IMPRINTS OF GAS ACCRETION IN MULTI-SPIN GALAXIES.

Lodovico Coccato (ESO)

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

OUTLINE OF THE TALK

- Panoramic of galaxies with multi-spin components. Focus on counter-rotation and Polar-rings.
- How gas accretion and multi-spin galaxies are connected? Some mechanisms.
- How can we study the properties of the individual components?

MULTI-SPIN GALAXIES

Galaxies that contain two or more components (stars and/or gas) that have remarkably different kinematics with respect to each other ("kinematically distinct" / "kinematically decoupled" components).

Several types, depending on the nature, morphology, and kinematic properties of the individual components.

MULTI-SPIN GALAXIES

✓**Counter-rotations**. Stars rotating along opposite direction with respect to other stars and/or gas. 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).

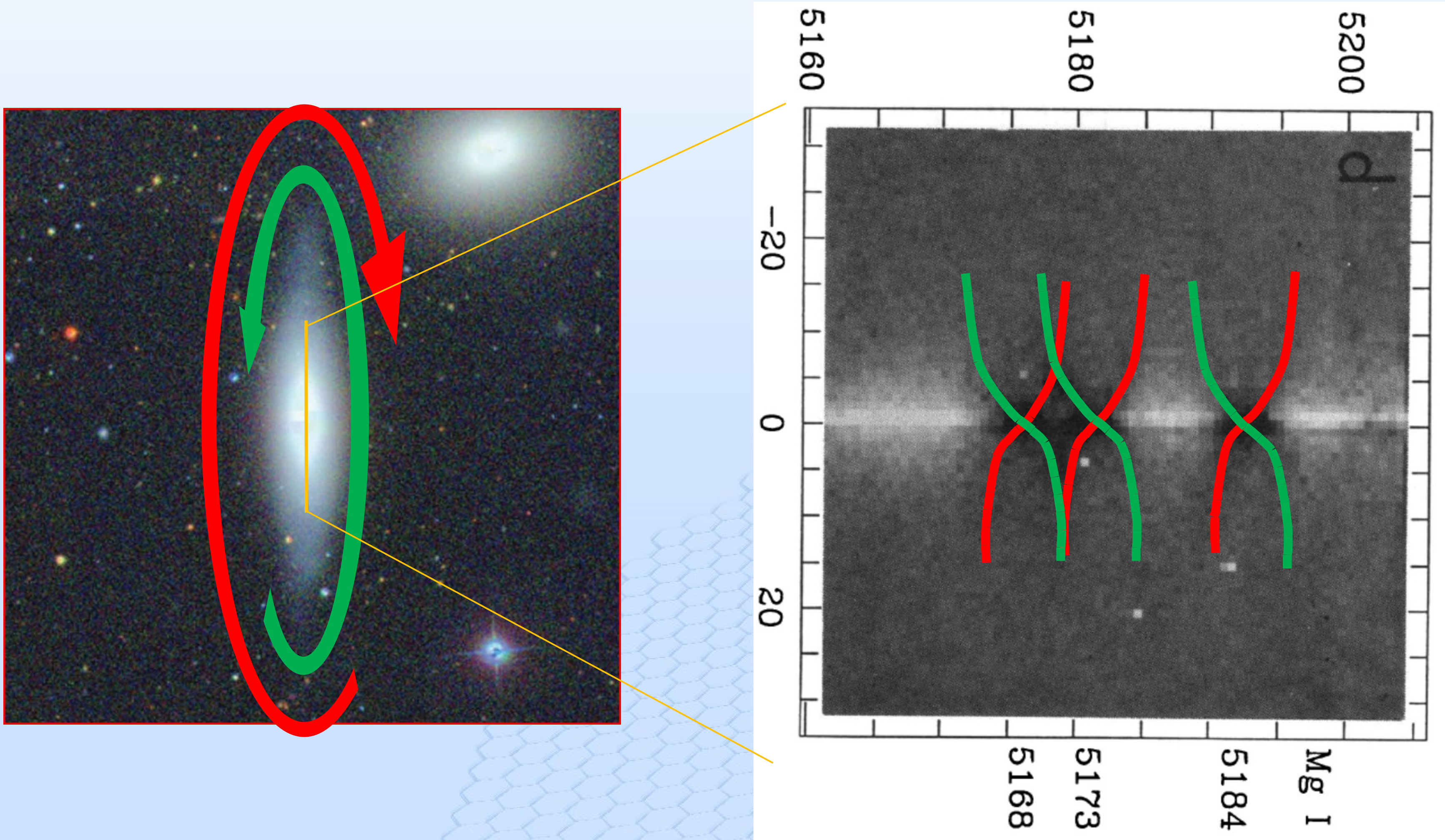
→ *See Corsini's talk.*

✓**Structural components**. Nuclear stellar disks, Bulge/disk (can have same spin direction, but different rotation amplitude).

✓**Misaligned/Orthogonal structures**. Warps, Polar Ring/Disk galaxies (e.g. NGC 4650A).

MULTI-SPIN GALAXIES

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

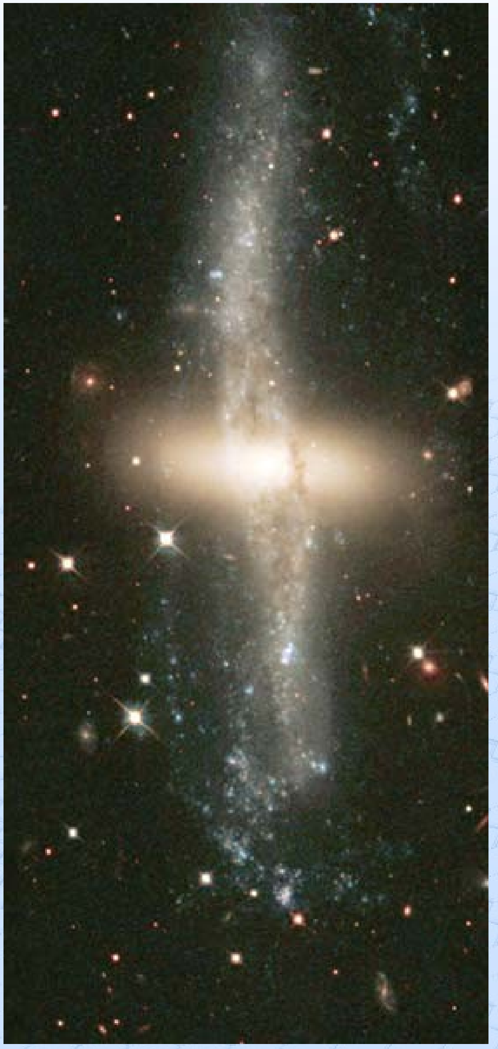


Rubin et al. (1992)

MULTI-SPIN SYSTEMS IN GALAXIES

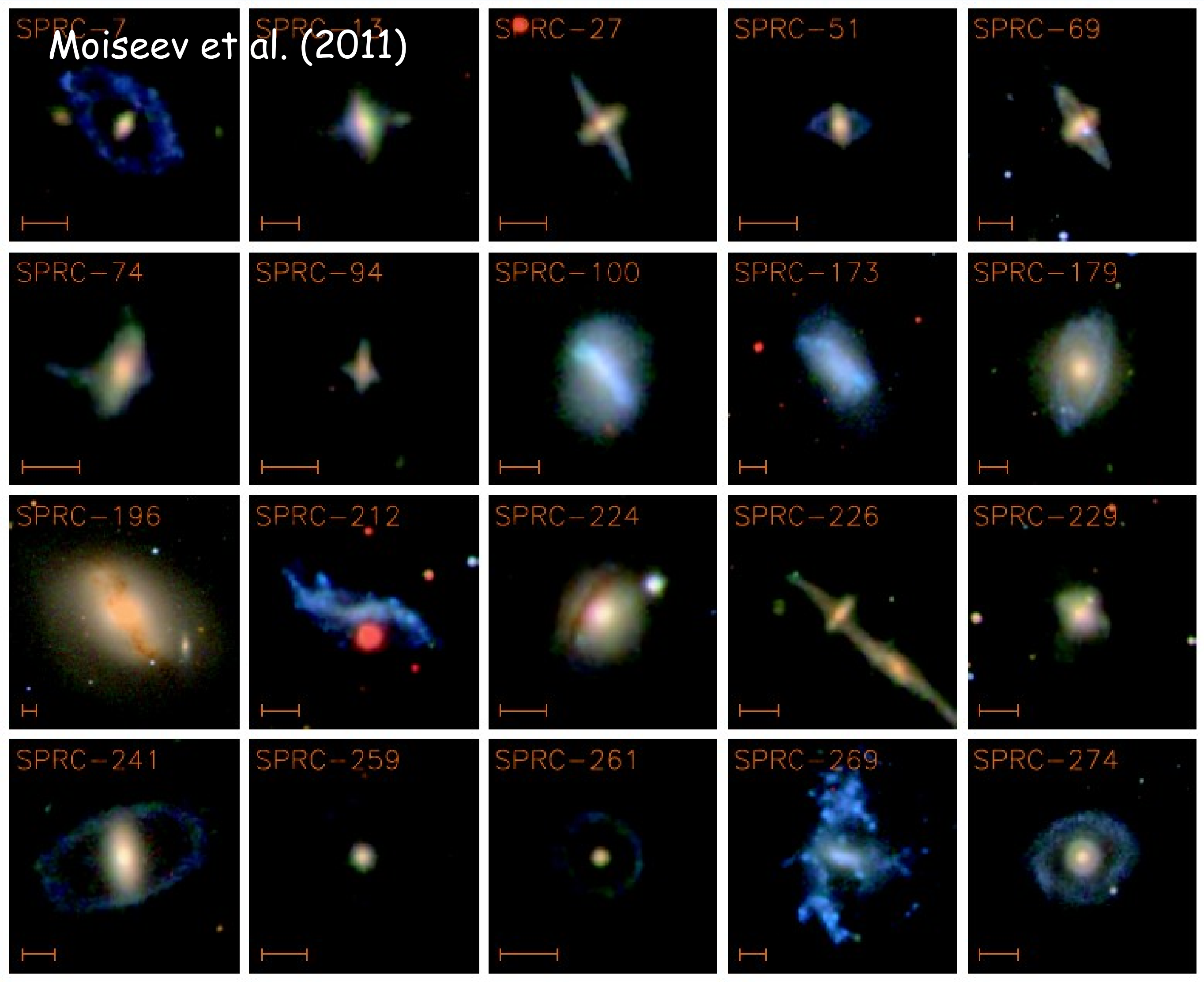
Misaligned/Orthogonal structures

Warp: UGC 3697 (Integral galaxy)



Polar disk: NGC 4650A

MULTI-SPIN SYSTEMS IN GALAXIES

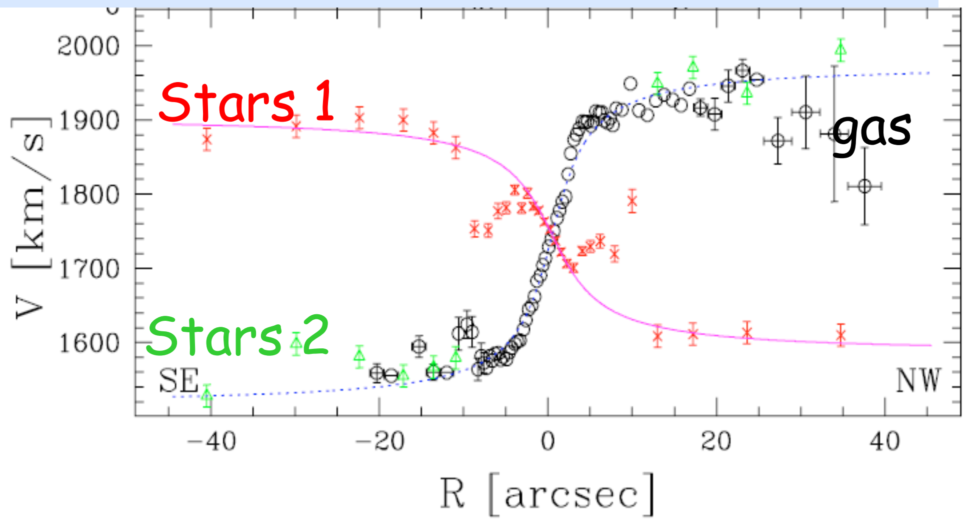


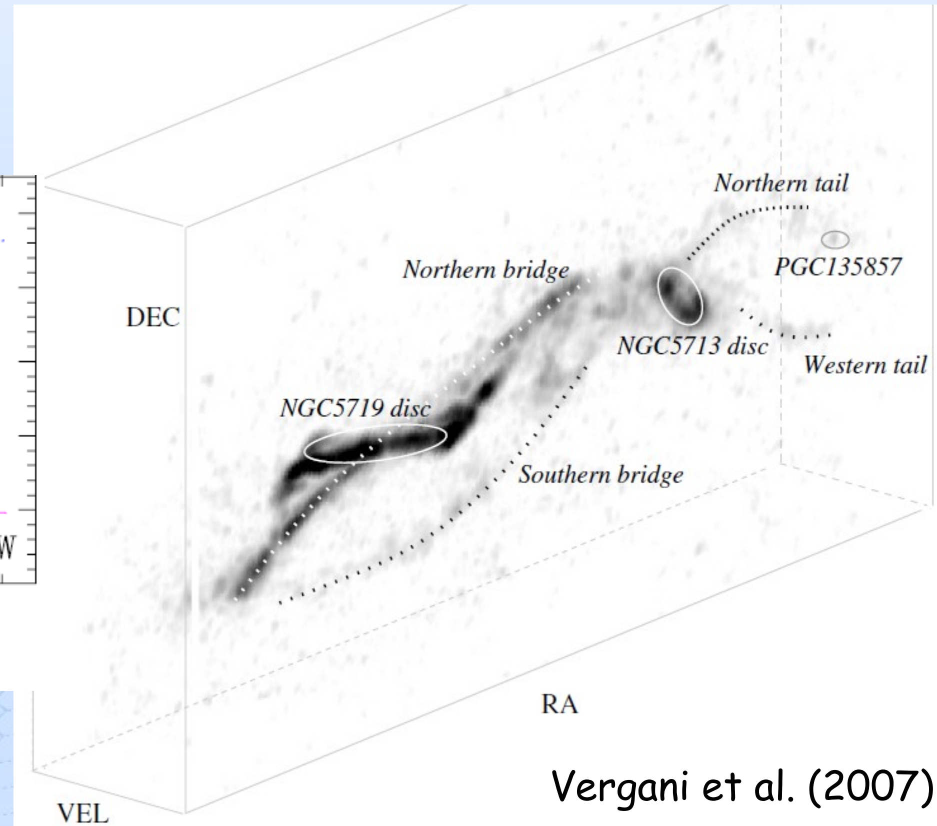
Polar ring as kinematic probe to trace the shap of dark matter halo:

The flattening of the DM halo is different in different objects. It could indicate multiple formation scenarios for PRGs (Moiseev et al. 2014).

GAS AND MULTI-SPIN GALAXIES

Observational indication of the connection between gas accretion and multi-spin galaxies. NGC 5719: on-going gas accretion on a counter-rotating galaxy.





Vergani et al. (2007)

GAS AND MULTI-SPIN GALAXIES
Counter-rotating gas/stellar disks

Gas infall

Thakar & Ryden (1996) explored 3 mechanisms:

- Episodic gas infall.
- Continuous gas infall.
- Merger with gas-rich dwarf

- Both gas infall mechanisms work well and produce substantial counter-rotating gas disk without upsetting the stability of the original galaxy. Rate of gas infall must be small to preclude heating. Typically, the scale of the counter-rotating disk is smaller than that of the pre-existing disk. Radial profile of counter-rotating disk sometimes is non exponential. Counter-rotating gas disk forms stars.

- Merger with dwarf rich not efficient: only very small galaxies will prevent disk heating → need for multiple-mergers of small systems on similar orbit (stream) → possible, but requires long time.

GAS AND MULTI-SPIN GALAXIES
Counter-rotating gas/stellar disks

Gas-rich major mergers (1/2)

- Barnes & Hernquist (1991); Hernquist & Barnes (1991); Barnes (1992). The “tidal trauma” drives the gas to the center of the remnant: very efficient in forming ellipticals with kinematically decoupled cores; but not efficient in forming large scale counter-rotating stellar disks like NGC 4550.

- Puerari and Pfenniger (2001). Mergers between progenitors with comparable masses (halo + disk). Co-planar and anti-parallel configuration minimize the disk heating. Parabolic orbit encounter is more efficient (the two disk have larger velocity difference) than circular orbit encounter. If the gas is in the prograde galaxy, a large amount is expelled in the process. If the gas is in the retrograde galaxy, a large fraction remains in the remnant. Very efficient in forming large scale counter-rotating stellar disks .

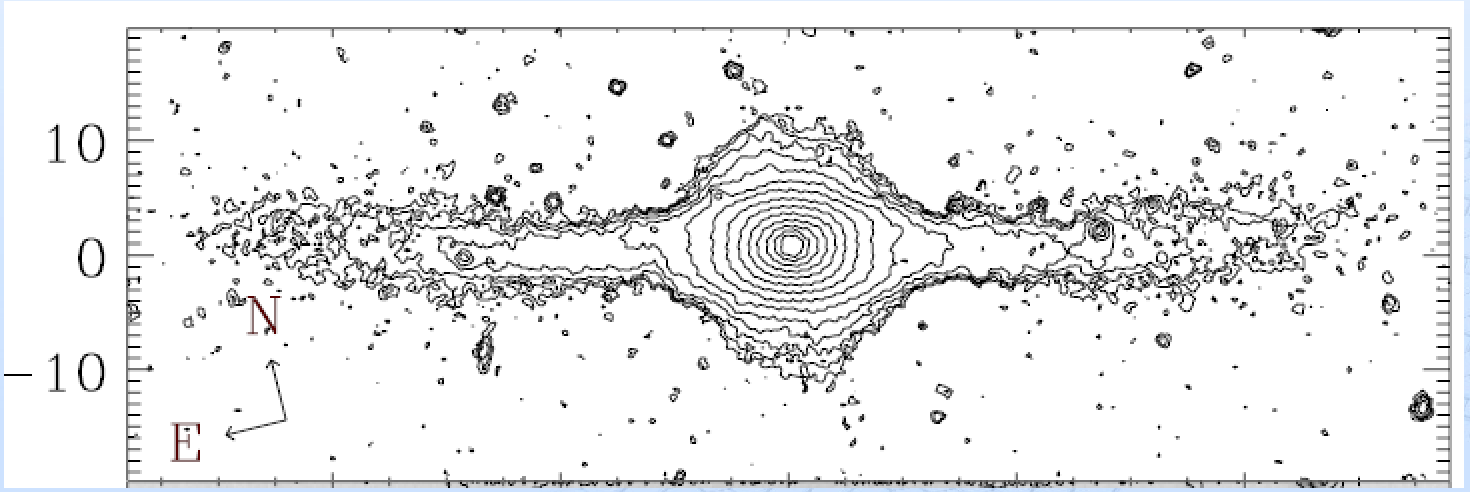
GAS AND MULTI-SPIN GALAXIES
Counter-rotating gas/stellar disks

Gas rich major merges (2/2)

- Crocker et al (2009). Successfully simulated the formation of NGC 4550 and the different thickness of its two counter-rotating disks.

- Algorry et al. (2014). Major mergers do not play significant role in the formation of massive counter-rotating disks; gas accretion along filaments (followed by star formation) is more efficient.

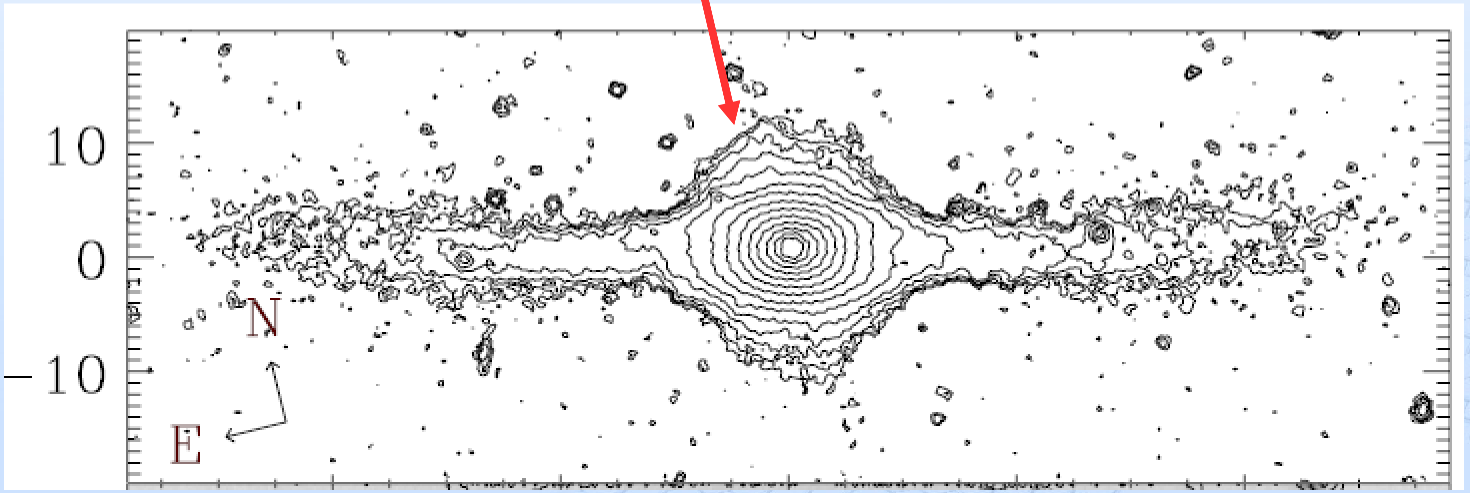
GAS AND MULTI-SPIN GALAXIES
Orthogonal components



IC 5181 (Pizzella et al. 2014)

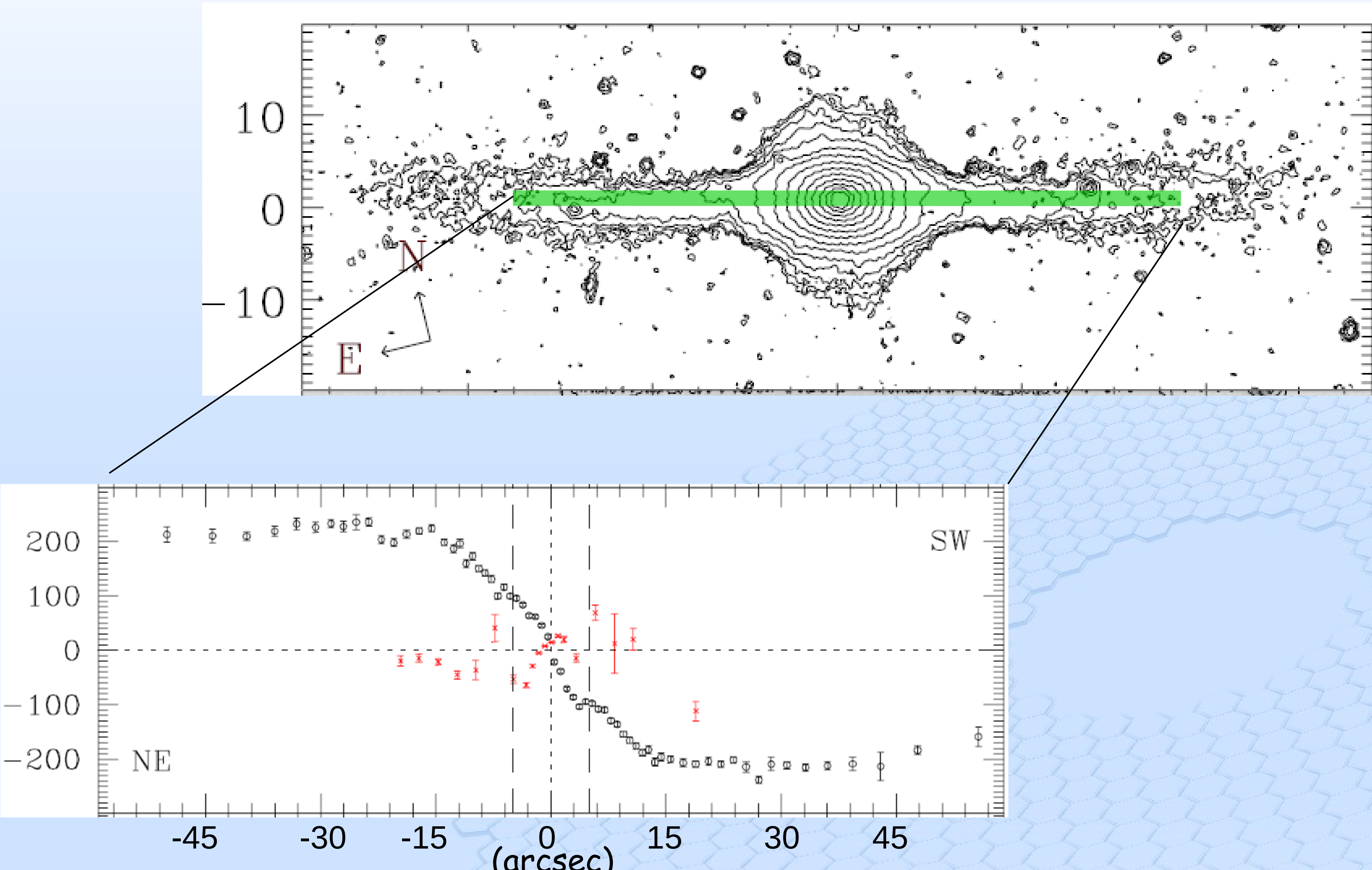
GAS AND MULTI-SPIN GALAXIES
Orthogonal components

Gas accretion along the minor axis

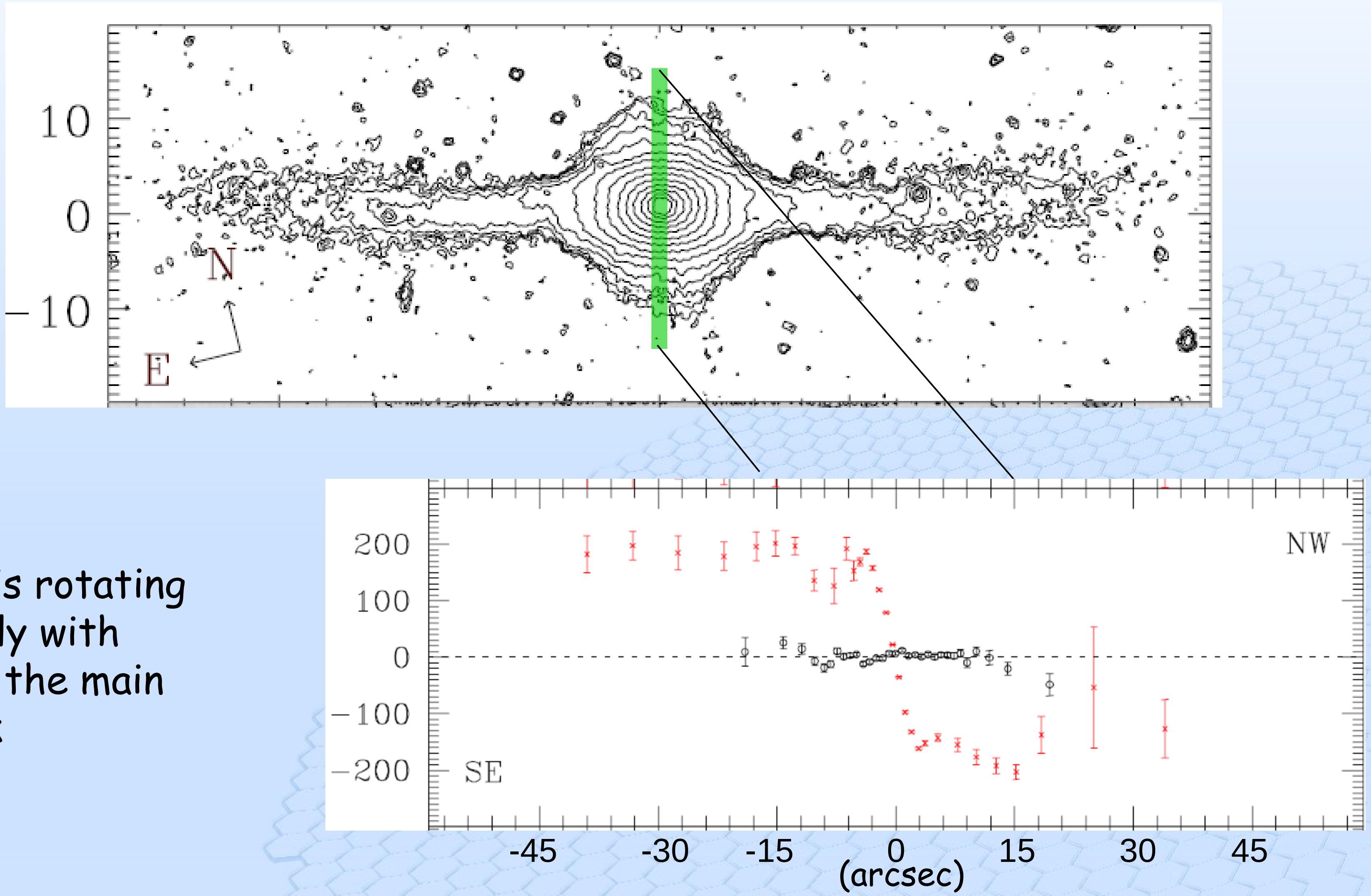


IC 5181 (Pizzella et al. 2014)

GAS AND MULTI-SPIN GALAXIES
Orthogonal components

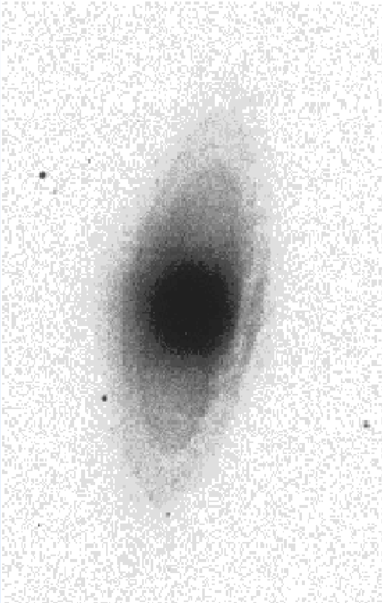


GAS AND MULTI-SPIN GALAXIES
Orthogonal components

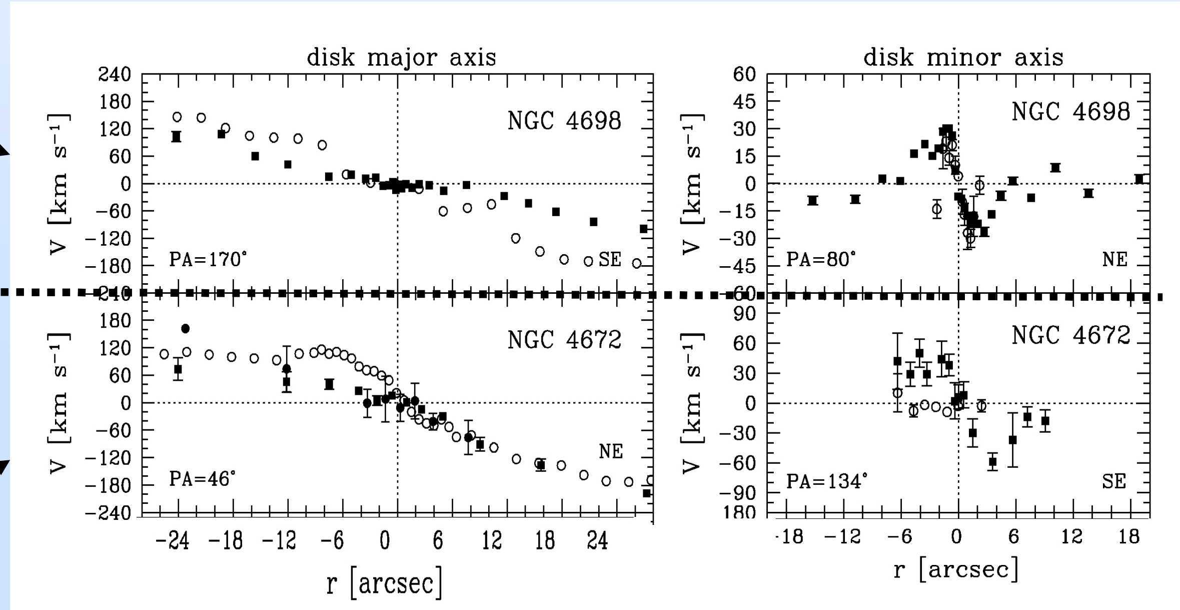


Gas (only) is rotating orthogonally with respect to the main galaxy disk

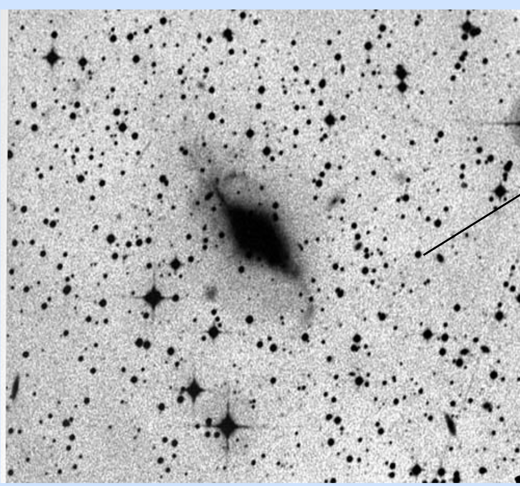
GAS AND MULTI-SPIN GALAXIES
Orthogonal components



Gas starts to form stars: NGC 4698



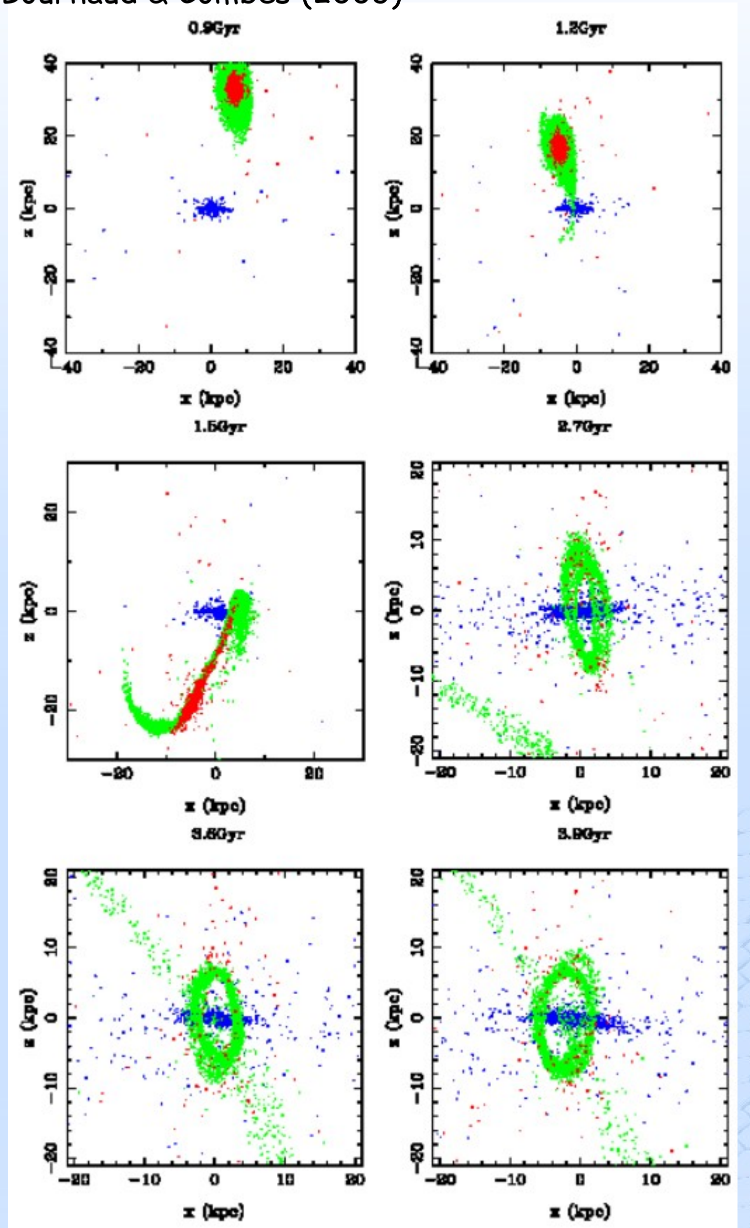
Bertola & Corsini (1999)



Only stars are left: NGC 4672

GAS AND MULTI-SPIN GALAXIES

Bournaud & Combes (2003)



Orthogonal components

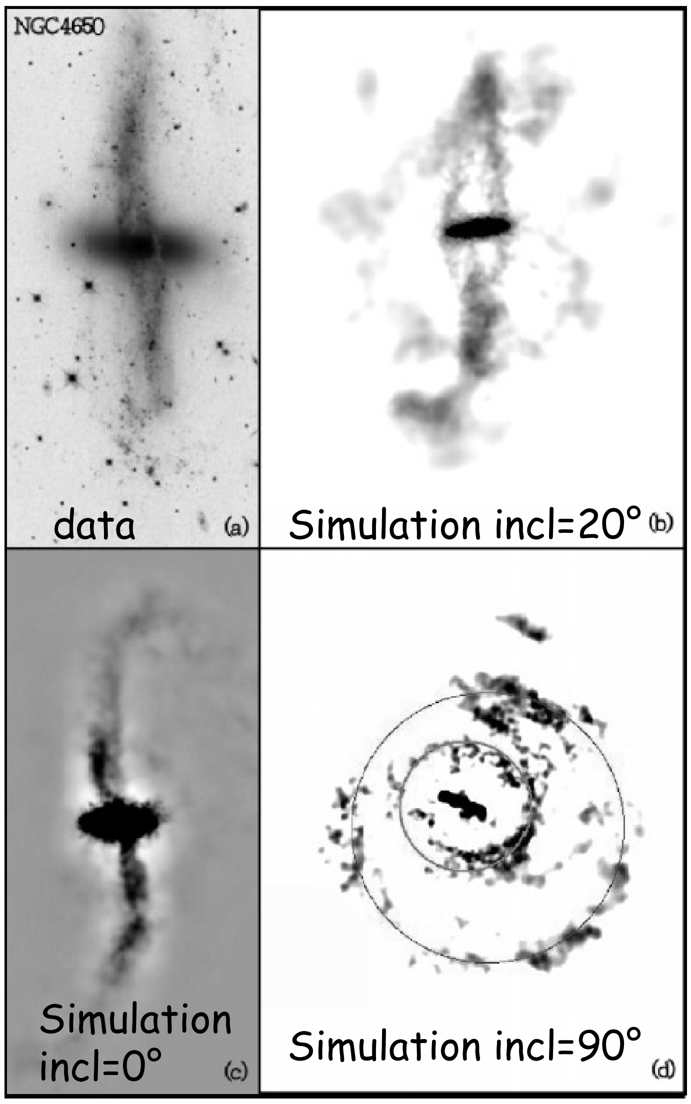
Formation of Polar Rings via accretion of gas/stars captured during an encounter (e.g., Bournaud & Combes 2003).

Fundamental parameters in the encounter:

- Relative velocity between the 2 galaxies.
- Inclination of the orbits and the equatorial planes.
- Minimum distance in the encounter (remember: this is not a merging event).

Stability: from few Gyr (highly inclined disks) to 10 Gyr.

GAS AND MULTI-SPIN GALAXIES
Orthogonal components

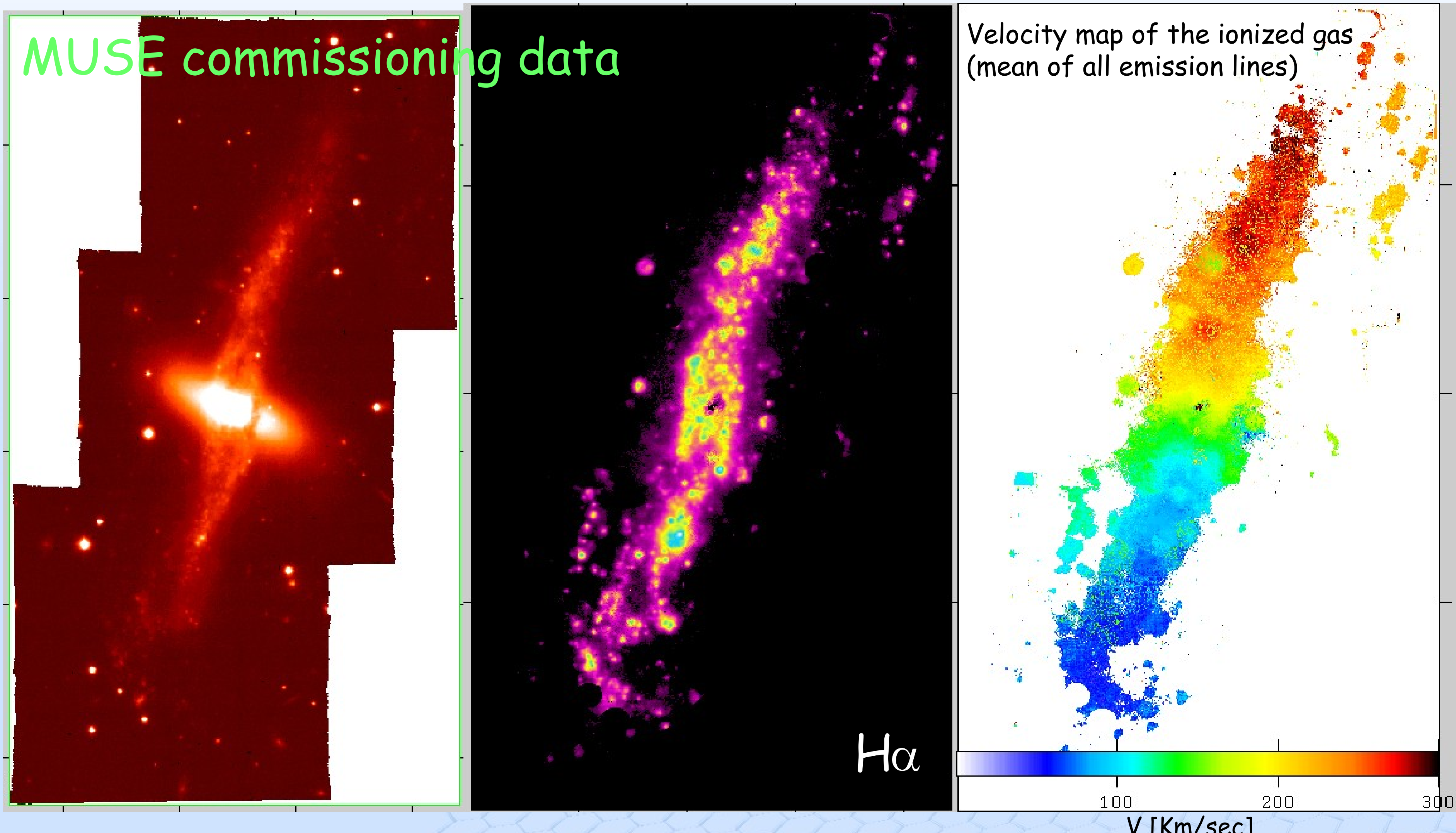


Formation of Polar Rings via accretion of pristine cold gas infalling along mega-parsec scale filaments (e.g. Macciò et al. 2006).
Pristine gas implies low metal content in the newly formed stars.

Main difference with NGC 4550A:
Simulations: 2 rings
Observations: NGC 4650 seems to host a polar DISK...

A polar ring can evolve into a polar disk (Mapelli et al. 2008)

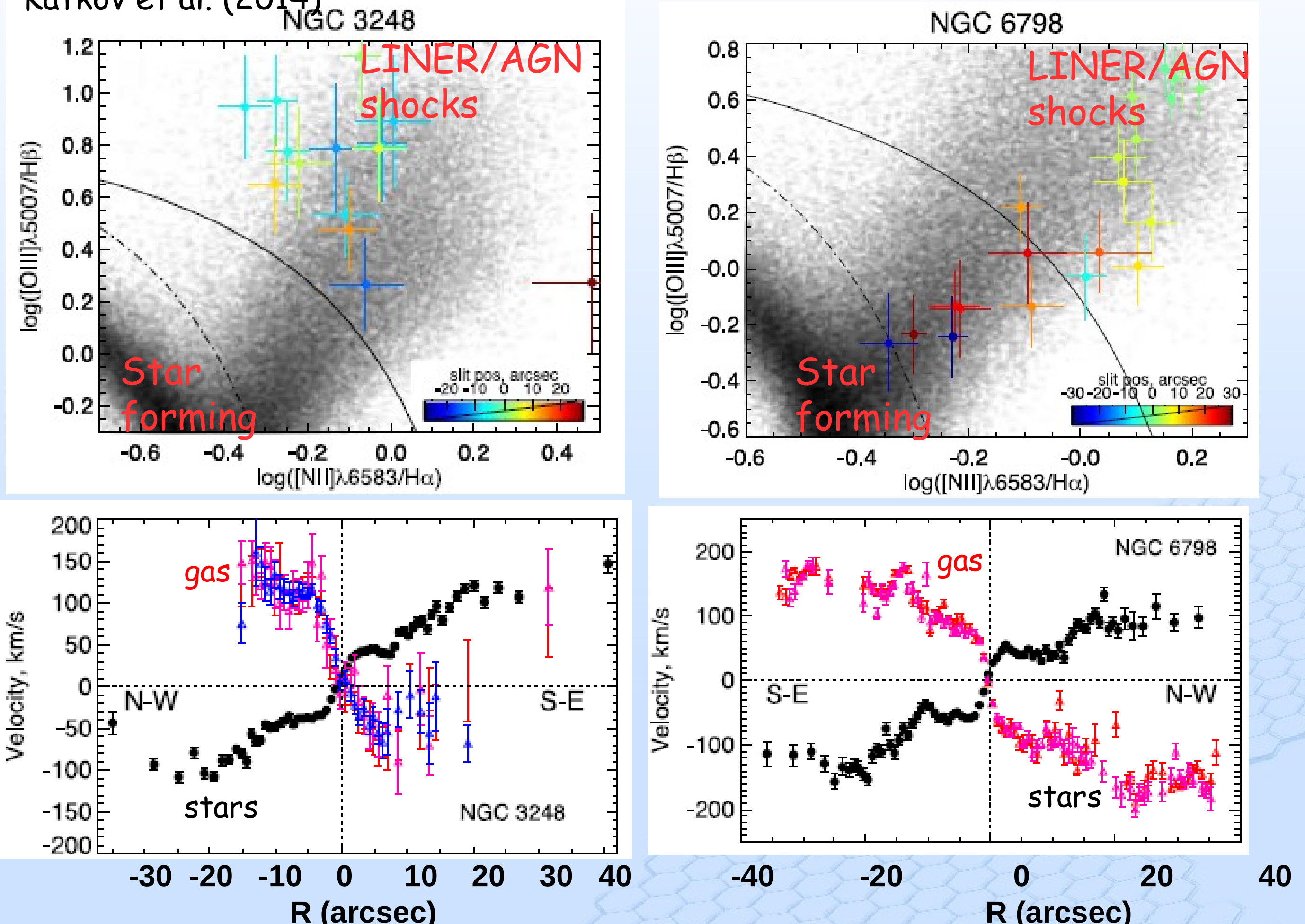
GAS AND MULTI-SPIN GALAXIES
Orthogonal components



...stay tuned for NGC 4650A: MUSE insights are coming (Iodice et al. 2015, submitted)

Information from the gas metallicity (counter-rotations)

Katkov et al. (2014)



Sample of 12 isolated S0,

- 7 with extended gas disk
- 5 gas/star counter-rotations

Gas on plane close to the stellar disk → excitation via SF. Smooth accretion in the plane of the stellar disk, with no shocks.

Gas on inclined/polar plane w.r.t. the stellar disk → excitation via shocks (lines/agn regime in BPT diagrams). Gas gets shocked when crossing the stellar disk.

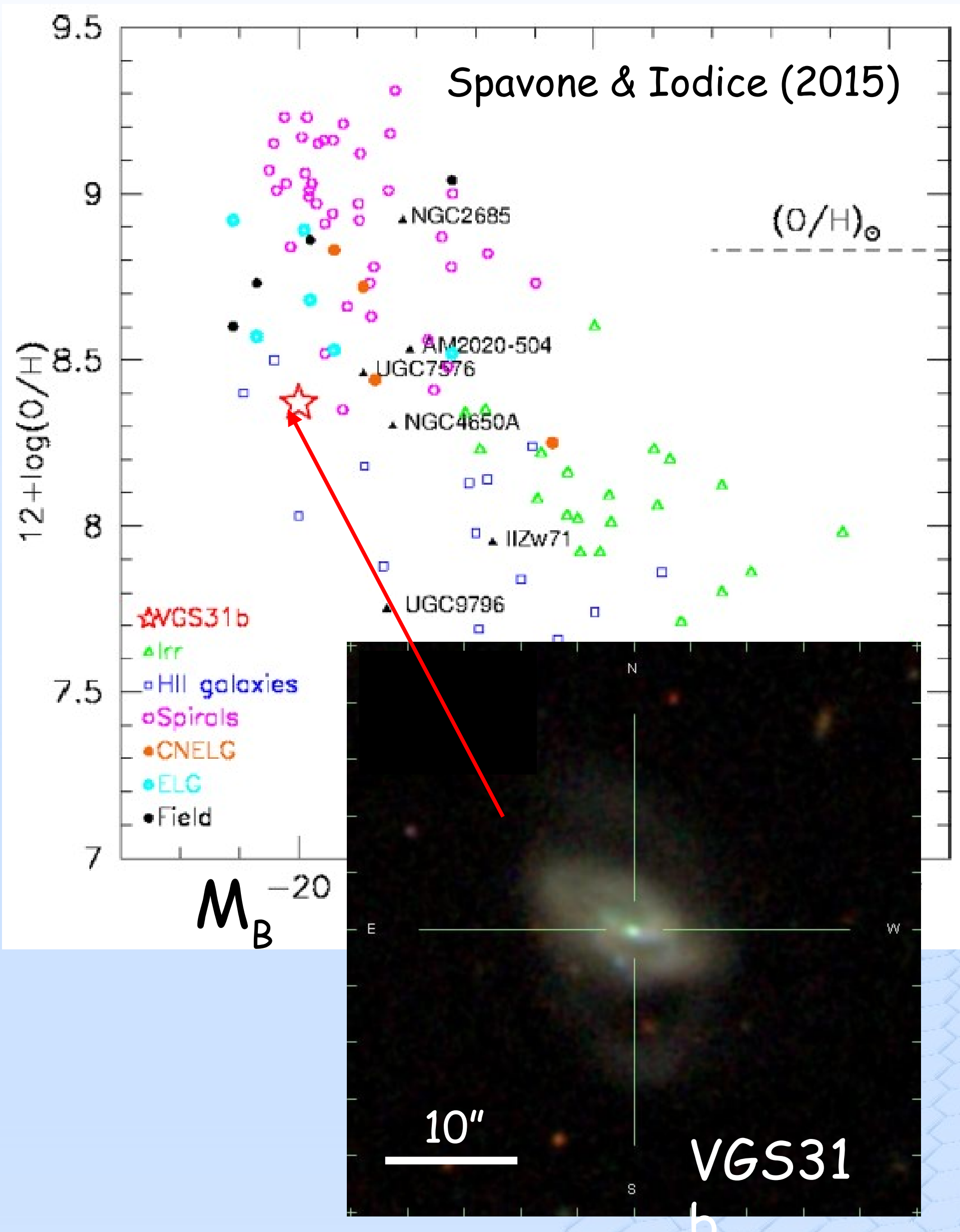
In galaxies with gas/star counter-rotation, there is a correlation between

→ complex structure of the gas LOSVD (suggesting warps and inclined plane) and excitation via shocks

→ regular structure of the gas LOSVD (suggesting gas in the same plane of the stars) and excitation via Star Formation

→ *but see O. Silchenko's talk for the complete picture*

Information from the gas metallicity (polar-rings)



Cold accretion via cosmic filaments (e.g., Macciò et al. 2006):

✓Gas Metallicity is lower than that of spirals of the same luminosity

✓Metallicity derived by SFR is higher that the metallicity derived via chemical abundances

SFR = 0.02 $M_{\odot}$ yr^{-1} → 0.2 $Z_{\odot}$ <Z<0.5 $Z_{\odot}$
Z_lines = 0.3 $Z_{\odot}$
(depends a bit on the used models)

Accretion via galaxy encounter (e.g. Bernaud & Combes 2003)

Stellar mass of the ring:
Needed: ~10^{10} $M_{\odot}$
·Measured (integrated colors): ~10^{8} $M_{\odot}$

Favored scenario for NGC VSG31b:
→ cold accretion

STEP FORWARDS

Aims:

1. Understand the formation mechanisms of multi-spin galaxies
2. Understand the links between the gas and the stellar components

Strategy: Study the properties of the individual structural components in a multi-spin galaxy. For example:

1. Measure their kinematics and light distributions.
2. Date their formation.
3. Measure their metallicity.
4. Correlations with the gas distribution.

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

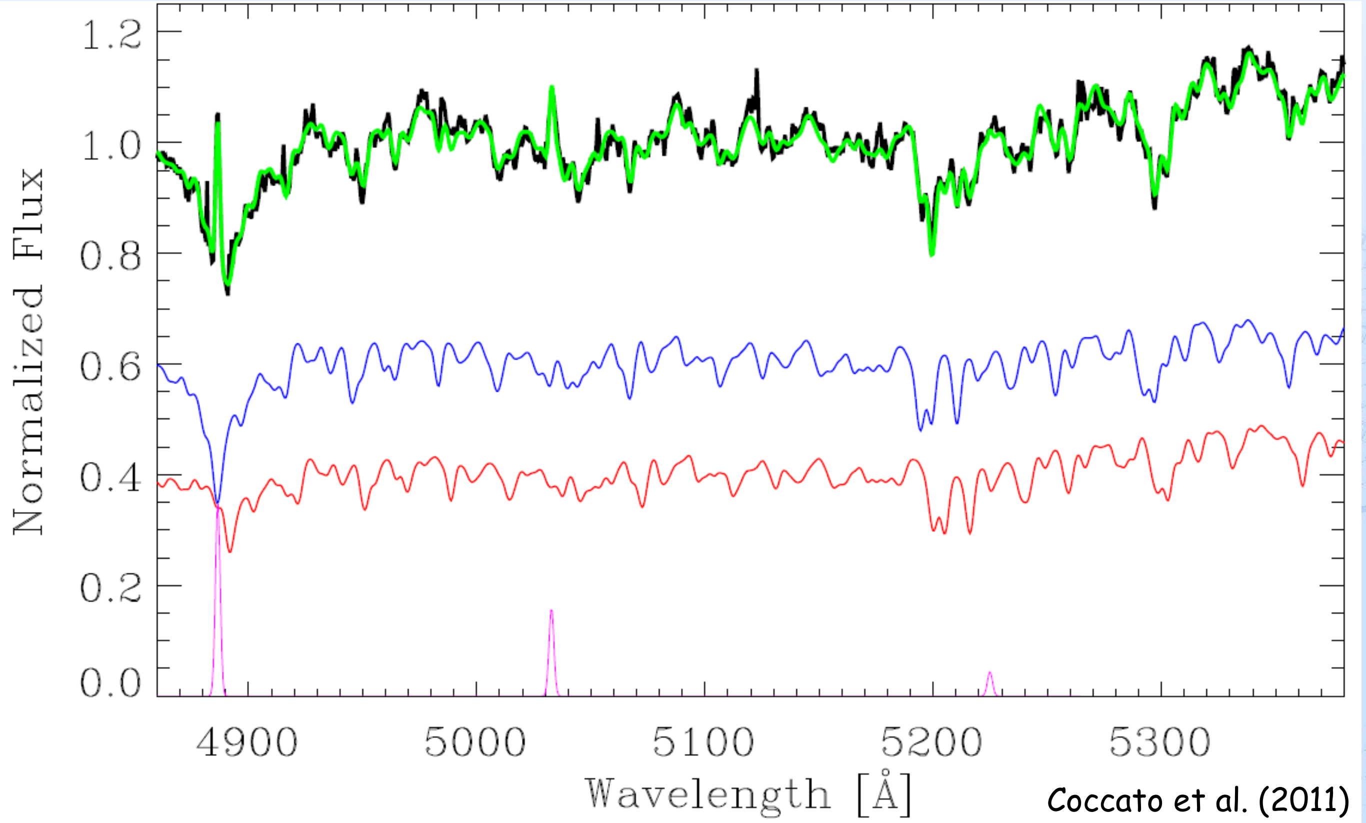
Challenge: Separate the two components from the observed spectrum and measure them independently.

SOLUTION ⟶

SPECTRAL DECOMPOSITION:

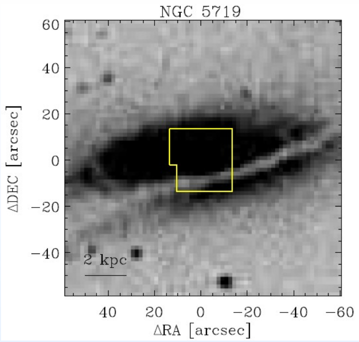
Disentangling kinematics *and* stellar populations of two components

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

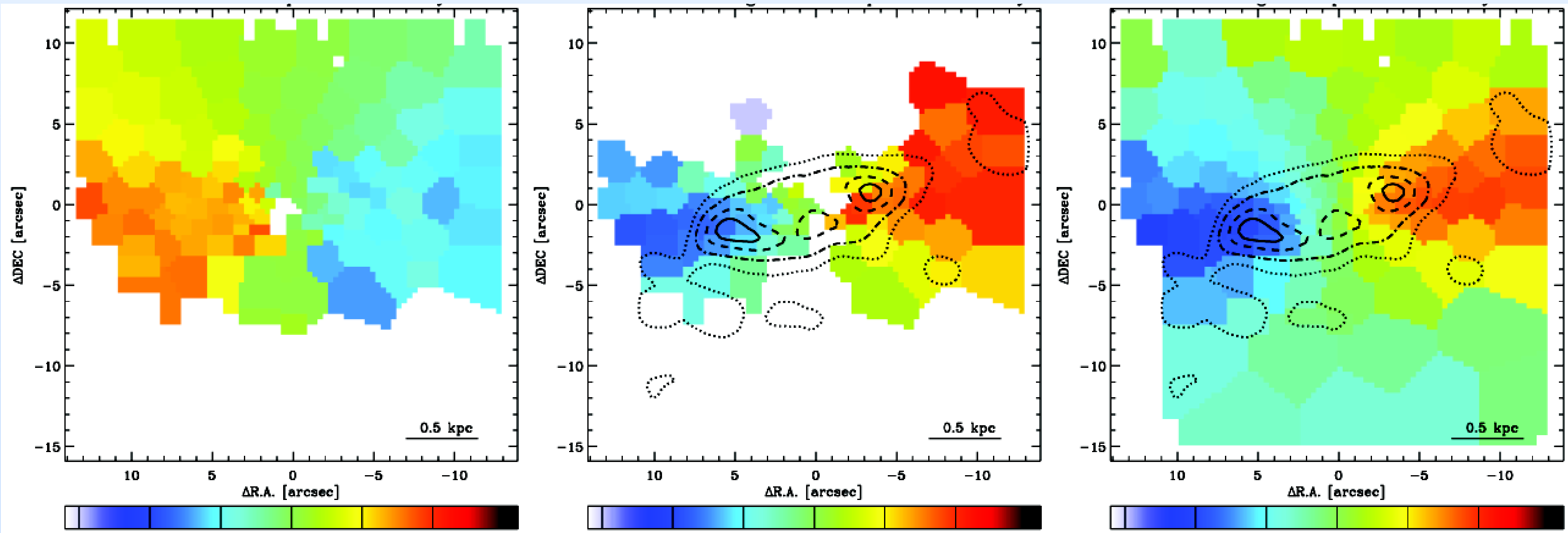
Differences in the position of absorption line features and in the Hβ equivalent widths between the two stellar components (→different kinematics and stellar populations).



NGC 5719

Coccato et al. (2011)

Main component | Secondary component | Ionized gas



-300 -200 -100 0 100 200 300
V [km/sec]

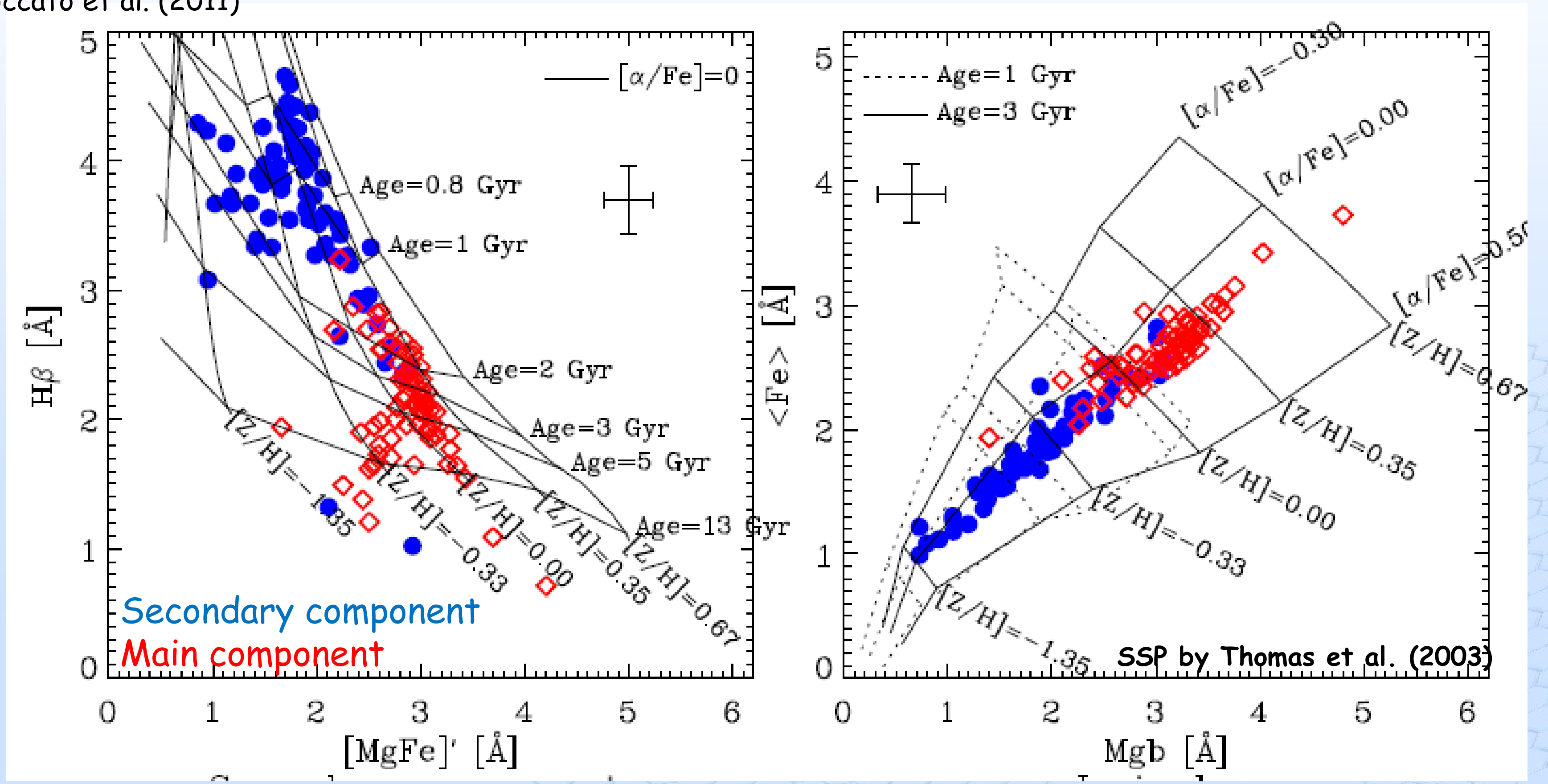
-300 -200 -100 0 100 200 300
V [km/sec]

-300 -200 -100 0 100 200 300
V [km/sec]

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.

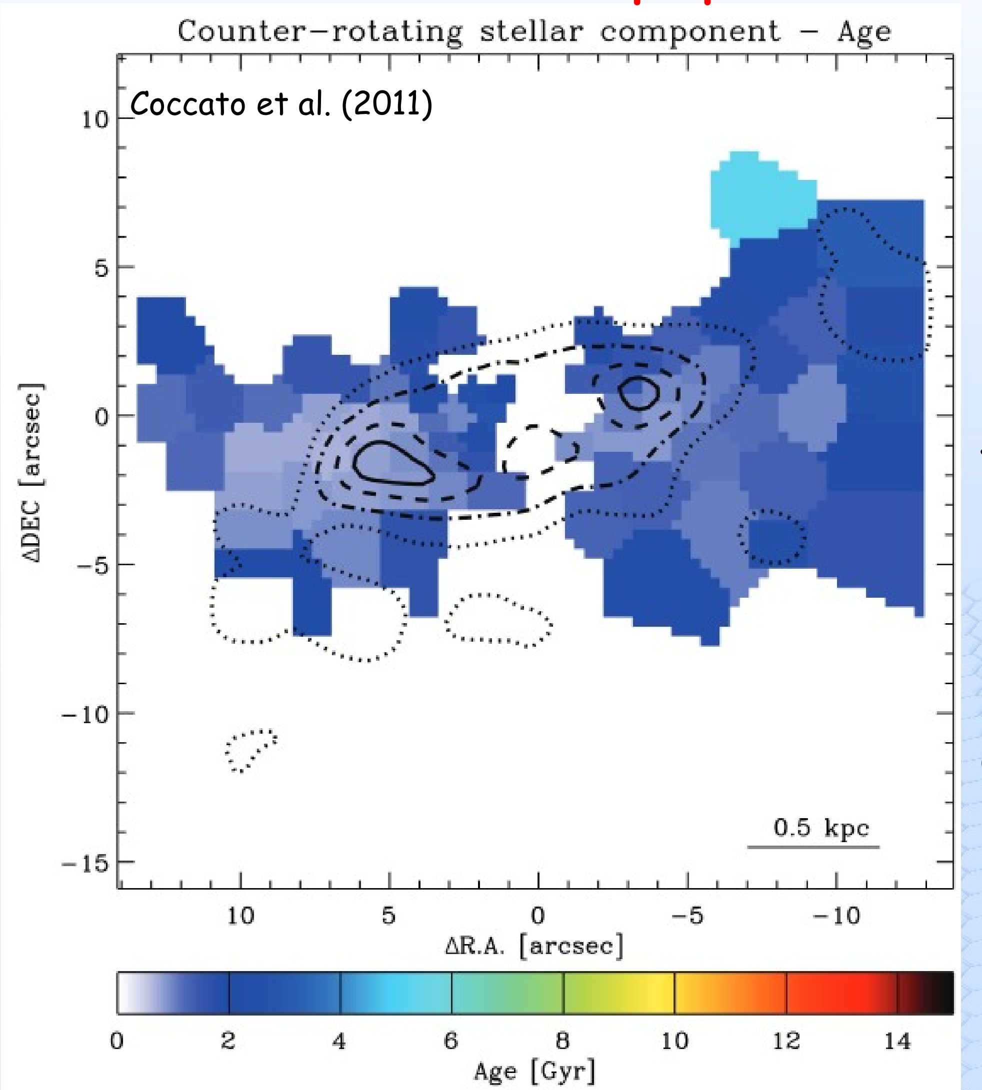
NGC 5719 – Stellar populations of the 2 components

Coccato et al. (2011)



1. The line strength indices of the two components are well separated in the diagnostic plots, indicating different stellar population properties.
2. The secondary component, which is kinematically associated to the gas component, is younger and less metal rich than the main component.

NGC 5719 – Stellar populations of the 2 components

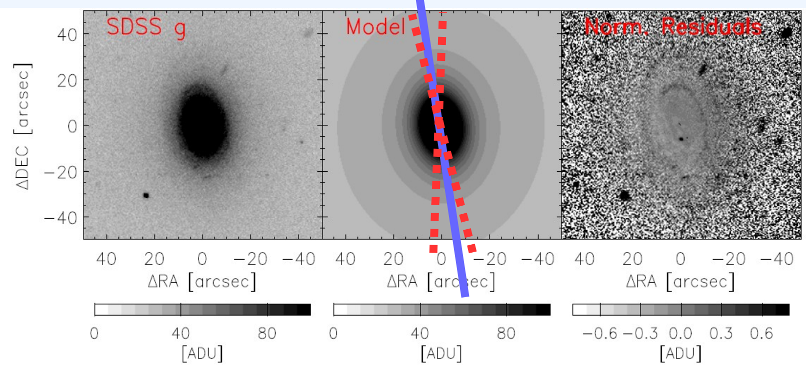


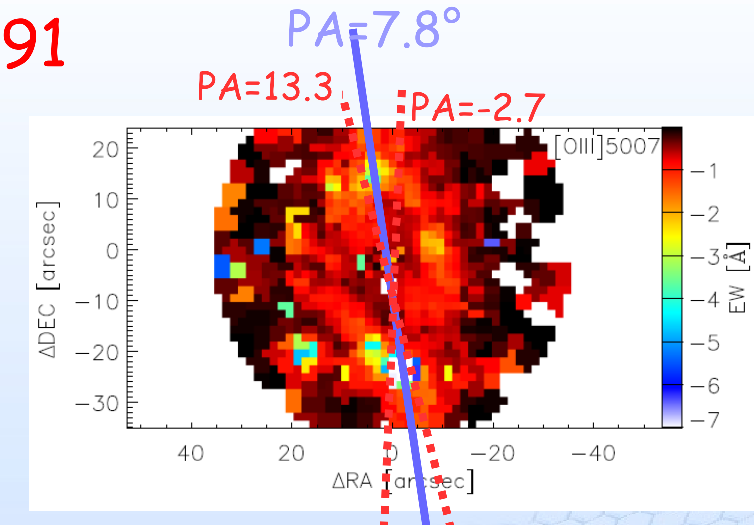
Spatial distribution of Hβ: disk with blobs / ring-like structure.

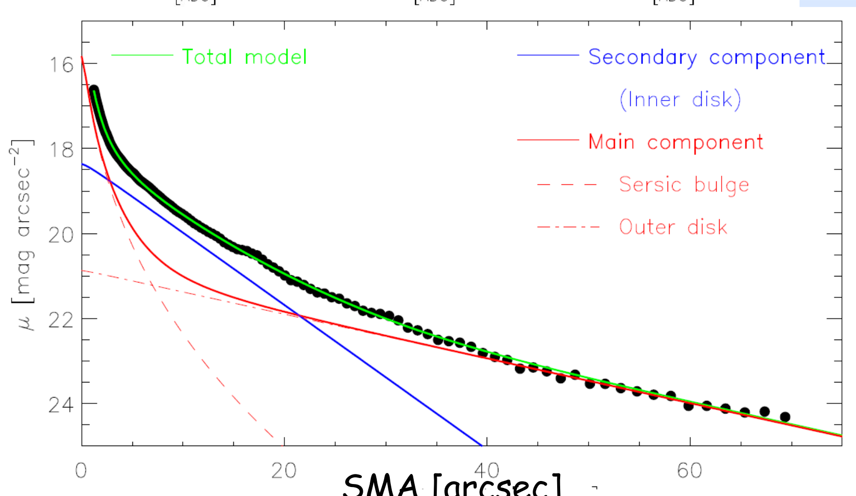
The peaks of Hβ emission nicely correlates with the location of the youngest stars of the secondary component.

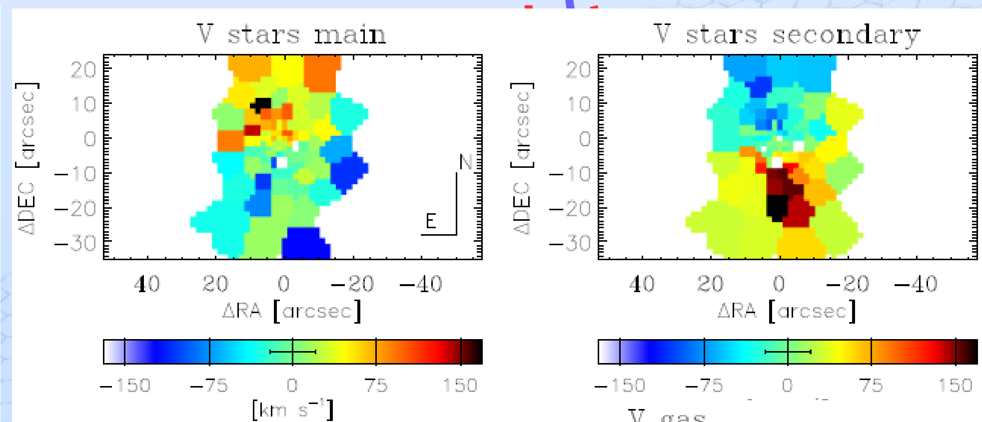
Another example: NGC 4191

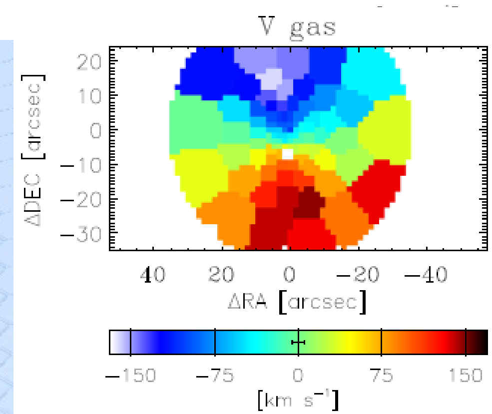
Coccato et al. (2015, submitted)











Main: 10 ± 3 Gyr; 6.2±2.3 10^{10} $M_{\odot}$; Z/H~solar

Secondary: 4 ± 4 Gyr; 8.3±7.7 10^{8} $M_{\odot}$; Z/H ~ solar

Gas is best aligned with the secondary component

SUMMARY

1. Gas accretion is a fundamental ingredient for the formation of multi-spin galaxies.
   - Most likely there is not an unique formation process.

2. The properties of the gas in a multi-spin galaxy gives us clues to the accretion details.
   - ✓ Accretion on the same plane of the stars vs on a plane orthogonal to that of the stars.
   - ✓ Cold inflow from large filaments vs accretion from satellites.

3. In counter-rotating galaxies, the ionized gas component is associated with the youngest and less massive component. Metal content is usually different → gas accretion followed by star formation.

4. Importance of the spectral-decomposition in:
   - ✓ Studying the properties of the individual kinematic components in multi-spin systems: age, metallicity, light distribution.
   - ✓ Identifying the links with the ionized gas component.

Results: global properties 1/2

	Age [Gyr]	[Z/H]	[α/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 4138			
Main	6.3 ± 3.6	-0.24 ± 0.46	0.24 ± 0.19
Secondary	1.1 ± 0.3	-0.04 ± 0.27	0.08 ± 0.21
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 ± 0.5	-0.30 ± 0.02	0.14 ± 0.02

Secondary [illegible] nized gas. Younger, le[illegible] metal and α-elements content. *Supporting the gas accretion + star formation scenario.*

But more statistics is needed (upcoming IFU surveys).

SPECTRAL DECOMPOSITION:

Output parameters in the procedure:

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: (i) F can be fixed via photometric decomposition; (ii) $SPC(\lambda)$ can be constrained from regions where the other component is absent; (iii) kinematics can be constrained by independent methods.

How to disentangle scenarios using Age separation

FORMATION

Galaxies with large scale stellar counter-rotation

G=1-M =fraction of counter-rotating galaxies produced by **gas accretion+star formation**

M = fraction of counter-rotating galaxies produced by **binary mergers**

OBSERVATIONS

100% the secondary component is the youngest. Fraction: 1-M

50% the secondary component is the youngest. Fraction: M/2

50% the secondary component is the oldest. Fraction: M/2

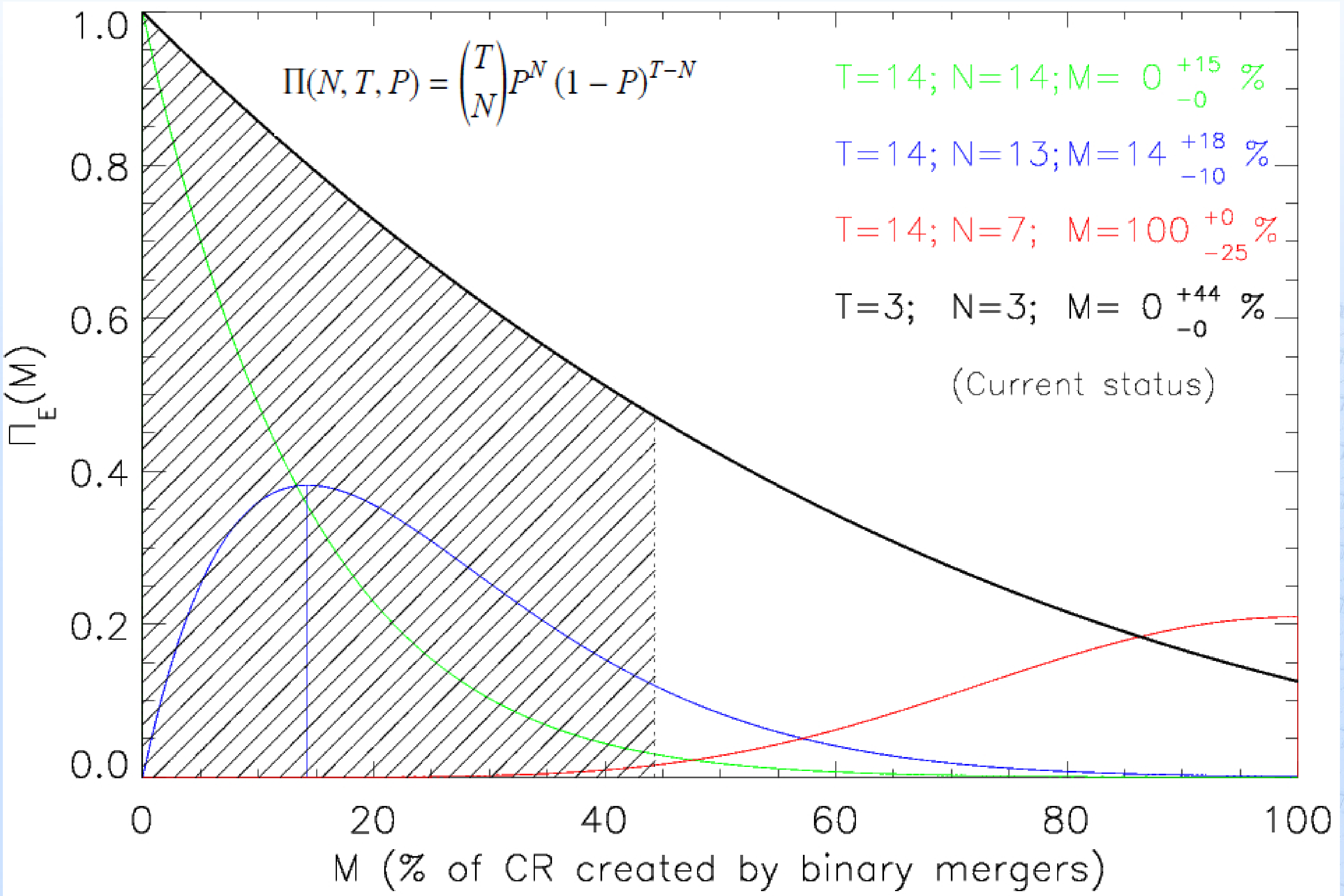
Probability P to find a counter-rotating galaxy with secondary component younger than the main component.

P(M) = 1-M +M/2=1-M/2

Probability that the secondary component is the youngest in exactly N galaxies out of a sample of T:

$$\Pi(N,T,P) = \binom{T}{N} P^{N} (1-P)^{T-N}$$

The component rotating as the gas is the youngest in 3/3 galaxies (all published)



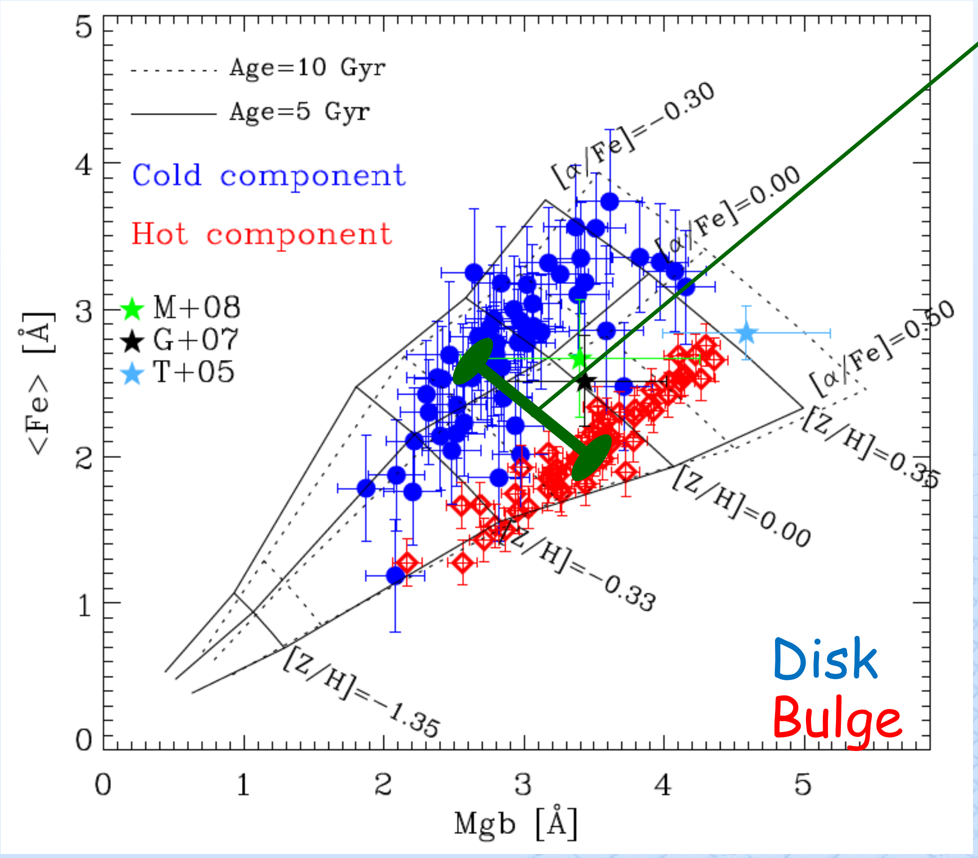
SOCRATE

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	Observed (VIMOS/IFU)
NGC 3593	S0/a	Coccato et al. 2013 (VIMOS/IFU)
NGC 3608	E2	
NGC 3796	S	
NGC 4138	S0	Pizzella et al. 2014 (Asiago Telescope, long-slit)
NGC 4191	S0	Observed (Virus-W) – paper in progress
NGC 4259	S0	Observed (Virus-W) – inconclusive data
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.

NGC 7217: spectral decomposition

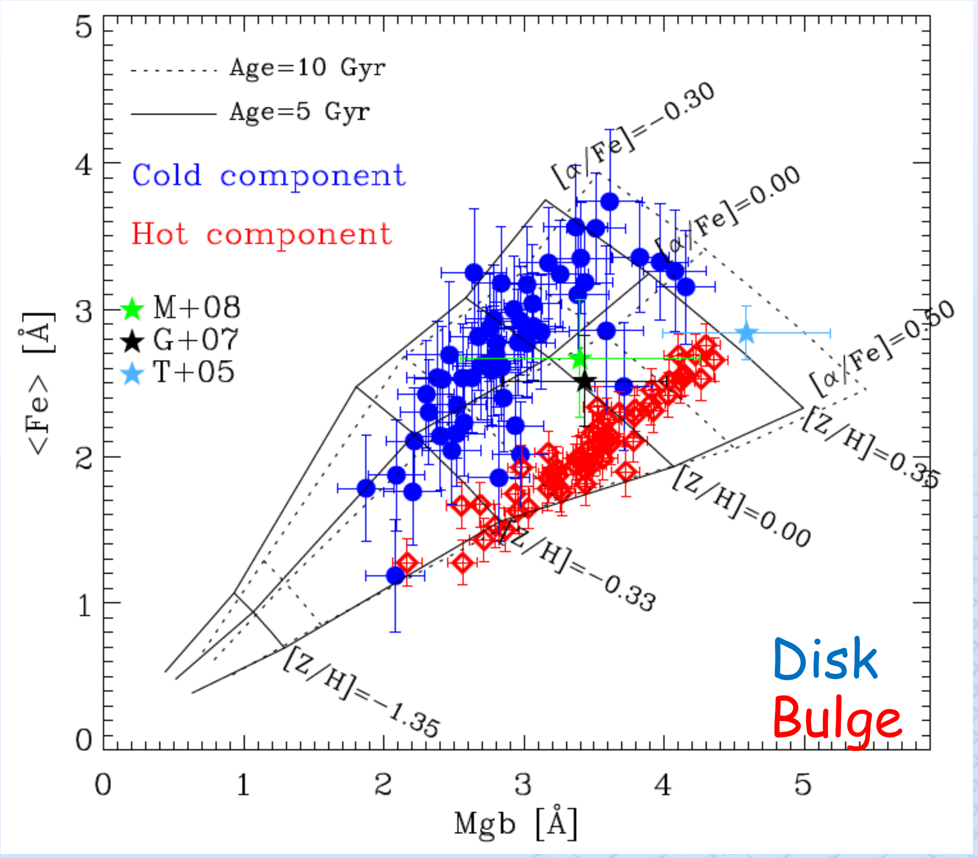


Mgb and ‹Fe› offset: passive evolution of a single stellar population, which gradually builds up both α-elements and other metals over time.

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



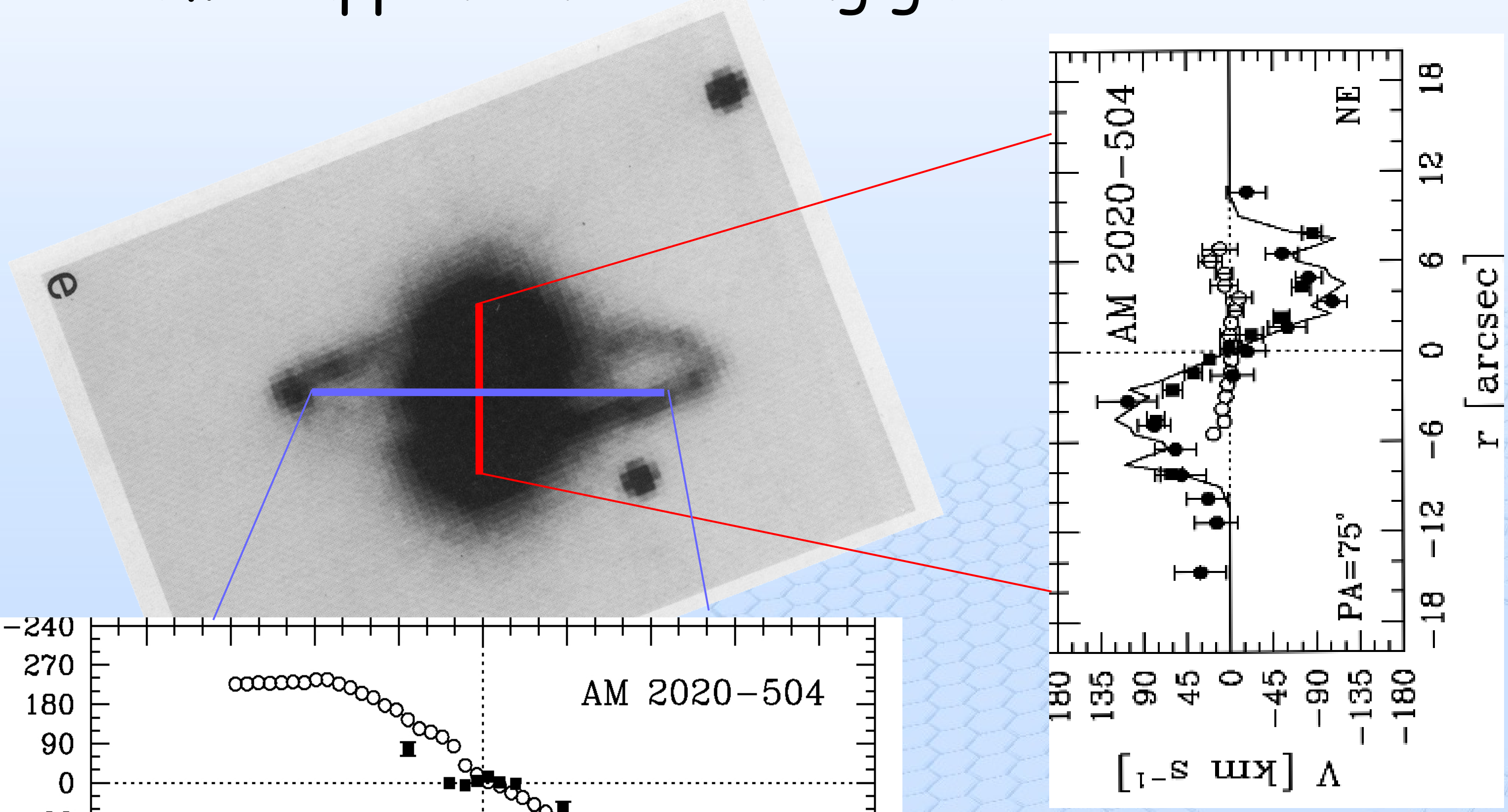
Suggested formation scenario:

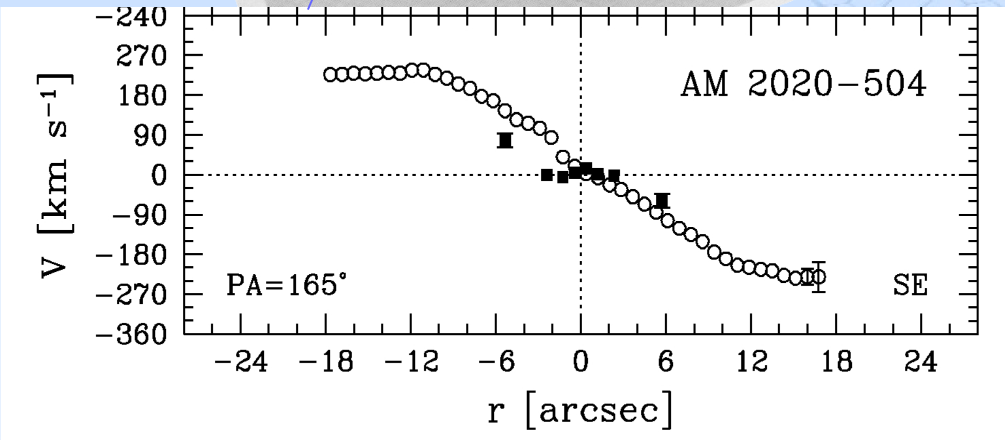
The spheroidal component of NGC 7217, formed through a major merger. Properties more similar to those of an elliptical galaxy than to those of the bulges of spirals.

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

GAS AND MULTI-SPIN GALAXIES
Orthogonal components

The same happens in Polar ring galaxies:





Rotation of the gas along the host galaxy minor axis