Spheroids, Bulges, and HST

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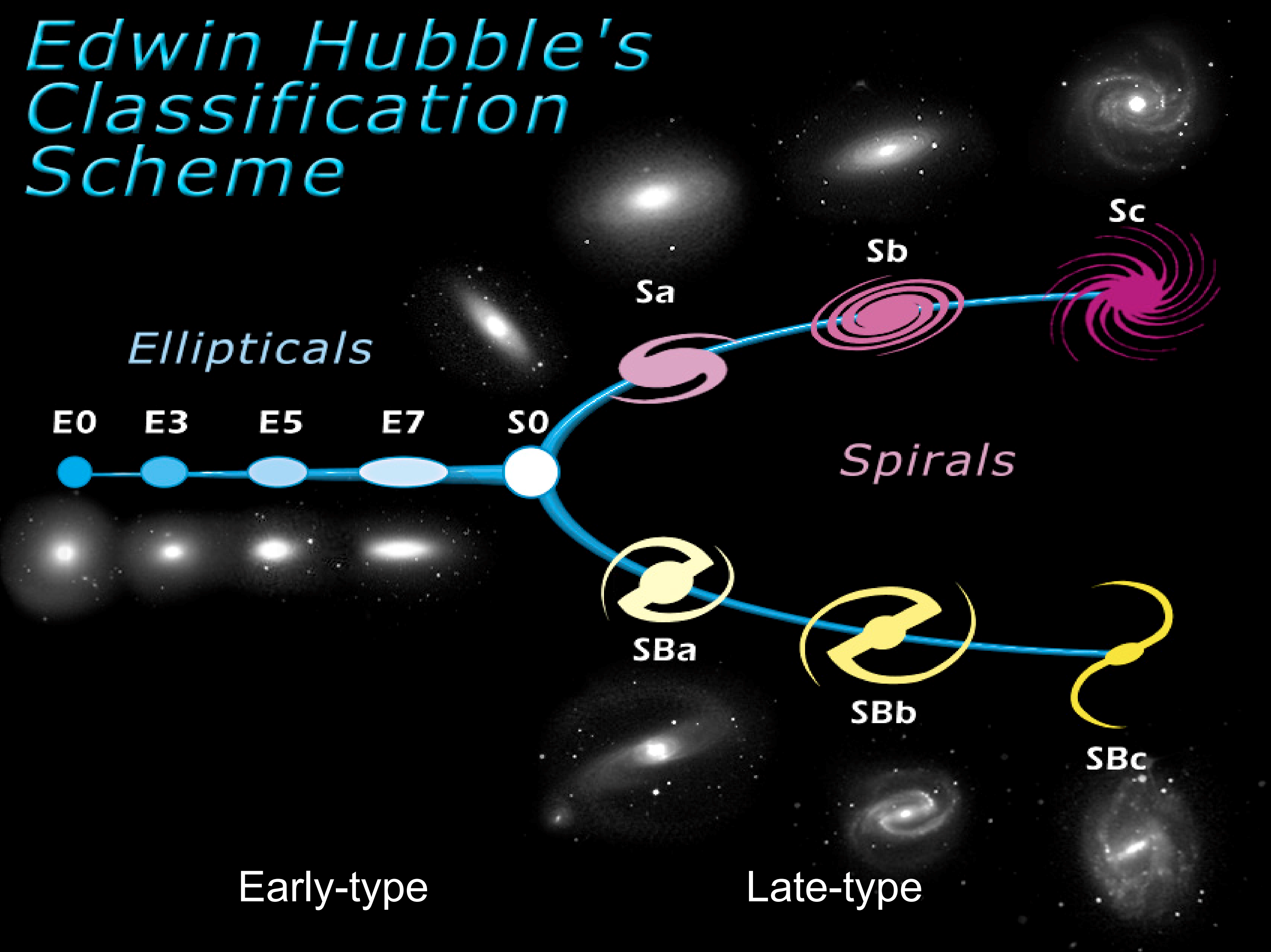
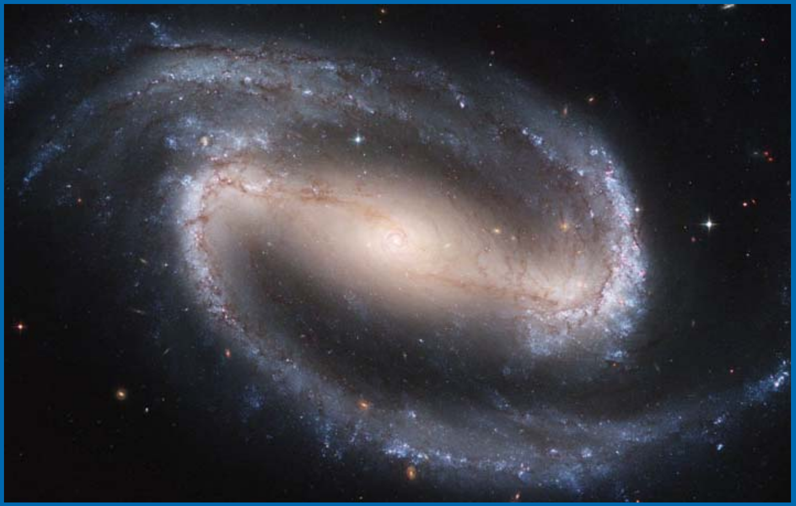
Leiden Observatory

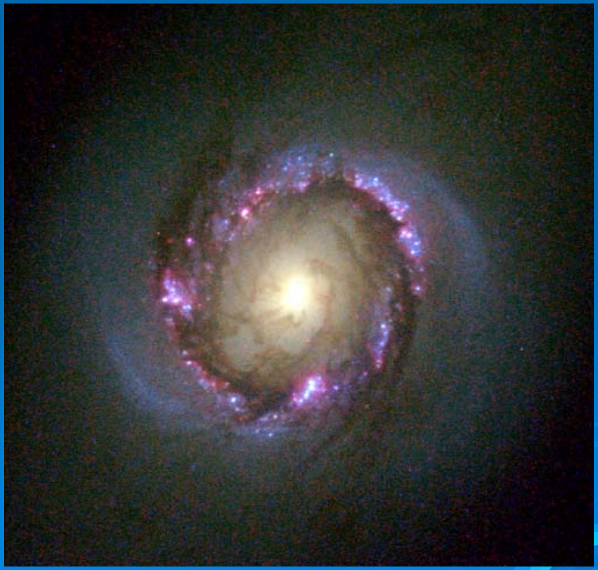
- Early- and late-type galaxies
- E/S0 galaxies
- Bulges of spiral galaxies
- Emission-line gas
- Central black holes
- The Future



Edwin Hubble's Classification Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc
Early-type
Late-type

Spiral Galaxies

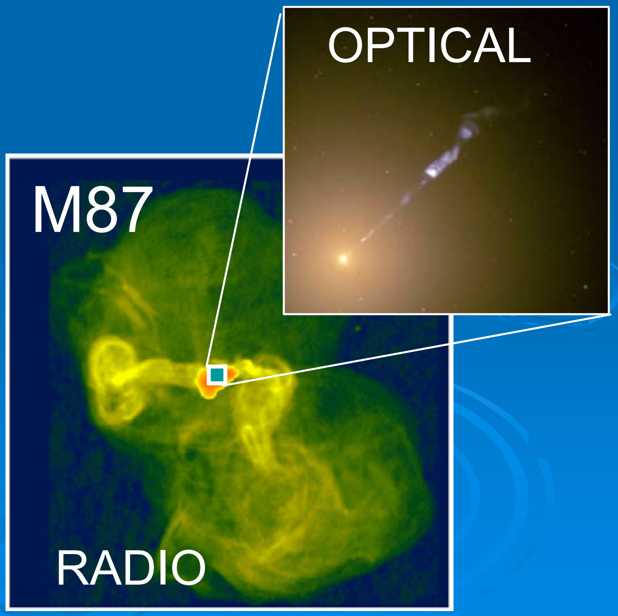




Elliptical Galaxies

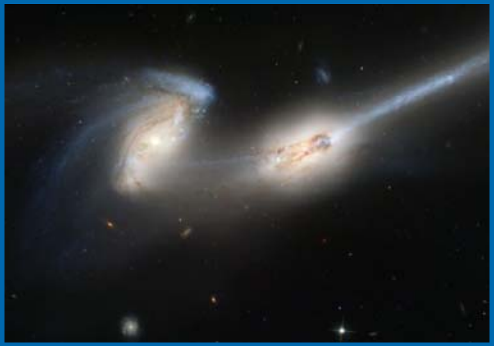
'Activity'

- Some galaxies contain 'active nucleus'
  - Radio jets, X-rays, optical spike
- Cause: supermassive black hole
- Most galaxies active in the past
- Black hole must still be there
  ⇒ most normal galaxies have (inactive) central black hole
- Black hole influences galaxy structure & evolution



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



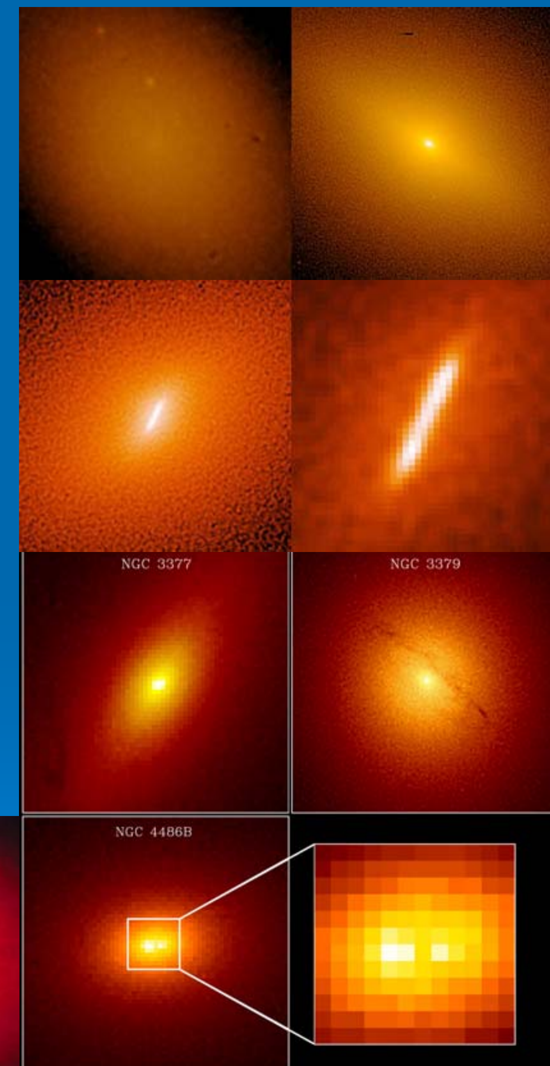
- Galaxy encounters still occur
  - Deformation, stripping, merging
- Black hole also influences evolution

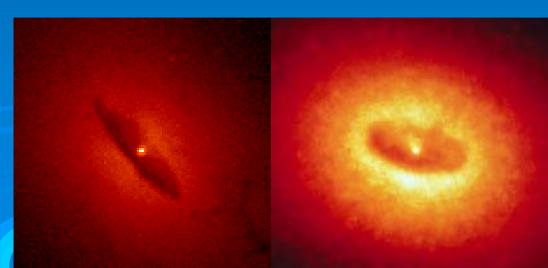
Observational Approaches

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

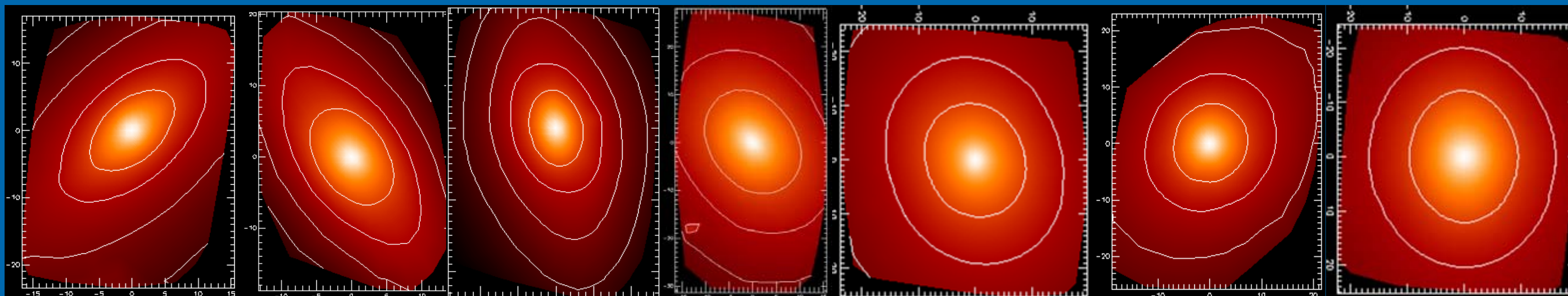
HST and E/S0 galaxies

- Giant and normal E/S0s
  - Distinct central luminosity profiles
  - Cores, cusps, and central dips
- Nuclear disks (gas/dust/stars)
- STIS spectroscopy ⇒ black hole masses
- Nuclear and global properties correlate

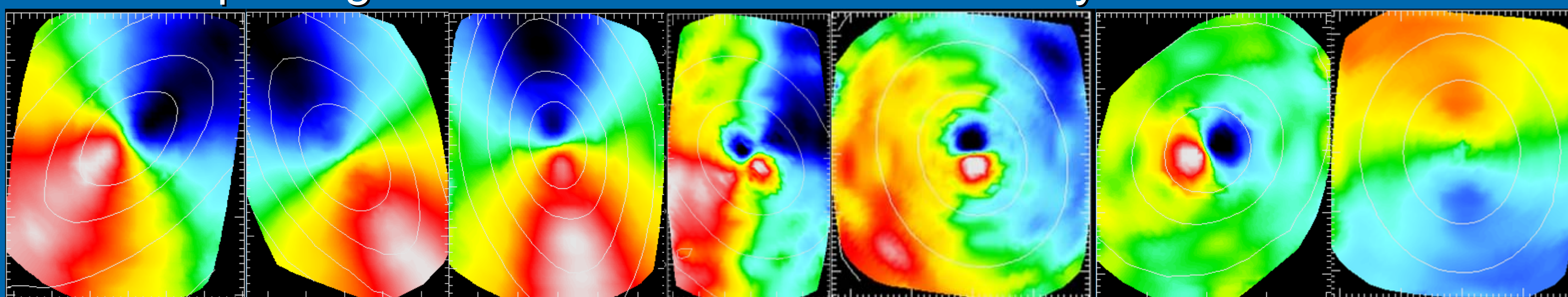




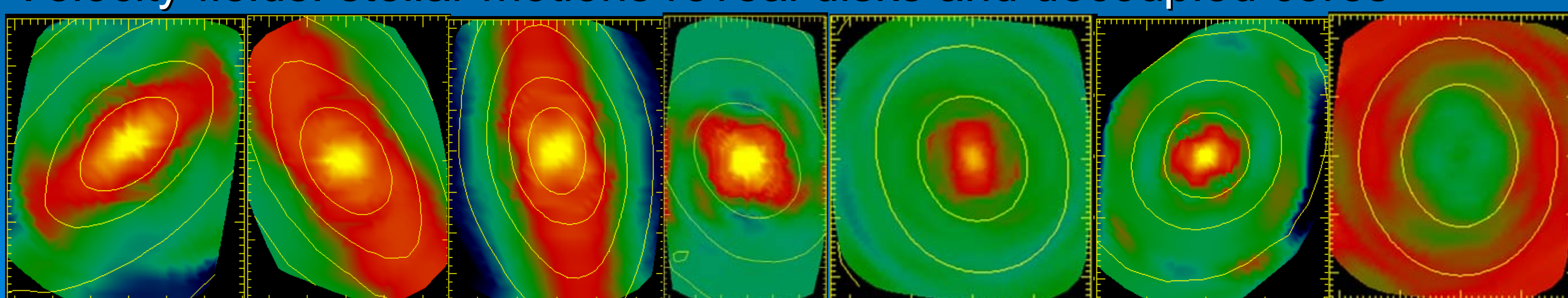
SAURON Spectroscopy



Seven elliptical galaxies from the SAURON survey



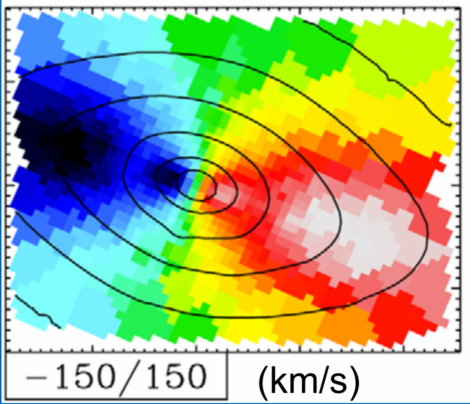
Velocity fields: stellar motions reveal disks and decoupled cores



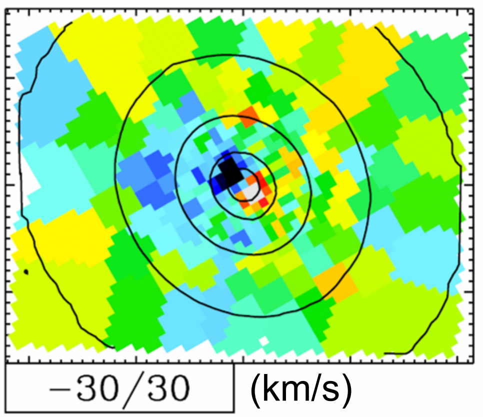
Maps of magnesium line strength: age and metal abundance of stars

Structure of E/S0 Galaxies

- Oblate fast rotators (E & S0)
  - High specific angular momentum
  - Embedded stellar disk
  - Can be strongly anisotropic
  - Generally steep luminosity cusp
- Weakly triaxial slow rotators (E)
  - Some central rotation, but negligible specific angular momentum
  - Not necessarily strongly anisotropic
  - Generally shallow luminosity cusp



Fast rotator (NGC 4660)

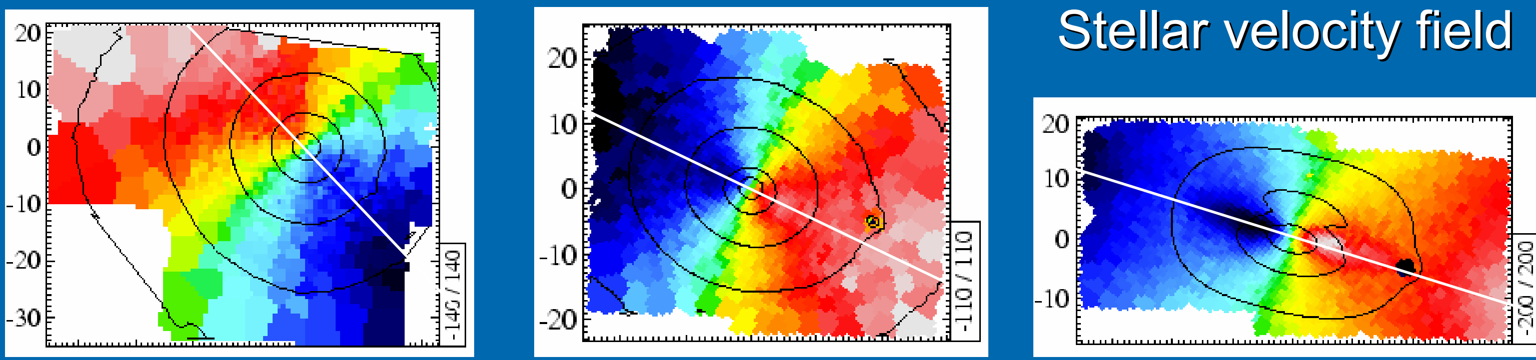


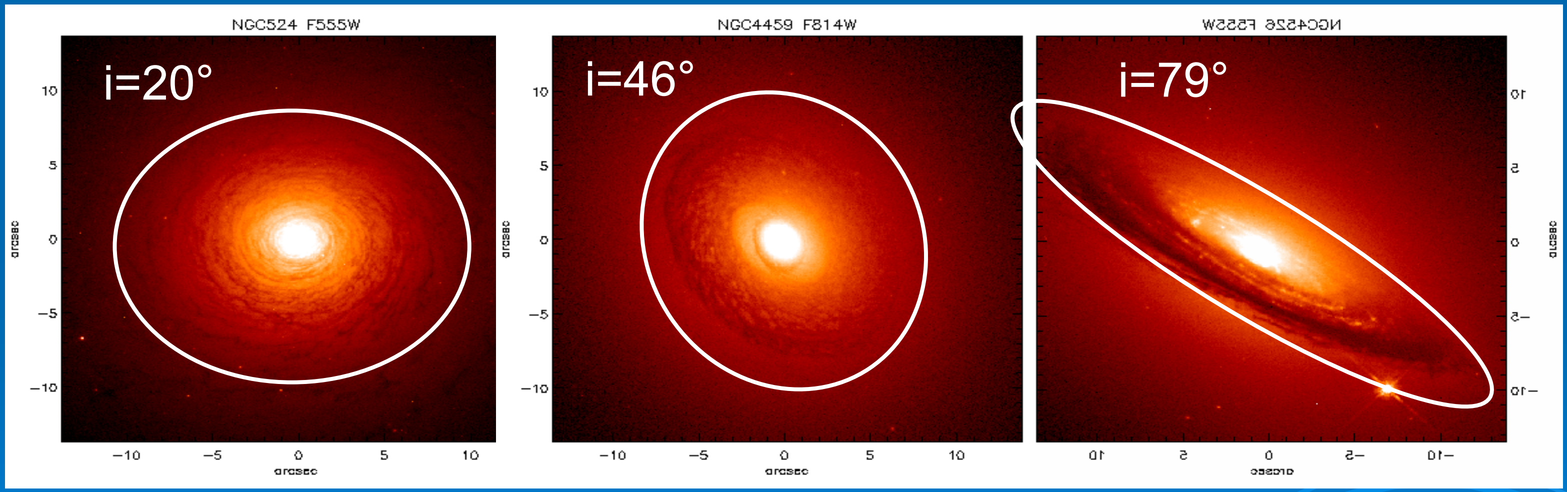
Slow rotator (NGC 4458)

Emsellem et al 2007, Cappellari et al 2007, MNRAS, and Falcón-Barroso talk

Fast Rotators

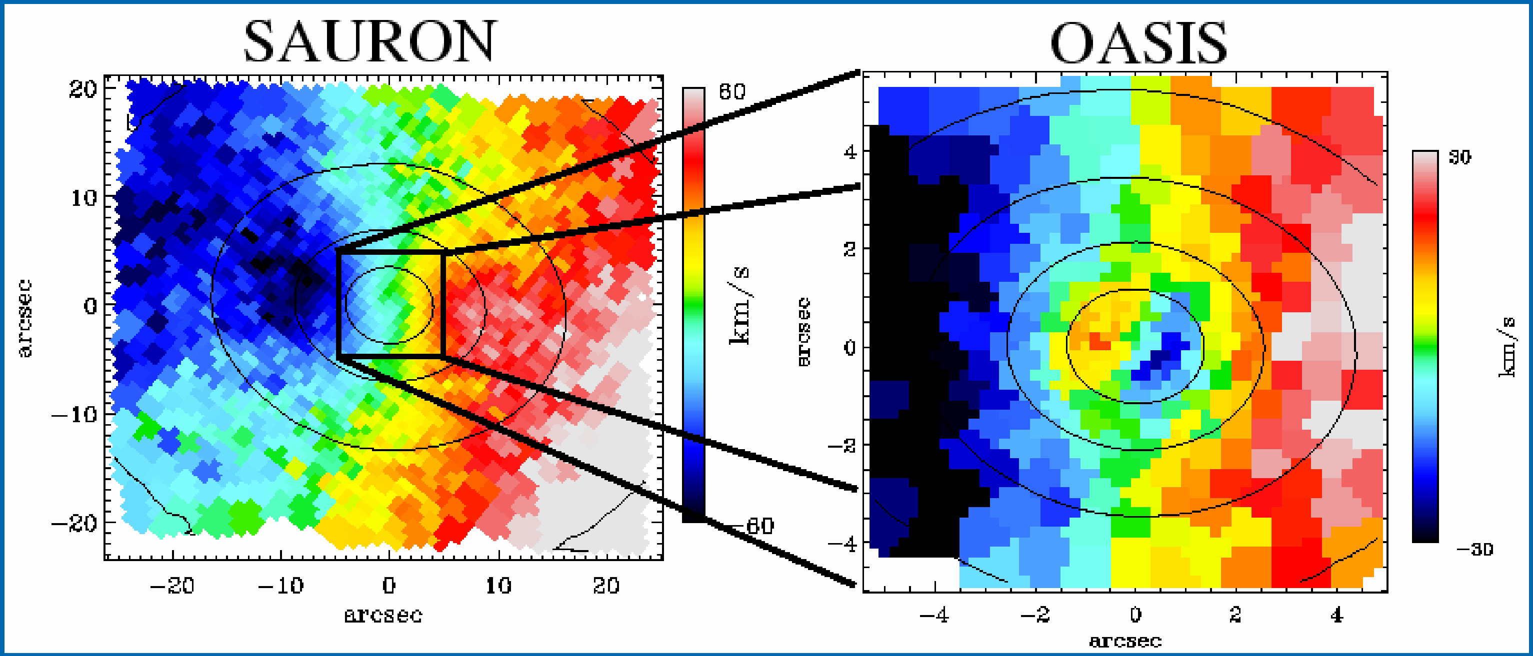
Stellar velocity field





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

Kinematic structure on all scales

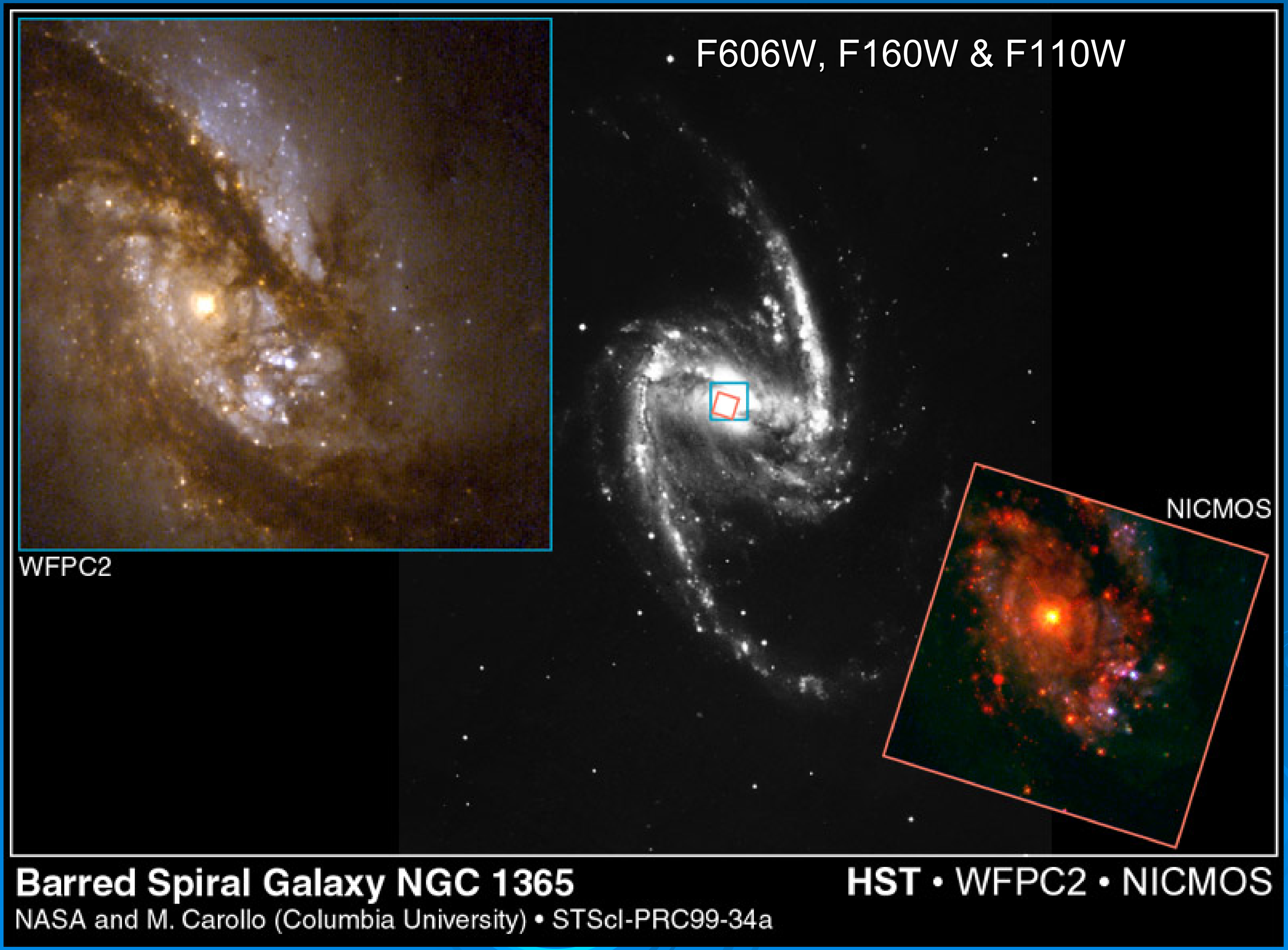


NGC 4382

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

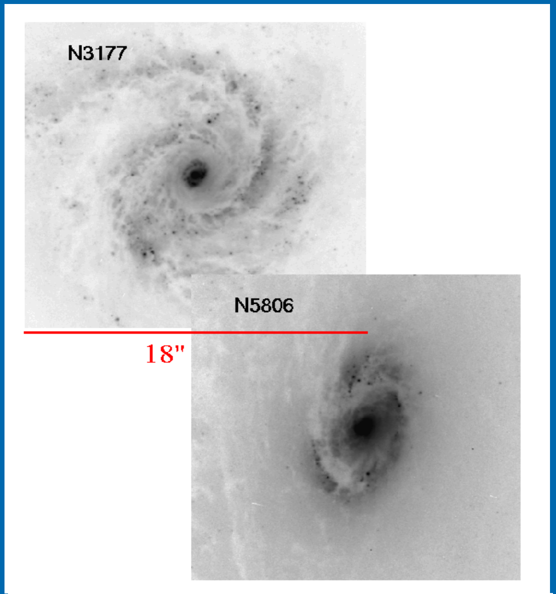
- SAURON: global kinematics and line-strengths
- OASIS: spatial resolution: zoom-in on nucleus
- Allows study of orbital structure near central BH
- STIS: even sharper, but incomplete view

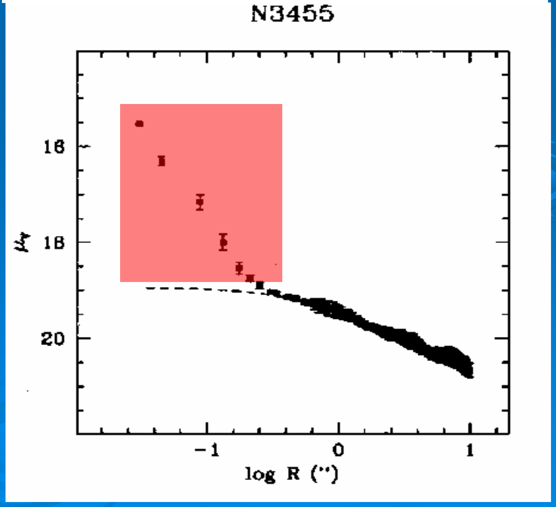
Bulges in Spiral Galaxies



Structure of Smallest Bulges

- HST revealed large nuclear complexity in late-type spirals
- Many ~exponential stellar density profiles
- These ‘bulges’ may be disks (e.g. Kormendy 1993)
- Many have nuclear star cluster
- Formation mechanism unclear





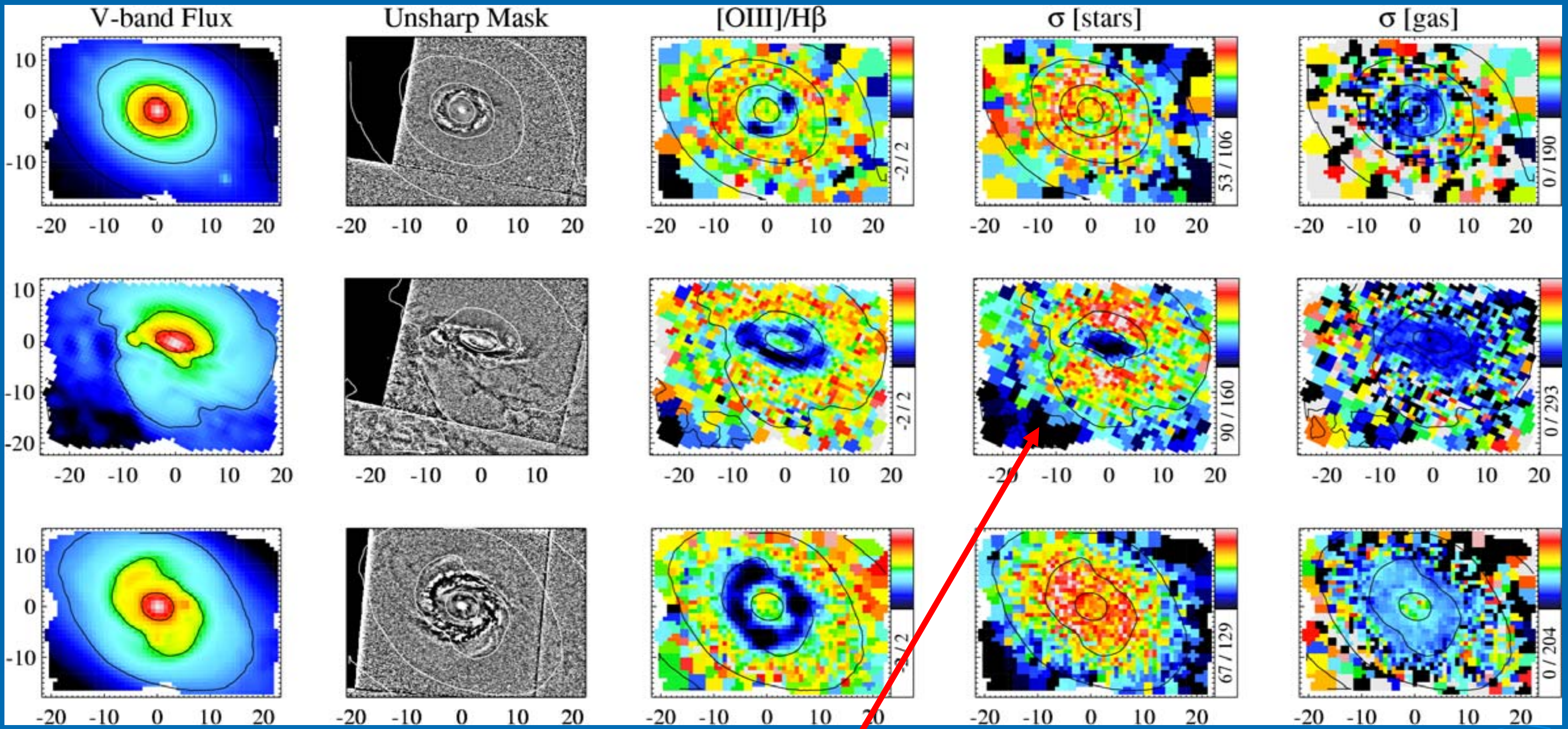
Carollo et al. 1997-2007; Böker, van der Marel et al.

Velocity dispersion drops

NGC 4245

NGC 4274

NGC 4314



- ~50% of Sa-Sc spirals: central minimum in σ
- These ‘bulges’ are central disks
- Range of star formation histories

Falcón-Barroso et al. 2006; Ganda et al. 2006, Peletier et al. 2007, MNRAS

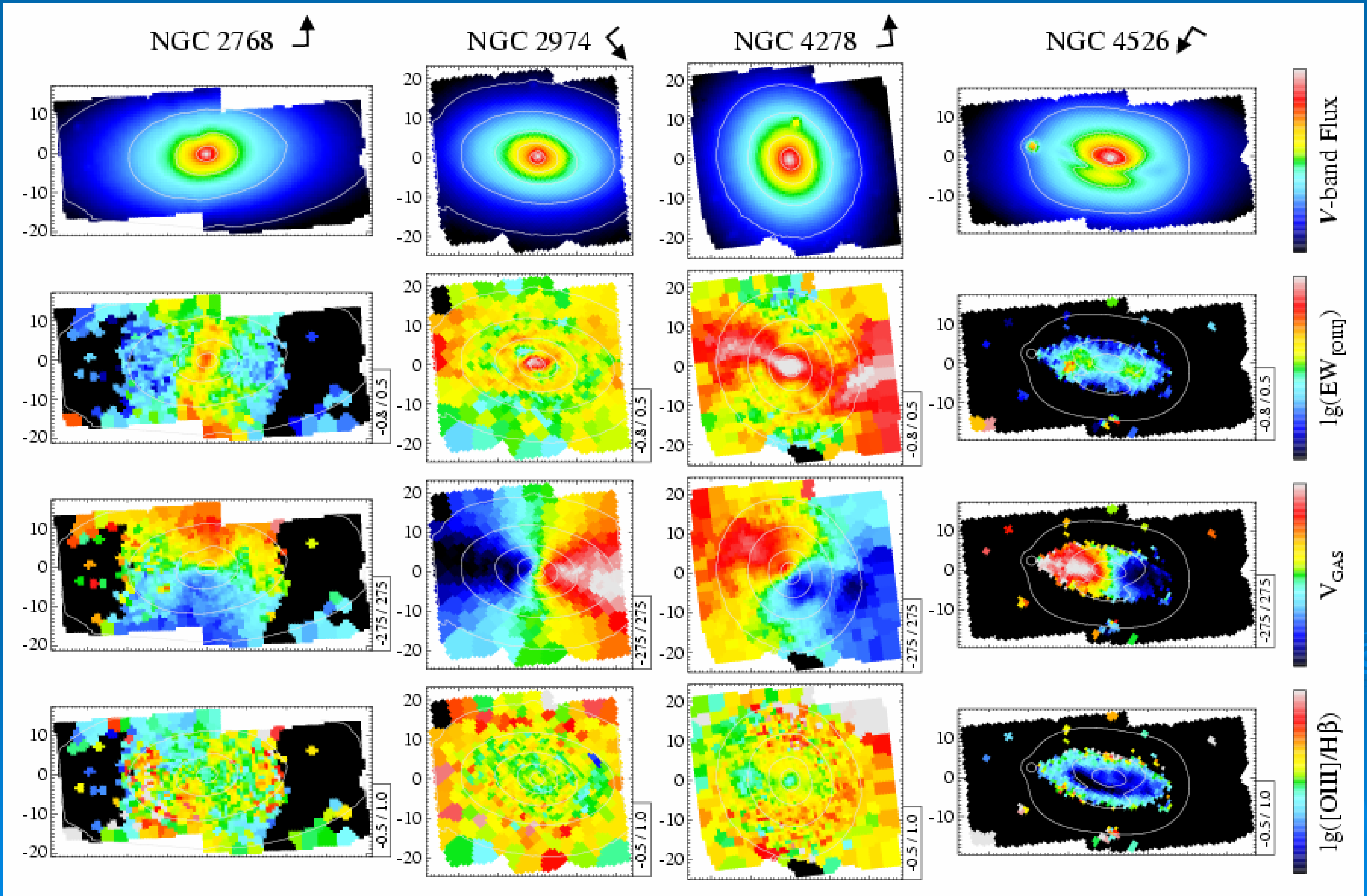
Nature of Bulges

- Bulges seem to be two component systems
  - Slow-rotating, spheroidal, $R^{1/4}$, old
  - Fast-rotating, disk-like, exponential, star forming
- When disk-like component dominates
  - Exponential profile
  - Velocity dispersion drop
- Variety of star formation histories
  - HST multi-color studies (WFPC2/NICMOS/ACS Carollo et al. 2007)
  - SAURON line strength measurements

Ionized Gas in E/S0s

- >75% of E/S0s have extended emission-line gas
  - – Narrow-band imaging Macchetto et al. 1996, AAS, 120, 463
  - – SAURON spectroscopy Sarzi et al. 2006, MNRAS, 366, 1151
  - – Detection rate: S0: 83%, E: 66%
  - – Drops to 55% in Virgo cluster (3/9 E's)
- Gas distribution and kinematics is diverse
  - – Includes non-axisymmetric motions
  - – Gas origin cannot be purely external or internal
- Wide range of [OIII]/Hβ among and within galaxies

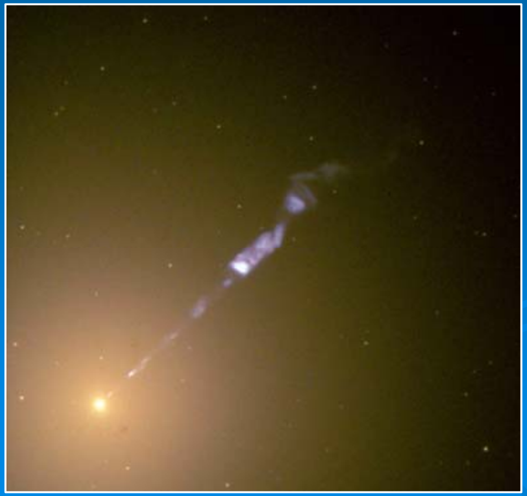
Some Examples

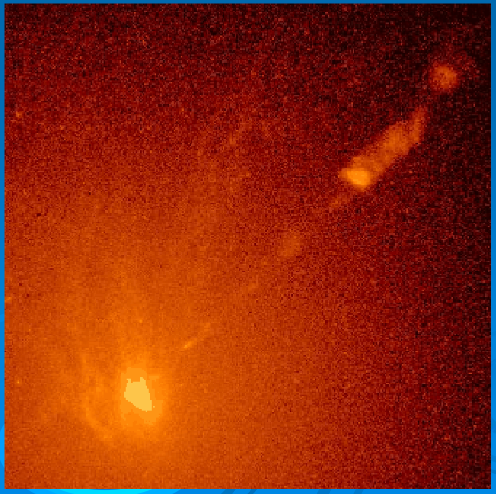


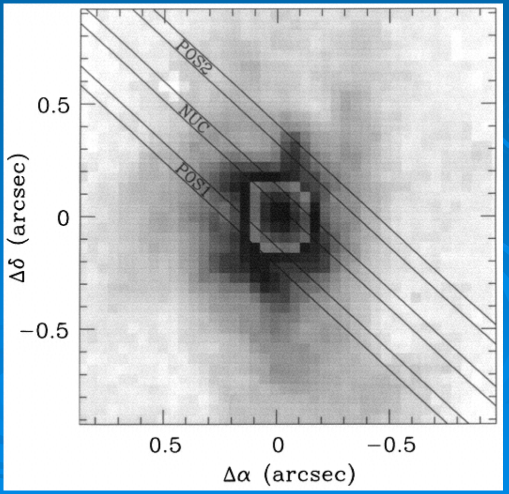
Sarzi et al. 2006, MNRAS, 366, 1151

Nuclear Ionized Gas

- Prominent in active nuclei and bulges
  - ~20% have regular dust disks
  - Hα, [NII] kinematics (FOS, FOC, STIS) resolves region where black hole dominates, but is often irregular
- HST observed over 100 objects
  - Up to ~100 Mpc distance
  - ~20% ~fitted by circular rotation ⇒ black hole masses

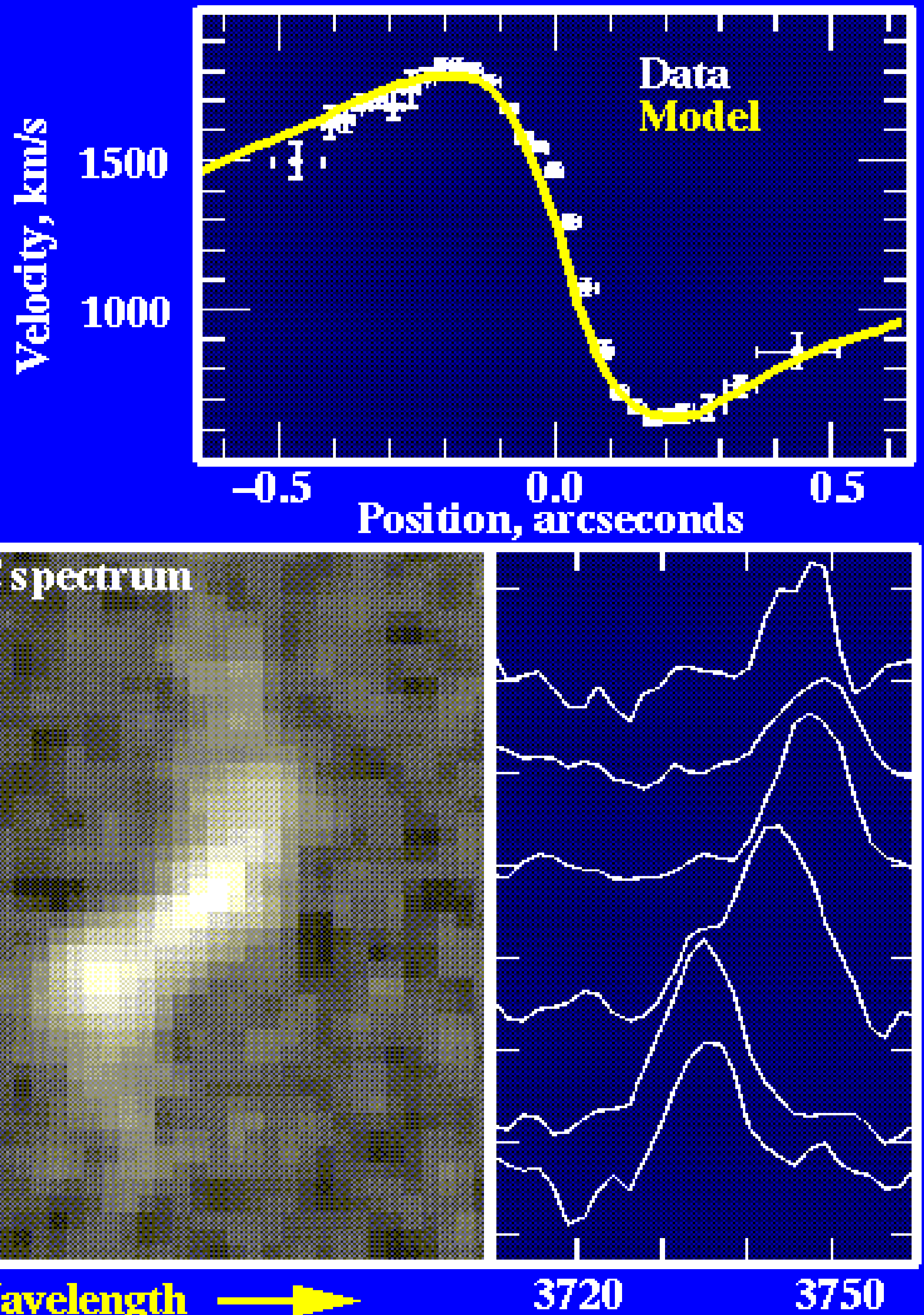






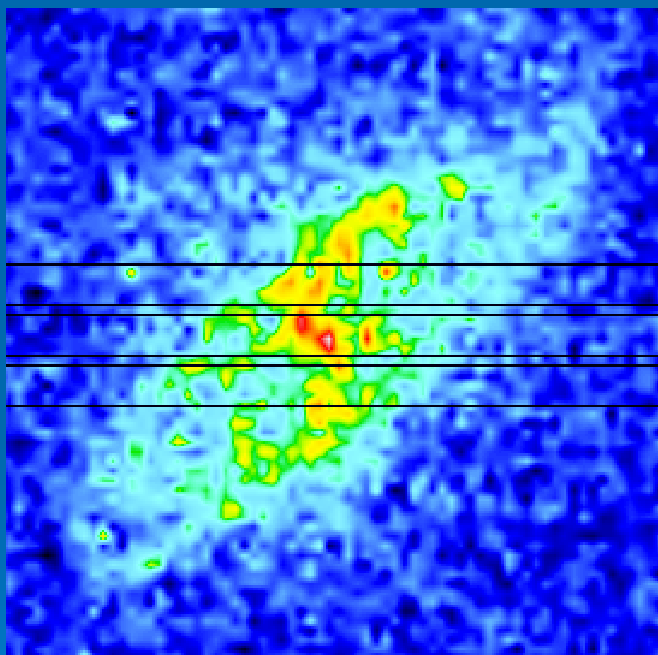
Velocity Profiles in the M87 Core

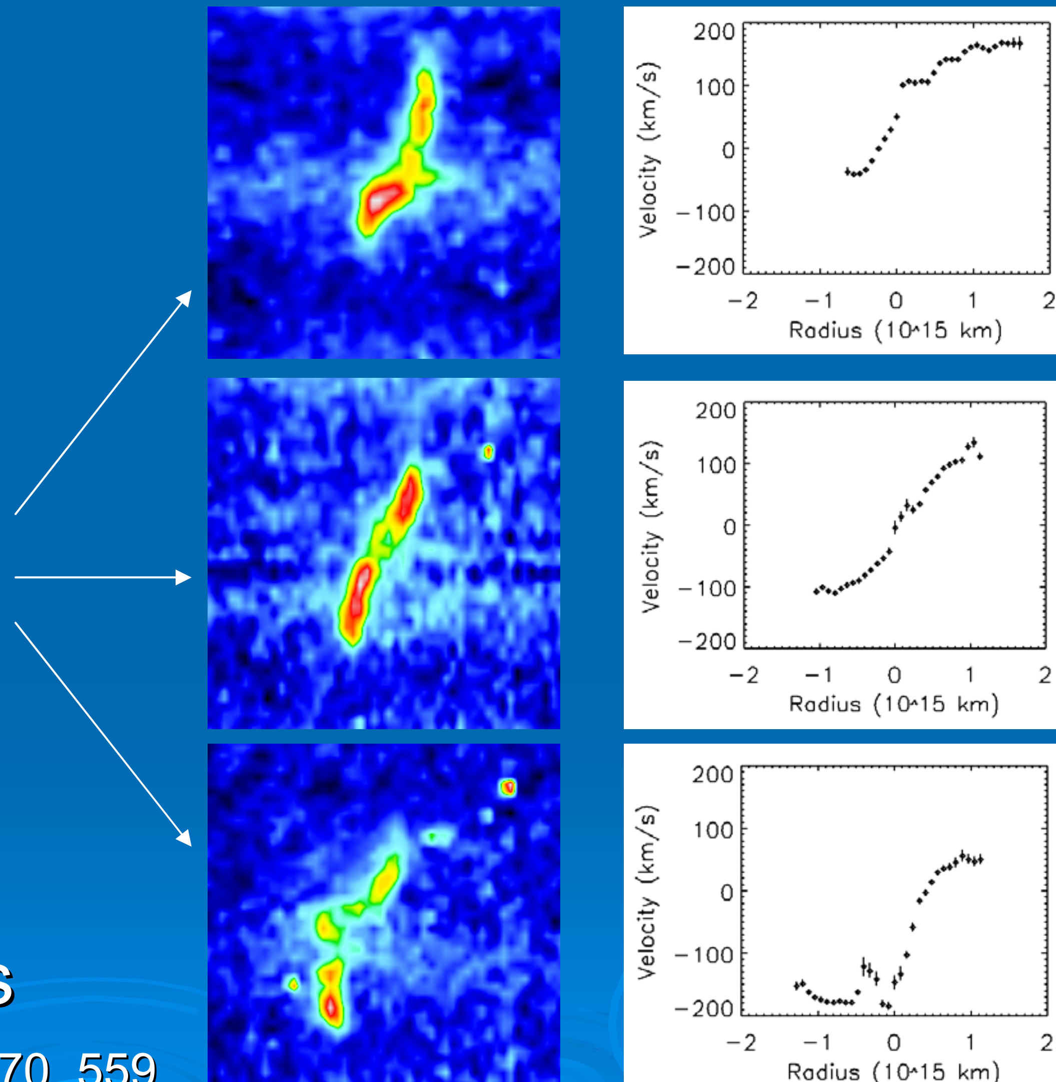
Model: central mass 3.2×10^9 solar masses



Macchetto et al. 1997

Central Gas Disk in NGC 3379



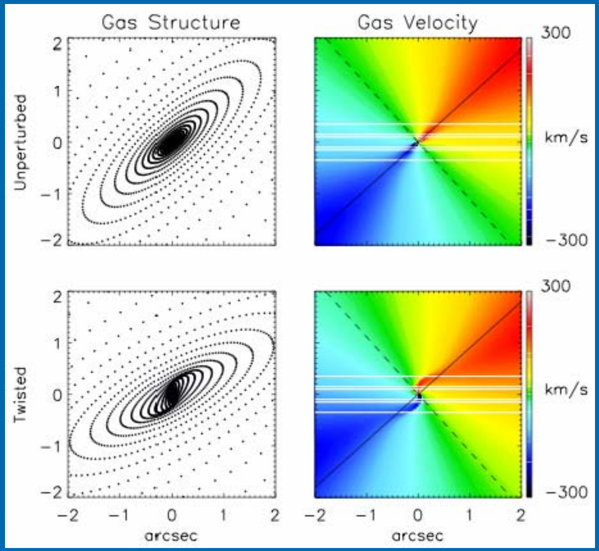


Hα along 3 STIS slits

Shapiro et al. 2006, MNRAS, 370, 559

The Black Hole in NGC 3379 (E1)

- M_{BH} from stellar motions and from gas kinematics
- Regular central gas disk
  - Three parallel STIS slits
  - Gas motions not circular
  - Twisted model consistent

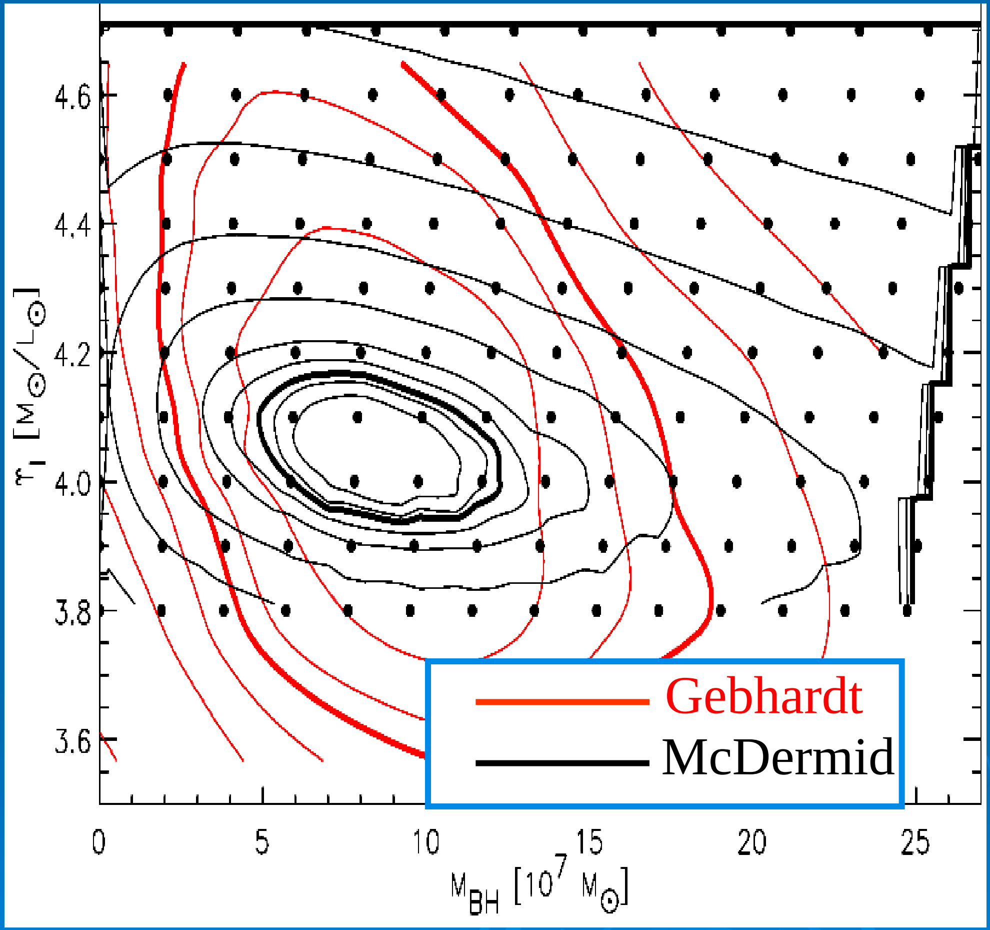


- Stellar kinematics
  - SAURON: low spatial resolution: upper limit on M_{BH}
  - OASIS: lower limit on M_{BH}, insufficient field of view
  - Combination: FOV and resolution: accurate M_{BH}
- Masses consistent

Shapiro et al. 2006, MNRAS, 370, 559

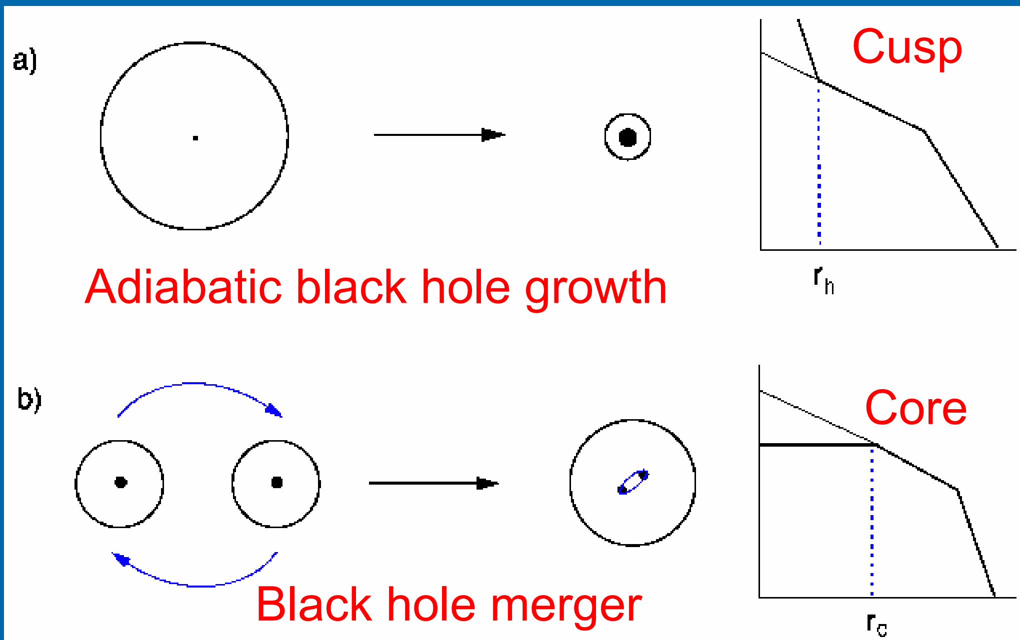
The Black Hole in NGC 821 (E6)

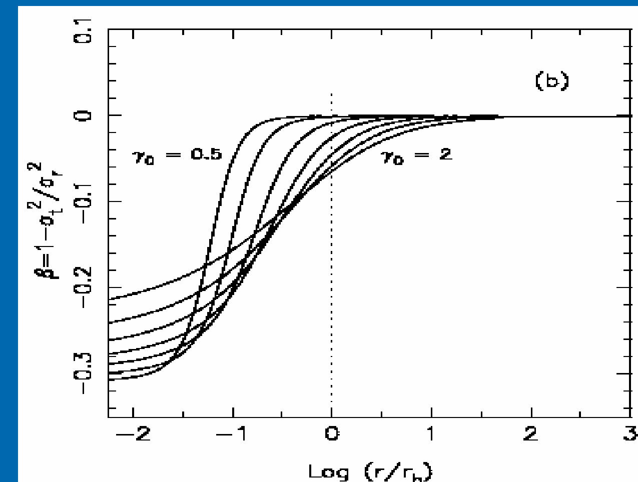
- Different data sets
  - SAURON + STIS
  - Long-slit + STIS
- Independent codes
  - Nukers, Valluri & Leiden group
  - Different orbit sampling
  - Different regularization
- Good agreement
  - M_{BH} statistical error smaller when 2D kinematics used



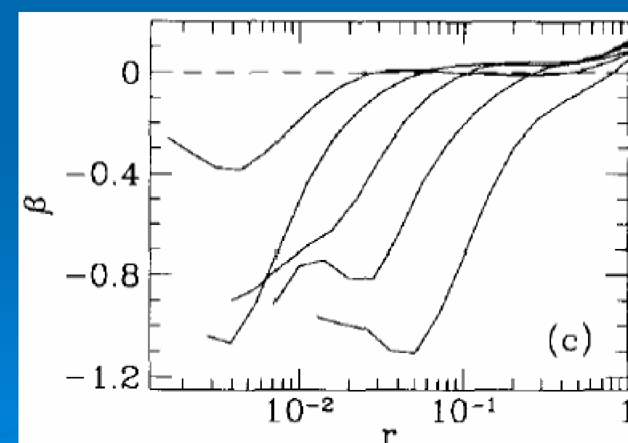
McDermid et al. 2007

Nuclear Orbital Structure





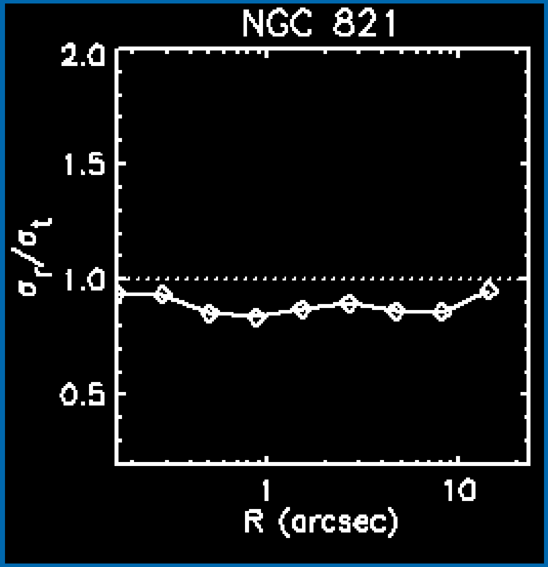
Merritt 2004

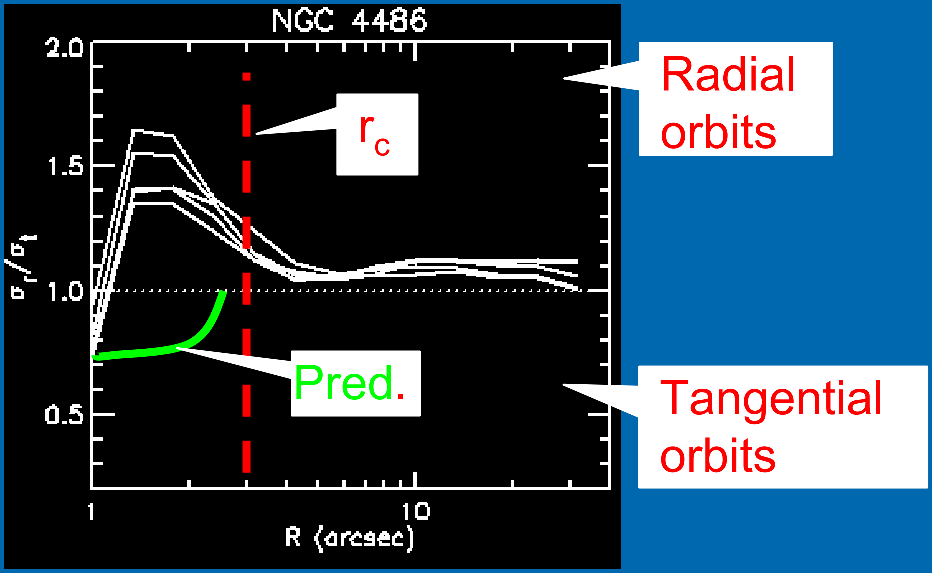


Quinlan & Hernquist 1997

Binary black hole mergers expected to result in <u>tangentially</u> biased orbits inside core radius

Observed Orbital Distributions





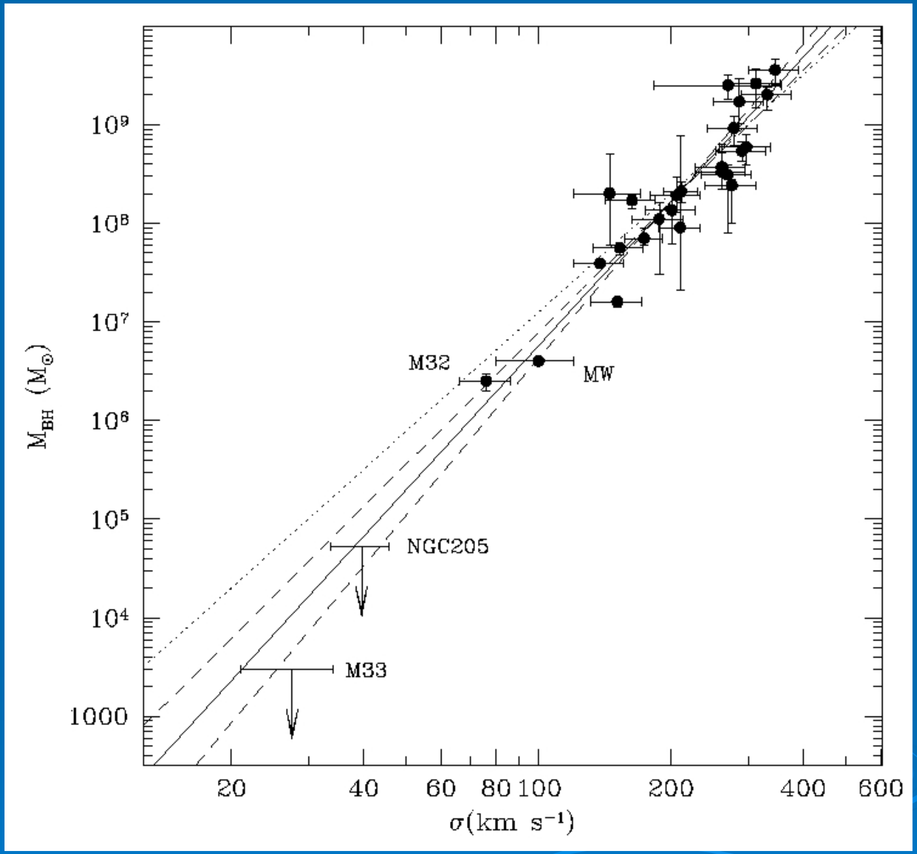
- Nearly isotropic velocity distribution at large radii
- Isotropic (N821) or radial (M87) motion inside core
- Similar results for other giant ellipticals (incl N3379)
- Not formed by binary-black hole merger?

M_{BH} from Stellar Kinematics

- BH masses for ~25 E/S0 galaxies and bulges
  - Based on one STIS slit, and ~2 ground-based slits
  - M_{BH} accuracy can be improved by using *integral-field* data; this also provides accurate M/L's and inclinations
  - Possible for all nearby E/S0s in HST/STIS archive
- Limitations
  - Only for bright nearby nuclei
  - Modest spatial resolution at Virgo (0.2" slit)
  - Not enough S/N for core galaxies in Virgo: these are targets for AO-assisted IFU's on 8m groundbased telescopes (e.g. SINFONI on VLT)

Black Hole Demographics

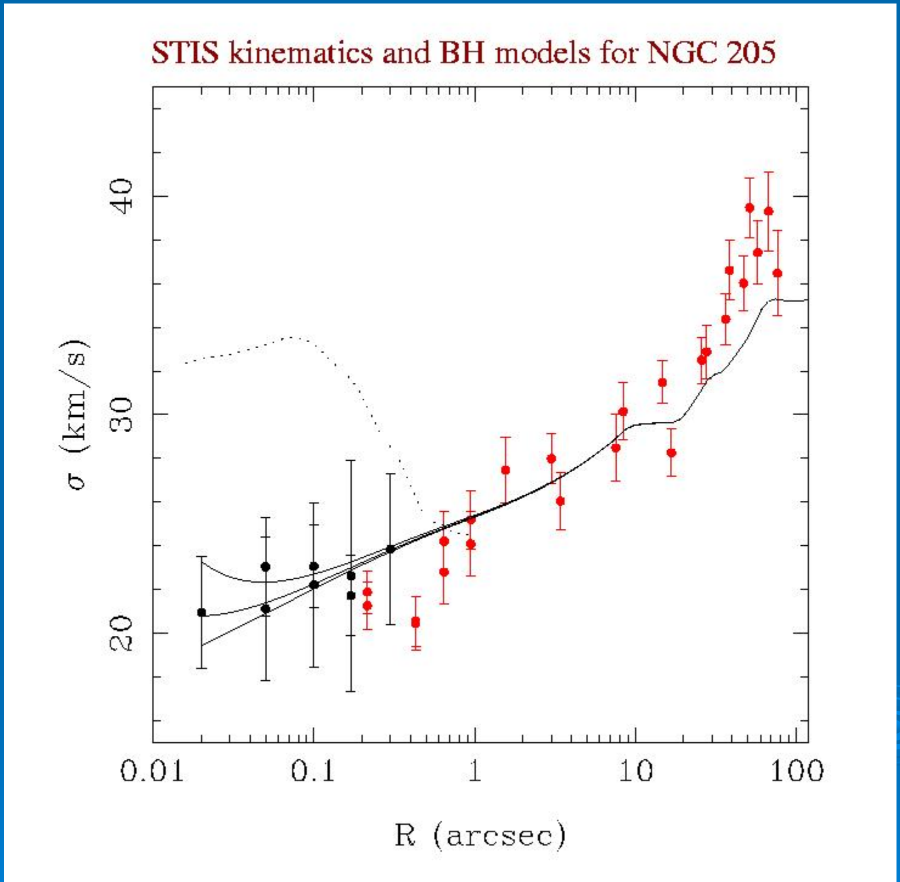
- Ellipticals
  - Be careful with masses from gas kinematics
  - Need stellar kinematics for core galaxies (8m)
- Spirals
  - Not many masses, especially < $4x10^7$ $M_\odot$
  - Late type disks: no BH?
- Scatter
  - Observational errors
  - Systematics (triaxiality, asymmetries)
  - Related to merger history?



Ferrarese & Ford 2005

Galaxies without Black Holes

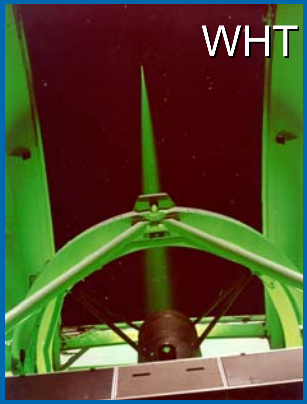
- M33 and NGC 205
  - Central star cluster
  - No AGN
  - Strong upper limit on black hole mass
- If they have a BH, then its mass is well below the (M_{BH},σ) relation



Valluri et al. 2005, ApJ 628, 137

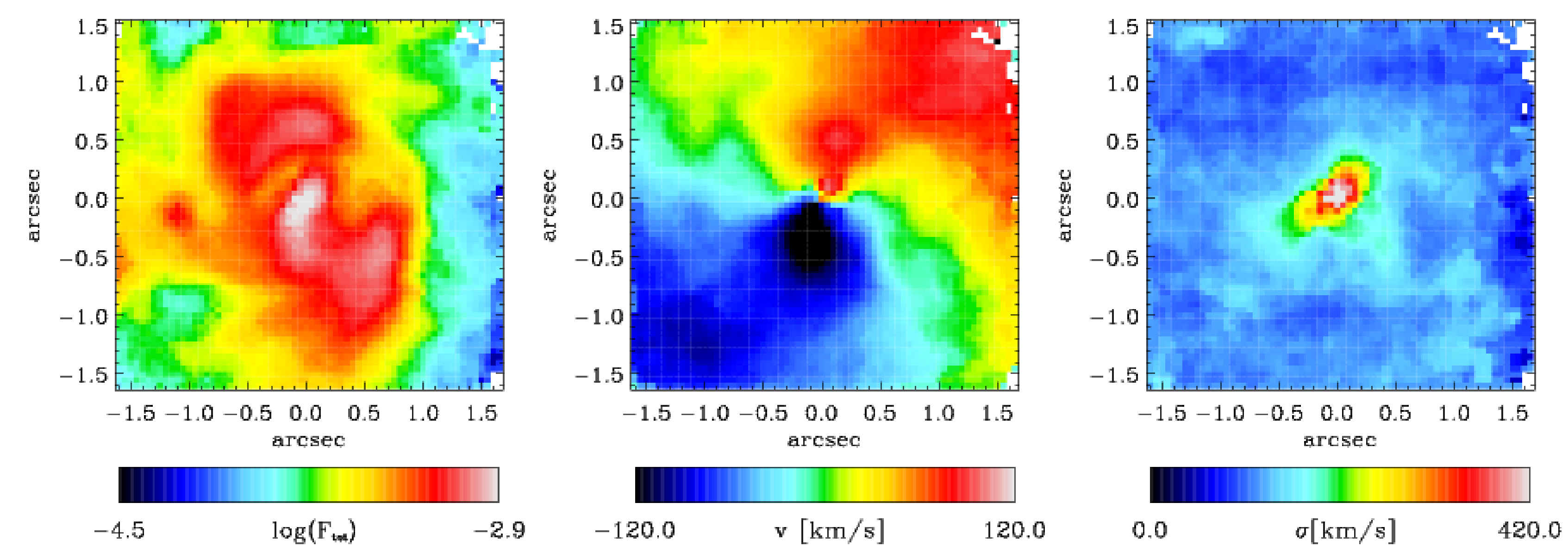
The Future

- Increased resolution needed:
  - Zooming in on nuclei & more distant objects
- Adaptive optics
  - Natural guide star: few objects
  - Increased sky coverage with laser
- Nuclei
  - Integral-field spectroscopy to constrain orbital structure near black hole
  - Infra-red wavelengths: probe dusty nuclei (SINFONI/NIFS/OSIRIS)
  - Optical wavelengths: stellar populations (OASIS/GMOS/MUSE)



Centaurus A

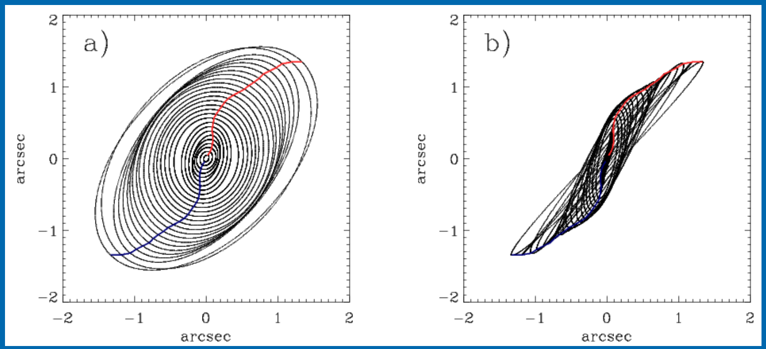
Cen A with SINFONI on VLT



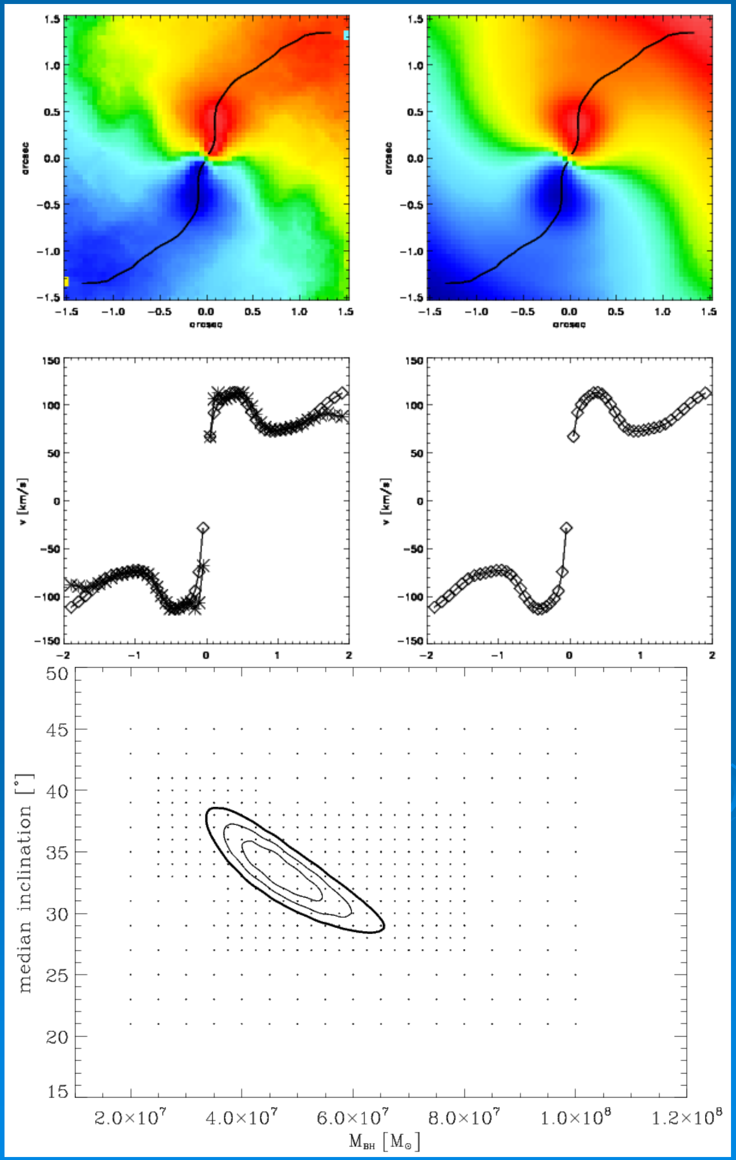
Häring-Neumayer et al. 2007

- H_2 emission at 2.12 μm: regular rotation
- Stellar kinematics from CO bandhead
- AO assisted spectroscopy: spatial resolution 0"12
- Excellent constraints on M_{BH}: gas and stars

The Black Hole in Cen A



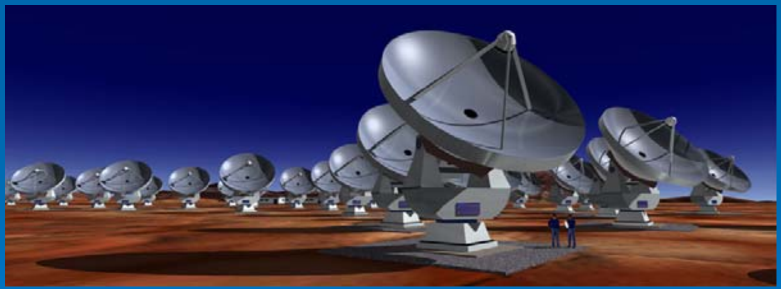
- Gas disk twisted & warped
  - Tilted ring model: excellent fit
  - Include velocity dispersion
- $M_{BH} = 4.5 \times 10^7 M_\odot$
- Same value found for dynamical model that fits stellar kinematics

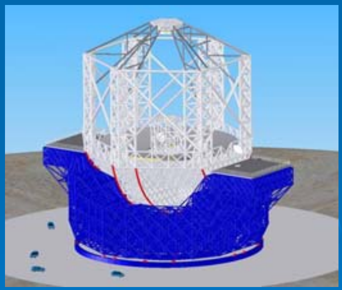


Häring-Neumayer et al. 2007

Conclusions

- HST transformed our understanding of spheroids and bulges
  - Cores, cusps, gas, nuclear star clusters, black holes
  - Triggered much follow-up ground-based work
- VLT^{++}, ALMA, JWST, and ELT to come



Thank you Duccio!