The mystery of the double nucleus in the Andromeda galaxy

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Global asymmetry (m=1 mode) in galaxies – kpc scale

What does “m=1 mode” mean ?

The surface density is decomposed into a Fourier series:

$$\mu(r,\psi)=\mu_0+\sum_m A_m \cos\left(m\,\psi-\psi_m(r)\right)$$

The m=1 mode means the presence of global dipole asymmetry.

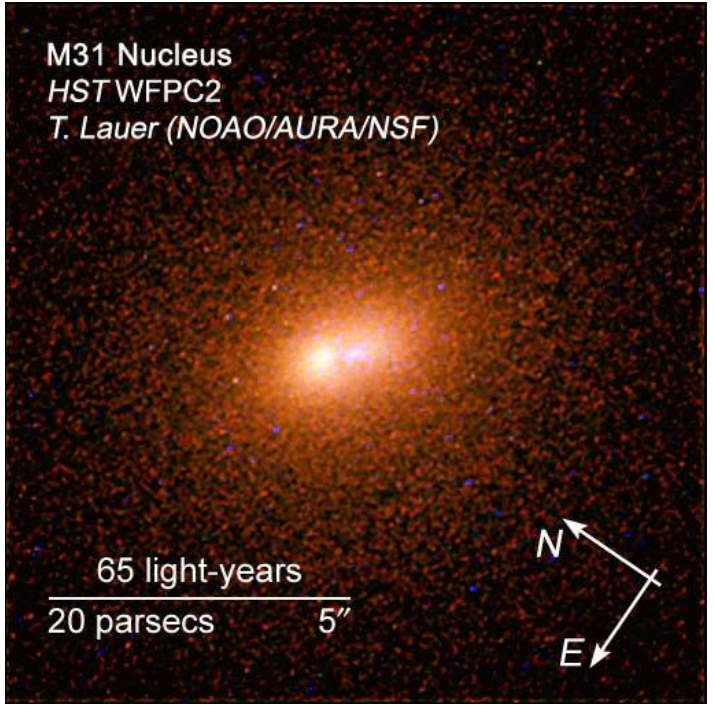
- 2/3 of galaxies (total 149) have m=1 asymmetry (Bournaud et al. 2005)
- N-body simulations of an isolated self-gravitating stellar disk, without a bulge, halo, or central mass, show the spontaneous growth of a global m=1 mode. (Saha, Combes & Jog 2007)
- Asymmetry in kpc-scales and symmetry in pc-scales

Galaxy (M101) with m=1 mode



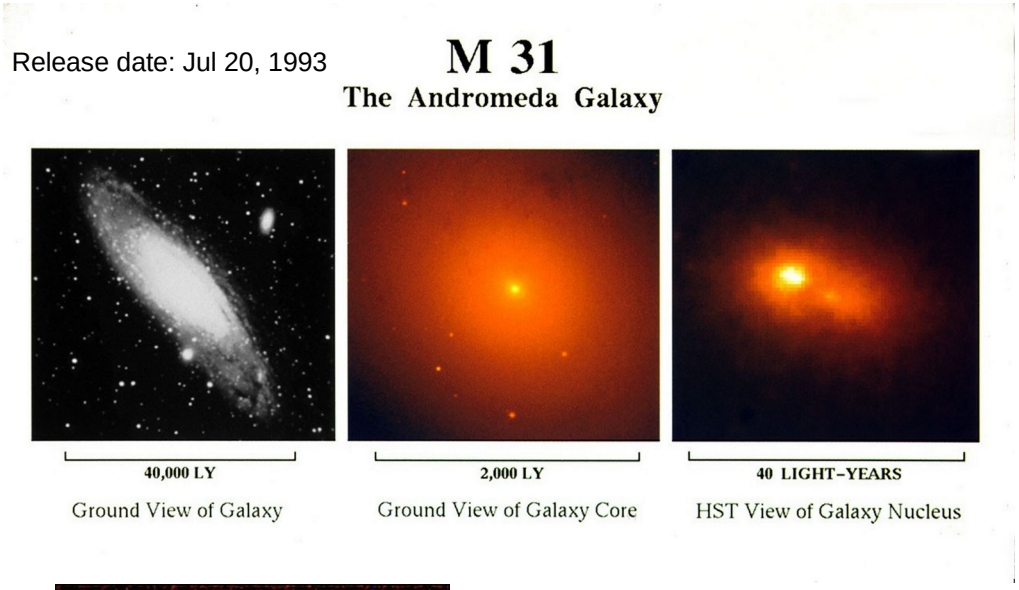
Andromeda galaxy (M31)

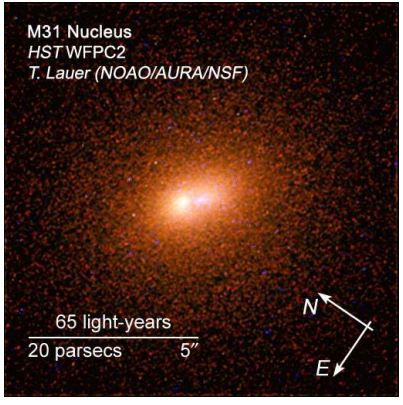
The asymmetry in the nucleus – pc-scale





First observations of the double nucleus in M31





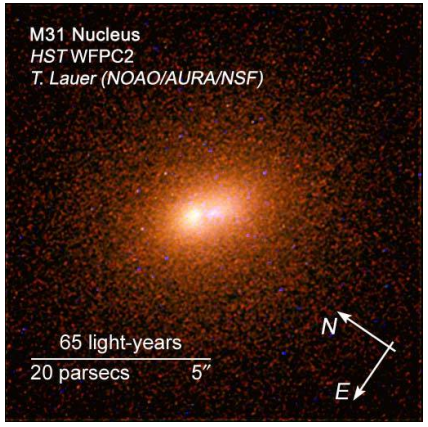
HST with angular resolution = 0.1″

P1–P2 separation: 0.49″ = 1.9 pc

- First mention of an “anomalous” brightness profile
  (Light, Danielson & Schwarzschild 1974)
- HST confirmed the presence of two bright peaks (P1- P2)
  (Lauer et al. 1993)

- Morphology of the nucleus – inclination, and the offset between the peaks and the center *(Lauer et al. 1998)*
- High-precision kinematic data *:*
  P2 coincides with the SMBH position and
  P1 corresponds to a stellar density peak
  (Kormendy & Bender 1999)

The idea of an eccentric stellar disk in M31



THE ASTRONOMICAL JOURNAL VOLUME 110, NUMBER 2 AUGUST 1995

AN ECCENTRIC-DISK MODEL FOR THE NUCLEUS OF M31

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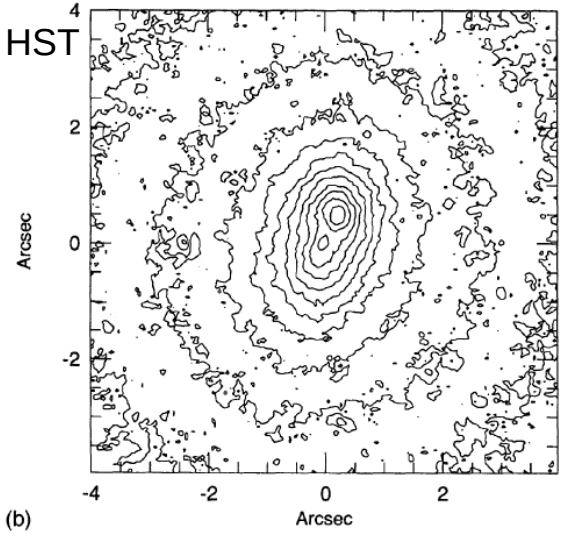
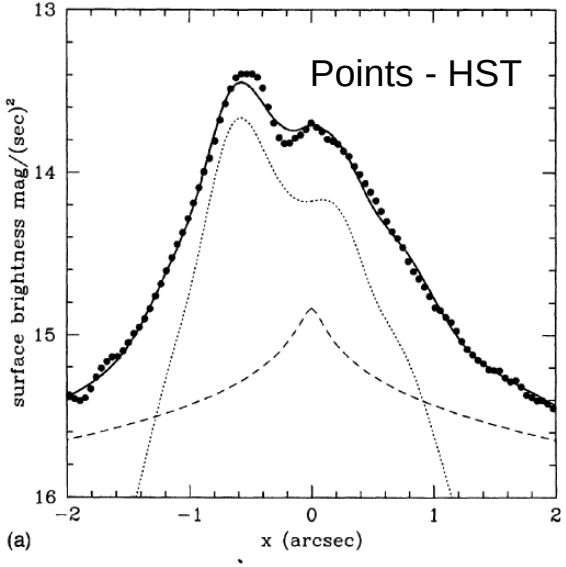
HST





Tremaine (1995):

The apparent **double structure arises because stars spend more time near apocentre (P1) than pericentre (P2)**, producing an asymmetric surface-brightness distribution with two apparent peaks.

Eccentric stellar disk in M31's nucleus: simulations

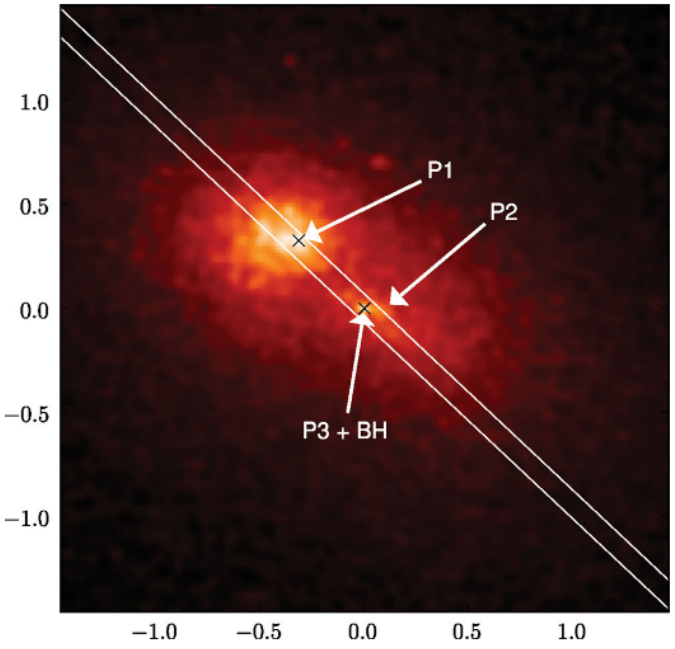
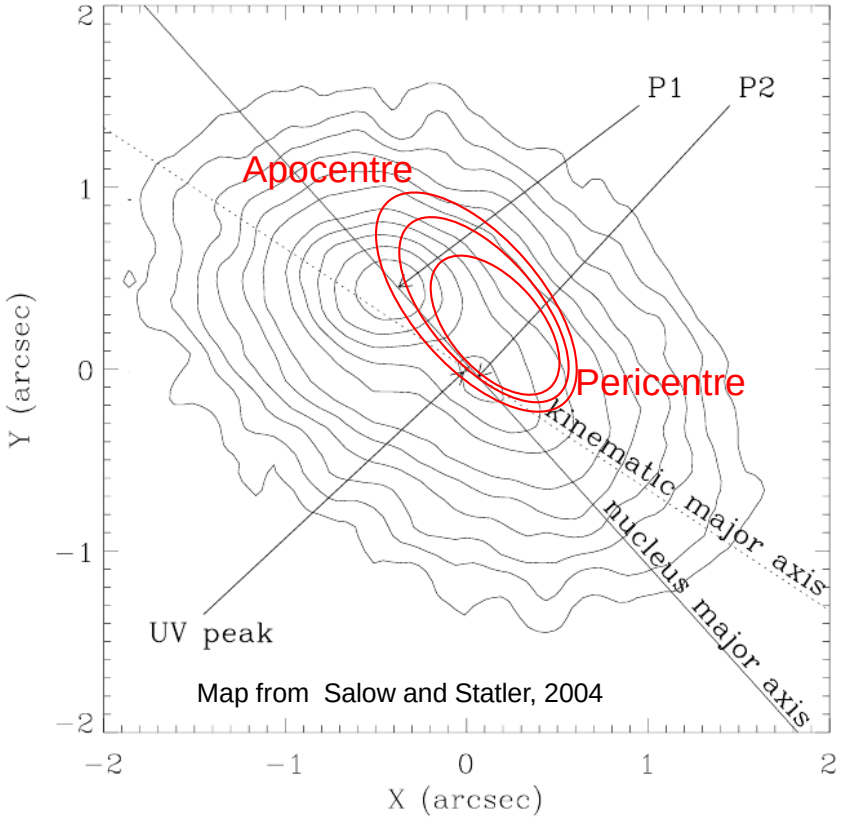
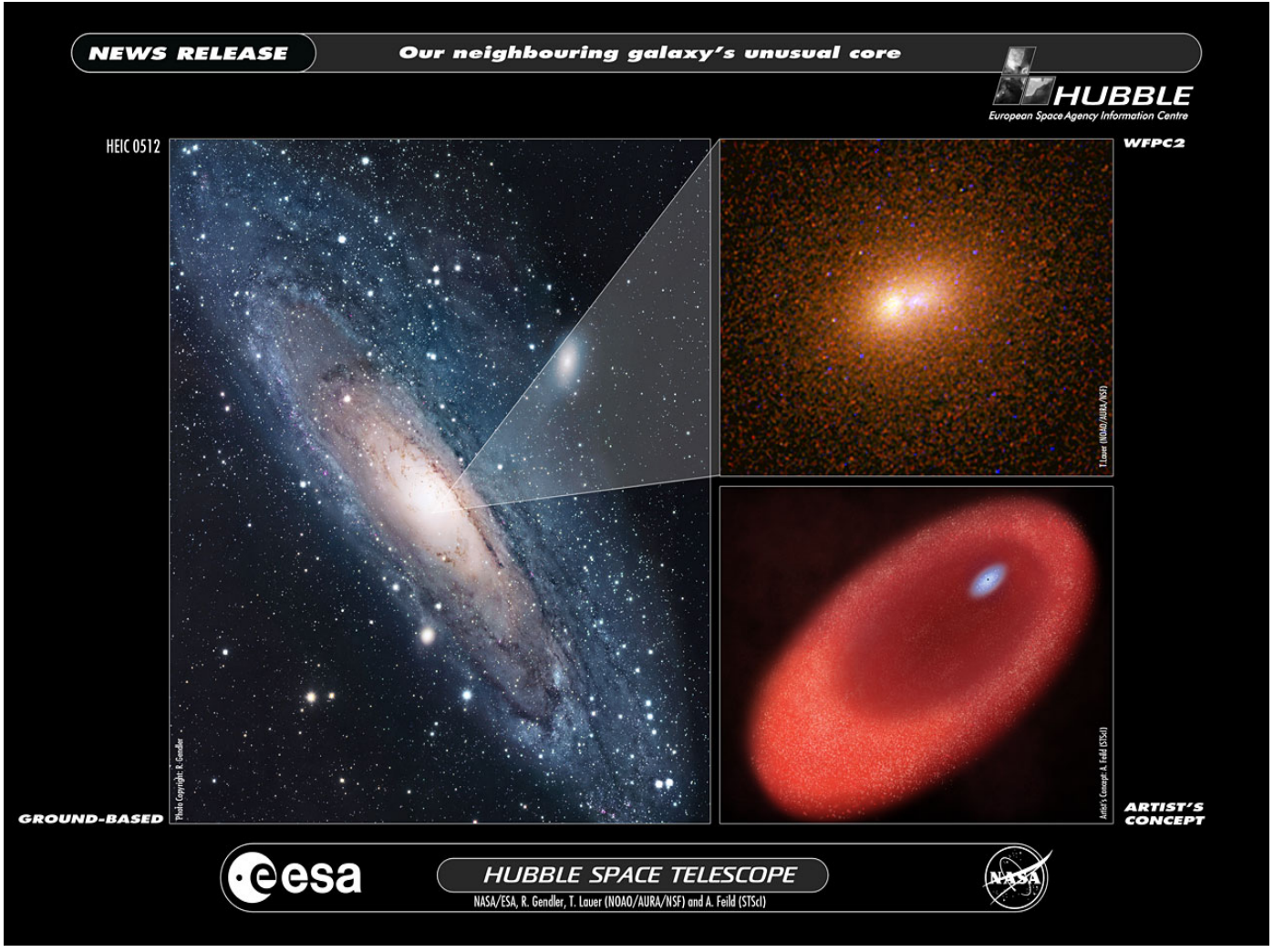


Figure 1. *V*-band image of the nucleus (Lauer et al. 1998) annotated to show the positions of P1, P2 and P3. The pair of white lines represents the positioning and width of the STIS slit (Bender et al. 2005). The brightest point in the image is at P1 and is marked with cross. Centred in the image and marked with a cross is the location of the black hole and P3. P2 is on the anti-P1 side of the black hole.

Disk thickness in M31's nucleus is obtained from models:
H/R=0.4-0.5 or σ_i = 40°–50° (Brown&Magorrian 2013)



Map from Salow and Statler, 2004

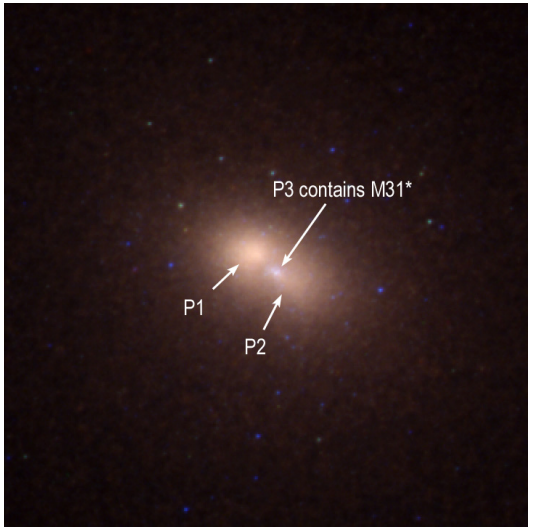


https://esahubble.org/images/heic0512a/

Release date: 20 September 2005

From a double to a triple nucleus





P1+P2 - old eccentric disk

P3 - disk of young stars

1991 : resolution ~0.1″→ P1 + P2

1998 : compact UV-region inside P2

2005 : P3 kinematics + SMBH mass ~$1.4\times10^{8}M_{\odot}$
(Bender et al. 2005)

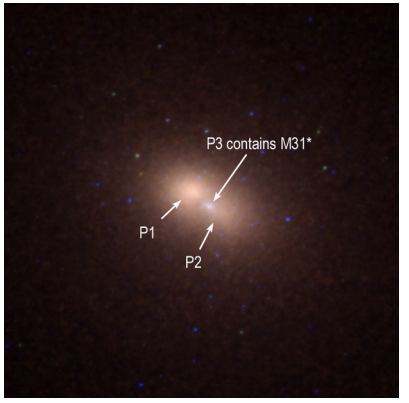
2011–2012 resolution ~0.03″→ **P3 resolved into stars**

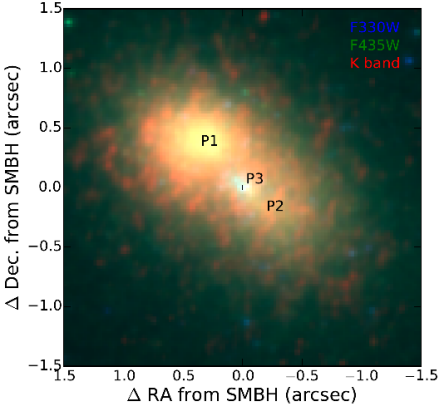
The “double nucleus” is actually a system of two nested stellar disks around the SMBH.

Formation scenario for the young P3 disk

Chang et al. 2007

- **Old stars in the P1+P2 eccentric disk** continuously lose mass.
- The non-axisymmetric gravitational potential removes angular momentum from the gas and drives it toward the central parsec.
- Stellar mass loss can accumulate up to $\sim 10^5 M_\odot$ of gas.
- The inner gas disk becomes gravitationally unstable, triggering a short burst of star formation .
- Such an episode could have formed **the young P3 disk (1 pc-scale)**.



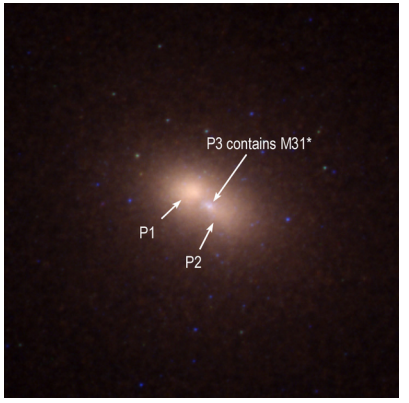


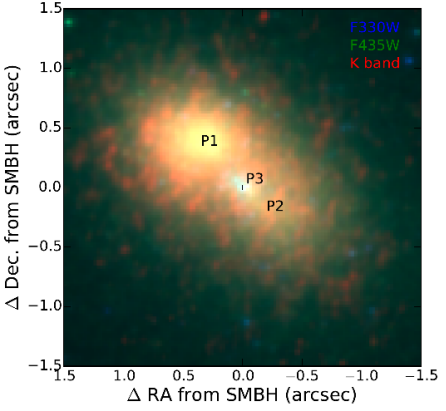
Lockhart et al. 2018

Formation scenario for the young P3 disk

Chang et al. 2007

- **Old stars in the P1+P2 eccentric disk** continuously lose mass.
- The non-axisymmetric m=1 gravitational potential removes angular momentum from the gas and drives it toward the central parsec.
- Stellar mass loss can accumulate up to $\sim 10^5 M_\odot$ of gas.
- The inner gas disk becomes gravitationally unstable, triggering a short burst of star formation .
- Such an episode could have formed **the young P3 disk (1 pc-scale)**.





Lockhart et al. 2018

BUT

ALMA observations in the CO(3–2) line revealed no molecular gas in the central parsec of M31, setting a 3σ upper limit of (M_{H2}<195$M_\odot$) (Melchior & Combes 2025)

M31*: a whispering SMBH

M31 = LLAGN (Low-Luminosity Active Galactic Nucleus) or
LINER 2 / Transition Object

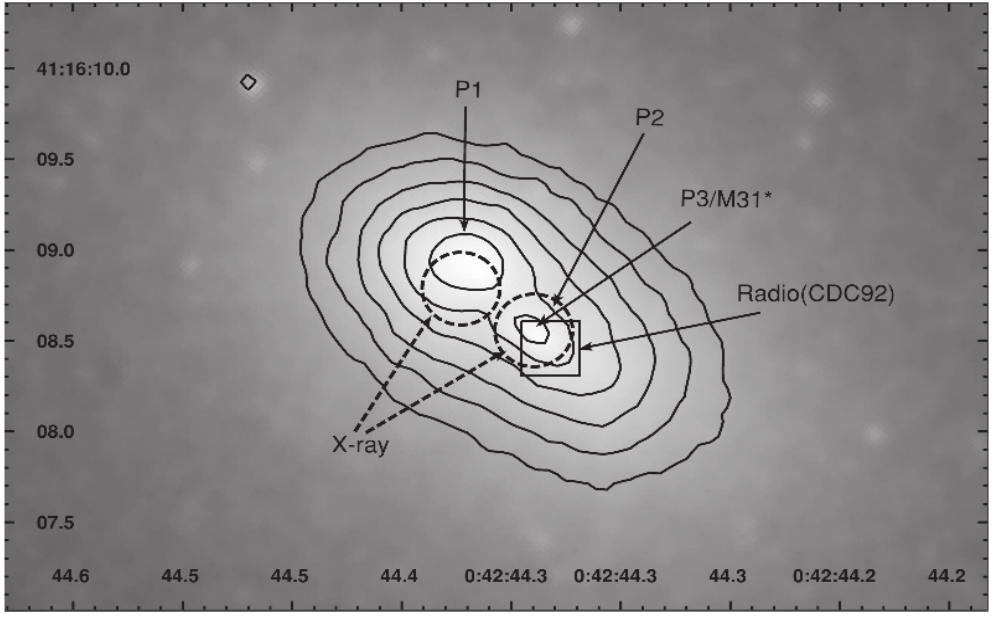
Compact Variable Radio core (VLA, VLBA) –>
SMBH 10^8 M_{sun} is marginally active

Accretion rate is about 10^{-6} (ADAF as in Sgr A* in MW)

Nucleus is seen only in **narrow lines** – **Type 2** →
it means that it should be edge-on

The nucleus is “dormant” analogous to Sgr A*, not a classical Seyfert.

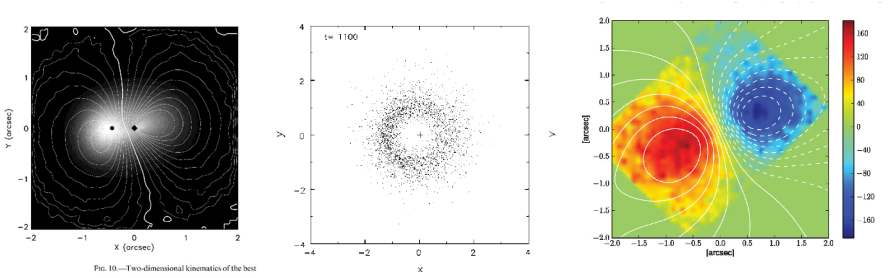
Compact Variable Radio core M31* (VLA, VLBA)



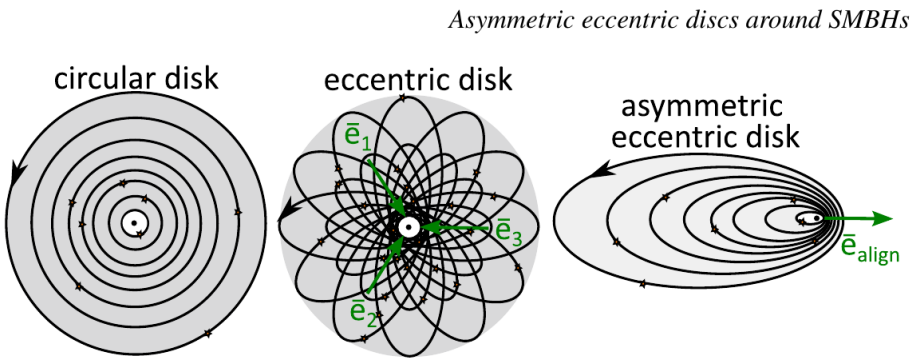
Garcia et al. 2010

Simulations of asymmetry in the disk of M31

- **Asymmetry (m=1 mode) is imposed in the initial state**
  - Bacon, Emsellem & Combes (2001)
  - Jacobs & Sellwood 2001;
  - Peiris & Tremaine 2003;
  - Salow & Statler 2004;
  - Brown & Magorrian 2013;
  - Wernke & Madigan 2021+



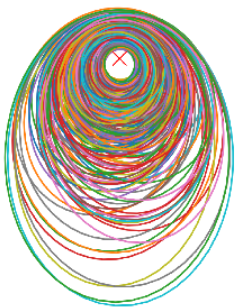
The initial asymmetry in a thin eccentric stellar disk is gradually destroyed (Rantala & Naab 2024)



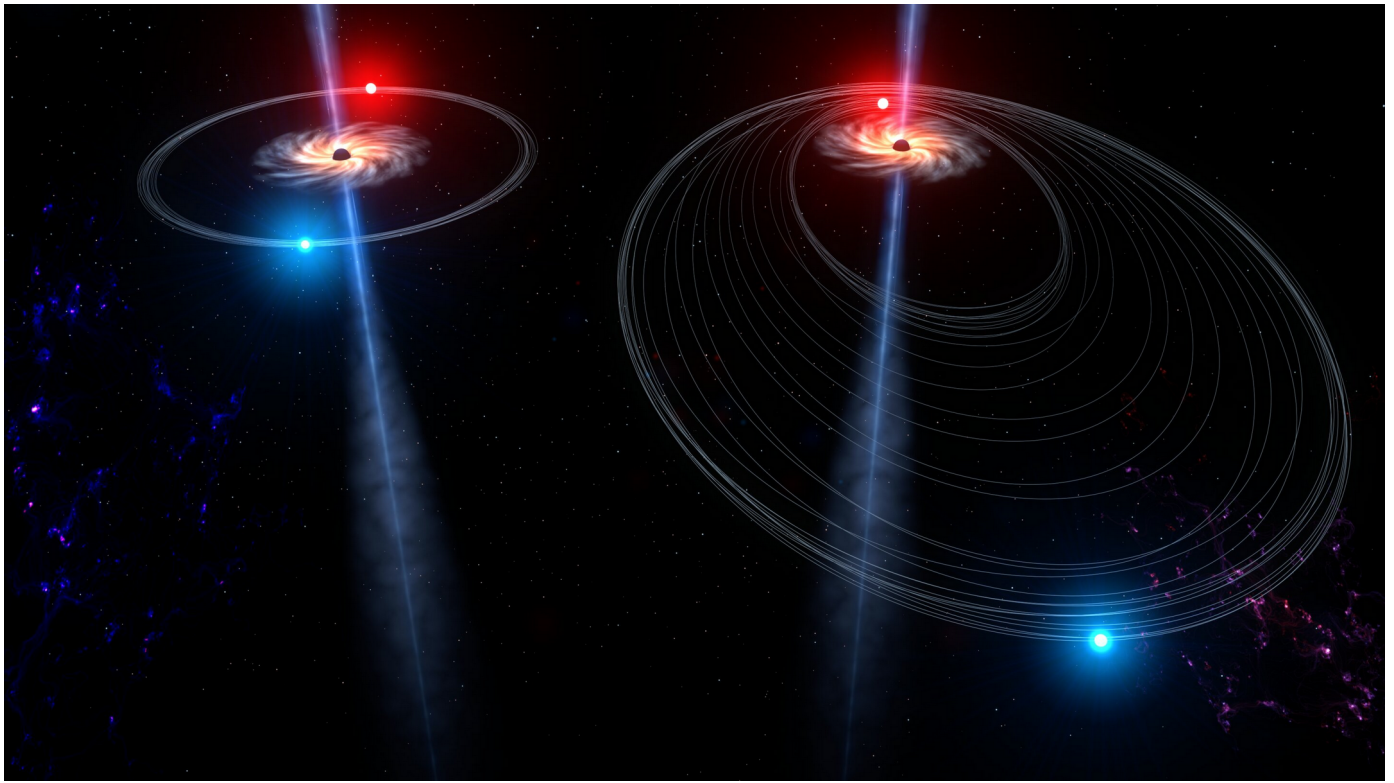
Kick of SMBH as a trigger of m=1 mode formation

Akiba and Madigan 2021, 2023





(b) N-body result.



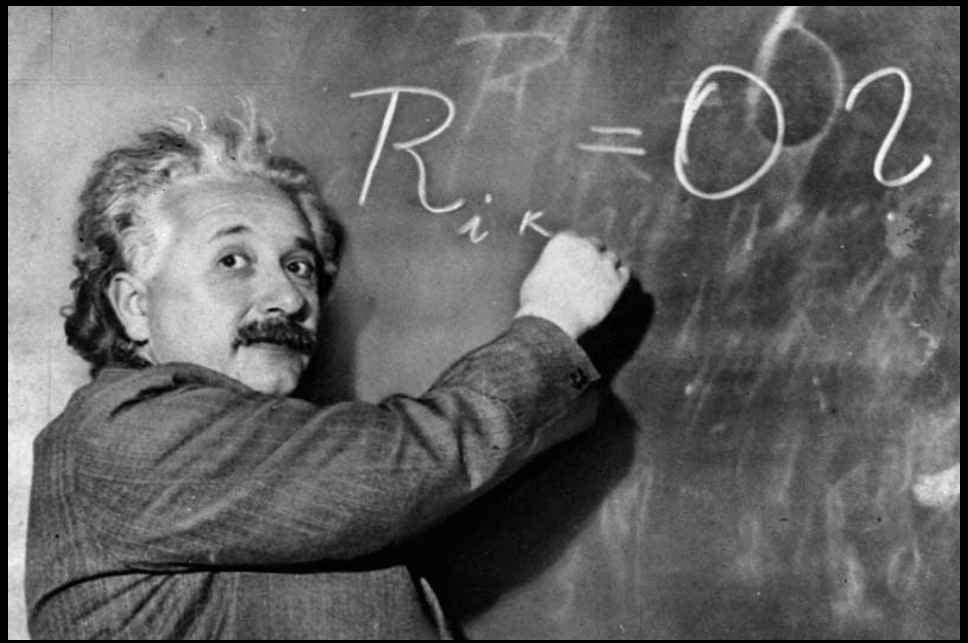
To create an asymmetry, it is like scoring a goal: you have to kick in the right direction.



Is the Andromeda galaxy unique?

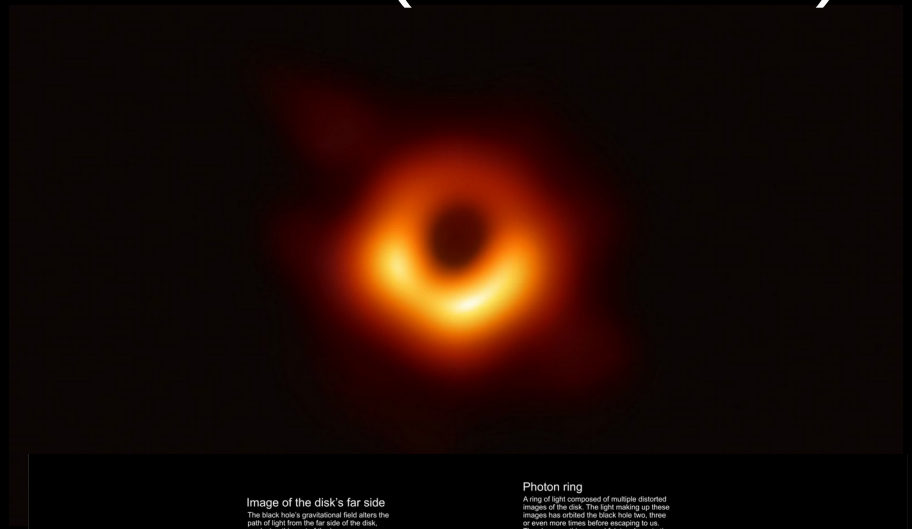
Are black holes a defect of the theory, or do they really exist in nature?

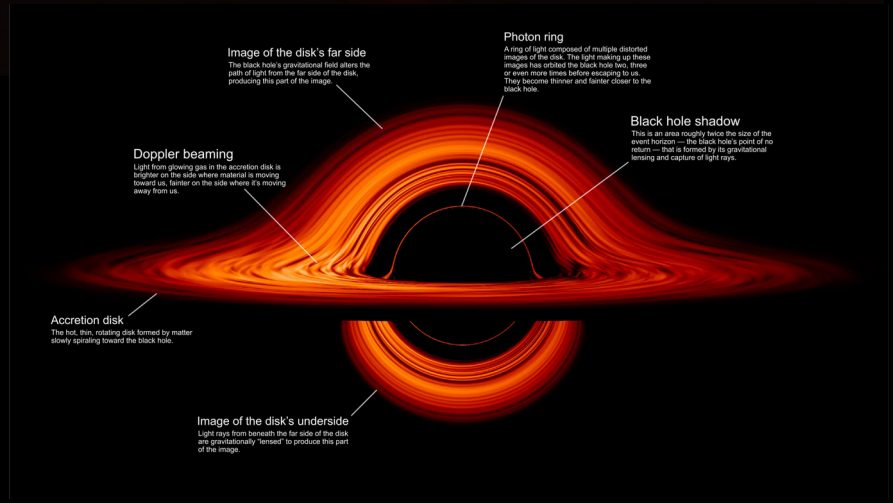
100 years of discussions



The first picture of a black hole in M87 (NGC 4486)

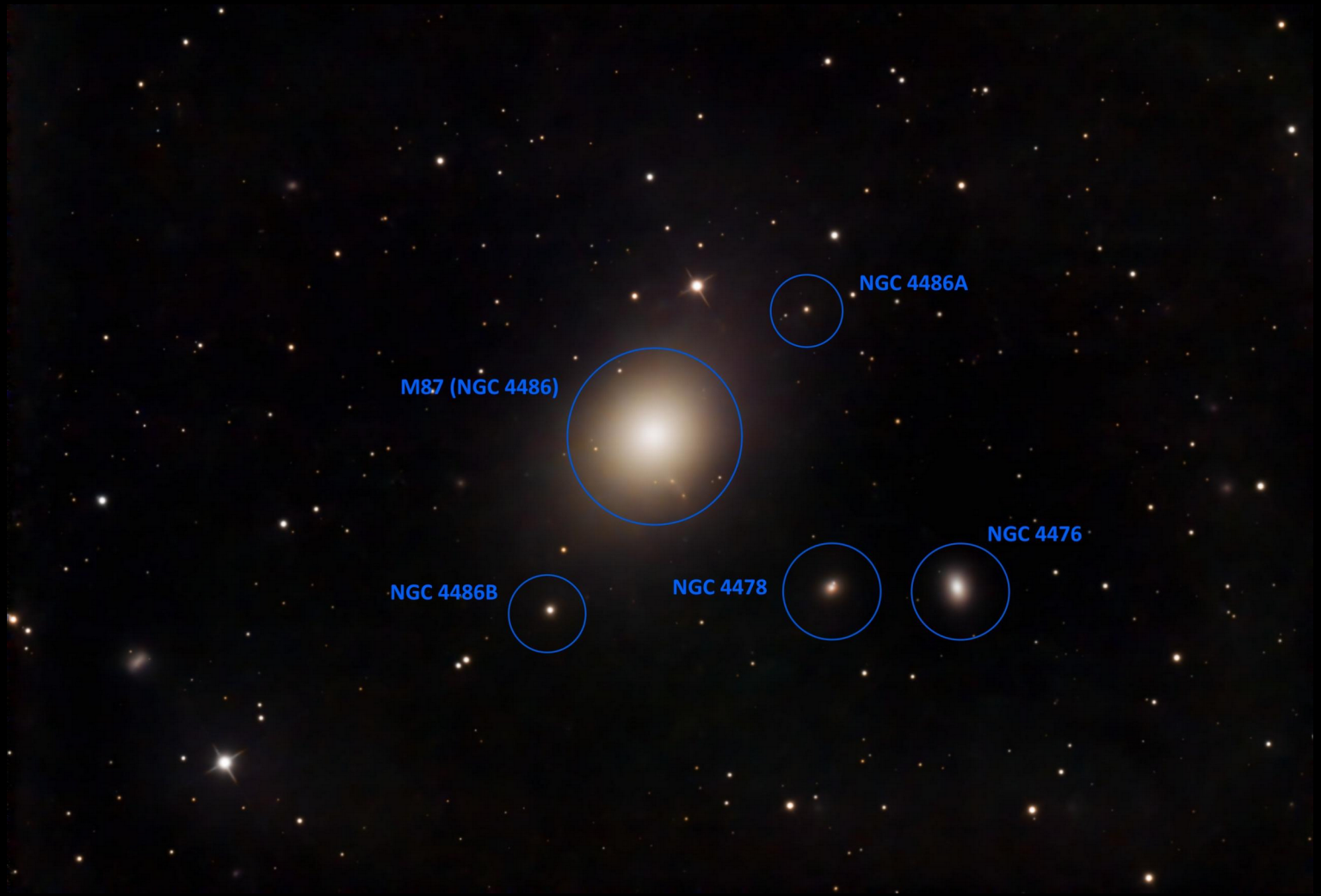






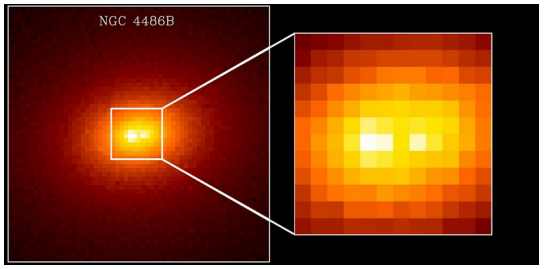
Credits: ESO; EHT Collaboration (2019); NASA/GSFC/J. Schnittman

Double nucleus in NGC 4486B



Double nucleus in NGC 4486B

Lauer et al. 1996

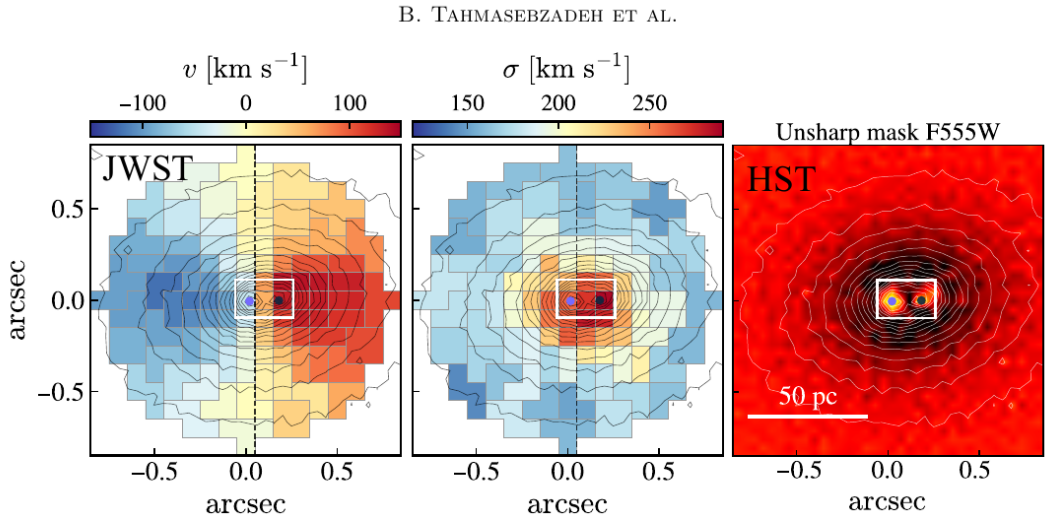


$M_{BH} \simeq 3.6 \times 10^8 M_\odot$, about 8% of the galaxy stellar mass.

Tahmasebzadeh et al. 2025

A JWST View of the Overmassive Black Hole in NGC 4486B

The velocity dispersion map reveals an offset peak, indicating that the true dynamical center (black hole) does not coincide with the brightest nucleus (P1), **supporting the eccentric disk model.**



Tahmasebzadeh et al. 2026

Possible Evidence for a Recent Binary SMBH Merger and Recoil

GW recoil following SMBH coalescence can transform an initially circular stellar disk **into an eccentric, apsidally aligned structure**

Molecular tori in AGNs



The unified scheme of AGNs

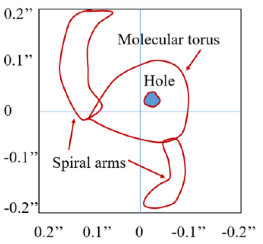
- clumpy torus obscure the central region (Sy2, radio galaxies)
- accretion disk is seen on some angle (Sy1, quasars)

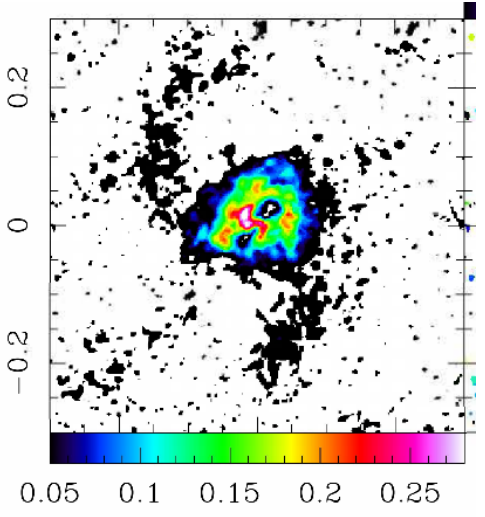
Continuum map at 0.86 mm of the NGC 613

High-resolution mapping of molecular tori with ALMA

"The molecular torus in NGC 613 appears similarly to a ring, depleted in molecular gas near the center. The depletion region is displaced by 3 pc toward the NW from the AGN position, ***meaning some m = 1 asymmetry in the torus****."*

Combes et al. 2026



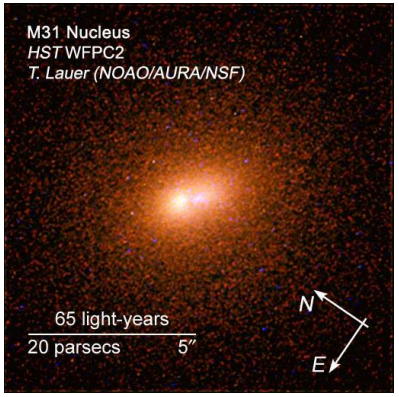


The torus mass: $M_{\rm tor}/M_{\rm BH} \sim 0.3$

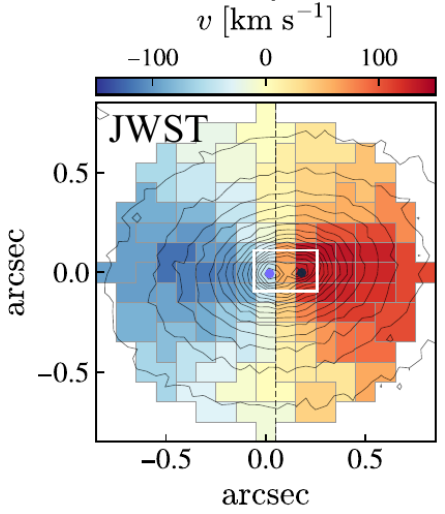
Stellar nuclear disks

AGN molecular tori

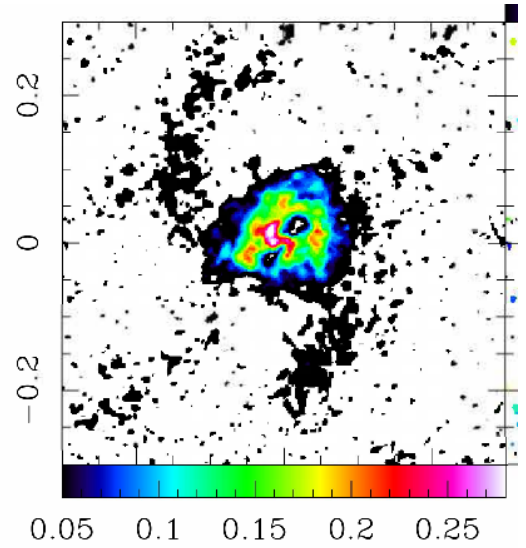
M 31 (HST)



NGC 4486B (HST, JWST)



NGC 613 (ALMA)



The presence of similar asymmetries in different systems may suggest a common origin that is **not tied to external perturbations** (e.g. mergers or secondary SMBH), but arises **from intrinsic dynamical processes**.

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Astronomy & Astrophysics

Global $m = 1$ slow mode in a near-Keplerian self-gravitating torus: Applications to stellar nuclear disks and AGN molecular tori

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N-body simulations: initial conditions and code

Initial distribution: random distribution within the limits

e=[0,..,e_{max}], i=[-i_{max},..,i_{max}], R_0=[0,..,R_{max}]

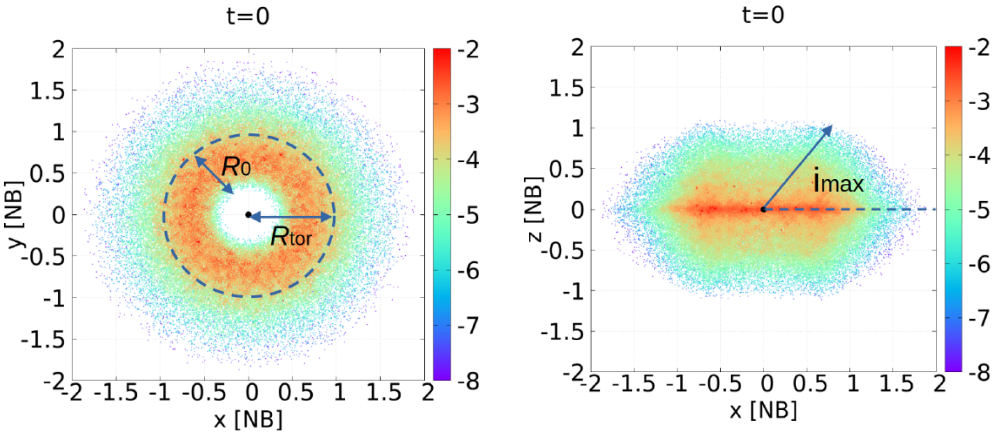
Main runs: "run-e_{max}-i_{max}-R_0"

Table 1. The geometrical parameters of the system.

Run	e_{max}	i_{max}, °	R_0
0.5-60-0.3	0.5	60	0.3
0.5-45-0.3	0.5	45	0.3
0.5-30-0.3	0.5	30	0.3
0.2-60-0.3	0.2	60	0.3
0.8-60-0.3	0.8	60	0.3
0.5-60-0.6	0.5	60	0.6
0.5-60-0.9	0.5	60	0.9

Notes. For all these runs the torus mass $M_{tor} = 0.1$, the particle number $N = 128k$, softening parameter $\epsilon = 10^{-2}$.

We generate the random distribution of particles in Keplerian elements with symmetry relative to the equatorial plane.

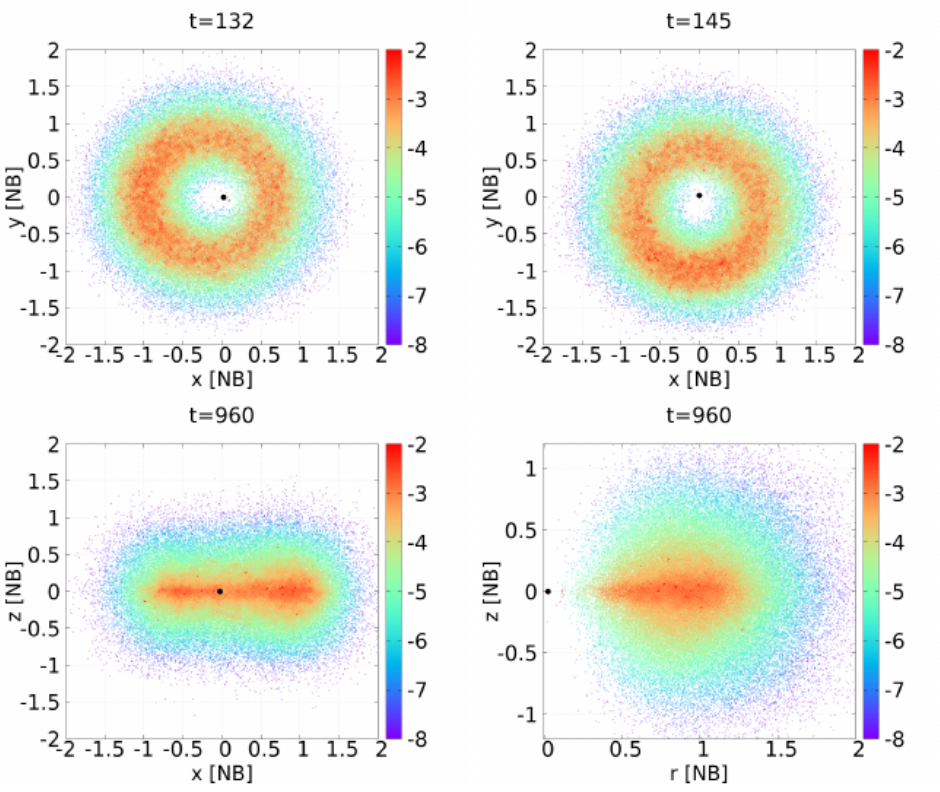


M_{tor} =0.1, 0.06, 0.01

Unit System: M_{bh}=M_c=1, G=1, R_{tor} =1

N-body code: Hermite integration scheme with hierarchical individual block time steps using GPUs φ−GPU code (Berczik et al.)

Formation of the overdensity



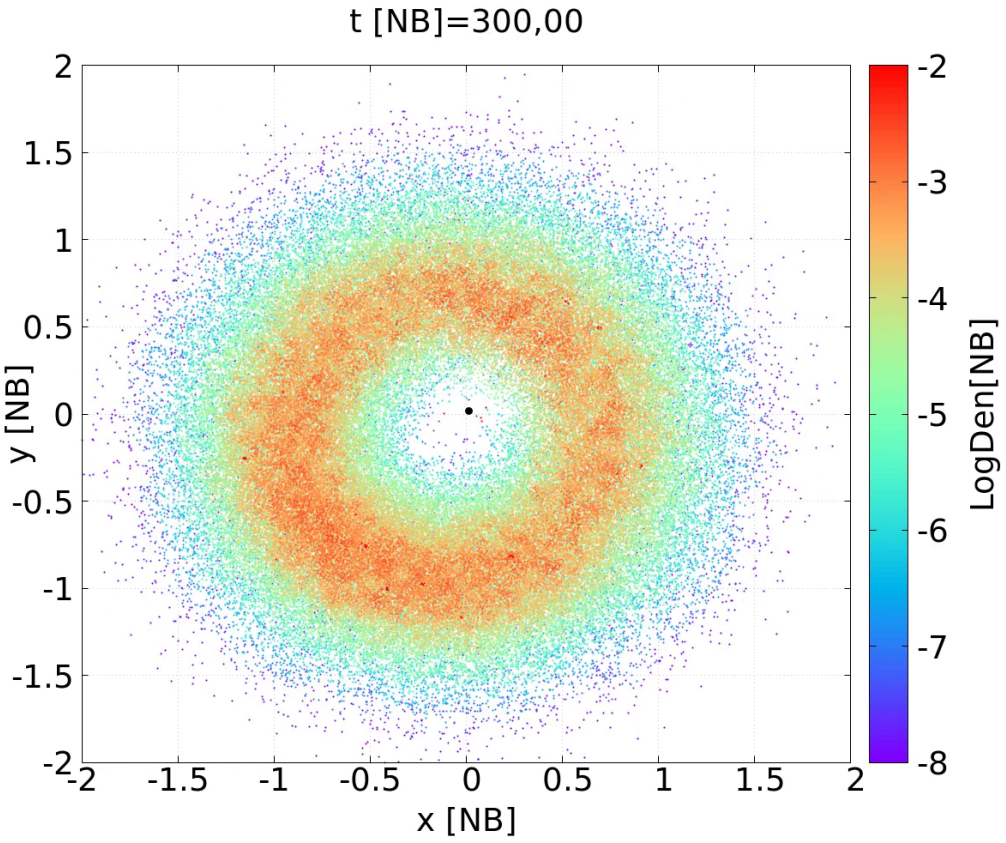
Initial: M_{tor} =0.1

e=[0,..,0.5], i=[-60,..,60], R_0=[0,..,0.3]

The asymmetry in a self-gravitating torus forms naturally without any external perturbation and persists throughout the entire simulation.

This overdensity is a coherent phase pattern that moves in the prograde direction relative to the global orbital motion, with a period much longer than the orbital period of the torus, which is characteristic of **a slow mode.**

Formation of the overdensity



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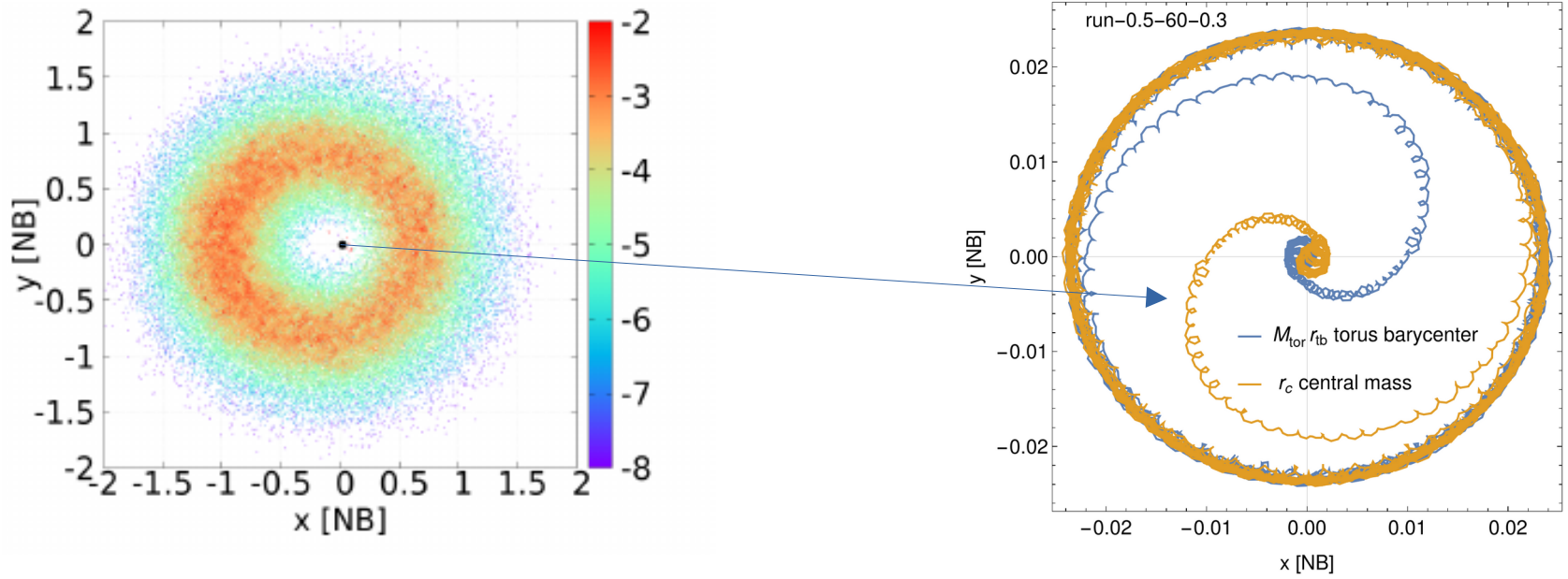
This overdensity is **a coherent phase pattern** that moves in the prograde direction relative to the global orbital motion, with a period much longer than the orbital period of the torus, which is characteristic of **a slow mode**.

Motion of the SMBH and torus barycenter

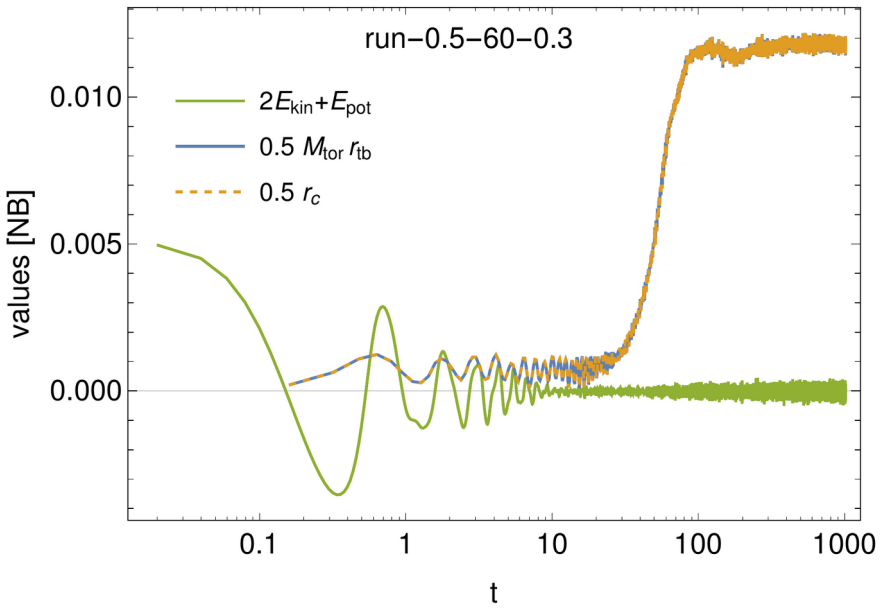
Motion of the central mass (SMBH) and torus barycenter



The SMBH moves away from the center and settles into an orbit of nearly constant radius, exhibiting additional loop-like motions.

Spontaneous formation of the asymmetry

Virial value vs SMBH and barycenter motions



A stable overdensity (lopsided m=1 mode) forms once the torus reaches its equilibrium state.

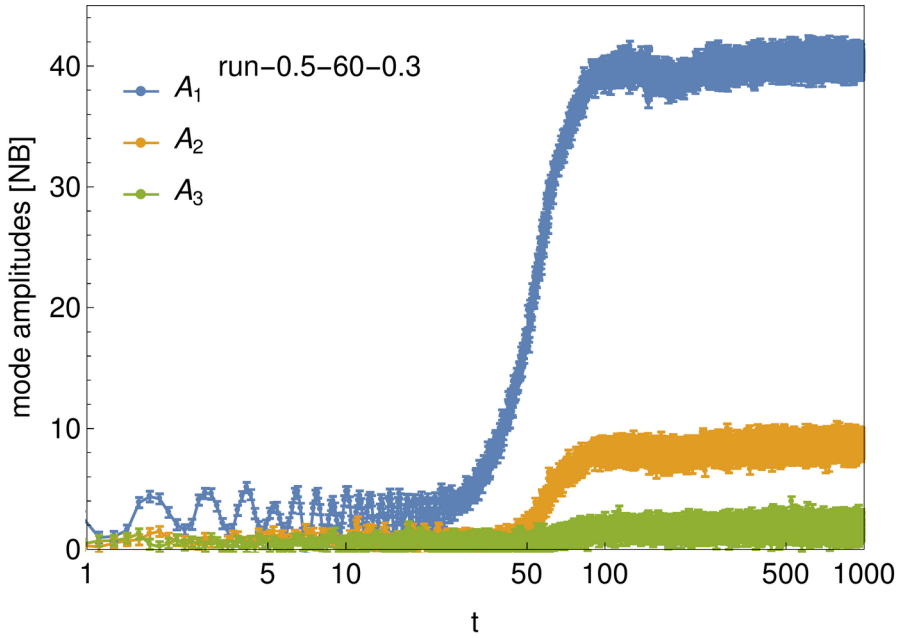
Evolution of the mode amplitude: role of m=1 mode

Fourier decomposition of the density:

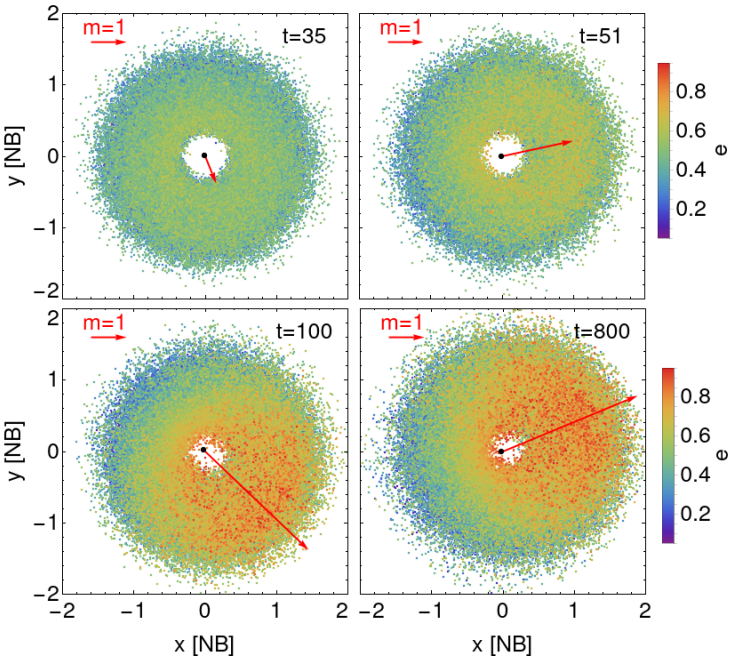
$$\Sigma(\psi;t)=\Sigma_0(t)+\sum_m [a_m(t)\cos(m\,\psi)+b_m(t)\sin(m\,\psi)]$$

Amplitude: $A_m=\sqrt{a_m{}^2+b_m{}^2}$

Phase: $\Phi_m=\arctan(b_m/a_m)$

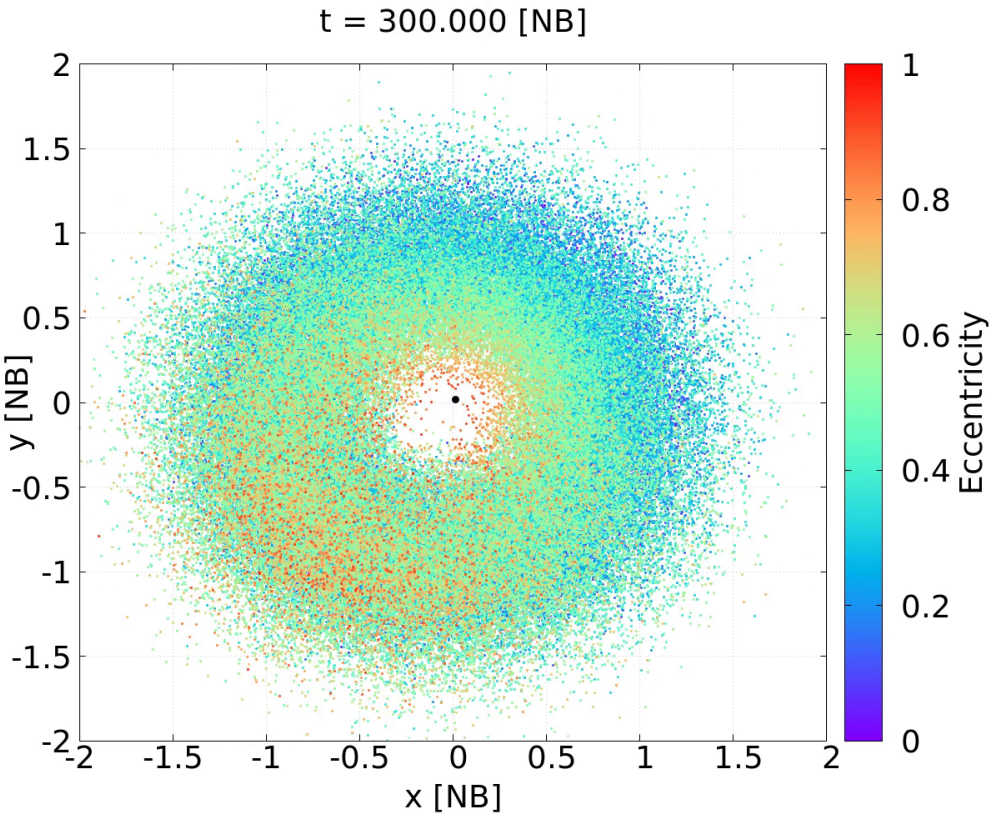


The eccentricity distribution and m=1 mode



A lopsided structure develops, with particles reaching higher eccentricities, forming a global overdensity aligned with the phase of the m = 1 mode

Appearance of eccentric orbits (e>0.5)

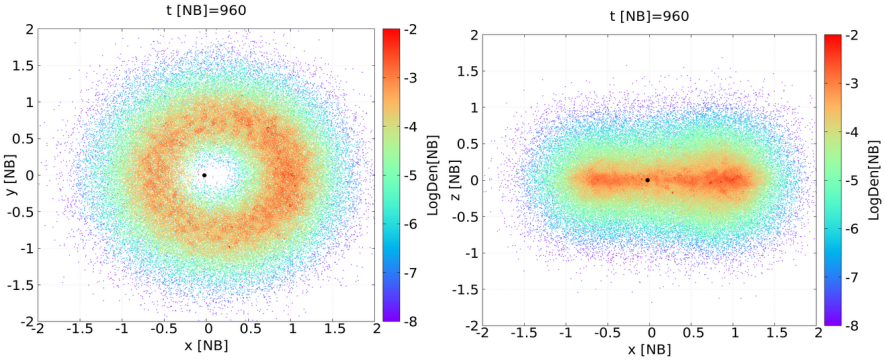


run-0.5-60-0.3

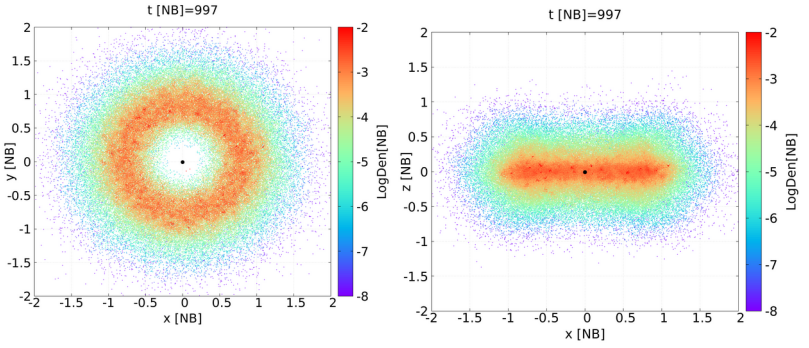
- The **spontaneous** development of the lopsided m=1 mode coincides with the appearance of particles with **higher eccentricities**.
- Their **semi-major axes become aligned**, forming a transient overdensity (a density-wave pattern).
- Different particles contribute to the overdensity at different times – this is **a phase pattern**.

Effect of initial thickness

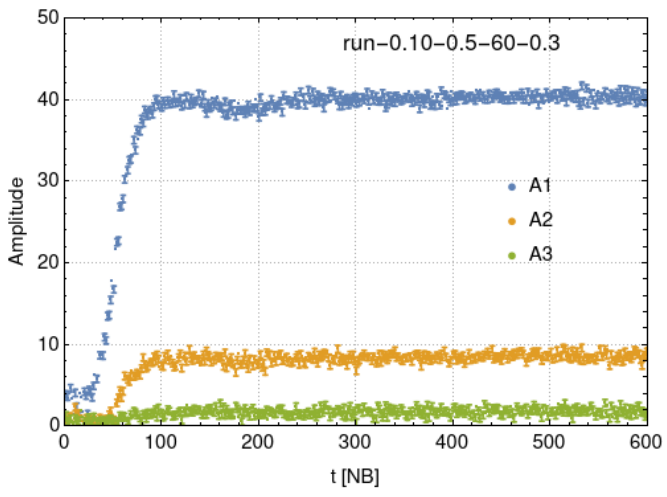
Initial maximum i**nclination =60 deg**

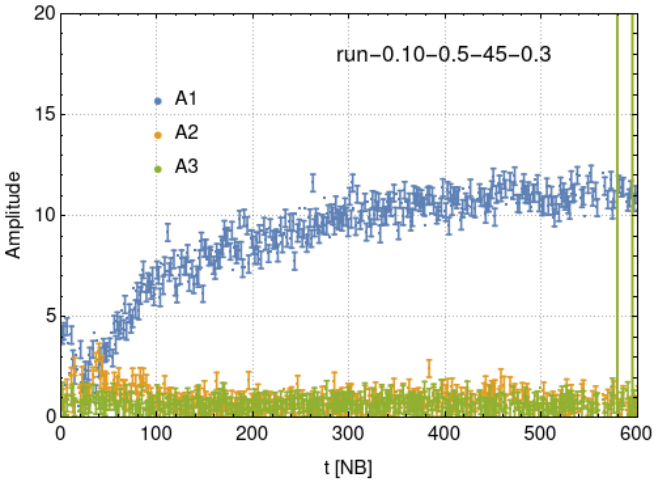


Initial maximum i**nclination =45 deg**



The thicker torus is more asymmetrical



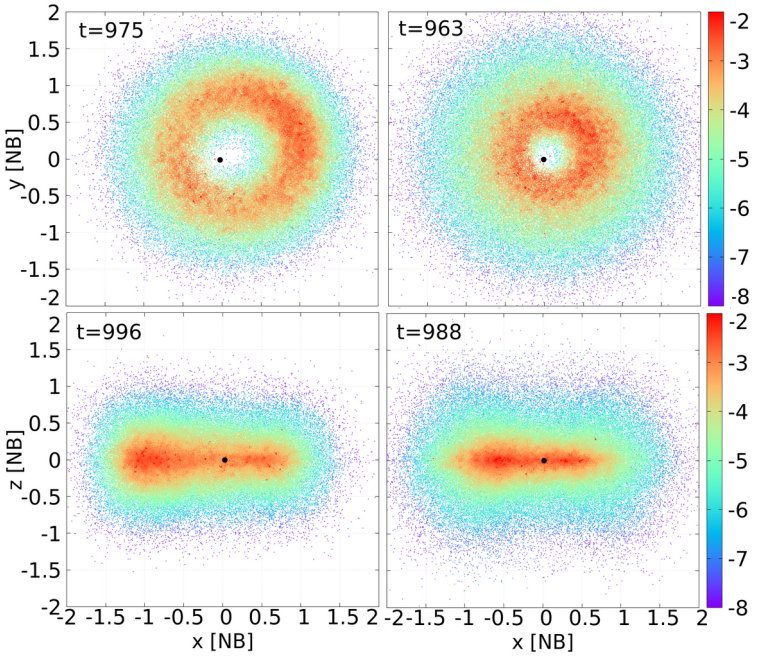


Dependence on the initial eccentricities and semi-major axes

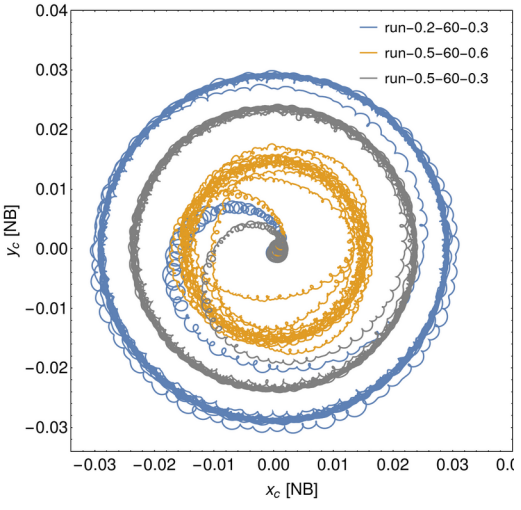
In initial condition: M_{tor} =0.1 i=[-60,..,60]

"run-e_{max}-i_{max}-R_0"

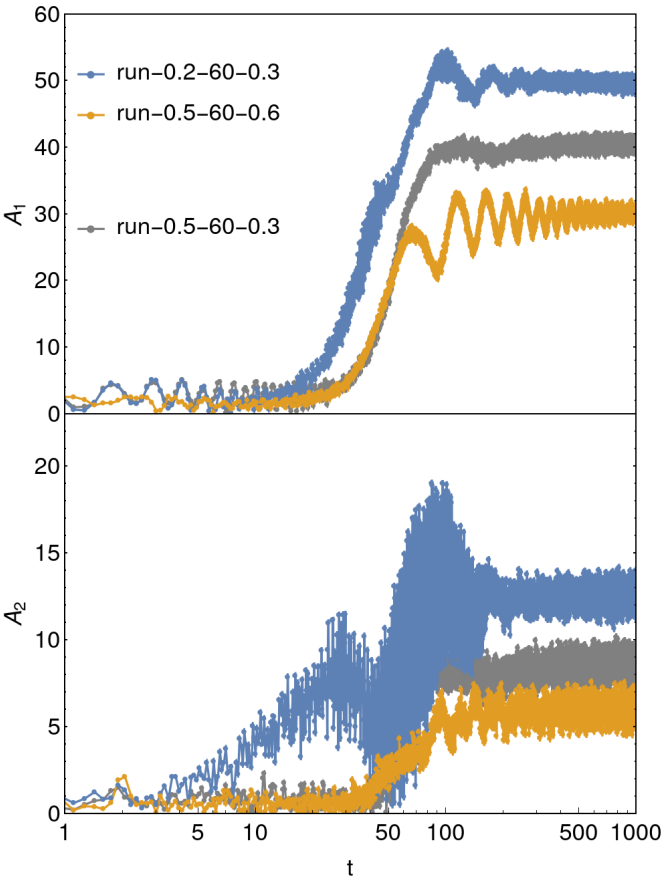
e_{max}=0.2 R_0=0.6



The orbit of the central mass

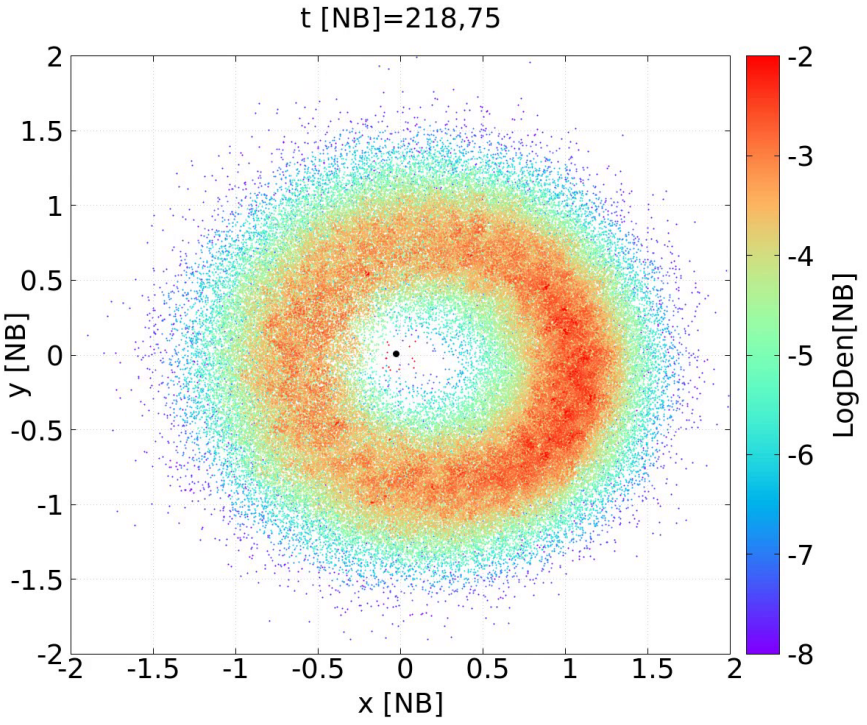


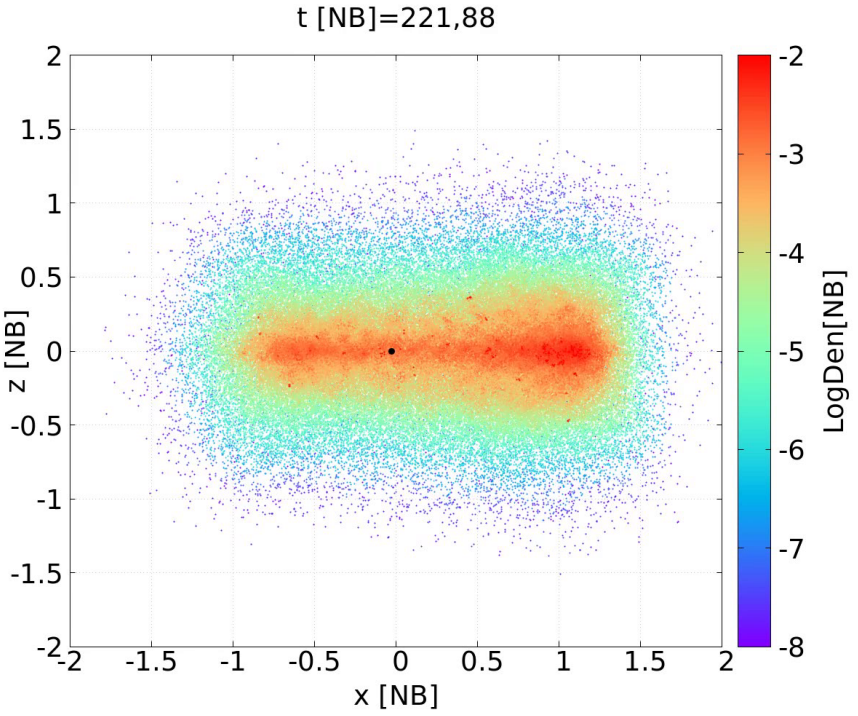
Amplitude of modes



Dependence on the initial eccentricities

More circular orbits in initial state (e_{max}=0.2); M_{tor} =0.1





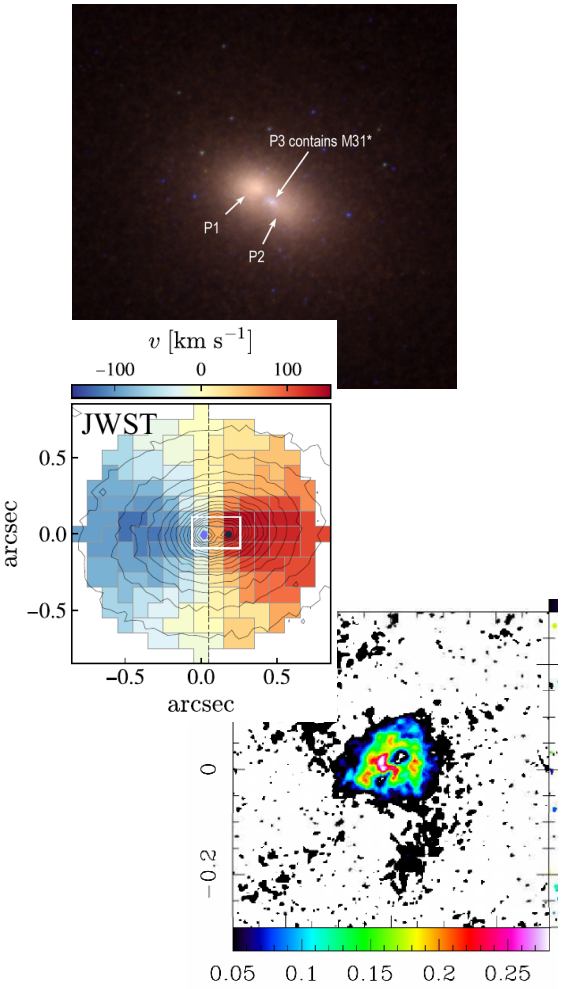
What is the possible explanation for the origin of the double nucleus in the Andromeda galaxy?

<u>Conditions required for the formation of an Andromeda-like asymmetric disk:</u>

- *A sufficiently massive stellar torus*
- *A geometrically thick configuration (an old stellar system)*

Gravity then drives the subsequent evolution, leading to an asymmetric torus.

A thick self-gravitating torus is intrinsically non-axisymmetric.

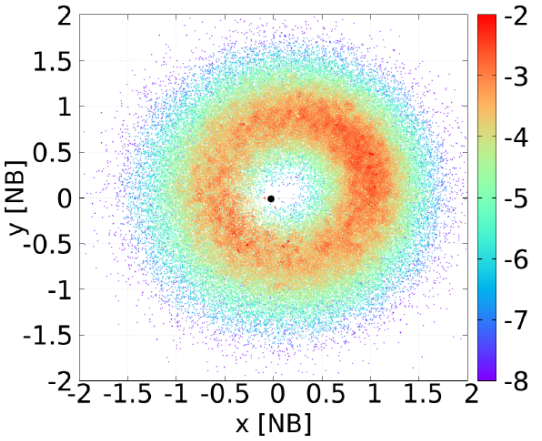


Possible observational test of SMBH displacement

- The global m=1 mode displaces the SMBH from the barycentre of the nuclear system.
  - For M31, the expected offset is of order $\Delta\theta_{BH} \sim 6$ mas.
  - For NGC 4486B $\Delta\theta_{BH} \sim 2$ mas
  - The displacement should be directed approximately opposite to the stellar overdensity.

- It can be tested with high-precision radio astrometry of M31* with future high-sensitivity radio interferometric observations.

$$\Delta r_{BH} \sim 2\times10^{3} r_s \sim 0.02 \text{ pc}$$



A detected SMBH offset — and especially its direction relative to the m=1 overdensity — could help distinguish an intrinsic self-gravitating mode from an externally induced asymmetry.

Next steps for M31

— to increase the number of stars (1 million)
— the rotation curve
— moments 0, 1, 2

— recoil kick of SMBH vs spontaneous m=1 mode

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