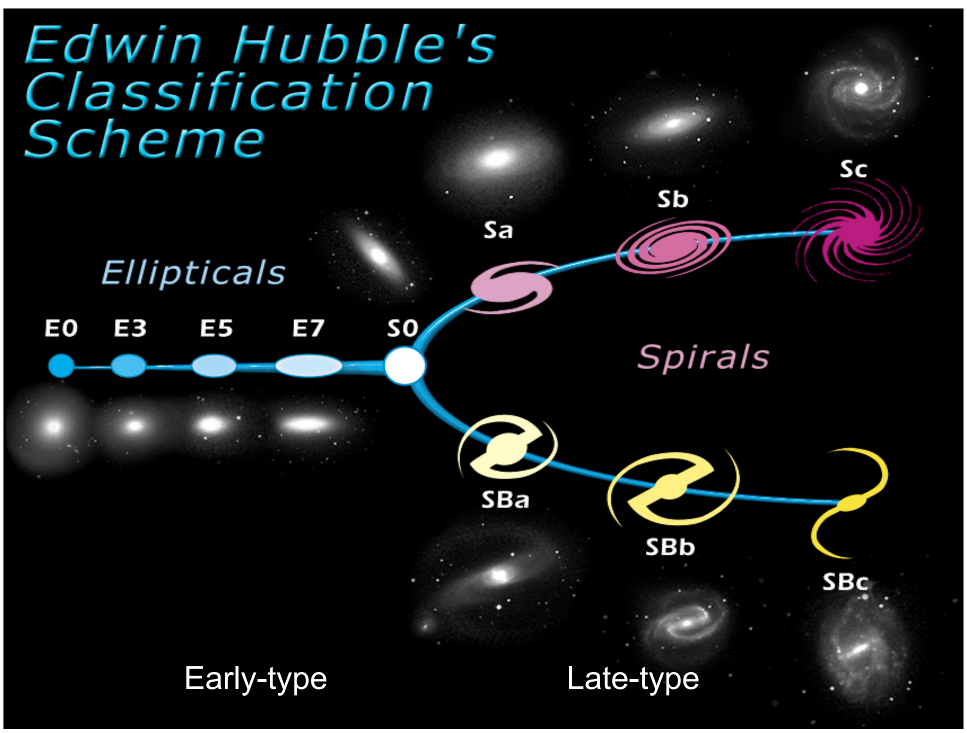
Recent Results from the SAURON Survey

- Early-type galaxies
- Fast and slow rotators
- Triaxial objects
  - Kinematically decoupled cores
  - Black holes
- Summary



Galaxy Formation and Evolution

- Galaxies form by hierarchical accretion/merging
  - Matter clumps through gravitation
  - Primordial gas starts forming first stars
  - Stars produce heavier elements
  - Subsequent generations of stars contain more metals

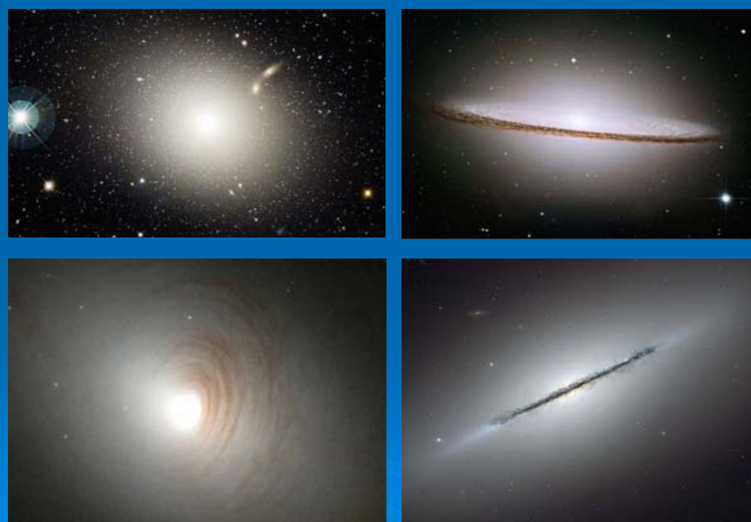
- Galaxy encounters still occur
  - Deformation, stripping, merging
  - Galaxies continue to evolve
- Central black hole also influences evolution

Observational Approaches

- Study very distant galaxies
  - Observe evolution (far away = long ago)
  - Objects faint and small: little information
- Study nearby galaxies
  - Light not resolved in individual stars
  - Objects large and bright: internal structure
  - Infer evolution through archaeology
  - Fossil record is cleanest in early-type galaxies

- Study resolved stellar populations
  - Ages, metallicities and motions of stars
  - Archaeology of Milky Way and its neighbors

Early-type Galaxies



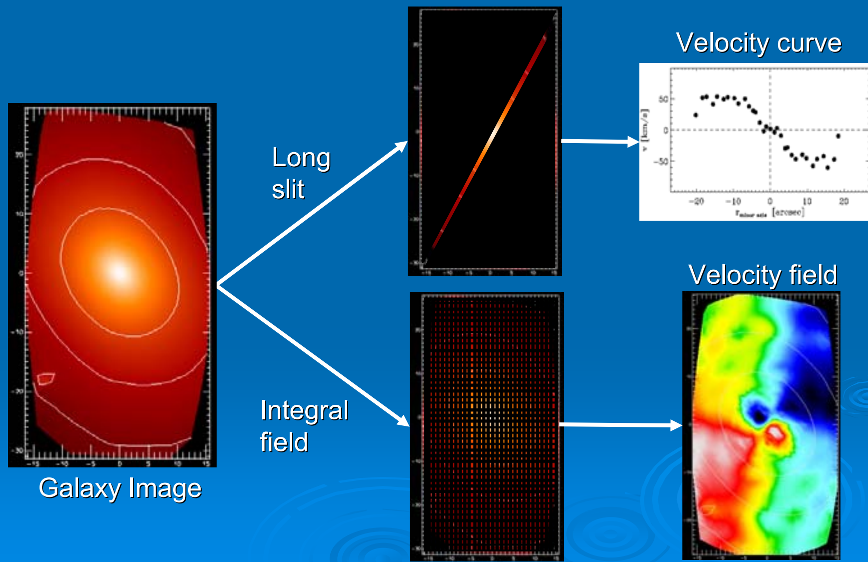
The SAURON Project

- Systematic study of *representative* sample of 48 nearby E/S0 galaxies and 24 Sa bulges
- Ground-based integral-field spectroscopy + imaging
  – Kinematics of stars/gas and line-strengths
  – Large-scale surface-brightness distribution
- Hubble Space Telescope imaging

- Construction of models to determine:
  – M/L, intrinsic shape and stellar motions
  – Mass of central black hole, and relation to galaxy structure
  – Origin and properties of ionised gas
  – History of metal enrichment of the stars

de Zeeuw et al. 2002, MNRAS, 329, 513

Integral-field Spectroscopy



Integral-field Spectrographs

- Various optical designs (lenslets, fibers, slicers)
- Most emphasis on small fields, high resolution, assisted by adaptive optics (e.g., OASIS™; SINFONI)
- Need *panoramic* spectrograph to study galaxies
  - Use lenslets to maximize throughput (TIGER™ design)
  - Field of view to cover galaxy in a few pointings
  - 1500 spectra in a single exposure

⇒ SAURON ™Lyon

Bacon et al. 2001, MNRAS, 326, 23

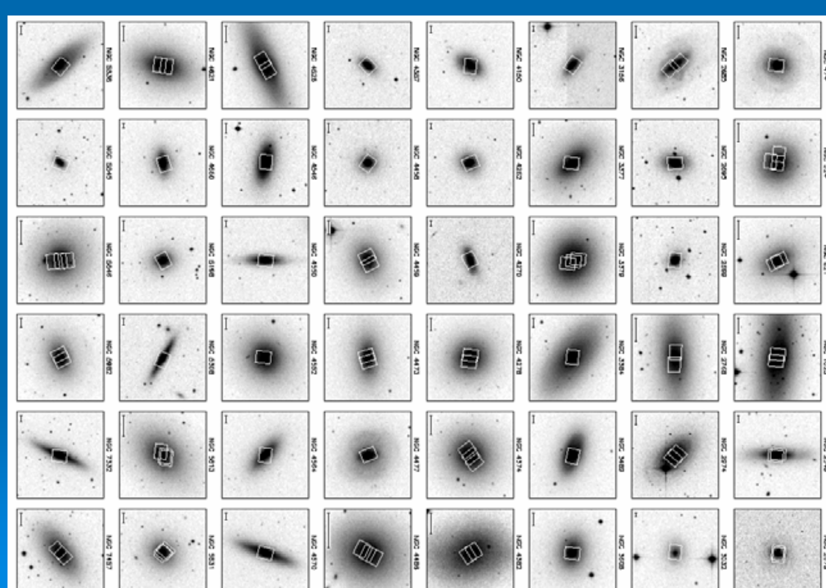
The SAURON Team

- 3 co-PIs:
  - Bacon, Davies, de Zeeuw
- 9 co-investigators
  - Cappellari, Emsellem, Falcon-Barroso, Krajnović, Kuntschner, McDermid, Peletier, Sarzi, van de Ven
- 7 associates
  - R. van den Bosch, Bureau, Houghton, Morganti, Oosterloo, Shapiro, Weijmans
- http://www.strw.leidenuniv.nl/sauron

SAURON on the WHT

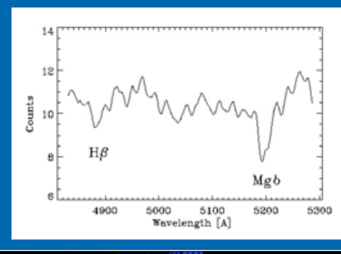
- Main survey
  - 56 nights (36 clear) in 99-03: ~150000 spectra
  - Full set of analysis tools developed
  - Many papers (mostly in MNRAS), more to come
  - Follow-up observations in e.g., HI, CO & Galex/Spitzer
- Collaborative projects
  - Late-type spirals (Ganda et al. 2006, 2007)
  - Seyfert galaxies (Dumas/Emsellem/Mundell et al. 2006, 2007)
  - M100 (Allard, Knapen et al. 2005, 2006)
  - Stellar kinematics at 3-5 R_e (Weijmans et al. 2008)
  - Lyα blobs at redshift 3.2 (Bower/Wilman et al. 2004, 2005)

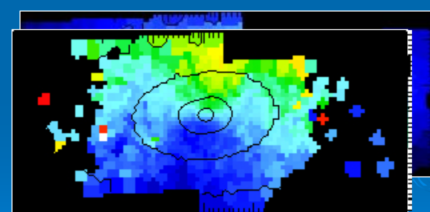
48 Representative E/S0 Galaxies



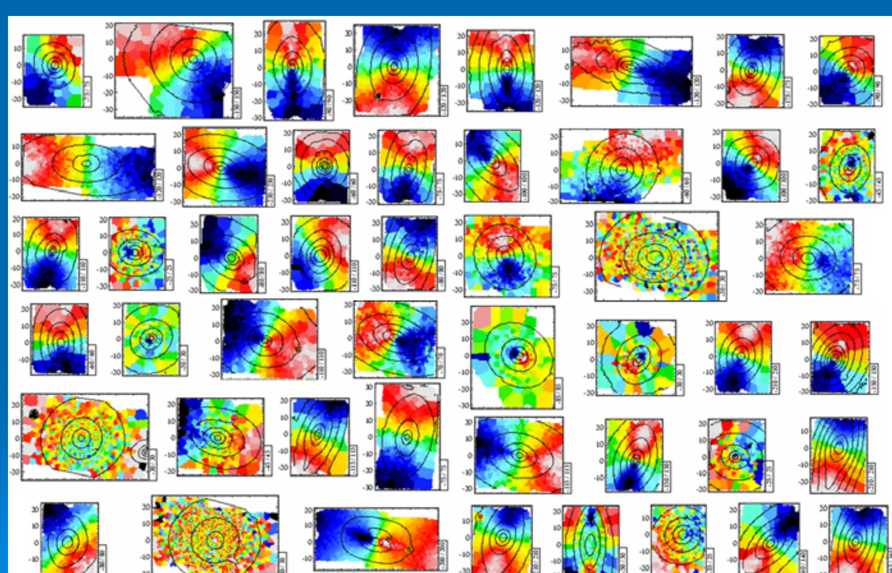
Integral Field Data

- Total flux
  - Morphology, photometry
- Absorption lines
  - Stellar kinematics
    - V, σ, higher moments h_3, h_4
  - Line strength indices
    - Hβ, Mgb, Fe5015, Fe5270
- Emission lines
  - Gas distribution
    - Hβ, [OIII], [NI]
  - Gas kinematics
    - V(Hβ), V([OIII]), FWHM(Hβ), FWHM([OIII])



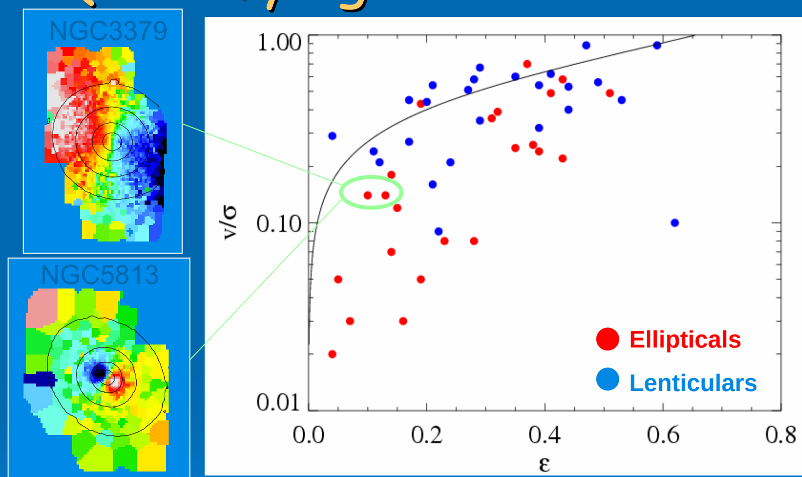


SAURON Stellar Velocity Fields



Emsellem et al. 2004, MNRAS, 352, 721

Quantifying Kinematics: V/σ

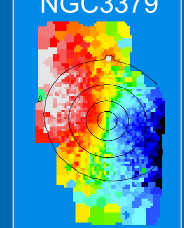


- V/σ quantifies rotation vs. random motion
- Rotating galaxies are 'flatter' (higher ε)
- No clear relation with 'E/S0' or velocity maps

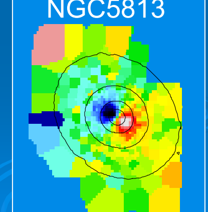
Kinematic Classification

- Two classes of early-type galaxies
  - Either ordered rotation or no rotation except in central component
  - Standard V/σ parameter cannot always distinguish these
- New parameter
  - Use entire velocity field to define rotational state
  - Parameter $\lambda_R = \frac{\langle R \times |V| \rangle}{\langle R \times \sqrt{V^2 + \sigma^2} \rangle}$
  - Test against dynamical models

NGC3379



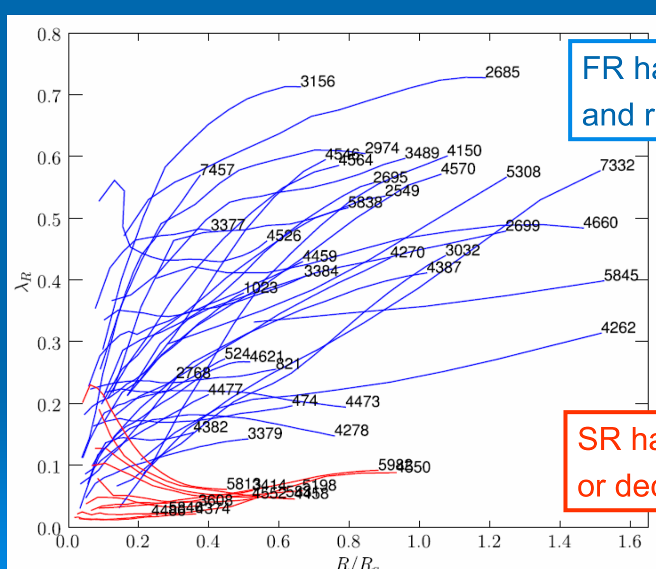
NGC5813



Emsellem et al. 2007, MNRAS, 379, 401
Cappellari et al. 2007, MNRAS, 379, 418

λ_R versus ellipticity ε

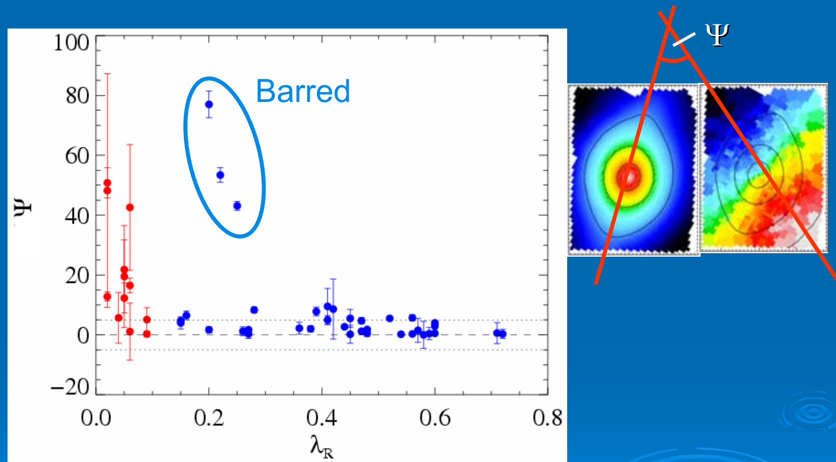
Radial Profile of λ_R



FR have high and rising λ_R

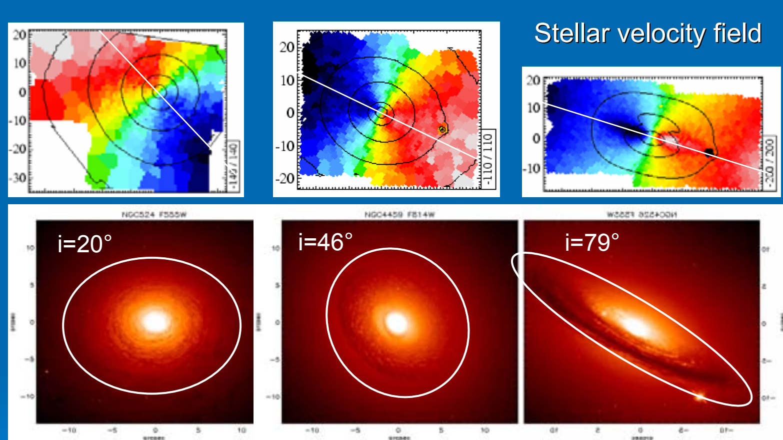
SR have quite flat or decreasing λ_R

Kinematic Misalignment



- Fast rotators: generally well-aligned systems
- Slow rotators: less symmetry

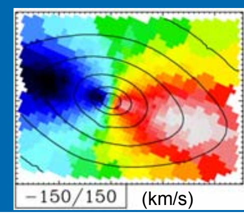
Fast Rotators



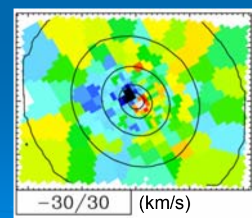
- Stellar kinematics resembles that of circular disk
- Embedded in nearly stationary spheroid/bulge

Structure of E/S0 Galaxies

- Oblate fast rotators (E & S0)
  - High specific angular momentum
  - Embedded stellar disk
  - Often radially anisotropic in disk plane
  - Generally steep luminosity cusp
- Triaxial slow rotators (E)
  - Some central rotation, but negligible specific angular momentum
  - Not necessarily strongly anisotropic
  - Generally shallow luminosity cusp



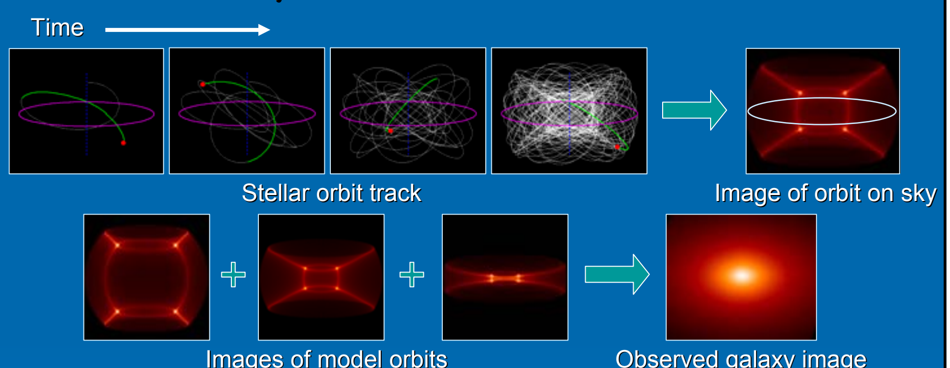
Fast rotator (NGC 4660)



Slow rotator (NGC 4458)

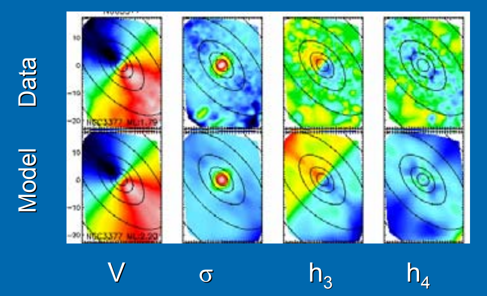
Emsellem et al 2007, Cappellari et al 2007, MNRAS, 379, 401 & 418

Dynamical Models

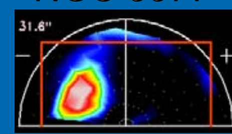


- Generate library of orbits for given potential
- Find combination that reproduces observed properties: mass, velocity, velocity dispersion…
- Determine: M/L, black hole mass, orbit structure

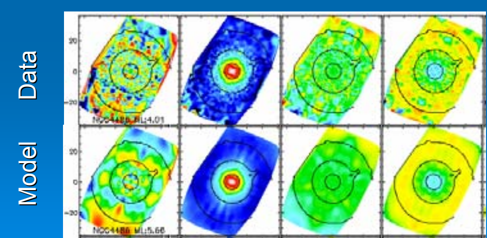
A Fast and a Slow Rotator



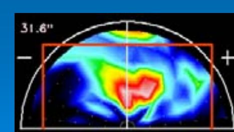
NGC 3377



Normal rotation

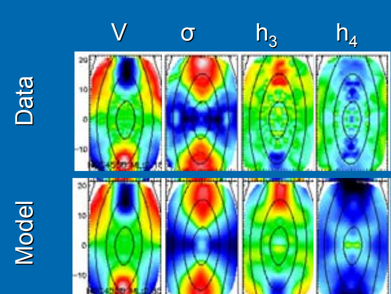


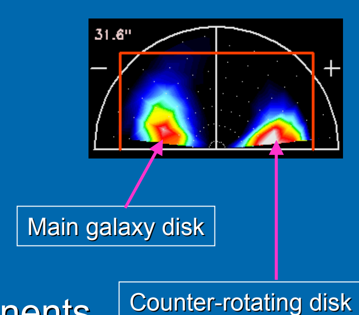
M87



No mean rotation

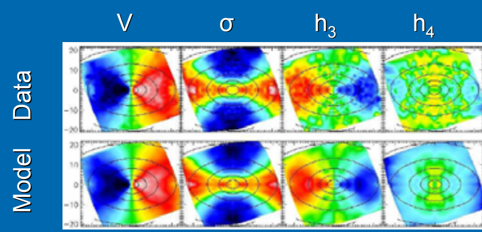
NGC 4550

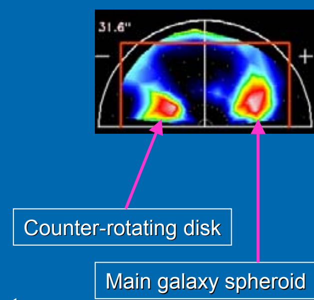




- Two counter rotating components
  - Double-peaked absorption lines (Rix et al. 1992)
  - SAURON: accurate decomposition, in phase space
- Both components are disks
  - Same mass
  - Different scale height

NGC4473

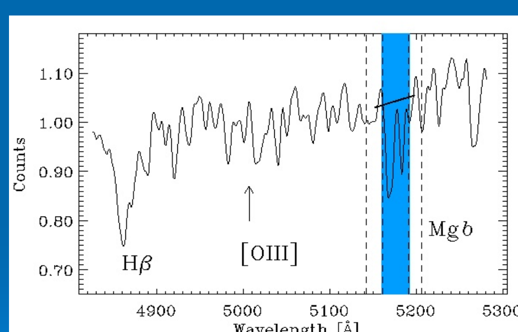




- Two counter-rotating components
  - Absorption lines not double-peaked
  - Mass decomposition only possible in phase space
- Flatter component is 30% of total mass

Line-strengths

- SAURON covers Hβ, Fe5015, [OIII], Mg*b* & Fe5270
- Measure Lick/IDS indices



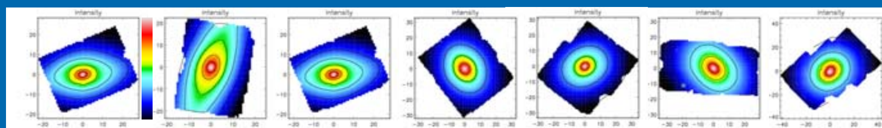
- Stellar population models ⇒ luminosity-weighted age and metallicity

Kinematics and Line-strengths

N
E

NGC 4546 | NGC 4570 | NGC 4660 | NGC 4382 | NGC 4406 | NGC 4365 | NGC 4374

I



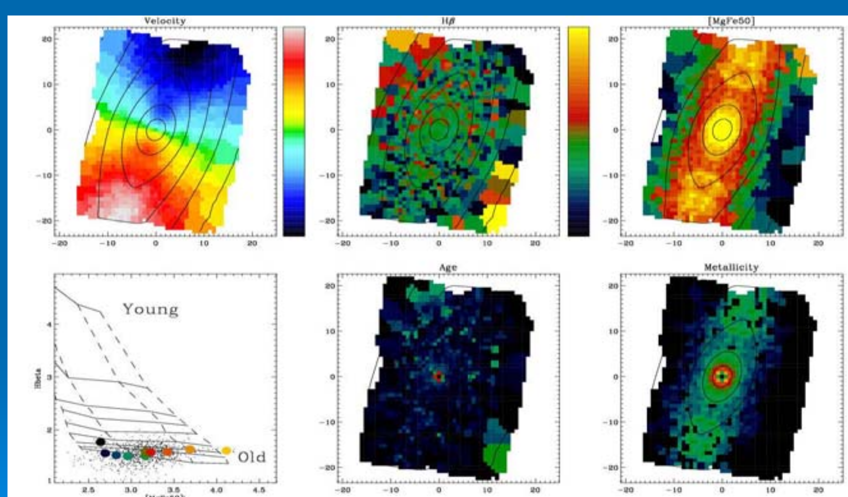
V

Mg*b*

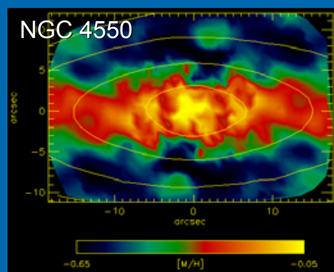
Fe

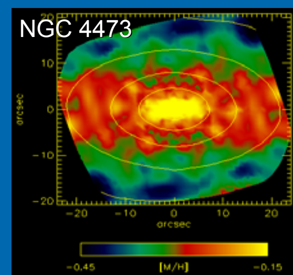
Kuntschner et al. 2006, MNRAS, 369, 497

The Fast Rotator NGC 4570



The Counter-rotating Disks

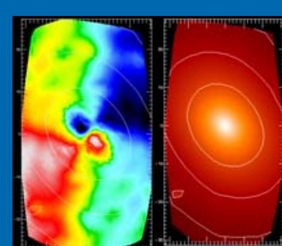


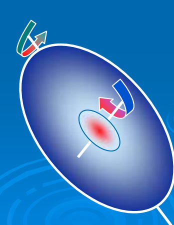


- Metallicity enhanced in flatter disk
- These counter-rotating disks are ~coeval

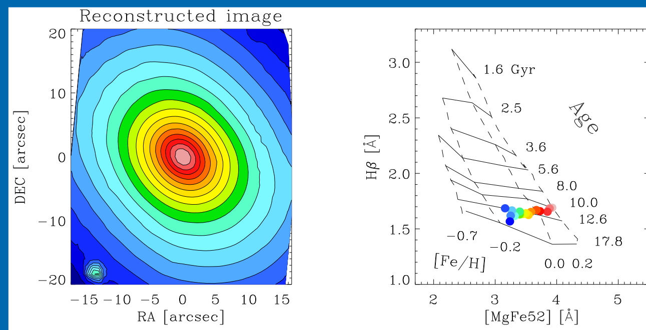
NGC 4365

- Kinematically Decoupled Core
  - Long-axis rotator, core rotates around short axis (Surma & Bender 1995)
- SAURON kinematics:
  - Rotation axes of main body and core misaligned by 82°
  - Consistent with triaxial shape, both long-axis & short-axis tubes occupied
- Customary interpretation:
  - Core is distinct, and remnant of last major accretion





Formation of NGC 4365

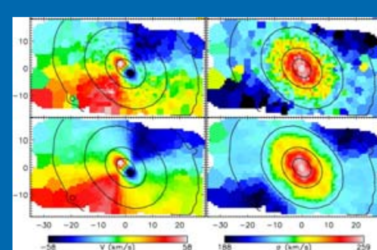


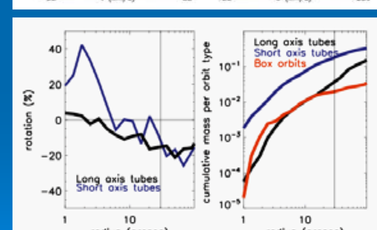
- Core & main body: common star formation history
- No recent star formation: triaxial structure long-lived
- Core remnant of last major accretion on nearly perpendicular orbit more than 12 Gyr ago?

Davies et al. 2001, ApJ, 548, L33

Triaxial Dynamical Model

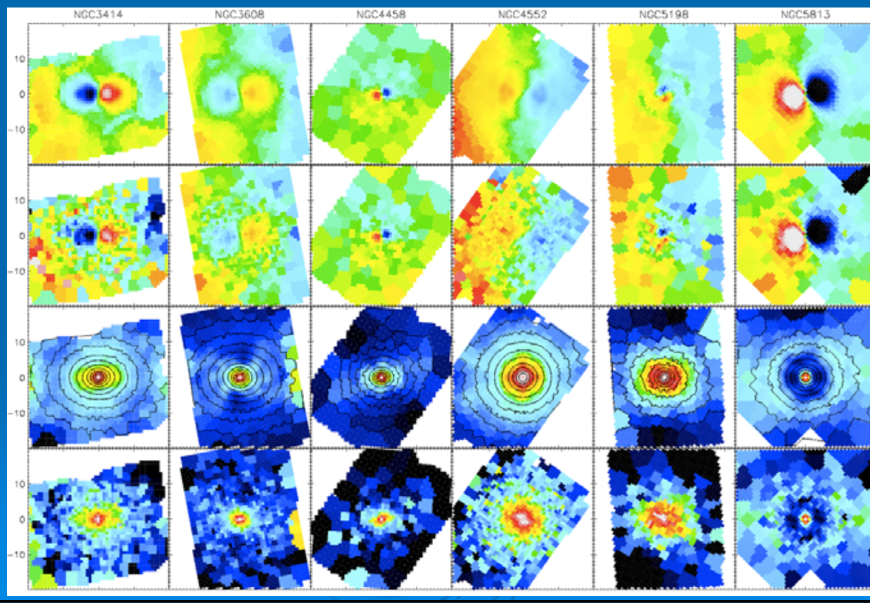
- Parameters
  - Two axis ratios, two viewing angles, M/L, M_{BH}
- Best-fit model
  - Fairly oblate (0.7:0.95:1)
  - Short axis tubes dominate, but ~50% *counter rotate*, except in core; cf NGC4550
  - Long-axis rotation dominates except in core
  - KDC *not* a physical subunit, but appears so because of embedded counter-rotating structure



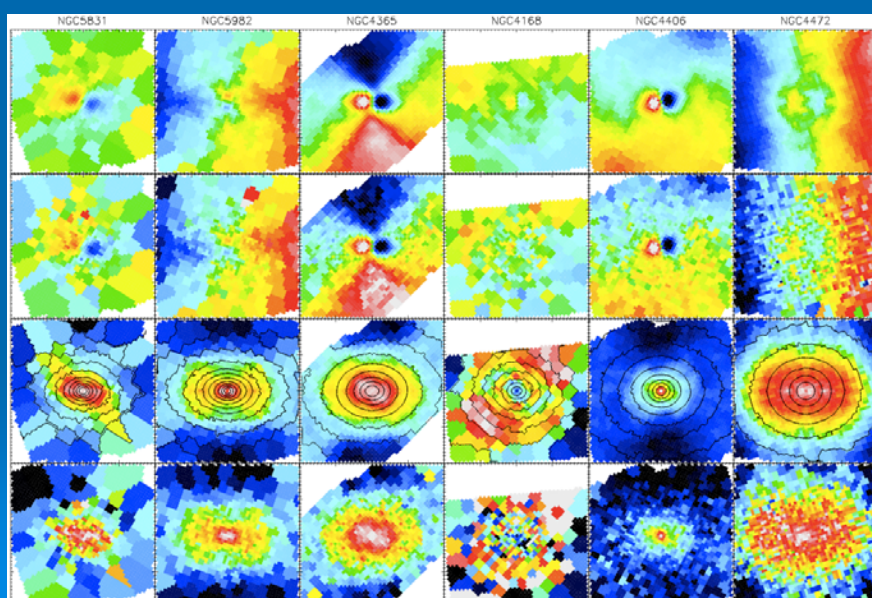


van den Bosch et al. 2008, MNRAS

Slow Rotators: Triaxial Models

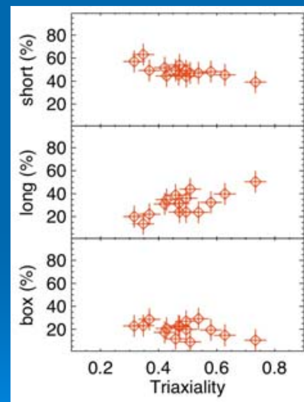


Slow Rotators: Triaxial Models



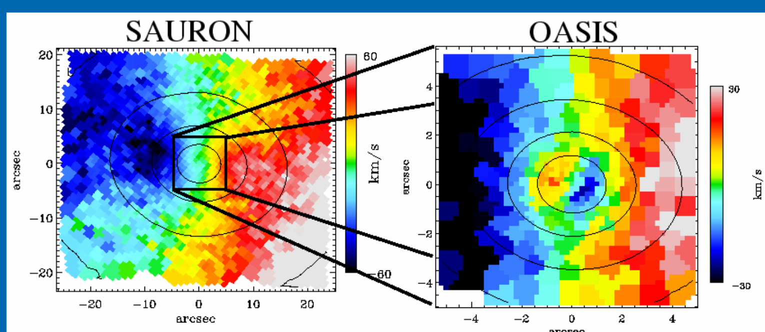
Properties

- 11 slow rotators in representative SAURON sample
  - Range of triaxiality: $0.2 \leq T \leq 0.7 \Rightarrow$ no prolate objects
  - Mildly radially anisotropic
  - Most have 'KDC'
- Dynamical structure
  - Short axis tubes dominate (like FR)
  - Smooth variation with radius
  - Similar to dry merger simulations
    Jesseit et al. 2005, MNRAS, 360, 1185
  - No sudden transition at R_{KDC}
- KDC not distinct from main body
  - In harmony with smooth Mgb and Fe gradients



van den Bosch et al. 2008, in prep.

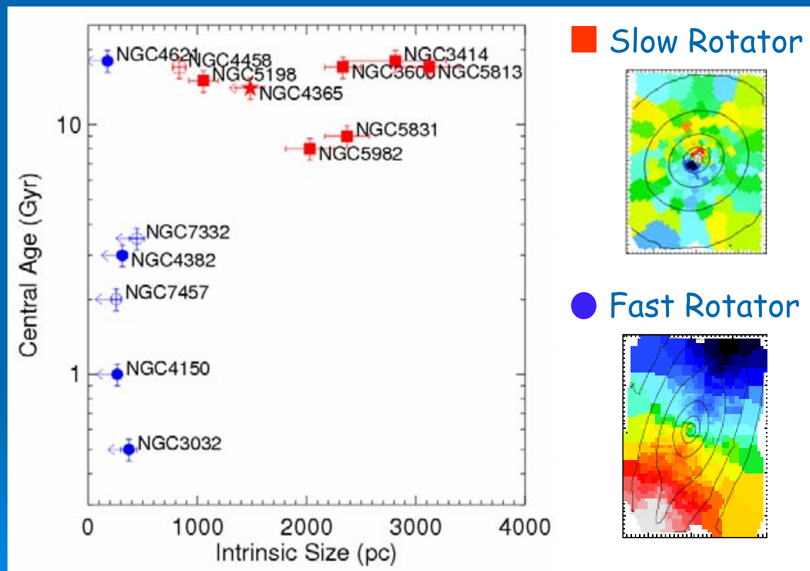
Kinematic structure on all scales



NGC 4382 McDermid et al., 2006, MNRAS, 373, 906

- SAURON: global kinematics and line-strengths
- OASIS: spatial resolution: zoom-in on nucleus
- Allows study of orbital structure near central BH
- STIS: even sharper, but incomplete view

Ages and Sizes of 'KDC's'



McDermid et al. 2006, MNRAS, 373, 906

Central Black Holes

- Many M_{BH} measurements with orbit-based models
  - General orbital structure
  - Axisymmetric (oblate) geometry
- M32 now modeled in general triaxial geometry
  - Oblate shape preferred, *same* black hole mass and M/L
- N3379
  - Misalignment $\Delta\Psi \sim 5^o \Rightarrow T \sim 0.15$
  - Nearly face-on ($i \sim 40^o$)
  - Observed dust lane ~ polar ring
  - M_{BH} *doubles* compared to oblate model
  - Systematic effect in (M_{BH}, σ) at large σ?

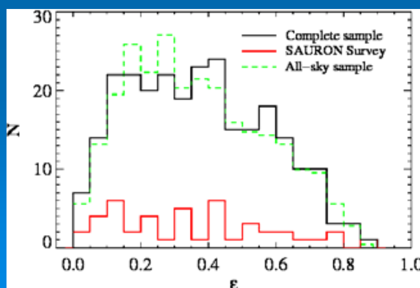
van den Bosch & de Zeeuw 2008, MNRAS, submitted

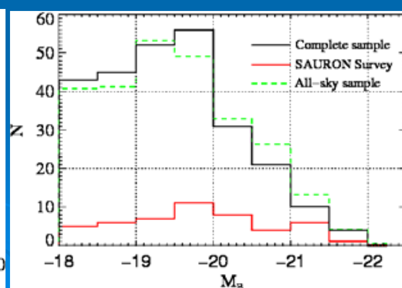
Summary

- Early-type galaxies: rich variety of structure
  - Kinematic classification based on SAURON spectroscopy
  - Line strength maps ⇒ age and metallicity maps
- Fast rotators
  - Nearly oblate, embedded stellar disk
  - Gas accretion and star formation
- Slow rotators
  - Triaxial shape
  - Decoupled cores not separate from main galaxy
  - Structure formed long ago in dry merger
  - Black hole mass derived in oblate geometry suspect

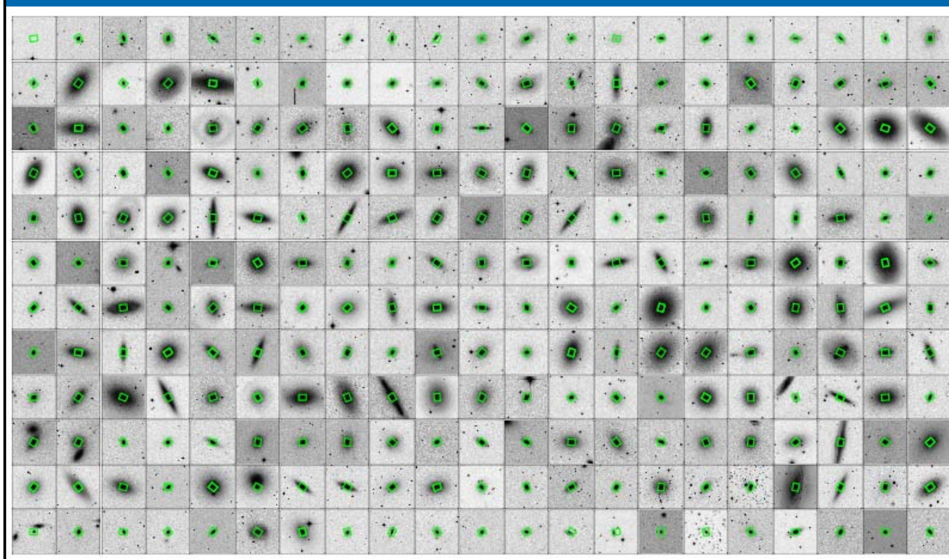
Complete Survey: ATLAS^{3D}

- 48 E/S0's: selection introduces complex biases
- Need *complete* volume-limited sample ⇒
  - 266 additional objects
  - Measure only V and σ: short exposure times
  - 40 nights on WHT, data taken, and reduced
  - PI's: Cappellari, Emsellem,Krajnovic, McDermid





ATLAS^{3D}



PI's: Emsellem, Cappellari, Krajnovic, McDermid