Recent advances in investigation of active galactic nuclei

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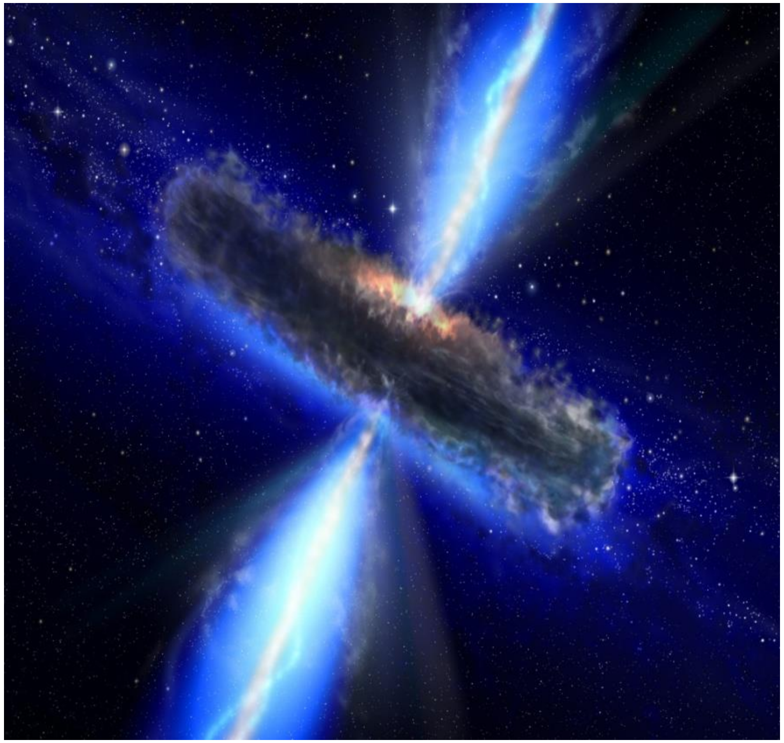
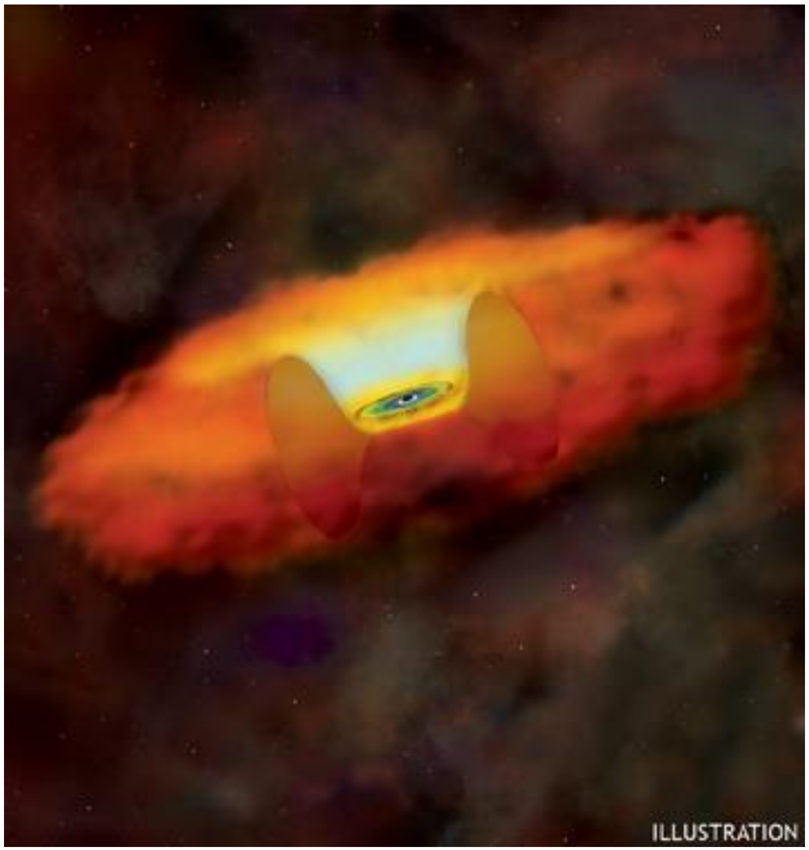
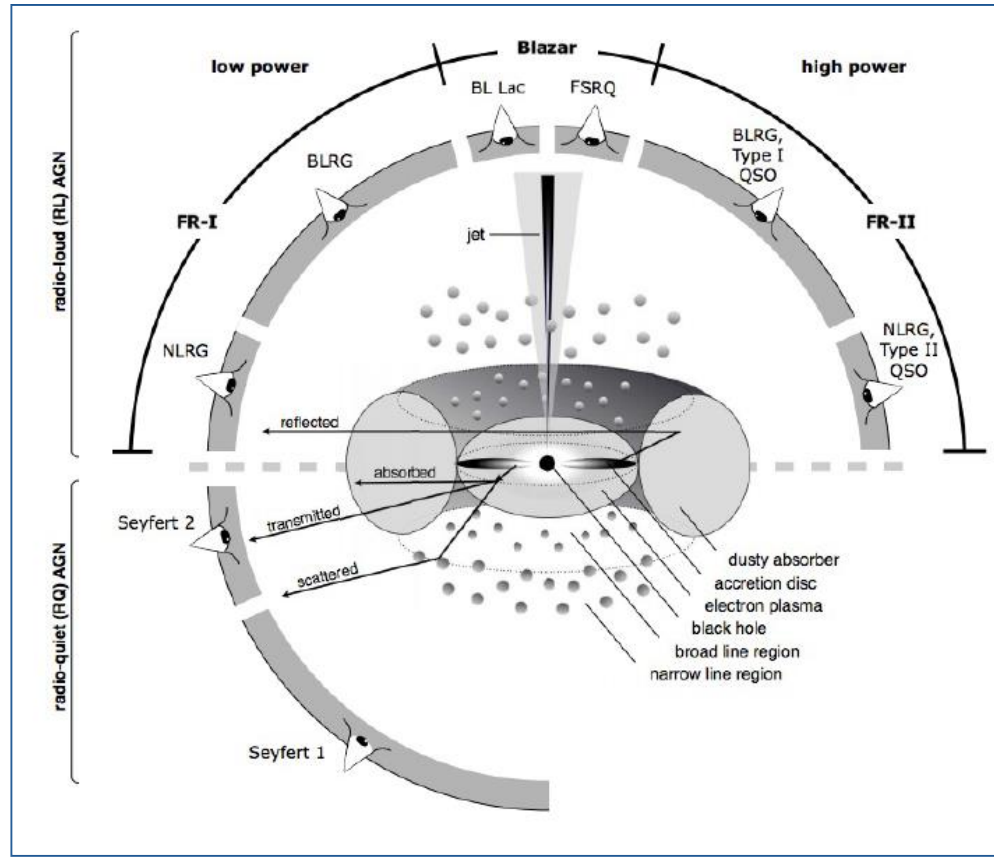


Unified Scheme of AGNs

The differences between AGNs (1,2 types) are explained by the different orientation of the torus relative to an observer



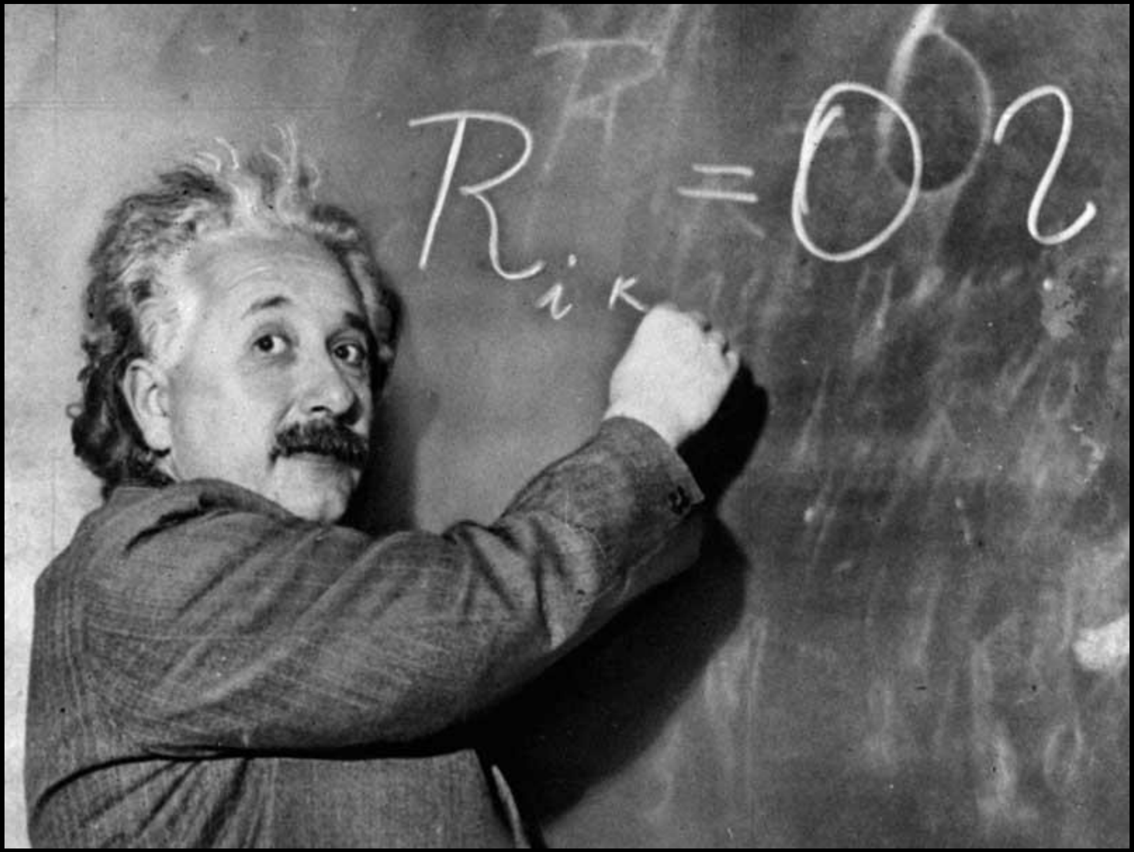


AGN investigation by different telescopes

The World's Main VLBI Stations

Black holes are defect of theory or these objects exist in Nature?

100 years of discussions



The Astrophysical Journal Letters, 853:L25 (7pp), 2018 February 1 https://doi.org/10.3847/2041-8213/aaa8df

CrossMark

ALMA Reveals an Inhomogeneous Compact Rotating Dense Molecular Torus at the NGC 1068 Nucleus

Masatoshi Imanishi (今西昌俊)[1,2], Kouichiro Nakanishi (中西康一郎)[1,2], Takuma Izumi (泉拓磨)[1], and Keiichi Wada (和田桂一)[3]

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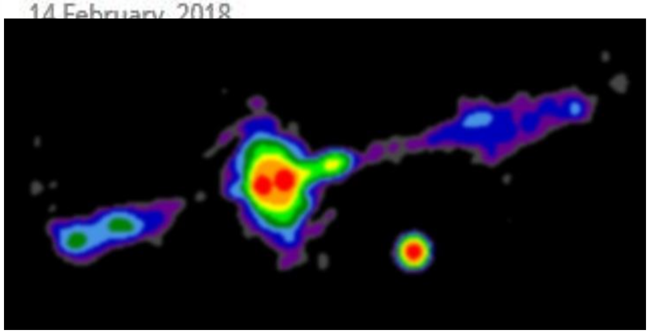
February 13, 2019

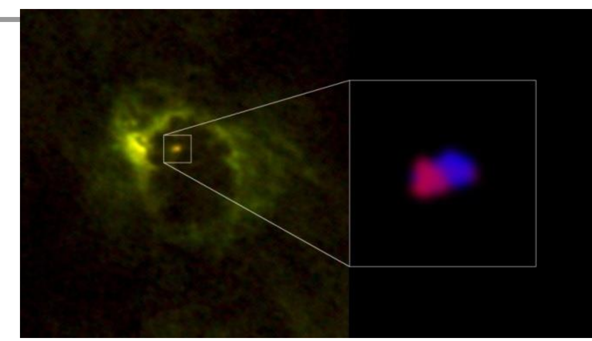
ALMA observations of molecular tori around massive black holes ⋆

F. Combes[1,2], S. García-Burillo[3], A. Audibert[1], L. Hunt[4], A. Eckart[5], S. Aalto[6], V. Casasola[4,7], F. Boone[8], M. Krips[9], S. Viti[10], K. Sakamoto[11], S. Muller[6], K. Dasyra[12], P. van der Werf[13], and S. Martin[14,15]

ALMA Observes a Rotating Dust and Gas Donut around a Supermassive Black Hole

14 February, 2018





The Astrophysical Journal Letters, 884:L28 (6pp), 2019 October 20 https://doi.org/10.3847/2041-8213/ab3c64

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Counter-rotation and High-velocity Outflow in the Parsec-scale Molecular Torus of NGC 1068

C. M. Violette Impellizzeri[1,2], Jack F. Gallimore[3], Stefi A. Baum[4], Moshe Elitzur[5], Richard Davies[6], Dieter Lutz[6], Roberto Maiolino[7], Alessandro Marconi[8,9], Robert Nikutta[10], Christopher P. O'Dea[4], and Eleonora Sani[11]
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What we know from observations

- ❑ Geometrically thick shape of the torus (VLT, ALMA, statistic in IR)

- ❑ The mass of the torus is about $10^5 M_{sun}$ which is 1%-10% of the mass of super massive black hole (rotation curves - VLA, VLBI, emission in molecules - ALMA)

- ❑ Clumpy structure with Gaussian distribution of clouds

- ❑ The presence of orbital motion

- ❑ Dispersion of velocity in the torus

- ❑ Non-keplerian motion

- ❑ External accretion

- ❑ Counter-rotation in the torus of NGC 1068

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Dynamical model of an obscuring clumpy torus in AGNs – I. Velocity and velocity dispersion maps for interpretation of ALMA observations

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N-body simulation of the clumpy torus with SMBH

Initial condition

N=10^5 clouds

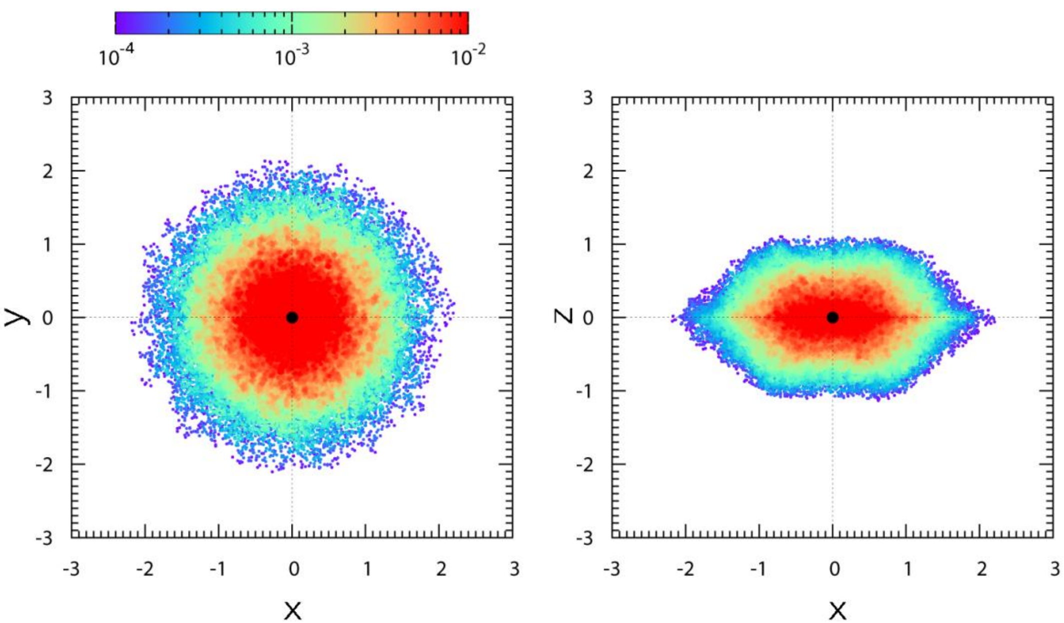
with random distribution in orbital elements + biconic regions

High-order Hermite integration with GPU

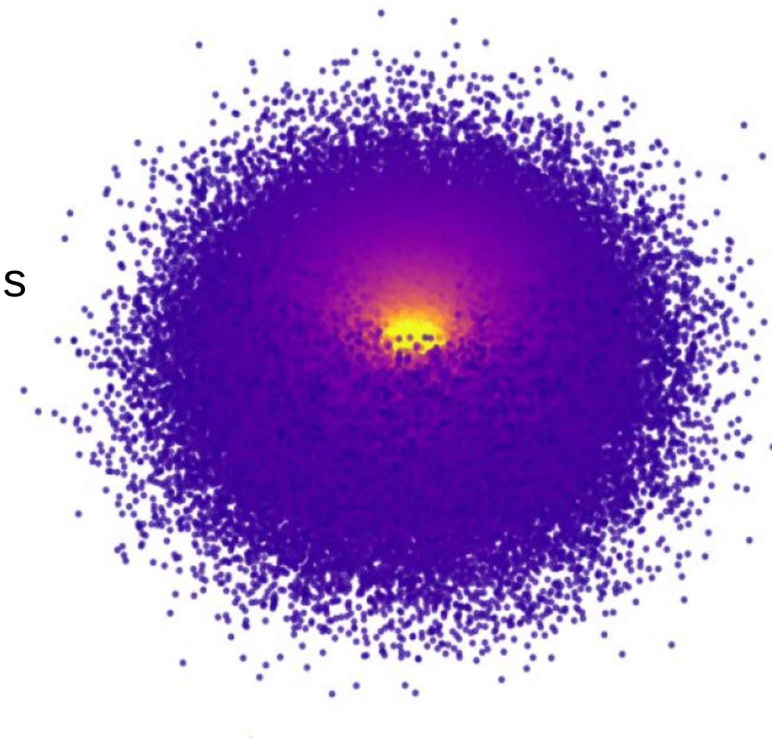
$$\mathbf{a}_k = -\frac{G M_{\rm smbh}}{R^2}\frac{\mathbf{r}_k}{r_k^3} + \frac{\mathbf{F}_k}{m_k}.$$

$$\mathbf{F}_k = -\frac{G m_k}{R^2}\sum_{j=1}^{N} m_j \frac{\mathbf{r}_k - \mathbf{r}_j}{\left(|\mathbf{r}_k - \mathbf{r}_j|^2 + \varepsilon^2\right)^{3/2}}$$

3D distribution in the equilibrium state



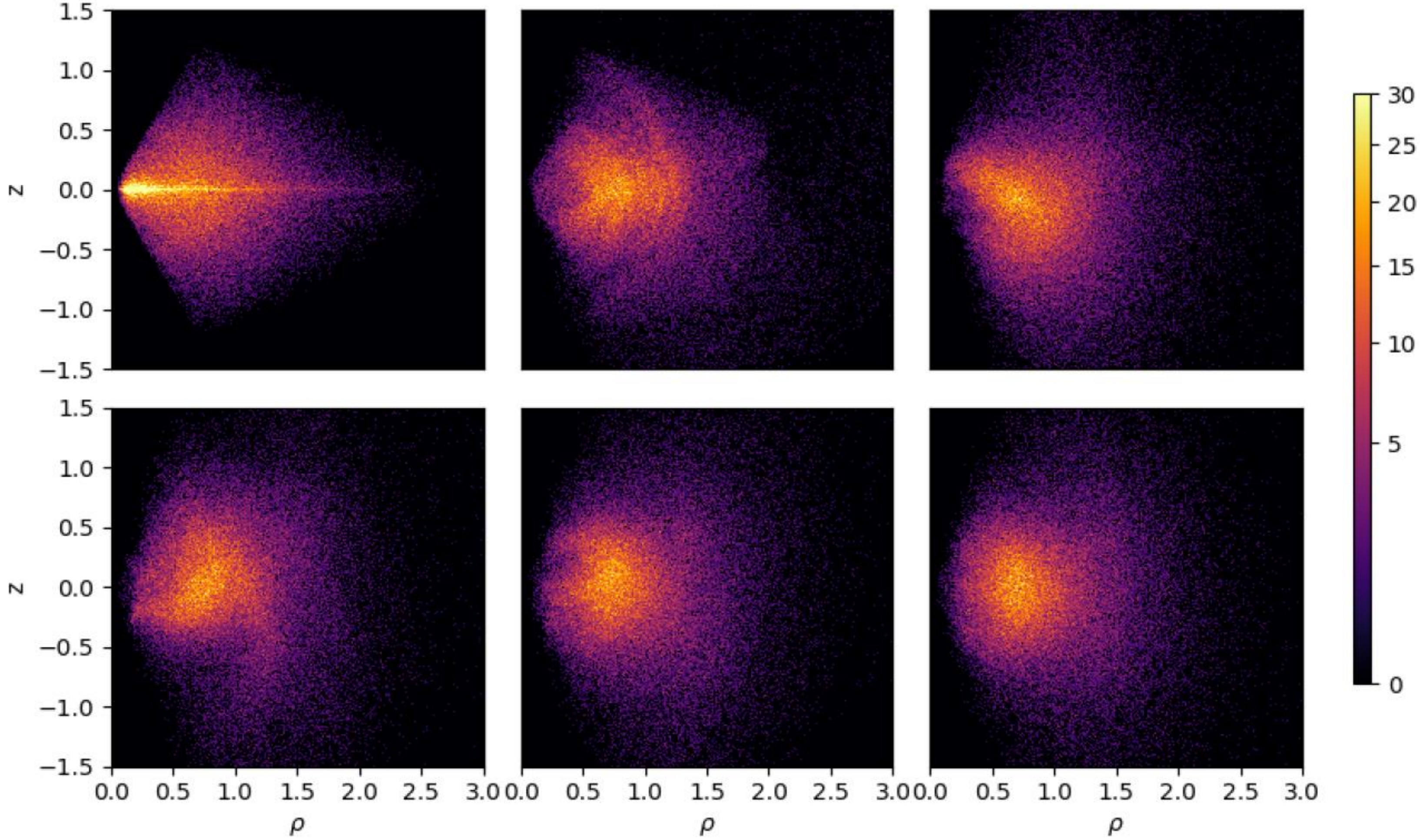
1 000 periods



Density distribution in the torus cross-section

$t = 0, 2, 48, 115, 320$, and 1000 periods

$M_{torus}=0.02\ M_{smbh}$

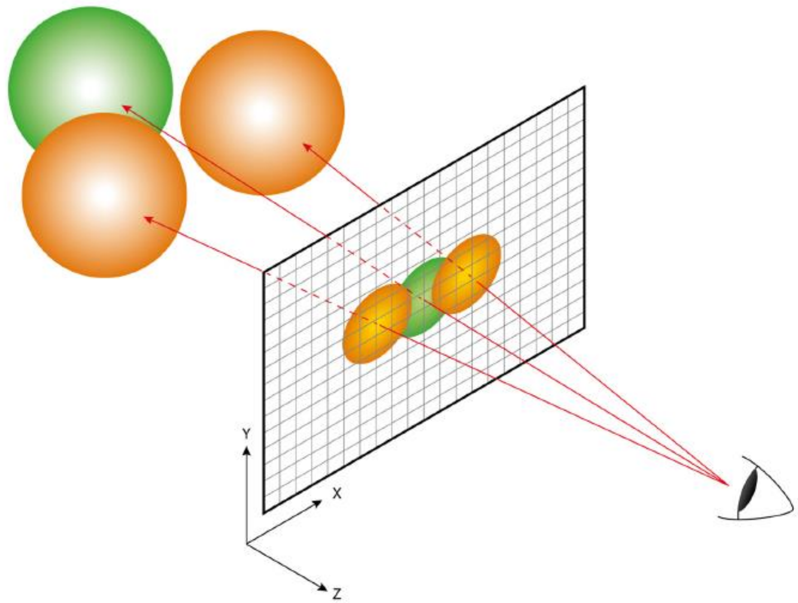


[3] The animated results of simulations are presented on web page: http://www.astron.kharkov.ua/models/AGN/torus2020.html

The velocity and dispersion maps: simulations

Scheme of algorithm

- Results of N-body simulations
- Ray tracing procedure
- Dividing on cells - mimic ALMA resolution



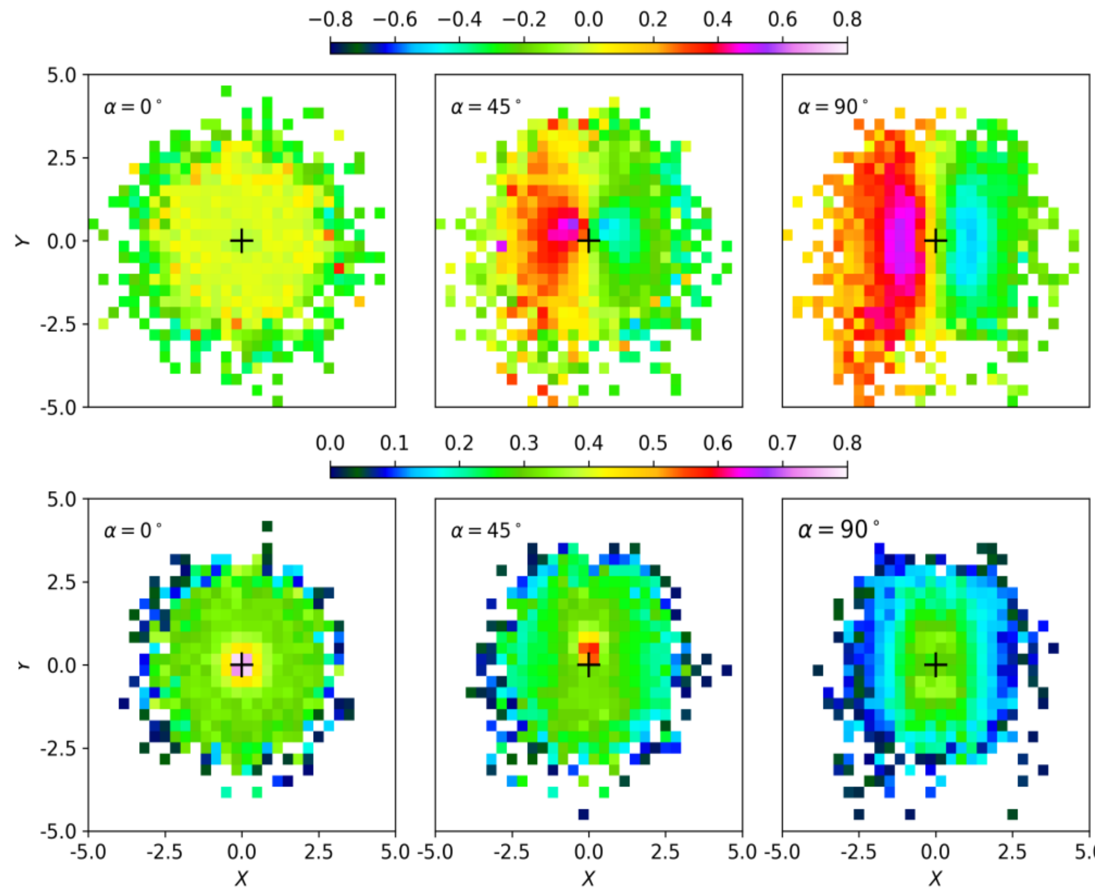
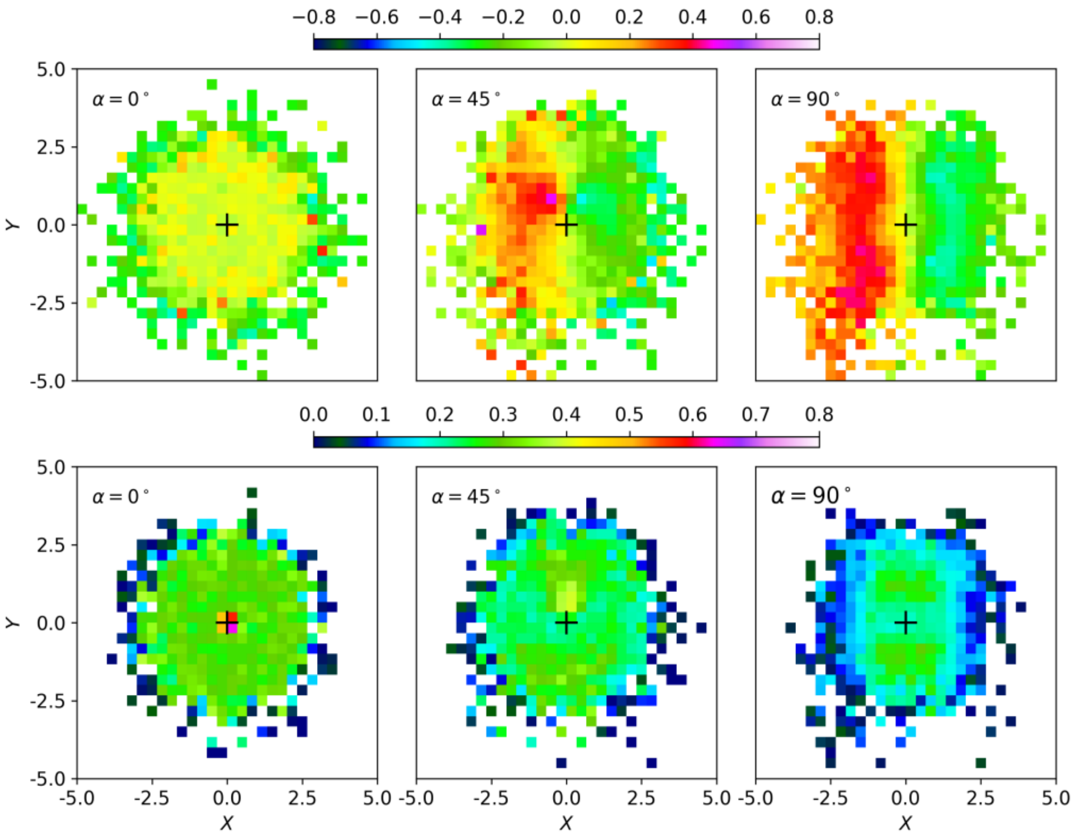


Figure 11. Line-of-sight velocity (*top*) and dispersion maps (*bottom*) of a clumpy torus for N=128k clouds on t = 1000 periods with different inclination angles $\alpha = 0°$ (*left*), $\alpha = 45°$ (*middle*), $\alpha = 90°$ (*right*) for a single relative cloud radius $\varepsilon_{\rm cl} = 0.01$ and an initial half-opening angle of the wind $\theta = 30°$.

The velocity and dispersion maps: simulations

Interpretation of ALMA observations for Sy galaxies



SMBH mass in NGC 1068

Table 1. Visible velocity (in km s^{-1}) on the distance 3 pc for the SMBH mass $M_{\rm smbh} = 5 \times 10^6 M_\odot$.

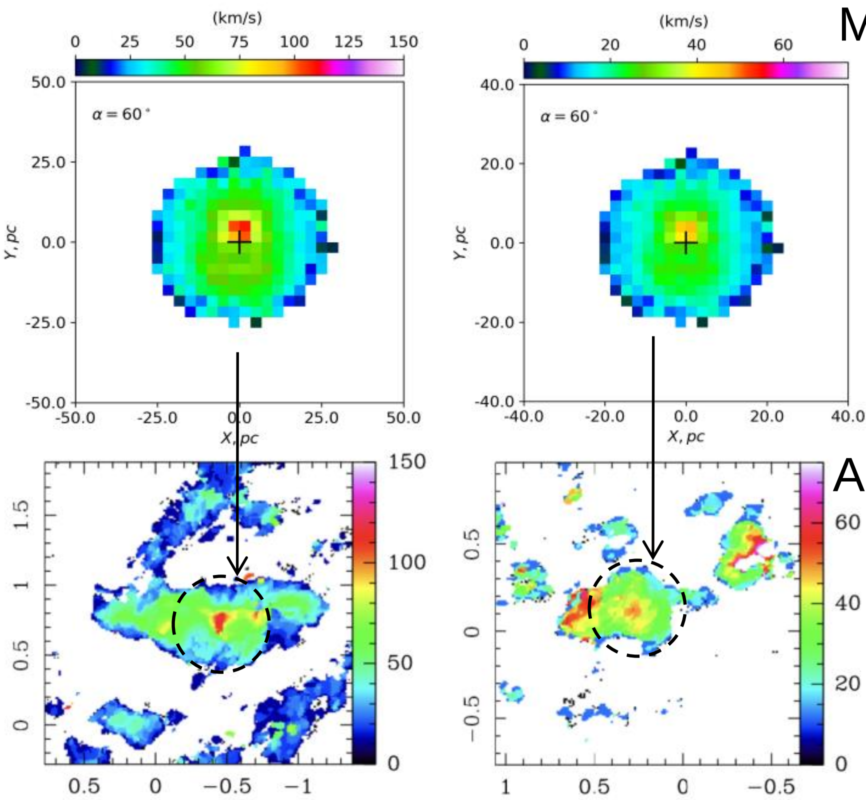
		$\varepsilon_{\rm cl} = 0.01$	$\varepsilon_{\rm cl} = 0.025$
	$\alpha = 30^\circ$	24	17
$\theta = 30^\circ$	$\alpha = 45^\circ$	31	20
	$\alpha = 60^\circ$	35	21
	$\alpha = 30^\circ$	26	20
$\theta = 45^\circ$	$\alpha = 45^\circ$	33	23
	$\alpha = 60^\circ$	36	23

Single cloud radius ε_{cl}=0.025

The model dispersion maps of NGC 1326 and NGC 1672

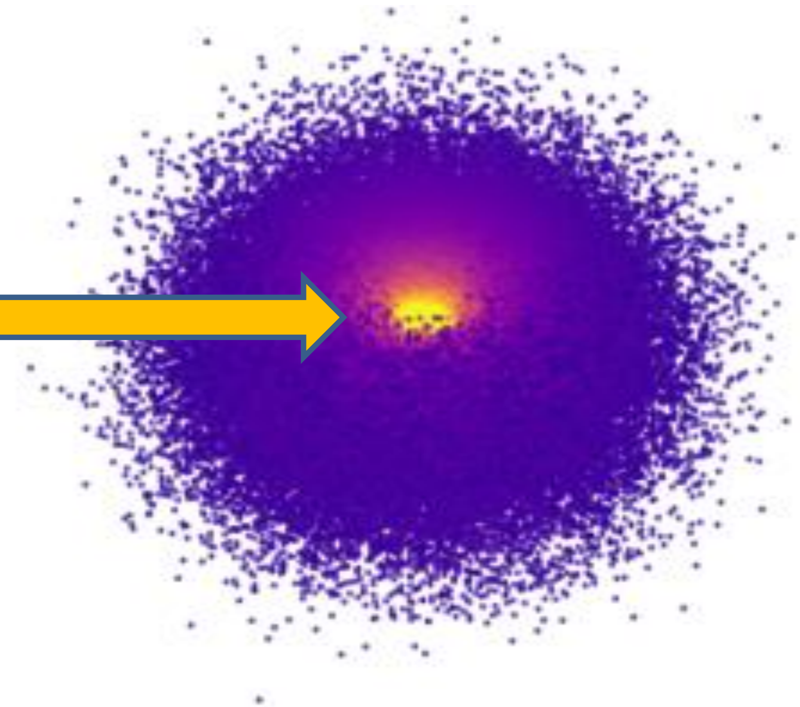
NGC 1326 **NGC 1672**

Model



ALMA

Figure 15. Our model velocity dispersion maps (*top*) and ALMA observational maps (*bottom*) of NGC 1672 (*left*) and NGC 1326 (*right*) in CO(3-2) line from (Combes et al. 2019) with velocity dispersion scales in km s^{-1}, angular offsets in arcsec with respect to the phase centre.



Parameters of SMBHs

NGC 1326

$M_{\rm smbh} = 1 \times 10^8\, M_\odot$

$\alpha = 45^\circ$ with $\varepsilon_{\rm cl} = 0.025$

NGC 1672

$M_{\rm smbh} = 1.5 \times 10^7\, M_\odot$

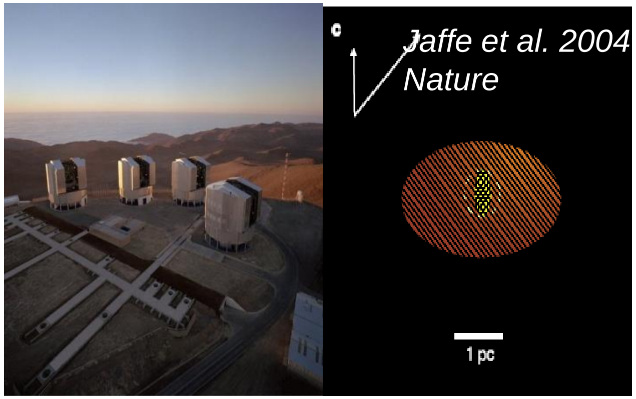
$\alpha = 45^\circ$ with $\varepsilon_{\rm cl} = 0.025$

Our dispersion maps demonstrate peculiarities in the tori that are related to the torus throat

Temperature of clouds in the torus: semi-analytical approach

Idea: to find parameters of NGC 1068 (mm, ***ALMA***) which are in good agreement with the temperature distribution (IR, ***VLTI/MIDI***).

IR observation of torus in NGC 1068



Scheme of algorithm

- Results of N-body simulations
- Ray tracing procedure - from accretion disk
- Analytical solution for the cloud temperature heating by accretion disk
- To take into account an anisotropic emission of accretion disk
- Ray tracing procedure - from an observer

The temperature of the cloud: $$T_{\rm cl} \approx 770{\rm K}\, \dot{M}^{1/4} \left(\frac{r}{1{\rm pc}}\right)^{-1/2}.$$

Anisotropy: $$T_{\rm cl} \propto r^{-1/2} F(\theta)^{1/4}$$

where $$F(\theta) = \frac{1}{3}\cos\theta(1 + 2\cos\theta)$$

Temperature of clouds in the torus

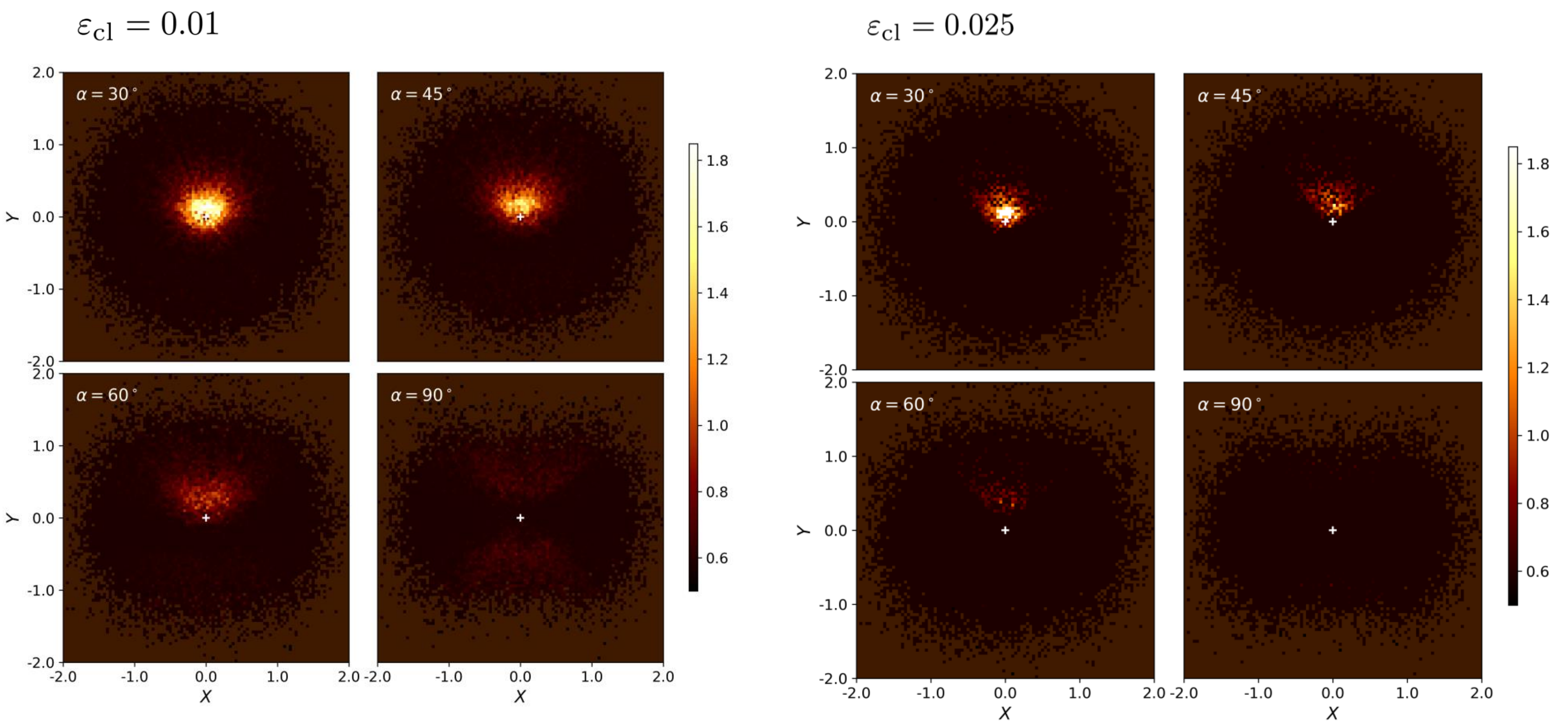
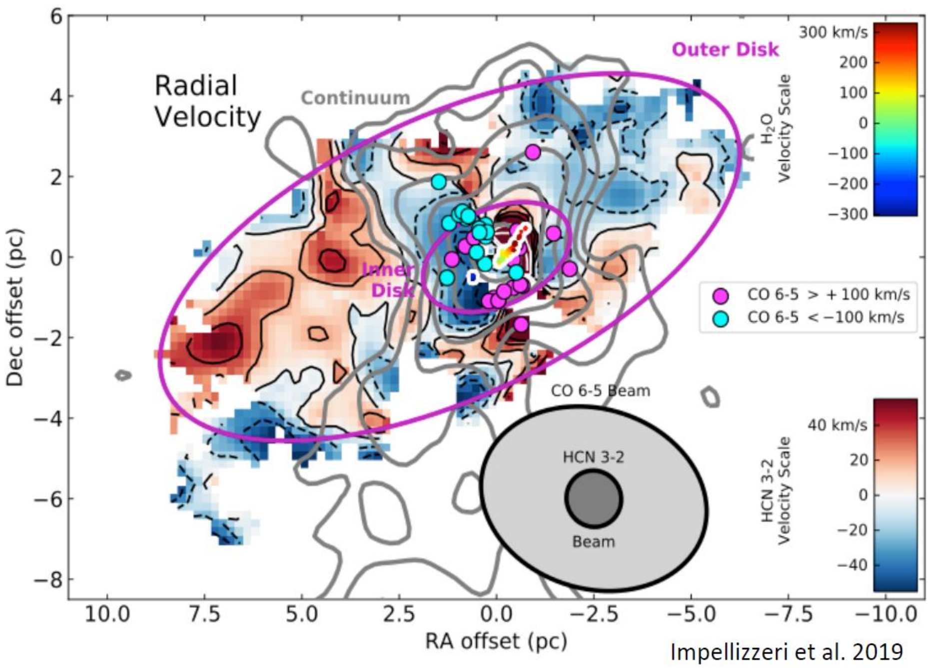
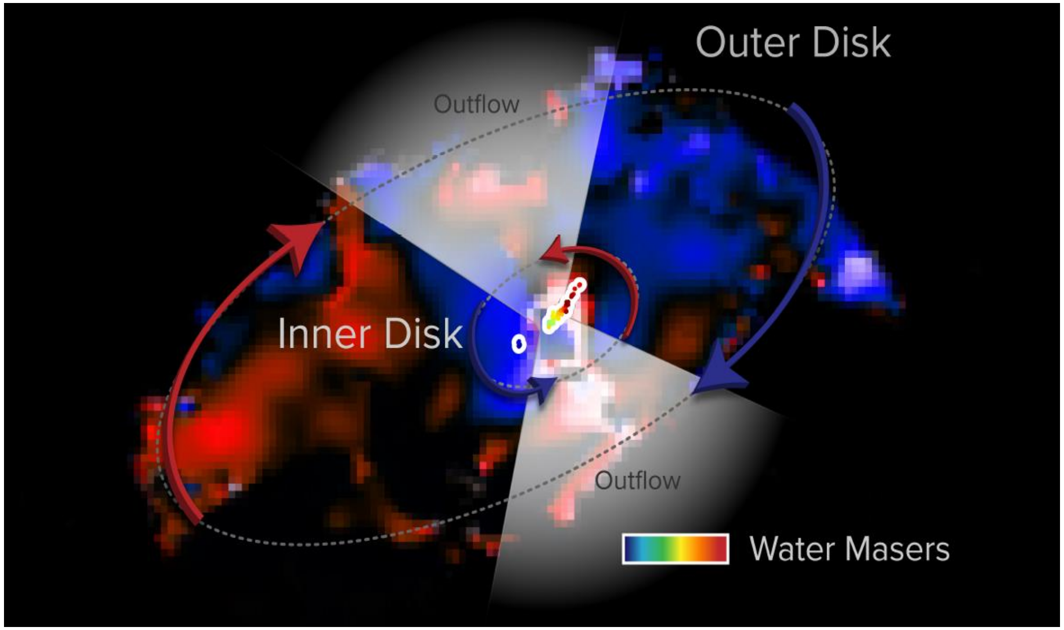


Figure 18. Temperature distribution maps of N=128k clouds, on $t = 1000$ period with different inclination angles α: 30° (*top left*), 45° (*top right*), 60° (*bottom left*), 90° (*bottom right*) for a single cloud radius $\varepsilon_{\rm cl} = 0.01$ and the initial half-opening angle of the wind $\theta = 45°$.

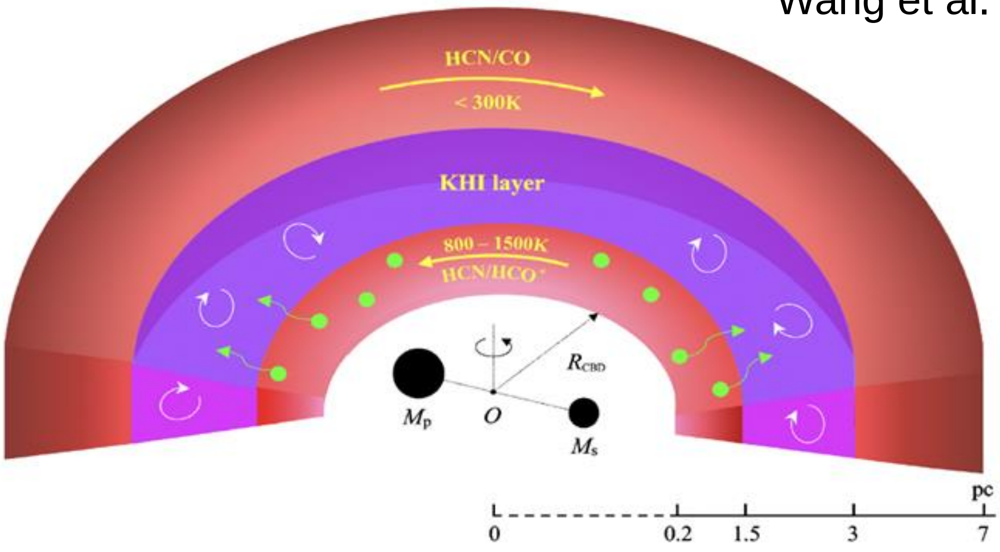
Counter-Rotation in the Parsec-Scale Molecular Torus of NGC 1068



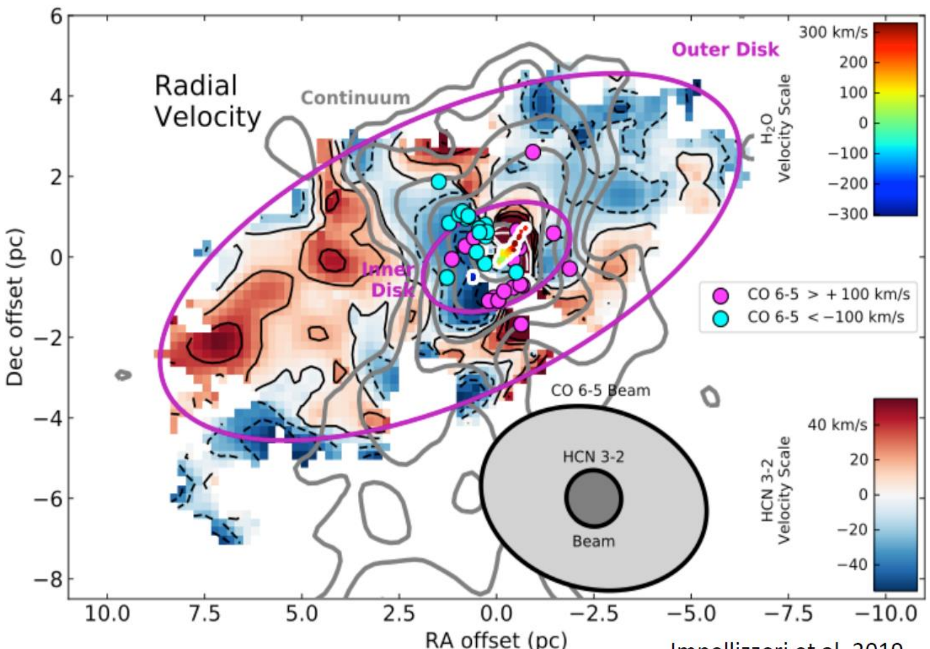


A close binary of super massive black holes ?

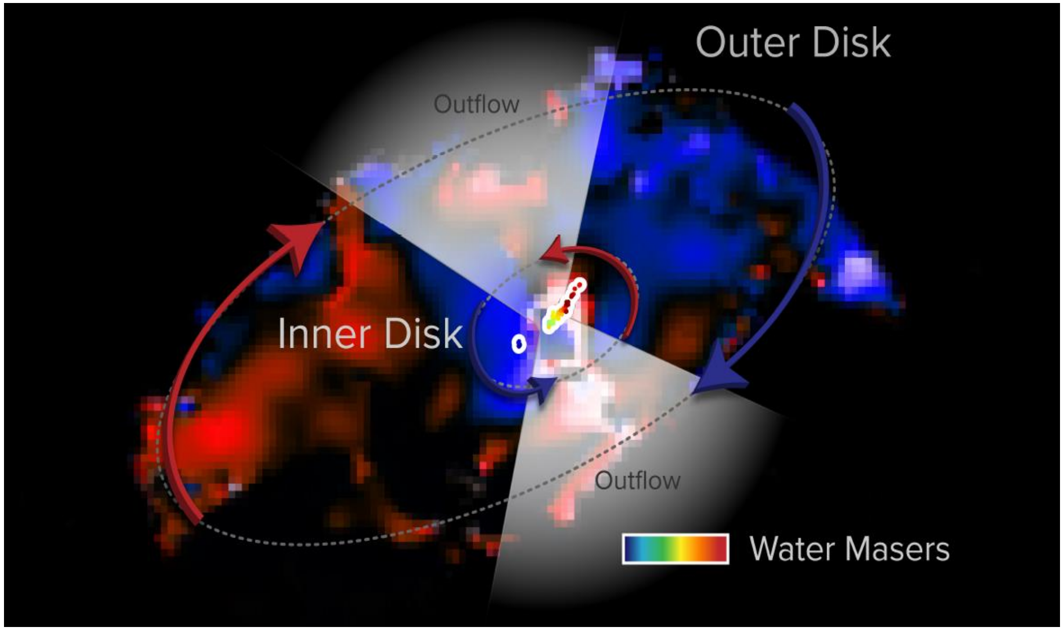
Wang et al. 2020

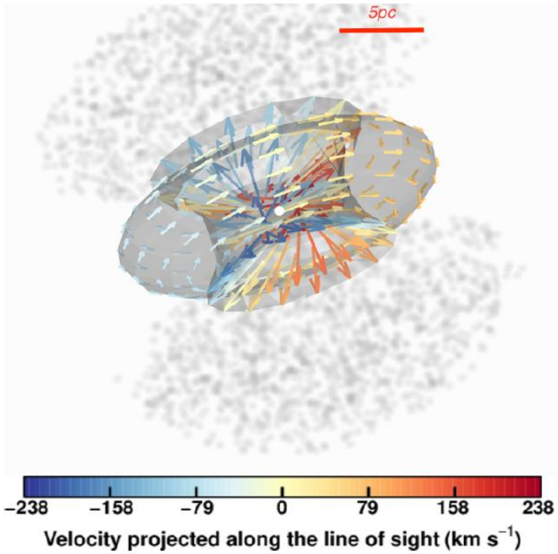


Counter-Rotation in the Parsec-Scale Molecular Torus of NGC 1068



Impellizzeri et al. 2019





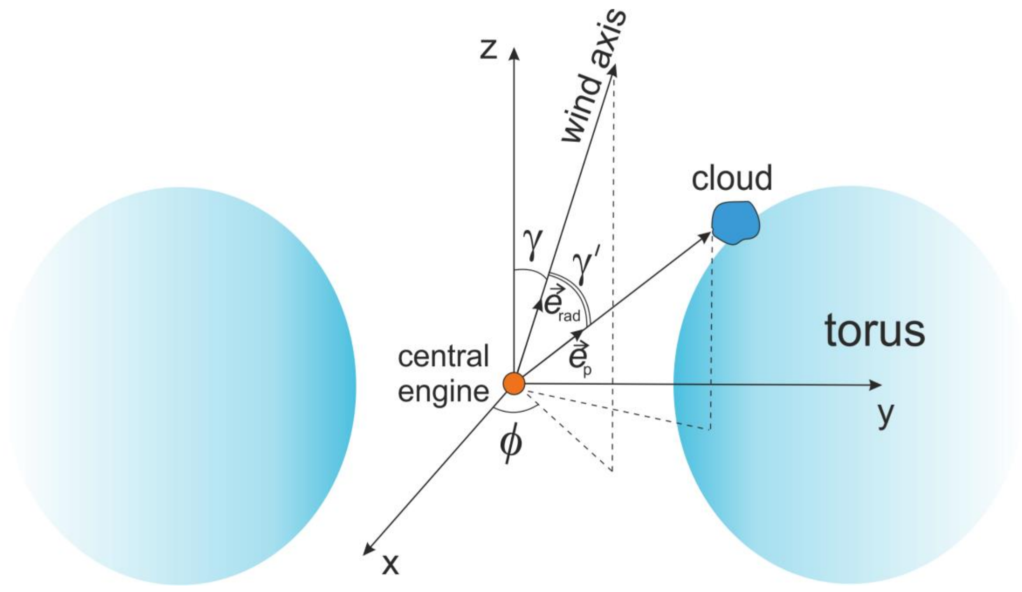
The counter-rotation is the result of wind influence and projection effects

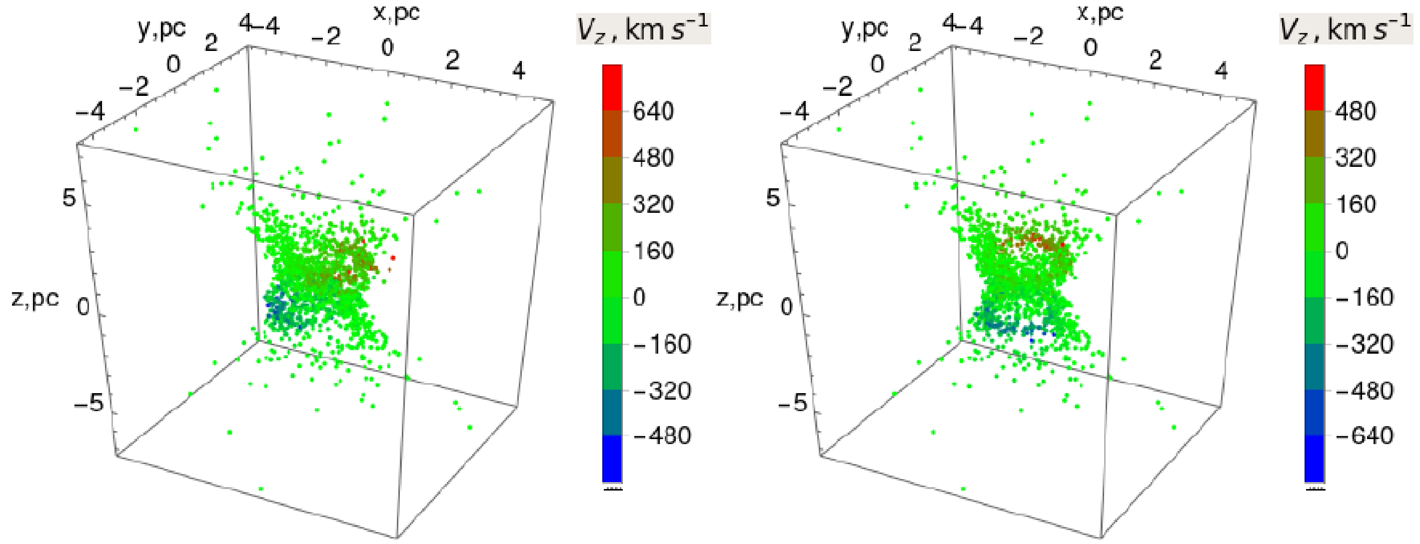
?

The scheme of AGN with the asymmetrical wind

To create an asymmetry in the velocity map we need to create some asymmetry in AGNs

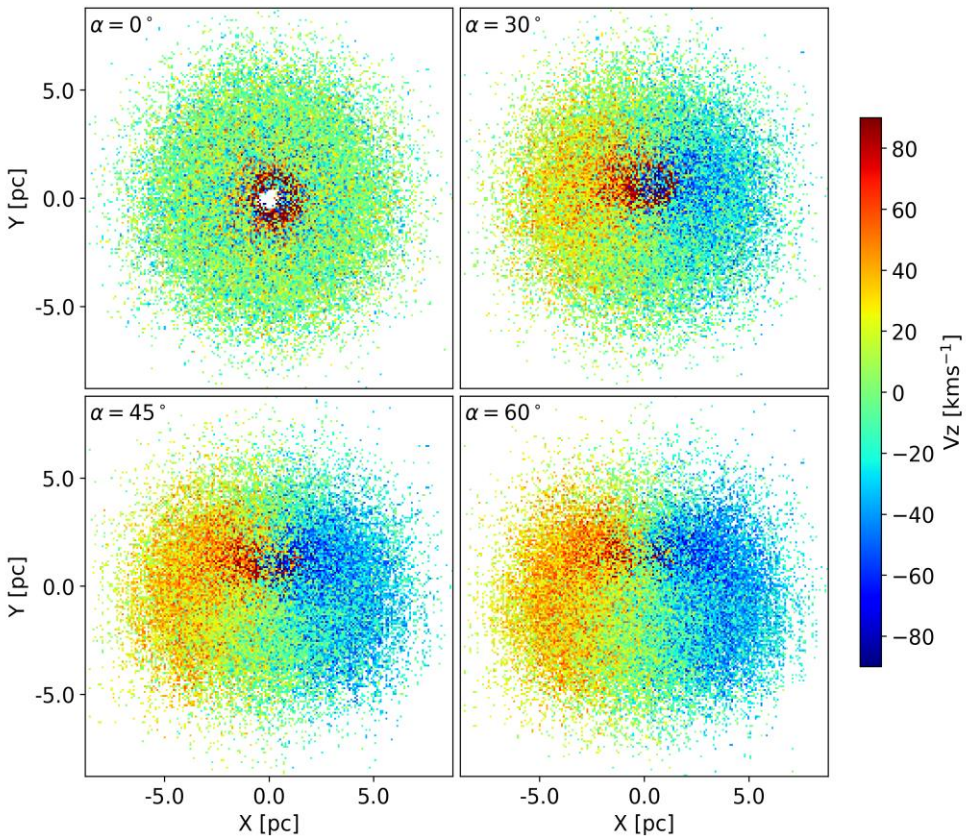
We are taking into account the wind influence on the clouds in torus throat



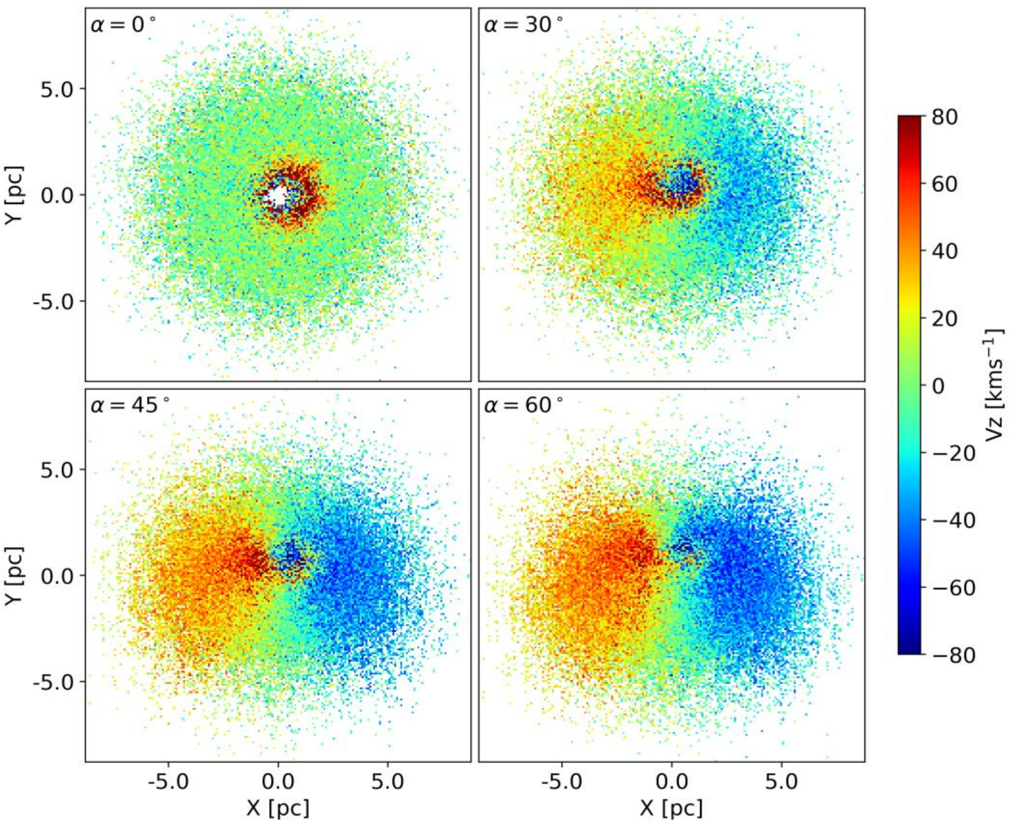


The simulation of apparent counter-rotation in NGC 1068

Relative cloud radius = 0.025



Relative cloud radius = 0.01



The counter-rotation can be a result of the acting of an asymmetrical wind together with the obscuration effects (+ projection).

Conclusion

•The model velocity and velocity dispersion maps for the torus are constructed using the resulting distribution of clouds from the *N-body* simulations. We take into account, the obscuration effects by a ray-tracing algorithm adapted to the ALMA resolution.
The resulting maps are in a good agreement with the ALMA observational maps.

•We found a new estimation of the SMBH mass in NGC 1068 taking into account the influence of the torus self-gravity. We obtain $M_{smbh} = 5 \times 10^6 M_{sun}$ for the range of the torus inclination angles $\alpha = 45^{\circ}{-}60^{\circ}$ and for the relative radii of the clouds $\varepsilon_{cl} = 0.025$.

•The model maps demonstrate that the peaks of the velocity dispersion maps are related to a throat of the torus which can be seen by an observer at some inclination angles. We built the model velocity dispersion maps for NGC 1326 and NGC 1672 with the corresponding parameters.

•The temperature distributions maps of the clouds in the torus were constructed for the case of NGC 1068. We took into account the obscuration effects by means of a ray-tracing algorithm. To reconcile the temperature and the velocity dispersion maps we choose the same radius of clouds (and the same angles of torus inclination). In this case, the maximum in the temperature distribution is related to the throat of the torus.

•The observational counter-rotation in the torus of NGC1068 can be the result of wind influence and projection effects