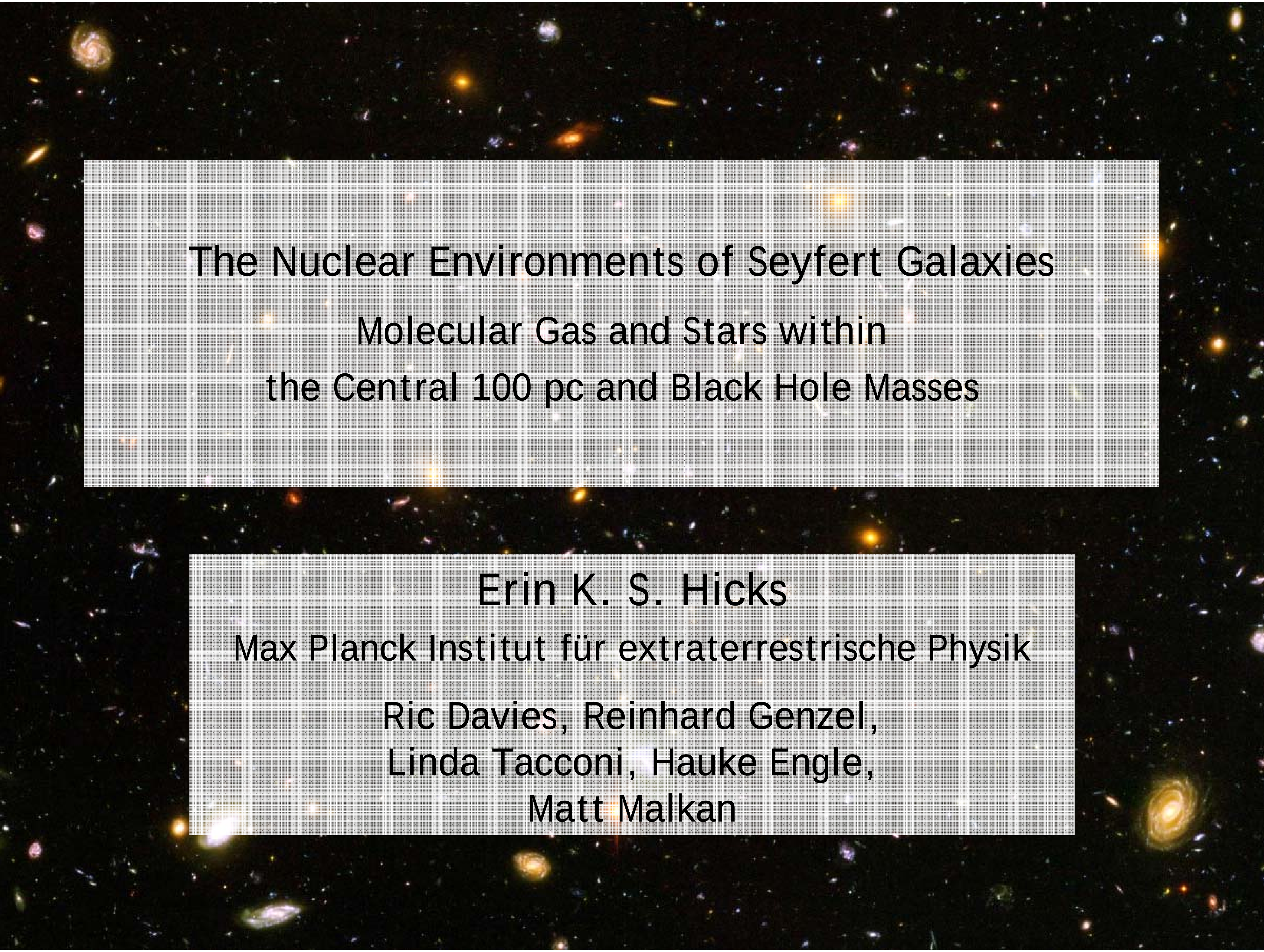


The Nuclear Environments of Seyfert Galaxies

Molecular Gas and Stars within
the Central 100 pc and Black Hole Masses

Erin K. S. Hicks
Max Planck Institut für extraterrestrische Physik

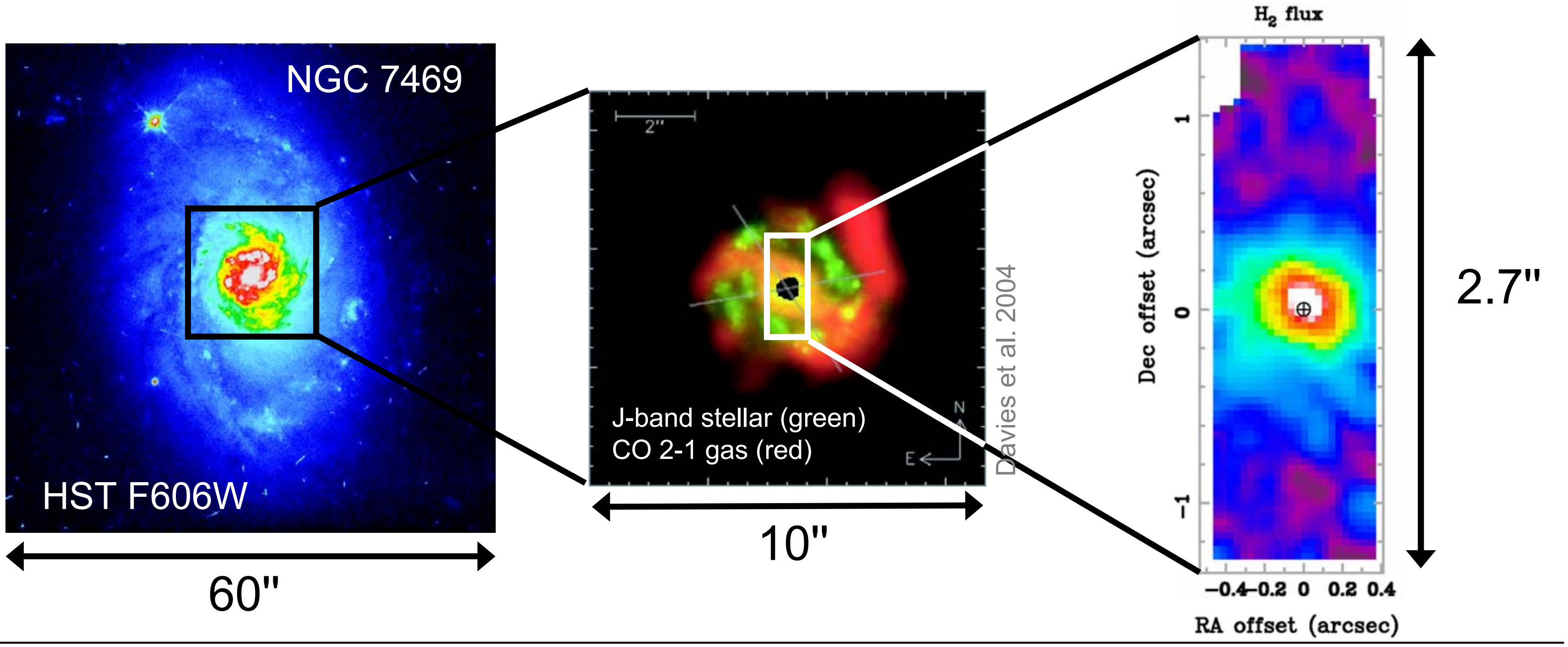
Ric Davies, Reinhard Genzel,
Linda Tacconi, Hauke Engle,
Matt Malkan

Survey of Nearby AGN: Primary Goals

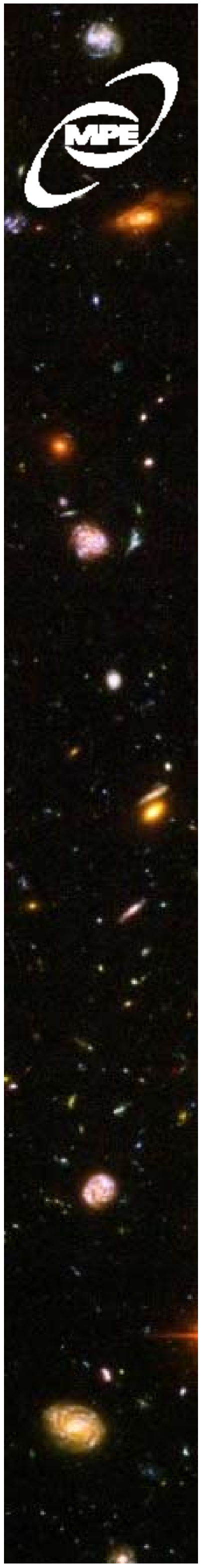
- *Molecular Gas* – measure distribution and kinematics
  - understanding its role in obscuring and fueling the AGN

- *Star Formation* – determine extent, intensity, and star formation history
  - link between AGN activity and nuclear star formation

- *Black Hole Masses* – model spatially resolved stellar and gas kinematics
  - calibrating reverberation mapping method & M_{BH} w/ host galaxy



Davies et al. 2004

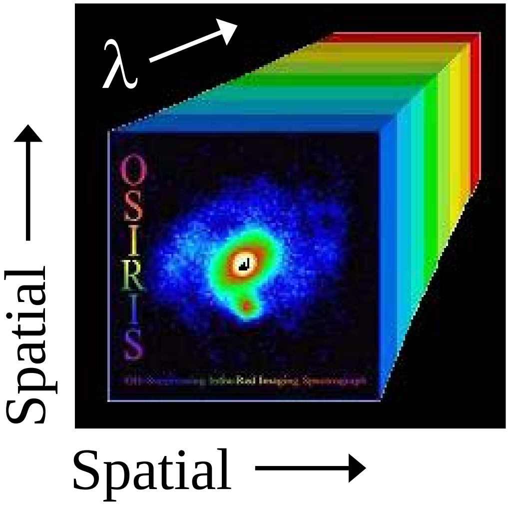


Observations: Adaptive Optics w/ IFUs

Requirements:

1) High spatial resolution ~10 pc (≤ 0".1 for nearby Seyferts)
   - Adaptive Optics: natural & laser guide star

2) Measurement of stellar & gas 2-D morphology and kinematics
   - Minimize AGN emission by using near-infrared spectroscopy (*H*- & *K*-band)
   - Integral field imaging spectroscopy: SINFONI on VLT UT4
     OSIRIS on Keck II



The Sample of Observed AGN

SINFONI Data

Sy 1s & 2s

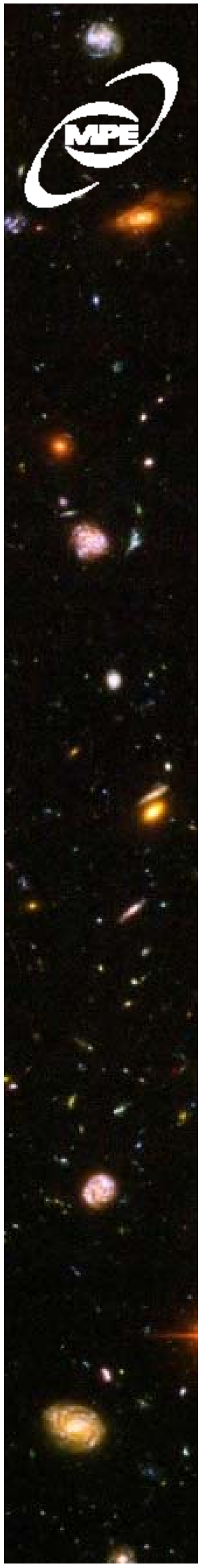
Object	Resolution
NGC 1097	21 pc
NGC 3227	5
NGC 3783	37
NGC 4593	14
NGC 7469	19
NGC 1068	6
Circinus	4

OSIRIS Data

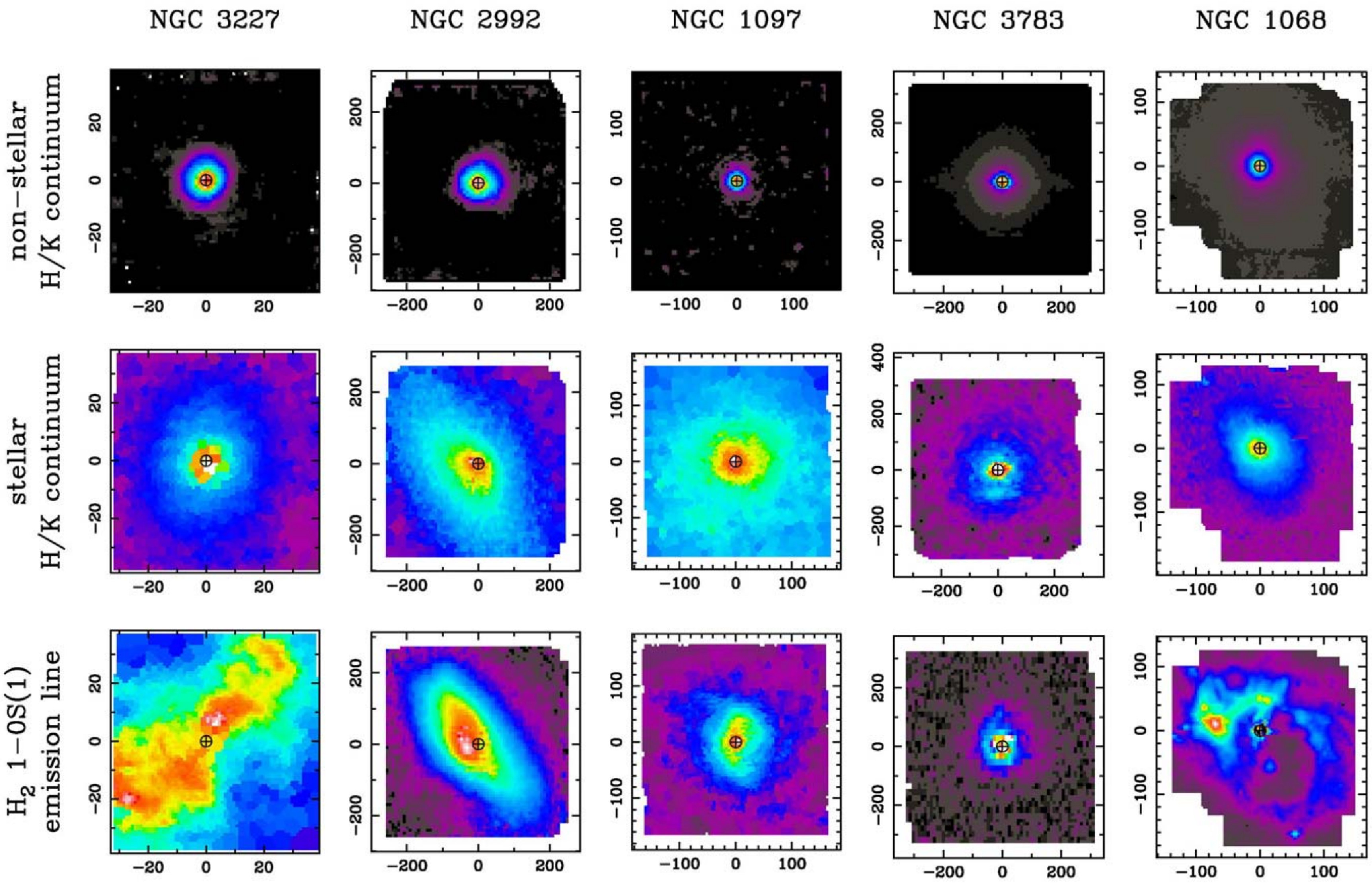
All Reverb. Mapped Sy 1s

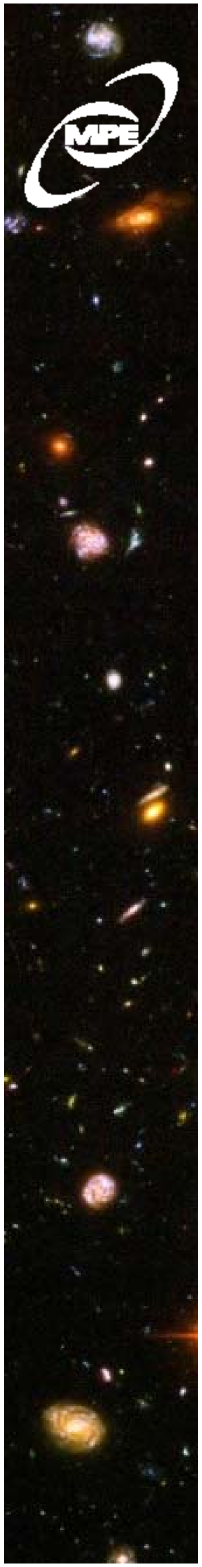
Object	Resolution
NGC 3227	5 pc
NGC 3516	11
NGC 4051	2
NGC 4151	5
NGC 4593	12
NGC 5548	20
NGC 6814	21
NGC 7469	40
IC 4329a	7
Mrk 817	20
Mrk 590	33
Mrk 79	41
Mrk 110	28
Akn 120	45

Mean Resolution: 18 pc

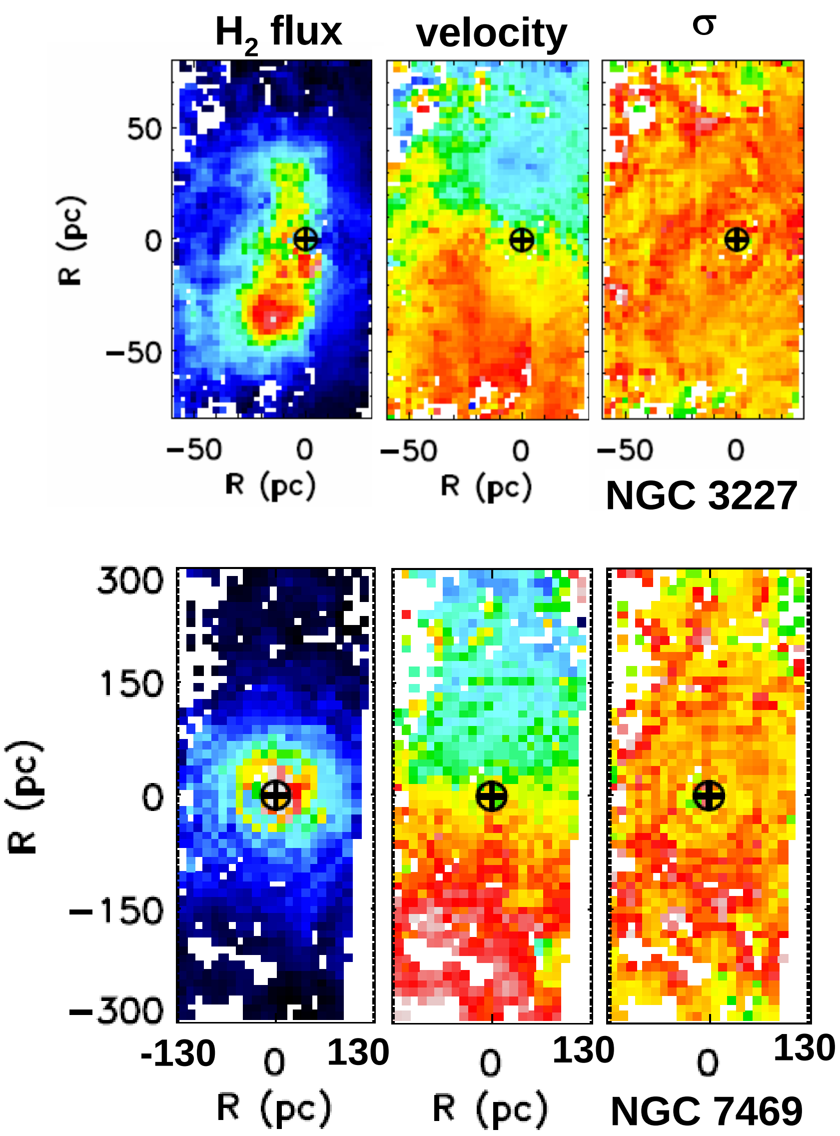


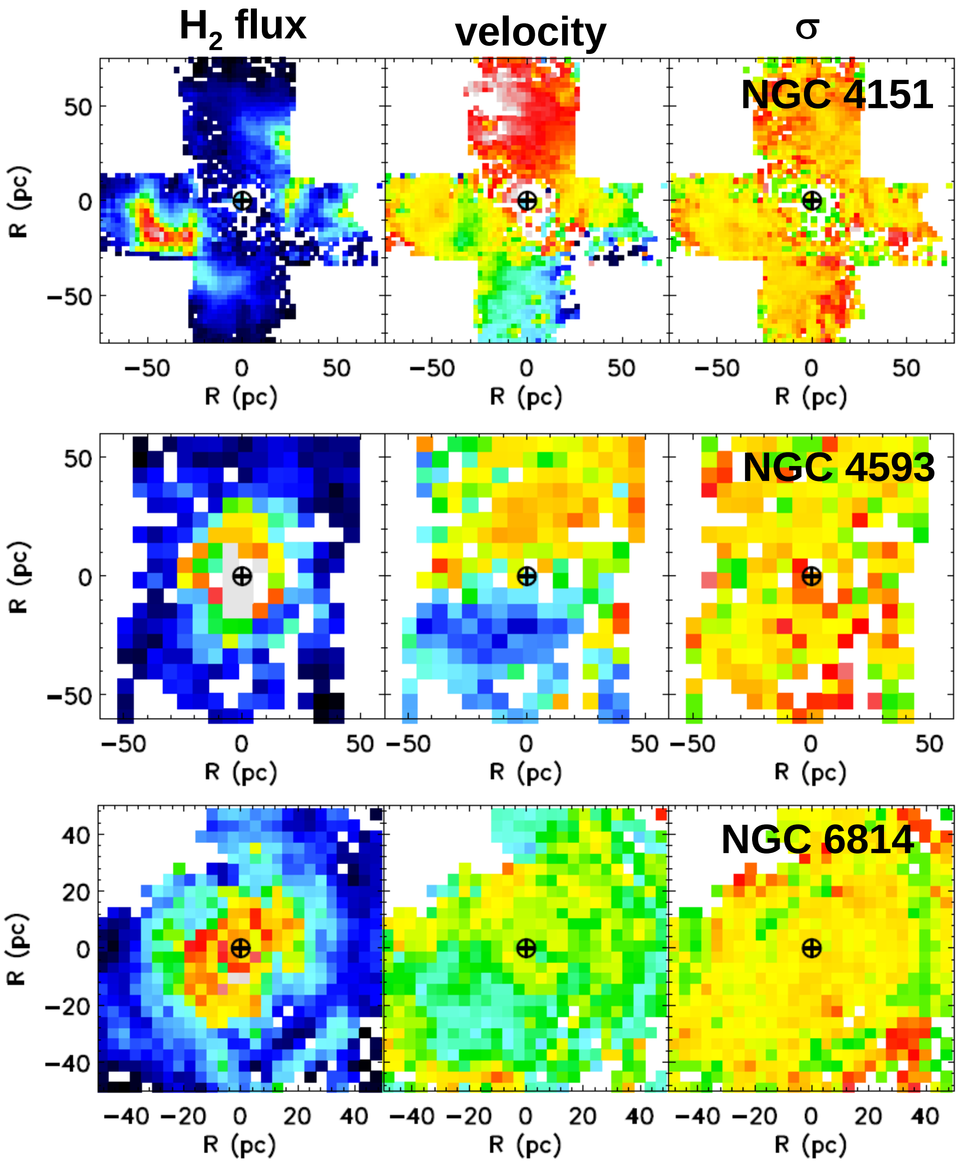
Examples of SINFONI Data

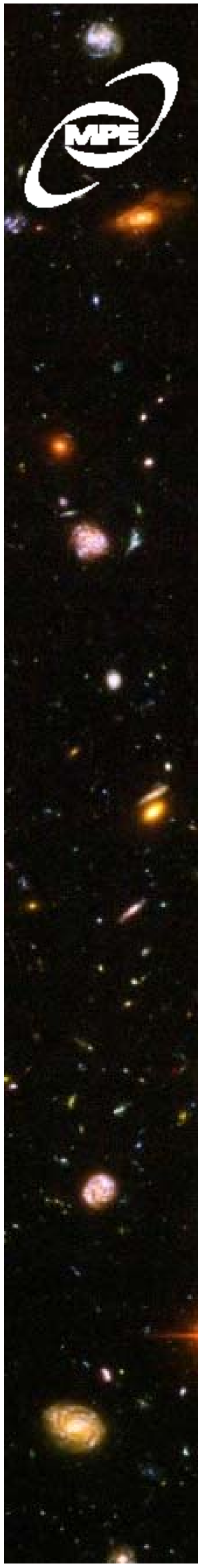




Examples of OSIRIS Data







H_2 1-0 S(1) Flux Distribution

Size Scale

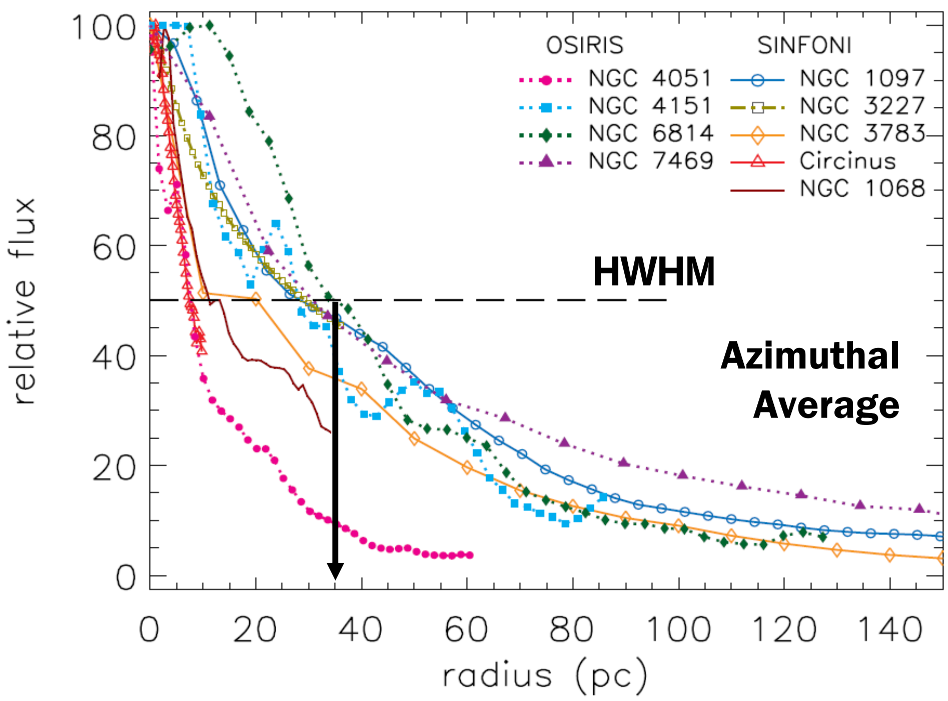
- ✧HWHM < 35pc

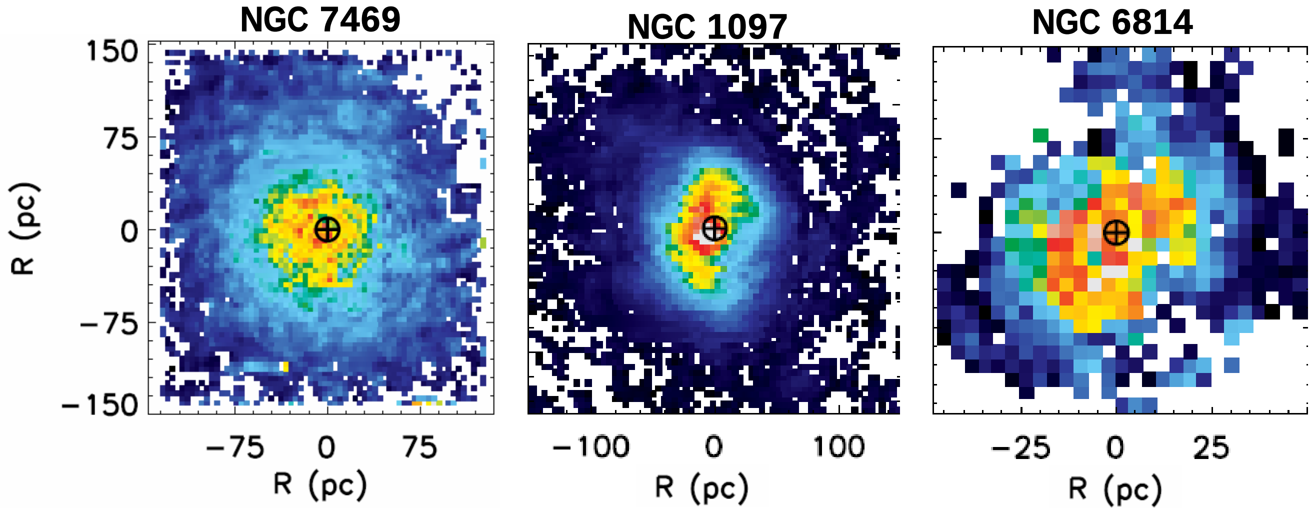
2D velocity field

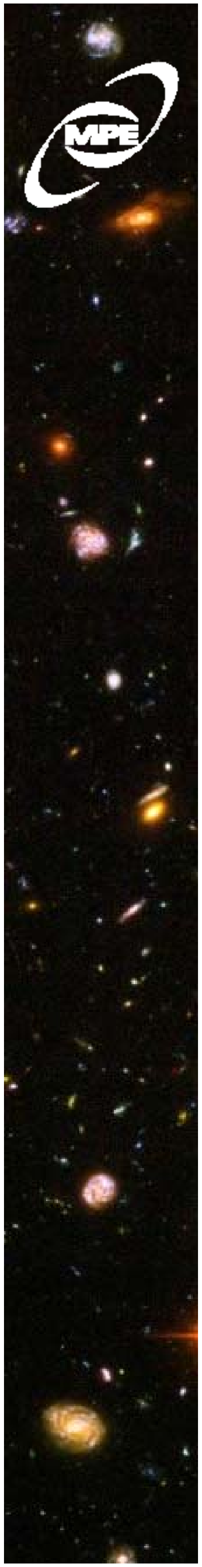
Velocity Dispersion

Dynamical Mass

Column density







H_2 1-0 S(1) Flux Distribution

Size Scale

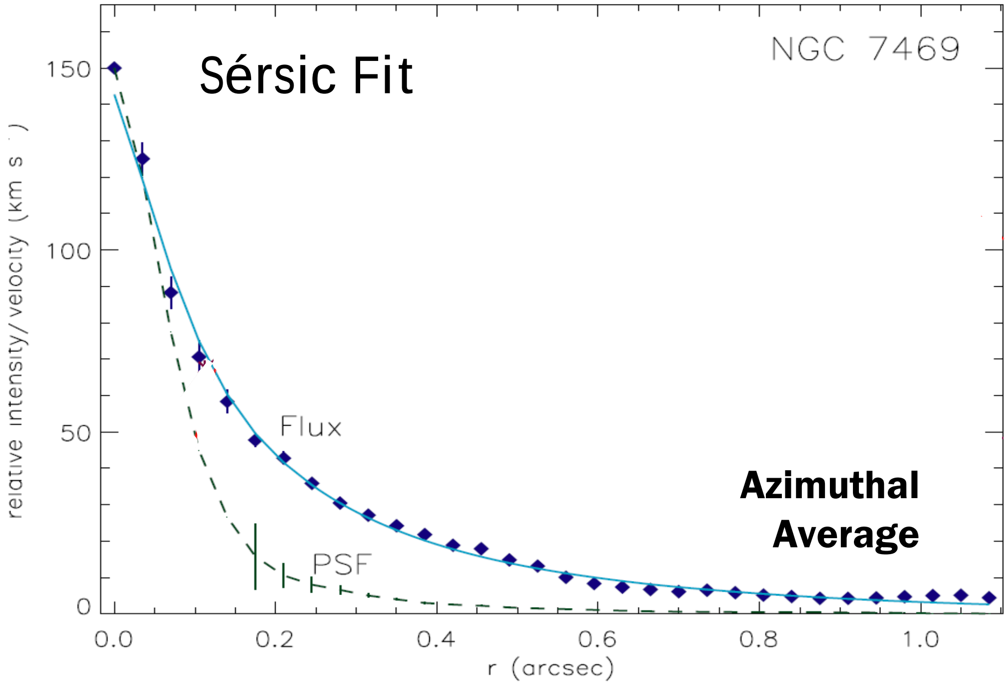
- ✧HWHM < 35pc
- ✧Sérsic *n* = 1.5±0.5

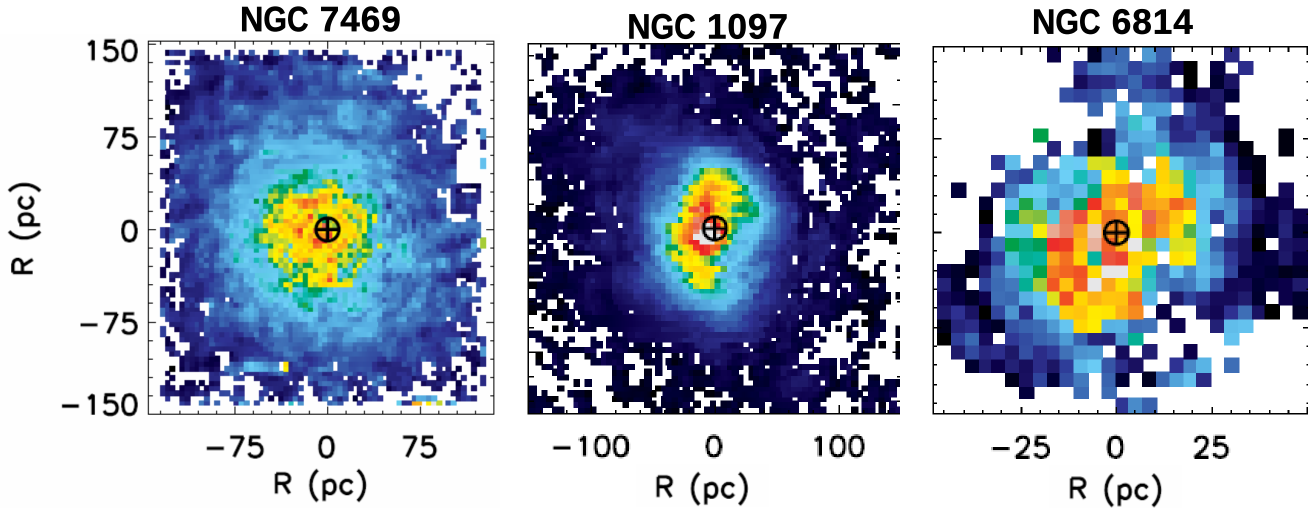
2D velocity field

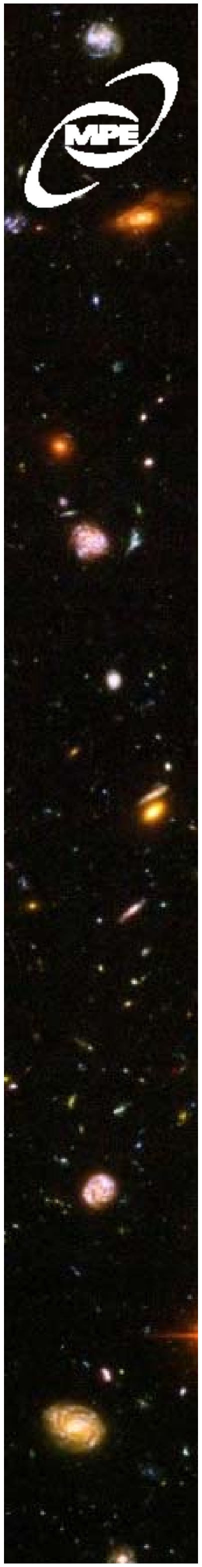
Velocity Dispersion

Dynamical Mass

Column density







Rotational Velocity

Size Scale

- ✧HWHM < 35pc
- ✧Sérsic n = 1.5±0.5

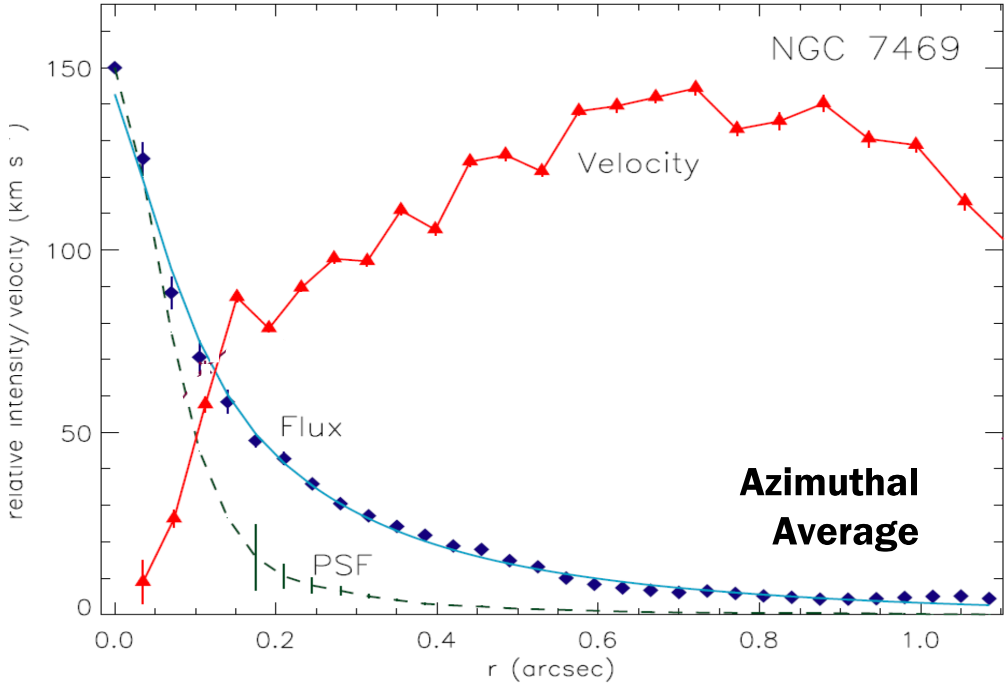
2D velocity field

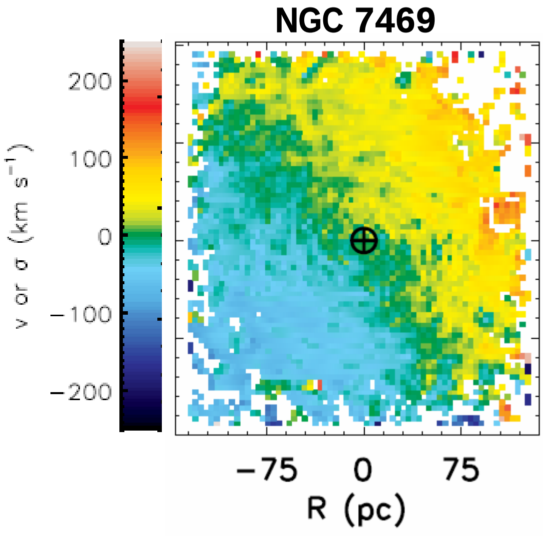
- ✧disk-like to ~20pc

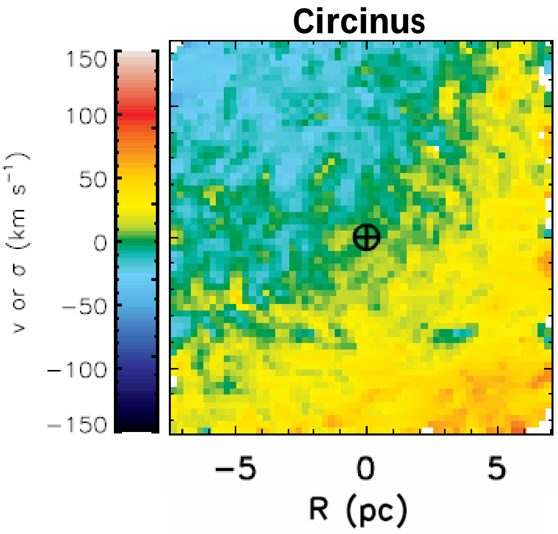
Velocity Dispersion

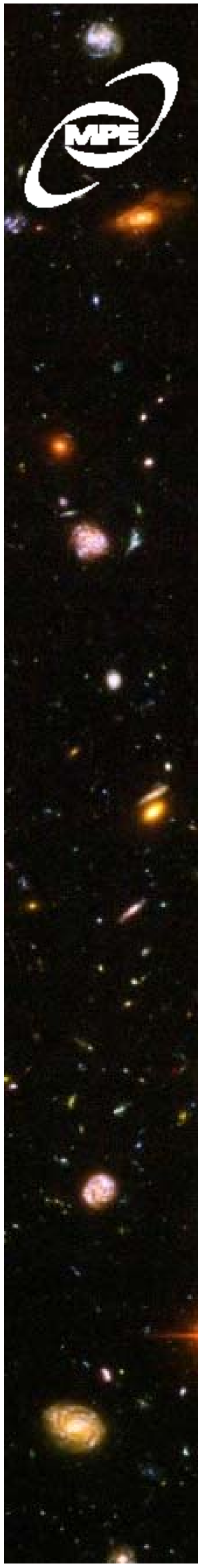
Dynamical Mass

Column density









Size Scale

- ✧HWHM < 35pc
- ✧Sérsic n = 1.5±0.5

2D velocity field

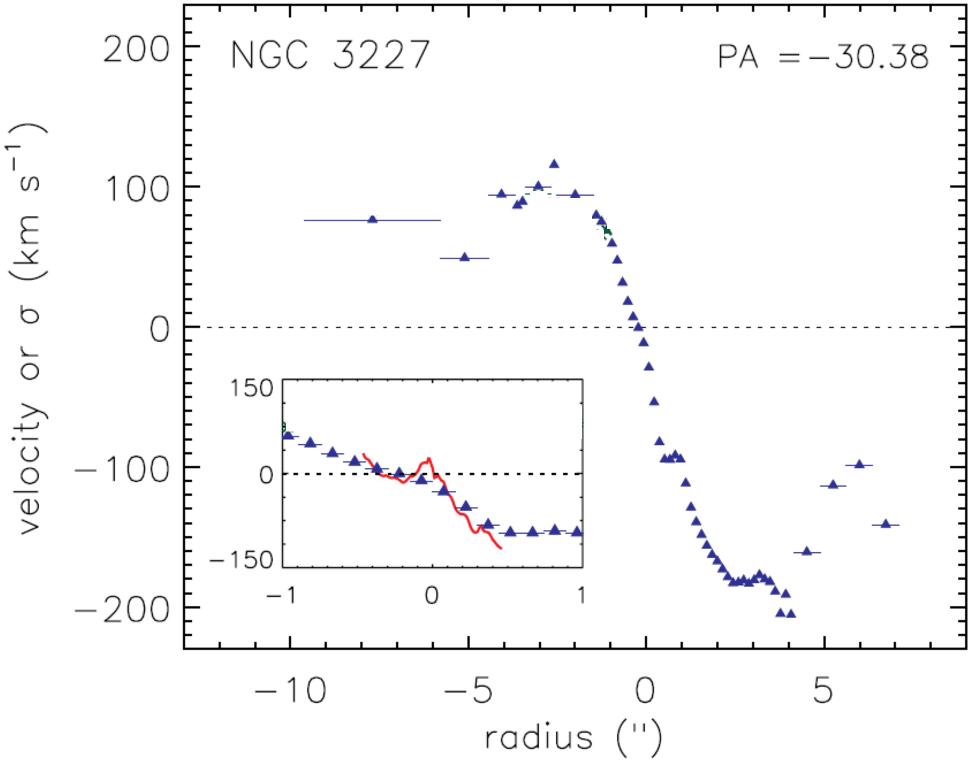
- ✧disk-like to ~20pc
- ✧rotating w/ host

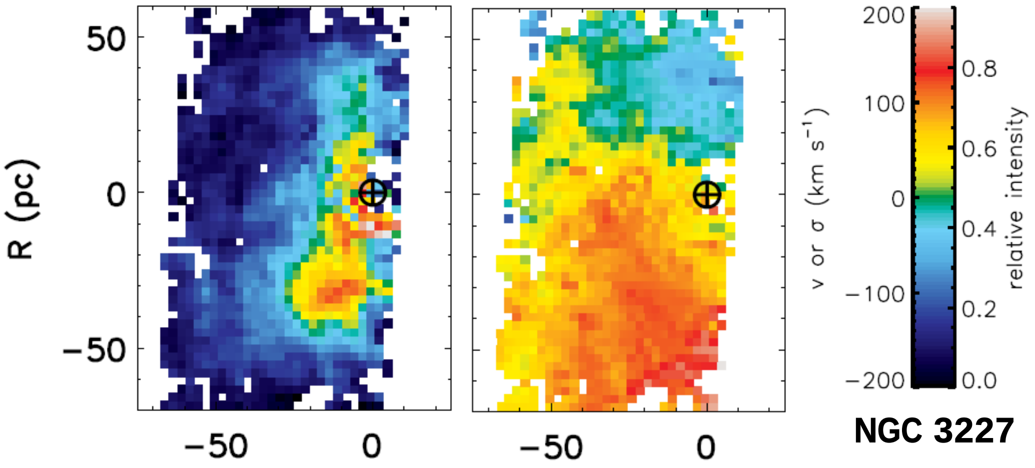
Velocity Dispersion

Dynamical Mass

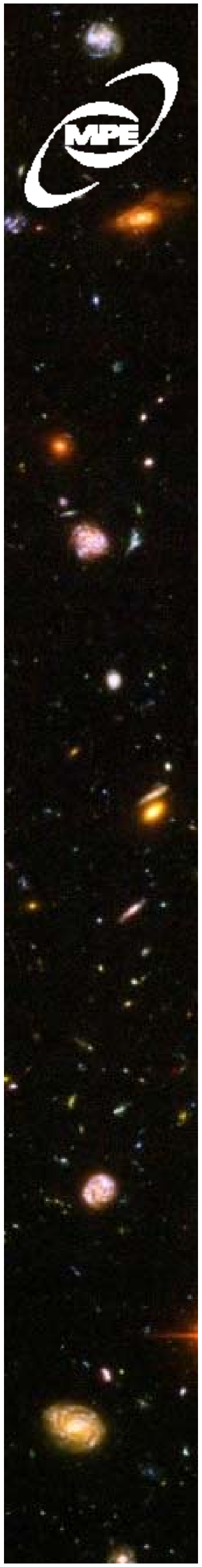
Column density

Rotational Velocity





NGC 3227



Significant Velocity Dispersion

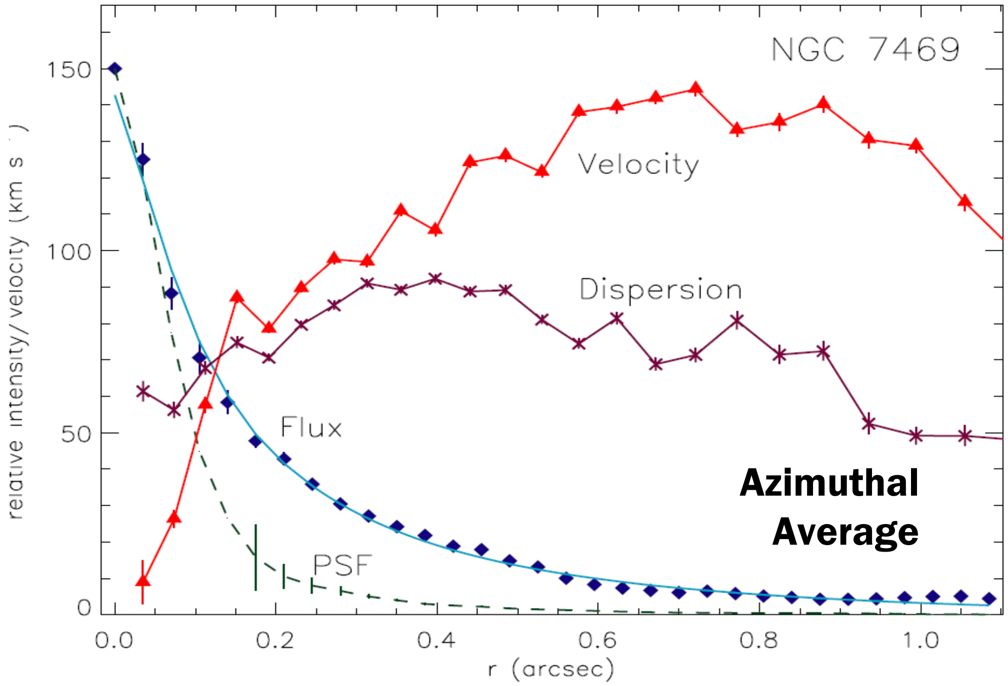
Size Scale
- ✧HWHM < 35pc
- ✧Sérsic *n* = 1.5±0.5

2D velocity field
- ✧disk-like to ~20pc
- ✧rotating w/ host

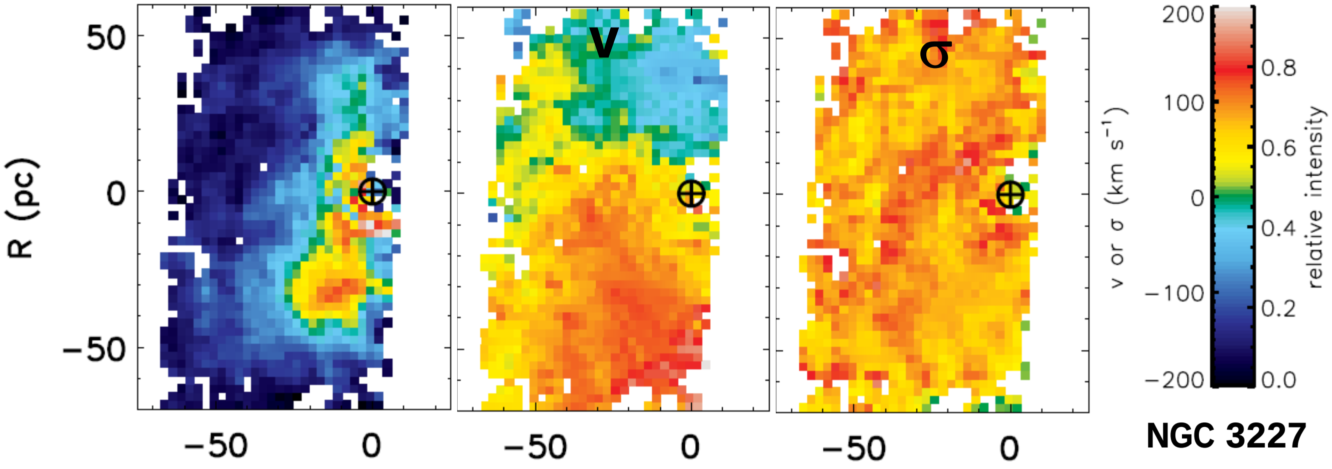
Velocity Dispersion

Dynamical Mass

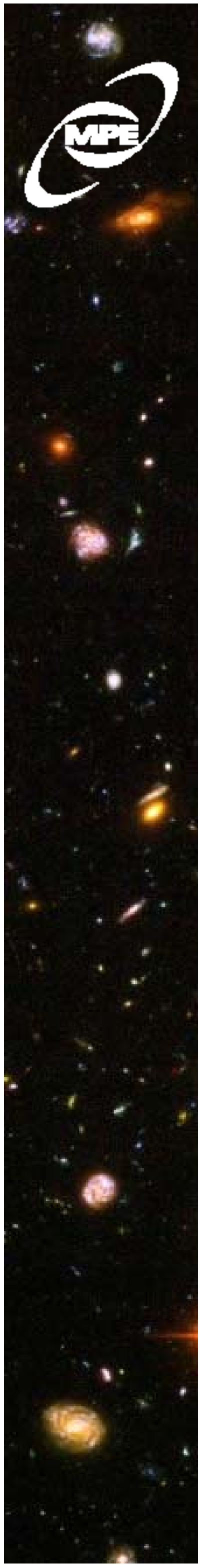
Column density



Azimuthal Average



NGC 3227



Significant Velocity Dispersion

Size Scale

✧HWHM < 35pc

✧Sérsic *n* = 1.5±0.5

2D velocity field

✧disk-like to ~20pc

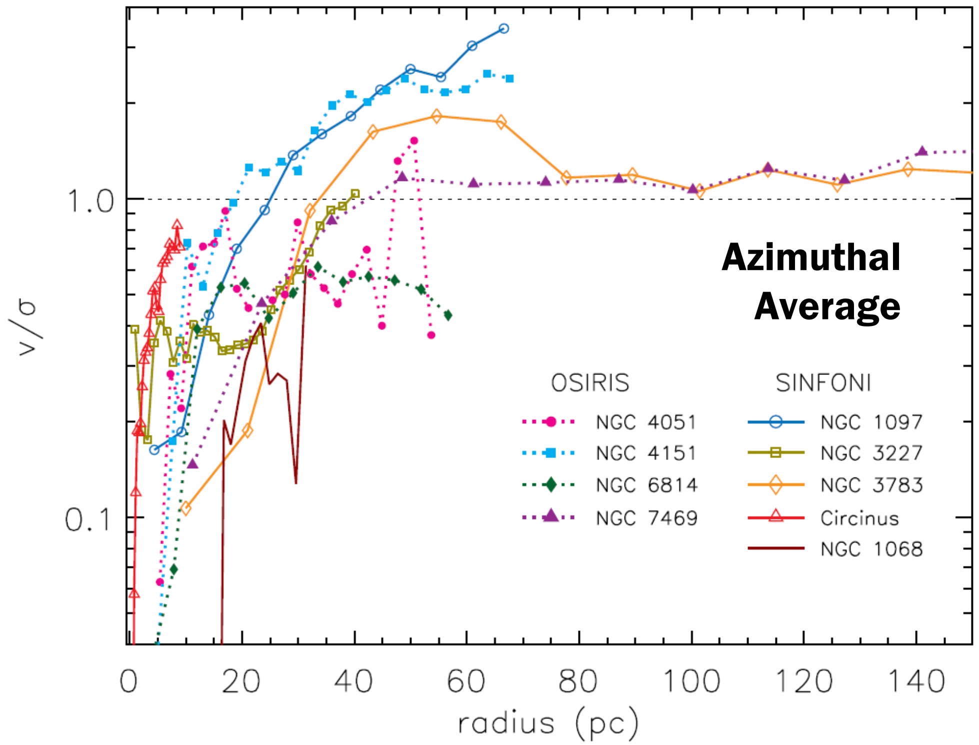
✧rotating w/ host

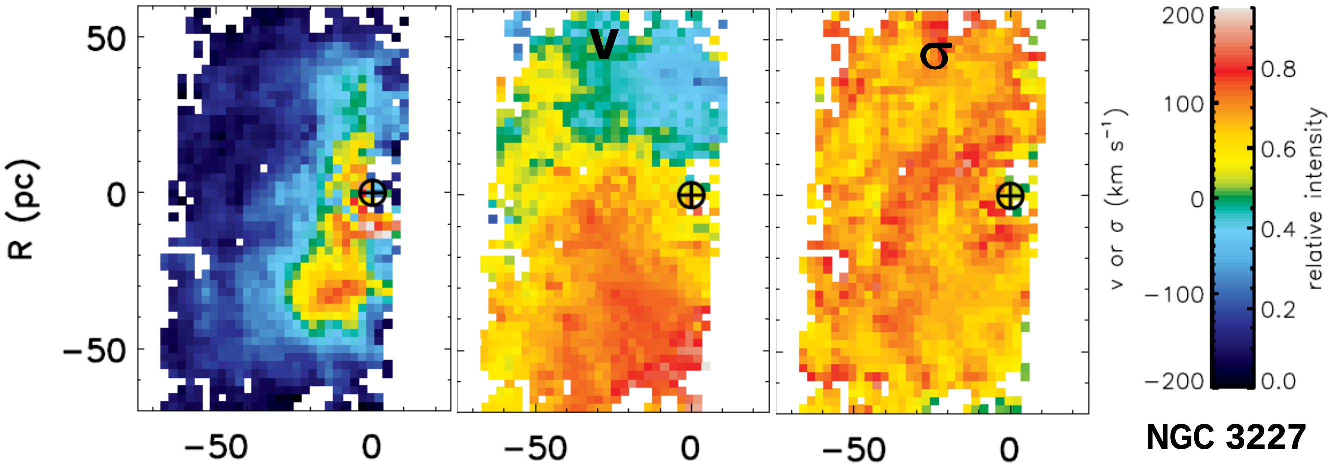
Velocity Dispersion

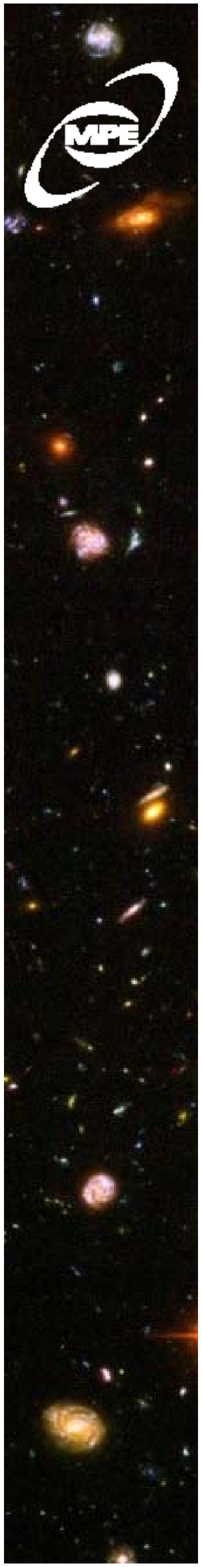
✧$v_{rot}/\sigma = 0.9 \pm 0.4$

Dynamical Mass

Column density







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✧HWHM < 35pc

✧Sérsic *n* = 1.5±0.5

2D velocity field

✧disk-like to ~20pc

✧rotating w/ host

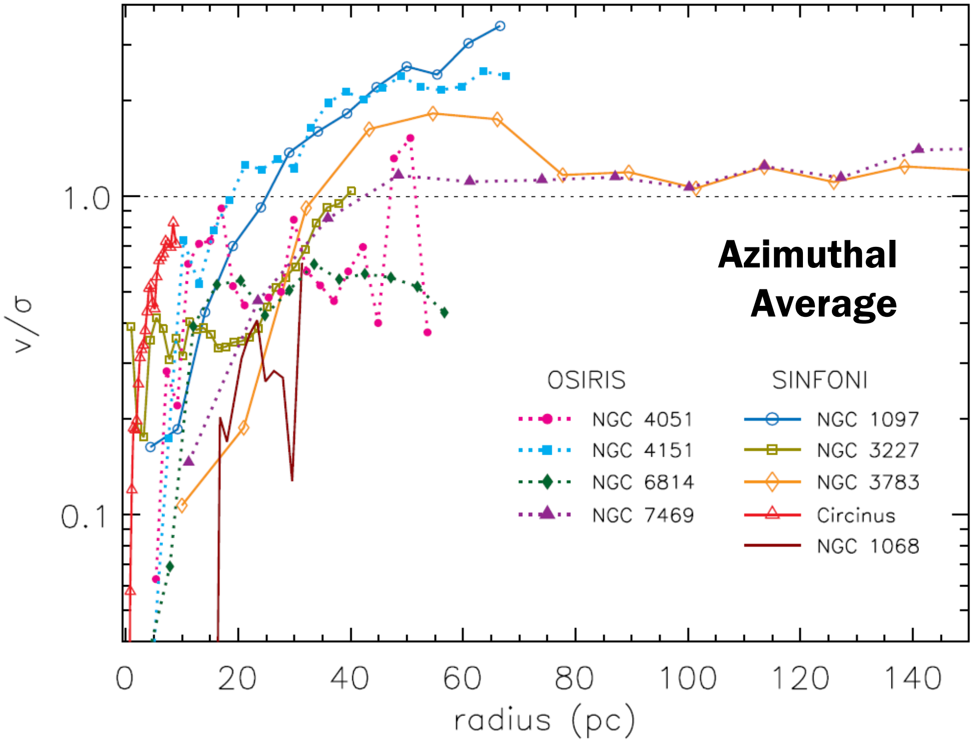
Velocity Dispersion

✧$v_{rot}/\sigma = 0.9 \pm 0.4$

✧$z_o/r = 0.8 \pm 0.4$

Dynamical Mass

Column density



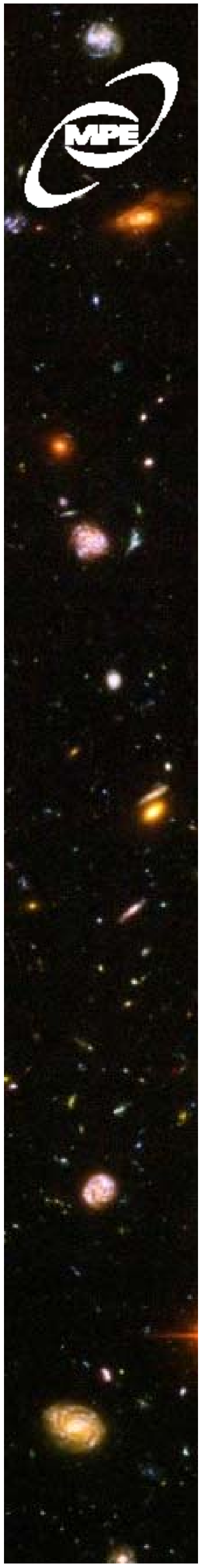
Disk Height:

$$z_o = \sigma^2 / 2\pi G\Sigma$$

$$z_o = r\,(\sigma/v_{rot})$$

On average:

z_o/r (30pc) = 0.8 ± 0.4



Dynamical Mass

Size Scale

- HWHM < 35pc
- Sérsic *n* = 1.5±0.5

2D velocity field

- disk-like to ~20pc
- rotating w/ host

Velocity Dispersion

- $v_{rot}/\sigma = 0.9 \pm 0.4$
- $z_o/r \;\; = 0.8 \pm 0.4$

Dynamical Mass

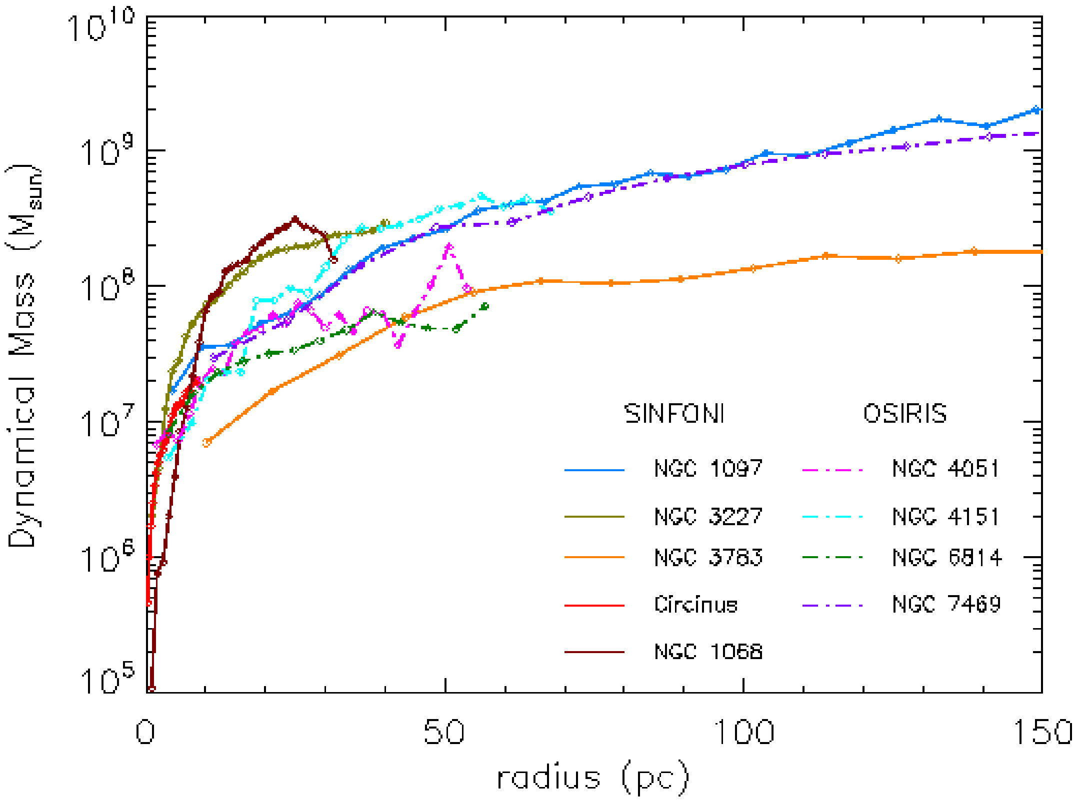
- Account for σ
- $M_{dyn} = (1.0 \pm 0.6) \times 10^8 \, M_\odot$

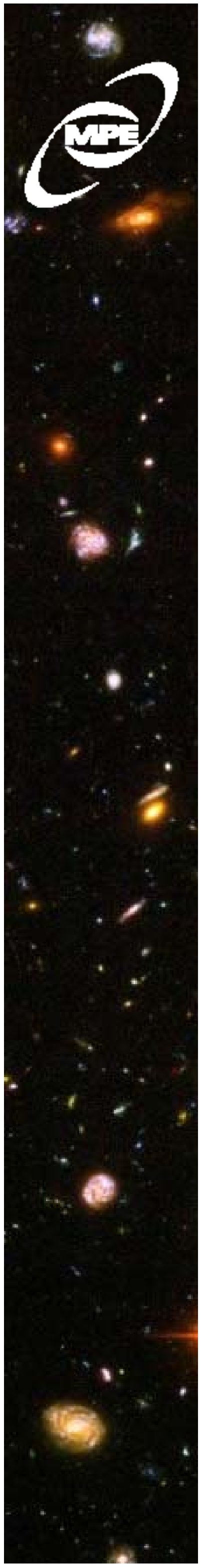
Column density

Accounting for the velocity dispersion:

$$\mathbf{M_{dyn} = (v_{rot}^2 + 3\sigma^2)\, R \,/\, G}$$

Average M_{dyn} (30pc) = $(1.0 \pm 0.6) \times 10^8 \, M_\odot$





Estimating Column Density

Size Scale

- ✧HWHM < 35pc
- ✧Sérsic *n* = 1.5±0.5

2D velocity field

- ✧disk-like to ~20pc
- ✧rotating w/ host

Velocity Dispersion

- ✧$v_{rot}/\sigma = 0.9 \pm 0.4$
- ✧$z_o/r = 0.8 \pm 0.4$

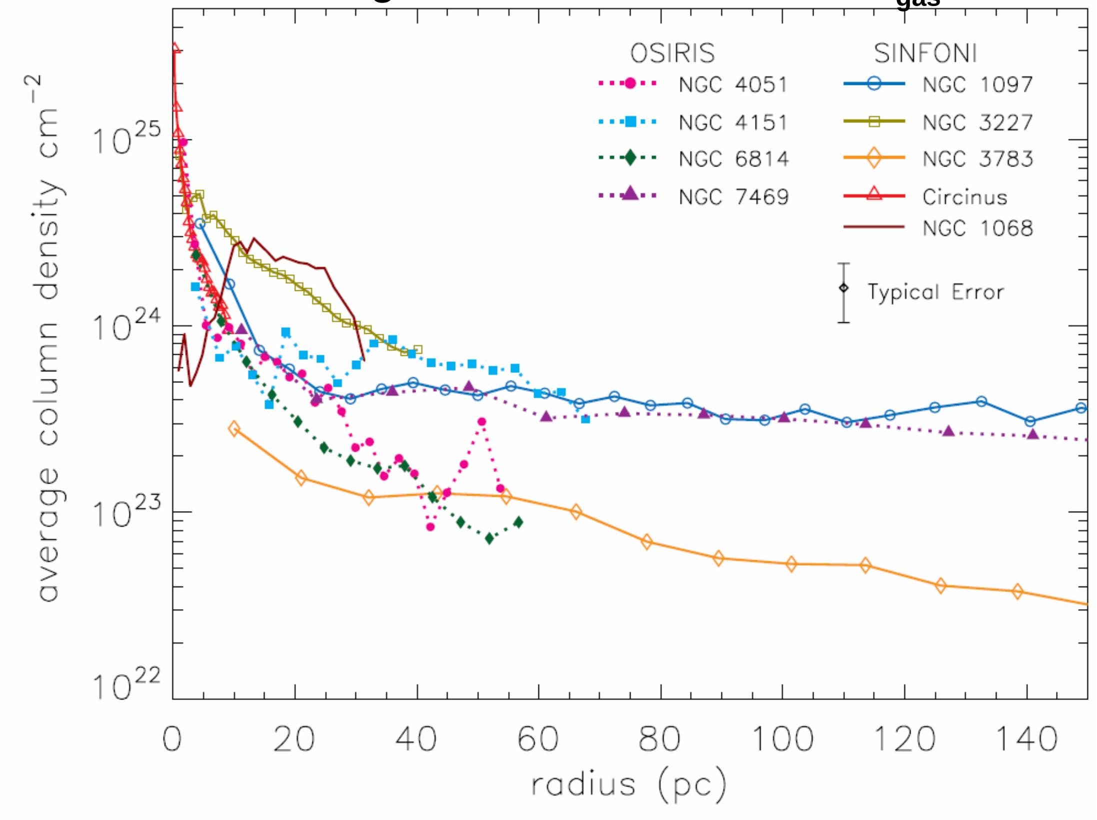
Dynamical Mass

- ✧Account for σ
- ✧$M_{dyn} = (1.0 \pm 0.6) \times 10^8 M_\odot$

Column density

- ✧$N_H \sim 10^{22-23}$ cm^{-2}
- ✧clumpy!

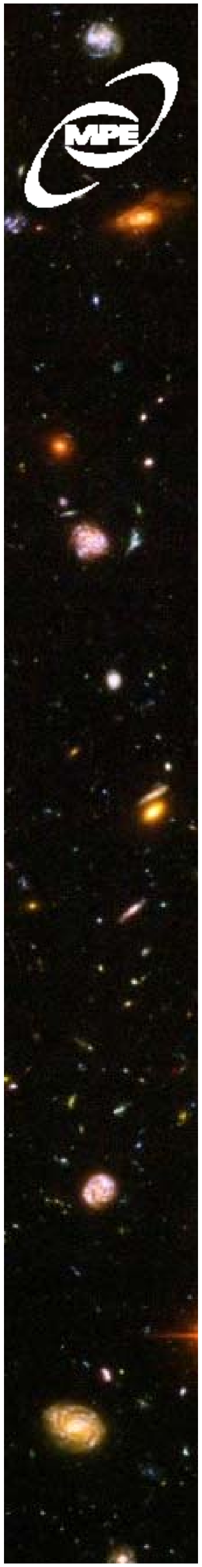
Assuming a uniform distribution & f_{gas} = 10%



$$M_{gas} = M_{dyn} \times f_{gas}$$

Average $N_H = (4.9 \pm 3.3) \times 10^{23}$ cm^{-2}

f_{gas} typically about 10% in central 100 pc



Estimating Column Density

Size Scale

✧HWHM < 35pc

✧Sérsic n = 1.5±0.5

2D velocity field

✧disk-like to ~20pc

✧rotating w/ host

Velocity Dispersion

✧$v_{rot}/\sigma = 0.9 \pm 0.4$

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Dynamical Mass

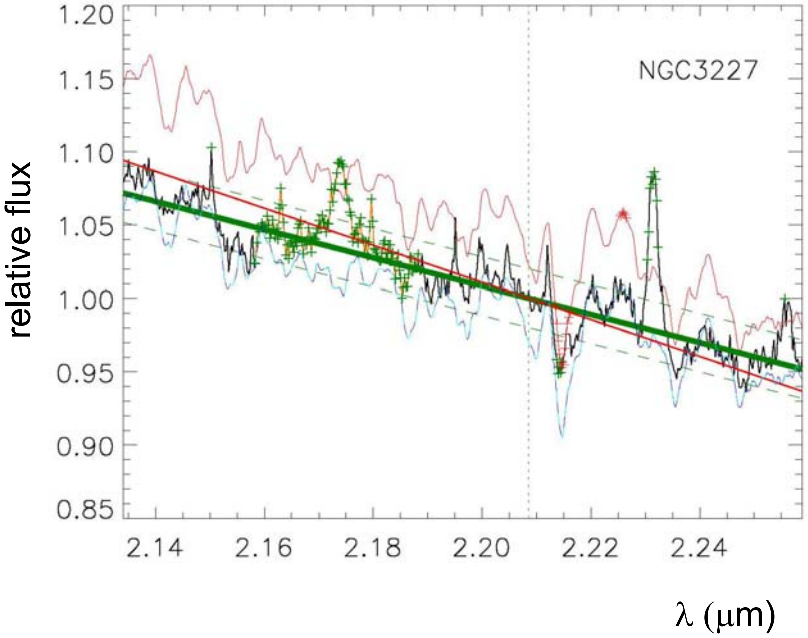
✧Account for σ

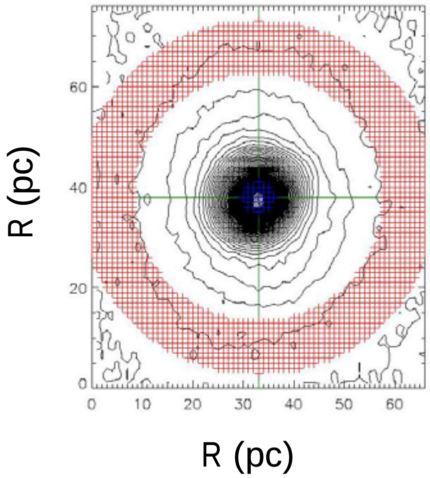
✧$M_{dyn} = (1.0 \pm 0.6) \times 10^8 M_\odot$

Column density

✧$N_H \sim 10^{22-23}$ cm^{-2}

✧clumpy!

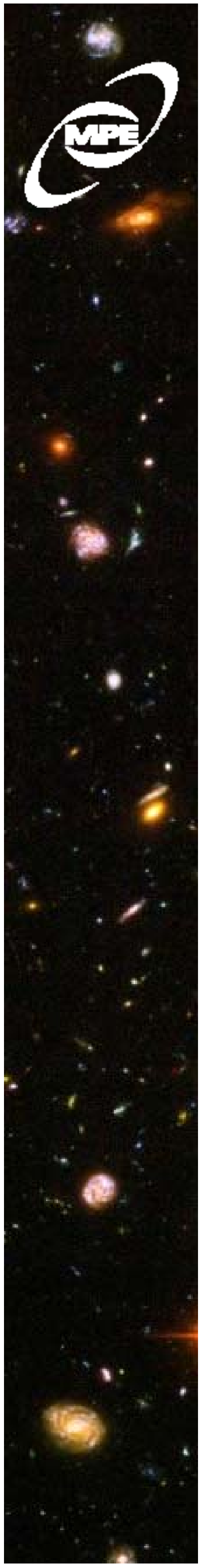




$A_v \sim$ 5mags → $N_H \sim 10^{22}$ cm^{-2}

Stellar extinction implies lower column densities → clumpy medium

In many cases the gas is still optically thick



Properties of the Molecular Gas

Size Scale

- HWHM < 35pc
- Sérsic $n = 1.5 \pm 0.5$

2D velocity field

- disk-like to ~20pc
- rotating w/ host

Velocity Dispersion

- $v_{rot}/\sigma = 0.9 \pm 0.4$
- $z_o/r = 0.8 \pm 0.4$

Dynamical Mass

- Account for σ
- $M_{dyn} = (1.0 \pm 0.6) \times 10^8 M_\odot$

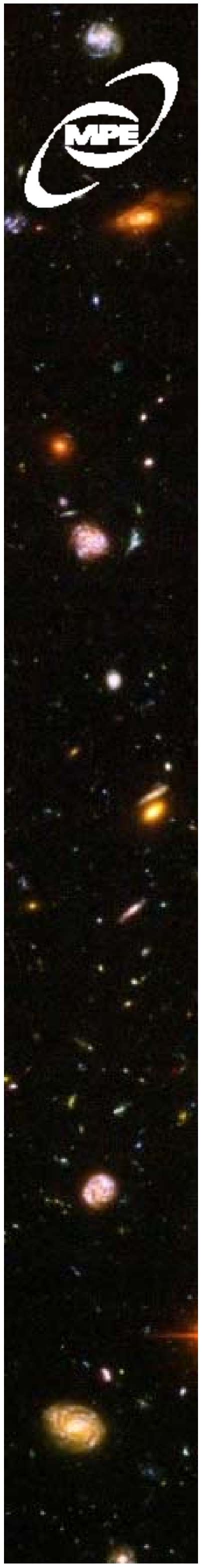
Column density

- $N_H \sim 10^{22-23}$ cm^{-2}
- clumpy!

The molecular gas on scales of ~10 pc is in a geometrically and optically thick disk

This gas is likely
to be associated with
(the global structure of)
the obscuring 'torus'

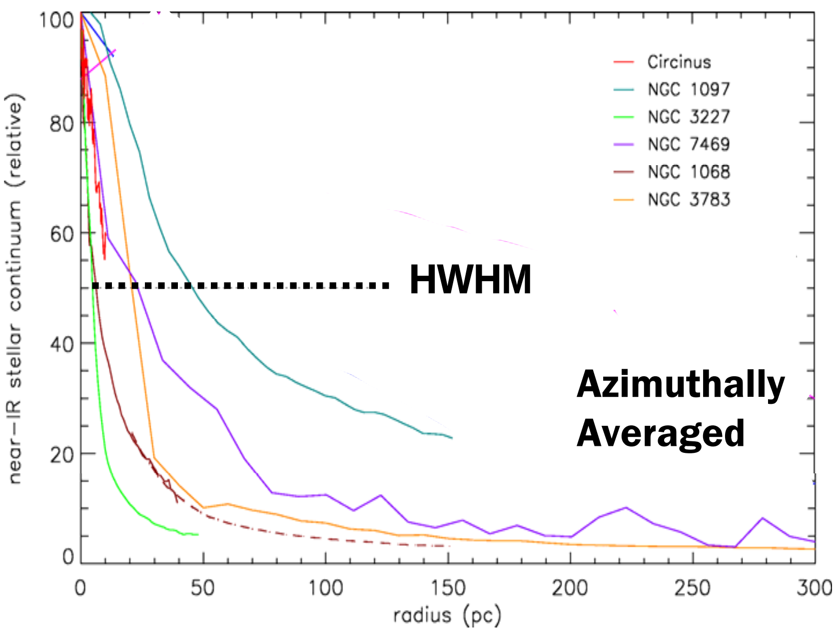
Hicks et al. 2009

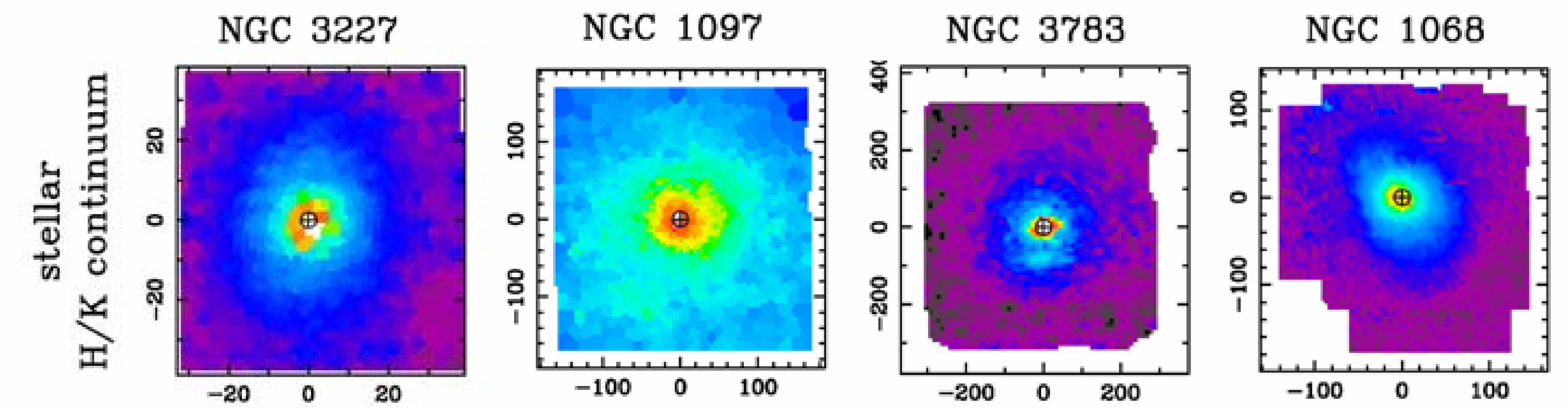


Nuclear Star Clusters

- Additional nuclear stellar component on scales of a few 10s of parsecs
- Evidence of stellar nuclear disks
- H_2 and stellar kinematics are very similar

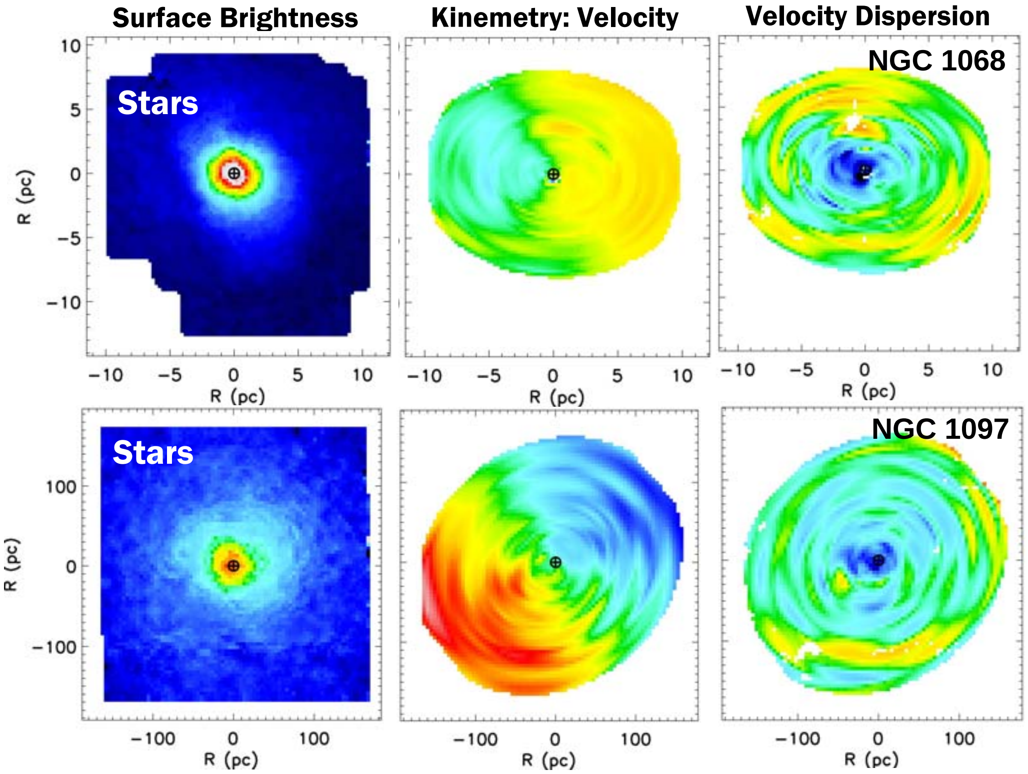
Stellar Light Profile - CO bandheads



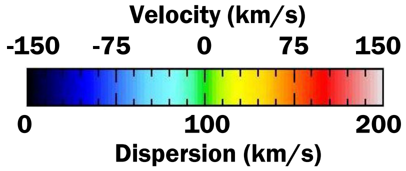


Davies et al. 2007

Nuclear Star Clusters



Stellar Dispersion 'sigma'-drops



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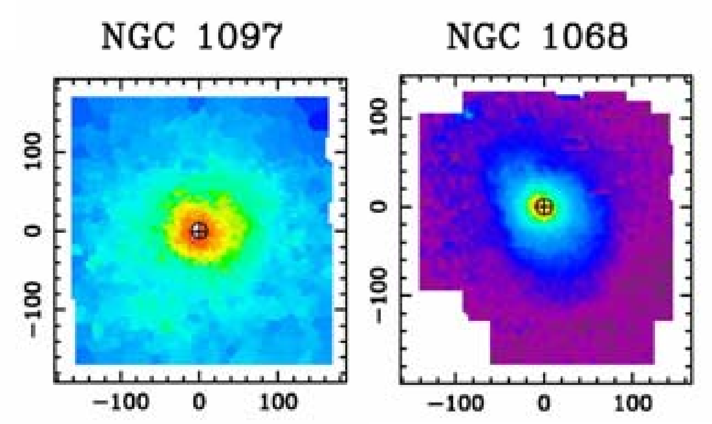
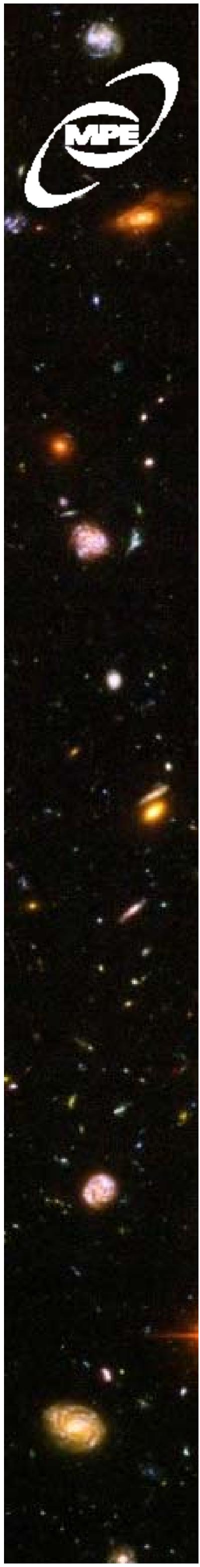
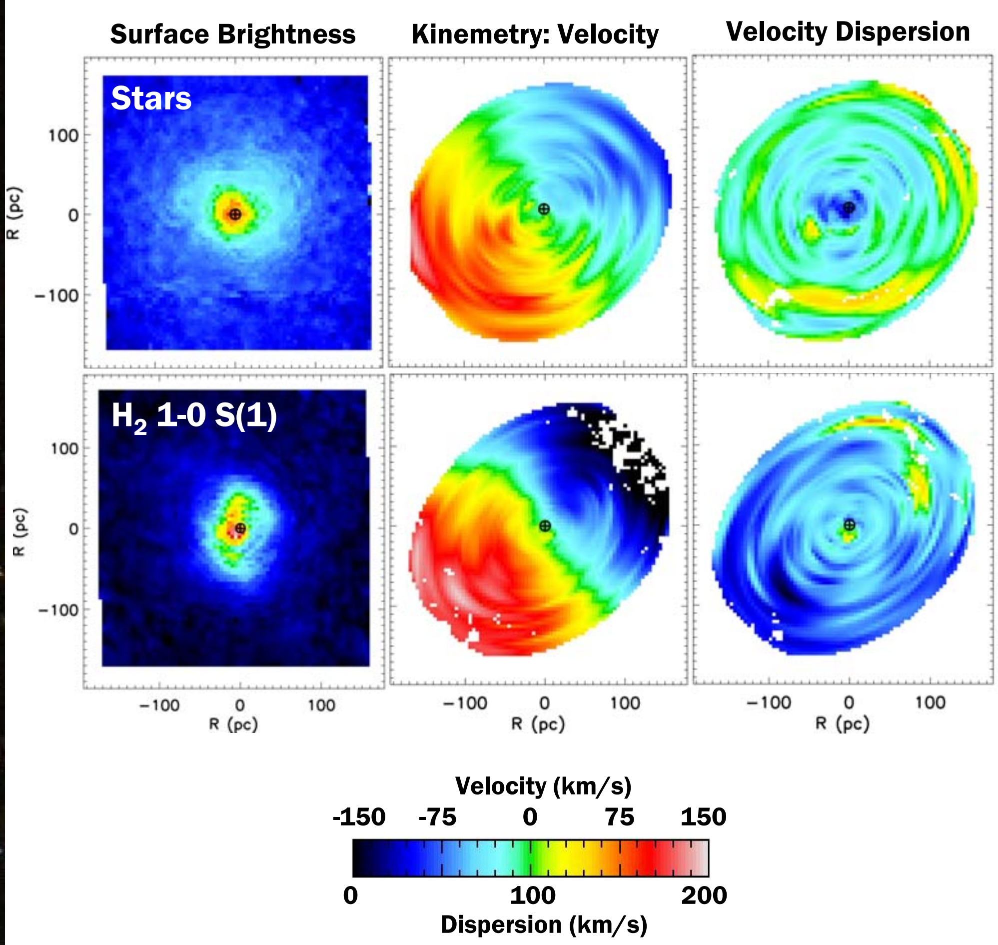




Nuclear Star Clusters

NGC 1097



- Additional nuclear stellar component on scales of a few 10s of parsecs
- Evidence of stellar nuclear disks
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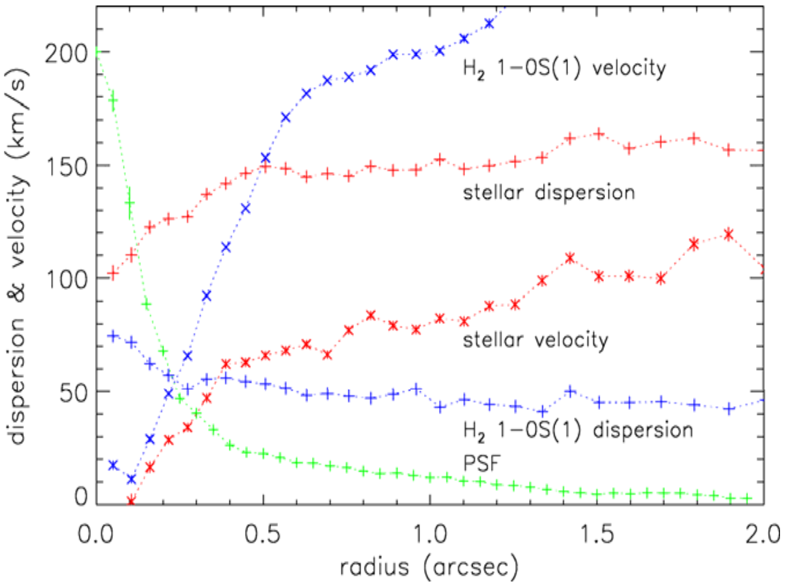
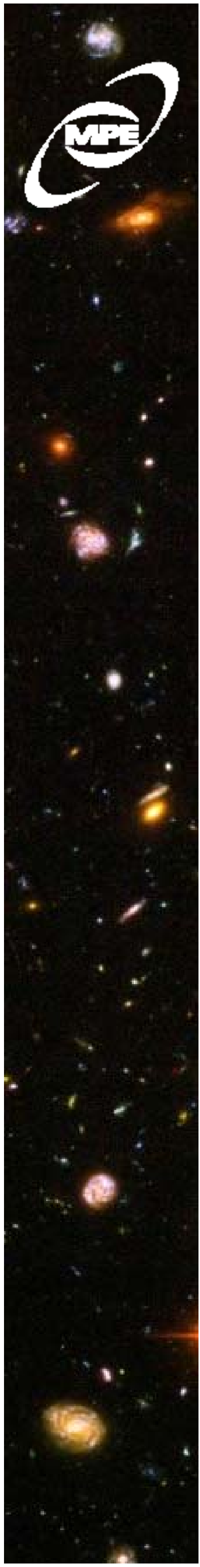
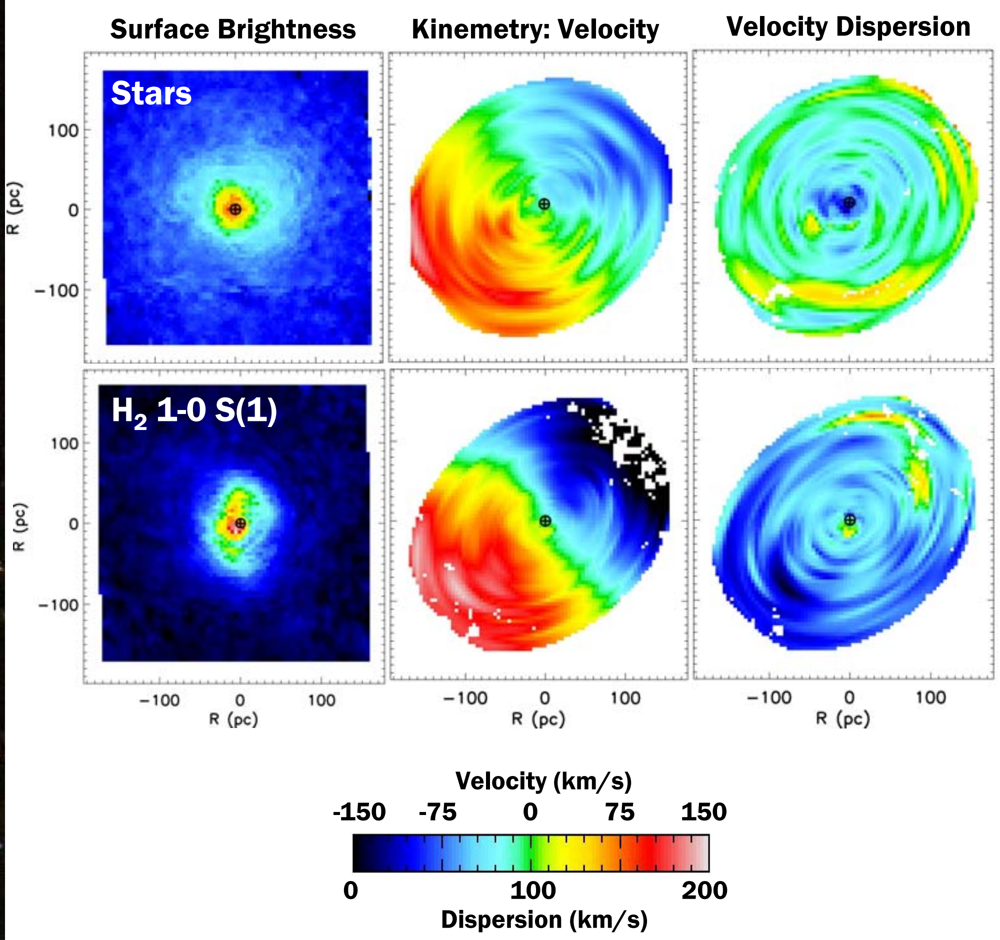




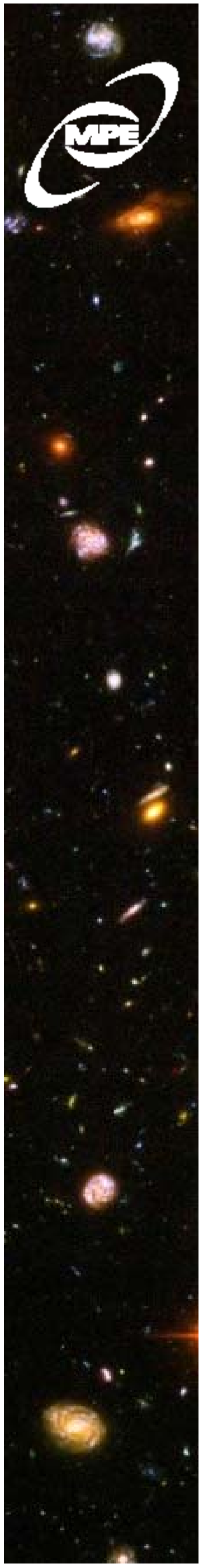
Gas vs. Stellar Kinematics

NGC 1097



- Additional nuclear stellar component on scales of a few 10s of parsecs
- Evidence of stellar nuclear disks
- H_2 and stellar kinematics are very similar

gas and stars are spatially mixed in a thick disk



Gas vs. Stellar Kinematics

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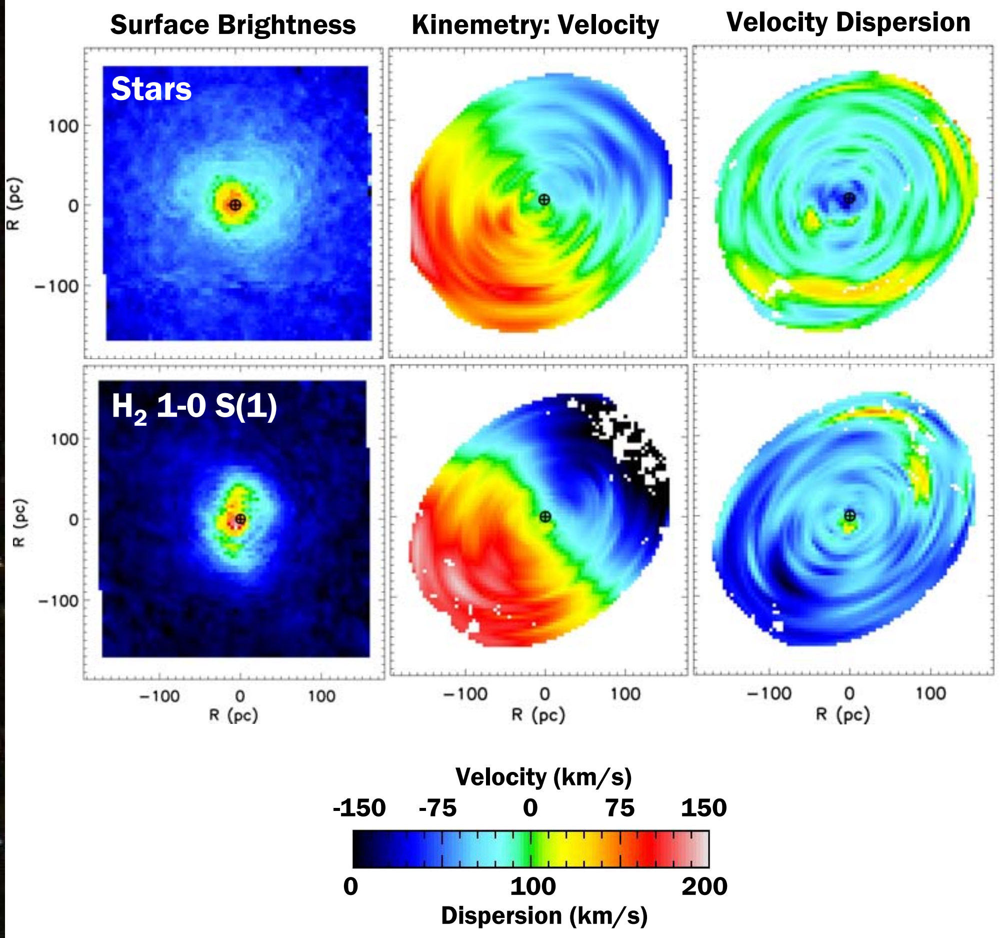
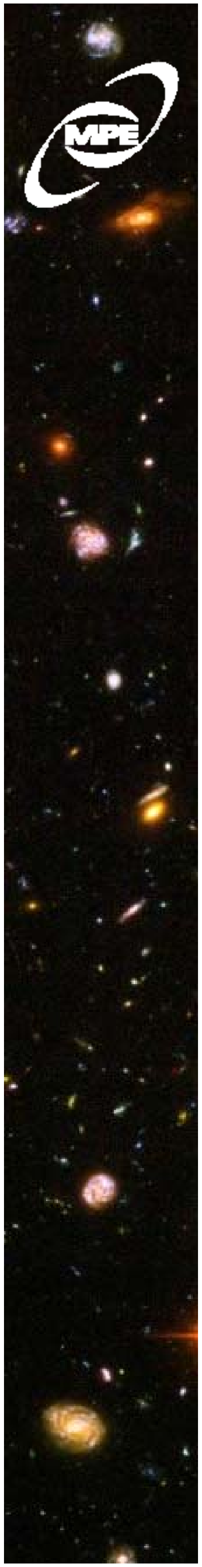


- ✧ Additional nuclear stellar component on scales of a few 10s of parsecs
- ✧ Evidence of stellar nuclear disks
- ✧ H_2 and stellar kinematics are very similar

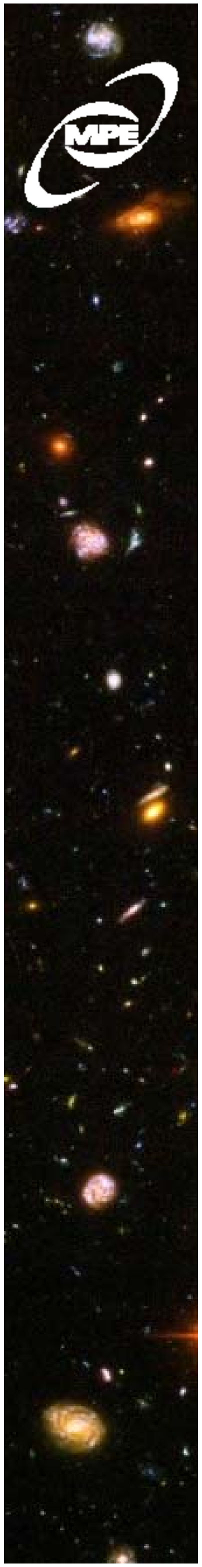
bulk of the molecular gas traces the gravitational potential



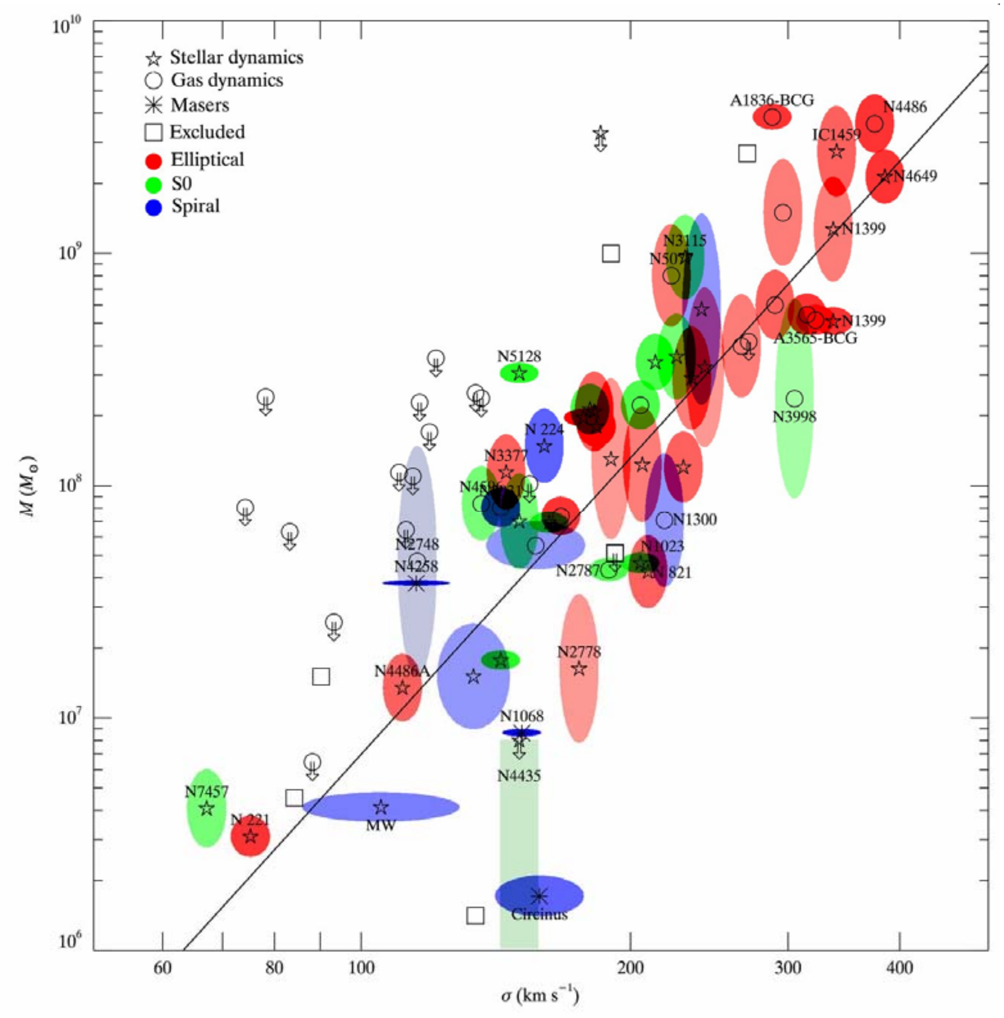
Maintaining the High Velocity Dispersion

Energy must be injected into the system in order to maintain the bulk motion of the H_2 clouds.

- ✗ Radial out/in flow (e.g. Elitzure & Shlosman 2006) No kinematic evidence
- ✗ Disk warp (Nayakshin 2005, Caproni et al. 2006) No kinematic evidence
- ✗ Supernovae (Wada & Norman 2002) SNR 1-4 orders of magnitude too low (Davies et al. 2007)
- ✗ Stellar winds (Nayakshin & Cuadra 2007) Only able to achieve $z_0 \sim$ few pc
- ✗ Radiation pressure from the AGN (Krolic 1992, 2007) Only able to contribute to z_0 on smaller scales
- ✧ Radiation pressure from the stars (Thompson et al. 2005) Able to achieve $z_0 \sim$ 10s pc, but only during peak SF
- ✧ Gravitational energy from gas inflow (Vollmer et al. 2008) Able to achieve $z_0 \sim$ 10s pc



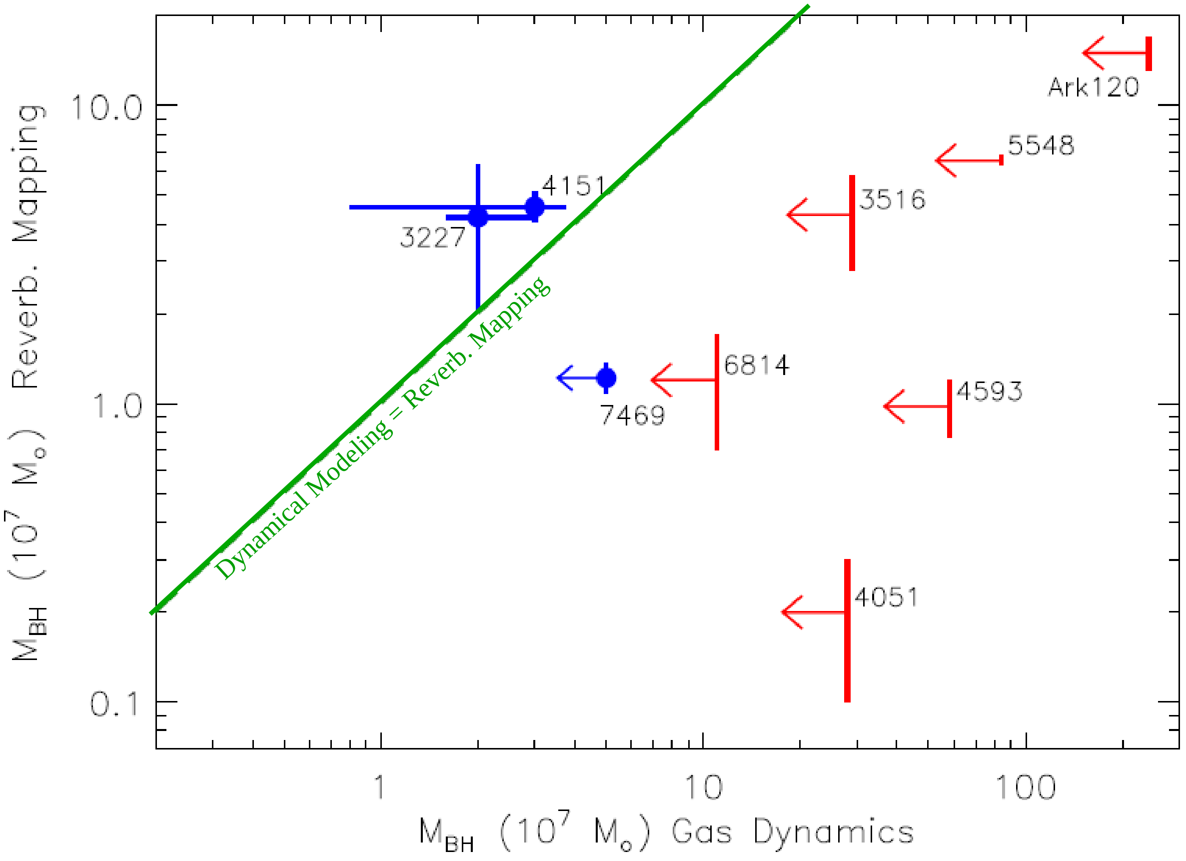
Measuring M_{BH} Directly in Seyfert Galaxies & Calibration of Reverberation Mapping Method



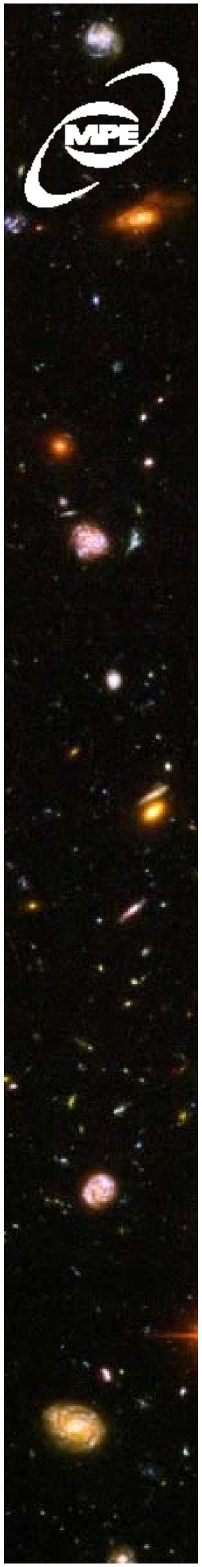
Gültekin 2009

Do Seyferts and other AGN really lie on the M_{BH}-σ relation?

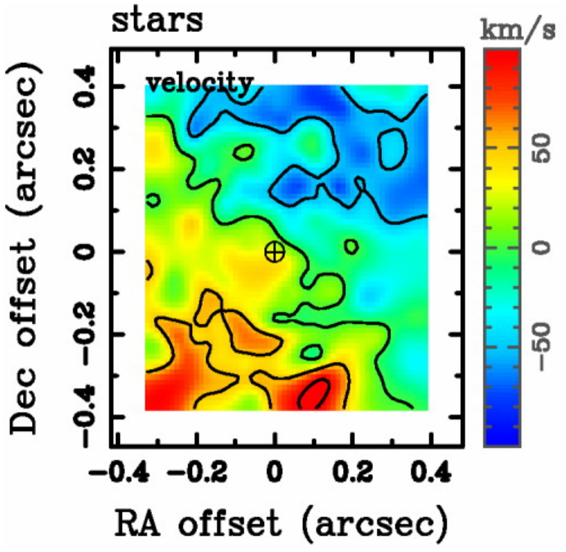
Measuring M_{BH} Directly in Seyfert Galaxies & Calibration of Reverberation Mapping Method

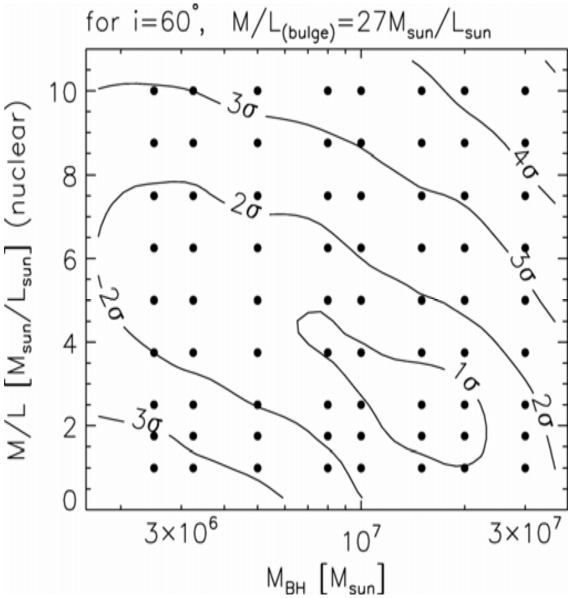


Hicks & Malkan 2009

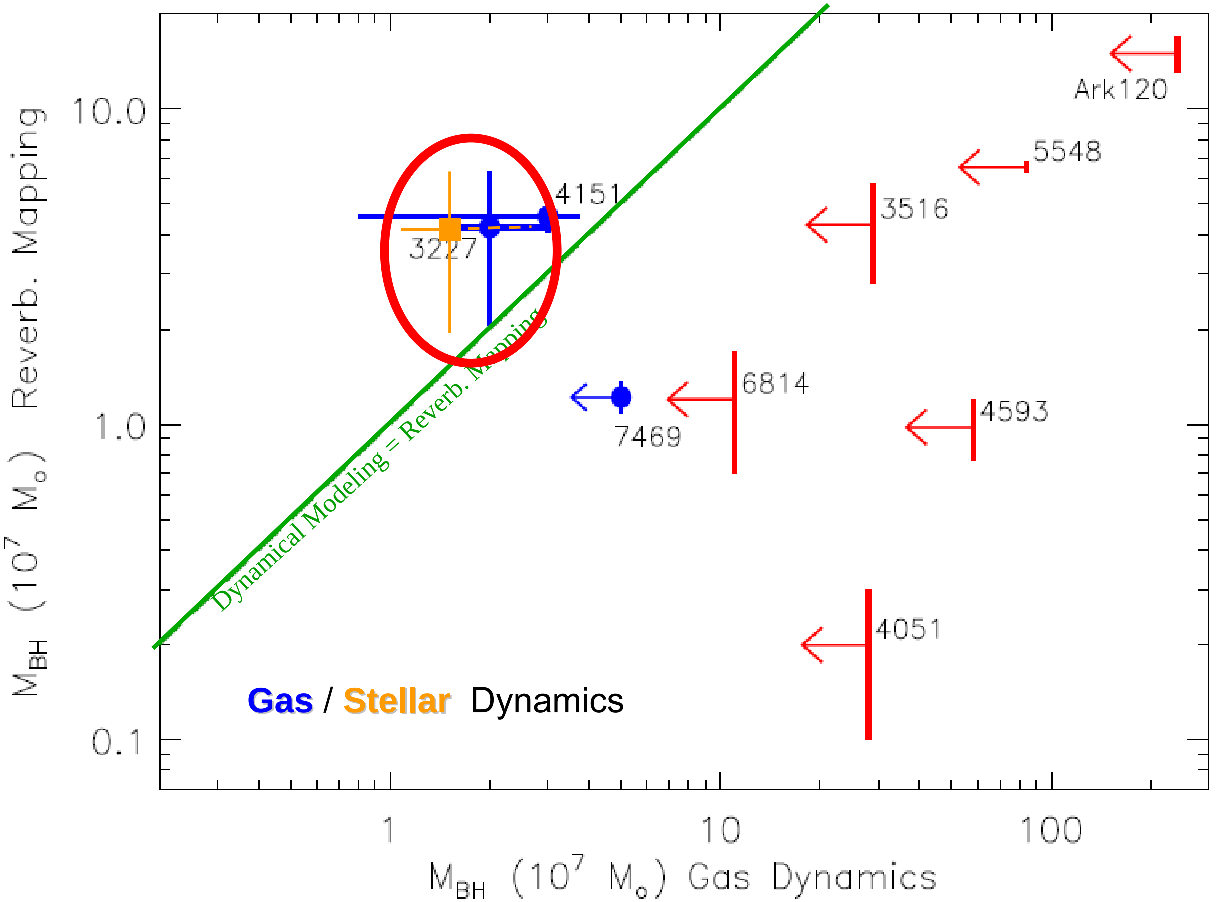


Measuring M_{BH} Directly in Seyfert Galaxies & Calibration of Reverberation Mapping Method

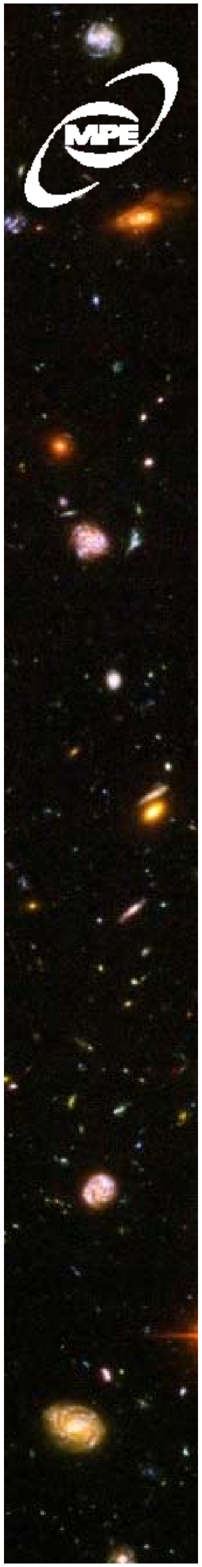




Davies et al. 2005

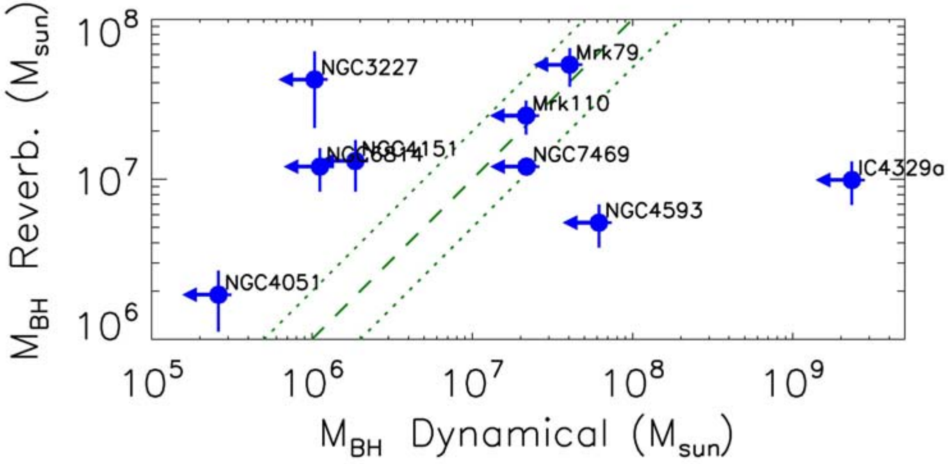


These Seyferts suggest that reverberation mapping is accurate to a factor of 3

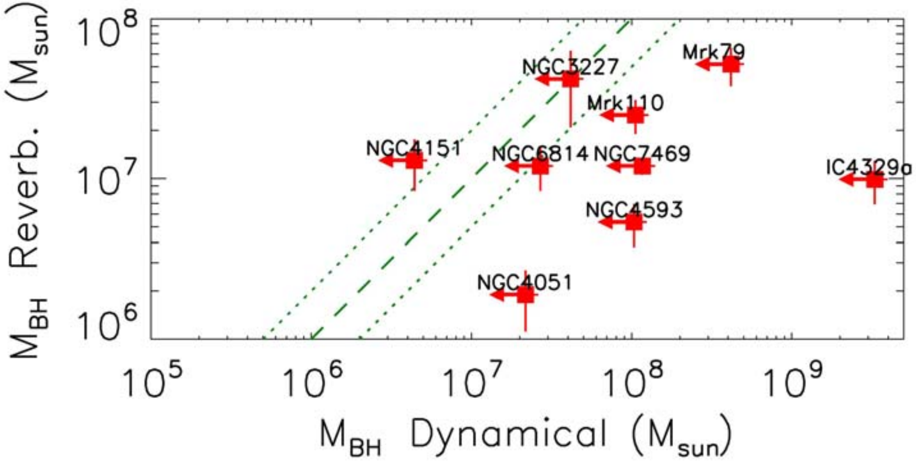


Calibration of Reverberation Mapped M_{BH} Estimates

neglecting velocity dispersion



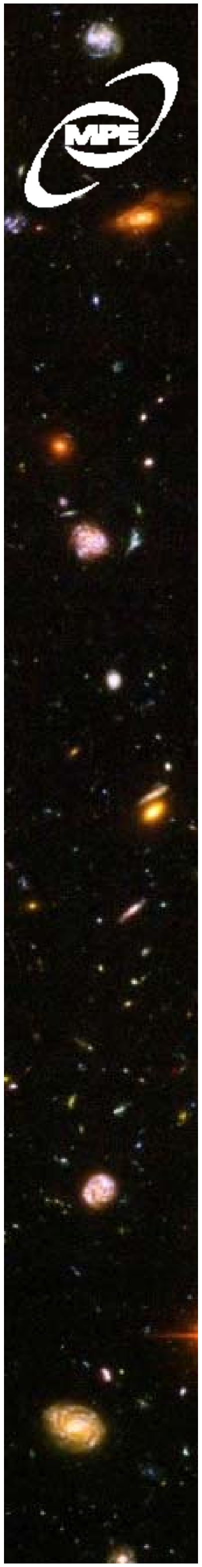
accounting for velocity dispersion



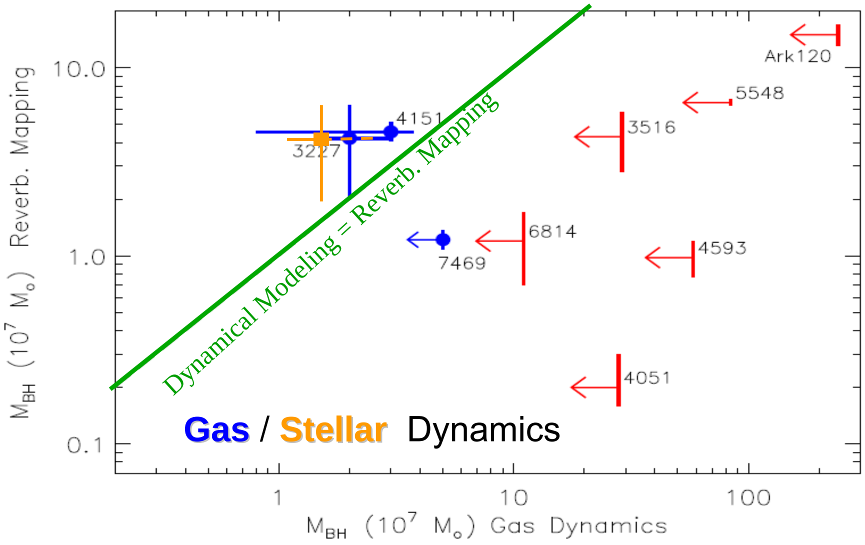
Upper limits based on velocity gradient of H_2 kinematics across the smallest reliably measured radius (typically ~20 pc)

$$M_{dyn} = (v^2+3\sigma^2)\ R\ /\ G$$

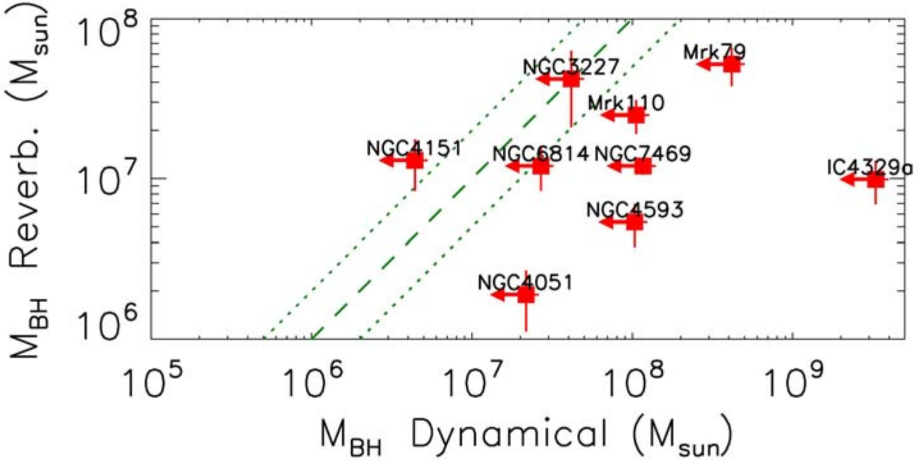
Reverberation mapping does not significantly over estimate M_{BH}



Calibration of Reverberation Mapped M_{BH} Estimates



accounting for velocity dispersion



Sample of 14 Reverberation Mapped Seyfert 1 Galaxies:

Modeling of molecular gas kinematics

- ➢ Include velocity dispersion

(e.g. Hicks & Malkan 2009; Neumayer et al. 2009)

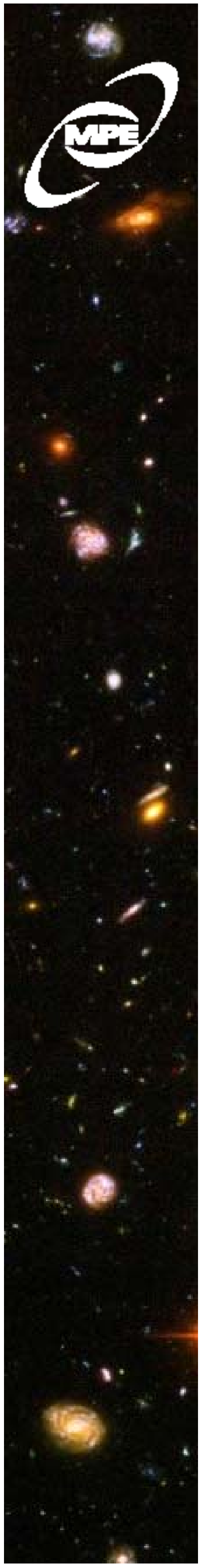
Modeling of stellar kinematics

- ➢ Schwarzschild orbit superposition models

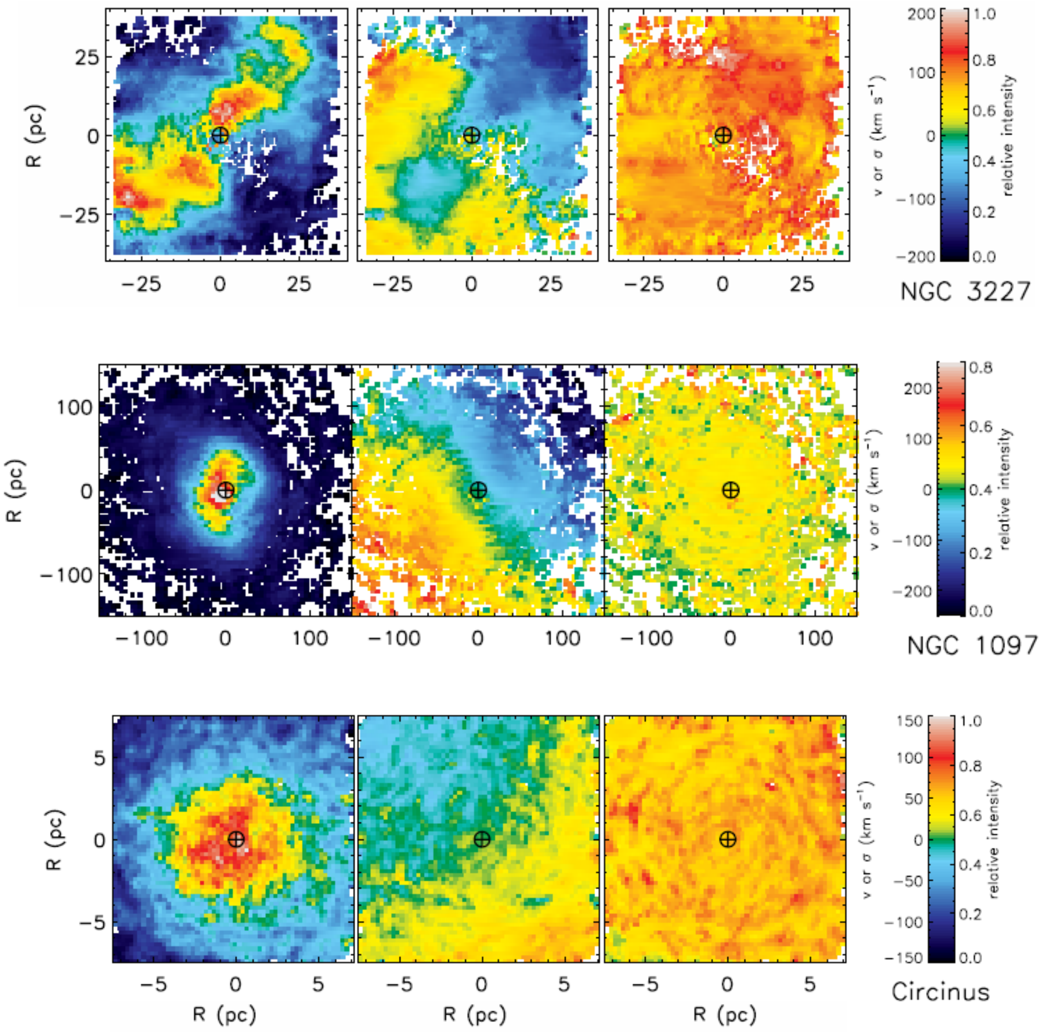
(e.g. Davies et al. 2006; Thomas et al. 2004)

- ➢ NMAGIC: *N*-particle Made-to-measure code

(e.g. de Lorenzi et al. 2007)



Survey of the Central 100pc of Nearby AGN



- ✓ Molecular gas on scales of ~10 pc in a geometrically and optically thick disk
- ✓ Nuclear star cluster on scales of ~10 pc
- ✓ Stars and gas are spatially mixed
- ✓ Molecular gas traces the gravitational potential, thus suitable for estimating M_{BH}
- ✓ Calibration of reverberation mapping feasible with sample of 14 galaxies