The Role of Molecular Hydrogen in Obscuring AGN

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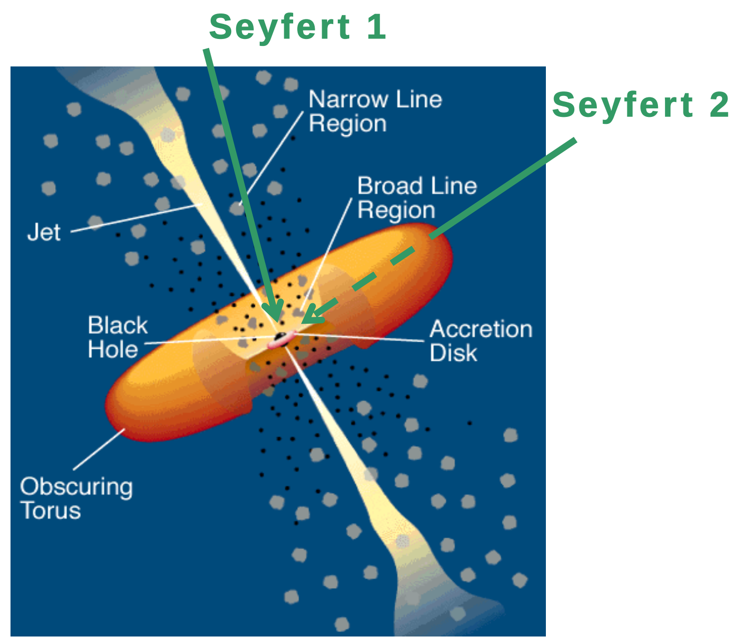
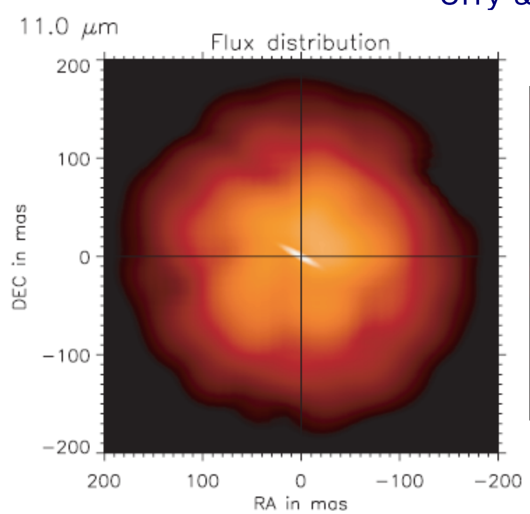
AGN Unification Model: the 'Torus'

Obscuring medium is optically & geometrically thick.

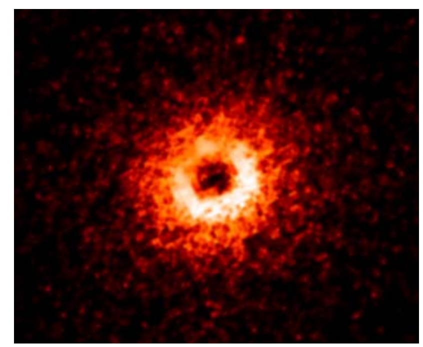
- Warped disk traced by masers on scales of < 1 pc
- IR interferometric techniques reveal thermal emission on a scale < 10pc
- Models of clumpy tori suggest they extend out to scales of 10-60 pc
- X-ray observations indicate the column density (at least on the small scales measured) is $10^{22\text{-}24}$ cm^{-2}, i.e. optically thick



Urry & Padovani 1995



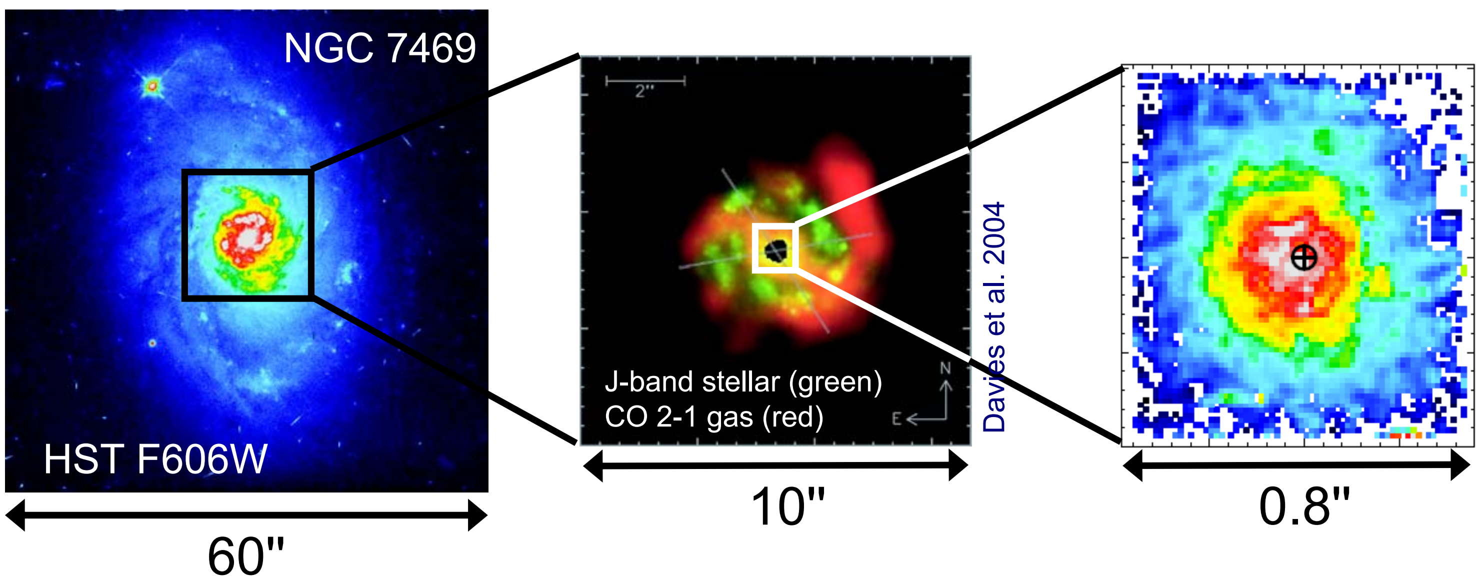
Circinus; Tristram et al. 2007



Clumpy torus model; Hönig et al. 2006

Motivation for Characterizing Nuclear H_2

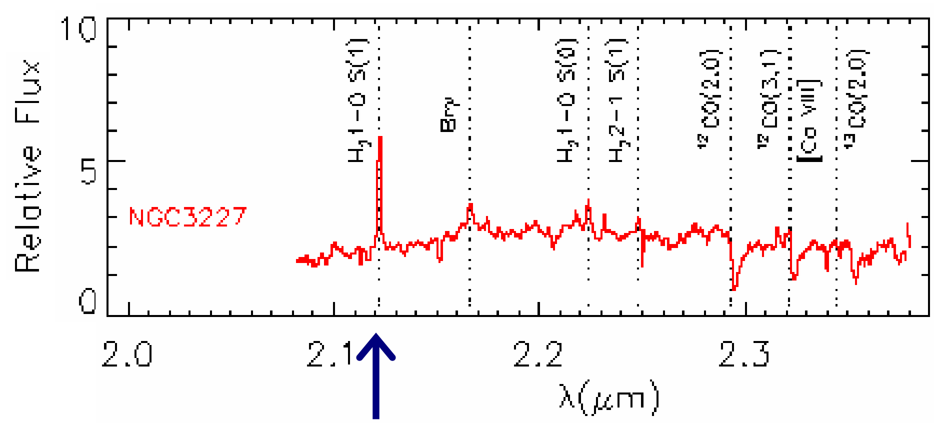
- H_2 traces the cooler, and presumably more extended, gas in the nuclear region
- Relationship between H_2 and the nuclear star formation (Davies et al. 2007)
- H_2 contribution to obscuring & fueling of the AGN



Little is known about molecular hydrogen within the central 100pc of AGN, especially in Seyfert 1 galaxies.

Measurements of the Central 100pc: Distribution & Kinematics

- High spatial resolution
  - Adaptive optics with AGN as the AO reference
  - *K*-band minimizes the AGN emission and for local AGN contains the H_2 1-0 S(1) 2.1218 μm emission line
- 2-D Kinematics: integral field spectometers
  - SINFONI on VLT UT4
  - OSIRIS on Keck II



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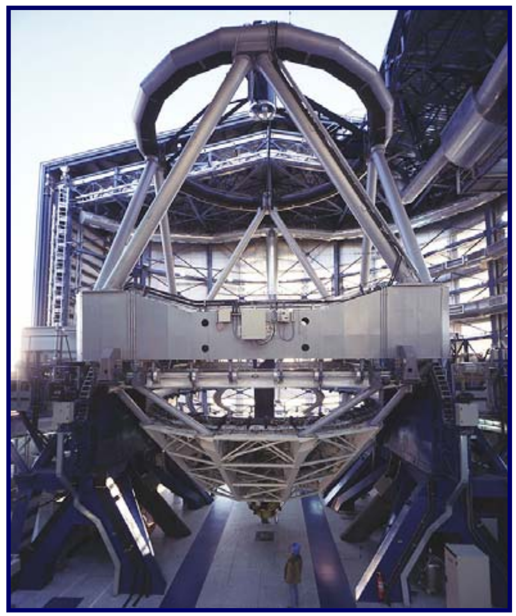

The Sample of Observed AGN

	Object	Classification	D (Mpc)	Resolution	
SINFONI Data	NGC 1097	Sy 1 / LINER	18	0.25"	21 pc
	NGC 3227	Sy 1	17	0.07"	5 pc
	NGC 3783	Sy 1	42	0.18"	37 pc
	NGC 4593	Sy 1	36	0.08"	14 pc
	NGC 7469	Sy 1	66	0.06"	19 pc
	NGC 1068	Sy 2	14	0.09"	6 pc
	Circinus	Sy 2	4	0.22"	4 pc
OSIRIS Data	NGC 3227	Sy 1	17	0.07"	5 pc
	NGC 4051	Sy 1	9	0.06"	3 pc
	NGC 4151	Sy 1	13	0.07"	4 pc
	NGC 6814	Sy 1	21	0.07"	7 pc
	NGC 7469	Sy 1	66	0.06"	19 pc

Mean Resolution: 20 pc

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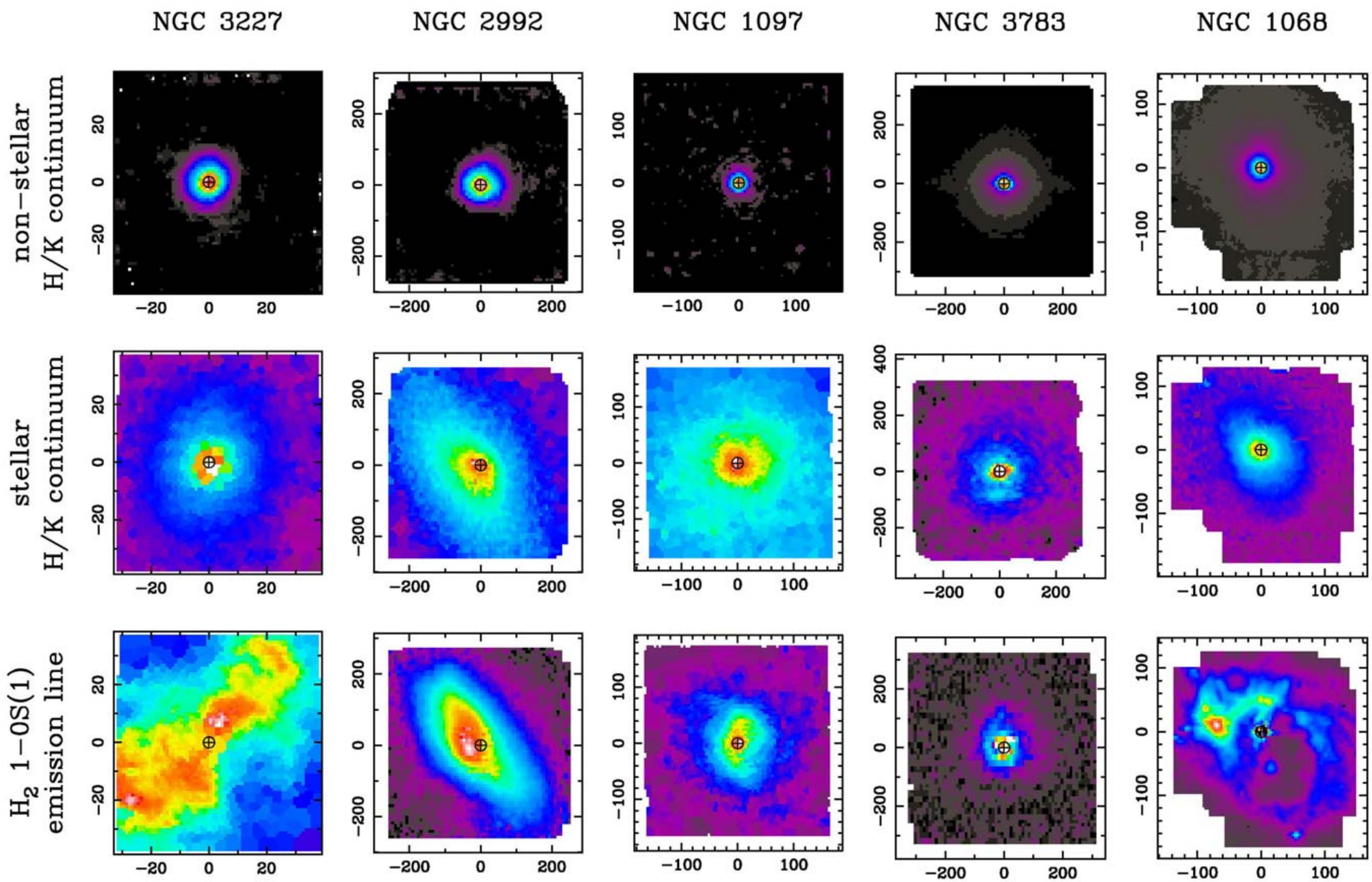
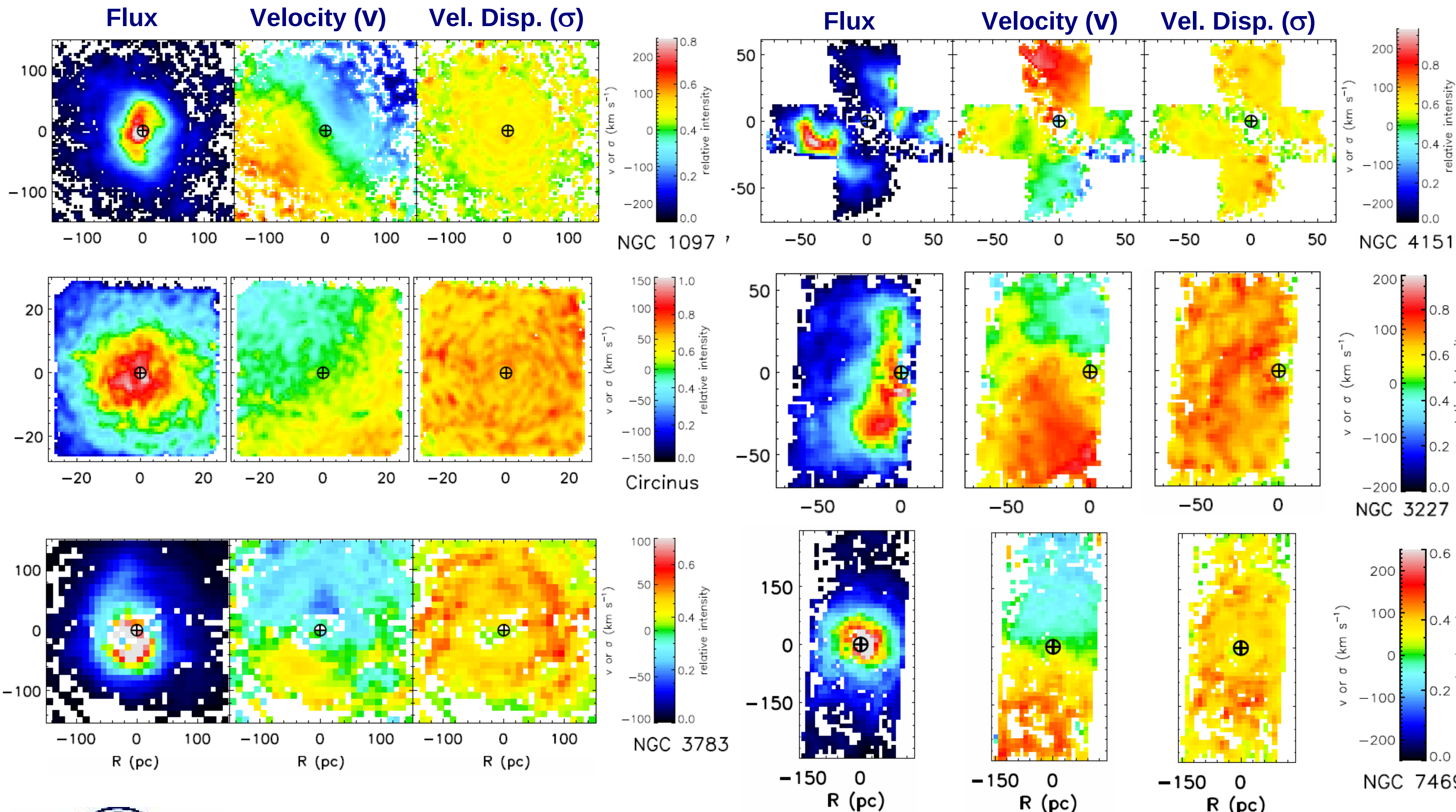
3D Near-IR Data: AGN, Stellar, & H_2 Emission



Erin K. S. Hicks – June 2008 – ESO 3D

3D Near-IR Data: Flux, Velocity, & Dispersion



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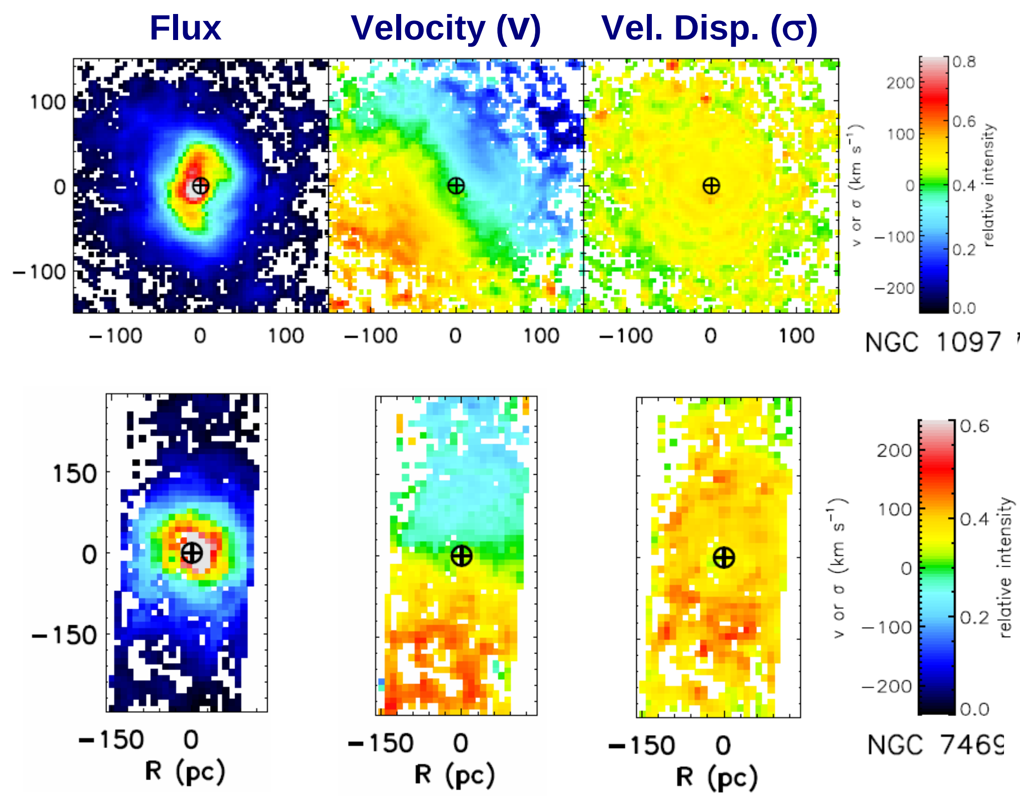
Properties of the Nuclear Molecular Hydrogen

- **Size Scale**
- **2D Velocity Field**
- **Velocity Dispersion**
- **Dynamical Mass**
- **Column Density**



- **Size Scale**
  - HWHM < 35 pc
  - Disk-like profile
- **2D Velocity Field**
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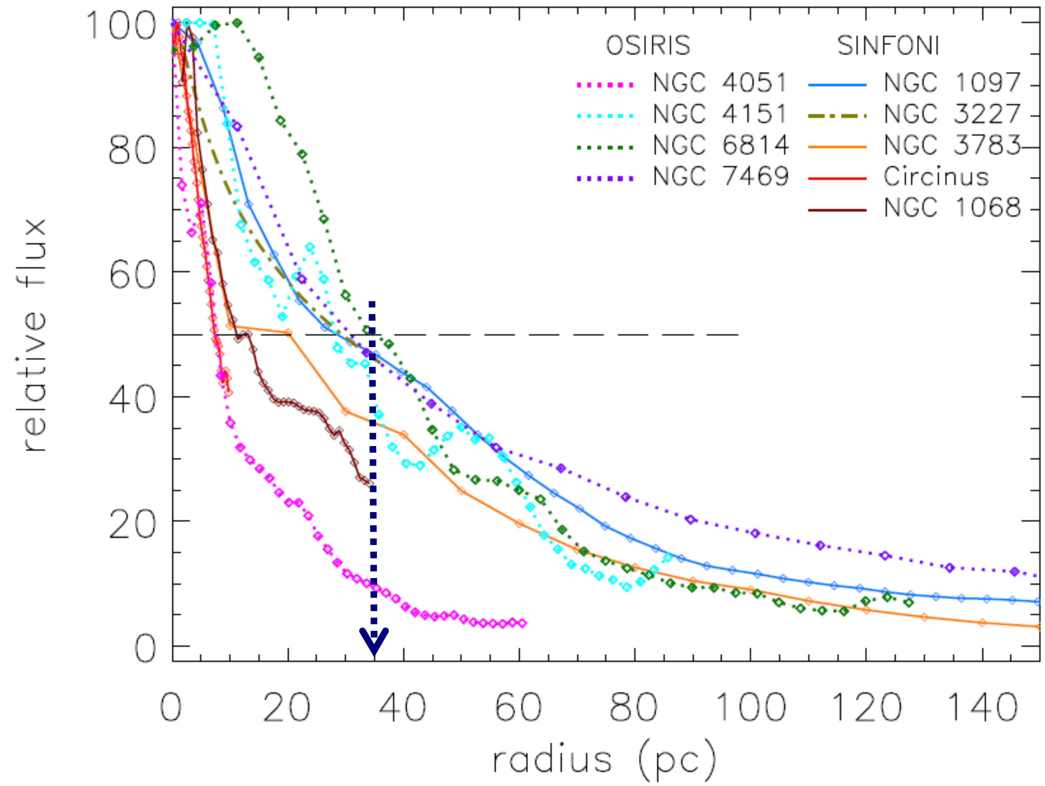
Flux Distribution



HWHM of radial average is less than 35 pc

Sérsic fits suggest disk-like distributions

n = 1.6 ± 0.4 on average

- **Size Scale**
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  - Disk rotation down to ~20 pc
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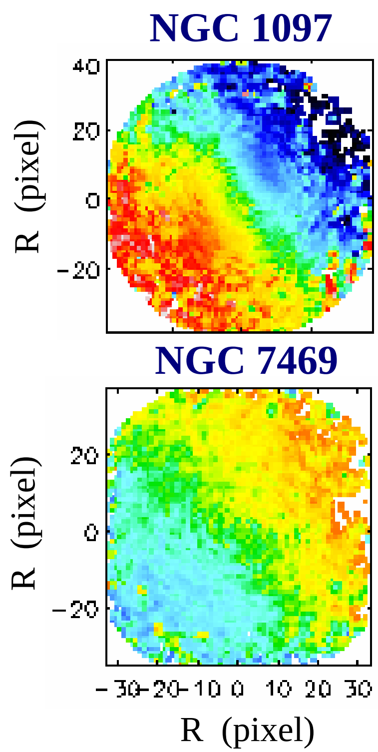
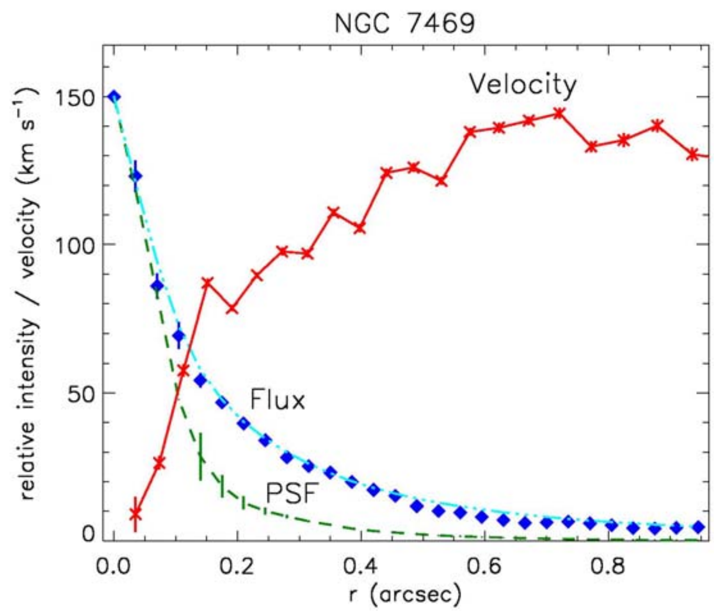
Rotational Velocity





Best fit PA and inclination angle determined using kinemetry.
(Krajnović et al. 2006)

- Ordered velocity field suggests disk rotation
- No evidence of a warp down to smallest scales measured

Rotational Velocity

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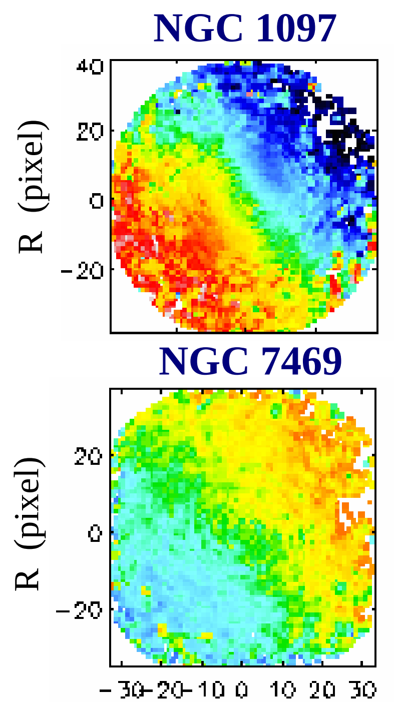

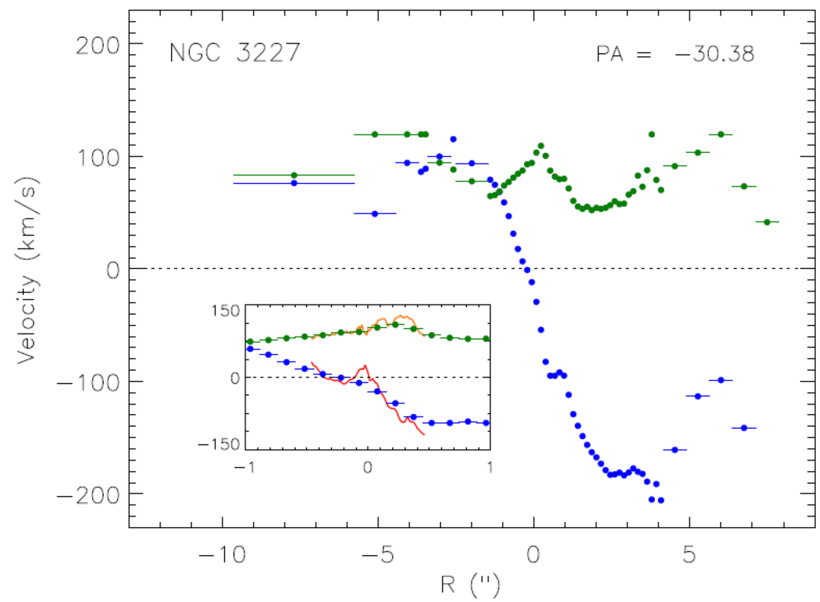

- Consistent with larger scale disk rotation (ISAAC)
- Consistent with rotation of cold molecular gas (e.g. CO 2-1; Schinnerer et al. 2000a,b & Davies et al. 2004)

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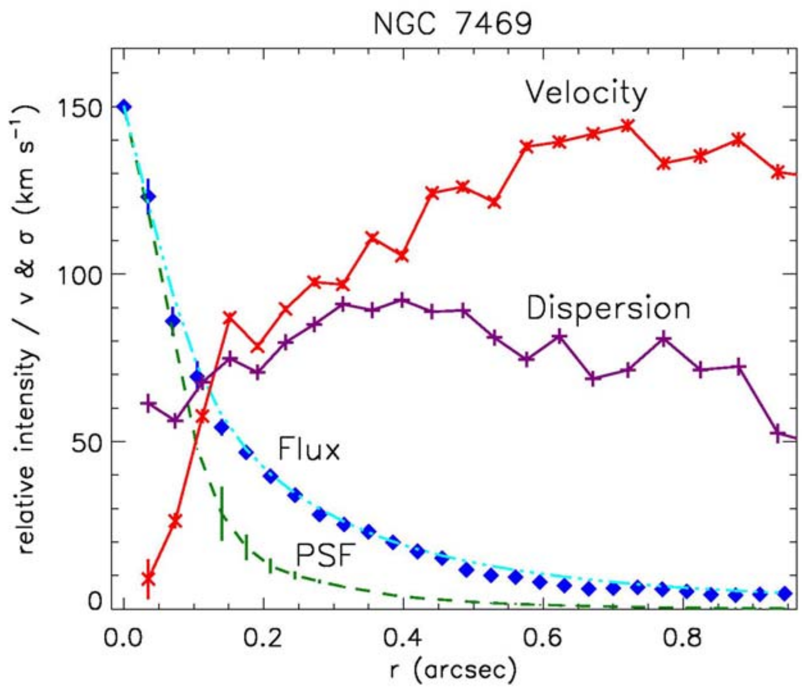
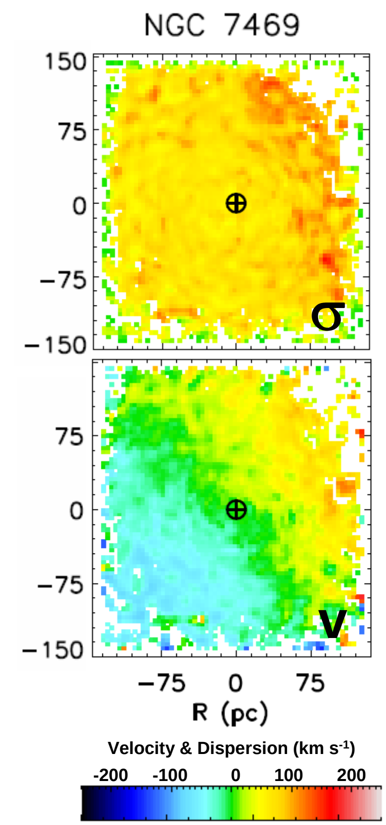
Velocity Dispersion

- High σ implies bulk motion, i.e. thick disk
- Average $v_{rot}/\sigma = 0.9 \pm 0.3$ at 30 pc
- Random motions significant w.r.t. $v_{rotation}$





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  - $v_{rot}/\sigma < 1$
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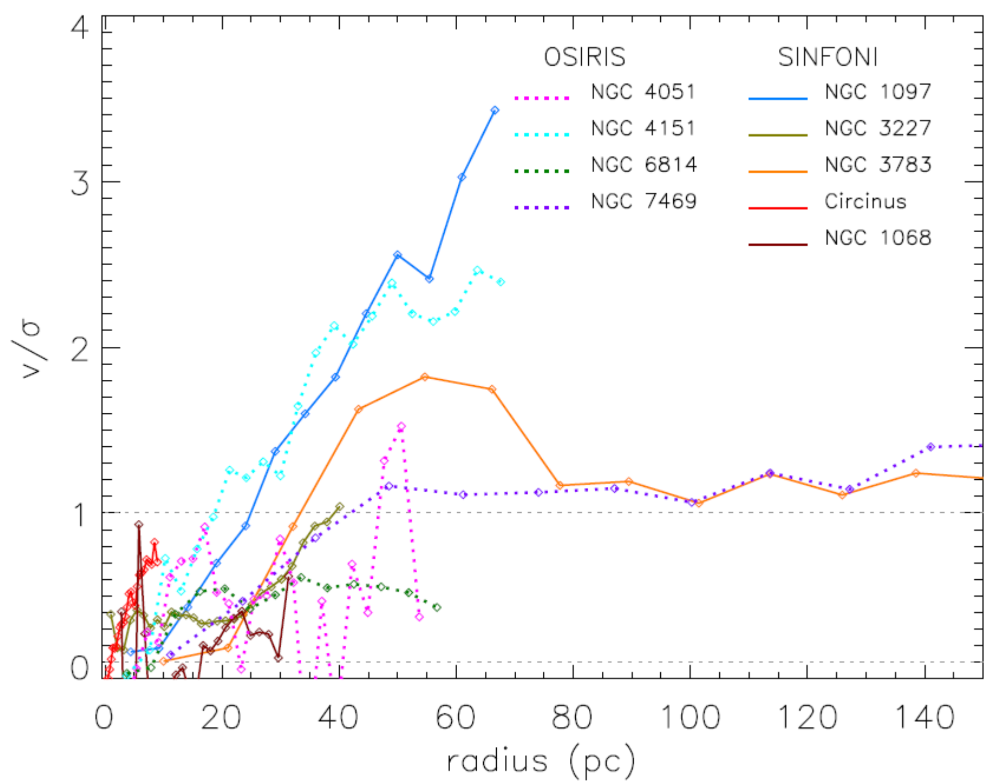

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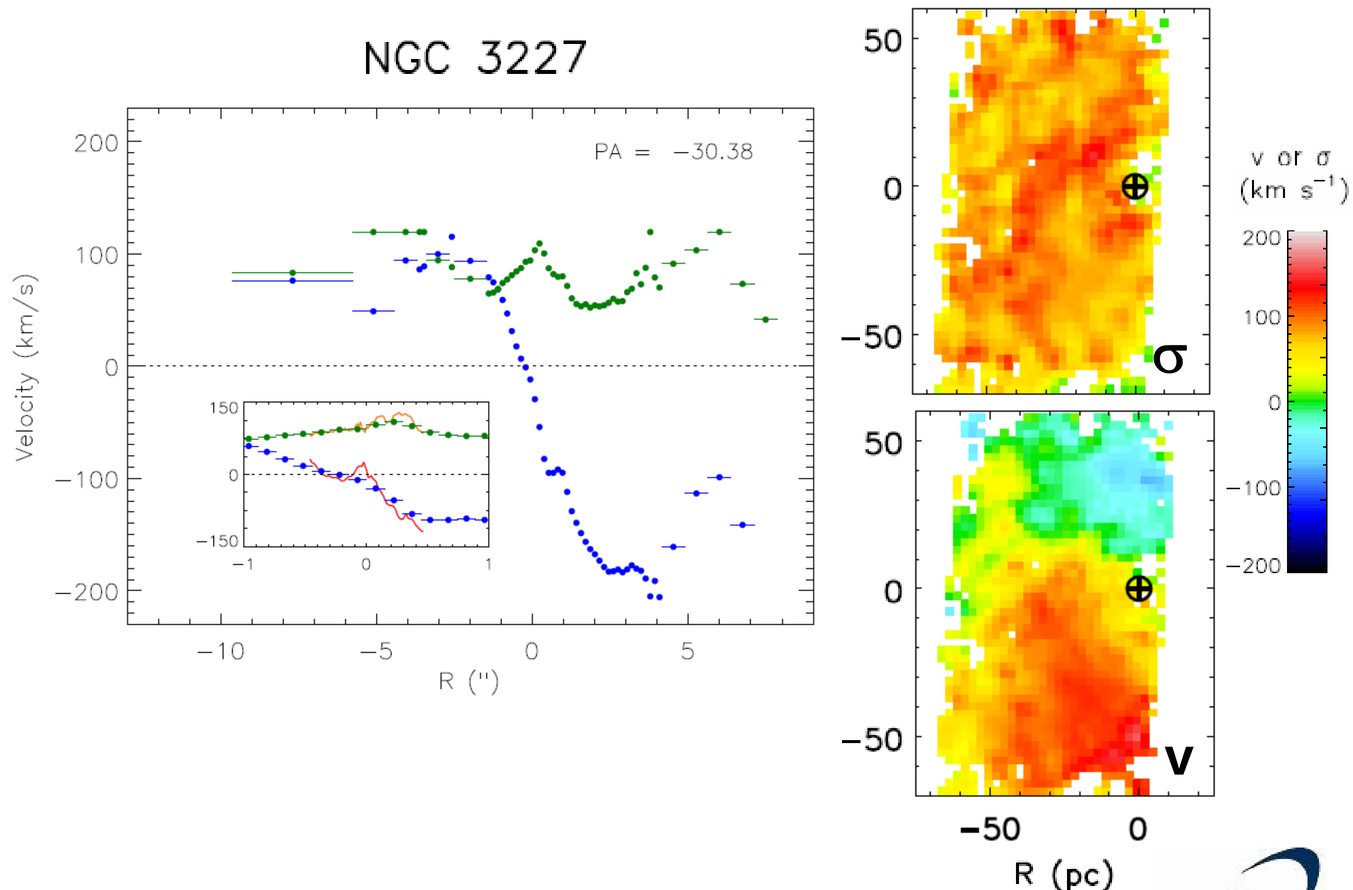
Velocity Dispersion

- Elevated dispersion is confirmed with ISAAC data outer disk σ ~ 45 km s^{-1}
  - H_2 excitation via 20-40 km s^{-1} shocks



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  - $v_{rot}/\sigma < 1$
  - $z_o/r = 1.3 \pm 0.2$
- **Dynamical Mass**
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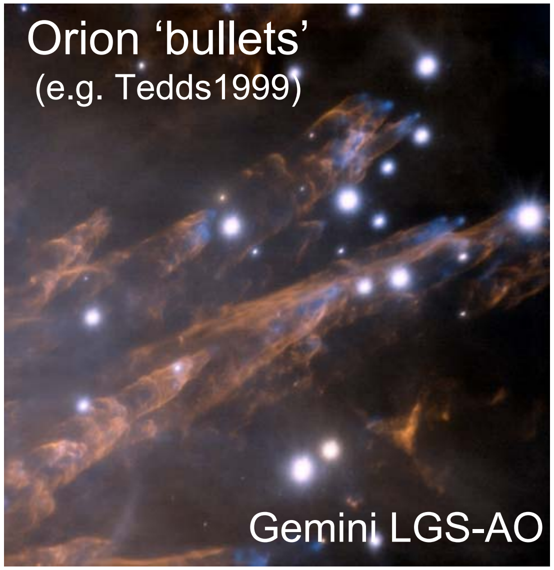
Estimated Disk Height

- Elevated dispersion is confirmed with ISAAC data outer disk $\sigma \sim 45\ \mathrm{km\ s^{-1}}$
  - H_2 excitation via 20-40 km s^{-1} shocks
- Higher σ possible with bow shocks
  - e.g. Orion bullets, HH99B have 80-120 km s^{-1} oblique shocks



Disk Height:

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

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

On average:

z_o/r (30pc) = 1.3 ± 0.2

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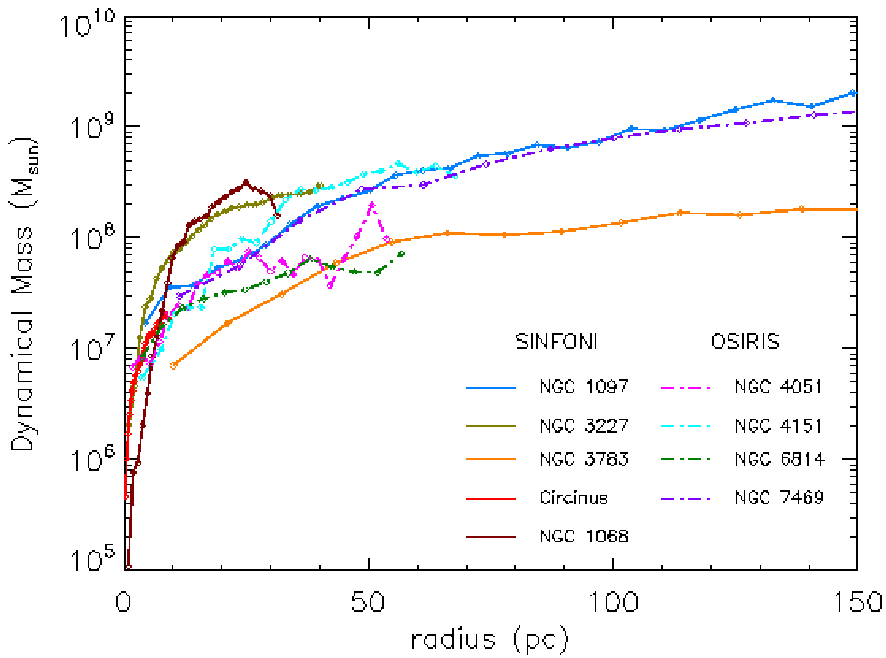
- **Dynamical Mass**
  - account for σ
  - $M_{dyn} \sim 10^8\ M_\odot$
- **Column Density**

Estimated Dynamical Mass



- Dynamic mass estimate must account for the significant velocity dispersion:

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

- Average M_{dyn} (30pc) = $(1.0 \pm 0.7) \times 10^8\ M_\odot$

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Estimated Column Density

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

Estimating f_{gas} :

1. SBs and ULIRGs 10-20 %
2. $L_{CO\ 2\text{-}1} \rightarrow M_{H2}$ 10-60 %
3. $L_{H2} \rightarrow M_{gas}$ 8-90%
4. Kennicutt-Schmidt Law
   $\Sigma_{SFR} \rightarrow \Sigma_{gas}$ 24-90 %

⇨ Assuming f_{gas} > 10% gives a ***lower limit* on $\mathbf{N_H}$**

Size Scale
- HWHM < 35 pc
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2D Velocity Field
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Velocity Dispersion
- $v_{rot}/\sigma < 1$
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Dynamical Mass
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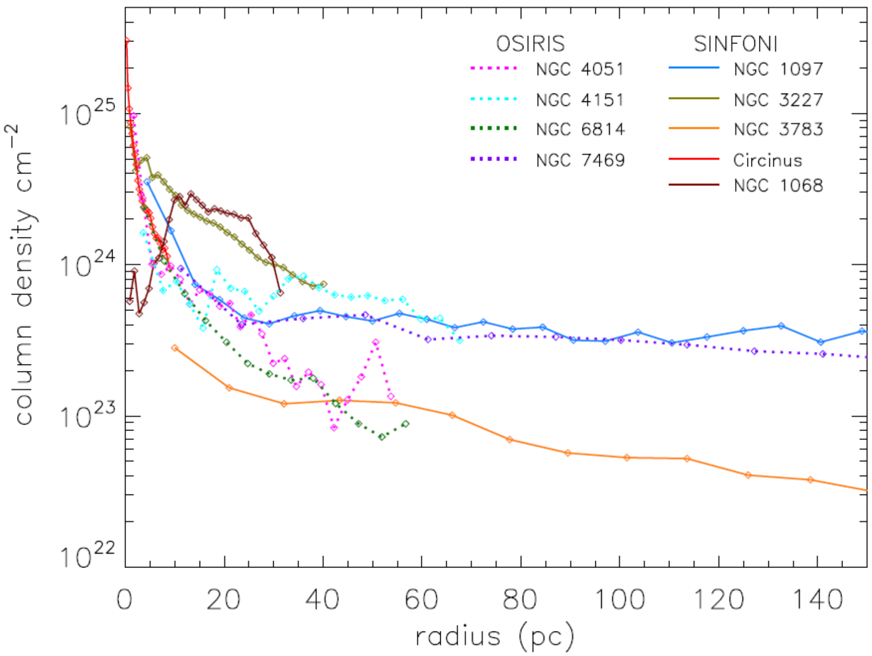
Column Density
- $N_H > 10^{23}$ cm^{-2}

Estimated Column Density



N_H is at least 10^{23} cm^{-2}, which *is* enough to obscure an AGN

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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'

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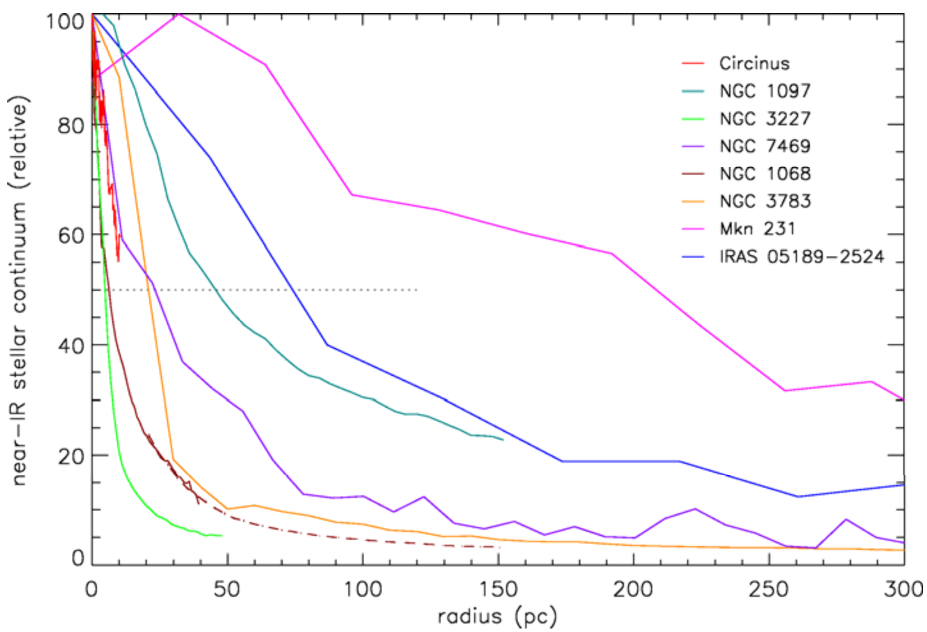
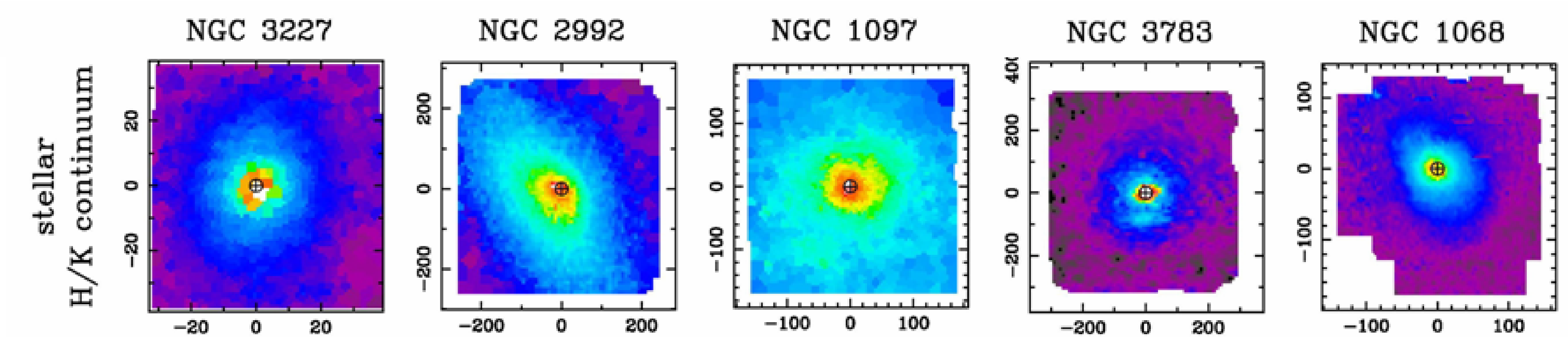
Nuclear Stellar Disks



- Similar spatial scales, with a HWHM stellar light distribution of ~ 50pc
- Evidence of stellar nuclear disks
- H_2 and stellar kinematics are very similar

Davies et al. 2007



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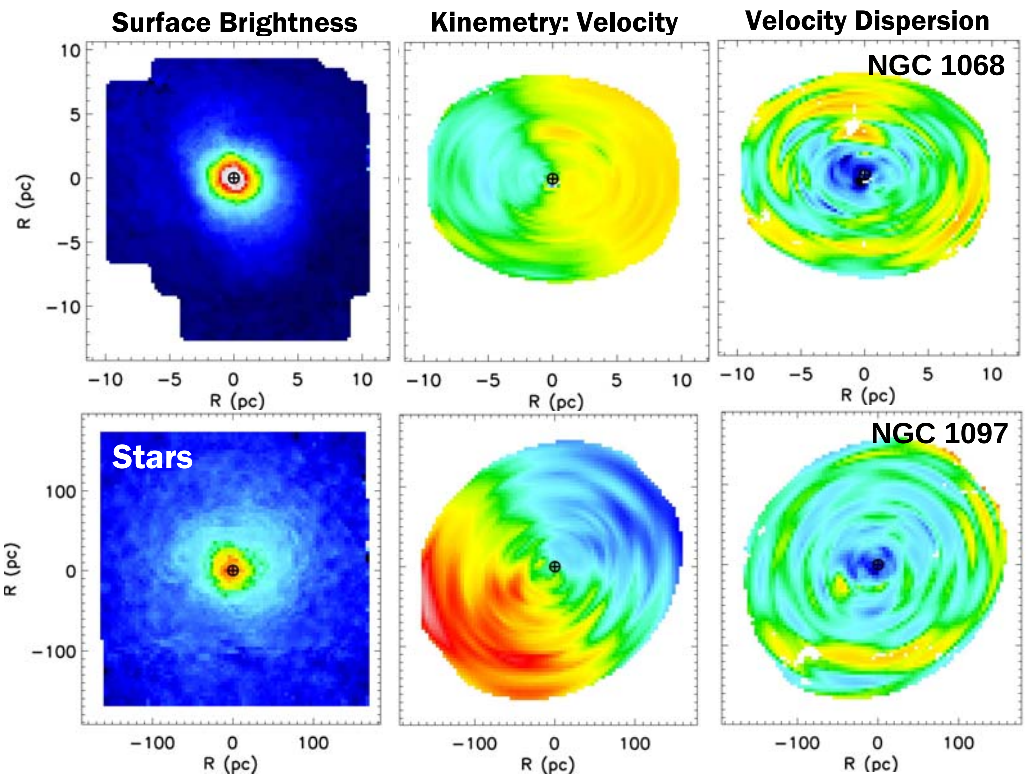

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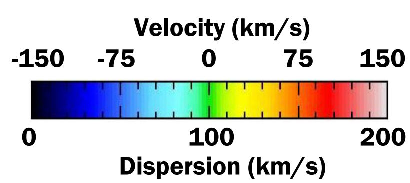
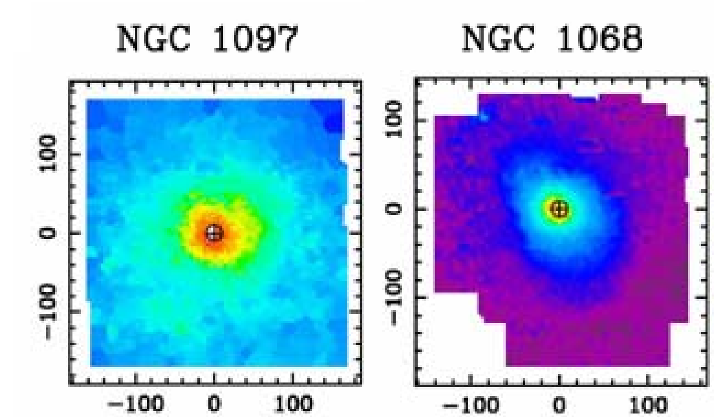
Stellar Dispersion 'sigma'-drops





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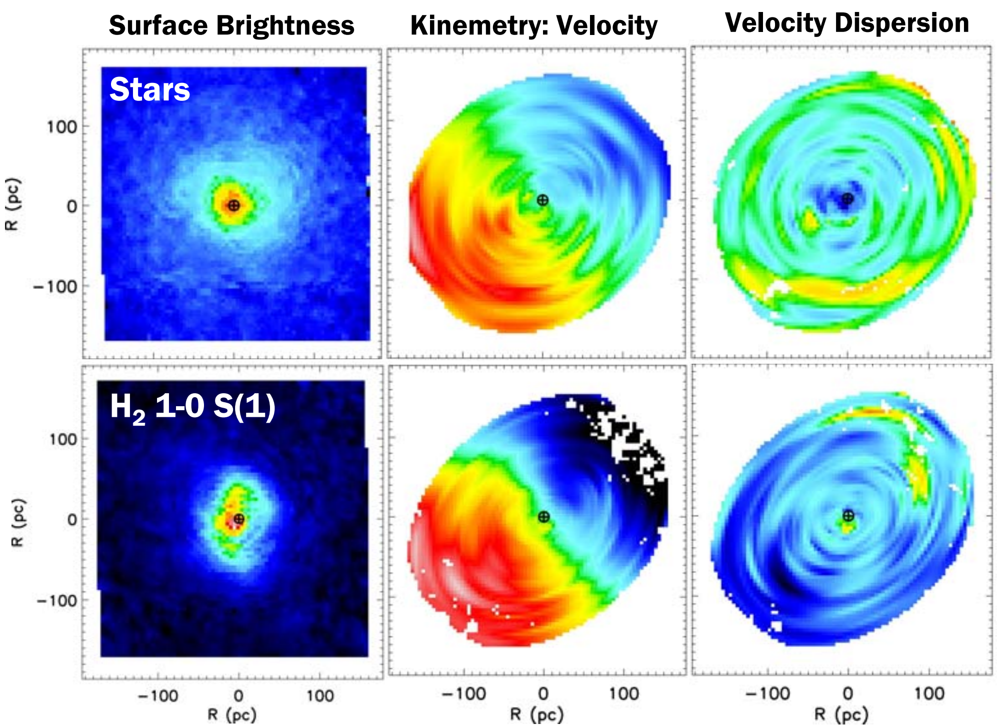
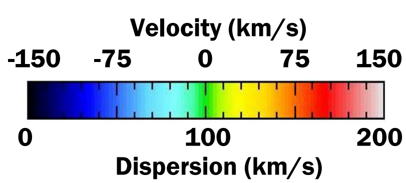
Nuclear Stellar Disks



NGC 1097: comparison of stars and H_2



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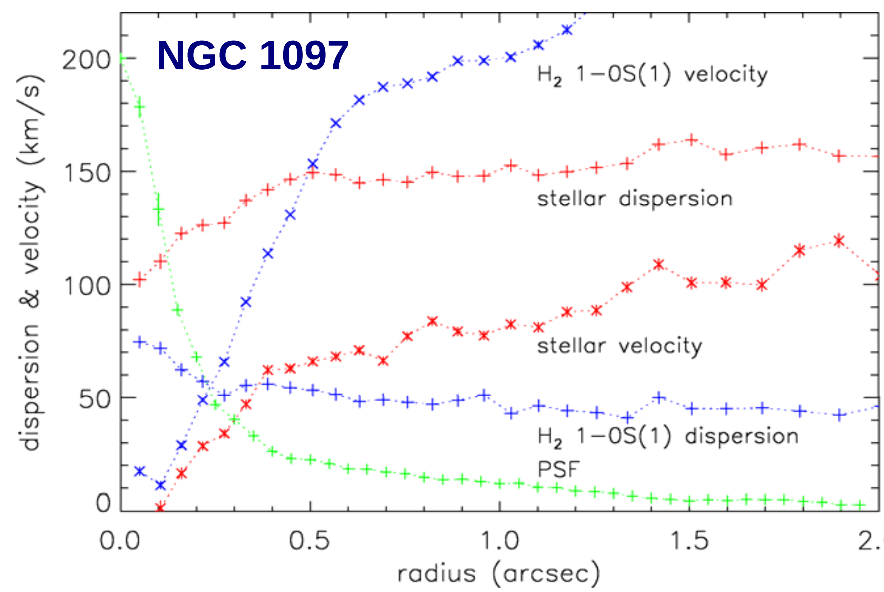

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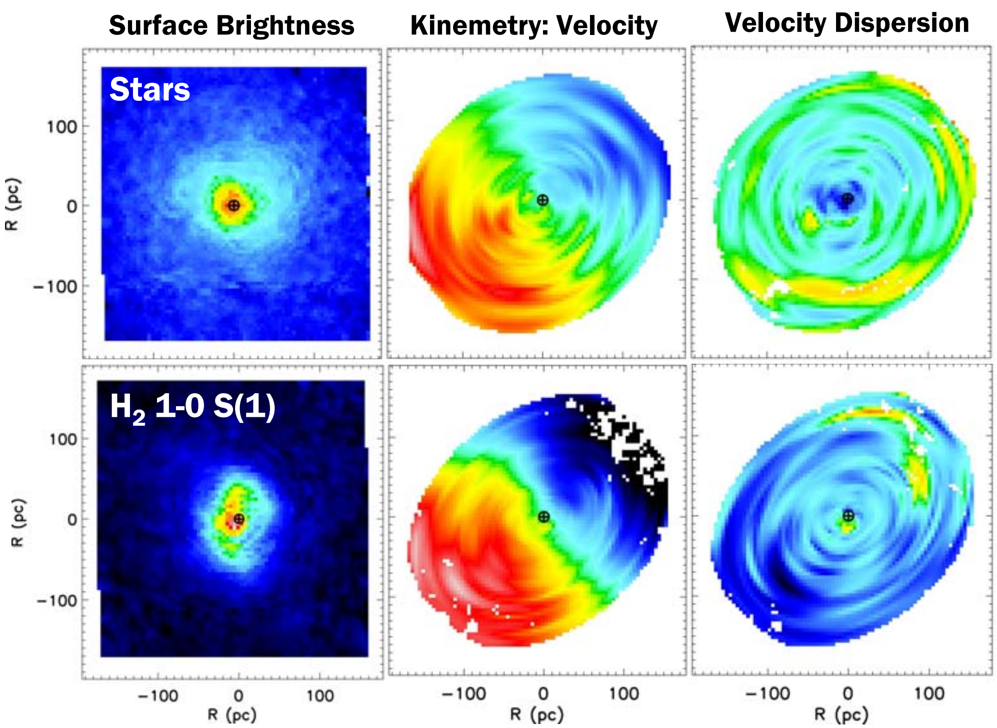

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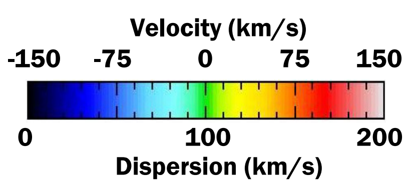

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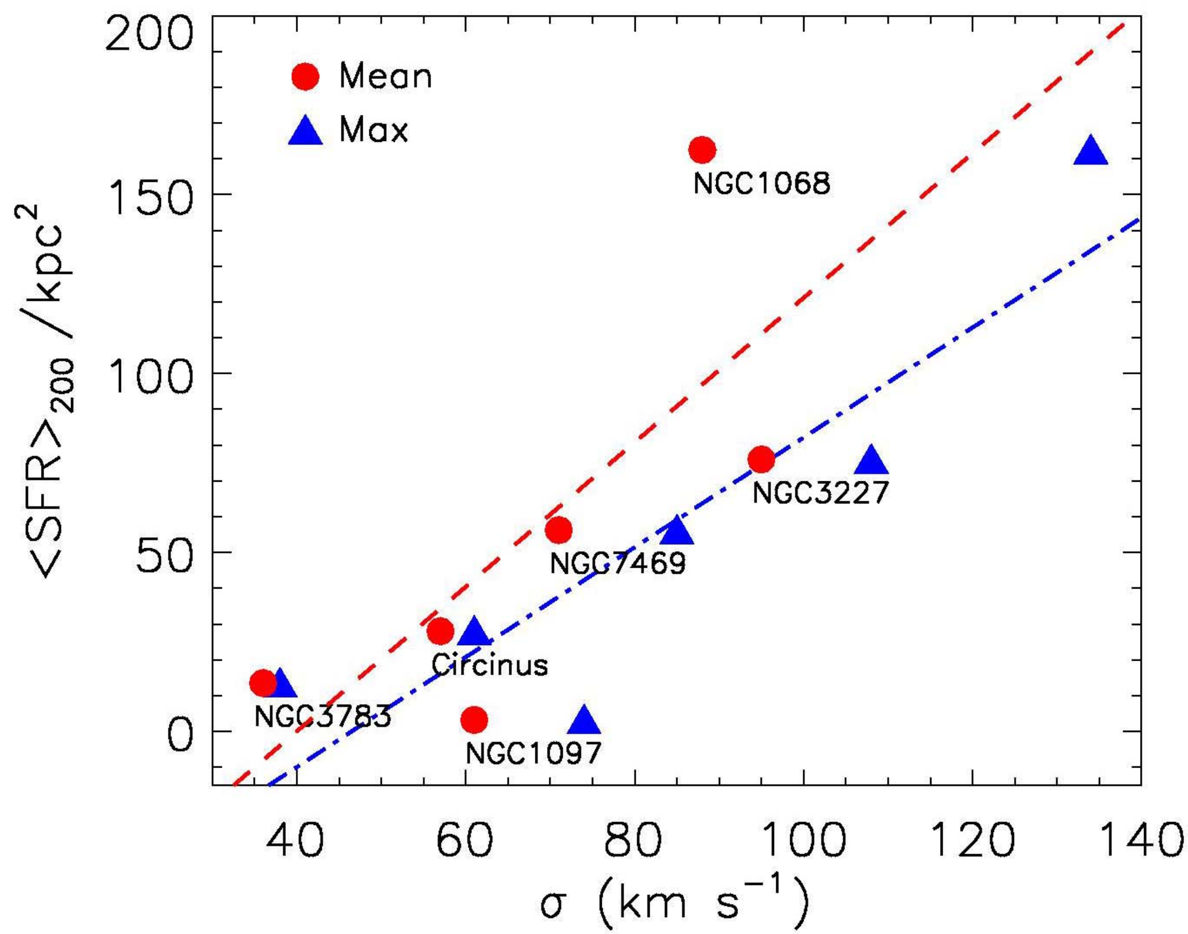
gas and stars are spatially mixed in a thick disk

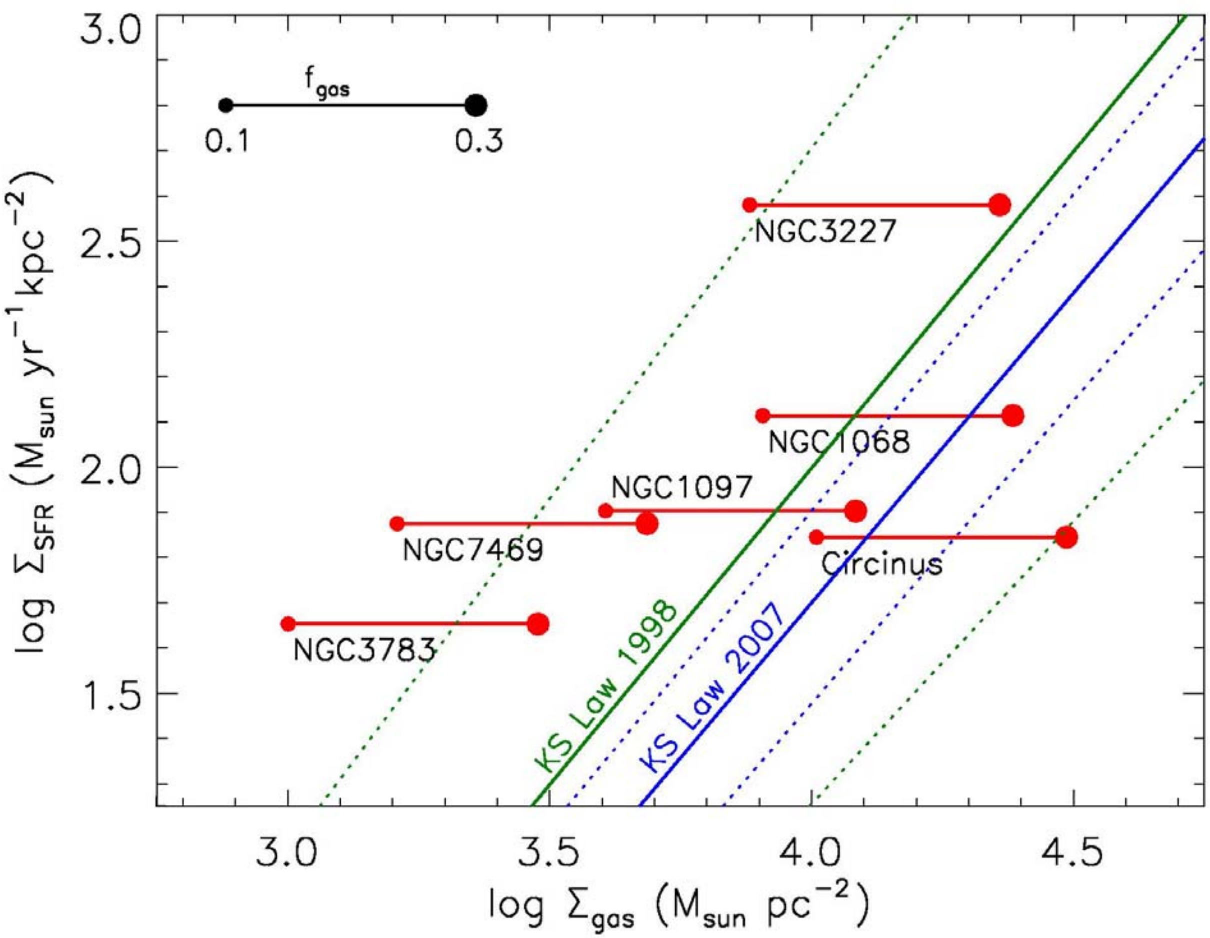
Velocity Dispersion Correlates with SFR



<SFR> from Davies et al. 2007

Linear Correlation Coefficients > 0.7

Kennicutt-Schmidt Law in the Central 100pc of AGN



Maintaining the High Velocity Dispersion

Energy must be injected into the system in order to maintain the bulk rotation 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 2007) Only able to achieve $z_0 \sim$ few pc
- ✧ Radiation pressure from the stars (Thompson et al. 2005) Able to achieve $z_0 \sim$ 10s pc

➡ Stellar radiation pressure is the most likely mechanism, although supernovae, stellar winds, and AGN radiation pressure can contribute.

Speculation on Gas, Star Formation, and Fueling of AGN

- intense starbursts occur in the central 10s of pc around AGN
- intensity of the nuclear starburst likely depends on inflow rate to this region
- velocity dispersion of gas depends on starburst intensity via radiation pressure

low starburst intensity → low gas dispersion → no thickening → no torus
intense starburst → high gas dispersion → thickened central region → torus

Both scenarios can fuel an AGN

The Role of Nuclear H_2 and SB in Obscuring AGN

Typical properties for the observed AGN:

HWHM $\leq$ 35 pc

Sersic $n = 1.6 \pm 0.4$

At a radius of 30 pc:

$v_{rot}/\sigma = 0.9 \pm 0.3$

$z_o/r = 1.3 \pm 0.2$

$M_{dyn} = (1.0 \pm 0.7) \times 10^8\ M_\odot$

$n_H > 10^{23}\ cm^{-2}$

The obscuring medium on scales of 10s pc is a dynamic structure with a greater fraction of lines of sight obscured with increasing rates of star formation.

In such a case, the Seyfert 1 vs. Seyfert 2 properties of an AGN would depend on the state of the nuclear starburst.

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