Kinematically distinct cores: the unexplained smoking guns of hierarchical formation

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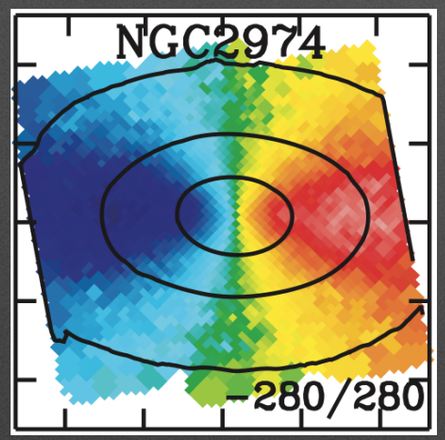
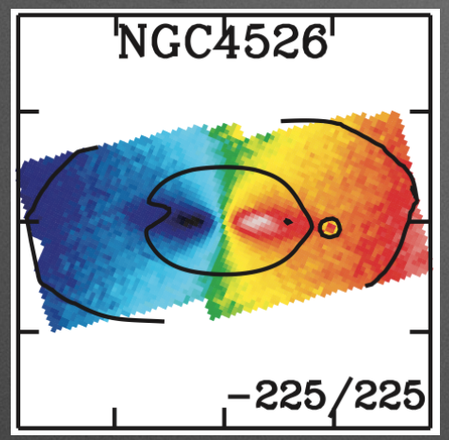
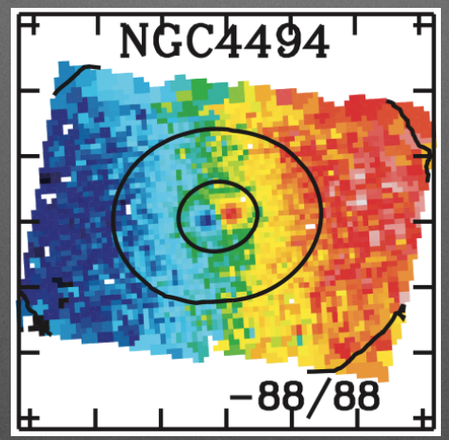
AIP

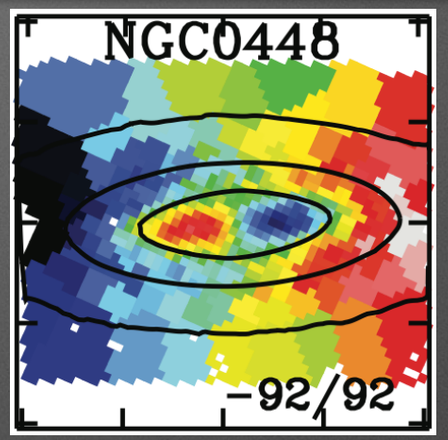
Kinematic decoupling in early-type galaxies

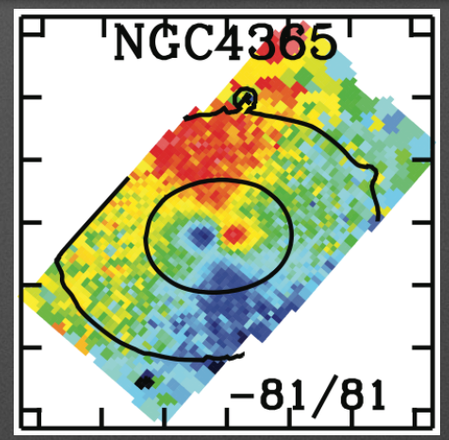
maps from ATLAS^{3D} survey (Krajnović et al. 2011)

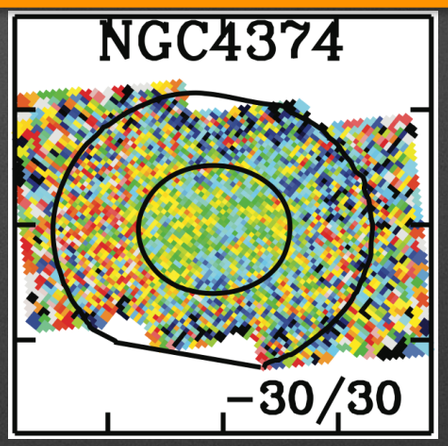


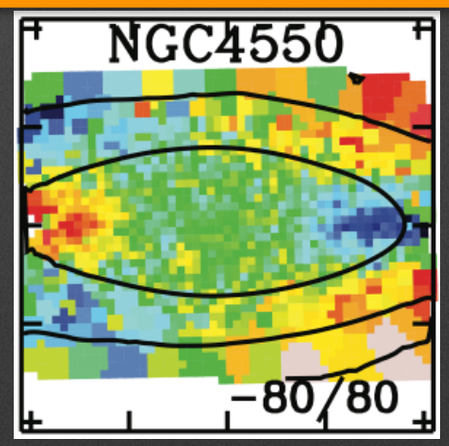










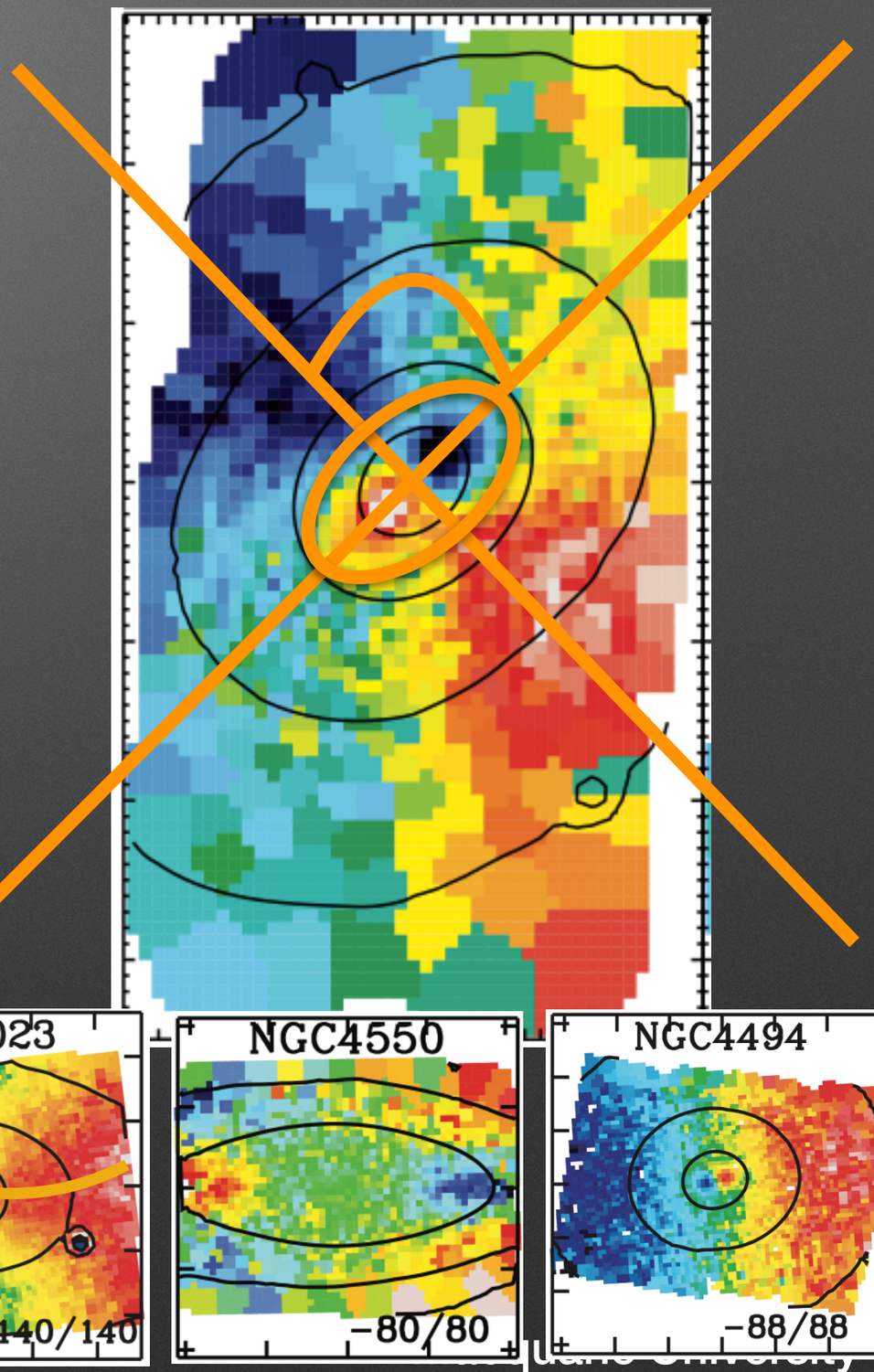


- velocity maps of early-type galaxies show ample evidence for complex kinematic structures
- what is their origin?
- how can they survive? (are they stable?)
- are these structures “decoupled” from the rest of the body?

What is a KDC?

- kinematically distinct core (KDC)
- kinematically decoupled component/core (KDC)
- kinematically peculiar core (KPC)
- dynamically decoupled cores?

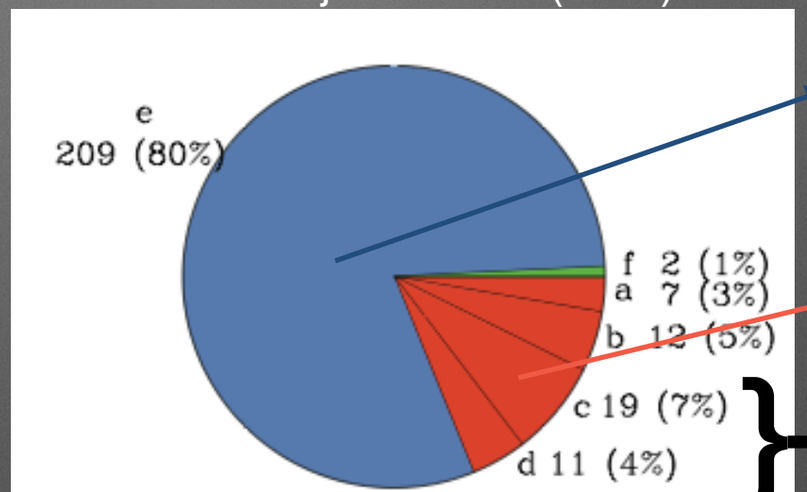
- Core: central region (nucleus)
- Distinct/peculiar maybe decoupled
- Definition:
  - change in the orientation of the velocity structure for more than 30 degrees (or we call it a “kinematic twist”)
  - velocity drops (nearly) to ZERO in the transition region



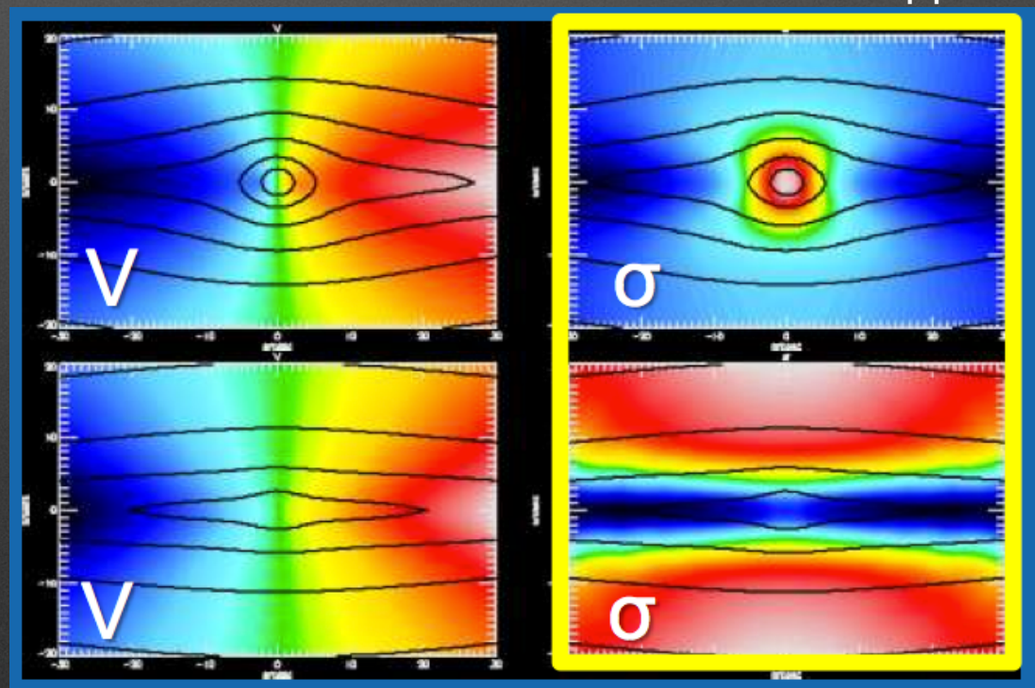
Why are KDCs special?

- They look cool (great PR)
- They are rare
  - found in early-type galaxies
  - actually, only <11% of early-type galaxies
- Kinematics of majority of galaxies is easy to predict based on their shapes (Cappellari et al. 2013)
- kinematics of KDCs is not easy to model

Krajnović et al.(2011)

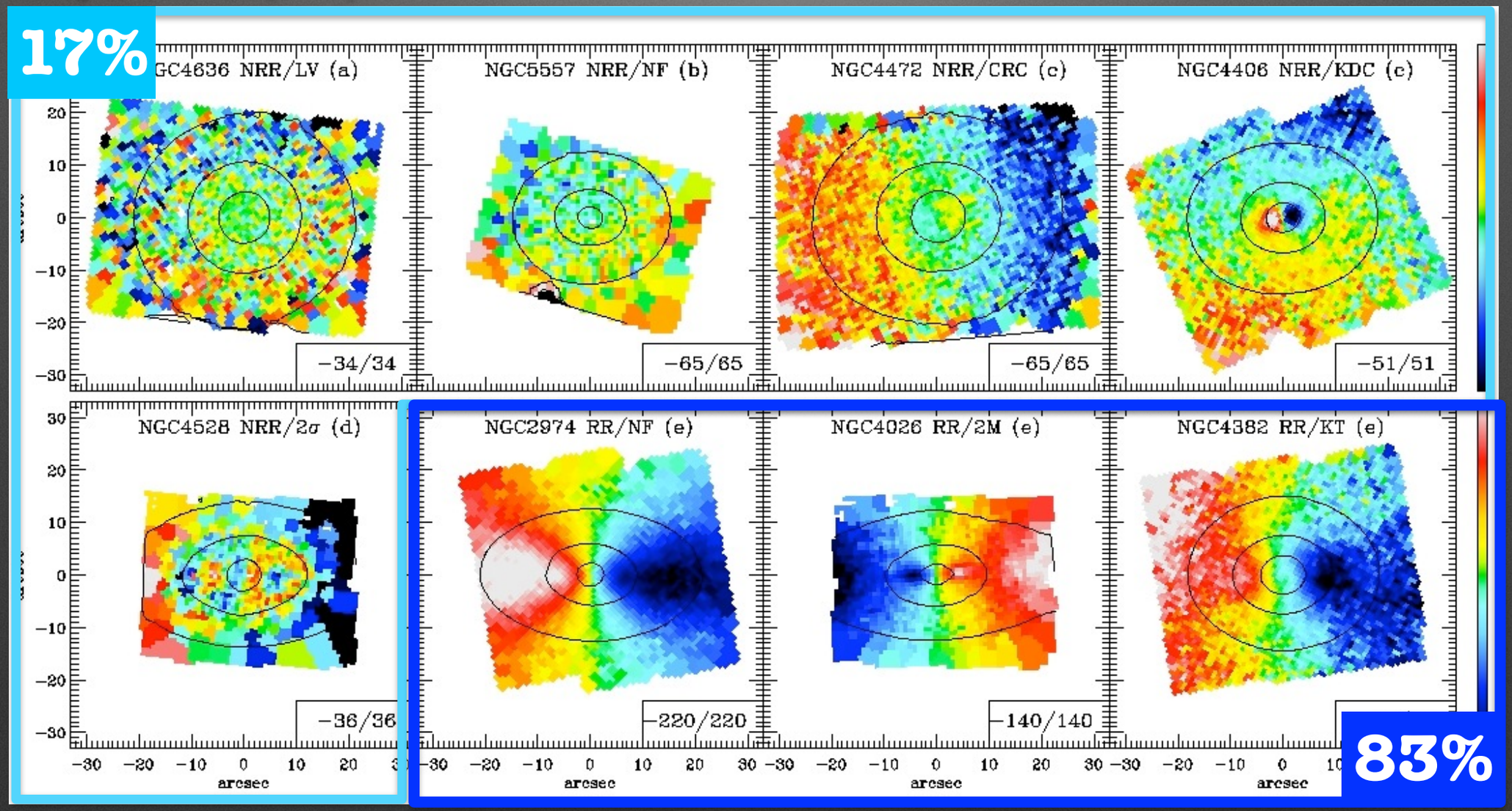


Cappellari 2011, conference talk



Kinematics of early-type galaxies

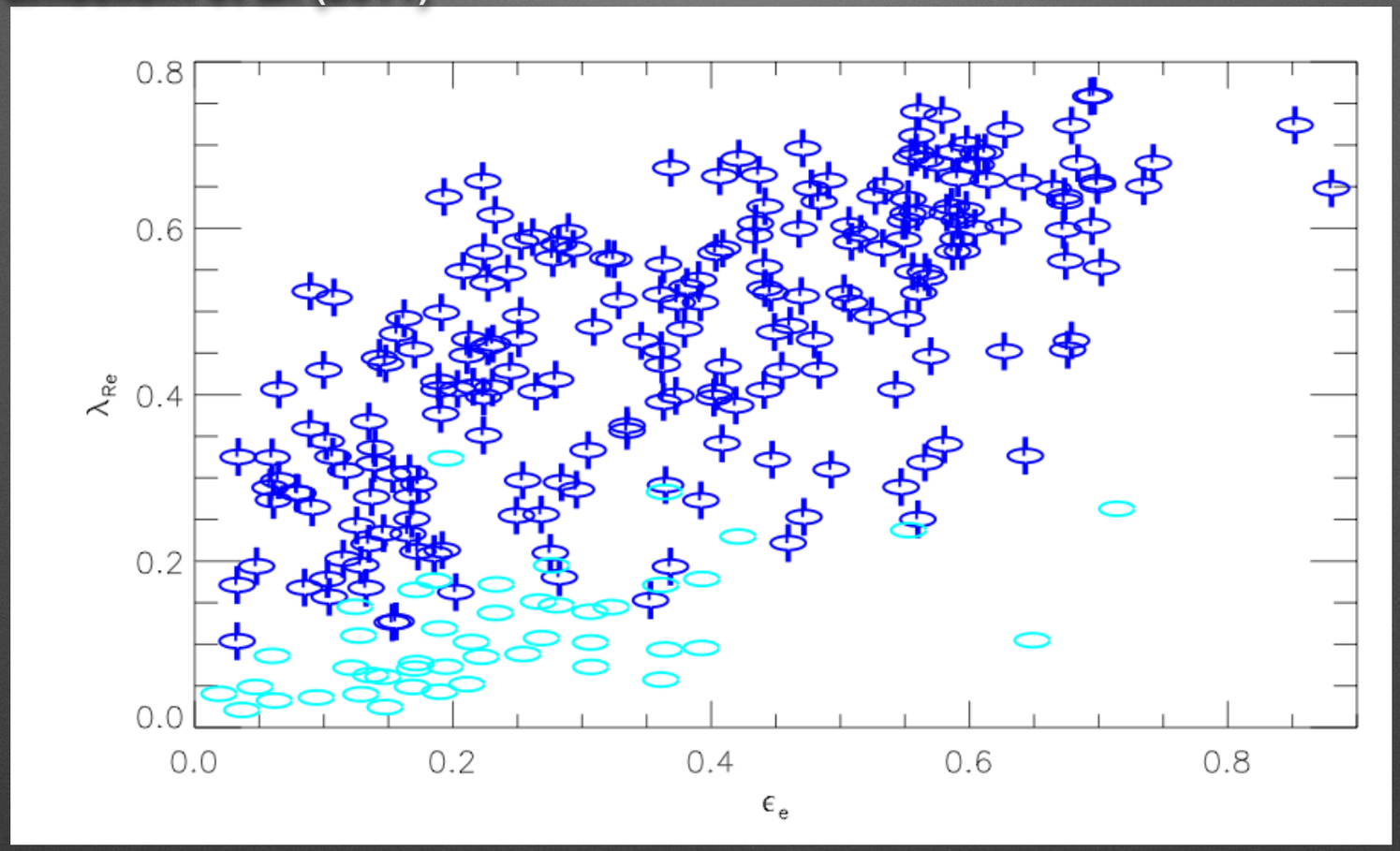
Krajnović et al. (2011)

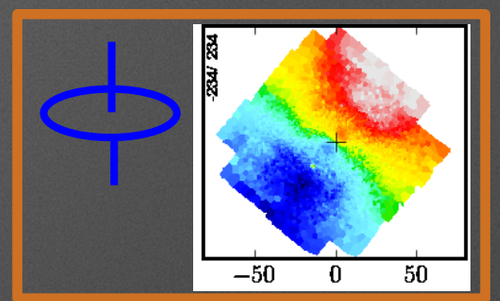


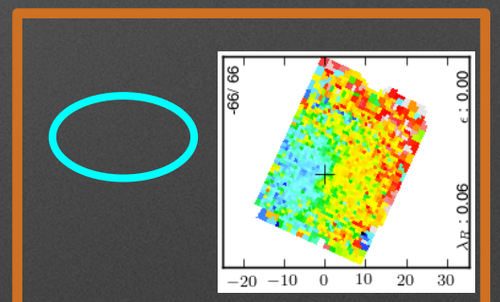
- Majority of ETGs have simple disc-like kinematics

Specific angular momentum - λ_R

Emsellem et al. (2011)





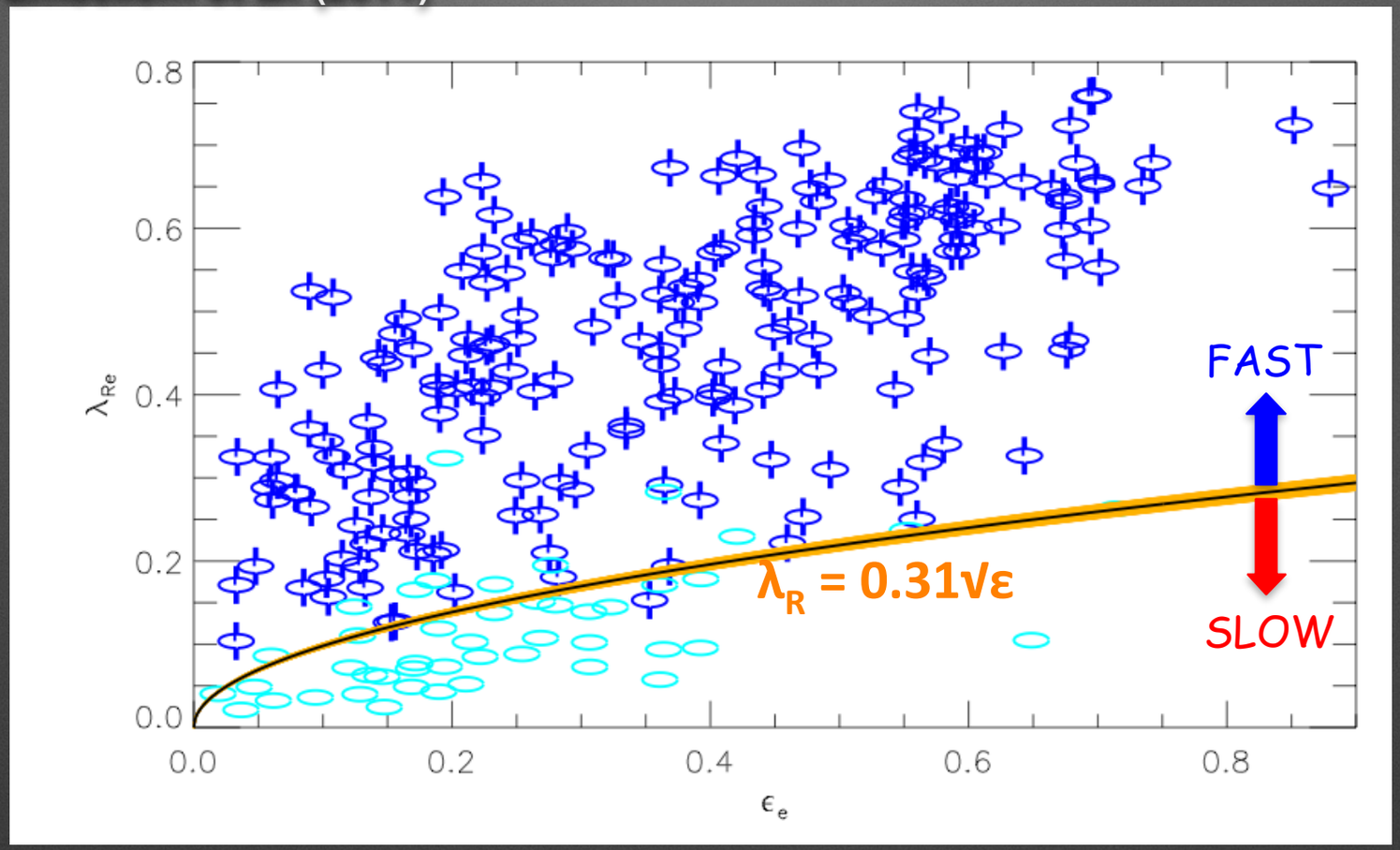


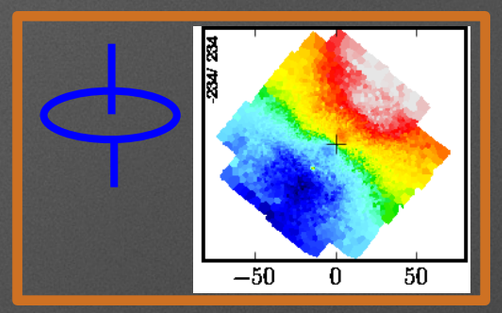
- Kinematic classification using ***specific angular momentum***, λ_R (Emsellem et al. 2007)
- Fast rotators: Regular, disk-like velocity maps
- Slow rotators: Non-regular velocity maps, KDCs, no net rotation

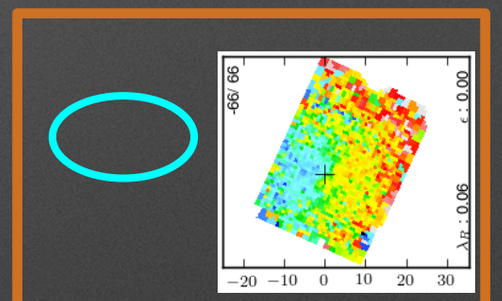
$$\lambda_R \equiv \frac{\langle R \cdot |V| \rangle}{\langle R\sqrt{V^2+\sigma^2} \rangle}$$

Specific angular momentum - λ_R

Emsellem et al. (2011)







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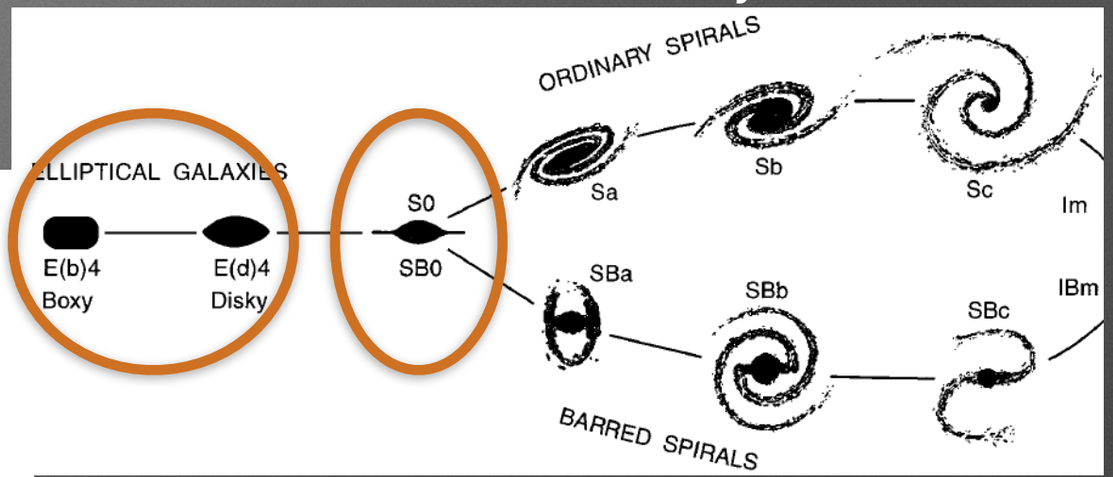
λ_R vs Hubble classes

Kormendy & Bender 1996



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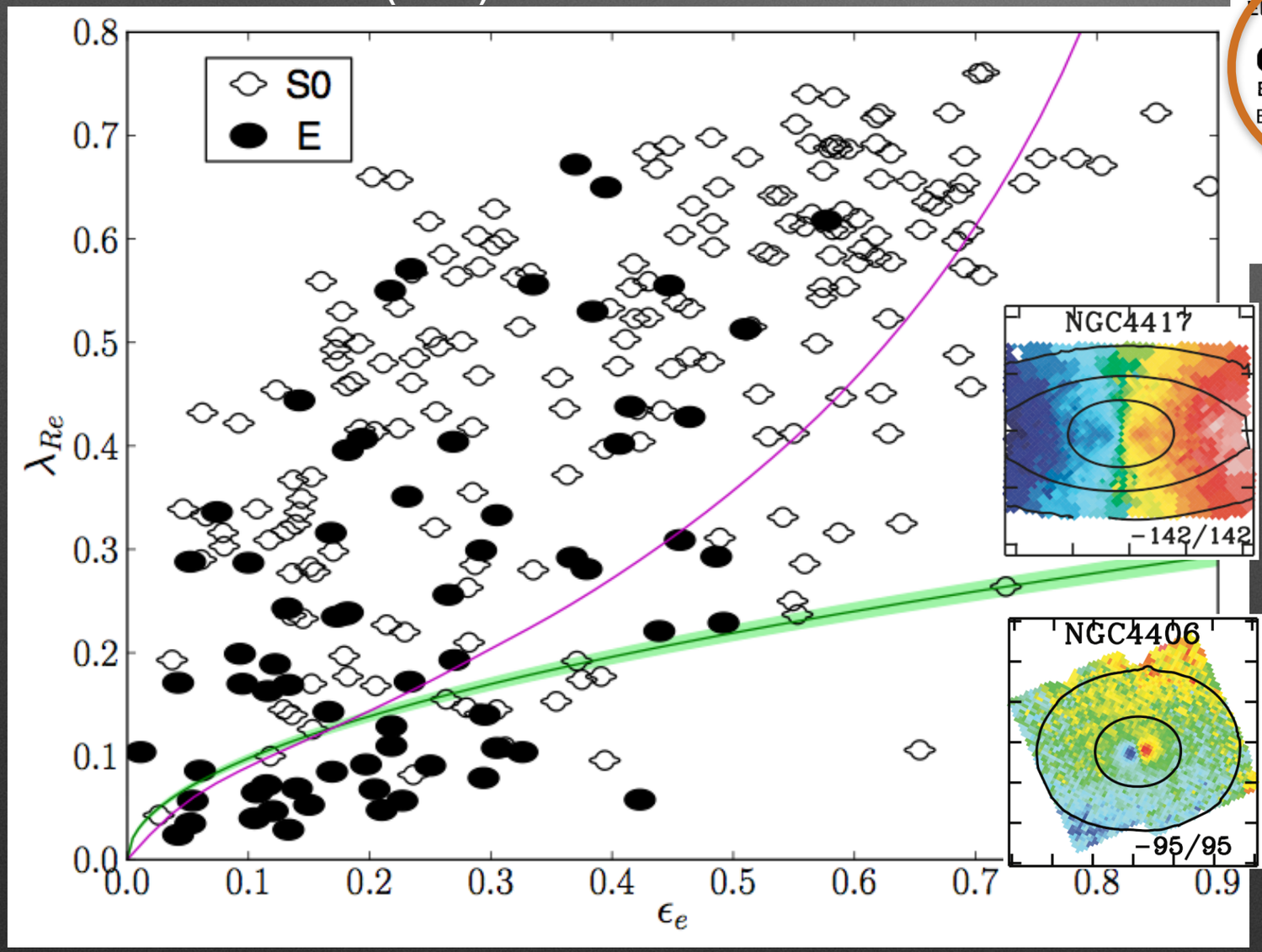
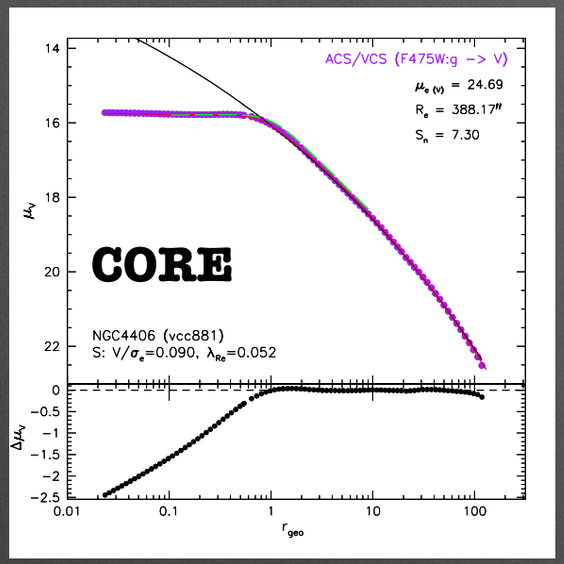
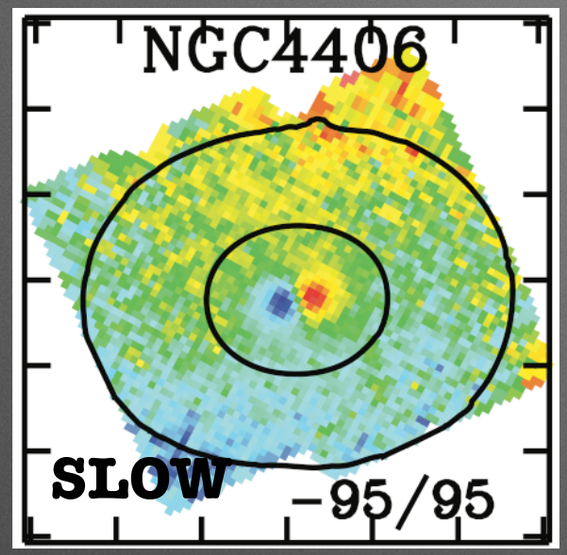
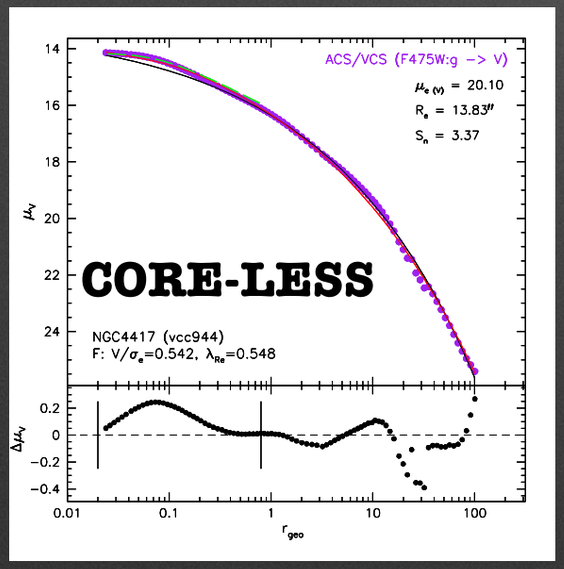


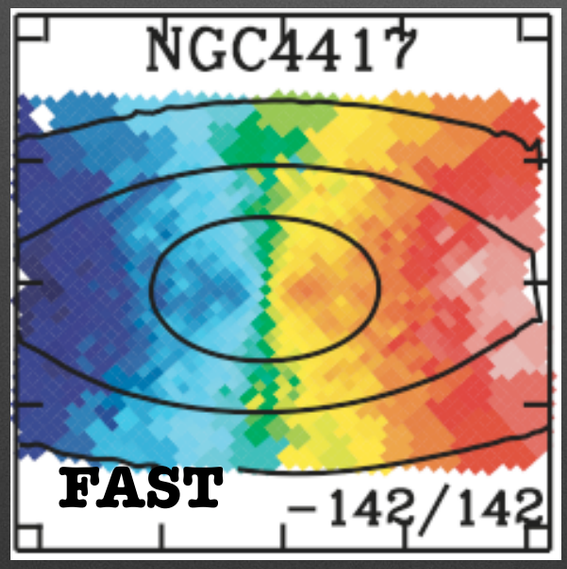
- 66% of E are FR
- 20% of FR are E
- FR ≈ S0 + E(d)
- SR = true ellipticals

Nuclear surface brightness profiles

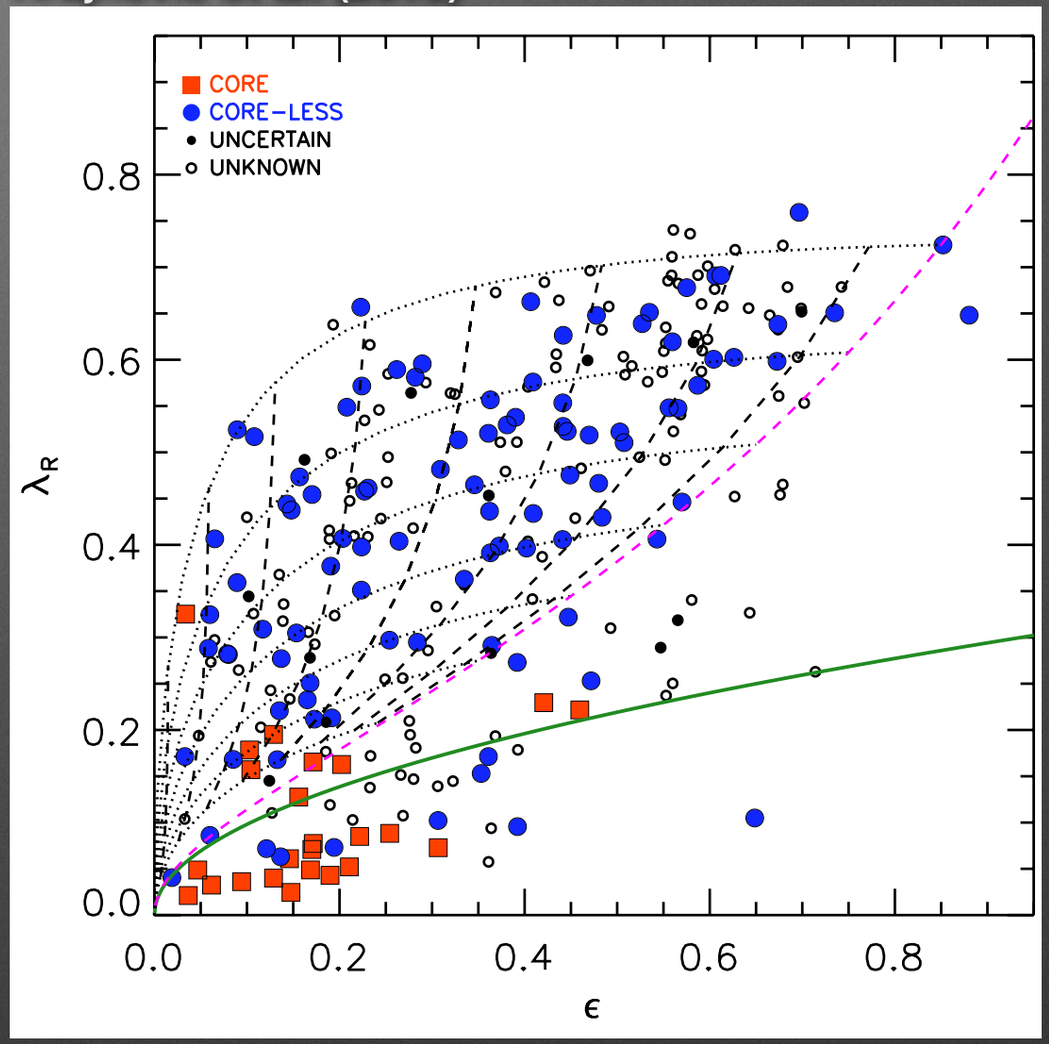








Krajnović et al. (2013)



- core galaxies are typically Slow Rotators, but not all
- most massive (lowest angular momentum) Slow Rotators have cores

Where do KDCs live?

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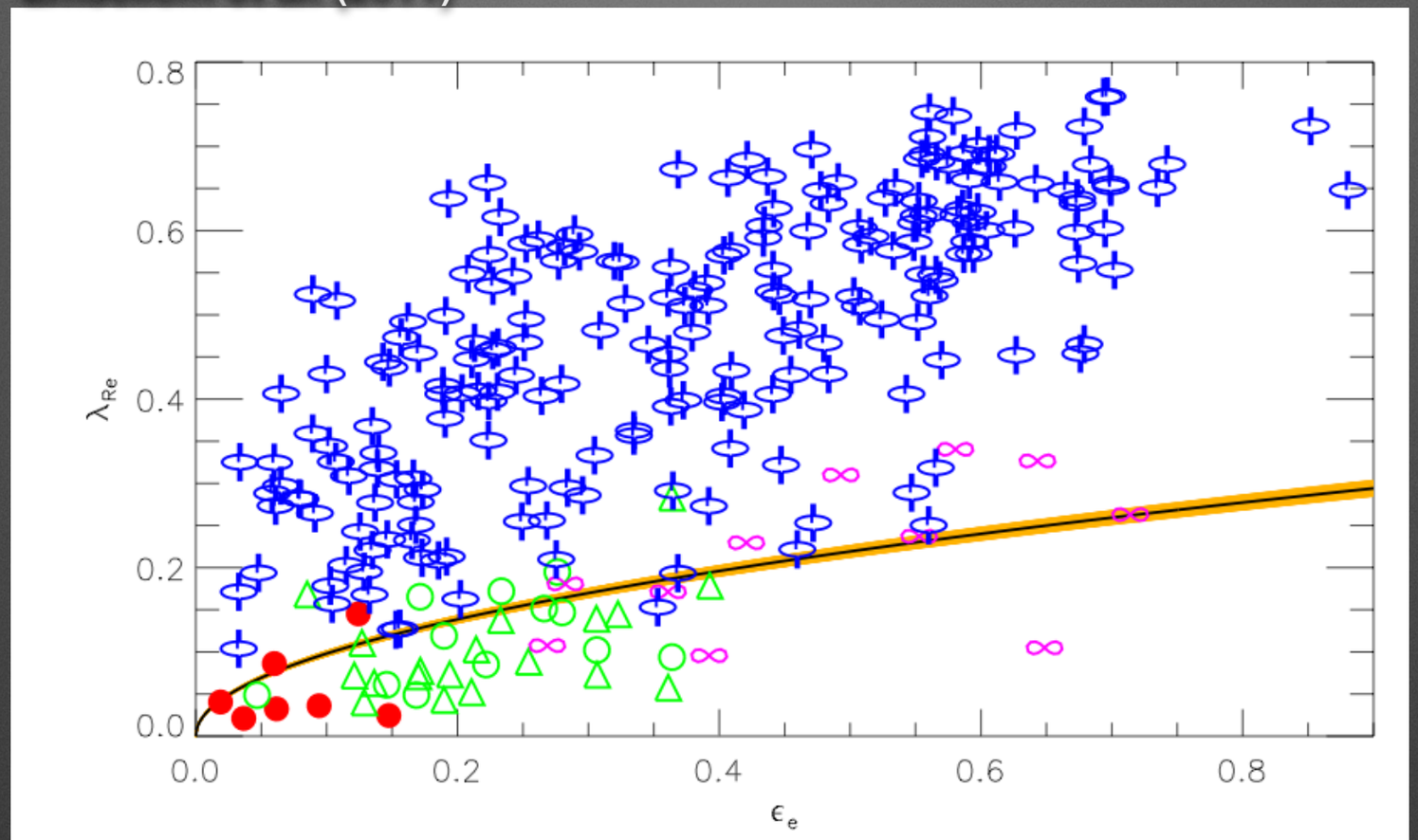
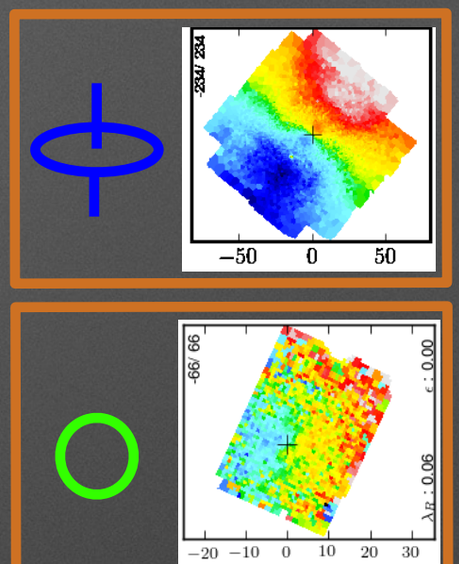
λ_R vs kinematic strucutre

Emsellem et al. (2011)

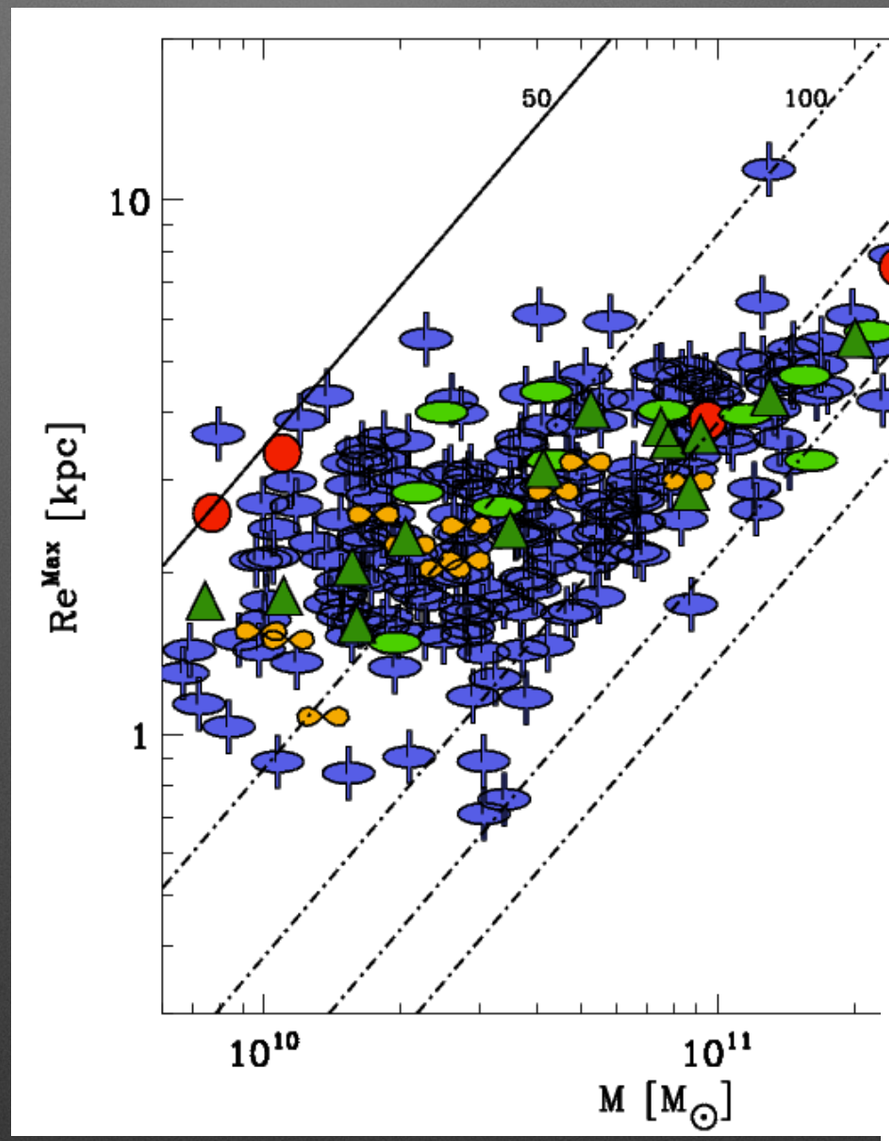


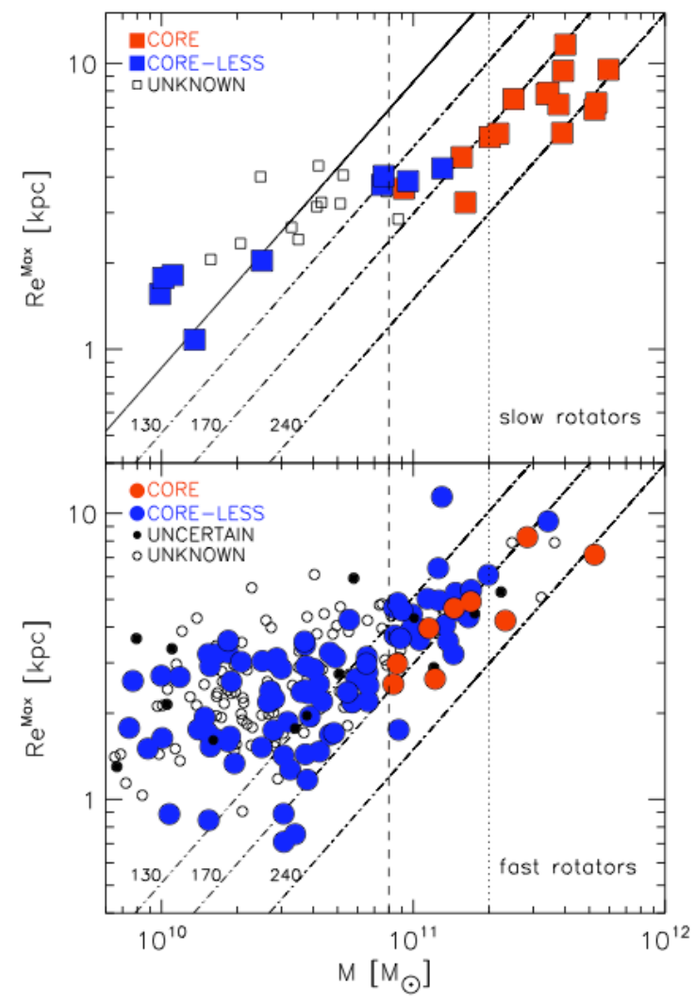


- (large) KDCs are almost exclusively found in slow rotators

KDCs on the mass - size

- massive slow rotators with cores often have KDCs
- core-less galaxies also contain KDCs
- KDC galaxies span range of masses

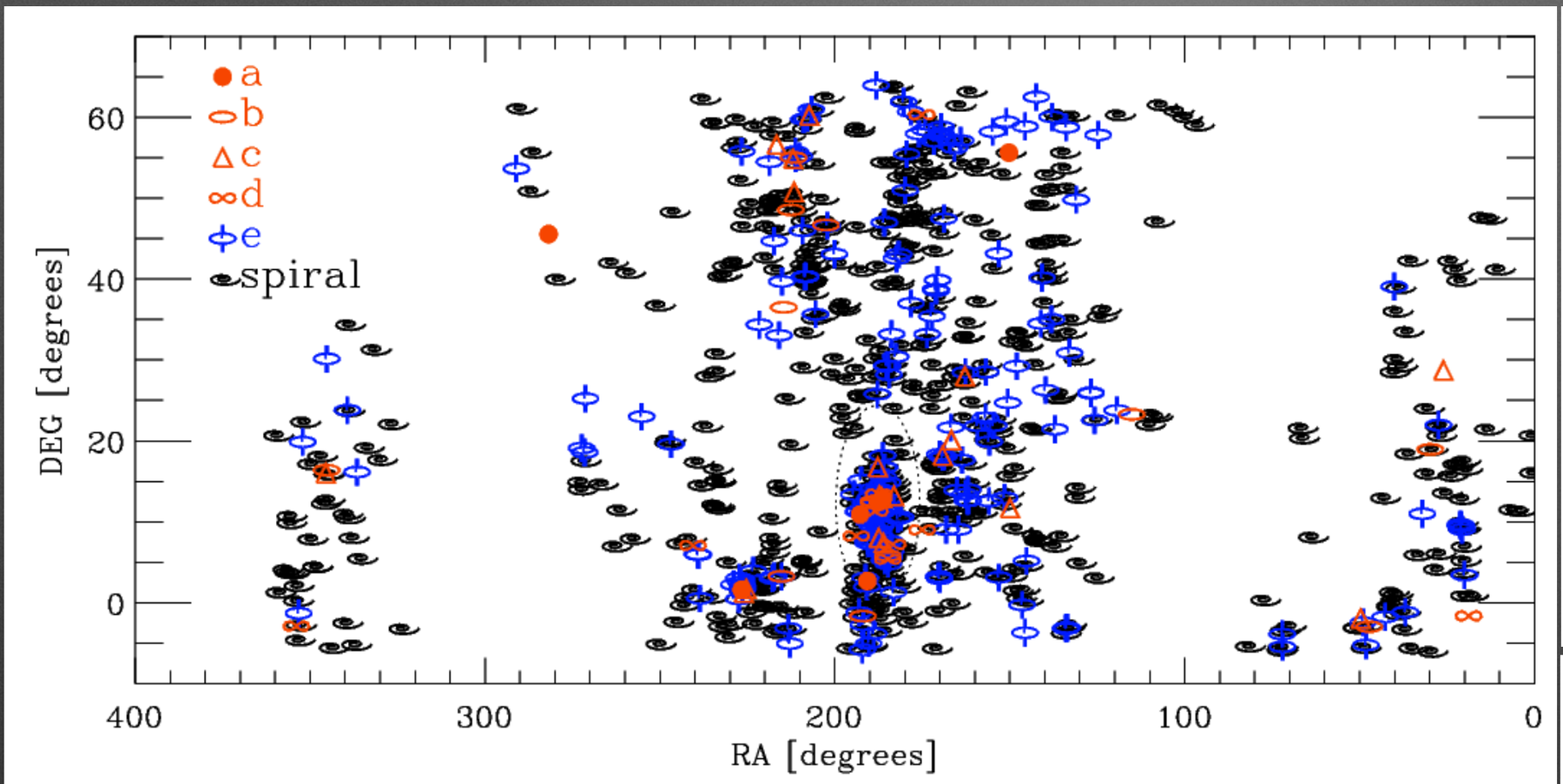


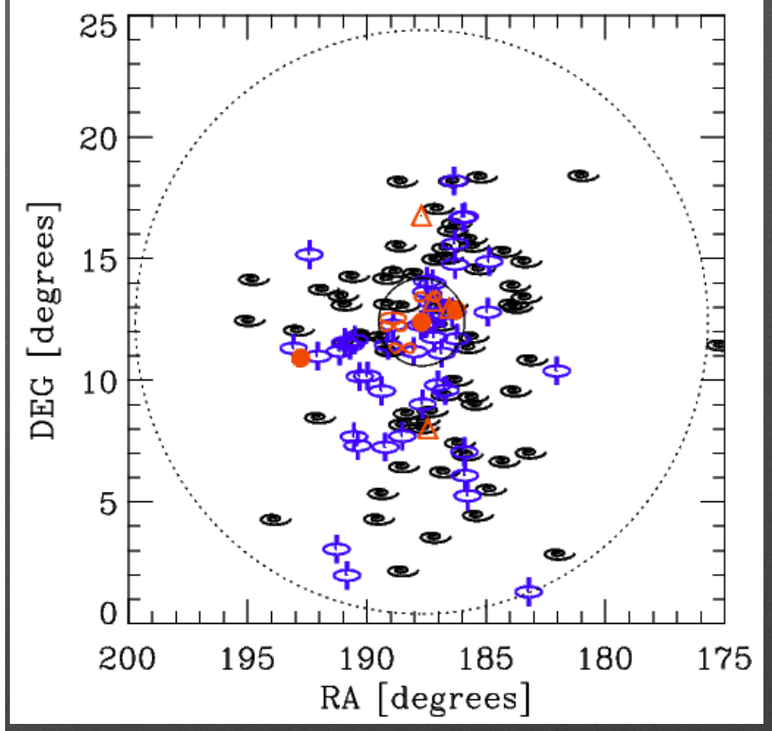


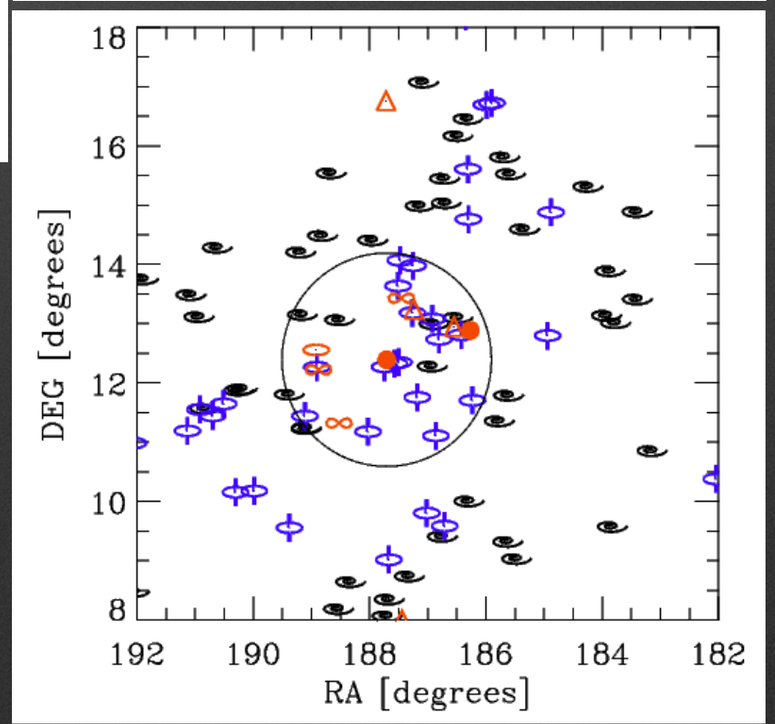
Krajnović et al. (2013)

KDCs and the environment

Krajnović et al. (2011)







- KDC galaxies found in dense environments
- follow the trend of massive slow rotators

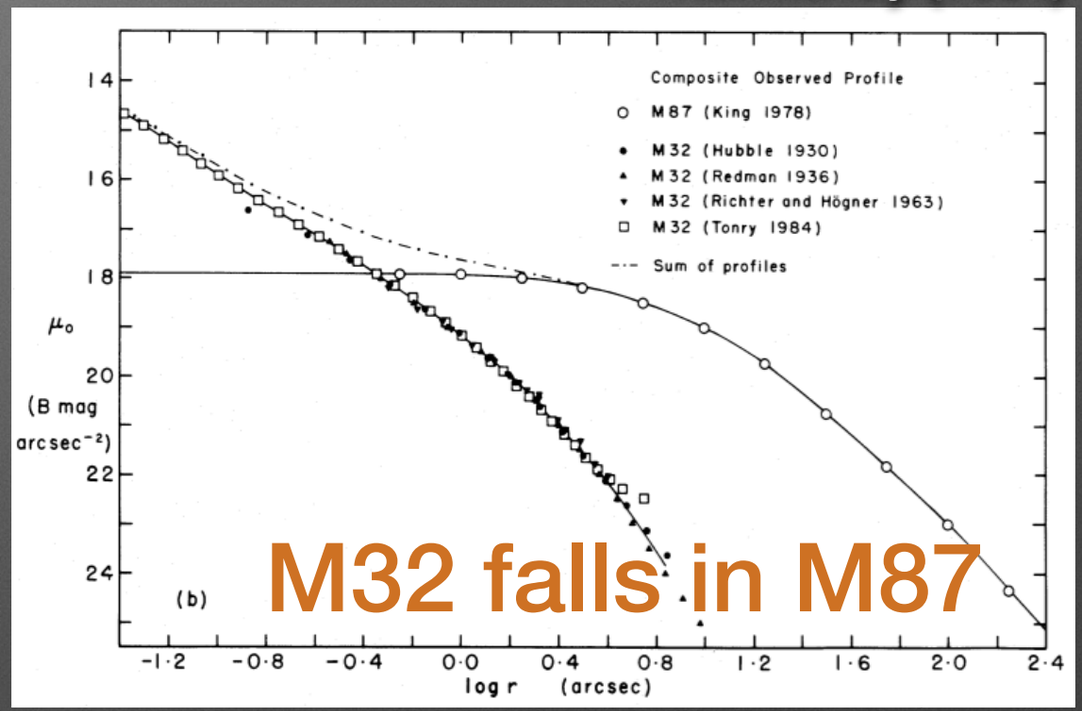
A historic prospective

(Ancient) History: 1980s

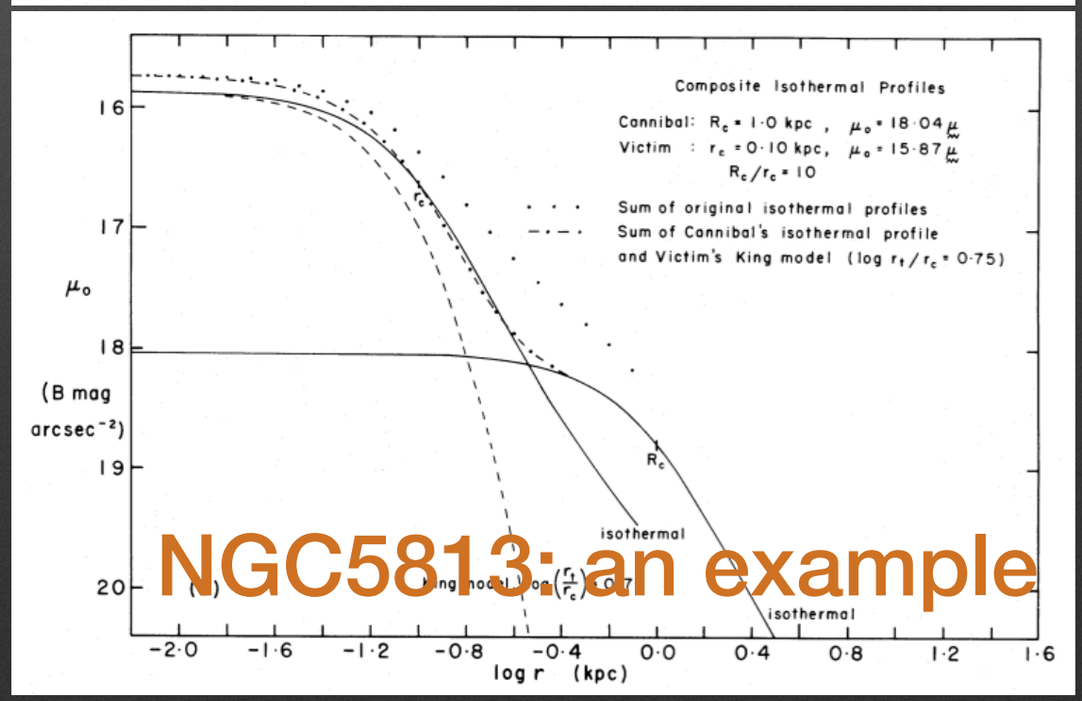
- Looking for evidence of past mergers (collapse vs merger): how should a remnant look like?

- it could have a core: ‘core-within-a-core’
  - small size, high surface brightness
  - rotation (more that the body), smaller dispersion
  - bluer colours
  - photometric twist
- Photometric searches:
  - King, Lauer, Jedrzejewski, Schechter, Kormendy…
  - Efstathiou, Elis, Carter (1982) - NGC5813

Kormendy (1984)



M32 falls in M87



NGC5813: an example

(Ancient) History: 1980s

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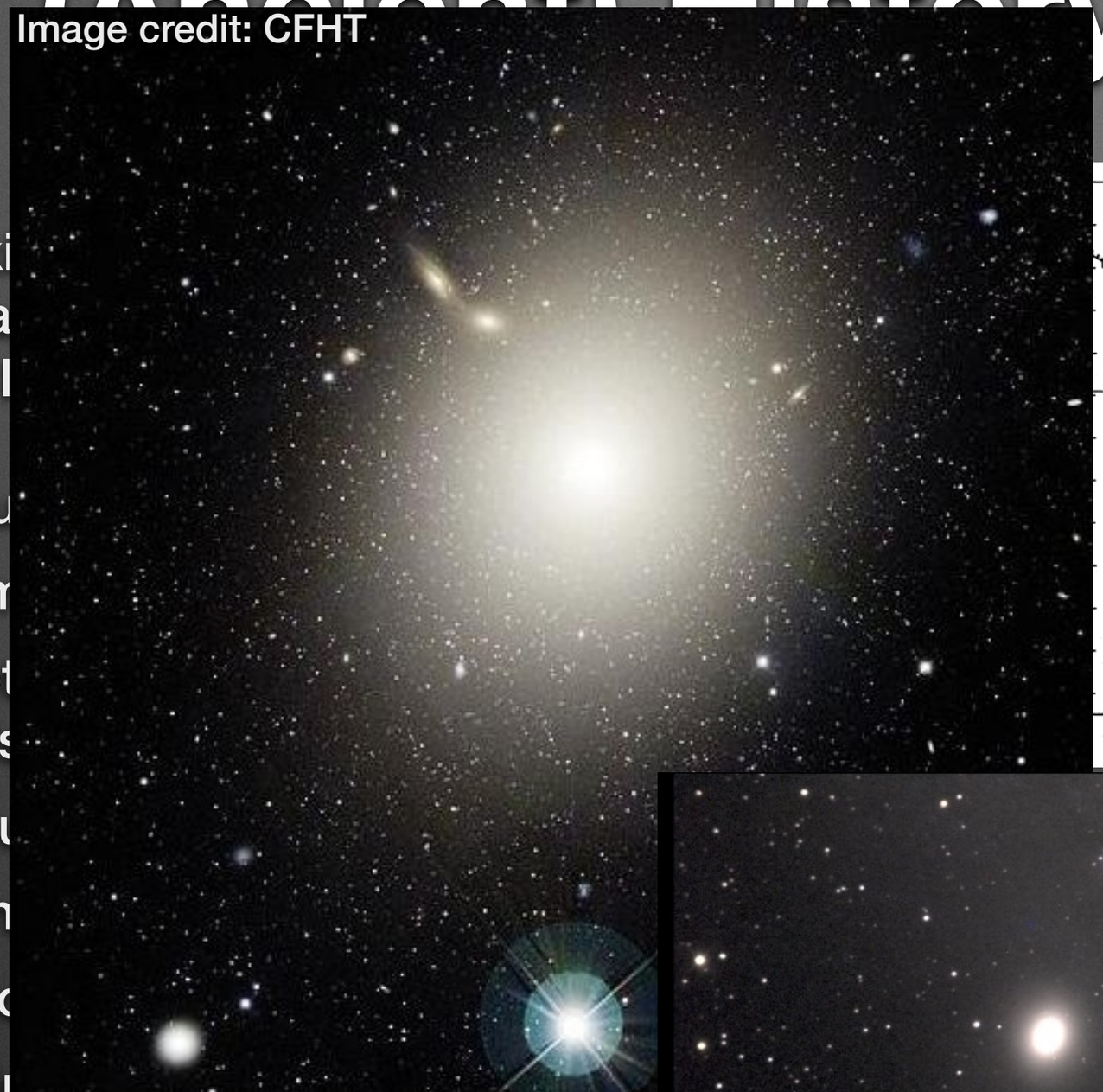
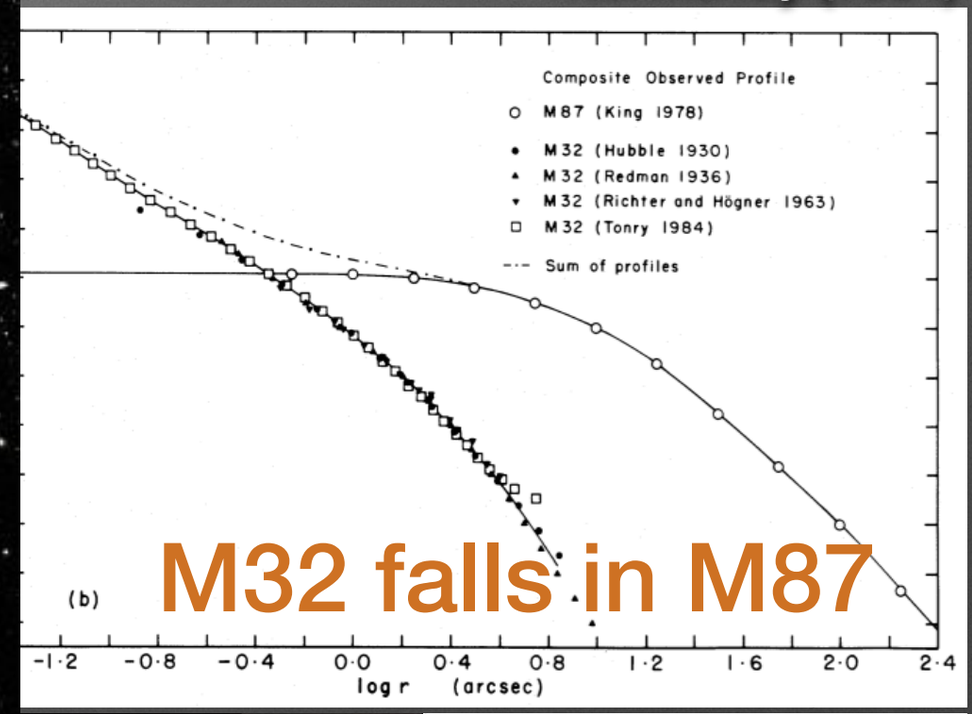
    Kormendy…
  - Efstathiou, Elis, Carter (1982)

Image credit: CFHT



Kormendy (1984)



M32 falls in M87

Image credit: Stacy Ladenburg & Emily MacLeod

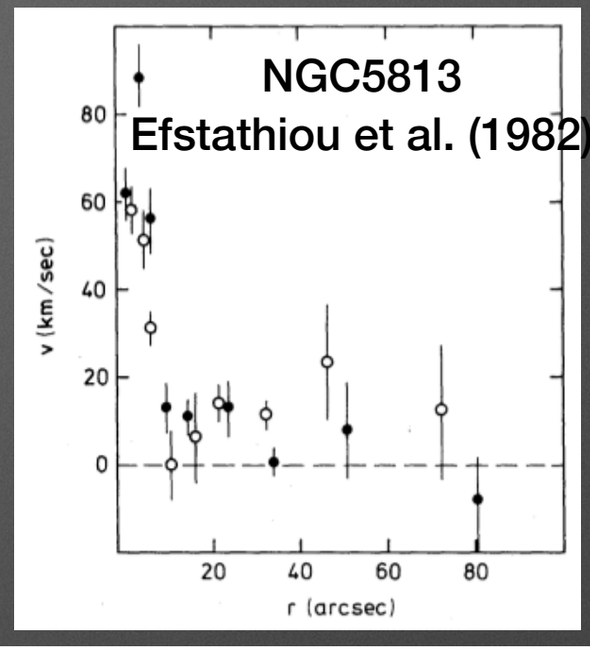
:an example

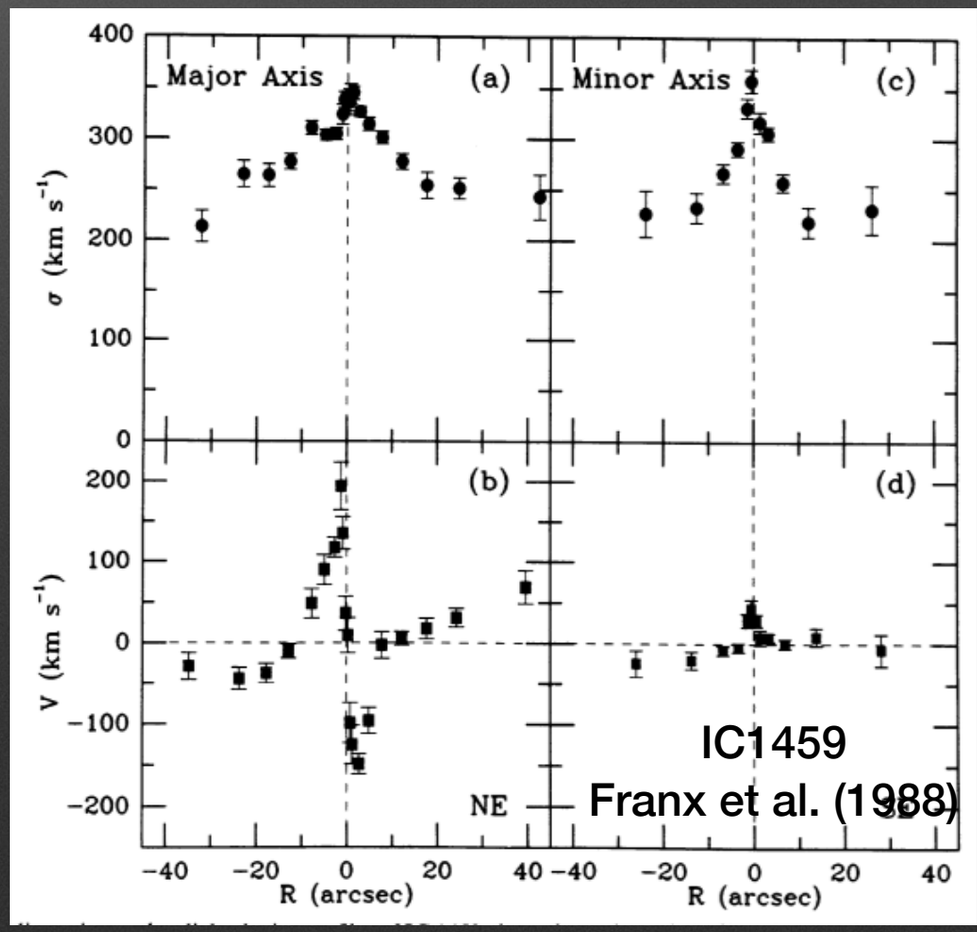
(Ancient) history: 1980s

- Kinematic searches:
  - Efstathiou, Elis, Carter (1982,1984) - NGC5813
  - Jedrzejewski & Schecter 1988 - NGC3608, NGC4494, NGC7626
  - Bender 1988 - NGC4365, NGC4406, NGC4494, and NGC5322
  - Franx & Illingworth 1988 - IC1459

- there are also other type of decouplings
  - gas rotates different from stars (Schweizer 1982, Bertola et al. 1988…)

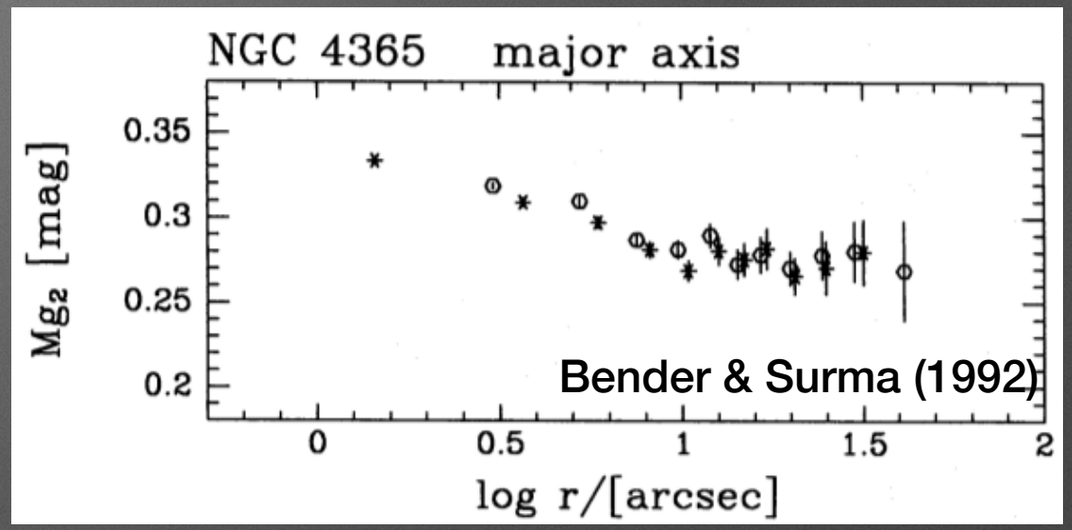
- what about the properties of the stellar populations (colour, age & metallicity)?



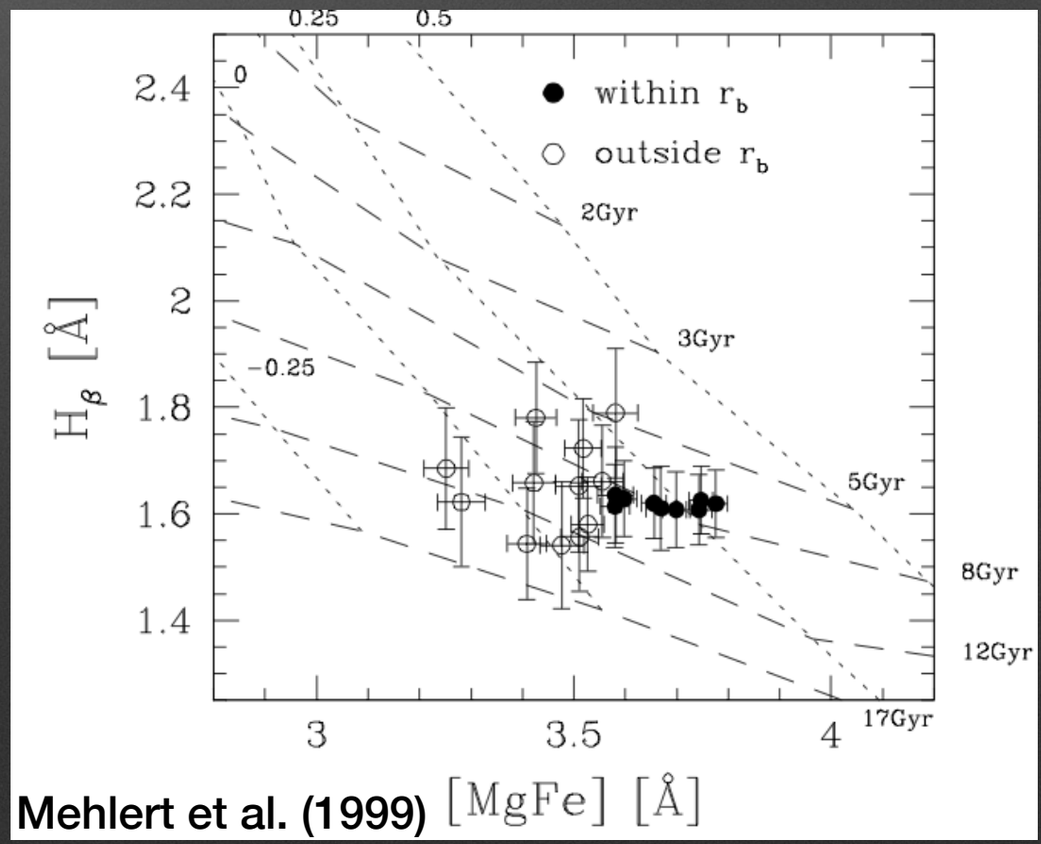


Stellar populations (1990)

- there are some trends in metellicities for galaxies with KDCs (e.g. Bender & Surma 1992, Carollo & Danziger 1994)
  - metal rich cores (more than large scales) -> not good for ‘core-within-a-core’
  - but other Es have similar trends (Gorgas et al. 1990….)
- no trends in colours from ground based imaging (Franx et al. 1990)
- no trends in colours from HST imaging (Carollo et al. 1997)



Bender & Surma (1992)



Mehlert et al. (1999)

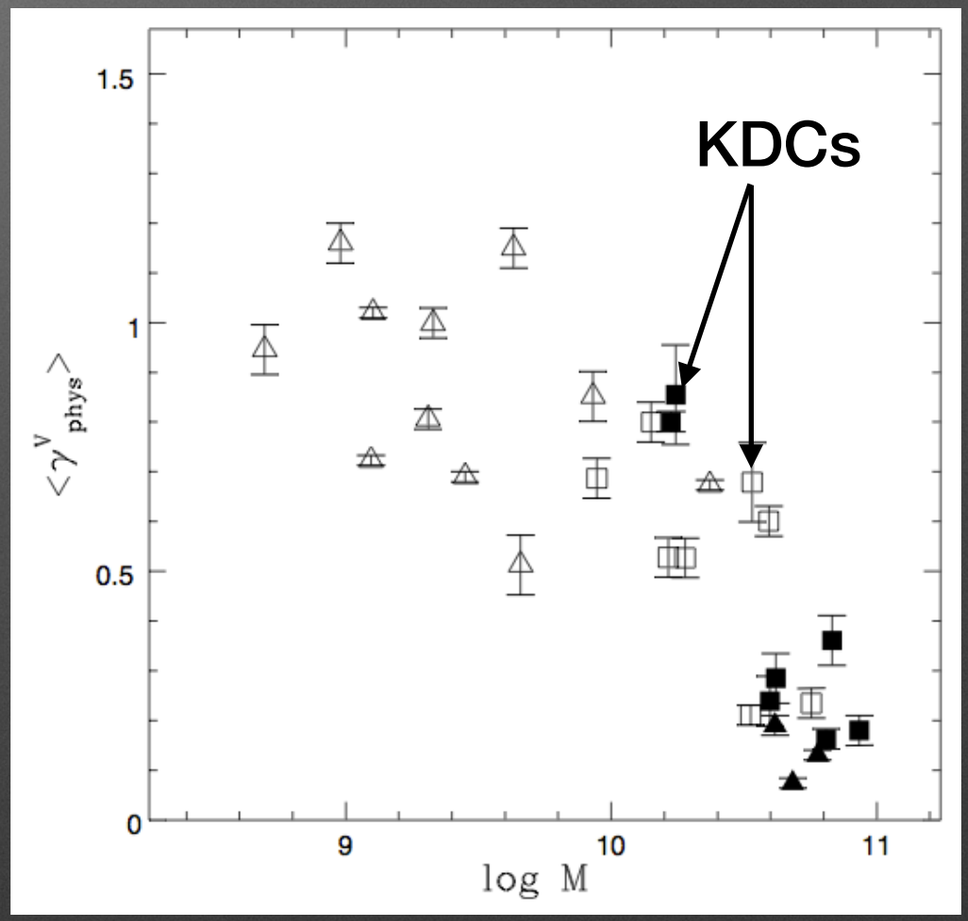
KDCs and light distributions

- no general trends in surface brightness profiles (e.g.Nuker nuclear slope; Forbes et al. 1995; Carollo et al. 1996)

- indication that some KDCs have discy isophotes (Mehlert et al. 1998) but not special w.r.t ETG

- KDC host galaxies are not different from other early-type galaxies

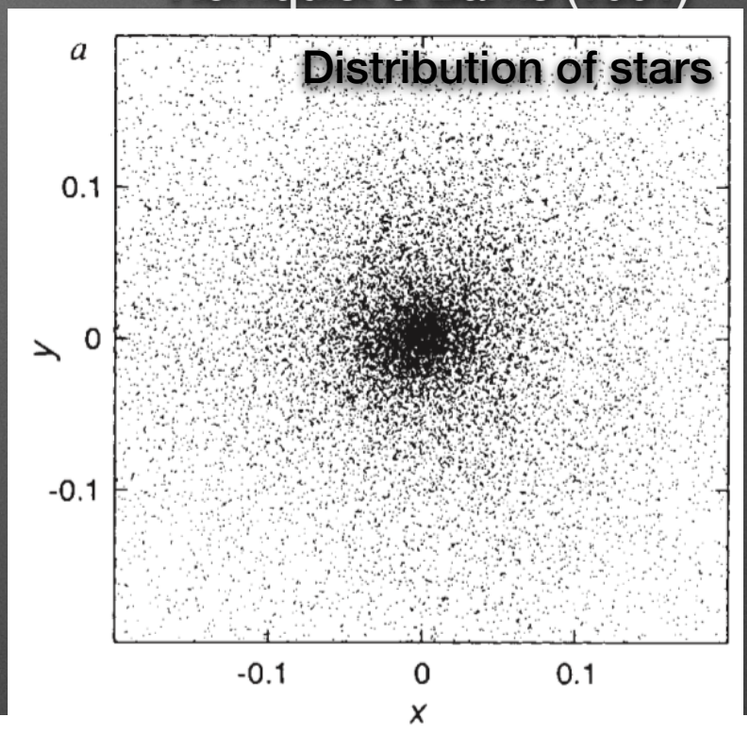
Carollo et al. 1996

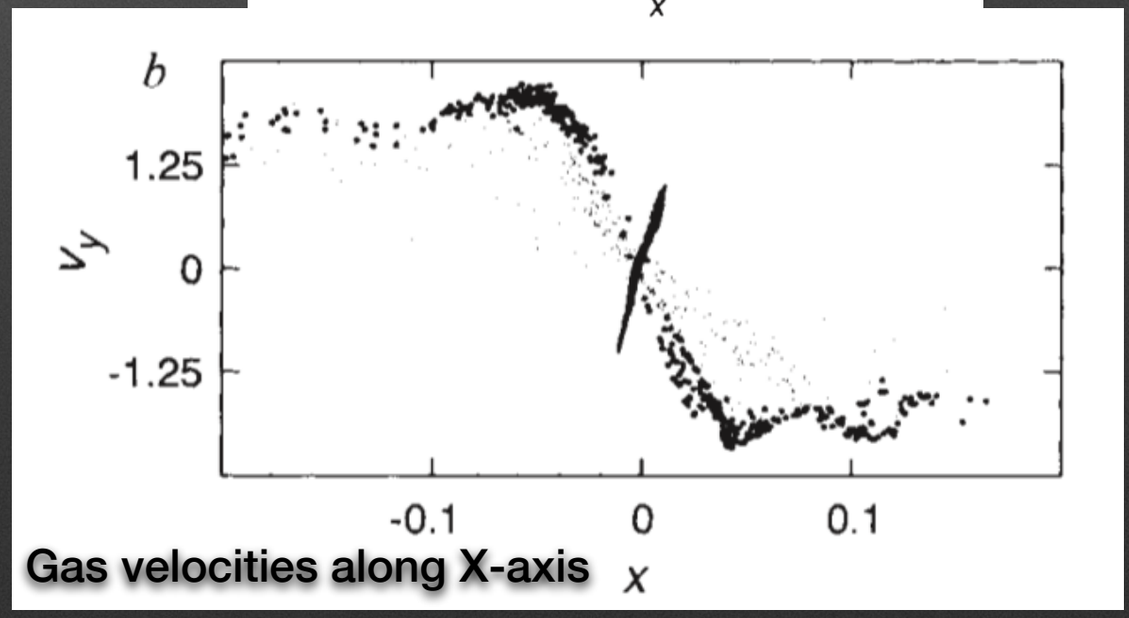


Interpretations: 1990

- KDC seemed to be often present in luminous (massive) Es (~1/3, Bender 1990)
- interpreted as evidence of mergers (Kormendy 1984; Franx & Illingworth 1988; Balcells & Quinn 1990; Hernquist & Barns 1991; Bender & Surma 1992….)
- 1) core-within-a-core (Kormendy 1984)
  - KDC rotation from the orbital spin (Franx & Illingworth 1988)
- 2) accretion of gas or gas rich satellite (Bertola et al. 1988; Franx & Illingworth 1988)
- 3) major mergers of gas rich spirals (Bender & Surma 1992)
- 4) early (hierarchical) formation when galaxies are clumpy and gas rich (Bender & Surma 1992)

Hernquist & Barns (1991)





Gas velocities along X-axis

KDC demographics

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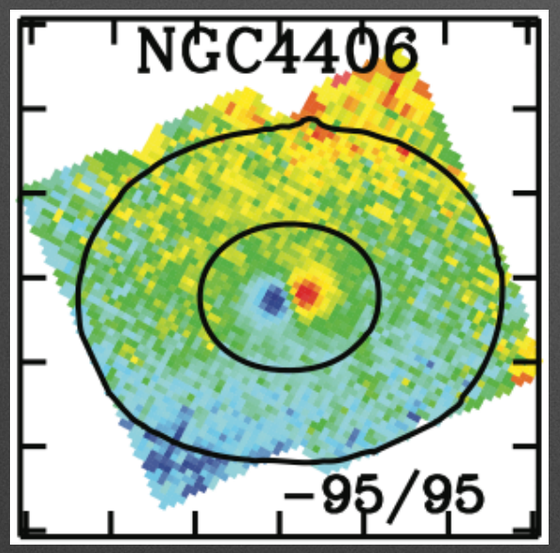
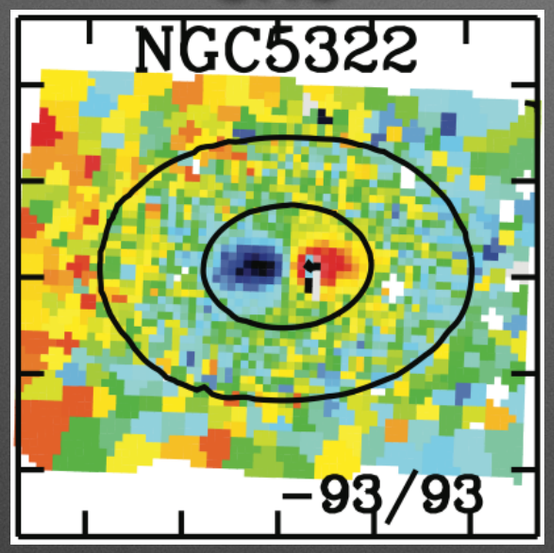
Different types of kinematic decoupling

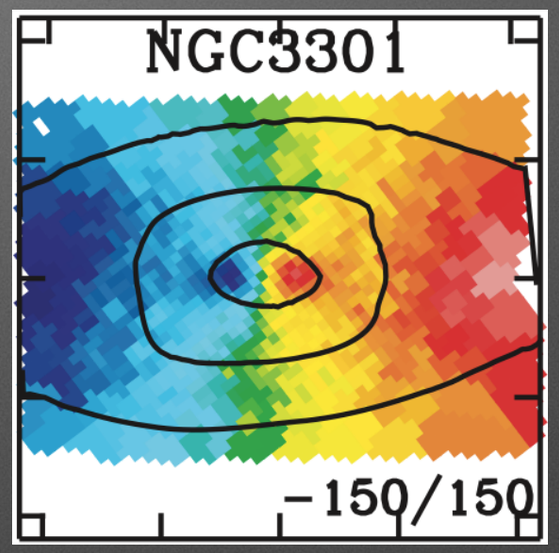
(classic) KDC



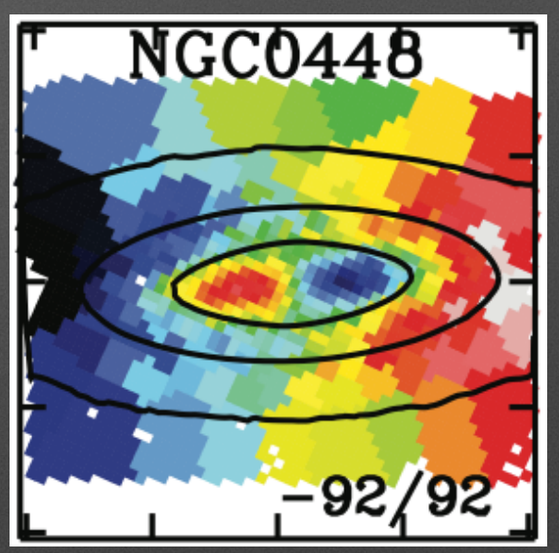
counter-rotating core
CRC

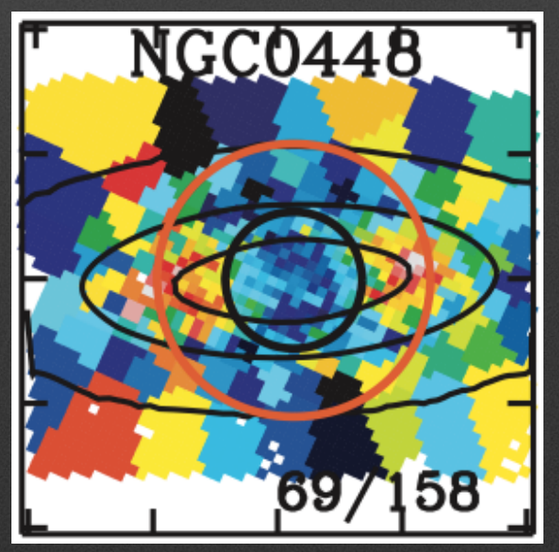


2M (2 maxima)



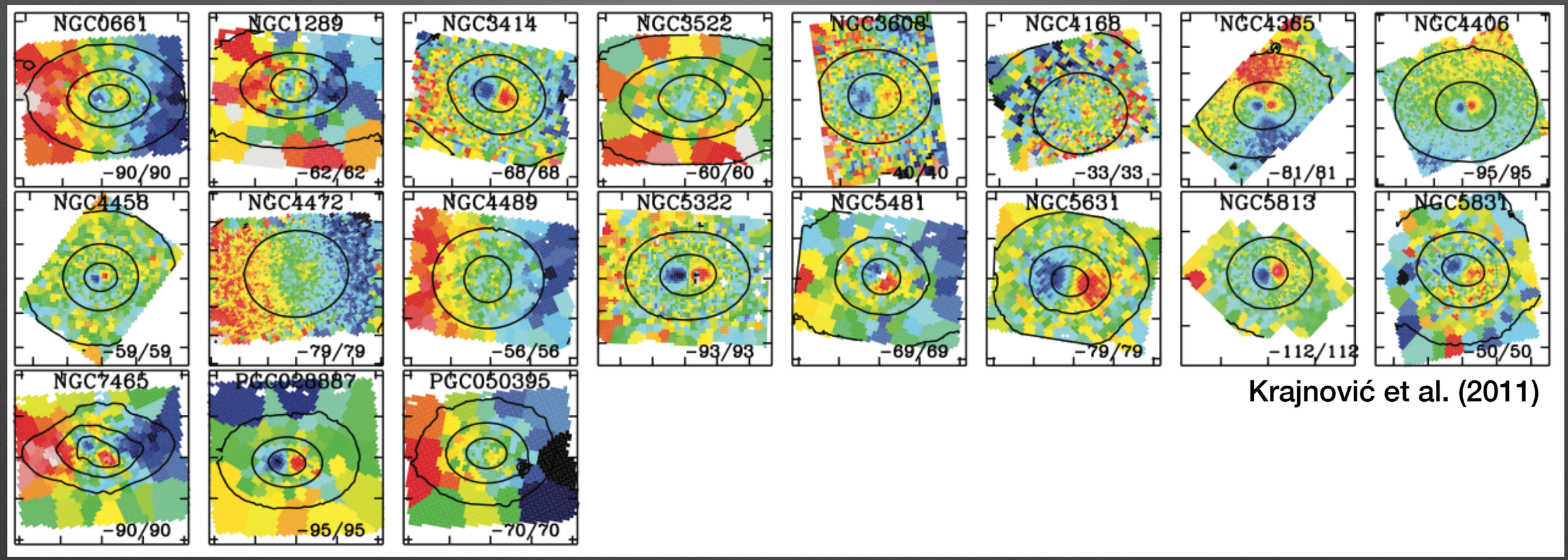
2σ -double σ peak





- a number of observed types of ‘decoupling’
- likely different internal structure
- not necessary of the same origin
- found in different types of ETGs

Large KDCs in early-types



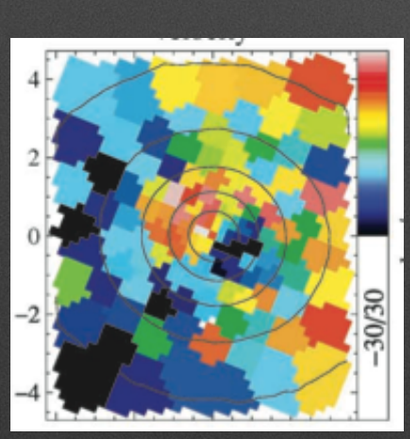
Krajnović et al. (2011)

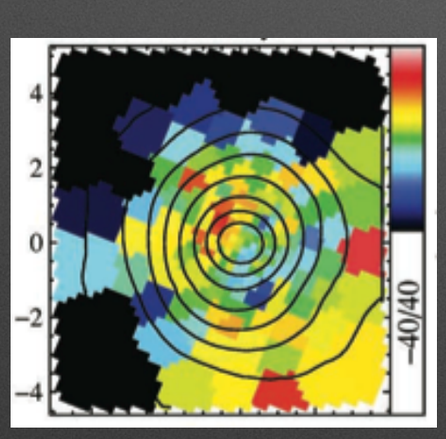
- Large (> 1 kpc in size)
- old, no special difference in stellar populations
- luminous & massive Slow Rotators

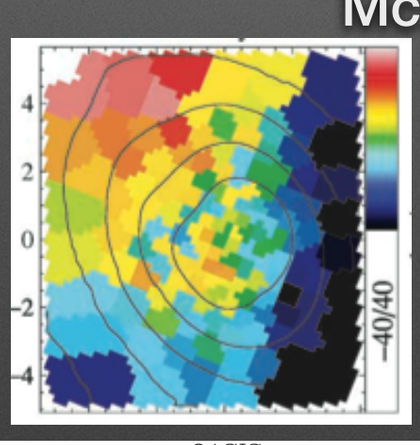
Small KDCs

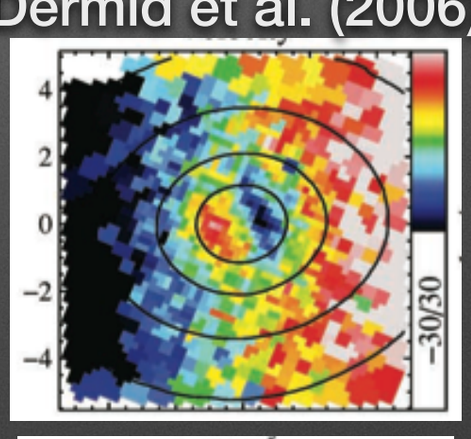
- Small (< 1 kpc in size)
- need high resolution IFUs (e.g. OASIS; McDermid et al. 2006)
- young
- typical (relatively massive) ETGs: fast rotators

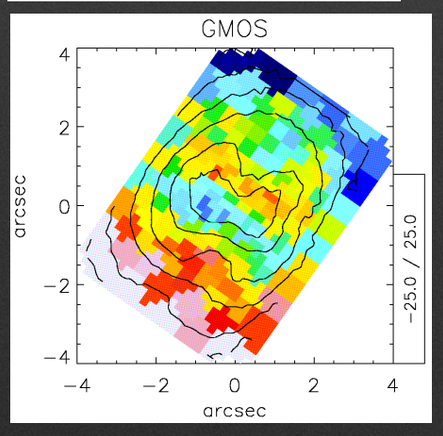
McDermid et al. (2006)

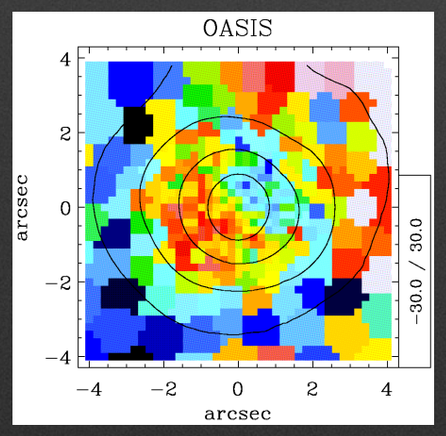


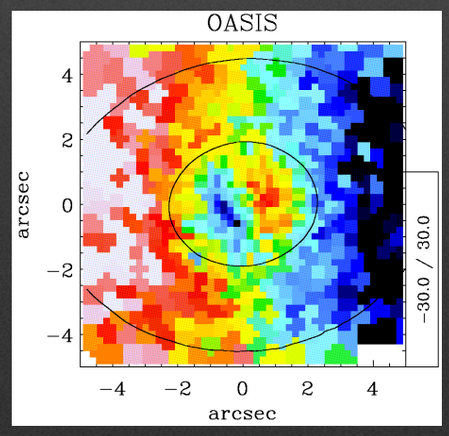


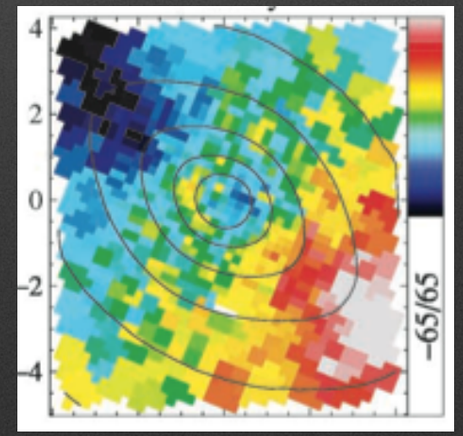


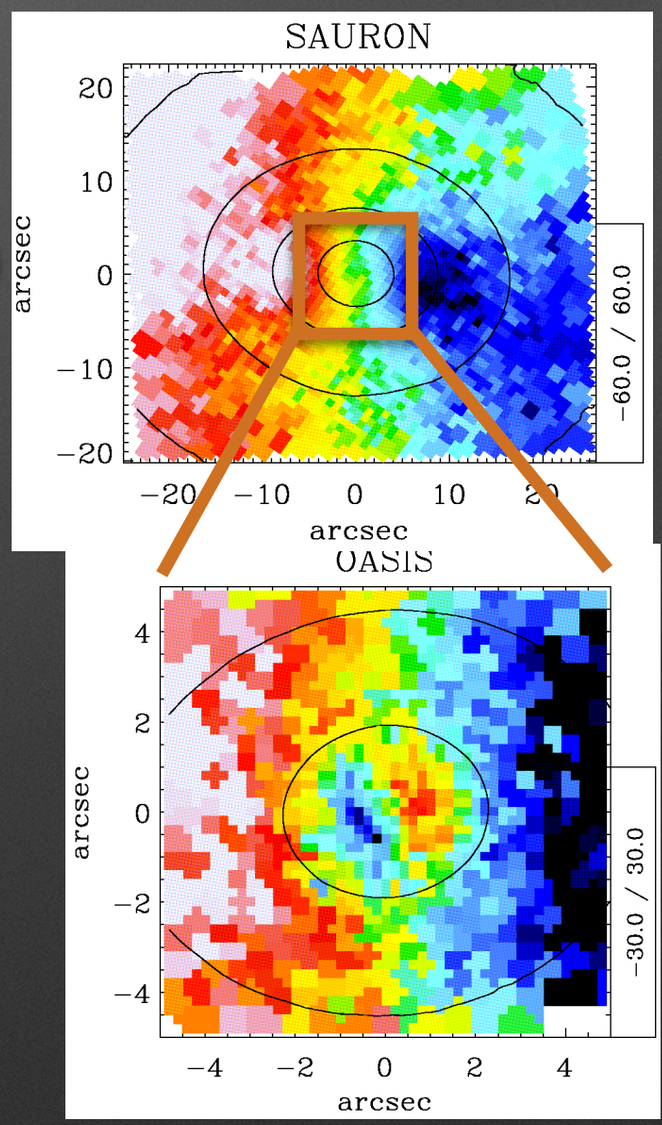






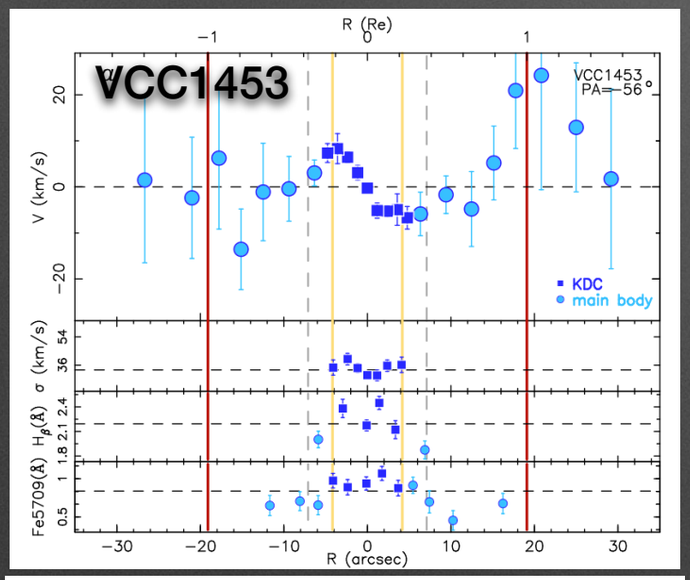


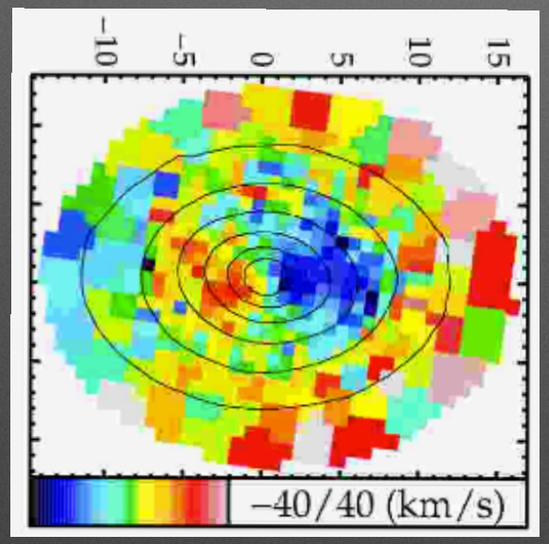




(Small) KDCs in dwarfs

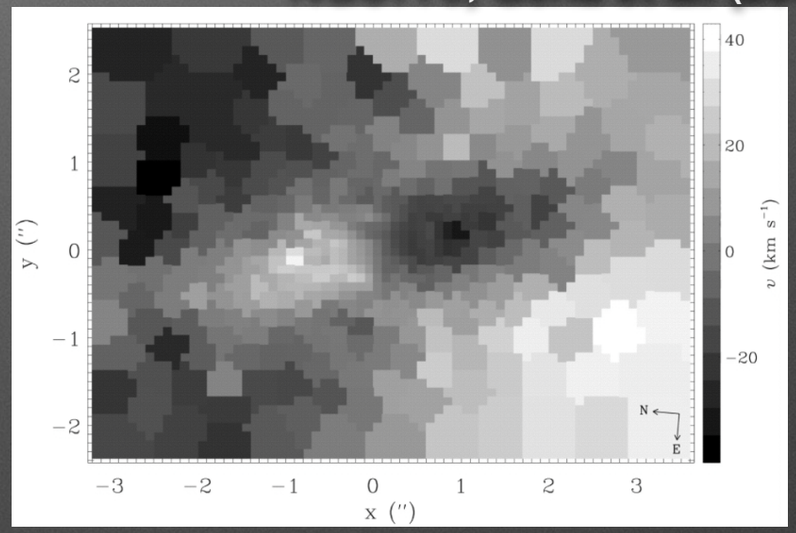
- KDCs in dwarf Ellipticals: Toloba et al. (2014), Geha et al. (2005), Koleva et al. (2011), Chilingarian et al. (2009), Rys et al. (2013), Guerou et al. (2015)

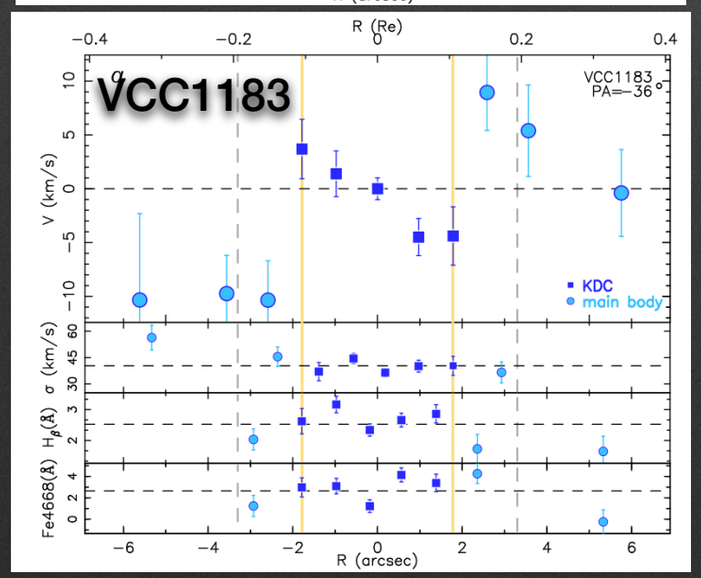




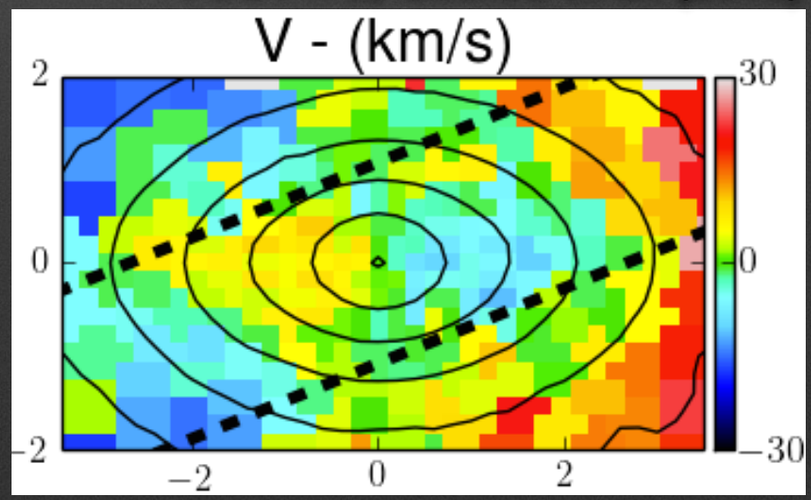
Rys et al. (2013), ID0918

NGC770; Geha et al. (2005)



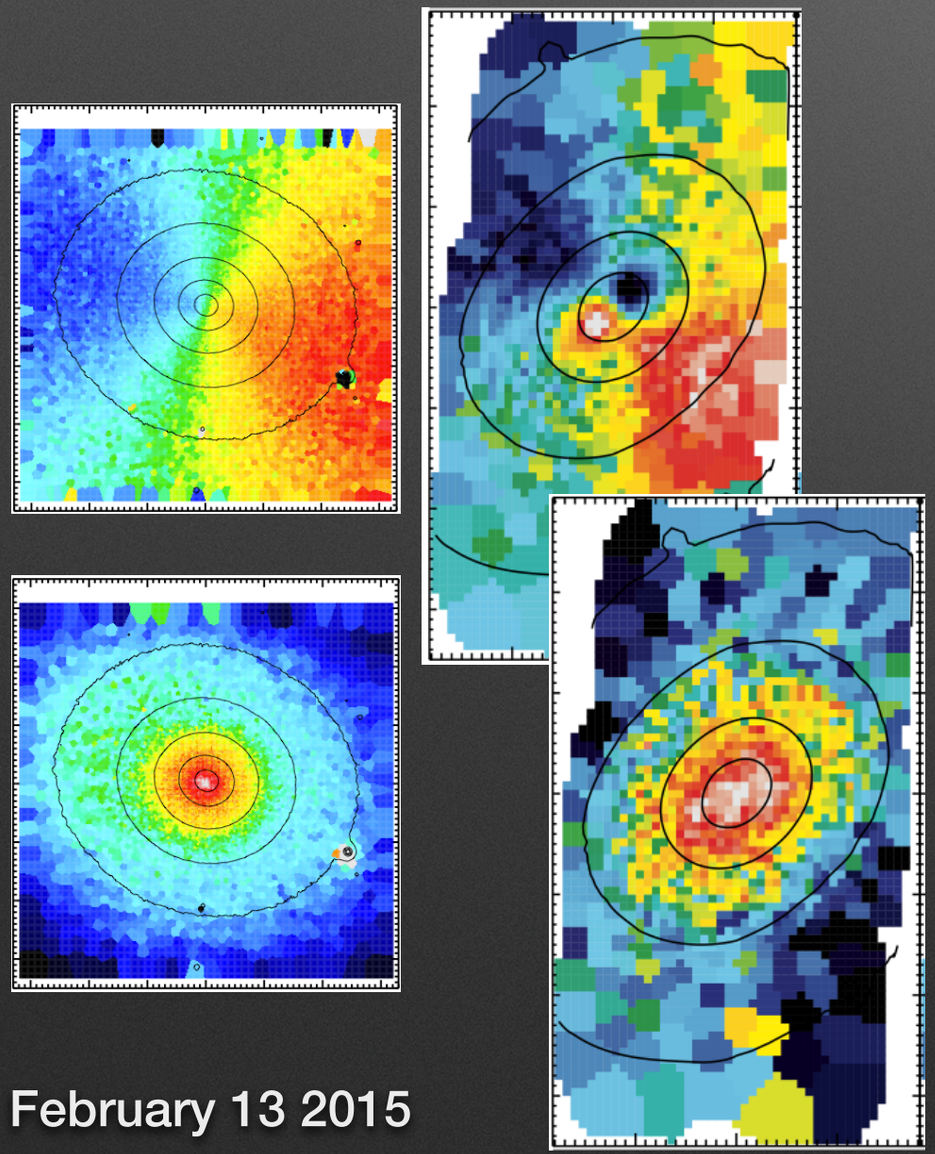


VCC1475; Guerou et al. (2015)

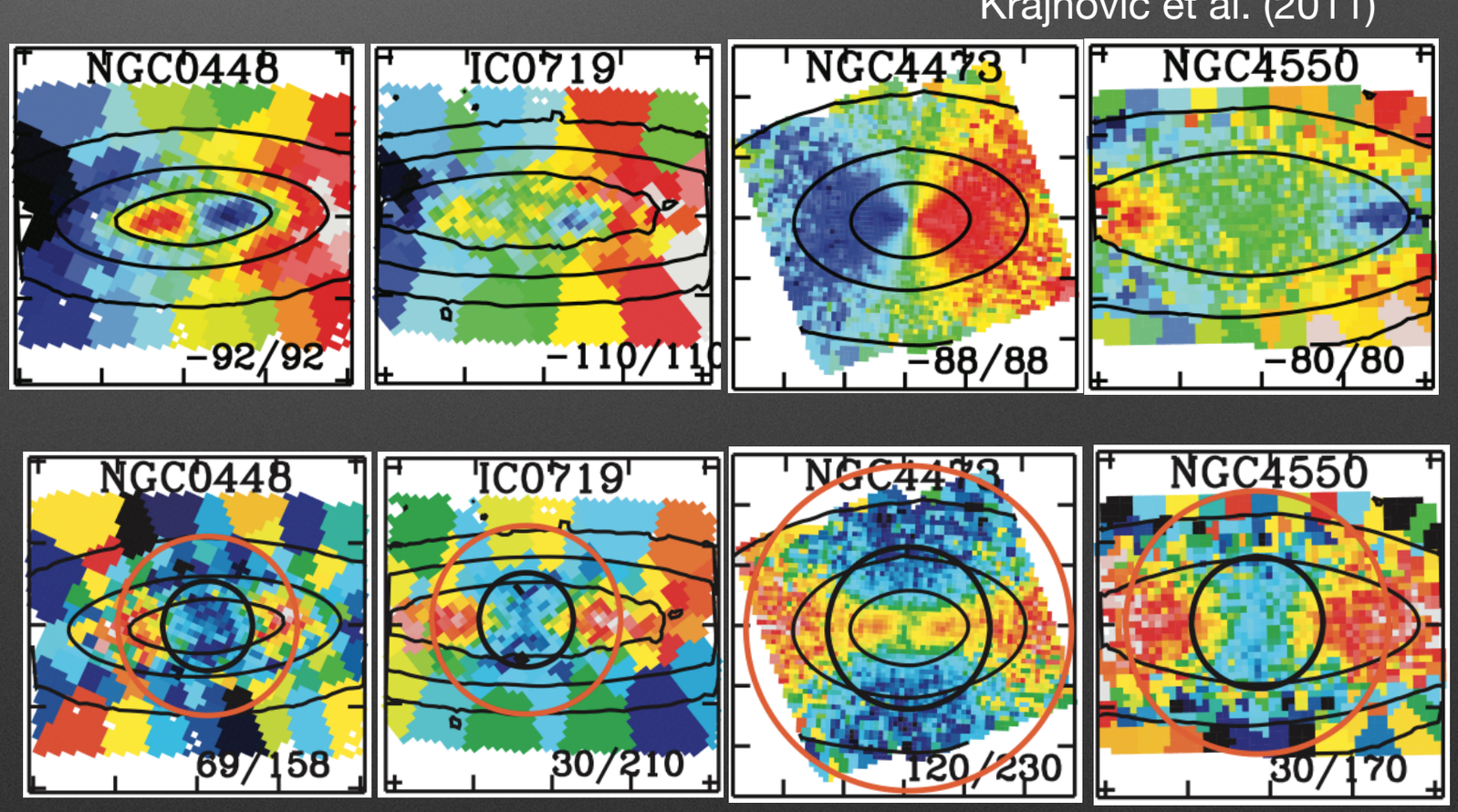


2σ - Counter-rotation

- Specific signature in the velocity dispersion - 2 peaks along the major axis
- 4% of ETG —> until now only in flat(-ish) (edge-on) Fast Rotators

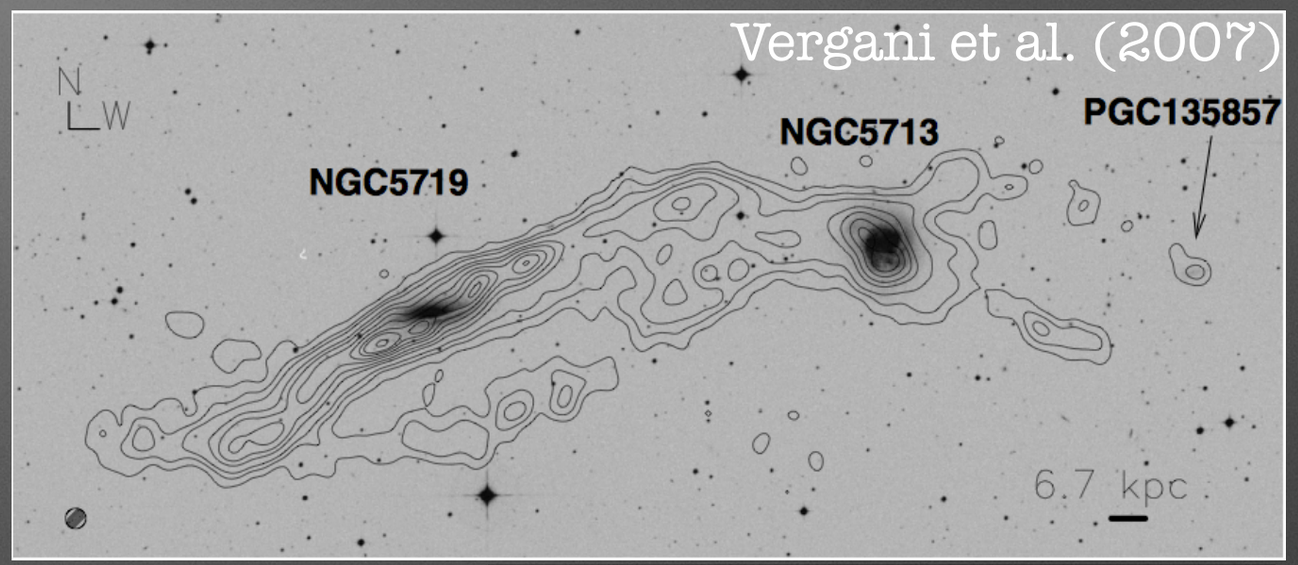


Krajnović et al. (2011)

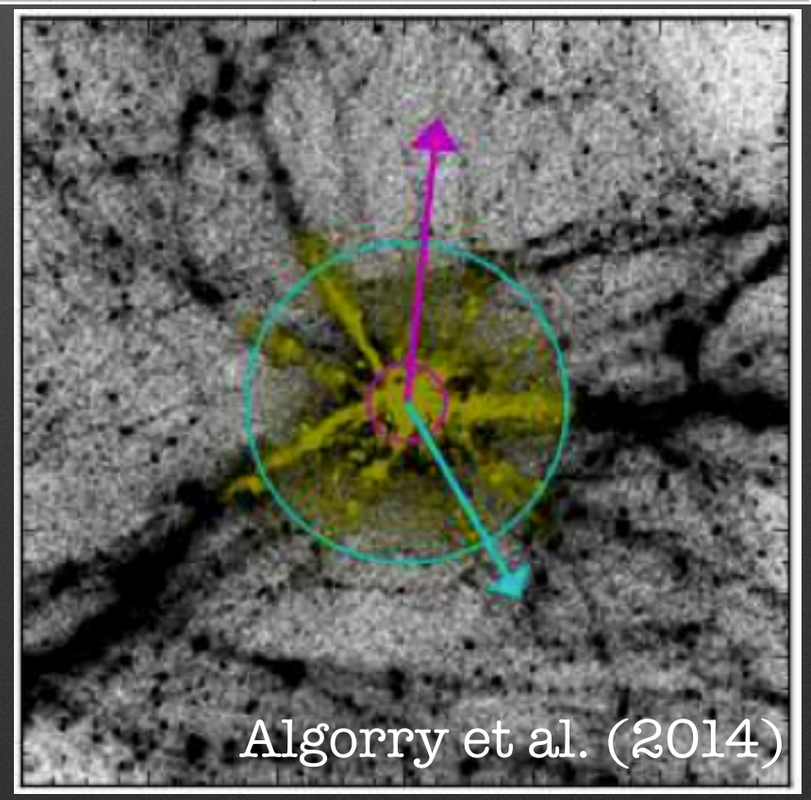


2σ - Counter-rotation

- 2σ peaks explained as counter-rotating **disc** (e.g. NGC4550; Rubin et al. 1992, Rix et al. 1992)
- or counter-rotating fast rotating structures (Cappellari et al. 2007)
- origin:
  - merger of two discs with opposite orbital spins (e.g. Bois et al. 2011)
  - capture of gas (e.g. Coccato et al. 2011)
  - intersection of cold streams (Algorry et al. 2014)



Vergani et al. (2007)


Algorry et al. (2014)

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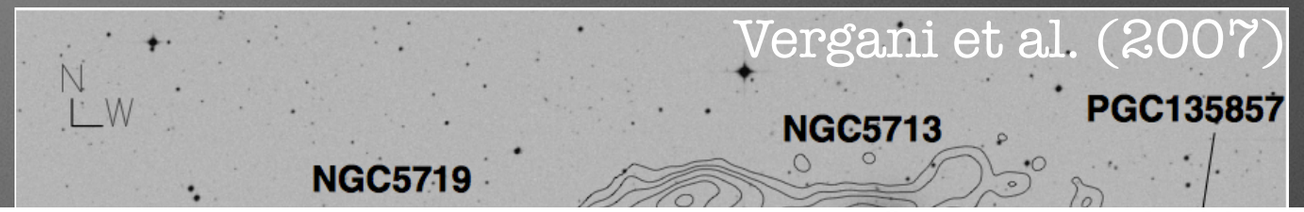

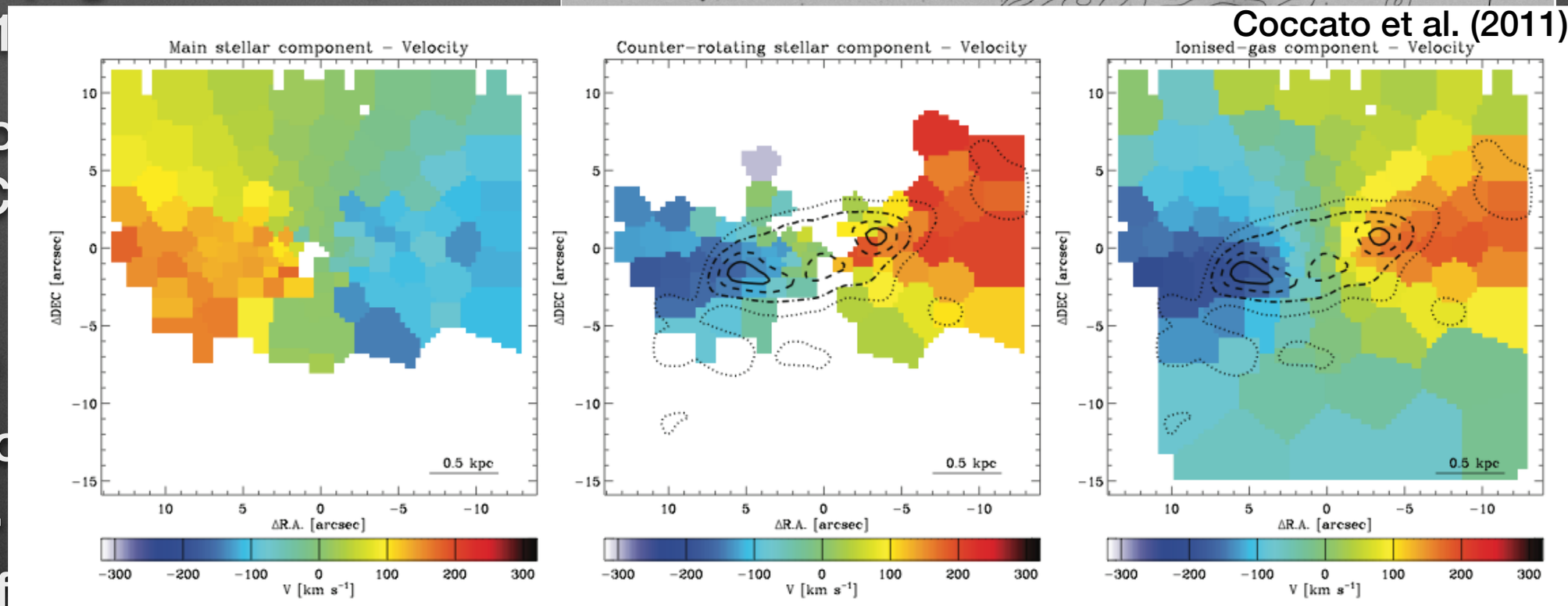

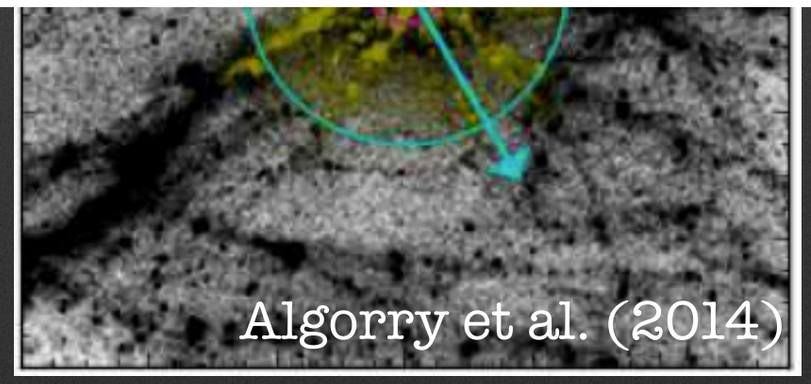

Stellar populations

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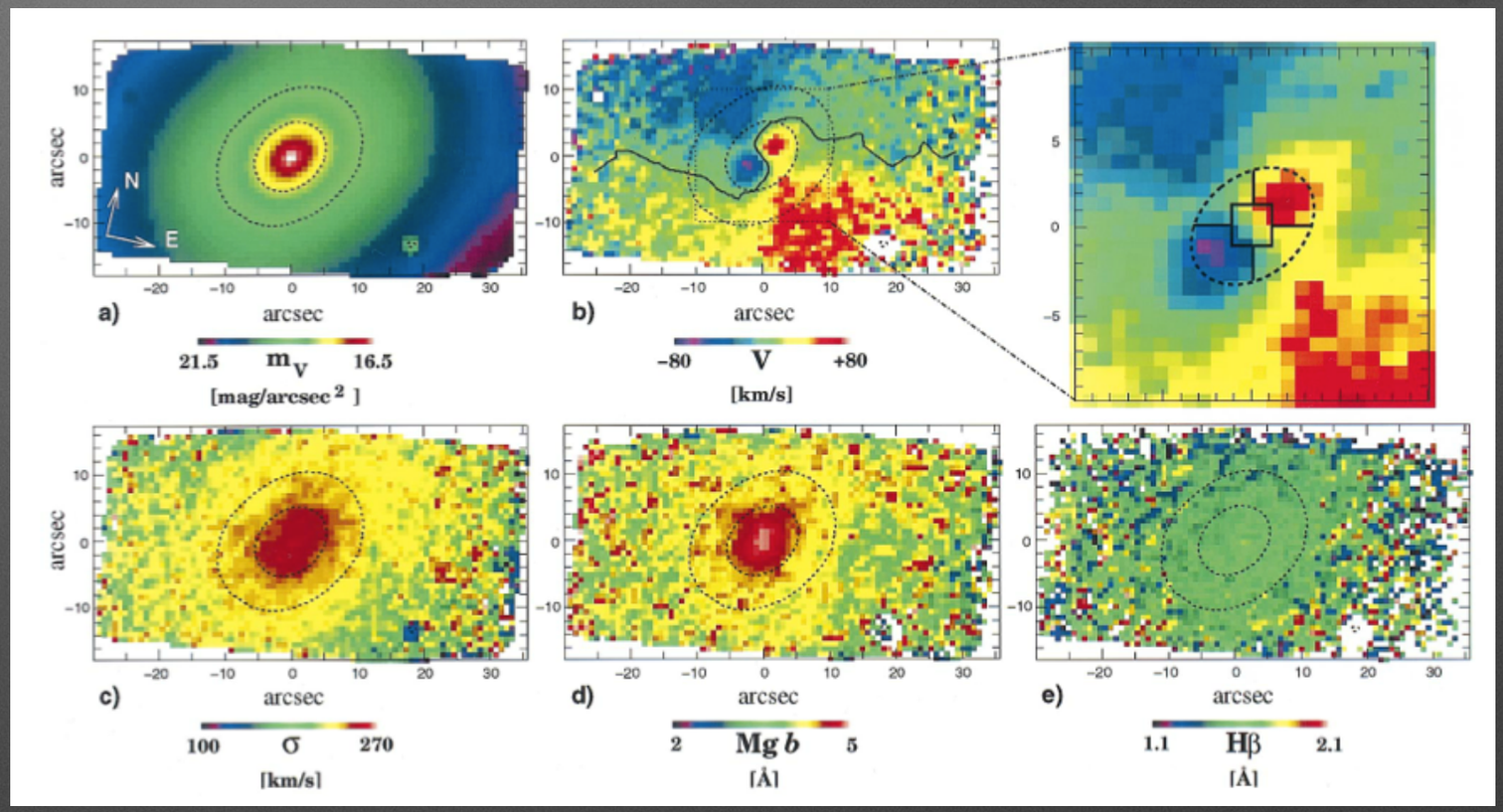
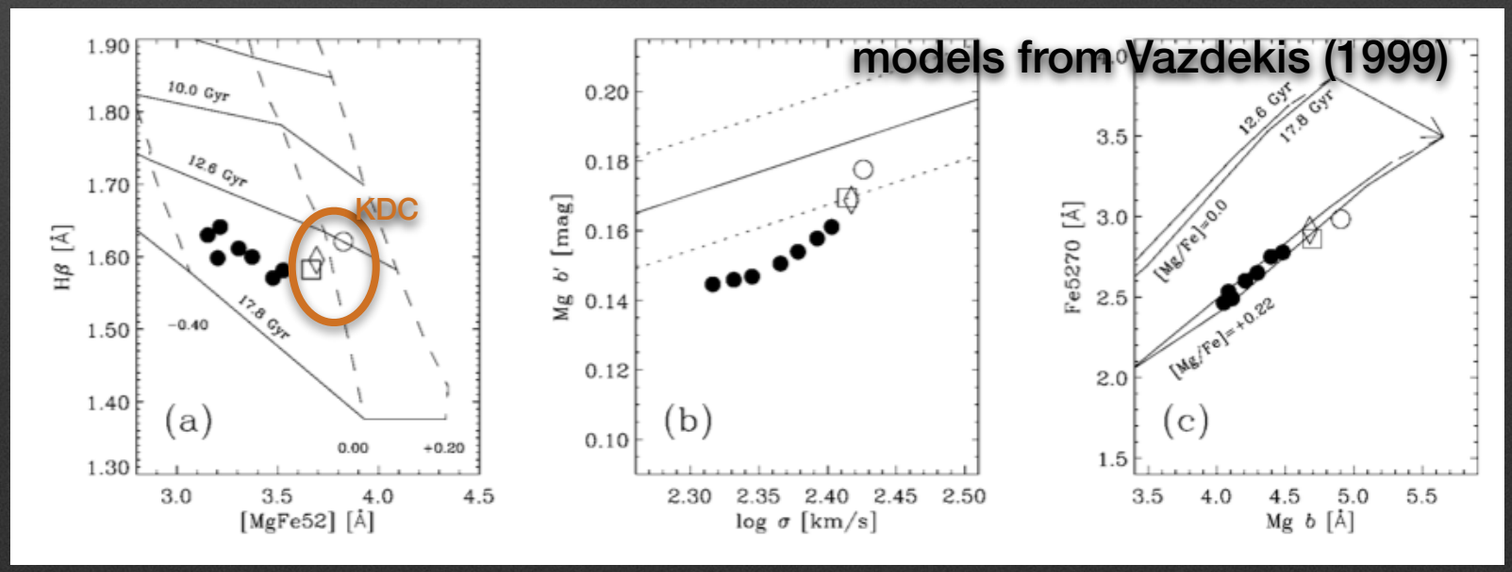
Stellar populations

- stars in KDCs formed at early time (>10Gyr)
- no significant (if any) difference between the KDCs and the rest of galaxies
- no clear evidence for recent merging
- found in (almost) all large scale KDCs (Franx et al. 1988, Davies et al. 2001, Kuntschner et al. 2006)

NGC4365; Davies et al. (2001)



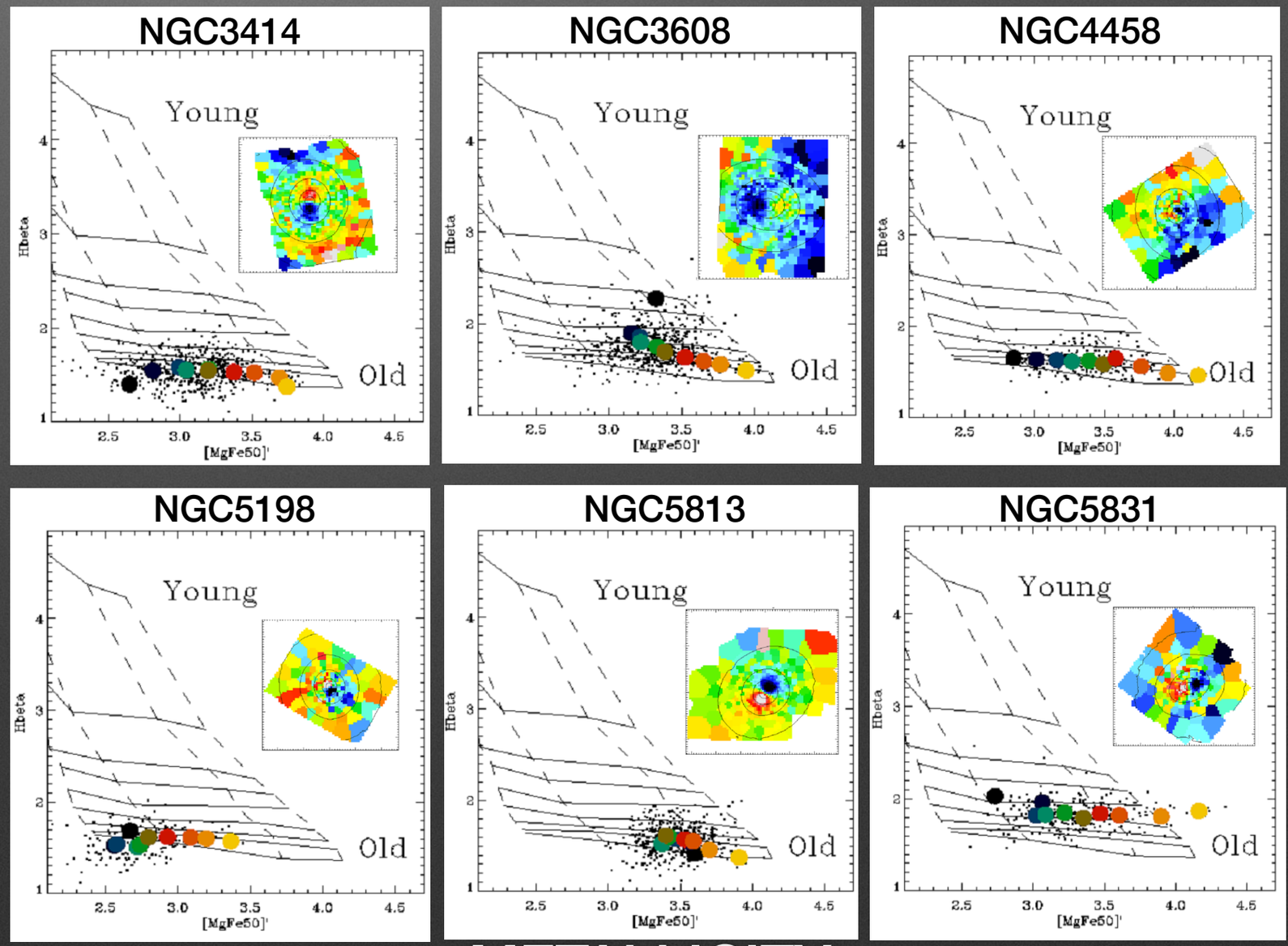


Stellar populations of large KDC galaxies

- SAURON sample (representative, not complete - there could be counter-examples)
- (all) KDCs are old
- metellicity increases towards the centre
- no age gradient (almost)

Radius →

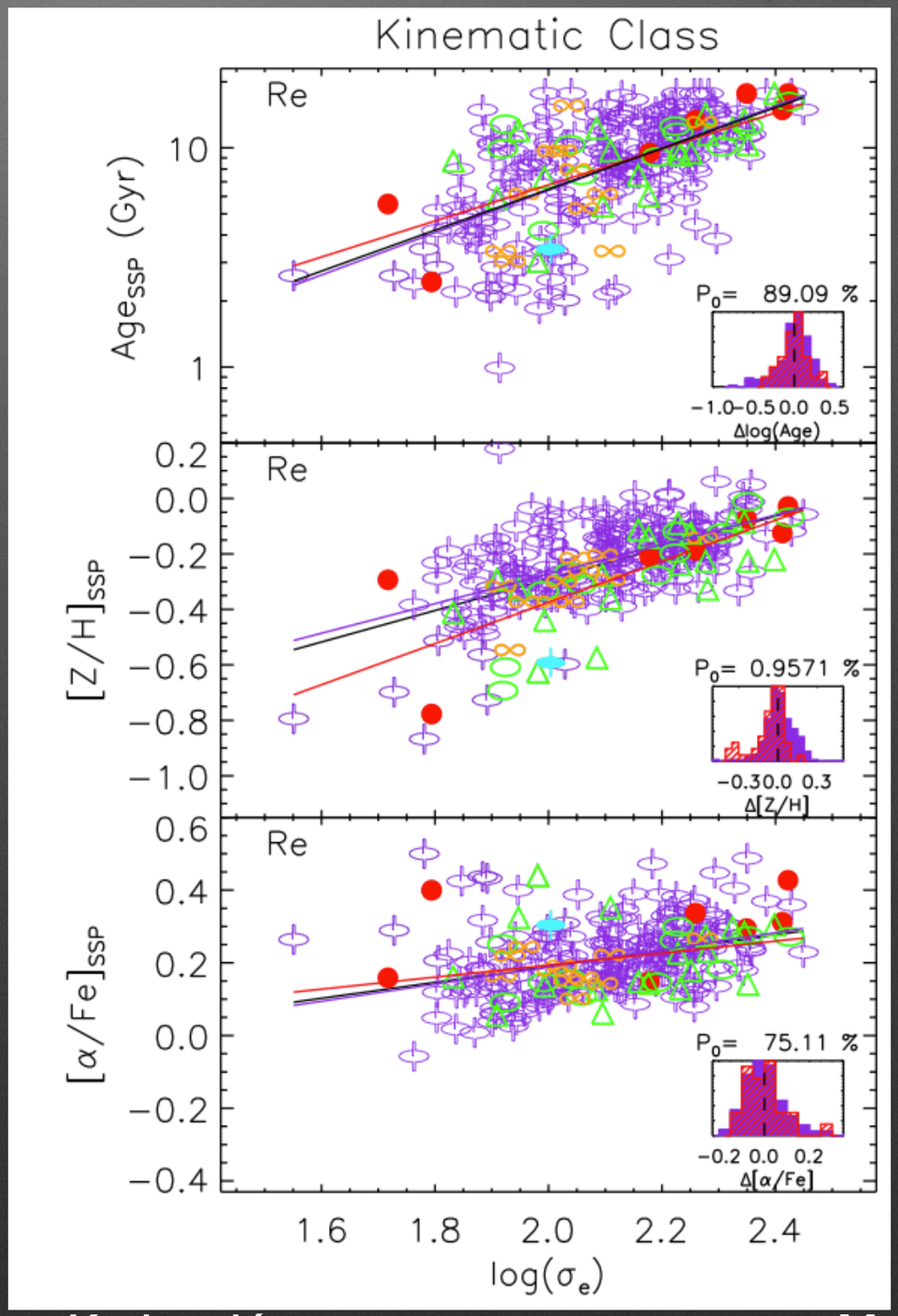
Kuntschner et al. (2006)



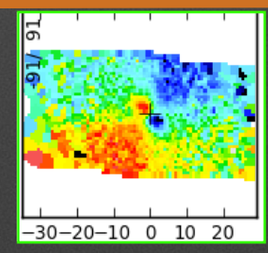
Stellar populations of large KDC galaxies

- Stellar populations are similar to other ETG of the same mass
  - Age, metallicity, abundance
- both for apertures and for gradients
- confirms other studies, but there are a some exceptions

McDermid et al. (2015)



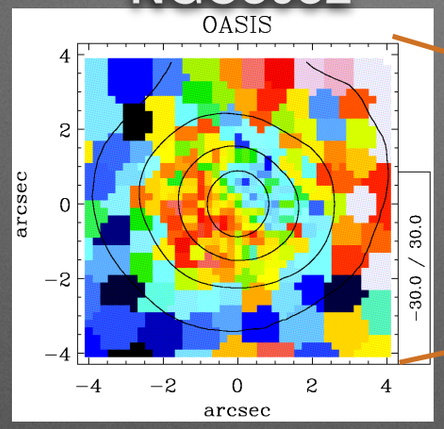
KDC



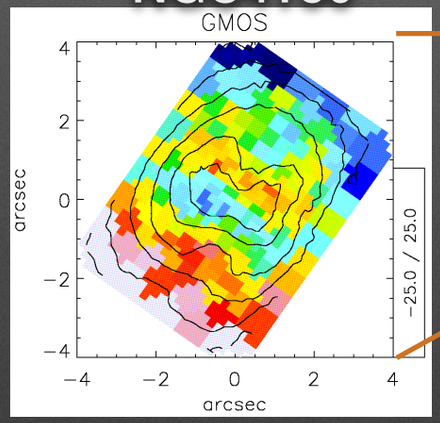
Stellar populations of small KDCs

- ETGs with young course often harbour small KDCs
- high spatial resolution necessary
- recent accretion of gas or (minor) dissipative mergers
- KDCs in dEs show same trend: young and metal rich (Toloba et al. 2014)

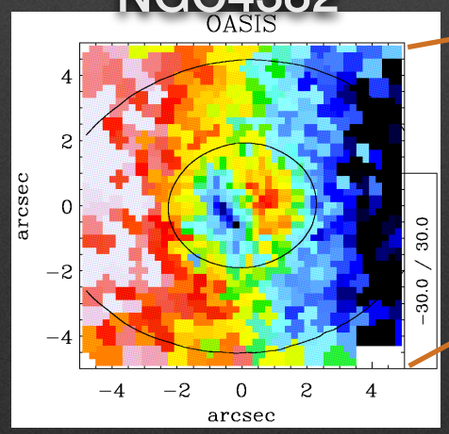
NGC3032



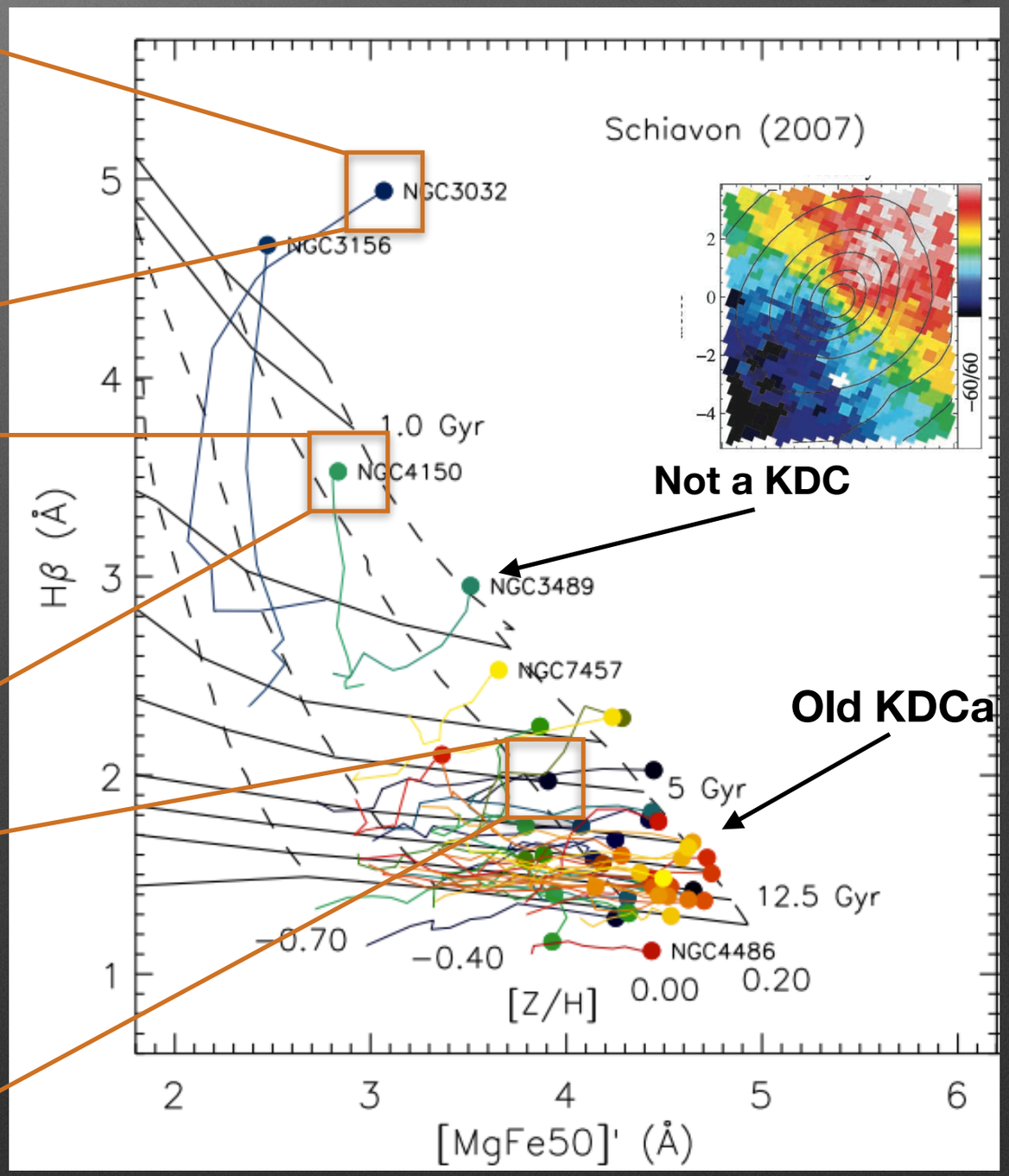
NGC4150



NGC4382



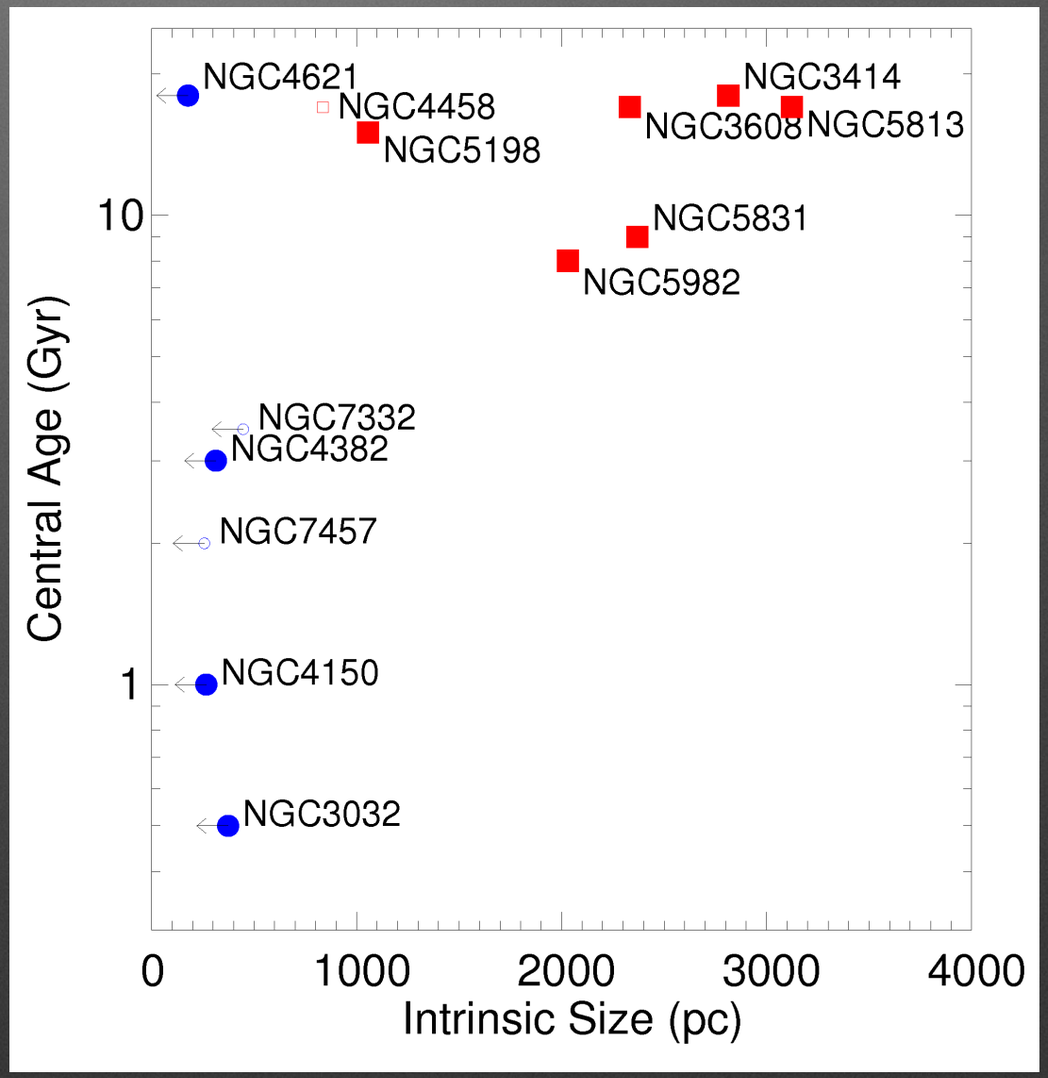
McDermid et al. (2006)



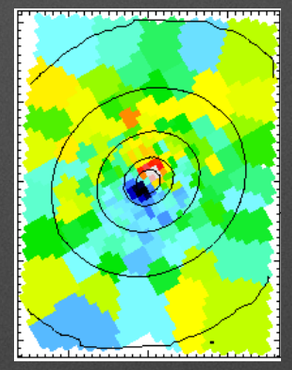
Dissipative mergers/accretion at work

McDermid et al. (2006)

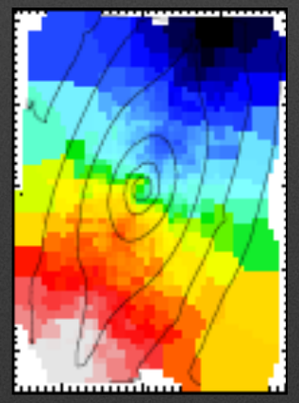
- Small KDCs in Fast Rotators - young
- Large KDCs in SLOW rotators - old
- Two different formation scenarios for KDC in FR and SR (dwarfs?)
- small KDC formation scenario:
  - KDC grows via SF (inside)
  - evidence of accretion or minor wet merger



Slow Rotator



Fast Rotator



Stability of KDC

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Stability of KDCs

- How stable are KDCs?
- Large scale KDCs (in Slow Rotators) — made of old stars —> stable over long periods (e.g. Davies et al. 2001)
- Slow Rotators often show signatures of triaxiality (photometric twists, misalignments between photometry and kinematics)
- Slow Rotators (and KDCs!) have complex internal orbital structure
- what about small KDCs, found in Fast Rotators?
  - in axisymmetric bodies
  - almost always (near to) counter-rotating (McDermid et al. 2006)

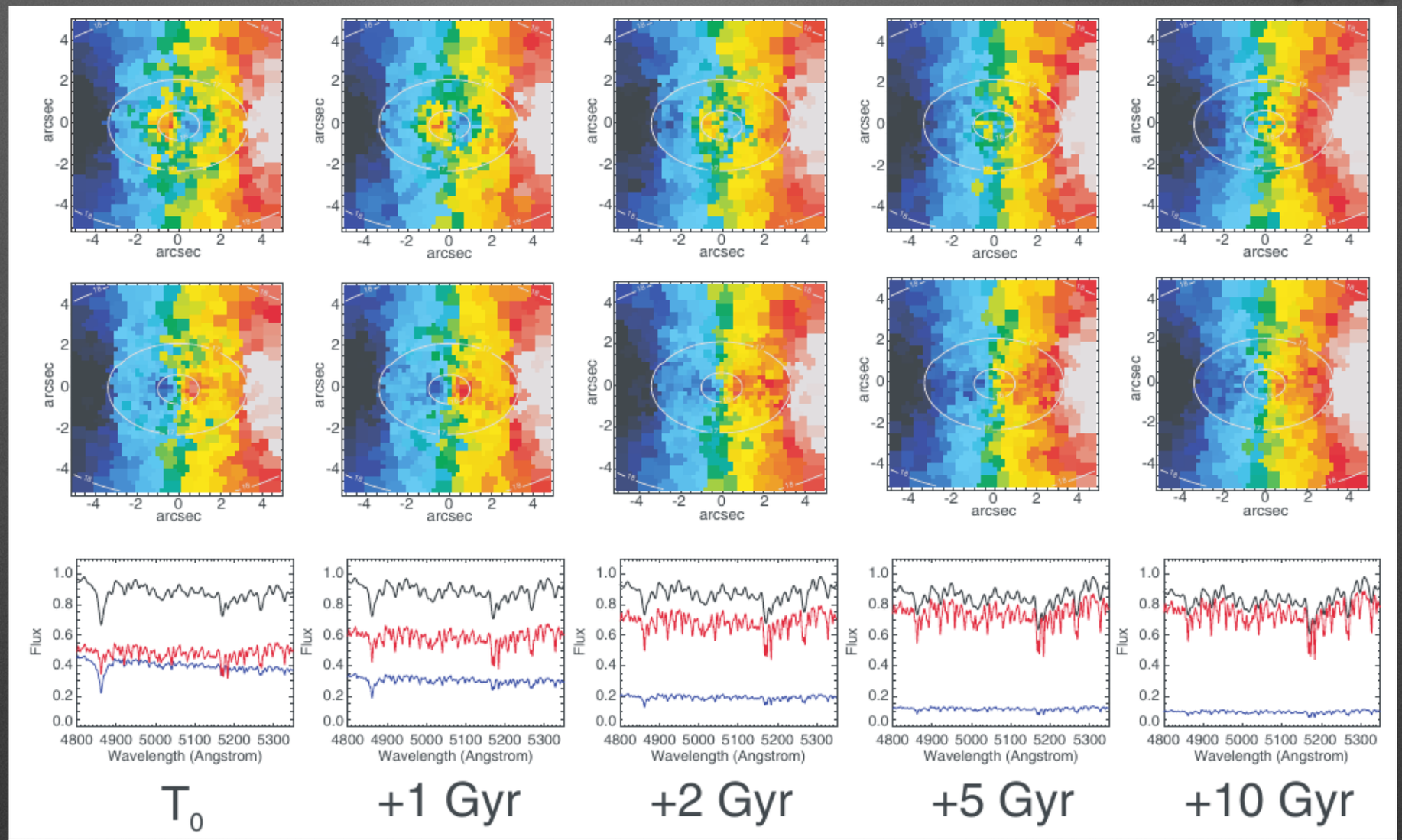
What happens to small KDCs?

McDermid et al. (2006)

KDC
(counter-rotating)

co-rotating

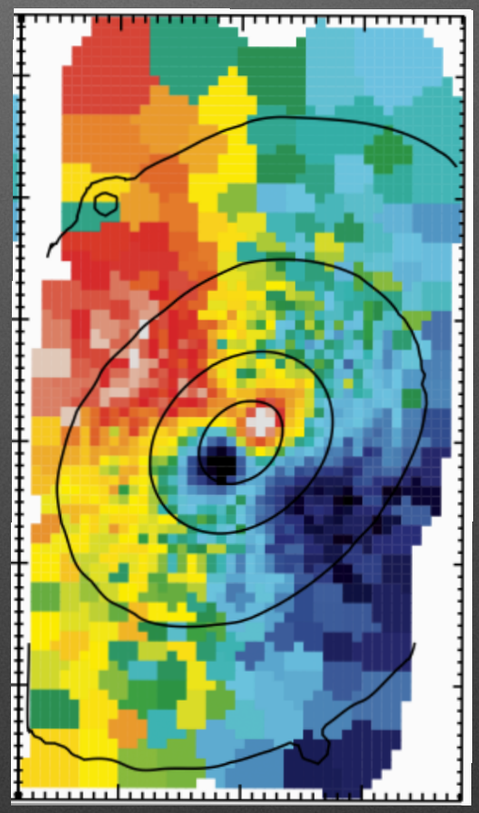
luminosity-weighted contribution of the two components

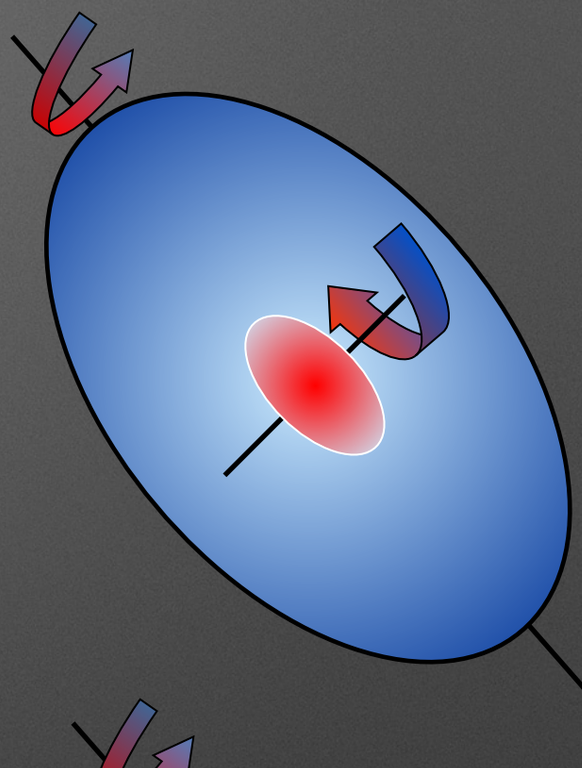


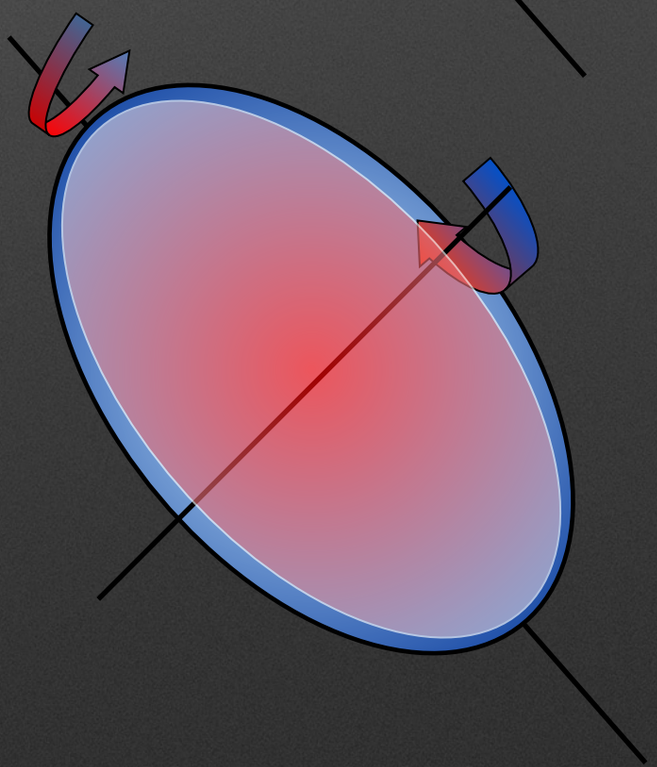
- apparent disappearance of the evolving young counter-rotating population in a larger old body (they are still there!)
- no dynamical reason for the KDC to disappear - just fading population of small total mass

Is kinematic decoupling real?

- is KDC apparent or intrinsic?
- are the two components physically separated or co-spatial?
- KDC as a result of luminosity averaging of sub-components
- influence on the formation scenarios







Orbital structure of KDCs

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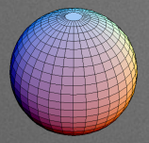
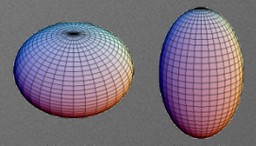
Orbital structure

Point-like

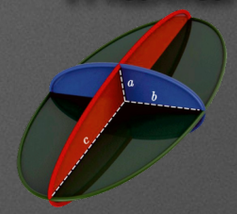
Spherical

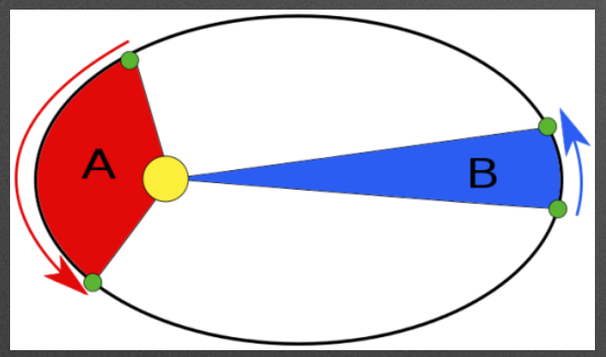


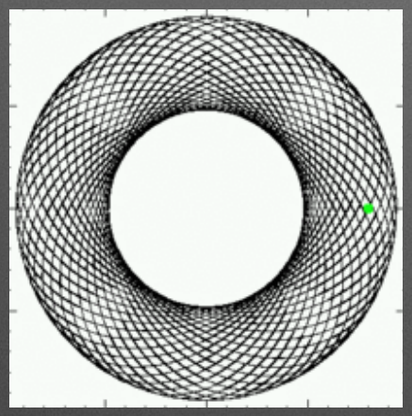
Axisymmetric

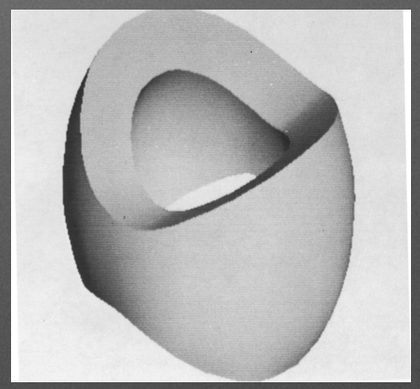


Triaxial

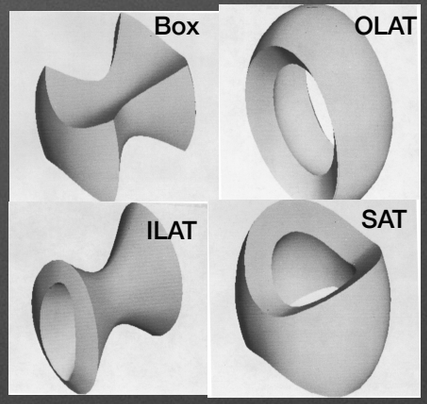








Statler (1987)



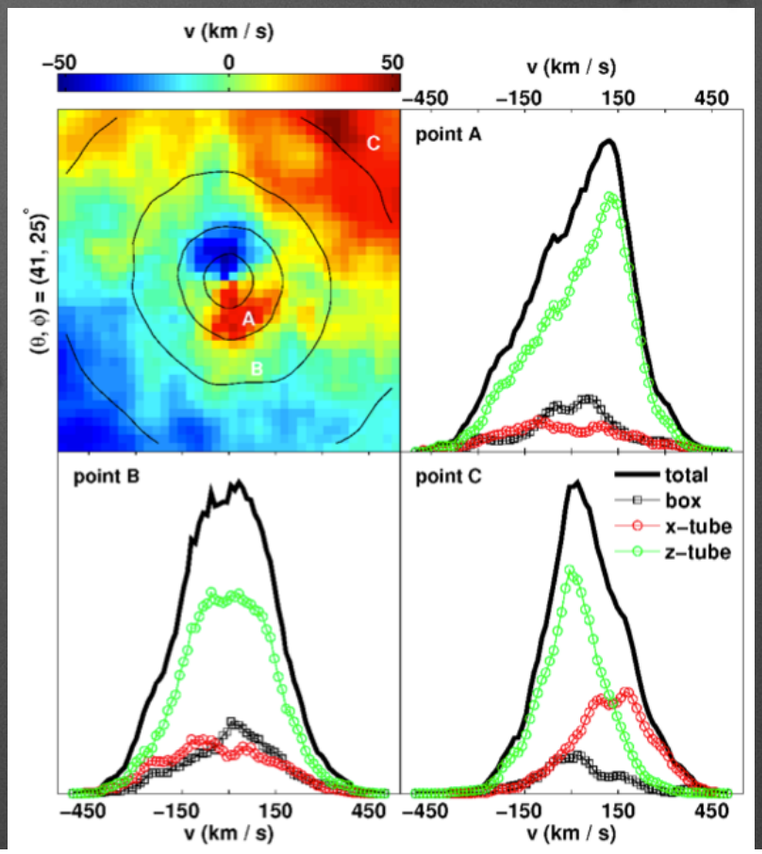
Statler (1987)

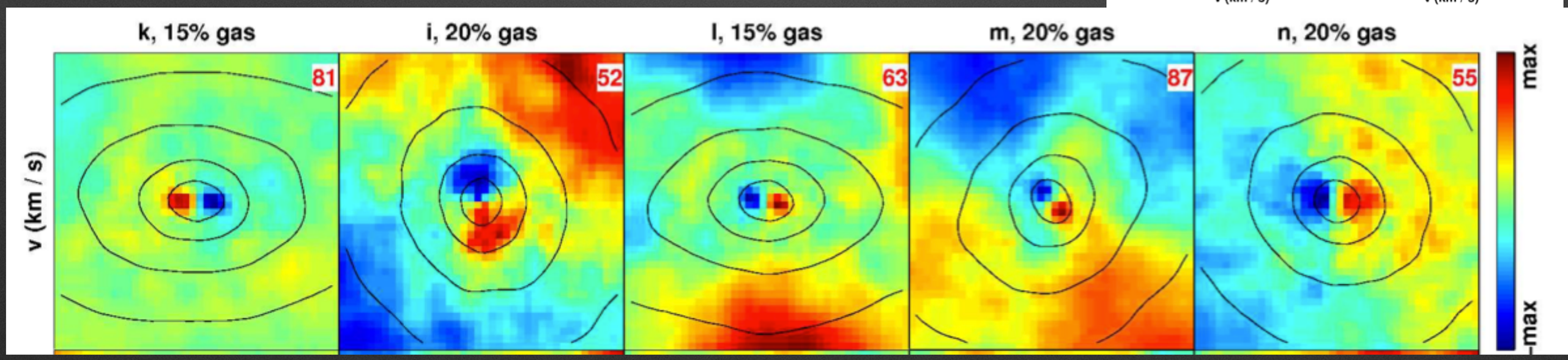
- simple orbits in simple potentials
- axisymmetric: 1 major orbital family: short axis tubes (of opposite angular momtum)
- triaxial: 3 major orbital families: short and long axis tubes and box orbits (no angular momentum) (e.g. de Zeeuw 1984)

Simulating KDC

- Not easy to make KDCs in simulations; high resolutions needed (e.g. Bois et al. 2010, Hoffmann et al. 2010)
- importance of dissipative mergers (KDCs in 1:1 mergers with 15-20% gas)
- dry mergers —> box orbits dominate cores
- wet mergers —> increasing importance of short axis tubes

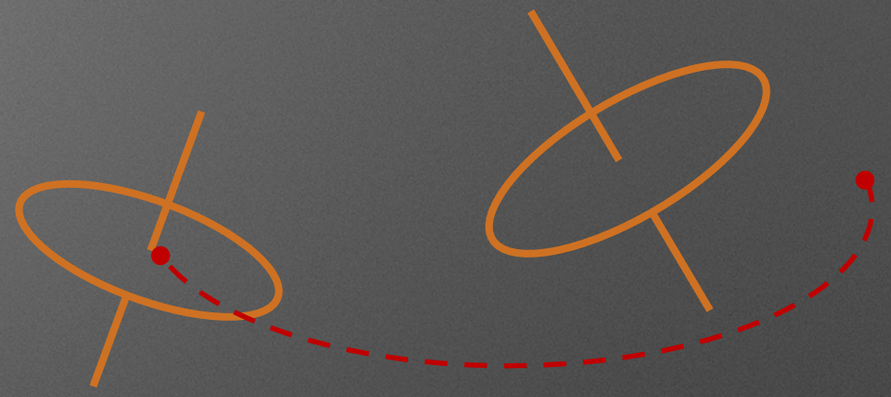
Hoffman et al. (2010)



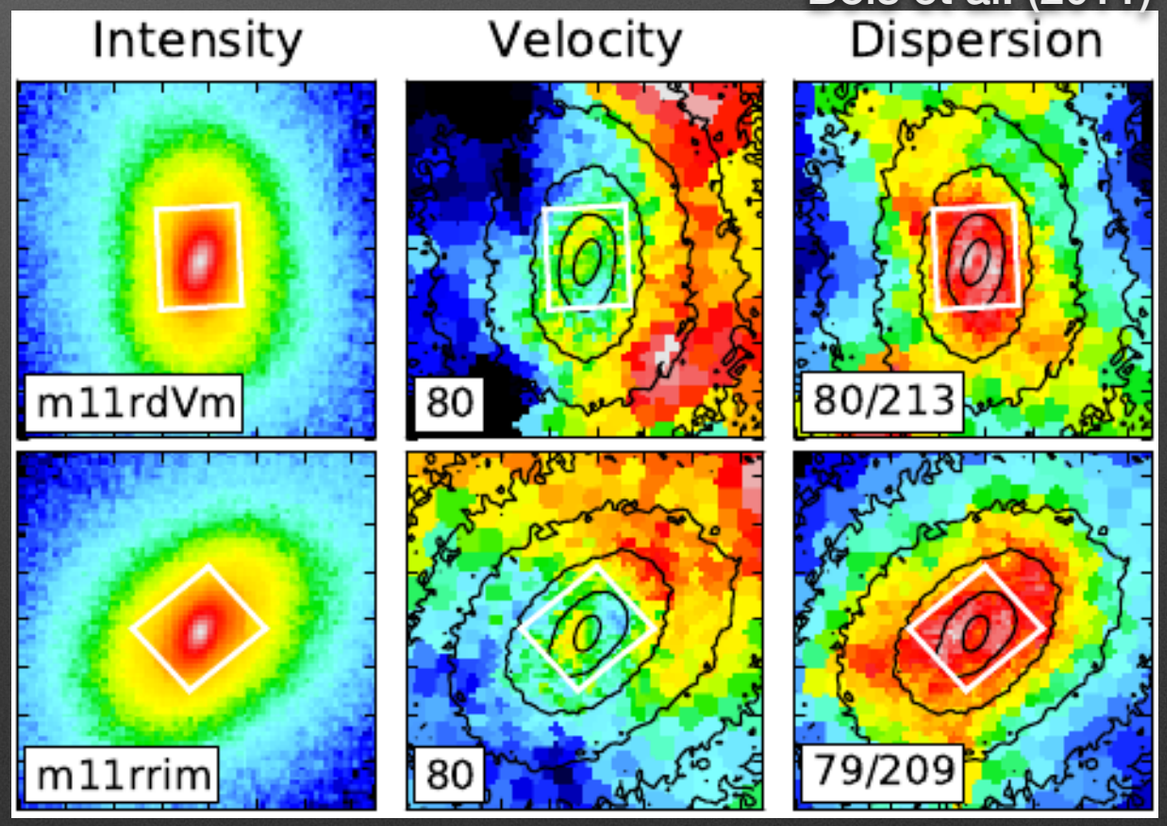


Simulating KDC - orbital structure

- slow rotators produced in major mergers often have KDC (Bois et al. 2011)
- 2σ structures (counter-rotating discs) found in both slow and fast rotators
- slow rotators not realistic: too flat

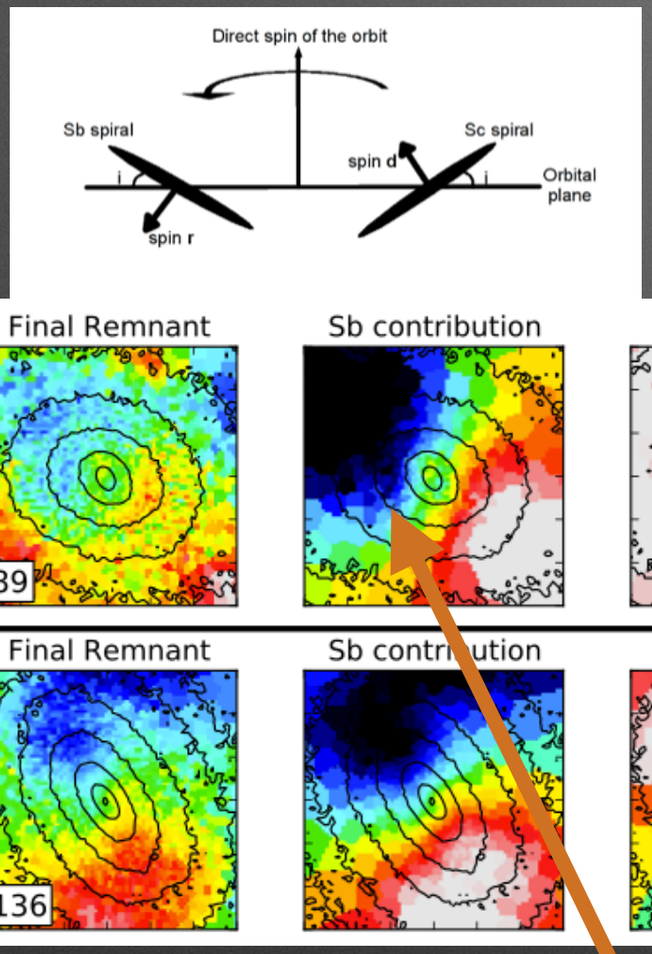


Bois et al. (2011)

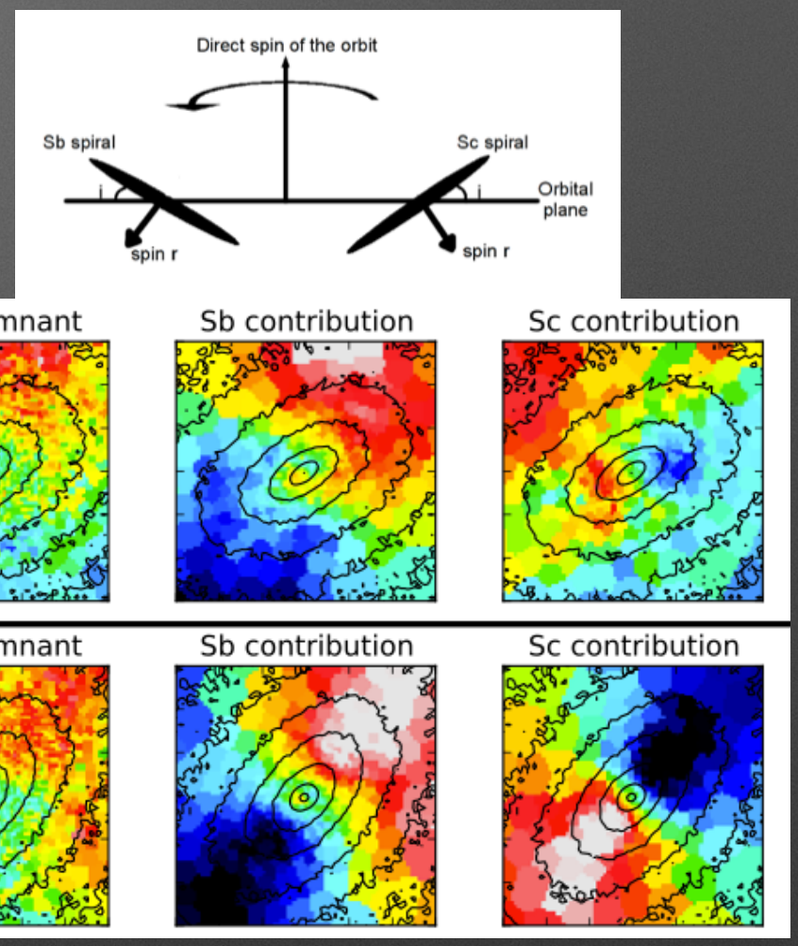


Orbital momentum shapes kinematic structure

Bois et al. (2010)



Bois et al. (2010)

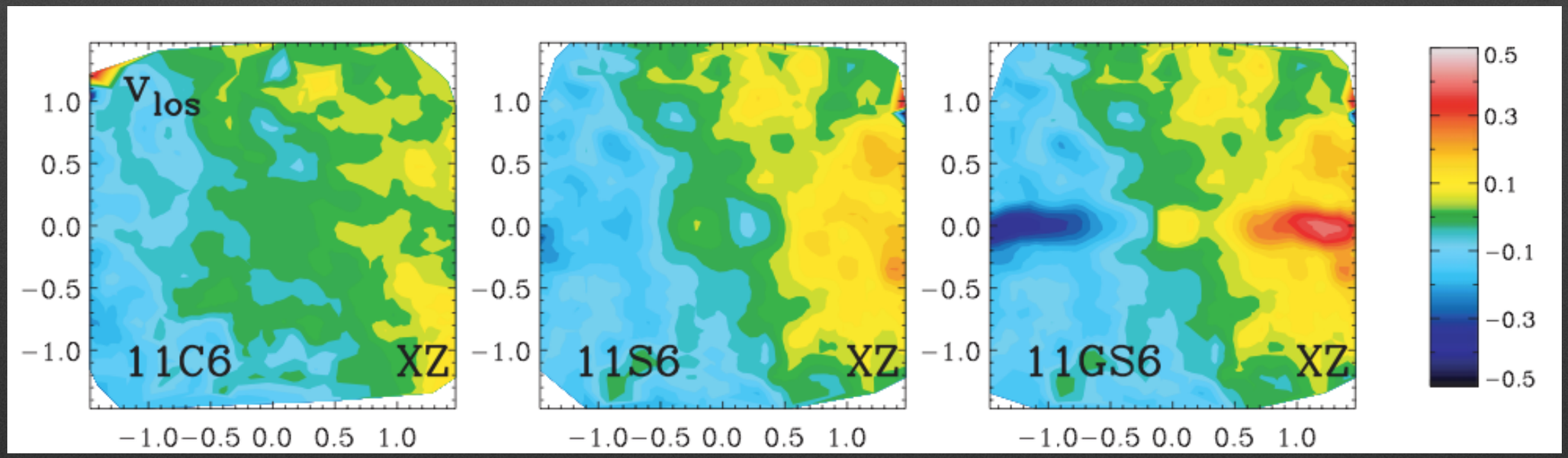


- two types of KDCs produced
  - 1) counter-rotating stellar systems - no real decoupling: KDCs is a luminosity-weighted average of overlapping orbits
  - 2) KDC made of decoupled components where orbital spins are in opposite directions

KDCs in Cosmo simulations

- not easy to produce; 1st KDC from cosmo simulations: Naab et al. (2007)
- found in slow rotators (as CRC)
- dissipative major (1:1) mergers (that create slow rotators)

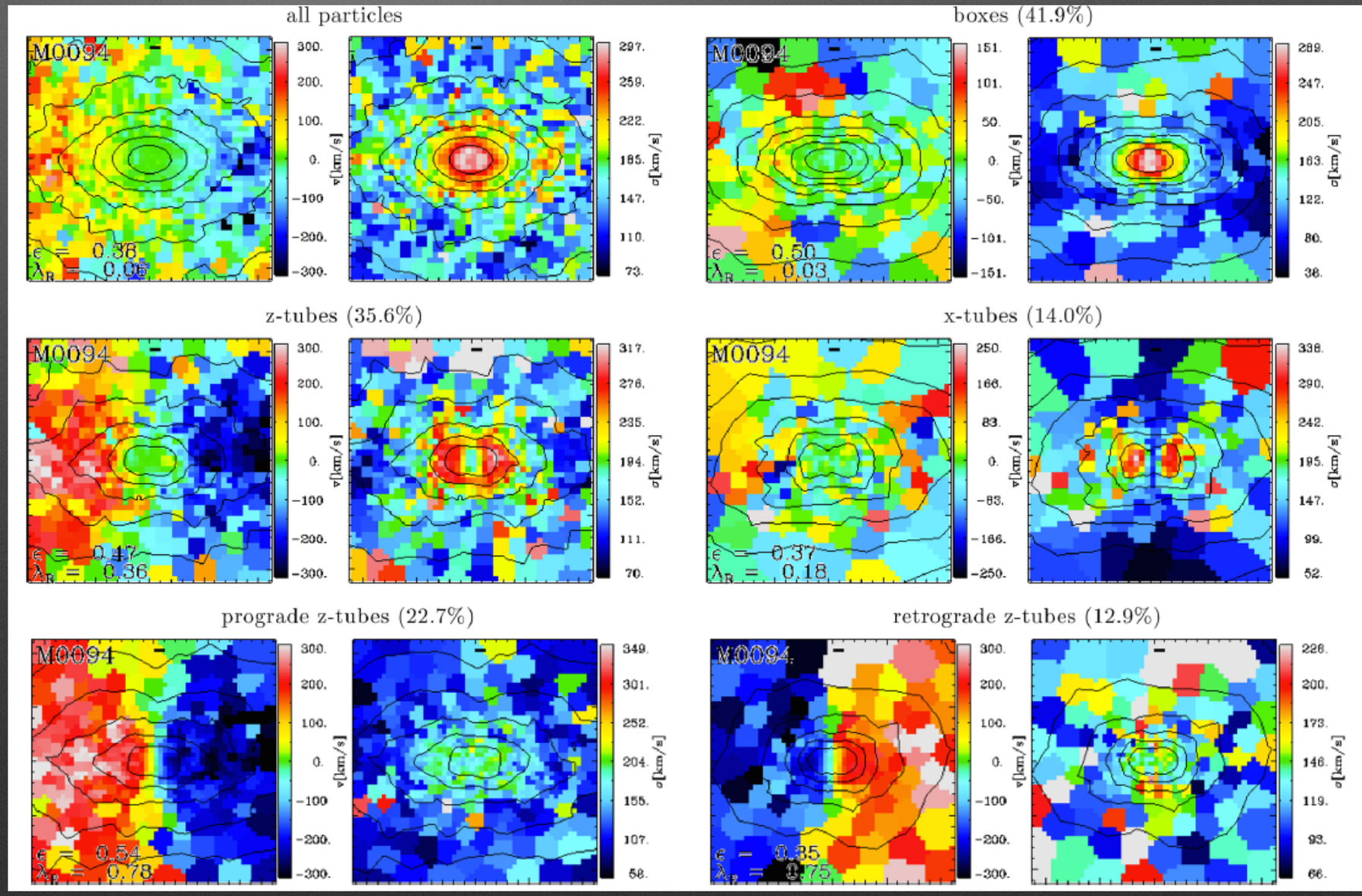
Jesseit et al. (2007)



Structure of KDCs (simulations)

- complex orbital structure
- rotation dominated by short-axis tubes (prograde and retrograde)
- overall kinematics by box orbits (no net angular momentum)
- triaxial body
- KDC is an ‘orbital composite’

Röttgers et al. (2014); Naab et al. (2014)



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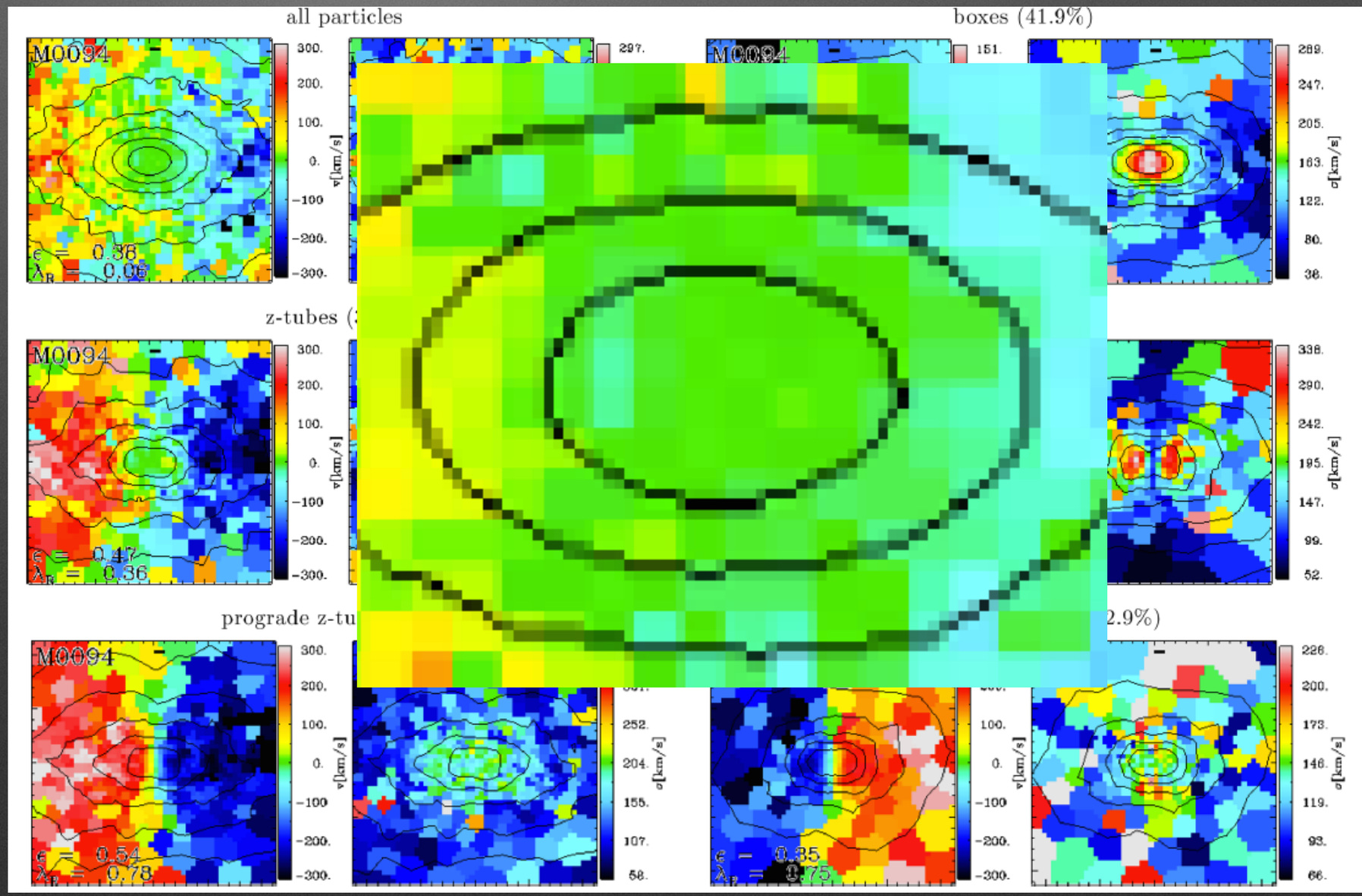

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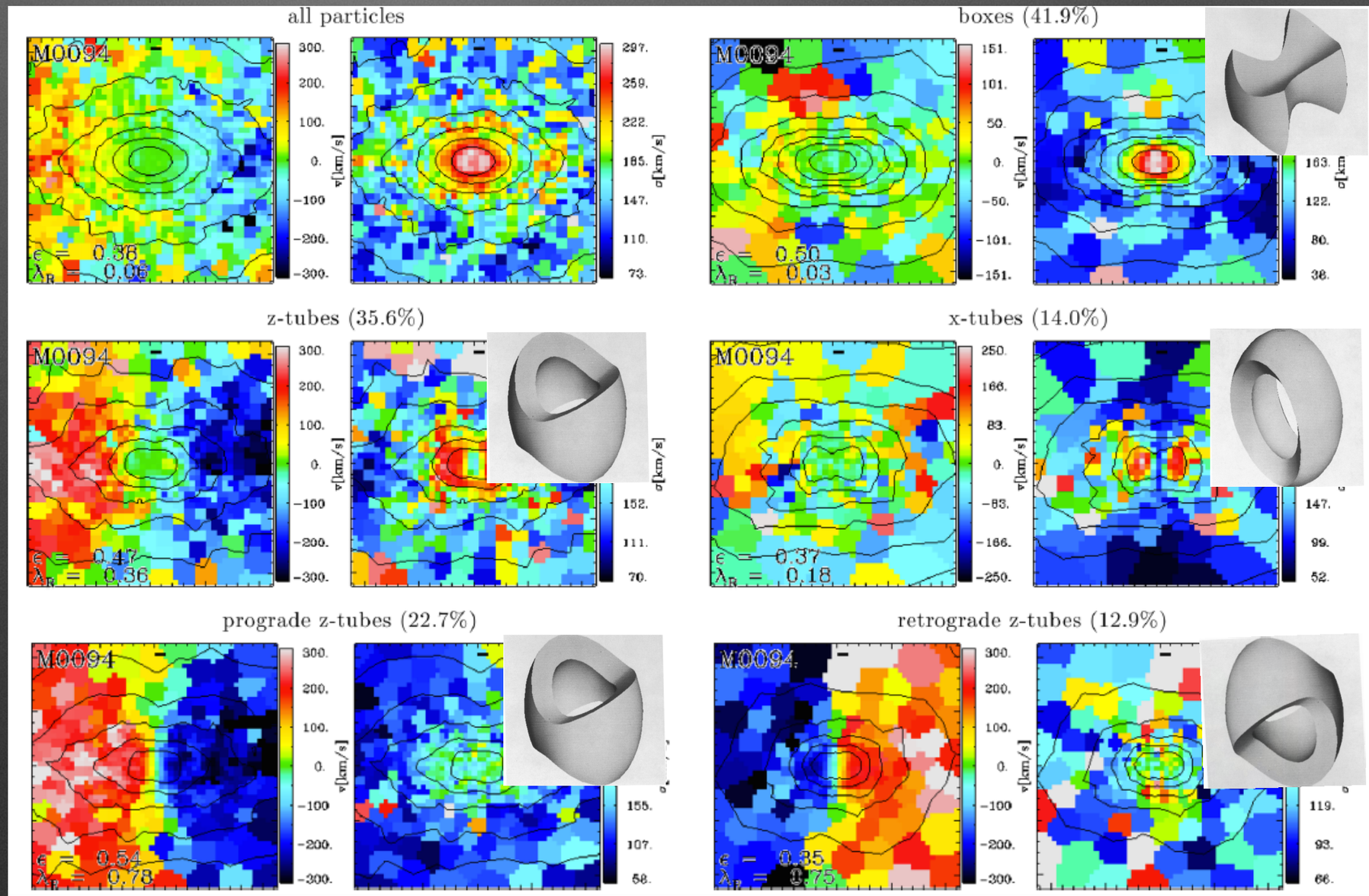


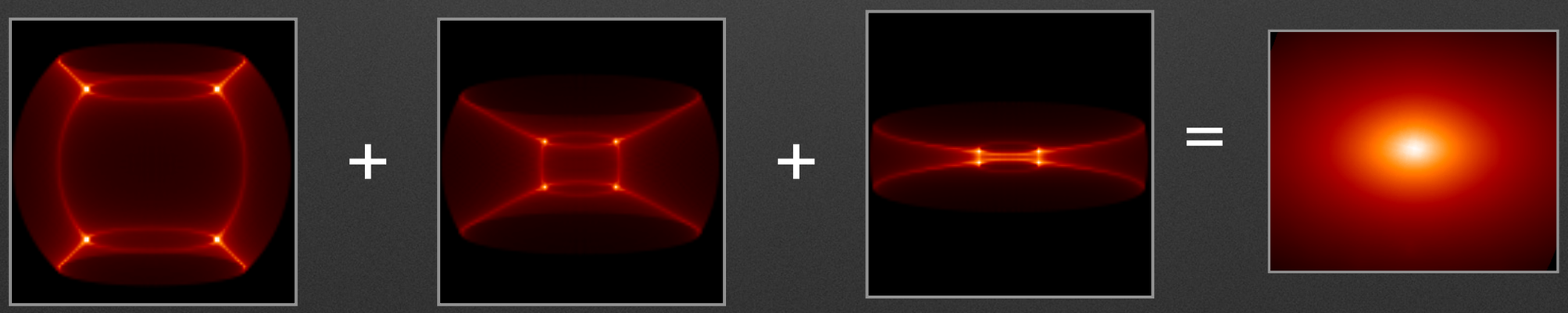
Dynamical modelling

February 13 2015 Davor Krajnović Macquarie University

Orbit based models

- orbit superposition dynamical models a la Schwarzschild (1979, 1982, 1993)
- Steps:
  - 1) parameterise light —> gravitational potential
  - 2) build an orbit library (assuming axisymmetry)
  - 3) chose from the orbit library those set of orbits that will reproduce the observed MUSE kinematics (and light distribution)

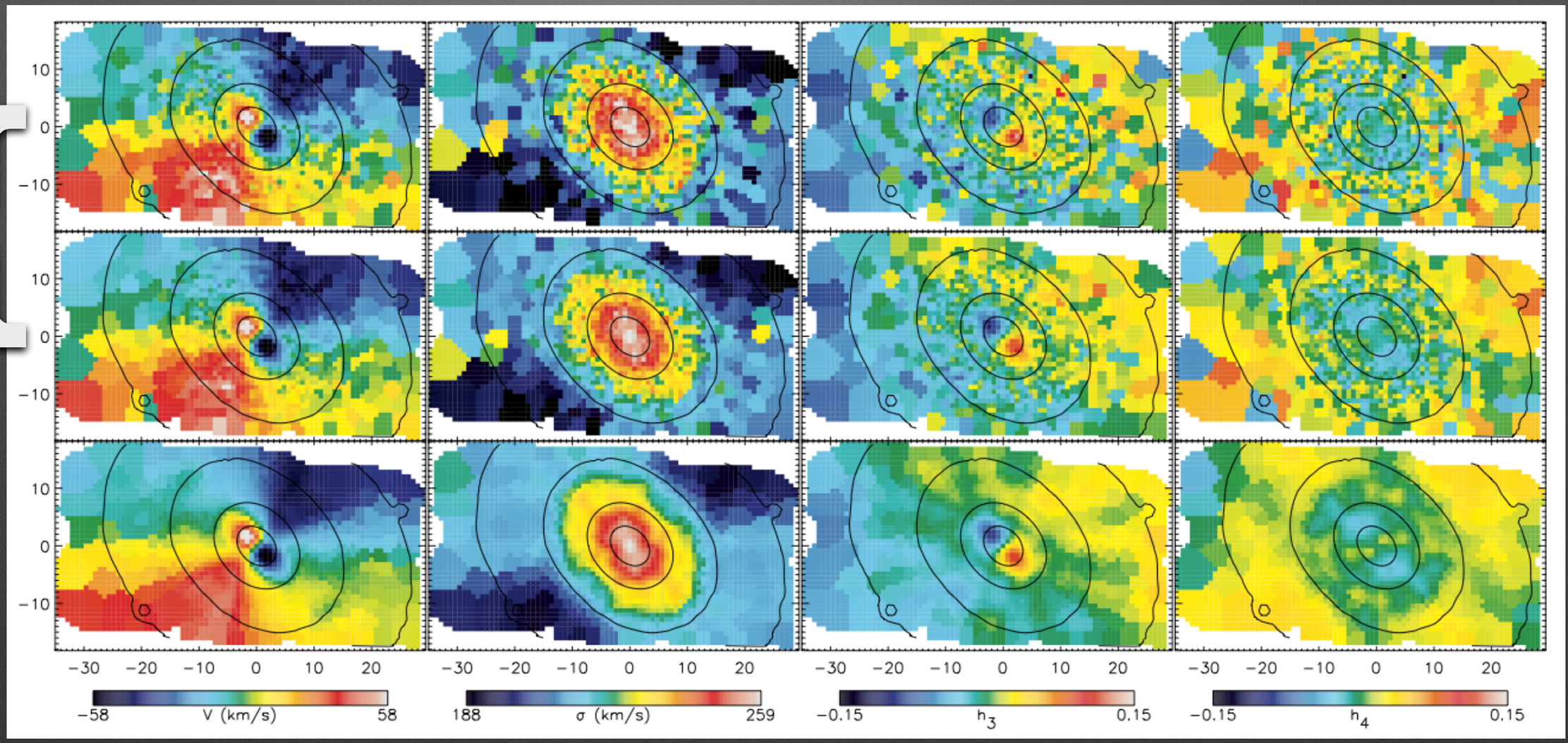
- axisymmetric (Rix et al. 1997; van den Marel et al. 1998; Cretton et al. 1998; Verolme et al. 2002; Cappellari et al. 2002,2006,2007; Krajnović et al. 2006,2009) and triaxial versions (van den Bosch et al. 2008, 2009a,b…) of ‘Leiden’ code



NGC4365 triaxial model

Data

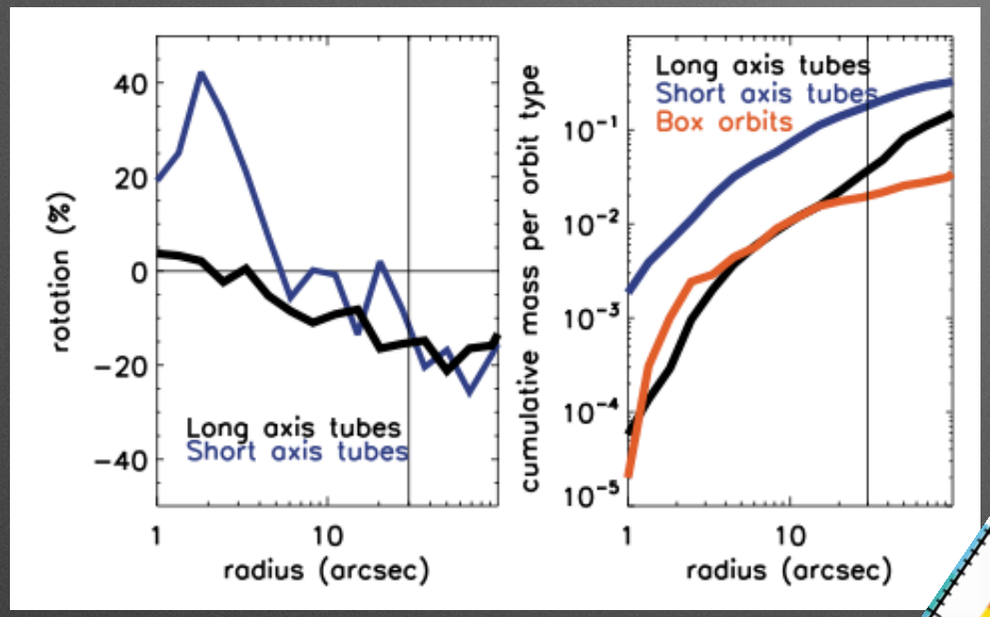
Model

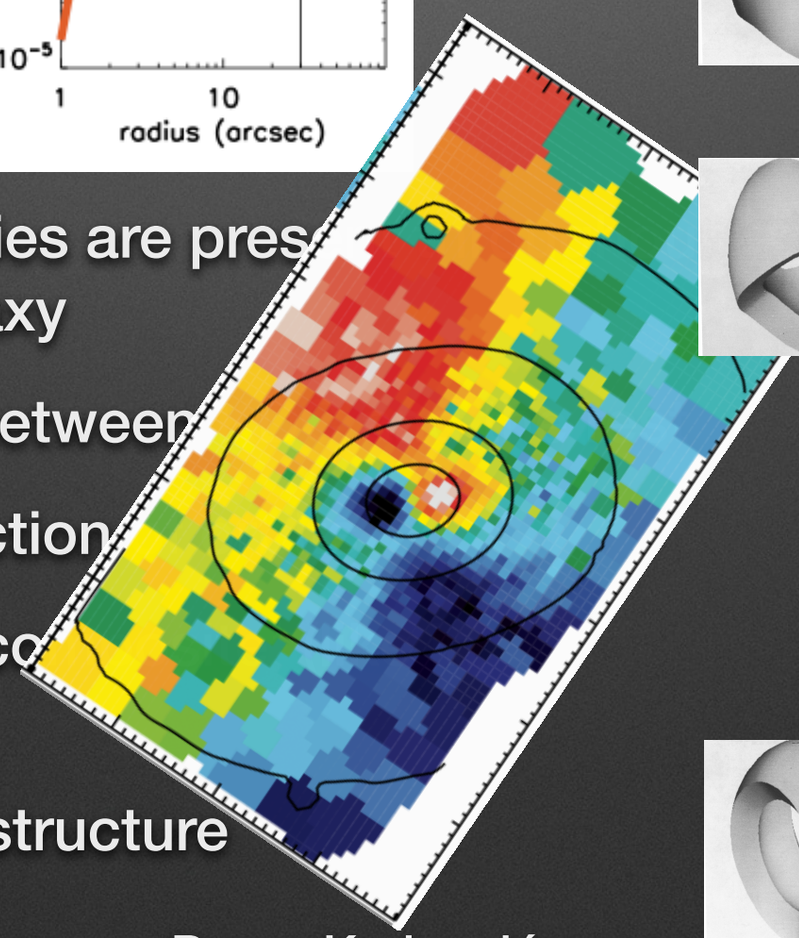


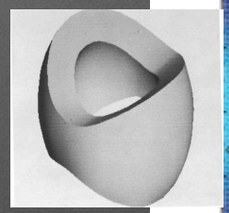
- triaxial Schwarzschild models (van den Bosch et al. 2009)
- include short-axis tubes, long-axis tubed and box orbits

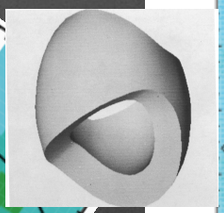
NGC4365 triaxial model

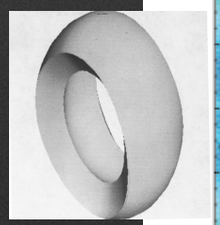
van den Bosch et al. (2008)

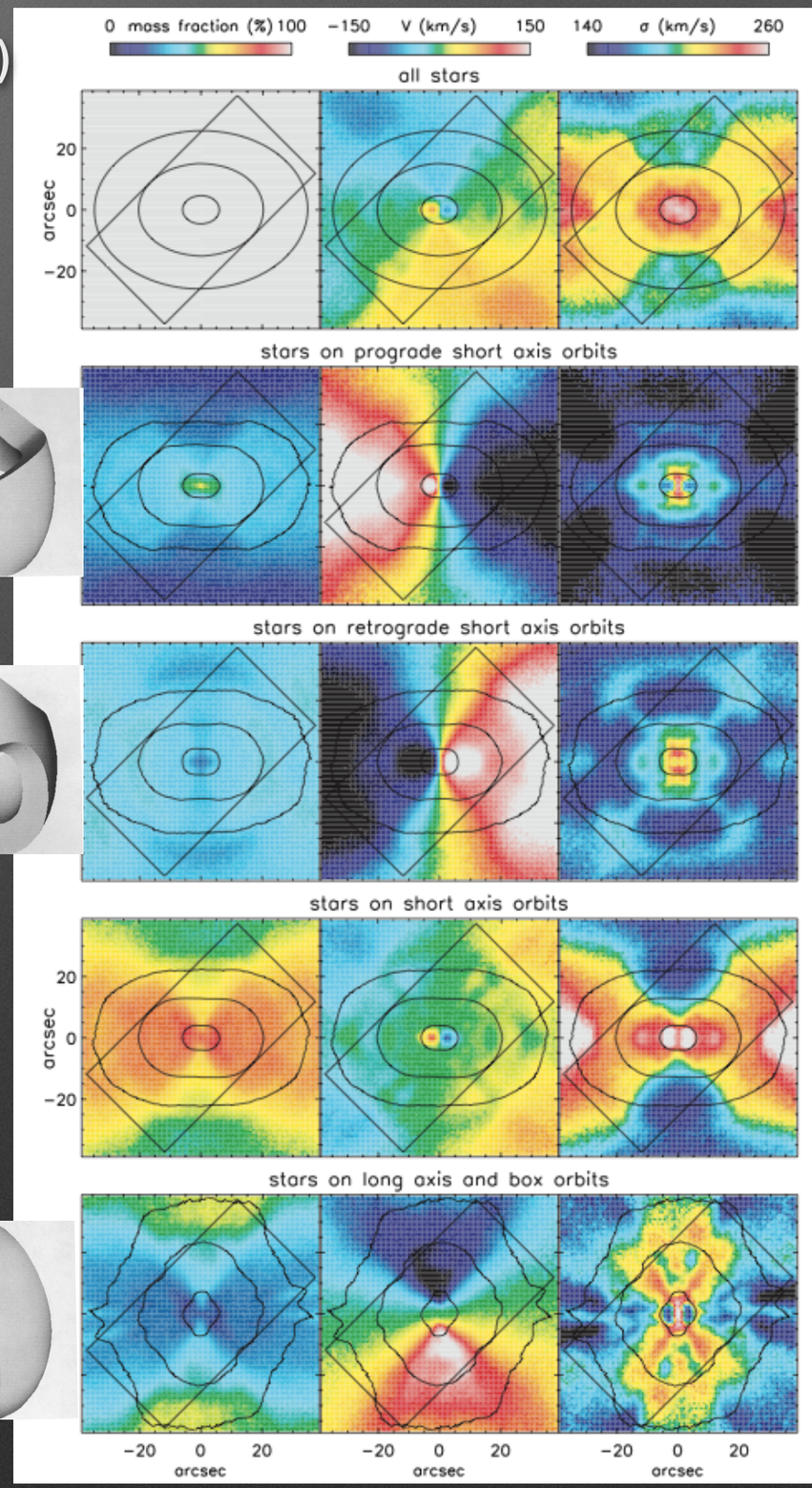












- several orbital families are pres
  the body of the galaxy
- no change in type betwee
- change in mass fractio
- KDC is the ‘orbital-co
  simulations
- dynamically stable structure

A puzzling case of NGC5813

February 13 2015

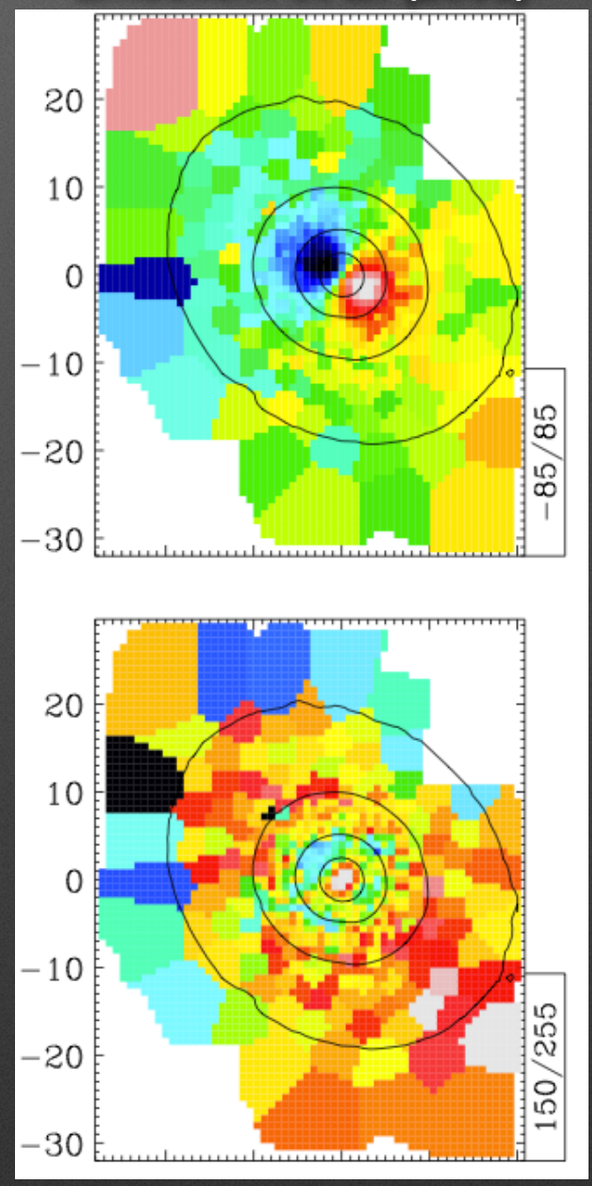
Davor Krajnović

Macquarie University

Unusual KDC

- the first discovered KDC (Efstathiou et al. 1982)
- ‘core-within-a-core’ galaxy
- inspiration for cannibalism scenario, but disproved with stellar pops
- photometric twist
- something is fishy with this galaxy
  - no rotation at large scales
  - sigma drop (within KDC)
    - a disk?

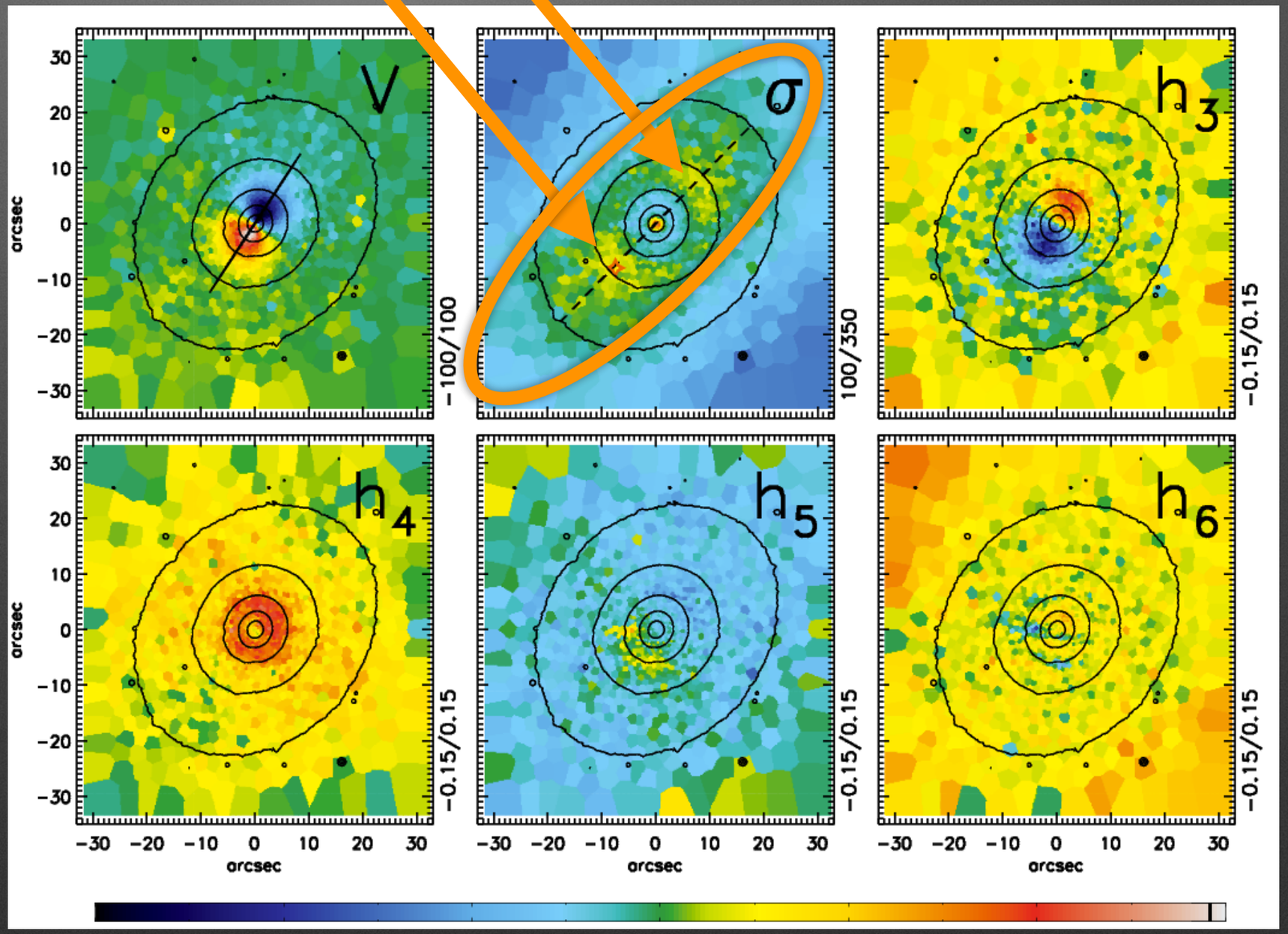
Emsellem et al. (2003)



NGC5813 MUSE kinematics

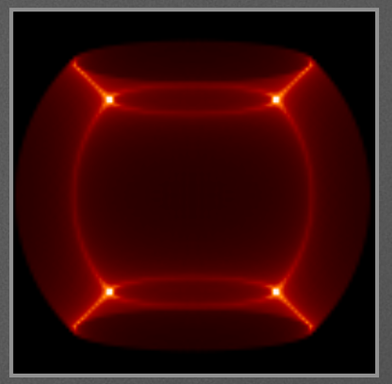
- Observed with MUSE during commissioning
- 2 peaks along the major axis on velocity dispersion map
- is NGC5813 made of two counter-rotating discs?
- A slow rotator made of discs?

Krajnović et al. (in prep)



Dynamical model

- Axisymmetric Schwarzschild dynamical model - exploring the orbital structure
- one type of orbits, but two families: short axis tubes with opposite spins
- 1) both *prograde* and *retrograde* orbits EVERYWHERE
  - within KDC one dominant (70%-30%)
  - outside equal (no rotation!)
- 2) neither component has very strong angular momentum
  - consistent with the 2 component LOSVD results



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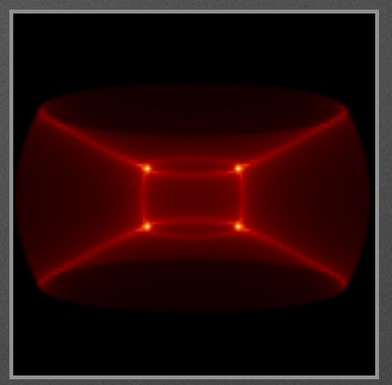

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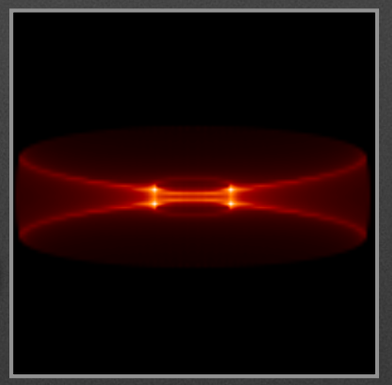

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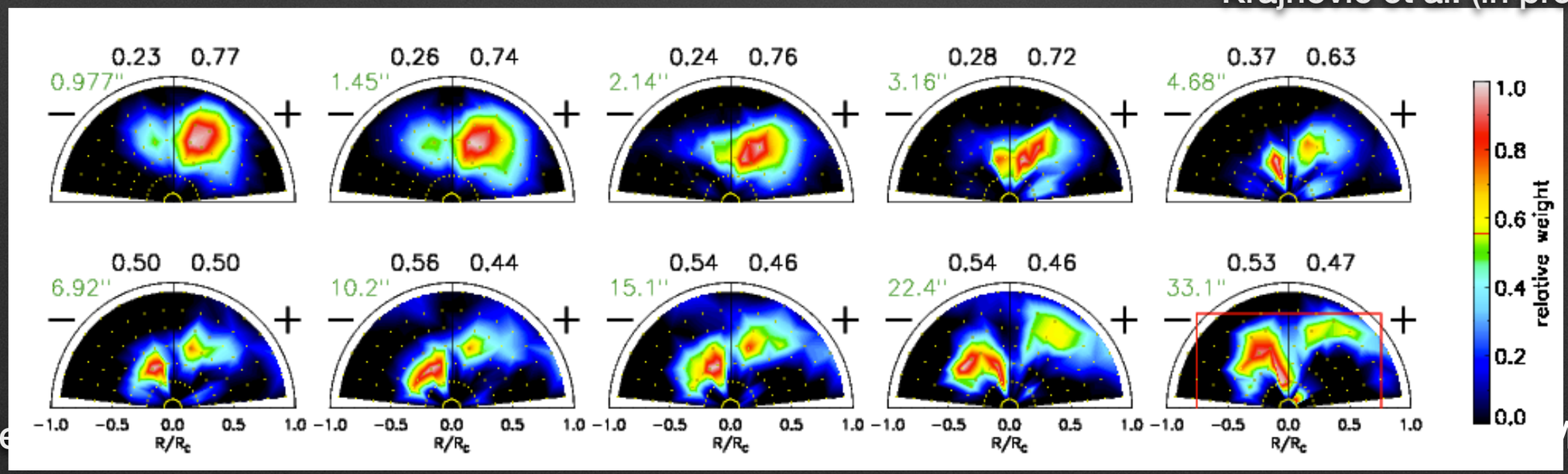

Consequences

1. Neither of the components is a disc!
2. NGC5813 is not a typical 2σ peak galaxy
3. KDC is not a separate (spatially localised) component, but part of an extended (galaxy wide) structure
4. Its origin could still be:
   - similar to a 2σ peak galaxy: accretion of gas/gas rich dwarf/two cooling flows building the galaxy
   - subsequent evolution (puffing up/destruction of the discs, possibly as a natural result of the group environment)
   - major merger (of two fast rotators) in the early universe

Outlook

- various kinds of (apparent) kinematic decoupling present, relatively common (~25% of cases); some not visible
- classic KDCs: in ~7-10 % of ETGs
- classic KDC:
  - large scale, in slow rotators
  - old, same stellar pops everywhere
  - dynamical stable (as seen by dynamical models and old stellar pops)
  - no decoupling: orbital-composite (at least for 2 of them)
- need to analyse more cases

Creation of KDCs

- a) early 1:1 merger (wet) with spins opposite to orbit
- b) dry merger (of galaxies with old stars) possible (but current simulation make them too flat!)
- c) early accretion of gas from a companion (like 2σ galaxies) or two cold flows
- a),b),c) + need to take into account subsequent evolution of minor mergers (as KDCs are in massive galaxies in dense environments)