Dynamical modeling and black holes of SAURON galaxies

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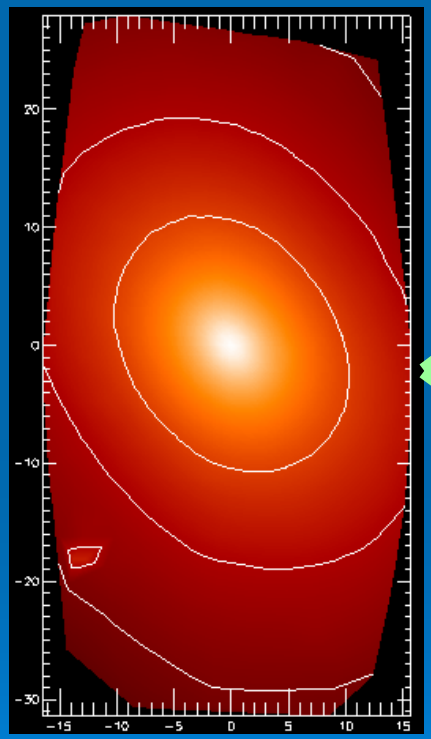
Outline

- The SAURON project
- Reliability of black hole masses
- The next step: orbital distributions
- Conclusions

The SAURON project

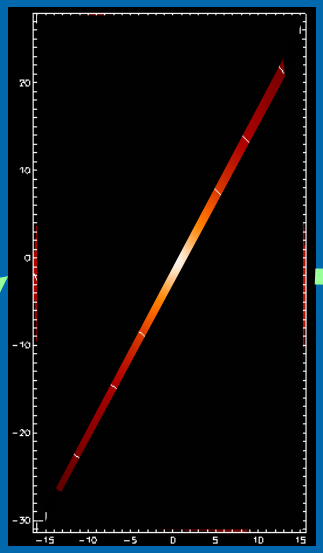
- Systematic study of representative sample of 48 nearby E/S0 and 24 spiral galaxies
- Integral-field spectroscopy from the ground
  - Stars + gas kinematics and line strength maps
- Hubble Space Telescope imaging (and some STIS spectroscopy)
- Construction of models to determine:
  - Intrinsic shape and orbital distribution of the stars
  - Mass of central black hole
  - History of metal enrichment of the stars

Integral-field spectroscopy

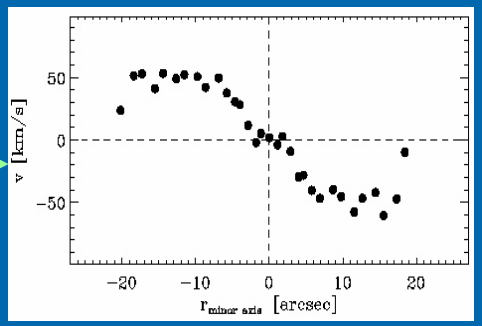


Galaxy Image

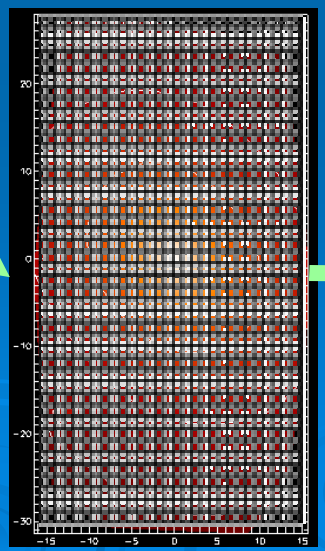
Long slit



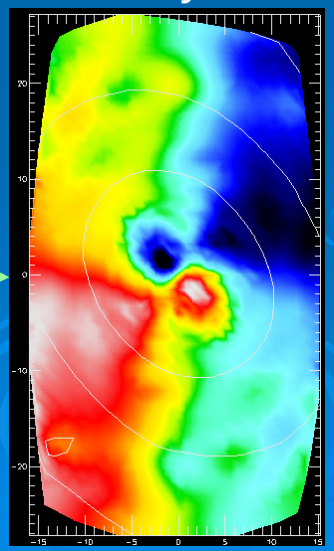
Velocity curve



Integral field



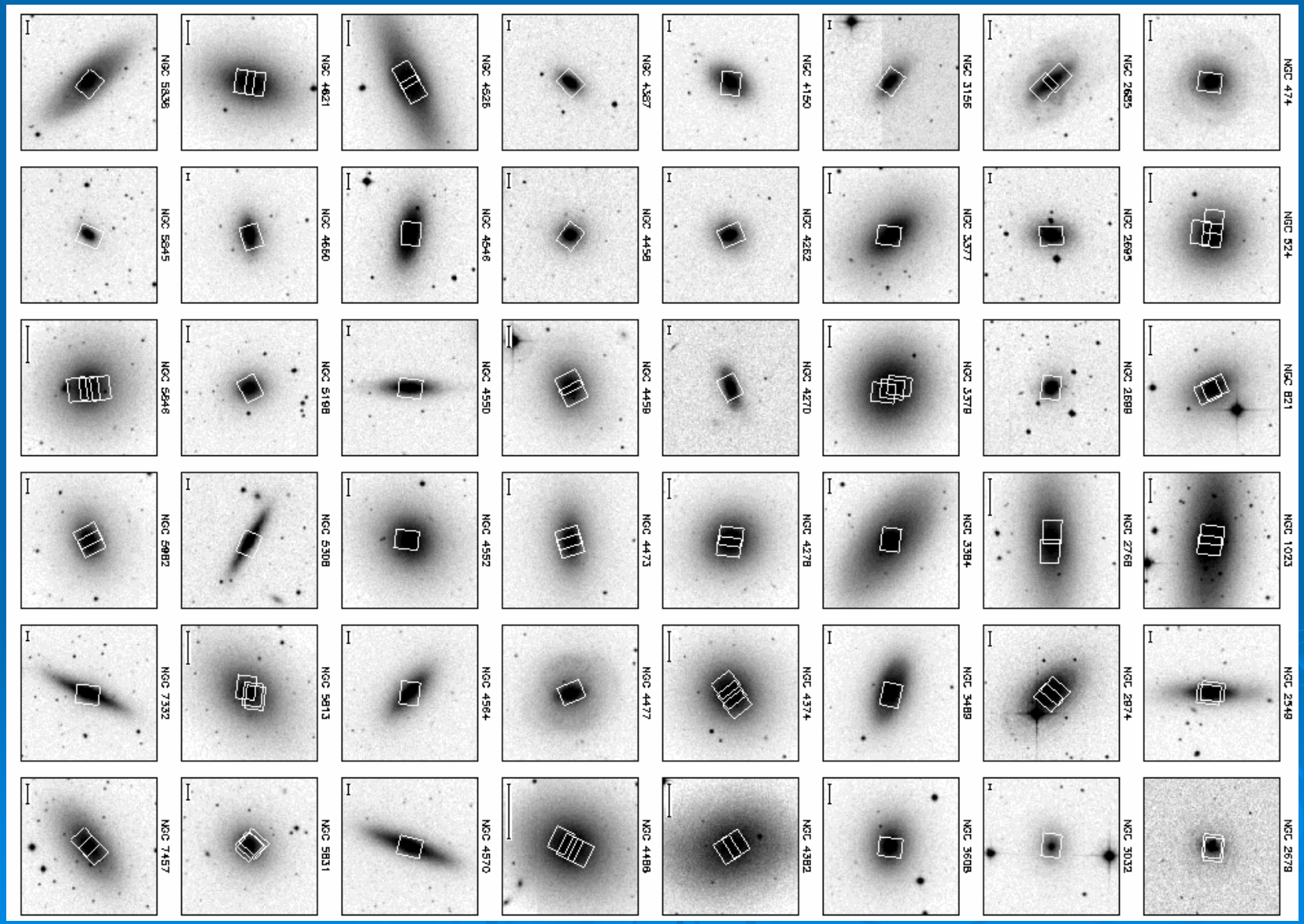
Velocity field



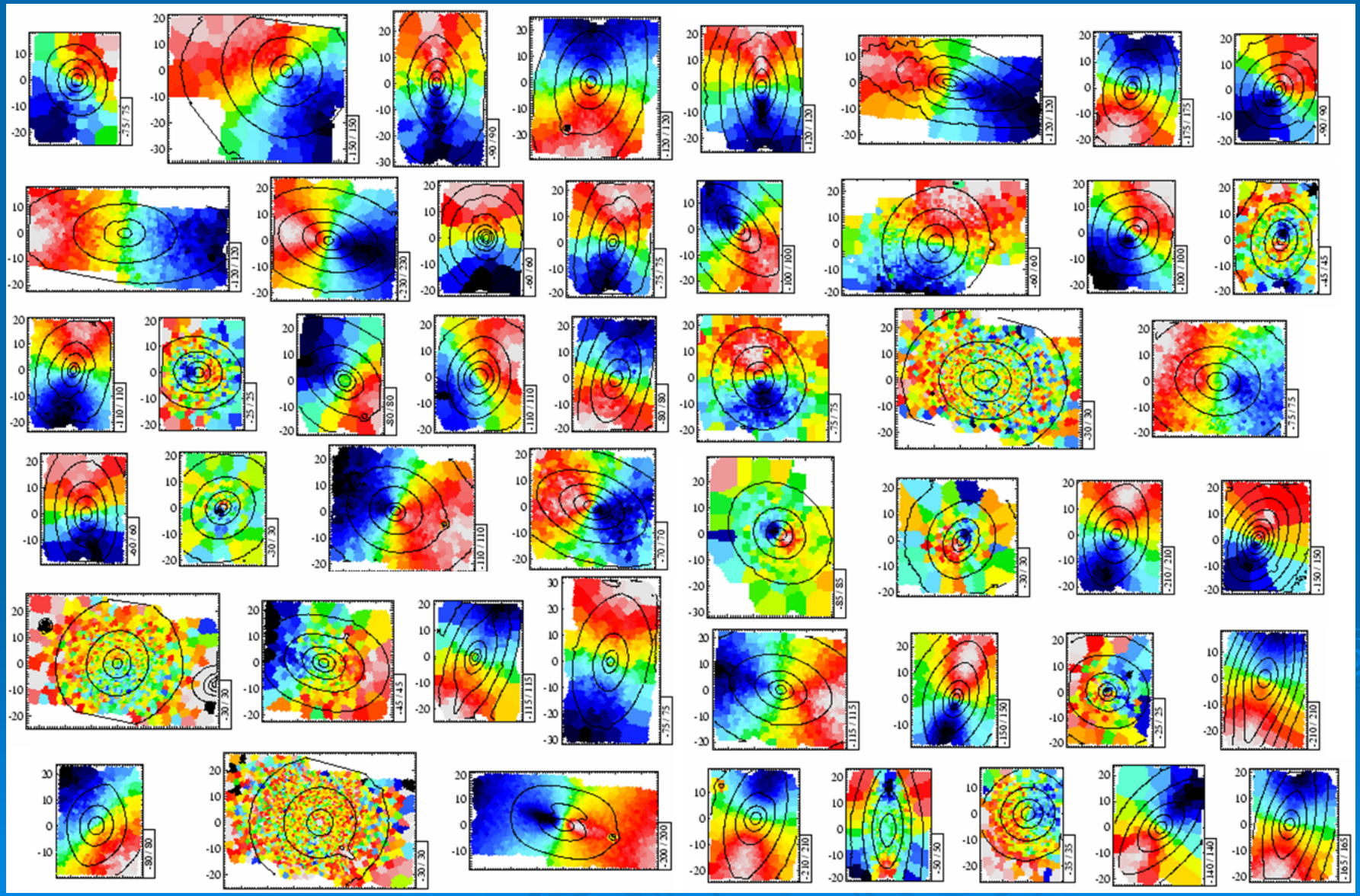
The SAURON team

- PIs: Bacon, Davies, de Zeeuw
  (Lyon) (Oxford) (Leiden)
- COIs: Bureau, Cappellari, Emsellem, Falcon-Barroso, Krajnovic, Kuntschner, McDermid, Peletier
- http://www.strw.leidenuniv.nl/sauron

48 representative early-type galaxies

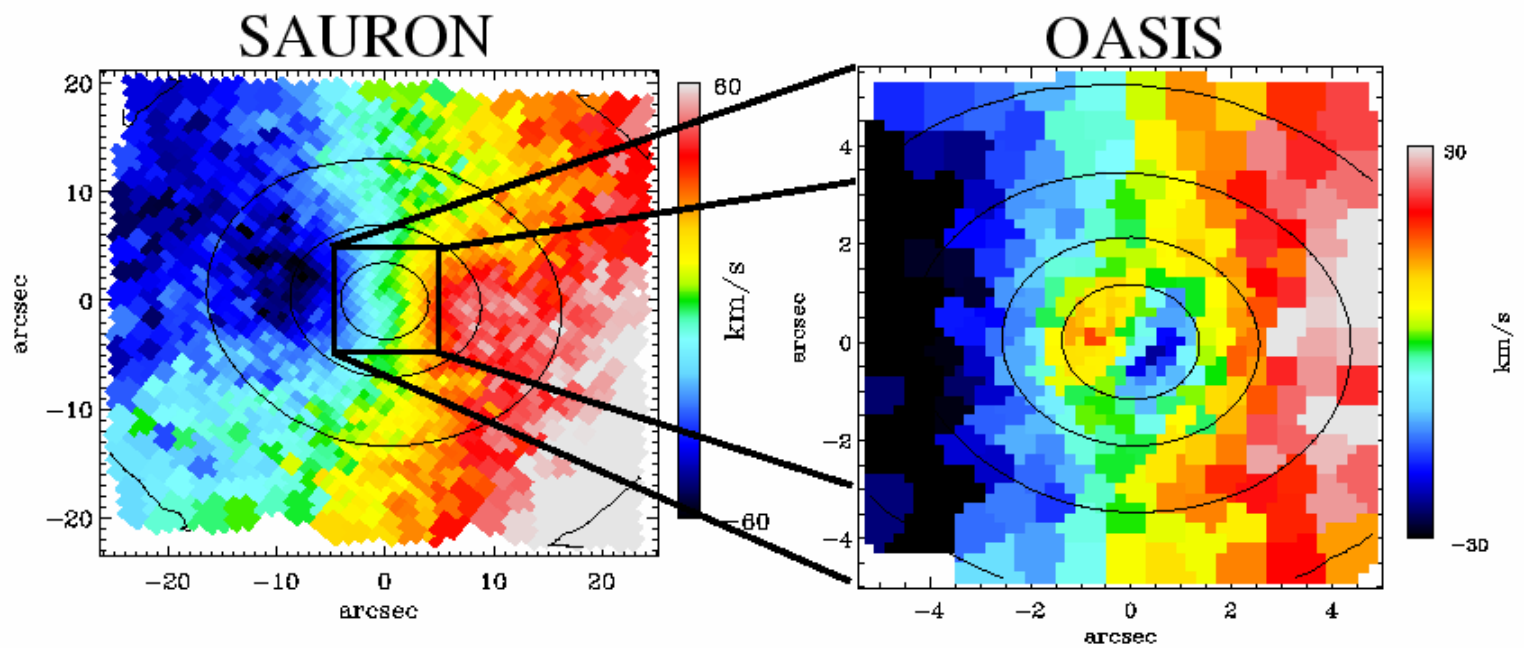


SAURON stellar velocity fields



Emsellem, et al. 2004, MNRAS, in press

Kinematic structure on all scales



NGC 4382 McDermid et al., 2004, AN, 325, 100

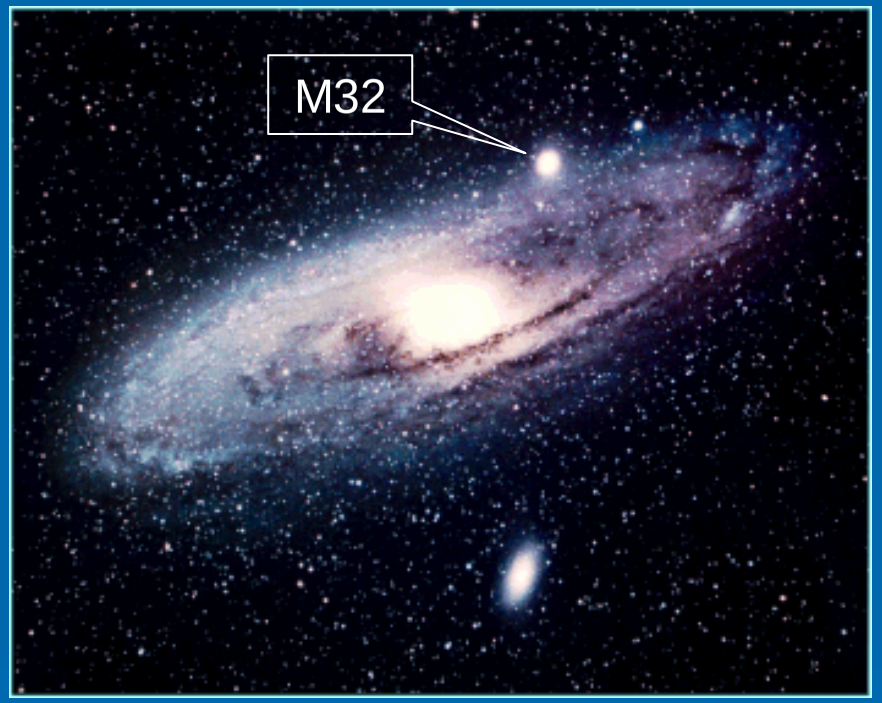
- SAURON: global kinematics and line-strengths
- OASIS spatial resolution: zoom-in on nucleus
- Allows study of orbital structure near central BH

Dynamical modeling: key aspects

- Statistically selected galaxy sample
- SAURON + OASIS two-dimensional kinematics
- Homogeneously reduced data
- Stable *I*-band HST photometry
- Accurate distances with surface-brightness fluctuations method
- Uniform modeling method and setup

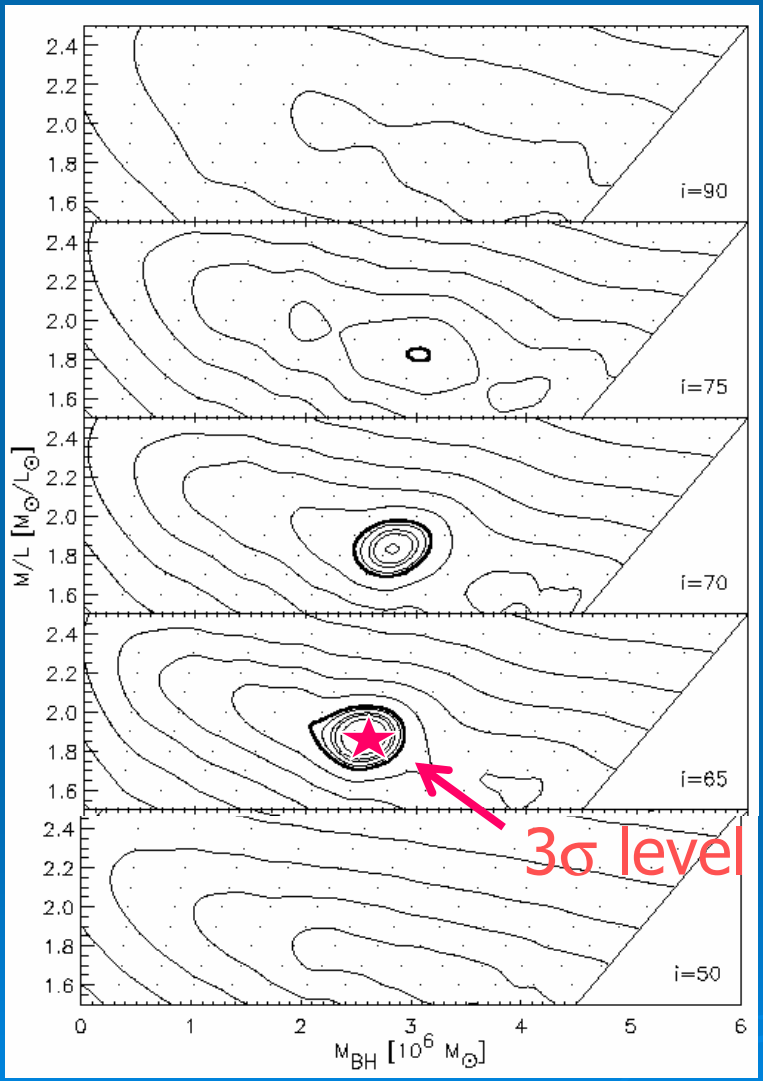
The Black Hole in M32

- Small companion of Andromeda Nebula
- D ~ 0.8 Mpc
- $M_{BH} \sim 3 \times 10^6 M_\odot$
- Influences kinematics inside ~ 0.1"



- Use stellar absorption-line spectroscopy:
  - Integral-field data to measure intrinsic shape and M/L
  - HST/STIS to measure BH mass
- Fit with numerical dynamical models

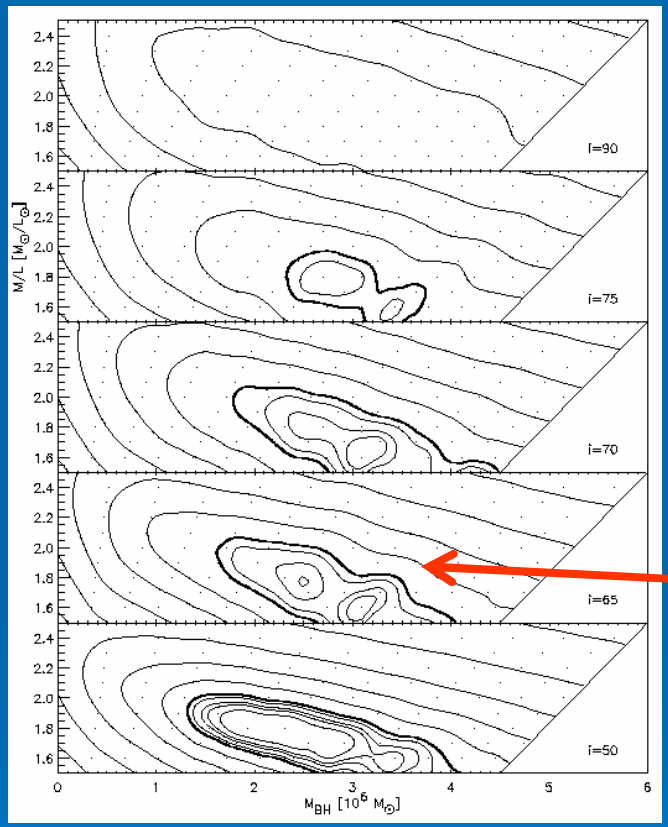
M32: Best-fitting Parameters



- Dynamical models for stellar motions have 3 parameters: M/L, M_{BH}, and inclination
- These are constrained by STIS and SAURON data
- $M_{BH} = (2.5 \pm 0.4) \times 10^6\ M_\odot$
- Agreement with earlier determination
  $M_{BH} = (3.4 \pm 1.6) \times 10^6\ M_\odot$
  (van der Marel et al. 1998, ApJ, 493, 613)

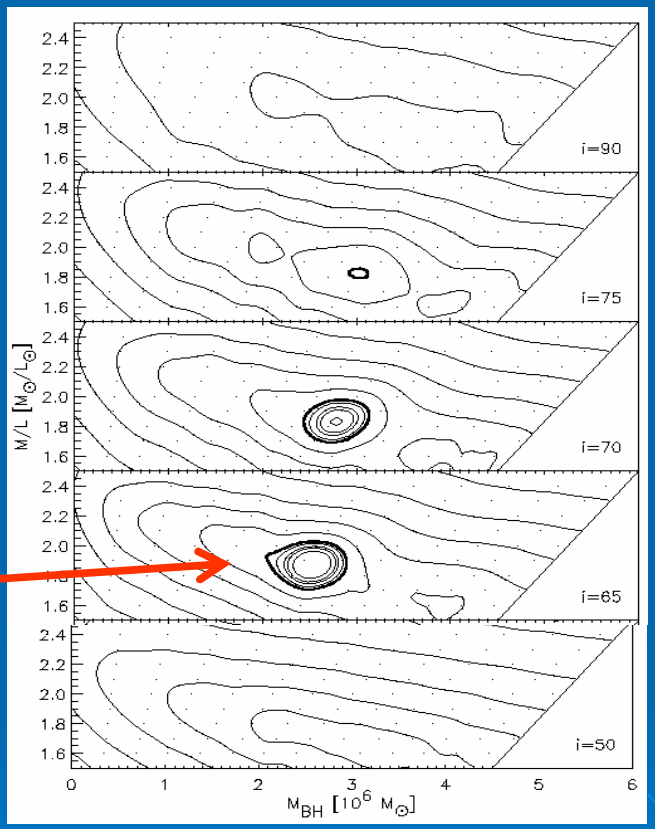
Verolme et al. 2002, MNRAS, 335, 517

M32: importance of 2D kinematics



Four slits + STIS

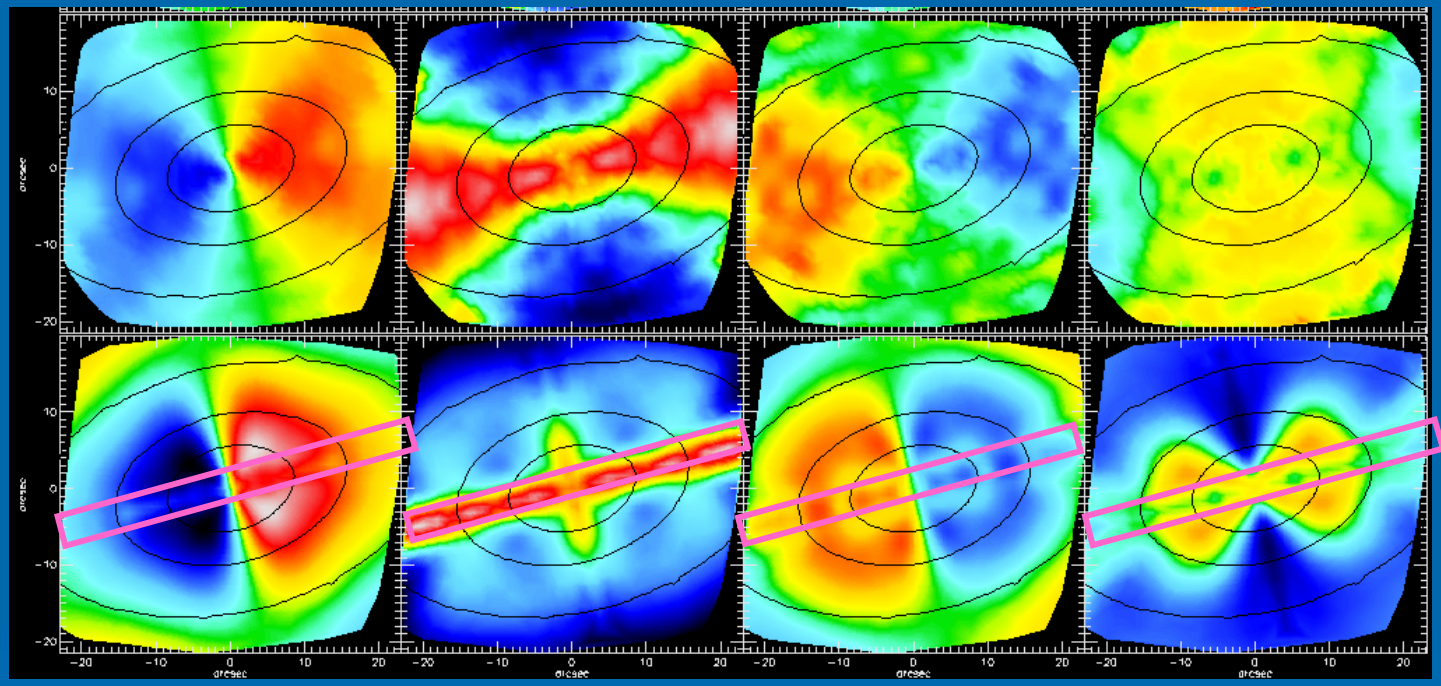
3σ level



SAURON + STIS

Model parameters and internal structure
strongly constrained by integral-field data

Effect of incomplete kinematics coverage



Symmetrized data for NGC4473

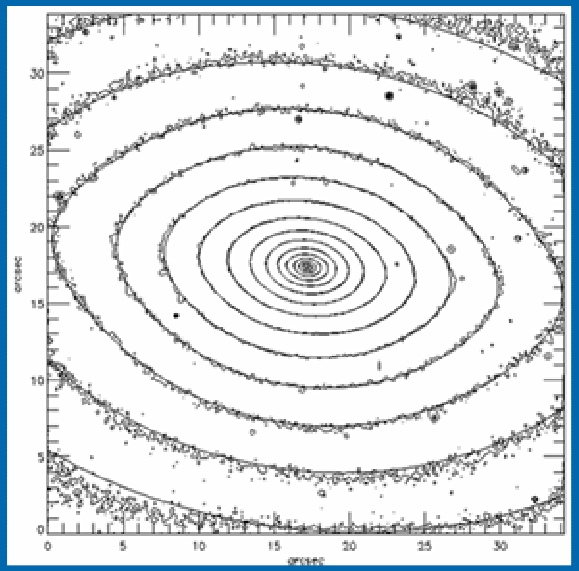
Axisymmetric model

V σ h_3 h_4

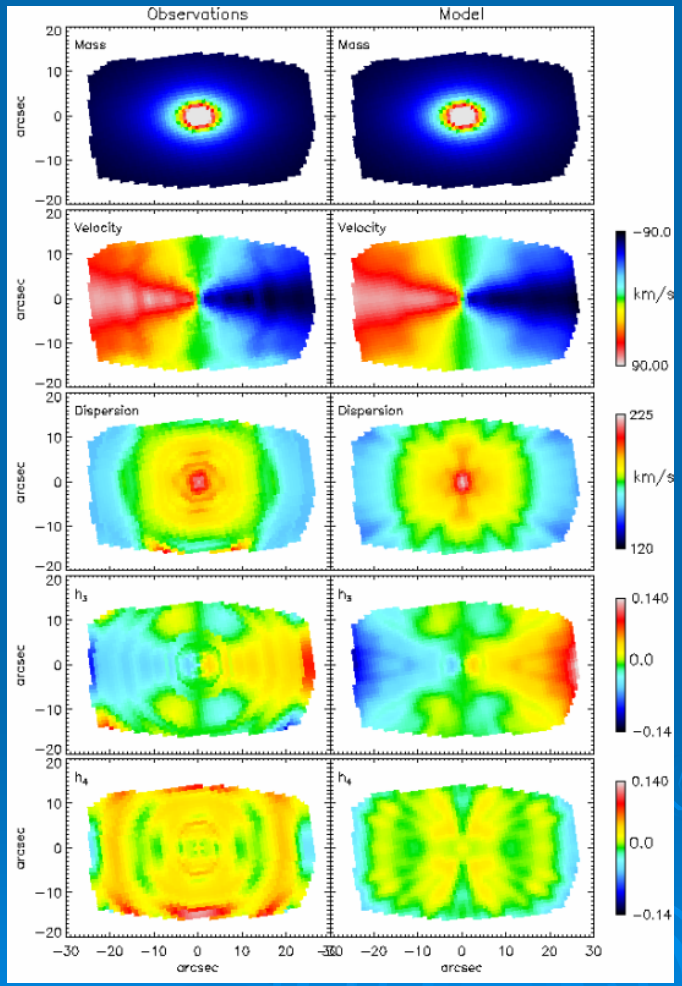
- Model fits major-axis kinematics perfectly
- Little can be recovered of the true orbital structure from incomplete kinematic coverage

The Black Hole in NGC 821

Disky Elliptical



Galaxy image



Symmetrized data and model

- Stellar kinematics:
  - SAURON 2D data
  - HST/STIS
- Fit with numerical dynamical models

Internal check: NGC 821

2058 orbits

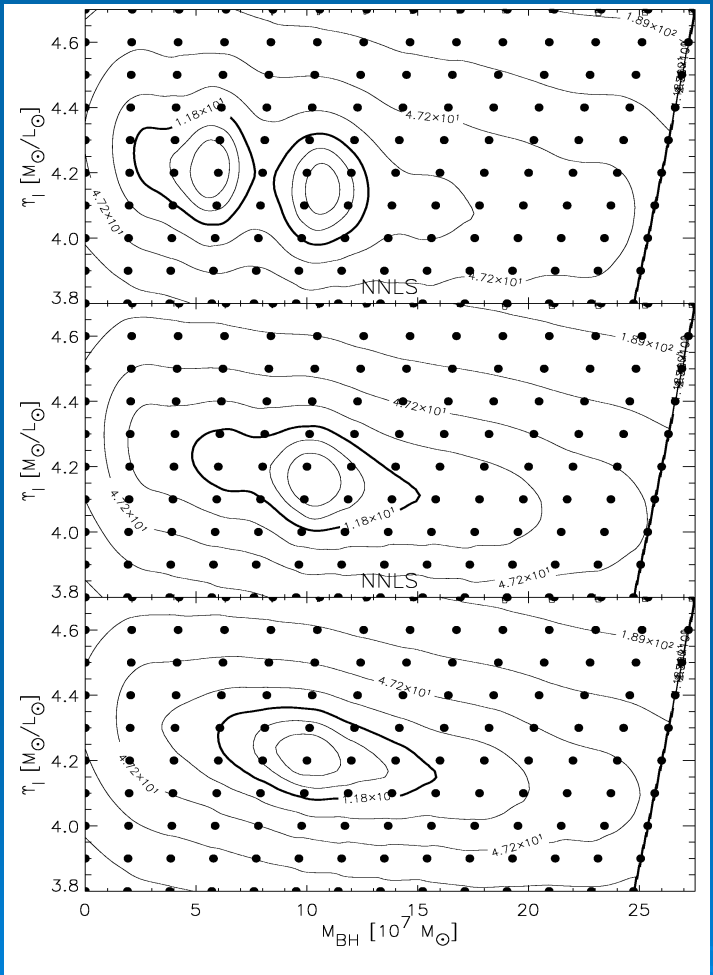
8200 orbits

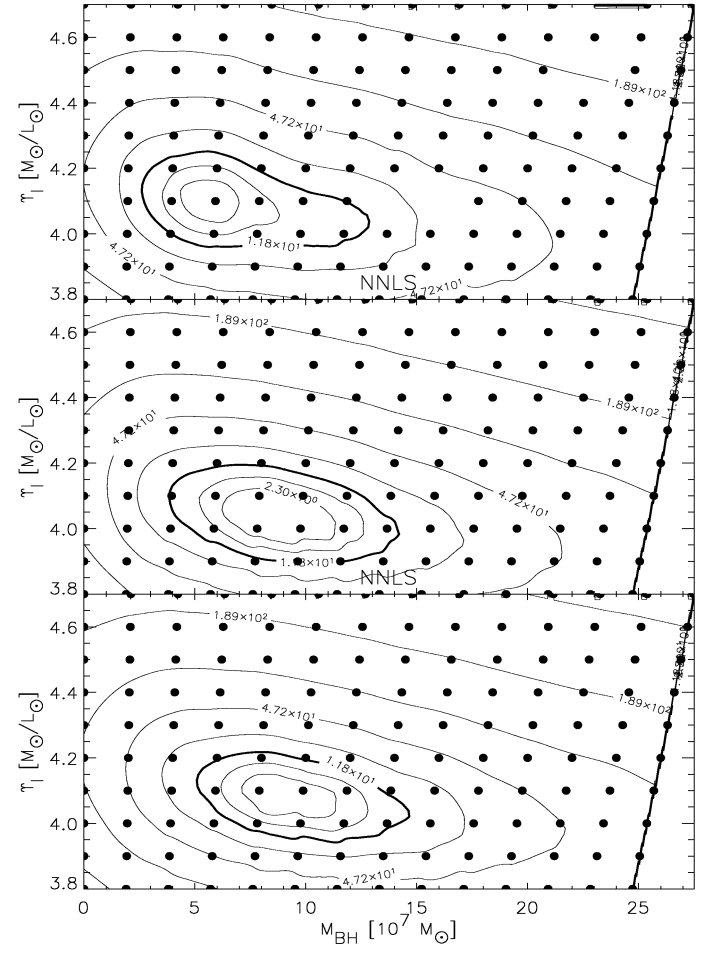
Regularisation

NONE

MEDIUM

EXTREME

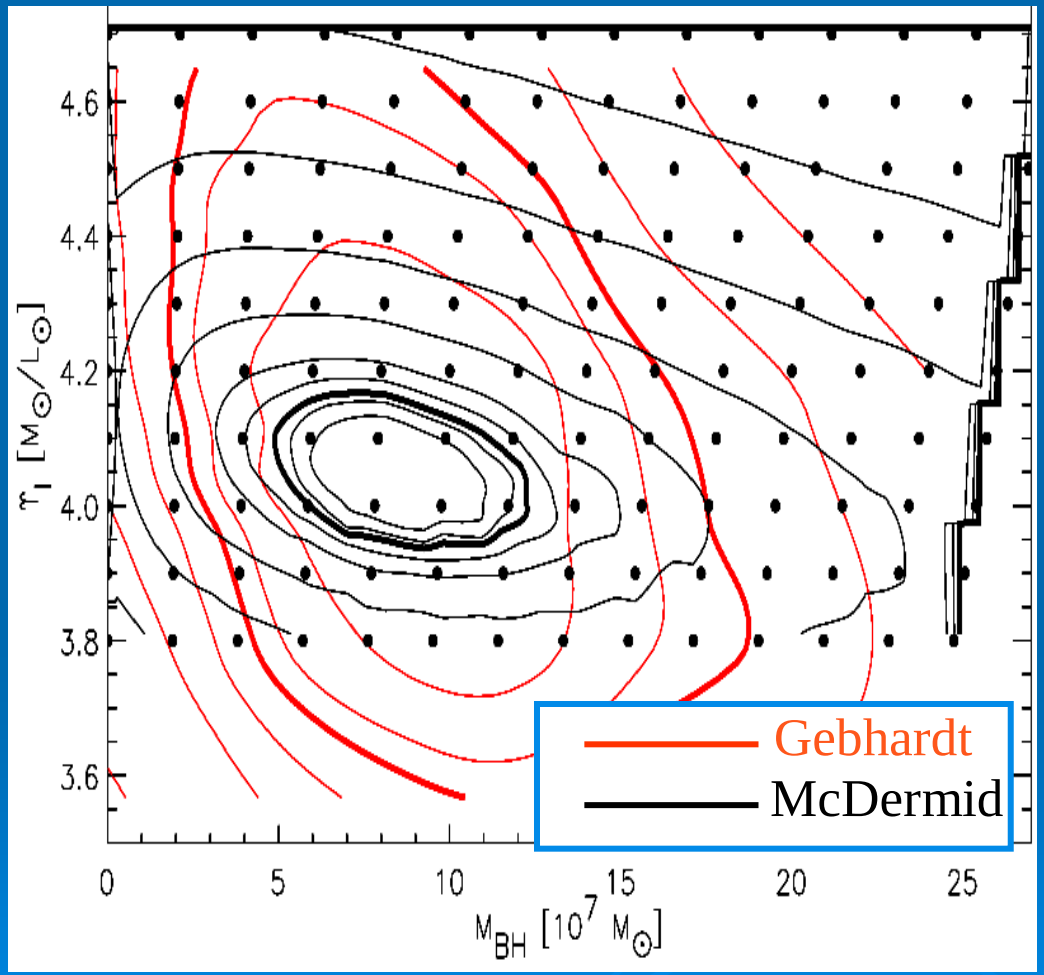




Internal uncertainties <30%

(McDermid et al. 2004)

External check: NGC 821

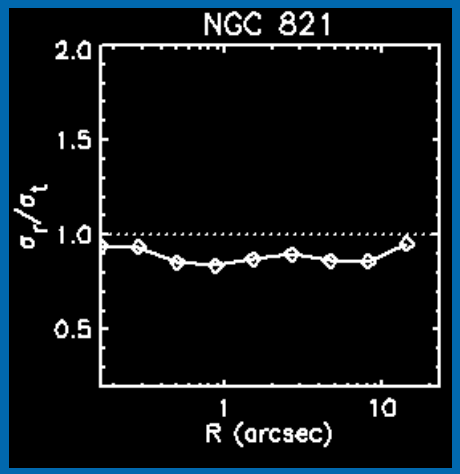


(cf. Richstone et al. 2004)

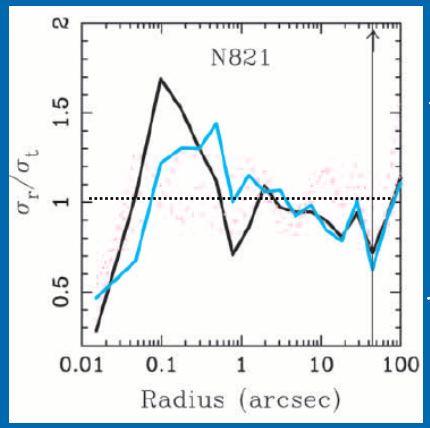
- Different data set
  - SAURON + STIS
  - Long-slit + STIS
- Independent codes
  - Nukers/Leiden group
  - Different orbit sampling
  - Different Regularisation
- Good agreement
  - M_{BH} statistical error decreases when two-dimensional kinematics is included

Orbital distribution: NGC 821

SAURON + STIS



long-slit + STIS



Radial orbits

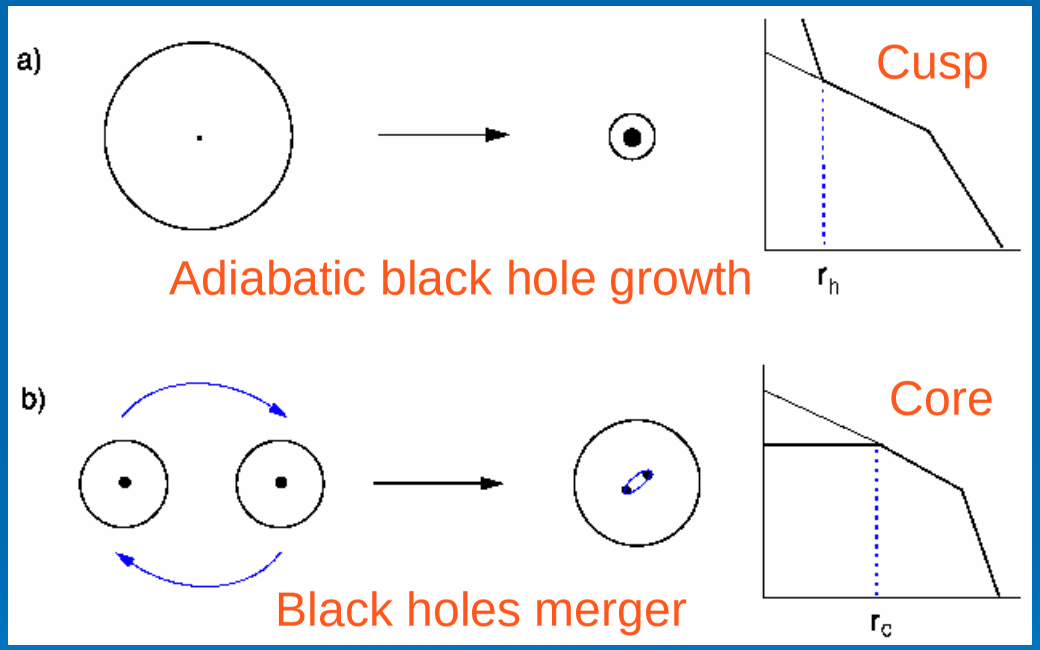
Tangential orbits

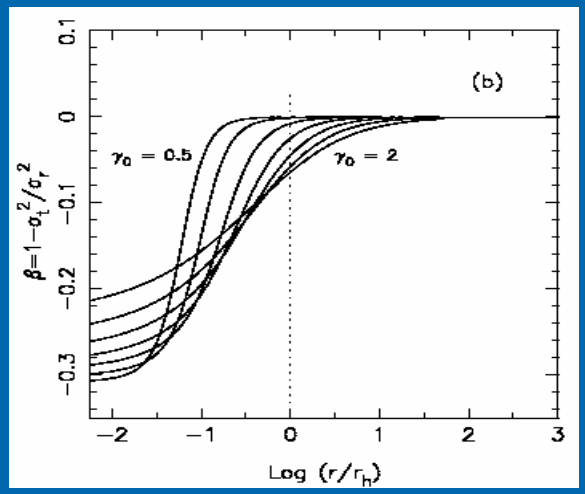
(McDermid et al. 2004) (Gebhardt et al. 2003)

- General agreement with independent determinations
- But 2D kinematics substantially decreases scatter of measurements
- Velocity distribution nearly isotropic (within ~10%)

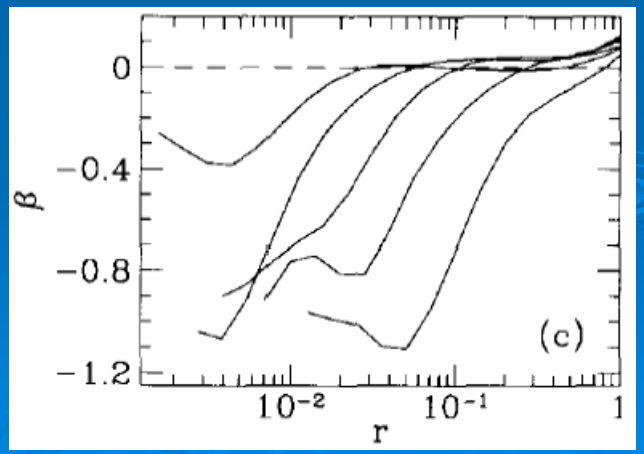
Importance of orbital distribution

(Merritt 2004)





(Merritt 2004)



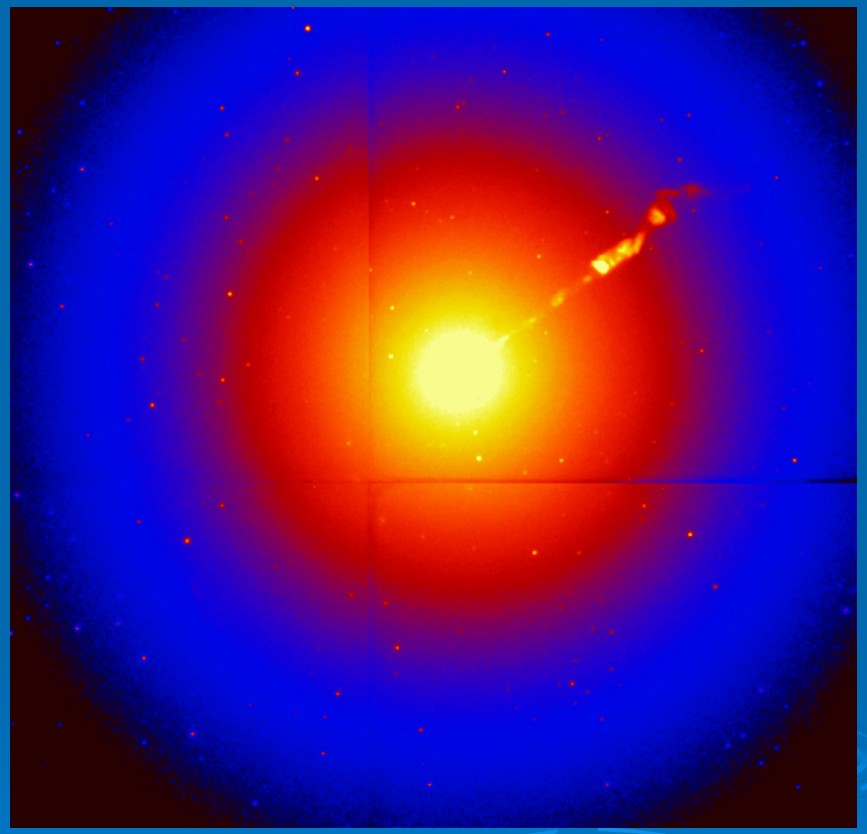
(Quinlan & Hernquist 1997)

Models of binary black hole mergers predict strong tangentially biased orbits inside core radius

(but see Milosavljevic & Merritt 2001)

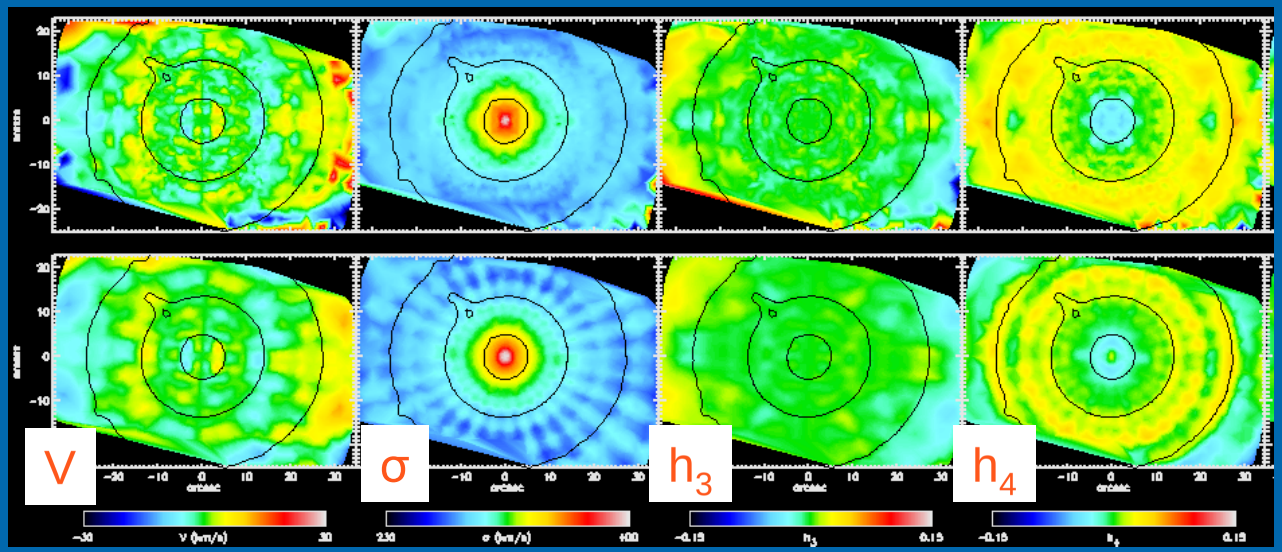
A textbook case: M87

- Prototypical giant elliptical (E0) with core
- At the center of Virgo galaxy cluster
- Synchrotron optical Jet
- Black hole ~3×10^9 $M_\bullet$ from HST gas kinematics
  (Macchetto et al. 1997)
- Well resolved core radius r_c~3”



HST/WFPC2 *I*-band

Dynamical modeling: M87

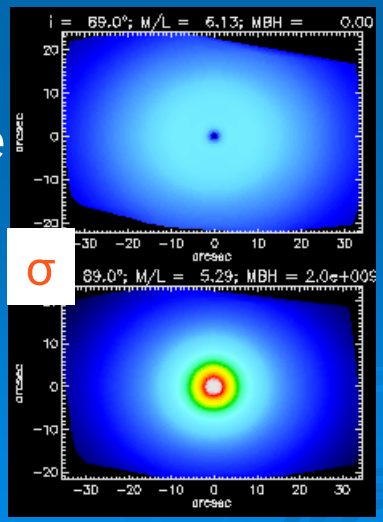


SAURON data (symmetrized)

Best fitting model

No Black Hole

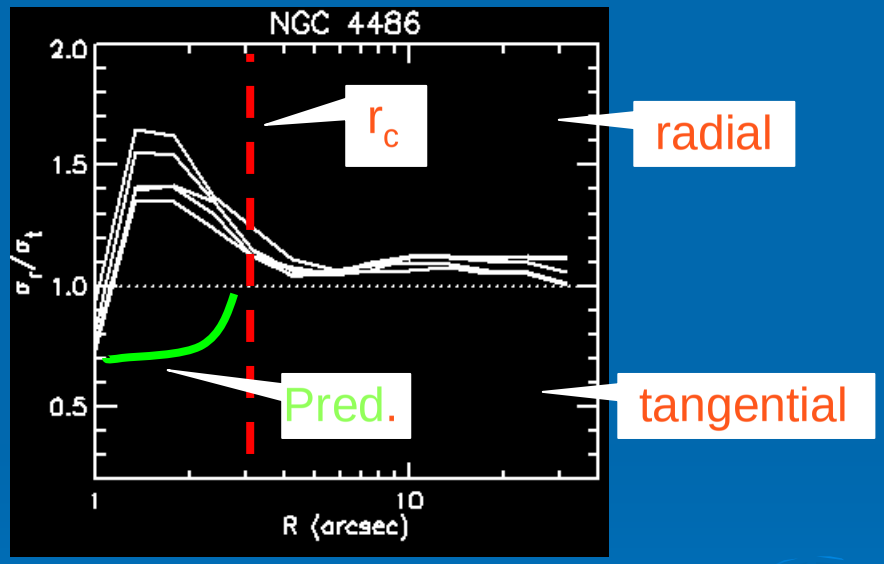
Black Hole
$3\times10^9\ M_\bullet$



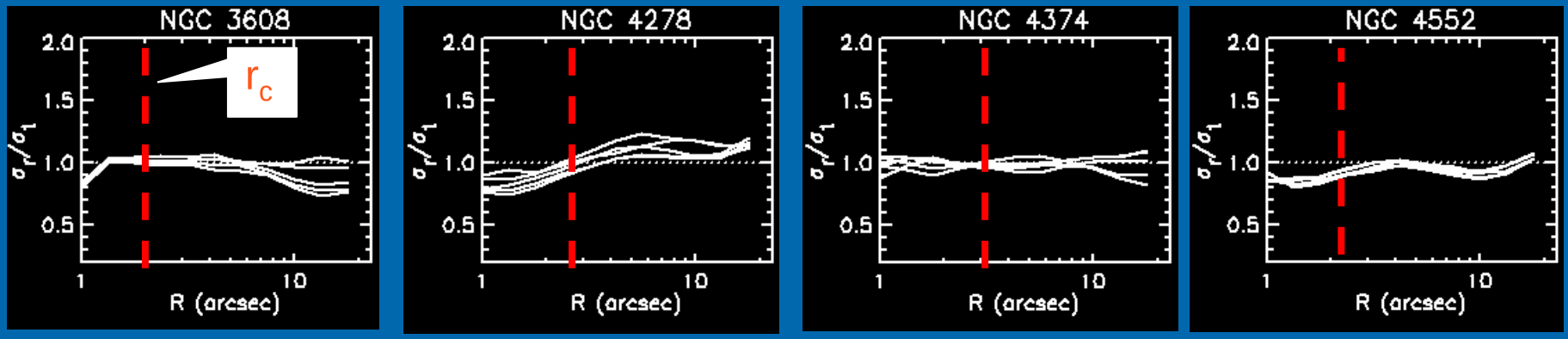
- Black hole dominates SAURON kinematics
- Kinematics well reproduced by model

Orbital distribution: M87

- Nearly isotropic velocity at large radii
- Radial orbits inside core radius r_c
- No evidence for tangentially biased orbits



Orbital distribution in core ellipticals



- Observables are smooth and homogeneous
- Velocity distribution remarkably isotropic
- No general trend inside r_c
- Accurate N-body models are needed

Conclusions

- Agreement between independent black hole masses determinations
- But systematic effects can be important
- 2D kinematics crucial for accurate orbital distributions
- Core elliptical galaxies remarkably isotropic
- Need comparison with reliable N-body models

- To be done:
  - Higher spatial resolution OASIS+STIS in all models
- The future:
  - Adaptive optic 2D kinematics (e.g. SINFONI on VLT)