NEW RESULTS ON COUNTER-ROTATING GALAXIES FROM 3D SPECTROSCOPIC PROJECTS

Enrico Maria Corsini
Dipartimento di Fisica e Astronomia
Università di Padova

La Laguna, 22nd June 2015

OUTLINE

✧ Topics
- Definition
- Classification
- Size
- Components
- Morphological signatures
- Kinematic signatures
- Statistics
- Stellar populations
- Formation scenarios

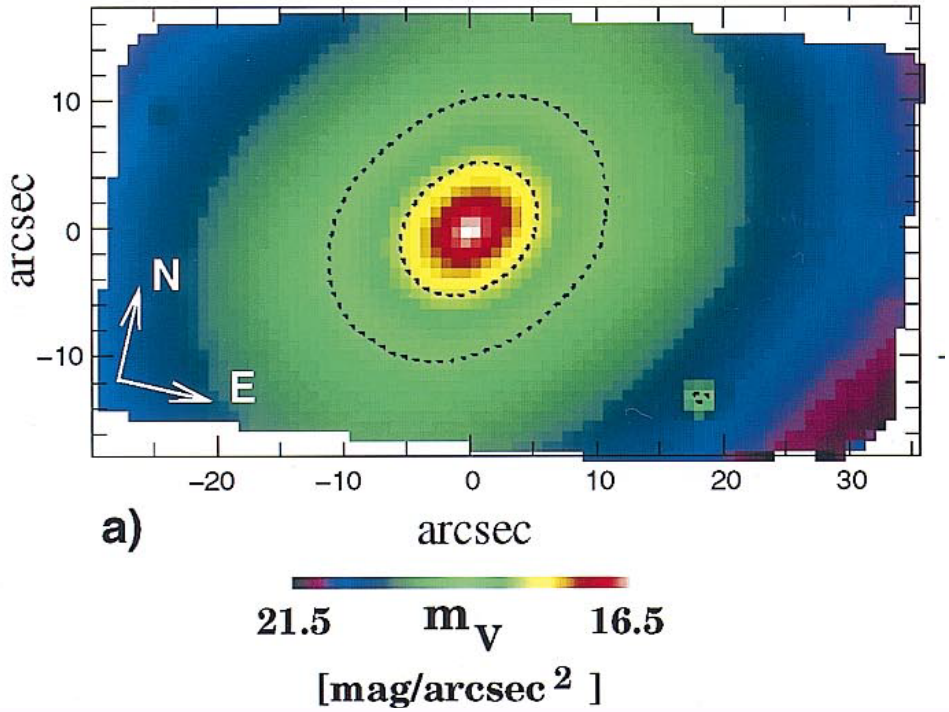
✧ Focus on
- Normal and bright galaxies
  (interacting galaxies = Barrera-Ballesteros, dwarfs = Ryś)
- Main-plane decoupled components
  (off-plane components = Coccato, Sil'chenko)

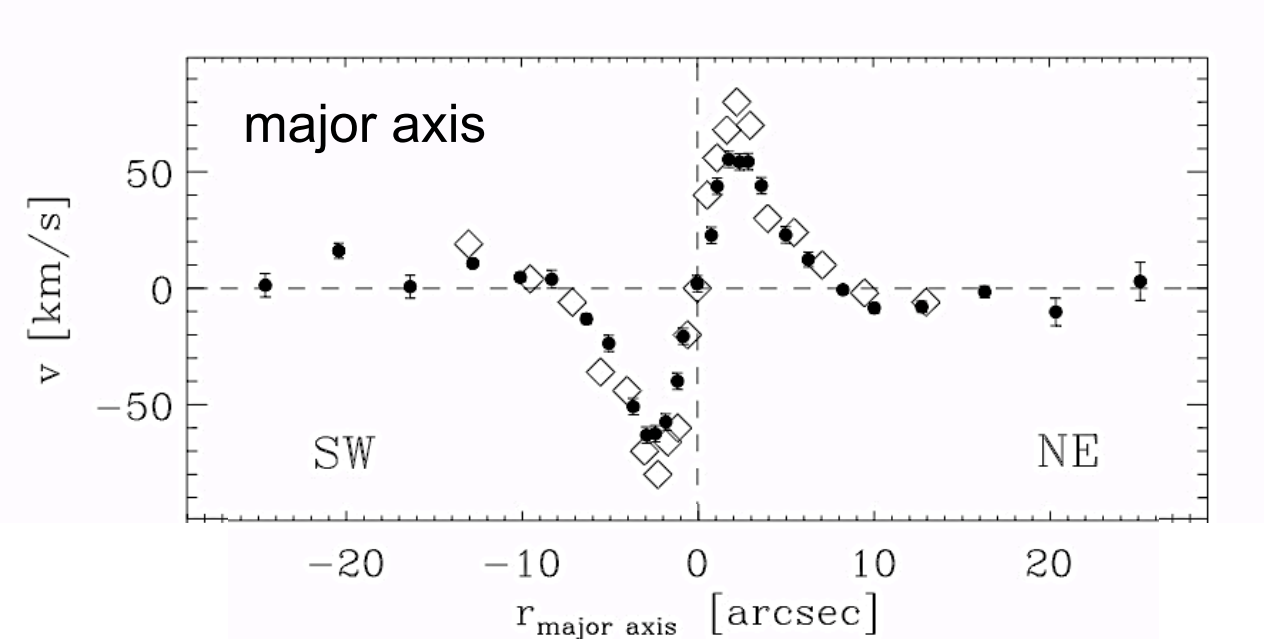
DEFINITION

Counter-rotation is observed when two galactic components have their angular momenta projected antiparallel onto the sky plane.

✧ intrinsic: the components rotate around the same axis

✧ apparent: the components rotate around skewed axes and the line of sight lies between them (multi-slit/IFU spectroscopy)

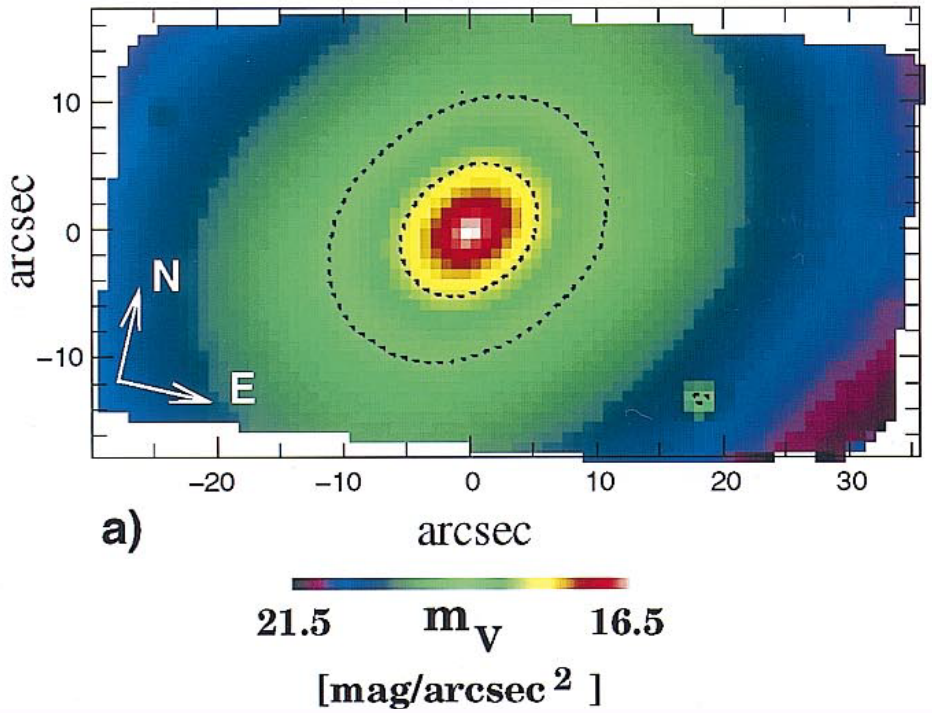


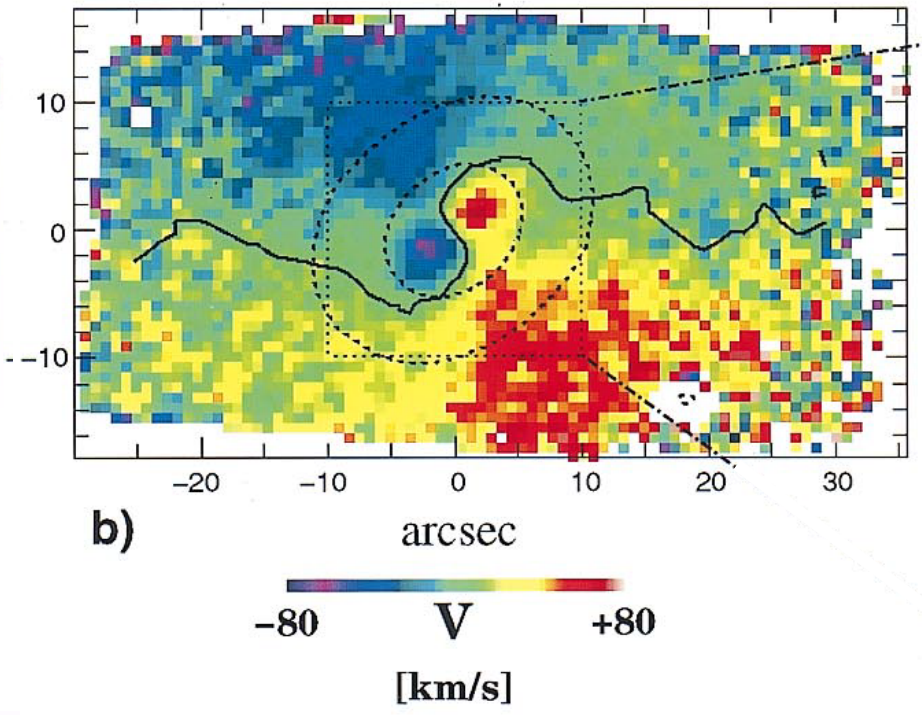


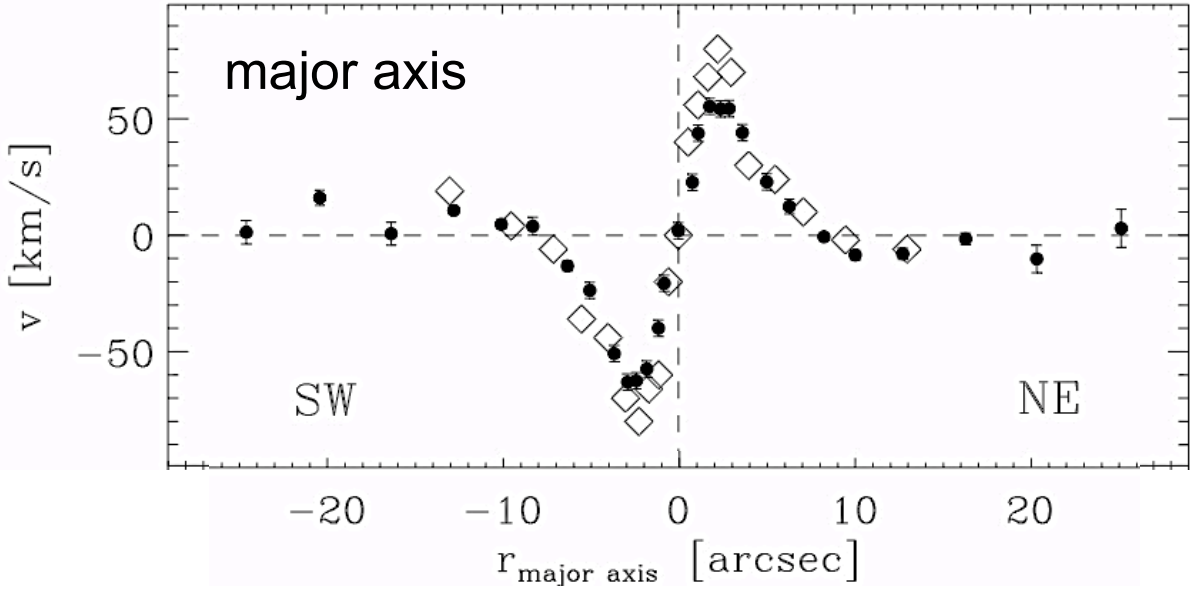
NGC 4365 – E3

isolated core

Surma & Bender (1995)







Davies et al. (2001)

NGC 4365 – E3

isolated core

Surma & Bender (1995)

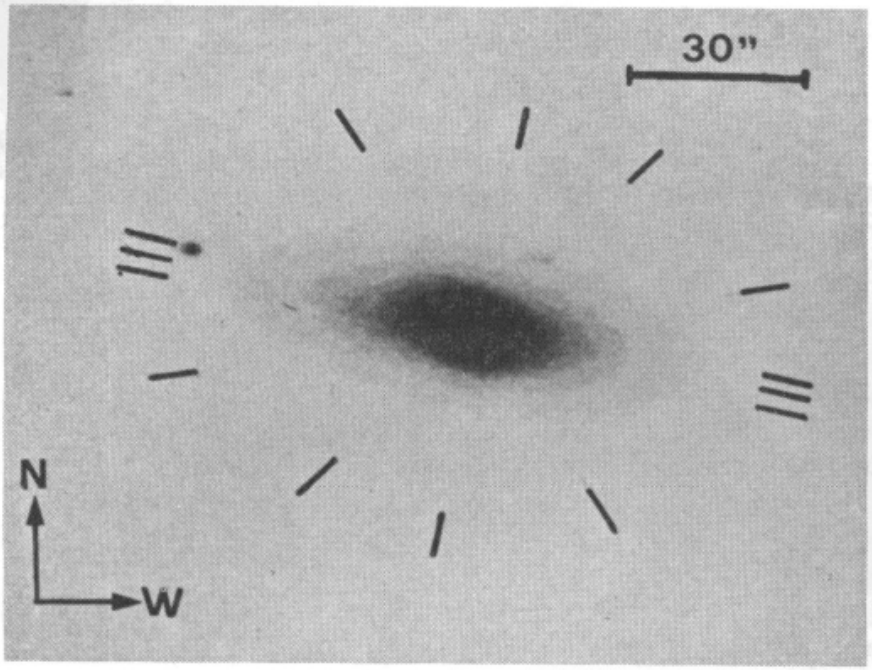
CLASSIFICATION

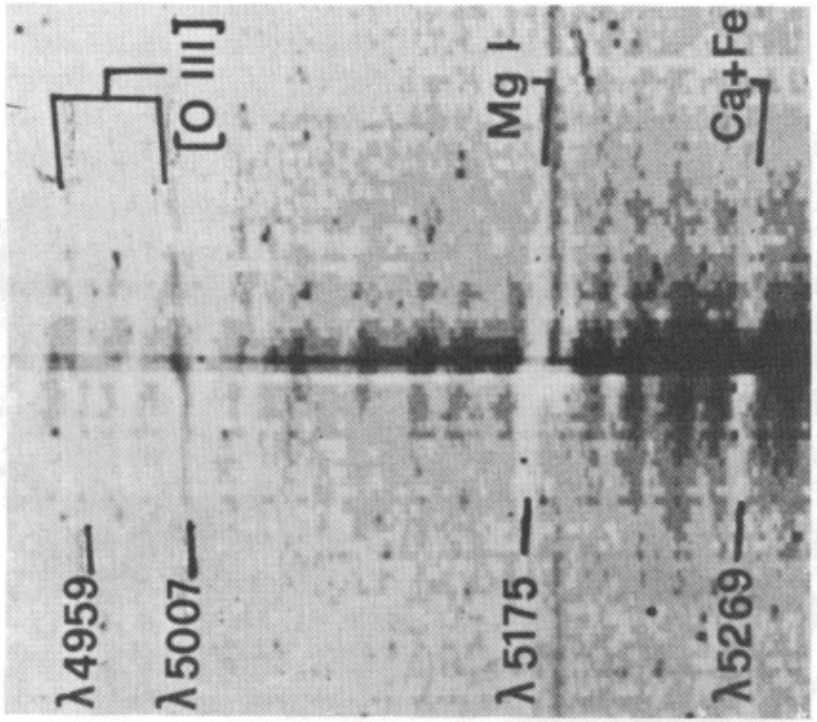
Counter-rotation occurs in a variety of forms

- ✧ gas vs stars: the gaseous disk counter-rotates with respect to the stellar body (e.g., NGC 4546)

- ✧ stars vs stars: two stellar components counter-rotate (e.g., NGC 4550)

- ✧ gas vs gas: two gaseous disks counter-rotate (e.g., NGC 7332)

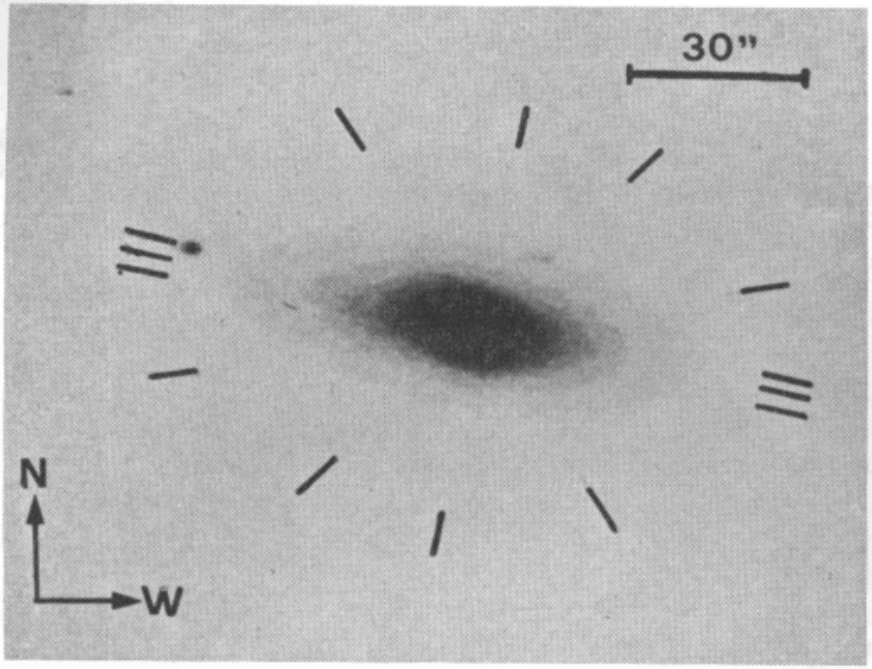


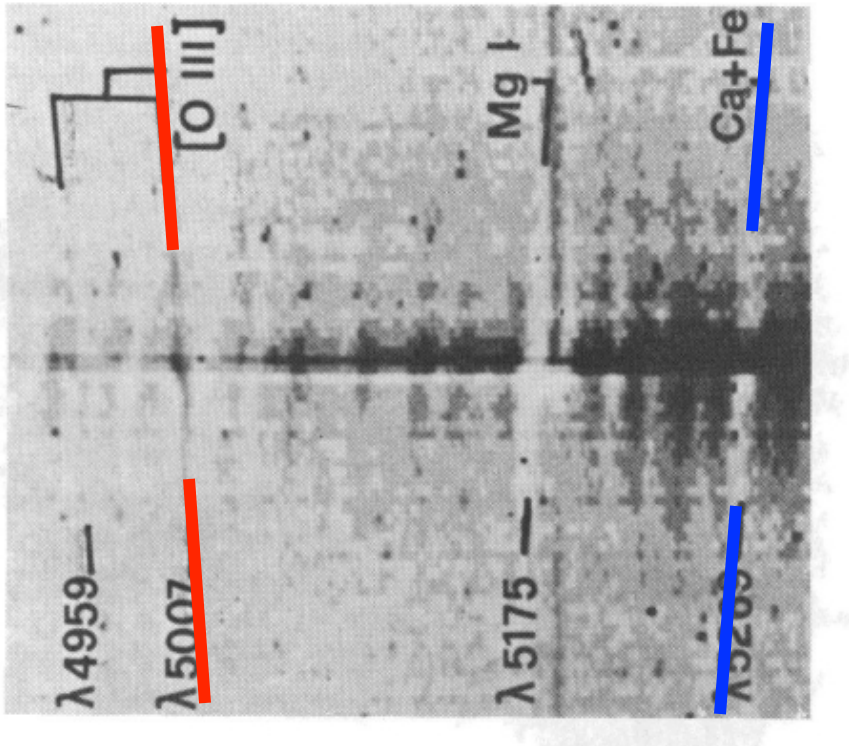


NGC 4546 – SB0

gas vs stars counter-rotation

Galletta (1987)





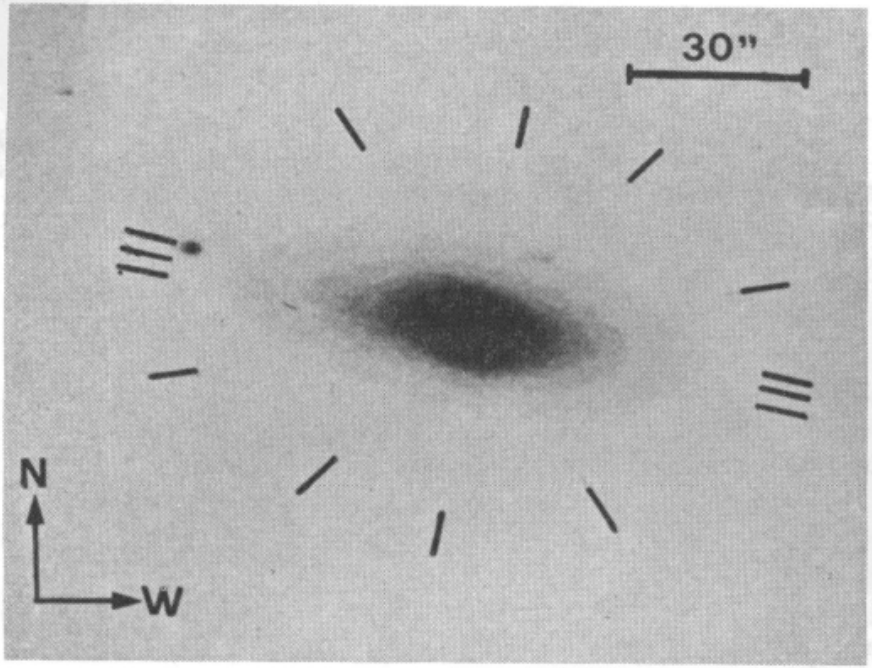
NGC 4546 – SB0

gas vs stars counter-rotation

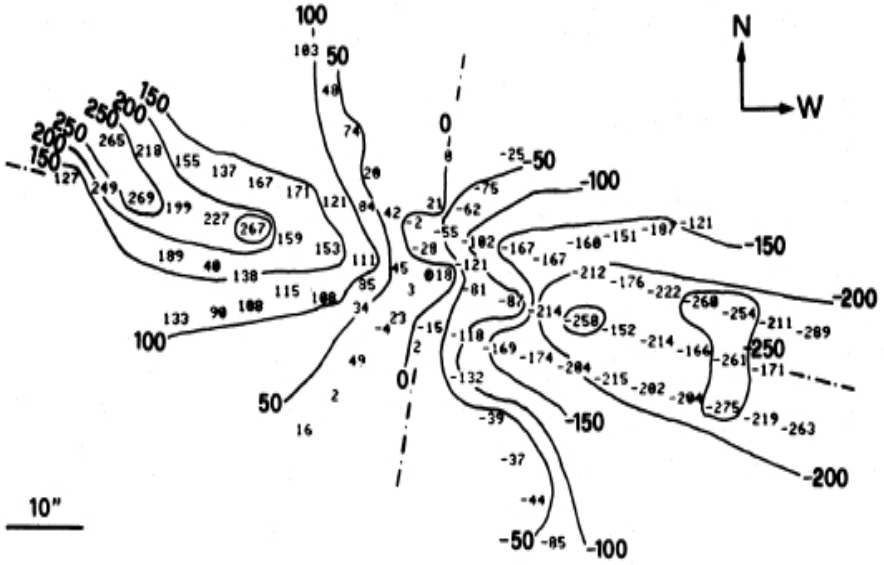
gas

stars

Galletta (1987)

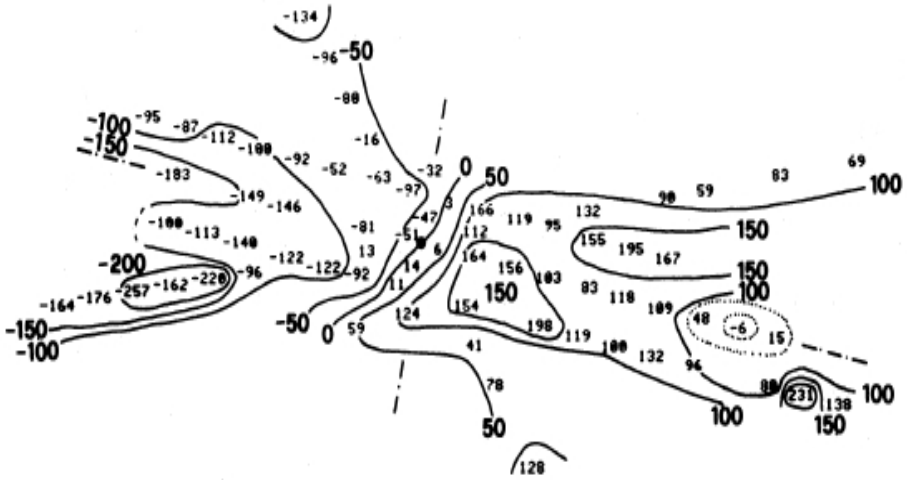


STARS



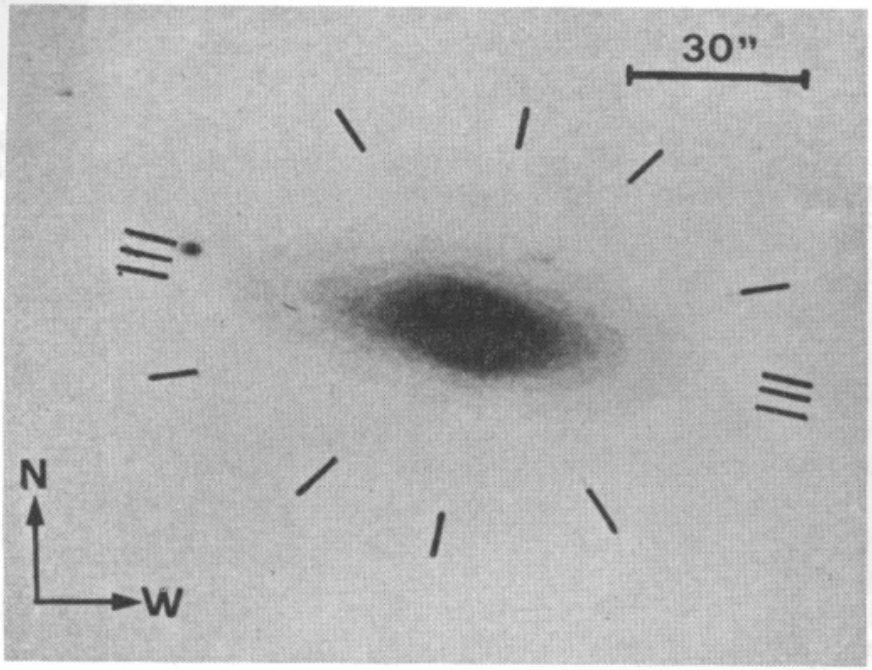
NGC 4546 – SB0

gas vs stars counter-rotation

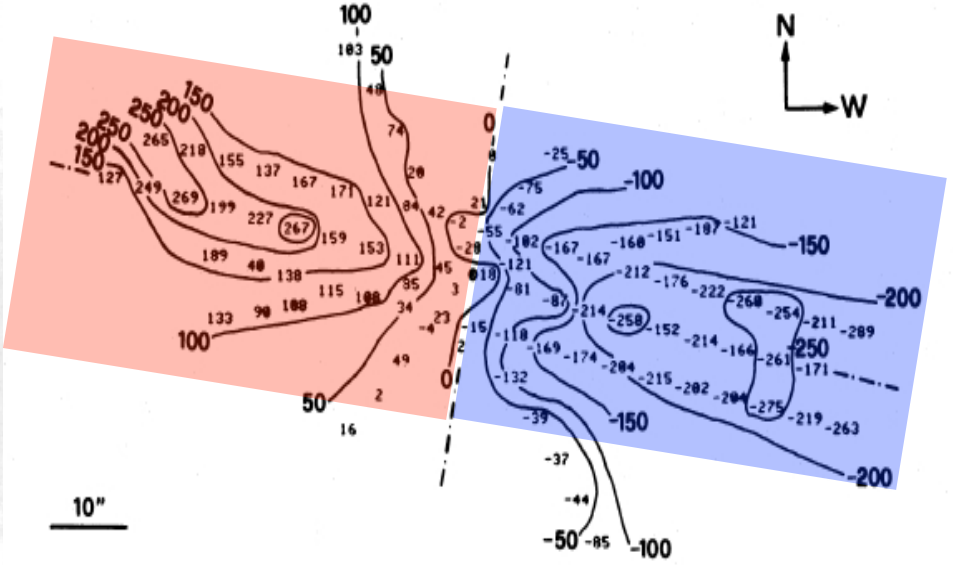


GAS

Galletta (1987)

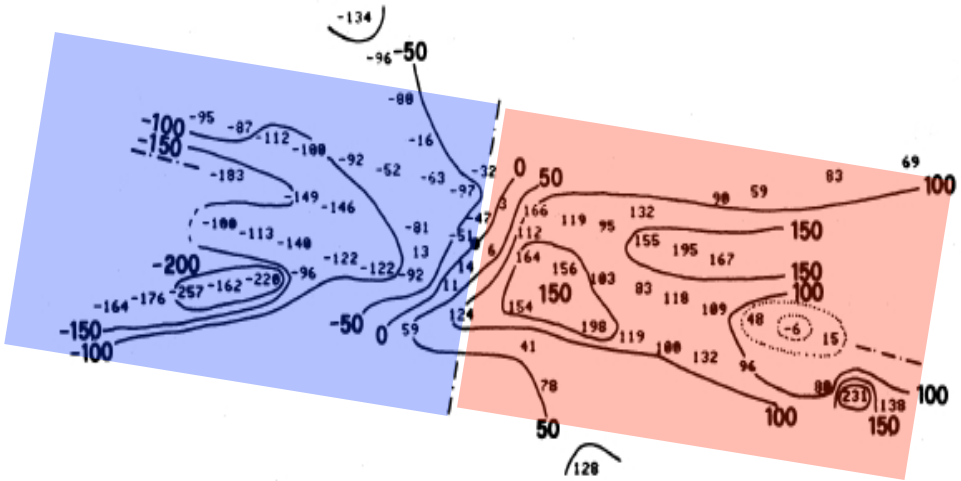


STARS



NGC 4546 – SB0

gas vs stars counter-rotation



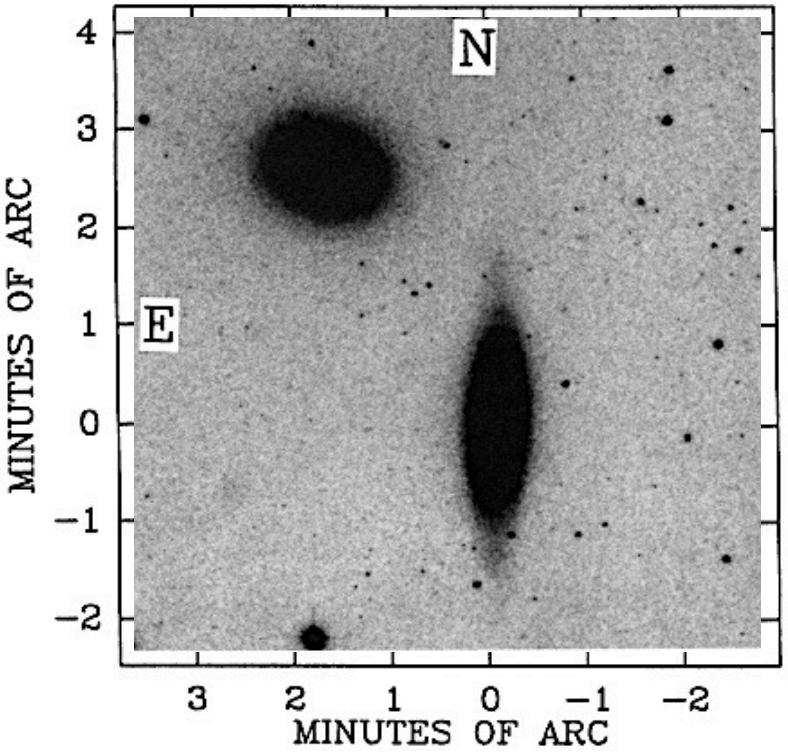
GAS

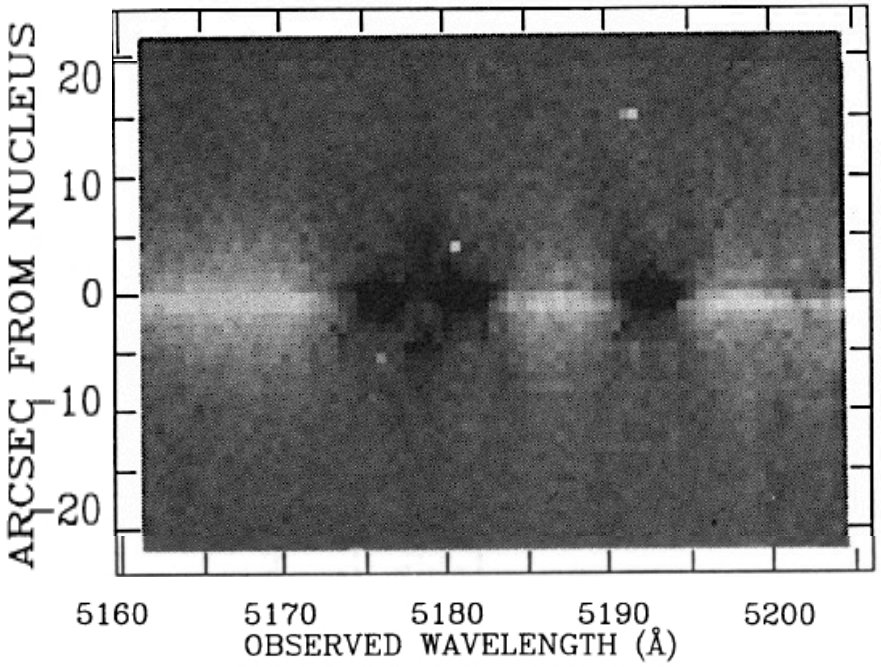
Galletta (1987)

CLASSIFICATION

Counter-rotation occurs in a variety of forms

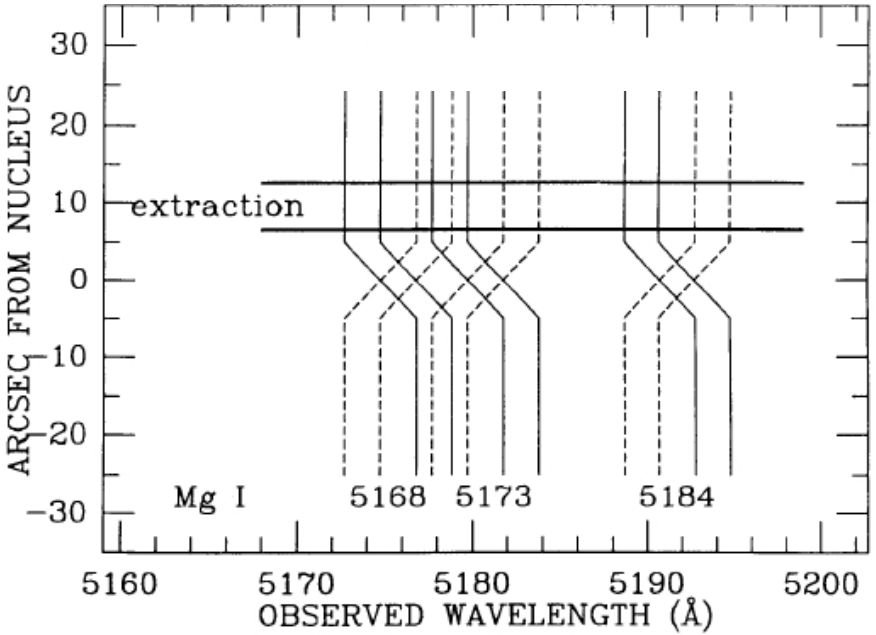
- ✧ gas vs stars: the gaseous disk counter-rotates with respect to the stellar body (e.g., NGC 4546)
- ✧ stars vs stars: two stellar components counter-rotate (e.g., NGC 4550)
- ✧ gas vs gas: two gaseous disks counter-rotate (e.g., NGC 7332)



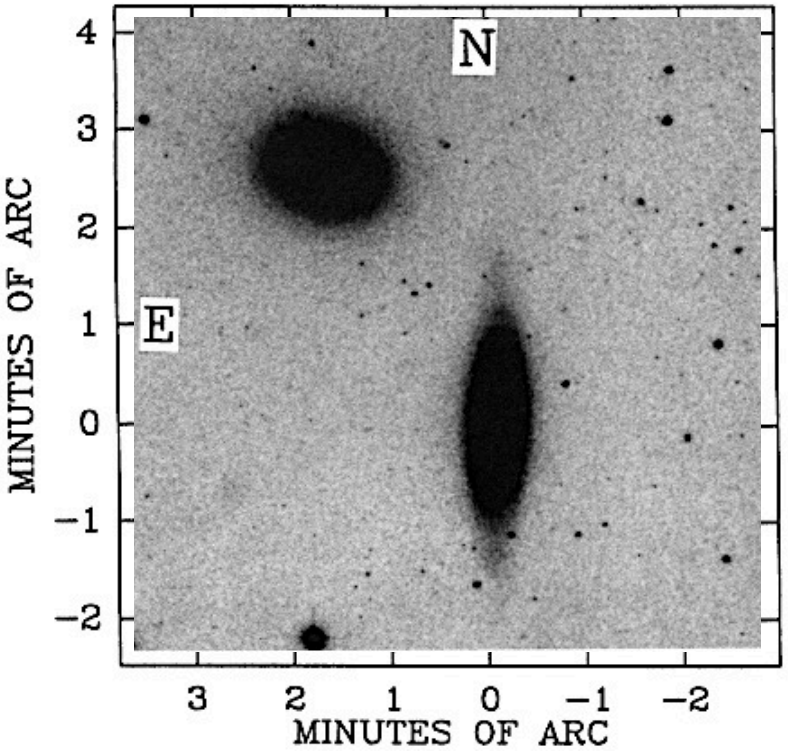


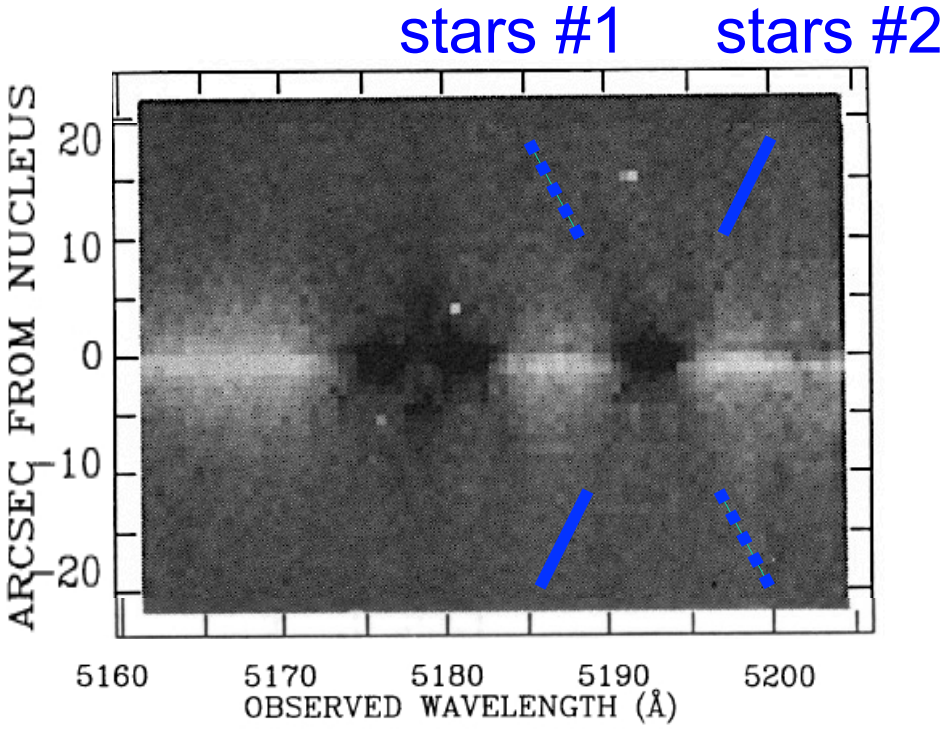
NGC 4550 – SB0

stars vs stars counter-rotation



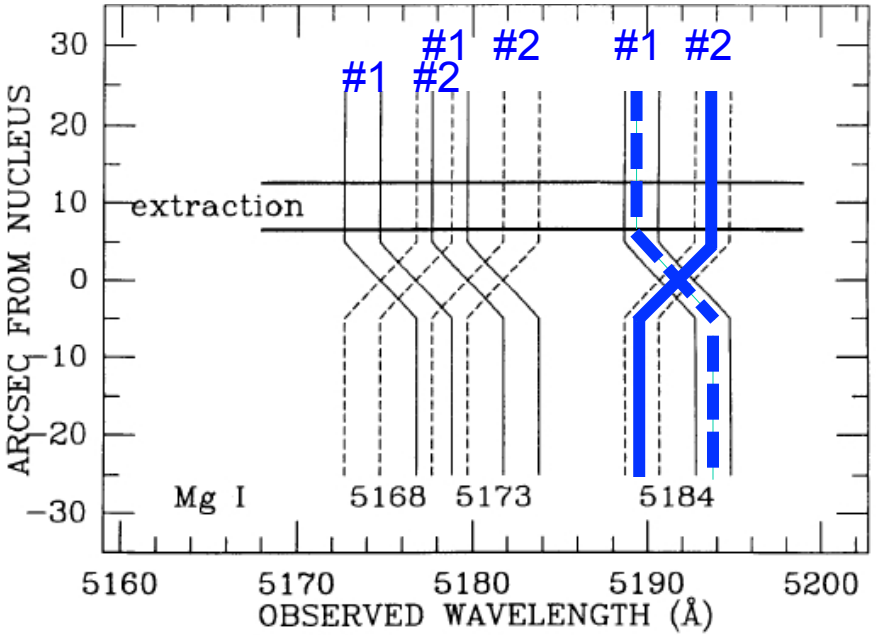
Rubin (1992)





NGC 4550 – SB0

stars vs stars counter-rotation



Rubin (1992)

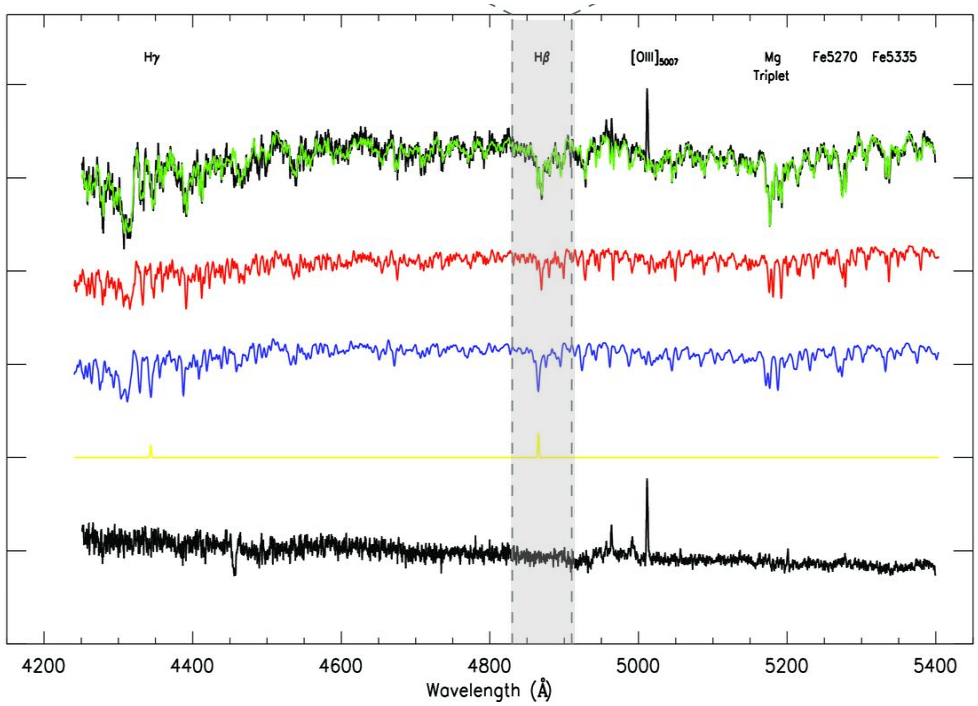
galaxy+fit

stars #1

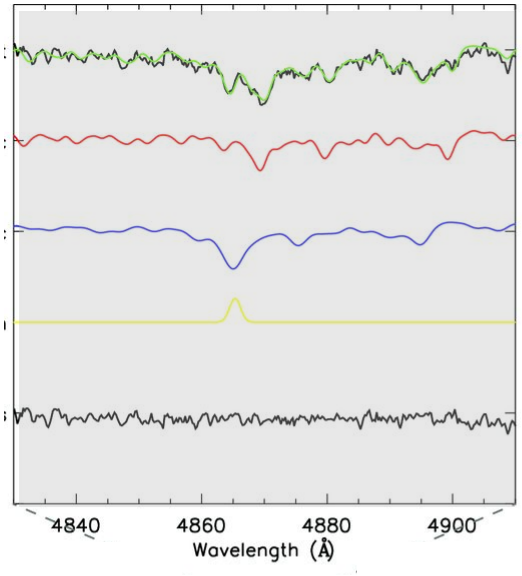
stars #2

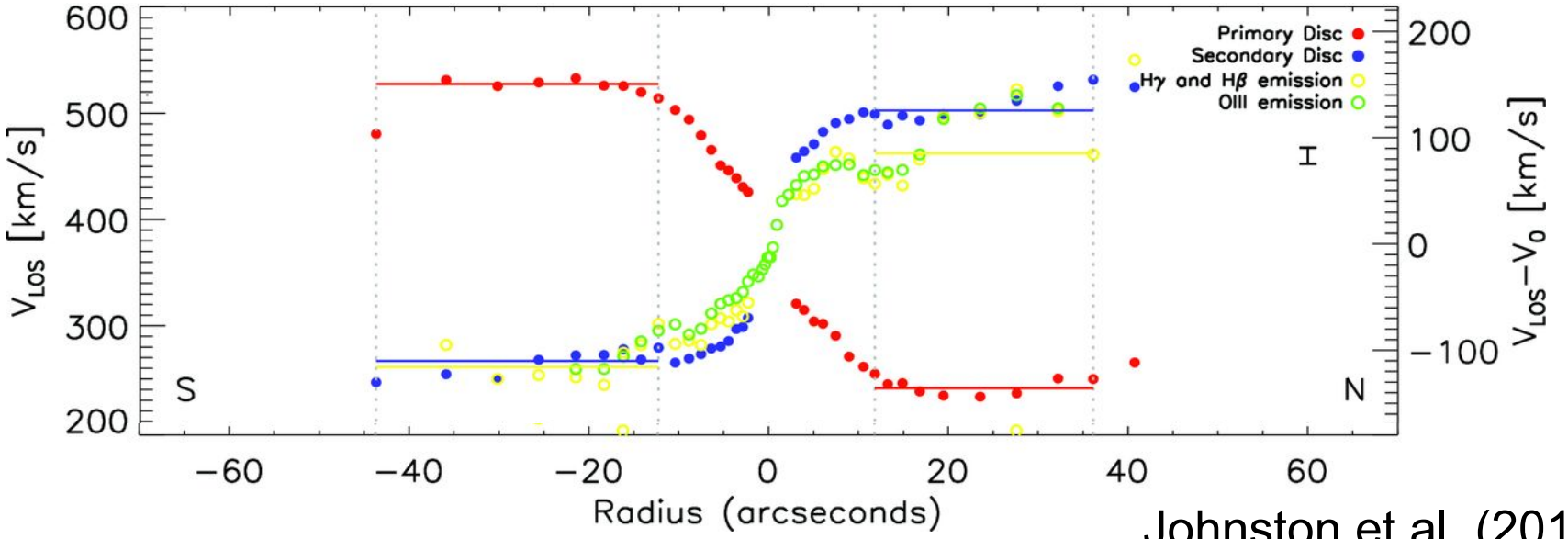
gas

residuals



Hβ region



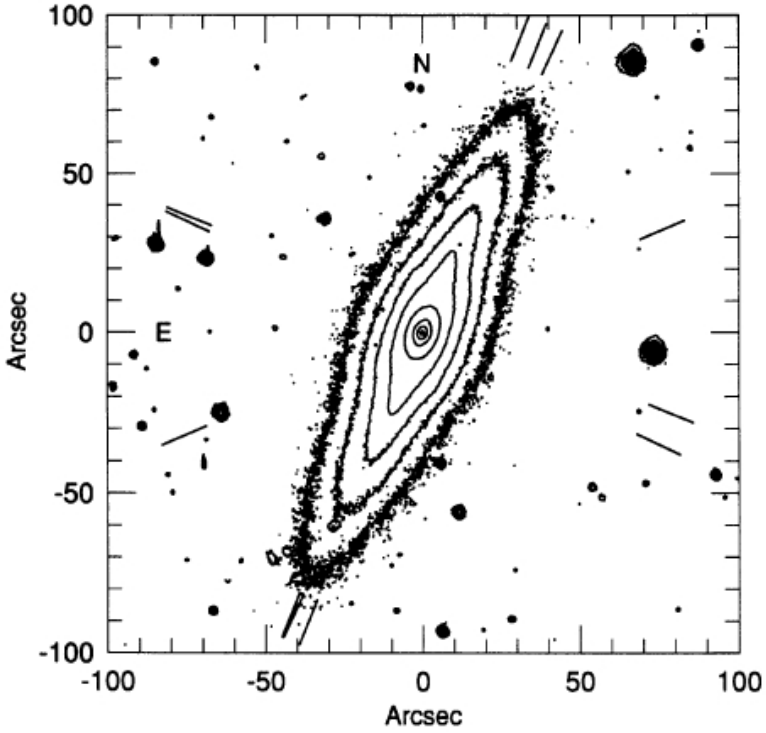


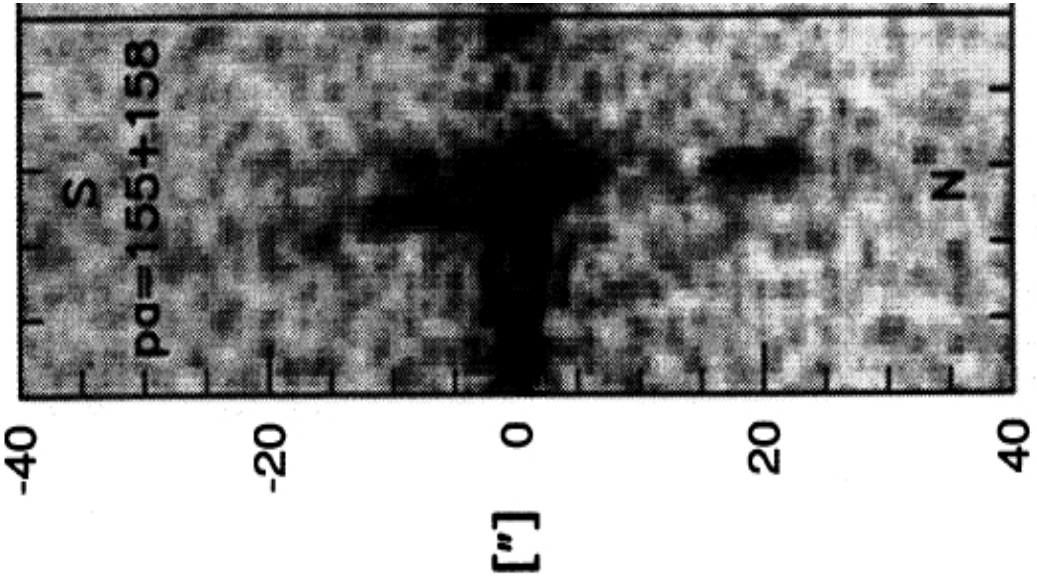
Johnston et al. (2013)

CLASSIFICATION

Counter-rotation occurs in a variety of forms

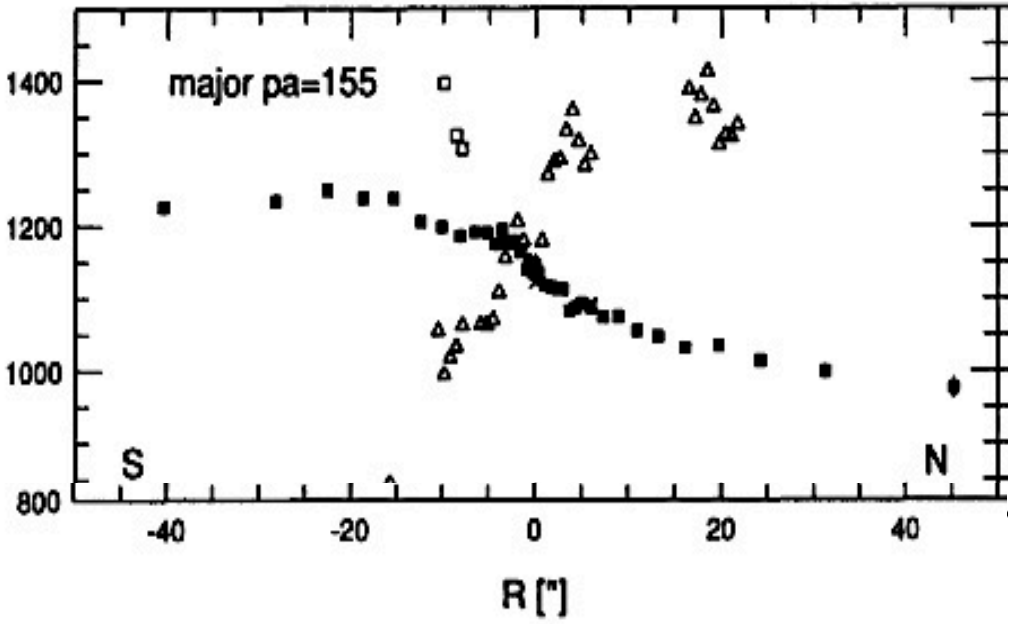
- ✧ gas vs stars: the gaseous disk counter-rotates with respect to the stellar body (e.g., NGC 4546)
- ✧ stars vs stars: two stellar components counter-rotate (e.g., NGC 4550)
- ✧ gas vs gas: two gaseous disks counter-rotate (e.g., NGC 7332)



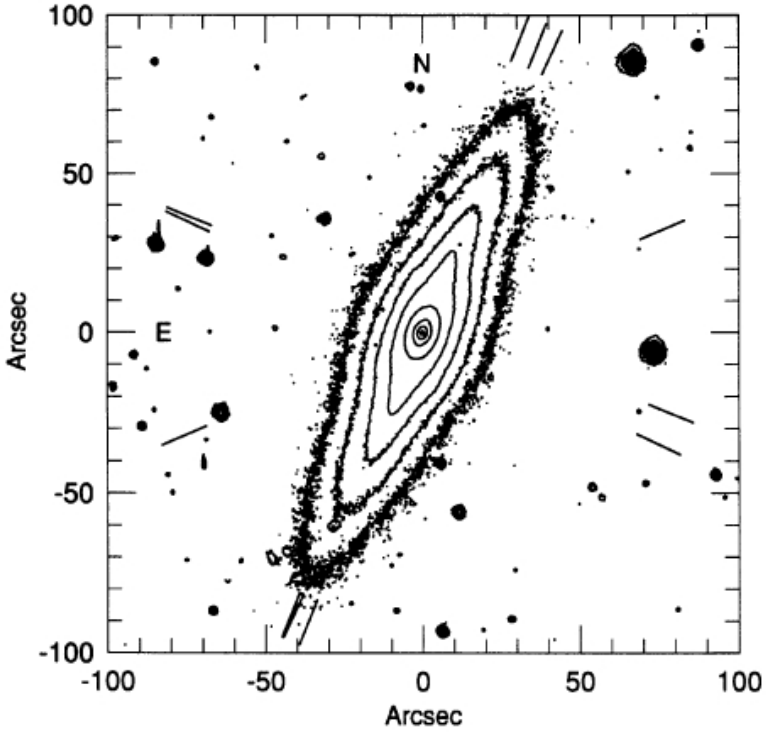


NGC 7332 – S0 pec

gas vs gas counter-rotation

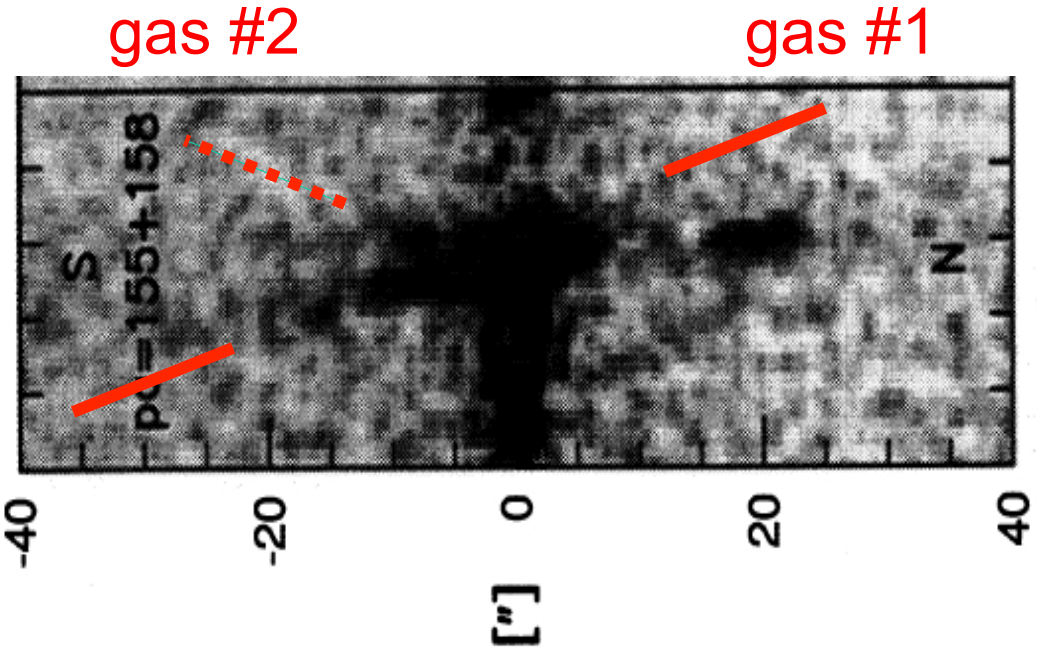


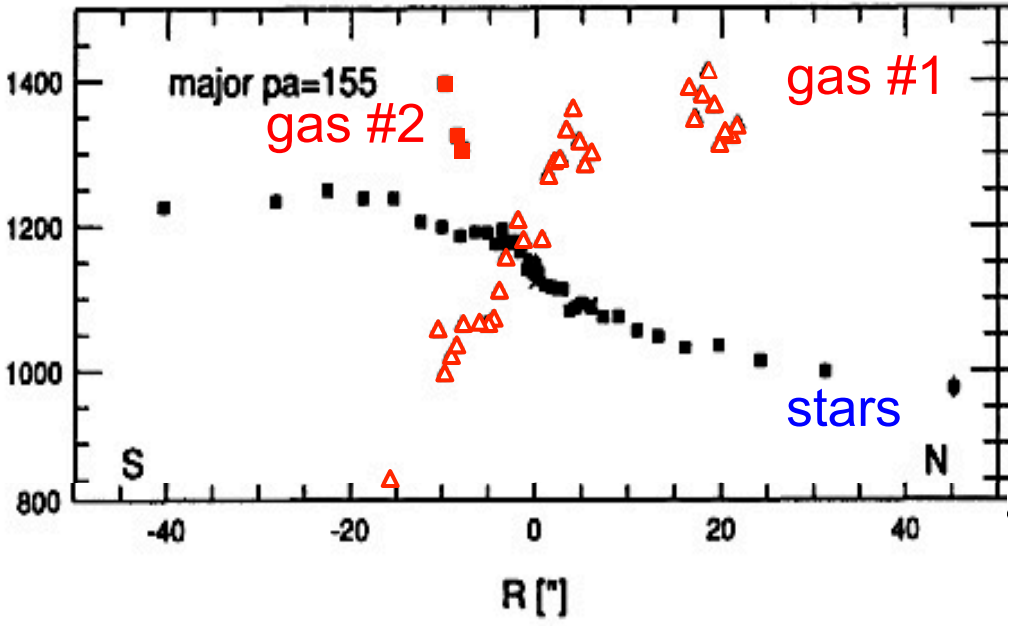
Fisher et al. (1994)



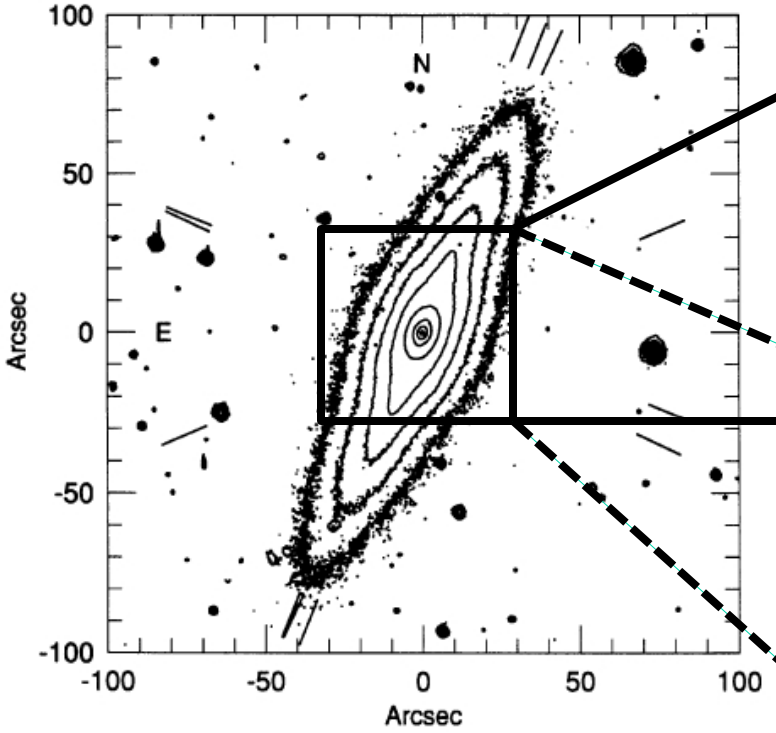
NGC 7332 – S0 pec

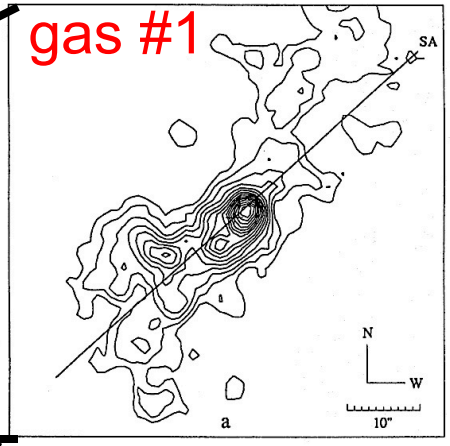
gas vs gas counter-rotation

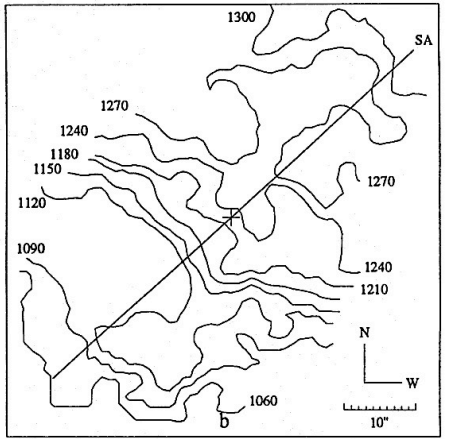


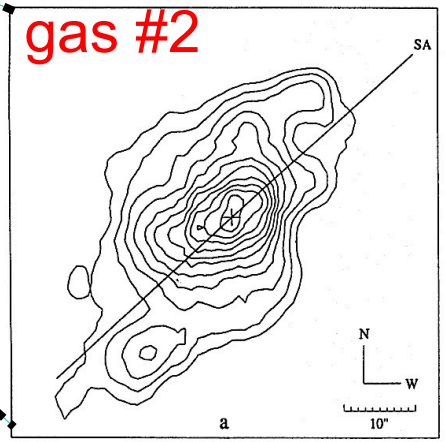


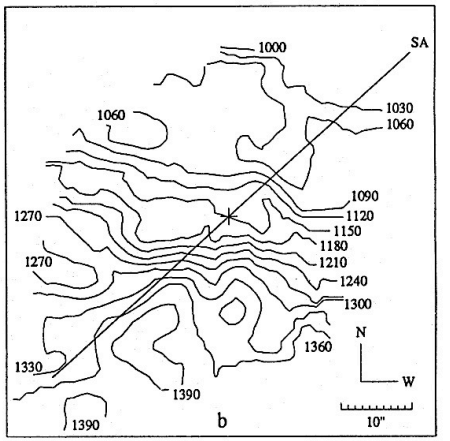
Fisher et al. (1994)

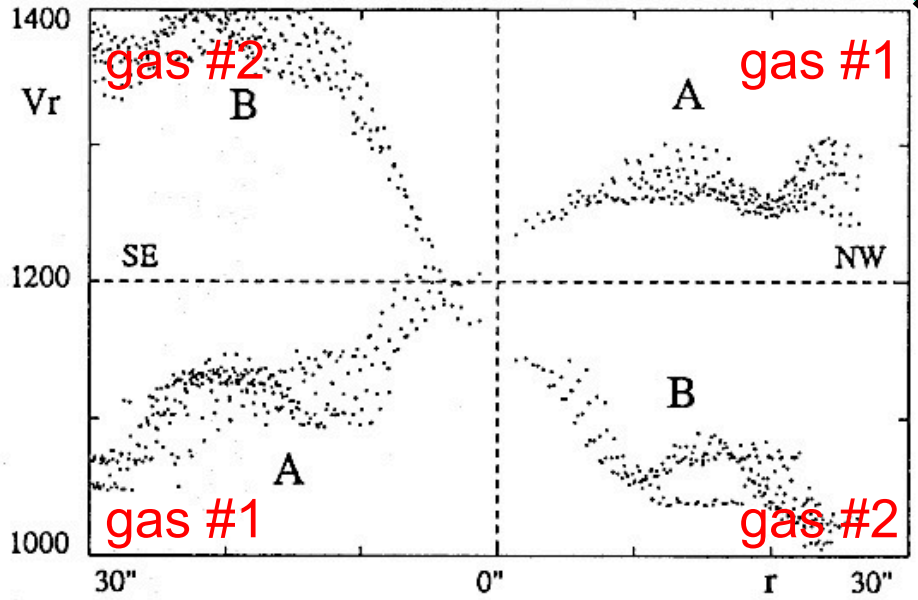








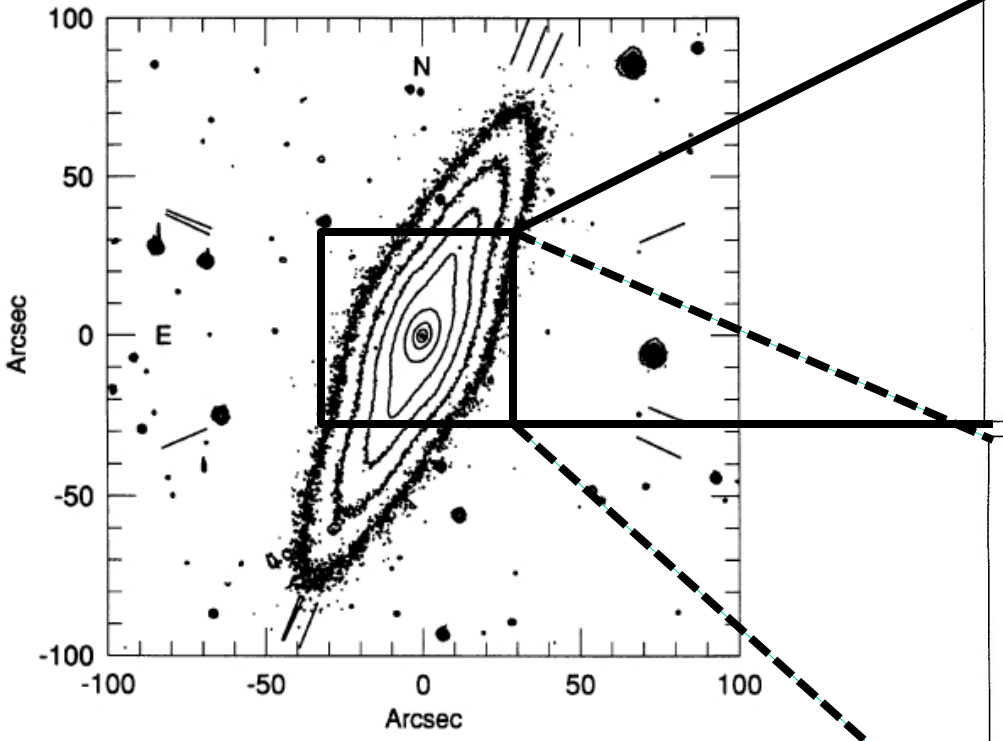


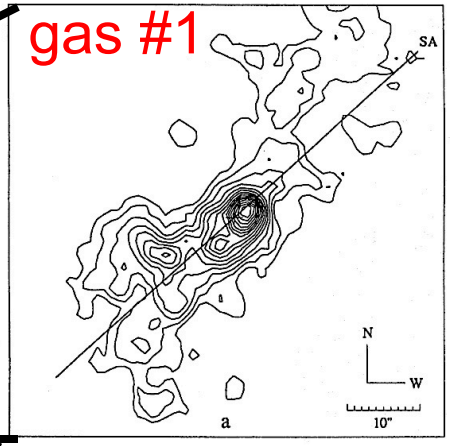


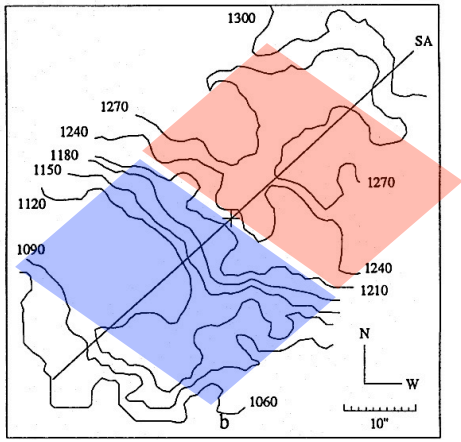
NGC 7332 – S0 pec

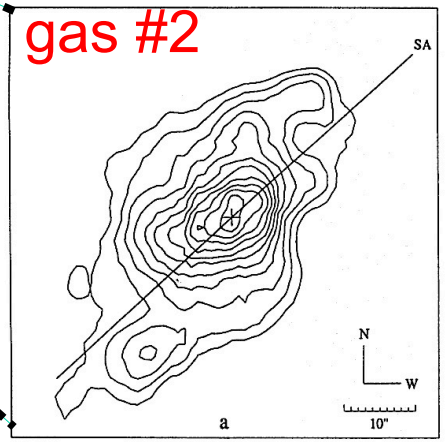
gas vs gas counter-rotation

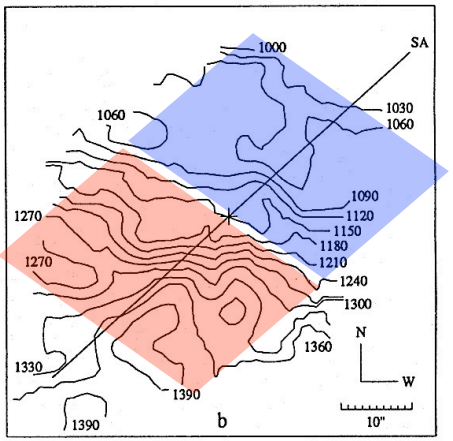
Plana & Boulesteix (1996)

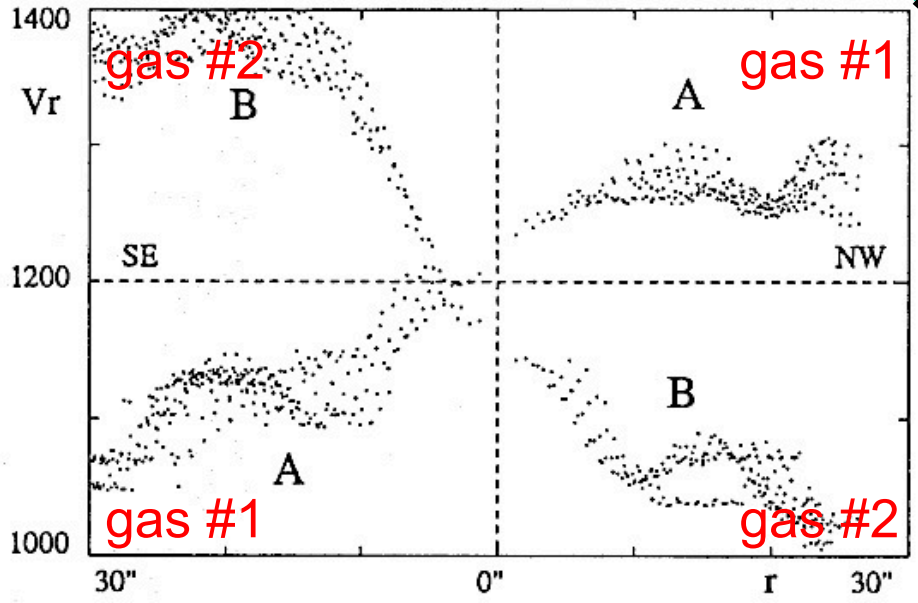












NGC 7332 – S0 pec

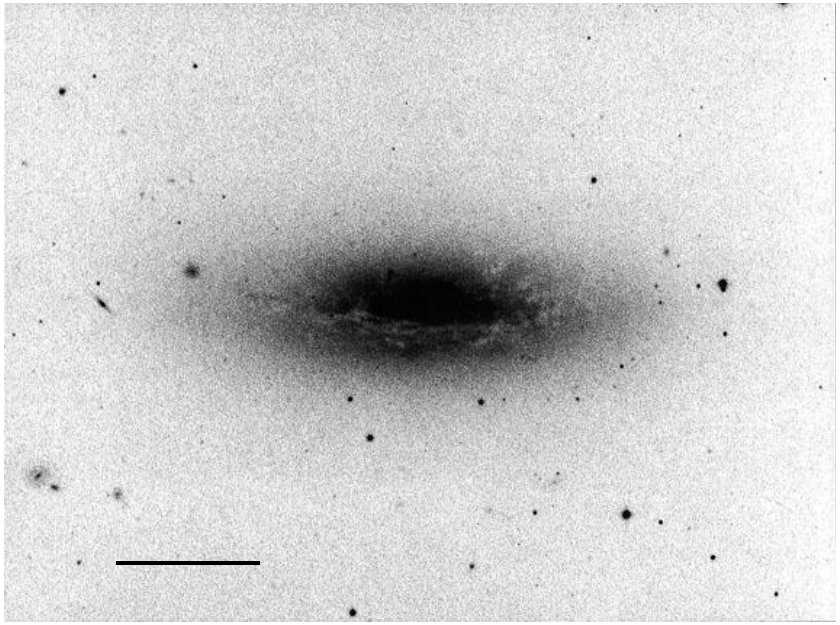
gas vs gas counter-rotation

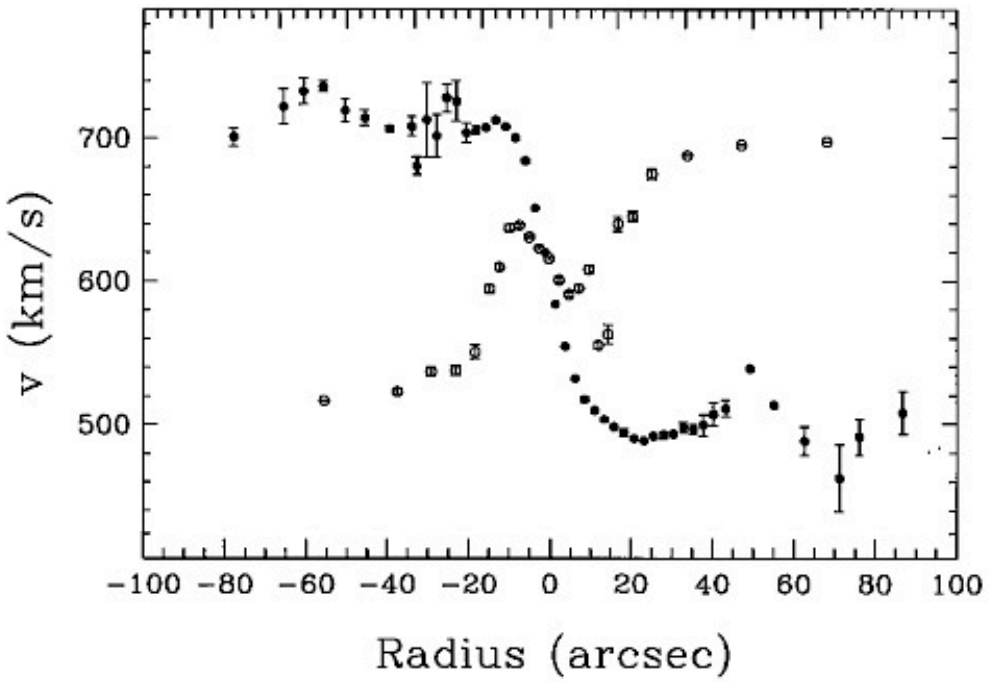
Plana & Boulesteix (1996)

SIZE

Counter-rotation is observed in

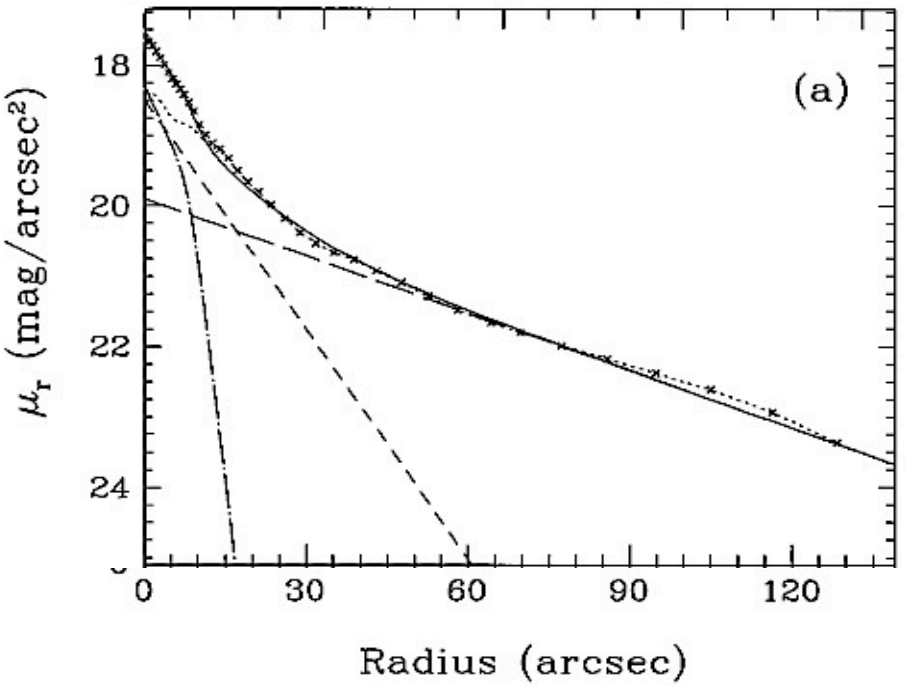
- ✧ inner regions of the galaxy (cores, small-scale disks, bulges, bars) (e.g., NGC 3593)
- ✧ outer regions of the galaxy (nested disks) (e.g., NGC 4826)
- ✧ overall the galaxy (large-scale disks) (e.g., NGC 3626)



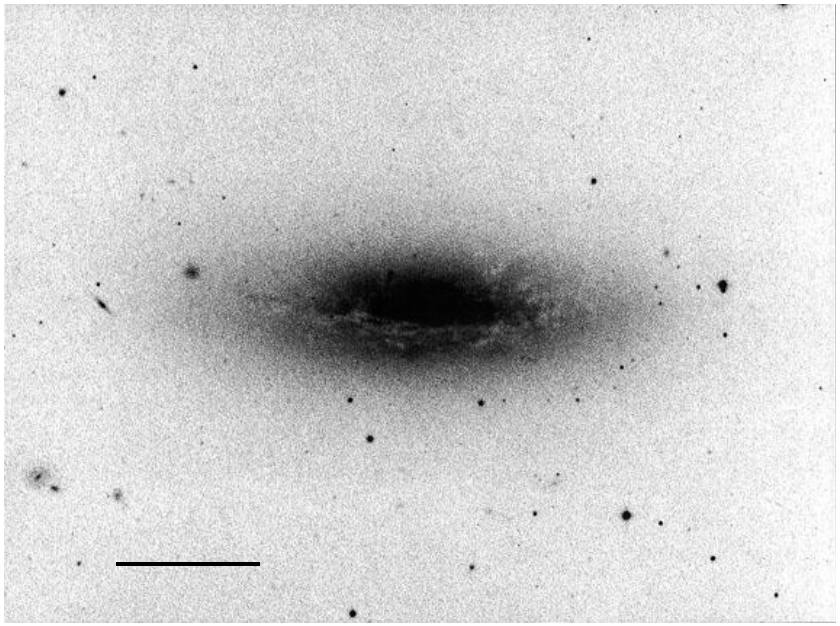


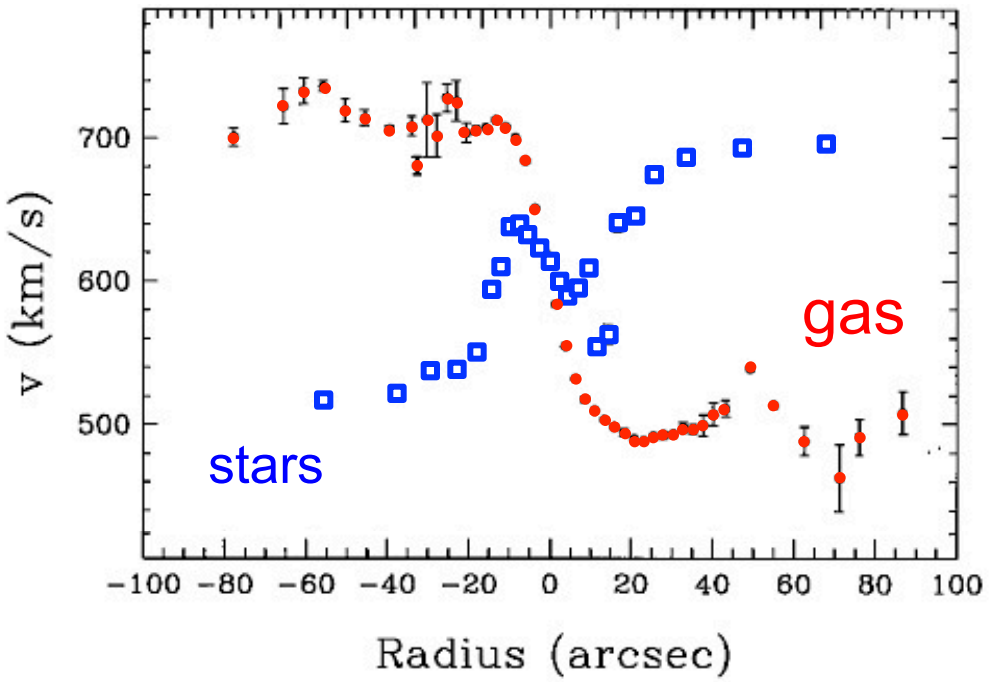
NGC 3593 – S0/a

inner counter-rotation



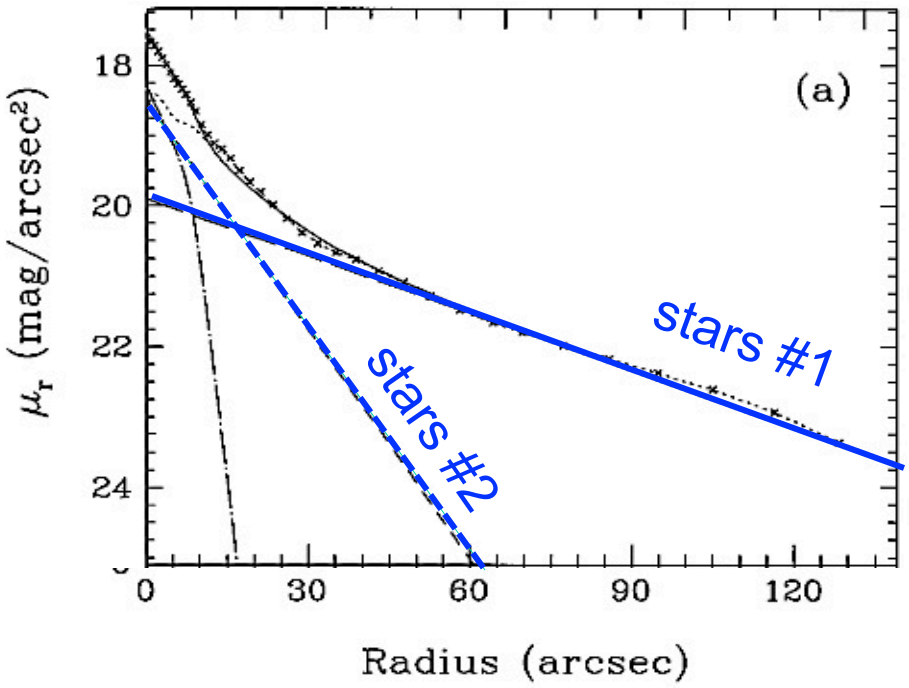
Bertola et al. (1996)





NGC 3593 – S0/a

inner counter-rotation

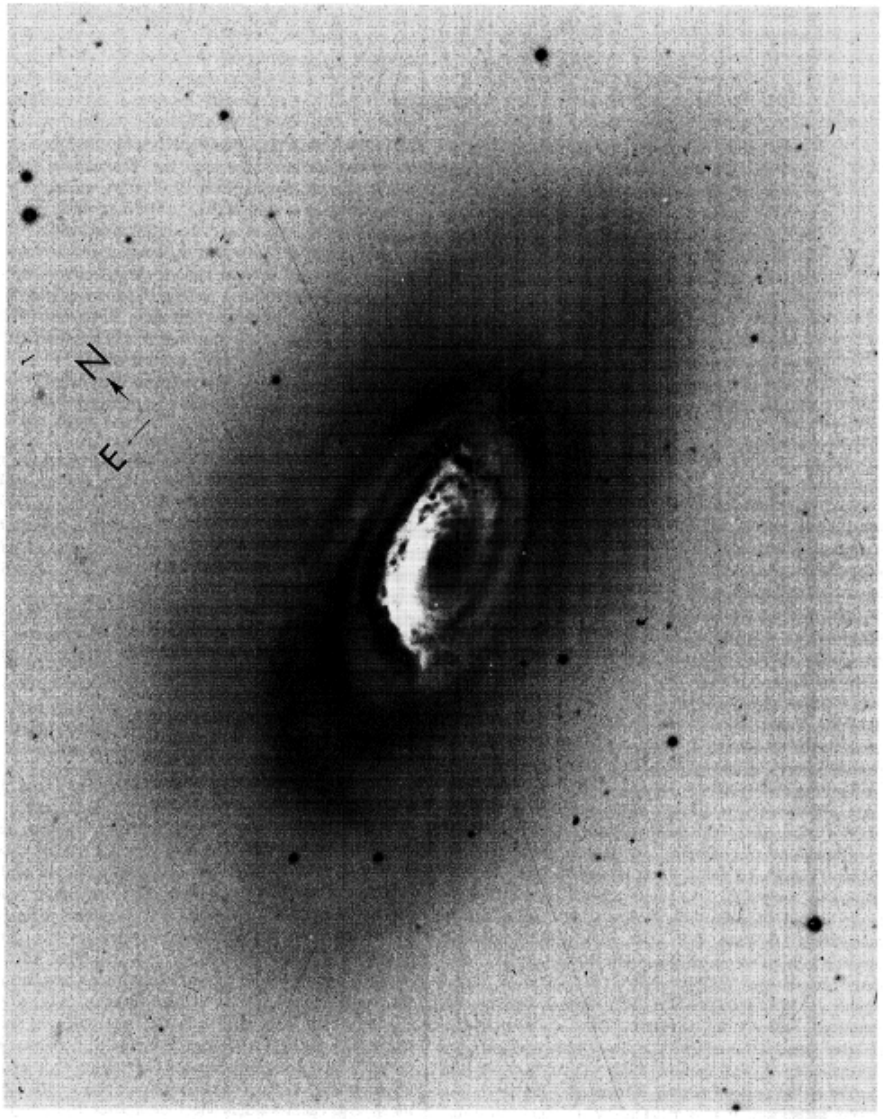


Bertola et al. (1996)

SIZE

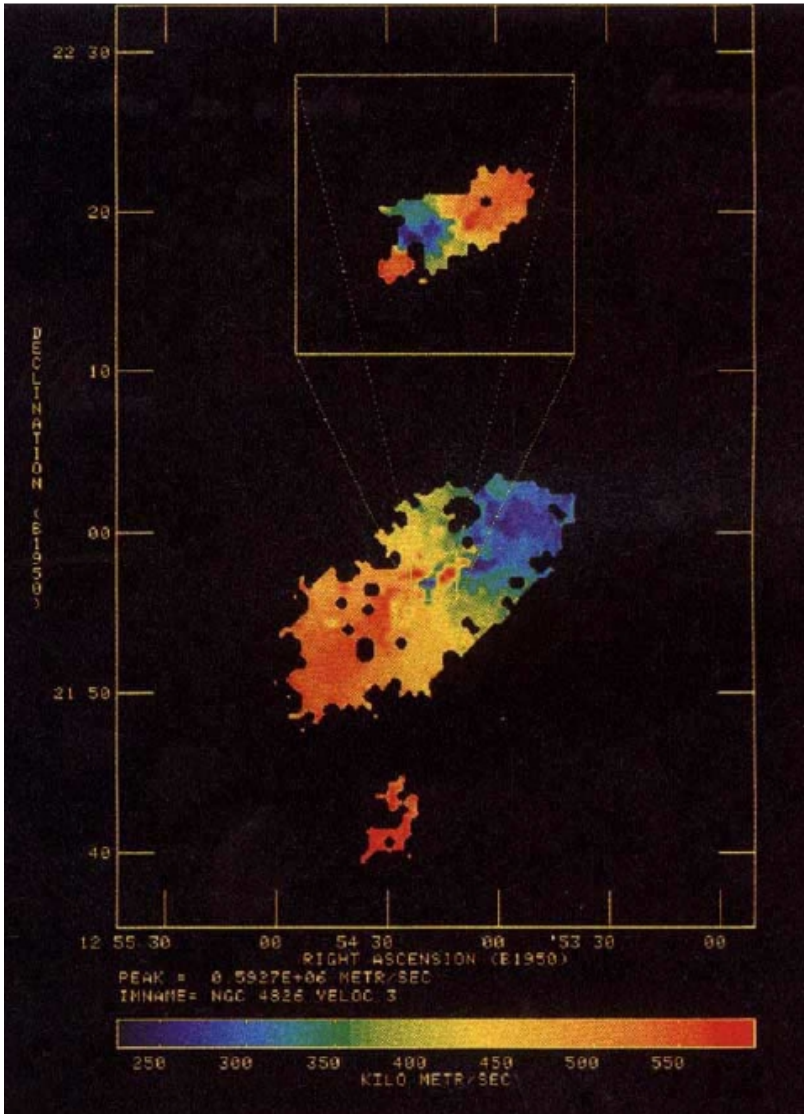
Counter-rotation is observed in

- ✧ inner regions of the galaxy (cores, small-scale disks, bulges, bars) (e.g., NGC 3593)
- ✧ outer regions of the galaxy (nested disks) (e.g., NGC 4826)
- ✧ overall the galaxy (large-scale disks) (e.g., NGC 3626)



NGC 4826 (M64) – Sab

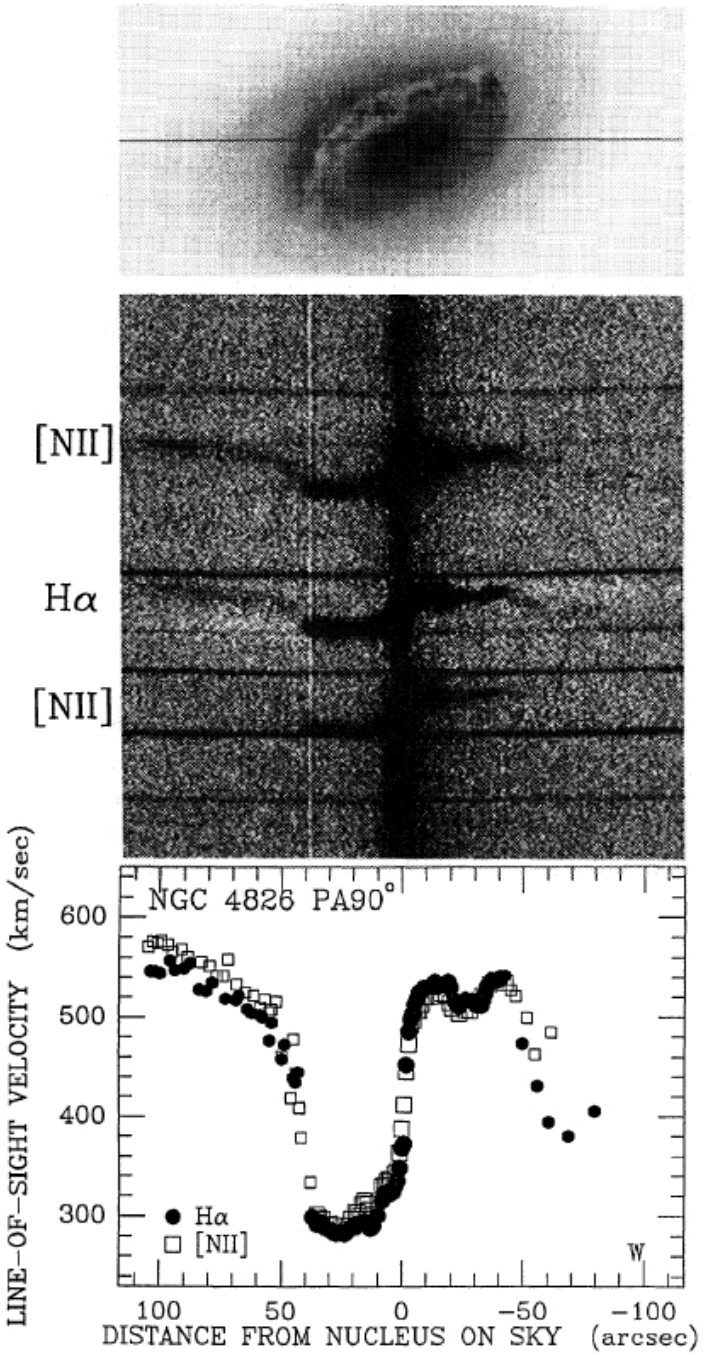
outer counter-rotation

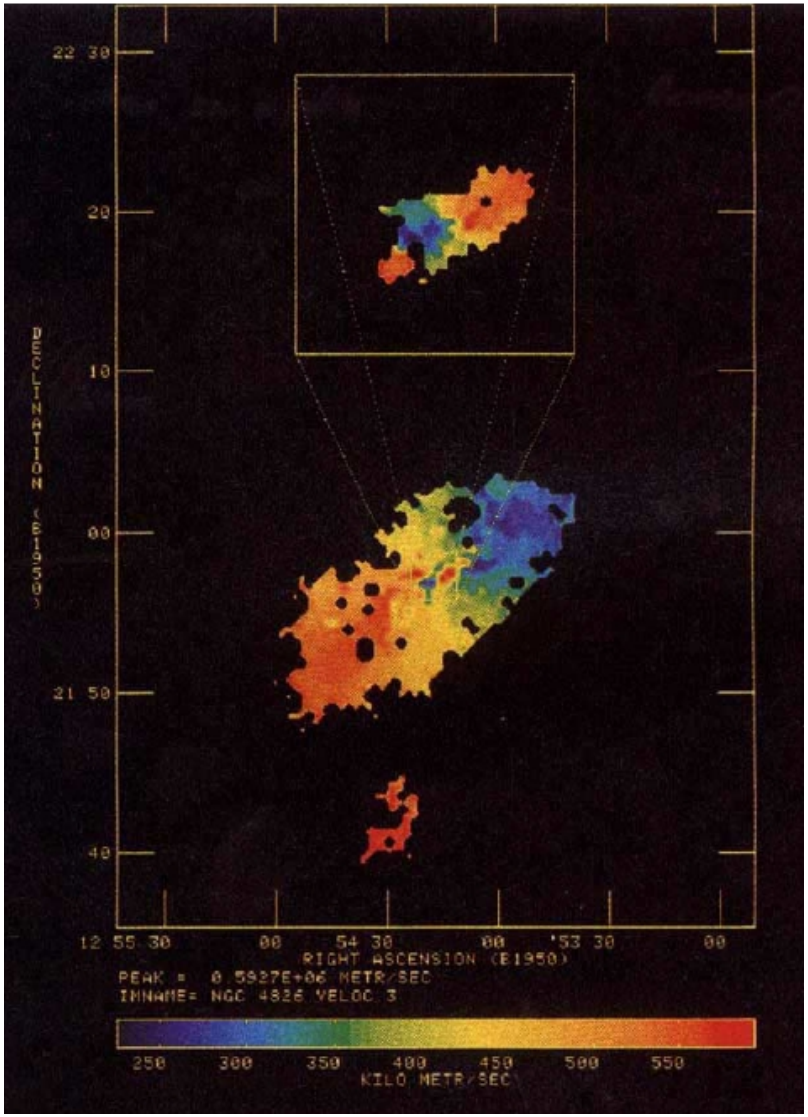


Braun et al. (1992): HI

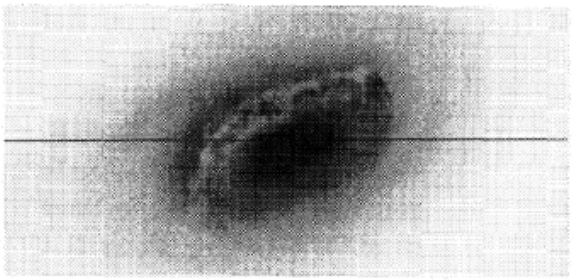
Rubin (1994): ionized gas

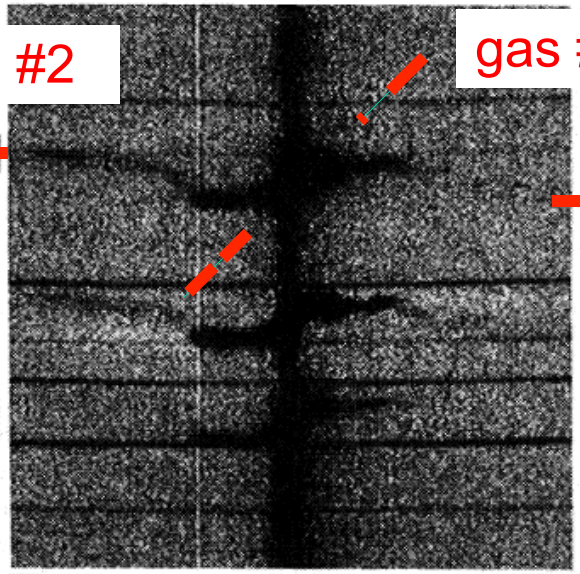
Rix et al. (1995): stars

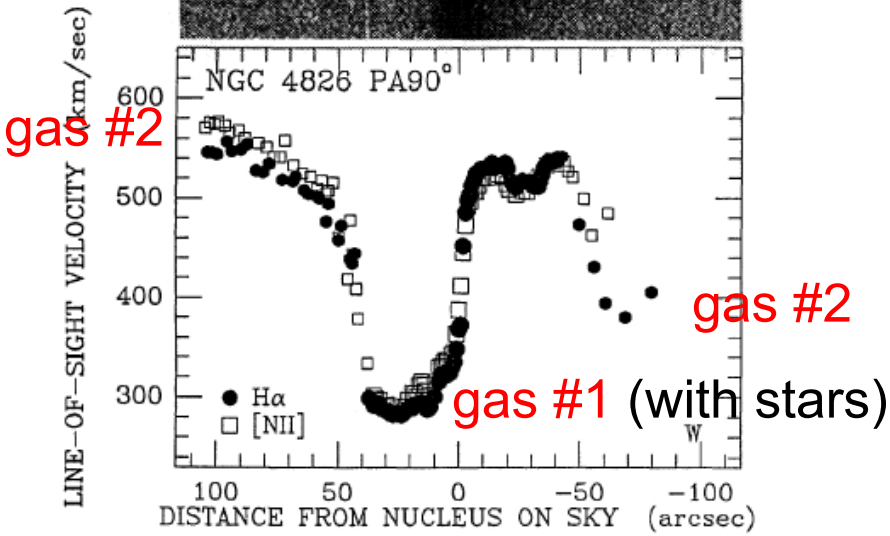


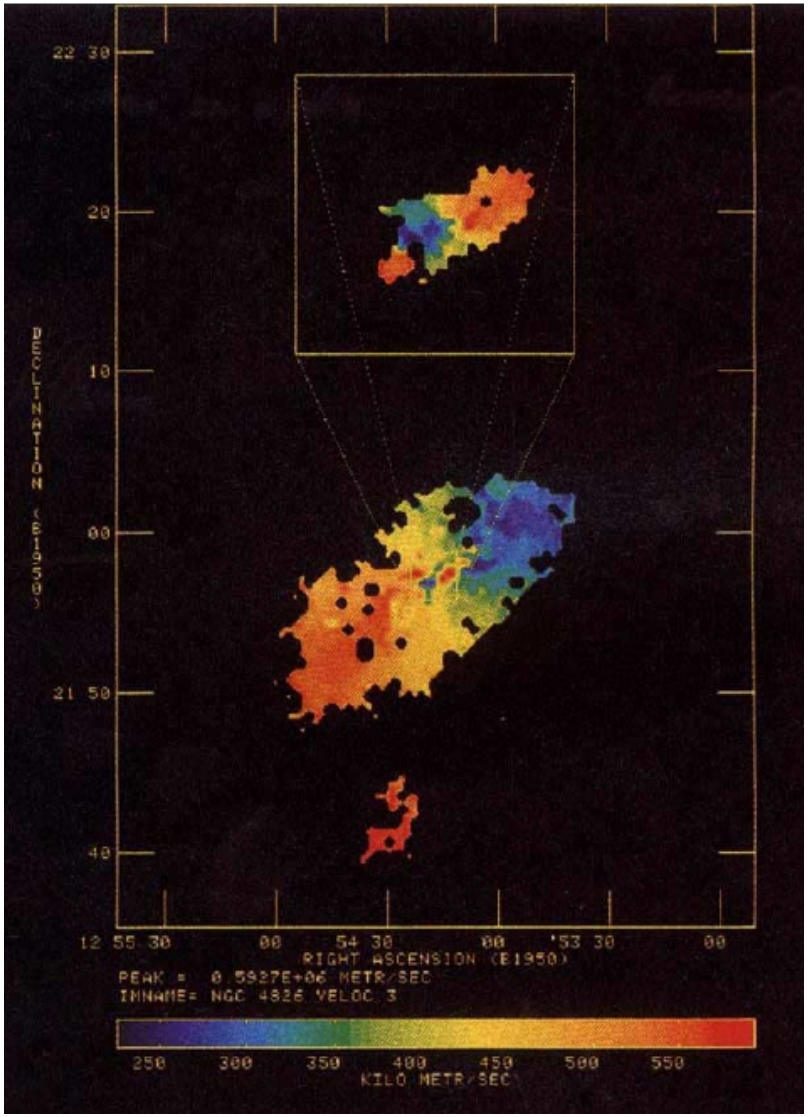


Braun et al. (1992): HI
Rubin (1994): ionized gas
Rix et al. (1995): stars







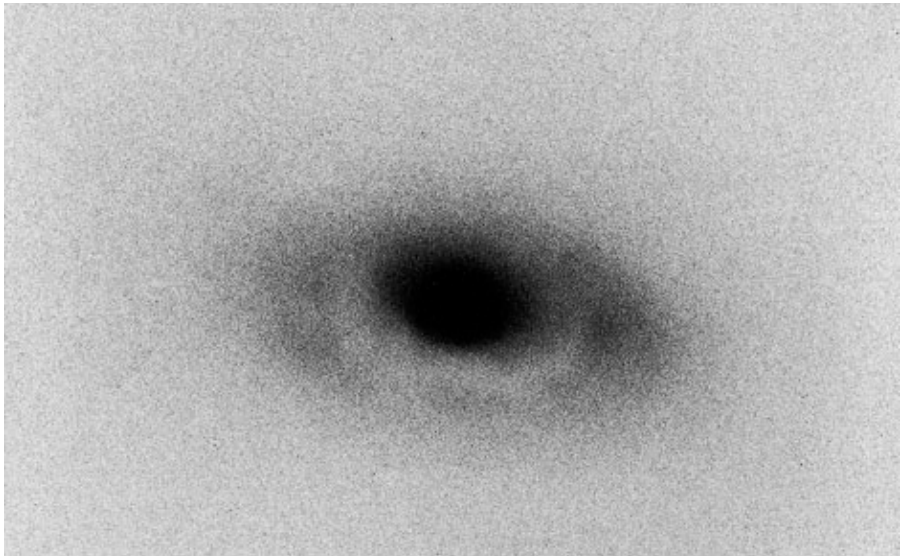


Braun et al. (1992): HI
Rubin (1994): ionized gas
Rix et al. (1995): stars

SIZE

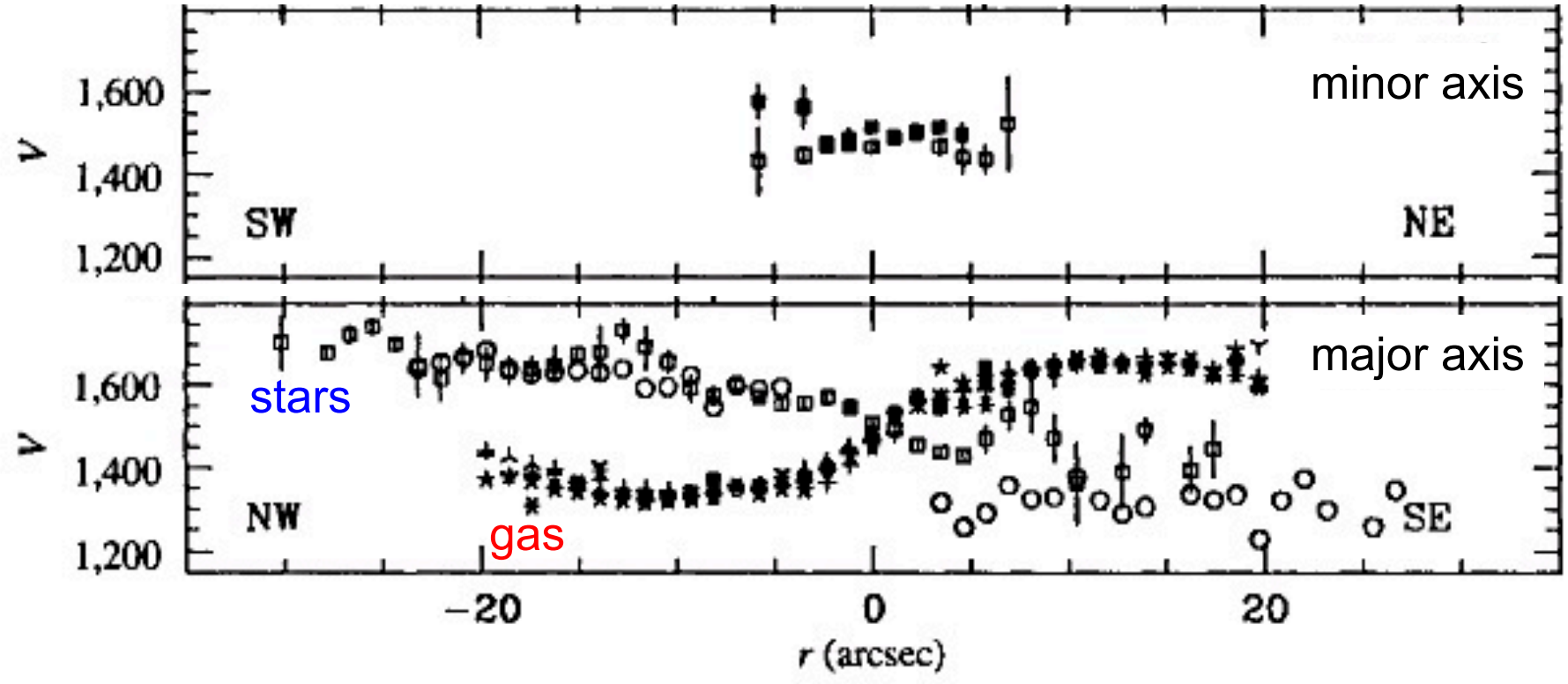
Counter-rotation is observed in

- ✧ inner regions of the galaxy (cores, small-scale disks, bulges, bars) (e.g., NGC 3593)
- ✧ outer regions of the galaxy (nested disks) (e.g., NGC 4826)
- ✧ overall the galaxy (large-scale disks) (e.g., NGC 3626)



NGC 3626 – S0/a
overall counter-rotation

Ciri et al. (1995)



COUNTER-ROTATING COMPONENTS

COMPONENT	HOST	TYPE	REGION
Core	E	stars vs. stars	inner
Bulge (?)	S0	stars vs. stars	inner
Disk	E, S0, S	gas vs. stars stars vs. stars gas vs. gas	inner outer overall
Secondary bar	SB0	stars vs. stars	inner
Stars in bar	SB0, SB	stars vs. stars	inner

MORPHOLOGICAL SIGNATURES

✧ Early-type galaxies harboring KDCs
- do not differ from galaxies without KDCs (Krajnovic et al. 2011)

✧ No late-type spirals with counter-rotation
- most of spirals are early (S0/a-Sab) with smooth arms
- arm suppression is predicted by simulations of multi-armed spirals triggered by density inhomogeneities (D'Onghia et al. 2013)

✧ No evidence of interaction
- same environment of galaxies with no counter-rotation (Bettoni et al. 2001)
- need for deep optical imaging (e.g., Duc et al. 2011) since fine structures due to accretion events have low surface brightness (~27 mag arcsec^{-2})

KINEMATIC SIGNATURES

The detection of a counter-rotating gaseous disk is straightforward

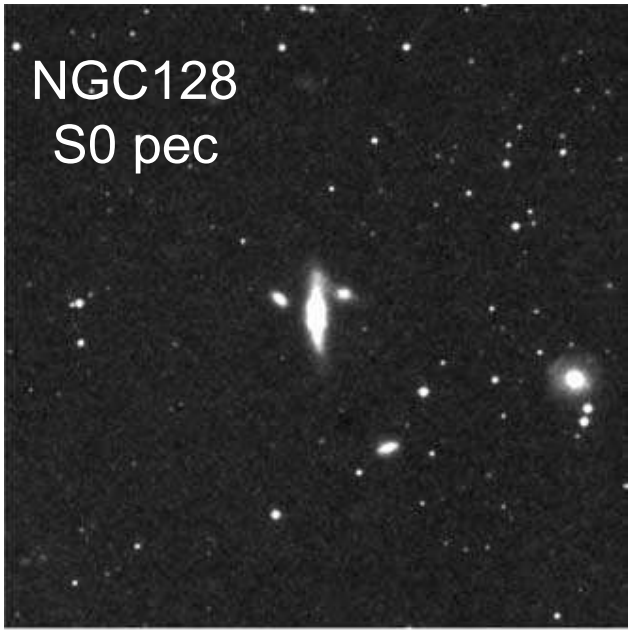
✧ opposite inclination of emission/absorption lines

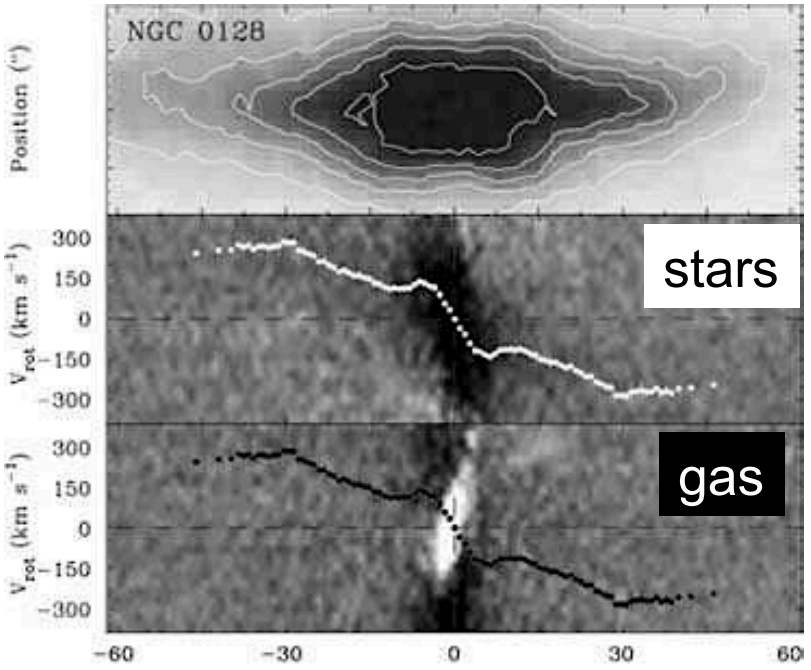
The detection of a counter-rotating stellar component

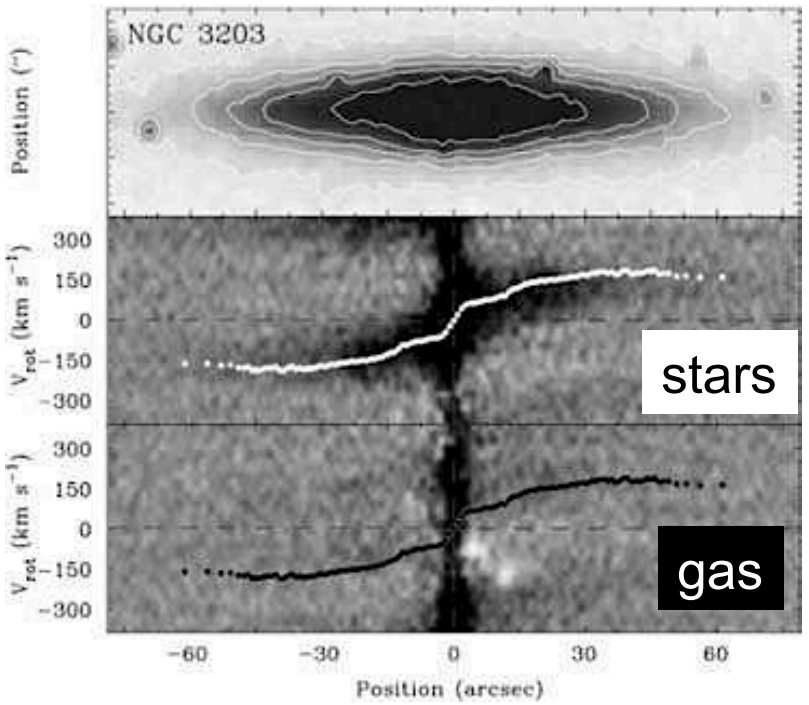
✧ depends on the fraction of retrograde stars, their velocity with respect to prograde stars, and instrumental setup

✧ requires a bimodal LOSVD

✧ can be suggested by a double-peaked velocity dispersion







Bureau & Chung (2006)

KINEMATIC SIGNATURES

The detection of a counter-rotating gaseous disk is straightforward

✧ opposite inclination of emission/absorption lines

The detection of a counter-rotating stellar component

✧ depends on the fraction of retrograde stars, their velocity with respect to prograde stars, and instrumental setup

✧ requires a bimodal LOSVD

✧ can be suggested by a double-peaked velocity dispersion

KINEMATIC SIGNATURES

The detection of a counter-rotating gaseous disk is straightforward

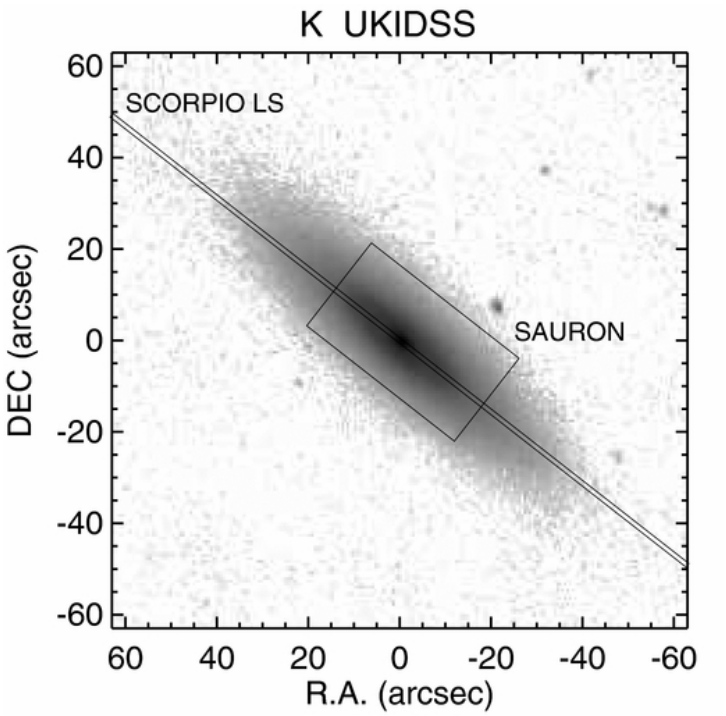
✧ opposite inclination of emission/absorption lines

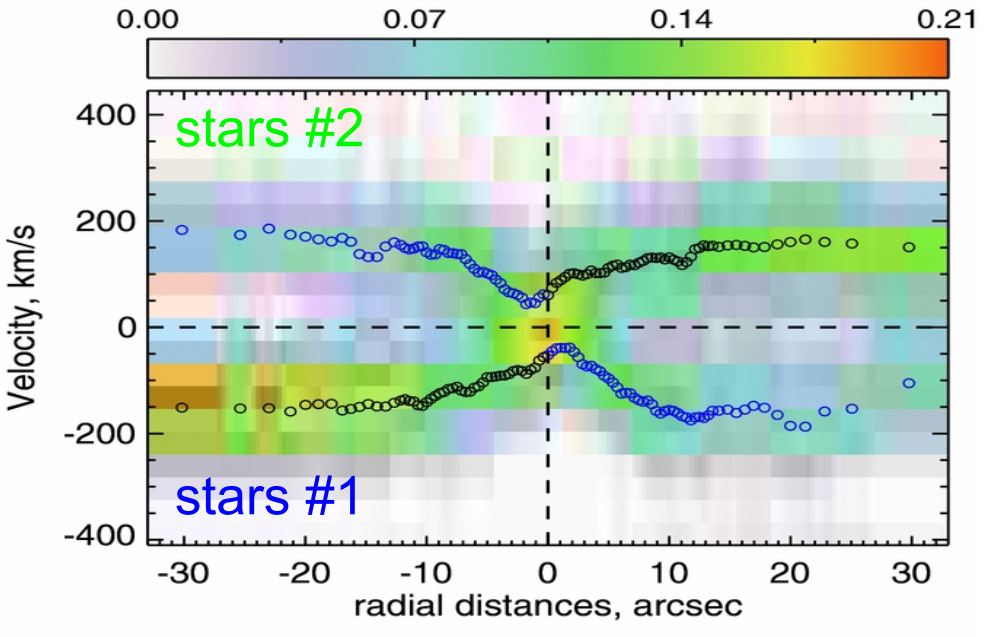
The detection of a counter-rotating stellar component

✧ depends on the fraction of retrograde stars, their velocity with respect to prograde stars, and instrumental setup

✧ requires a bimodal LOSVD

✧ can be suggested by a double-peaked velocity dispersion

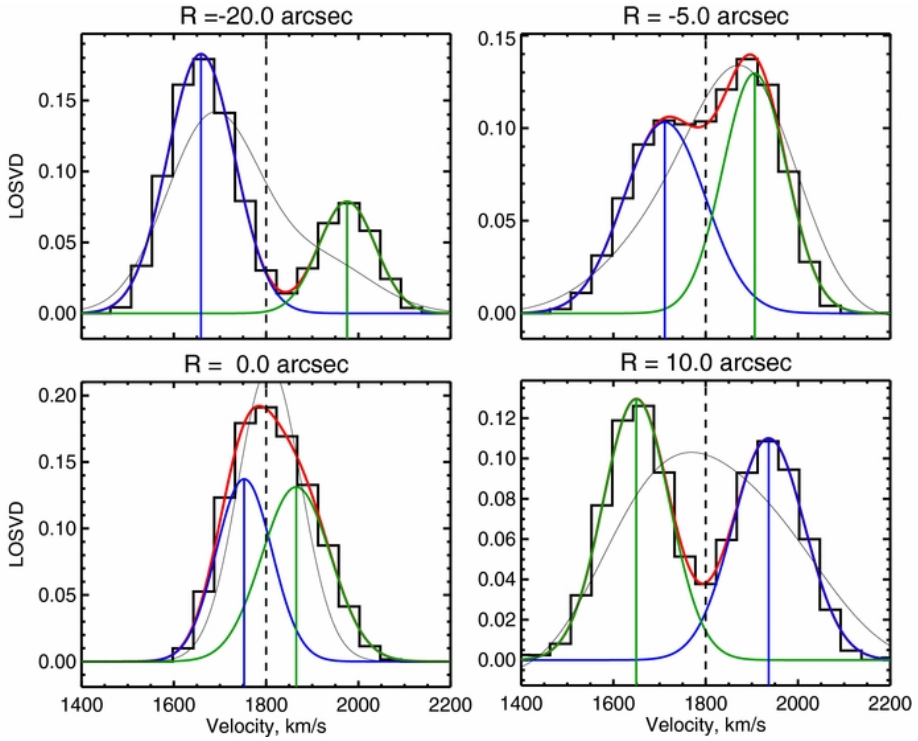




IC 719 – S0

counter-rotating stellar disks

Katkov et al. (2013)



LOSVD

fit = stars #1 + stars #2

Gauss-Hermite fit

KINEMATIC SIGNATURES

The detection of a counter-rotating gaseous disk is straightforward

✧ opposite inclination of emission/absorption lines

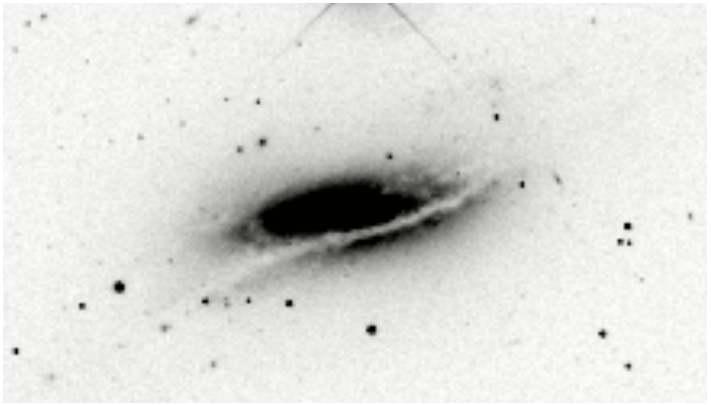
The detection of a counter-rotating stellar component

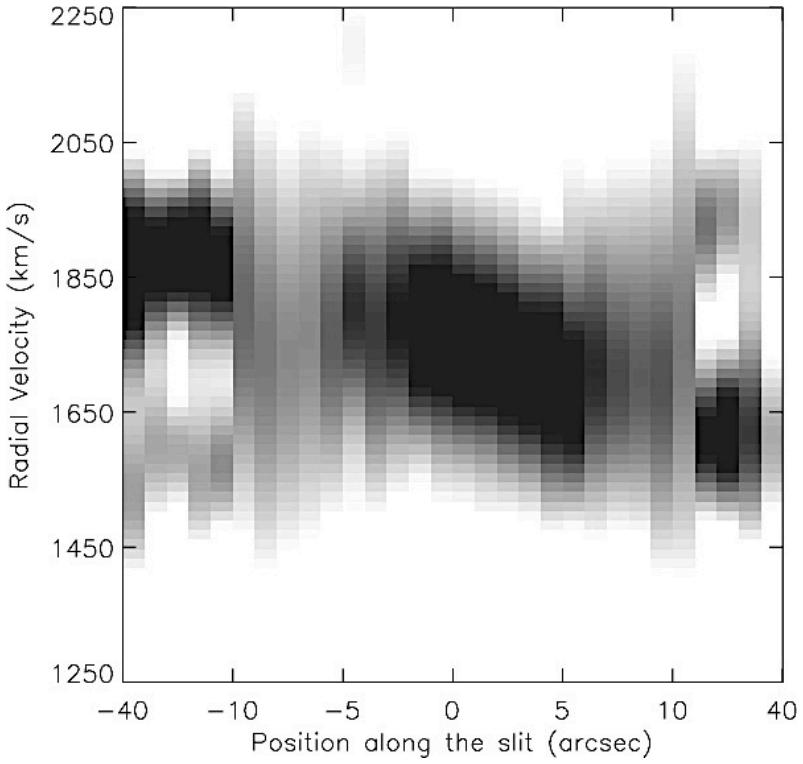
✧ depends on the fraction of retrograde stars, their velocity with respect to prograde stars, and instrumental setup

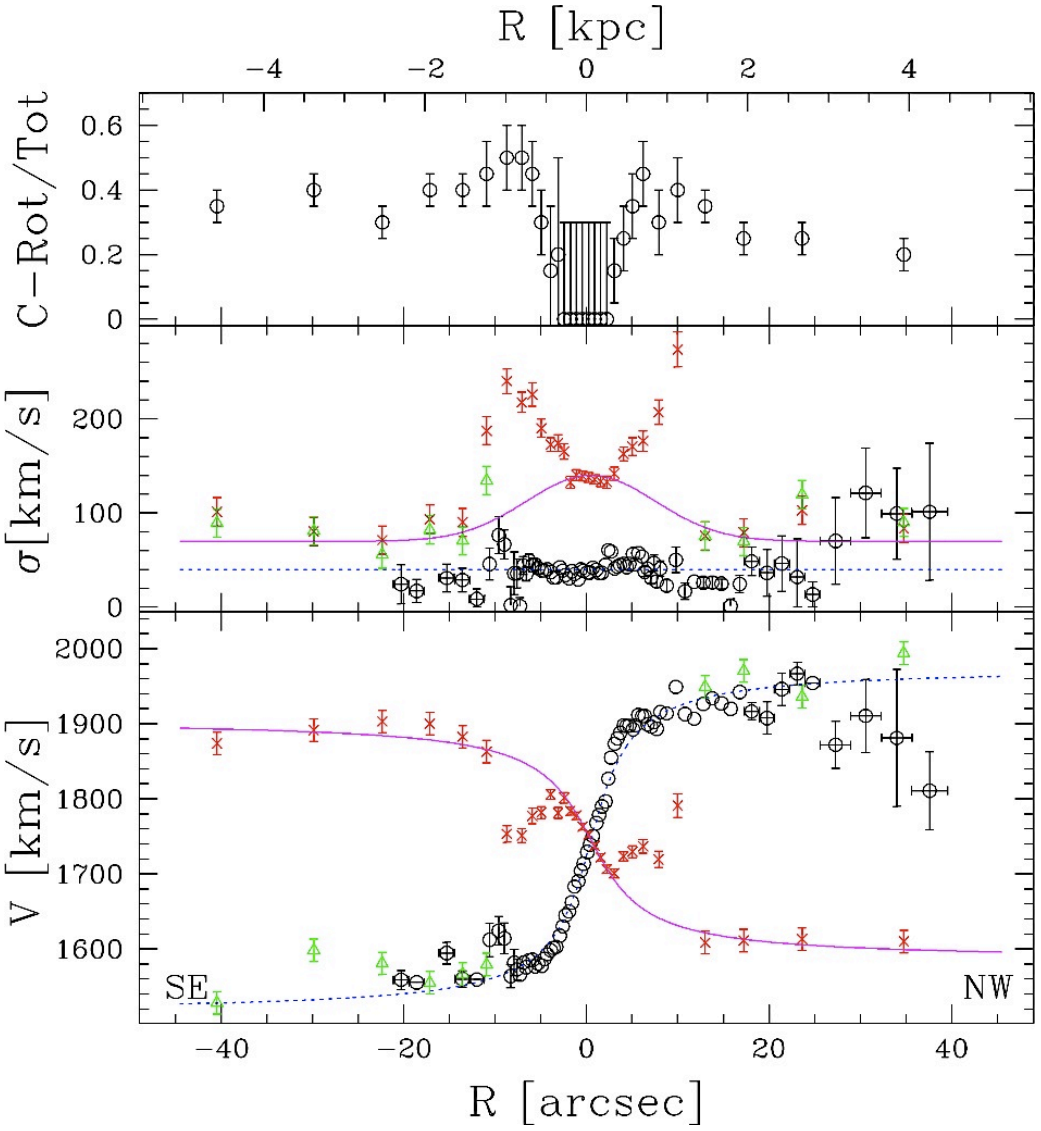
✧ requires a bimodal LOSVD

✧ can be suggested by a double-peaked velocity dispersion

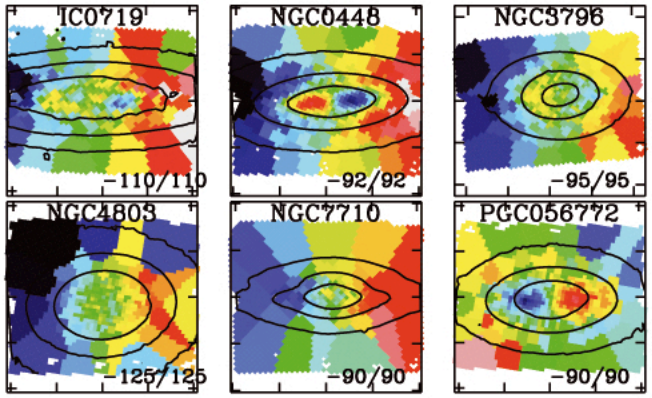
NGC 5719 – Sab
counter-rotating stellar disks



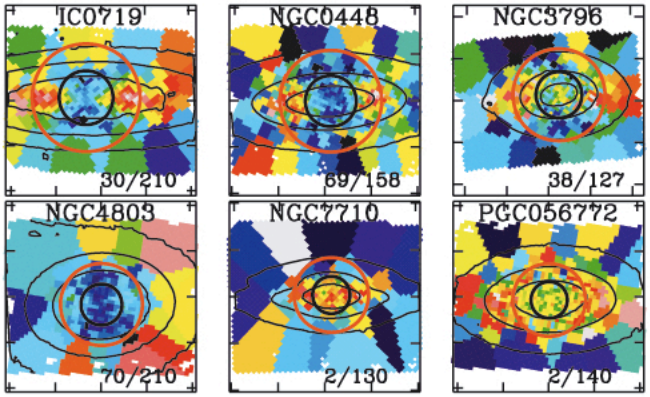




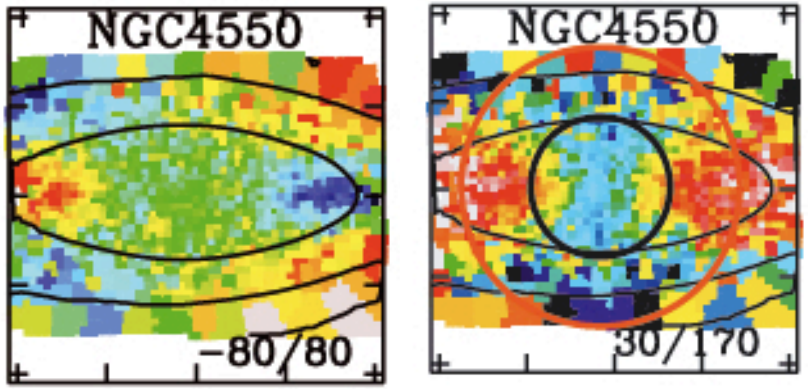
Vergani et al. (2007)



V



σ



double σ-peak galaxies

Krajnovic et al. (2011)

STATISTICS – EARLY-TYPE GALAXIES

long-slit data/IFU data

✧ Early-type galaxies - gas vs stars

- Bertola et al. (1990): 3/6 dust-lane Es = 50%
- Bertola et al. (1992): 9/26 S0s with gas = 35%
- Pizzella et al. (2004): 17/53 S0s with gas = 32%
- Davis et al. (2011): 9/133 E/S0s with gas = 7% (40% decoupled)

✧ Early-type galaxies - stars vs stars

- cores: Mehlert et al. (2000): 1/35 Coma E/S0s = 3%
  Krajnovic et al. (2011): 8/260 E/S0s = 4%
- disks: Kuijken et al. (1996): 0/17 S0s with gas = <10% (with 10% stars on retrograde orbits)

STATISTICS – SPIRALS

long-slit data/IFU data

✧ Spirals - gas vs stars

- Kannappan et al. (2001): 0/38 Sa-Sbc = <8%
- Pizzella et al. (2004): 2/50 S0/a-Sd = 4%
- Falcon-Barroso et al. (2006): 1/24 Sa = 4%
- Ganda et al. (2006): 0/18 Sb-Sd = 0%
- Barrera-Ballesteros et al. (2014): 0/77 Sa-Sc = 0%

✧ Spirals - stars vs stars

- Pizzella et al. (2004): 1/50 S0/a-Sd = 2%
- Falcon-Barroso et al. (2006): 1/24 Sa = 4%
- Ganda et al. (2006): 0/18 Sb-Sd = 0%

FORMATION SCENARIOS

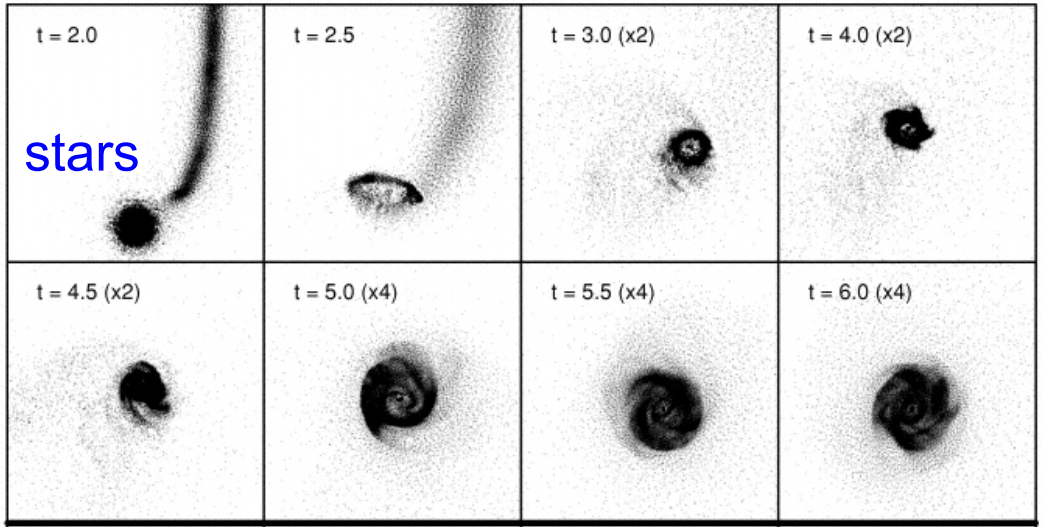
Different scenarios for building counter-rotating components

✧ external origin
- gas accretion: retrograde acquisition of gas and subsequent star formation (e.g., Thakar & Ryden 1996, 1998)
- minor merging: retrograde capture of a (gas-rich) dwarf companion (e.g., Balcells & Quinn 1990, Thakar et al. 1997)
- major merging: gas for cores (e.g., Hoffman et al. 2010) tuned initial conditions for disks (e.g., Crocker et al. 2009)

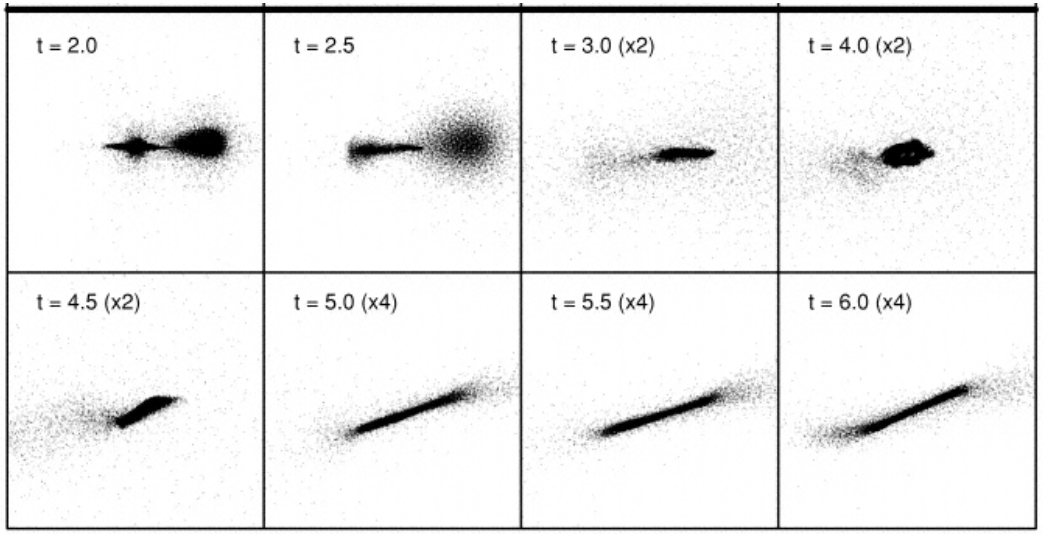
✧ internal origin
- bar structure: retrograde orbits trapped around x_4 family (Wozniak & Pfenniger 1997)
- bar dissolution: box-orbit stars are scattered onto clockwise/ counter-clockwise-streaming tube orbits (Ewans & Collett 1994)

infalling gas

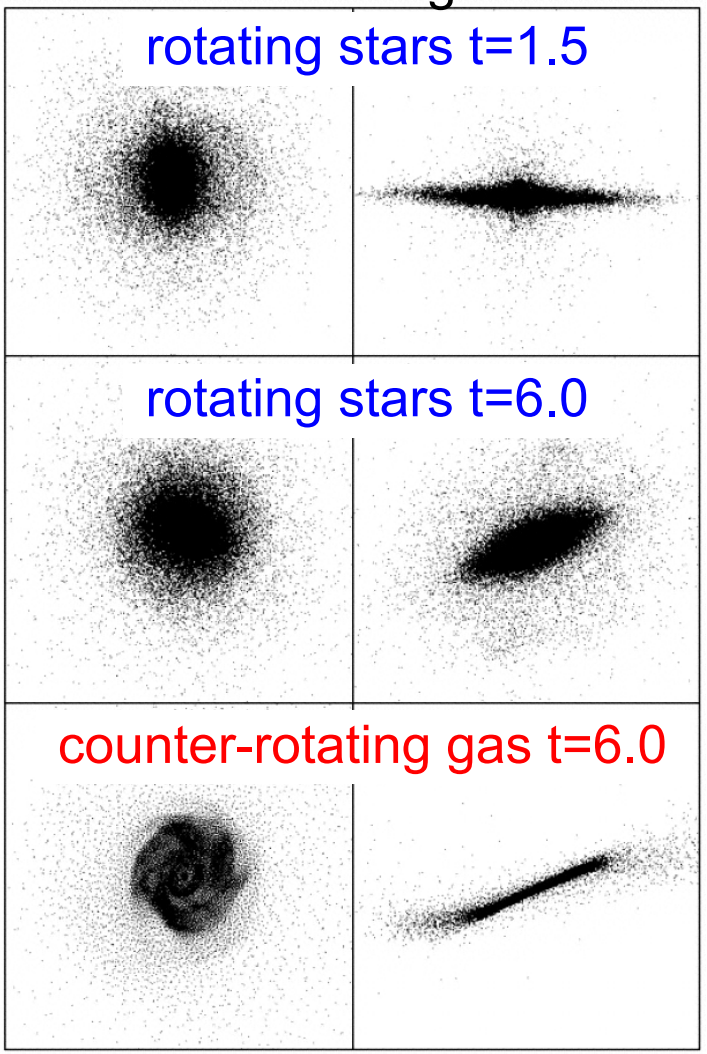
face-on view



edge-on view



face-on view edge-on view



Thakar & Ryden (1998)

FORMATION SCENARIOS

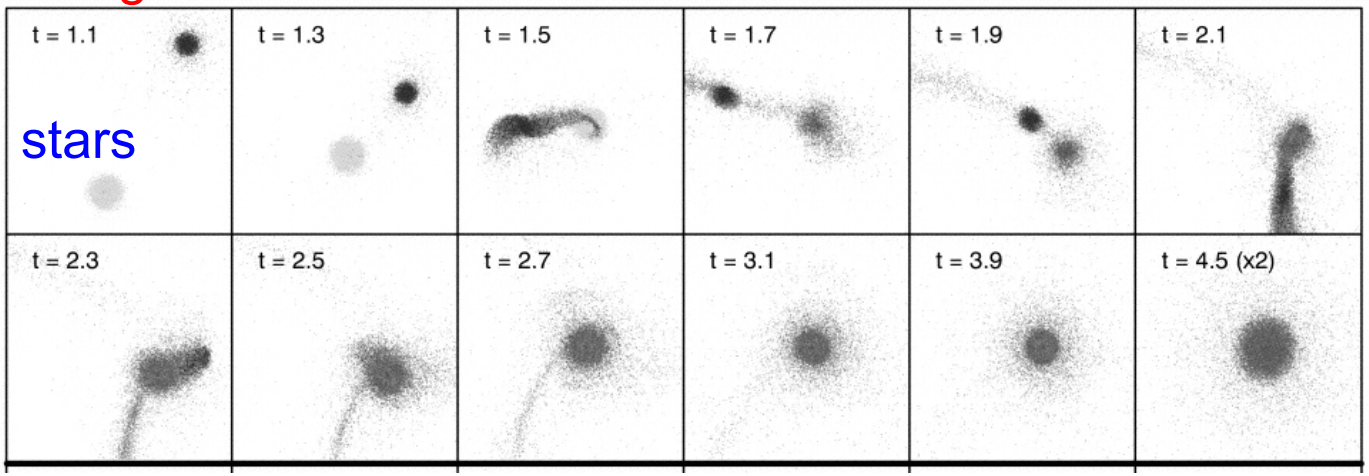
Different scenarios for building counter-rotating components

✧ external origin
- gas accretion: retrograde acquisition of gas and subsequent star formation (e.g., Thakar & Ryden 1996, 1998)
- minor merging: retrograde capture of a (gas-rich) dwarf companion (e.g., Balcells & Quinn 1990; Thakar et al. 1997)
- major merging: gas for cores (e.g., Hoffman et al. 2010) tuned initial conditions for disks (e.g., Crocker et al. 2009)

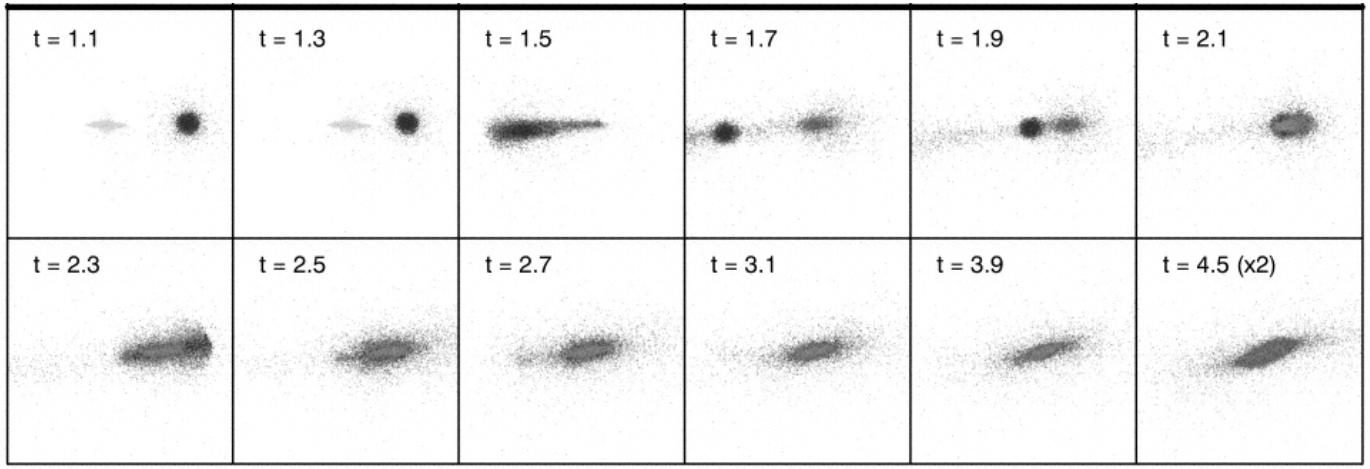
✧ internal origin
- bar structure: retrograde orbits trapped around x_4 family (Wozniak & Pfenniger 1997)
- bar dissolution: box-orbit stars are scattered onto clockwise/ counter-clockwise-streaming tube orbits (Ewans & Collett 1994)

gas-rich dwarf

face-on view

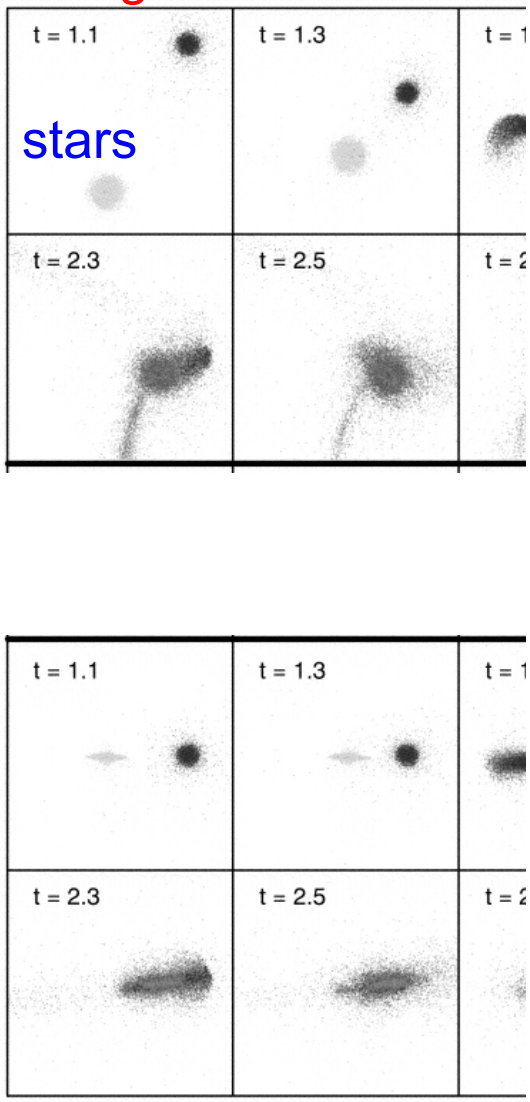


edge-on view

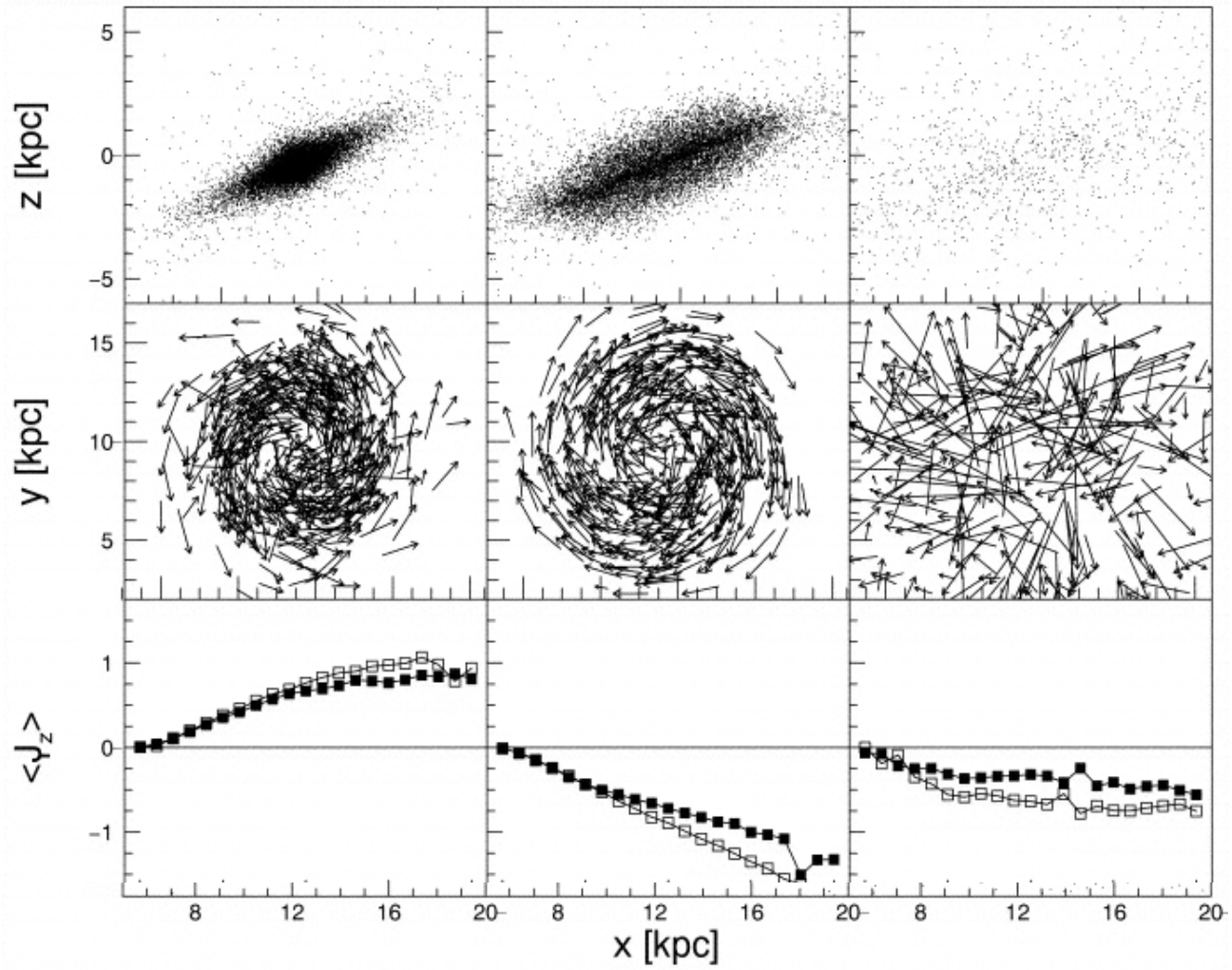


Thakar et al. (1997)

gas-rich dwarf



galaxy stars dwarf gas dwarf stars



Thakar et al. (1997)

FORMATION SCENARIOS

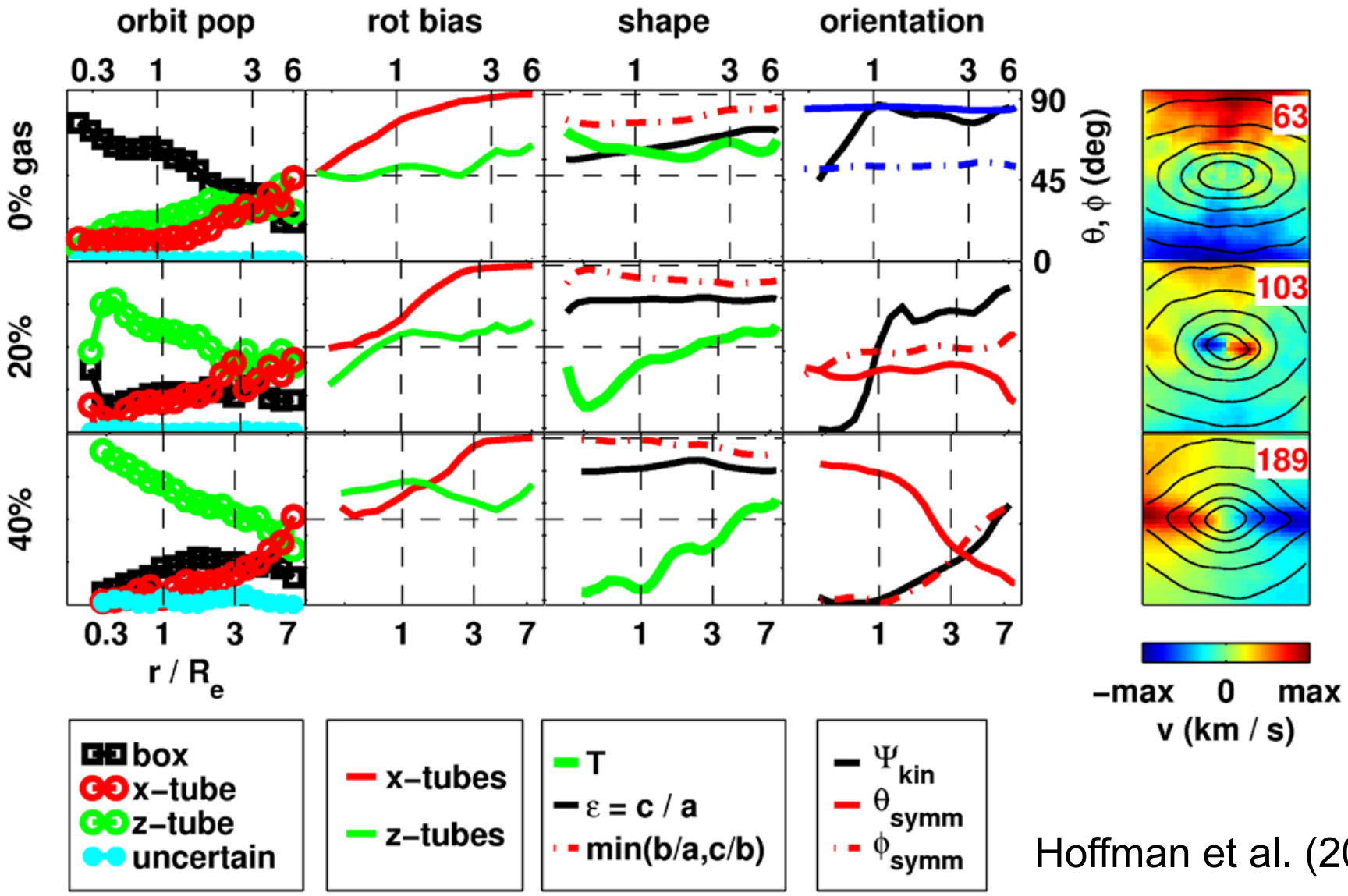
Different scenarios for building counter-rotating components

✧ external origin

- gas accretion: retrograde acquisition of gas and subsequent star formation (e.g., Thakar & Ryden 1996, 1998)
- minor merging: retrograde capture of a (gas-rich) dwarf companion (e.g., Balcells & Quinn 1990; Thakar et al. 1997)
- major merging: gas for cores (e.g., Hoffman et al. 2010) tuned initial conditions for disks (e.g., Crocker et al. 2009)

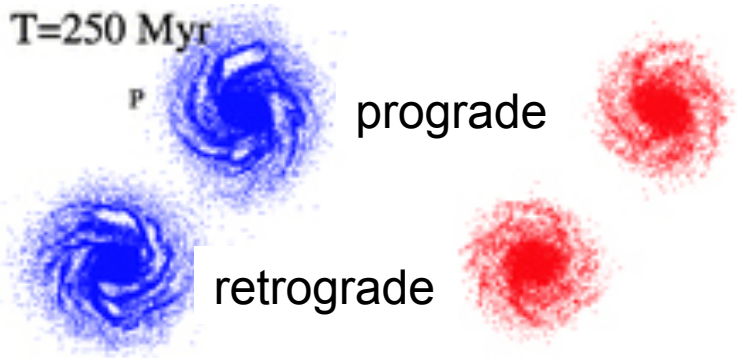
✧ internal origin

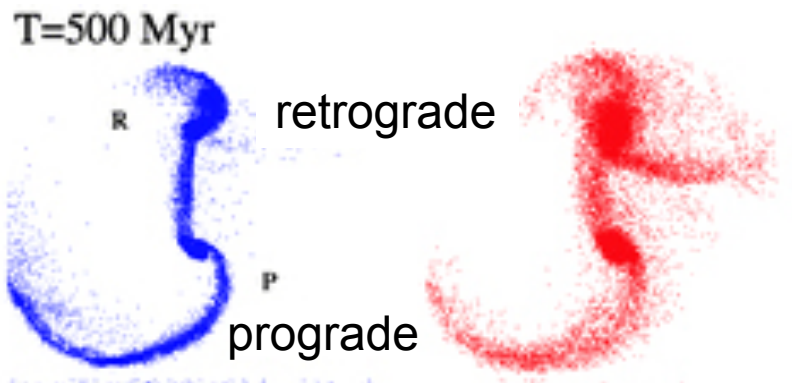
- bar structure: retrograde orbits trapped around x_4 family (Wozniak & Pfenniger 1997)
- bar dissolution: box-orbit stars are scattered onto clockwise/ counter-clockwise-streaming tube orbits (Ewans & Collett 1994)

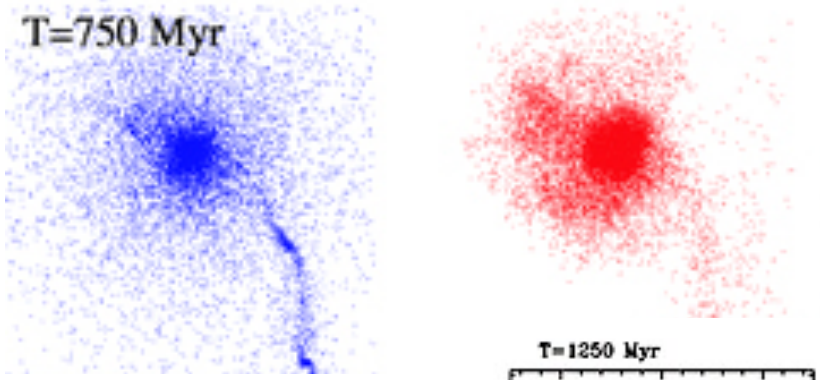


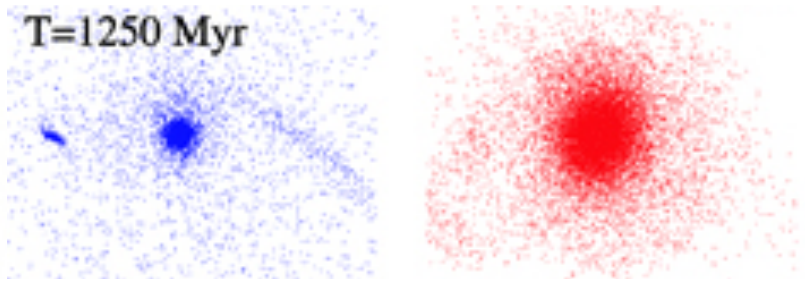
Hoffman et al. (2010)

gas stars

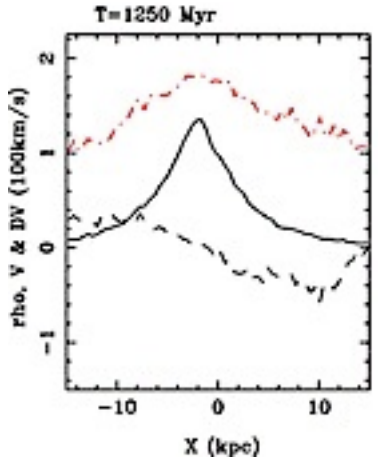




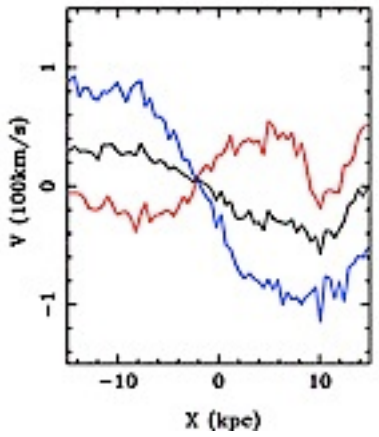




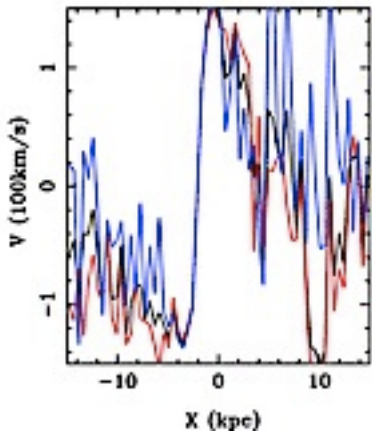
Crocker et al. (2009)



star density



star velocity



gas velocity

FORMATION SCENARIOS

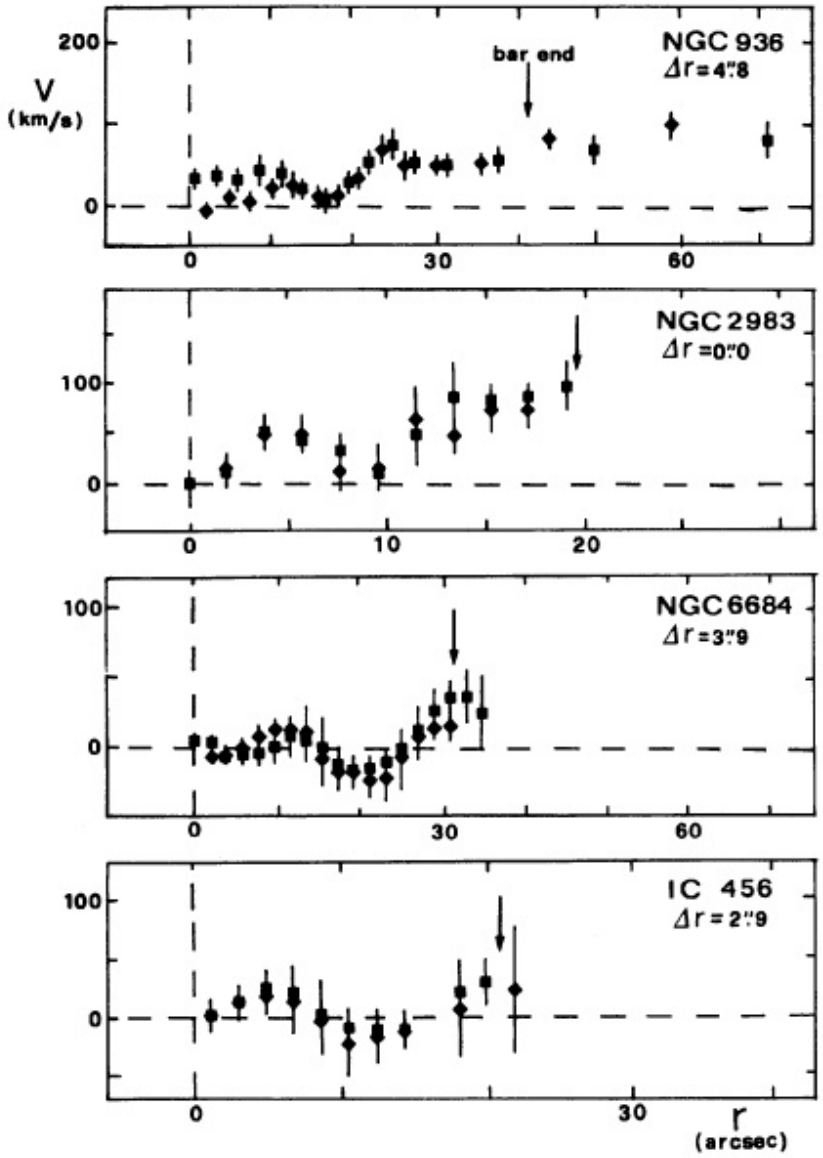
Different scenarios for building counter-rotating components

✧ external origin
- gas accretion: retrograde acquisition of gas and subsequent star formation (e.g., Thakar & Ryden 1996, 1998)
- minor merging: retrograde capture of a (gas-rich) dwarf companion (e.g., Balcells & Quinn 1990; Thakar et al. 1997)
- major merging: gas for cores (e.g., Hoffman et al. 2010) tuned initial conditions for disks (e.g., Crocker et al. 2009)

✧ internal origin
- bar structure: retrograde orbits trapped around x_4 family (Wozniak & Pfenniger 1997)
- bar dissolution: box-orbit stars are scattered onto clockwise/ counter-clockwise-streaming tube orbits (Ewans & Collett 1994)

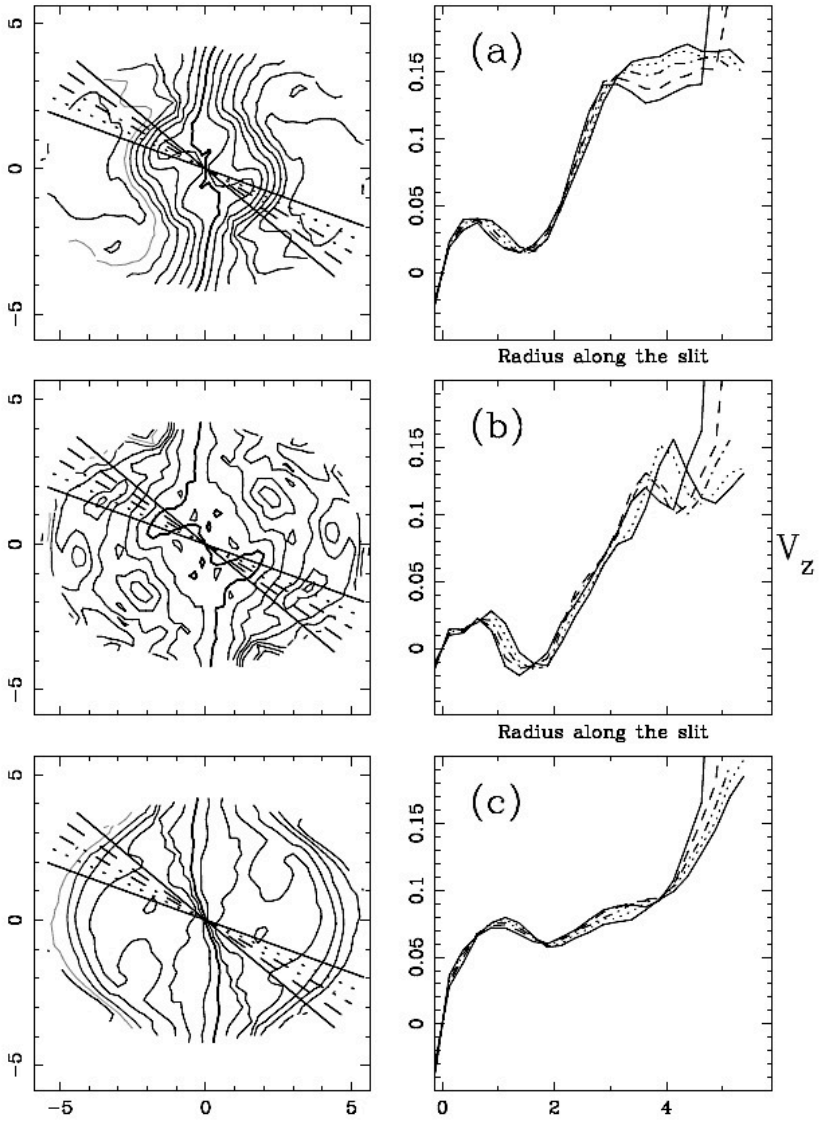
SB0s - local stellar counter-rotation

data



Bettoni (1989)

self-consistent models



Wozniak & Pfenniger (1997)

FORMATION SCENARIOS

Different scenarios for building counter-rotating components

✧ external origin
- gas accretion: retrograde acquisition of gas and subsequent star formation (e.g., Thakar & Ryden 1996, 1998)
- minor merging: retrograde capture of a (gas-rich) dwarf companion (e.g., Balcells & Quinn 1990; Thakar et al. 1997)
- major merging: gas for cores (e.g., Hoffman et al. 2010) tuned initial conditions for disks (e.g., Crocker et al. 2009)

✧ internal origin
- bar structure: retrograde orbits trapped around x_4 family (Wozniak & Pfenniger 1997)
- bar dissolution: box-orbit stars are scattered onto clockwise/ counter-clockwise-streaming tube orbits (Ewans & Collett 1994)

STELLAR POPULATIONS

The properties of the stellar populations are a key to disentangle between the different formation scenarios

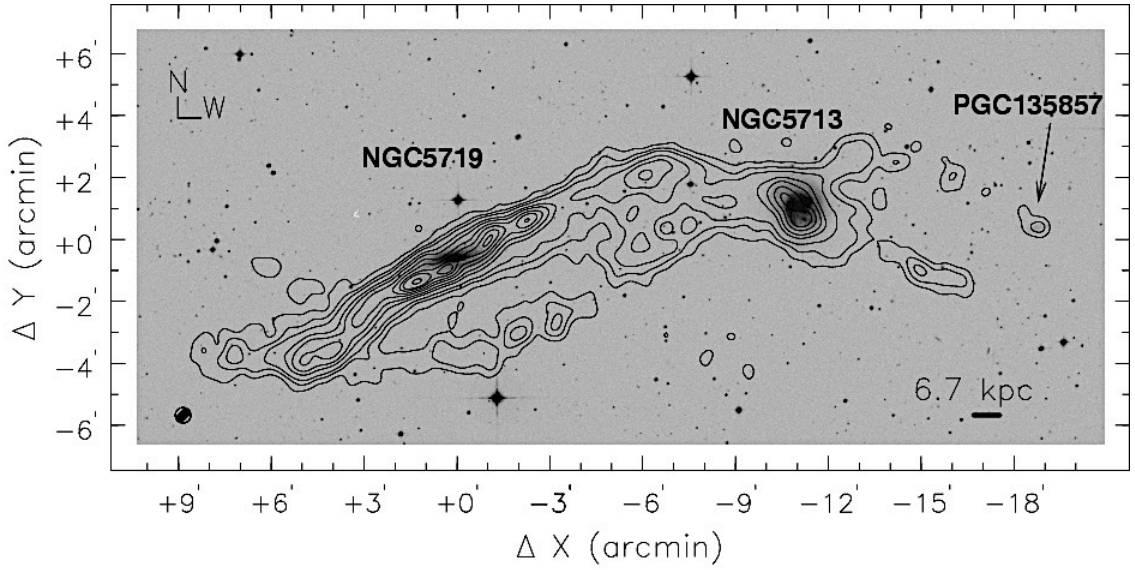
✧ external origin

- gas accretion: counter-rotating stars are associated with gas and younger than the host galaxy

- minor/major merging: counter-rotating stars are not always associated with gas and younger than the host galaxy

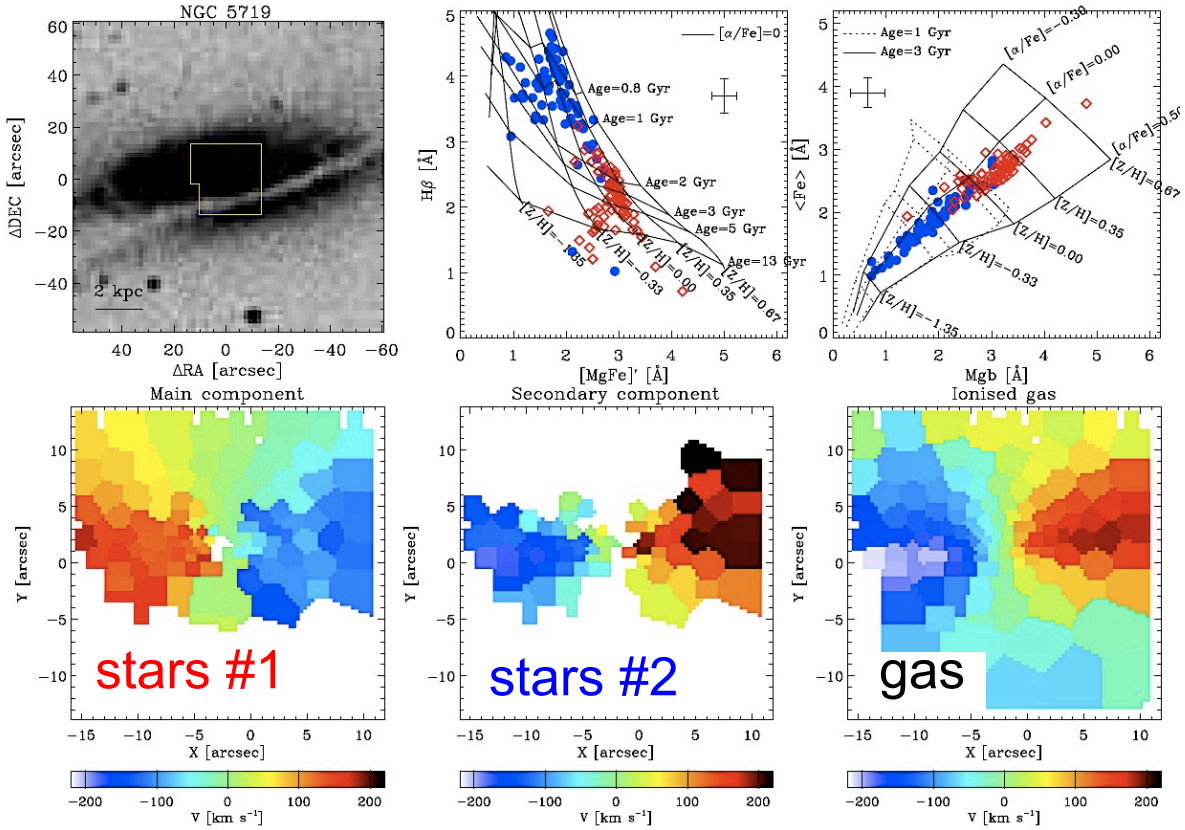
✧ internal origin

- bar dissolution: the two counter-rotating components have the same stellar population



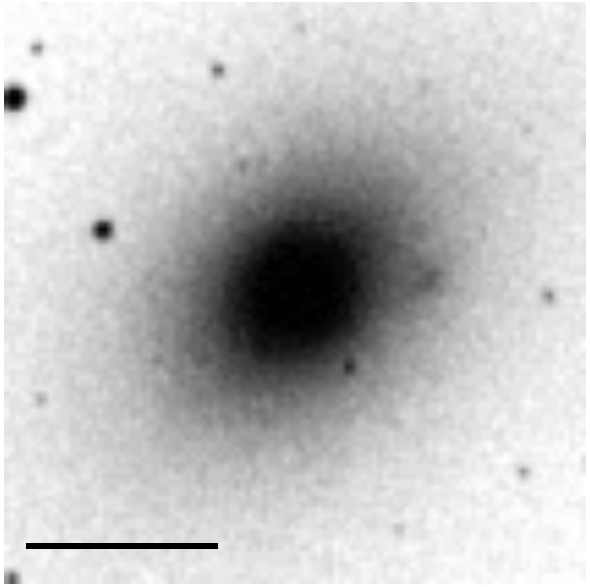
NGC 5719 – Sab
counter-rotating disks

Vergani et al. (2007)
Coccato et al. (2011)



stars #1
- older
- more metal-rich

stars #2
- younger
- less metal-rich

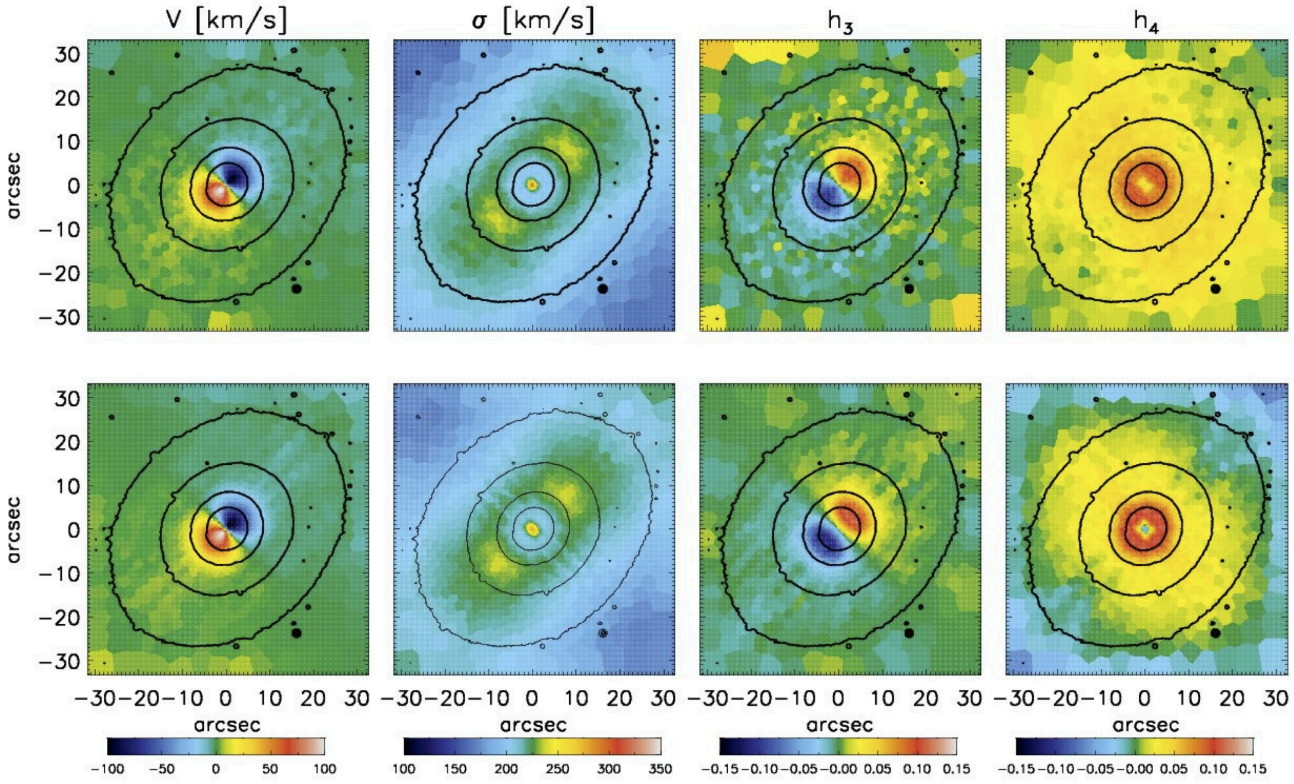


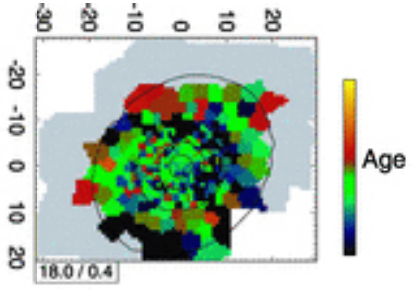
NGC 5813 – E1-2
counter-rotating core

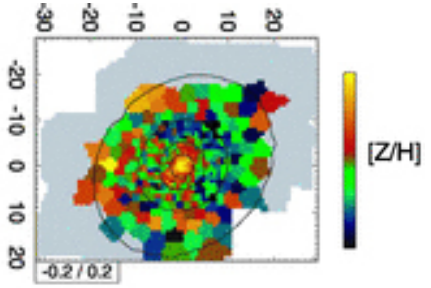
Kuntschner et al. (2010)
Krajnovic et al. (2015)

stars host
- old
- less metal-rich

stars core
- old
- more metal-rich







COUNTER-ROTATION: STATUS

- ✧ It shows a variety of forms (gas vs gas, stars vs stars, gas vs gas)
- ✧ It is observed in different regions (inner, outer, overall)
- ✧ No obvious morphological signatures (but not in late-type spirals)
- ✧ Obvious kinematic signatures (but LOSVD issue for detecting stars vs stars)
- ✧ It is not so rare (4% Es with stars vs stars; 30% S0s with gas vs stars; <10% S0s with stars vs stars; <10% spirals with gas/stars vs stars; most of SB0s)
- ✧ Both external (accretion) and internal (bar) processes explain the formation of counter-rotation
- ✧ Stellar populations promise to nail down the formation mechanism

COUNTER-ROTATION: FUTURE

- ✧ Photometry: deep imaging survey to look for fingerprints of accretion/merging events
- ✧ Kinematics: detailed analysis of LOSVD to look for undetected retrograde stars
- ✧ Statistics: volume/luminosity-limited samples to drive unbiased conclusions
- ✧ Simulations: not limited to few cases but exploring a wider parameter-space
- ✧ Stellar populations: to test predictions of the formation scenarios