MULTI-SPIN COMPONENTS IN GALAXIES: Dissecting kinematics and stellar populations

Lodovico Coccato (ESO)

in collaboration with:
L. Morelli; A. Pizzella; E. M. Corsini; E. Dalla Bonta' (University of Padova, Italy);
M. Fabricius (MPE); Enrica Iodice (INAF-OAC); M. Arnaboldi (ESO), and others

Based on:
- Coccato et al. 2011, MNRAS, 412, L113;
- Coccato et al. 2013, A&A, 459, 3;
- Fabricius et al. 2014, MNRAS (ArXiv: 1404.2272)

OUTLINE OF THE TALK

1. Panoramic of galaxies with multi-spin components. Some scenarios.

2. Presentation of a new method to study these systems: "spectral decomposition analysis".

3. Results of spectral decomposition on some multi-spin galaxies.

MULTI-SPIN GALAXIES

✓**Counter-rotations**. Stars rotating along opposite direction with respect to other stars and/or gas. (see Corsini 2014, arXiv: 1403.1263 for review). Different classes:

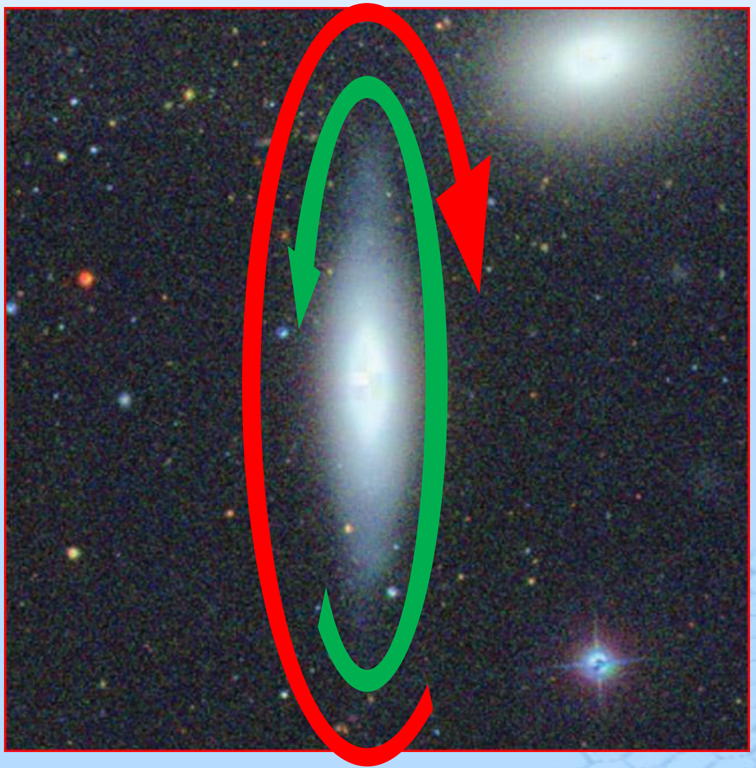
- ❖Nature: stars vs. stars, stars vs. gas, gas vs. gas, kinematically decoupled cores.
- ❖Extension: Kinematically decoupled cores (KDC); large-scale disks (e.g. NGC 4550).

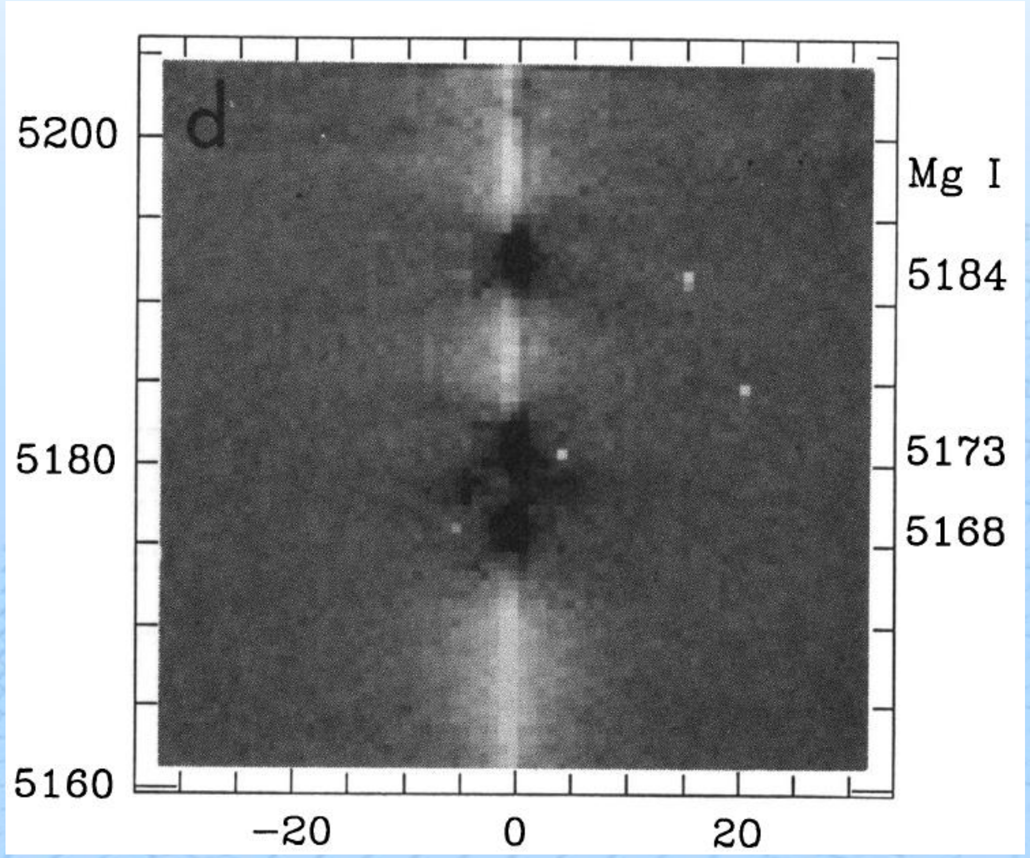
✓**Structural components**. Bulge/Disk. Nuclear stellar disks (same spin direction, but different amplitude).

✓**Misaligned/Orthogonal structures**. Warps, Polar Ring Galaxies, Polar disk galaxies.

MULTI-SPIN GALAXIES

Counter-rotations: NGC 4550 (large scale counter-roting stellar disks)

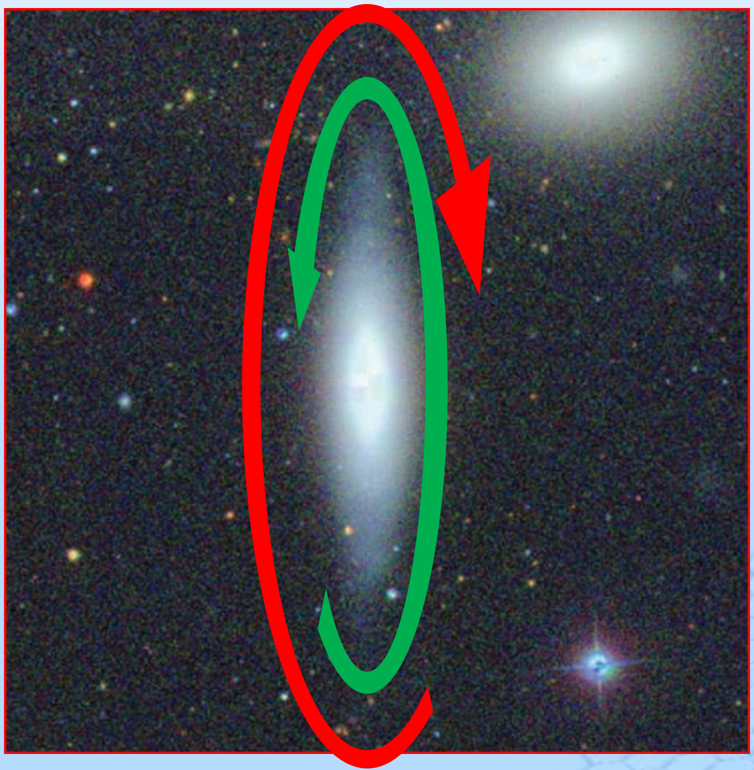


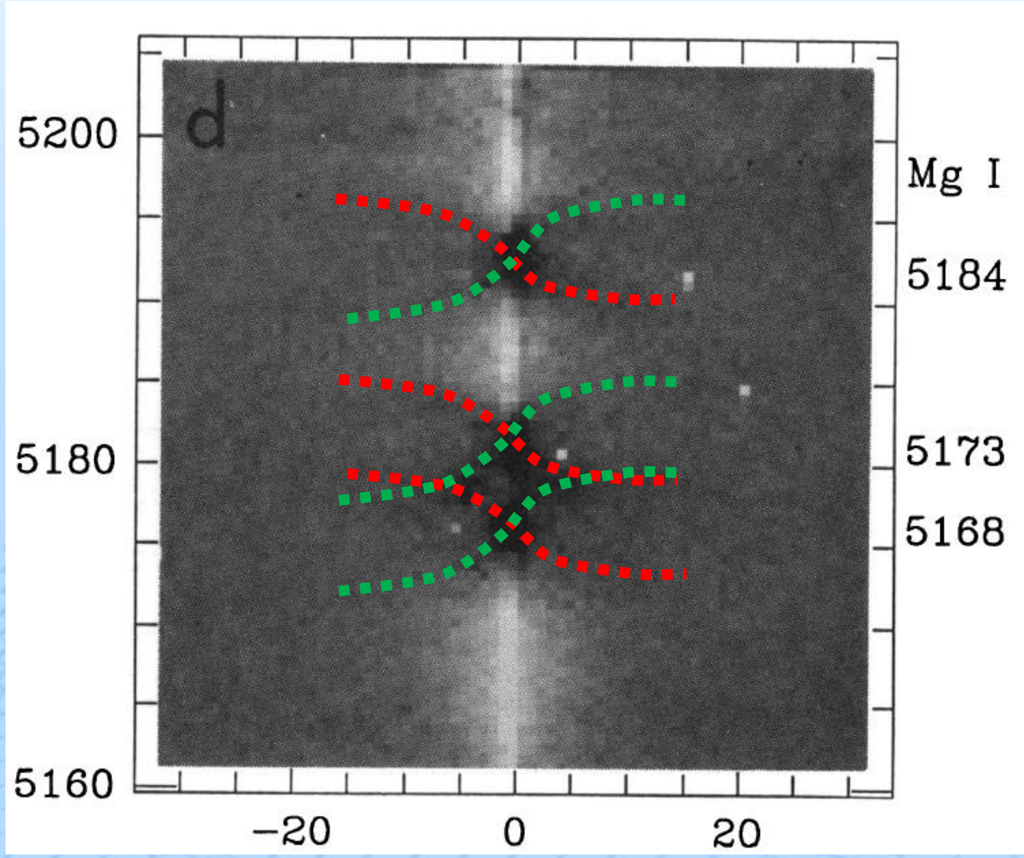


Rubin et al. (1992)

MULTI-SPIN GALAXIES

Counter-rotations: NGC 4550 (large scale counter-roting stellar disks)

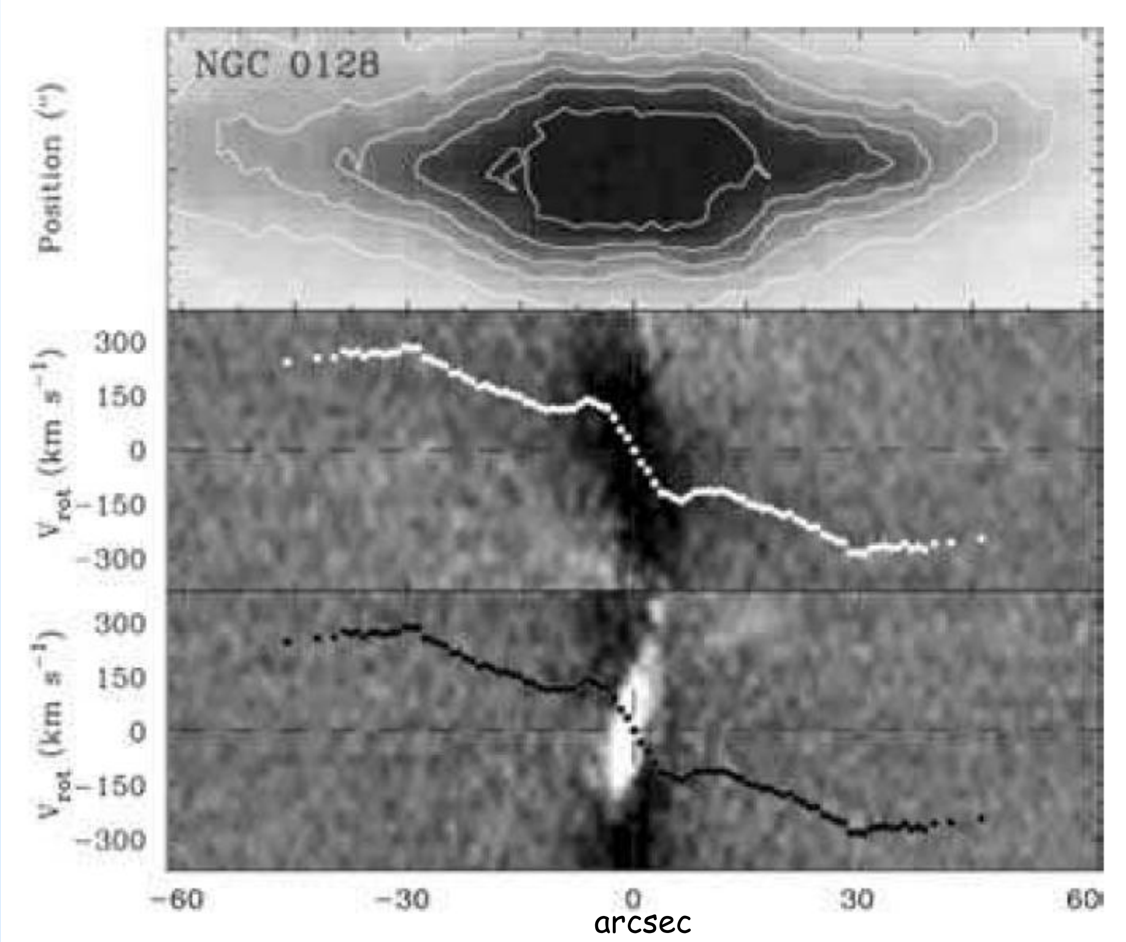




Rubin et al. (1992)

MULTI-SPIN GALAXIES

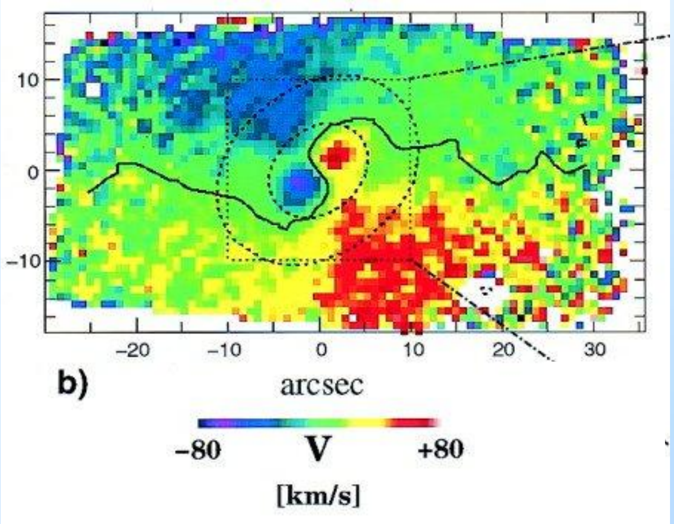
Counter-rotations: NGC 0128 Gas and stars counter-rotating



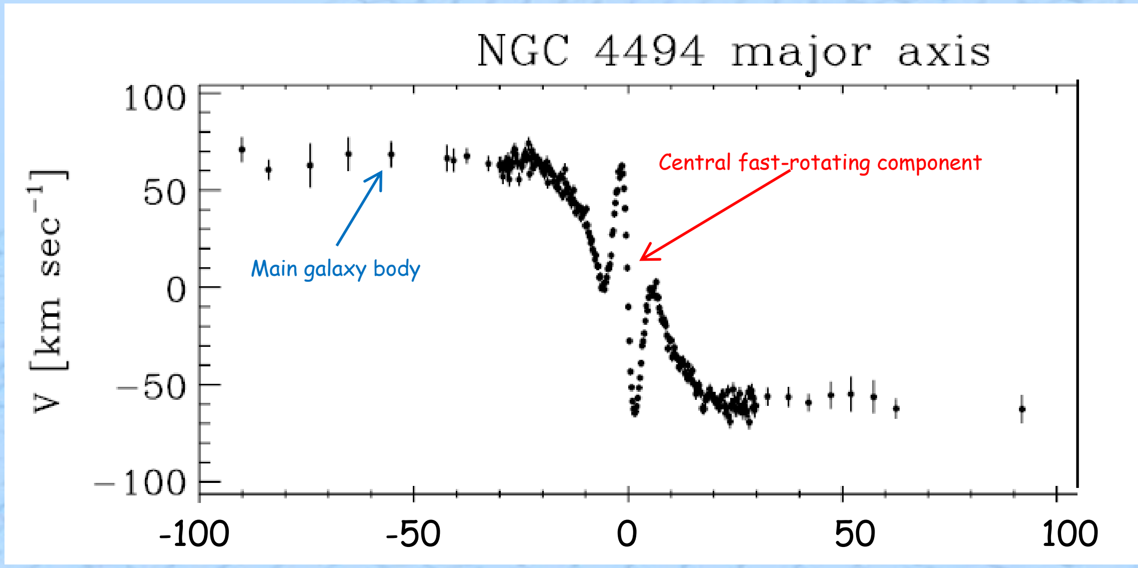
Bureau & Chung (2006)

MULTI-SPIN GALAXIES

Structural components: Kinematically Decoupled Cores



NGC 4365 (From SAURON)



Coccato et al. (2009)

MULTI-SPIN SYSTEMS IN GALAXIES

Misaligned/Orthogonal structures

Warp: UGC 3697 (Integral galaxy)

Polar disk: NGC 4650A

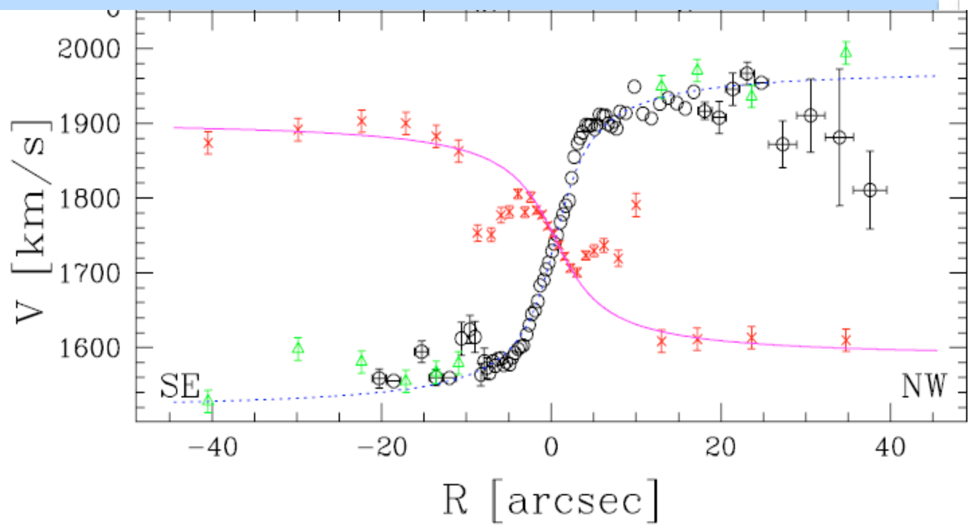
SCENARIOS

Counter-rotating galaxies:

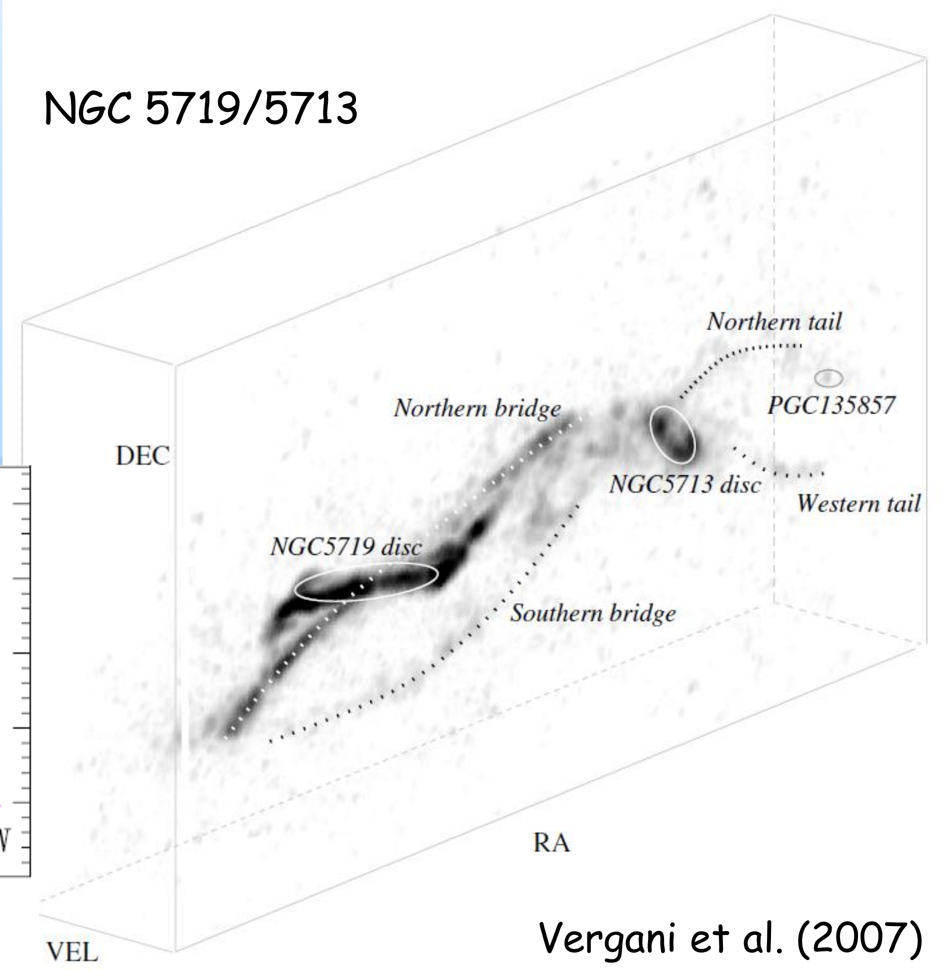
1. **Accretion of gas** on retrograde orbits plus subsequent star formation (Lovelace & Chou 1996; Thakar & Ryden 1996). *Secondary component is younger.*

   Accretion of gas along filaments (Algorry et al. 2014).

   Example: NGC 5719 direct observation of on-going gas accretion on a galaxy with stellar counter-rotation.



NGC 5719/5713



Vergani et al. (2007)

SCENARIOS

Counter-rotating galaxies:

2. **Galaxy binary mergers**: The properties of the counter-rotating disks depend on the nature of the progenitors and star formation history. According to simulations, mergers of galaxies:
   - ✓ *do not* play a significant role (Algorry et al. 2014).
   - ✓ can explain the presence of 50% counter-rotating stars in NGC 4550 and the different flattening of the two counter-rotating disks (Crocker et al. 2009).

SCENARIOS

Polar rings/disks:

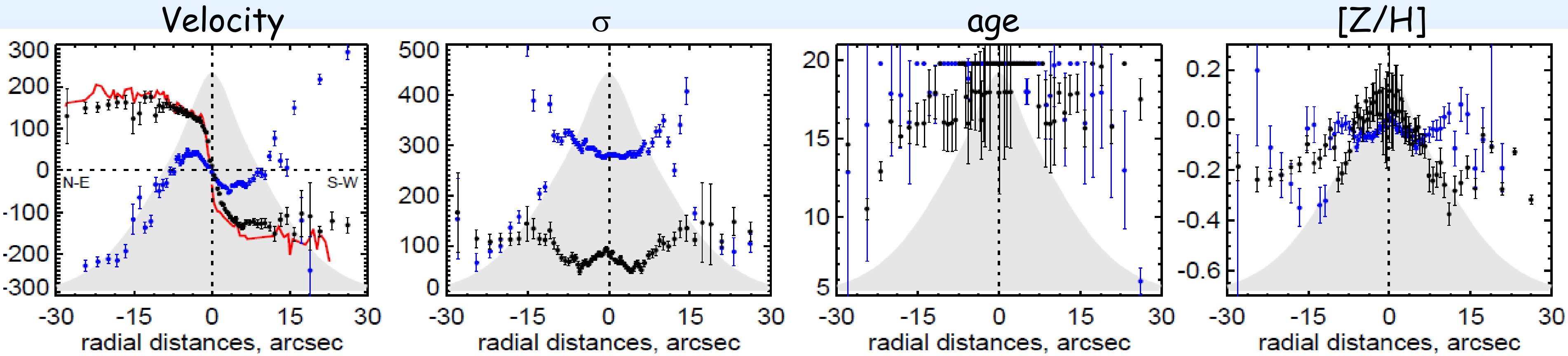
1. **Dissipative polar merger** of two disk galaxies with unequal mass (Bekki 1998; Bournaud & Combes 2003);

2. **Tidal accretion** of external material (gas and/or stars), captured by an early-type galaxy on a parabolic encounter (Reshetnikov & Sotnikova 1997; Bournaud & Combes 2003; Hancock et al. 2009);

3. **Cold accretion** of pristine gas along a filament (Macciò et al. 2006; Brook et al. 2008).

SCENARIOS

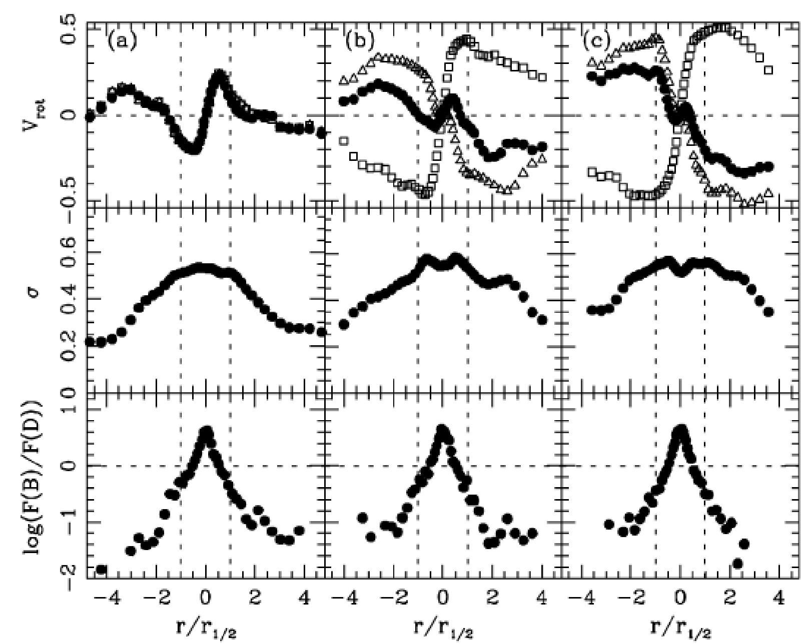
Counter-rotating bulge (NGC 524, Katkov+2011)



Binary merger simulations from Balcells & Gonzalez (1998)

a) $M_2:M_1 = 1$
b) $M_2:M_1 = 2$
c) $M_2:M_1 = 3$

□ Galaxy 1
△ Galaxy 2
● Total



MOTIVATIONS

To understand the properties and the formation mechanisms of multi-spin galaxies and their components we need to study the properties of both components:

1. Morphology (size, geometry)
2. Kinematics
3. Stellar population content (Age, metallicity…)

MOTIVATIONS

Aim: Study the spectral (and morphological) properties of the structural components in a galaxy, separately. For example:

1. Date the formation of the counter-rotating disk.
2. Measure the metallicity and abundance ratio of the decoupled components.
3. Unveil the real extension of a KDC and its kinematic properties.
4. Study the stellar populations of bulges by removing the contamination from the stars in the disk.
5. Properties of the thick and thing disks in spirals.
6. …

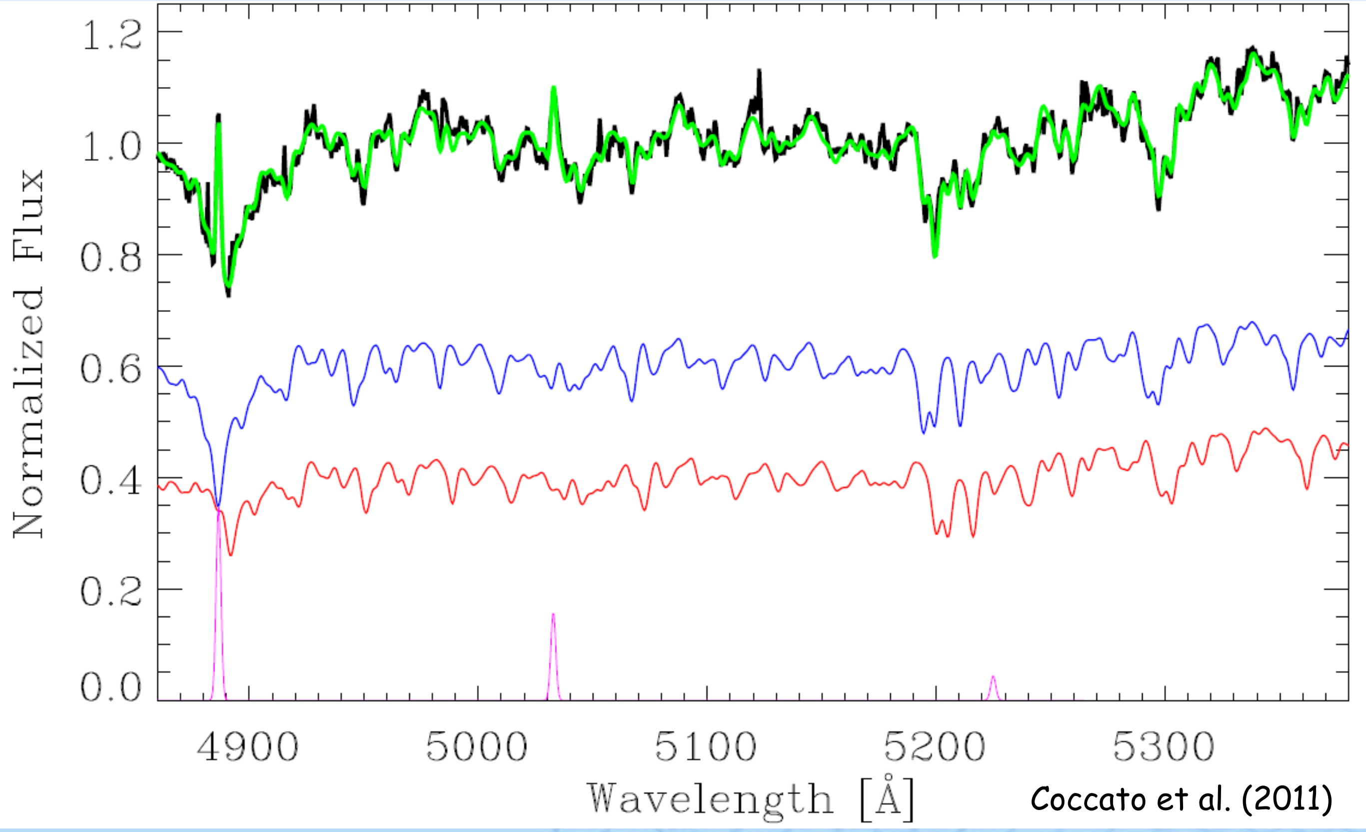
Complication: the different structural components (i.e. counter-rotating disks, bulge/disks) are *co-spatial:* the sum of their contributions is observed.

Challenge: Separate the two components and measure them independently.

SPECTRAL DECOMPOSITION:

disentangling kinematics *and* stellar populations of two decoupled

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



Galaxy spectrum

Best fit model

Secondary component

Main component

Ionized-gas component

Differences in the position of absorption line features and in the Hβ equivalent widths between the two stellar components (→different kinematics and stellar populations).

SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1 - F_1$: mean flux of the second component.

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

Parametric recovery of LOSVD

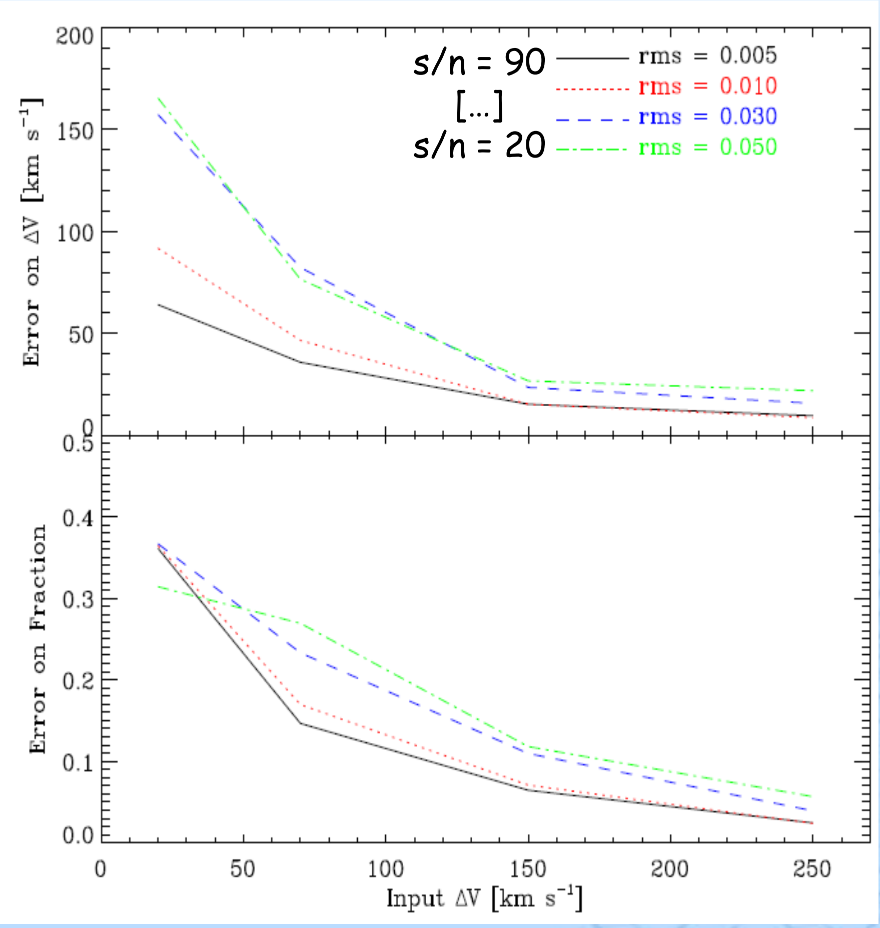
$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component.

$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

All are free parameters in the code; but, if required: F can be fixed via photometric decomposition; $SPC(\lambda)$ can be constrained from regions where the other component is absent; kinematics can be constrained by independent methods.

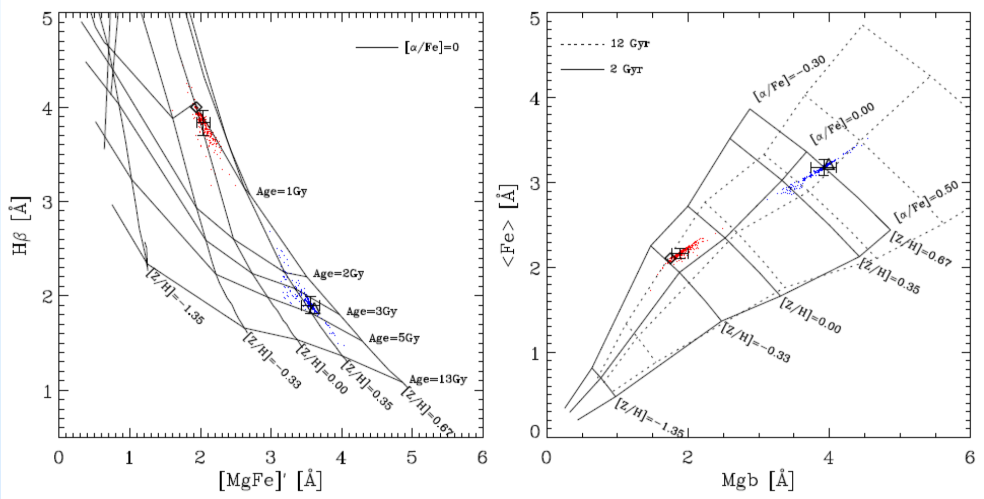
SPECTRAL DECOMPOSITION:

Errors on kinematics (simulations)

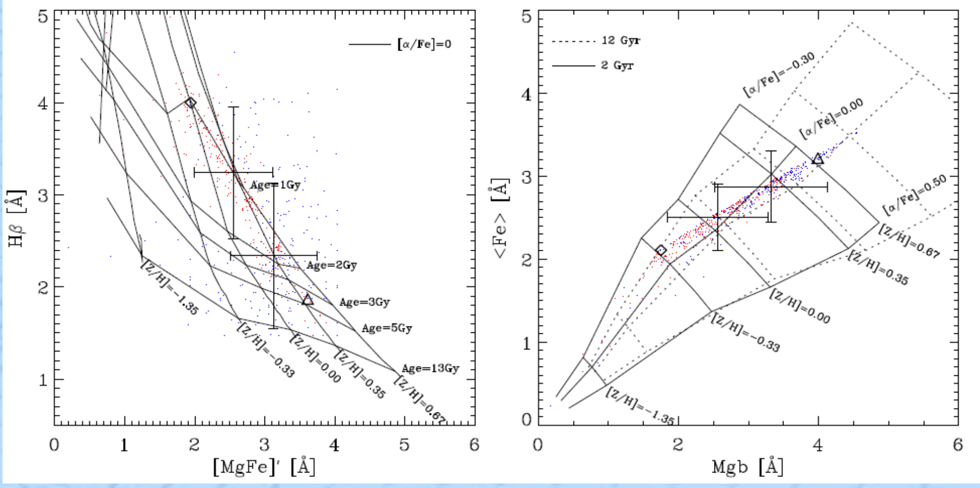


Errors on SSP (simulations)

ΔV > 150 km/sec ; rms = 0.005



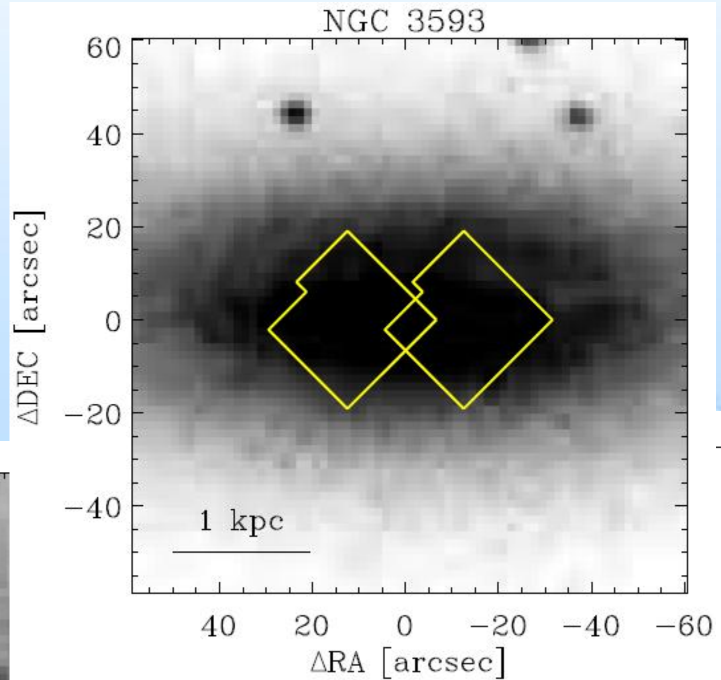
ΔV < 150 km/sec ; rms = 0.05

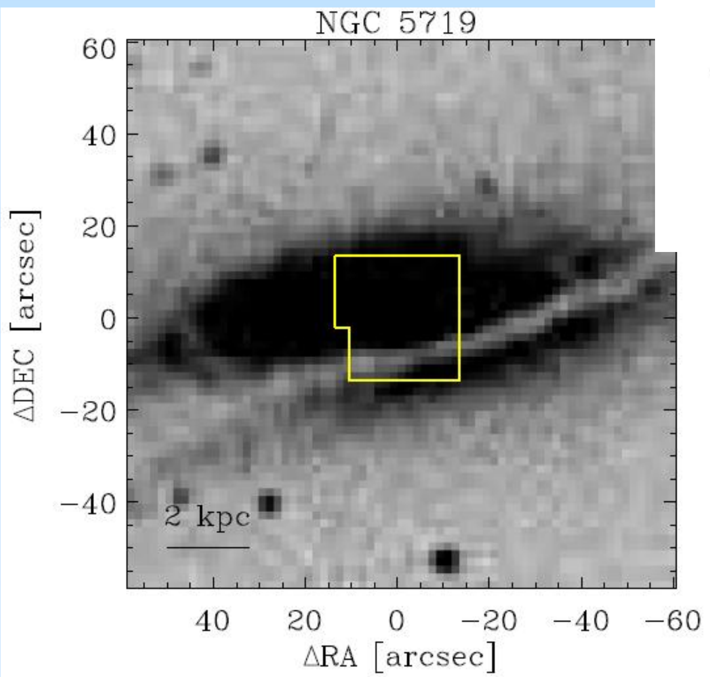


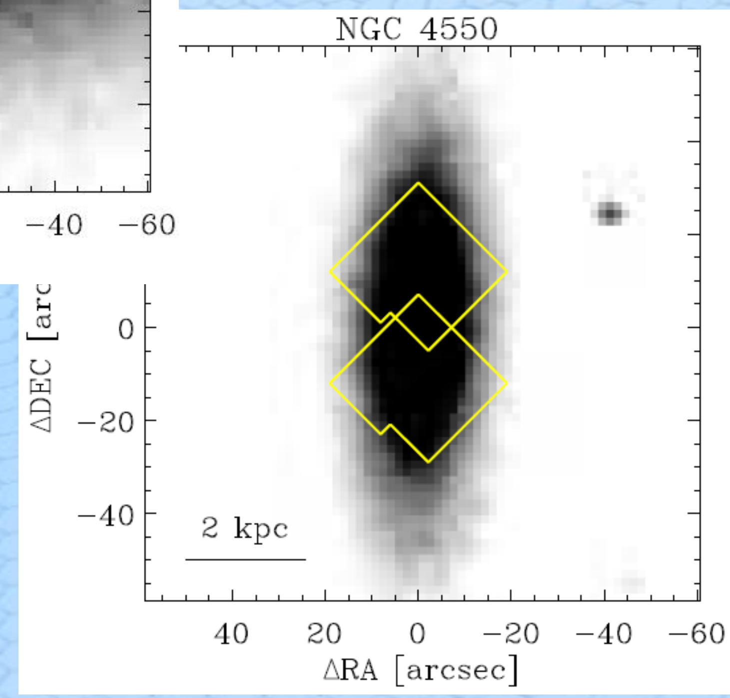
SPECTRAL DECOMPOSITION:

First application: large-scale counter-rotating stellar disks

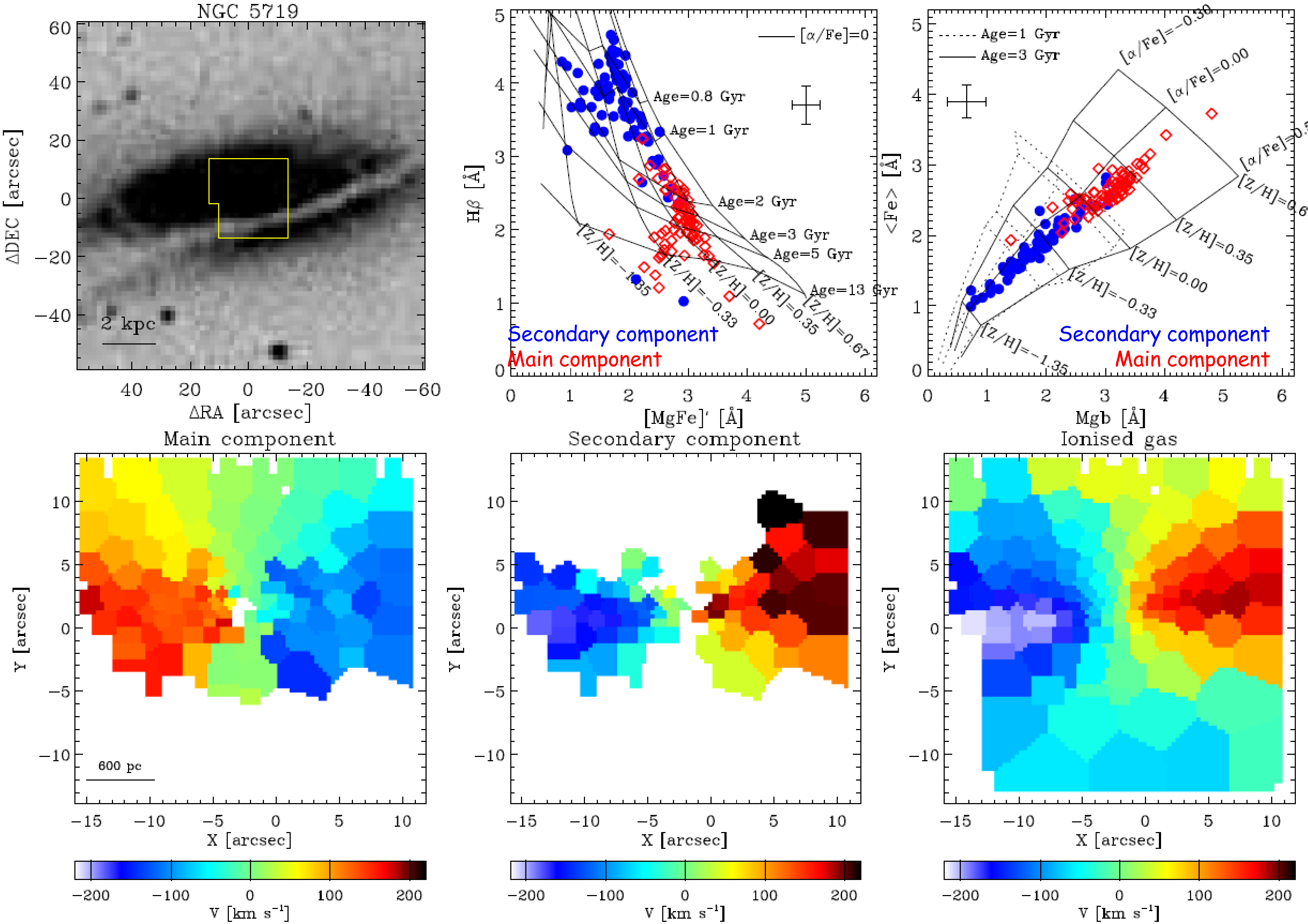
NGC 5719
NGC 3593
NGC 4550



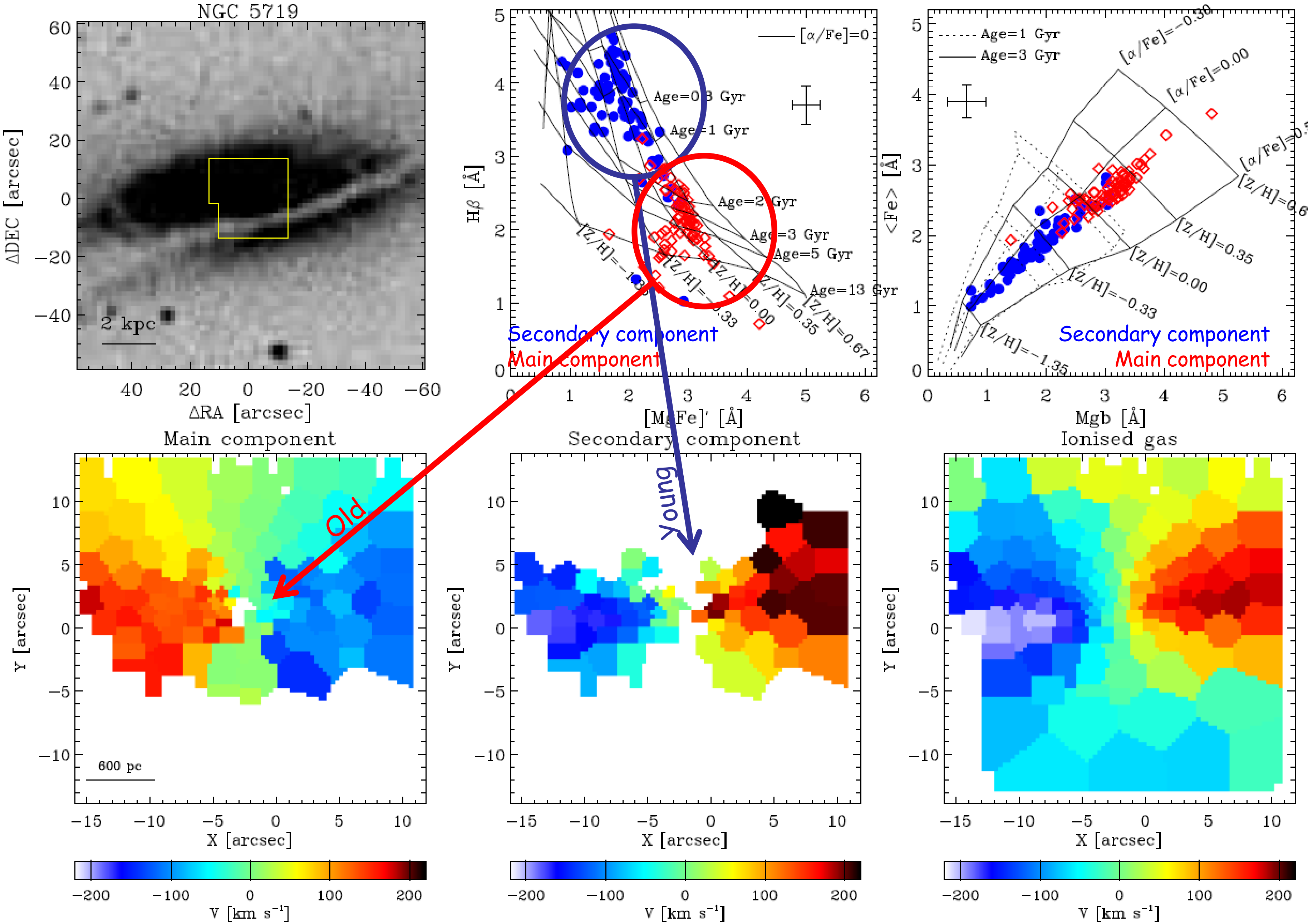




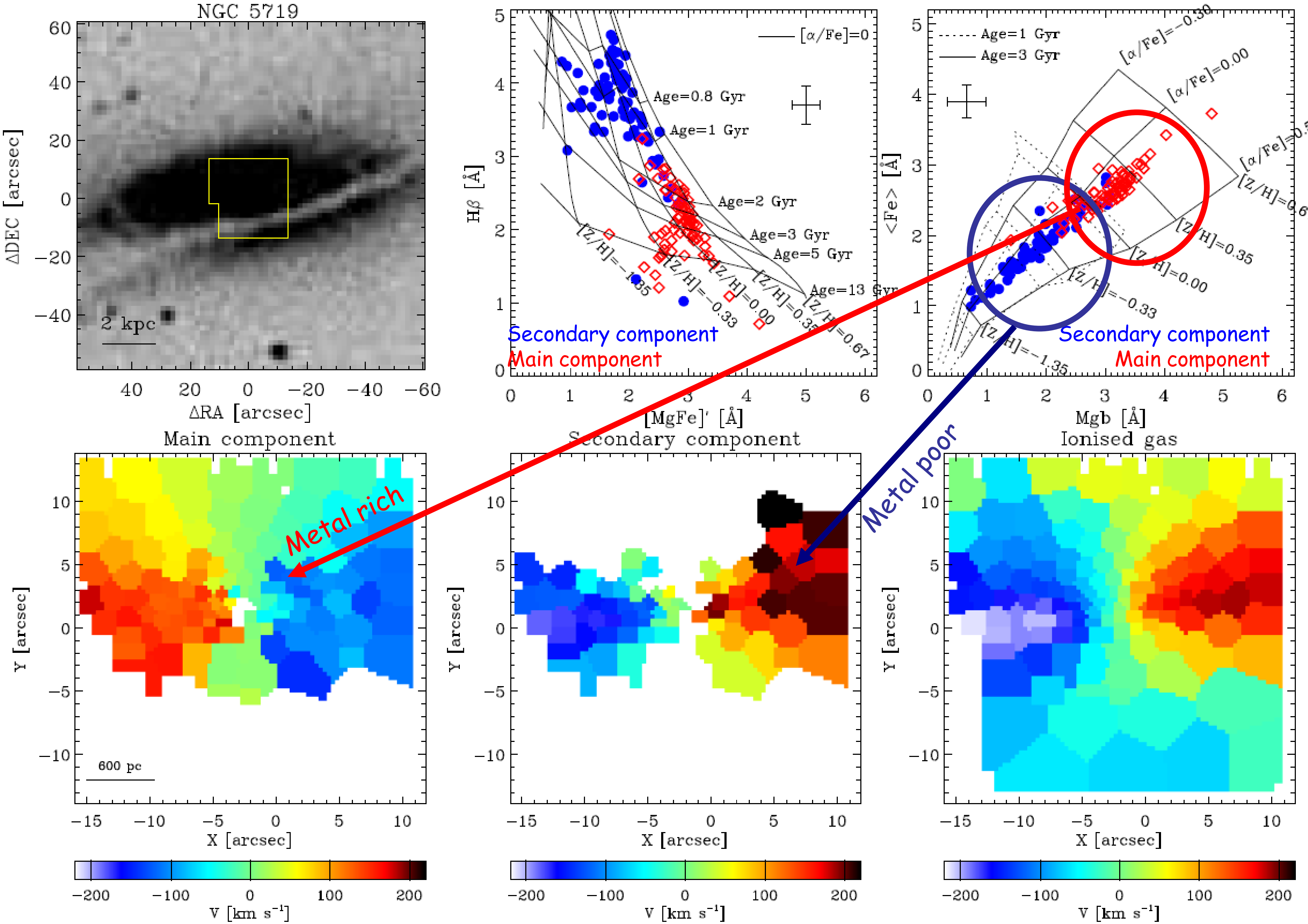
NGC 5719


NGC 5719
ΔDEC [arcsec]
ΔRA [arcsec]
2 kpc
Hβ [Å]
[MgFe]' [Å]
[α/Fe]=0
Age=0.8 Gyr
Age=1 Gyr
Age=2 Gyr
Age=3 Gyr
Age=5 Gyr
Age=13 Gyr
Secondary component
Main component
<Fe> [Å]
Mgb [Å]
Age=1 Gyr
Age=3 Gyr
Secondary component
Main component
Main component
Secondary component
Ionised gas
Y [arcsec]
X [arcsec]
600 pc
V [km s^-1]

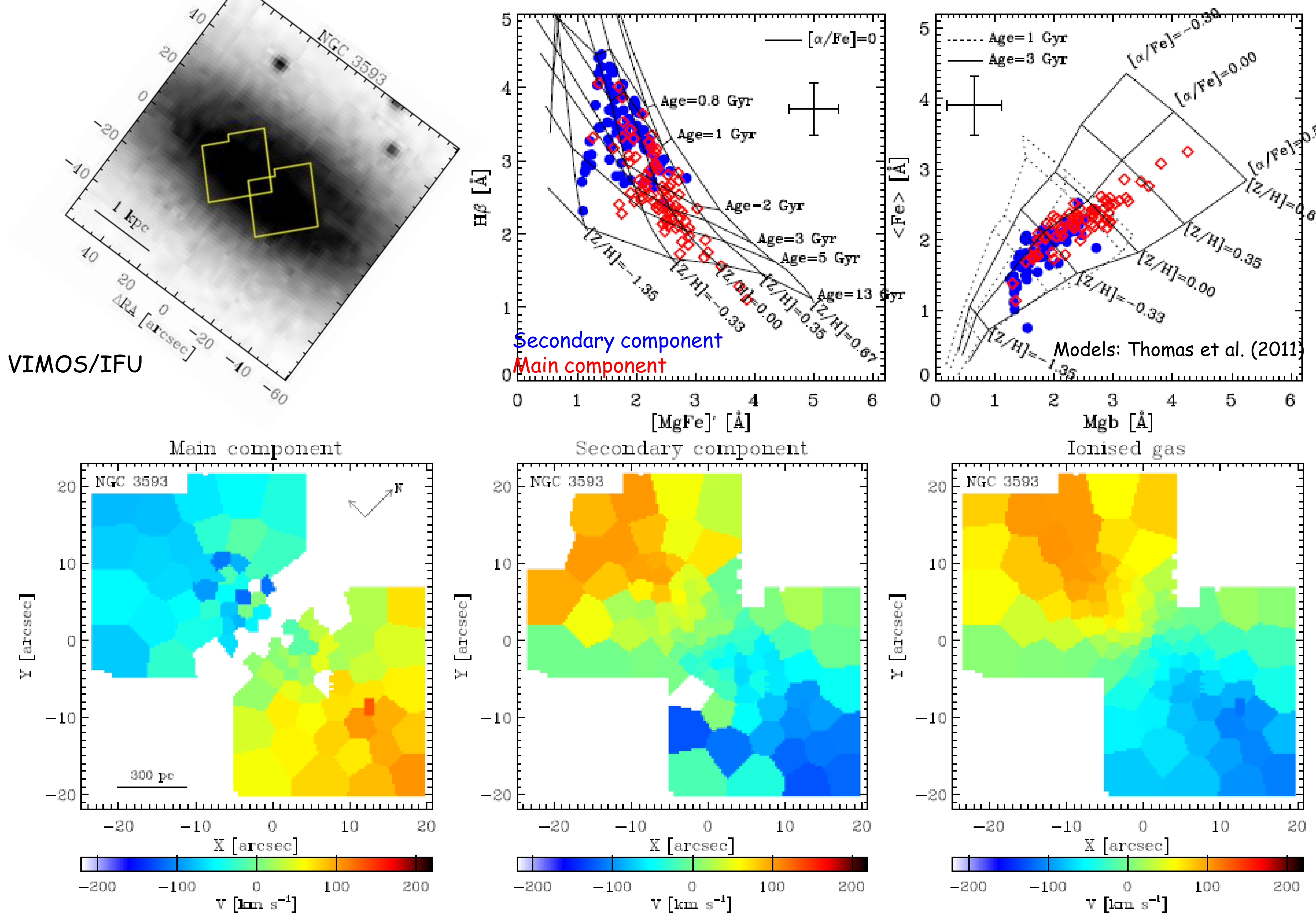
NGC 5719


NGC 5719
ΔDEC [arcsec]
ΔRA [arcsec]
2 kpc
Hβ [Å]
[MgFe]' [Å]
[α/Fe]=0
Age=0.8 Gyr
Age=1 Gyr
Age=2 Gyr
Age=3 Gyr
Age=5 Gyr
Age=13 Gyr
Secondary component
Main component
<Fe> [Å]
Mgb [Å]
Age=1 Gyr
Age=3 Gyr
[α/Fe]=−0.30
[α/Fe]=0.00
Old
Young
Main component
Secondary component
Ionised gas
Y [arcsec]
X [arcsec]
600 pc
V [km s⁻¹]

NGC 5719

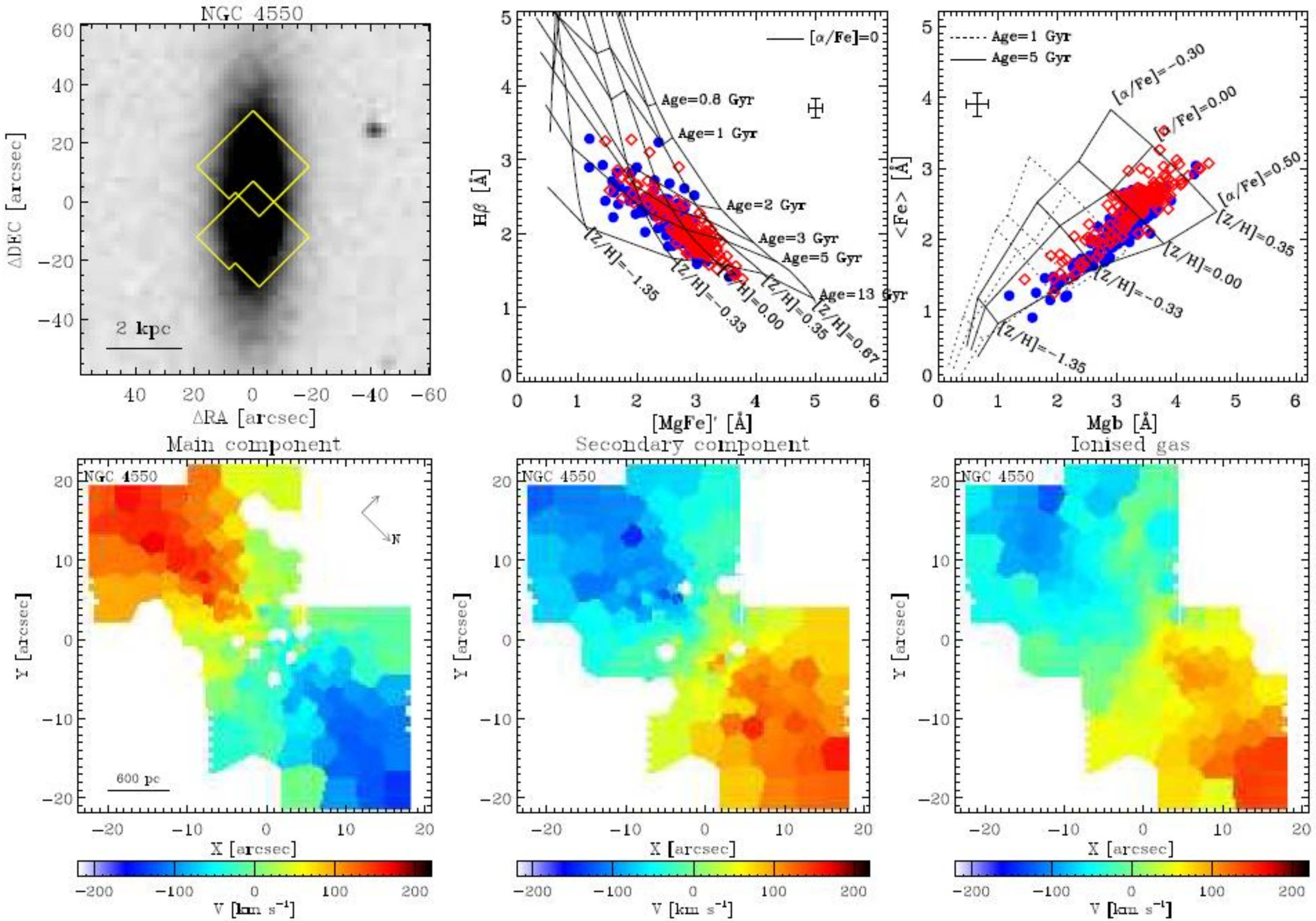

NGC 5719
2 kpc
ΔDEC [arcsec]
ΔRA [arcsec]
[α/Fe]=0
Age=0.8 Gyr
Age=1 Gyr
Age=2 Gyr
Age=3 Gyr
Age=5 Gyr
Age=13 Gyr
Hβ [Å]
[MgFe]' [Å]
Age=1 Gyr
Age=3 Gyr
[α/Fe]=−0.30
[α/Fe]=0.00
[α/Fe]=0.50
[Z/H]=0.67
[Z/H]=0.35
[Z/H]=0.00
[Z/H]=−0.33
[Z/H]=−1.35
<Fe> [Å]
Mgb [Å]
Secondary component
Main component
Secondary component
Main component
Metal rich
Metal poor
Main component
Secondary component
Ionised gas
600 pc
Y [arcsec]
X [arcsec]
V [km s⁻¹]

NGC 3593



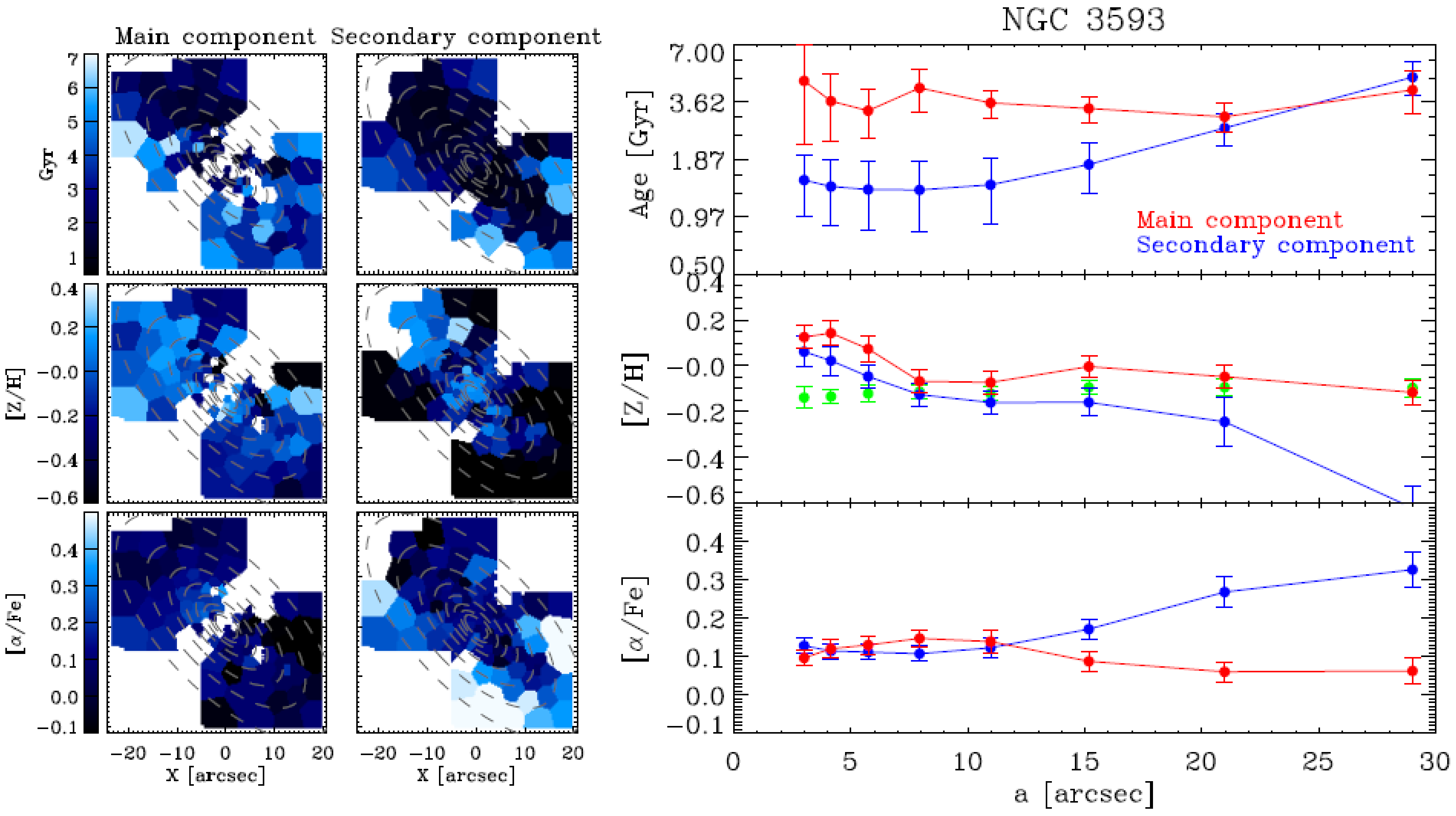
NGC 3593
1 kpc
ΔRA [arcsec]
VIMOS/IFU
Hβ [Å]
[MgFe]' [Å]
[α/Fe]=0
Age=0.8 Gyr
Age=1 Gyr
Age=2 Gyr
Age=3 Gyr
Age=5 Gyr
Age=13 Gyr
[Z/H]=-1.35
[Z/H]=-0.33
[Z/H]=0.00
[Z/H]=0.35
[Z/H]=0.67
Secondary component
Main component
<Fe> [Å]
Mgb [Å]
Age=1 Gyr
Age=3 Gyr
[α/Fe]=-0.30
[α/Fe]=0.00
[α/Fe]=0.50
Models: Thomas et al. (2011)
Main component
Secondary component
Ionised gas
300 pc
N
Y [arcsec]
X [arcsec]
V [km s⁻¹]

NGC 4550


NGC 4550
ΔDEC [arcsec]
ΔRA [arcsec]
2 kpc
Hβ [Å]
[MgFe]' [Å]
[α/Fe]=0
Age=0.8 Gyr
Age=1 Gyr
Age=2 Gyr
Age=3 Gyr
Age=5 Gyr
Age=13 Gyr
[Z/H]=-1.35
[Z/H]=-0.33
[Z/H]=0.00
[Z/H]=0.35
[Z/H]=0.67
<Fe> [Å]
Mgb [Å]
Age=1 Gyr
Age=5 Gyr
[α/Fe]=-0.30
[α/Fe]=0.00
[α/Fe]=0.50
[Z/H]=0.35
[Z/H]=0.00
[Z/H]=-0.33
[Z/H]=-1.35
Main component
Secondary component
Ionised gas
NGC 4550
Y [arcsec]
X [arcsec]
600 pc
N
V [km s⁻¹]

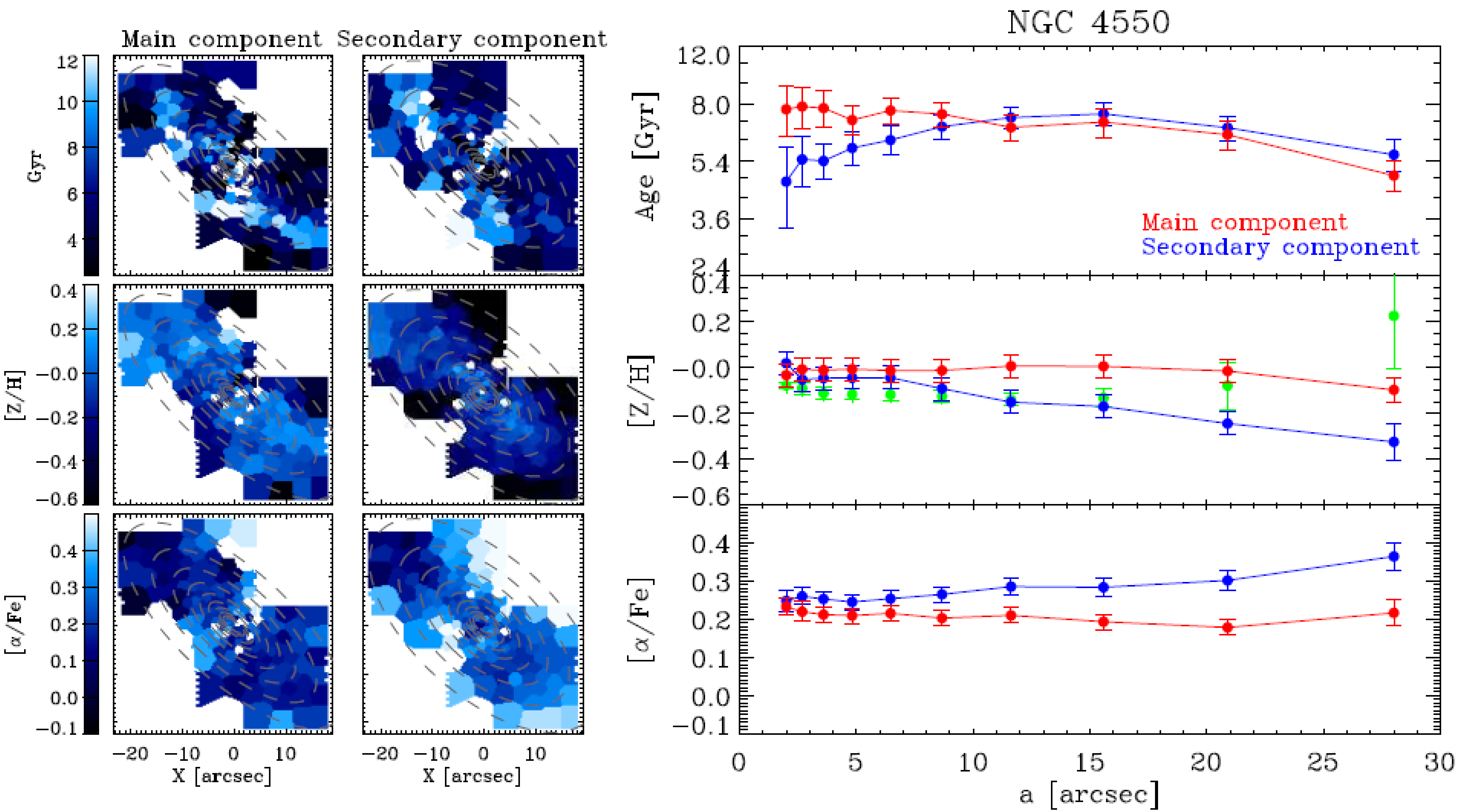
Stellar populations: Age, [Z/H], [α/Fe]

NGC 3593

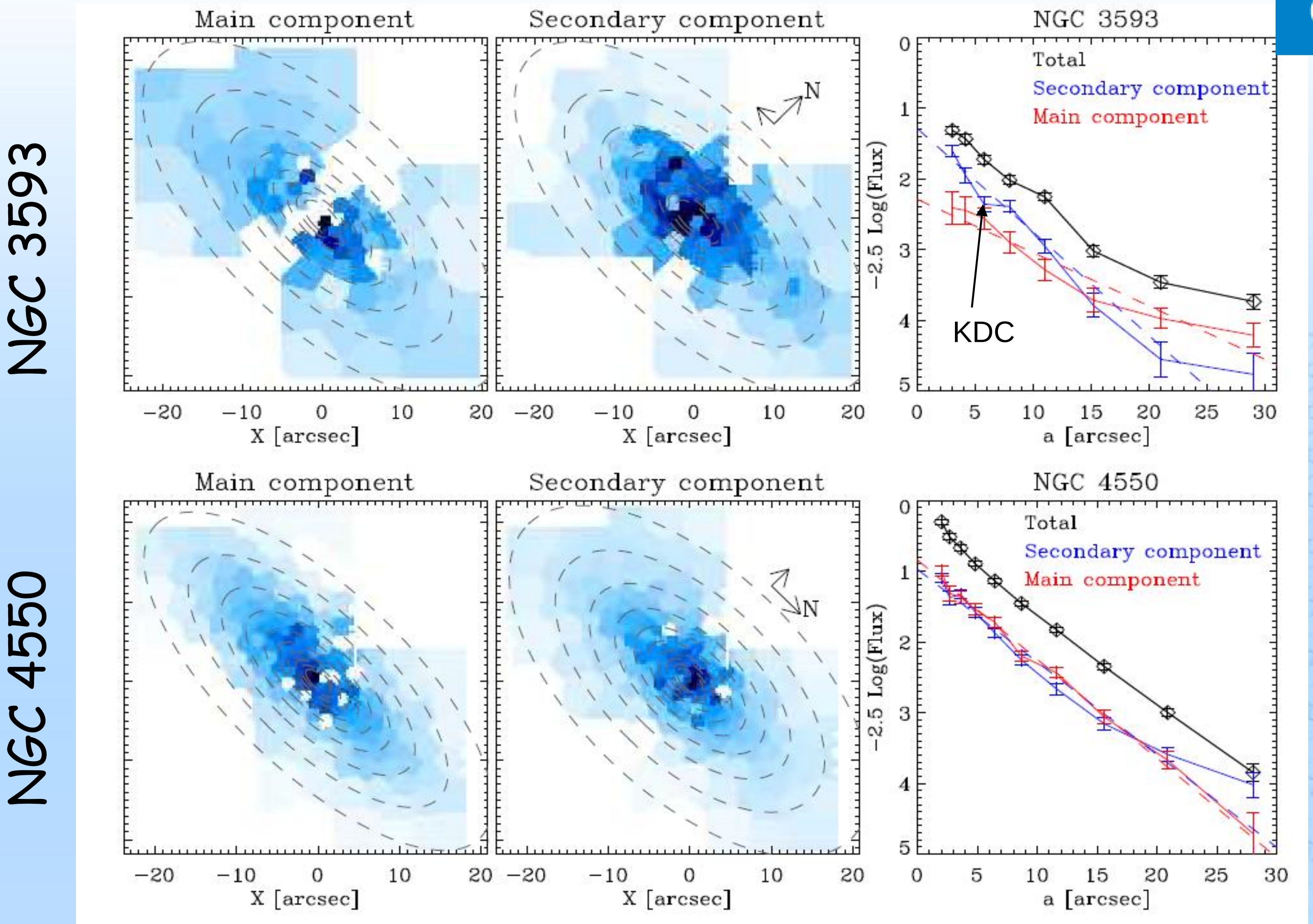


Stellar populations: Age, [Z/H], [α/Fe]

NGC 4550

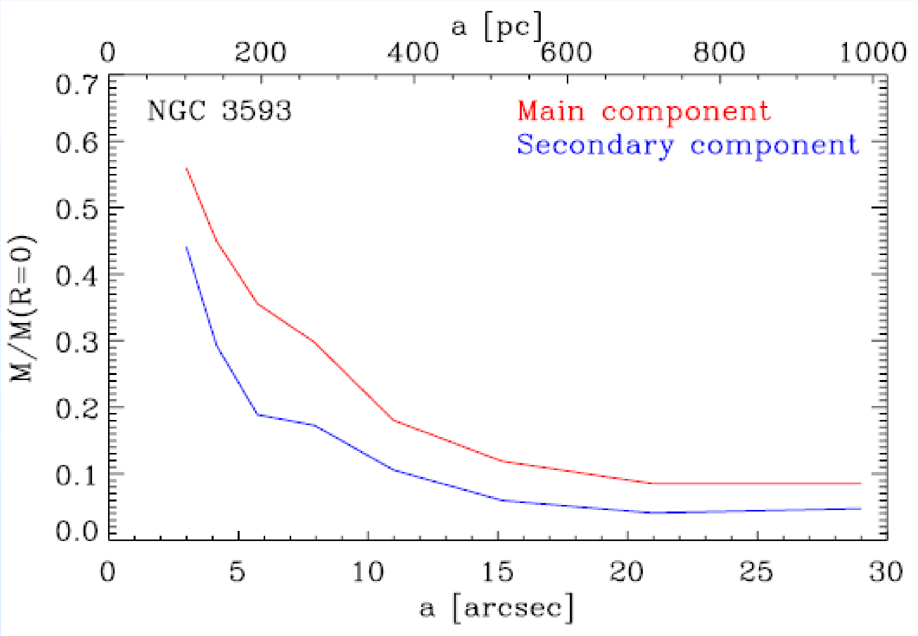


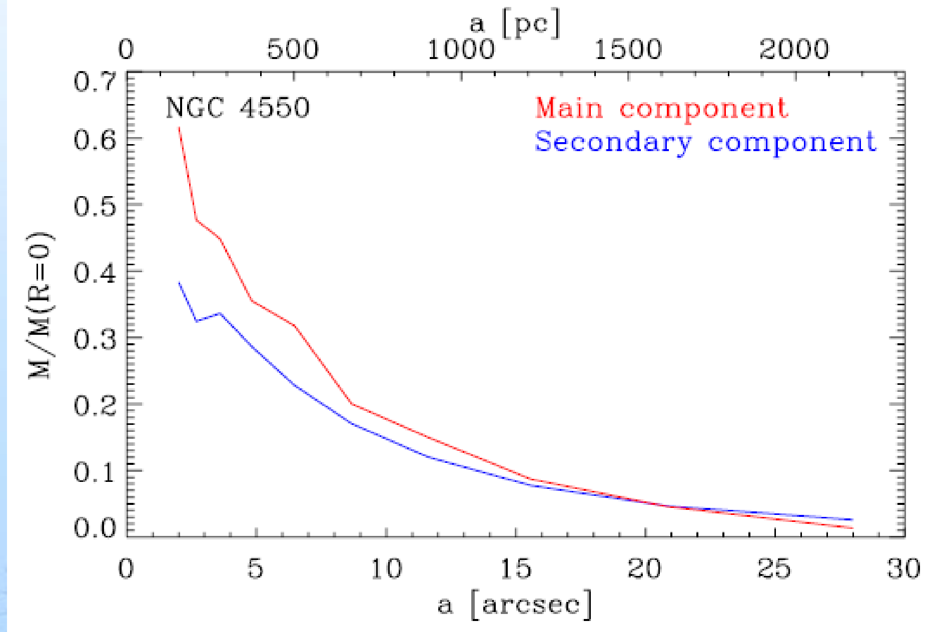
Surface brightness (kinematic) decomposition



STELLAR MASS PROFILE

Luminosity profile + stellar populations → M/L → mass profile





Although it dominates the light in the central regions, “KDC” in NGC 3593 is less massive than the stars in the galaxy.

The counter-rotating disks in NGC4550 have the same luminosity, but different mass profiles.

Results: global properties 1/2

Table 1: Luminosity-weighted values for the stellar population parameters of the stellar discs in NGC 3593, NGC 4550, and NGC 5719.

	$\overline{\text{Age}}$ [Gyr]	$\overline{[Z/H]}$	$\overline{[\alpha/Fe]}$
NGC 3593			
Main:	3.6 ± 0.6	-0.04 ± 0.03	0.09 ± 0.02
Secondary:	2.0 ± 0.5	-0.15 ± 0.07	0.18 ± 0.03
NGC 4550			
Main:	6.9 ± 0.6	-0.01 ± 0.03	0.20 ± 0.02
Secondary:	6.5 ± 0.5	-0.13 ± 0.04	0.28 ± 0.02
NGC 5719			
Main:	4.0 ± 0.9	0.08 ± 0.02	0.10 ± 0.02
Secondary:	1.3 ± 0.2	0.3 ± 0.02	0.14 ± 0.02

Secondary disk: Same direction of rotation as the ionized gas. Younger, less massive, different metal content, more α–enhanced than then main disk. → *Supporting the gas accretion + star formation scenario.*

But more statistics is needed (upcoming IFU surveys).

Results: global properties 2/2

Date the formation of the counter-rotating stellar disk

Galaxy	Formation of secondary comp.	After formation of main galaxy
NGC 3593	~2 Gyr	1.6 ±0.8 Gyr
NGC 4550	~7 Gyr	< 1Gyr
NGC 5719	~1.3 Gyr	2.7 ±0.9 Gyr

SUMMARY 1

Spectral decomposition technique that allows to separate the spectra of two kinematically distinct components in a galaxy.

1. It works on counter-rotating systems NGC 3593, NGC 4550, NGC 5179.

2. It allows to measure kinematics and stellar populations of ***both*** stellar components (plus ionized gas); morphologies, mass distributions of both components can be studied.

3. Secondary stellar component rotates in the same direction as the ionized gas.

4. Secondary components are always younger and have different [Z/H] than the main stellar components, and are more [α/Fe]. In agreement with the gas accretion plus star formation. Date the accretion event: ~2Gyr (NGC 3593, ΔT~1.6$\pm$0.8 Gyr), ~7Gyr (NGC 4550, ΔT<1Gyr), 1.3Gyr (NGC 5719, ΔT ~2.7$\pm$0.9 Gyr).

SPECTRAL DECOMPOSITION:

Next applications:

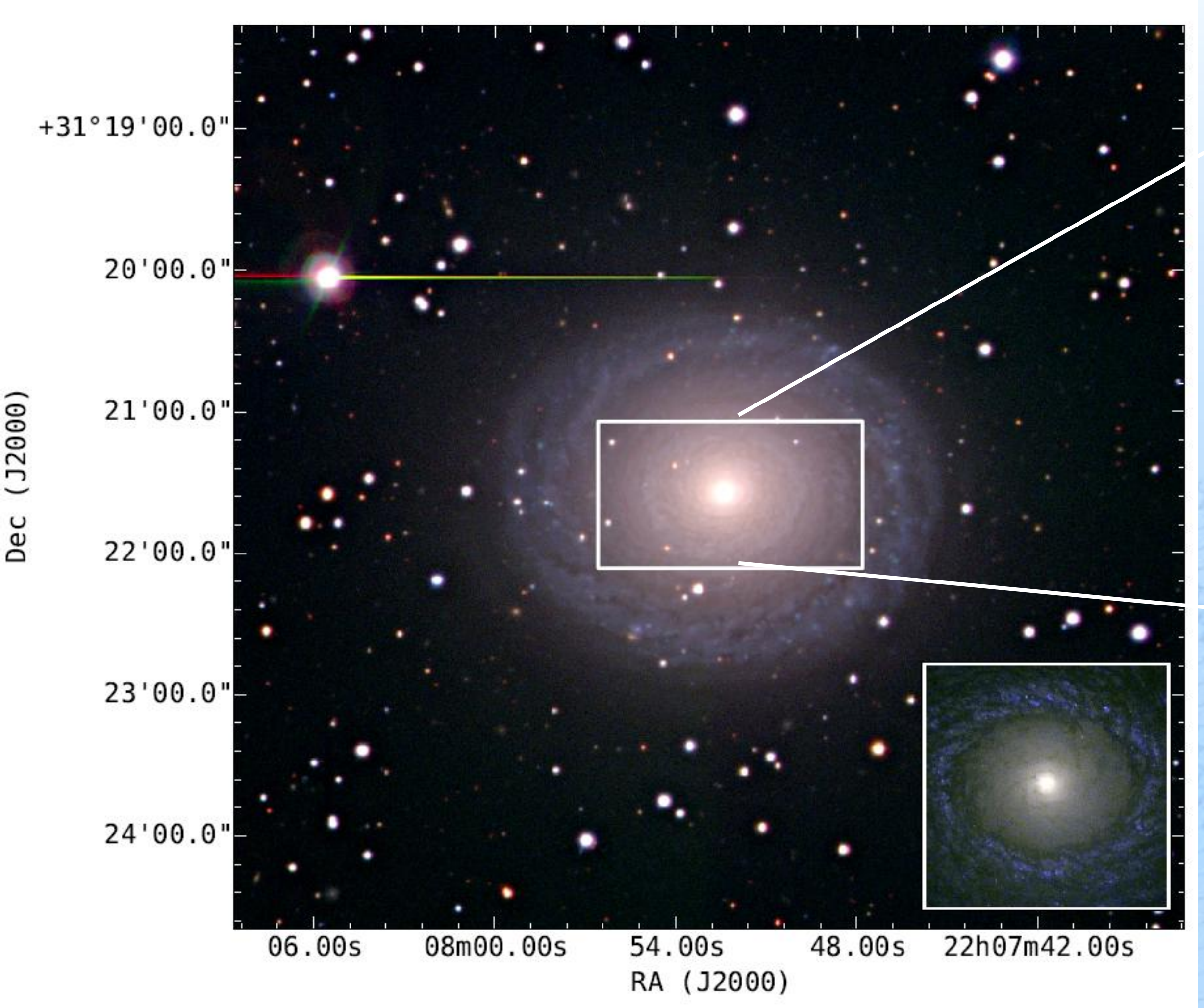
1. Bulge – disk decomposition

- remove the bulge (disk) contamination from the bulge (disk) light (NGC 7217, Fabricius et al. 2014)

2. Host galaxy – polar disk decomposition

- remove the polar disk contamination from the host galaxy (NGC 4650A)

NGC 7217



VIRUS-W

Range: 4880 – 5480 Å

σ_{INSTR}=15 km/sec

FOV: 105" x 55"

Sampl= 0.19 Å/pxl

Filling factor: 1/3

Exp. per fibre: 1.5 hrs

SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1-F_1$: mean flux of the second component.

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

Parametric recovery of LOSVD

$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component.

$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

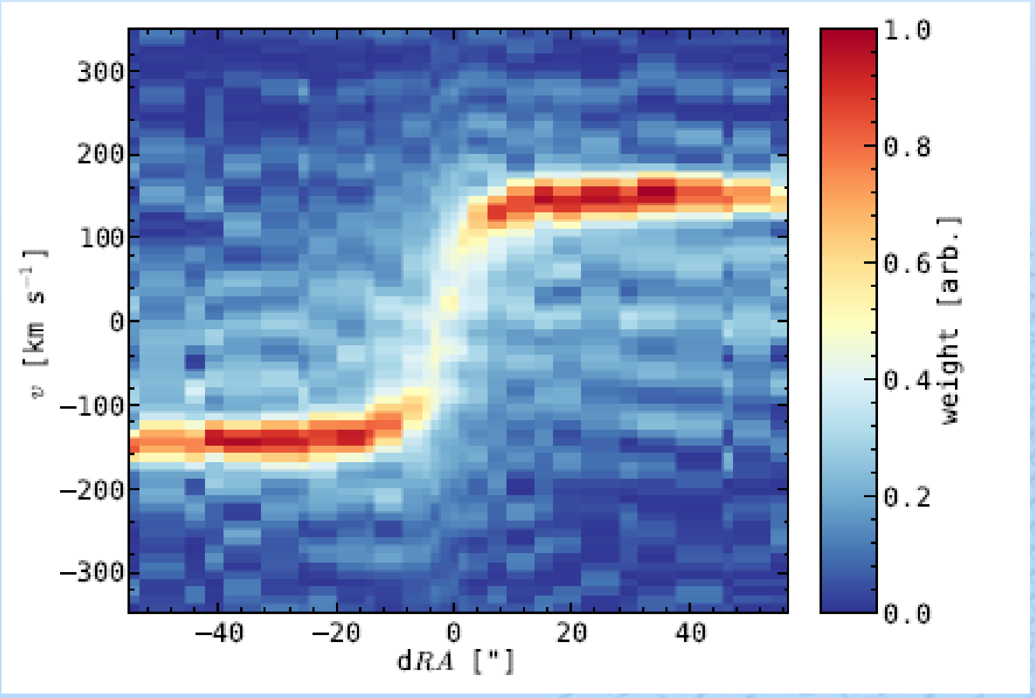
NGC 7217 Non parametric recovery of LOSVD

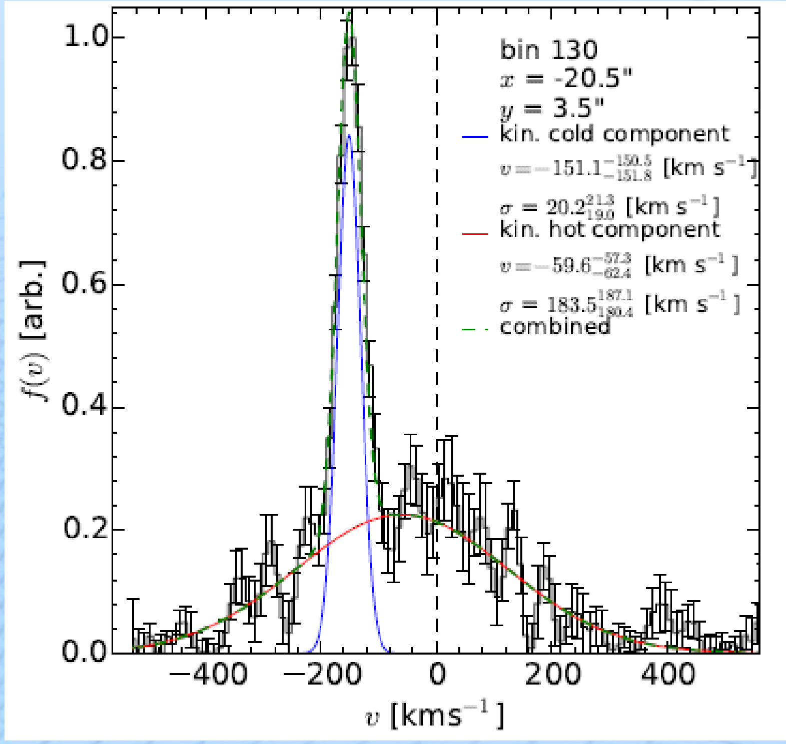
Problems: Short wavelength region, Low kinematic separation

- Large errors (esp. in the SSP recovery)

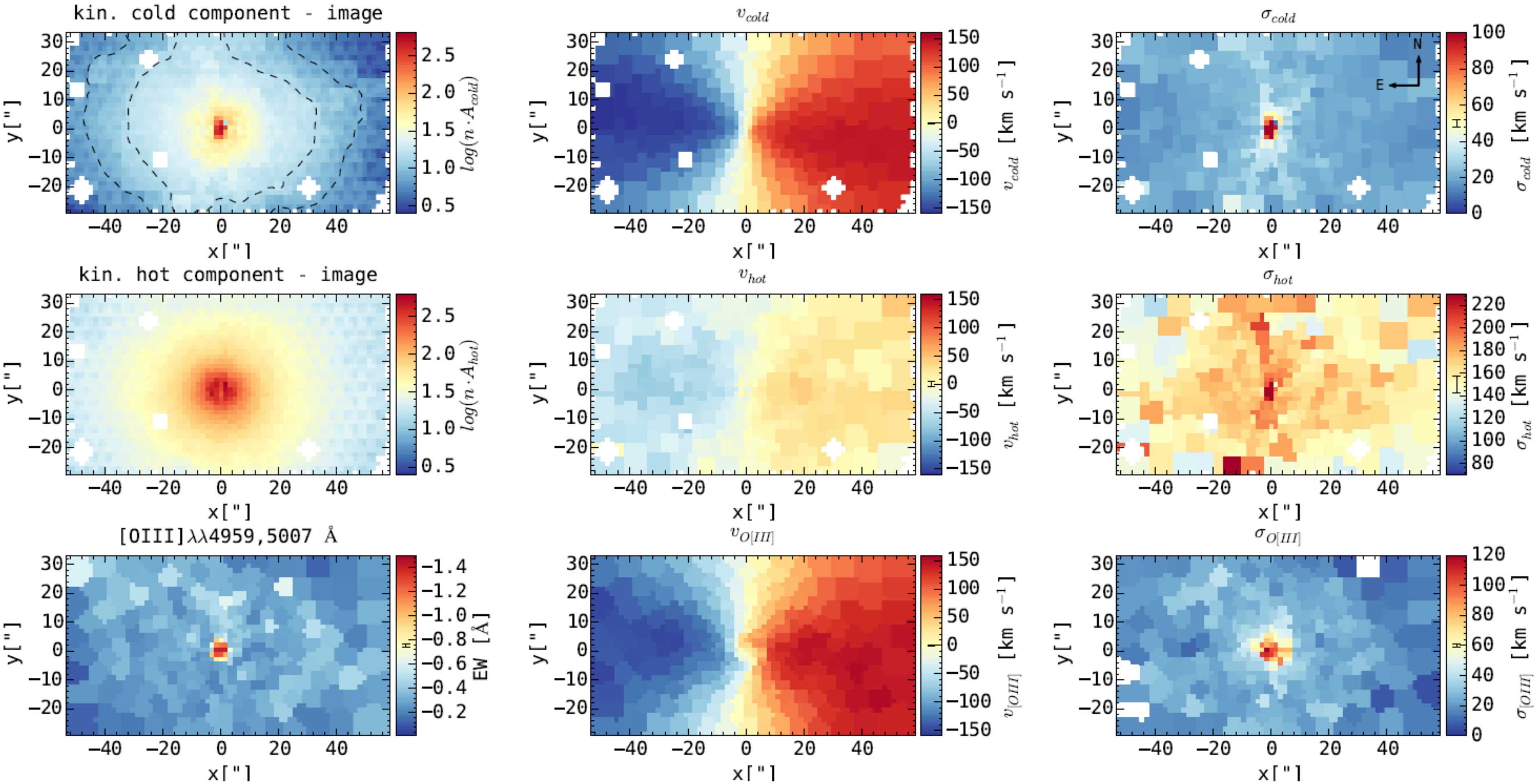
Solution: Use an independent routine to get the kinematics.

- Extension of Maximum Penalized Likelihood Method plus kinematic double-Gaussian decomposition





NGC 7217: Non parametric recovery of LOSVD



SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1 - F_1$: mean flux of the second component.

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

Parametric recovery of LOSVD

$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component.

$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1-F_1$: mean flux of the second component.

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

Parametric recovery of LOSVD

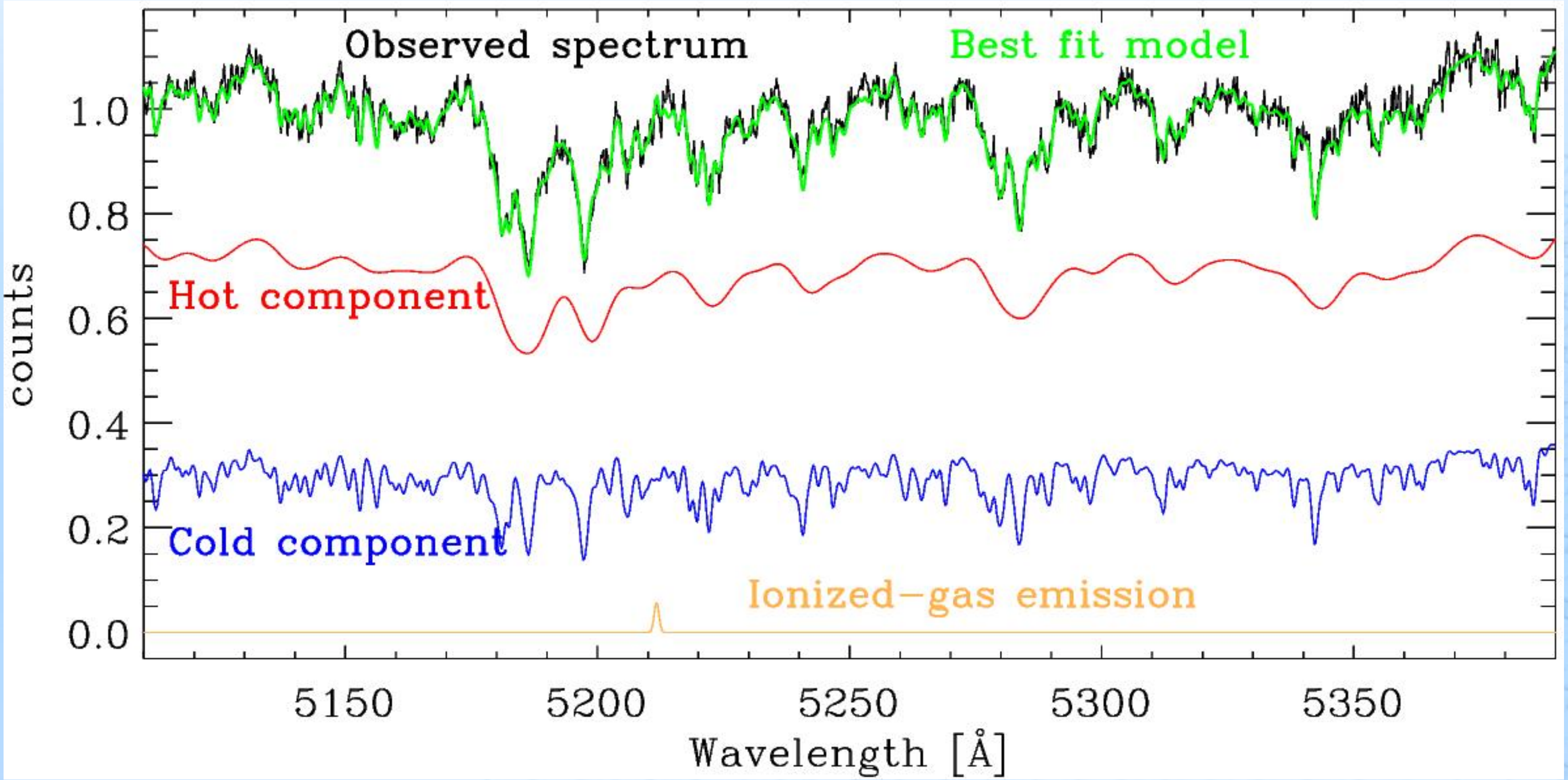
CONSTRAINED

$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component.

$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

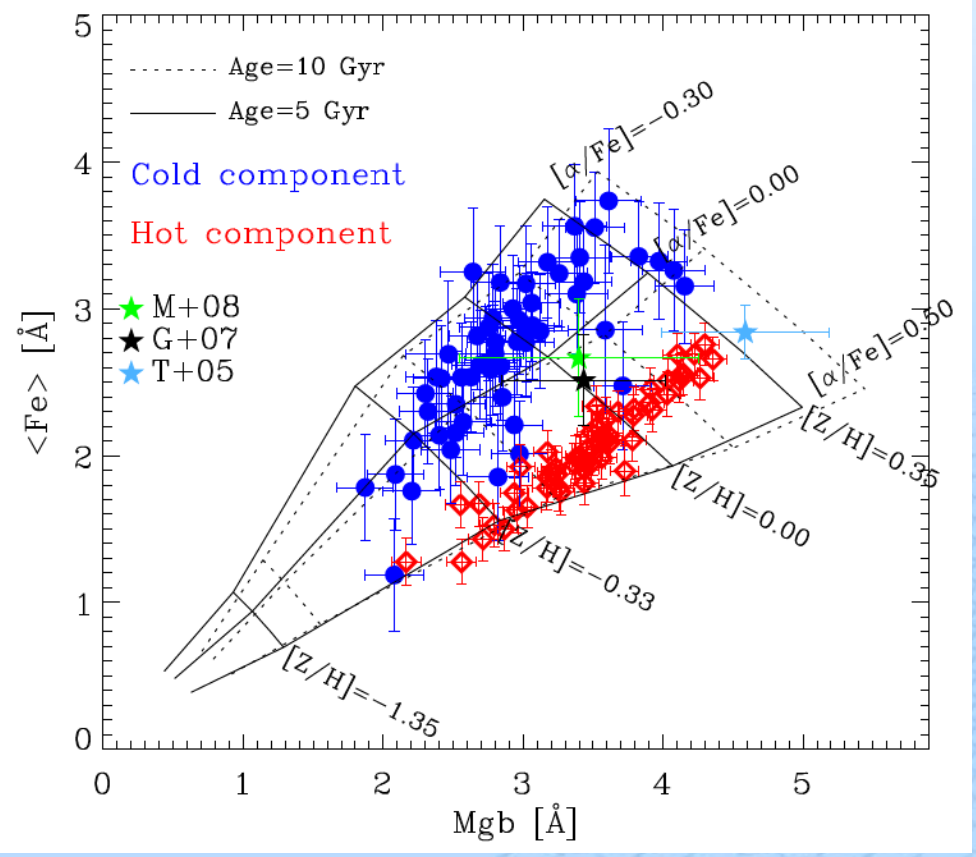
NGC 7217: spectral decomposition

The kinematics are constrained from the non parametric approach, and used as input in the spectral decomposition



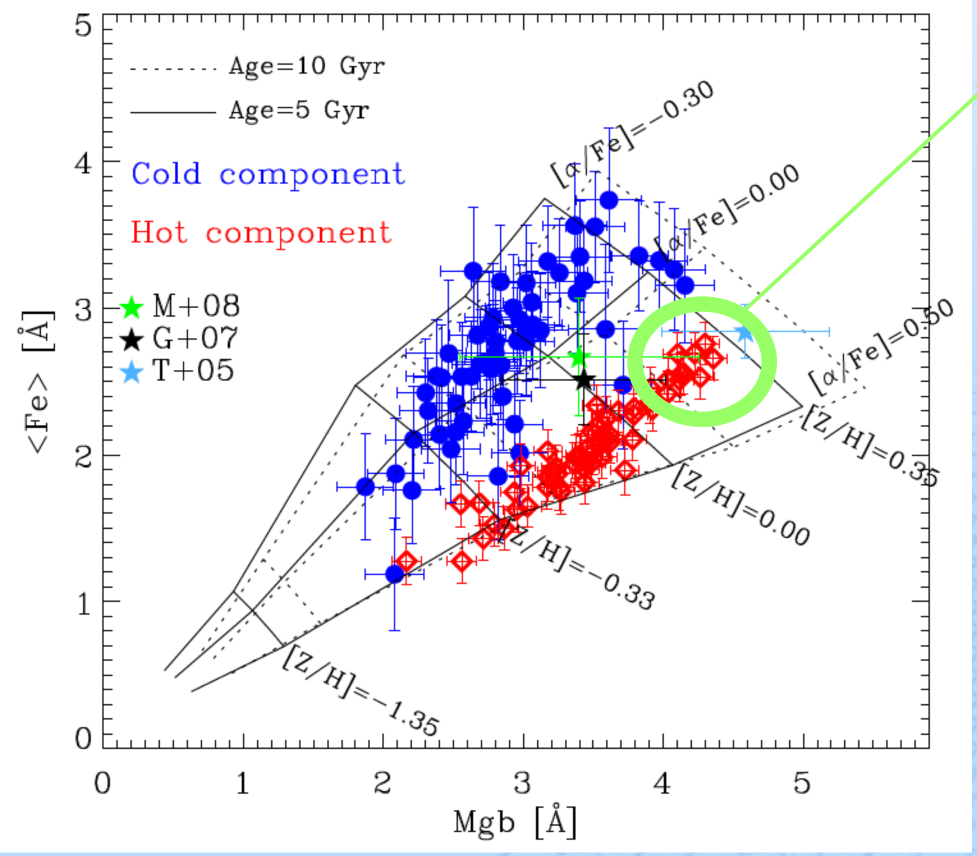
NGC 7217: spectral decomposition

The kinematics are constrained from the non parametric approach, and used as input in the spectral decomposition



NGC 7217: spectral decomposition

The kinematics are constrained from the non parametric approach, and used as input in the spectral decomposition

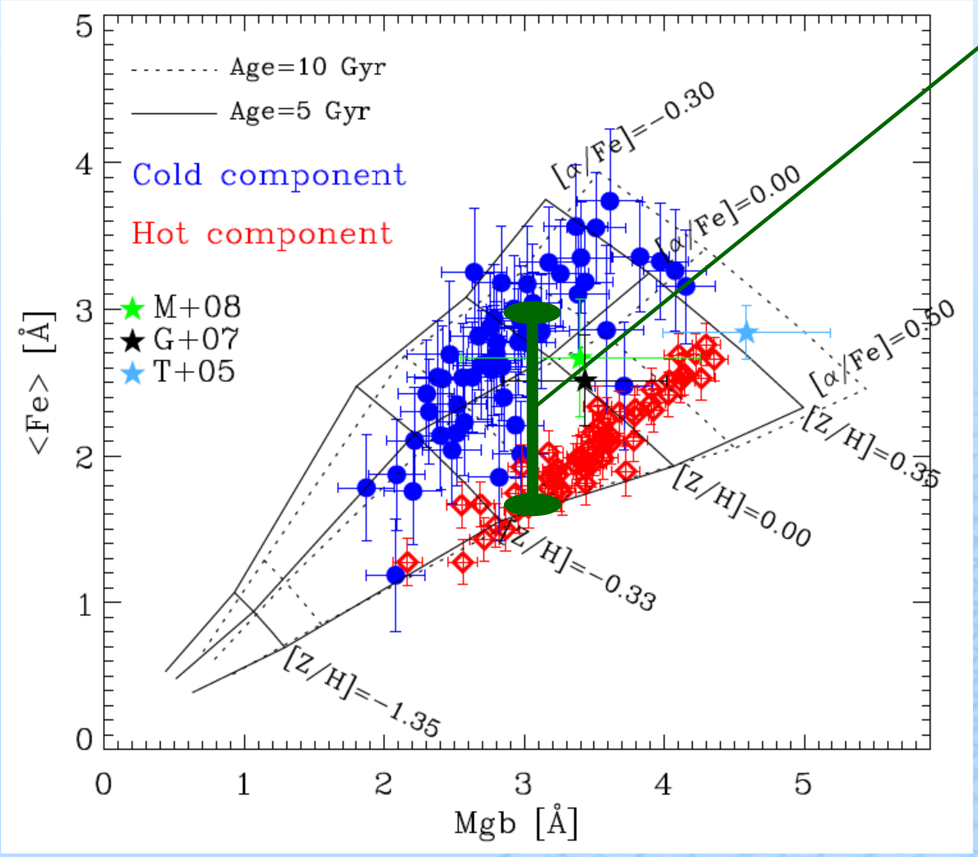


The central regions of the "bulge" have values more consistent with those of the central regions of ETGs (T+05), rather than those of bulges of spirals (G+07, M+08).

→ formation through a major merger?

NGC 7217: spectral decomposition

The kinematics are constrained from the non parametric approach, and used as input in the spectral decomposition



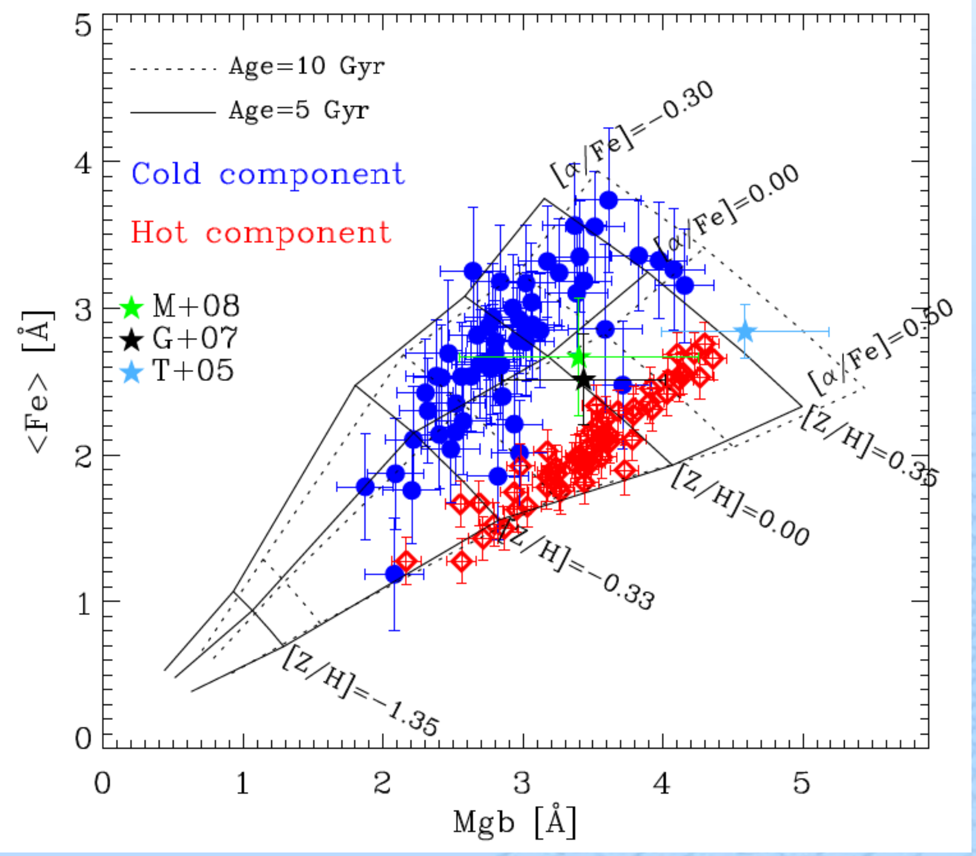
Mgb and <Fe> offset: passive evolution of a single stellar population, which gradually builds up both α-elements and other metals over time.

The formation of the stars in the disk may have restarted at much lower <Fe> than the spheroid
→ accretion of primordial gas

(see Fabricius+2014 for further details)

NGC 7217: Conclusions

The kinematics are constrained from the non parametric approach, and used as input in the spectral decomposition

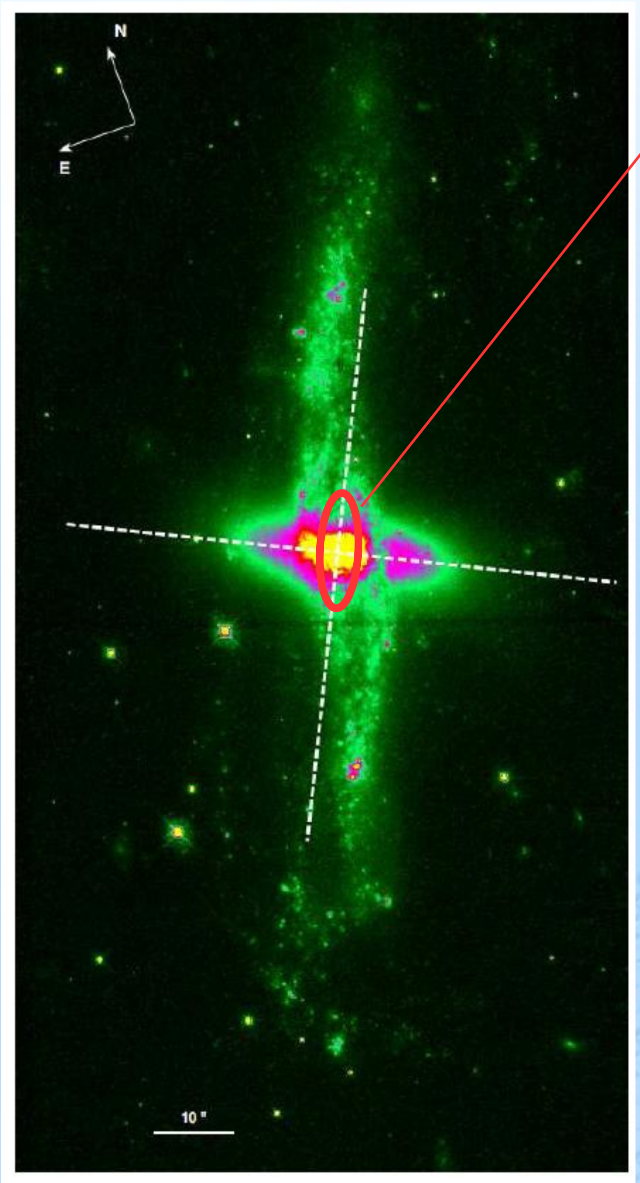


Suggested formation scenario:

The spheroidal component of NGC 7217, formed through a major merger. Properties more similar to those of an elliptical galaxy than to those of the bulges of spirals.

The disk component formed after the merger, primordial gas accretion followed by star formation.

NGC 4650A (Polar Disk galaxy)



Central spheroid and polar disk co-exist

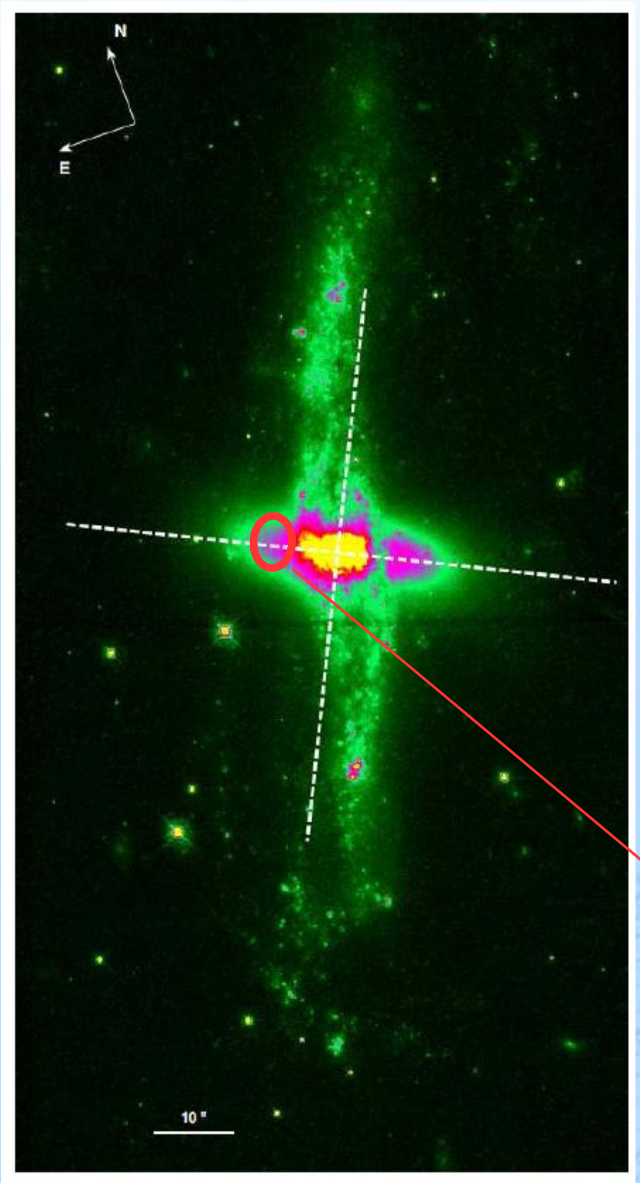
Problems: Short wavelength region, Low kinematic separation--> large errors

Solution:

I. Get the SSP from the spheroid from disk-free reginos

II. Constrain the flux ratio of spheroid and polar disk

NGC 4650A (Polar Disk galaxy)



Problems: Short wavelength region, Low kinematic separation--> large errors

Solution:

I. Get the SSP from the spheroid from disk-free reginos
II. Constrain the flux ratio of spheroid and polar disk

DISK-FREE region, get the spheroid best template from there

SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1-F_1$: mean flux of the second component.

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

Parametric recovery of LOSVD

$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component.

$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1 - F_1$: mean flux of the second component.

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

Parametric recovery of LOSVD

$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component

CONSTRAINED

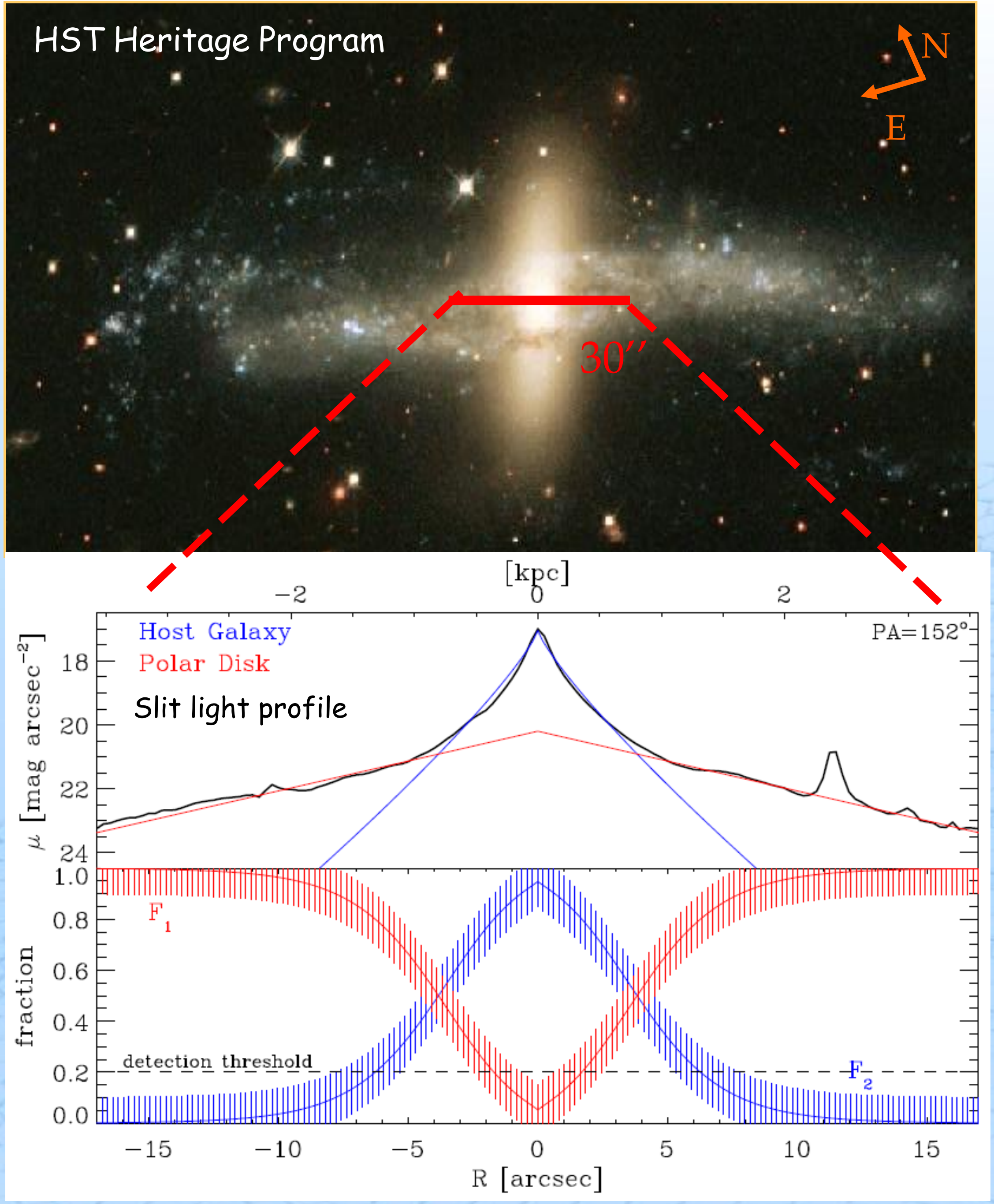
$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

NGC 4650A

Polar disk / spheroid decomposition

Coccato et al. (2014) A&A submitted

Photometric decomposition along the slit profile to constrain F_1 and F_2 in the spectroscopic decomposition.



SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1 - F_1$: mean flux of the second component.

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

Parametric recovery of LOSVD

CONSTRAINED

$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component

$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

SPECTRAL DECOMPOSITION:

PARAMETERS IN THE CODE:

F_1: Mean flux of first component.
$F_2 = 1-F_1$: mean flux of the second component.

CONSTRAINED

V_1, σ_1: kinematics of the first component.
V_2, σ_2: kinematics of the second component.

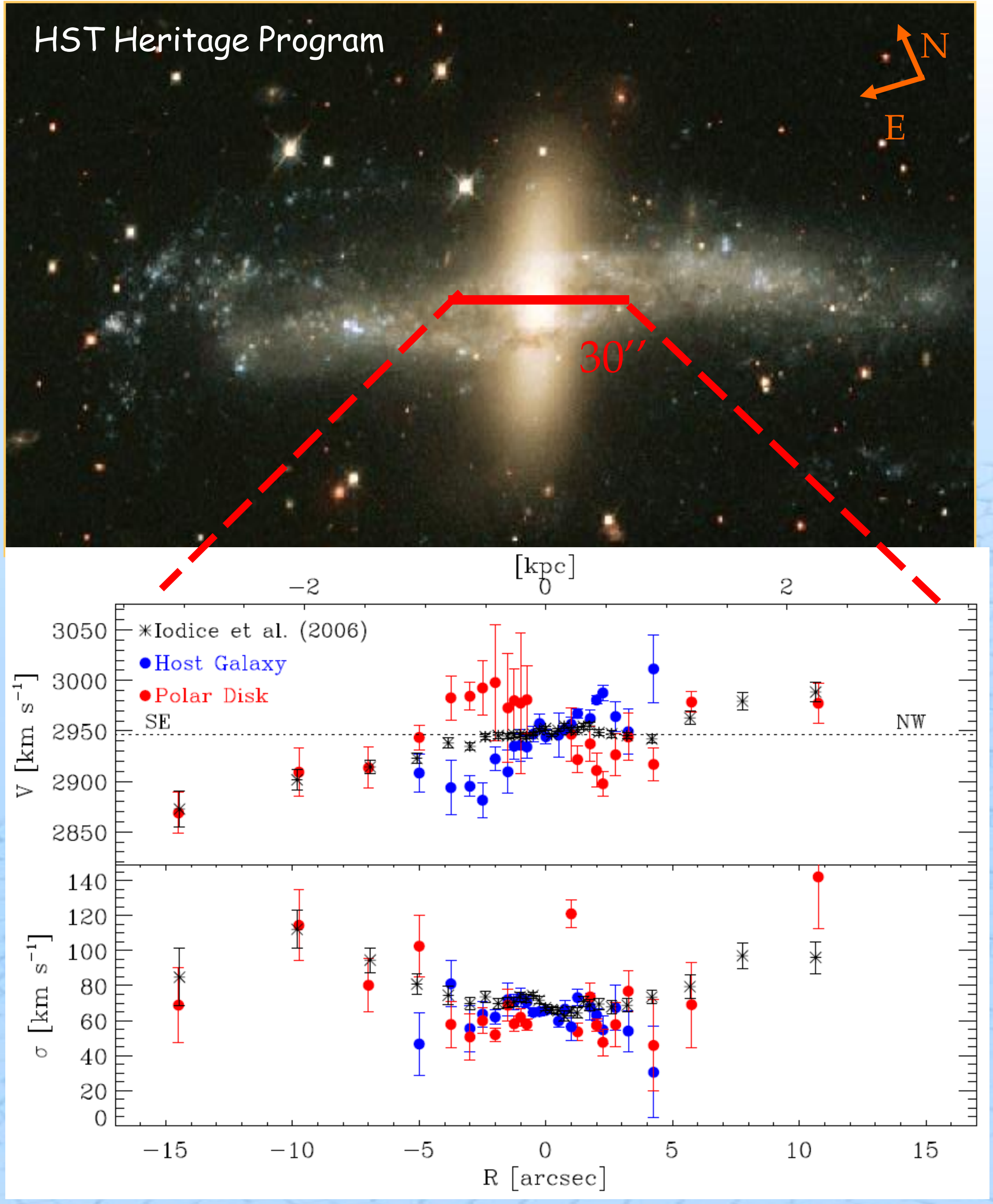
Parametric recovery of LOSVD

$SPC(\lambda)_1$: best fitting linear combination of stellar templates of the first component

CONSTRAINED

$SPC(\lambda)_2$: best fitting linear combination of stellar templates of the second component.

NGC 4650A



Kinematics
Rotation of host galaxy along the minor axis → **non axisymmetric potential.**

Counter-rotation of polar disk → **multiple accretion formation episode.**

Stellar content:
Spheroid: GIII (~50%) and KIII (~35%) plus contamination from young A,O,B stars (~15%). NON GRADIENTS.

Disk: GIII (~45%) and KIII (~35%) plus contamination from young A,O,B stars (~20%).
GRADIENT:
Young star fraction from 10% (R<1.5kpc) to 30% (R>1.5 kpc)
→ outer disk formed later?

SUMMARY 2

The spectral decomposition technique works also in more difficult cases, with small kinematic separation and short wavelength region.

- NGC 7217 (Bulge plus disk)
  - Get the kinematics from an independent method.
    - →Hints for formation mechanism: re-growing of a disk an a merger remnant.

- NGC 4650A (spheroid plus polar disk)
  - Get the spheroid population ($SPC(\lambda)_2$) from disk-free regions.
  - Get F1 and F1 from photometric decomposition of the slit profile.
    - →Counter-rotation of the polar disk, multiple accretion.
    - →Non axisymmetric potential.

SOCRATE

Study Of Counter Rotating gAlaxies with spectral decomposition TEchnique

(an ESO/MPE/Padova collaboration)

Galaxy	Type	Status
IC 719	S0	Katkov et al. 2013 (SAURON+SCORPIO data).
NGC 448	S0	
NGC 3593	S0/a	Coccato et al. 2013 (VIMOS/IFU)
NGC 3608	E2	
NGC 3796	S	
NGC 4138	S0	Observed (Asiago Telescope, long-slit), paper in preparation
NGC 4191	S0	Observed (Virus-W)
NGC 4259	S0	Observed (Virus-W)
NGC 4473	E5	
NGC 4528	S0	
NGC 4550	E7/S0	Johnston et al. 2012 (long-slit); Coccato et al. 2013 (VIMOS/IFU).
NGC 5719	Sab	Coccato et al. 2011 (VIMOS/IFU)
NGC 7710	S0	
PGC 056772	S0/a	

The secondary component associated to the ionized gas is the youngest in all the 5 studied galaxies.