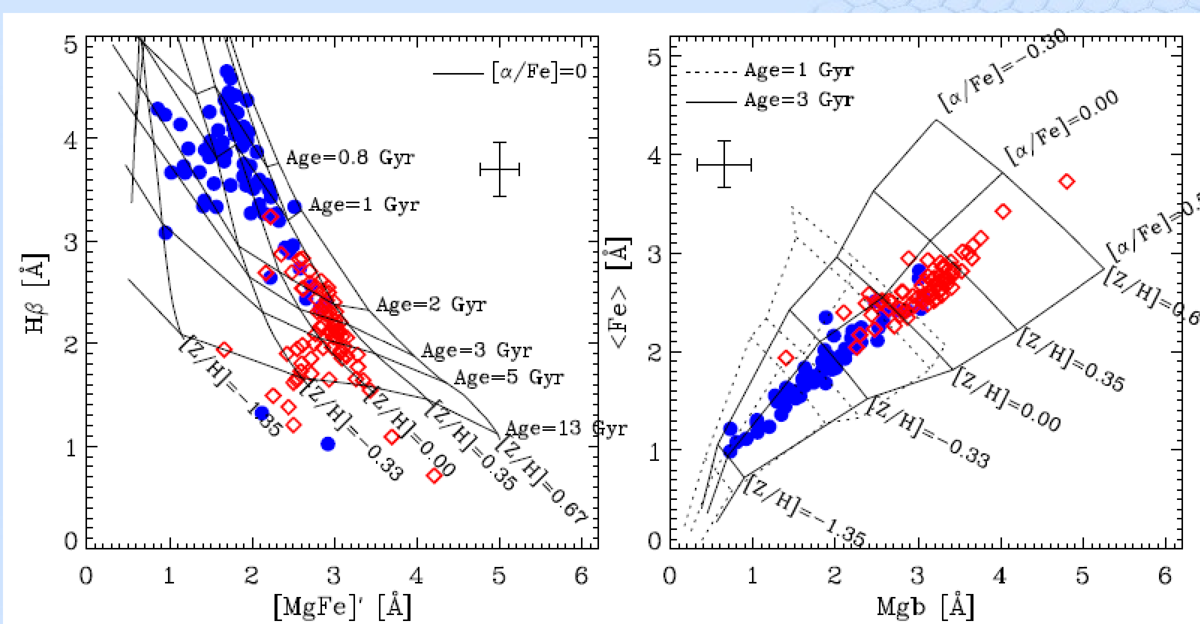
Coccato et al. (2013)

Other examples



There is an extremely clear difference in the properties of the stellar population of the 2 components

Coccato et al. (2013)



Secondary component
Main component

The results so far:

A number of counter-rotating galaxies have been studied so far.

In all the cases:

- The stellar component that rotates along the same direction as the ionized gas is younger, less massive, and has different [Z/H] and [α/Fe] content than the main galaxy disk.
- The [Z/H] and [α/Fe] content indicate the stars are born from already processed gas (metal enriched, alpha enriched…); not primordial

In some cases:

- It is possible to disentangle the morphology of the two stellar components.
- The secondary component is equally or less extended (no filament accretion) and thinner than the main stellar disk (no binary major merging).
- The decomposition reveals a much larger structure than what can be guessed by looking at the simple 1 component velocity field (some kinematically decoupled cores are the “top of the iceberg” of a much larger structure).

Observations are consistent with:

- Gas stripped from companion (we have evidence only in few cases).
- Gas accretion from free floating gas (e.g. ram-pressured stripped).
- Minor mergers with gas-rich satellites.

Observations do not suggest:

- Primordial as accretion along cosmic filaments.
- Binary galaxy major mergers.

CONCLUSIONS - SUMMARY

From an observational point of view we are able to:

- Separate the contribution of two counter-rotating stellar components and study them independently (spectral decomposition technique).
- Favor accretion of pre-enriched gas followed by star formation over major merger and filament accretion → this is consistent with the possibility that the gas stripped via ram-pressure process can be captured by other galaxies in an amount large enough to generate stellar structures such as counter-rotating large-scale stellar disks. But not a proof (e.g. gas-rich satellite mergers).

Next steps about ram pressure stripping & formation of structural components:

- Include the galaxies with star-vs-gas counter-rotation and study the gas properties (less “polluted” by stellar evolution – star formation, stellar winds and mass loss...).
- Compare the gas with the properties of the ram-pressure stripped gas.
- Deep photometry: can we find “images” of gas accretion as we have for ram-pressure stripping?

Next steps about the decomposition technique itself

- Spatial distribution of the mass-weighted stellar populations – gives more information than the luminosity-weighted analysis done so far.
- Apply the spectral decomposition to separate other structural components (bulge/disks) – ongoing.