Celestial Dynamics

Final Report

Molecular Gas in Nuclei of Galaxies

-- Gravitational Torques and AGN Feeding

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    - Evaluation of stellar potentials
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Introduction

- We discuss the efficiency of stellar gravity torques as a mechanism to account for the feeding of the central engines.
- The calculations allow us to discuss whether torques from the stellar potentials are efficient enough to drain the gas angular momentum in the inner 1kpc of these galaxies.
- The stellar potentials are derived using high-resolution NIR images and the averaged effective torques on the gas are estimated using the high-resolution (0.5"-2") CO maps of the galaxies.
- 4 low luminosity Active Galactic Nuclei (AGN): NGC 4321, NGC 4826, NGC 4579, and NGC 6951, are discussed.
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Data

- Radio observations
  - IRAM 30m single dish
    - $^{12}CO(1-0)$ / $^{12}CO(2-1)$
  - IRAM PdBI interferometer
    - $^{12}CO(1-0)$ / $^{12}CO(2-1)$

- NIR/Optical archive
  - HST NICMOS (Near Infrared Camera and Multi-Object Spectrometer)
  - HST WFPC2 (The Wide Field and Planetary Camera 2)

Gravitational Torques & AGN Fueling

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Gravitational Torques & AGN Fueling

- The first step is to derive the stellar potential in the nuclear disks of these galaxies.
- The NIR images are first deprojected according to the position angles and inclination.
- The potential is derived by a Fourier transform method.
- Assume a constant mass-to-light ratio, we can obtain the rotation curve (v_{rot}) from the observed CO data.

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Potential is then decomposed in the different m-modes

Amplitude of the m-mode

Phase of the m-mode

$$\Phi(R,\theta) = \Phi_0(R) + \sum_m \Phi_m(R)\cos(m\theta - \phi_m(R)) \qquad (1)$$

axial symmetry (circular motion)

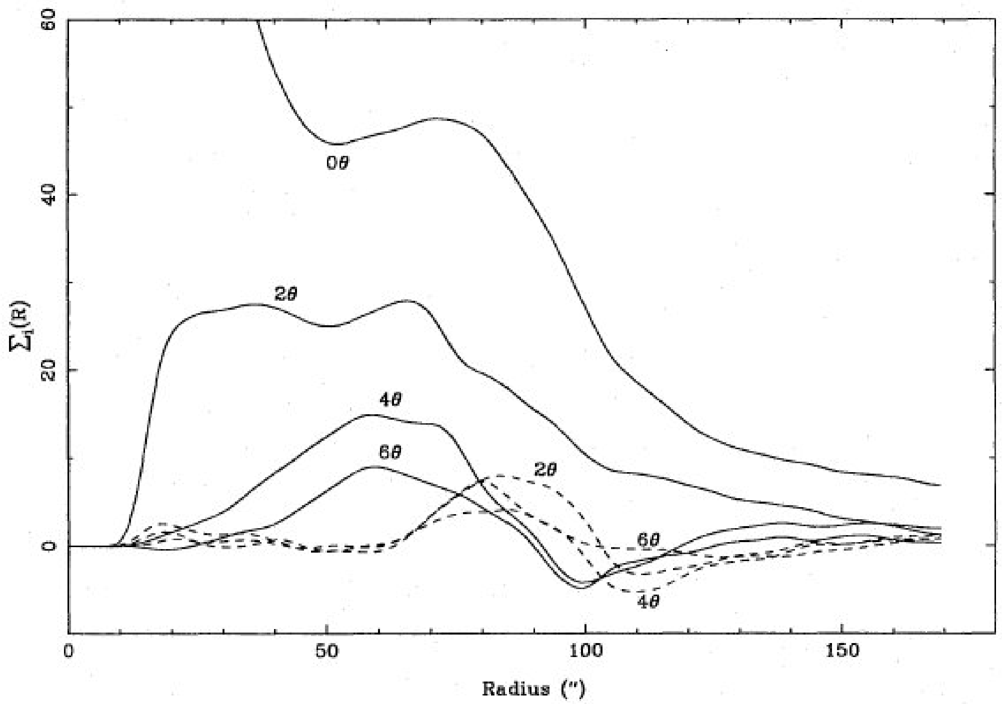

Fig. 3. The cosine $0\theta, 2\theta, 4\theta, 6\theta$ (solid) and the sine $2\theta, 4\theta, 6\theta$ (dashed) Gunn i Fourier surface brightness components

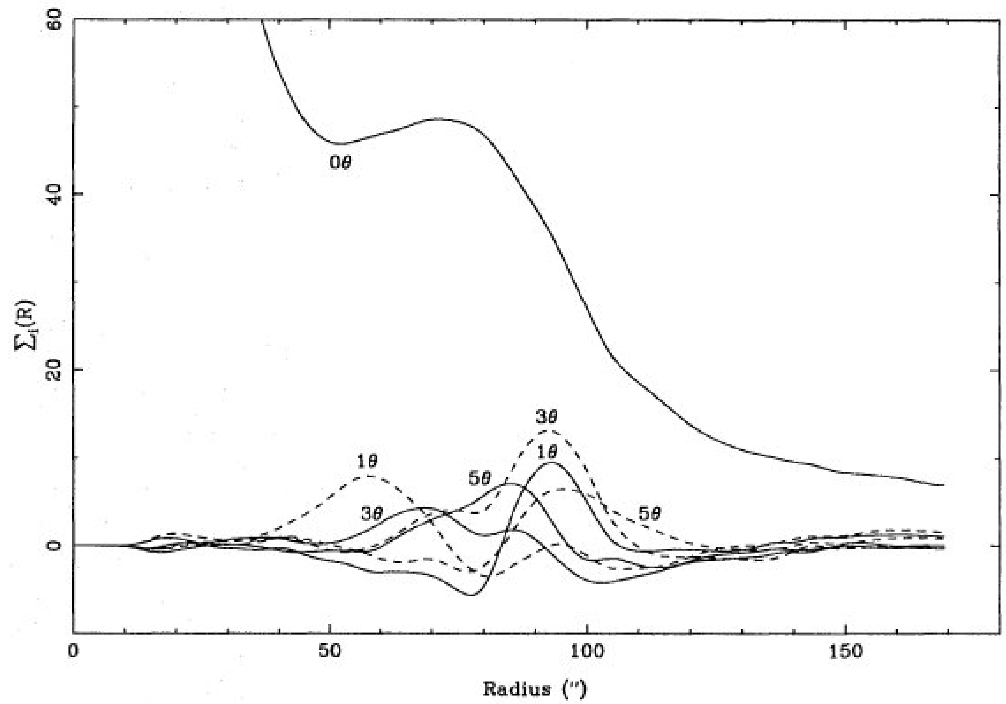

Fig. 4. The cosine $0\theta, 1\theta, 3\theta, 5\theta$ (solid) and the sine $1\theta, 3\theta, 5\theta$ (dashed) Gunn i Fourier surface brightness components

Define the strength of the m-Fourier component

$$Q_m(R) = m\Phi_m/R|F_0(R)|. \tag{2}$$

$$\Phi(R,\theta) = \Phi_0(R) + \sum_m \Phi_m(R)\cos(m\theta - \phi_m(R)) \tag{1}$$

The corresponding strength of the total non-axisymmetric perturbation is defined by

$$Q_{\mathrm{T}}(R) = \frac{F_{\mathrm{T}}^{\max}(R)}{F_0(R)} = \frac{\frac{1}{R}\left(\frac{\partial\Phi(R,\theta)}{\partial\theta}\right)_{\max}}{\frac{\mathrm{d}\Phi_0(R)}{\mathrm{d}R}} \tag{3}$$

$F_T^{max}(R)$ represents the maximum amplitude of the tangential force over all θ.

$F_0(R)$ is the mean axisymmetric radial force.

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After having calculated the forces per unit mass (F_x and F_y) from the derivatives of $\Phi(R,\theta)$ at each pixel, the torques per unit mass t(x,y) can be computed by:

$$t(x, y) = x\,F_y - y\,F_x. \tag{4}$$

The sense of the circulation of the gas in the galaxy plane determines the sign of t(x,y): +/- if the torque accelerates (decelerates) the gas at (x,y)

The gravitational torque maps weighted by the gas column density derived from the CO 1-0 and 2-1 lines, N(x,y).
t(x,y) x N(x,y) represent the effective variations of angular momentum density in the galaxy plane.

$$t(R) = \frac{\int_\theta N(x, y) \times (x\,F_y - y\,F_x)}{\int_\theta N(x, y)}. \tag{5}$$

$$t(x, y) = x\,F_y - y\,F_x. \quad (4)$$

The gravitational torque maps weighted by the gas column density derived from the CO 1-0 and 2-1 lines, N(x,y).
t(x,y) x N(x,y) represent the effective variations of angular momentum density in the galaxy plane.

To estimate the radial gas flow induced by the torques, we have first computed the torque per unit mass averaged over the azimuth.
The weighting function is:

$$t(R) = \frac{\int_\theta N(x, y) \times (x\,F_y - y\,F_x)}{\int_\theta N(x, y)}. \quad (5)$$

t(R) represents the time derivative of the specific angular momentum (L) of the gas averaged azimuthally,
t(R) = $dL/dt|_\theta$, (+)/(-) defines whether the gas gain/lose agnular momentum.

To evaluate the AGN feeding efficiency by deriving the average fraction of the gas specific angular momentum transferred in one rotation (T_{rot}) by the stellar potential, as a function of radius.

$$\frac{\Delta L}{L} = \frac{\mathrm{d}L}{\mathrm{d}t}\Big|_{\theta} \times \frac{1}{L}\Big|_{\theta} \times T_{\mathrm{rot}} = \frac{t(R)}{L_{\theta}} \times T_{\mathrm{rot}} \qquad (6)$$

$$t(R) = \frac{\int_{\theta} N(x,y) \times (x\,F_y - y\,F_x)}{\int_{\theta} N(x,y)}. \qquad (5)$$

$L_{\theta} = R \times v_{rot}$

$L/\Delta L$ determines how long will it take for the stellar potential to transfer the equivalent of the total gas angular momentum.

A small $\Delta L/L$ implies that the stellar potential is inefficient at present.

To calculate how much gas mass is involved in the transfer driven by the stellar potential, we have estimate dthe radial trend for the mass inflow (-) / outflow (+) of gas per unit length as a function of radius

$$\frac{\mathrm{d}^2 M}{\mathrm{d}R\mathrm{d}t} = \left.\frac{\mathrm{d}L}{\mathrm{d}t}\right|_\theta \times \left.\frac{1}{L}\right|_\theta \times 2\pi R \times N(x,y)\,|_\theta \qquad (7)$$

$N(x,y)|_\theta$ is the radial profile of N(x,y) averaged over the azimuth for a radial binning ΔR (corresponds to the original resolution of the NIR images).

The inflow/outflow rates integrated out to a certain radius R can be derived as:

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \sum \frac{\mathrm{d}^2 M}{\mathrm{d}R\mathrm{d}t} \times \Delta R. \qquad (8)$$

Gravitational Torques & AGN Fueling

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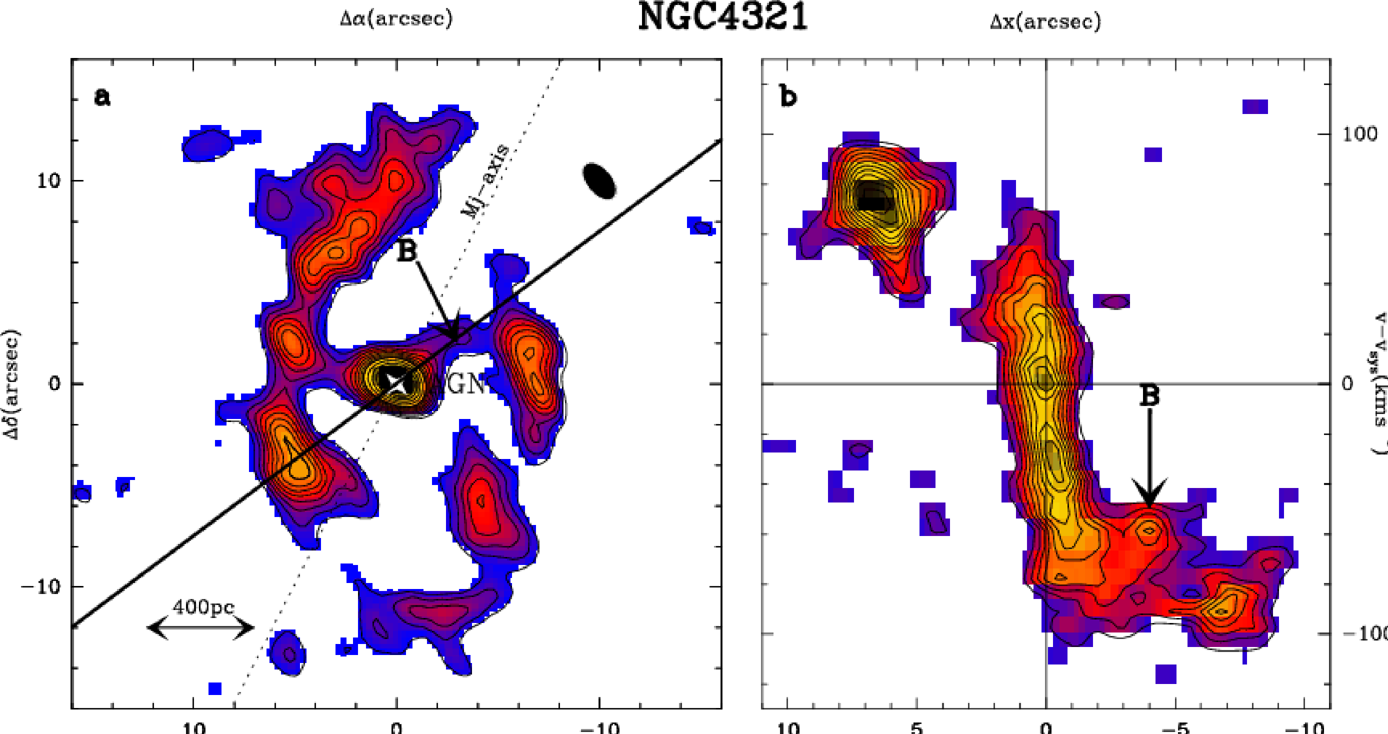
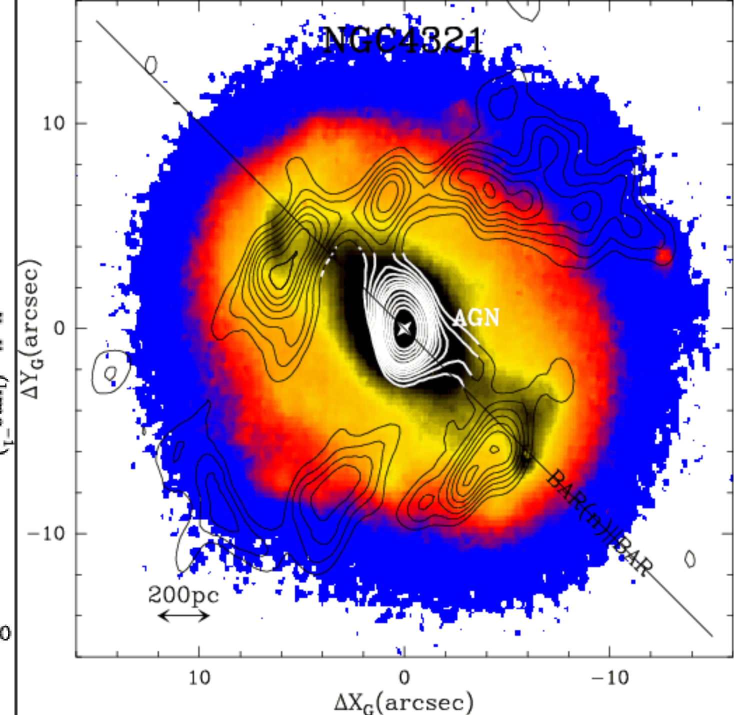
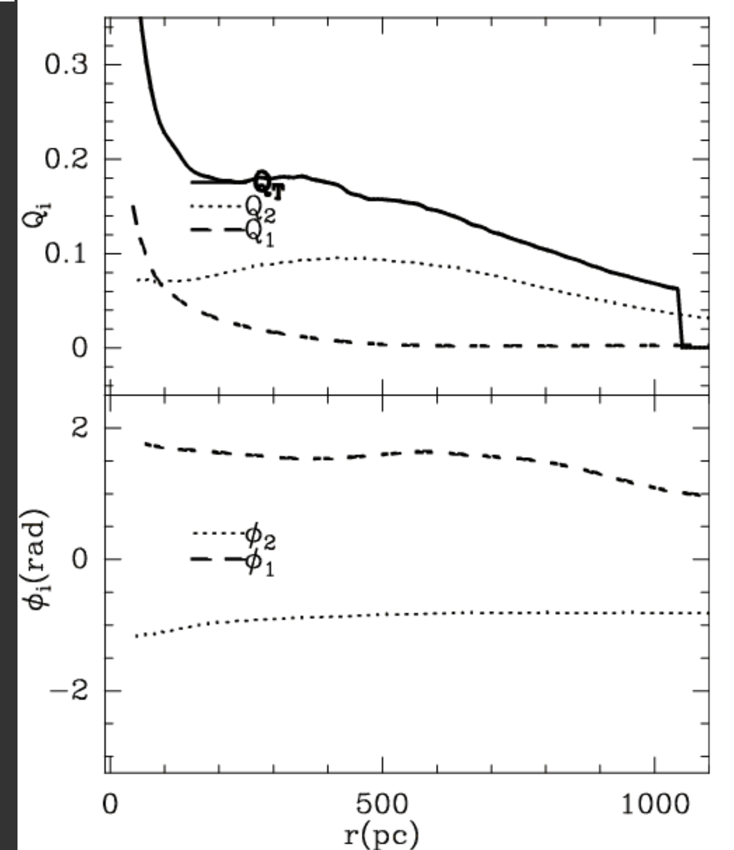


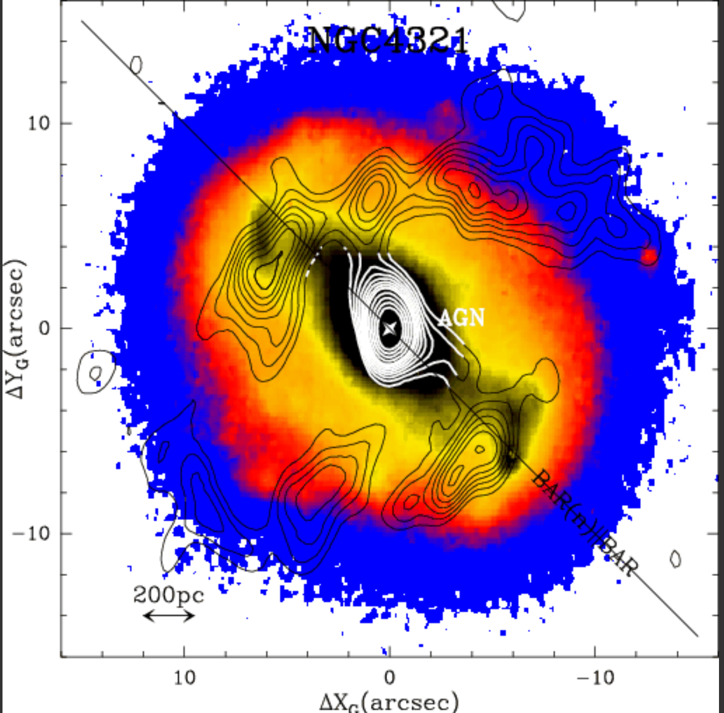


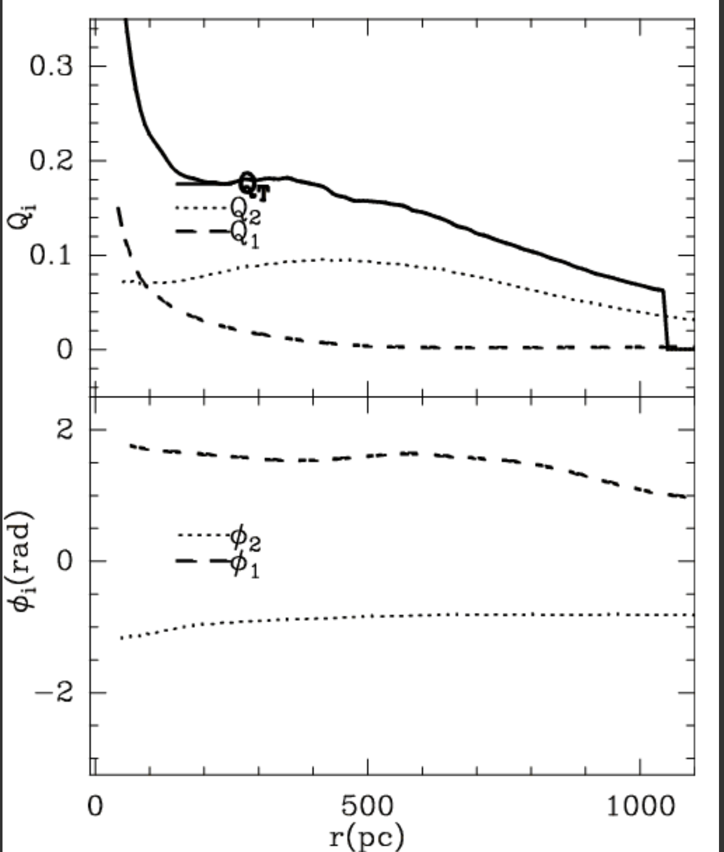
Molecular gas in the nucleus is concentrated in a two spiral arm structure that stars at r~550pc and extends out to r~1.2kpc.

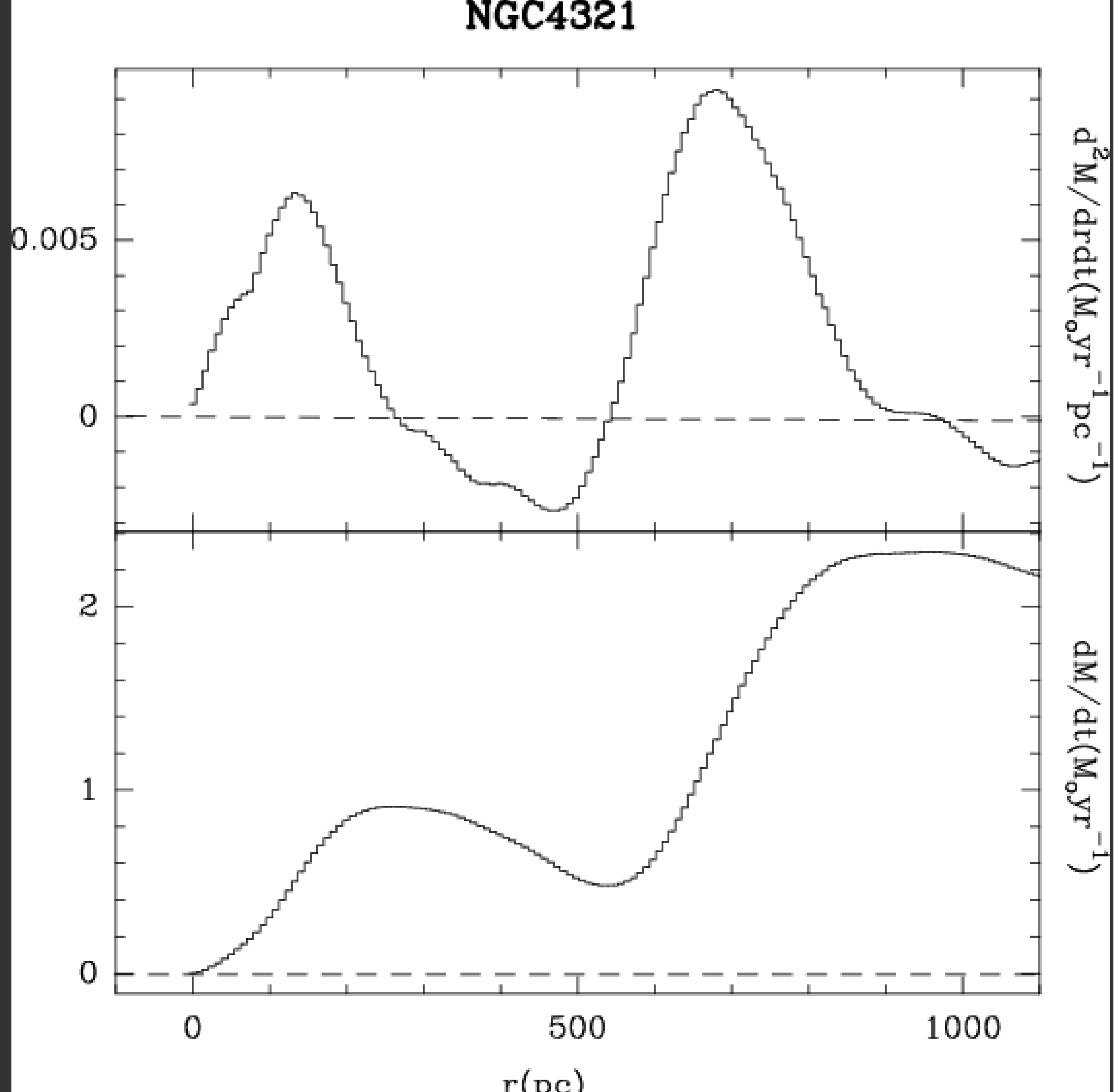
The discontinuity in radial velocities at B indicates that the molecular gas flow is decelerated.

The total strength of the potential is represented by Q_T. The nuclear bar strength is the main contributor to Q_T, which is <500pc

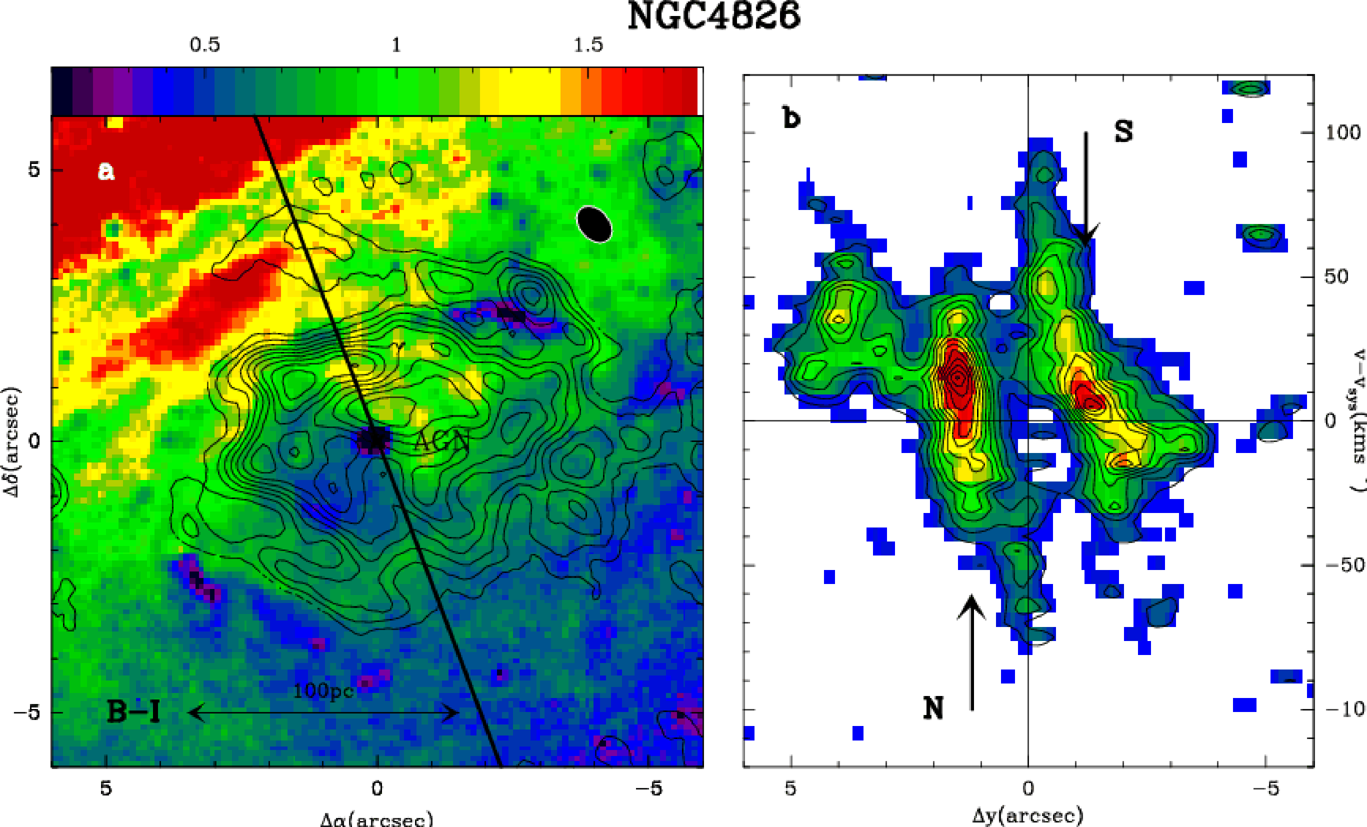


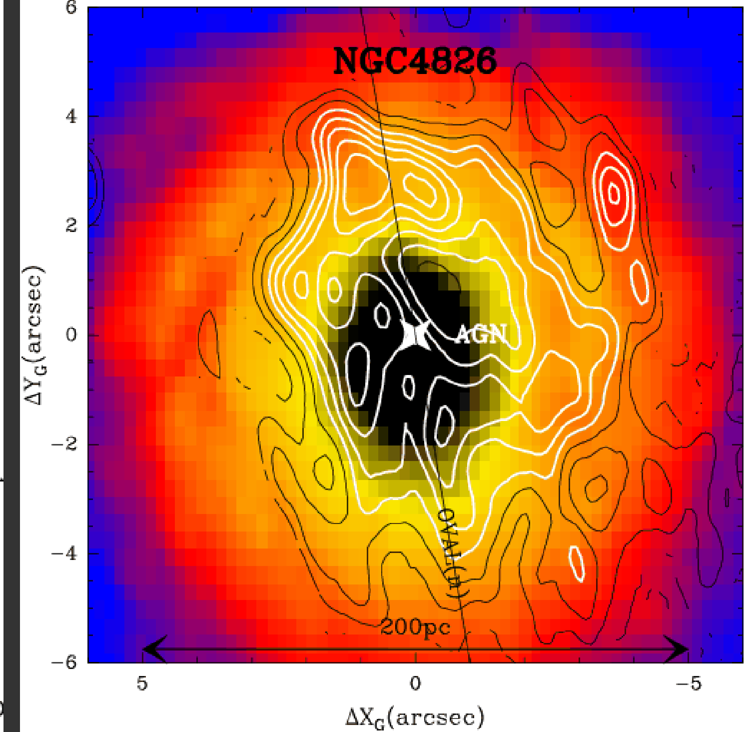






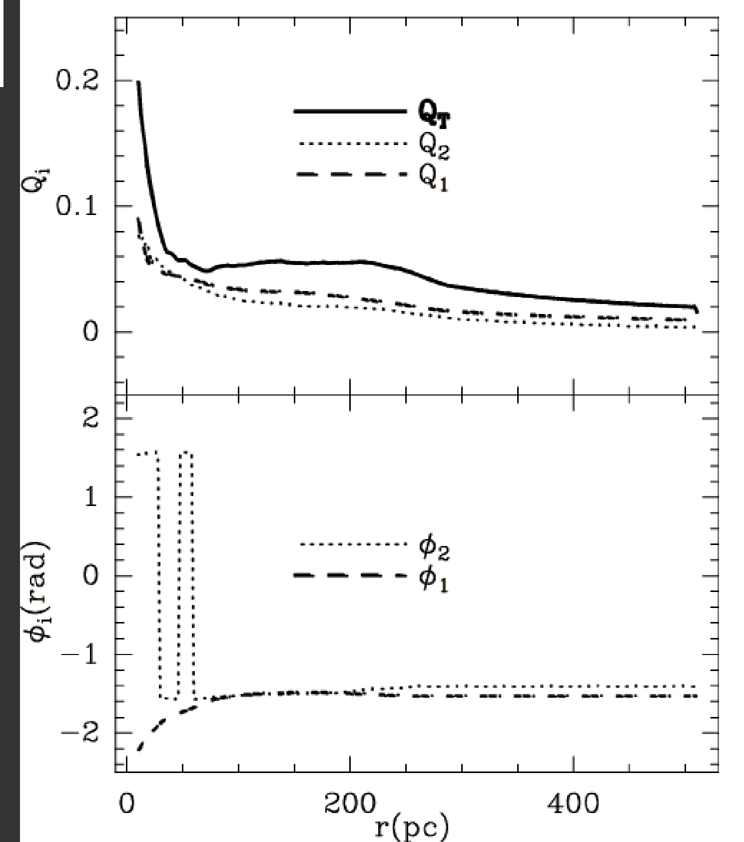
Mass inflow rates (dM/dt) are positive at all radii. This implies that the radial gas flow goes outward unless other mechanisms more efficiently transfer the gas angular momentum outwards.
AGN feeding driven by stellar torques is quenched at present in NGC 4321.

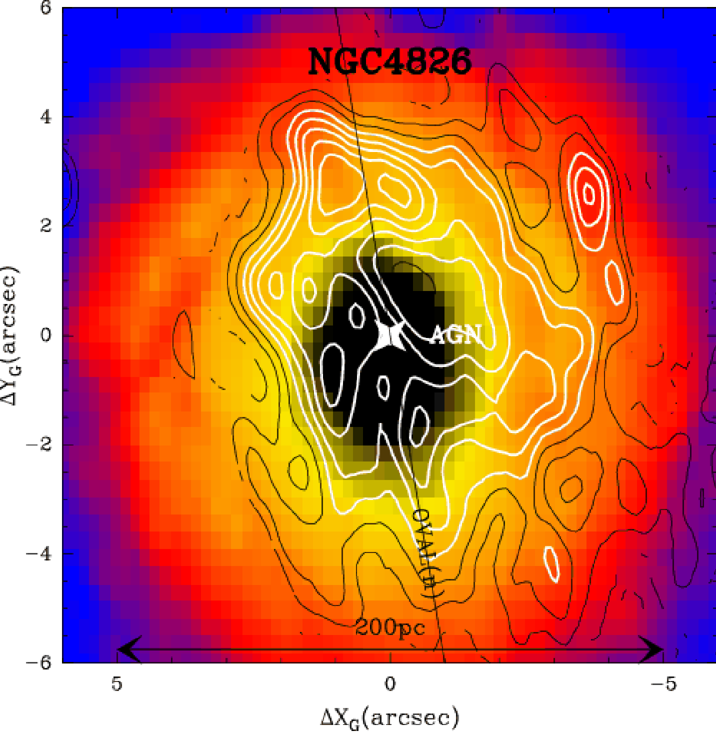


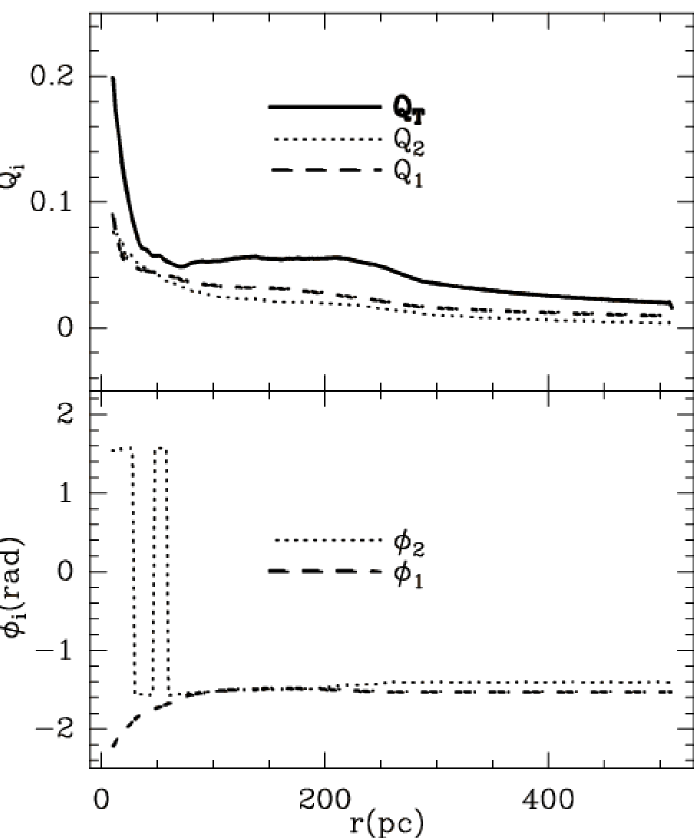


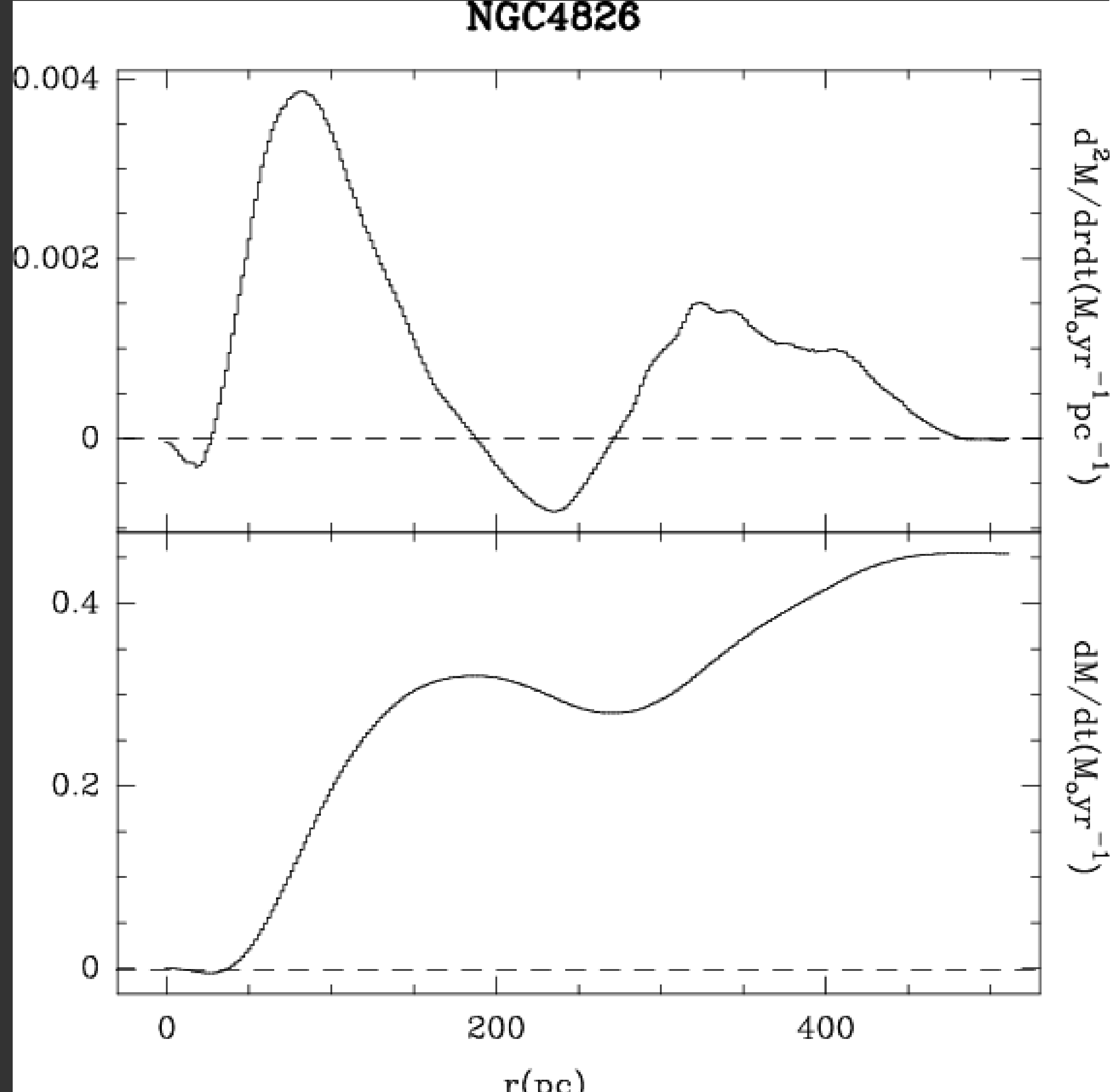
(left) The AGN locus is identified by a blue point-like source. It also coincides with a non-thermal ratio continuum peak measured at 6cm.
Strong streaming motions at the crossing of the ring edges (N, S)

(right) The central ~200pc region.
The deviations from axisymmetry of the stellar potential are exceedingly small at all radii except for r<75 where a weak oval perturbation is detected.

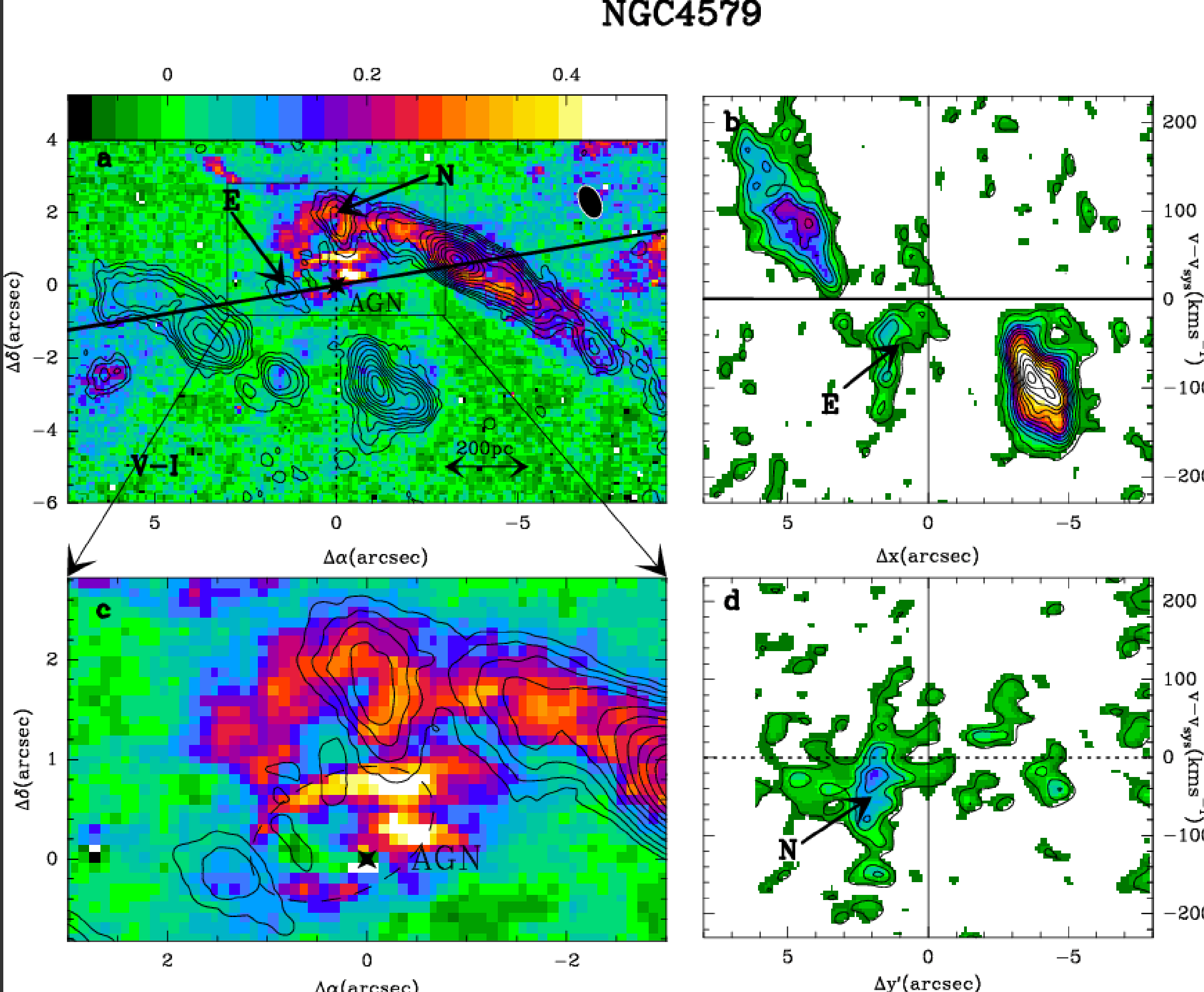


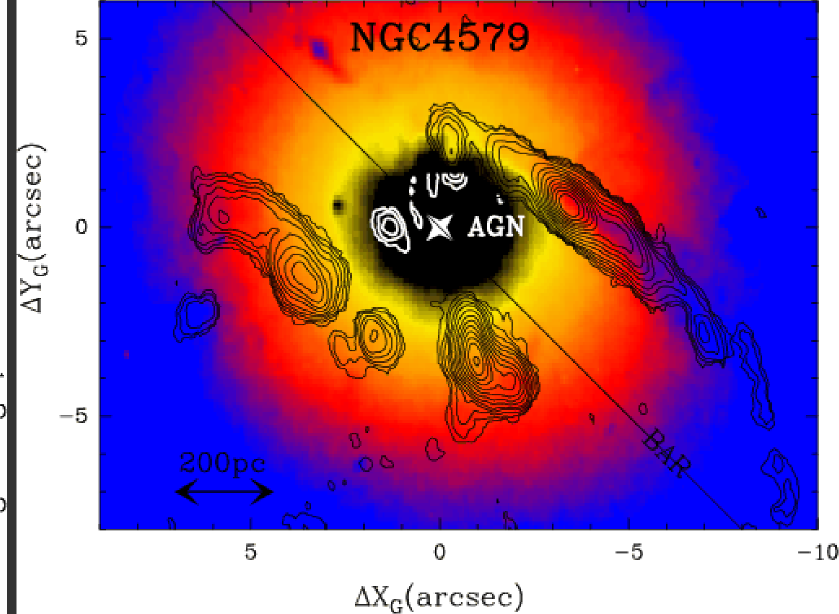


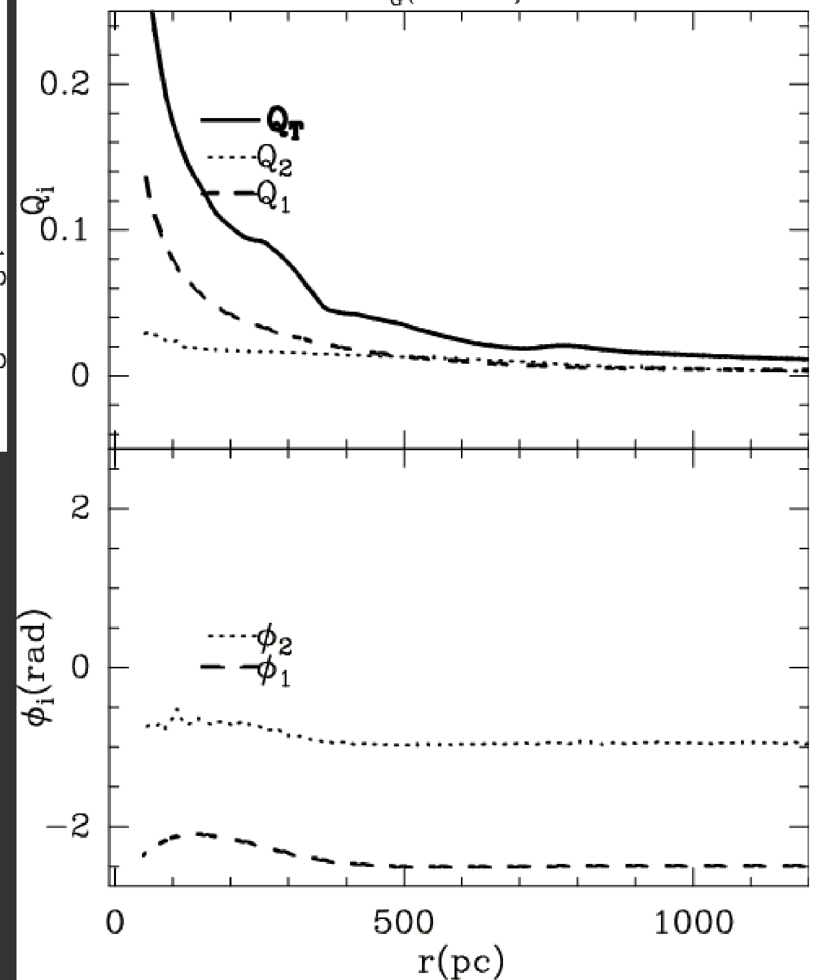




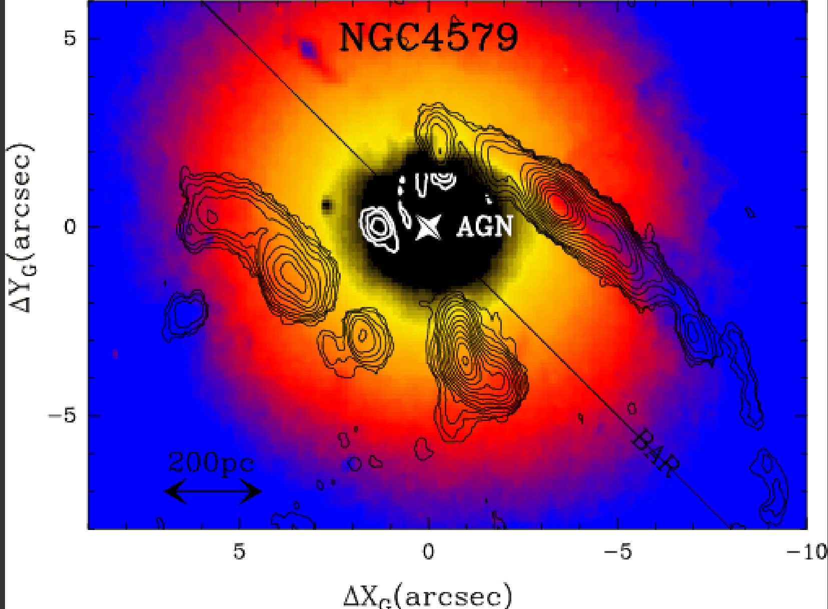
The overall feeding budget, quantified by the mass inflow rates, is positive inside the full field-of-view of the NIR image. This implies that the predicted radial mass flow should be dominated by outflow rather inflow motions.

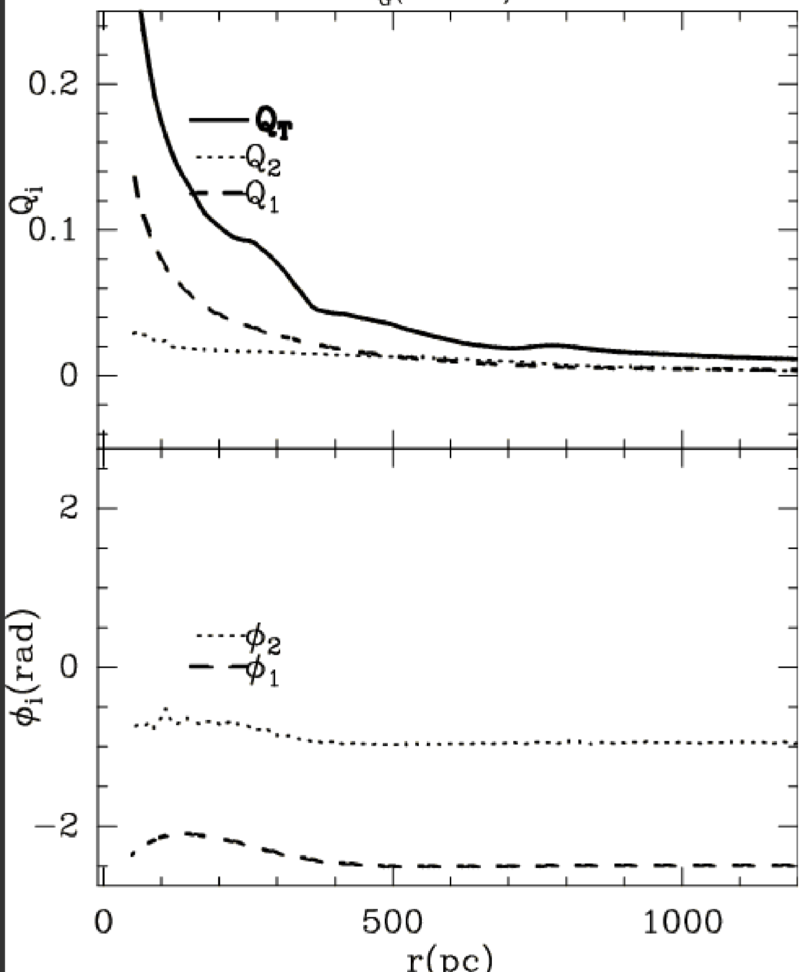


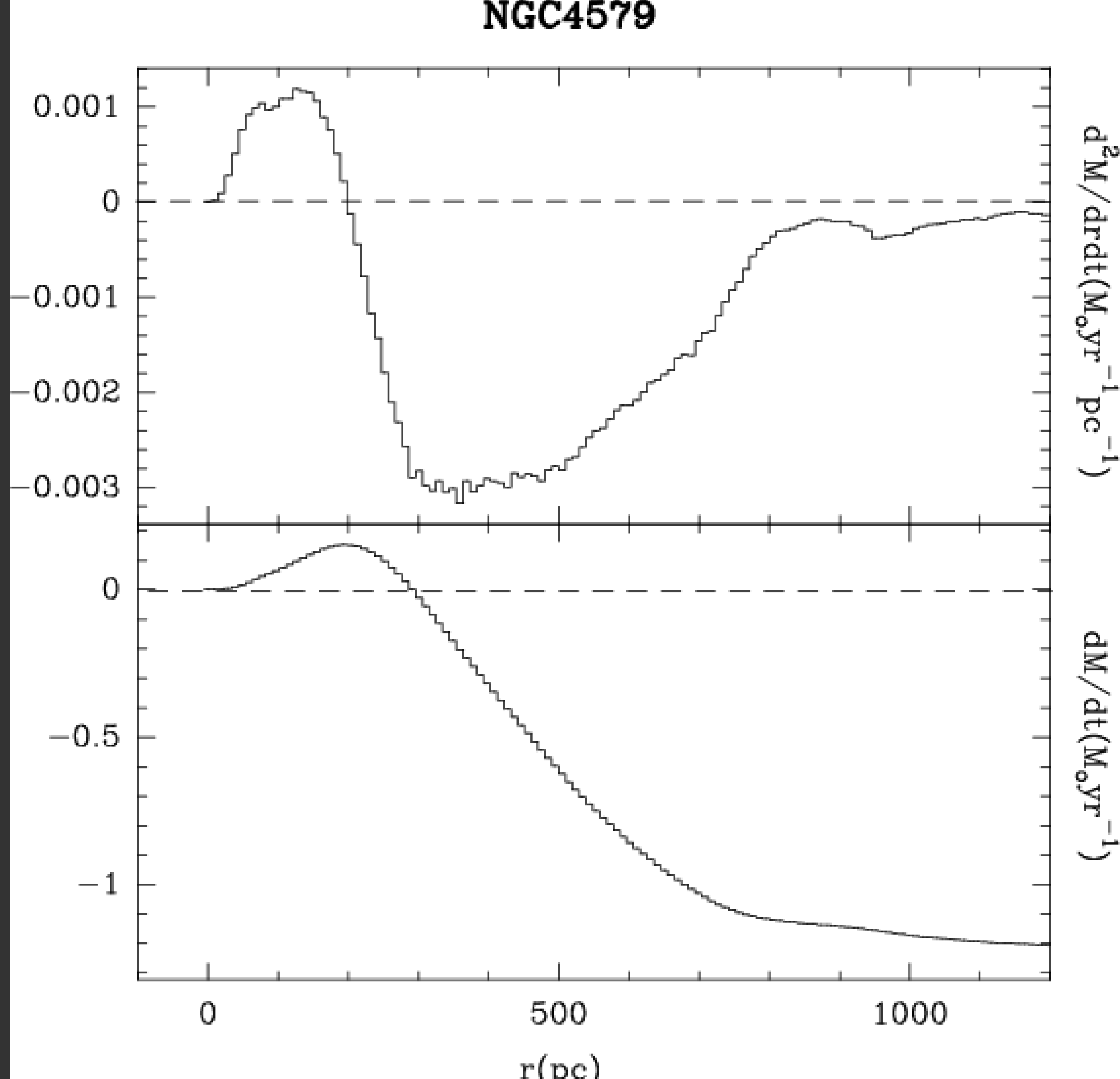




The central r~1 kpc region.
E, N: Non-circular motion.
The dominant stellar perturbation in the HST image of the disk is the large-scale 9 kpc bar.
The potential strength of the bar is dominated by an m=1 mode for r<250pc.

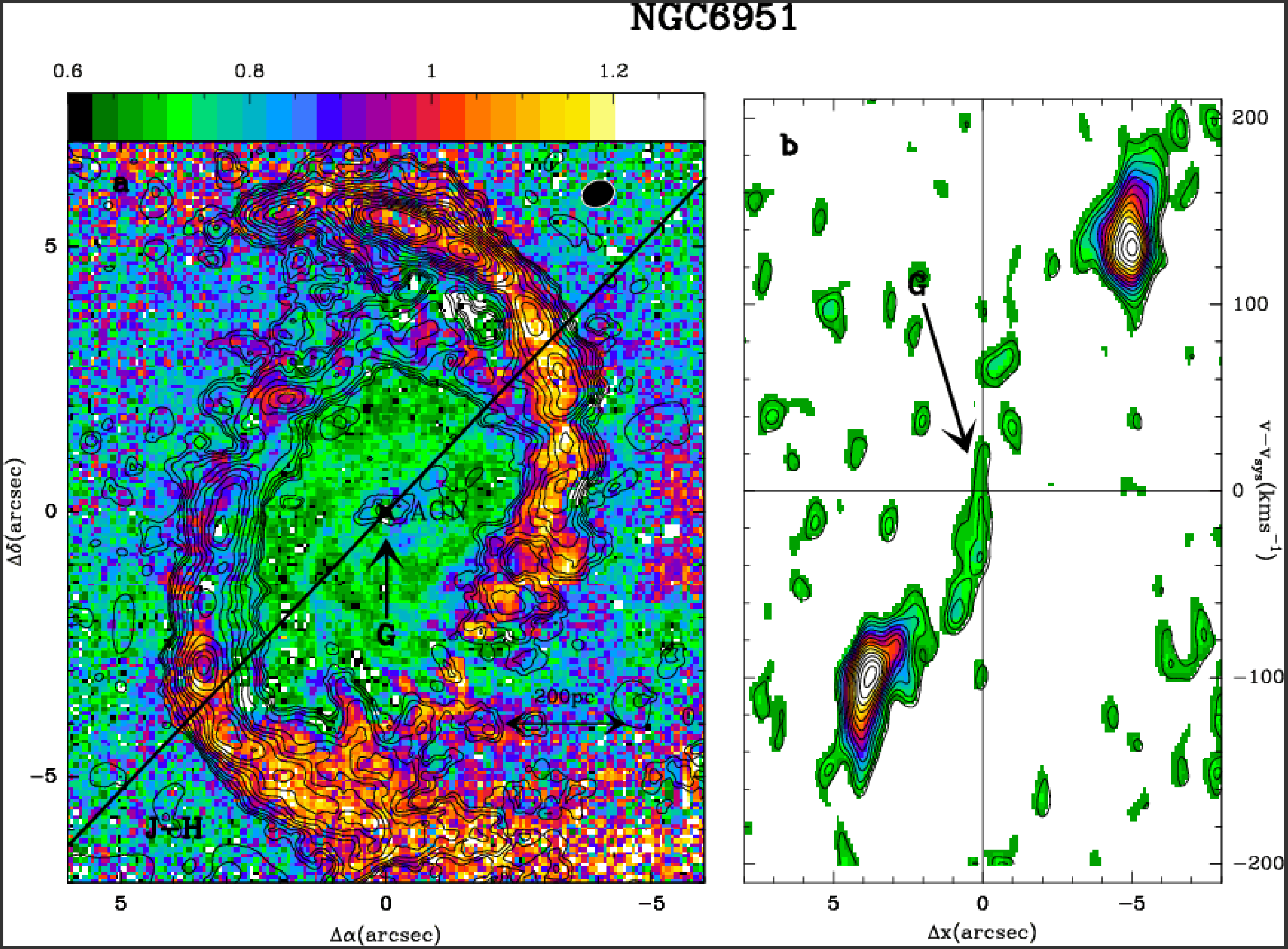


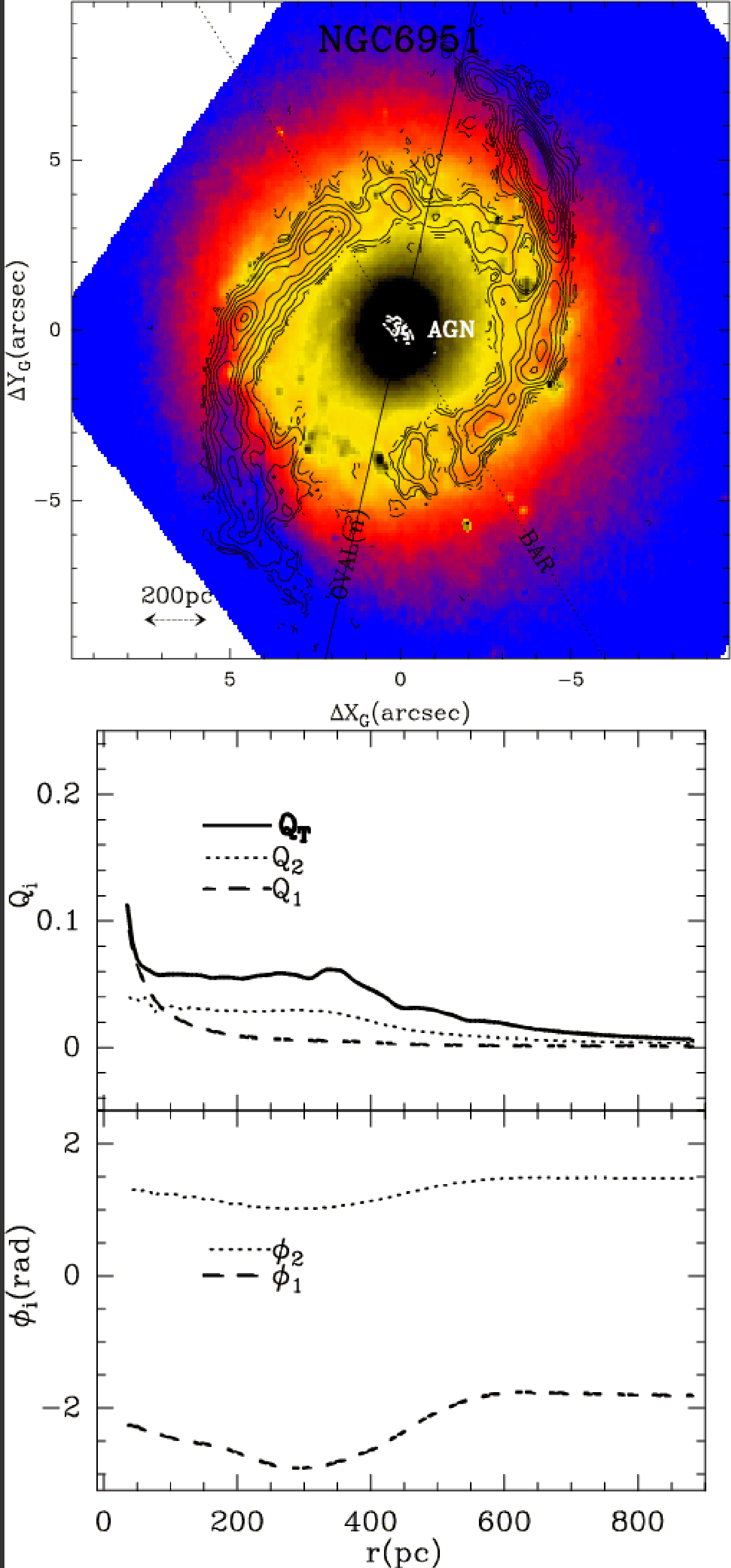




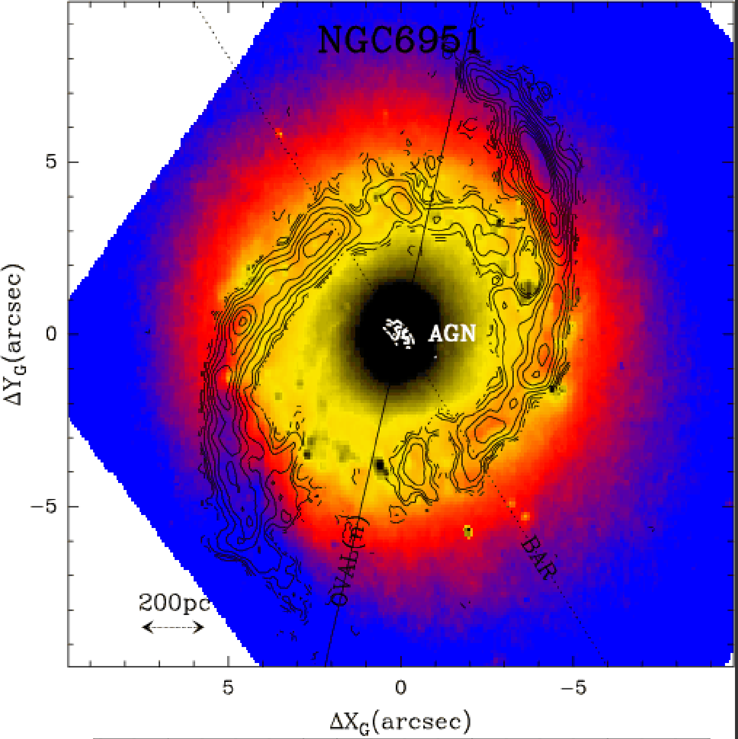
The overall mass inflow budget is (-) down to r~300pc due to the action of the large-scale bar.
Inside this radius, stellar torques do not favor AGN feeding.

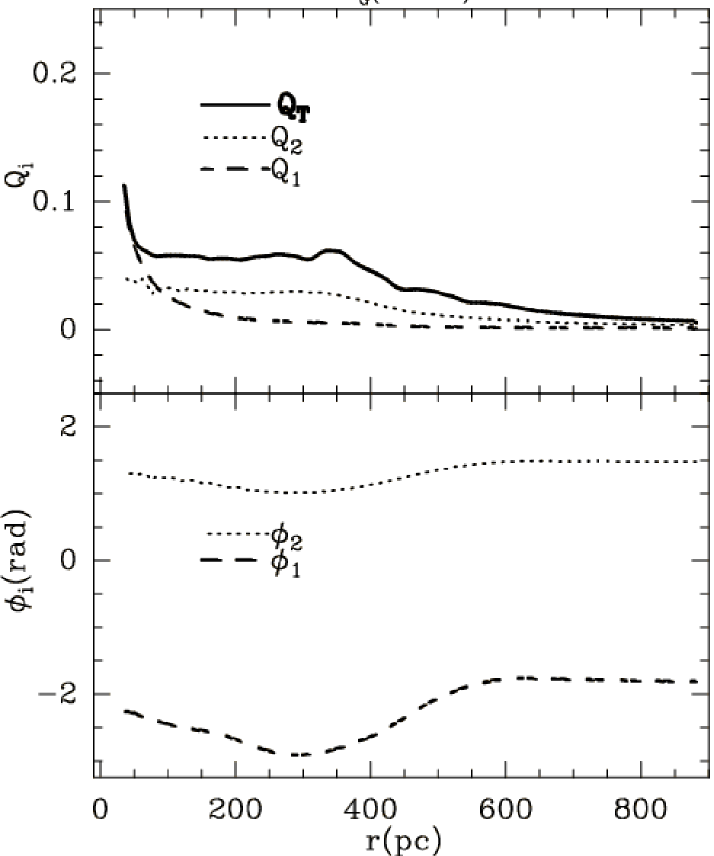
NGC 6951

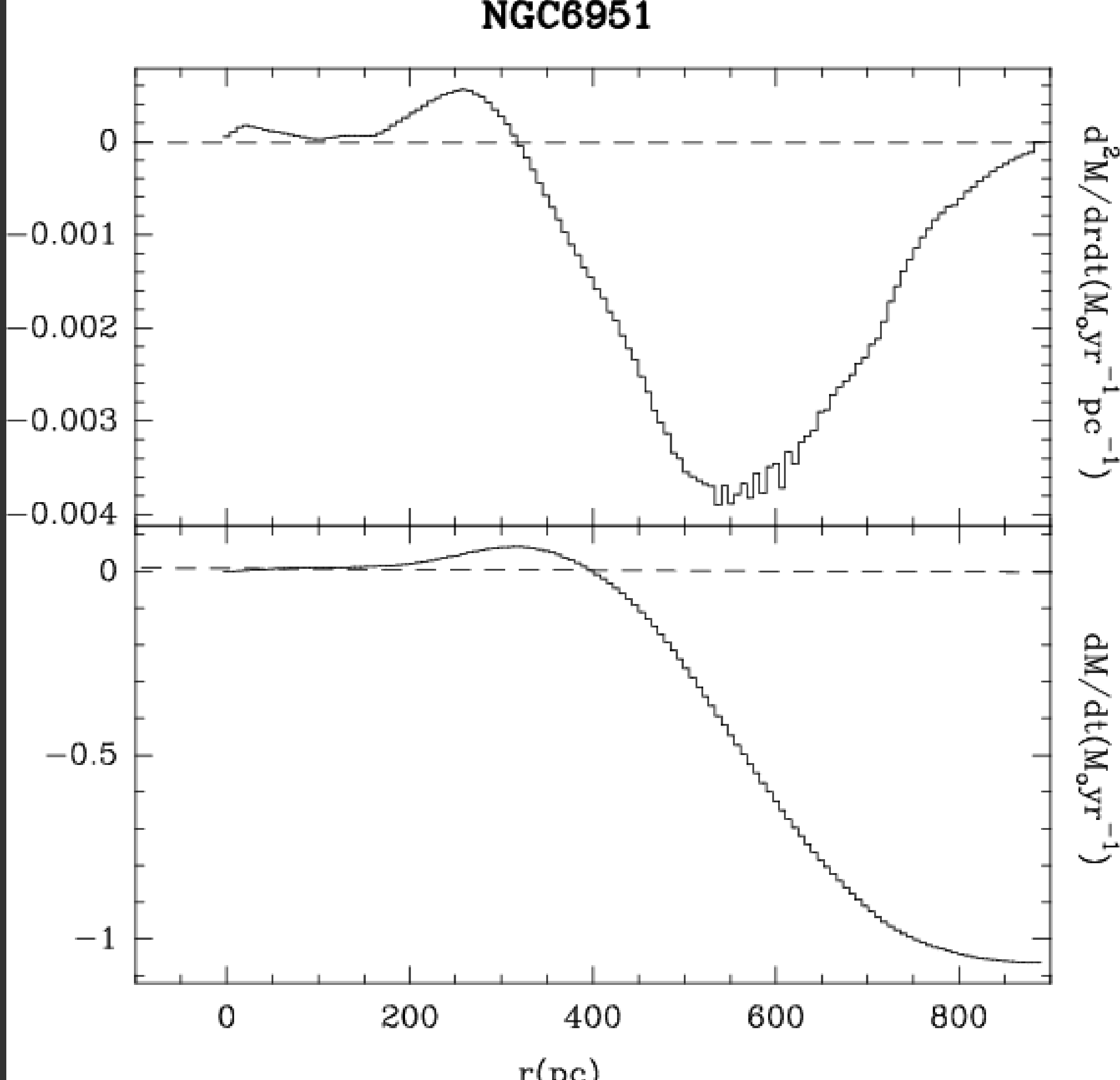




G: Compact molecular complex







Positive mass inflow rates (dM/dt) implies that the radial gas flow goes outward, and negative mass inflow rates implies that the radial gas flow goes inward.

Discussion & Conclusion

- Results indicate paradoxically that feeding should be thwarted close to the AGNs.
- In the 4 cases analyzed, gravity torques are mostly positive inside r~200pc, resulting in no inflow on these scales.
- As possible solution is that, the agent responsible for driving inflow to still smaller radii is transient and thus presently absent in the stellar potential.

References

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