Multi-spin galaxies

An observational overview

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Summary

- Introduction

- Some history

- The new instruments

- New perspective

What is a multi-spin galaxy (Rubin 1994)

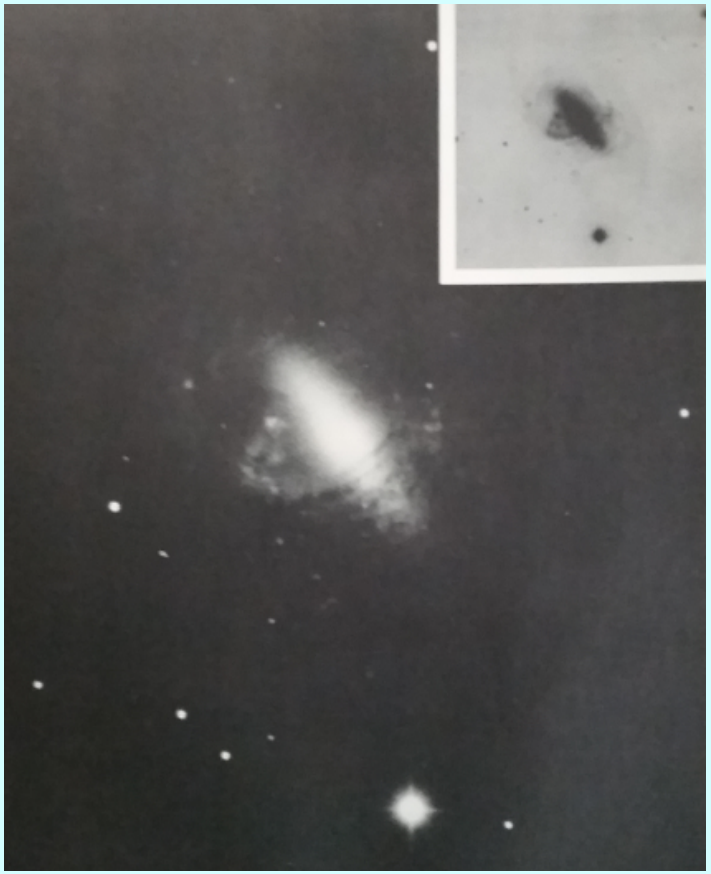
- A Galaxy with more than one rotation axis

- Kinematically distinct gas
- Kinematically distinct stellar components

- Polar ring galaxies
- Decoupled cores
- Counter-rotating galaxies
- (Warped galaxies)

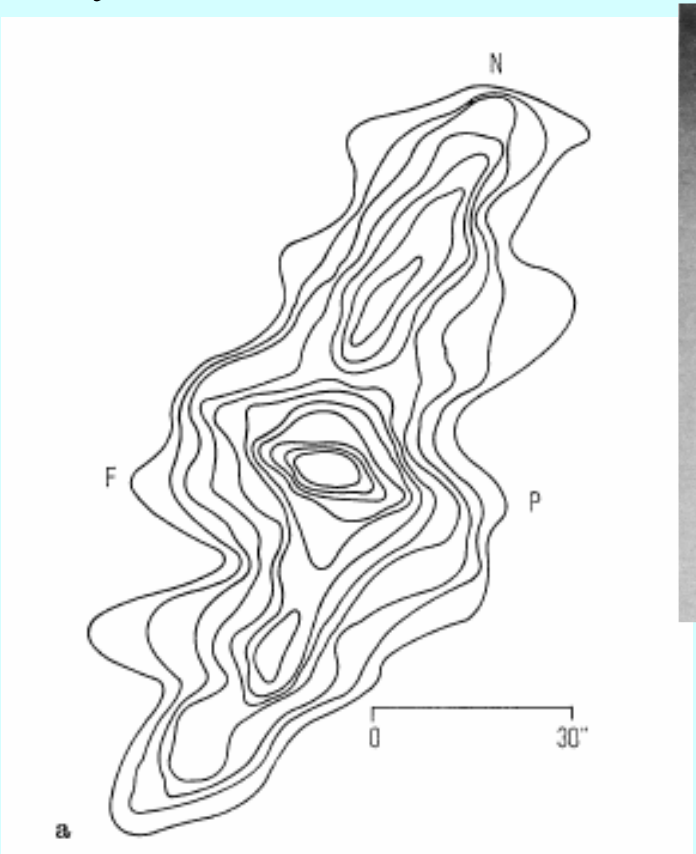
Some History …

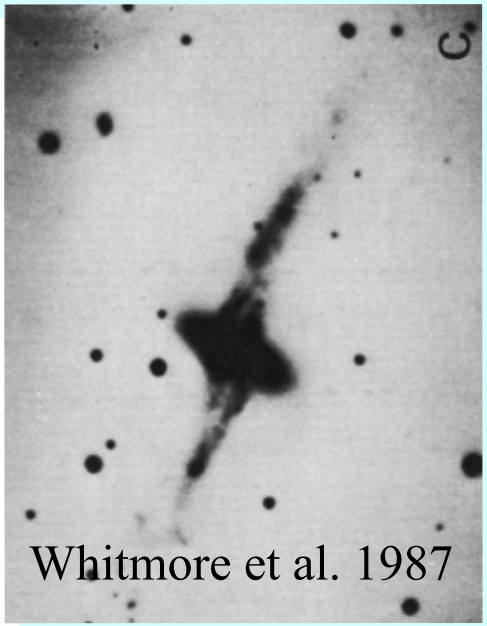
First Multi Spin objects identified are Polar Ring Galaxies.
- NGC 2685 Sandage (1961) "… perhaps the most unusual galaxy in the Shapley-Ames catalog."



Some History …

- NGC4650A Sersic (1967): "...a peculiar galaxy with very remarkable characteristics."

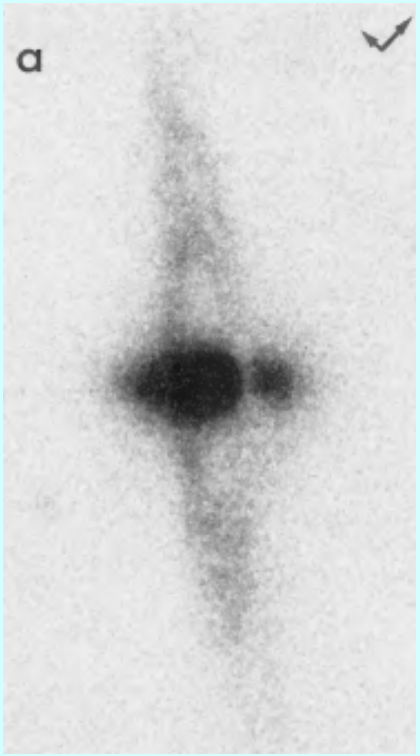




Whitmore et al. 1987

Acquired material?

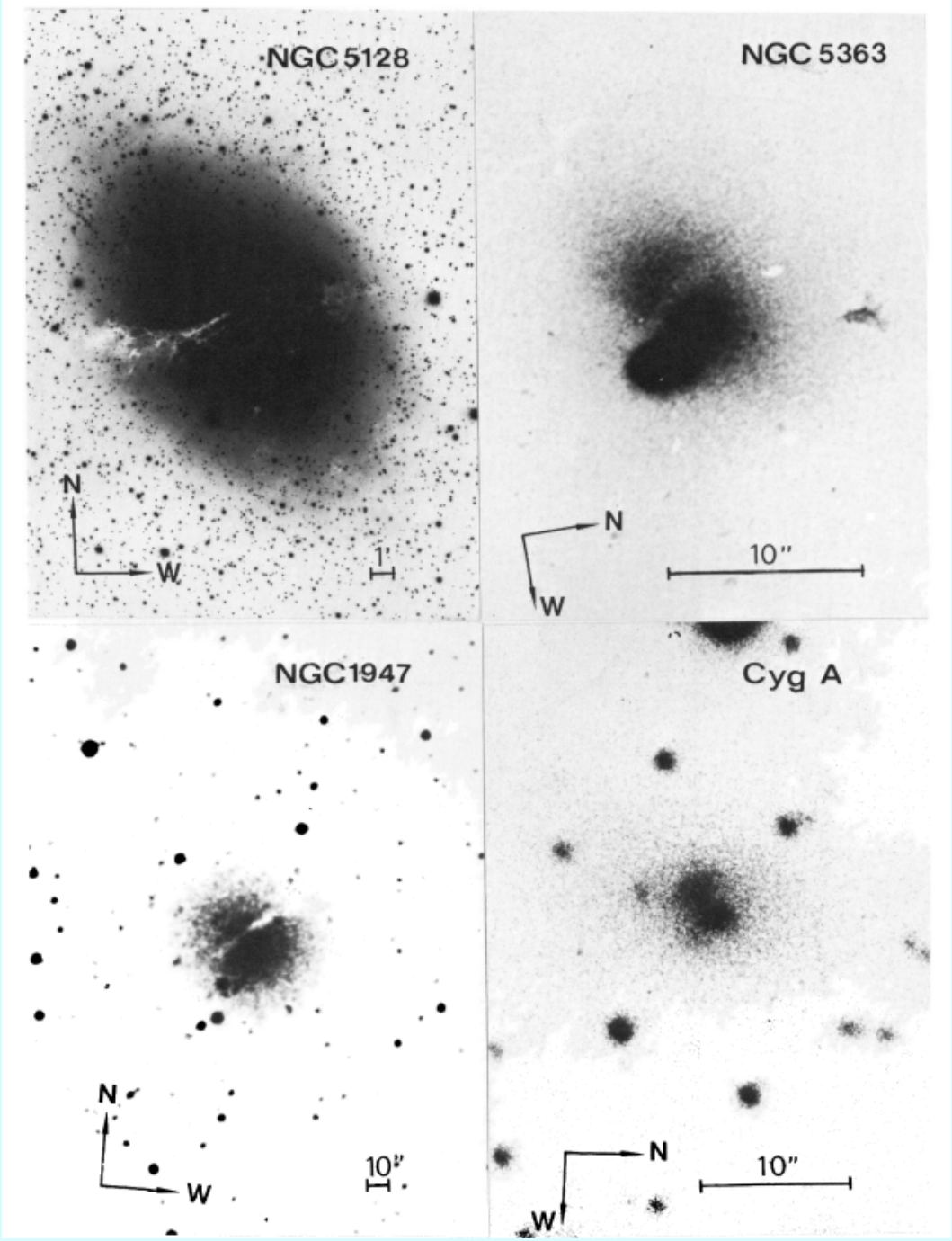
A0136-0801 Schweizer + 1983



Then also Ellipticals

Bertola & Galletta (1978)

Minor axis dust lanes



After 50 years…

Whitmore et al. (1990). Photographic atlas
~5% of S0 have a Polar Ring

- 6 confirmed
- 27 very good cantidates
- 73 possible candidates
- 51 possibly related Polar Ring

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157 candidates

Moiseev et al (2011): SDSS selected catalogue

- 70 best candidates
- 115 good Polar Ring
- 53 related Polar Ring
- 37 Polar Ring strongly inclined

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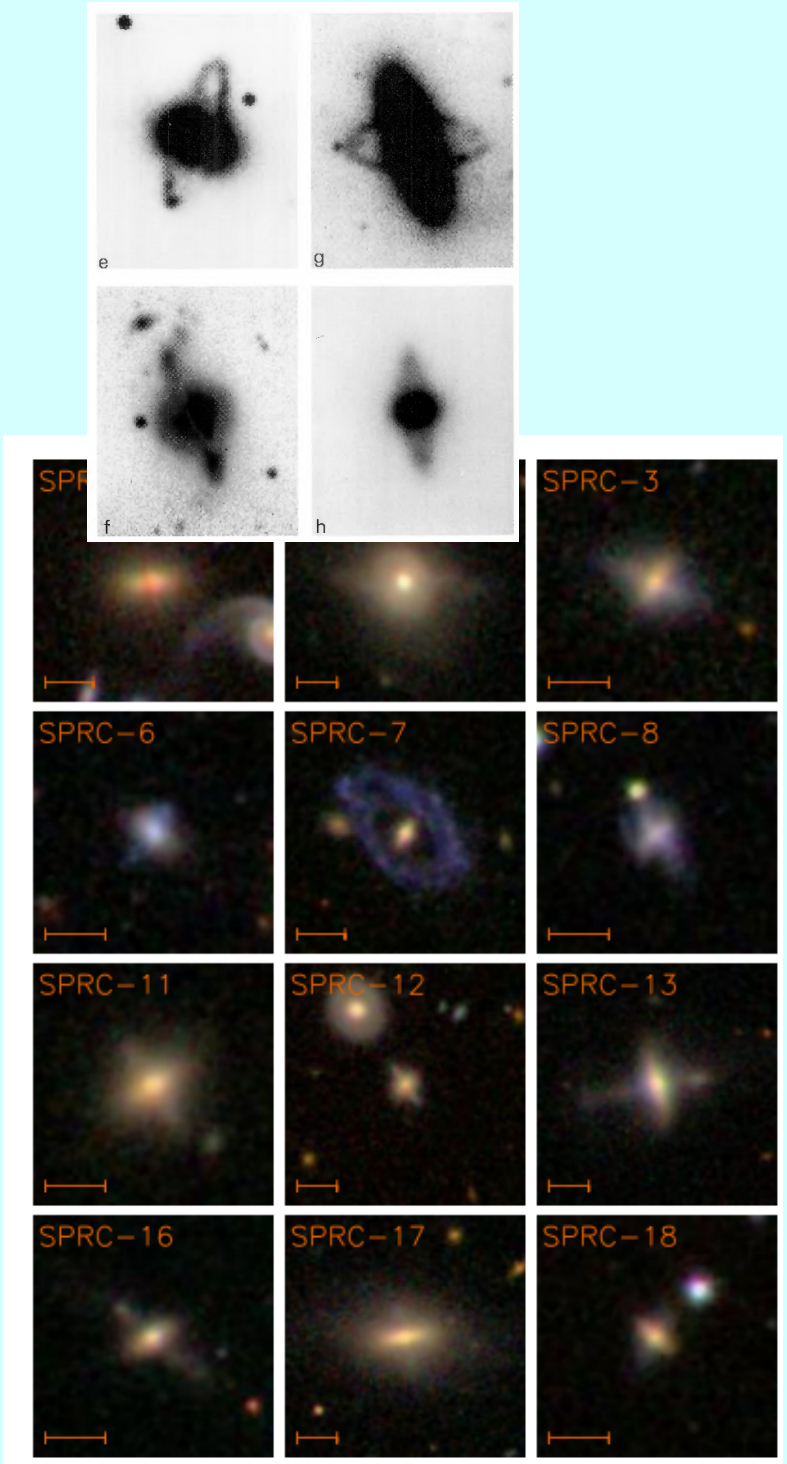
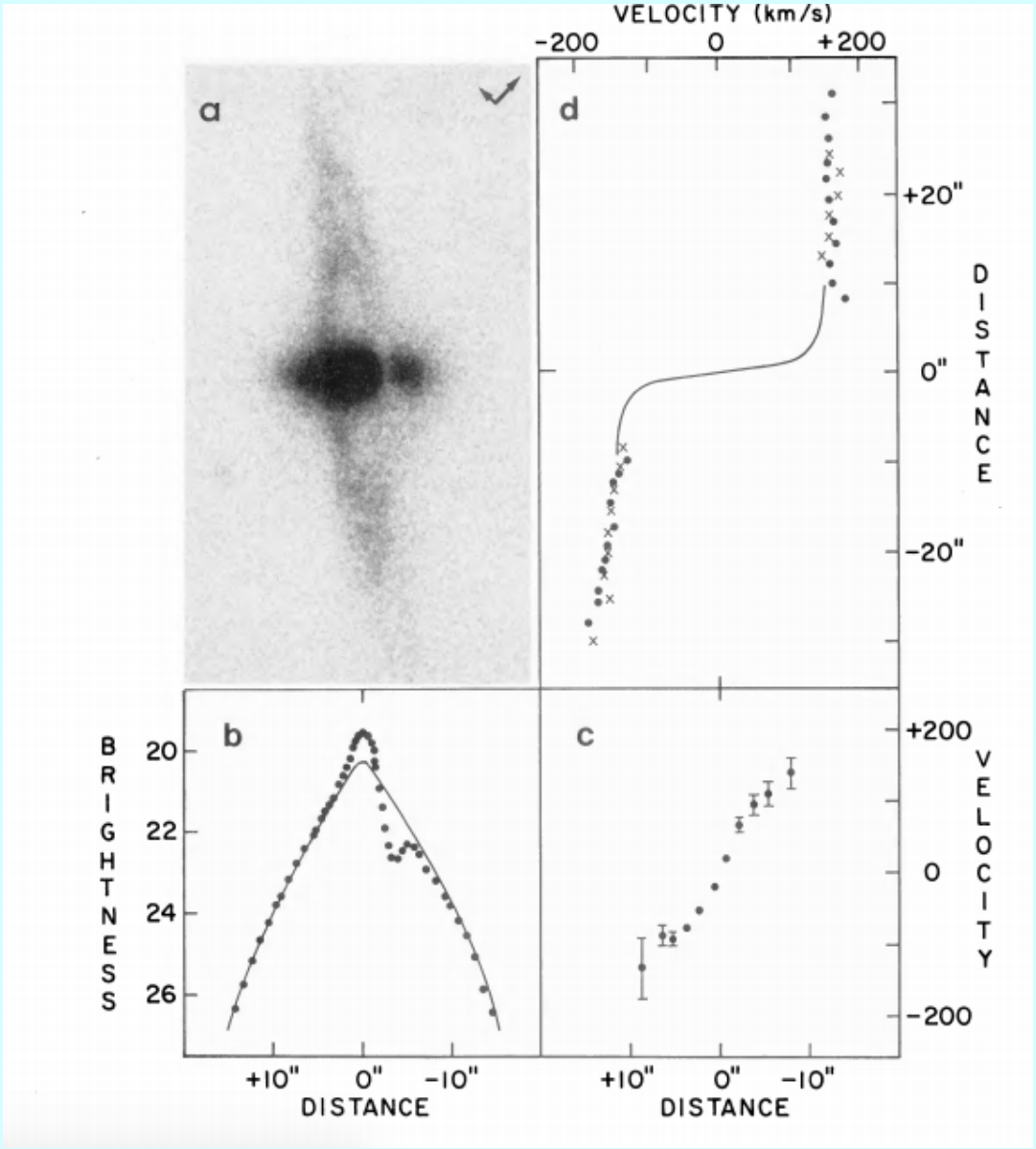
275 candidates



We need Kinematics



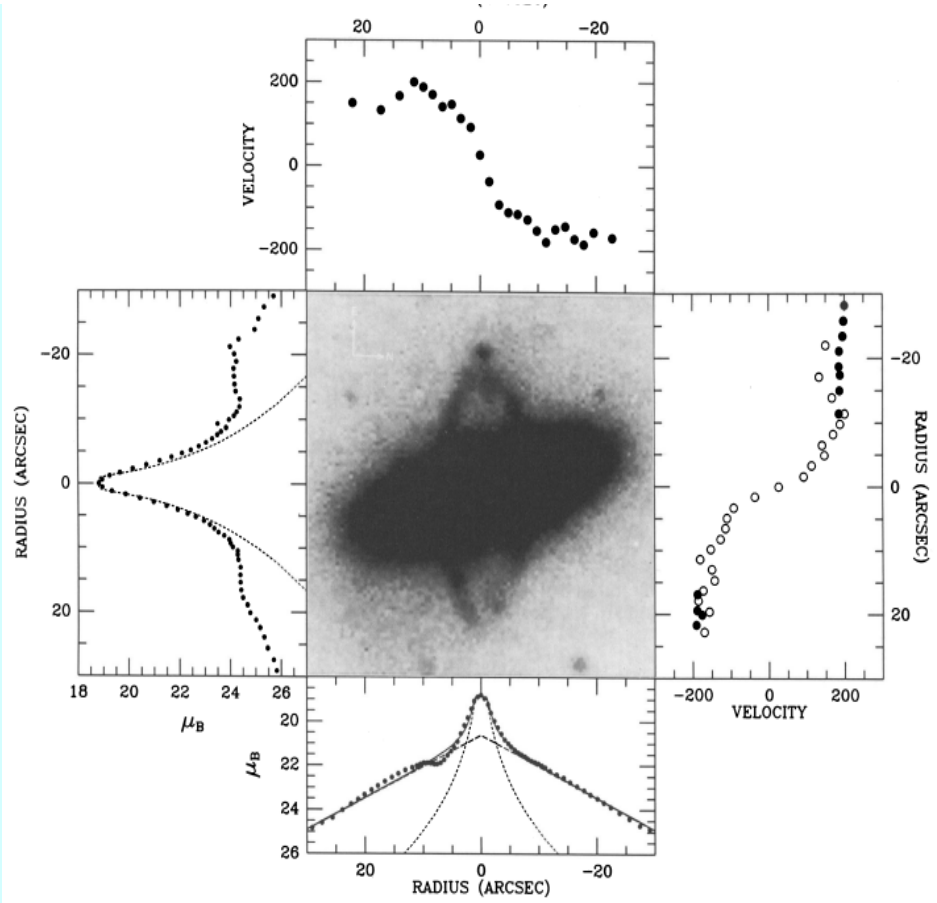
Schweizer et al. (1983)
A0136-0801

Possibility of sampling the mass distribution not only in the plane but in a volume.

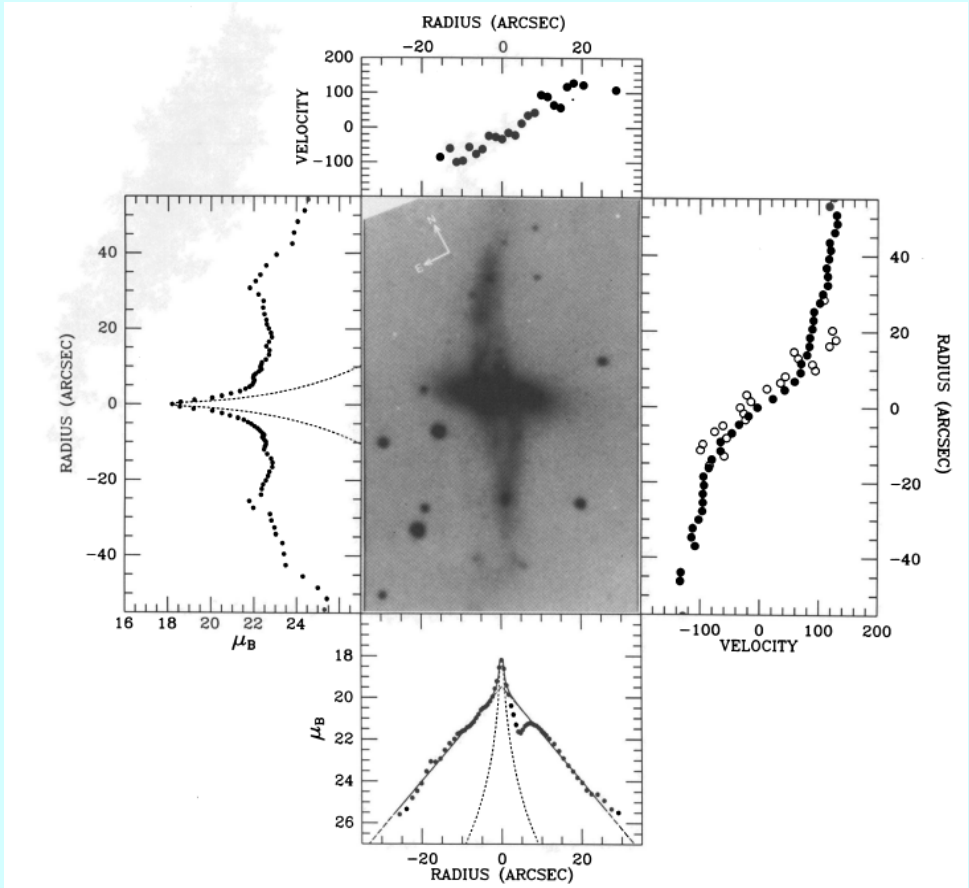
Testing the shape of the DM potential

We need Kinematics

Whitmore et al. (1987)
ESO 415-G26



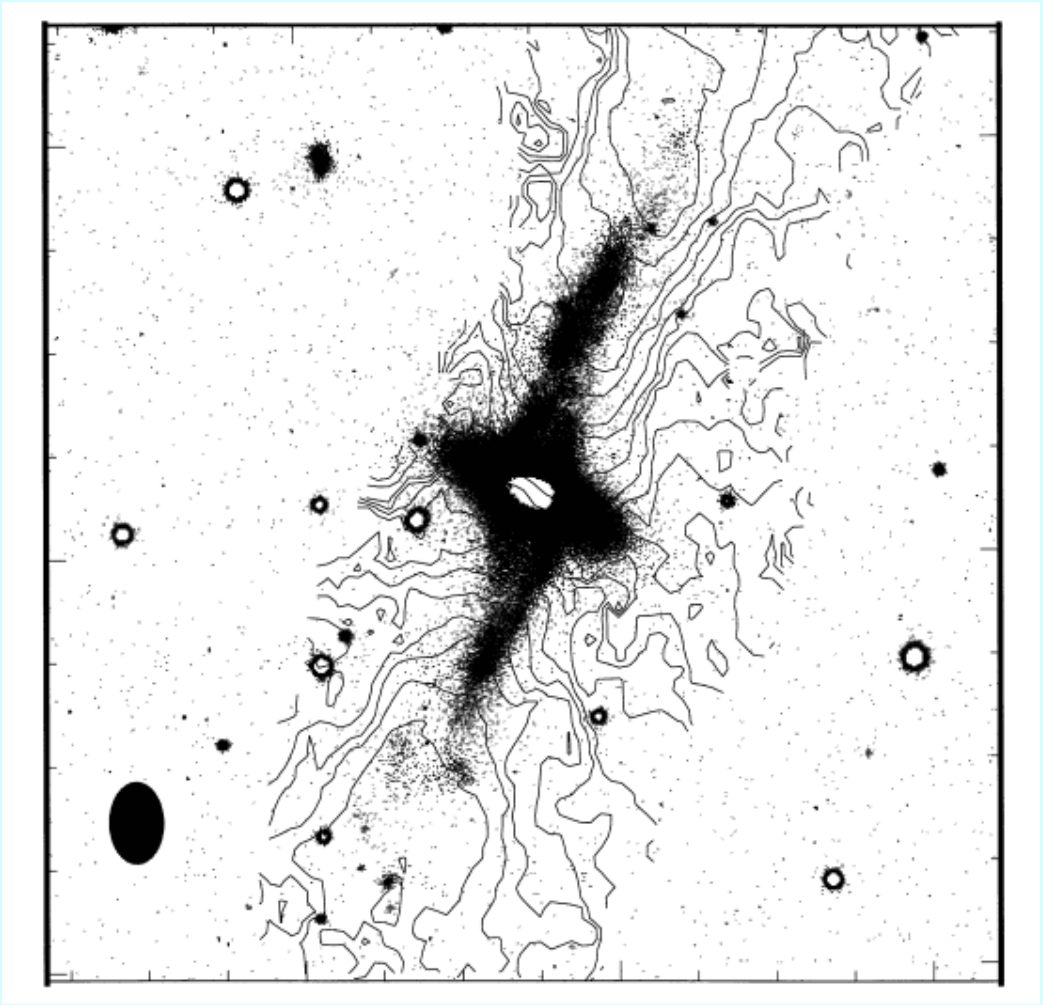
NGC 4650A



Kinematics HI

Arnaboldi (1997)
NGC 4650A

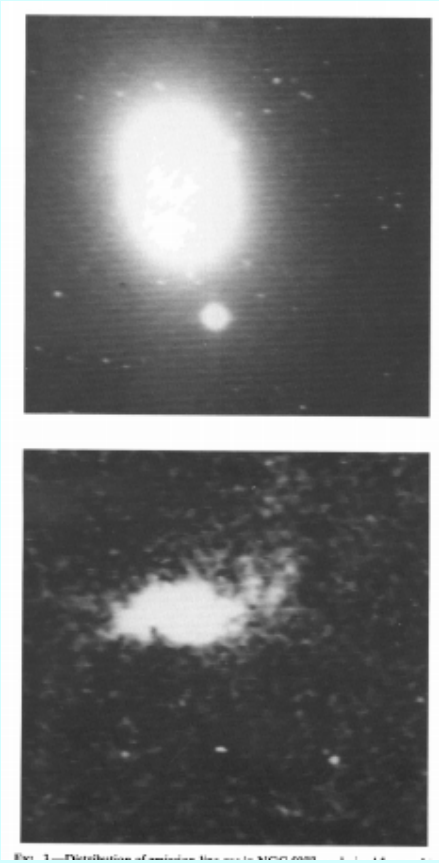
HI velocity field

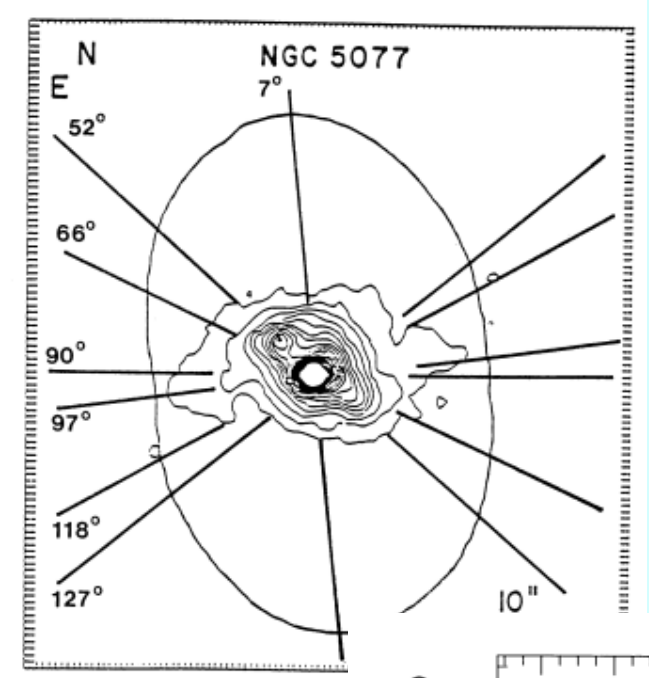


Elliptical galaxies, a test case: NGC 5077

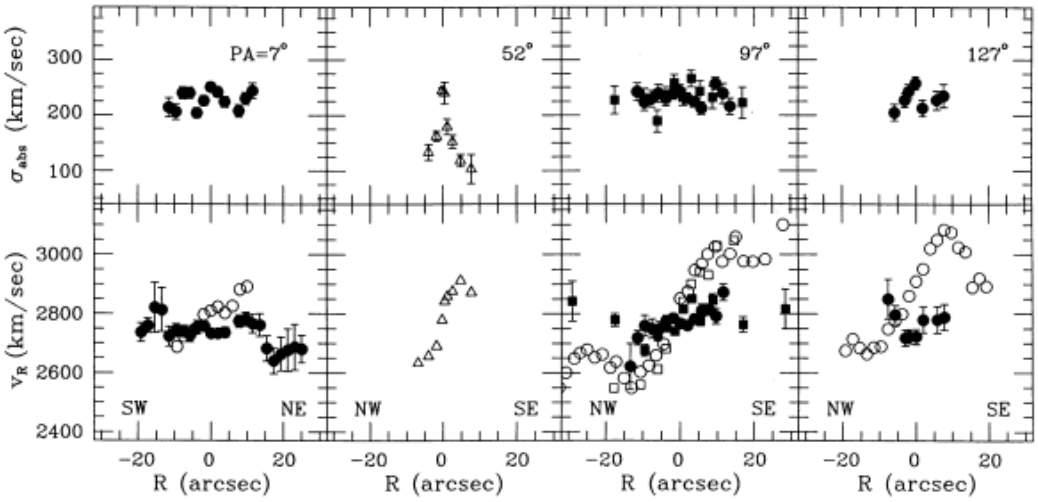
Bertola, Bettoni et al. (1991)

- Detailed kinematical mapping – long slit spectroscopy along several PAs



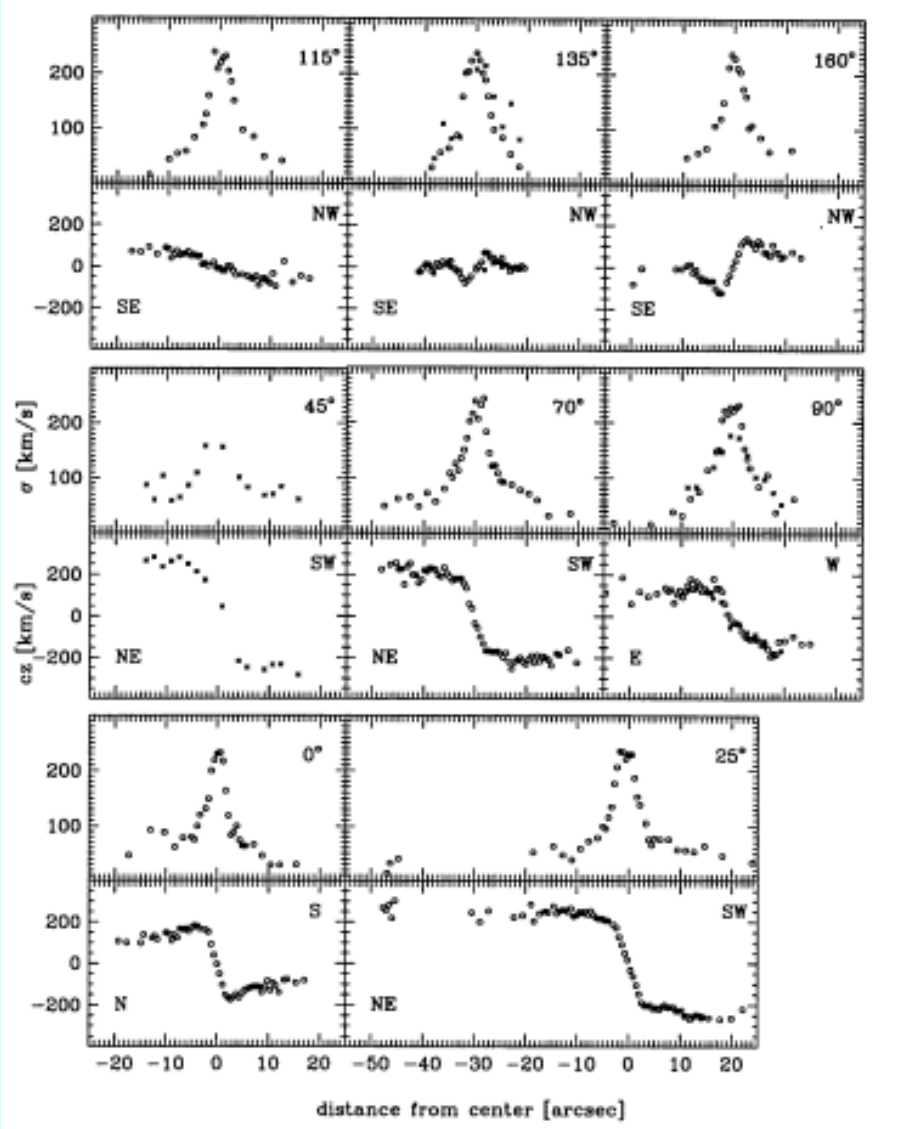


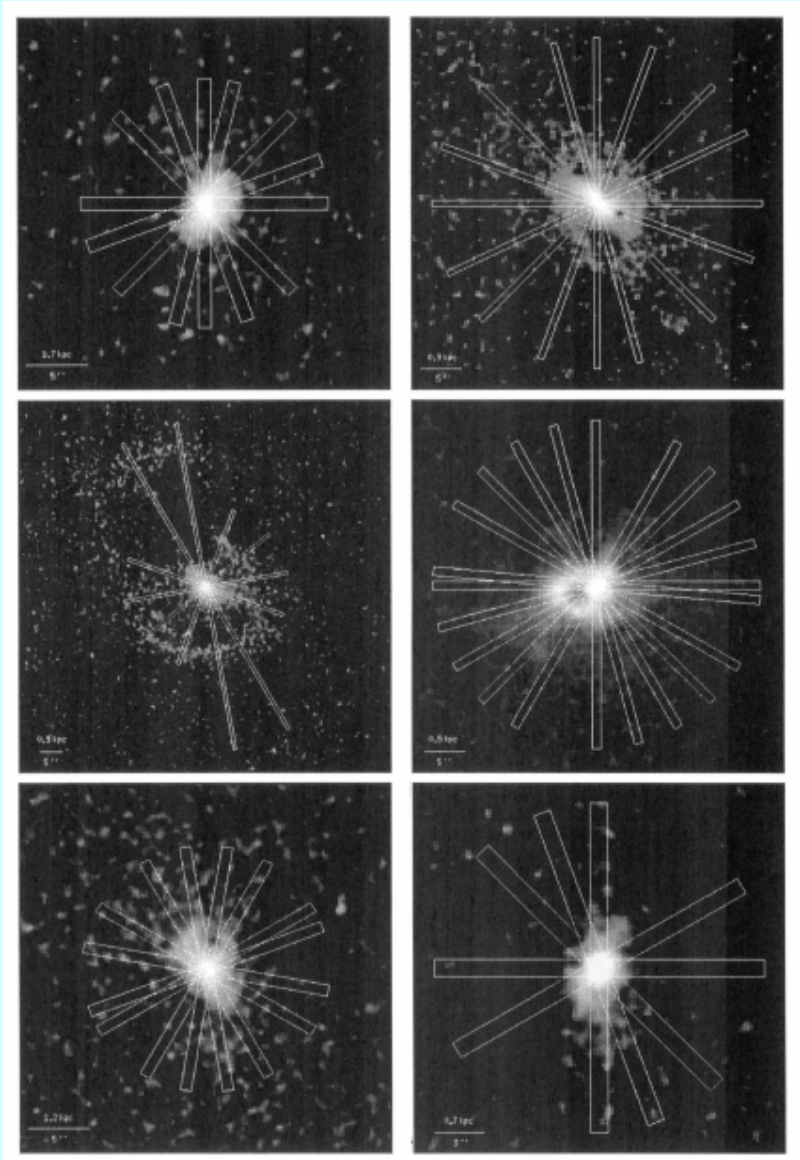
- Sampling the triaxial shape of the DM halo (Bertola & Capaccioli 1975)
- and the central mass density radial profile



Elliptical galaxies

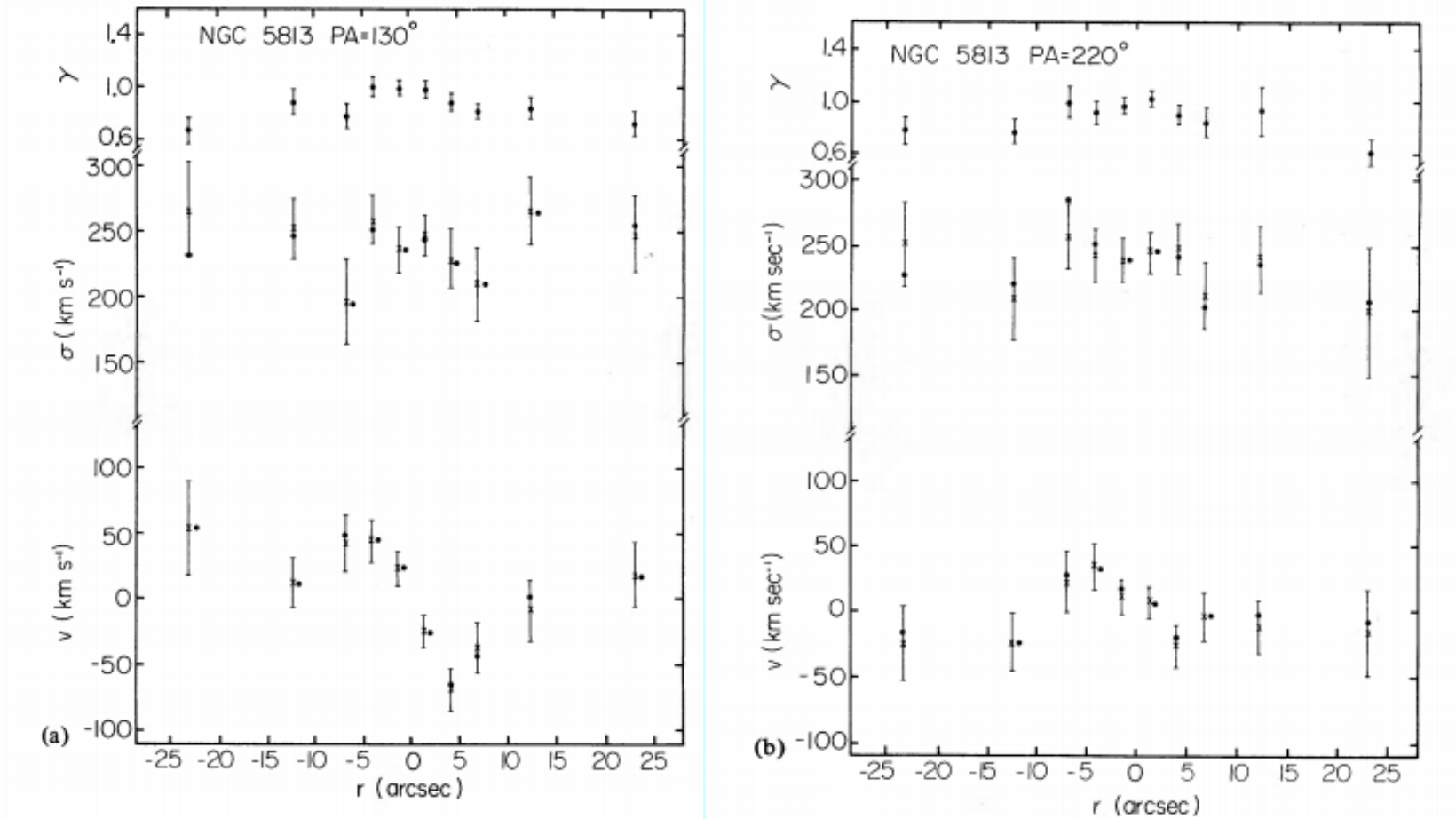
Zeilinger et al. (1996), Buson et al. (1993)





Decoupled cores….

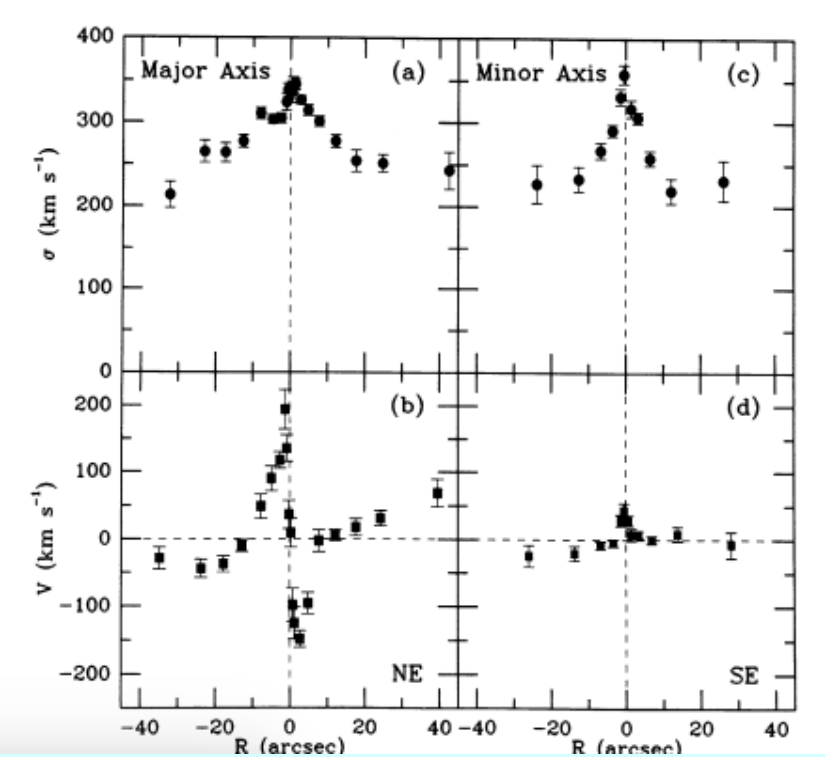
Decoupled cores can only be seen by means of spectroscopy
NGC 5813 – E1-E2 Efstathiou et al. (1980)



Decoupled cores….

-25% of elliptical galaxies show in the core a different kinematics than in the body of the galaxy (de Zeeuw & Franx 1991)

IC 1459 – E3 Franx & Illingworth (1988)



- Counter-rotation: is a particular case of multi-spin galaxies: when in one galaxy components with opposite spin co-exits (see review by Corsini 2014)

- Stars vs. Gas
- Stars vs. Stars
- Gas vs. Gas
- Stars vs. (Stars + Gas)

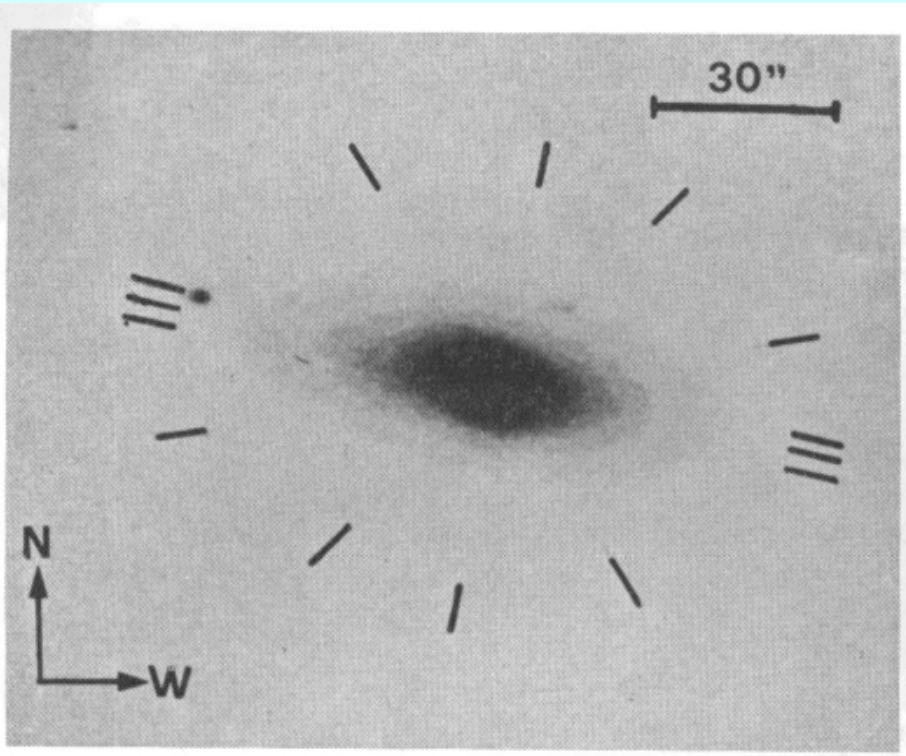
- whole galaxy
- inner/outer region

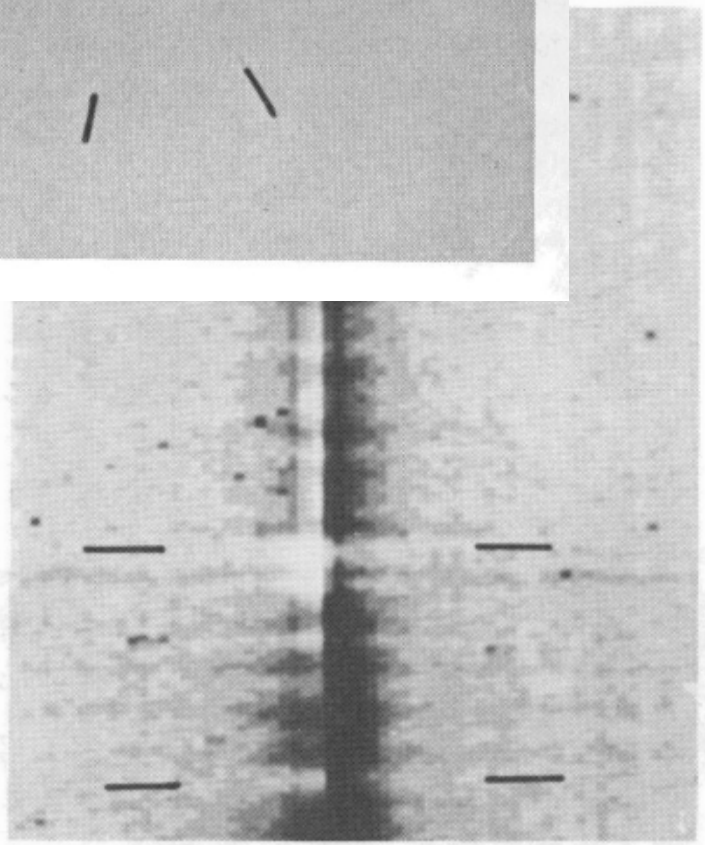
- About 15% of S0 counter-rotates Pizzella et al.(2004)
- We can detect up to a fraction of 20% (in luminosity) counter-rotating stars

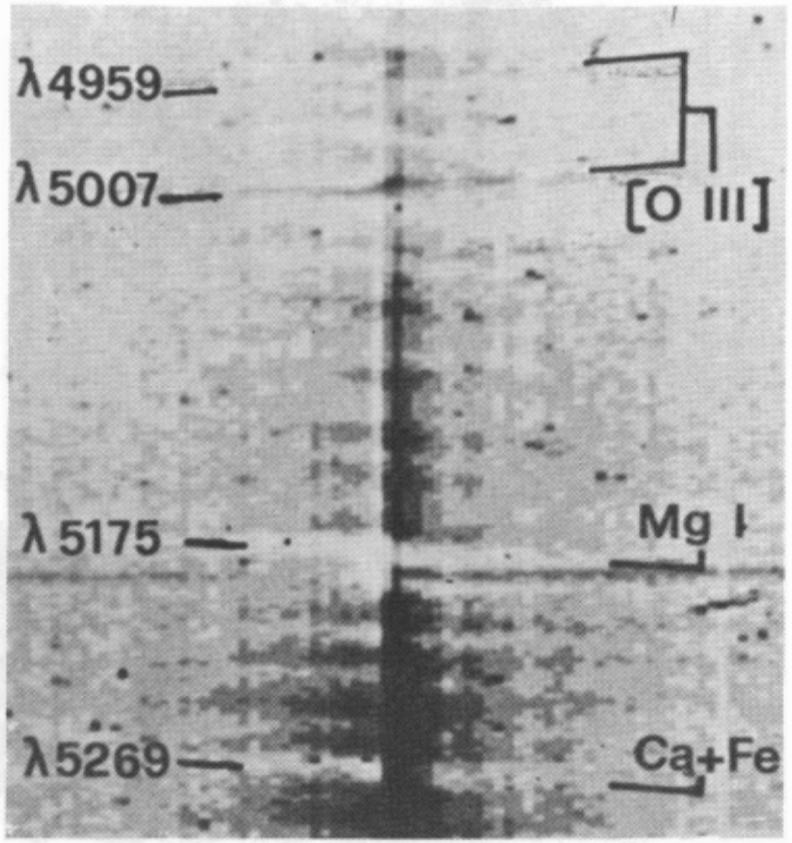
Gas vs Stars counter-rotation

NGC 4546 – SB0

Galletta (1987)

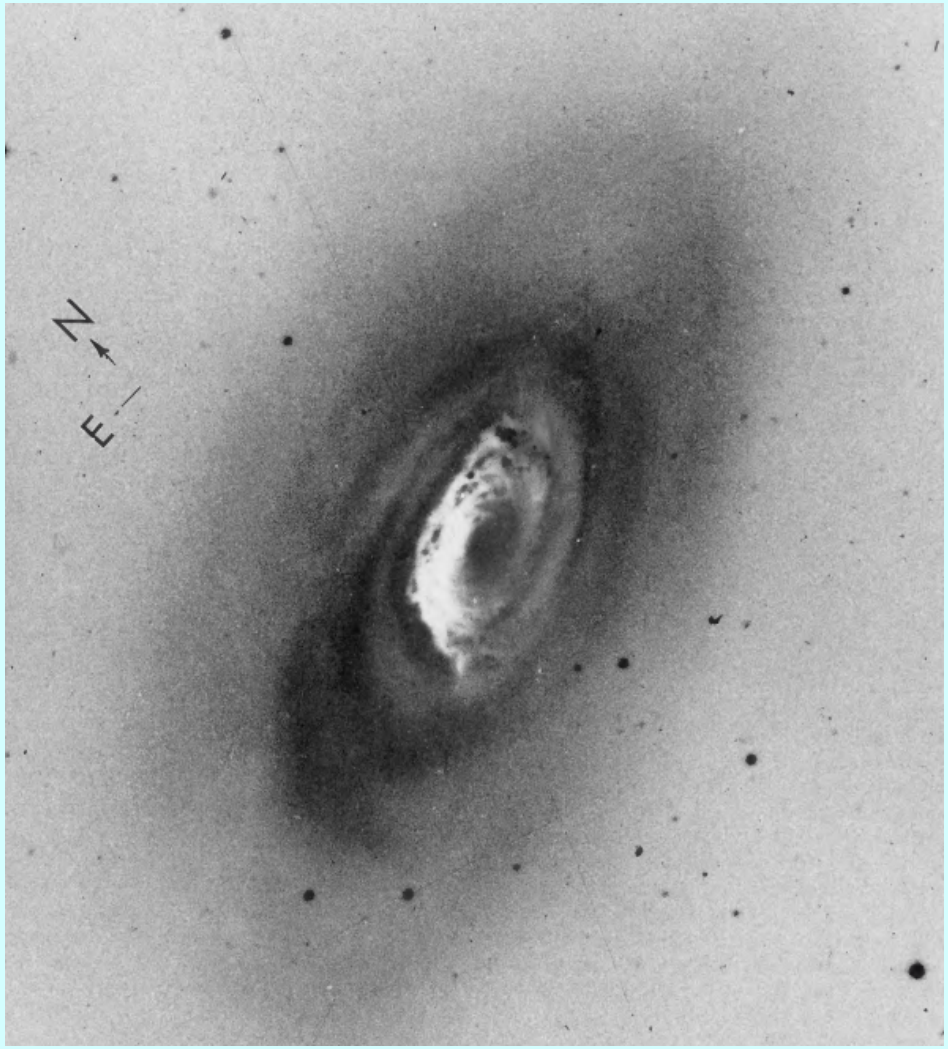


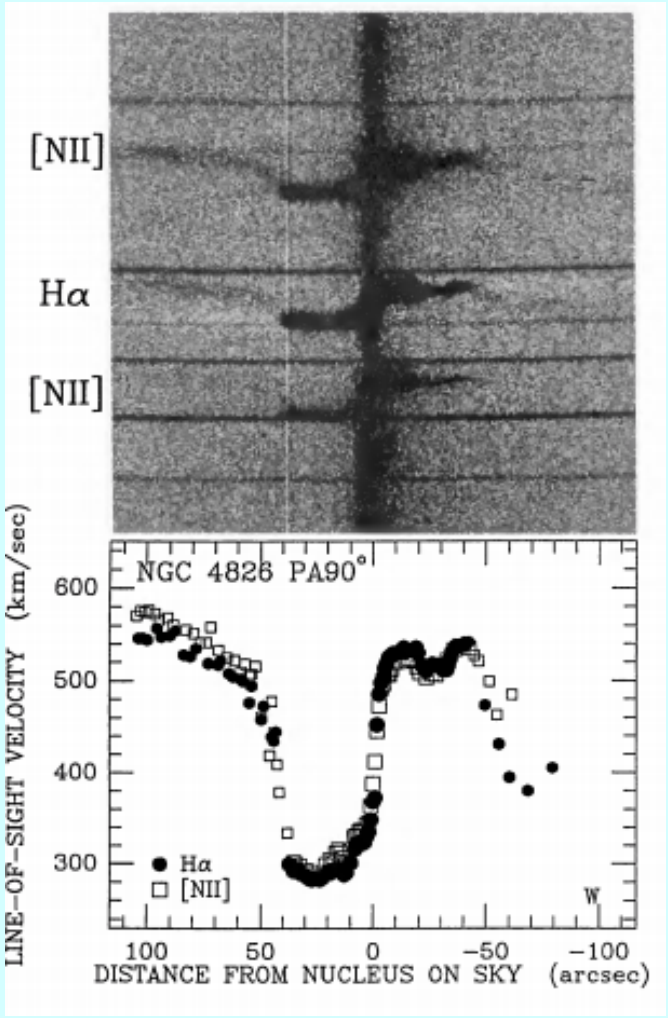




Gas vs Gas counter-rotation ….

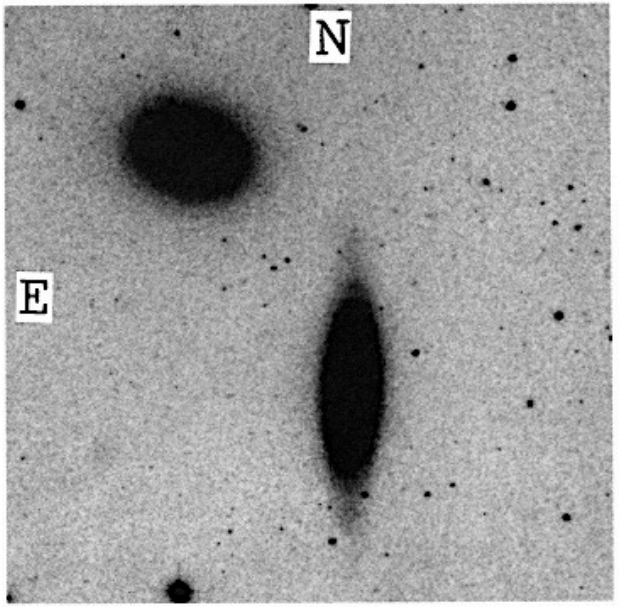
NGC 4826 Sab – Rubin (1994)

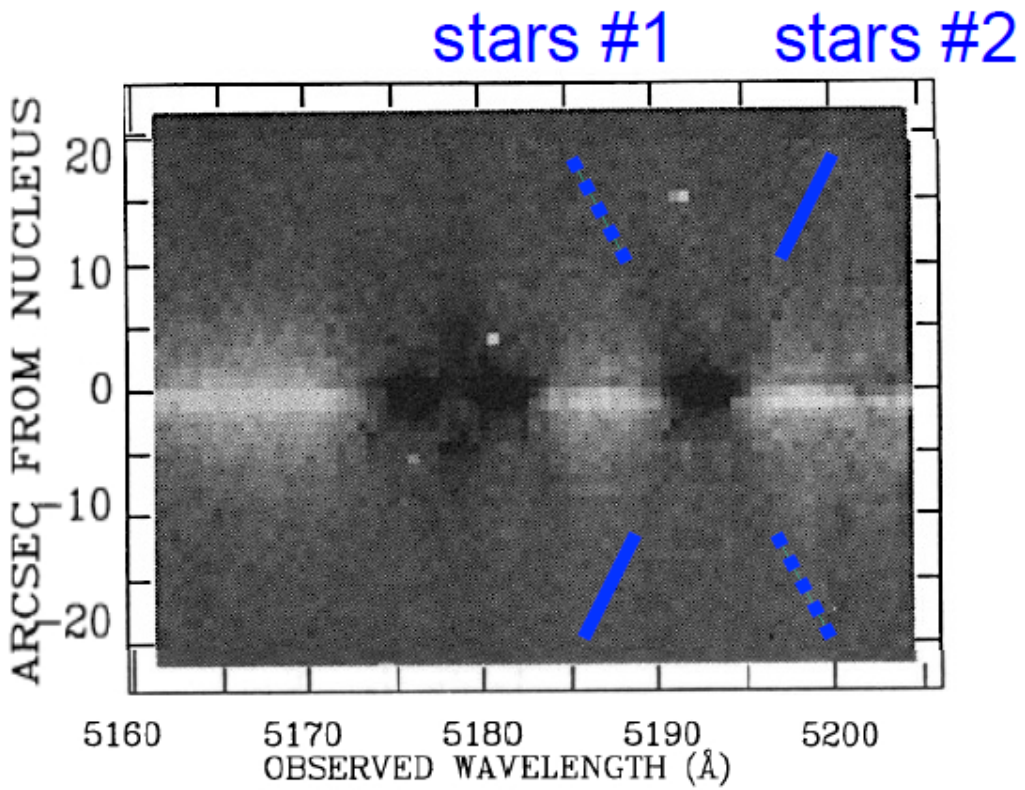


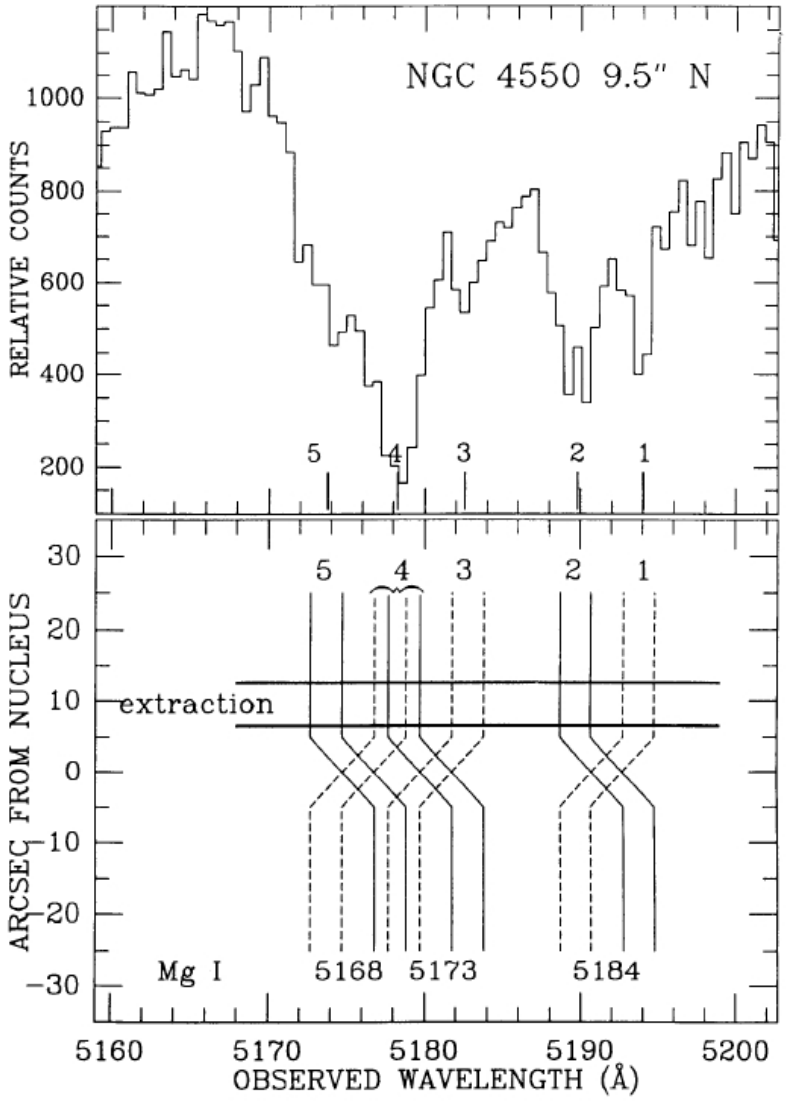


Stars vs Stars counter-rotation

NGC 4550 – SB0 Rubin (1992)





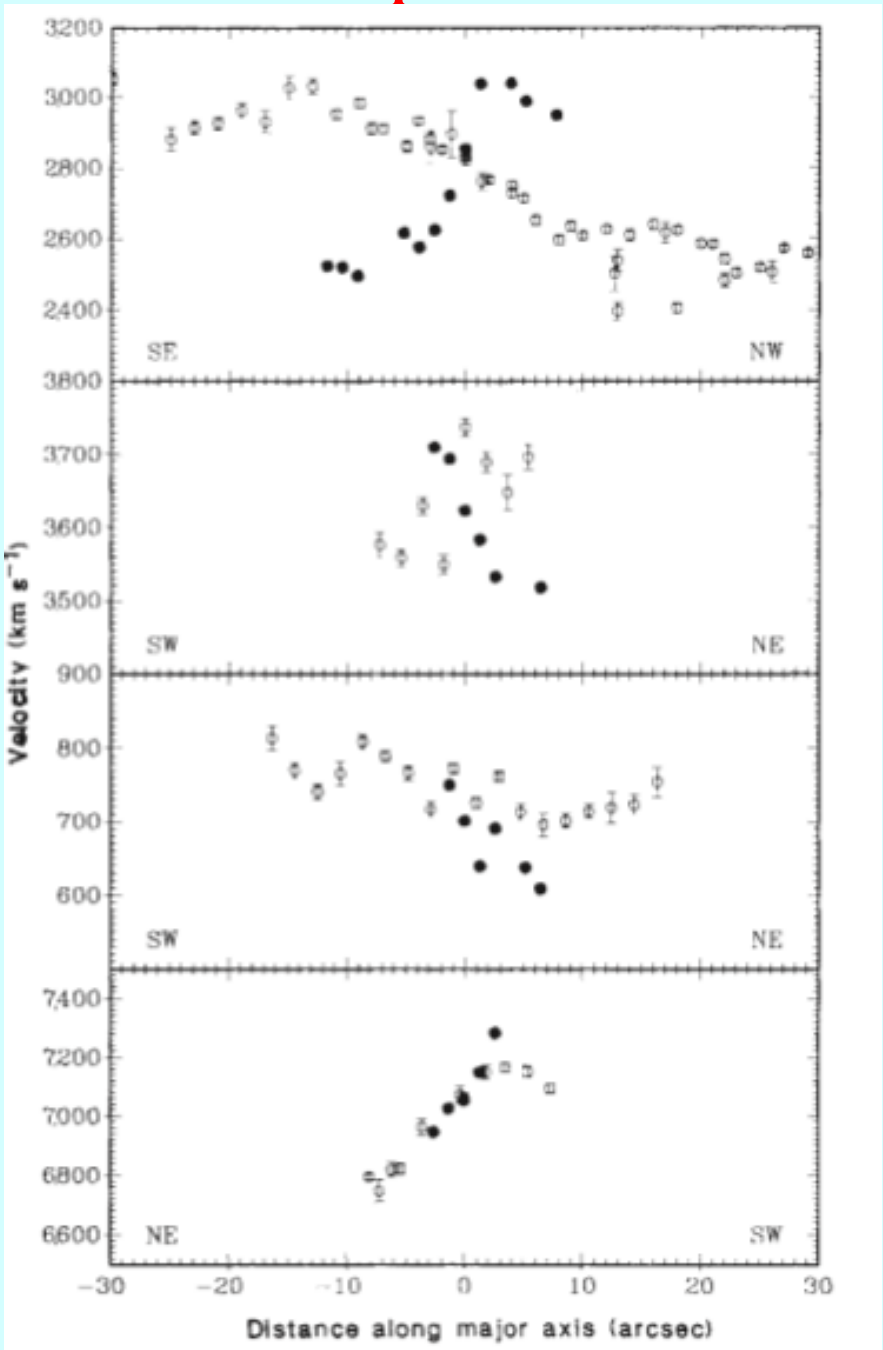


Counter-rotation in Ellipticals

Gas-Start counter-rotation in Ellipticals

50% of dust lanes E have counter-rotation: gas acquired from outside

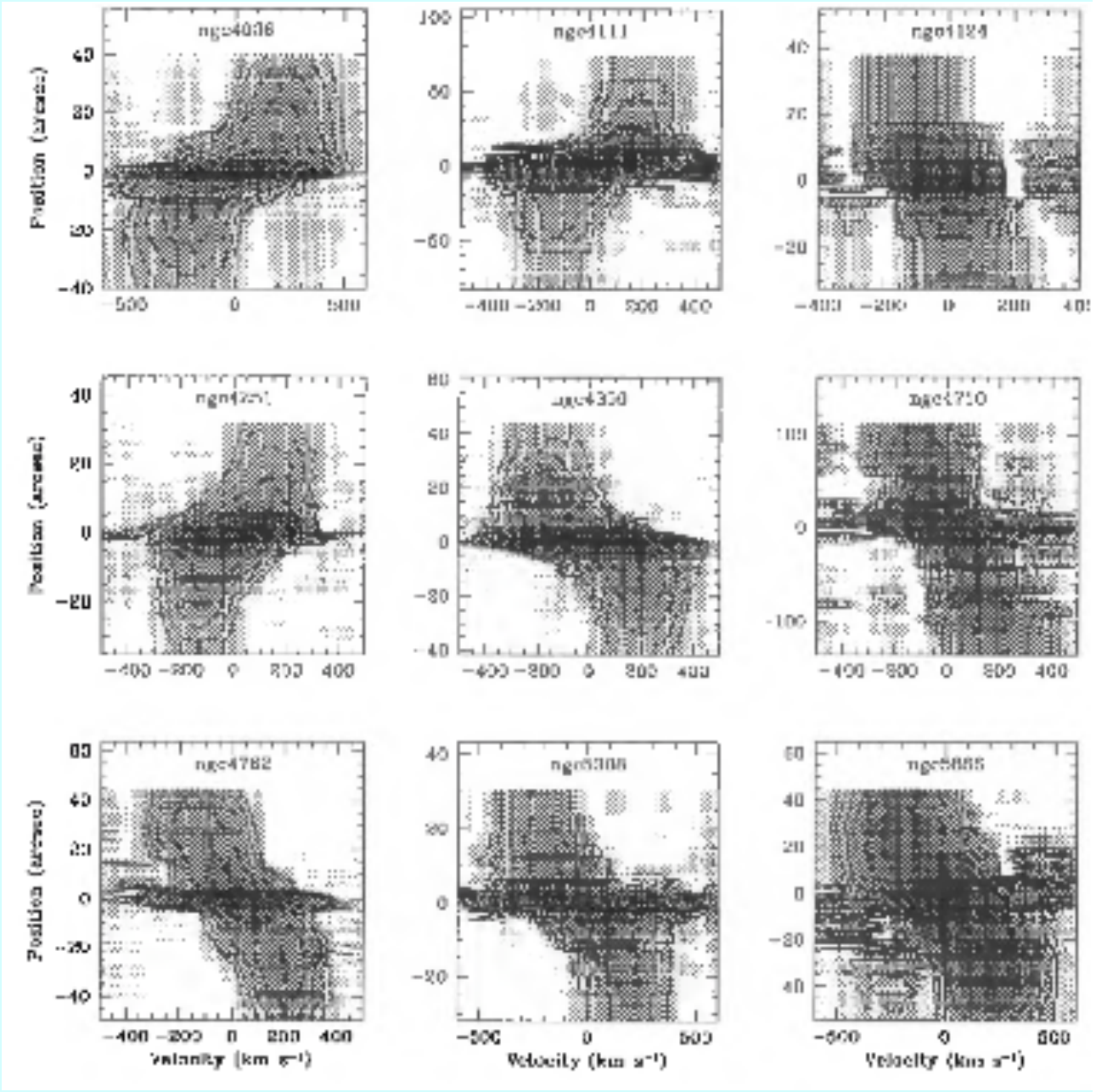
Bertola et al. (1992)



Gas decoupling in S0 galaxies

Kuijken & Merrifield, (1994)

24±8% gas vs star c.-r.

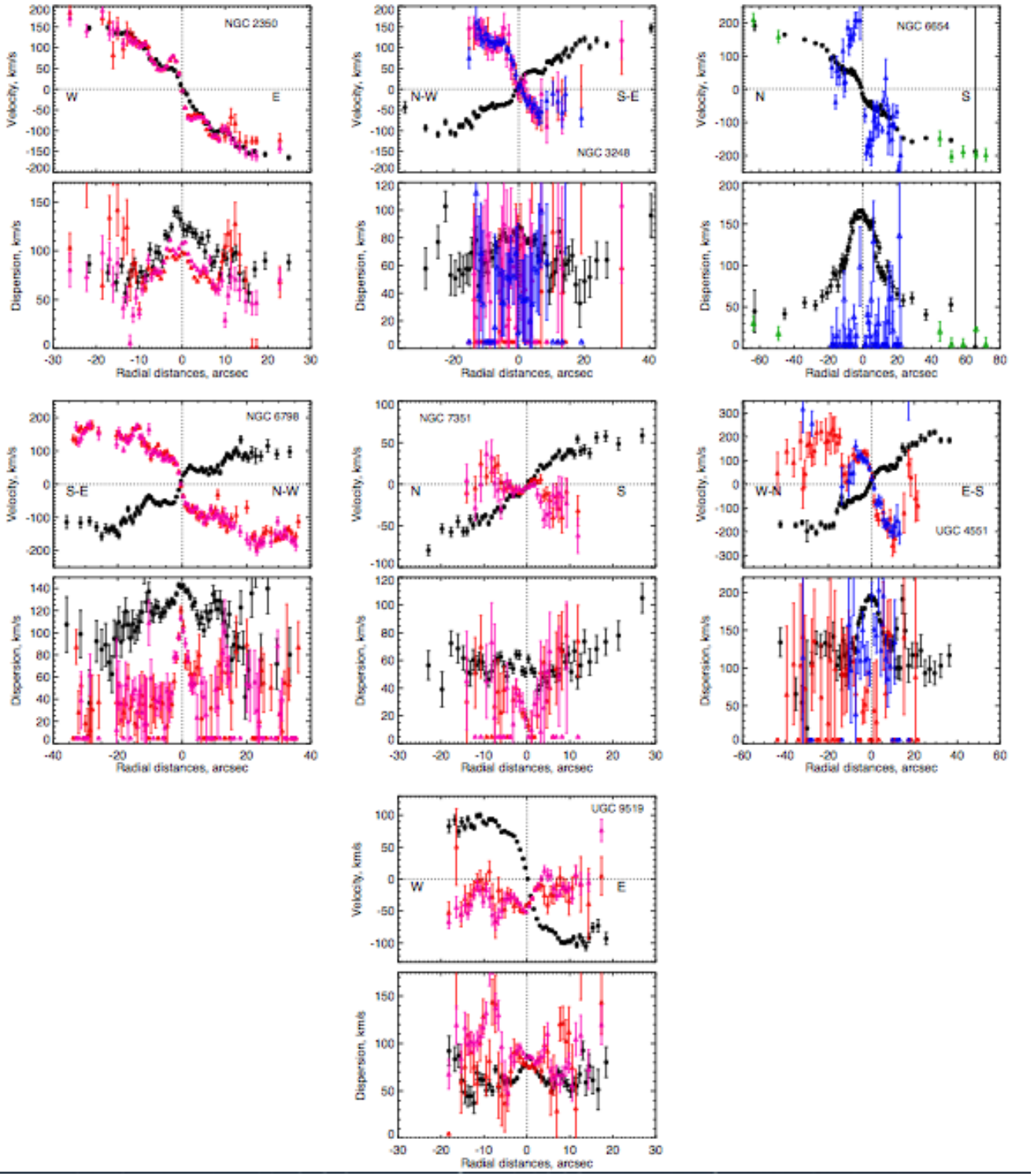


Gas decoupling in S0 galaxies

Katkov et al. (2014)

70% of isolated S0 galaxies

Gas accreted from outside the galaxies



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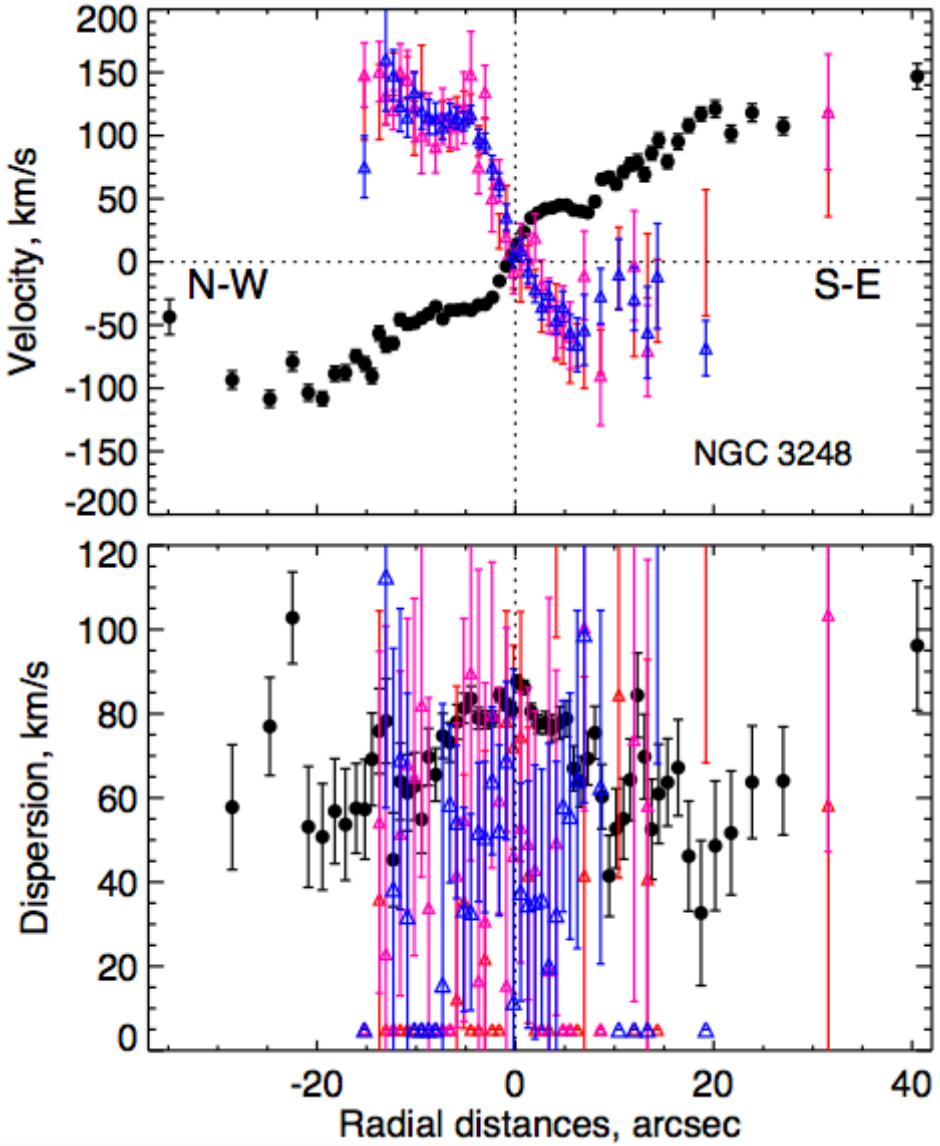
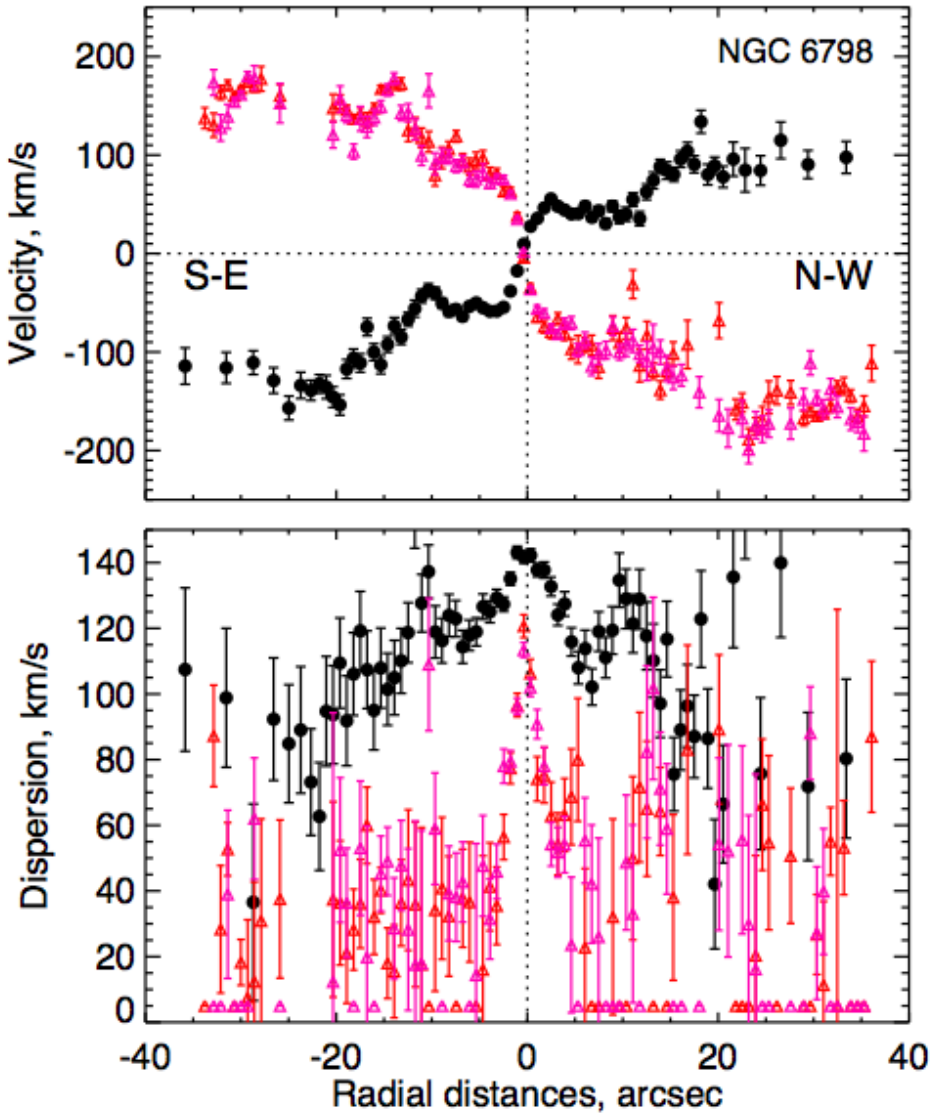
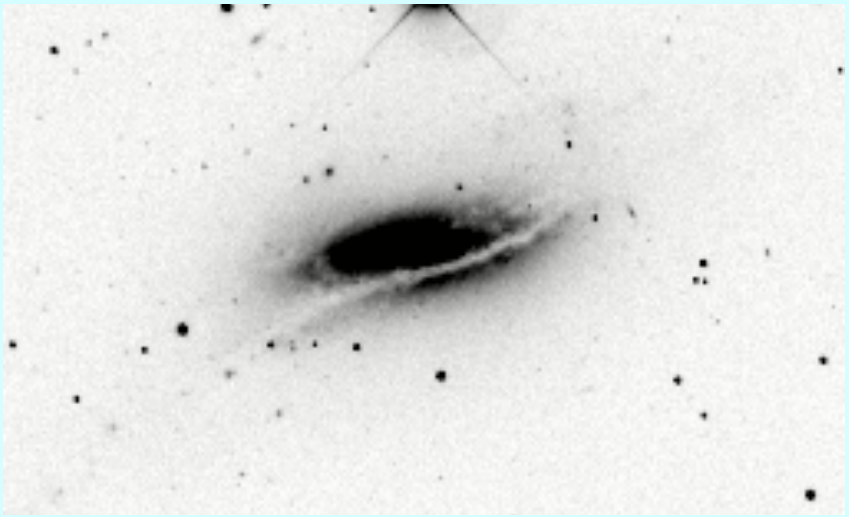


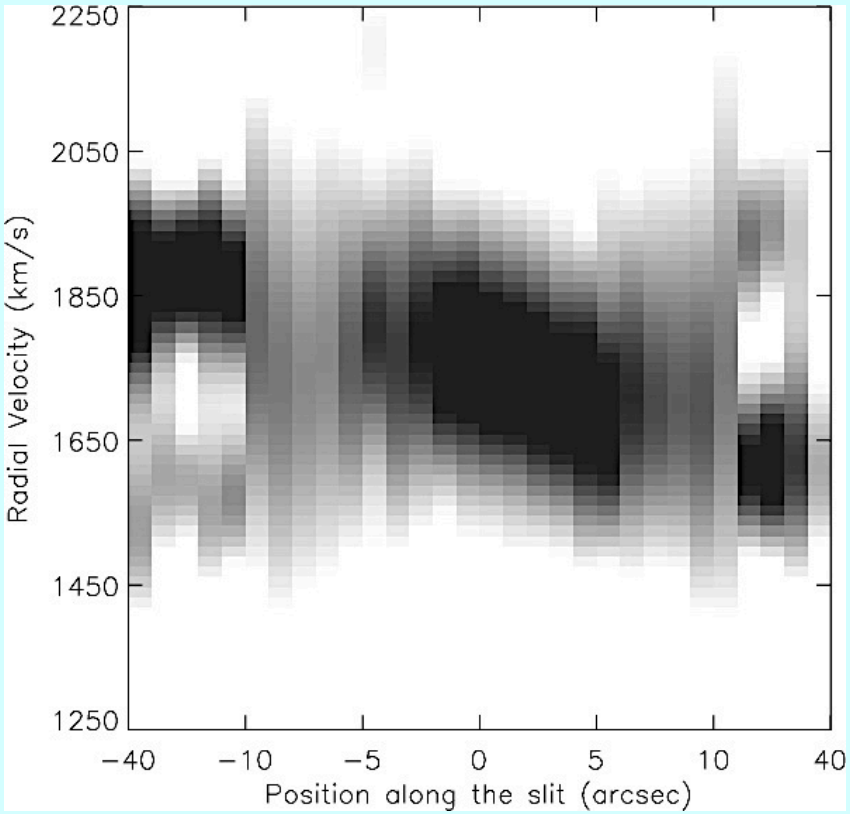


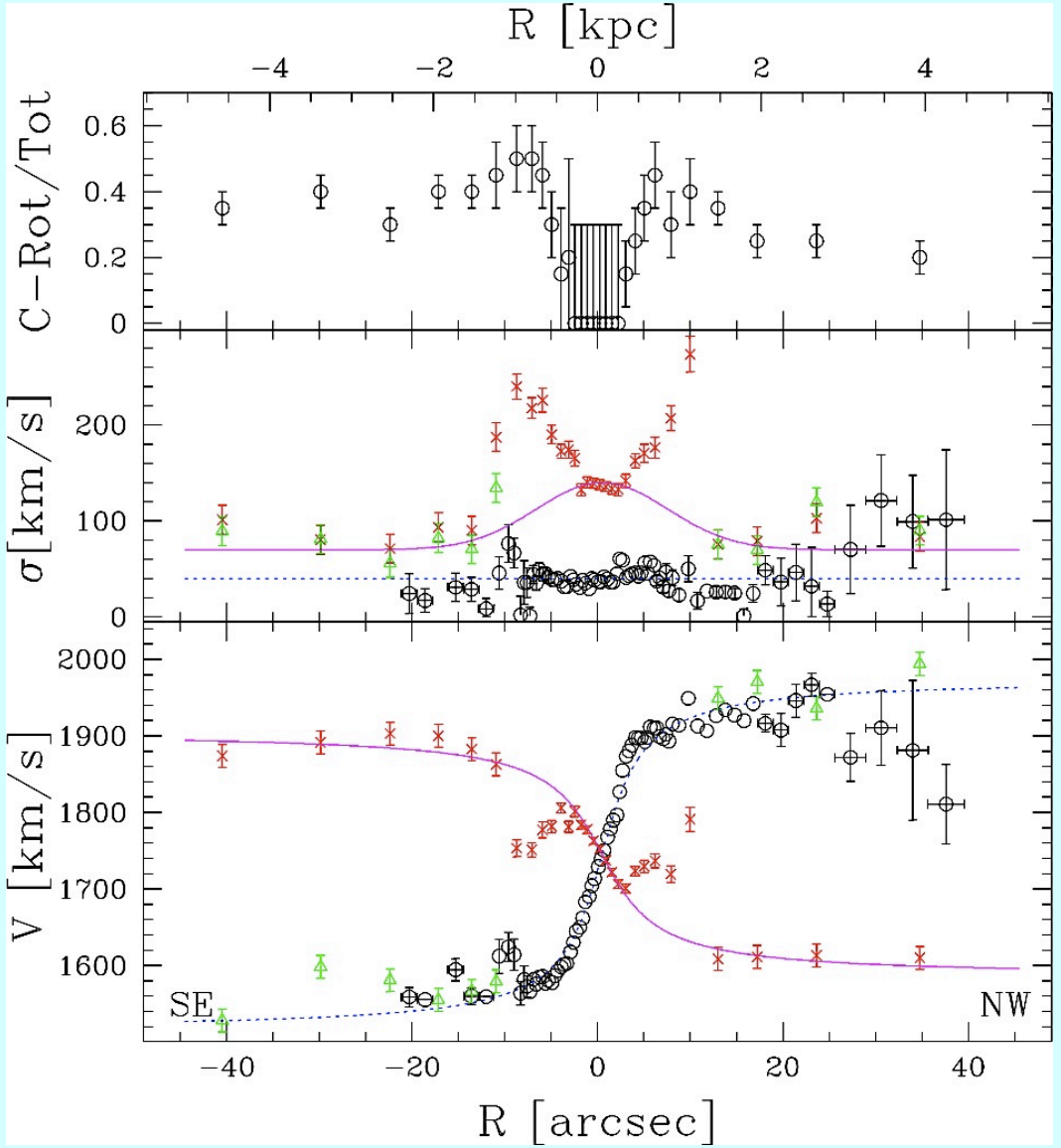
Outer Stars v. Stars counter-rotation

NGC 5719 – Sab

Vergani et al. (2007)



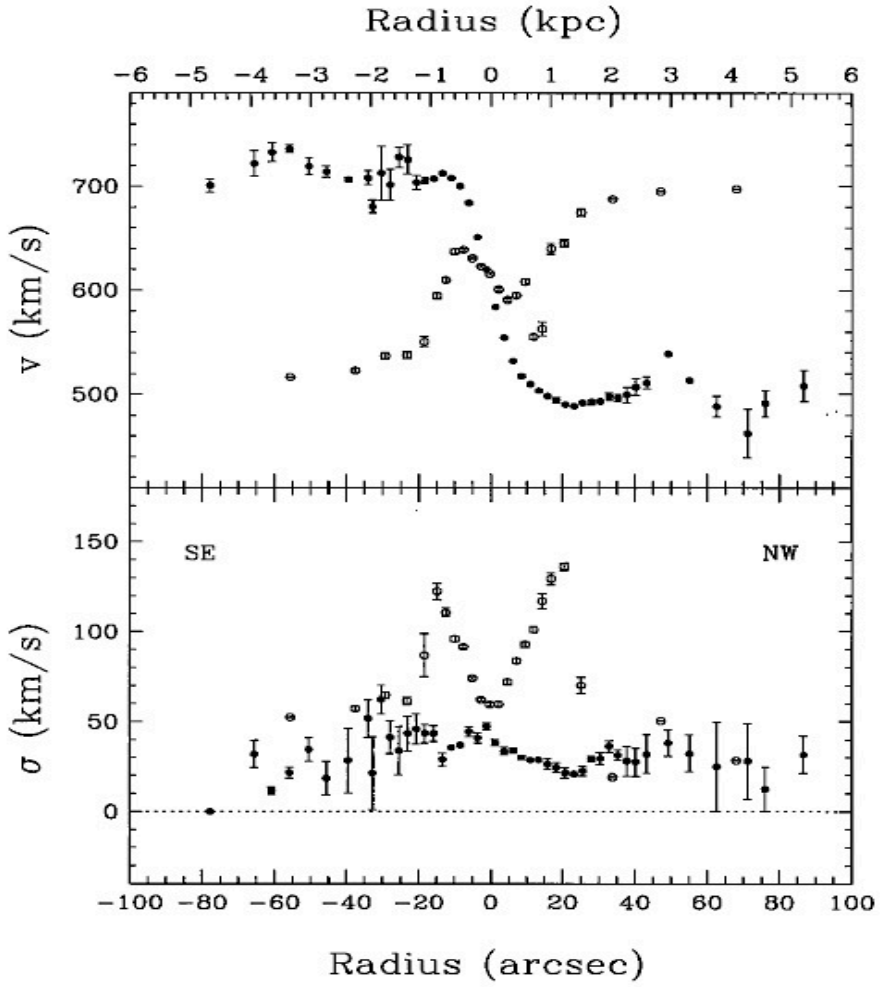


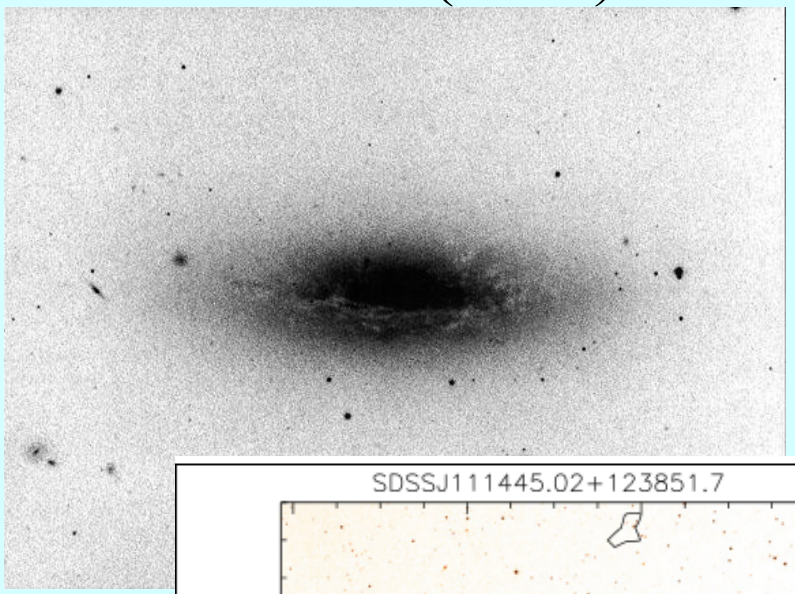


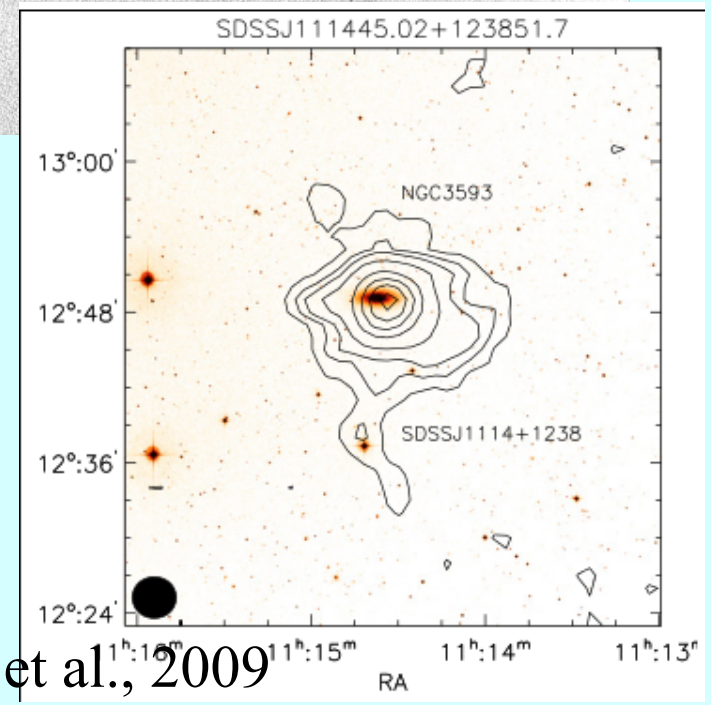
Inner Stars v. Stars counter-rotation

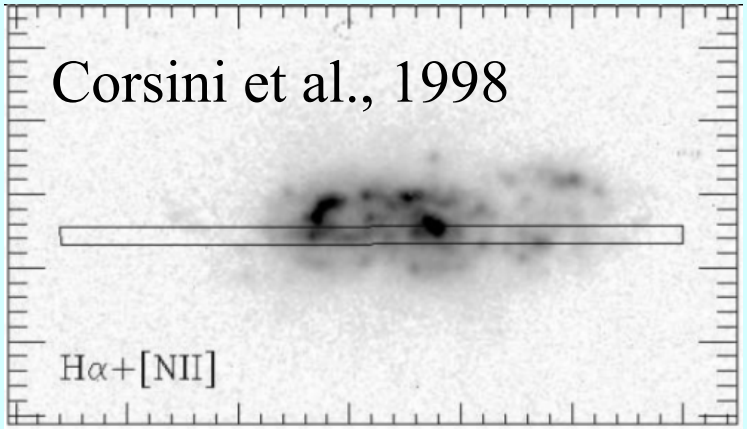
NGC 3593 – S0/a

Bertola et al. (1996)









Corsini et al., 1998

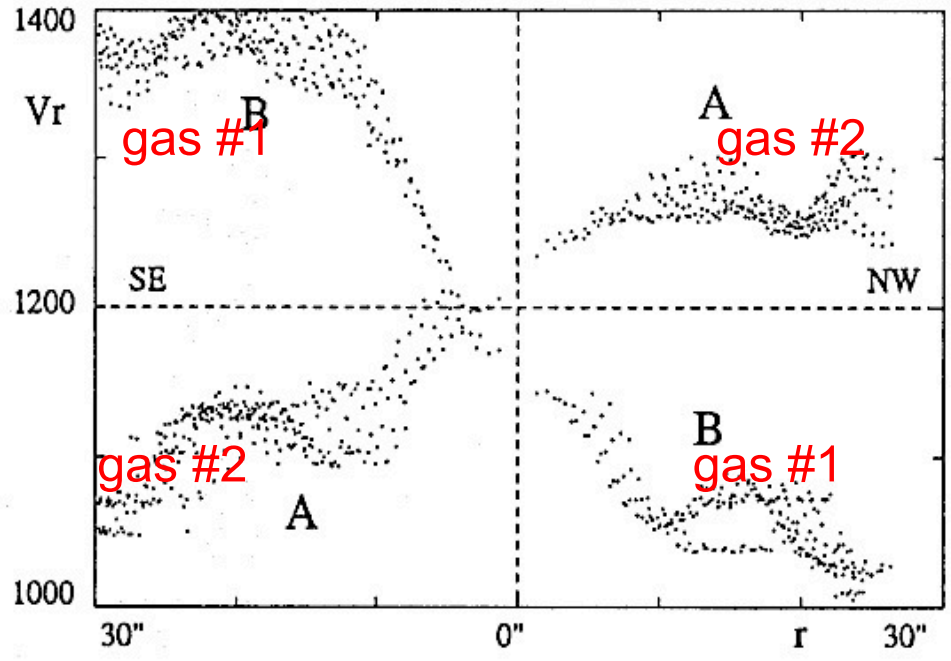
Grossi et al., 2009

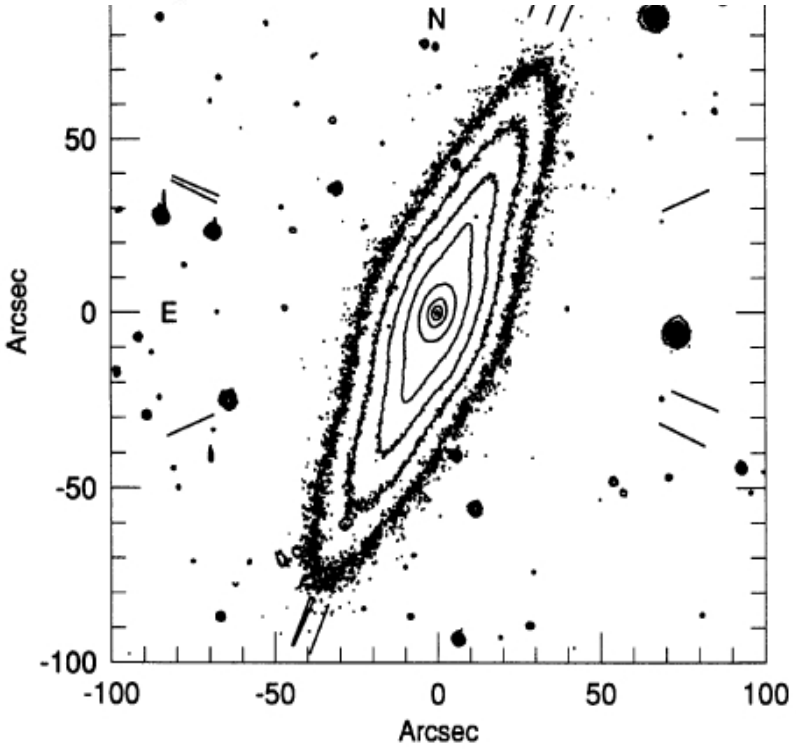
The advent of 2D-spectroscopy

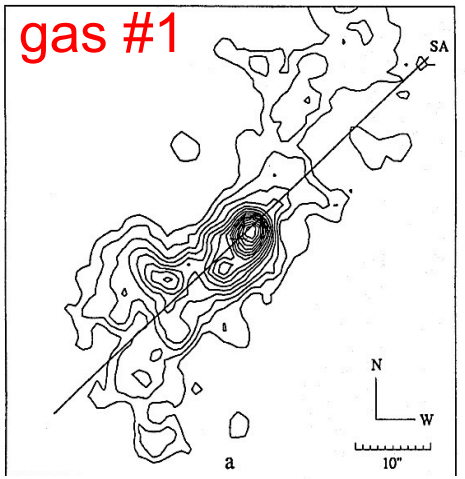
Gas vs Gas counter-rotation

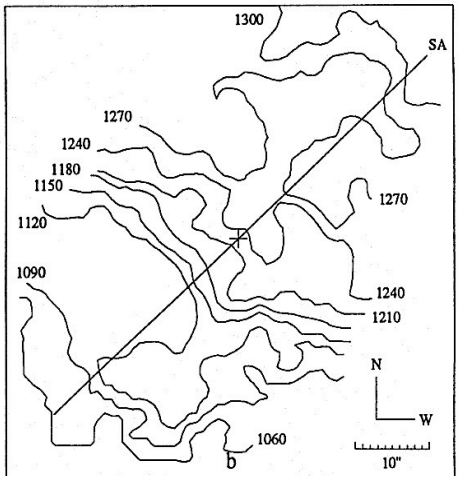
NGC 7332 – S0 pec – Perrot-Fabbry

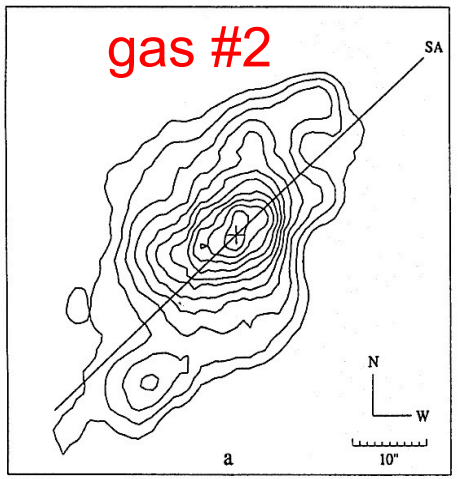
Plana & Boulesteix (1996)

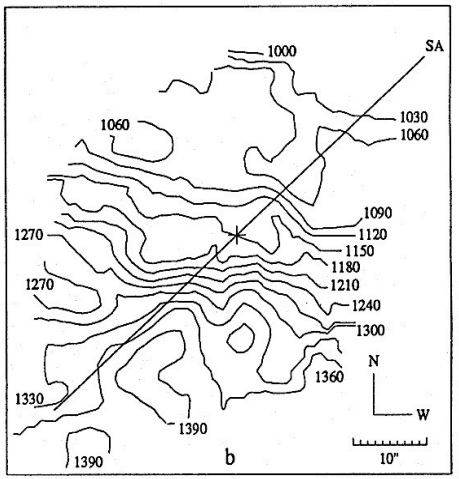






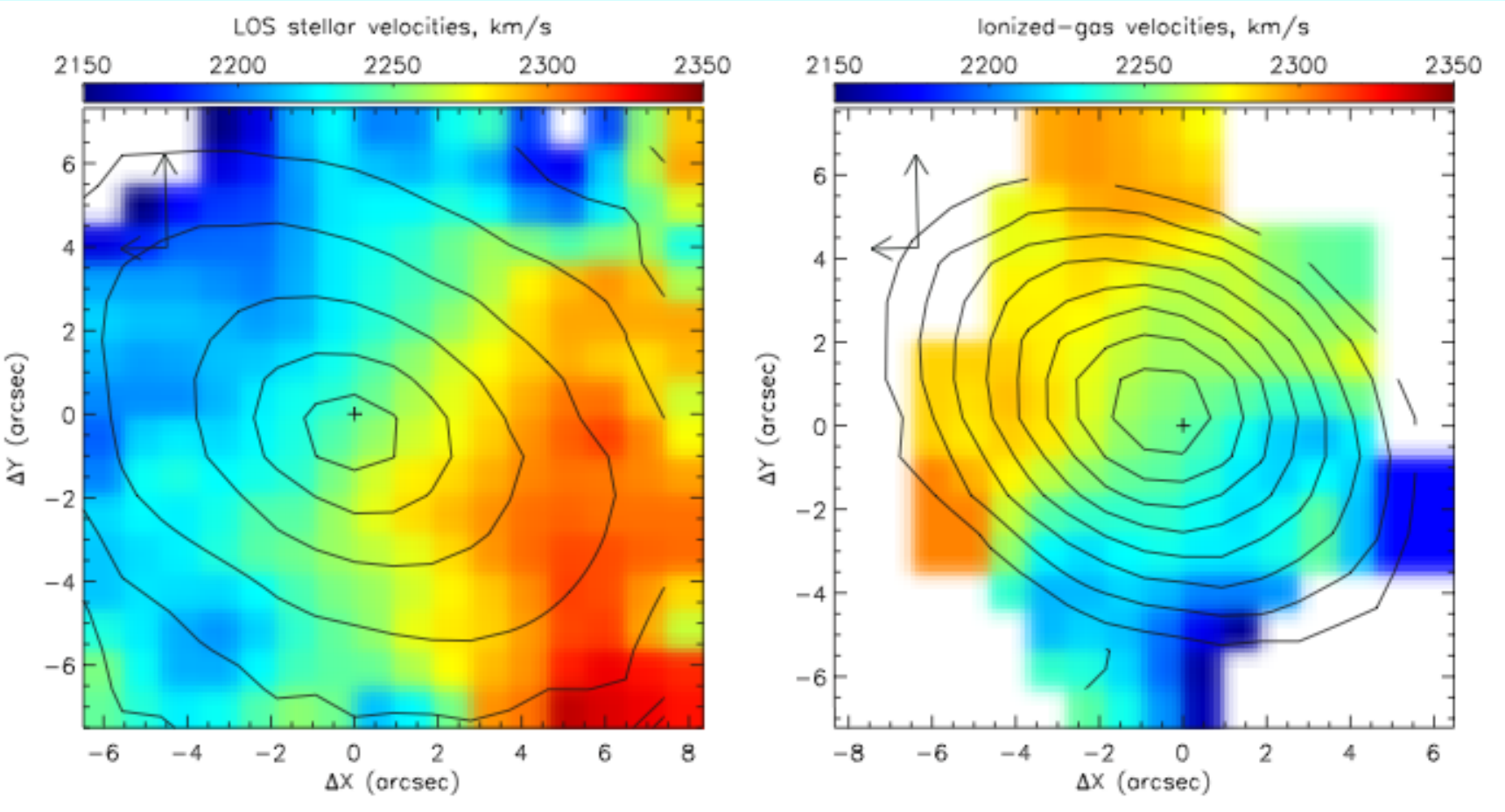






The advent of 2D-spectroscopy
Gas – Star counter-rotation

NGC 2551 – S0 Sil'chenko Moiseev, Afanasiev (2009) MPFS@BTA



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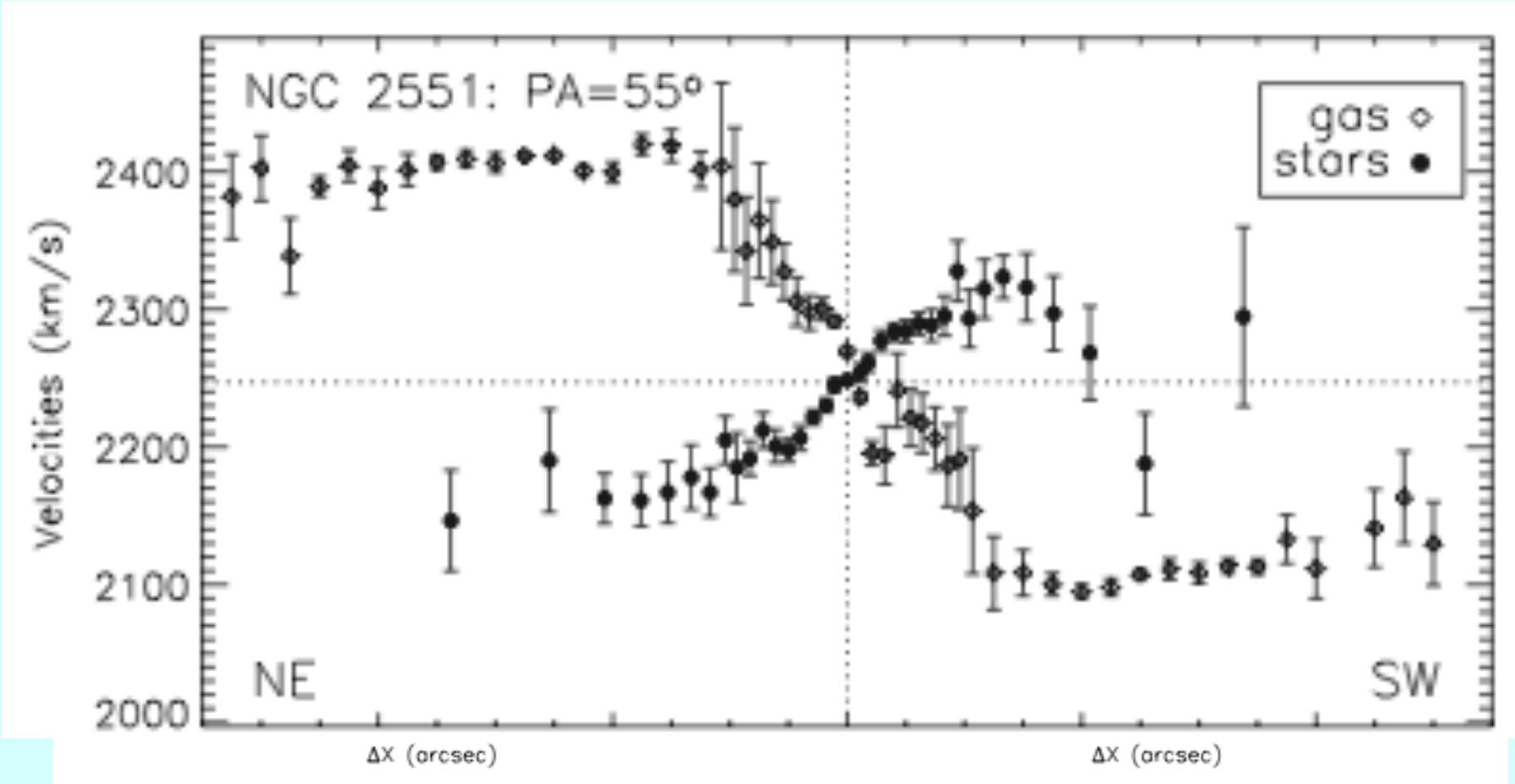
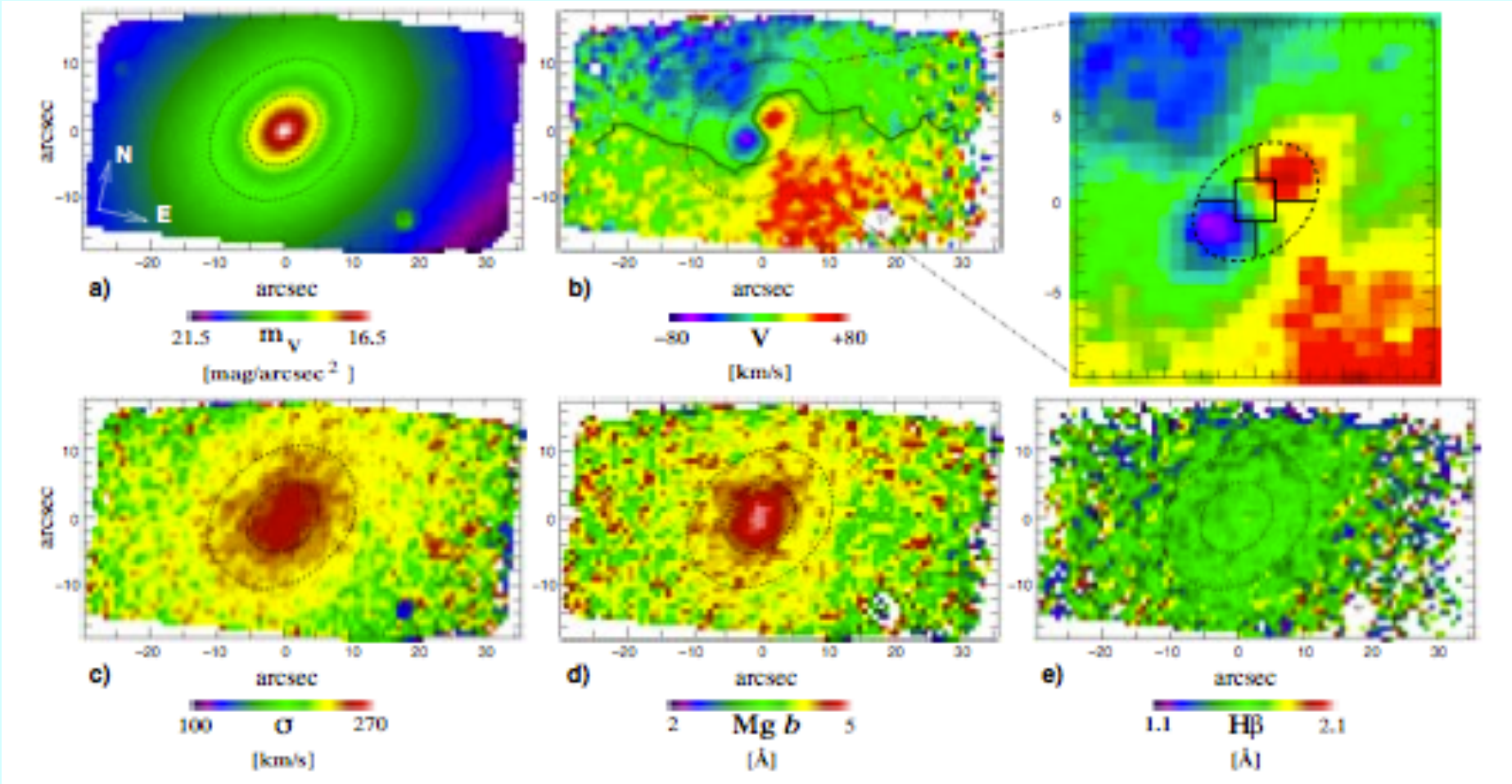


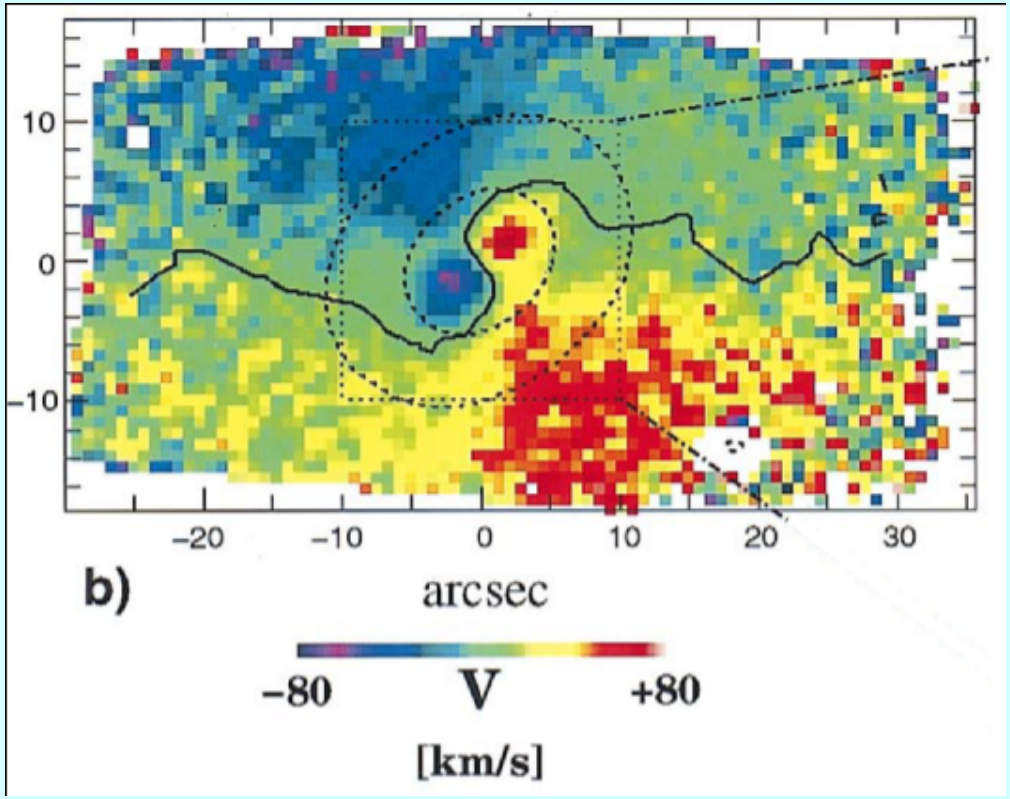
The advent of 2D-spectroscopy
Decoupled cores

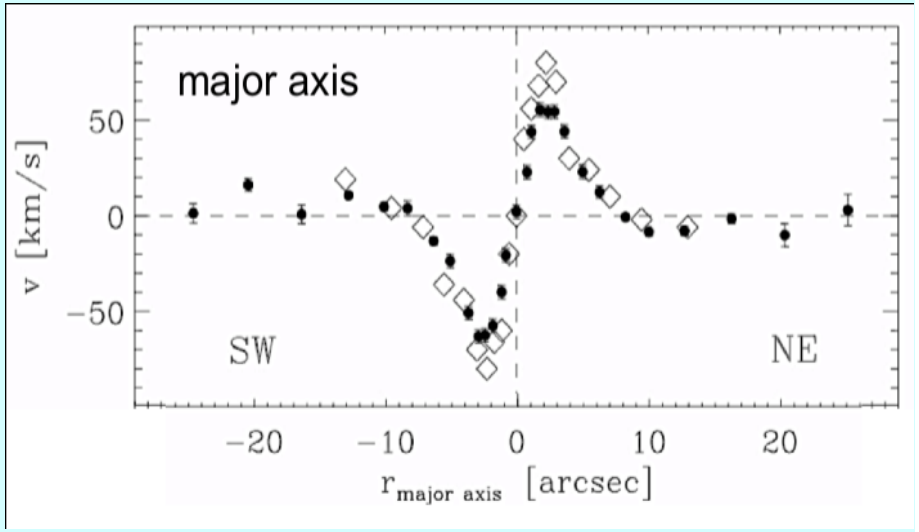
NGC 4365 – E3 Davies et al. (2008 - SAURON@WHT)



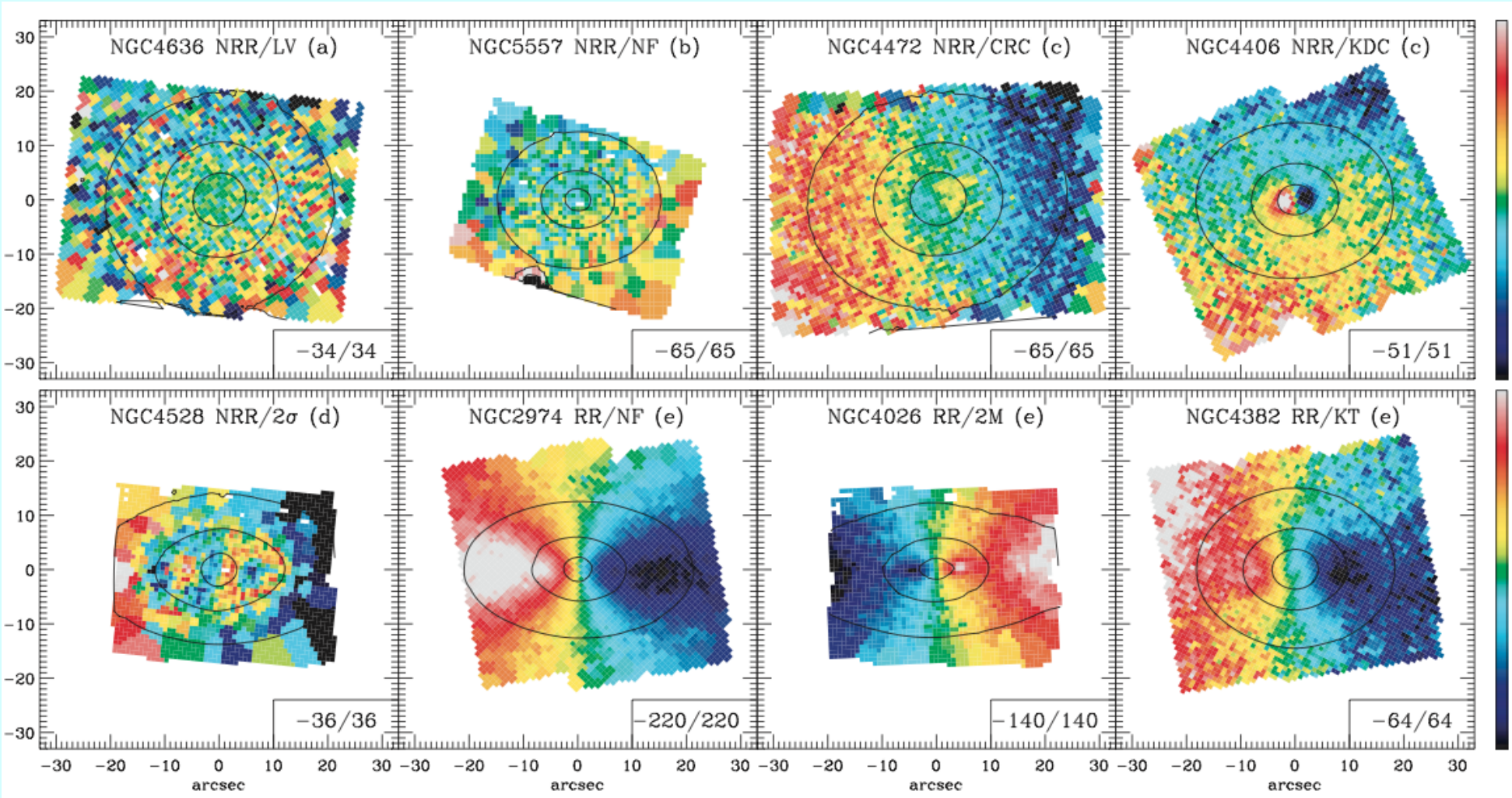
Decoupled cores

NGC 4365 – E3





Krajnovic et al. 2011 – SAURON
CRC – Counter-rotating cores
KDC – kinematically decoupled cores



Krajnovic et al. 2011 – SAURON
CRC – Counter-rotating cores
KDC – kinematically decoupled cores

Feature	RR	NRR	Comment
NF	171	12	No feature on the map
2M	36	0	Double maxima in the radial velocity profile
KT	2	0	Kinematic twist
KDC	0	11	Kinematically distinct core
CRC	1	7	Counter-rotating core
2σ	4	7	Double peak on a σ map
LV	0	7	Low-level velocity (non-rotator)

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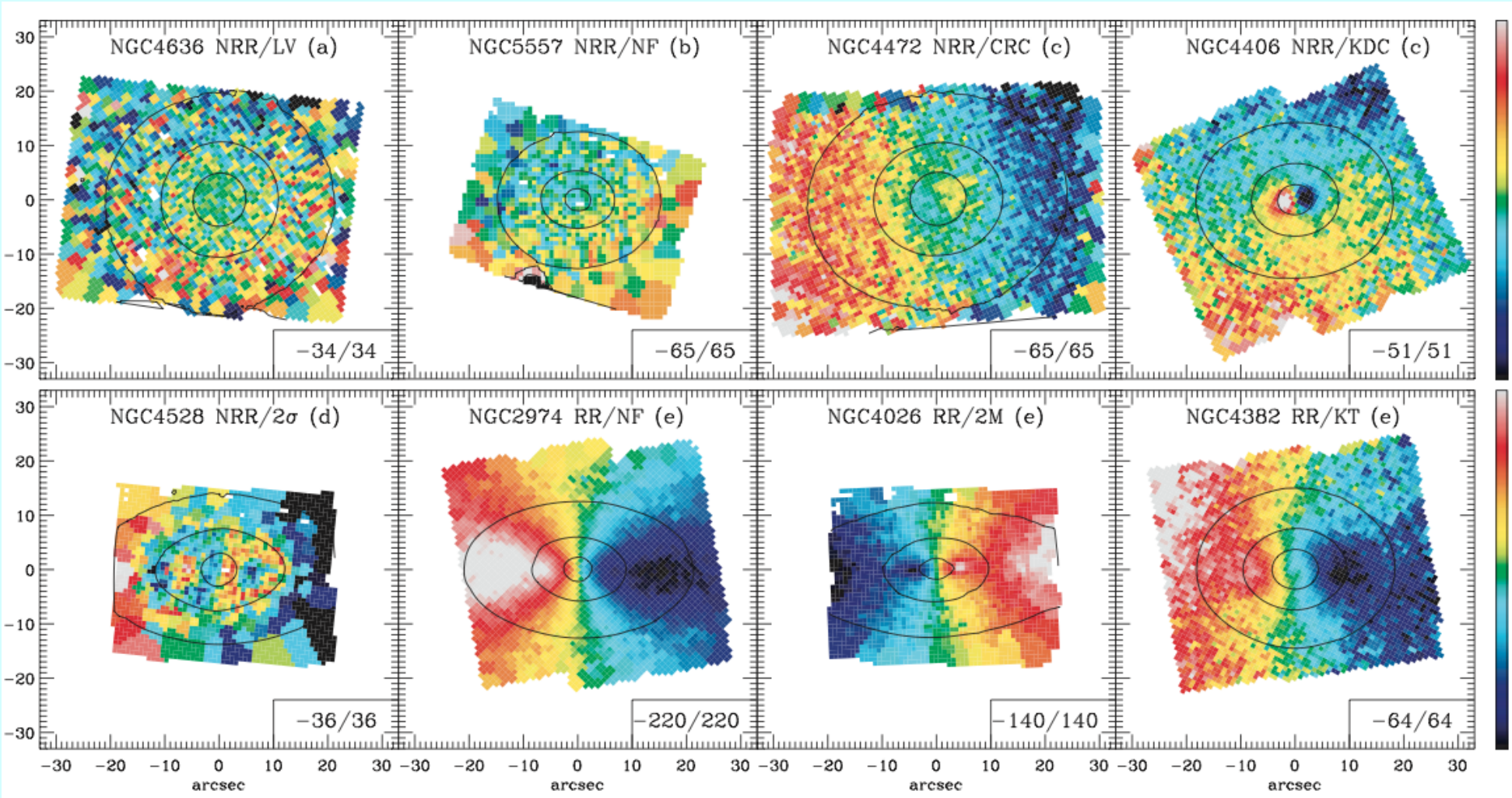
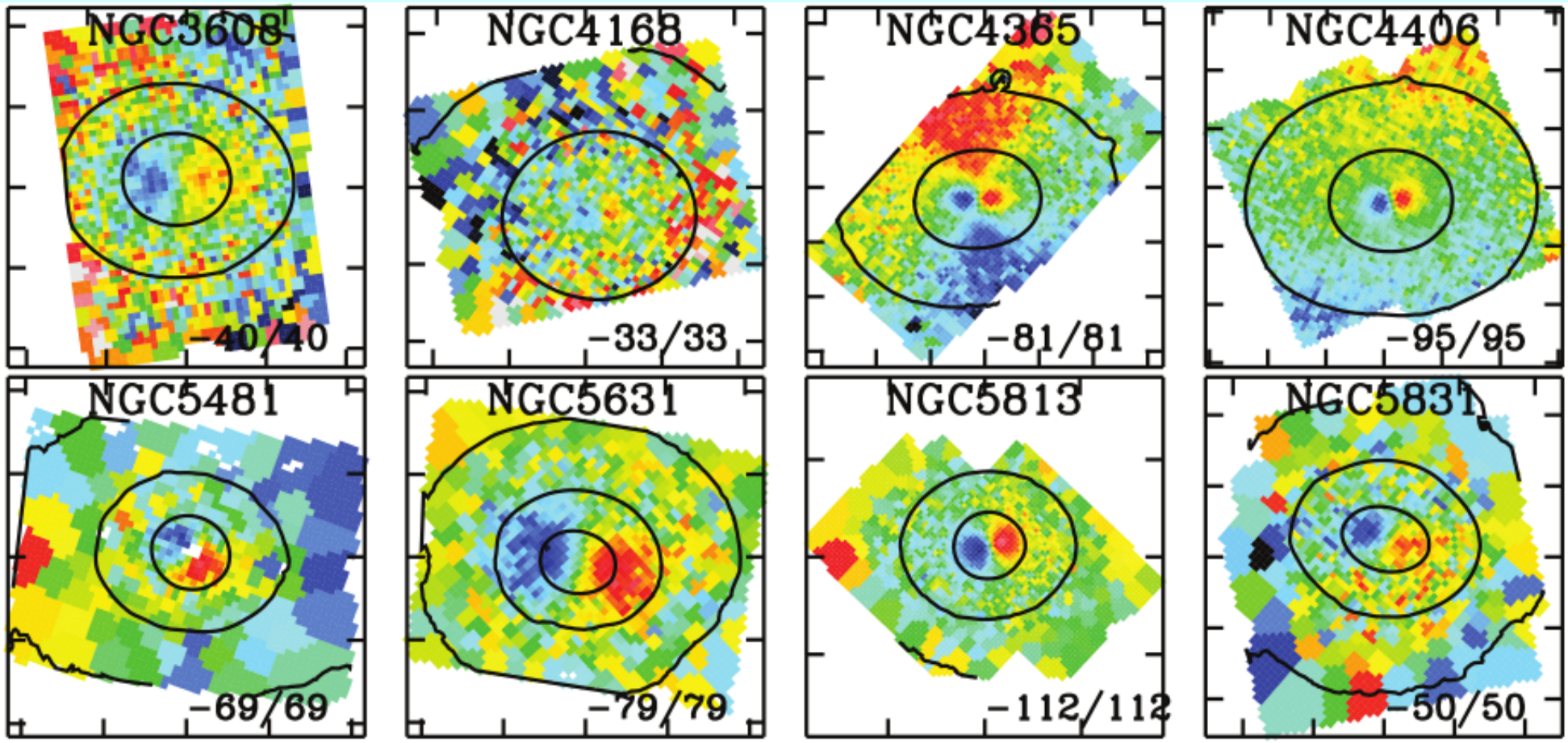
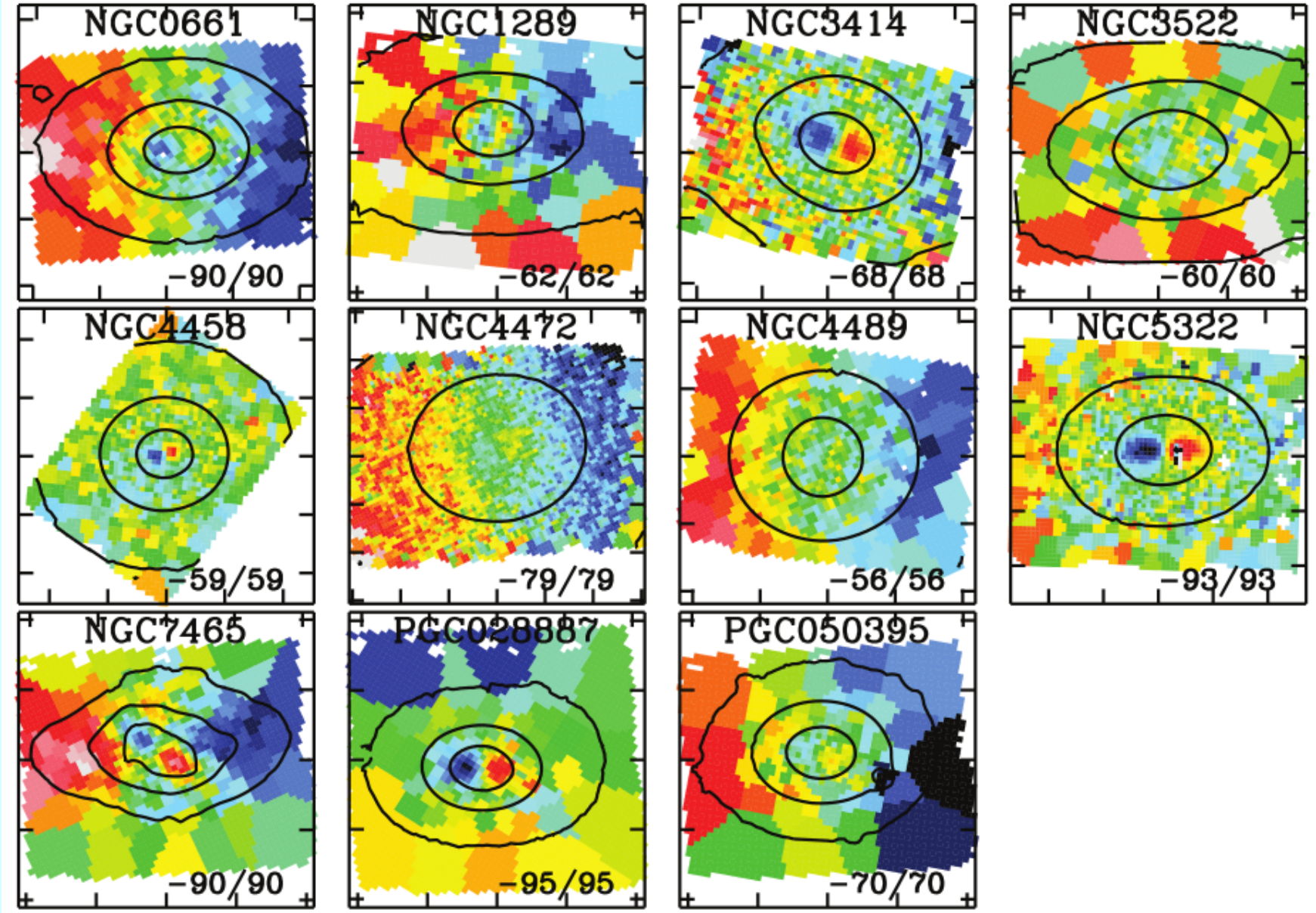


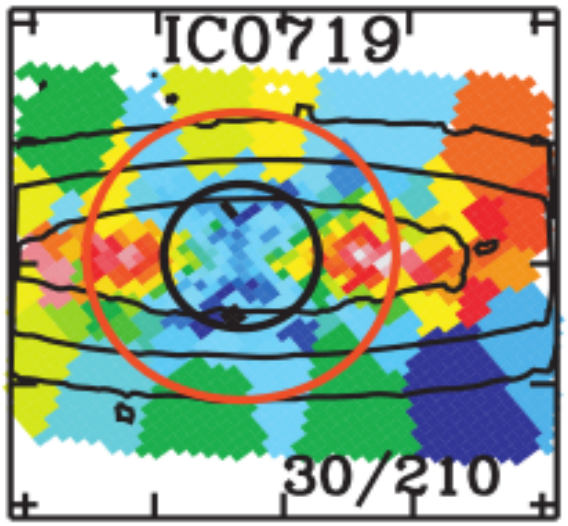
SAURON decoupled cores

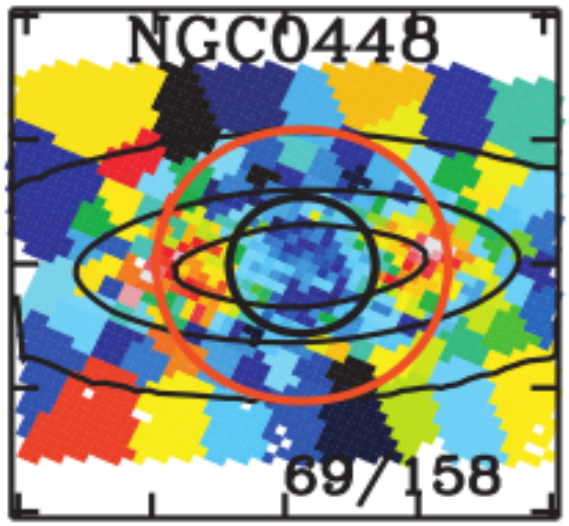


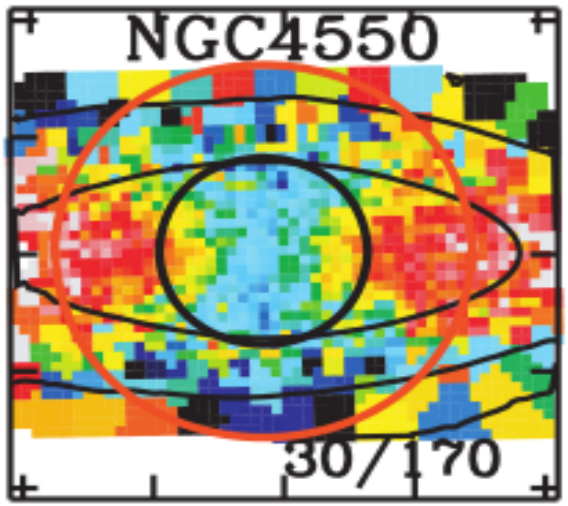
SAURON decoupled cores

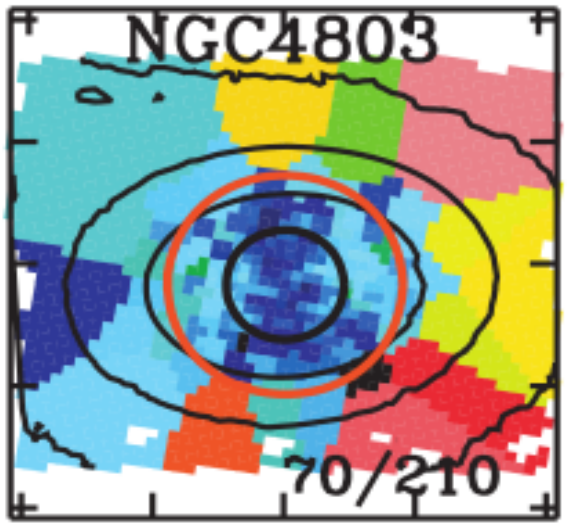


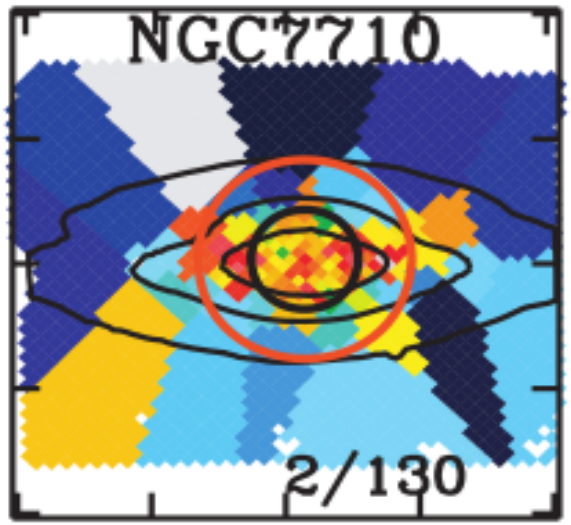
SAURON 2σ velocity dispersion



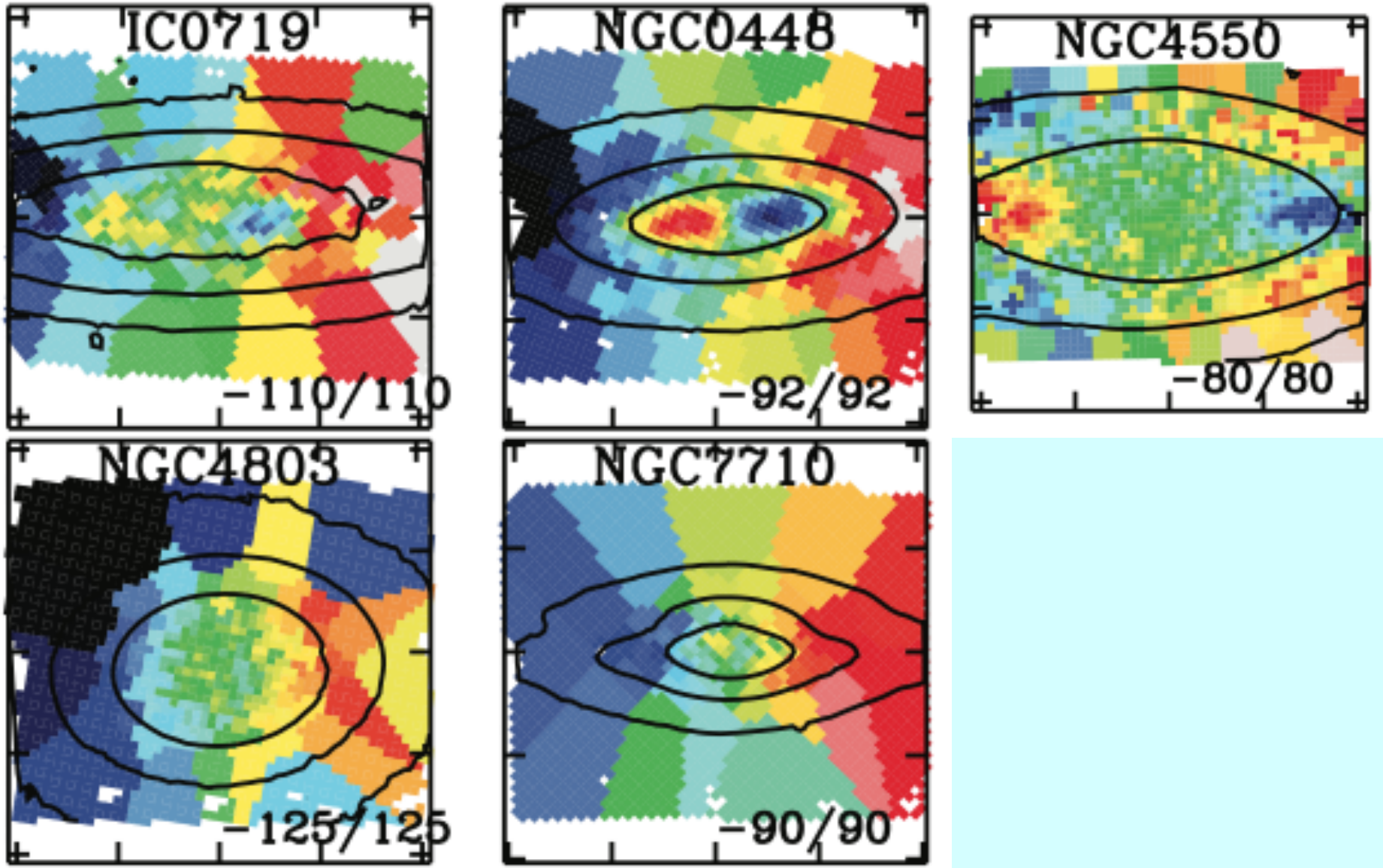




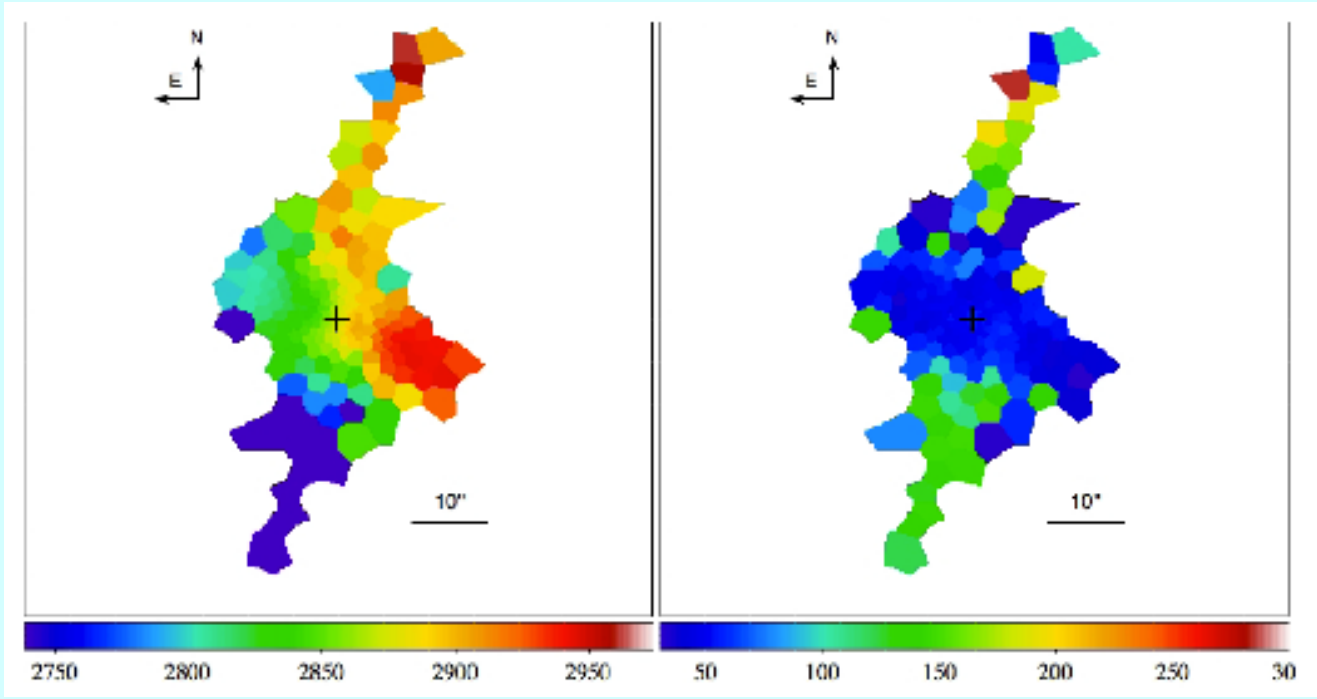




SAURON 2σ velocity

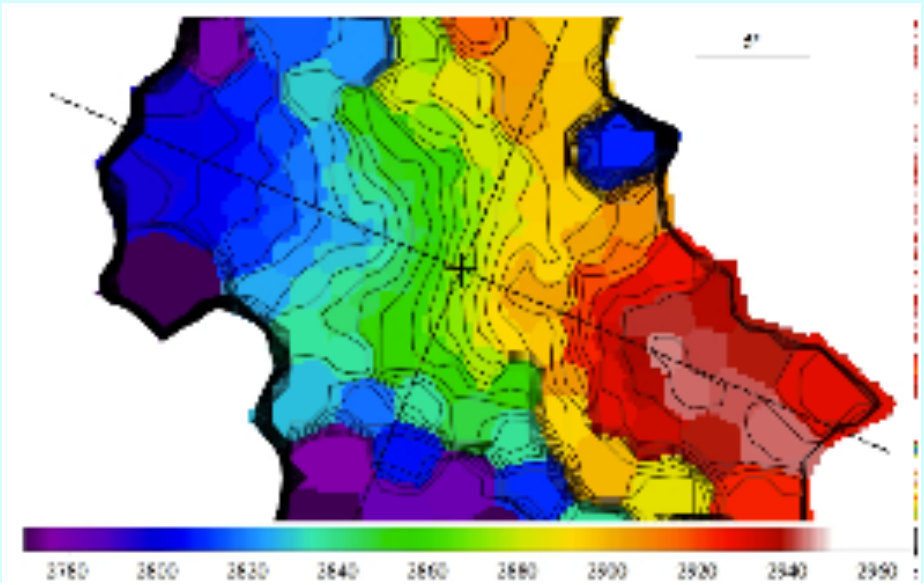


NGC 4650A
MUSE@VLT
Iodice et al. (2015)



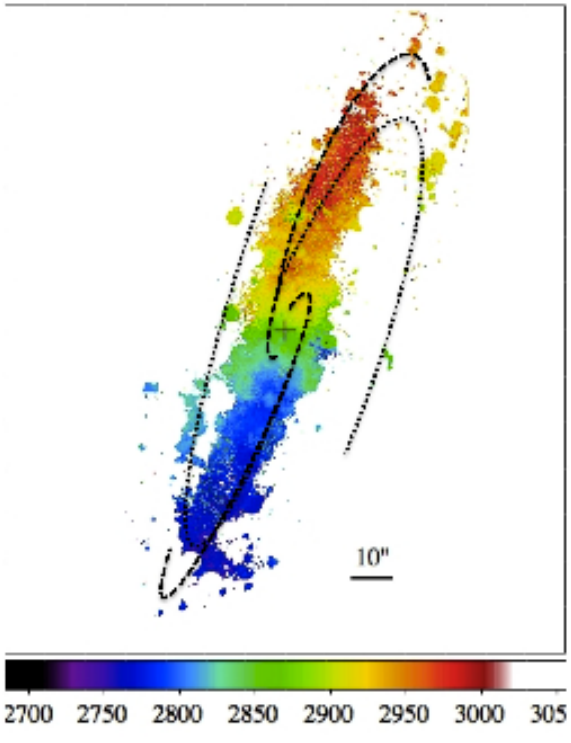
Stellar velocity

Stellar velocity dispersion

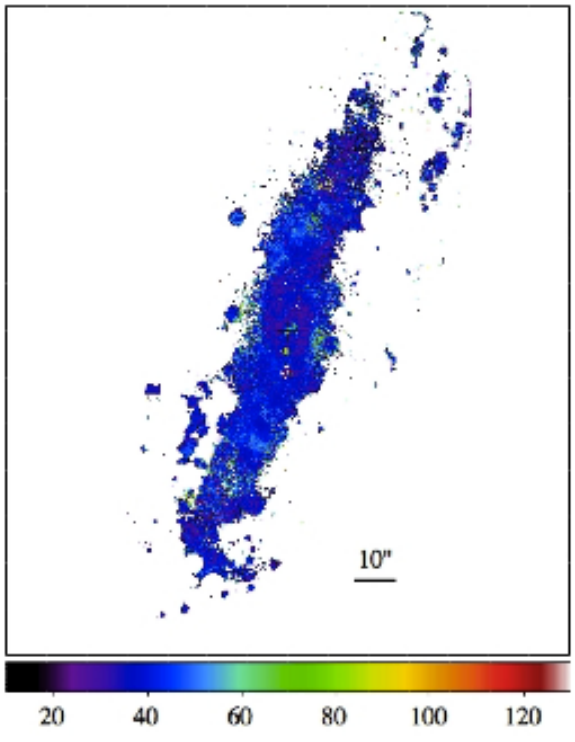


NGC 4650A

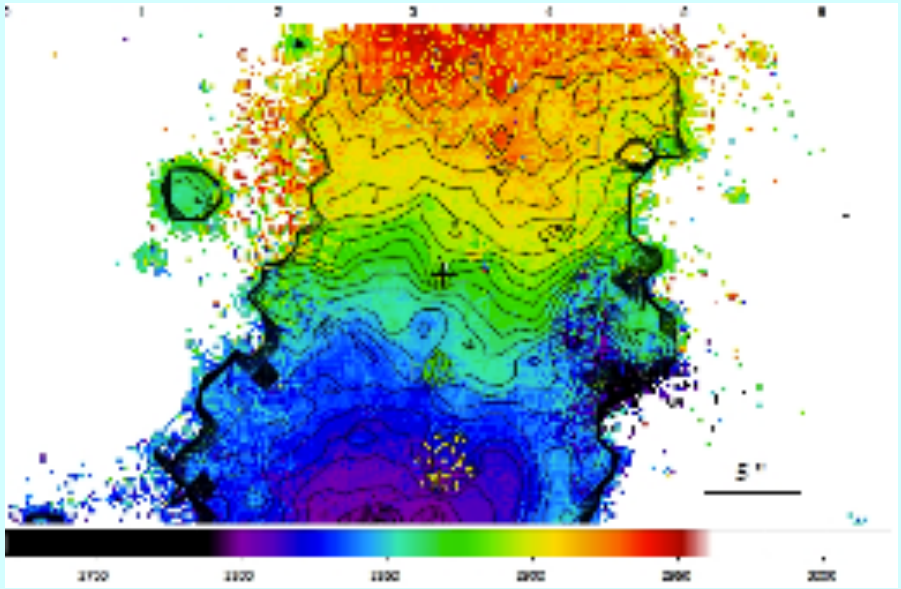
Iodice et al. (2015)



Ionized gas velocity

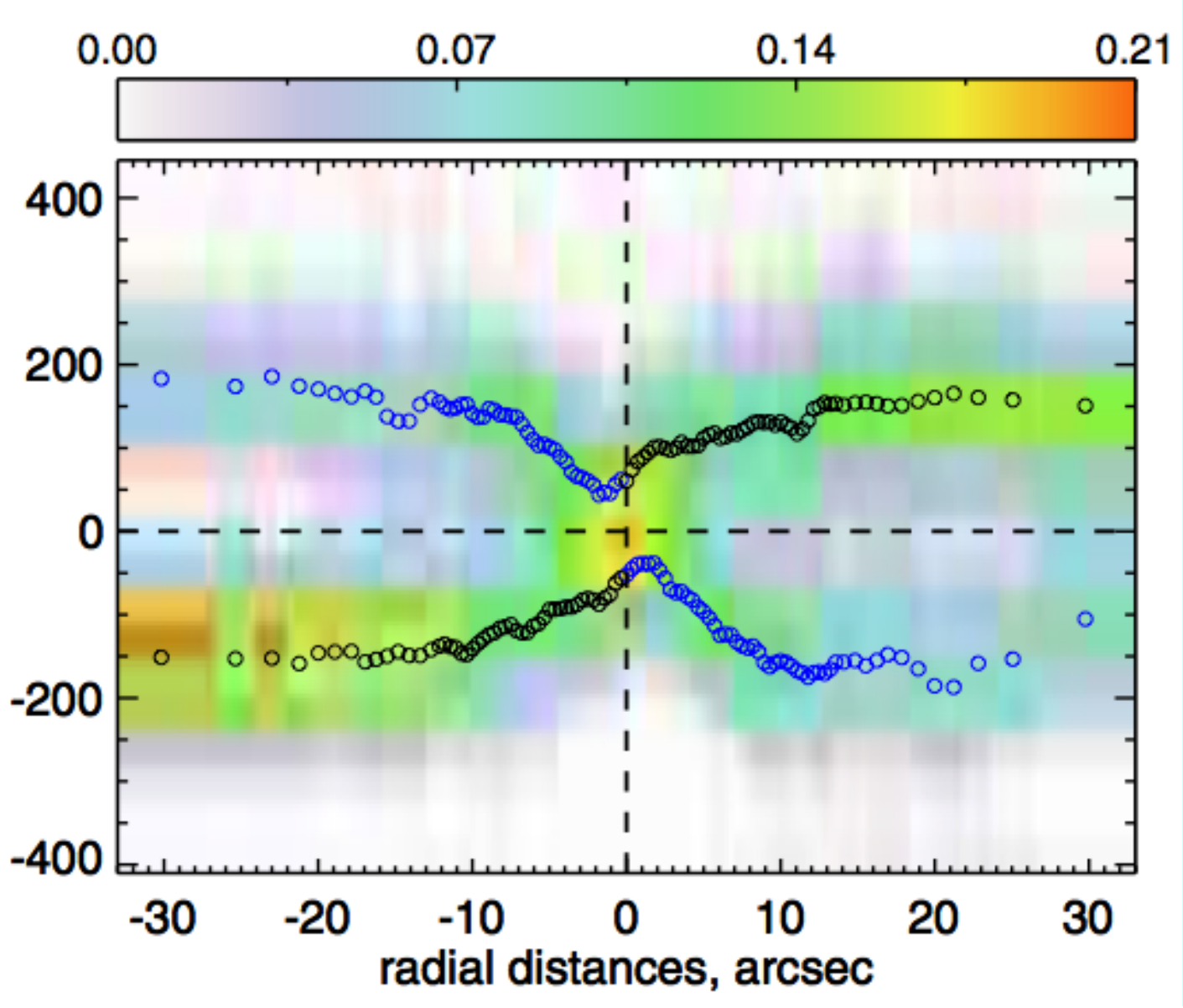


Ionized gas velocity dispersion



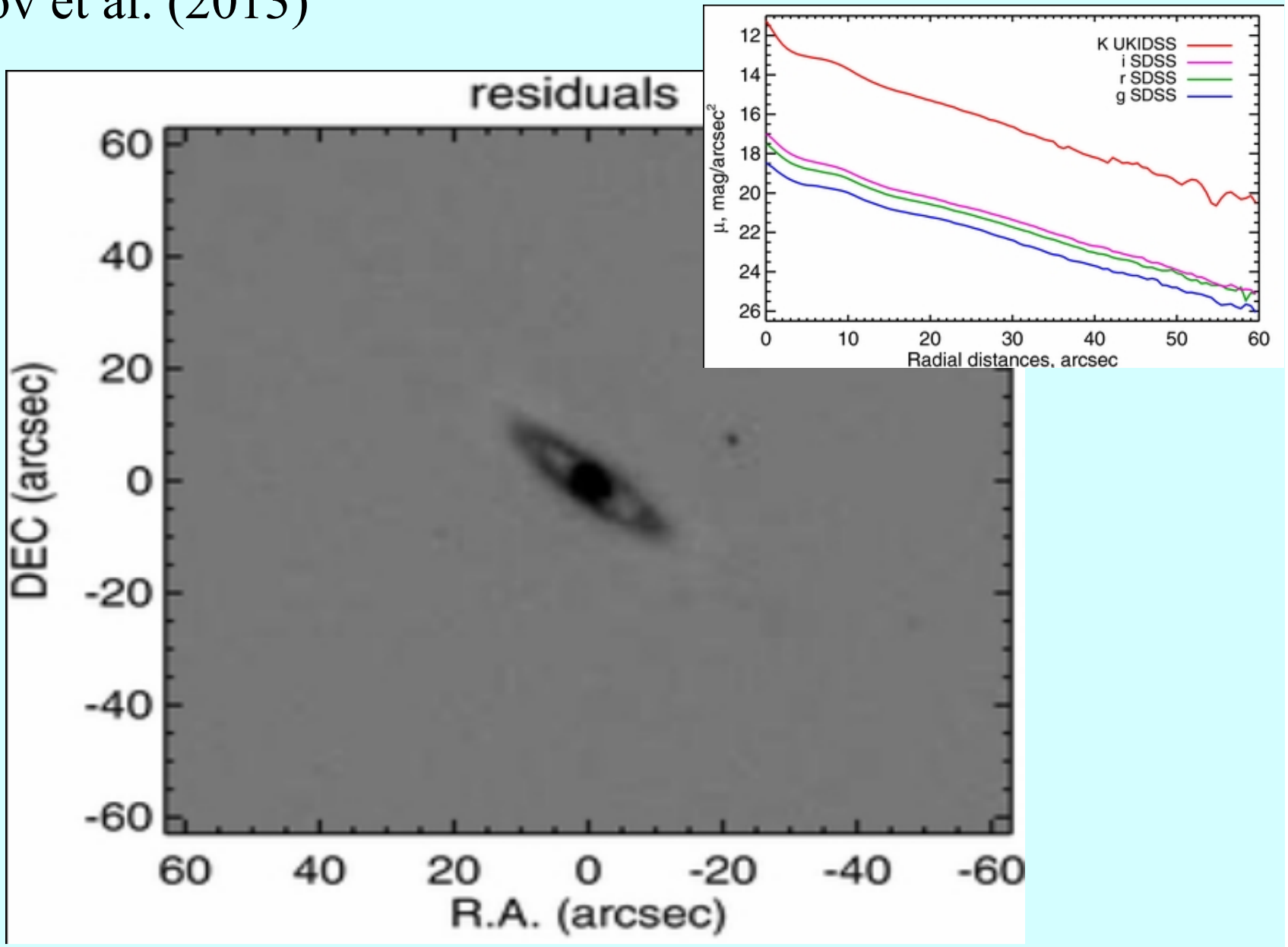
IC 719 SCORPIO-2@BAT

Katkov et al. (2013)

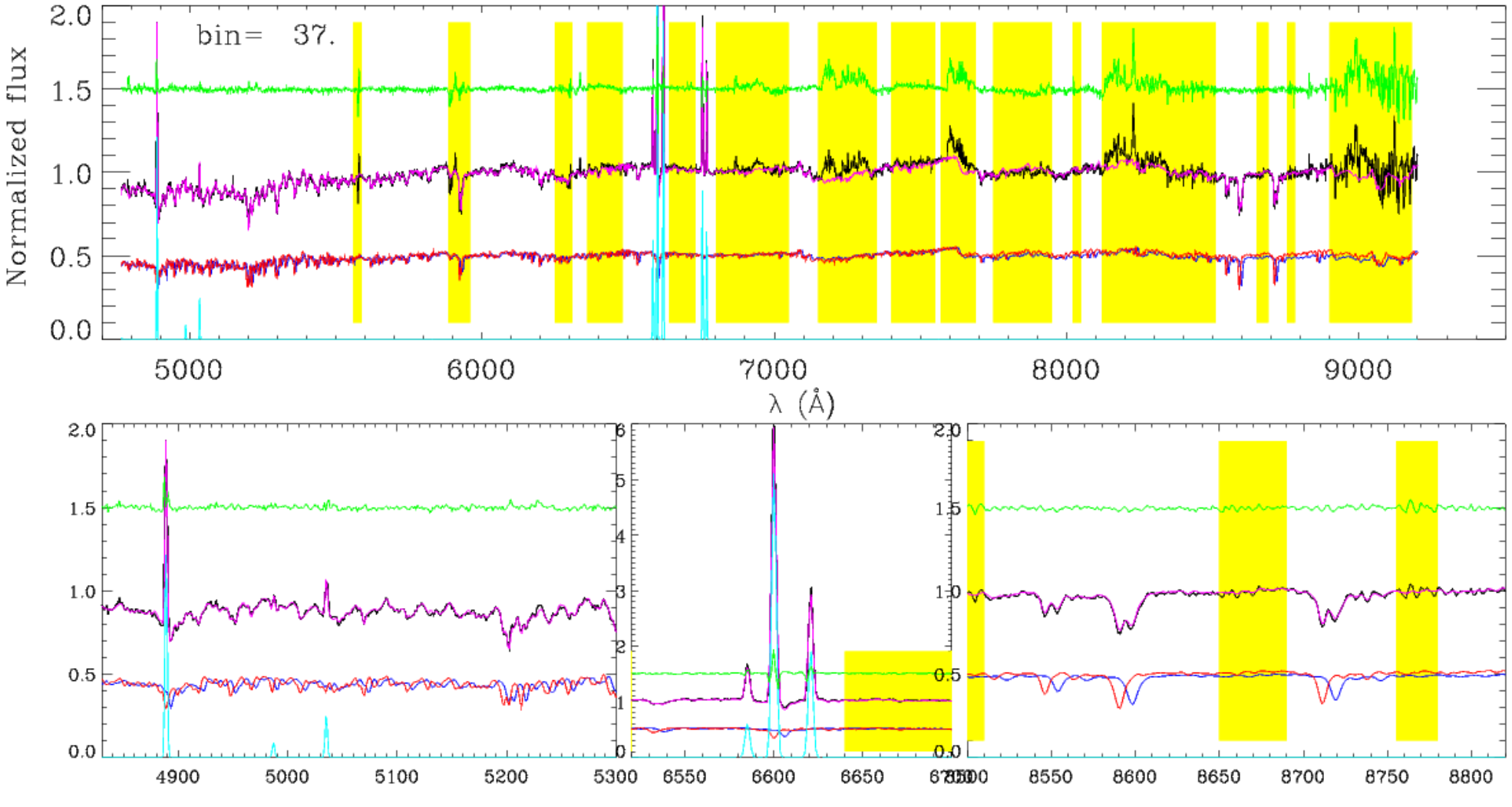


IC 719 UKIDSS photometry – Residual of a pure disk

Katkov et al. (2013)



MUSE@VLT - IC 719: full spectral fitting

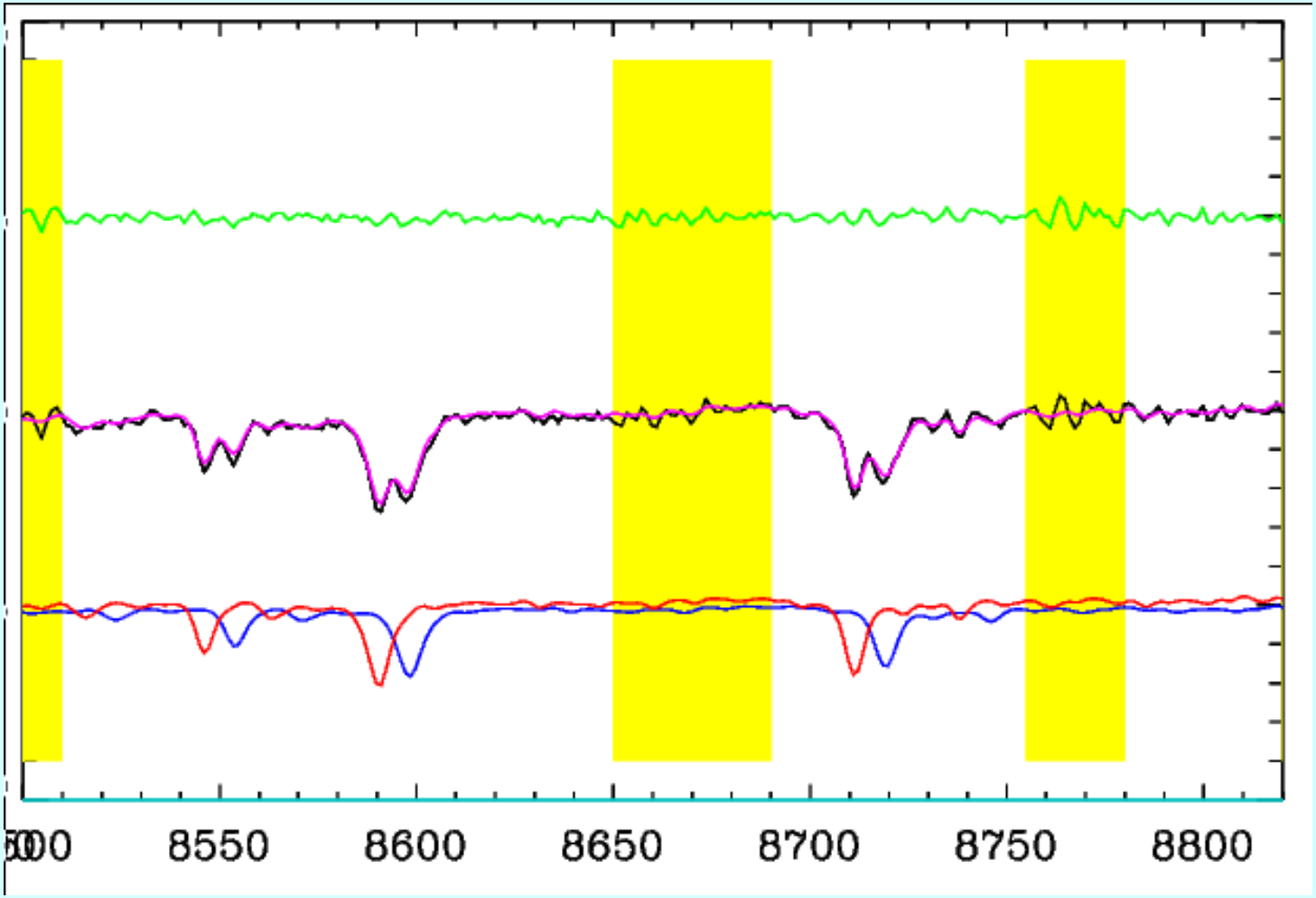


$\Delta\lambda$=2.5Å R=2000-3500 ; σ = 65 - 35 km/s

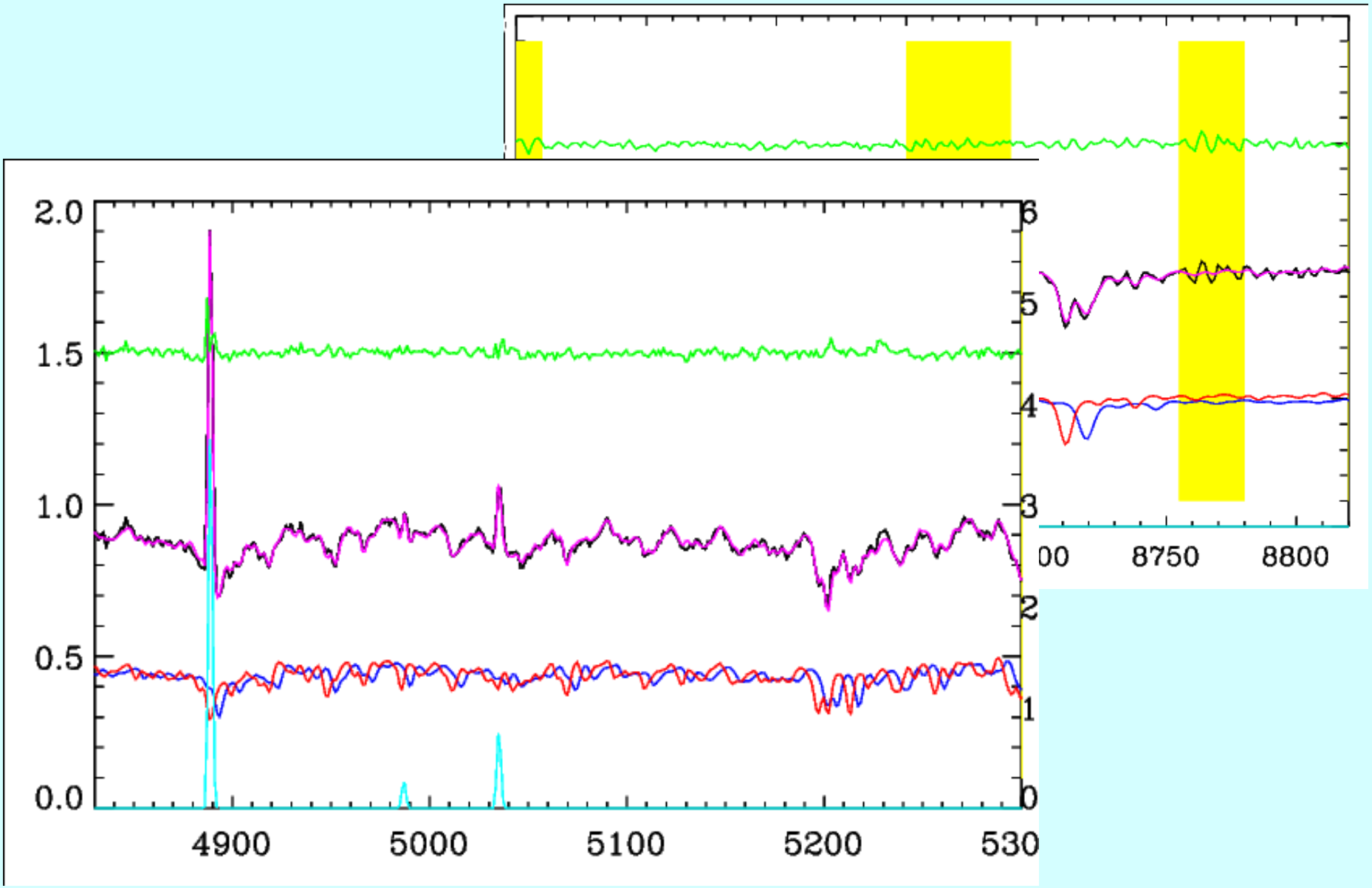
Stellar templates eMiles-MIUSCAT (Vazdekis et al. 2012)

pPXF (Cappellari & Emsellem 2004) based code (Coccato et al. 2011)

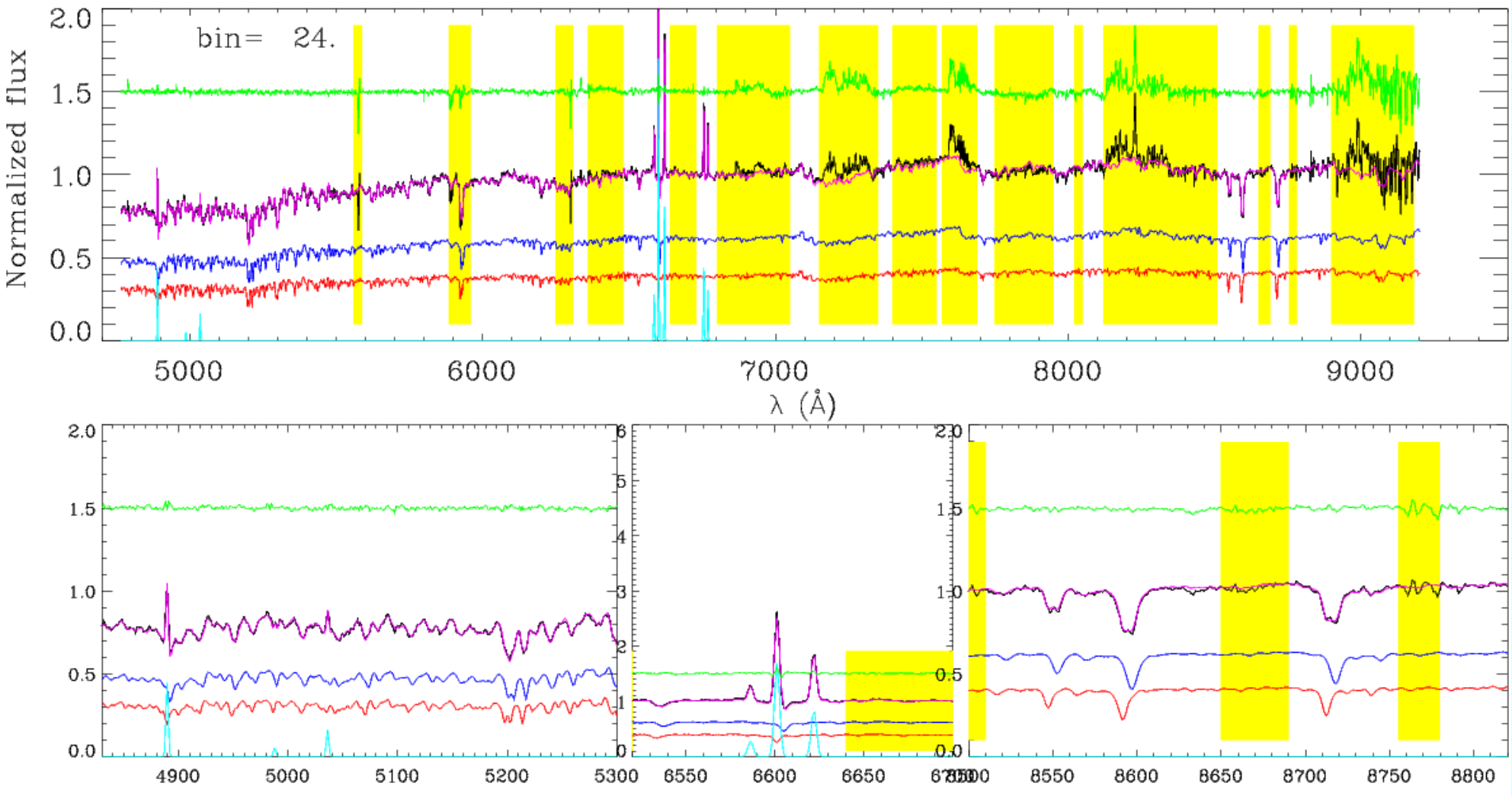
MUSE@VLT - IC 719: full spectral fitting



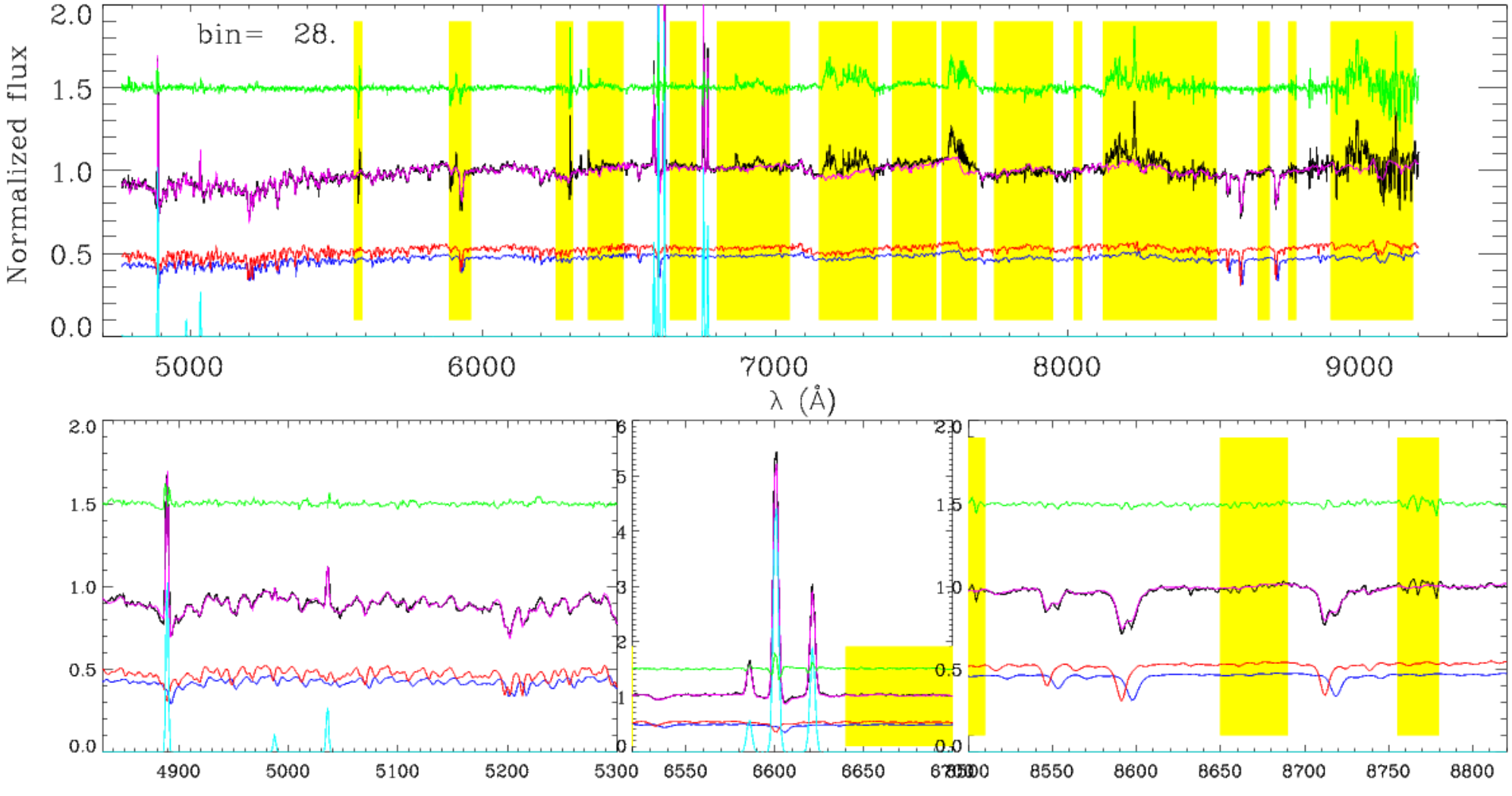
MUSE@VLT - IC 719: full spectral fitting



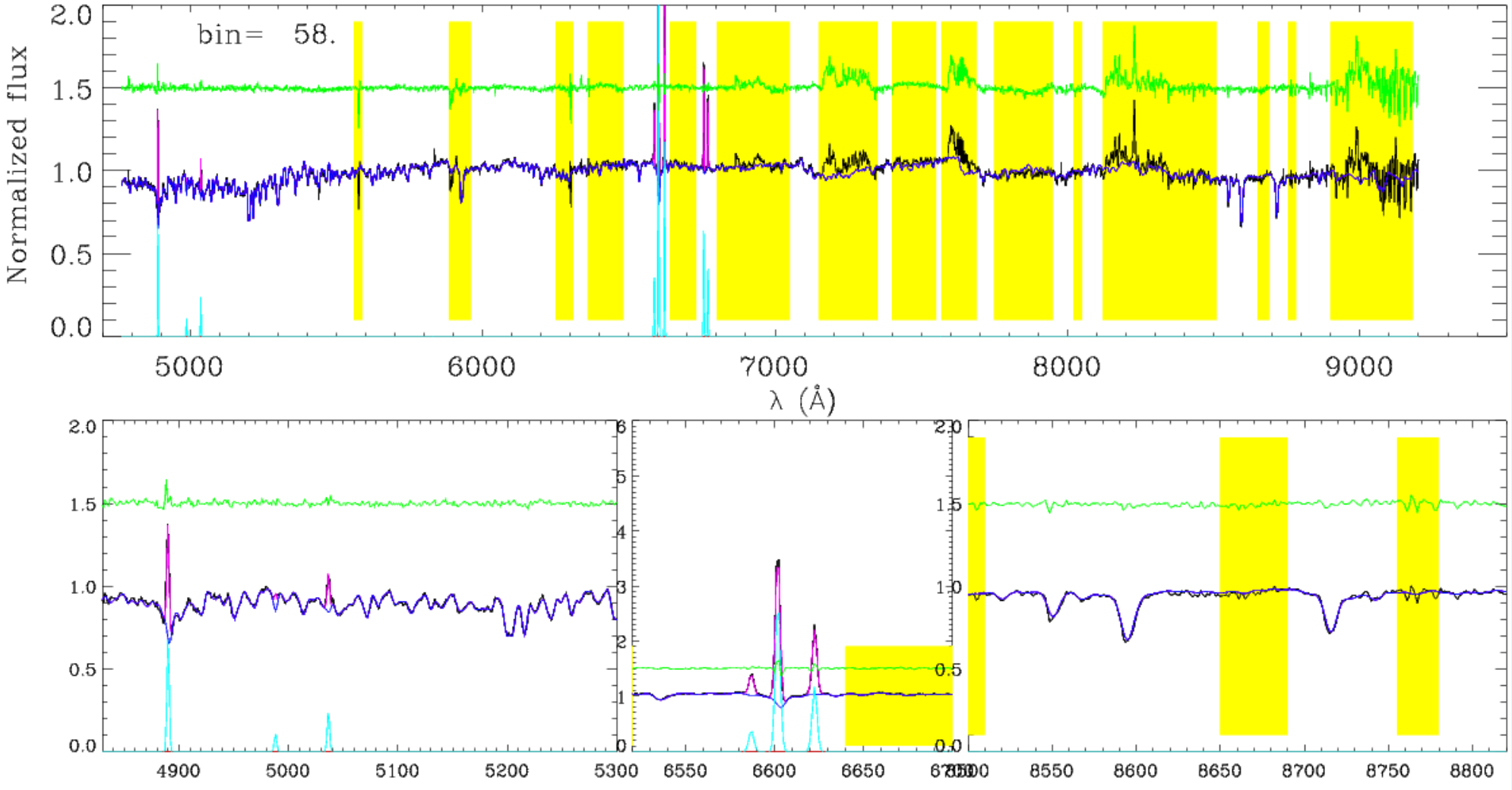
MUSE - IC 719: full spectral fitting



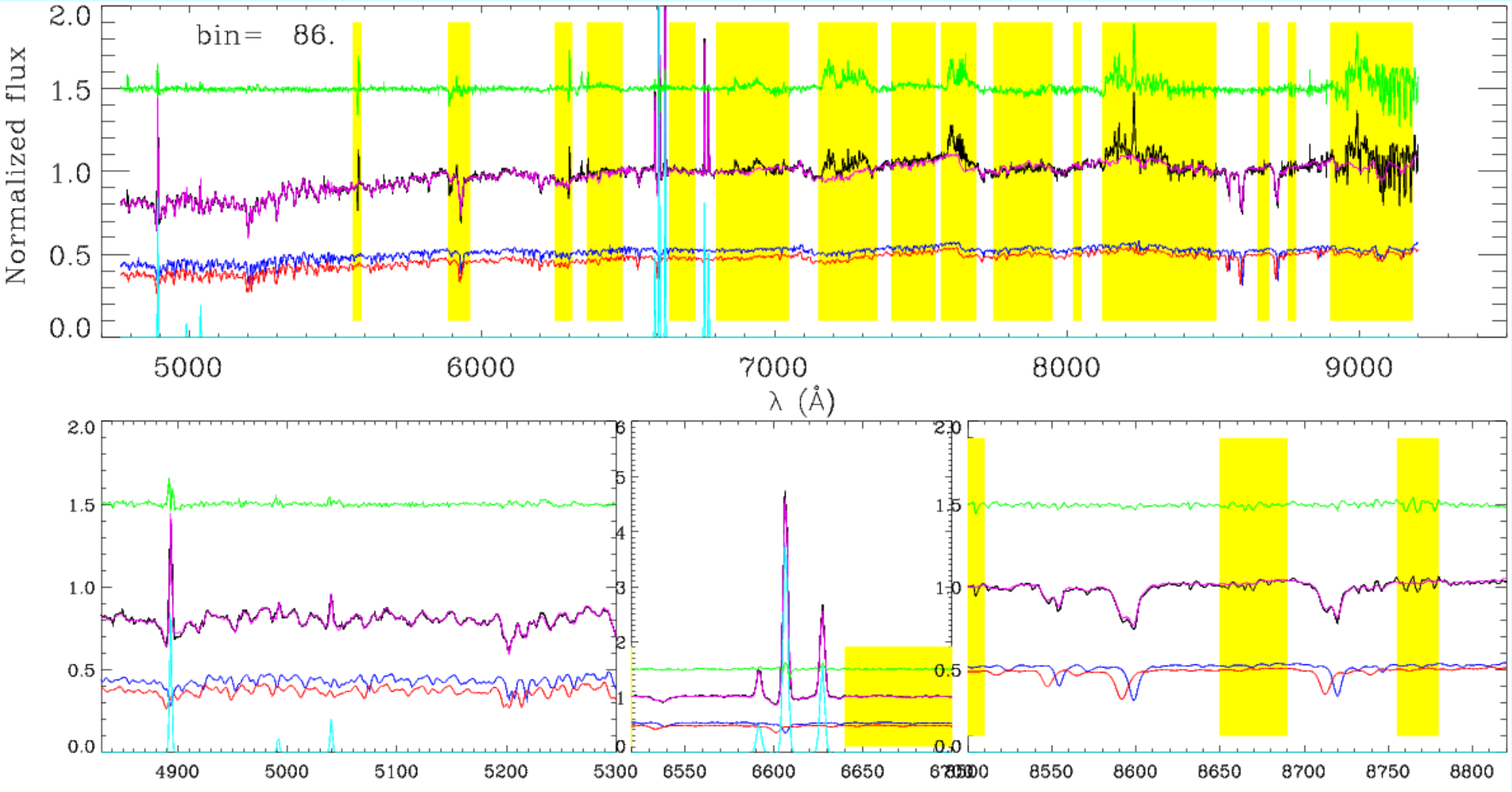
MUSE - IC 719: full spectral fitting



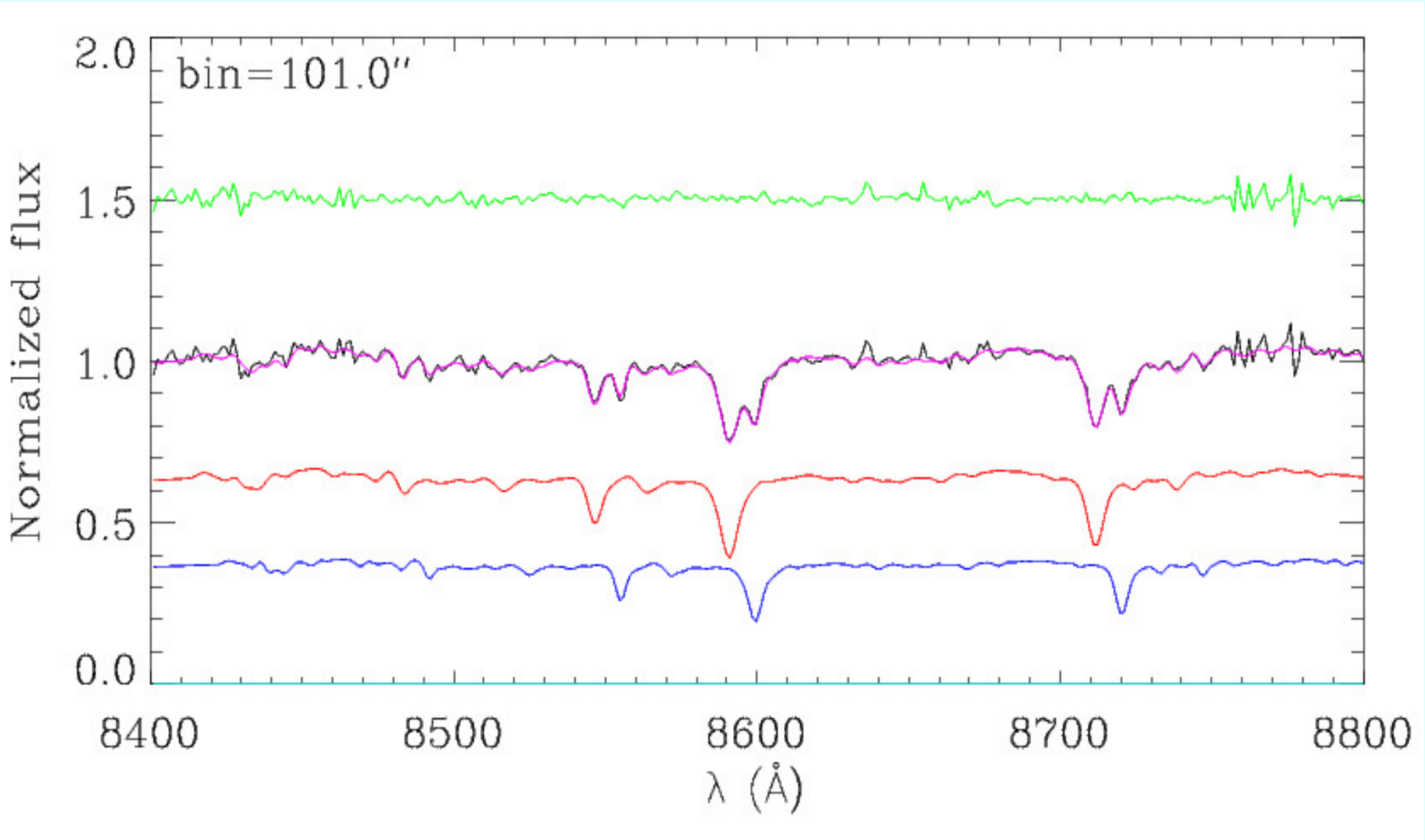
MUSE - IC 719: full spectral fitting



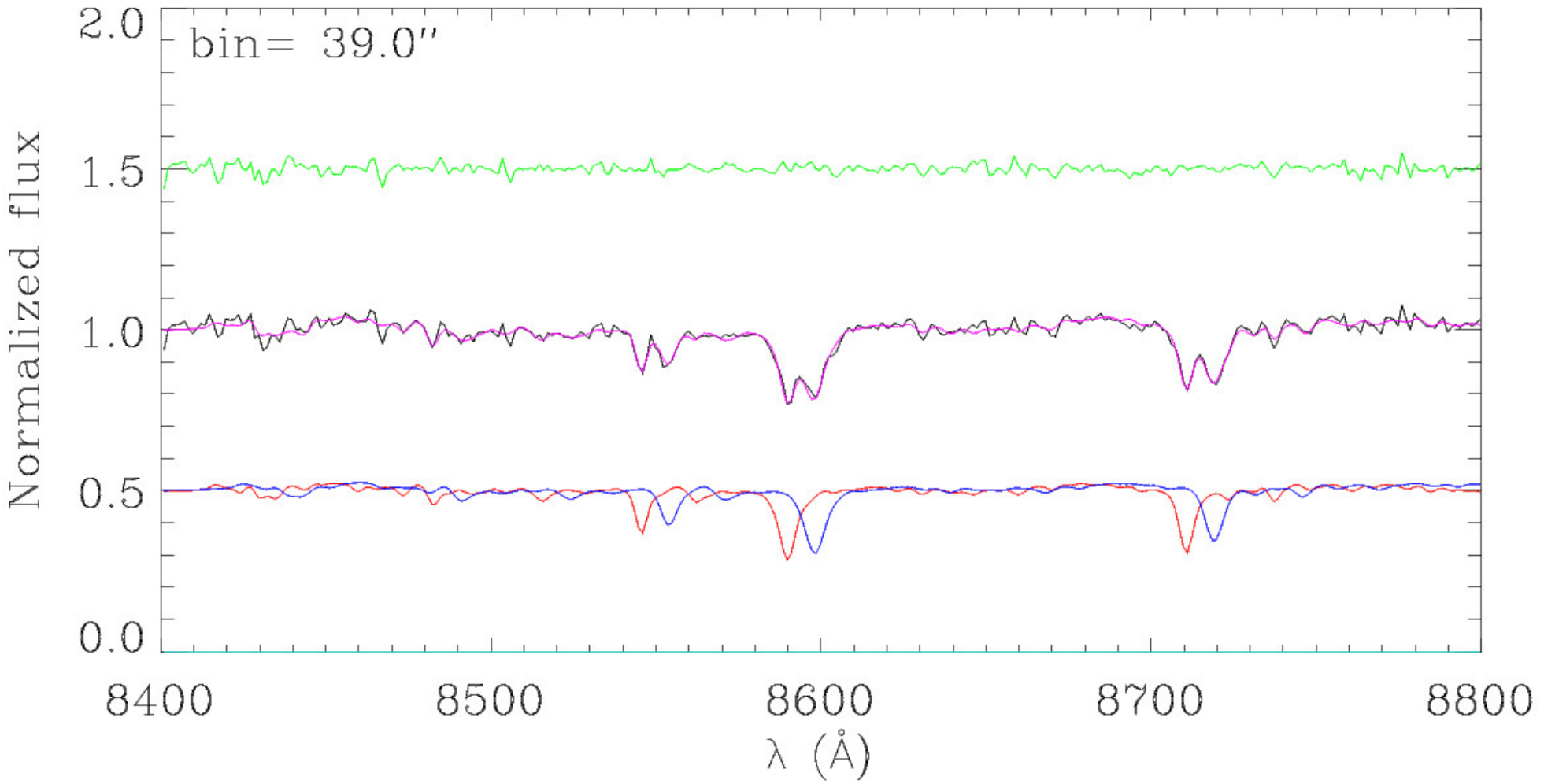
MUSE - IC 719: full spectral fitting



IC 719: Ca Triplet region

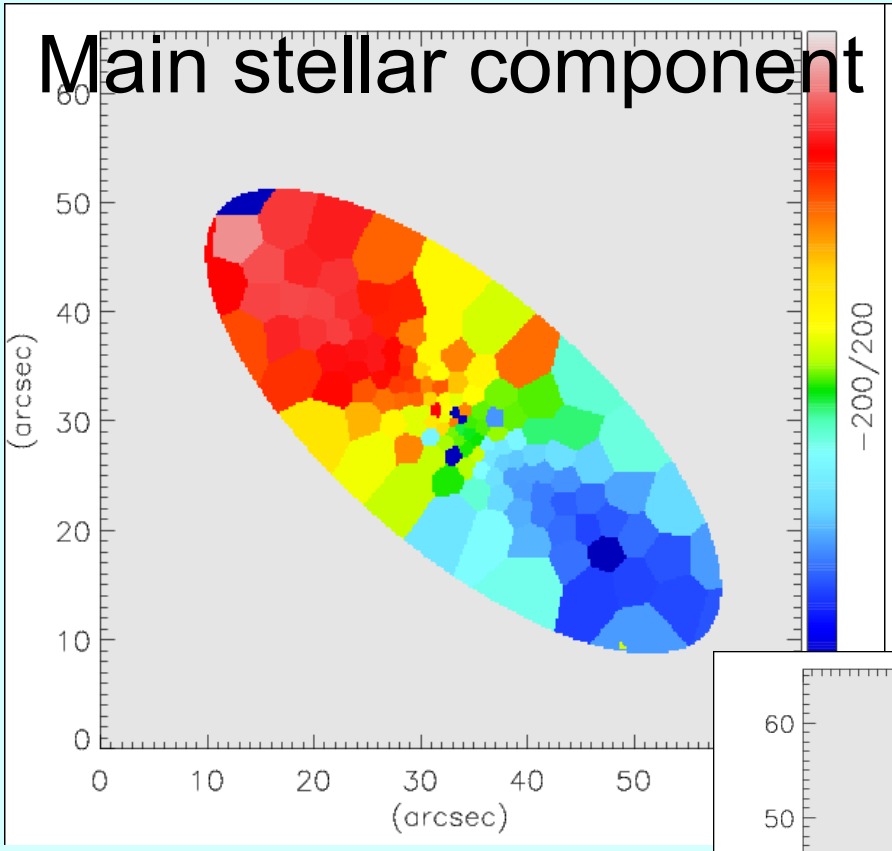


MUSE - IC 719 Ca Triplet region

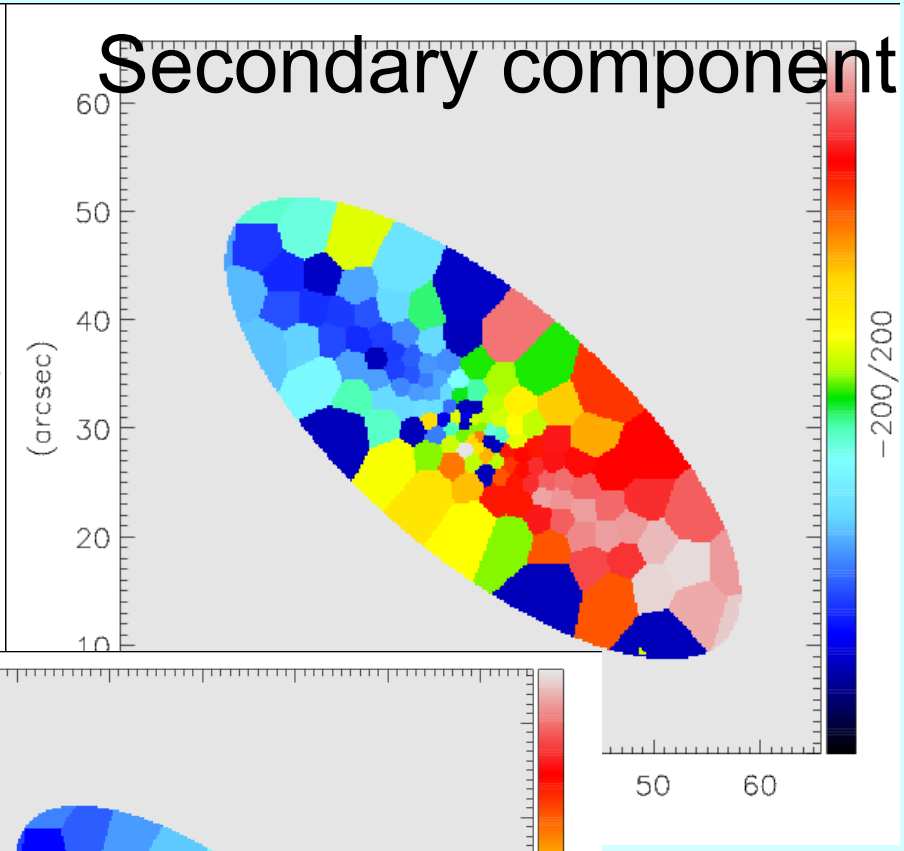


IC 719 kinematics -Velocity field

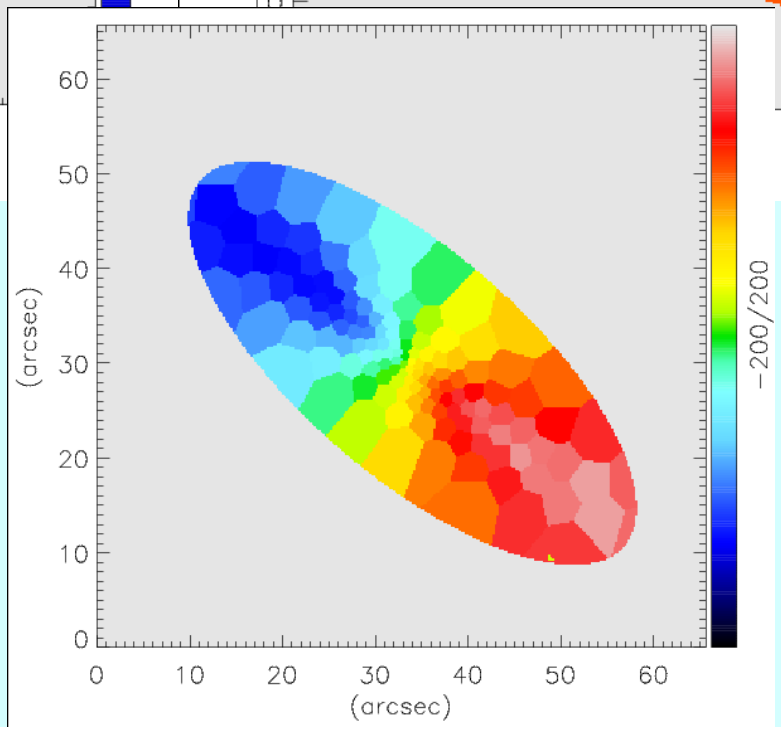
Main stellar component



Secondary component

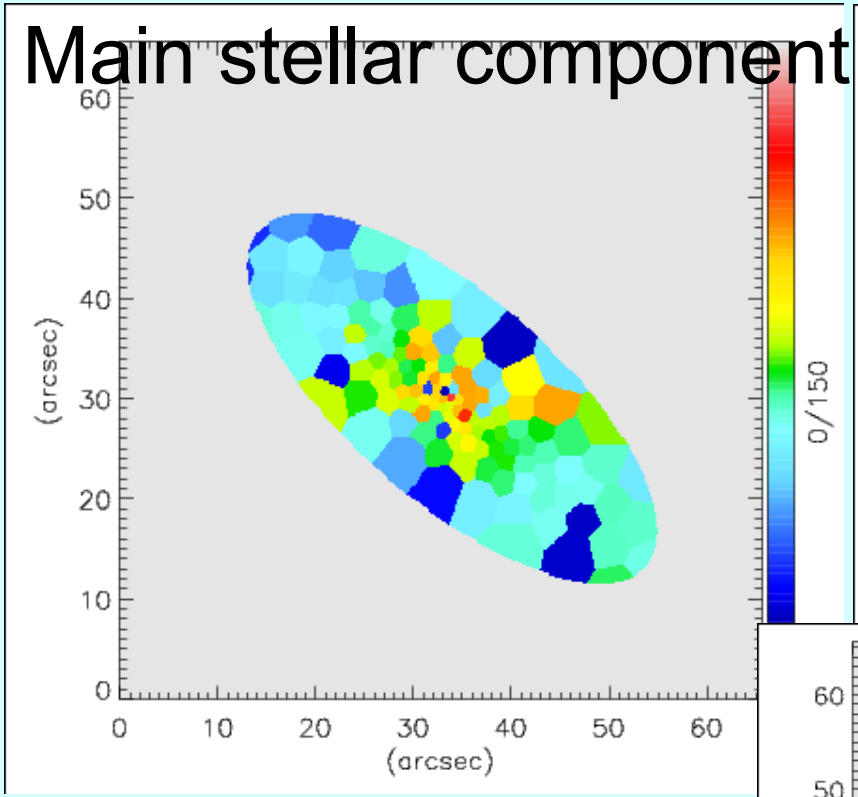


Ionized gas

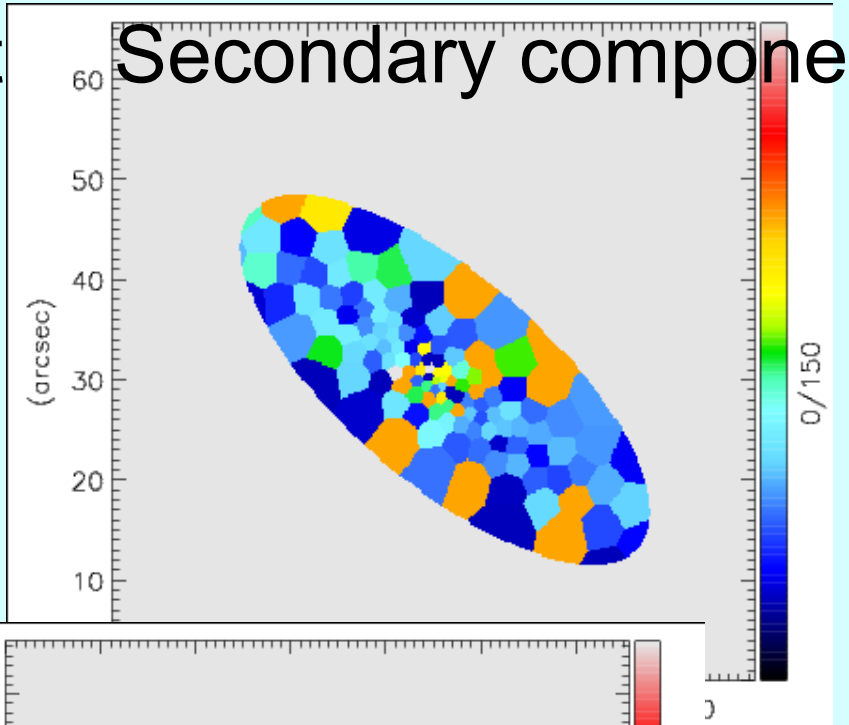


IC 719 kinematics -Velocity dispersion

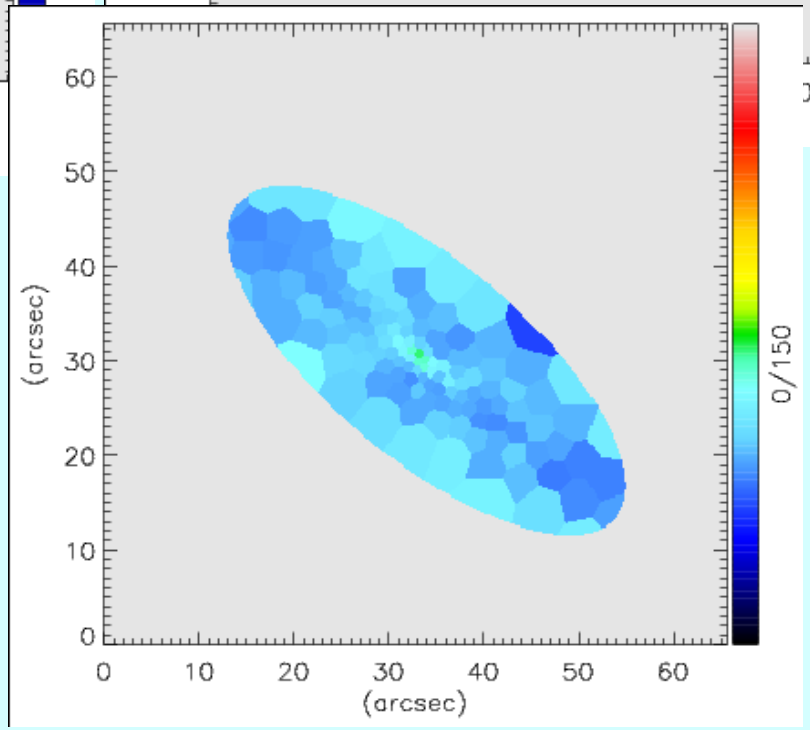
Main stellar component



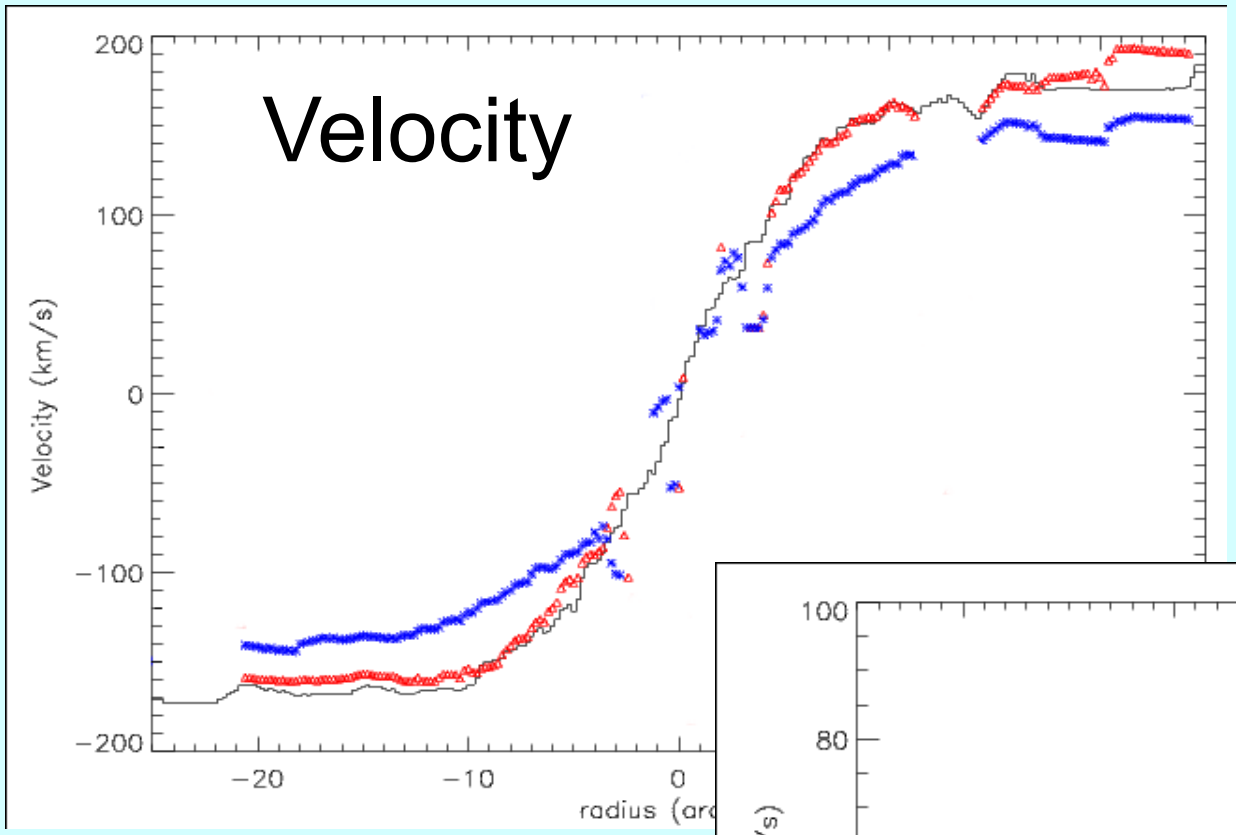
Secondary component

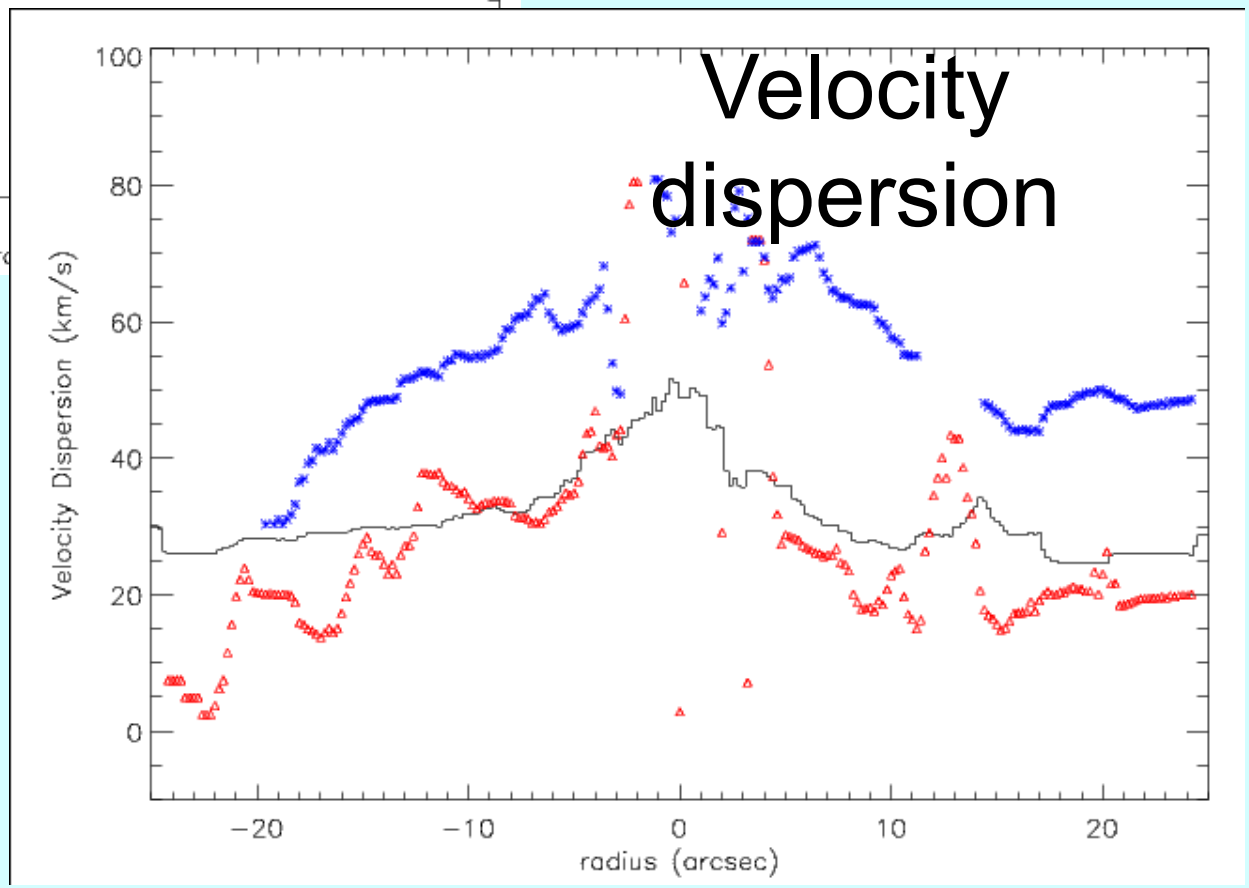


Ionized gas



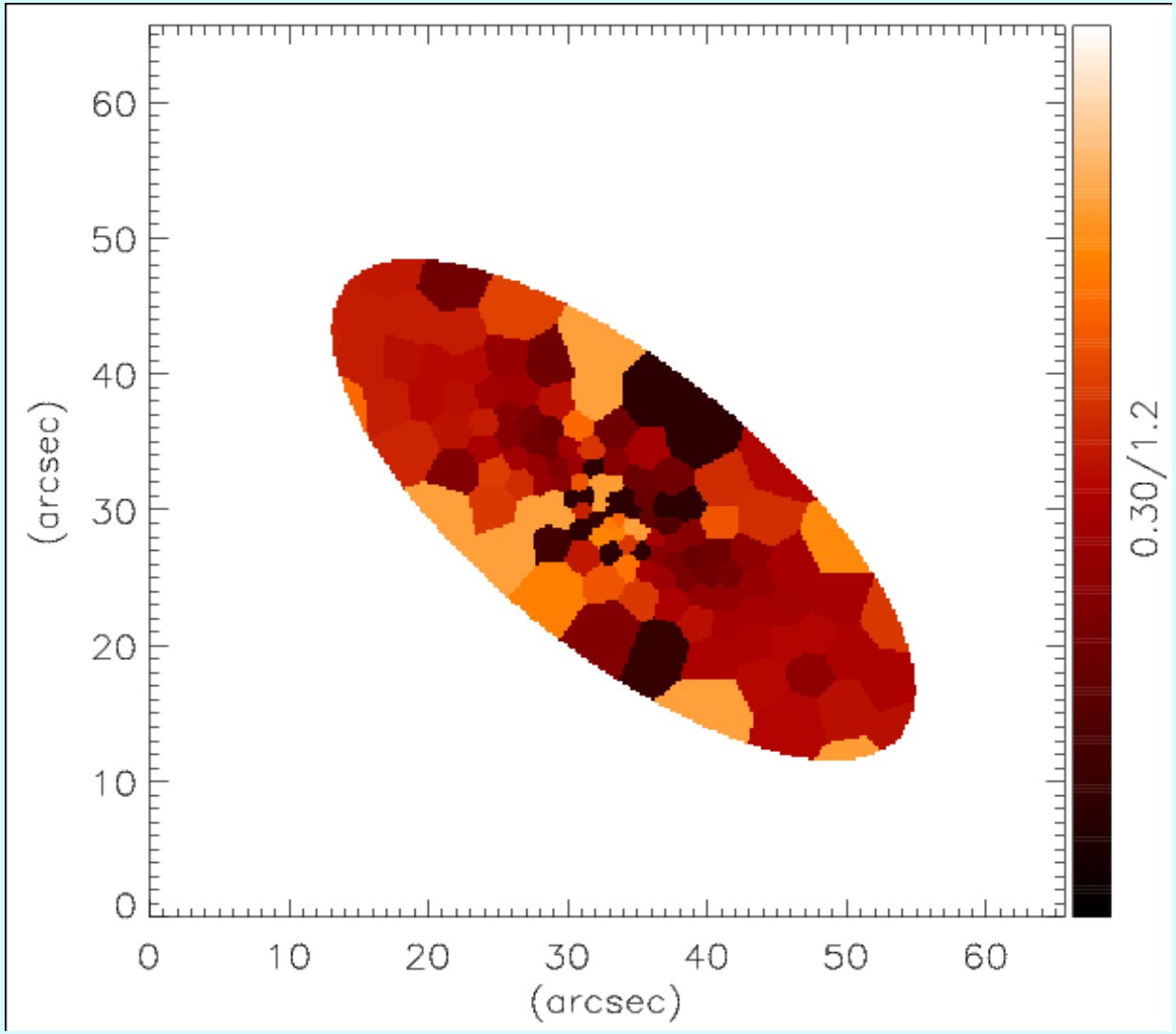
Major Axis


Velocity
200
100
0
−100
−200
Velocity (km/s)
−20
−10
0
radius (arc


Velocity dispersion
100
80
60
40
20
0
Velocity Dispersion (km/s)
−20
−10
0
10
20
radius (arcsec)

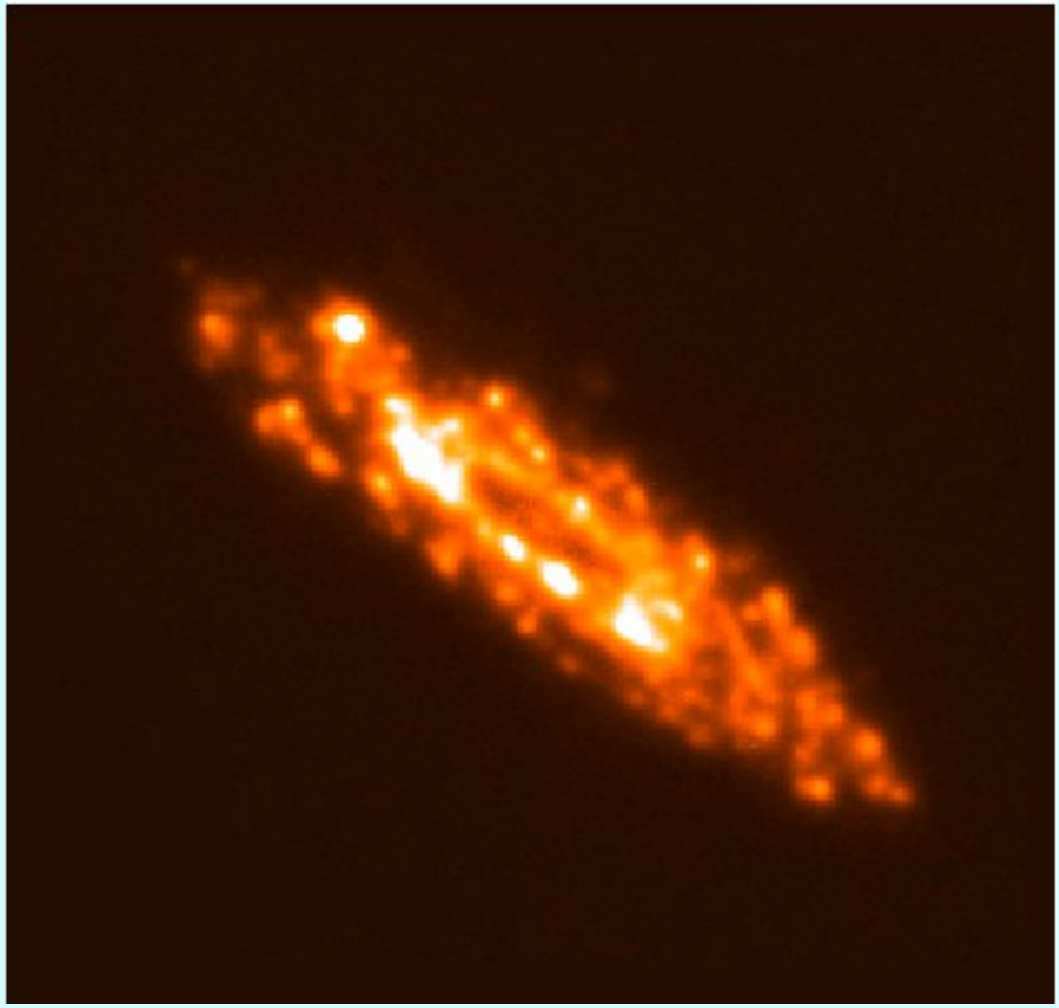
IC 719 spatial distribution of counterrotation

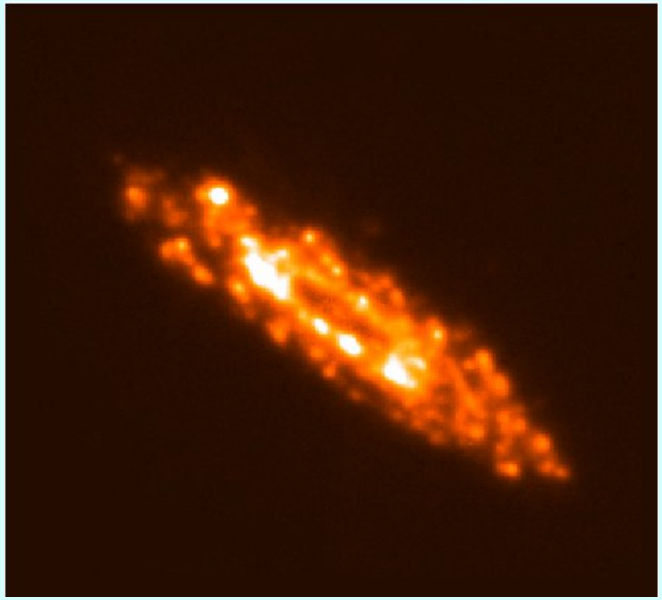
Main/Secondary



IC 719 2d maps

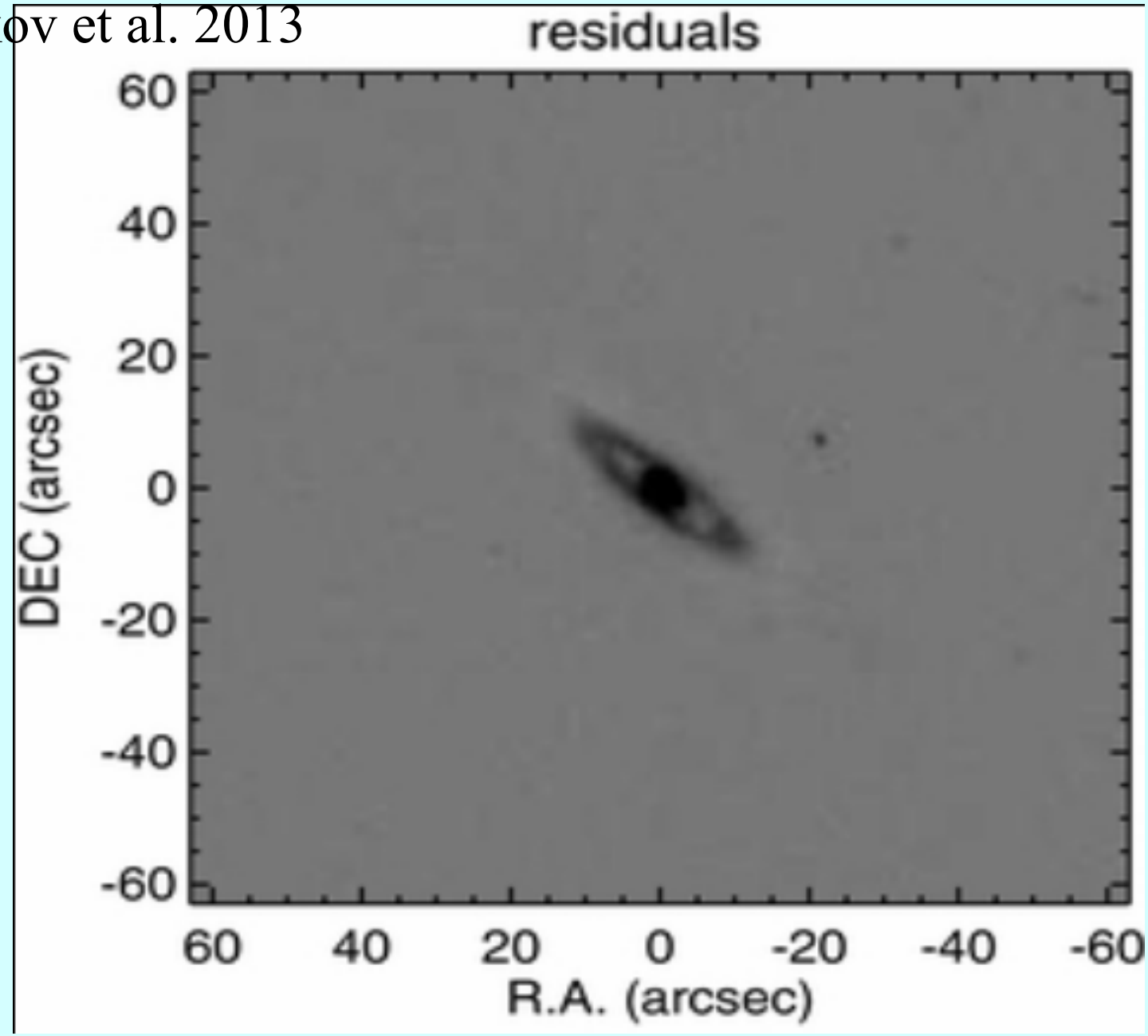
Hα image



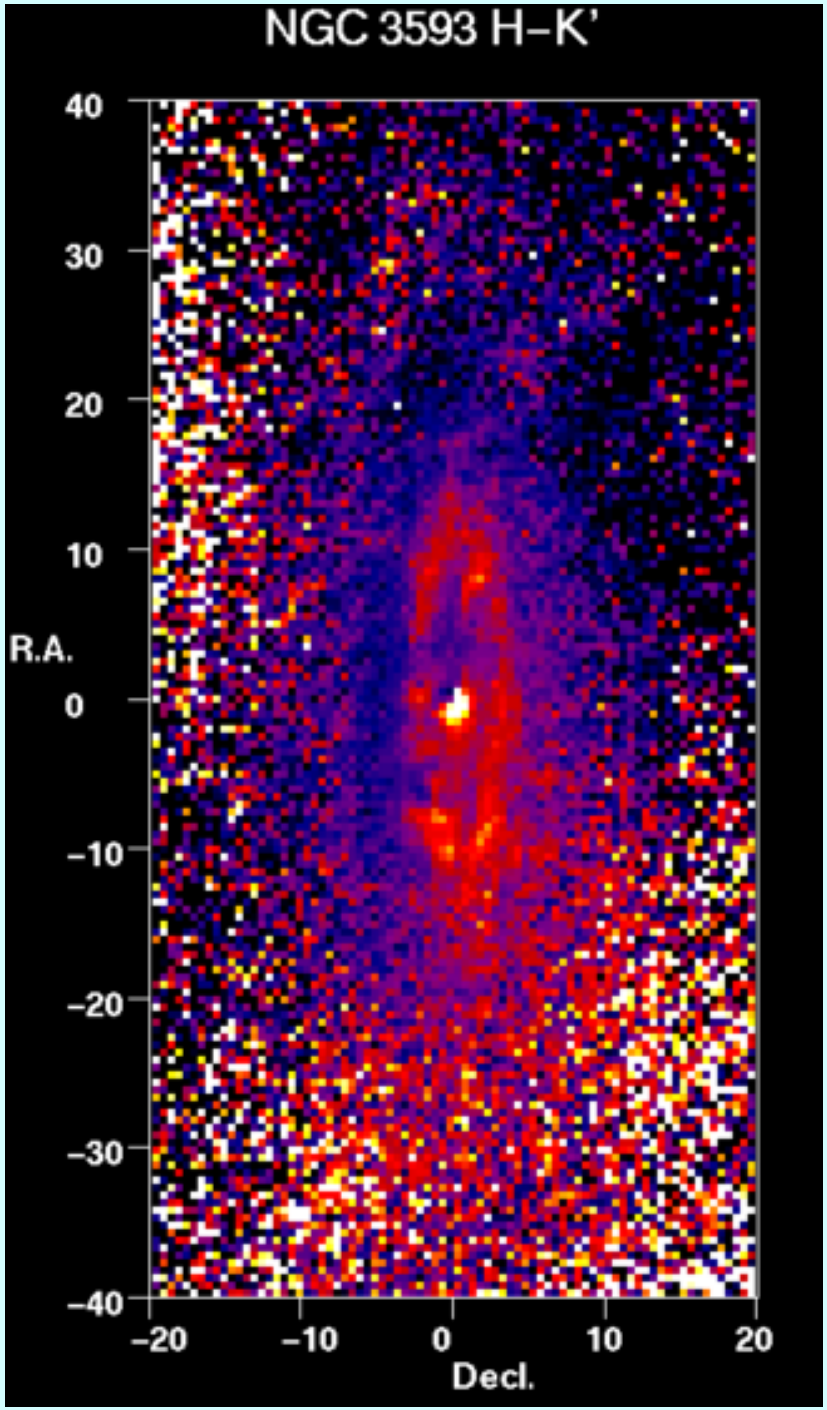


IC 719 UKIDSS photometry – Residual of a pure disk

Katkov et al. 2013

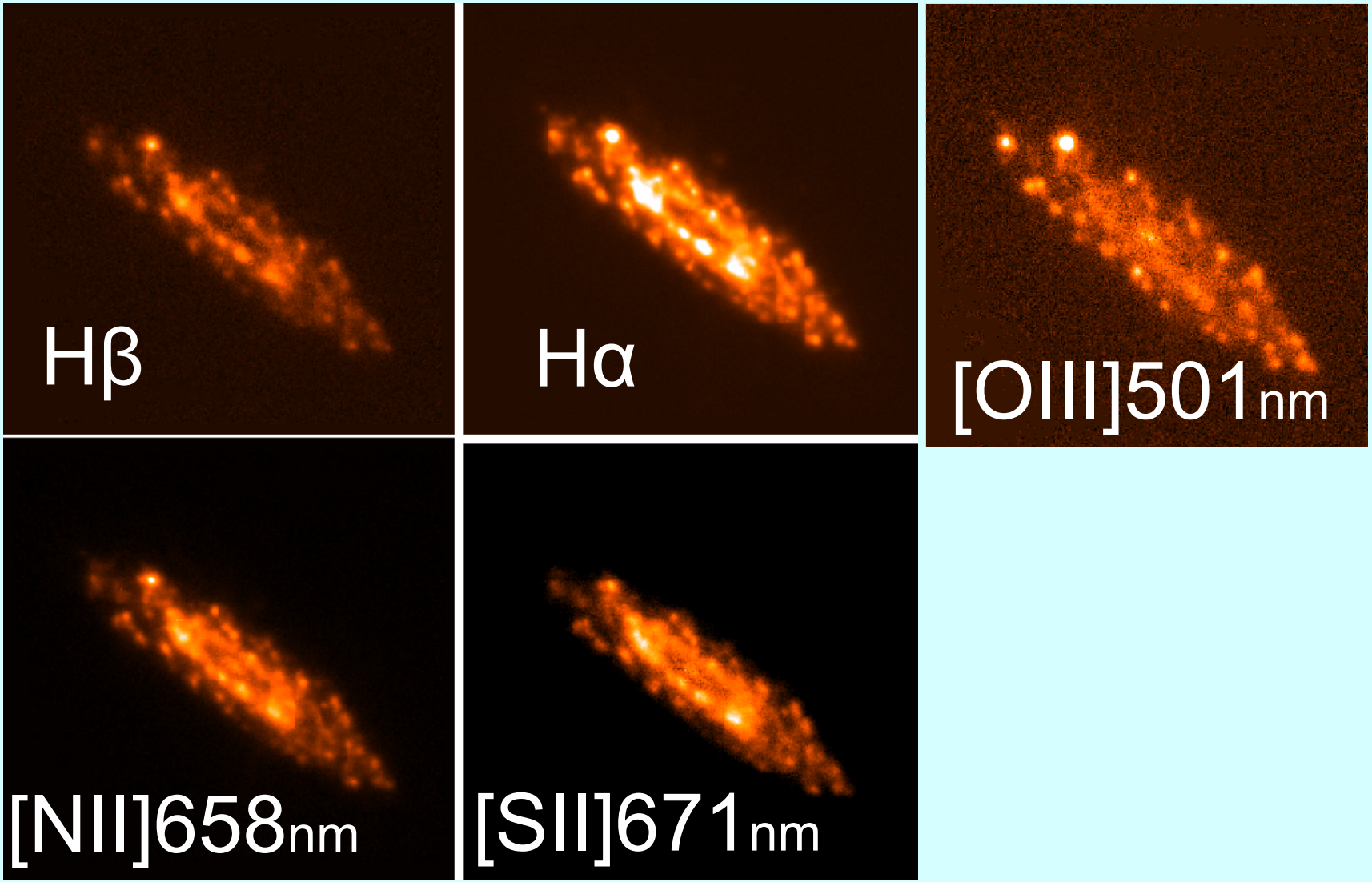


IRAC@2.2m ESO
Pizzella et al. 1999



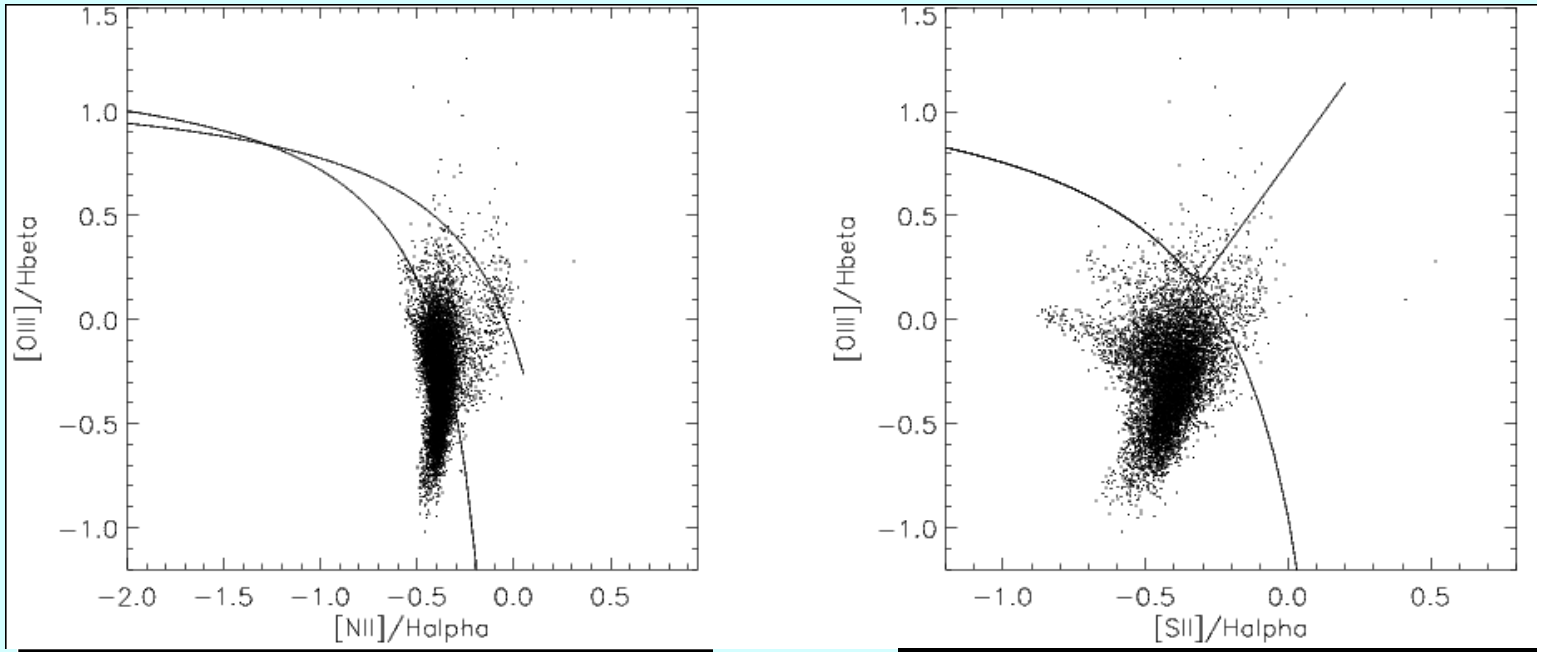
Can we identify some of the counter-rotating galaxies by means of NIR imaging?

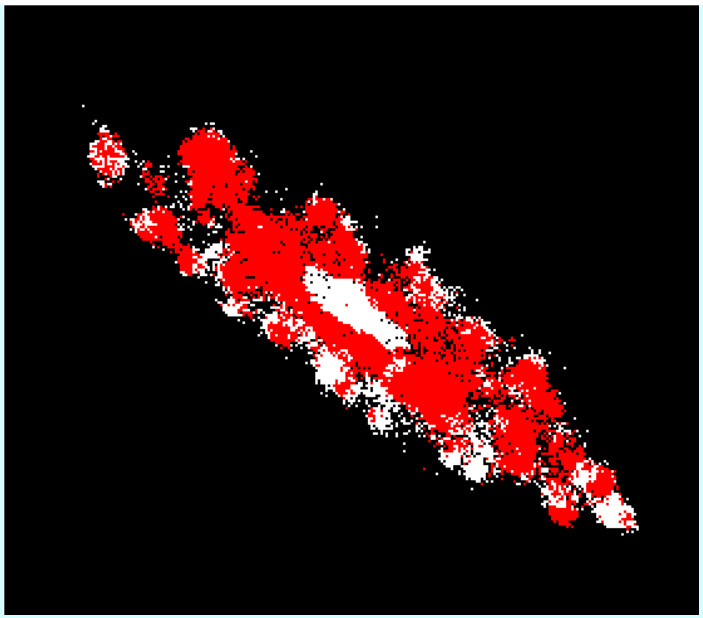
MUSE - IC 719 Narrow band imaging

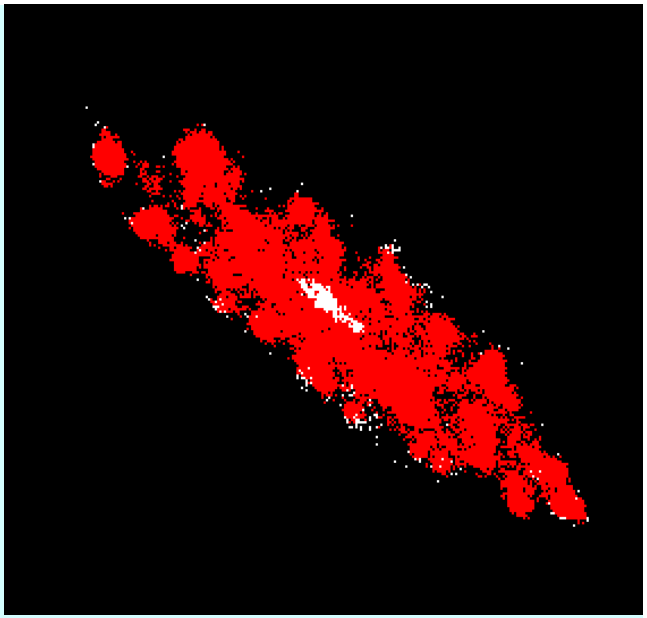


IC 719 BPT diagrams

Katkov,
Sil'chenko &
Afanasiev (2014)

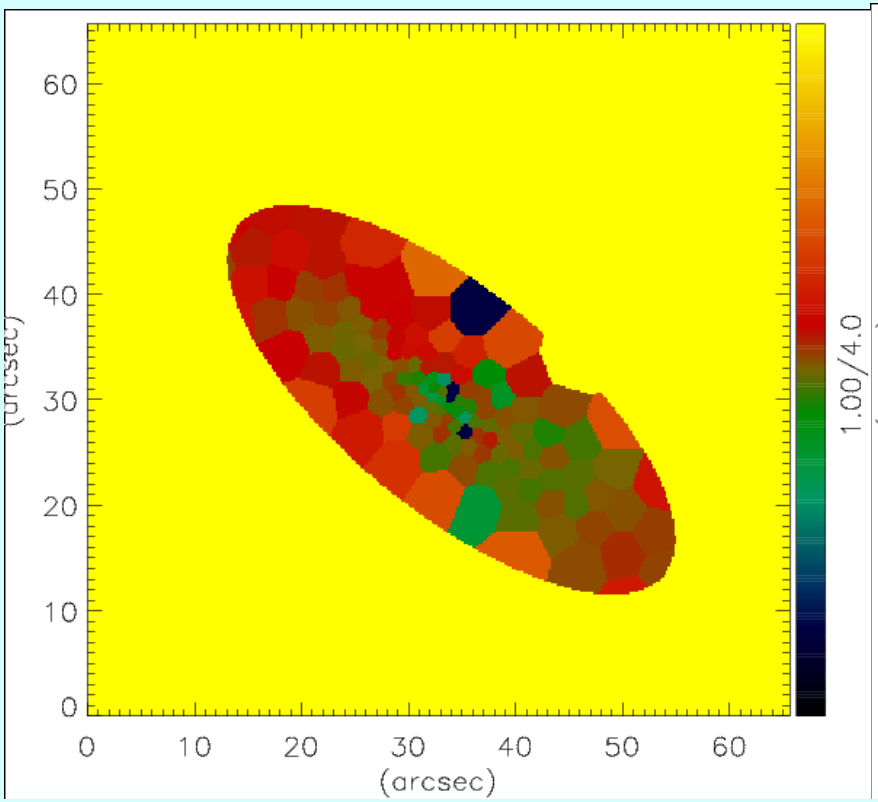




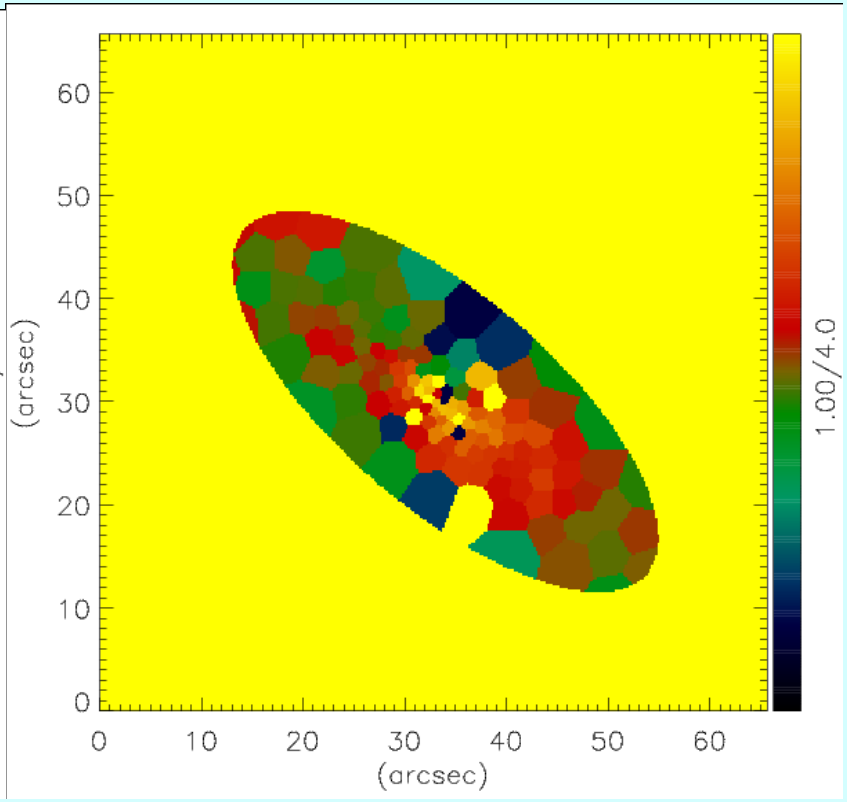


IC 719 2d maps: Lick Indices

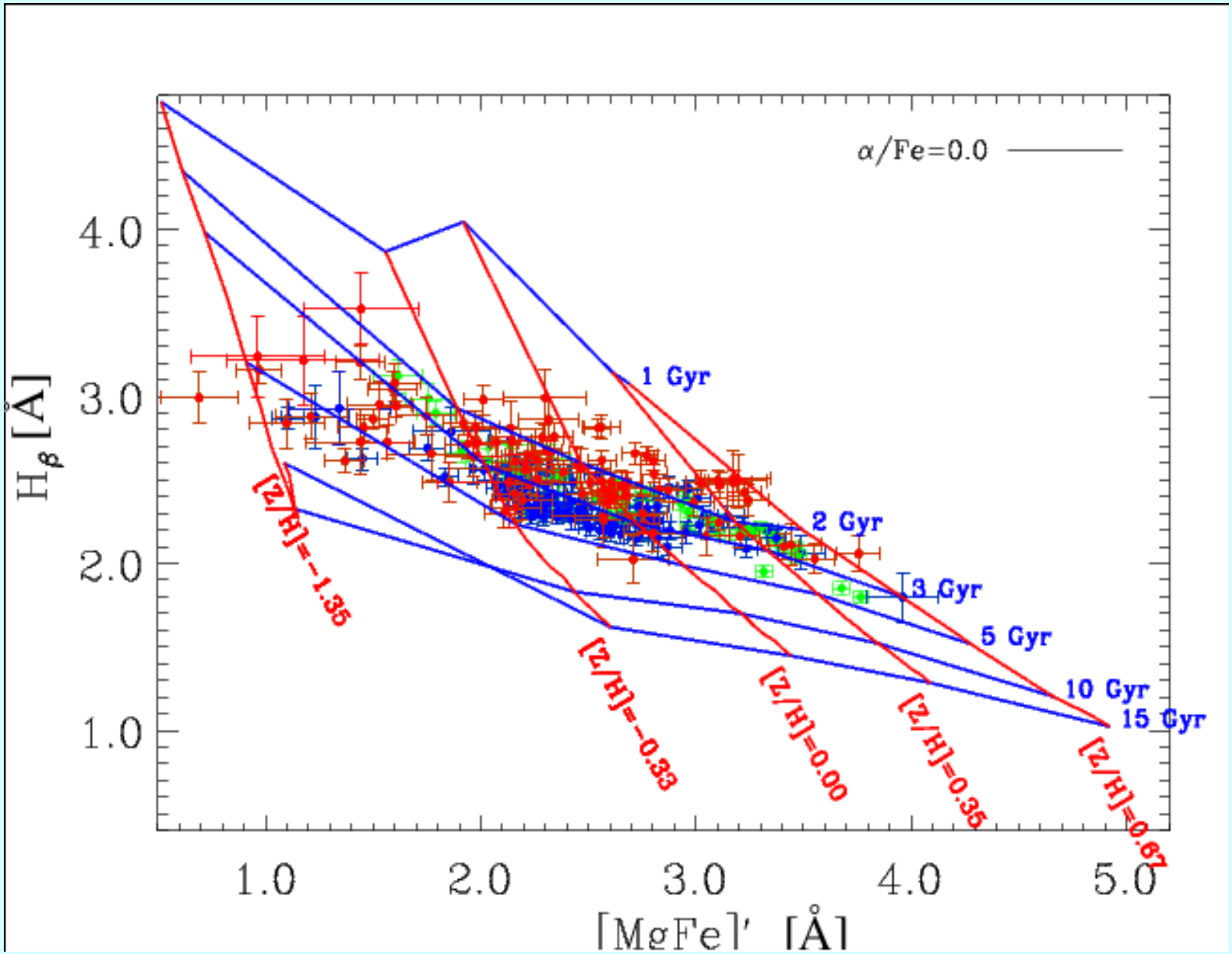
Hβ



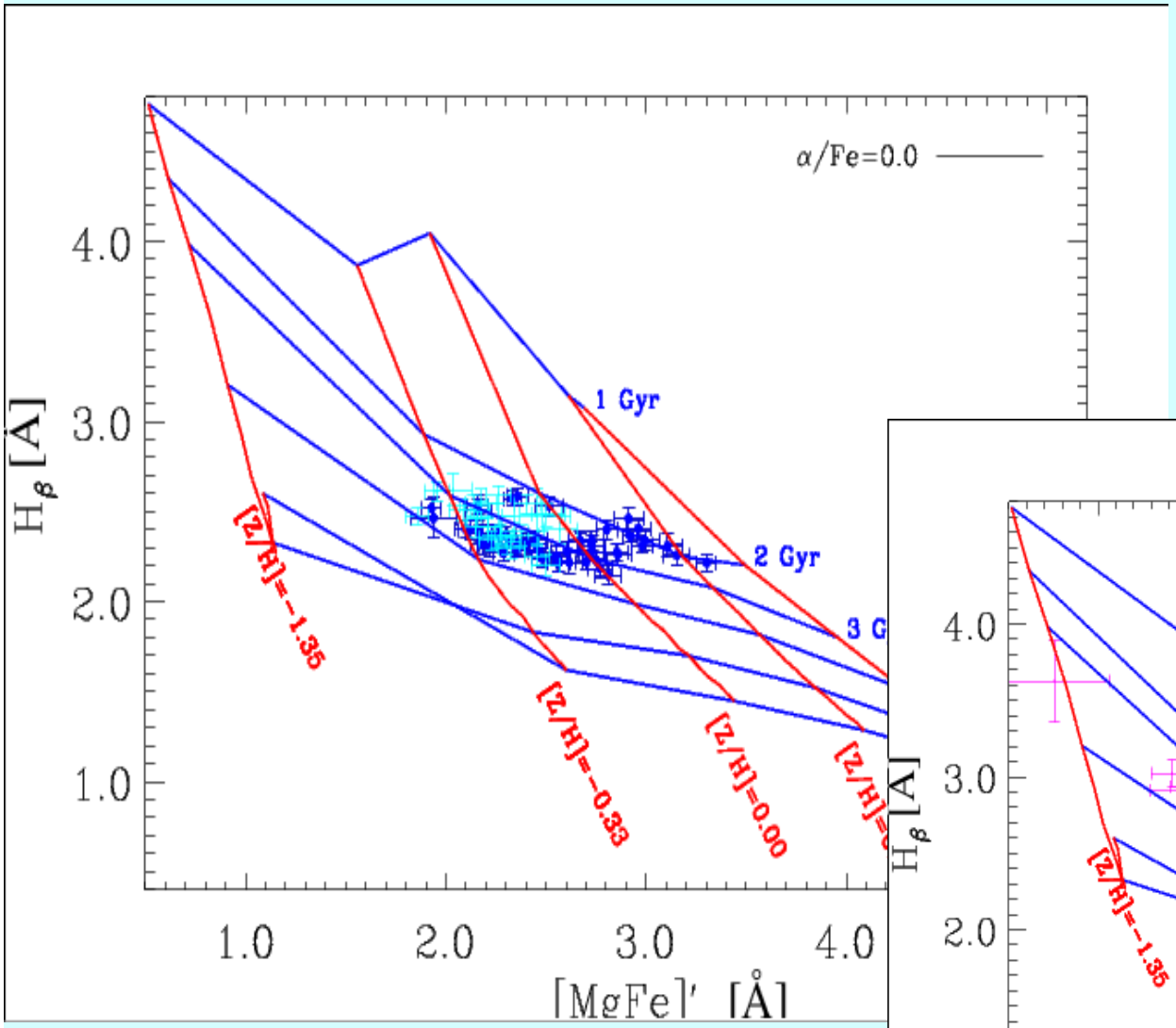
Mg

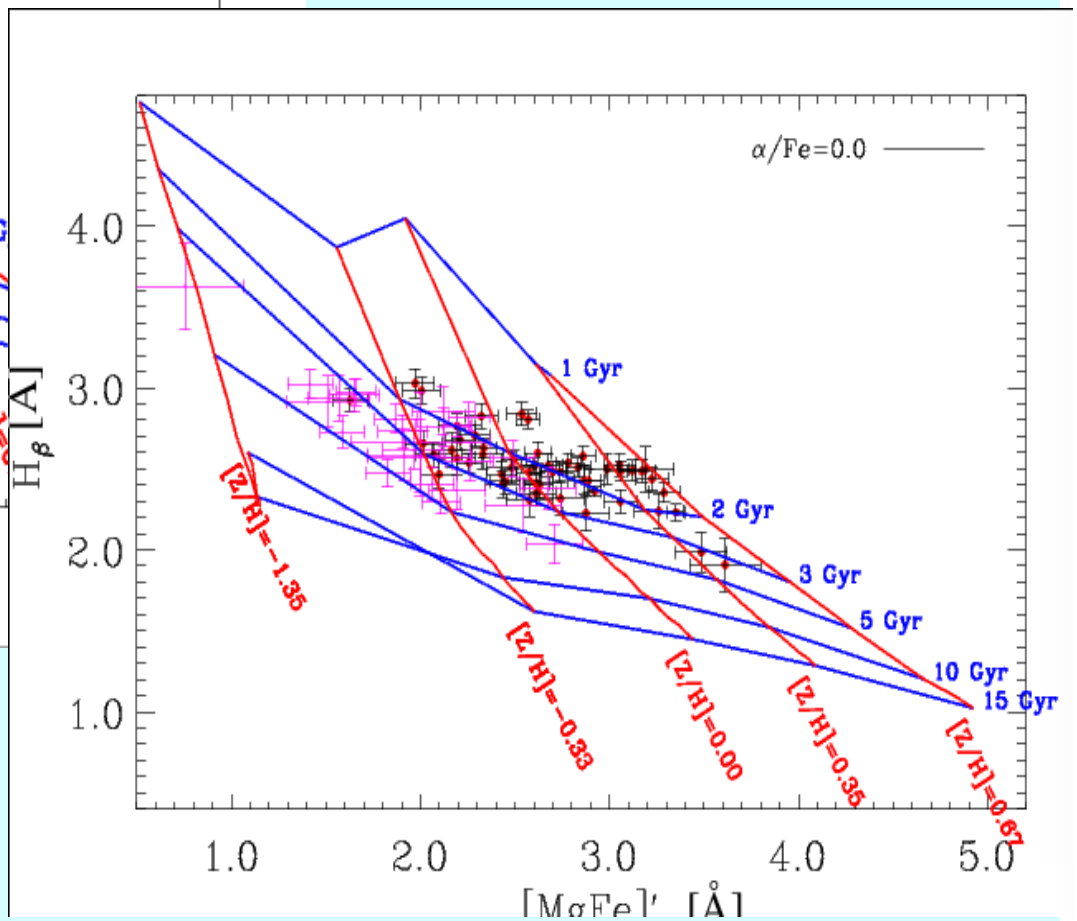


IC 719 ages and metallicities of stellar populations



IC 719 ages and metallicities of stellar populations





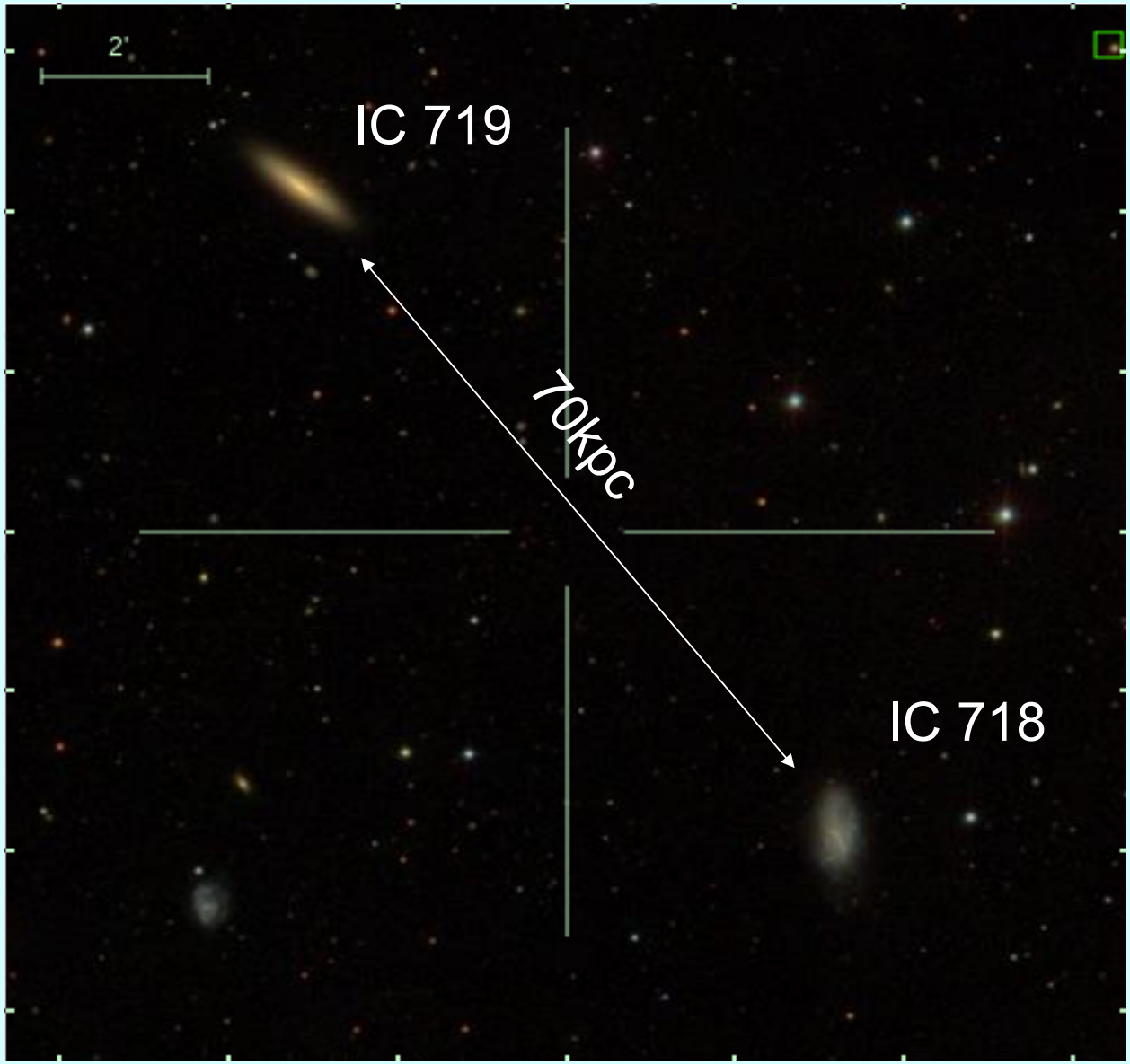
Some Results on counter-rotation
We can:

- Unblend the two counter-rotating components very well;

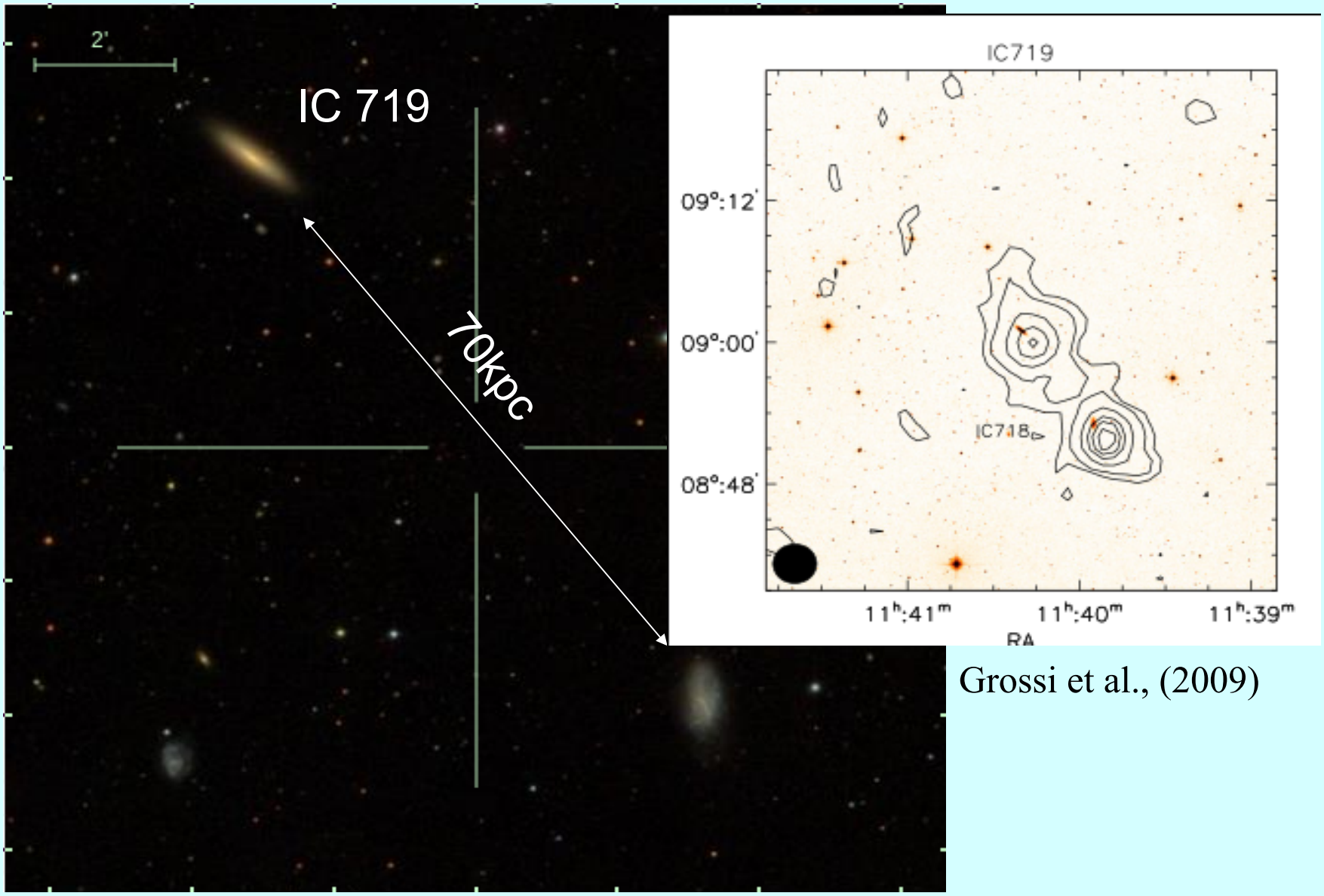
-Measure the kinematics (velocity and velocity dispersion) of the two stellar component and ionized gas with very good precision.

-Distinguish the stellar population of the two stellar components

The source of the gas?



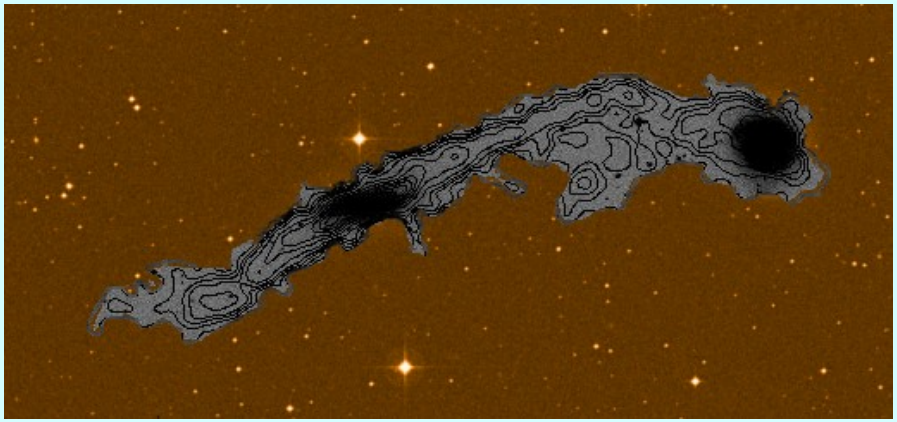
The source of the gas?

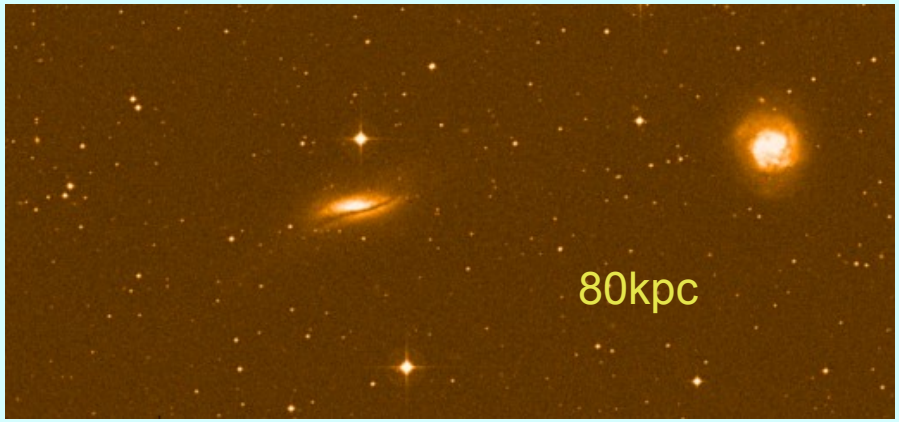


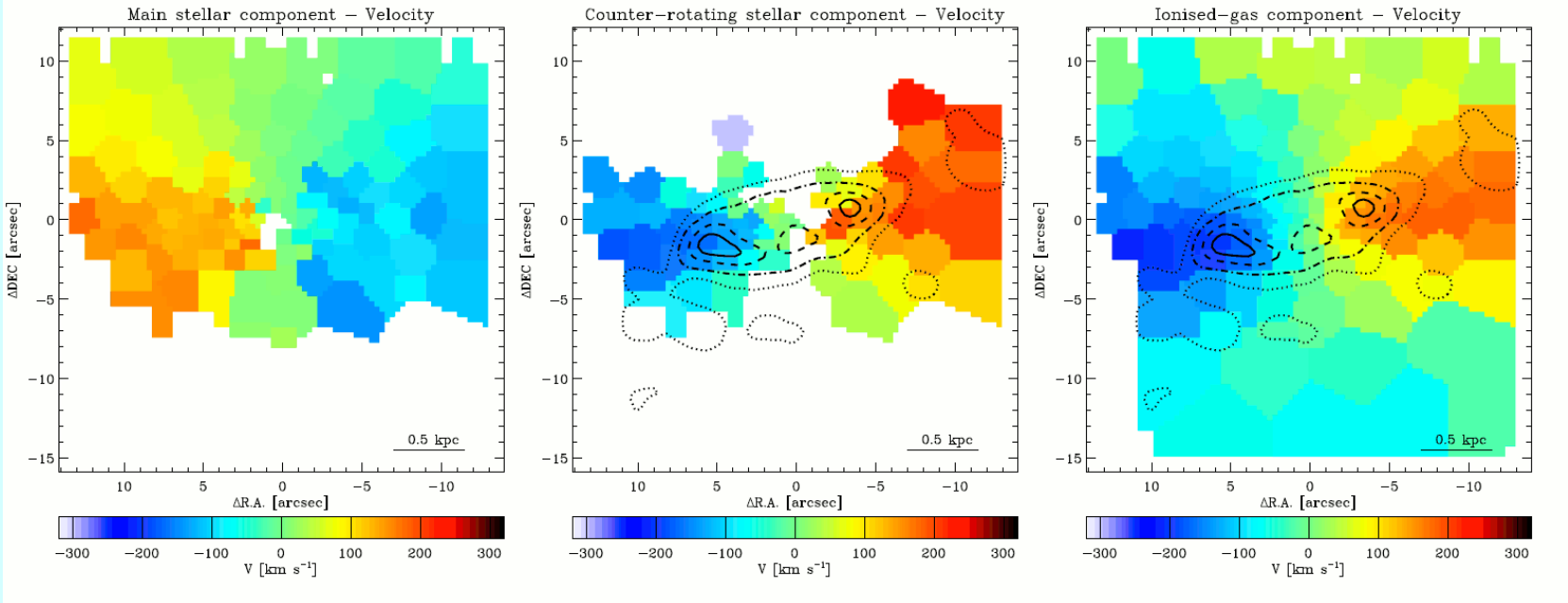
Grossi et al., (2009)

Stars vs. Stars + Gas

NGC 5719 – acquiring HI from NGC 5713 (Vergani et al. 2007)





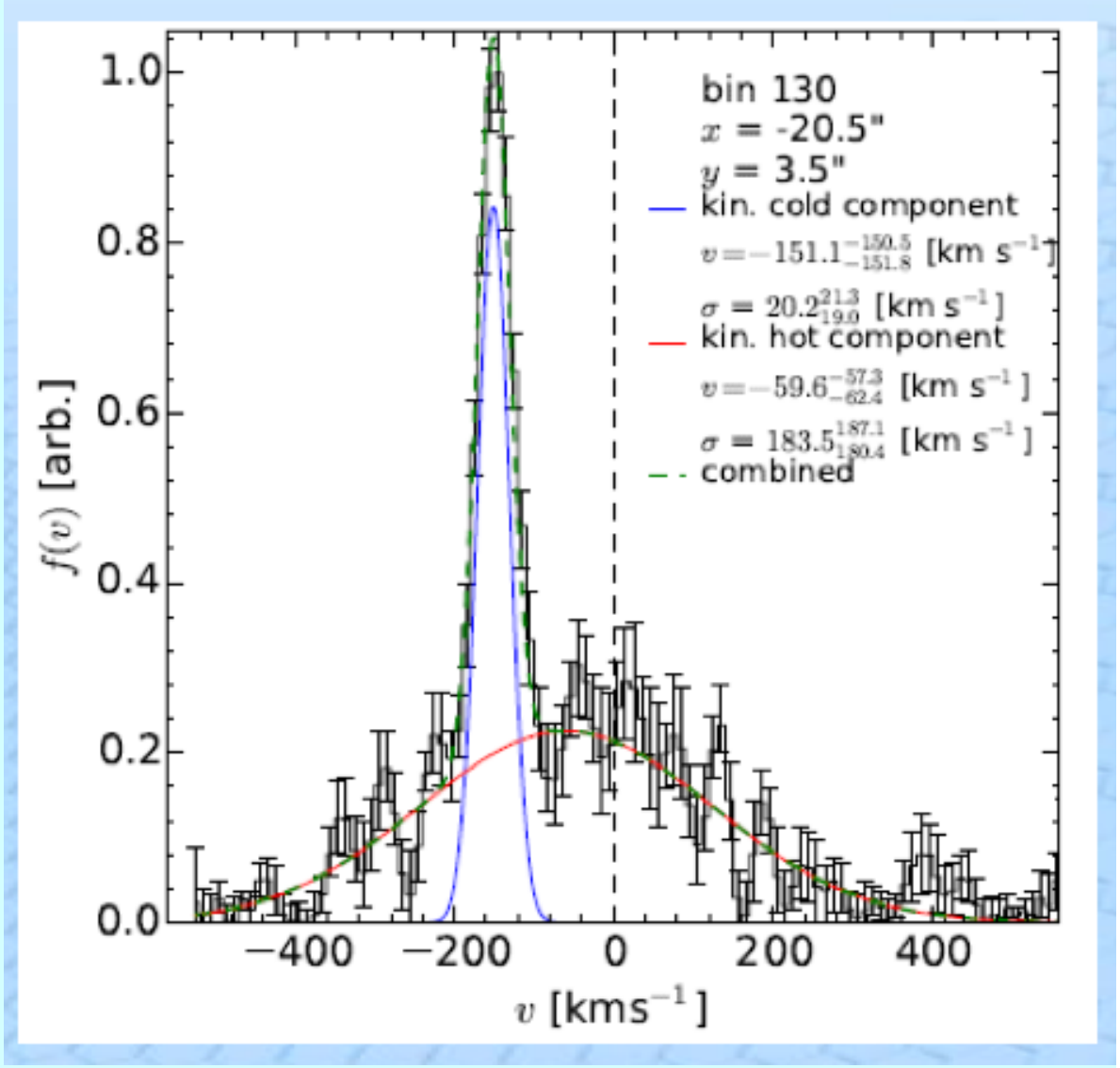


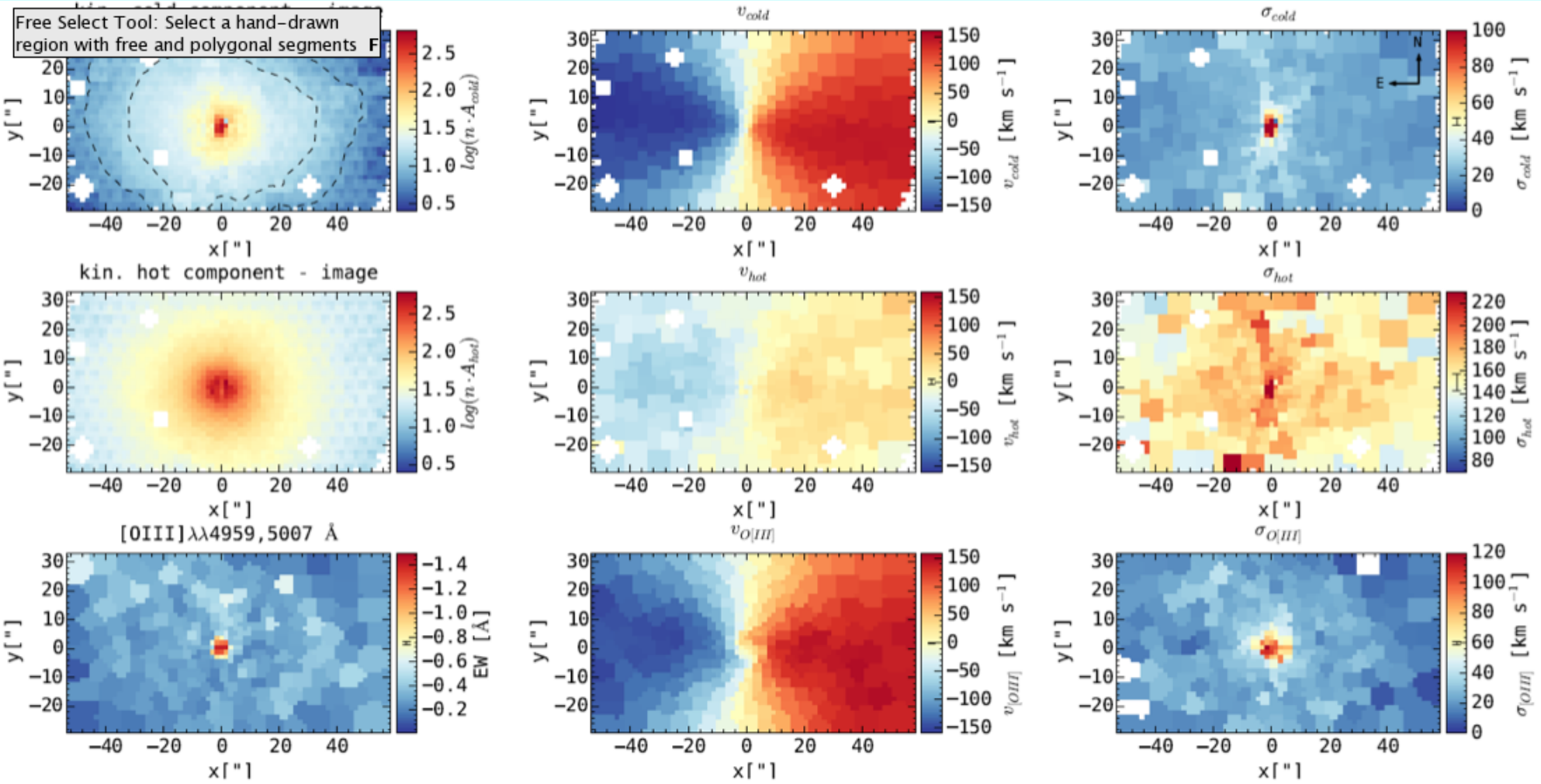
Bulge – Disk decomposition

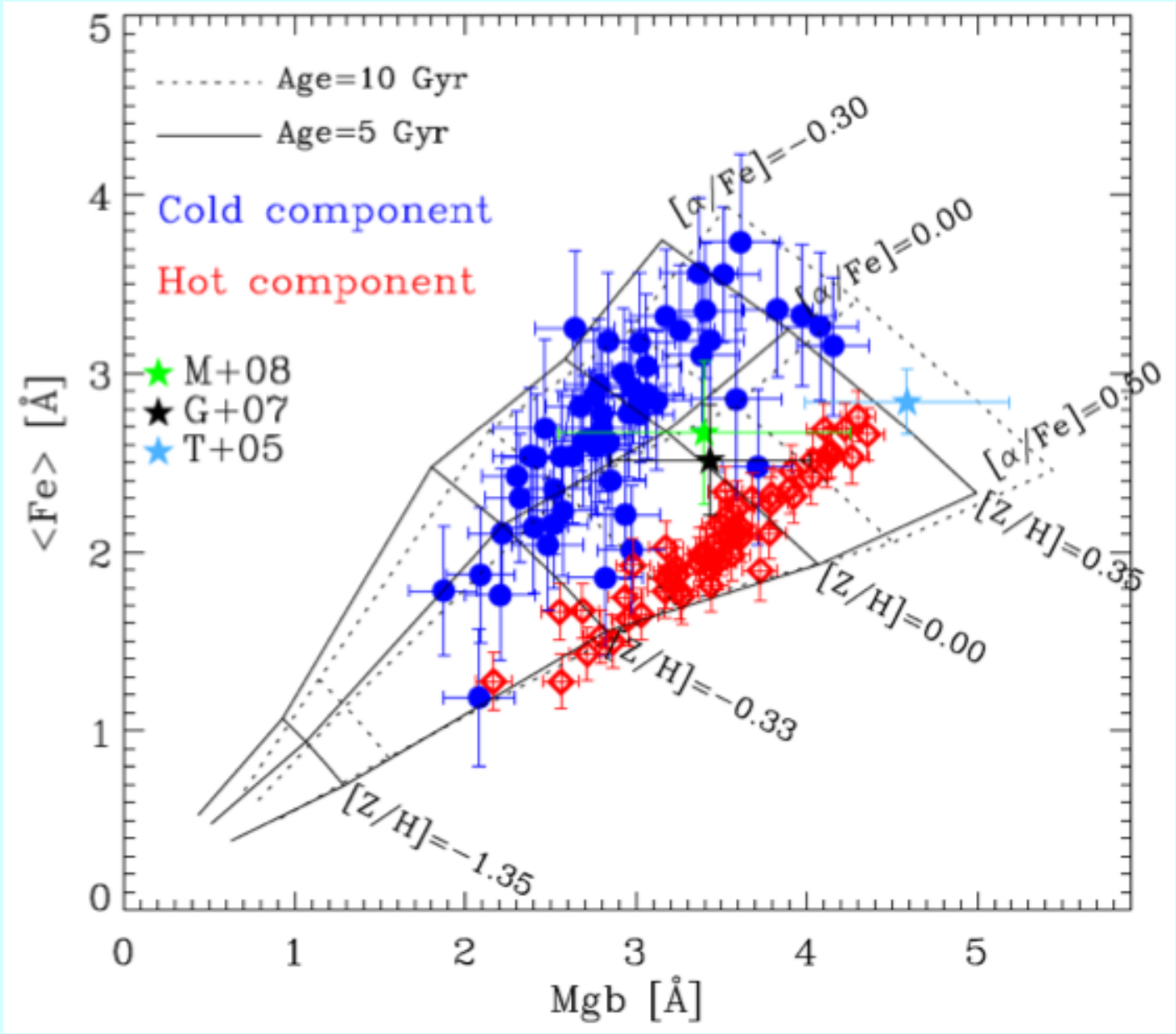
Bulge and disk have the same rotation axis but different kinematics

Fabricious et al (2014)

VIRUS-W@McDonald2.7m




Free Select Tool: Select a hand-drawn region with free and polygonal segments F
kin. hot component - image
[OIII]λλ4959,5007 Å
v_{cold}
σ_{cold}
v_{hot}
σ_{hot}
$v_{O[III]}$
$\sigma_{O[III]}$
$log(n \cdot A_{cold})$
$log(n \cdot A_{hot})$
EW [Å]
[km s^{-1}]
x["]
y["]
N
E


Age=10 Gyr
Age=5 Gyr
Cold component
Hot component
M+08
G+07
T+05
[α/Fe]=−0.30
[α/Fe]=0.00
[α/Fe]=0.50
[Z/H]=0.35
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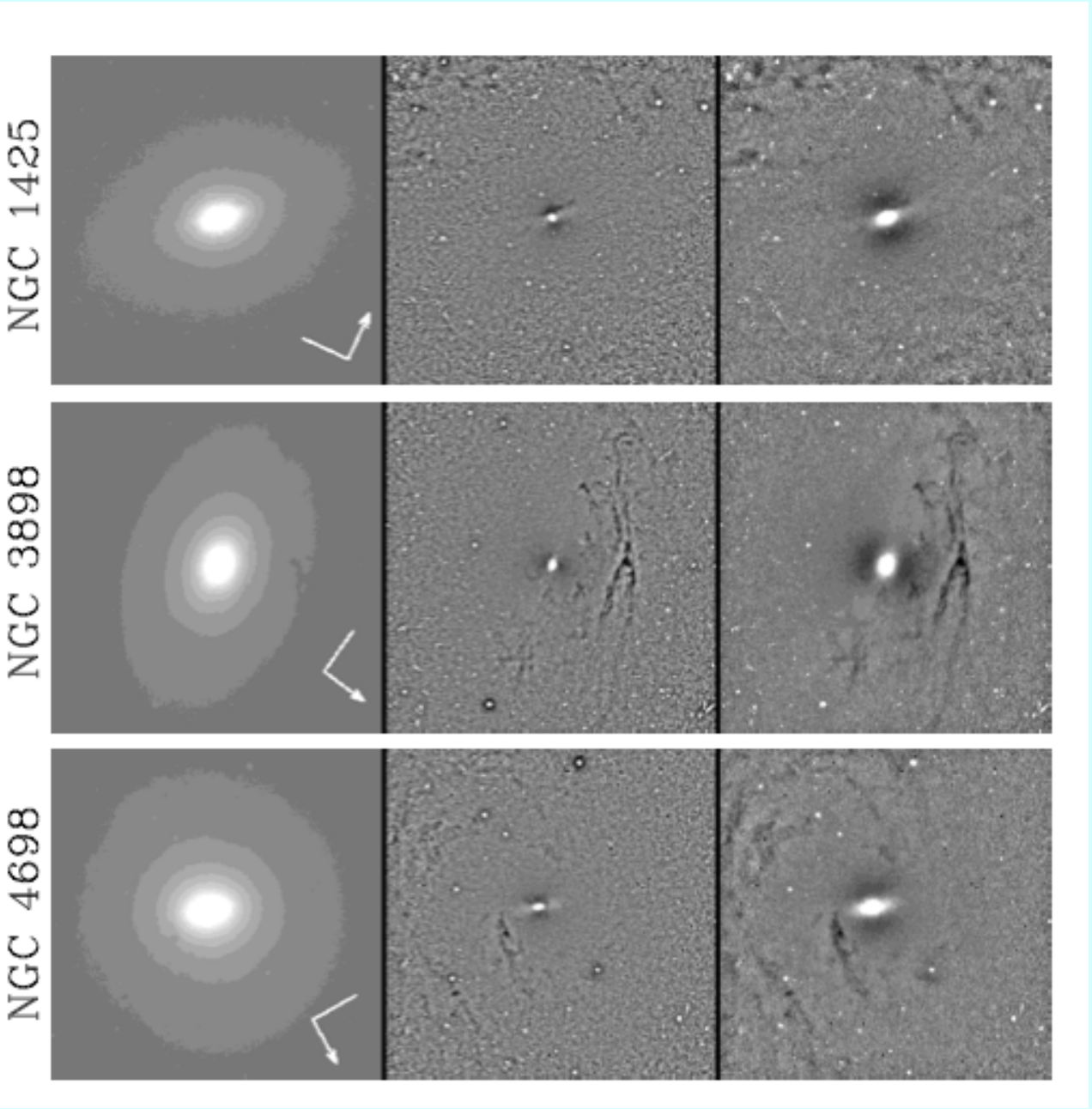
[Z/H]=−0.33
[Z/H]=−1.35
<Fe> [Å]
Mgb [Å]
0
1
2
3
4
5

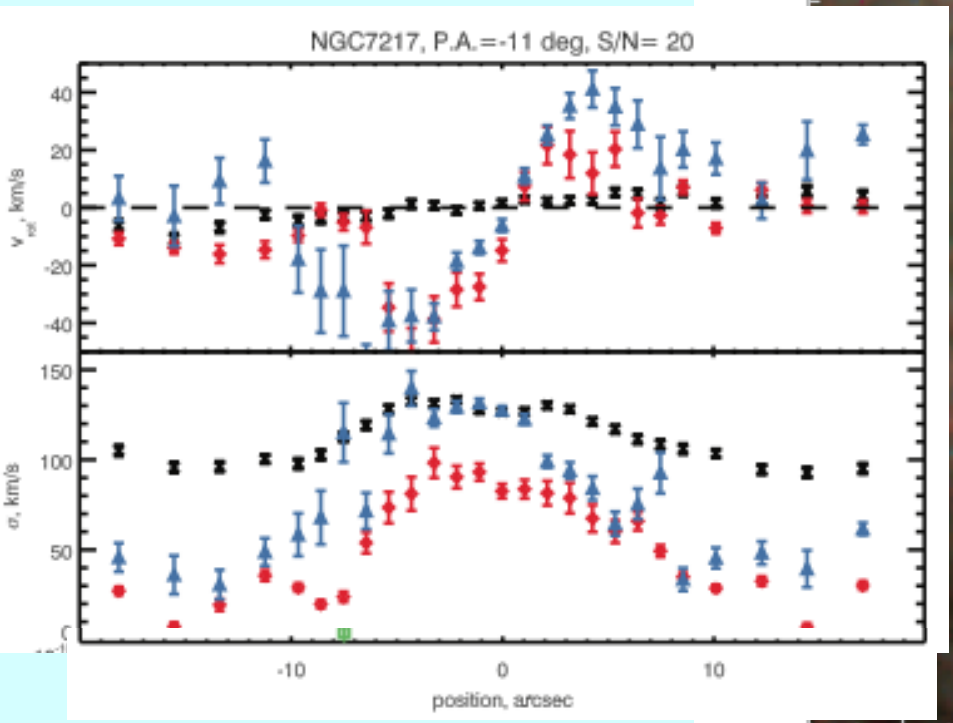
Nuclear Stellar disks

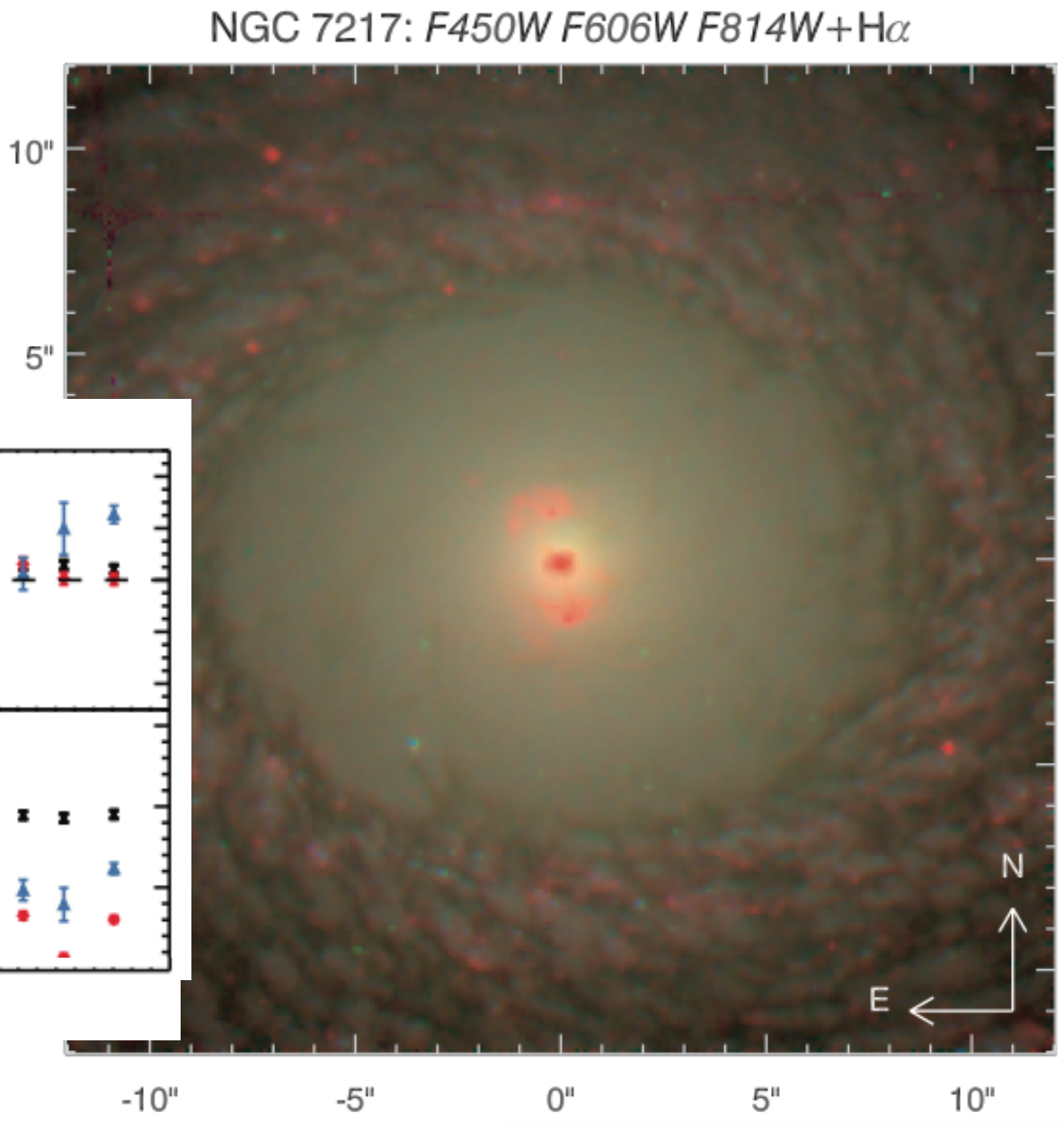
Scorza & Bender (1995)
Pizzella et al. (2002)
Morelli et al. (2004)



Inner Polar Ring – NGC 7217

Sil'chenko et al. (2011)





Conclusions

- Multi-spin galaxies are frequent among early type galaxies
-The components with different spin with respect to the host galaxy are generally considered as acquired from outside

- The development of IFU spectrographs allows now to study in great detail non only the kinematics of the multi-spin galaxies but also their stellar populations. We are in a new era!
(lots of data available, CALIFA, ATLAS3D, MUSE, MPFS…)

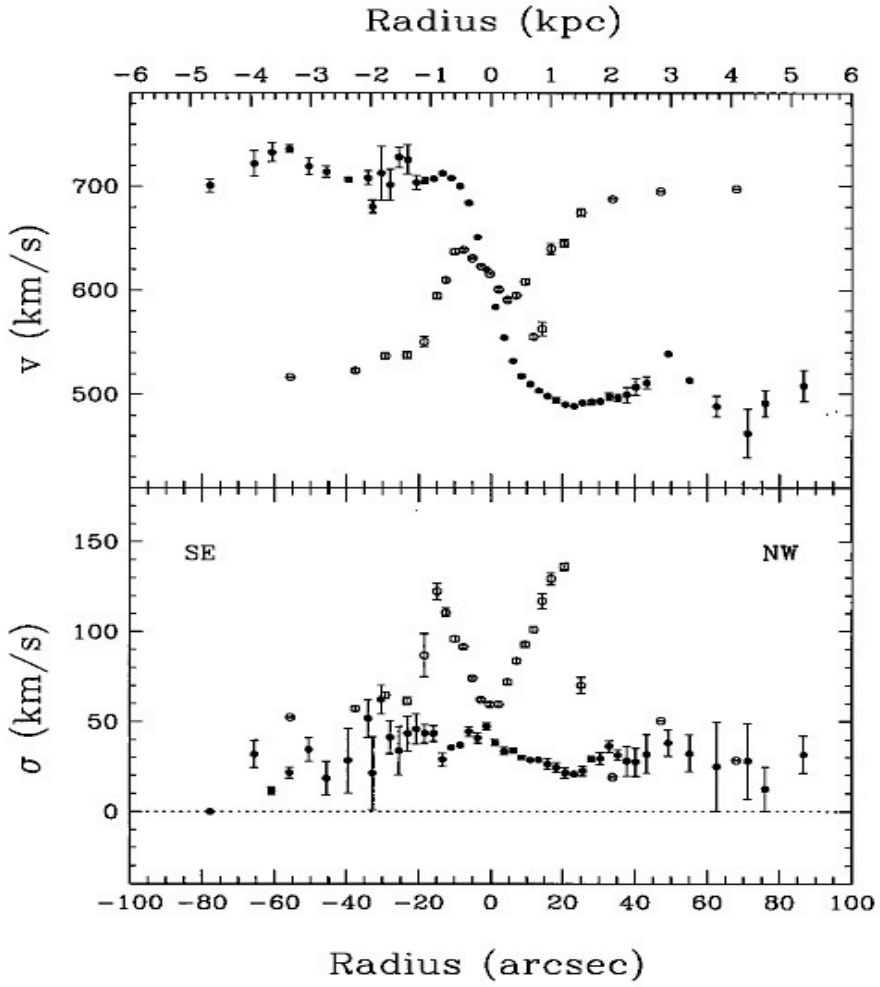
-We can call multi-spin galaxies also galaxies where two components have the same spin direction but different kinematics: Bulges, Nuclear stellar disks.

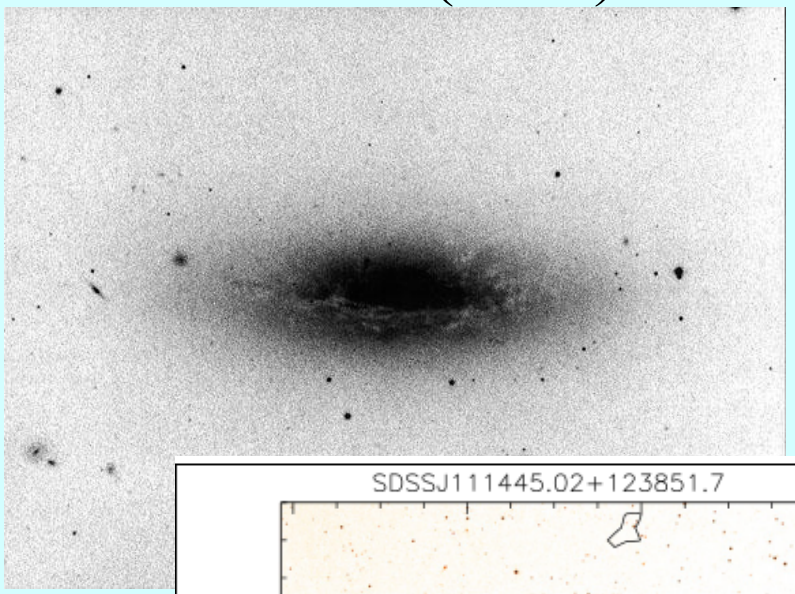
- GAIA: does our Galaxy have some decoupled components?

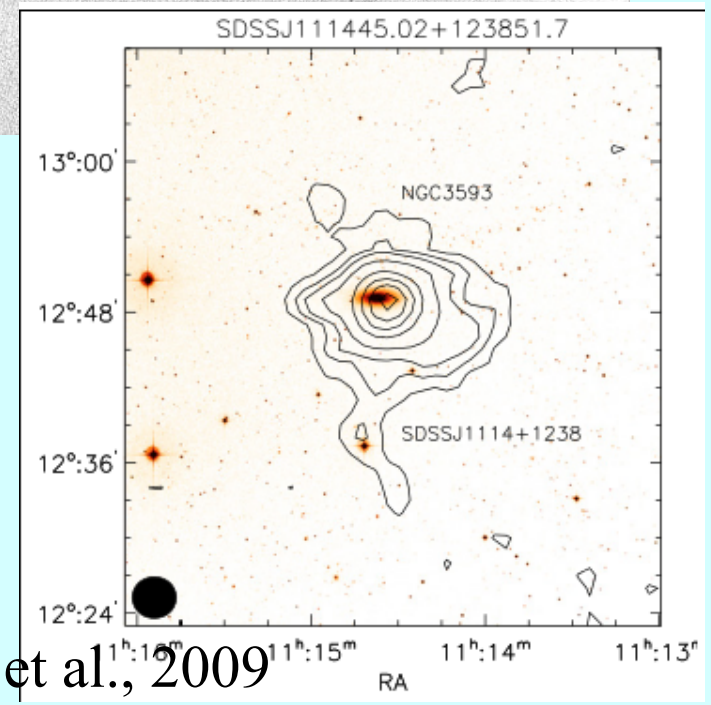
Inner Stars v. Stars counter-rotation

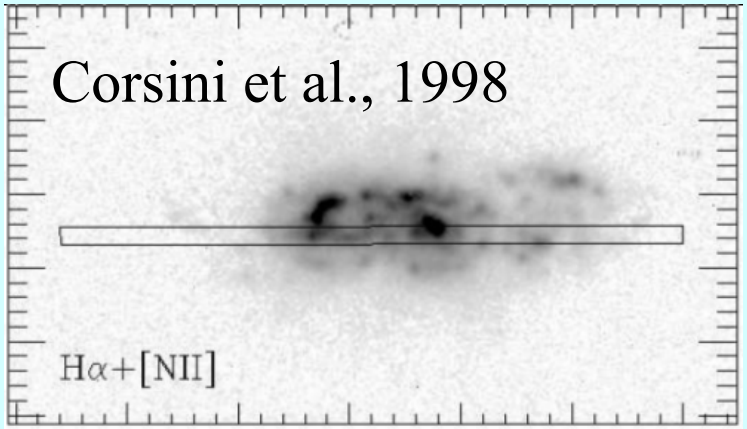
NGC 3593 – S0/a

Bertola et al. (1996)









Corsini et al., 1998

Grossi et al., 2009

Inner Stars v. Stars counter-rotation

NGC 3593 – S0/a

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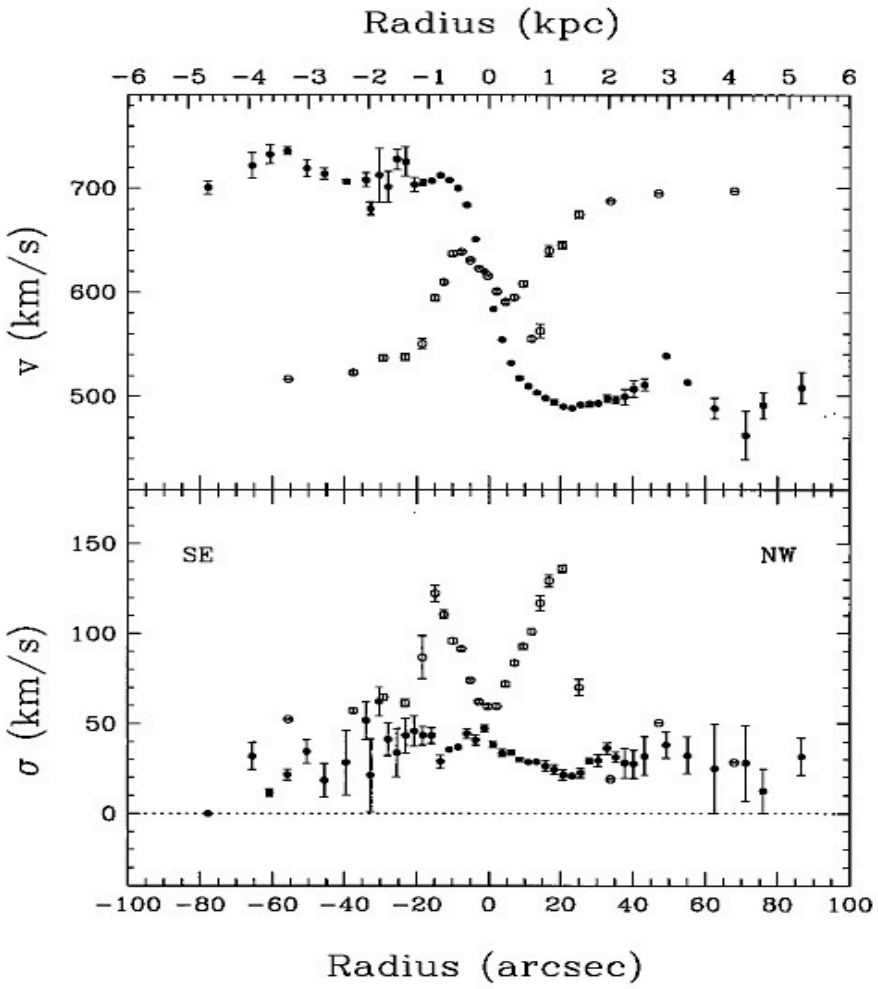
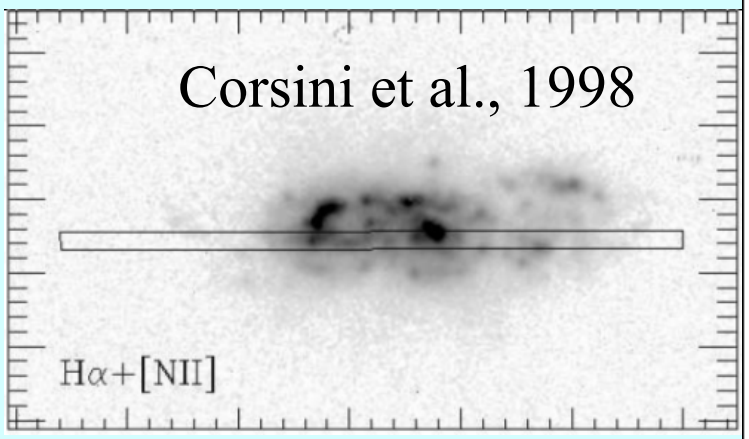
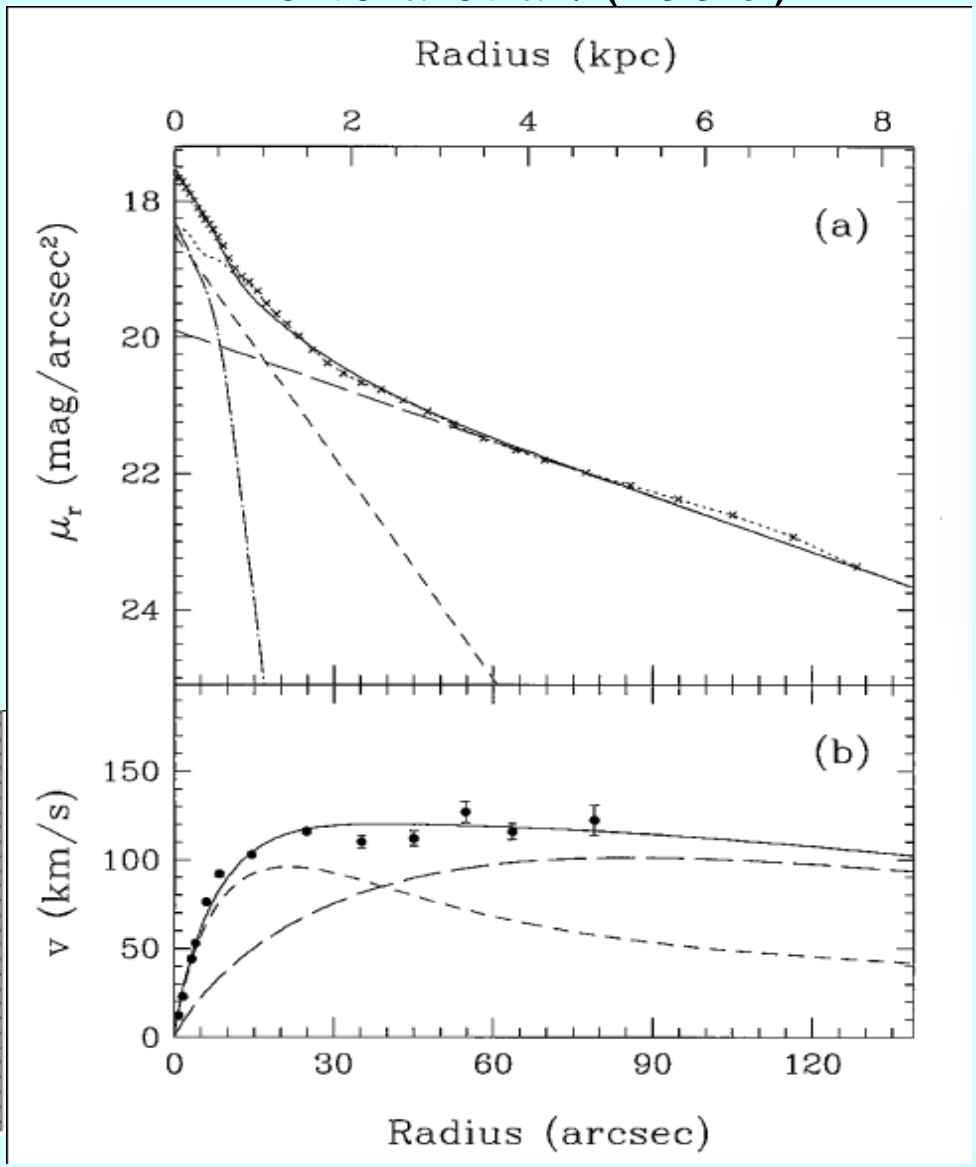


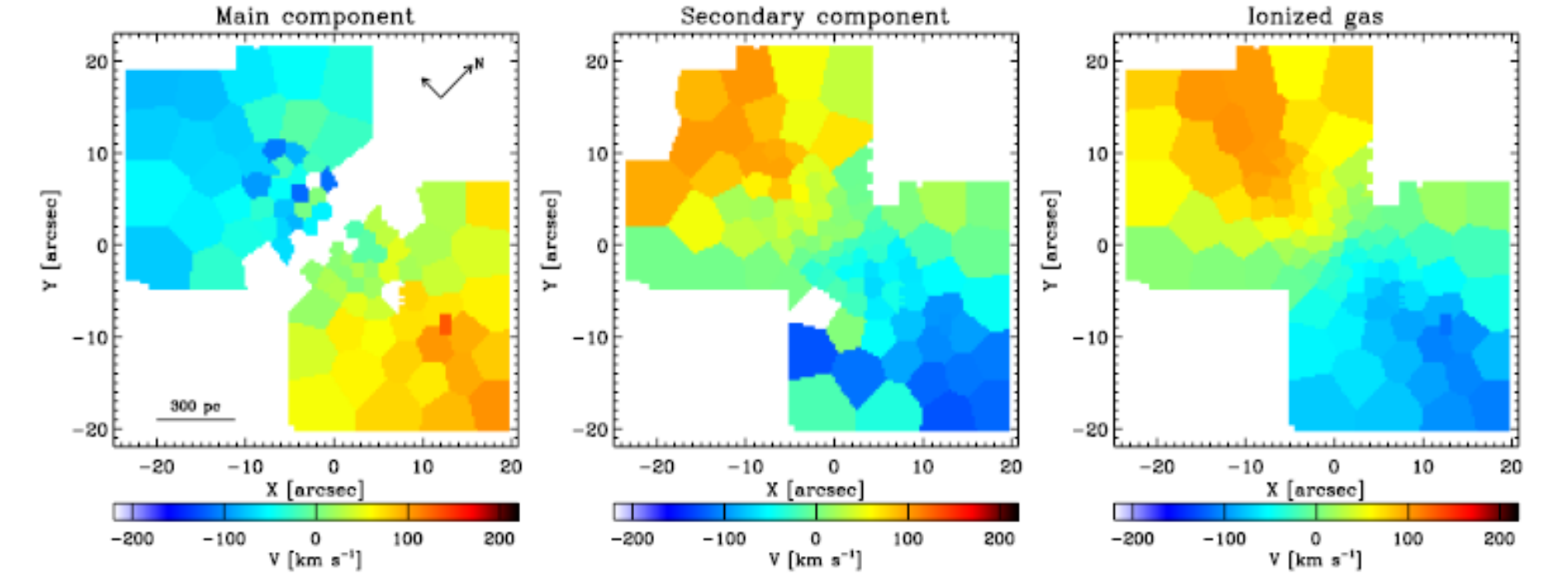


Corsini et al., 1998



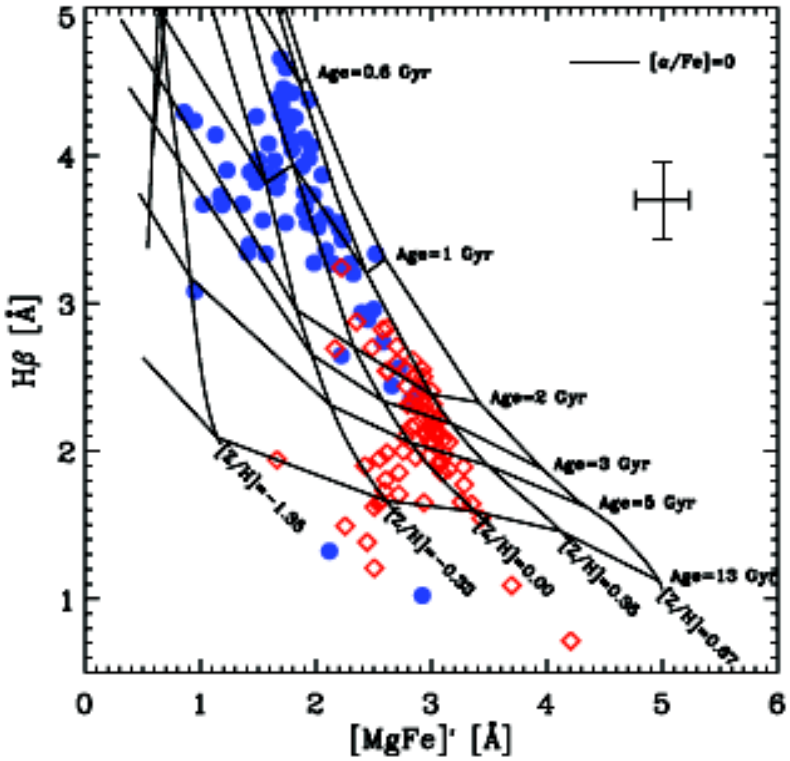
Stars vs. Stars + Gas

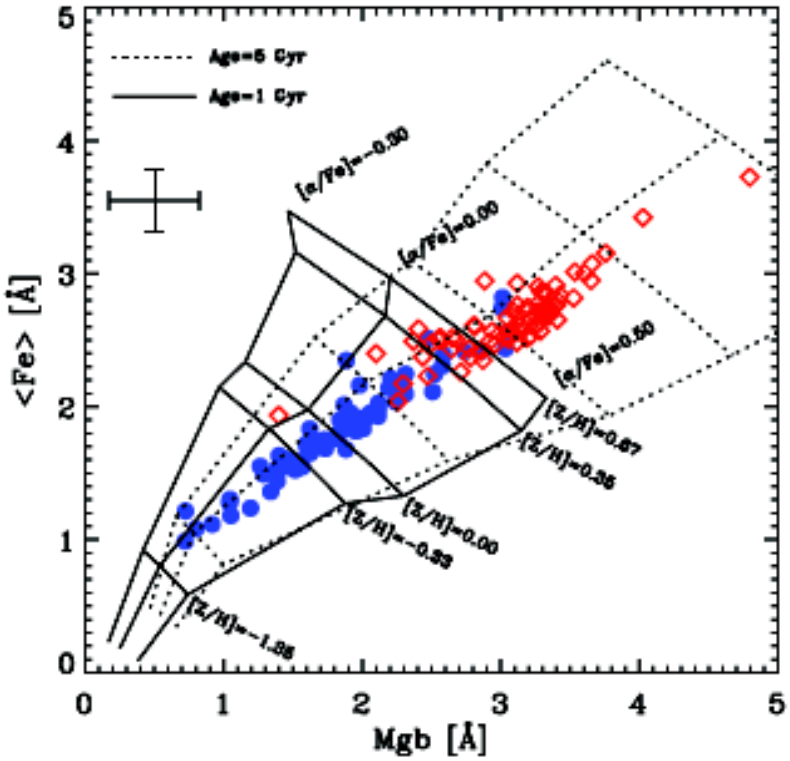
NGC 3593 – Sa (Coccato+ 2013)



Stellar Population

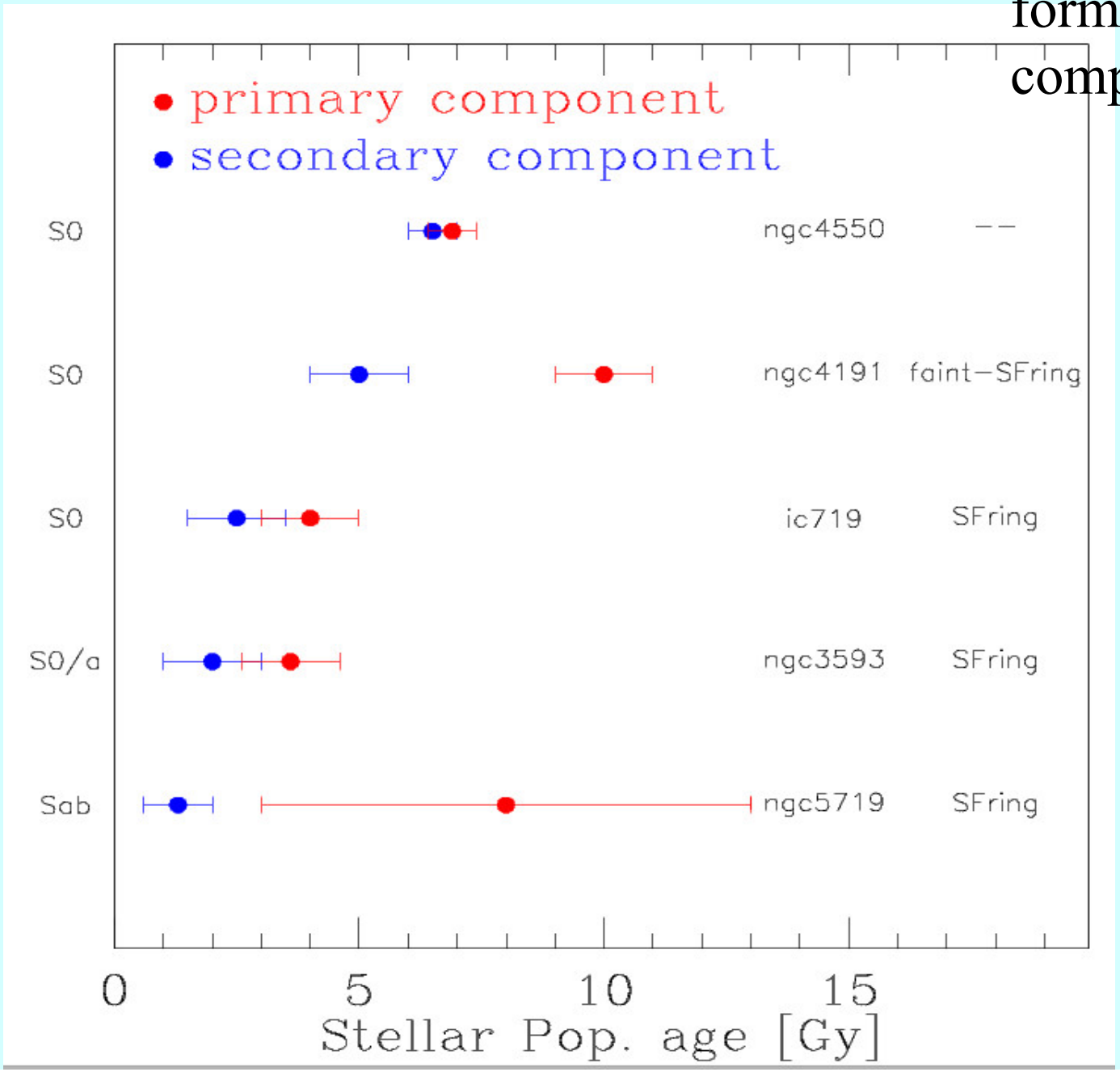
NGC 5719 – Sab (Coccato+ 2011)





Results and Conclusions

Counter-rotating stars formed after primary component



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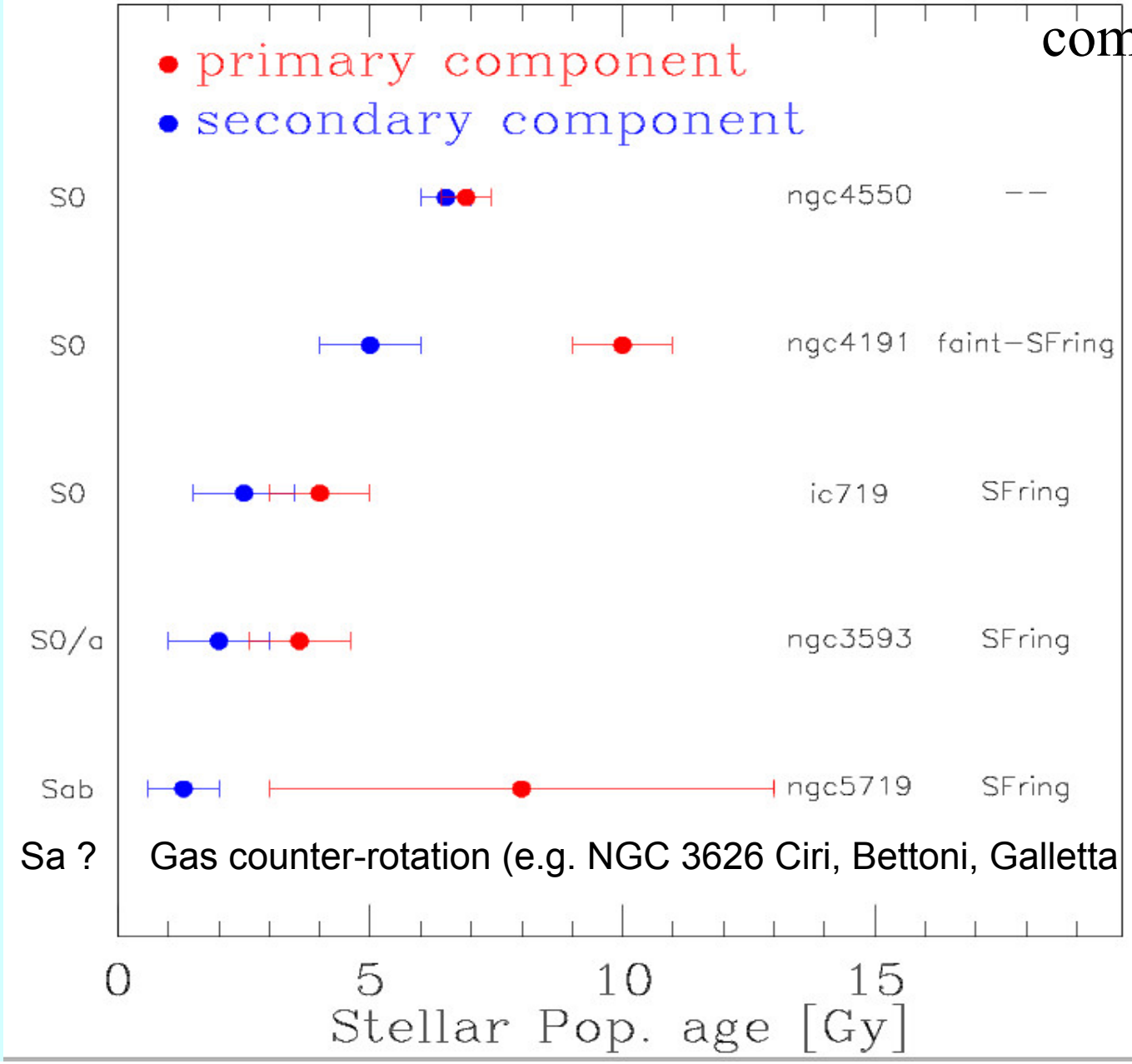
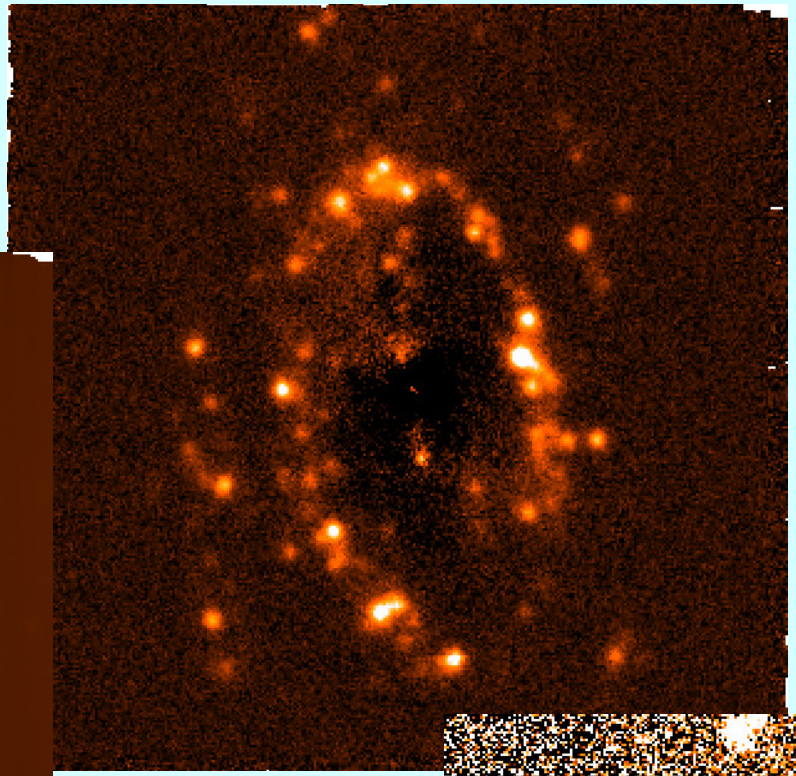


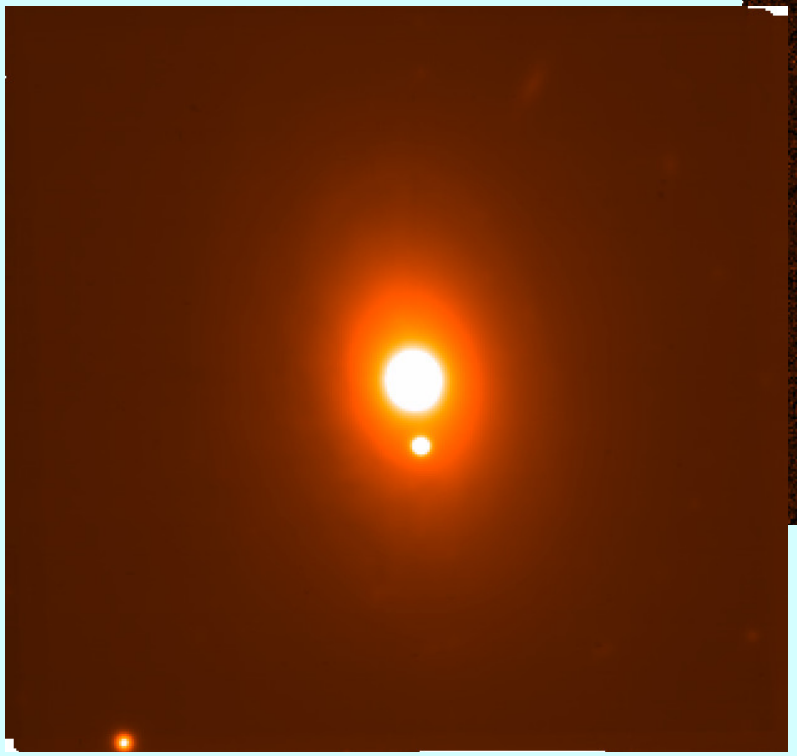
Sa ? Gas counter-rotation (e.g. NGC 3626 Ciri, Bettoni, Galletta 1995)

MUSE Results

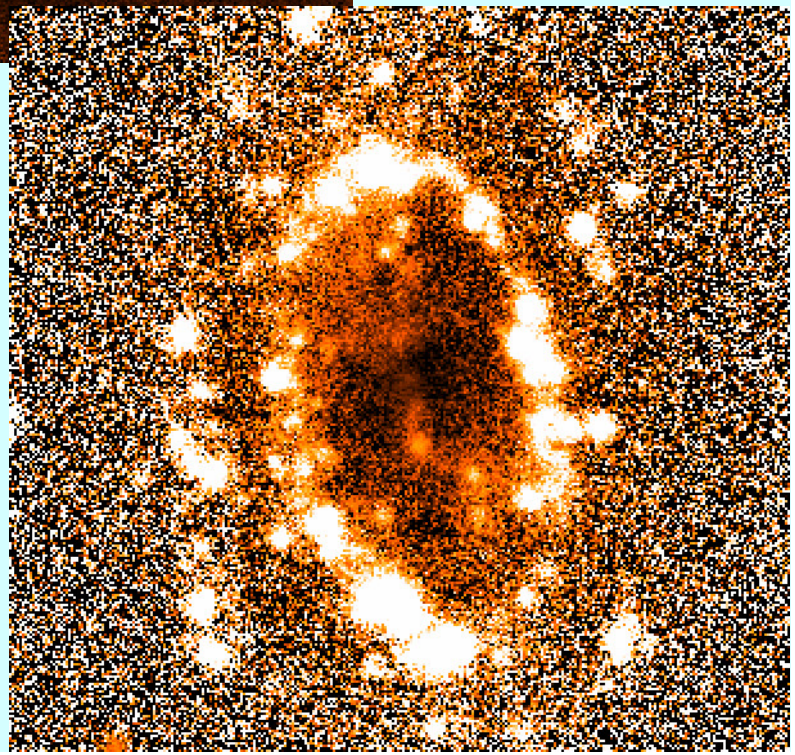
ngc 4191



1'x1' H-alpha

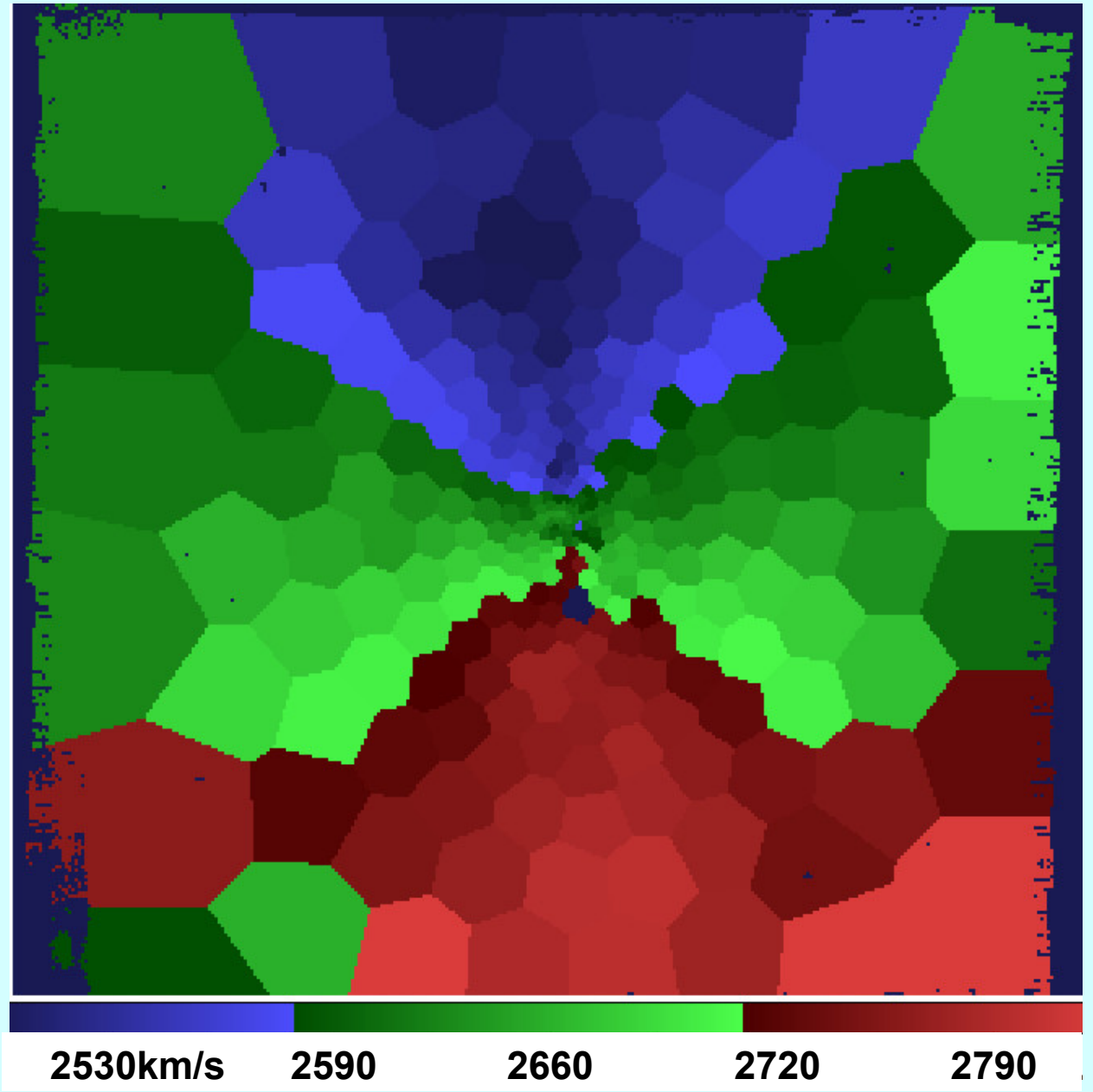


1'x1' muse image

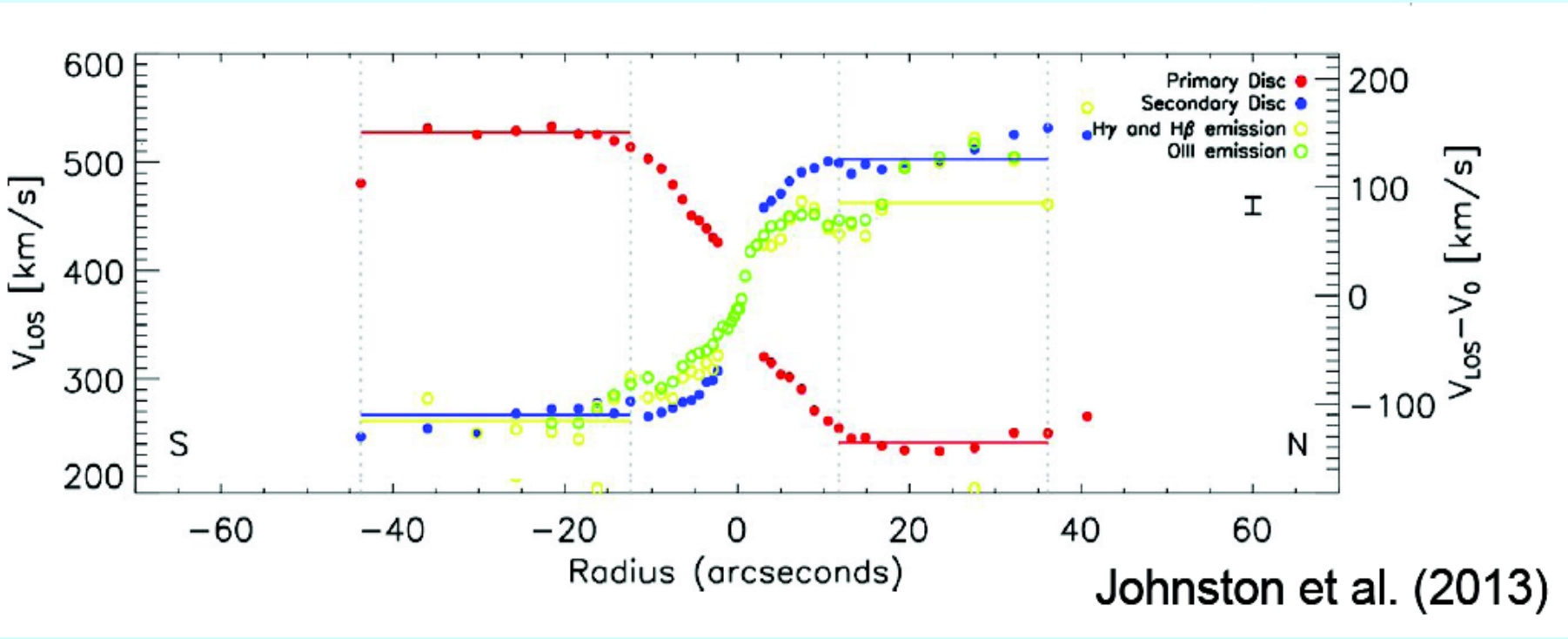


Halpha/[NII]

MUSE - Ionized Gas



Stars vs. Stars
NGC 4550 – S0 Rubin 1992



Johnston et al. (2013)

Introduction

- Galaxies do acquire material during their growth, either in form of gas or/and in form of stars. This may cause a violent change in the galaxy morphology (major merger).

When galaxies acquire gas it may sattle in some equilibrium plane and later form stars.

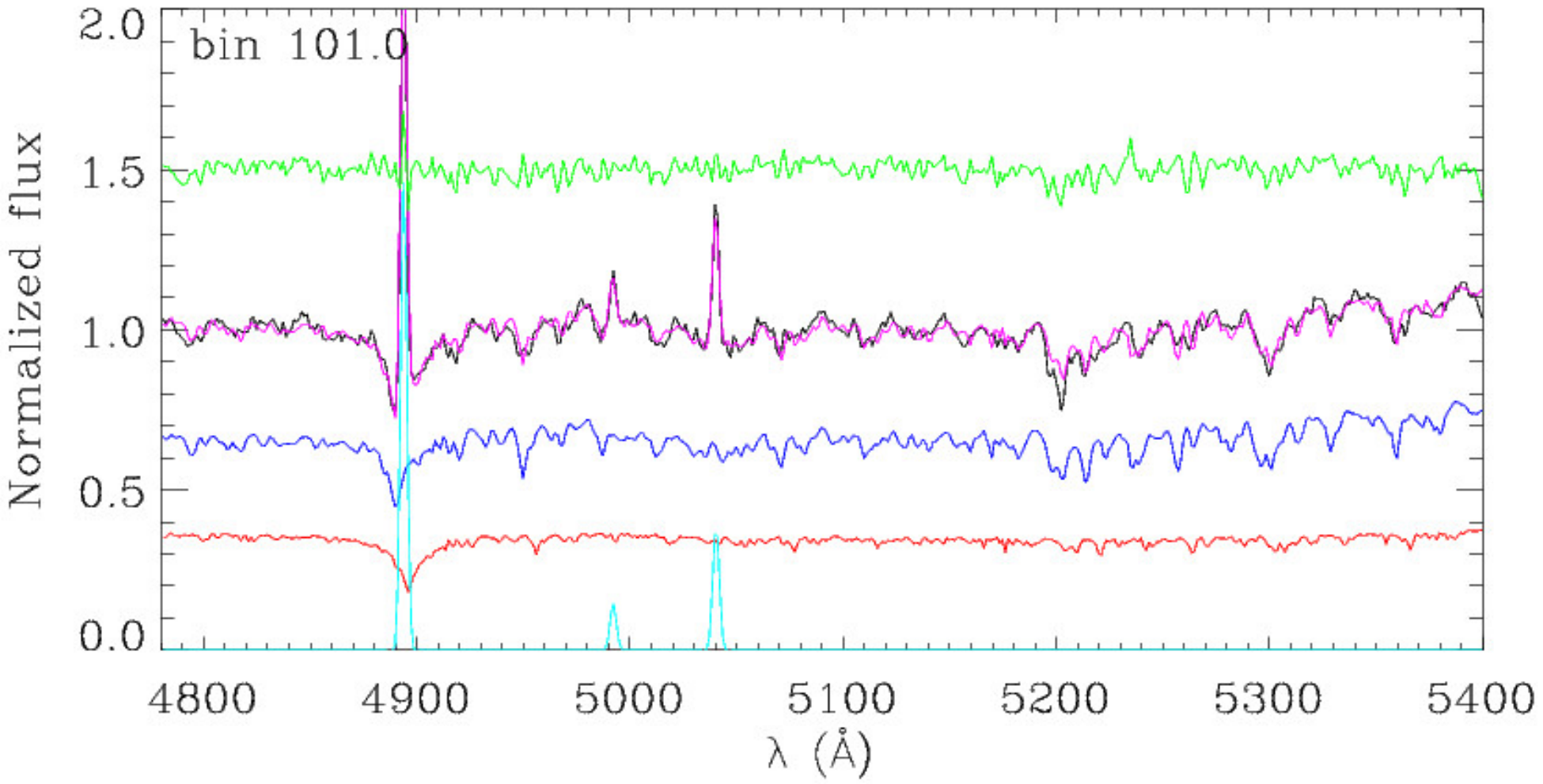
- Polar rings

- Counterrotating galaxies

- If the gas reaches the nucleus, it may form a nuclear disk (L. Morelli's talk)

S0 galaxies are generaly gas-poor systems. If they acquire a small gas cloud it is not whashed out by pre-existing gas and it may be traced.

MUSE- IC 719: Hbeta-Mg-Fe region



Introduction

- Counter-rotation: when in one galaxy components with opposite spin co-exits

- Stars vs. Gas
- Stars vs. Stars
- Gas vs. Gas
- Stars vs. (Stars + Gas)

- whole galaxy
- inner/outer region

- About 15% of S0 counter-rotates
- We can detect up to a fraction of 20% (in luminosity) counter-rotating stars

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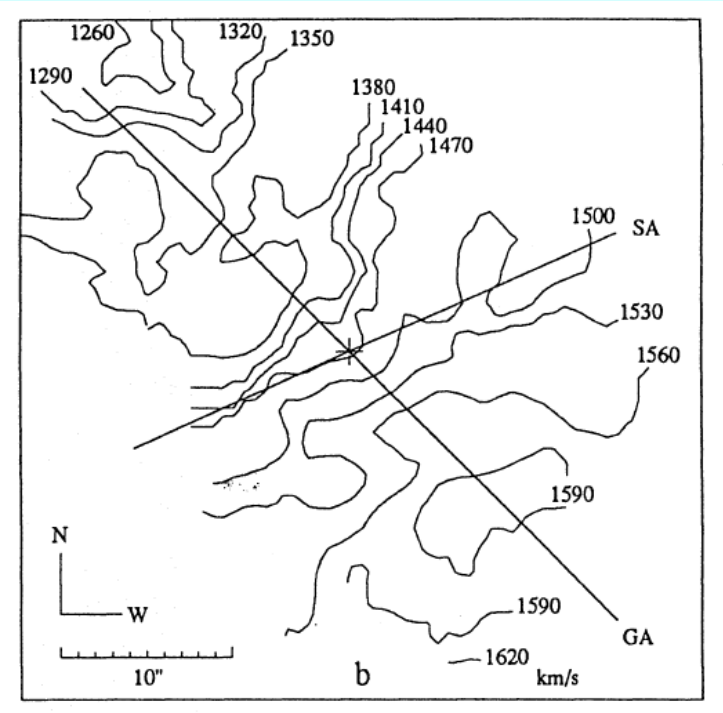
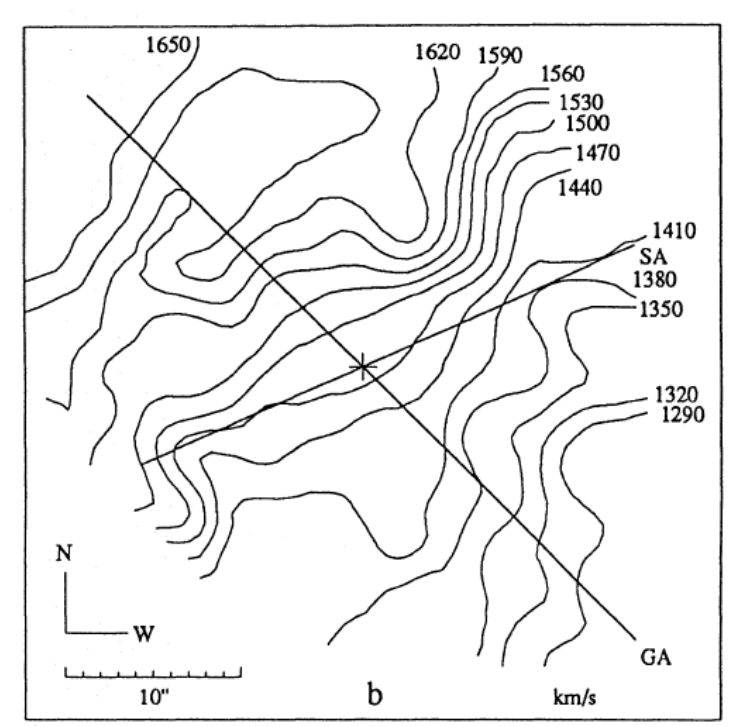
The advent of 2D-spectroscopy

Perrot-Fabbry - Plana & Boulesteix 1995

NGC 1052 – E4, two ionized gas components





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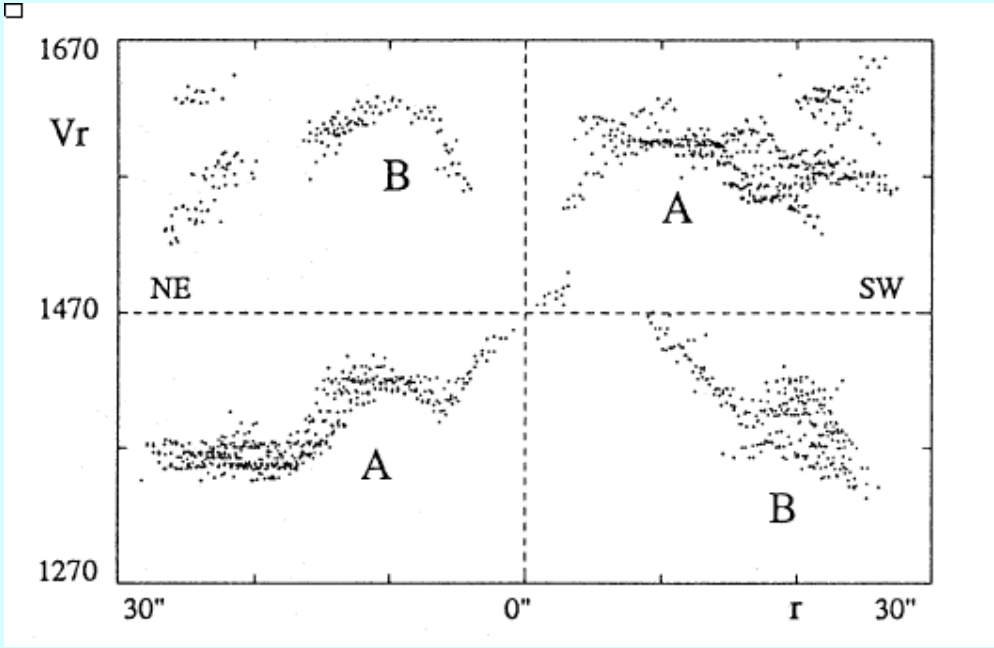
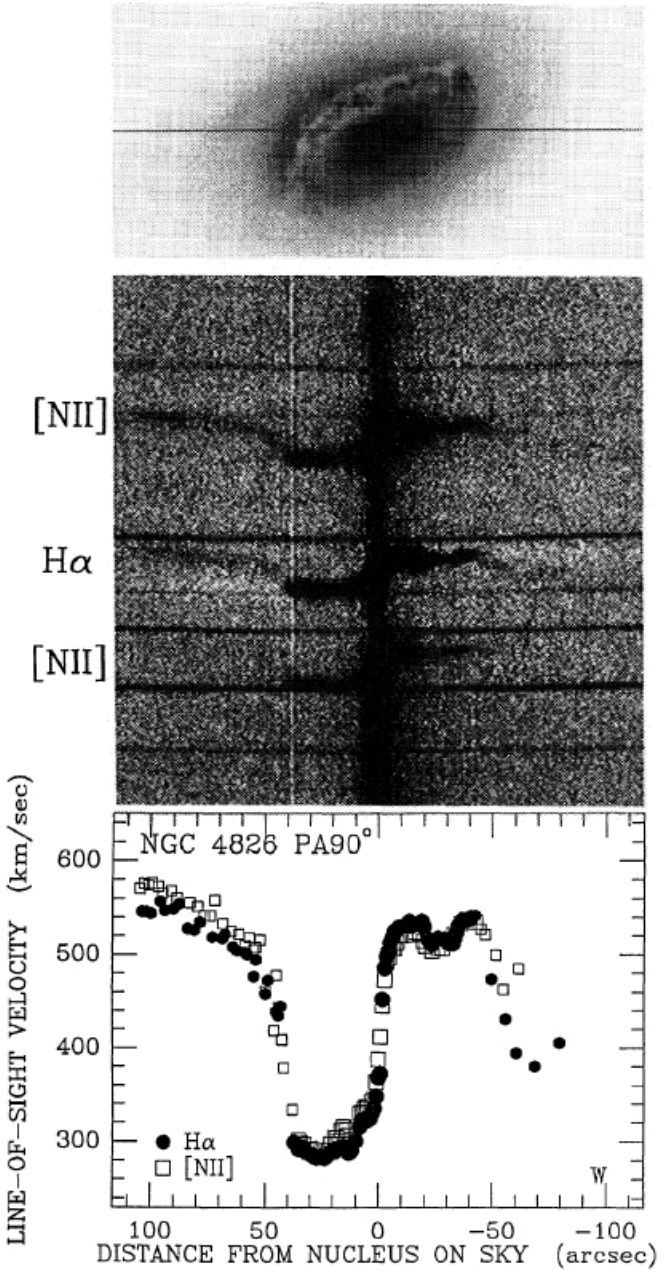


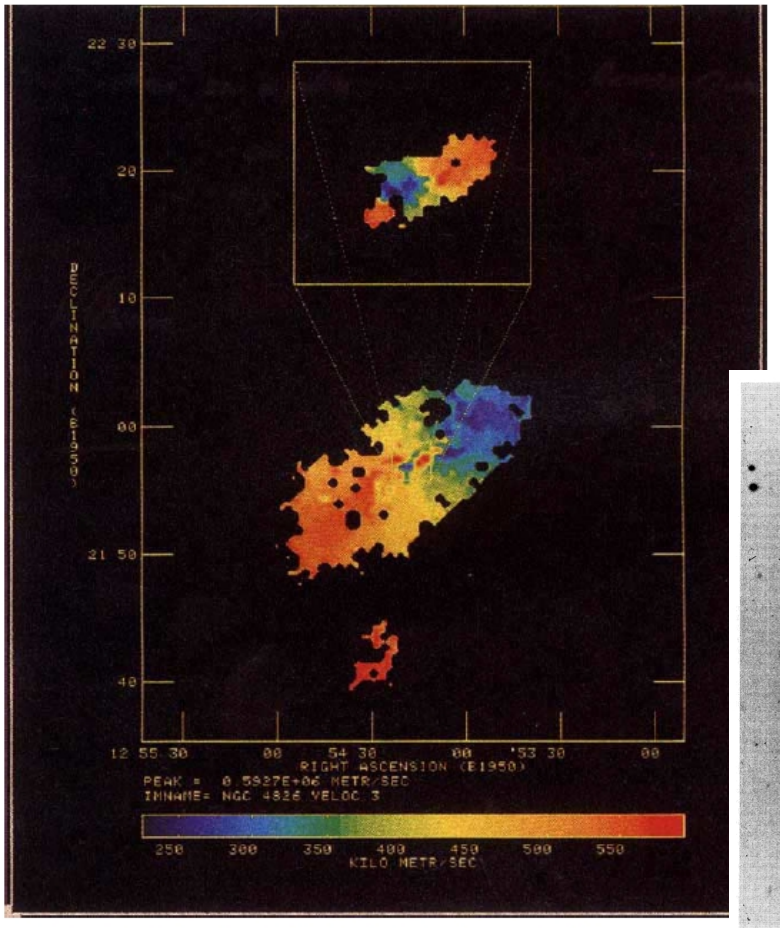
Outer Gas v. Gas counter-rotation

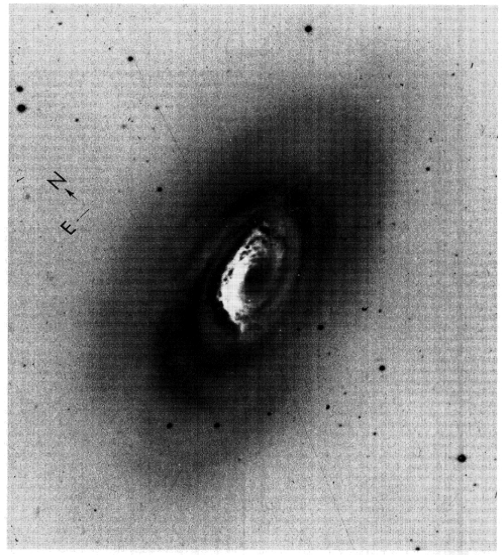
Rubin (1994): ionized gas

Braun et al. (1992): HI

Rix et al. (1995): stars

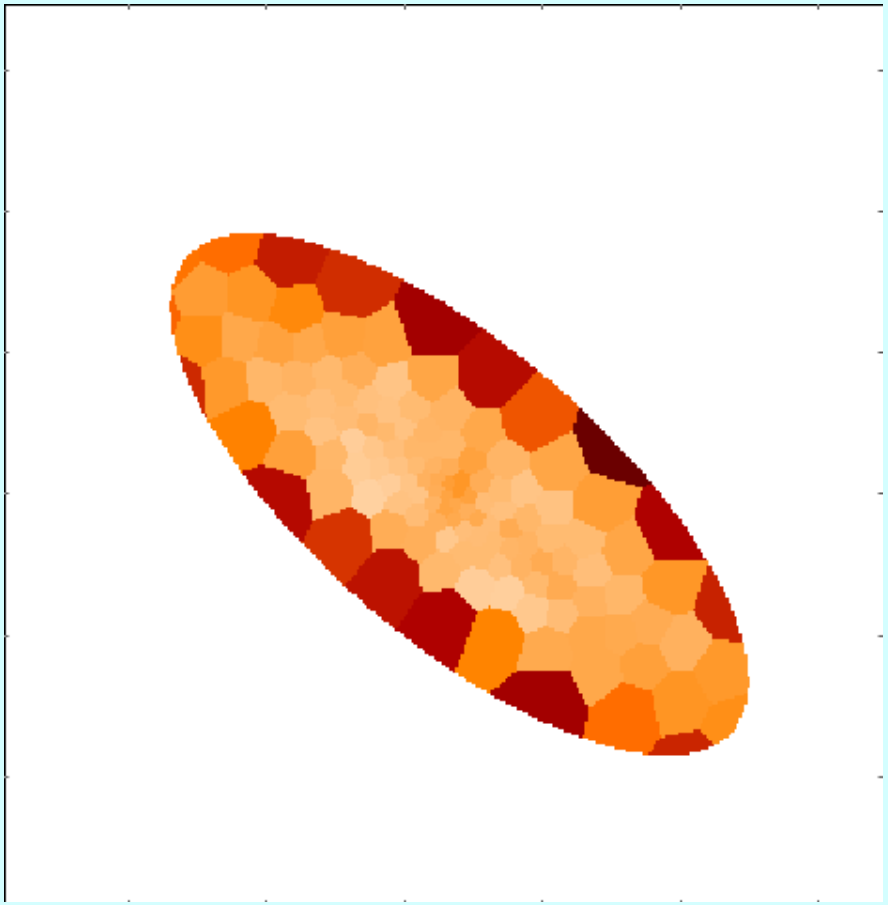






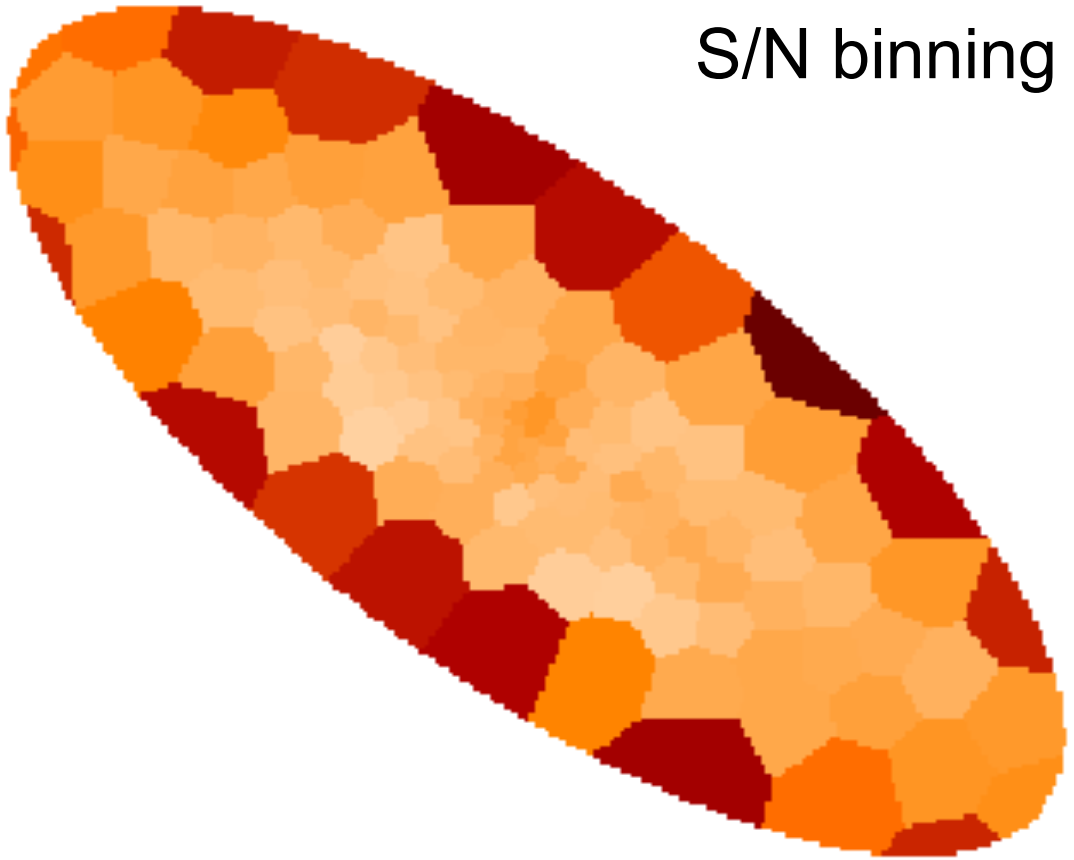
MUSE - IC 719: binning

Reconstructed image
spaxel 0.2”x0.2”, seeing~1.4”



S/N binning

MUSE - IC 719: binning



Introduction

Counter-rotating Galaxies are (extra)-ordinary laboratories that can be used to study ordinary galaxies.

How did they form?

- Acquisition of gas clouds or filaments (then turned into stars)?
- Acquisition of gas reach dwarf
- Minor merger?

Introduction

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- Minor merger?

- Study of the stellar population of the counter-rotating component

- Local Environment (companions, gas clouds)

- Numerical Simulations

The Sample

- We started an observational campaign aimed at studying the stellar populations of all known star-star counter-rotating galaxies

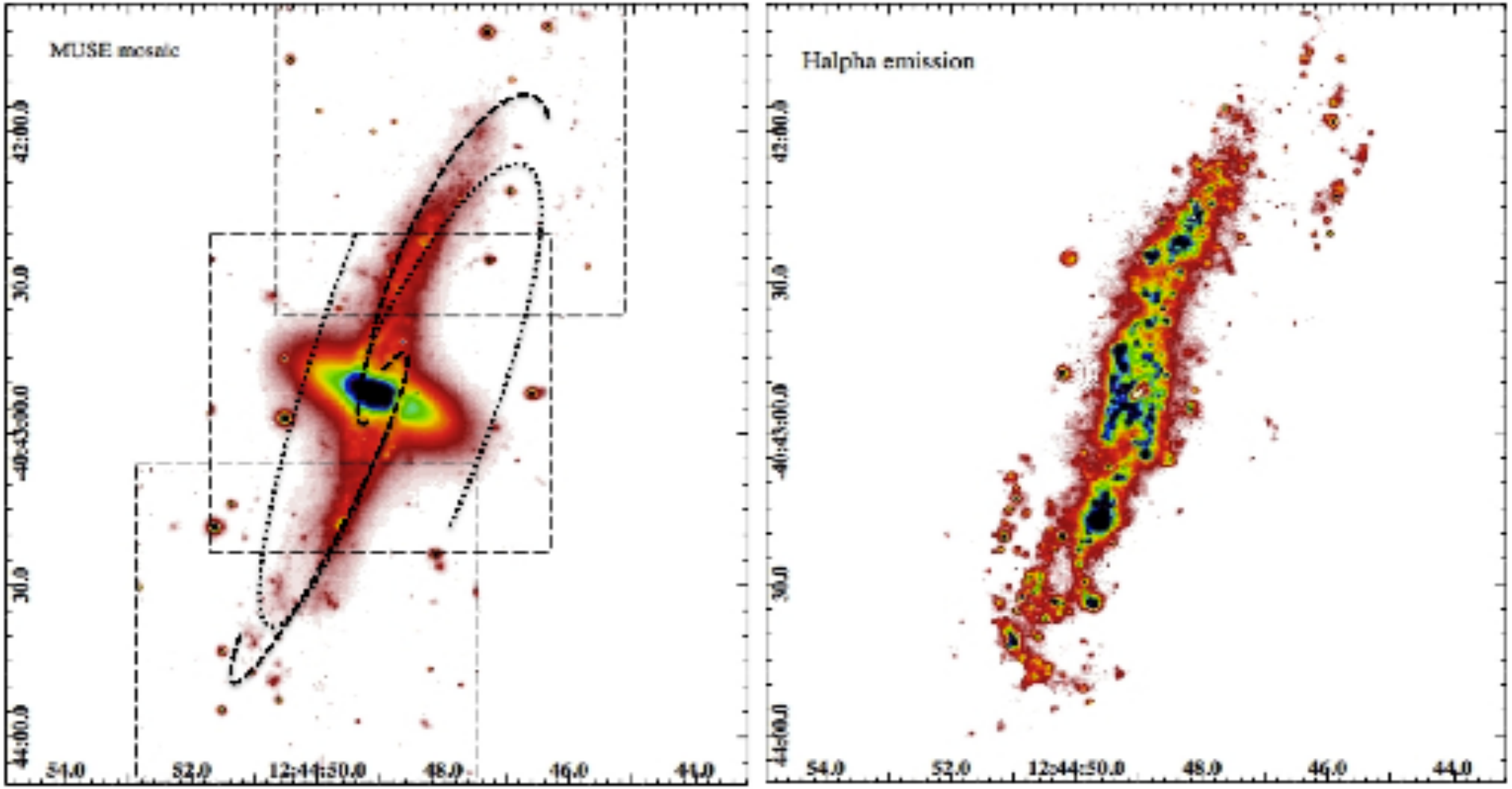
Done

- VIMOS ngc 5719, ngc 4550, ngc 3593
- VIRUS-B ngc 4191
- (ngc 4138 (1.22m Galileo/Asiago))

Just observed! 1hour integration each galaxy (one position)

- MUSE

ic719 (Katkov+ 2013), ngc 4473, ngc4191 (Coccato+ 2014)


MUSE mosaic
Halpha emission
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30.0
44:00.0
54.0
52.0
12:44:50.0
48.0
46.0
44.0