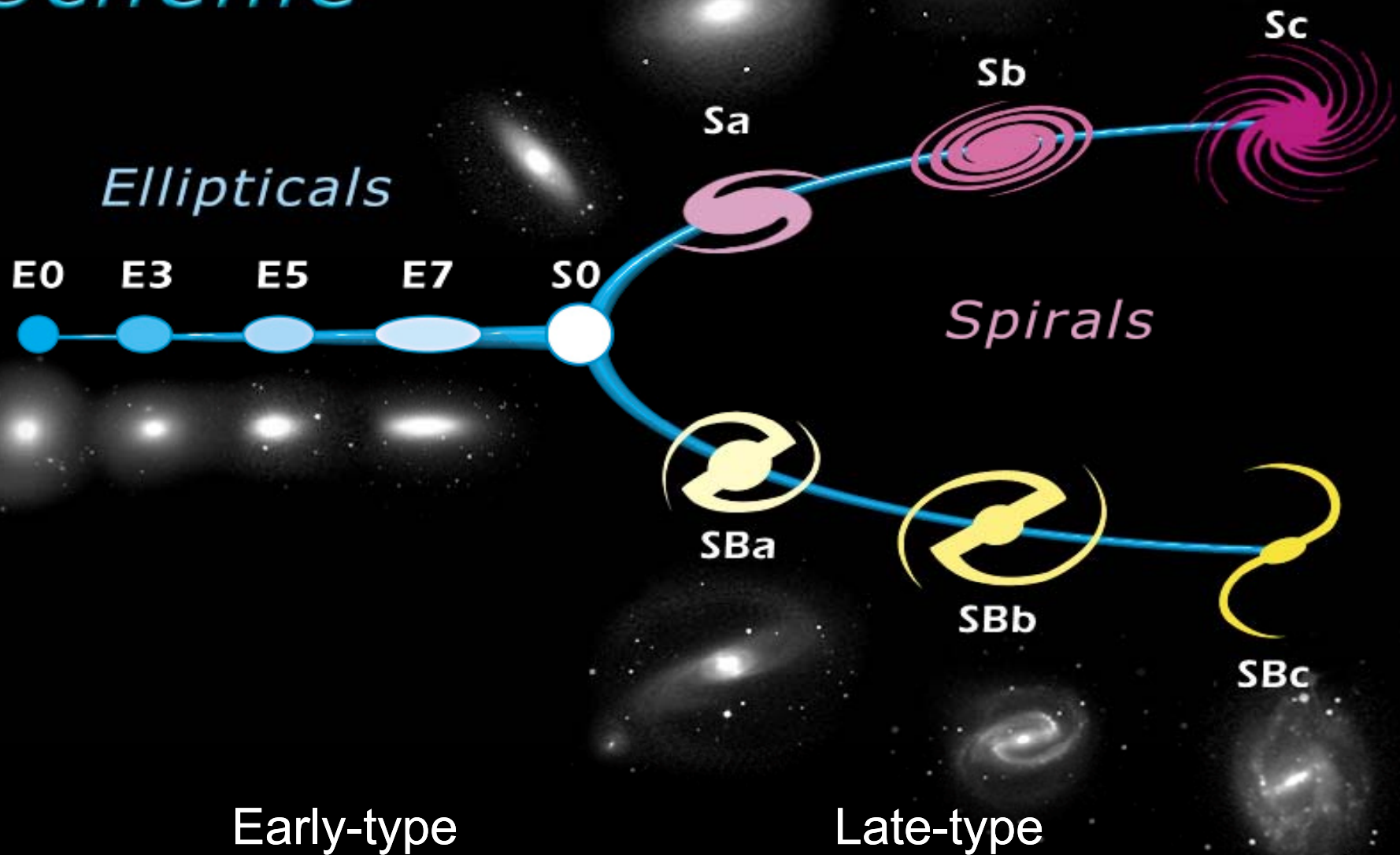


Recent Results from the



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

Edwin Hubble's Classification Scheme



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

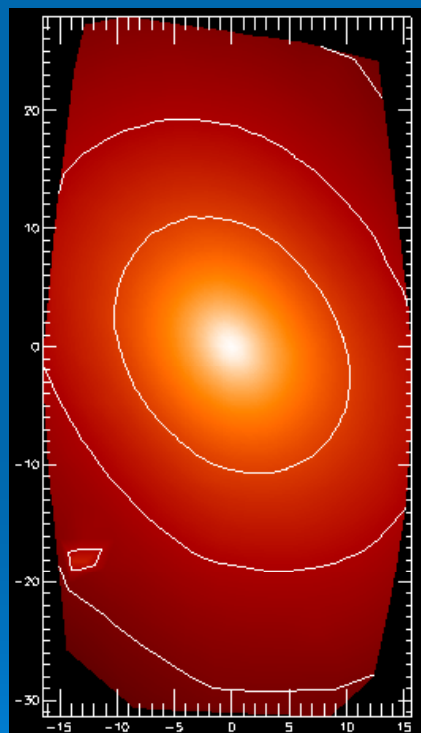


The Sauron Project

- 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

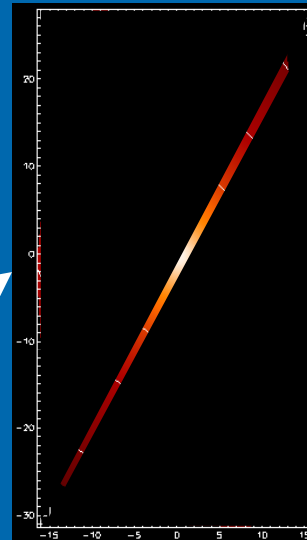


Integral-field Spectroscopy

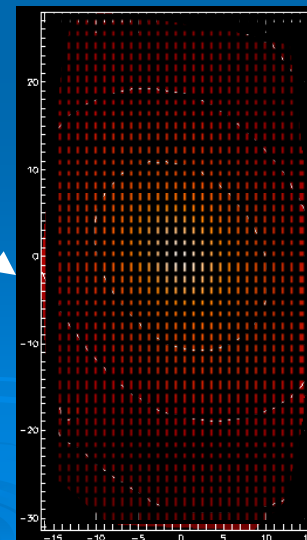


Galaxy Image

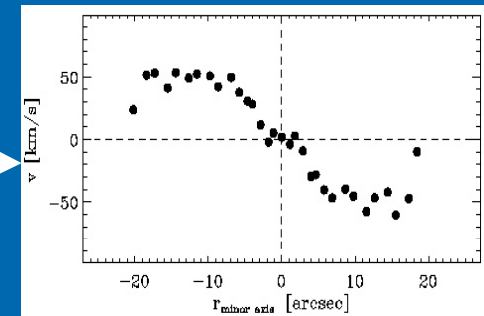
Long
slit



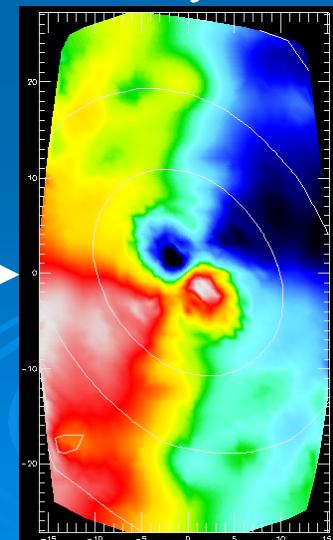
Integral
field



Velocity curve



Velocity field



Integral-field Spectrographs

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



TMLyon

Bacon et al. 2001, MNRAS, 326, 23

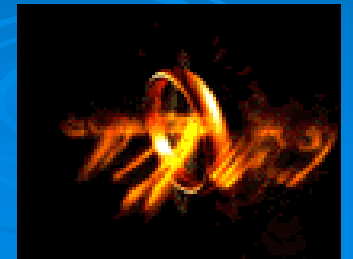


William Herschel Telescope

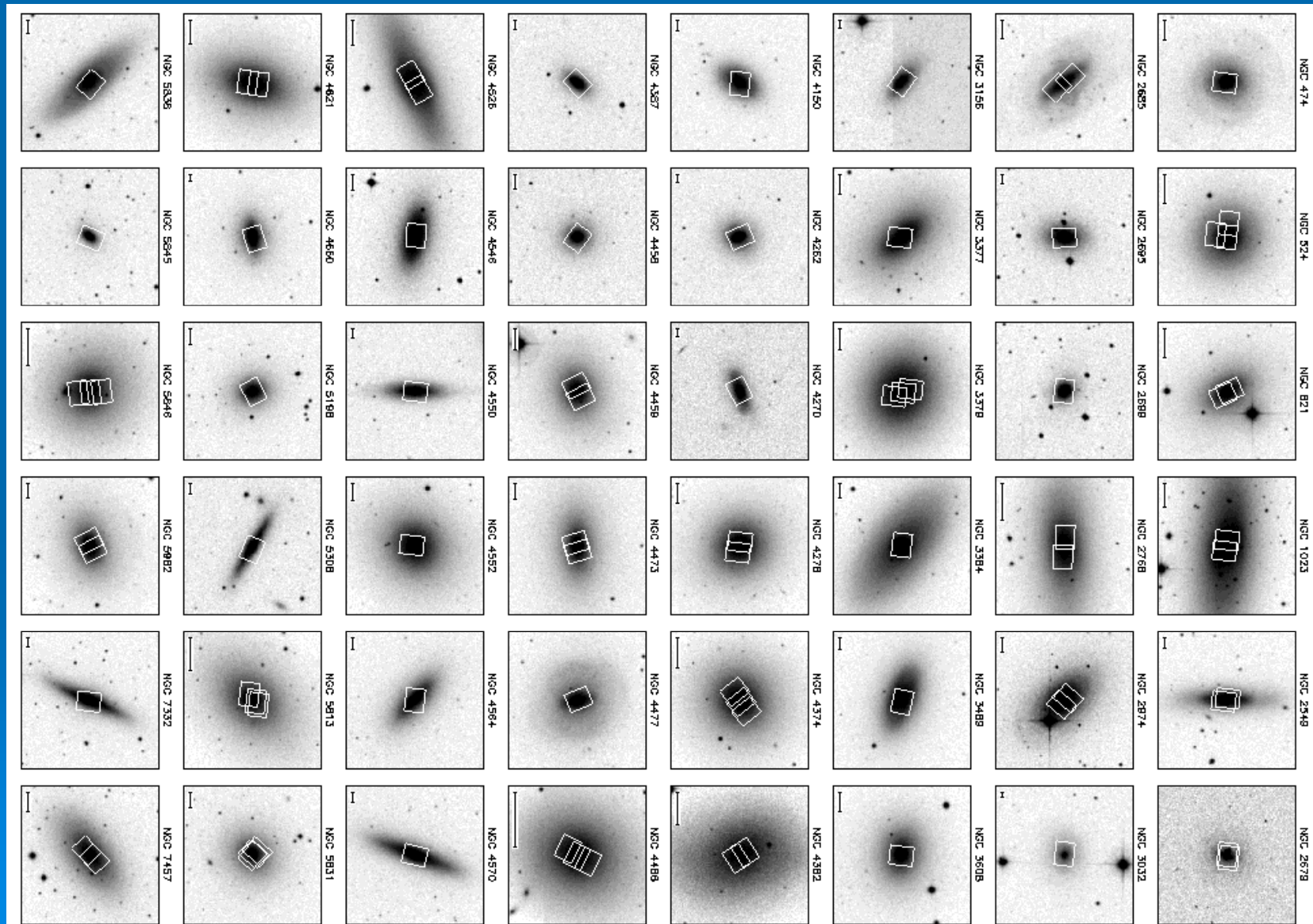


The Sauron Team

- 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, Ganda, Maier, Miller, Shapiro, Weijmans
- <http://www.strw.leidenuniv.nl/sauron>



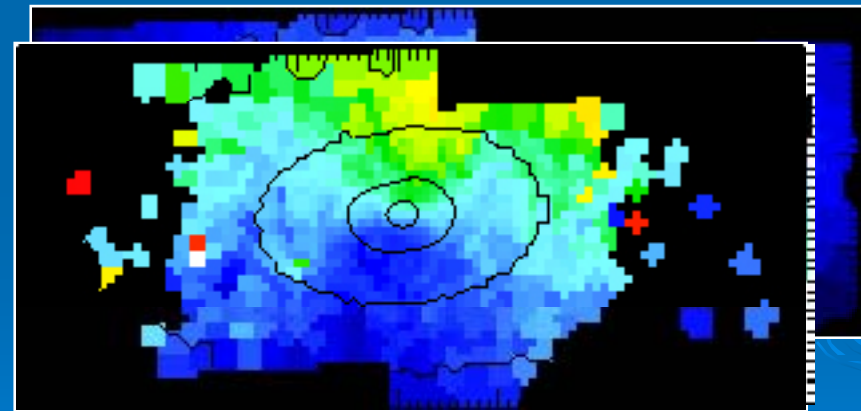
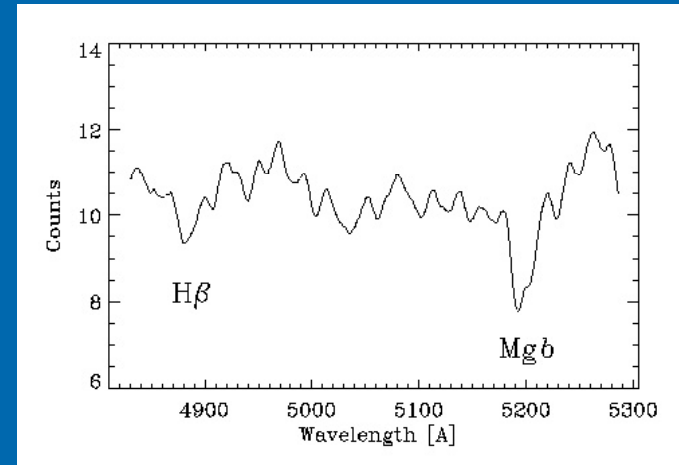
48 Representative E/S0 Galaxies





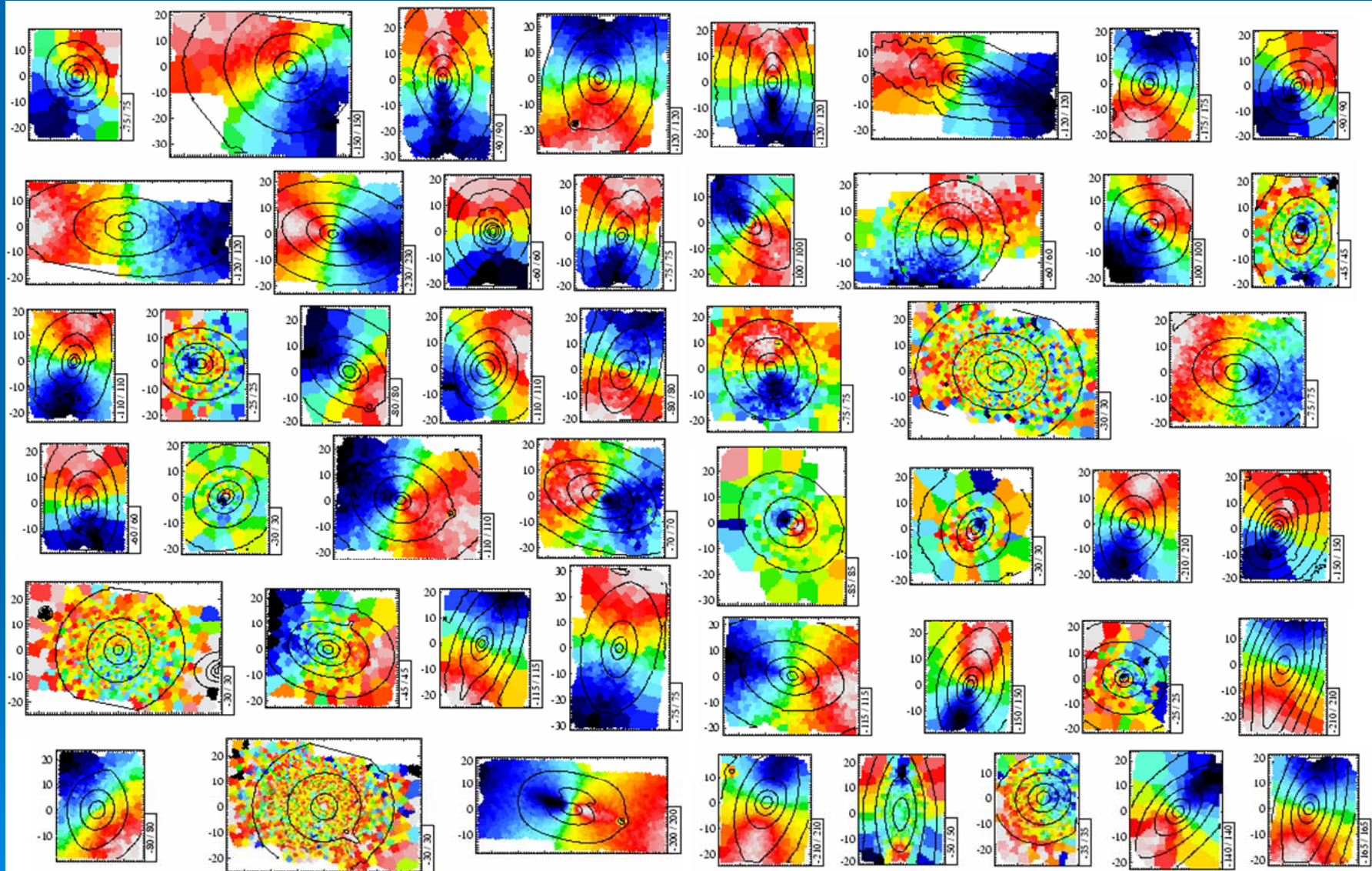
Integral Field Data

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



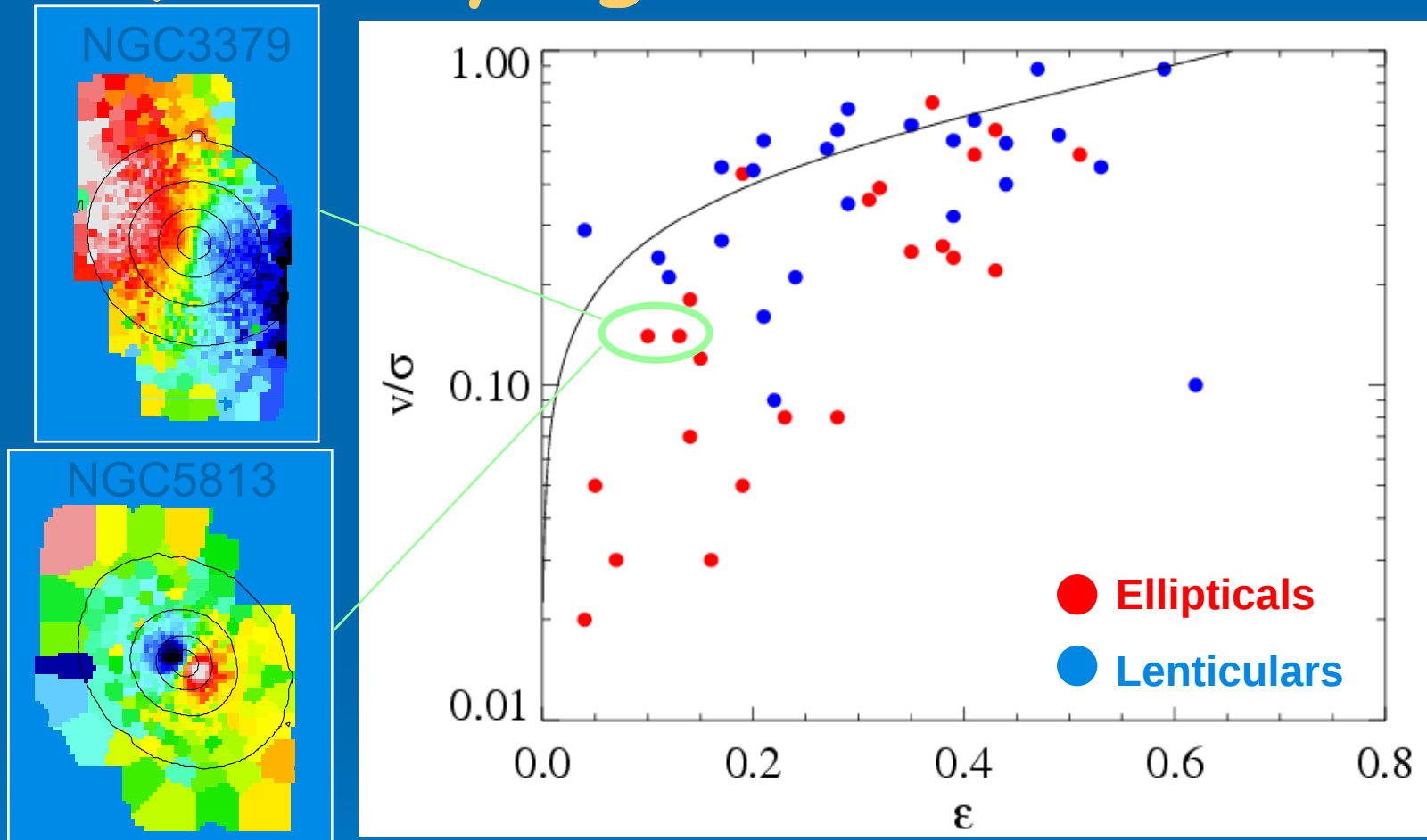
Stellar Kinematics

SAURON Stellar Velocity Fields



Emsellem et al. 2004, MNRAS, 352, 721

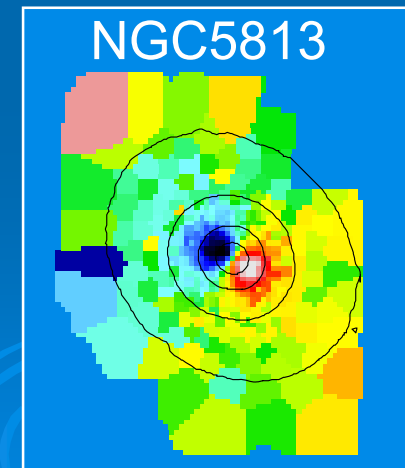
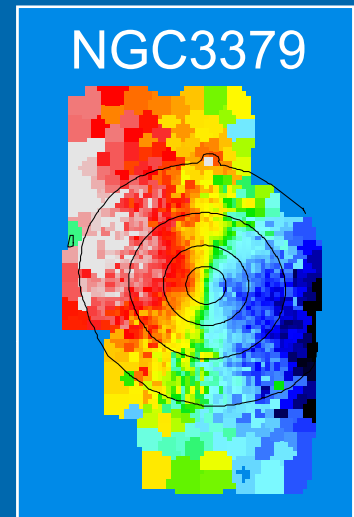
Quantifying Kinematics: V/σ



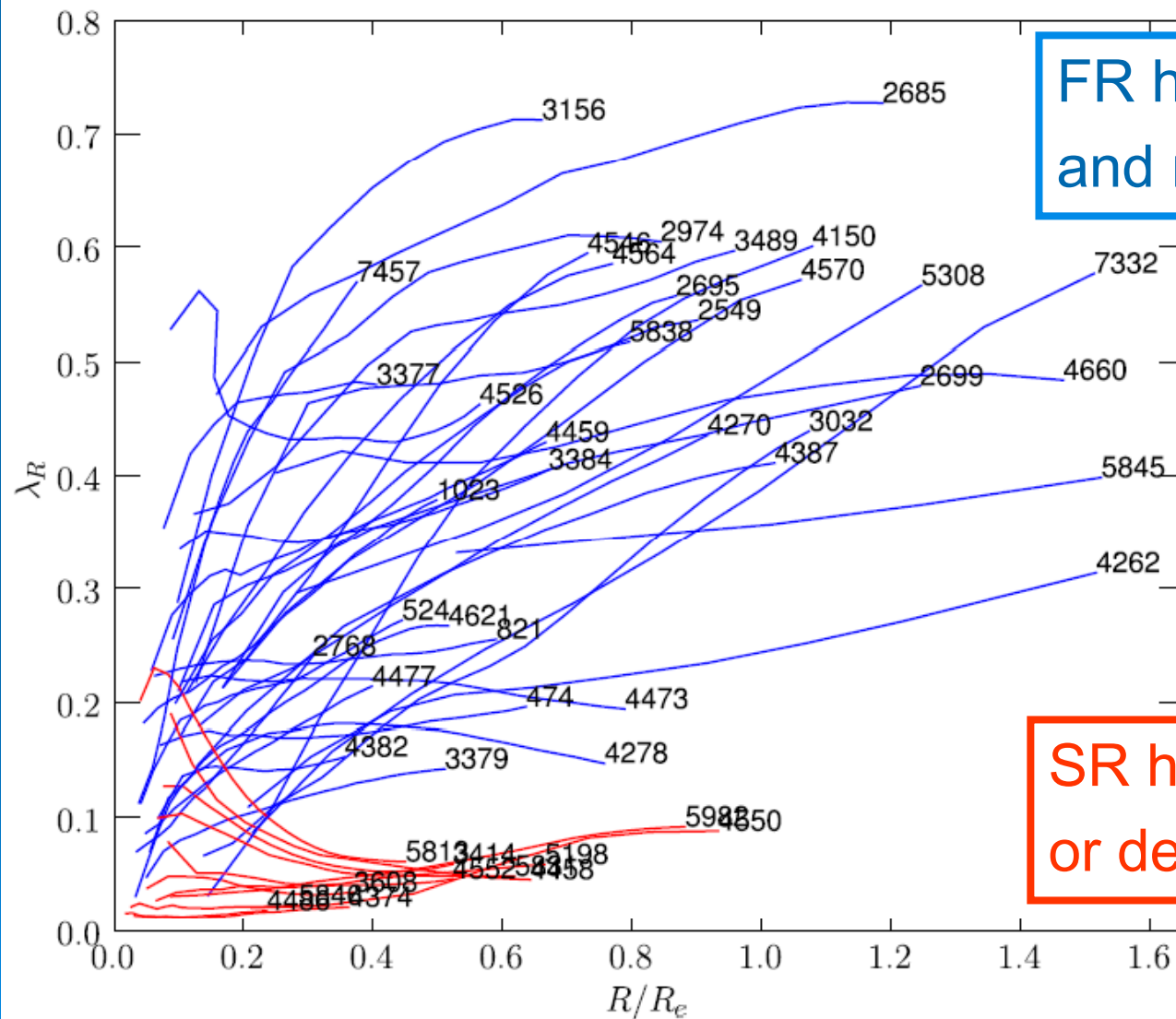
- V/σ quantifies rotation vs. random motion
- Rotating galaxies are 'flatter' (higher ϵ)
- No clear relation with 'E/S0' or velocity maps

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



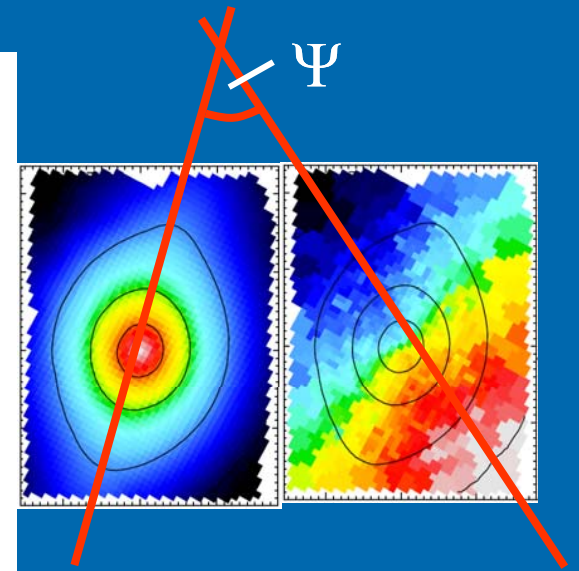
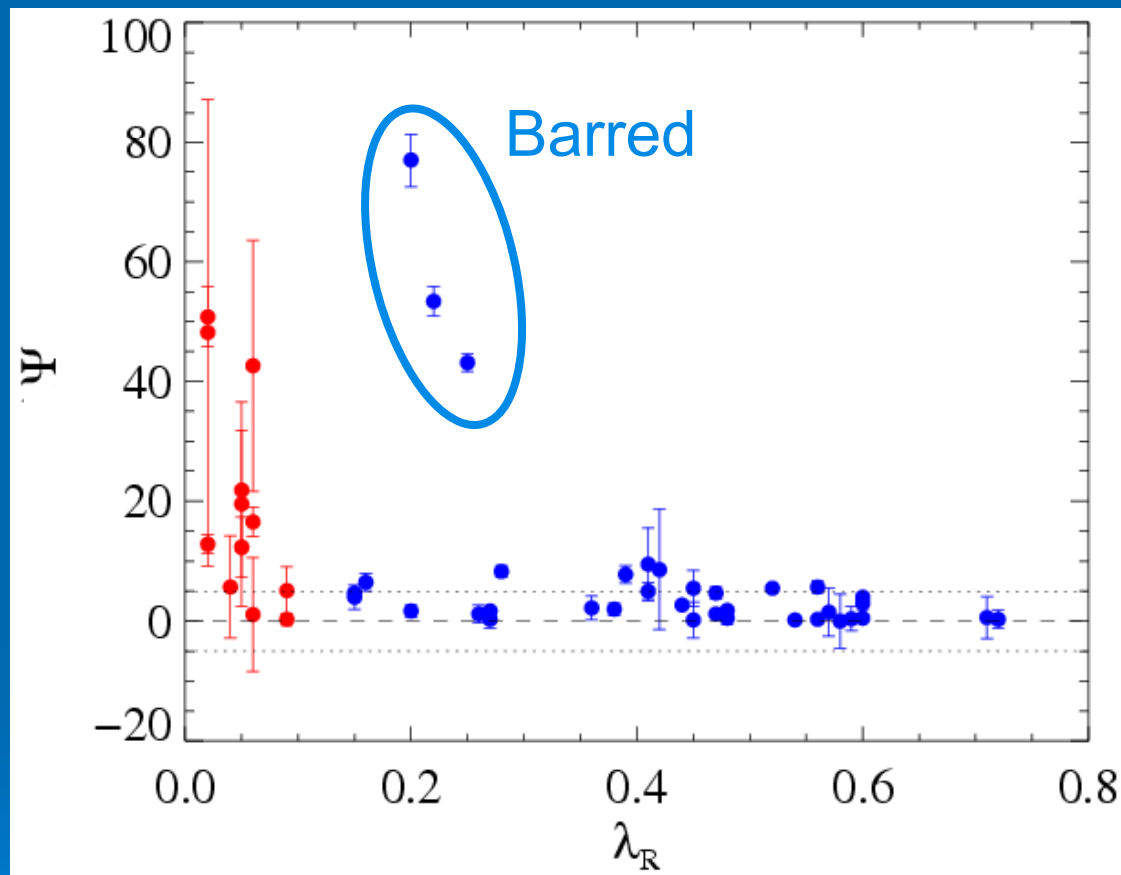
Radial Profile of λ_R



FR have high
and rising λ_R

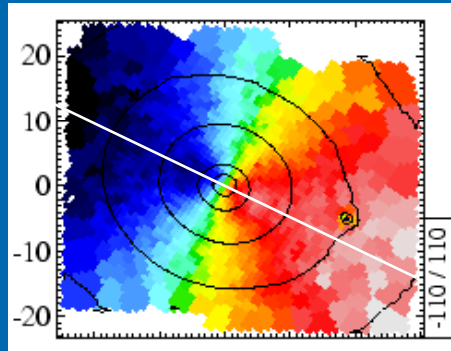
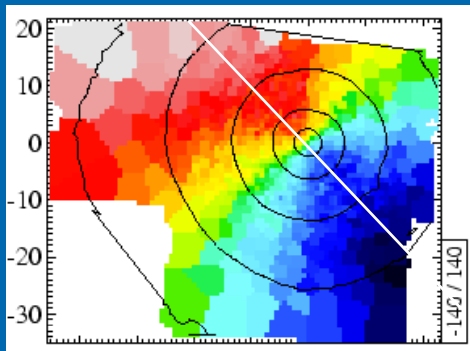
SR have quite flat
or decreasing λ_R

Kinematic Misalignment

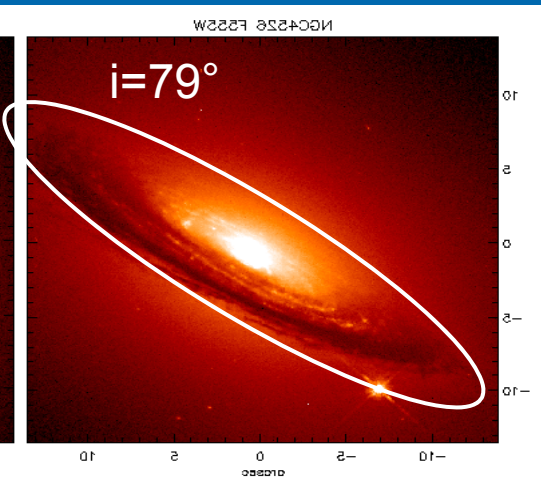
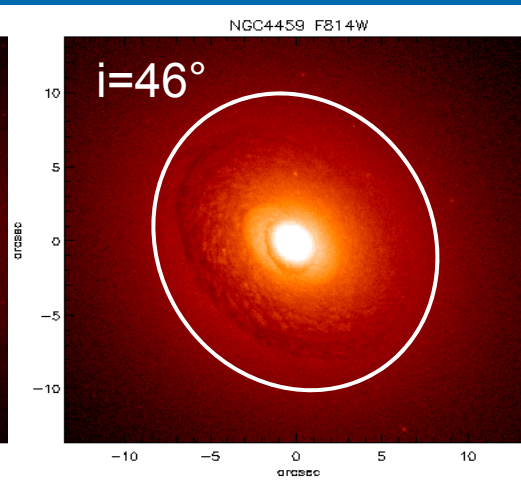
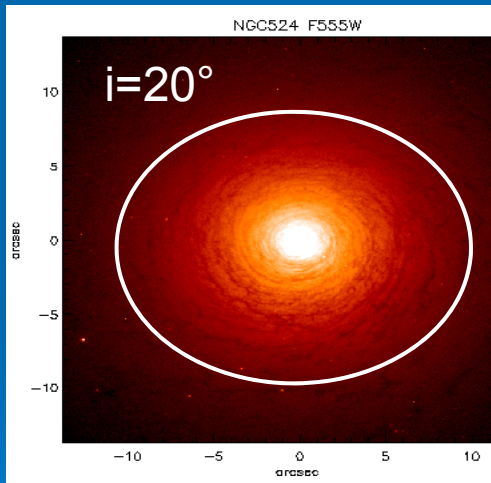
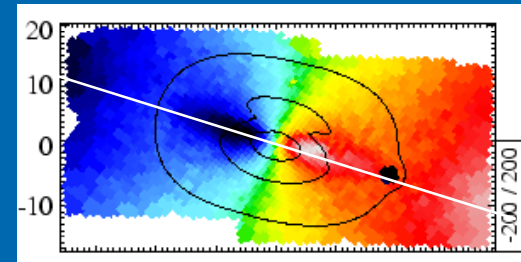


- Fast rotators: generally well-aligned systems
- Slow rotators: less symmetry

Fast Rotators



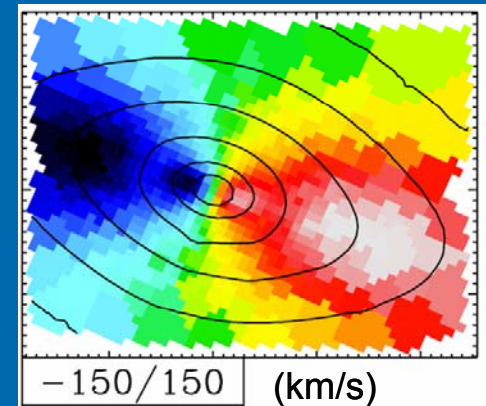
Stellar velocity field



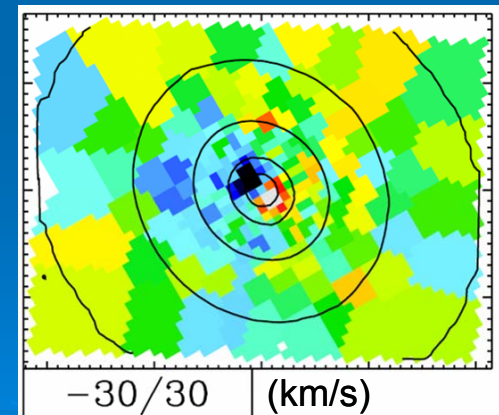
- Stellar kinematics resembles that of circular disk
- Embedded in nearly stationary spheroid/bulge

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



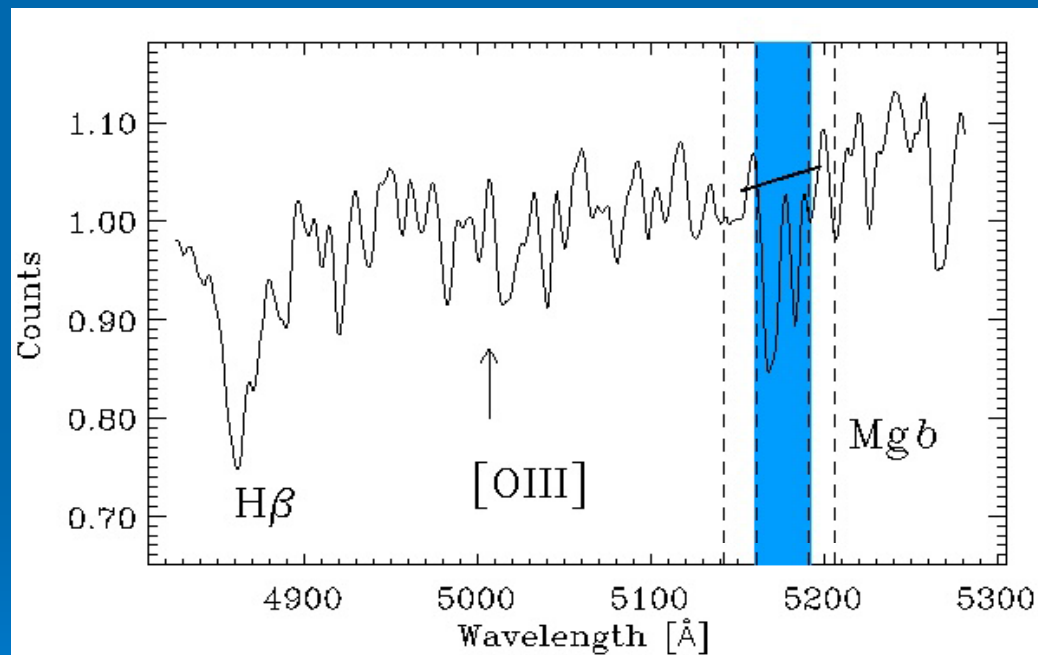
Fast rotator (NGC 4660)



Slow rotator (NGC 4458)

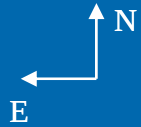
Line-strengths

- SAURON covers $H\beta$, Fe5015, [OIII], Mgb & Fe5270
- Measure Lick/IDS indices



- Stellar population models $\Rightarrow$ luminosity-weighted age and metallicity

Kinematics and Line-strengths



NGC 4546

NGC 4570

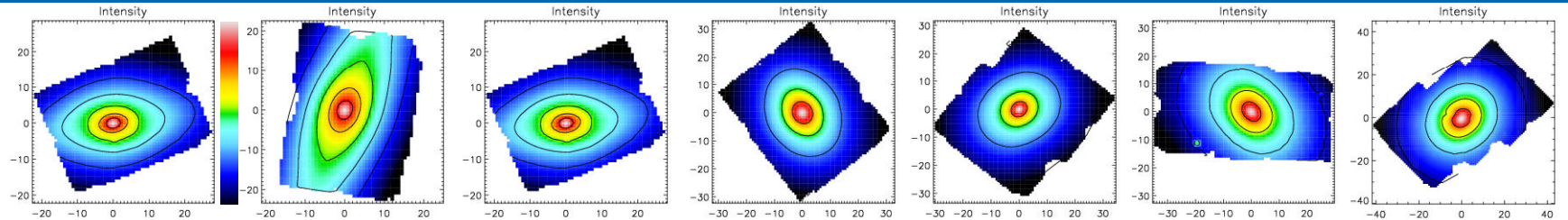
NGC 4660

NGC 4382

NGC 4406

NGC 4365

NGC 4374



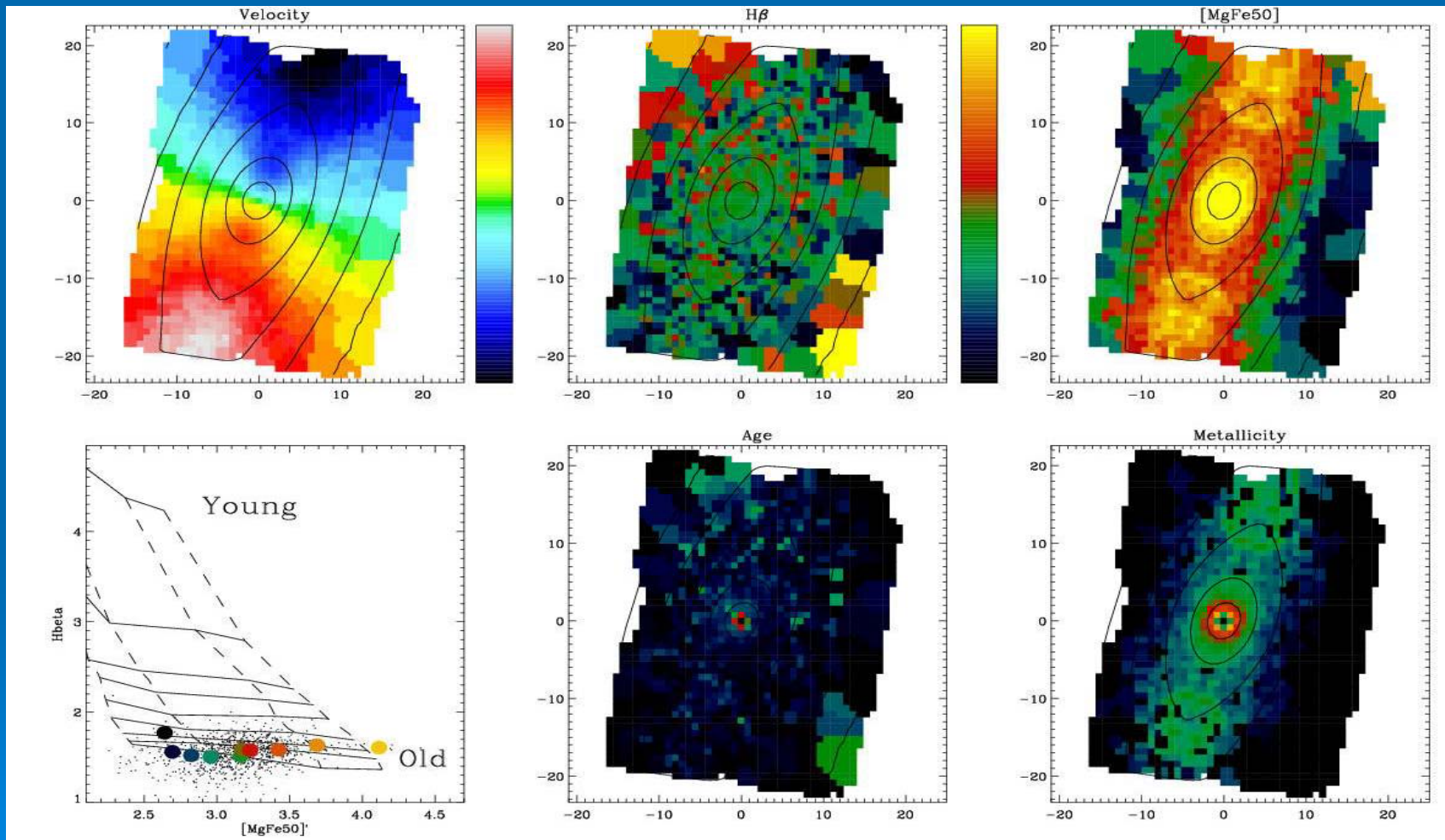
I

V

Mgb

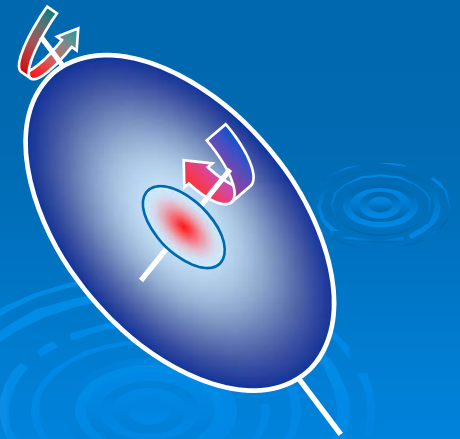
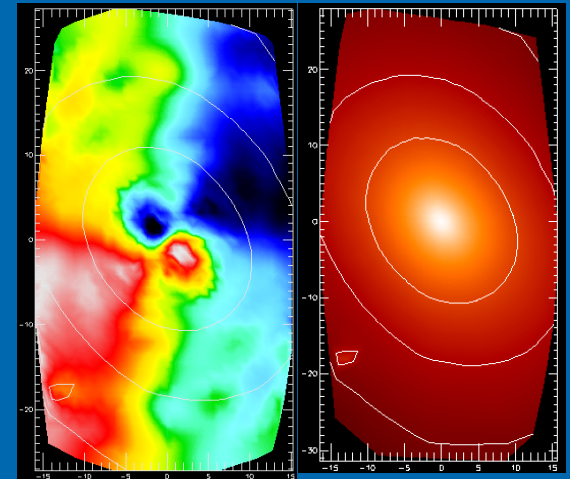
Fe

The Fast Rotator NGC 4570

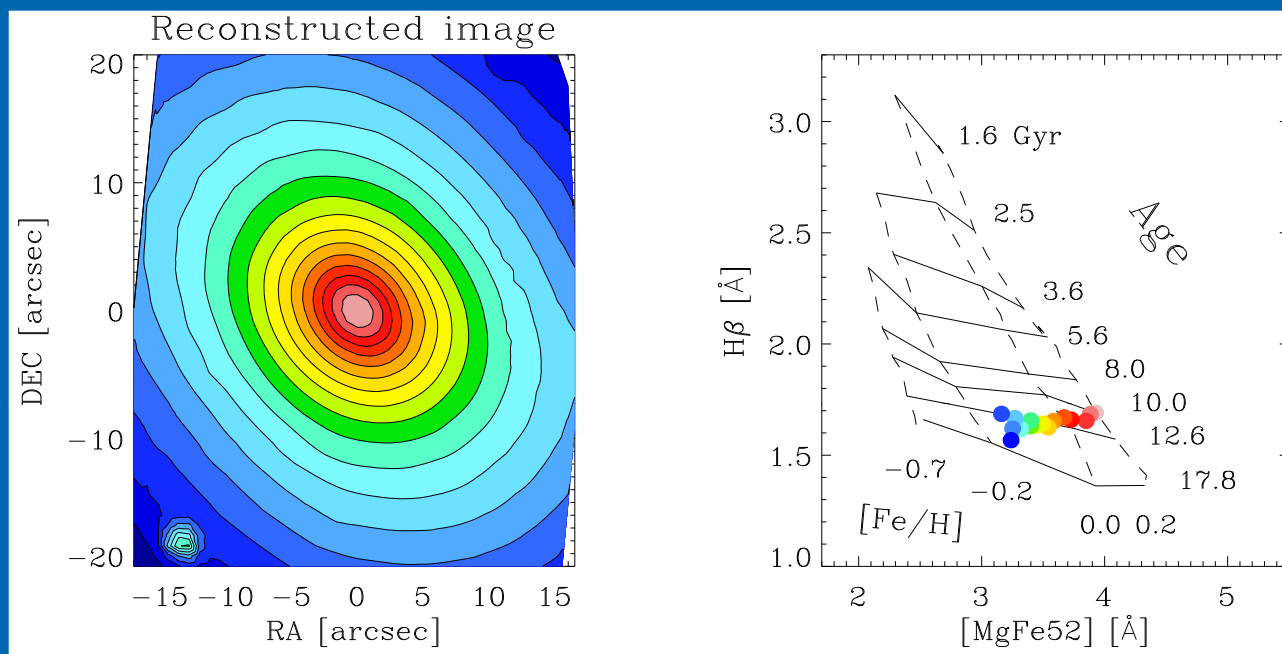


NGC 4365

- 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



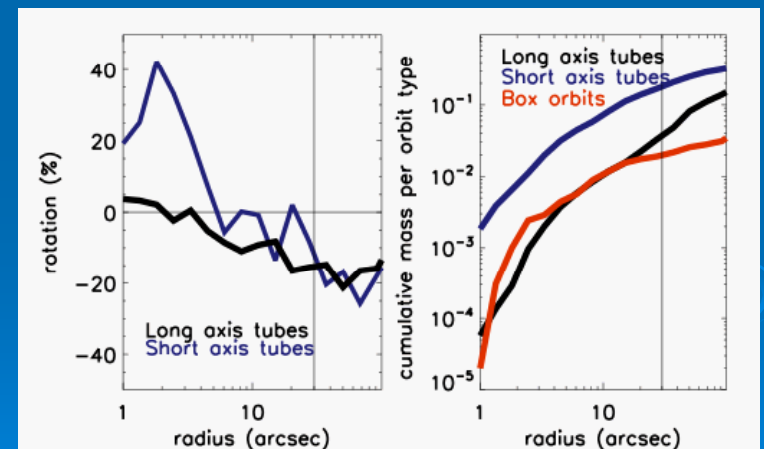
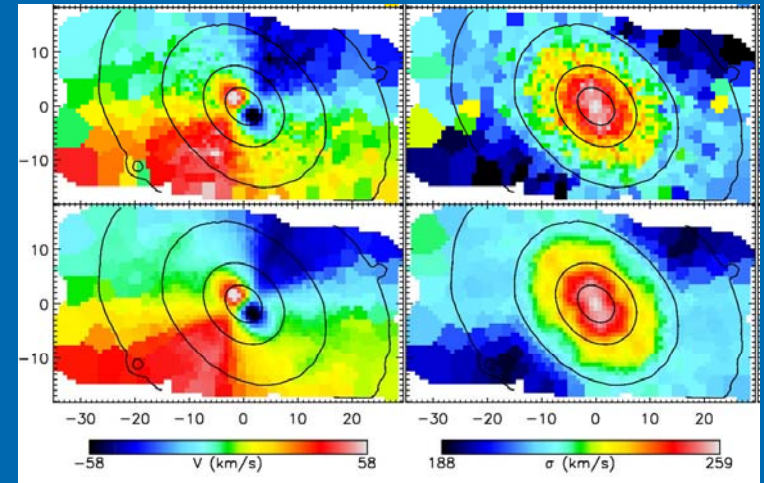
Formation of NGC 4365



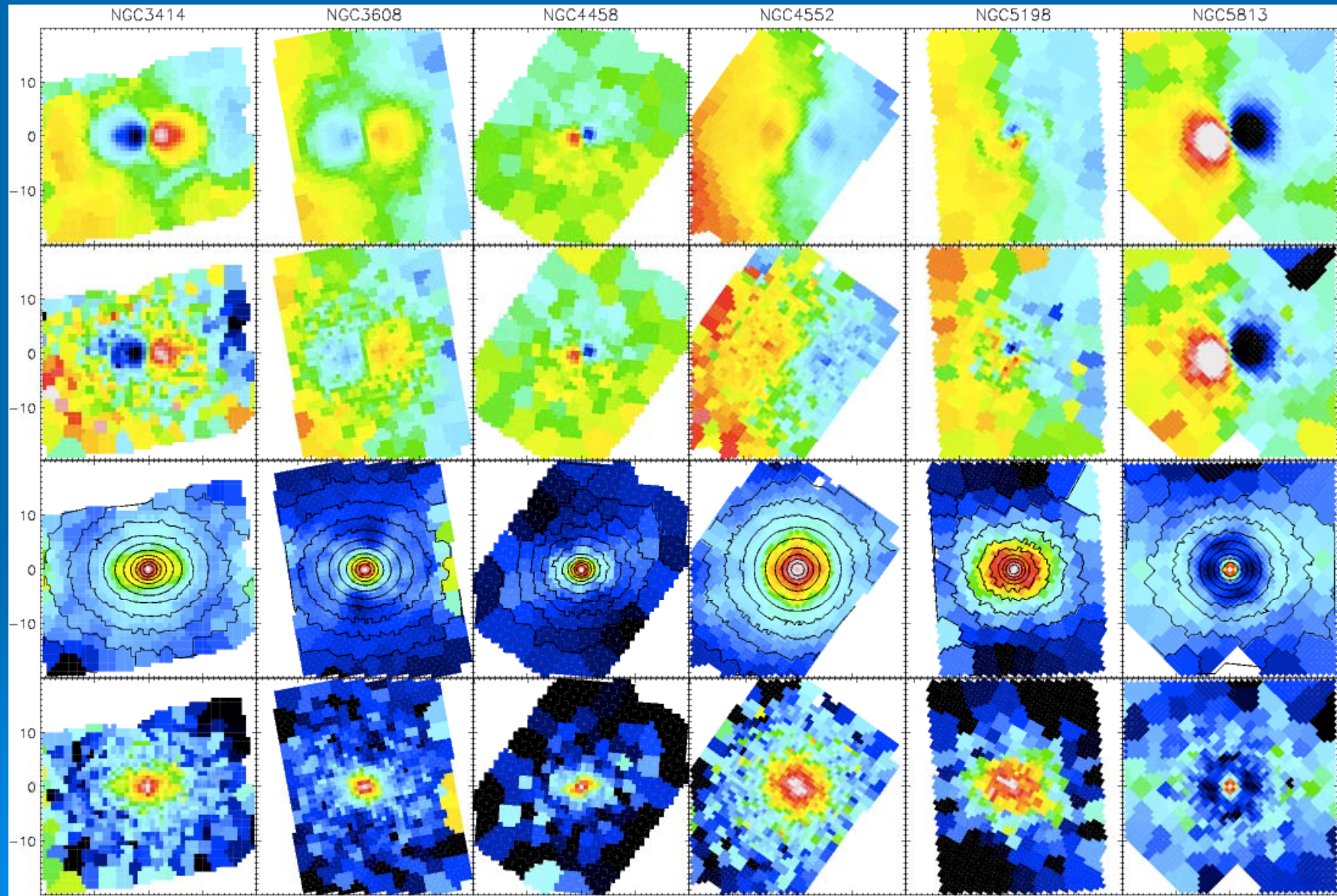
- Core & main body: common star formation history
- No recent star formation: triaxial structure long-lived
- Core remnant of last major accretion on nearly perpendicular orbit more than 12 Gyr ago?

Triaxial Dynamical Model

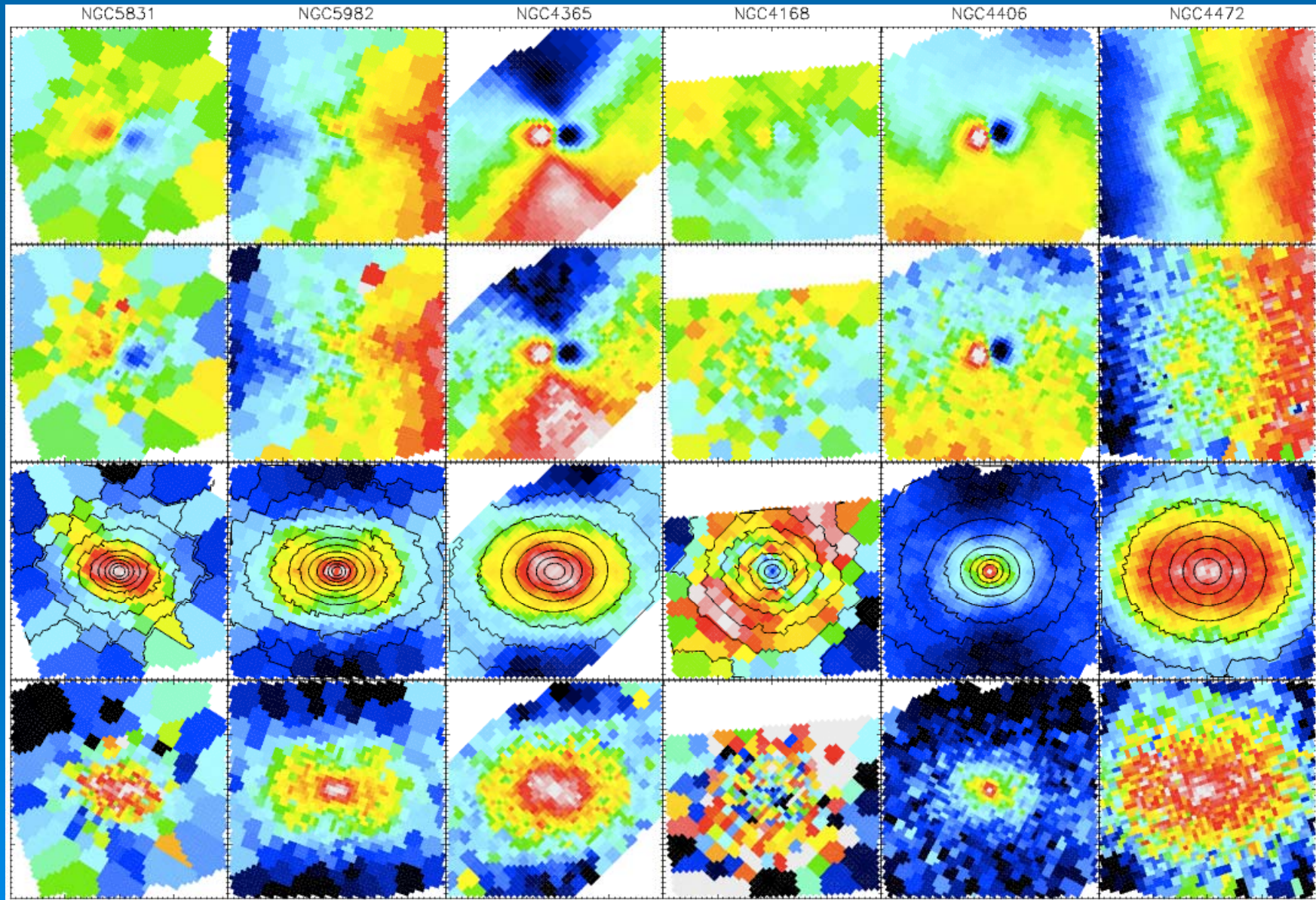
- Parameters
 - Two axis ratios, two viewing angles, M/L , M_{BH}
- Best-fit model
 - Fairly oblate (0.7:0.95:1)
 - Short axis tubes dominate, but $\sim 50\%$ *counter rotate*, except in core; cf NGC4550
 - Long-axis rotation dominates except in core
 - KDC *not* a physical subunit, but appears so because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



Slow Rotators: Triaxial Models

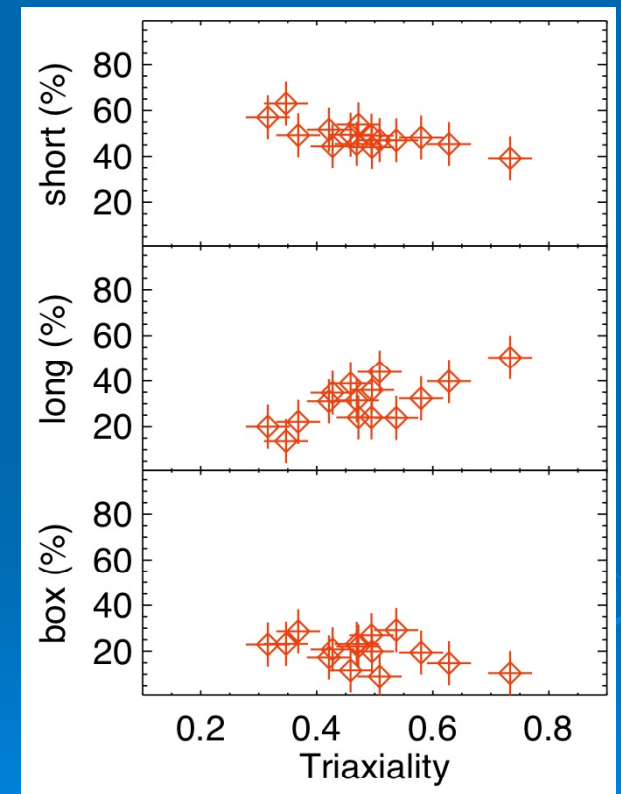


Slow Rotators: Triaxial Models



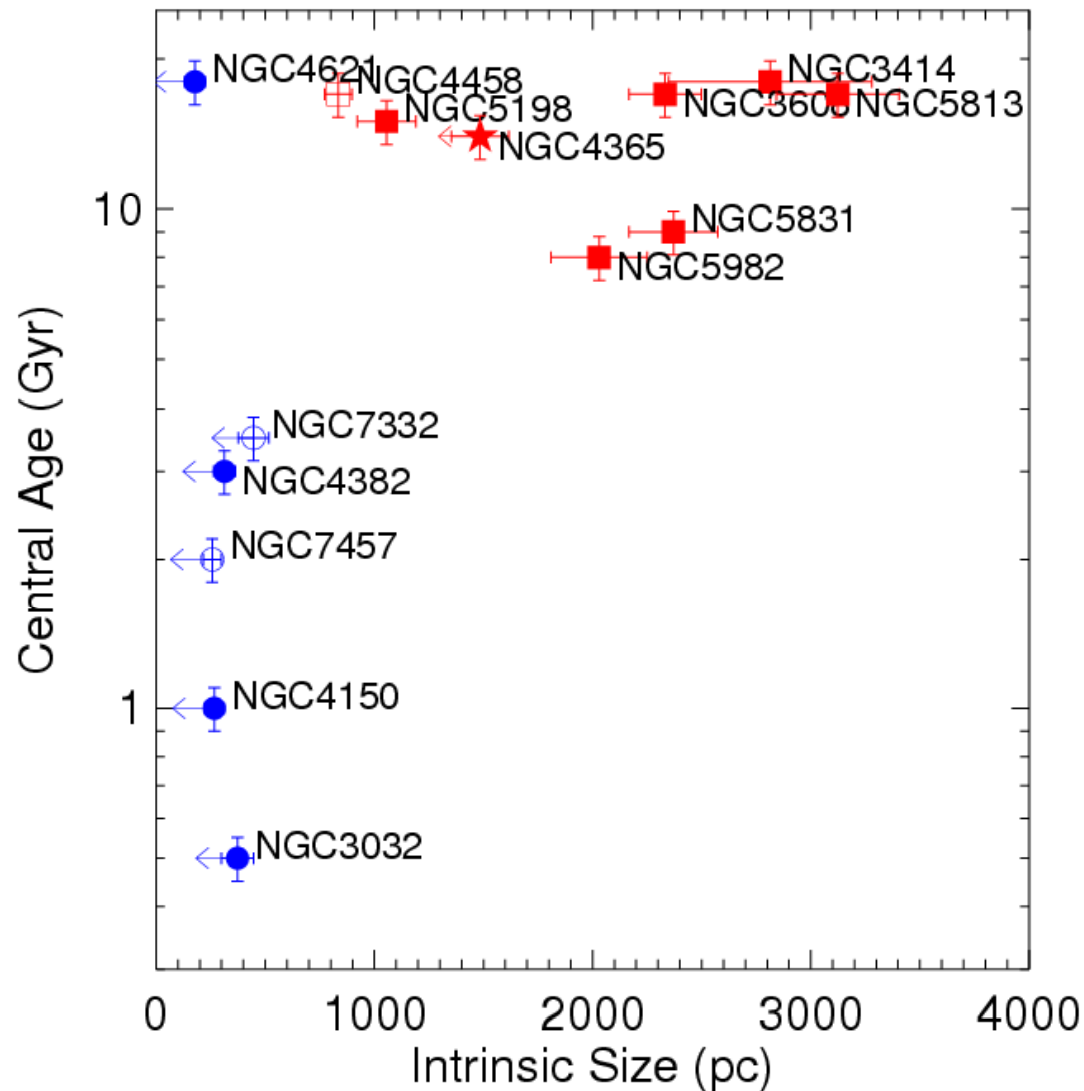
Properties

- 11 slow rotators in representative SAURON sample
 - Range of triaxiality: 0.2 $\bullet$ T $\bullet$ 0.7 $\downarrow$ 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

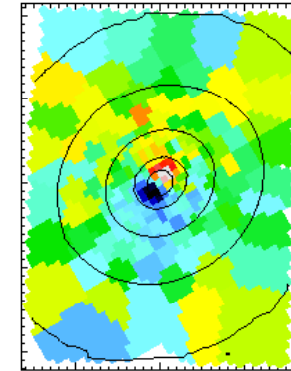


van den Bosch et al. 2008, in prep.

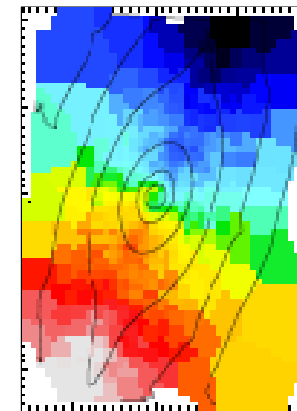
Ages and Sizes of 'KDC's'



■ Slow Rotator

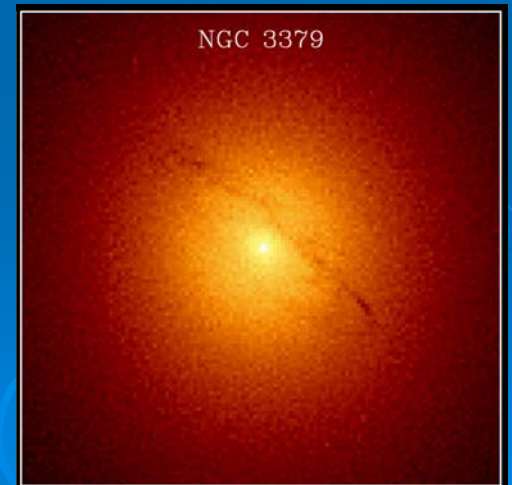


● Fast Rotator



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 $\sim 5^\circ$ $T \sim 0.15$
 - Nearly face-on ($i \sim 40^\circ$)
 - Observed dust lane $\sim$ polar ring
 - M_{BH} *doubles* compared to oblate model
 - Systematic effect in (M_{BH} , $\diamond$) at large $\diamond$?



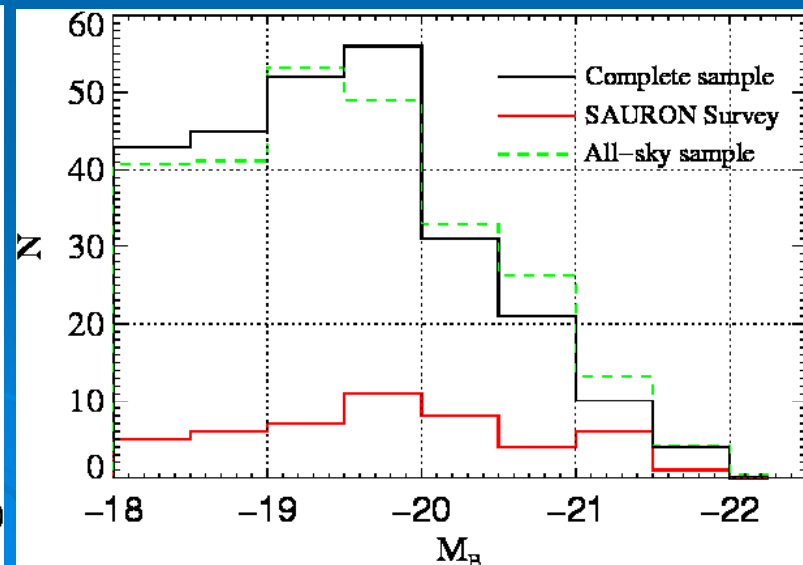
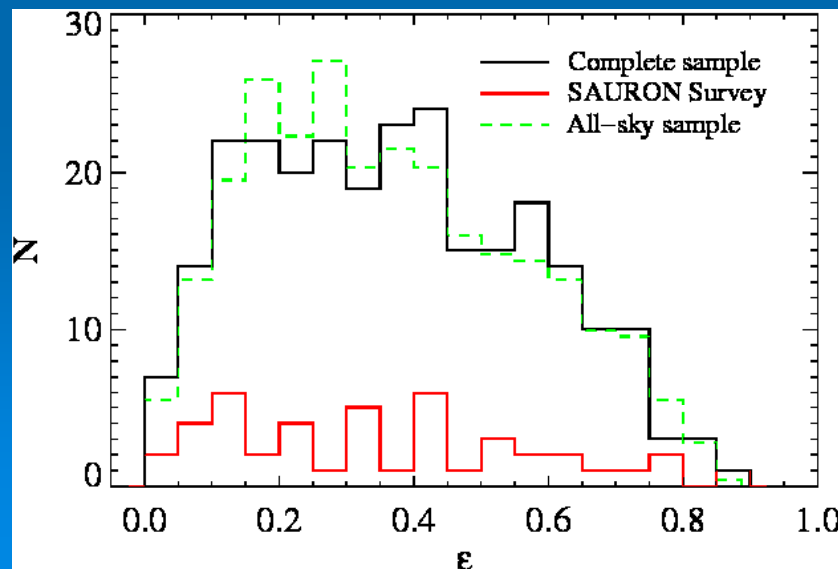
Summary

- 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

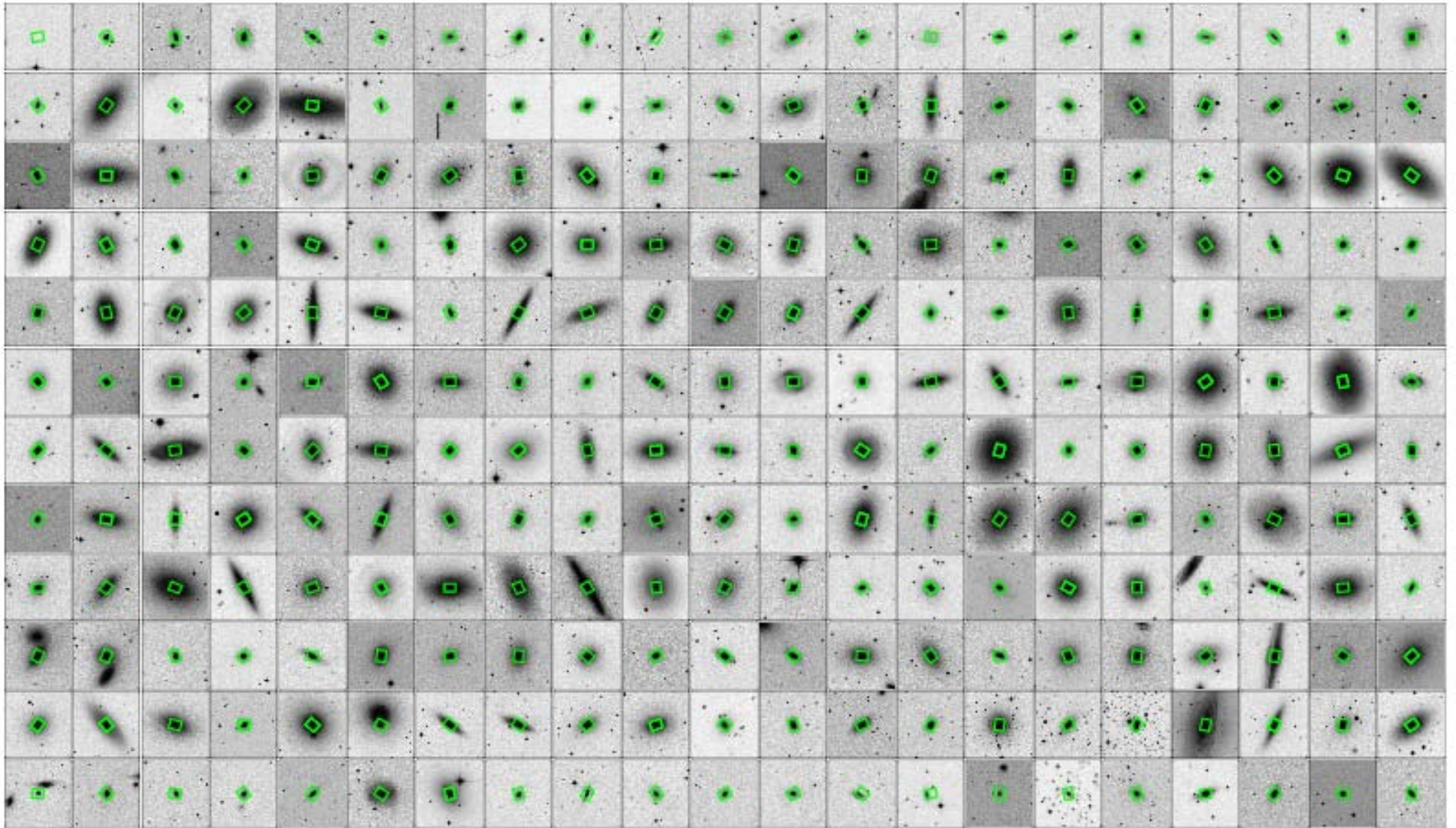


Complete Survey: ATLAS^{3D}

- 48 E/S0's: selection introduces complex biases
- Need *complete* volume-limited sample $\Rightarrow$
 - 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



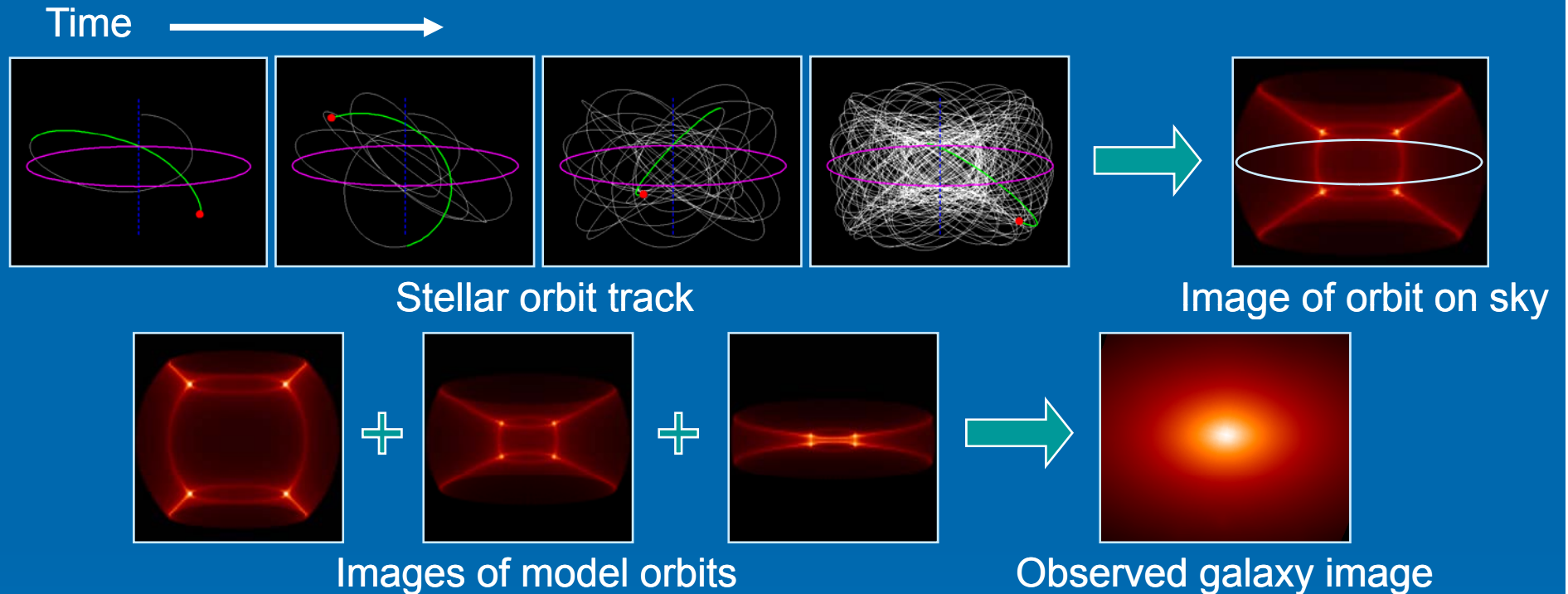
ATLAS^{3D}



PI's: Emsellem, Cappellari, Krajnovic, McDermid



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