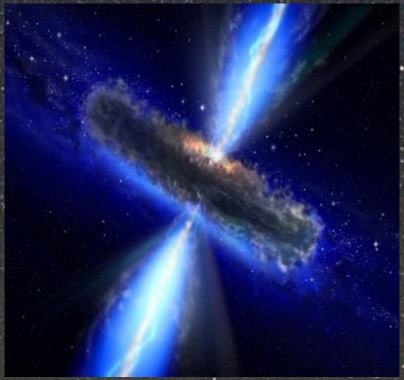
ALMA observations of AGNs: recent results and perspectives

E.Yu.Bannikova, A.V.Sergeev , N.A.Akerman

Institute of Radio Astronomy of NAS of Ukraine

V.N.Karazin Kharkiv National University

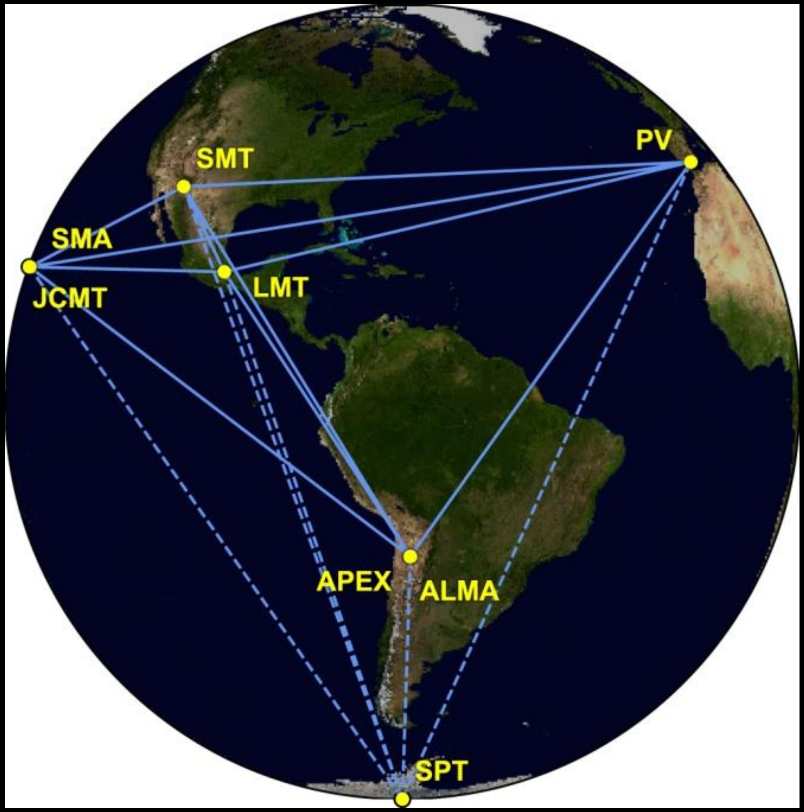


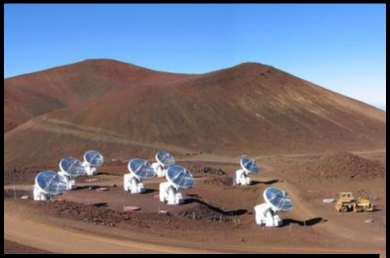
Content

- AGNs and unified scheme
- Maser emission from the torus (VLBI, VLA)
- IR emission (VLTI)
- Recent results of ALMA for the torus in NGC1068 (+ others AGNs)
- New questions ???

Event Horizon Telescope (EHT)

Arizona Radio Observatory
(ARO/SMT)
altitude 3149 meters





Submillimeter Array (SMA)
Mauna Kea, Hawaii
altitude 4115 meters

James Clerk Maxwell Telescope (JCMT)
Mauna Kea, Hawaii
Altitude 4120 meters

Pico Veleta (PV)
the Spanish Sierra Nevada
altitude 2850 meters

Large Millimeter Telescope
(LMT), Mexico,
altitude 4593 meters

South Pole Telescope (SPT)
Antarctica
altitude 2816 meters

Atacama Submm/mm Array
(ALMA), Chile
altitude 5074 meters

Atacama Pathfinderr Experiment
(APEX), Chile
altitude 5104 meters

The first picture of black hole

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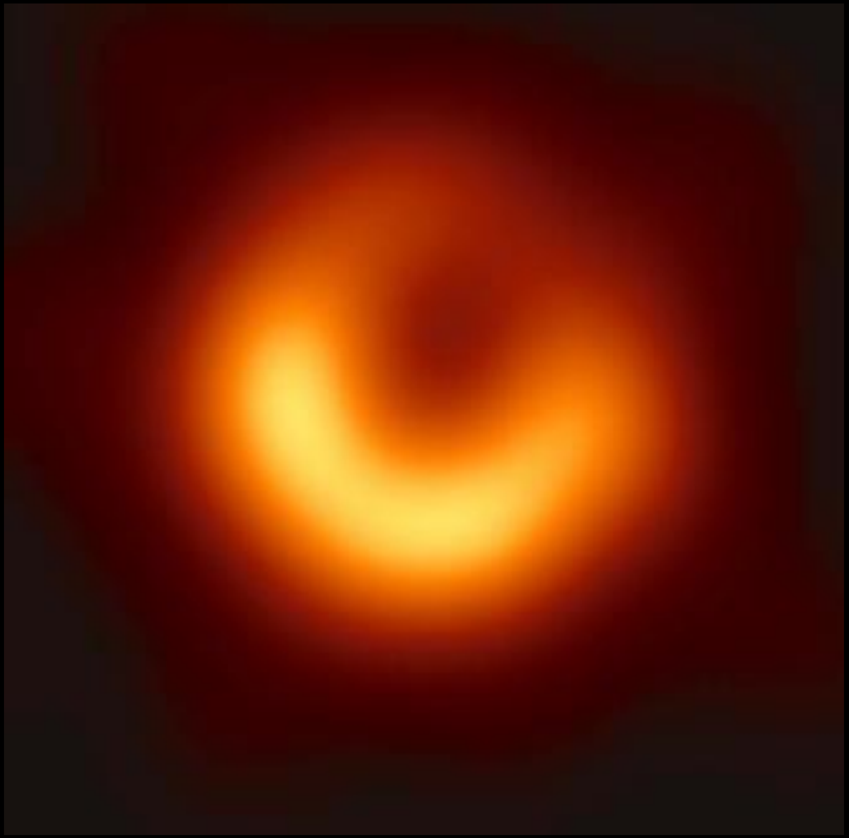

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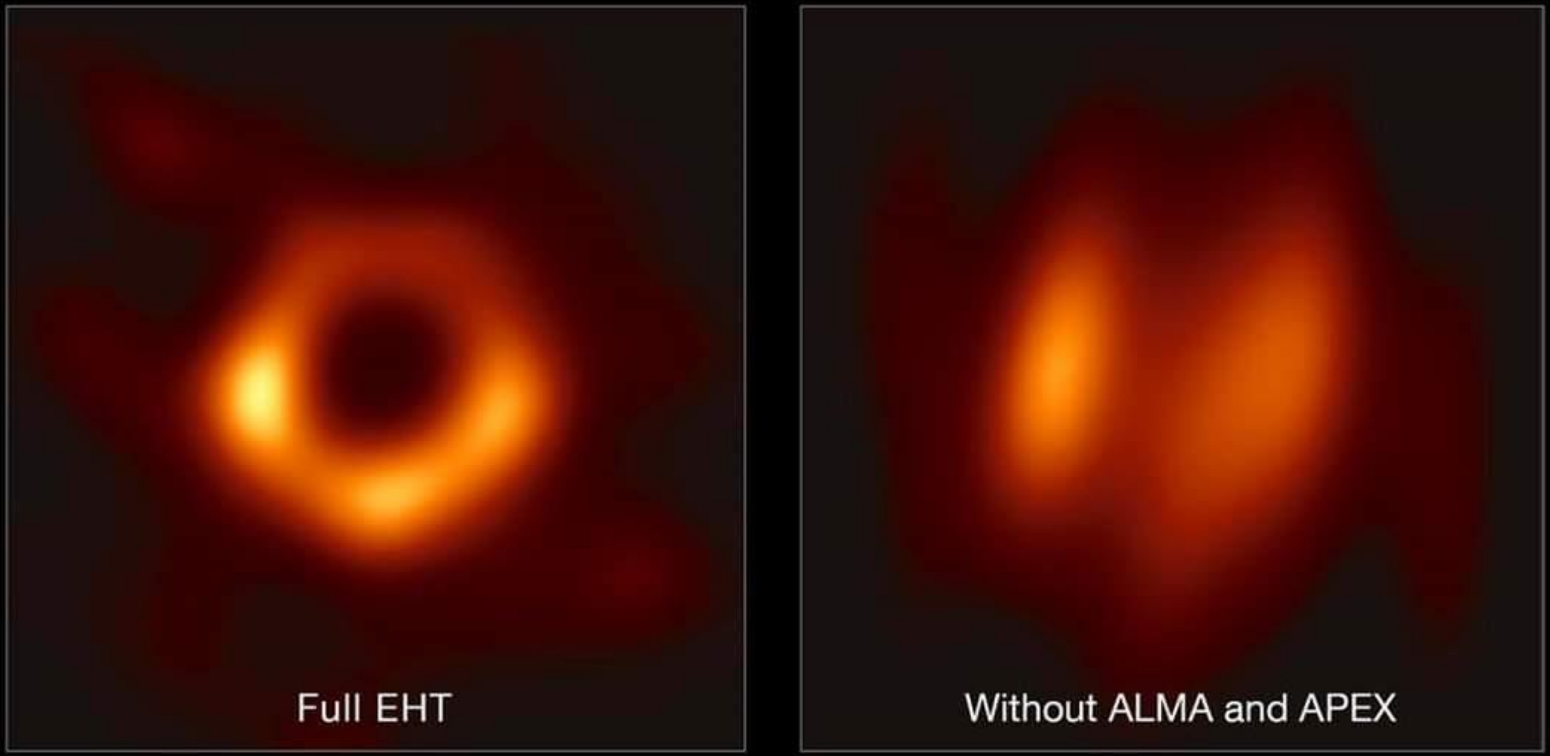
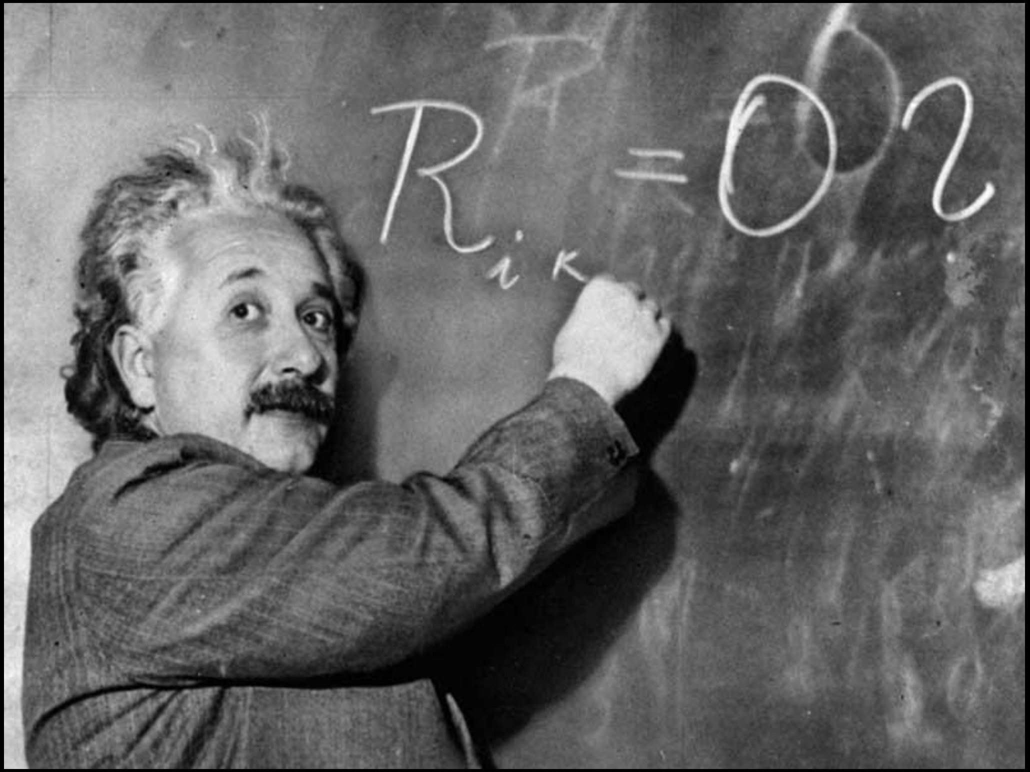


https://www.eso.org/public/images/eso1907t/

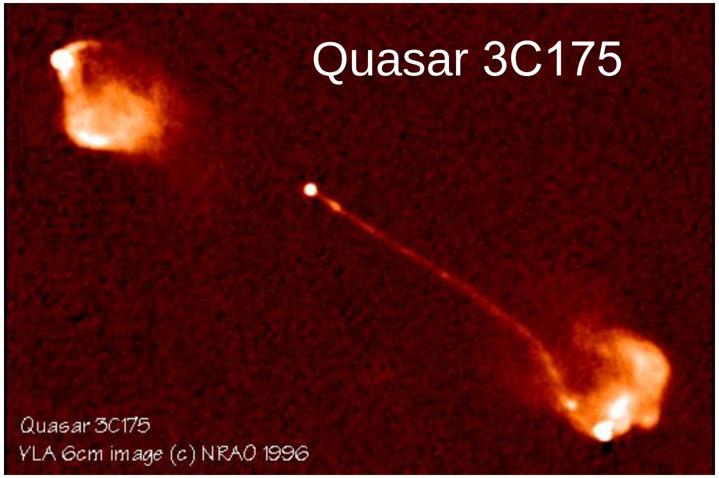
Black holes are defect of theory or these objects exist in Nature?

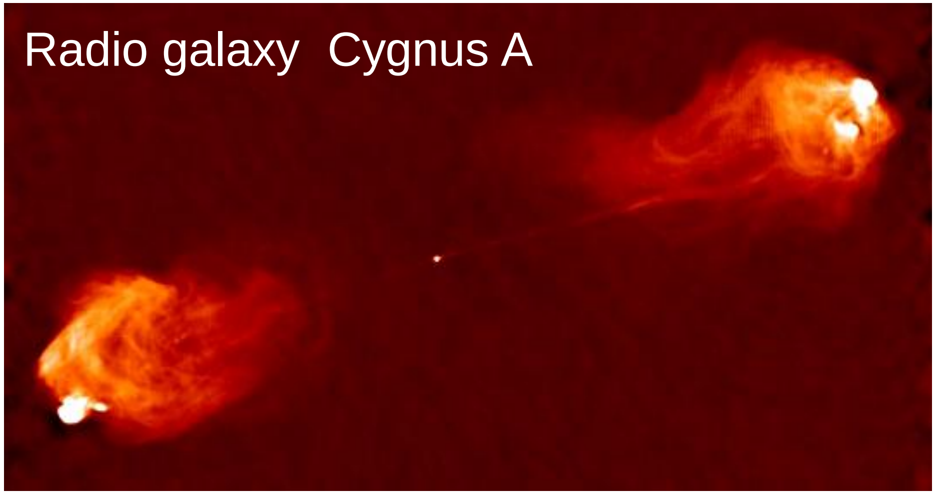
100 years of discussions



Different types of AGNs

- Seyfert galaxies 1,2
- Quasars
- Radio galaxies
- Blasars





Do these objects have the same central engine?

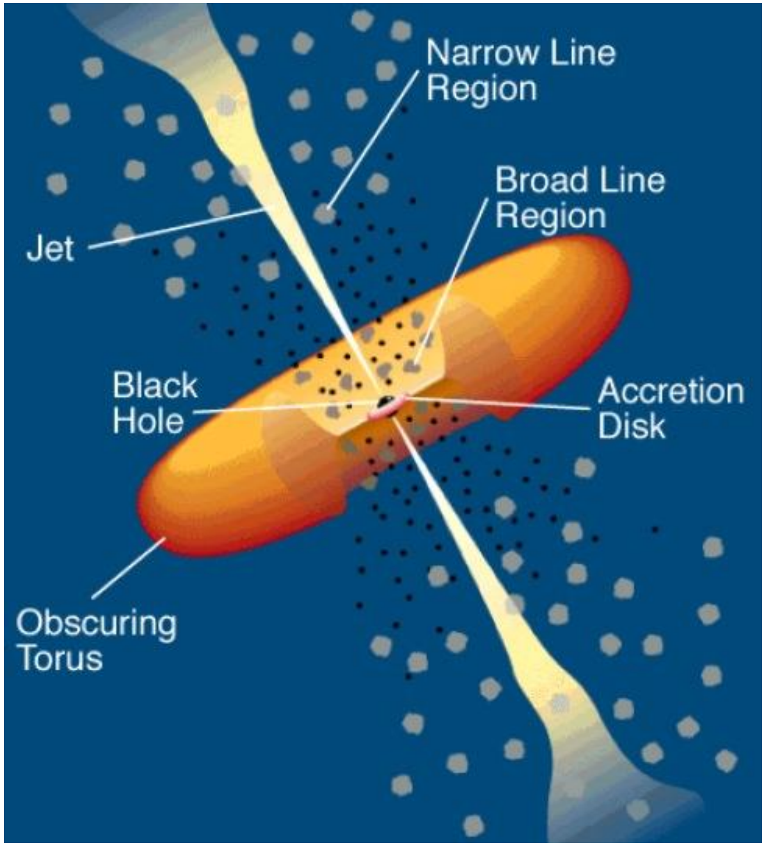
Obscuring torus: unified scheme

- The differences in AGN are explained by the orientation of the torus relative to an observer
  (Antonucci 1985, 1993; Urry & Padovani 1995)

- "Type 2": Full obscuration of the central engine and BLR is realized when the torus is seen edge-on.
- "Type 1": Torus is inclined at some angle to the line of sight

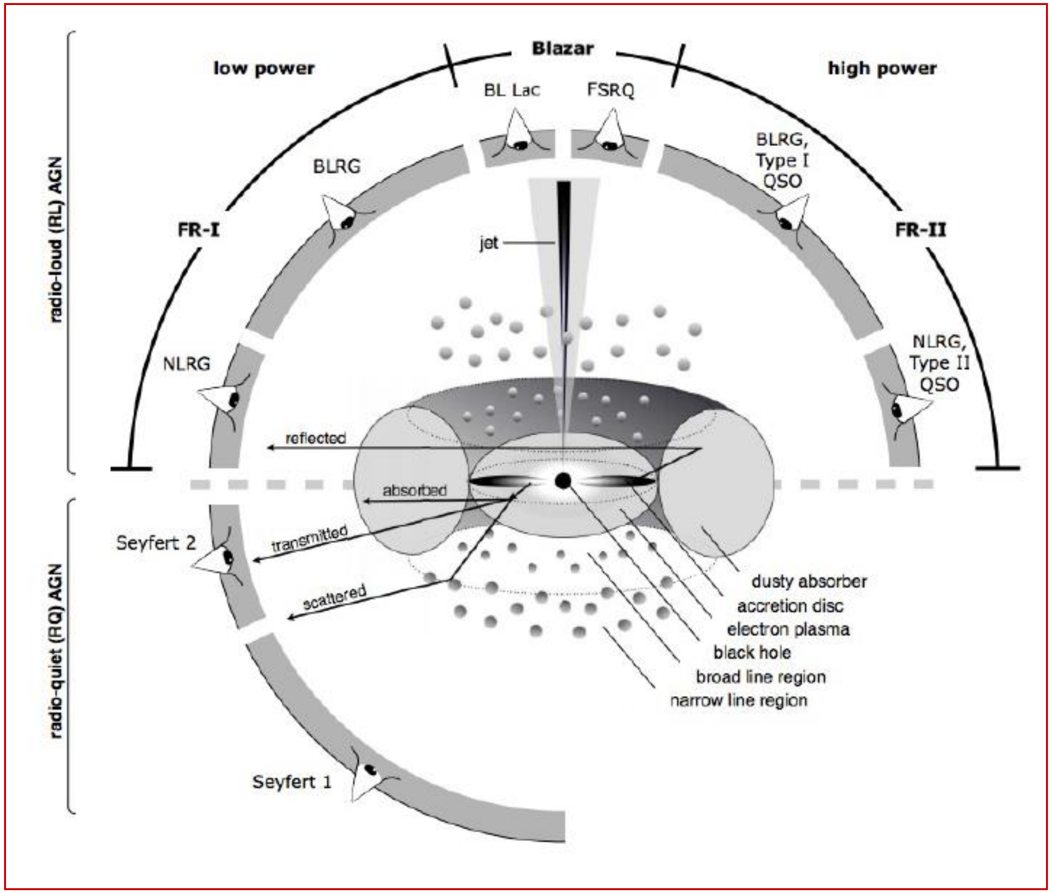
- Following from the statistical data, the torus must be geometrically thick in order to explain the observed properties of AGNs

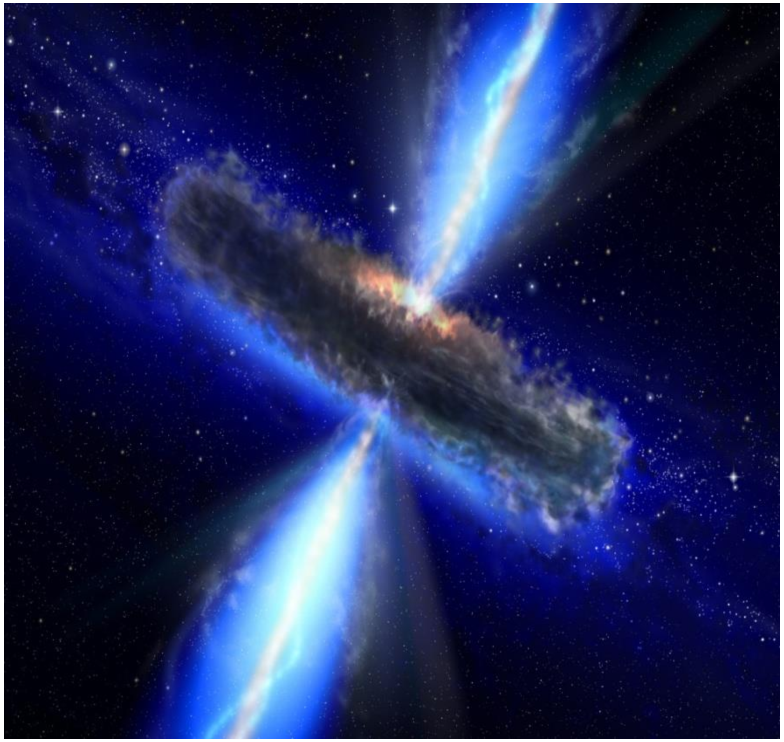
$$h/R \geq 0.7$$



Unified scheme of AGNs

- The central engine is the same.
- Obscuration of an accretion disk by geometrically thick dusty torus
- The differences in AGNs are related with orientation effects



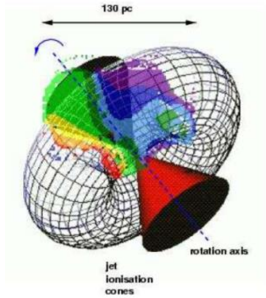


NGC 1068 Sy2, D=14Mpc

- *Claussen,Heiligman,Lo*, Circumnuclear water vapor masers in AGN, 1984,Nature
- *Gallimore et al.,* Direct image of obscuring disc in NGC1068, 1997, Nature
- *Jaffe et al.*, The central dusty torus in the active nucleus of NGC 1068, 2004, Nature

NGC 4258 D=7.2Mpc

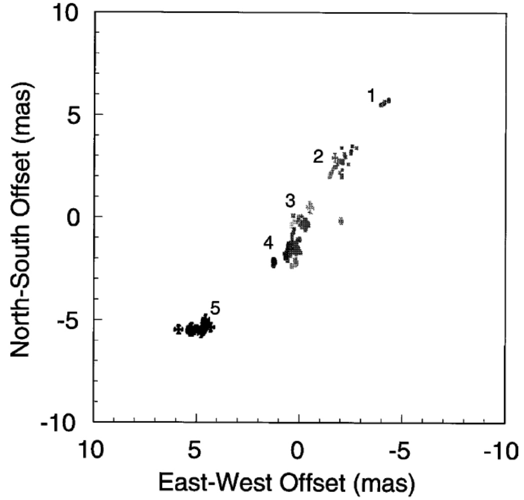
- *Myoshi et al. Evidence for black hole from high rotation velocities in a sub-parsec region of NGC4258,* 1995, Nature
- *Herrnstein,..,Diamond,..,Miyoshi,*, Geometrical distance to NGC4258 from orbital motion in nuclear disc, 1999,Nature
- *Klockner, Baan,Garrett* Investigation of the obscuring circumnuclear torus in the active galaxy Mrk231, 2003, Nature

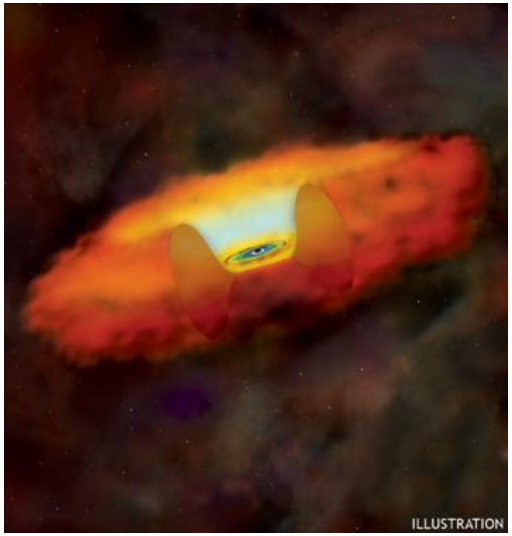


VLBI imaging of water maser emission from nuclear torus of NGC1068

Greenhill et al., 1996

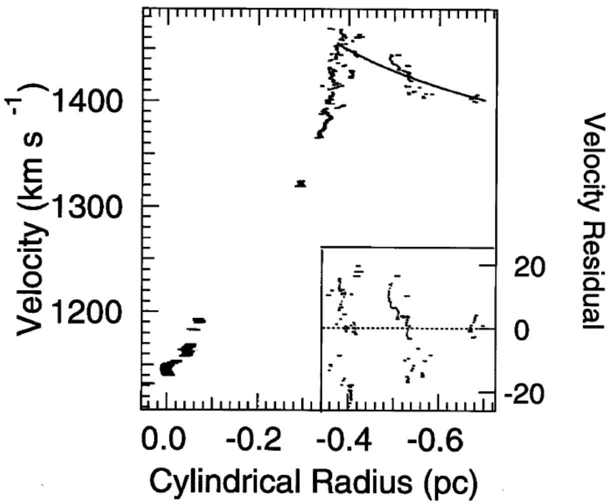
Orbital velocity is about 250 km/s on the radius (0.4-0.6) pc which corresponds to the mass of SMBH is $10^7 M_{sun}$





The radius of dust sublimation

$$r_{sub} \sim 0.4\text{пк}$$

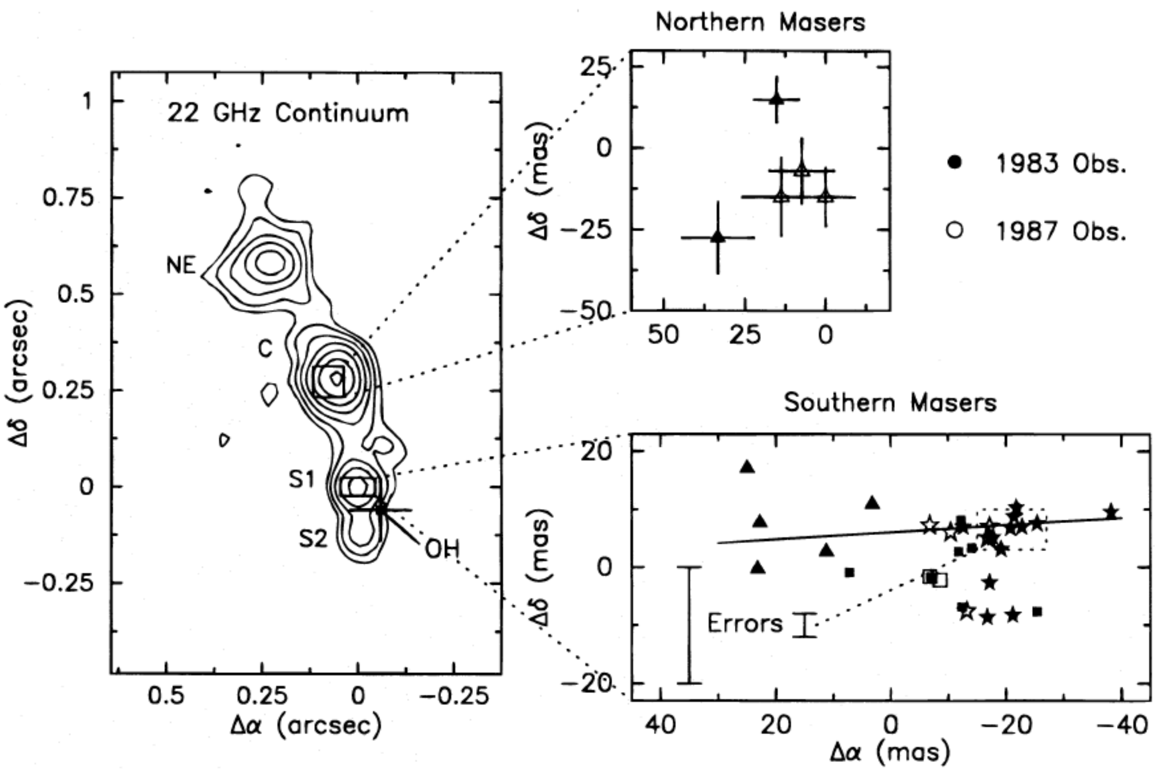


The rotation curve is not keplerian => self-gravity of the torus?

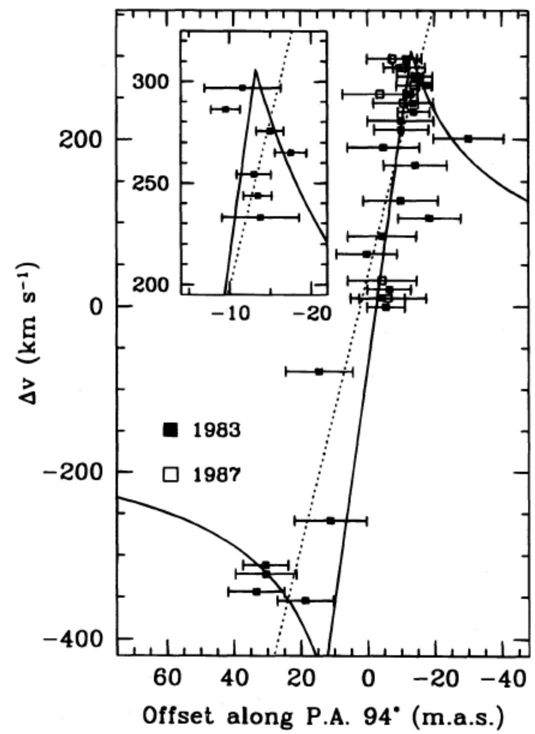
The radius of dust sublimation coincide with the scales of maser emission

H2O and OH masers as probes of the obscuring torus in NGC1068

Gallimore et al., 1996



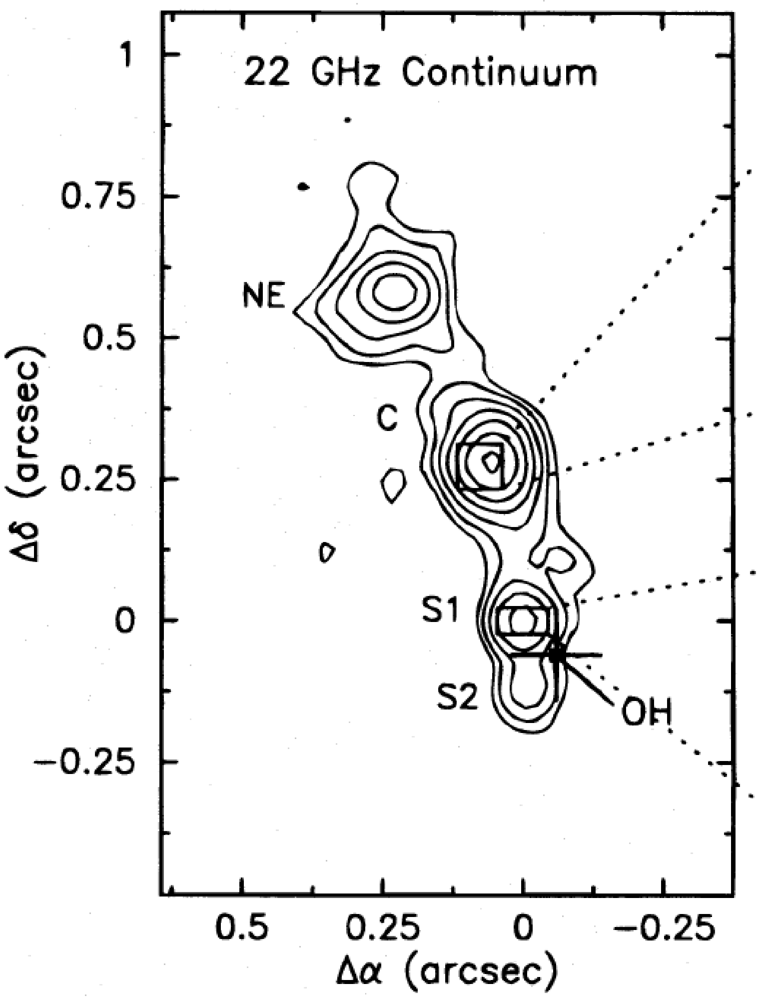
VLA observations

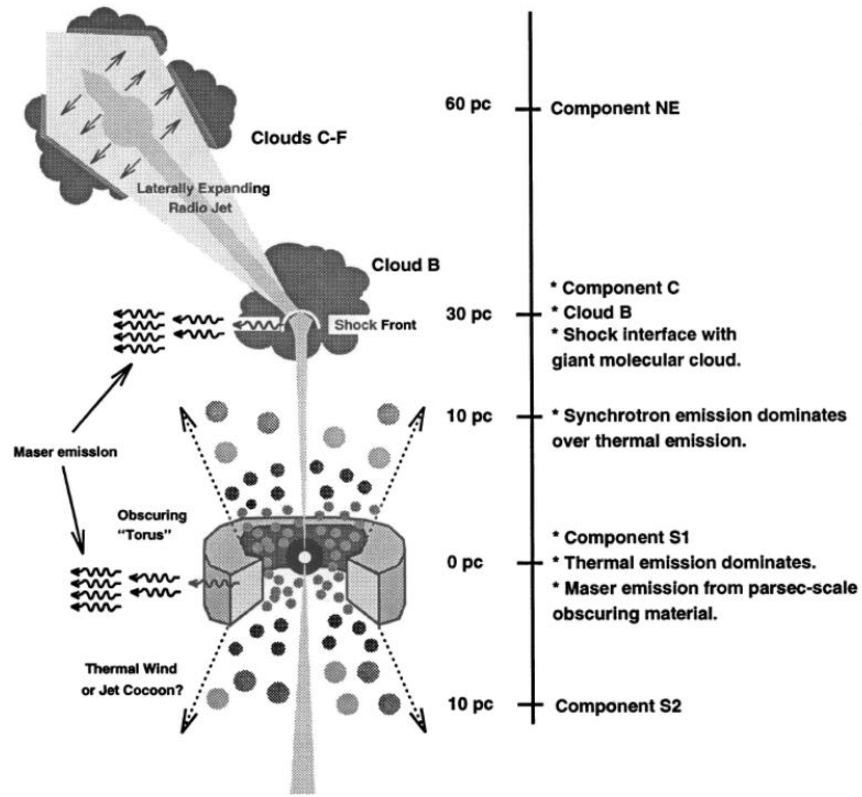


The mass of SMBH is about $10^7 M_{sun}$, the torus mass $=0.01 M_{SMBH}$

The subarcsecond radio structure in NGC1068: implication for the central engine and unified scheme

Gallimore et al., 1996

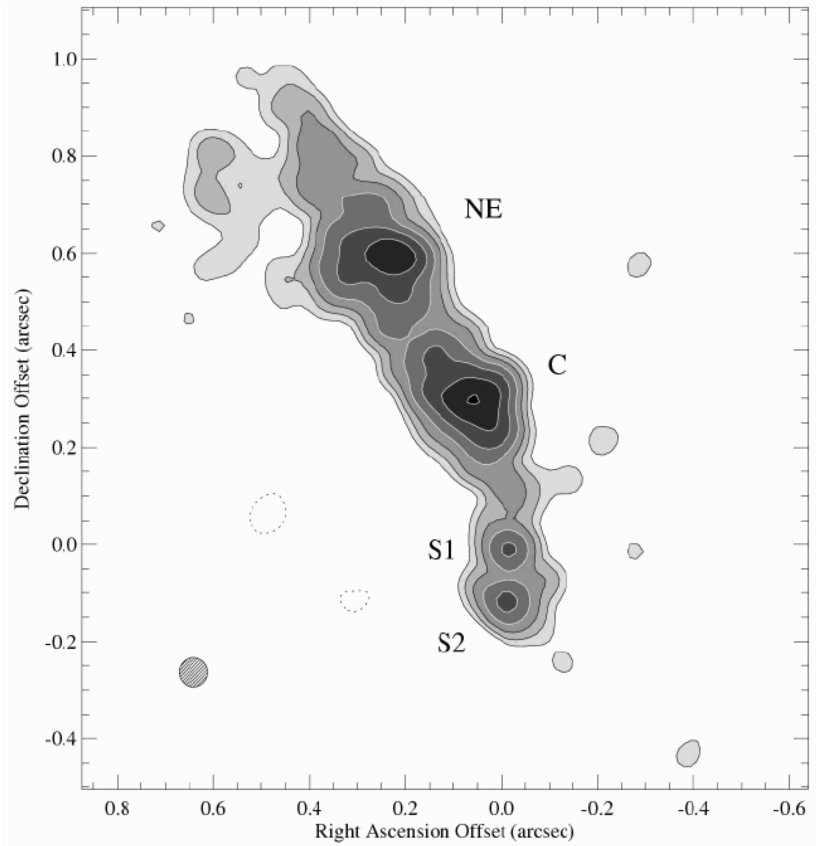


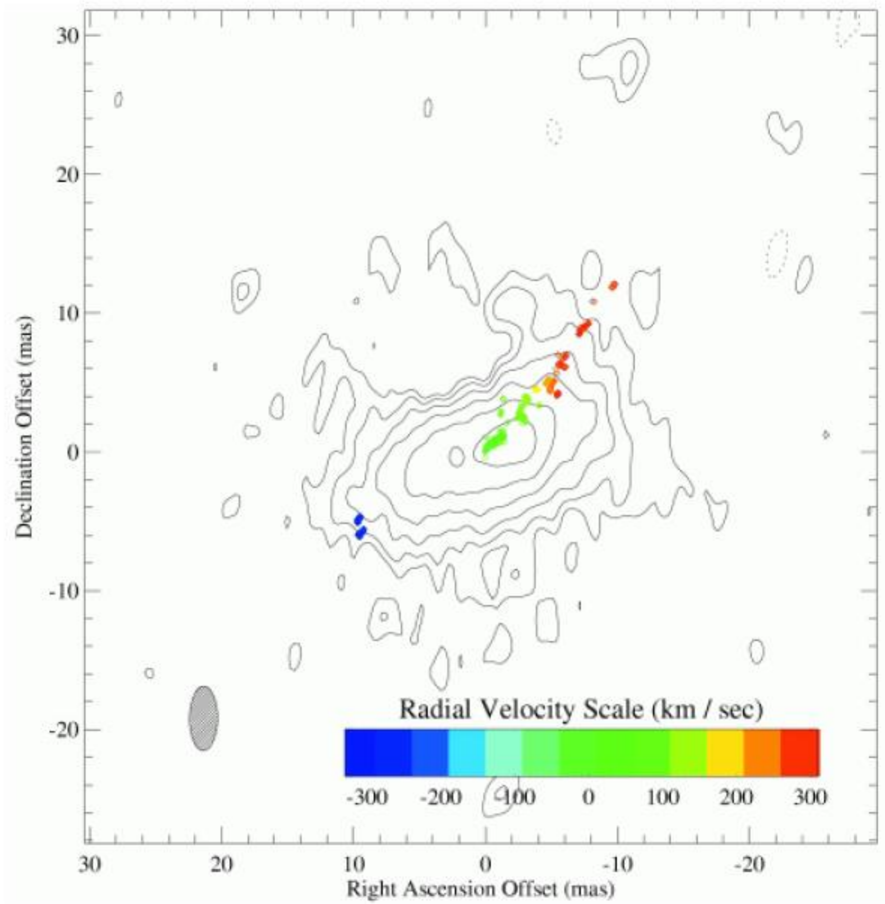


The parsec-scale radio structure of NGC1068 and the nature of the nuclear radio source

Gallimore et al. 2004

VLBA (5GHz)



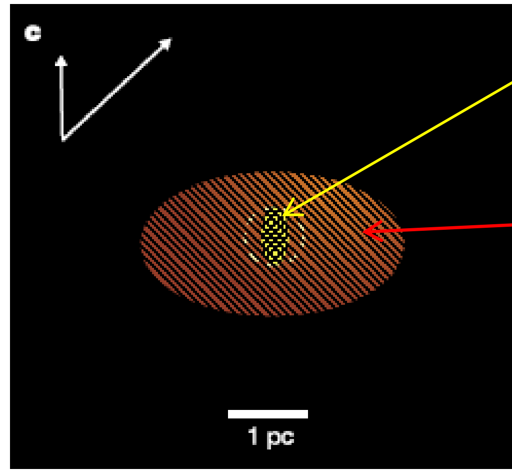


$1'' = 72$ pc

VLTI direct observation of the torus in IR band

Jaffe et al.2004, Nature

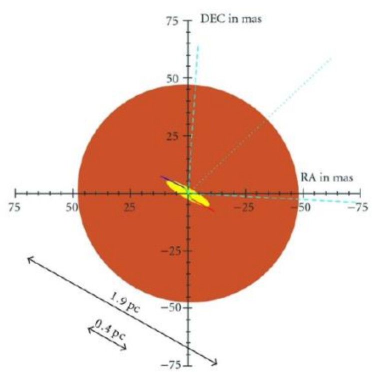
NGC 1068 (Sy2 galaxy – torus is edge on)

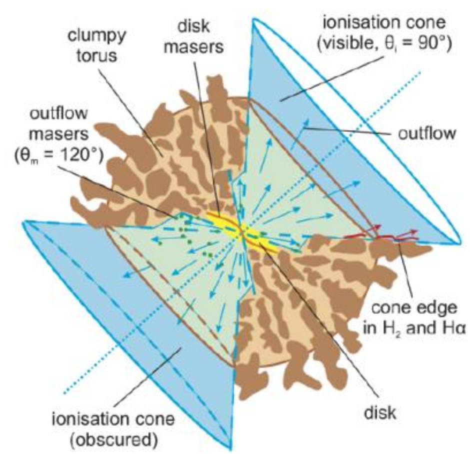


Hot component
T>800K

Warm componet
T=320K

Circinus





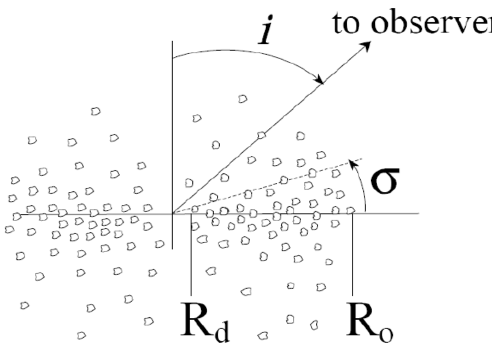
(Tristram et al.)

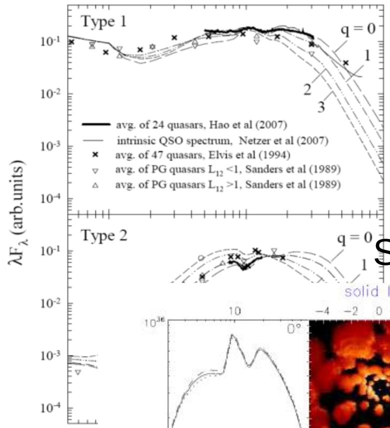
- The torus is geometrically thick
- Clumpy structure: the hot component is the radiation of the clouds in inner edge

Continuum vs clumpy structure in a torus

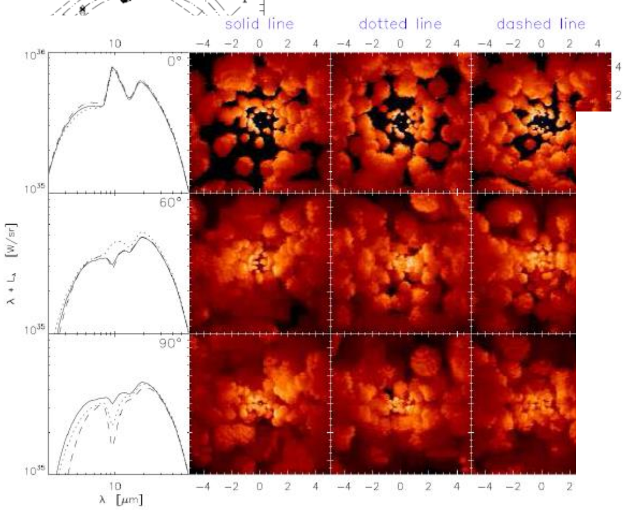
- Problem of the radiation transfer in torus => model SED
- Comparison with observational SED in IR band

Nenkova et al. 2008

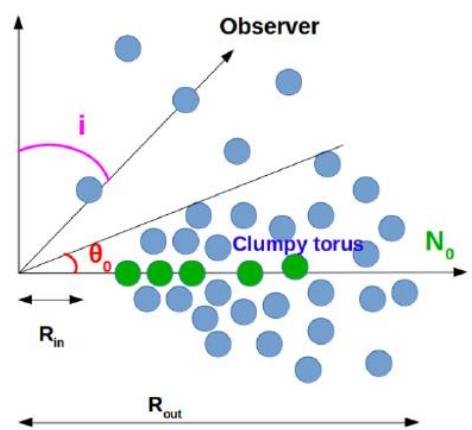




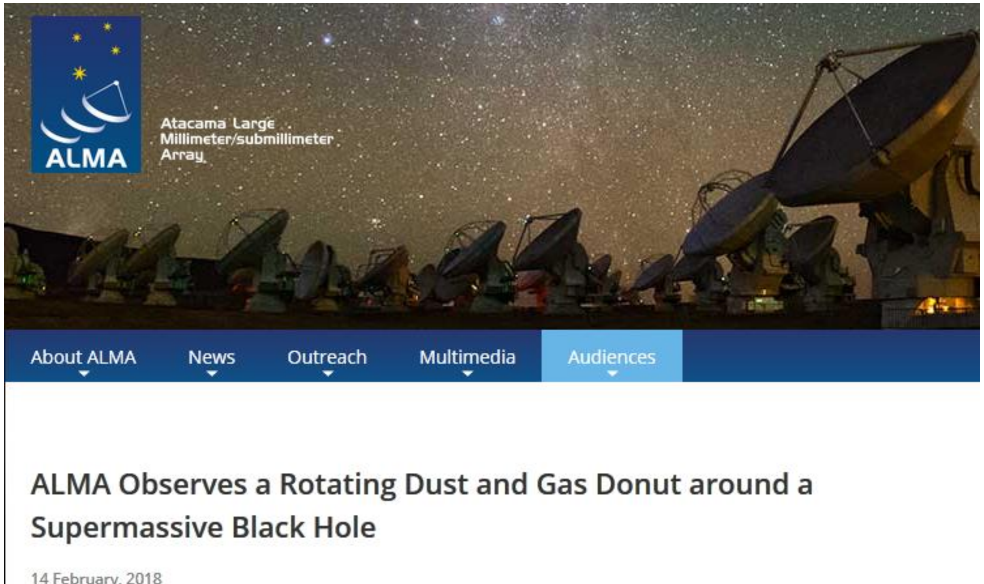
Schartmann et al. 2010



3DCAT code, 2017
Garcia-Gonzalez et al.

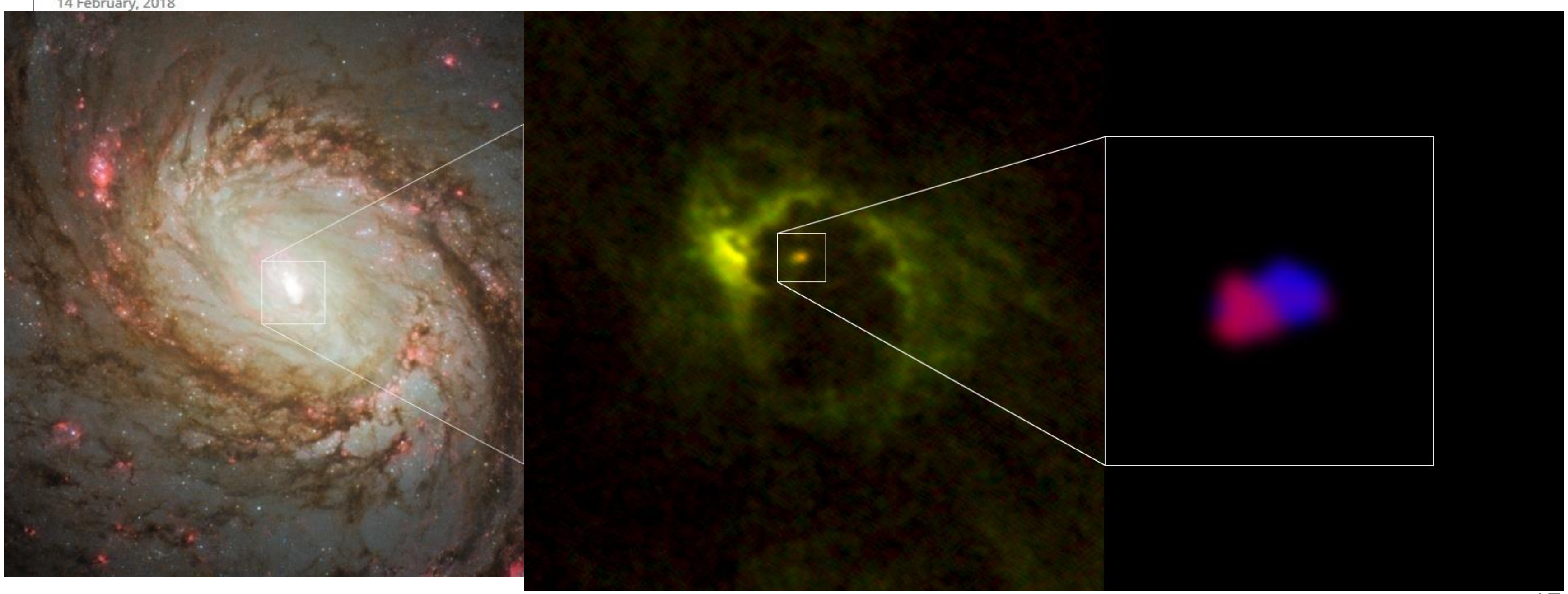


ALMA direct observation of the torus in mm band



Obscuring torus in NGC1068

The orbital motion in the torus

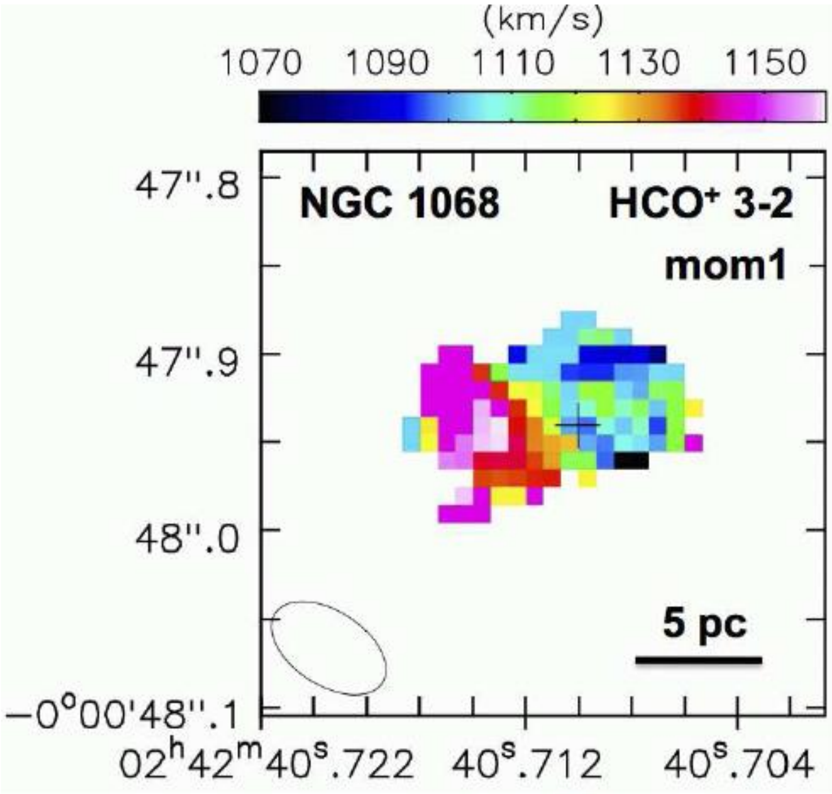


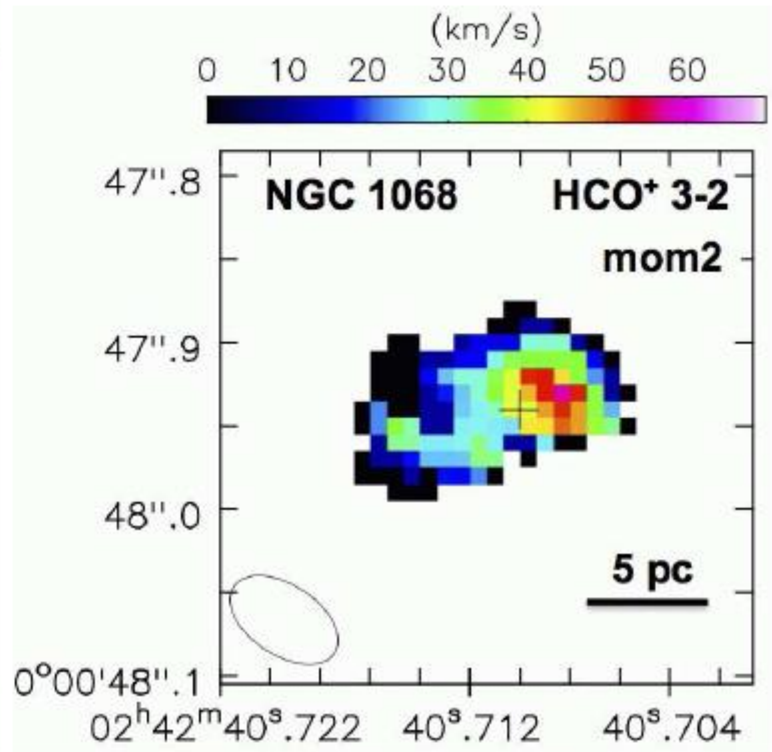
ALMA direct observation of the torus in mm band

Obscuring torus in NGC1068

Velocity distribution

Imanishi et.al 2018





There is an anisotropy in velocity dispersion.
Which is a reason of this anisotropy?

ALMA direct observation of the torus in mm band

Obscuring torus in NGC1068

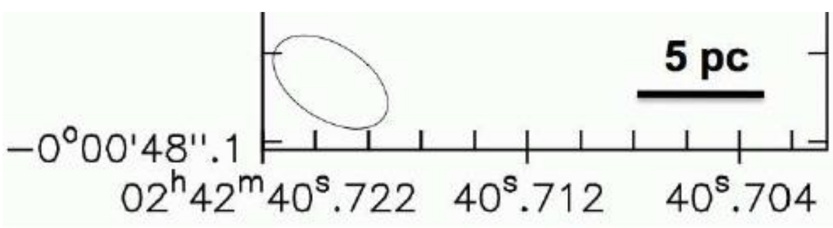
Velocity distribution

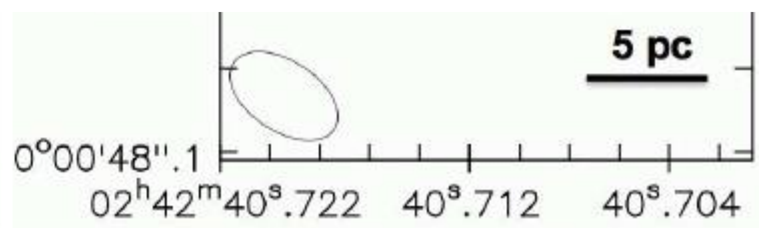
Imanishi et.al 2018

Astronomy & Astrophysics manuscript no. torus1
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]





There is an anisotropy in velocity dispersion.
Which is a reason of this anisotropy?

VLA direct observation of the torus in Cygnus A

Imaging the Active Galactic Nucleus Torus in Cygnus A

C. L. Carilli[1,2], R. A. Perley[1], V. Dhawan[1], and D. A. Perley[3]
[1] National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87 801, USA; ccarilli@nrao.edu
[2] Astrophysics Group, Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, UK
[3] Astrophysics Research Institute, John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK
Received 2019 March 6; revised 2019 March 14; accepted 2019 March 15; published 2019 April 5

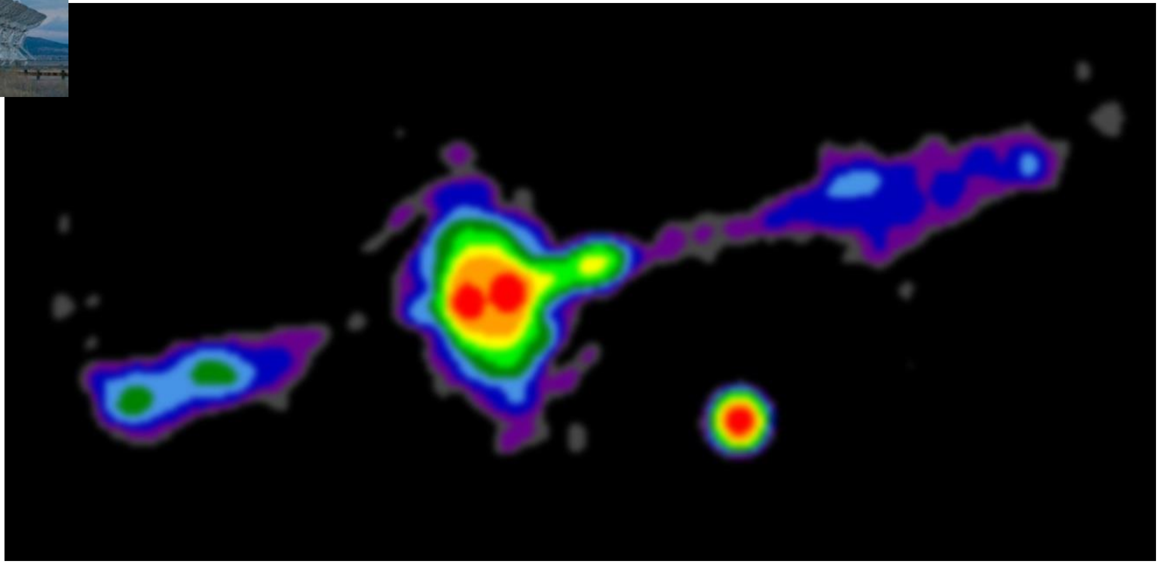
27 radio antennas (25 meters in diameter) located at the NRAO site in Socorro, New Mexico.

2 April, 2019

18-48 GHz with resolution 45mas

M_{SMBH}=2.5*$10^9 M_{Sun}$ R_{torus}=130pc

Radio galaxy

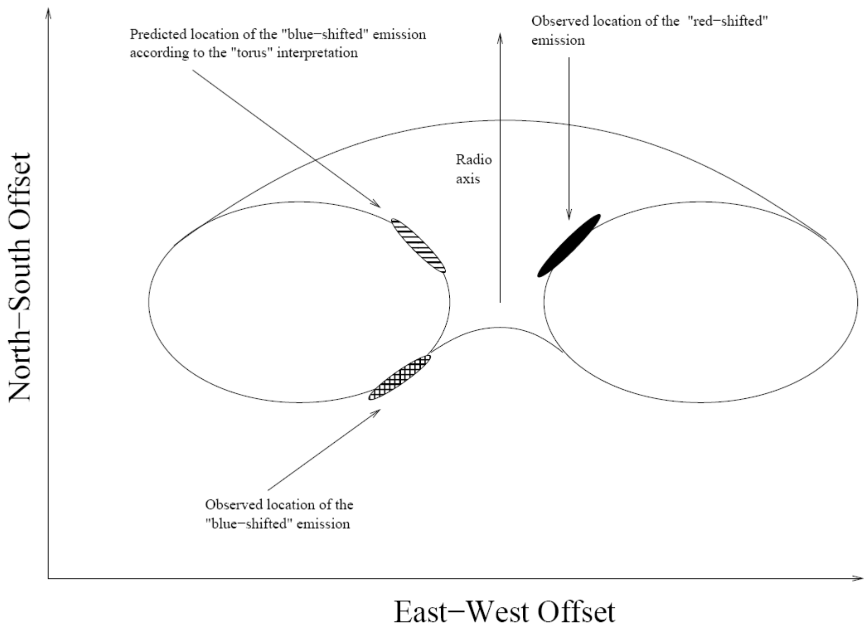


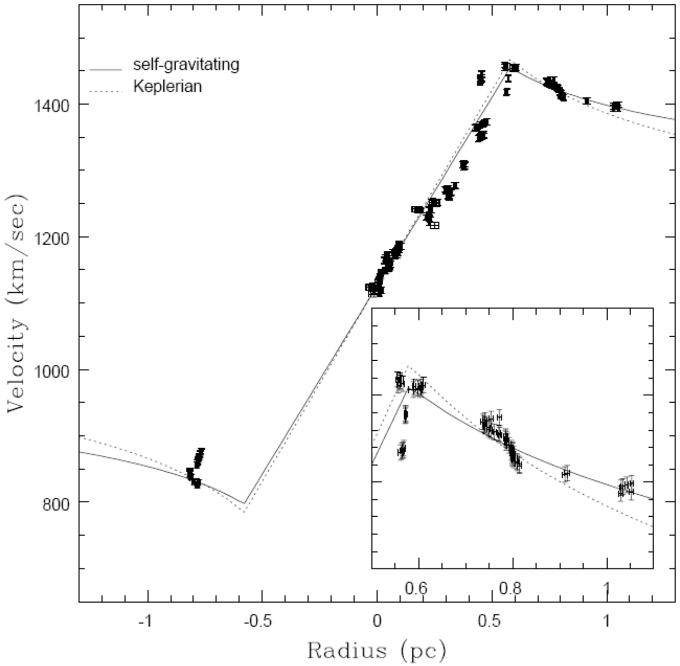
ALMA / VLA / VLTI direct observation of the tori

Galaxy	Type	R^{out}_{torus}, pc	$M_{torus}, 10^6 M_{Sun}$	$M_{BH}, 10^7 M_{Sun}$	$incl(°)$
NGC 1068	Sy 2	3.5 ± 0.5	2.	1.	$34-66$
NGC 613	Sy	14 ± 3	39 ± 14	3.7	46 ± 7
NGC 1326	LINER	21 ± 5	9.5 ± 1	2.5	60 ± 5
NGC 1365	Sy 1.8	26 ± 3	7.4 ± 2	6.9	27 ± 10
NGC 1566	Sy 1.5	24 ± 5	8.8 ± 1	1.3	12 ± 12
NGC 1672	Sy 2	27 ± 7	25 ± 3	2.5	66 ± 5
NGC 1808	Sy 2	6 ± 2	9.5 ± 1	6.2	64 ± 7
NGC 5643	Sy 2	13	11	0.28	65
Circinus	Sy 2	1.5	–	0.17 ± 0.03	> 75
Cygnus A	Radio galaxy	260	–	250 ± 70	–

Non-Keplerian rotation in the nucleus of NGC 1068: evidence for a massive accretion disk?

Lodato and Bertin, 2002





The torus is considered in the framework of the disk model.
In this case the mass of SMBH is comparable with the disk mass $M_\bullet \approx M_{disk} \simeq 8\ 10^6 M_\odot$

The mass of the torus is very heavy to survive!

Main properties of an obscuring torus in AGN

- ❑ Geometrically thickness of the torus (statistic, VLTI, ALMA)

- ❑ Torus mass (NGC1068) $10^5 M_{sun}$ is about 1%-10% of supermassive black hole (rotation curves VLA, VLBI)

- ❑ Clumpy structure of the torus with Gaussian distribution of clouds in cross-section. 10 clouds are on the line of sight and 1 cloud is on the 45 grad angle.

- ❑ Orbital motion (ALMA)

- ❑ Non-Keplerian motion (VLBI)

Dynamical model of the torus which take into account all observational properties

Self-gravitating torus in the field of the central mass: N-body simulation

- Initial condition: Keplerian torus
- M_{torus}=(0.02-0.1)M_c
- Number of particles $N \approx 10^4$

Bannikova et al. 2012
Bannikova & Sergeev, 2017

- Gravitating particles are the Plammer's spheres with radius ε=0.01

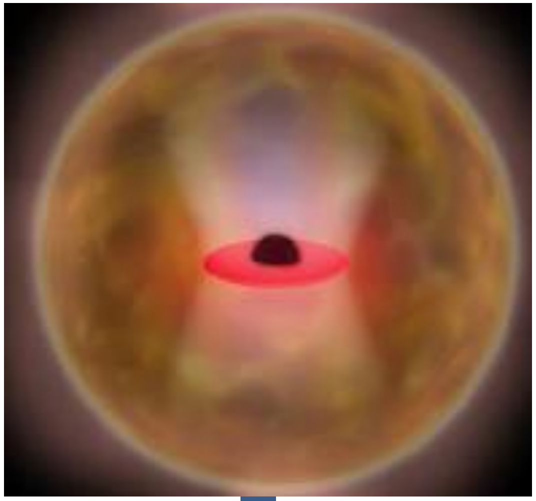
- The equations of motion

$$\mathbf{a}_i = -\frac{GM_c}{R^2}\frac{\mathbf{r}_i}{r_i^3} + \frac{\mathbf{F}_i}{m_i}$$

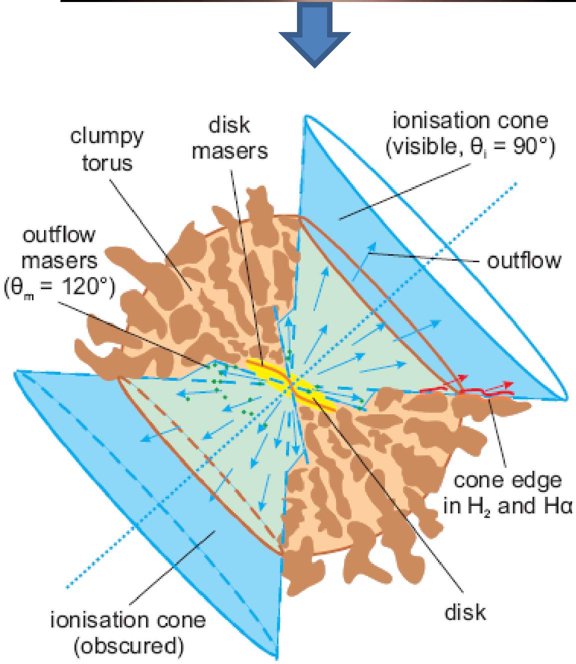
The total gravitational force acting on *i*-th particle

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

Formation of dusty torus in AGN



SMBH and accretion disk are embedded in spherical distribution of optically thick dusty clouds.



Picture from Tristram et al 2008

The beginning of active stage

leads to increase of wind energy and to anisotropy in the distribution of clouds. Within the wind cones clouds acquire additional impulse against grav. forces and fly out. The dusty clouds located outside of the wind cones are unaffected by the wind and continue to move in inclined and eccentric orbits forming toroidal structure.

Bannikova, 2016
Bannikova & Sergeev, 2017

Initial condition for N-body simulation

- Random distribution of the clouds by orbital elements
- Anisotropy in two polar directions (winds)

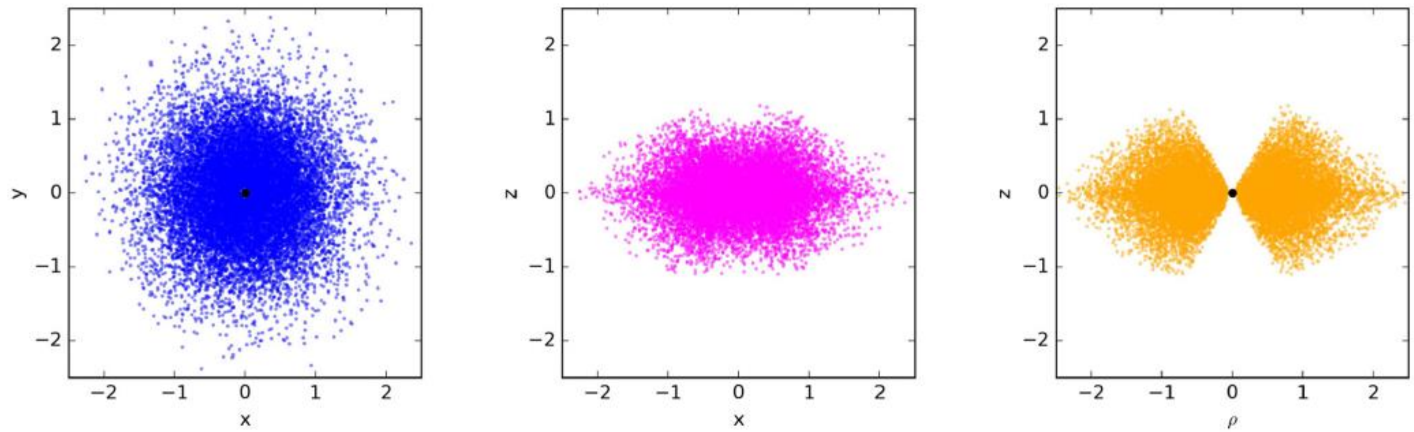
N=8192

$M_{torus}=0.01M_c$

All clouds are moving gravitational field of SMBH and
we take into account the grav. interactions between clouds

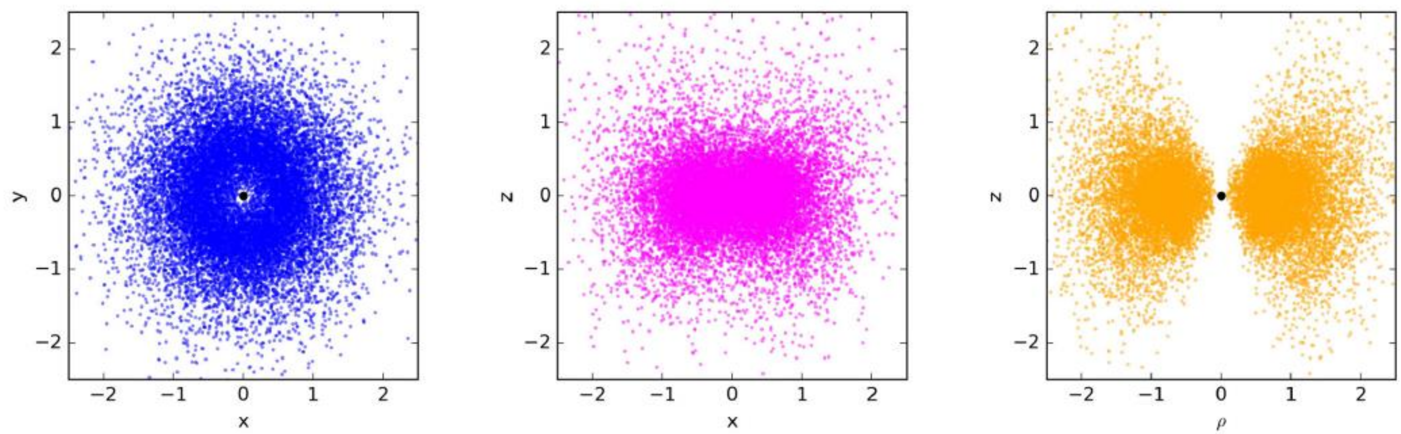
Initial state:

- Random distribution of the clouds by orbital elements
- Anisotropy in two polar directions (winds)

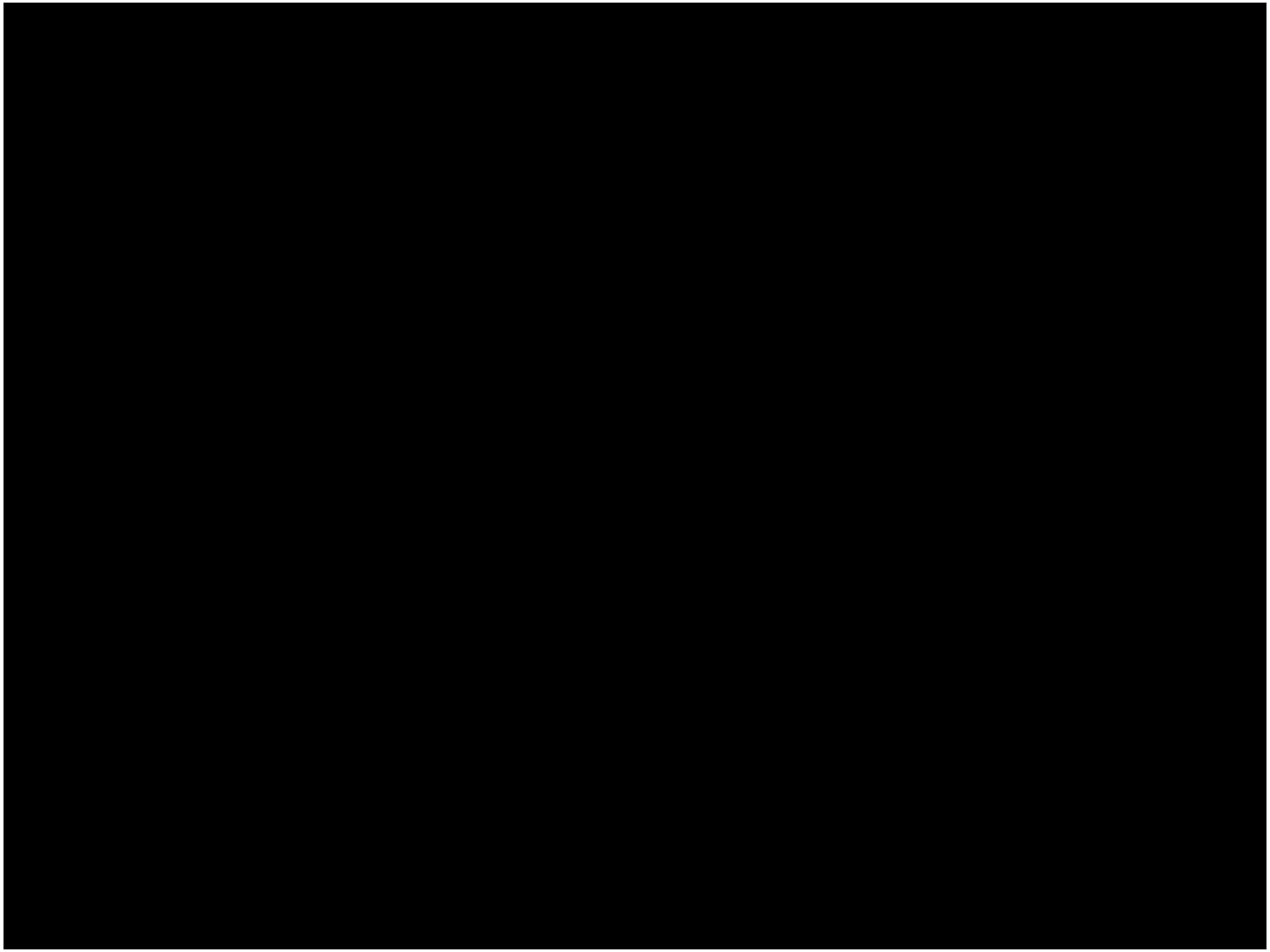


Equilibrium state:

- Thick toroidal structure
- Gaussian distribution of clouds



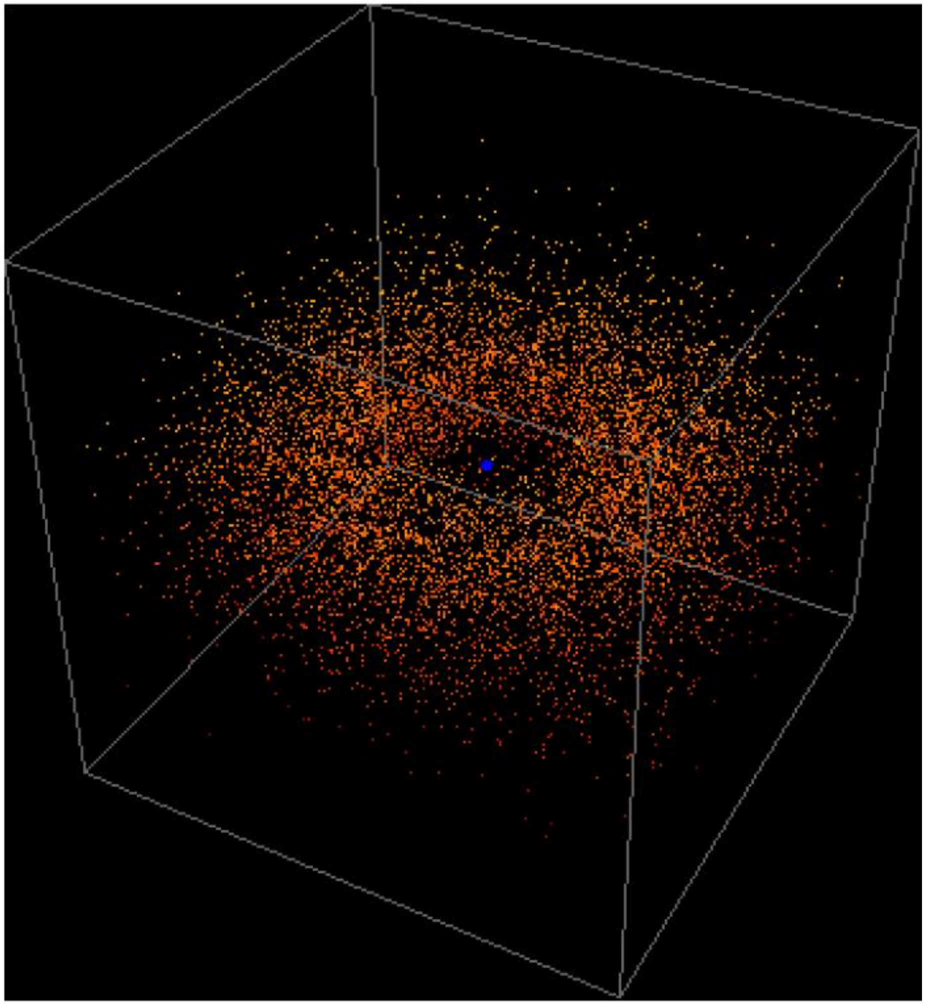
Dynamical model of obscuring torus in AGNs



Dynamical model of obscuring torus in AGNs

N=8192

$M_{torus}=0.05M_c$

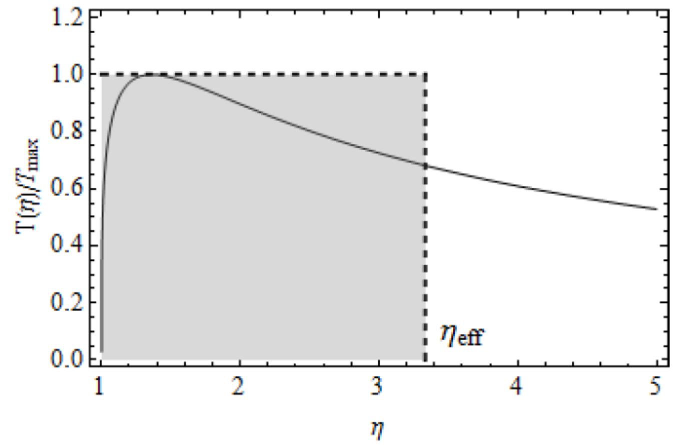


The temperature of the clouds in the torus

Present the disk with temperature profile as the disk with the luminosity which satisfy Shakura & Sunyaev model but with uniform temperature T_{max} and some effective radius R_{eff}

The luminosity of such a disk: $L = \pi \sigma_B T_{max}^4 R_{eff}^2$

$$T_{max} = 3.55 \cdot 10^5 K \times M_7^{-1/2} \dot{M}^{1/4}$$



The effective radius of accretion disk is

$$R_{eff} = \frac{\sqrt{6}}{f_{max}^2} r_g \simeq 10 r_g$$

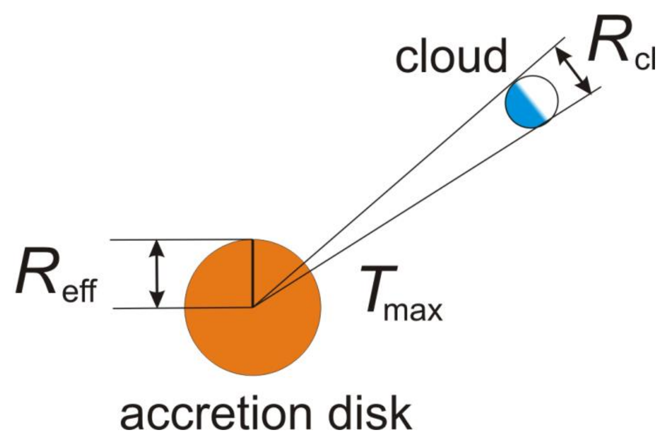
Assume that the clouds are in a thermal equilibrium with the accretion disk

$$T_{cl} = T_{disk} \sqrt{\frac{R_{eff}}{2R_c}}$$

Temperature of the cloud

$$T_{cl} \approx 660K \cdot \dot{M}^{1/4} \left(\frac{R_c}{1pc} \right)^{-1/2}$$

$$\dot{M} = 0.12 M_{\odot}/\text{рік}$$



For $R_{min} \simeq 0.2\text{пк}$ $\quad T_{cl}^{max} \simeq 830K$

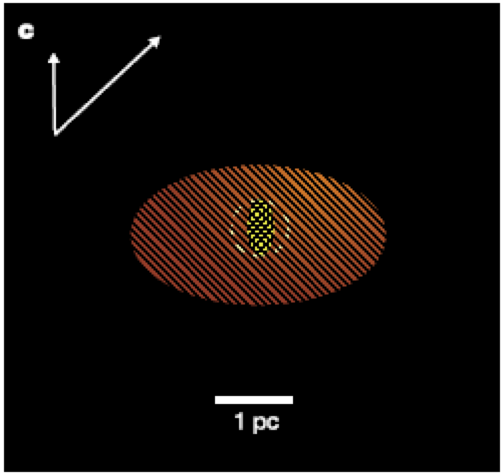
$R_{max} \simeq 3.8\text{пк}$ $\quad T_{cl}^{min} \simeq 190K$

⇒ coincide with VLTI observational data

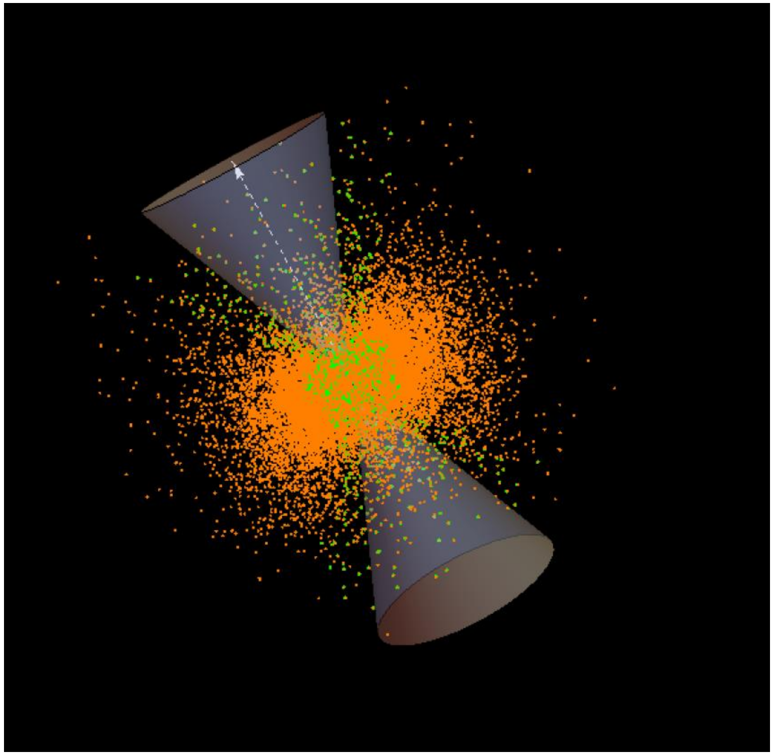
The temperature distribution in the torus

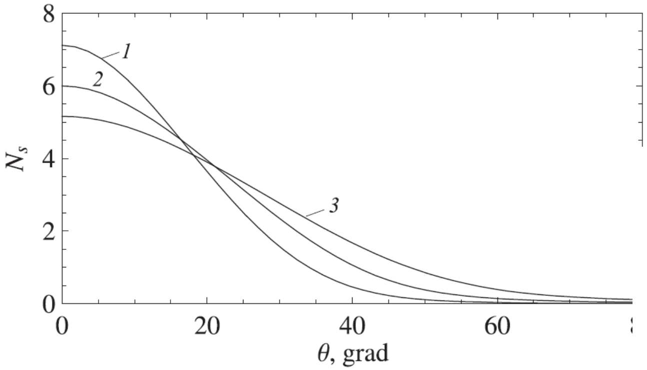
NGC 1068

VLTI observation in IR band
Jaffe et al.2004



N-body simulation of
clumpy torus



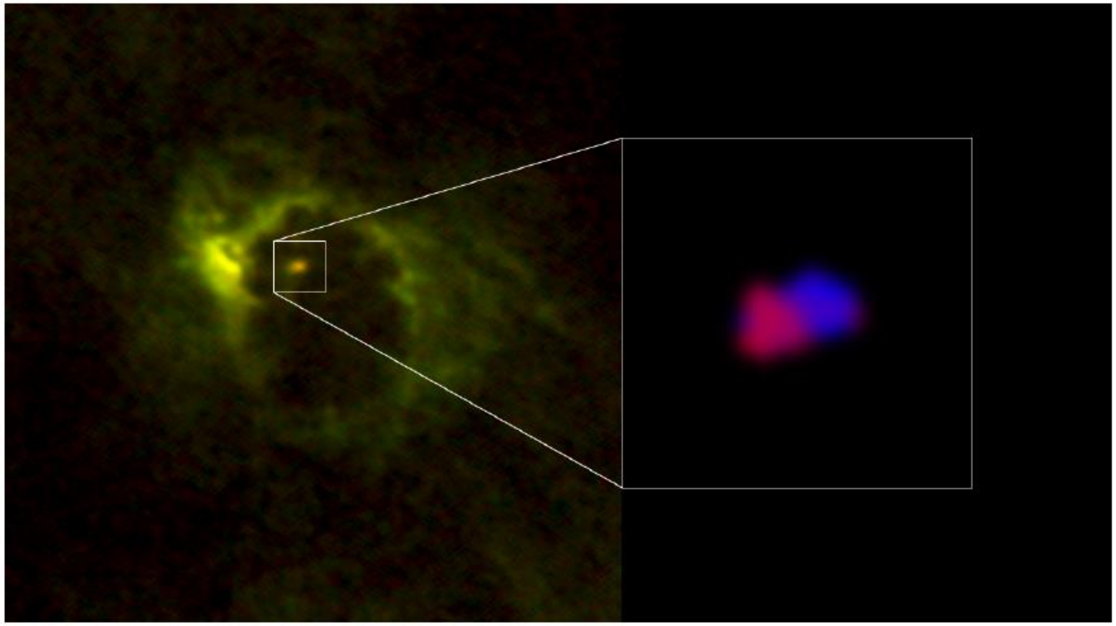


$$N_s(\theta) = \frac{N\varepsilon^2}{2} \frac{\int_0^\infty e^{-f(r,\theta)} dr}{\iint_S e^{-f(\eta,\zeta)} dS}$$

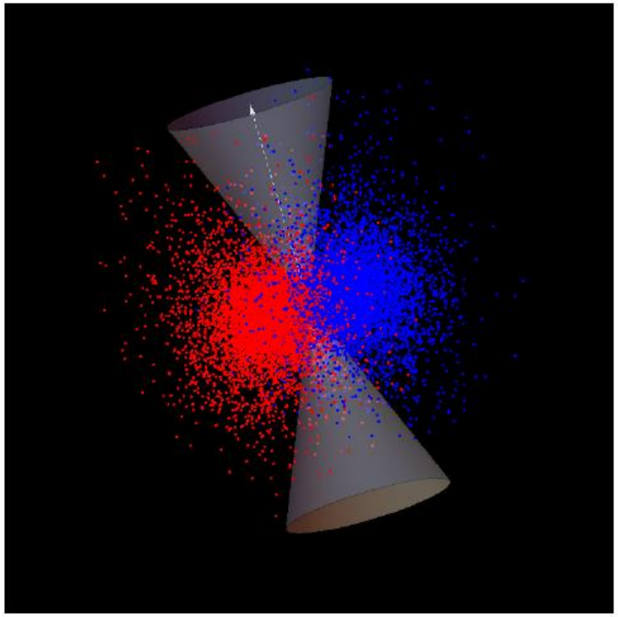
- number of clouds on the line of sight

The orbital motion in the torus

ALMA observations 2018:
torus in NGC1068



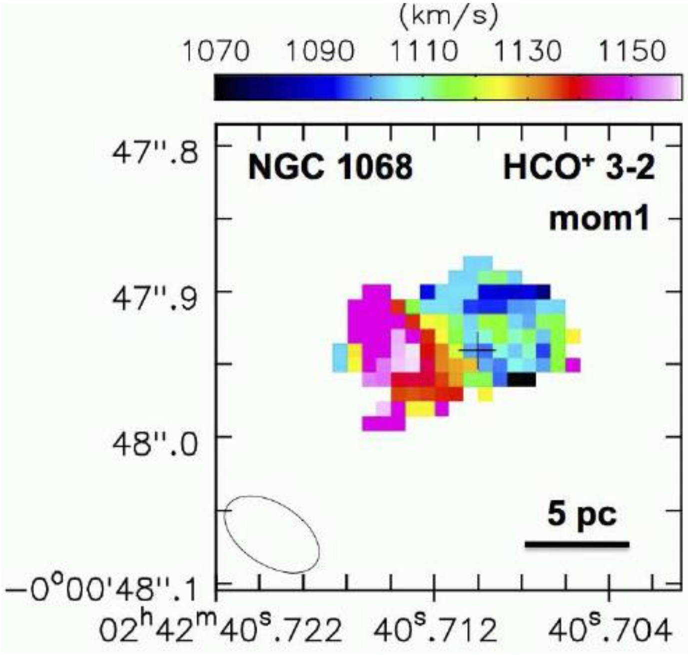
N-body simulation of
clumpy torus



Report of ESO, Feb.2018

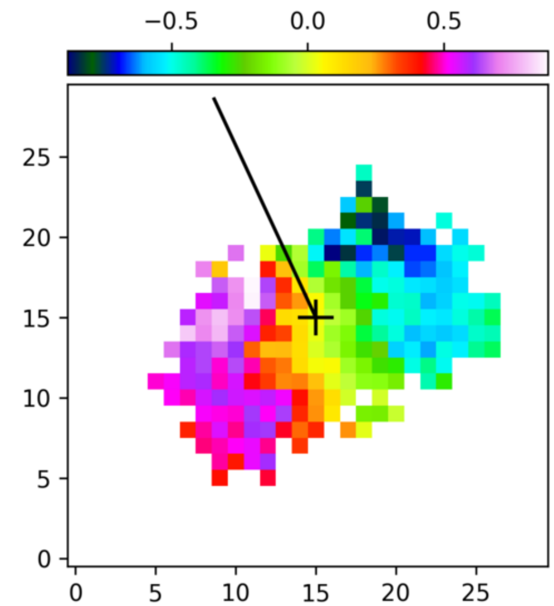
The velocity distribution in the torus of NGC1068

ALMA observation



Imanishi et al. , 2018

Our simulation



Bannikova et al. , in prep.

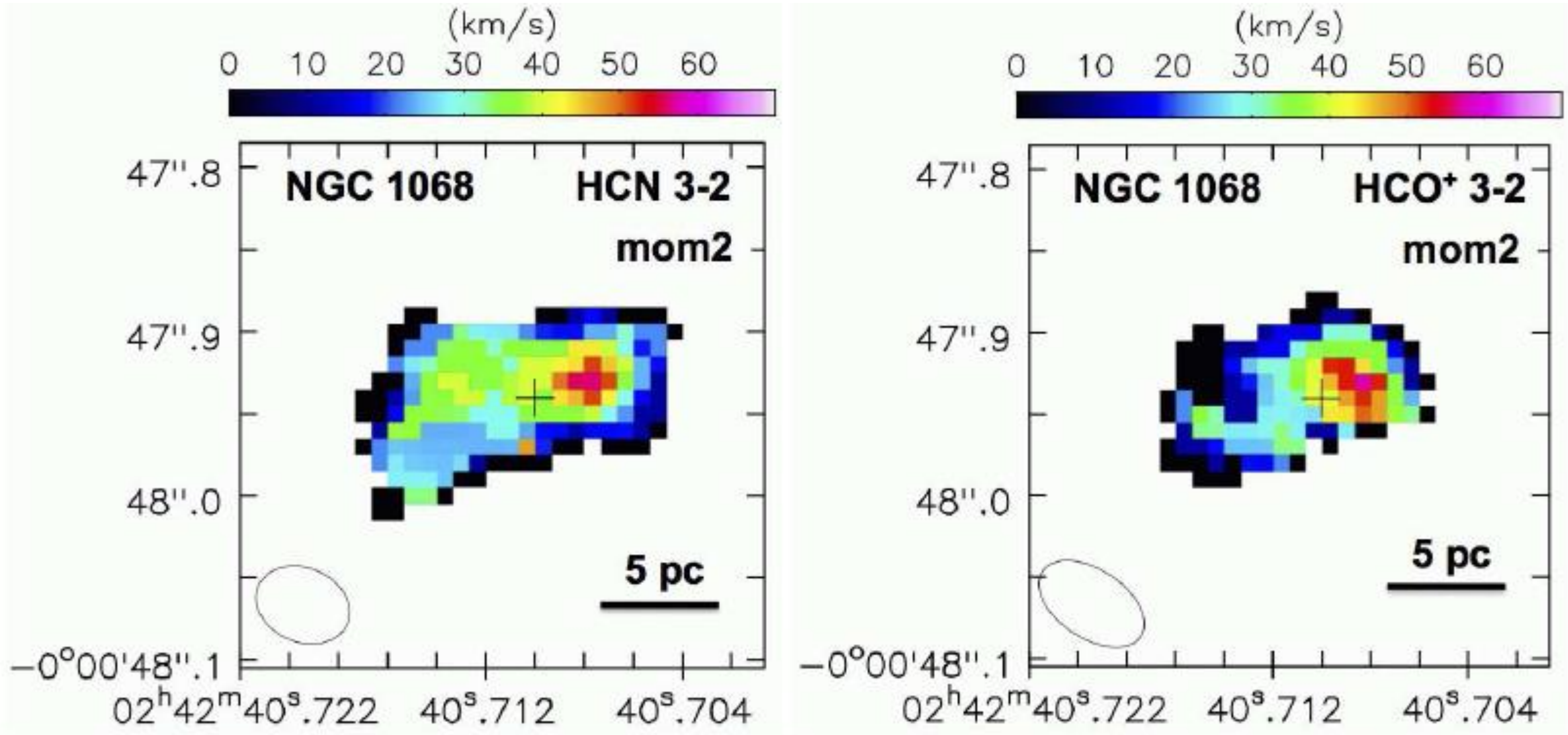
V_{obs}=20 km/s at distance r=3pc
for inclination=30grad V_{orb}=36 km/s
It means that $M_{smbh}=9*10^5 M_{sun}$
if the motion is keplerian

Our N-body simulation give the SMBH mass $M_{smbh}=5\ 10^6 M_{sun}$

The low velocity of the clouds in the torus can be explained by larger mass of SMBH

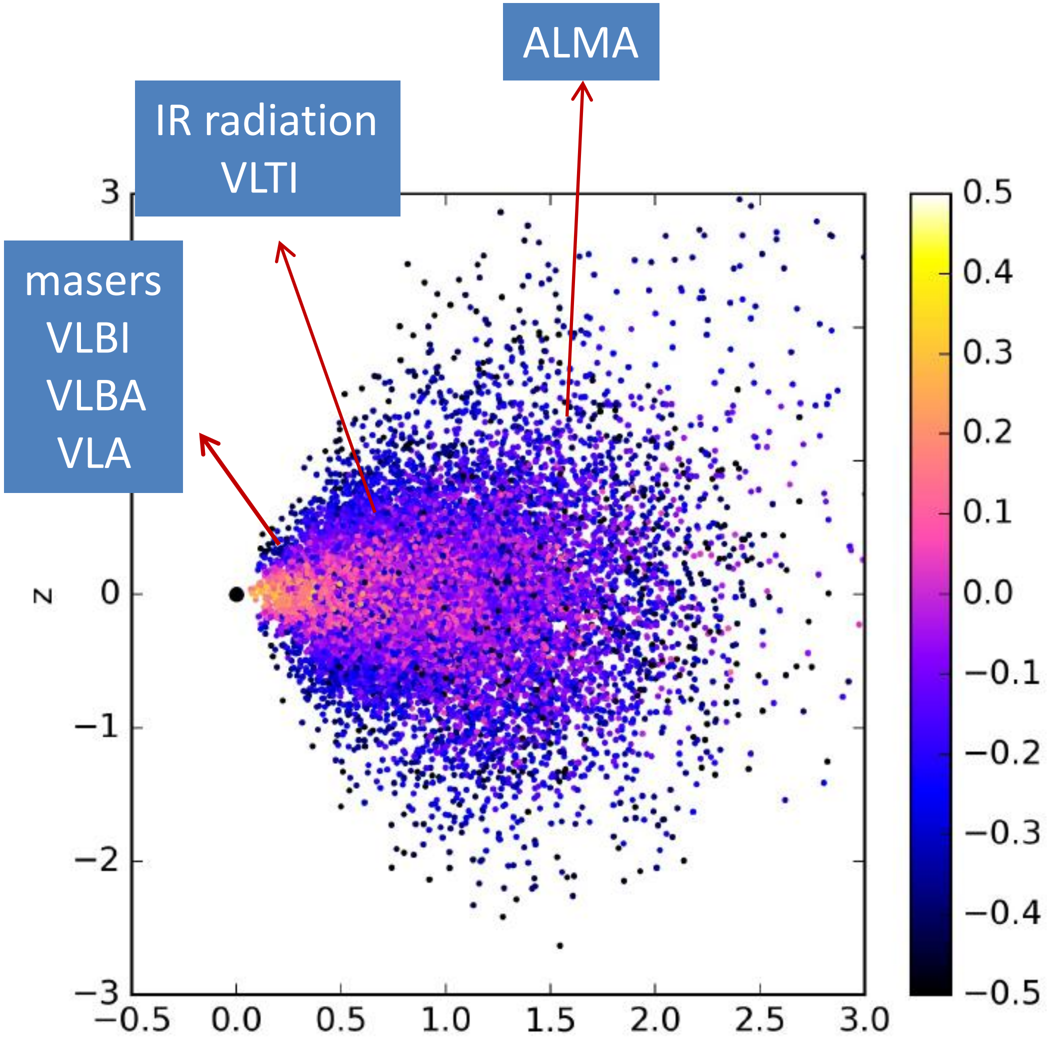
The velocity dispertion in the torus of NGC1068

ALMA observation



The anisotropy in velocity distribution can be a result of external accretion

Radiation of the dusty torus in different bands

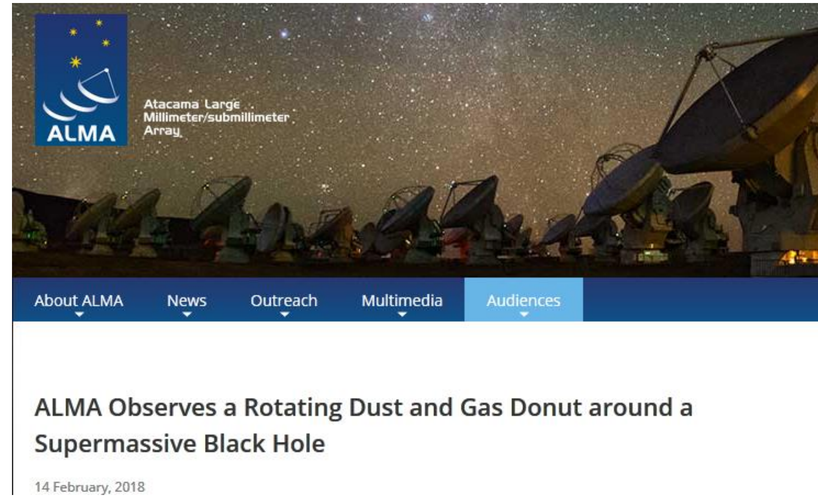


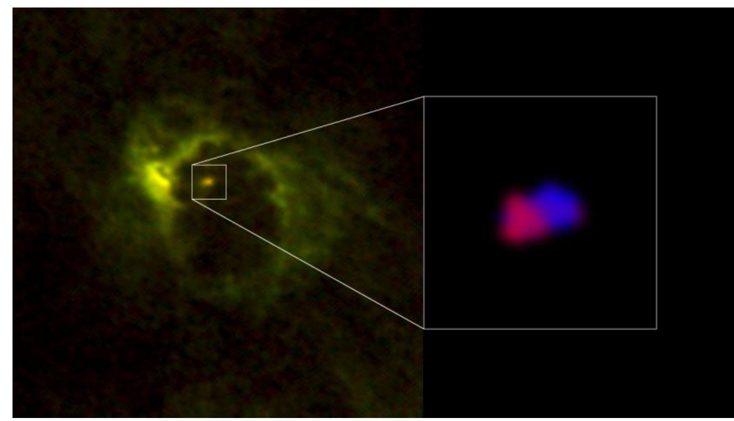
Conclusion

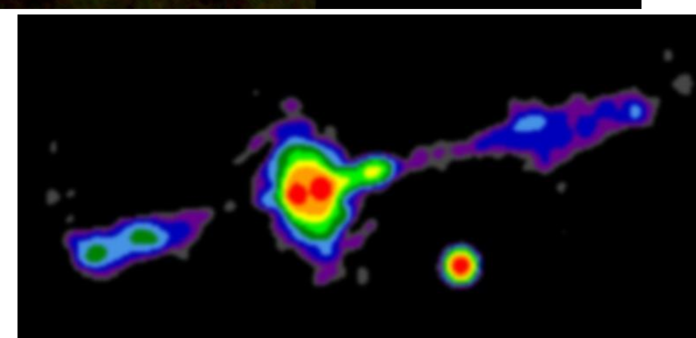
ALMA: new data for the central regions of AGNs. => New era in investigation of central engine in AGNs

New answers and new questions !!!

- Problem of the estimation of SMBH mass in NGC1068. We need to take into account the gravitational field of the torus.
- Anisotropy in intensity distribution and in velocity dispersion in NGC1068. This can tell us about event of external accretion. It needs to N-body simulation of this mechanism.
- The interpretation of new ALMA (+VLA for Cygnus A) observational data for others 7 galaxies



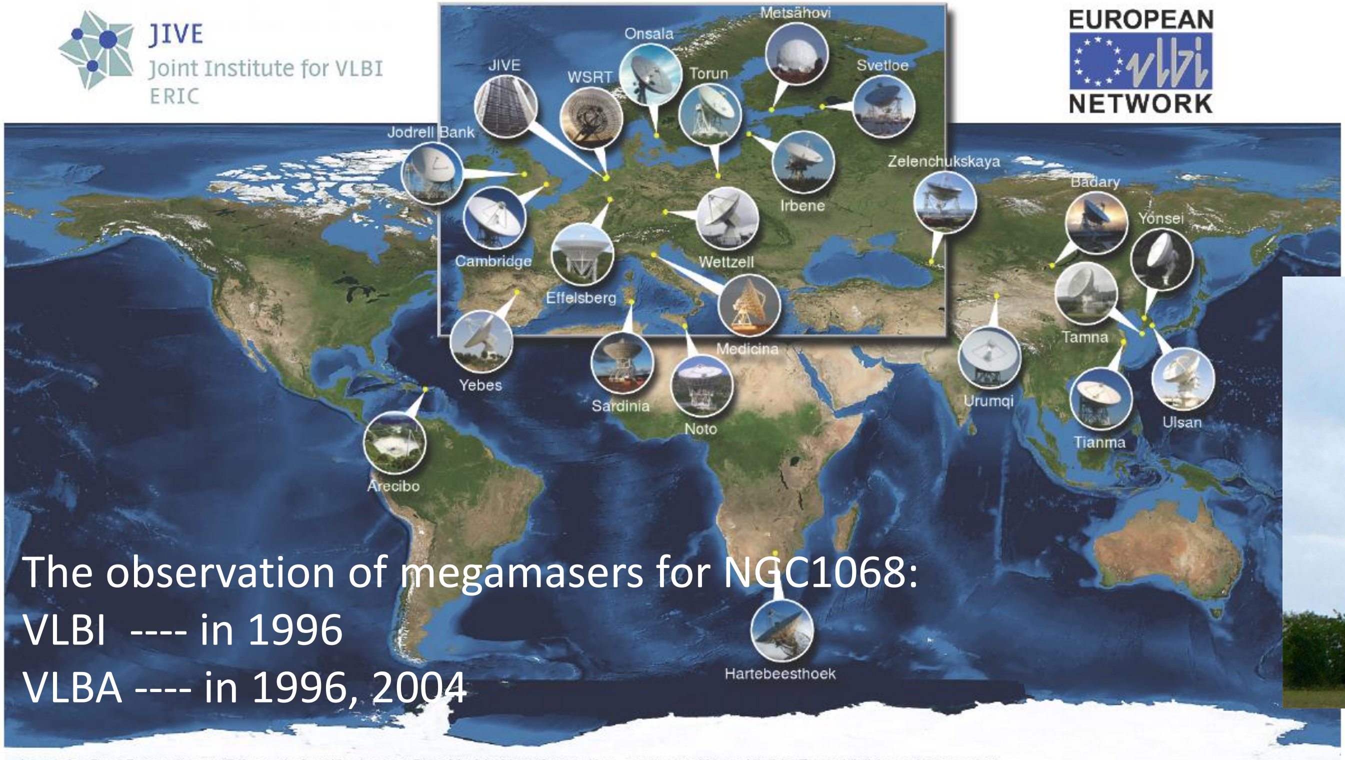




Some idea…

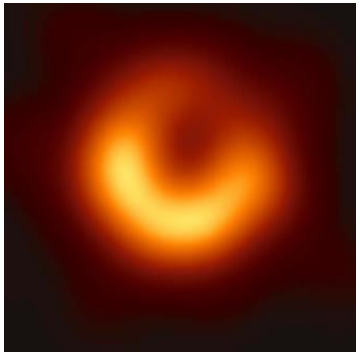
JIVE
Joint Institute for VLBI
ERIC

EUROPEAN vlbi NETWORK



The observation of megamasers for NGC1068:
VLBI ---- in 1996
VLBA ---- in 1996, 2004

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).



Era of black hole investigation