



# Supermassive black holes



# Plan of the lecture

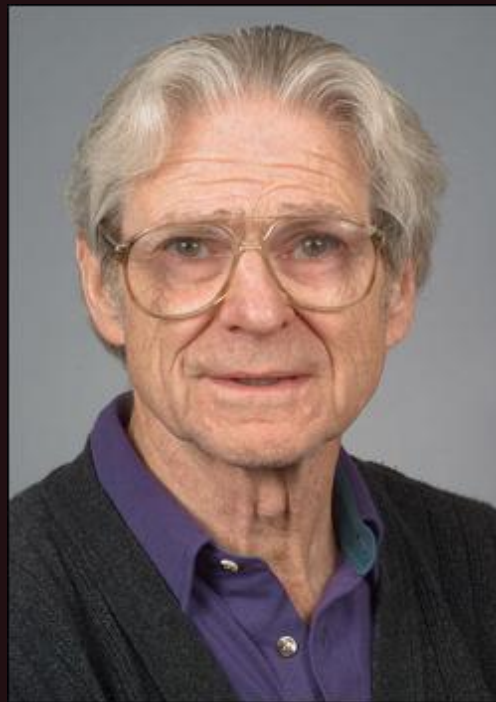
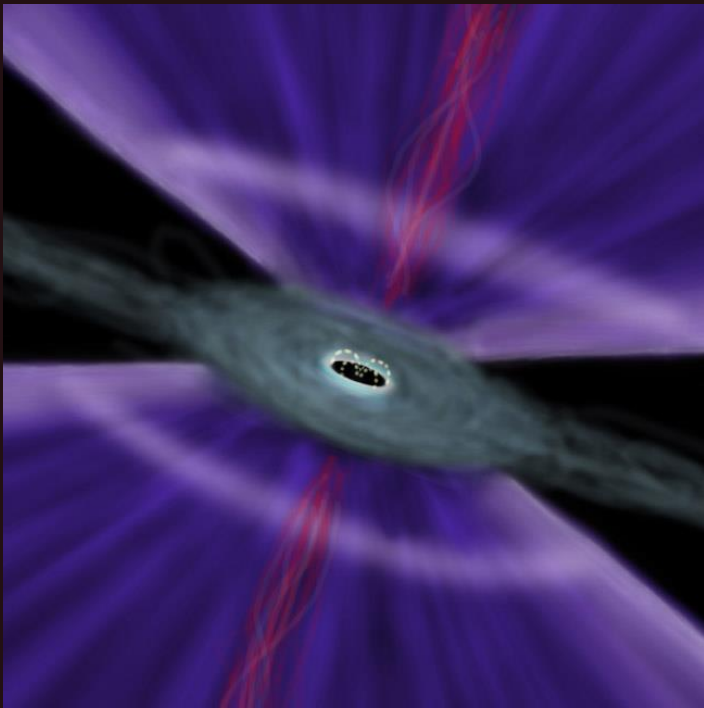
1. General information about SMBHs.
2. “Our” certain black hole: Sgr A\*.
3. SMBHs: from radio to gamma. AGNs.
4. Mass measurements

## Main reviews

- [arxiv: 1609.03562, 0907.5213](#) **Supermassive Black Holes**
- [astro-ph/0512194](#) **Constraints on Alternatives to Supermassive Black Holes**
- [astro-ph/0411247](#) **Supermassive Black Holes in Galactic Nuclei:  
Past, Present and Future Research**
- **arXiv: 0904.2615, 1001.3675, 1108.5102** **Mass estimates (methods)**
- **arXiv: 1302.2643** **The Mass of Quasars**
- **arXiv: 1504.03330** **Elliptical Galaxies and Bulges of Disk Galaxies:  
Summary of Progress and Outstanding Issues**
- **arXiv: 1501.02171** **The Galactic Center Black Hole Laboratory**
- **arXiv: 1501.02937** **Galaxy bulges and their massive black holes**
- **IMBHs: Koliapanos 1801.01095, Mezcua 1705.09667**
- **arXiv: 1707.07134** **AGN**

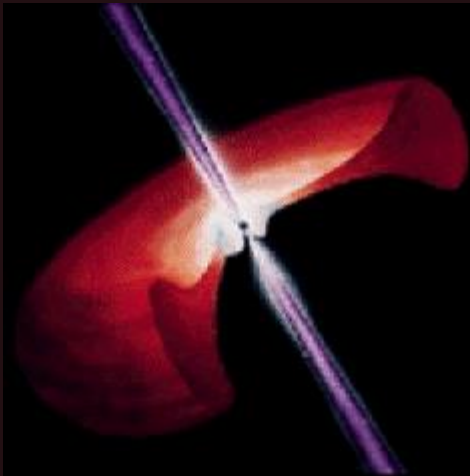
# Some history

The story starts in 60-s when the first quasars have been identified (Schmidt 1963). Immediately the hypothesis about accretion onto supermassive BHs was formulated (Salpeter, Zeldovich, Novikov, Linden-Bell).

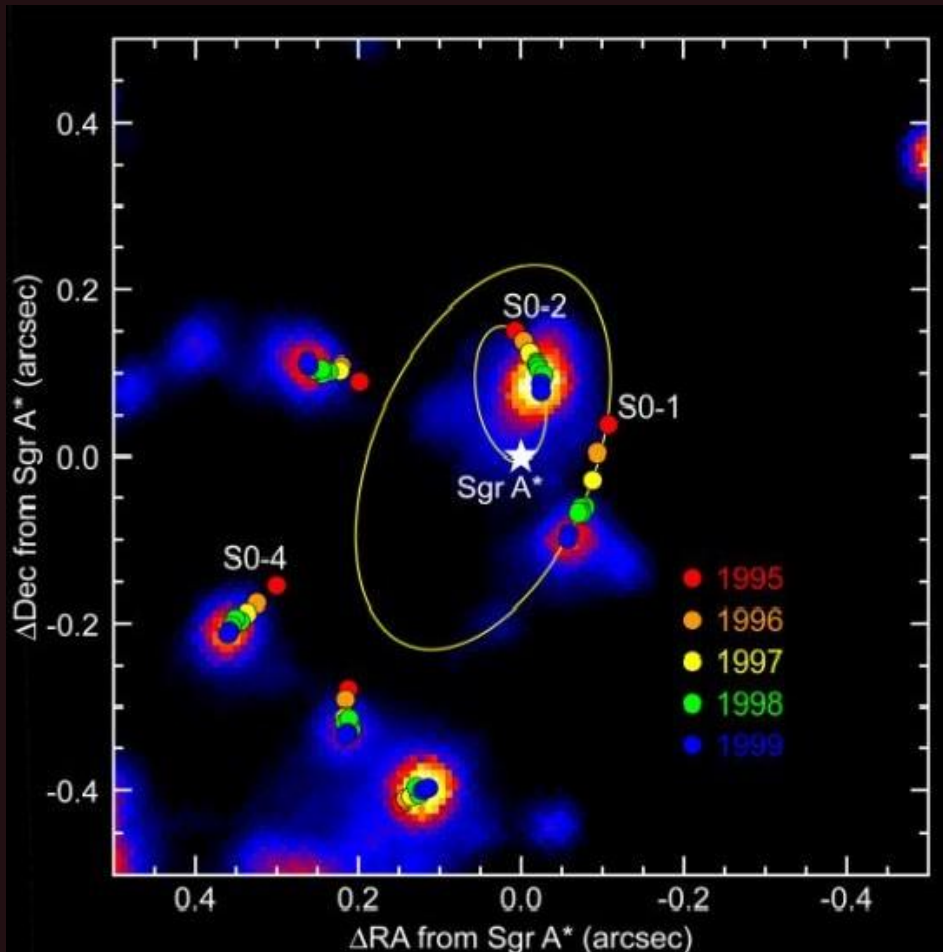


# General info

- All galaxies with significant bulges should have a SMBH in the center.
- SMBH are observed already at redshifts  $z \sim 6$  and even further
- Several percent of galaxies have active nuclei
- Now we know tens of thousand of quasars and AGNs, all of them can be considered as objects with SMBHs
- Measured masses of SMBHs are in the range  $10^6 - 10^{10}$  solar masses.
- Masses are well-measured for tens of objects.
- The most clear case of a SMBH is Sgr A\*.



# Sgr A\*



The case of Sgr A\* is unique. Thanks to direct measurements of several stellar orbits it is possible to get a very precise value for the mass of the central object.

Also, there are very strict limits on the size of the central object. This is very important taking into account alternatives to a BH.

The star SO-2 has the orbital period 15.2 yrs and the semimajor axis about 0.005 pc.

See [astro-ph/0309716](https://arxiv.org/abs/astro-ph/0309716) for some details

# The region around Sgr A\*



The result of summation of 11 expositions by Chandra (590 ksec).

Red 1.5-4.5 keV,  
Green 4.5-6 keV,  
Blue 6-8 keV.

The field is 17 to 17 arcminutes  
(approximately 40 to 40 pc).

Multiwavelength observations of Sgr A\*  
are summarized in 1501.02164.

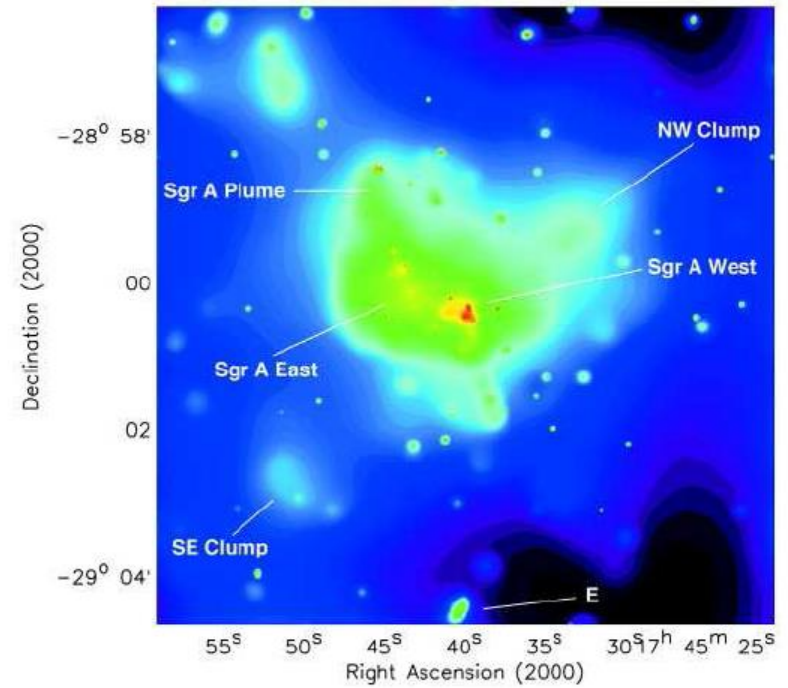
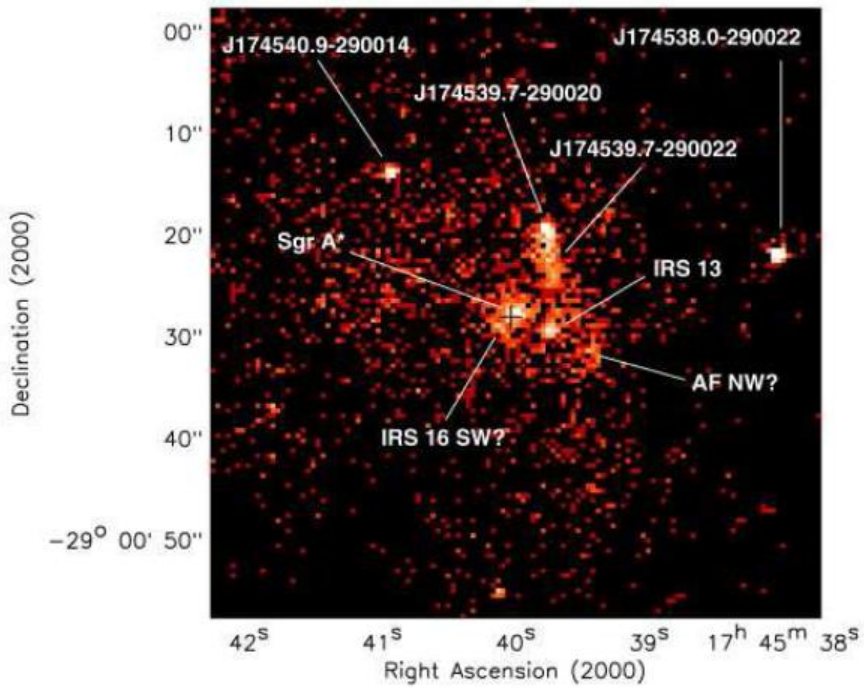
(Park et al.; Chandra data)  
[astro-ph/0311460](https://arxiv.org/abs/astro-ph/0311460)

# A closer look

Chandra. 2-10 keV

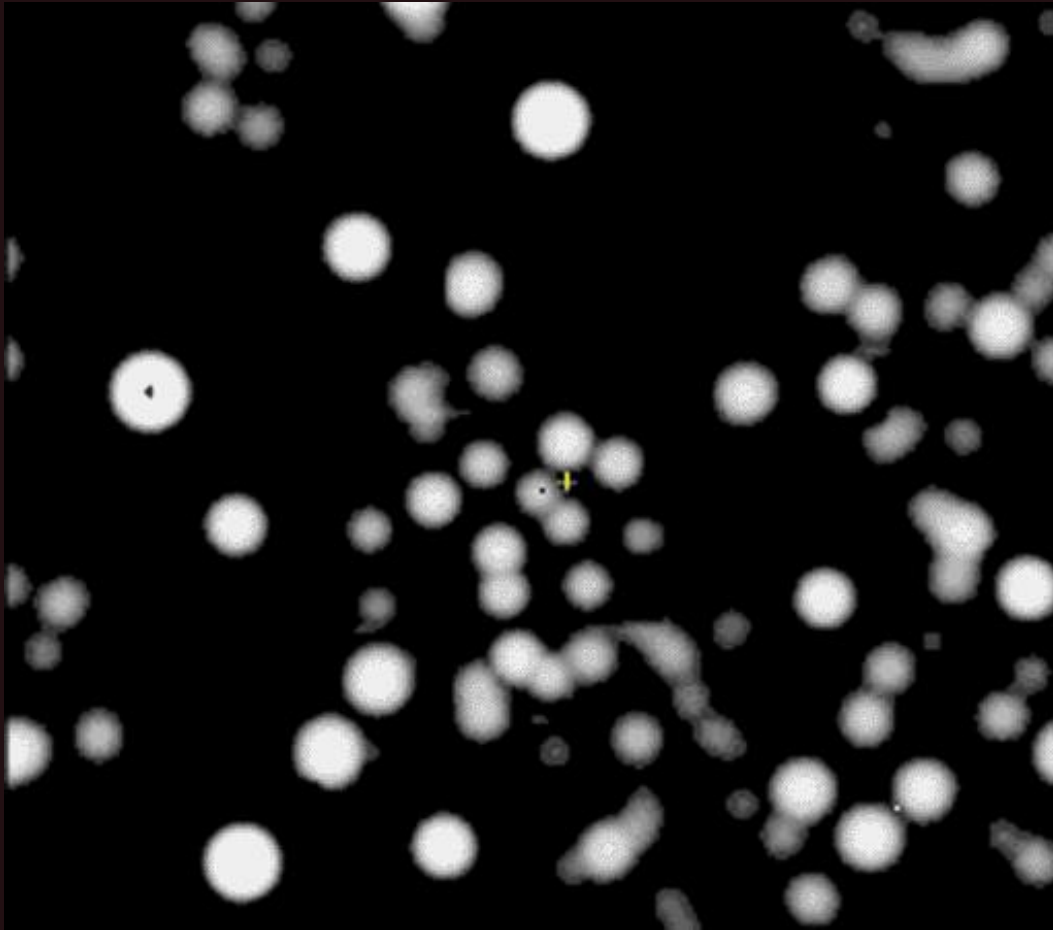
2.4 pc

20 pc



1007.4174

# Stellar dynamics around Sgr A\*

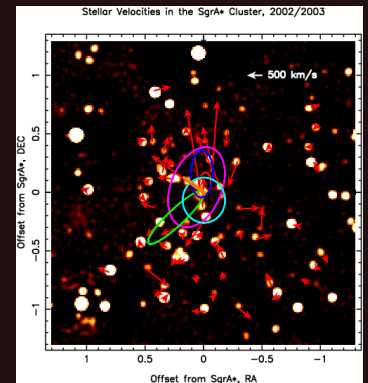


With high precision we know stellar dynamics inside the central arcsecond ([astro-ph/0306214](#))

The BH mass estimate is  $\sim 4 \cdot 10^6 M_\odot$

It would be great to discover radio pulsars around Sgr A\* ([astro-ph/0309744](#)).

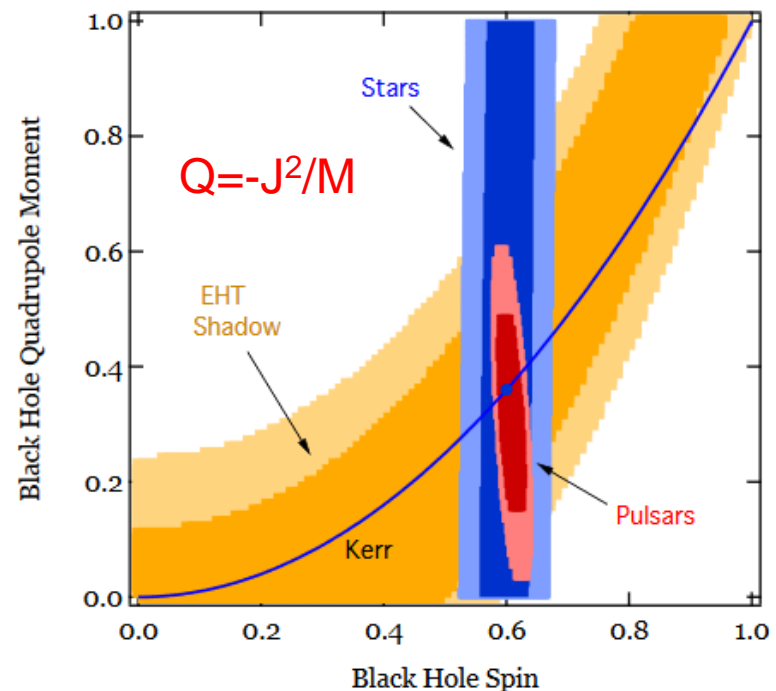
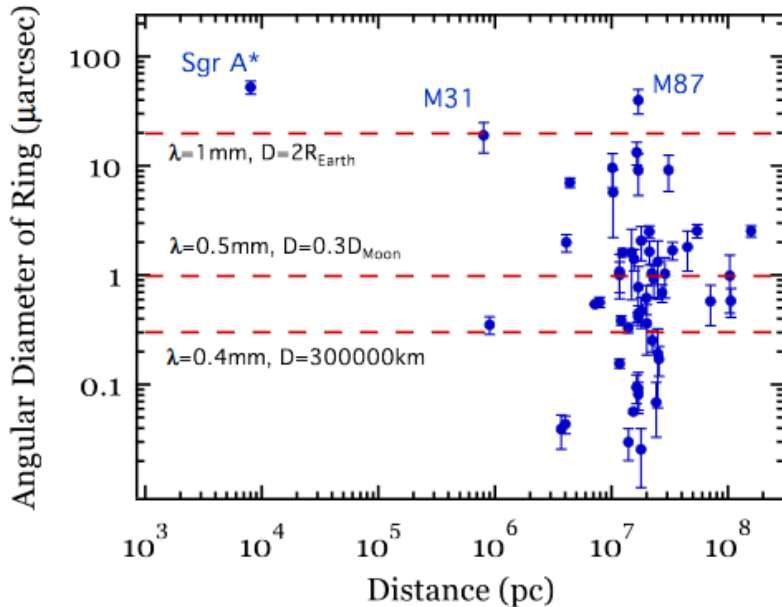
(APOD [A. Eckart](#) & [R. Genzel](#) )



See more data in 0810.4674

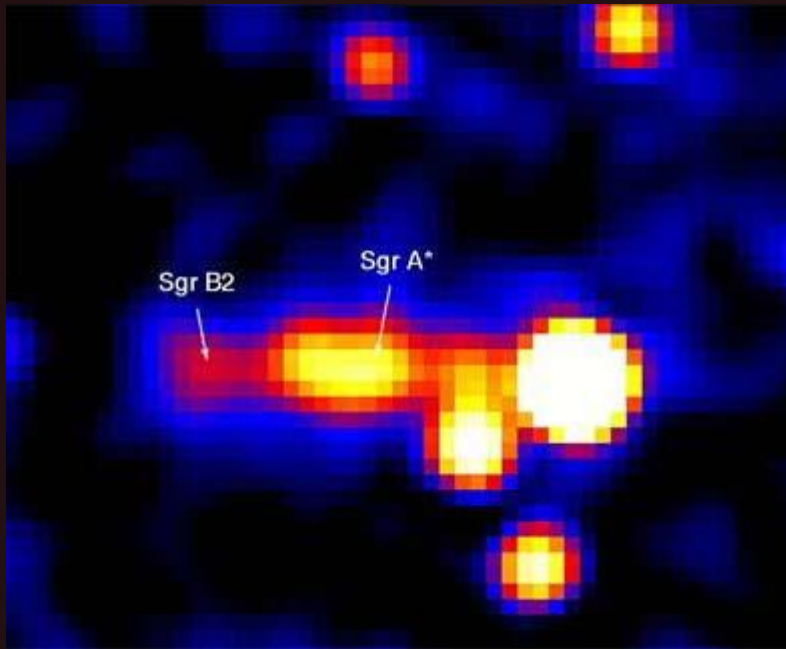
Stars-star interactions can be important: [arXiv 0911.4718](#)

# General relativity test, EHT, etc.



In the very near future Sgr A\* might be the best laboratory to study GR. EHT observations and identifications of PSRs in the vicinity of the BH might help to probe the no-hair theorem and determine the main properties of the BH with high precision.

# Observations aboard Integral



(Revnivtsev et al.)

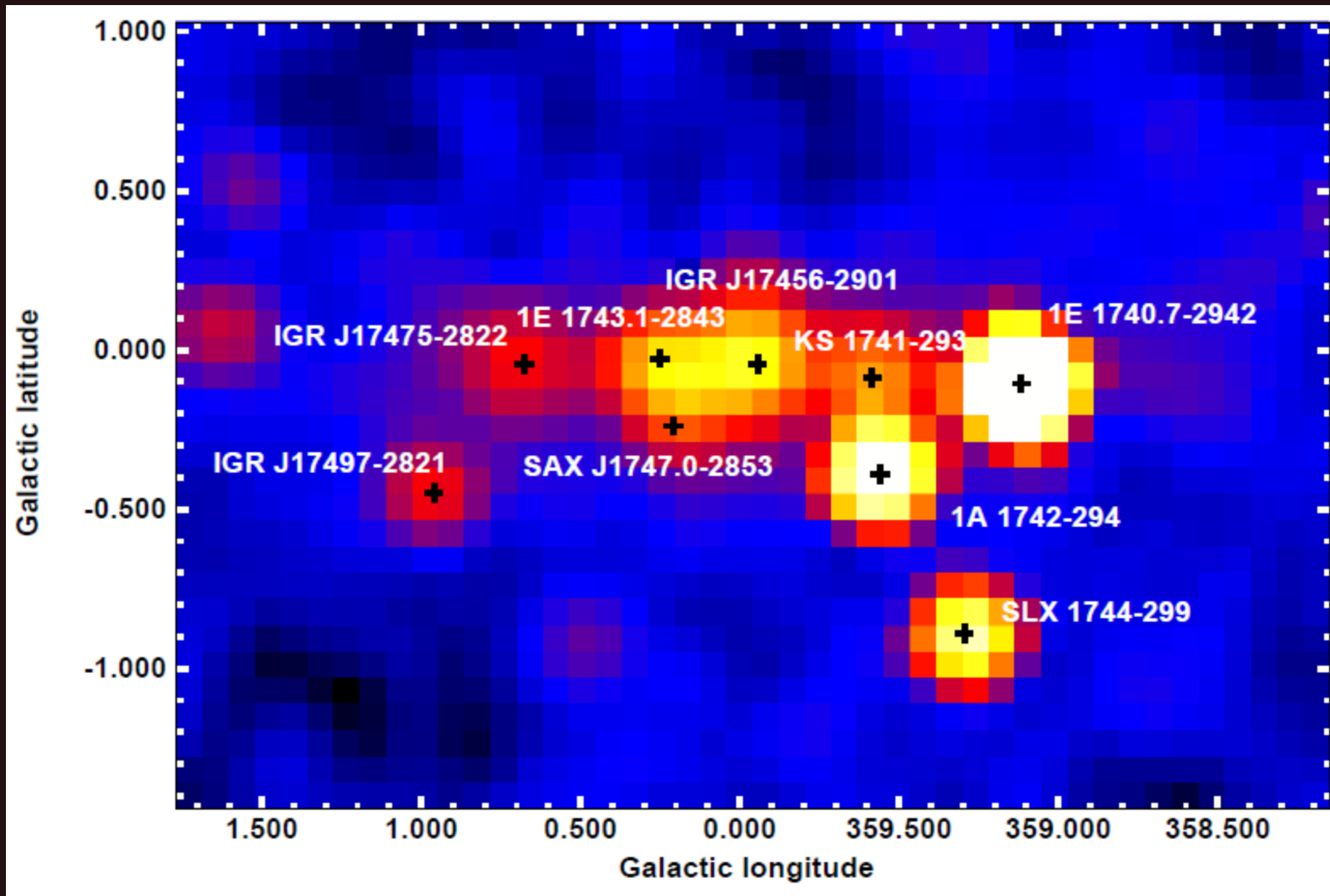
**The galactic center region  
is regularly monitored  
by Integral.**

At present “our” black hole is not active.  
However, it was not so in the past.

It is suspected that about 350 years ago  
Sgr A\* was in a “high state”.  
Now the hard emission generated by Sgr A\*  
at this time reached Sgr B2.  
Sgr B2 is visible due to fluorescence  
of iron.

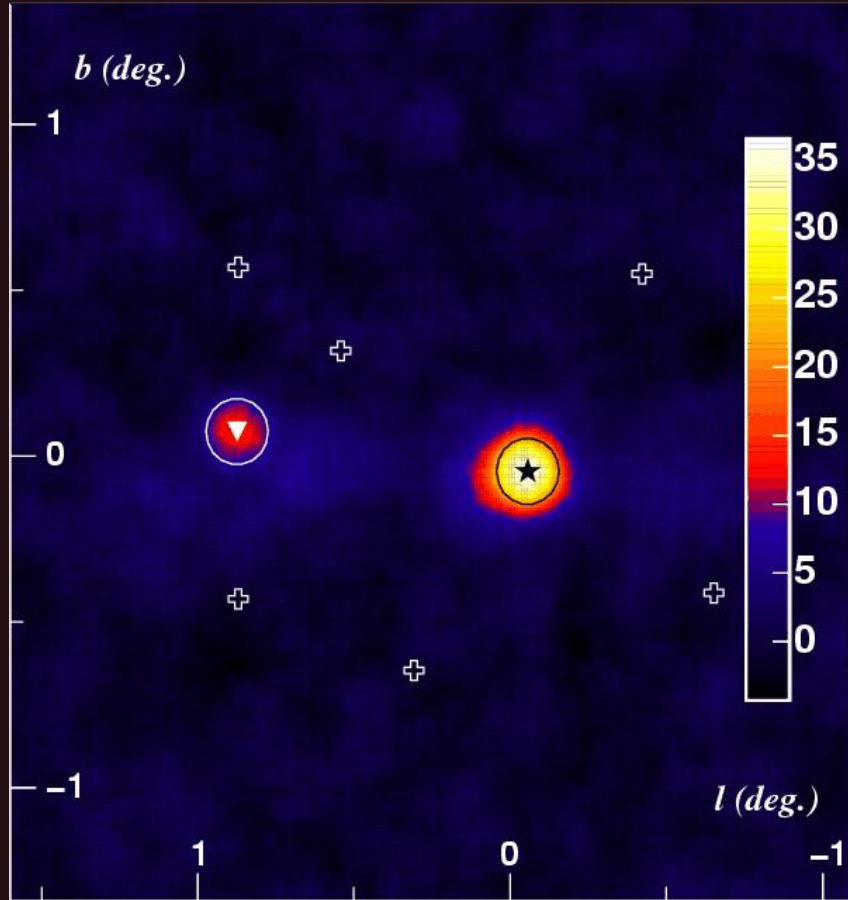
Probably, there have been several strong  
flares in the past 1307.3954.

# More Integral data



1007.4174

# Sgr A\* and H.E.S.S.



See [astro-ph/0503354](#), 0709.3729

Still, resolution is not good enough to exclude the contribution of some near-by (to Sgr A\*) sources.

(Aharonian et al. 2005)

# X-ray bursts from Sgr A\*

Bursts can happen about once in a day.  
The flux is increased by a factor of a few  
(sometimes even stronger).

A bright burst was observed on Oct. 3, 2002  
([D. Porquet et al. astro-ph/0307110](#)).

Duration: 2.7 ksec.

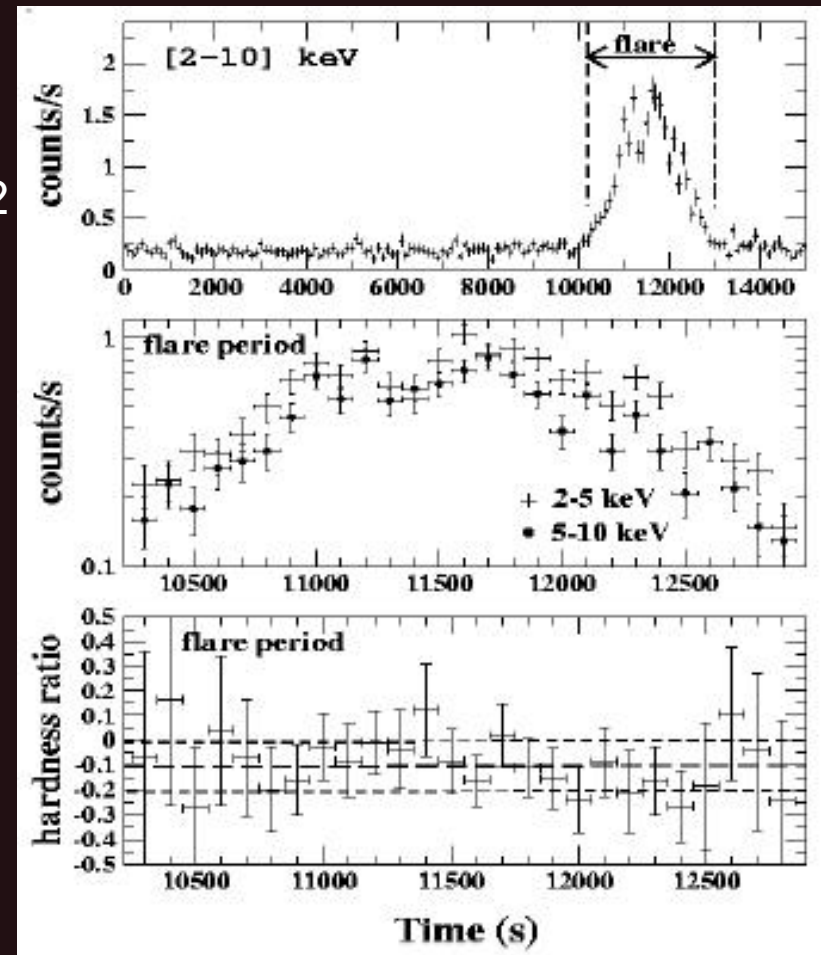
The flux increased by a factor  $\sim 160$ .

Luminosity:  $3.6 \cdot 10^{35}$  erg/s.

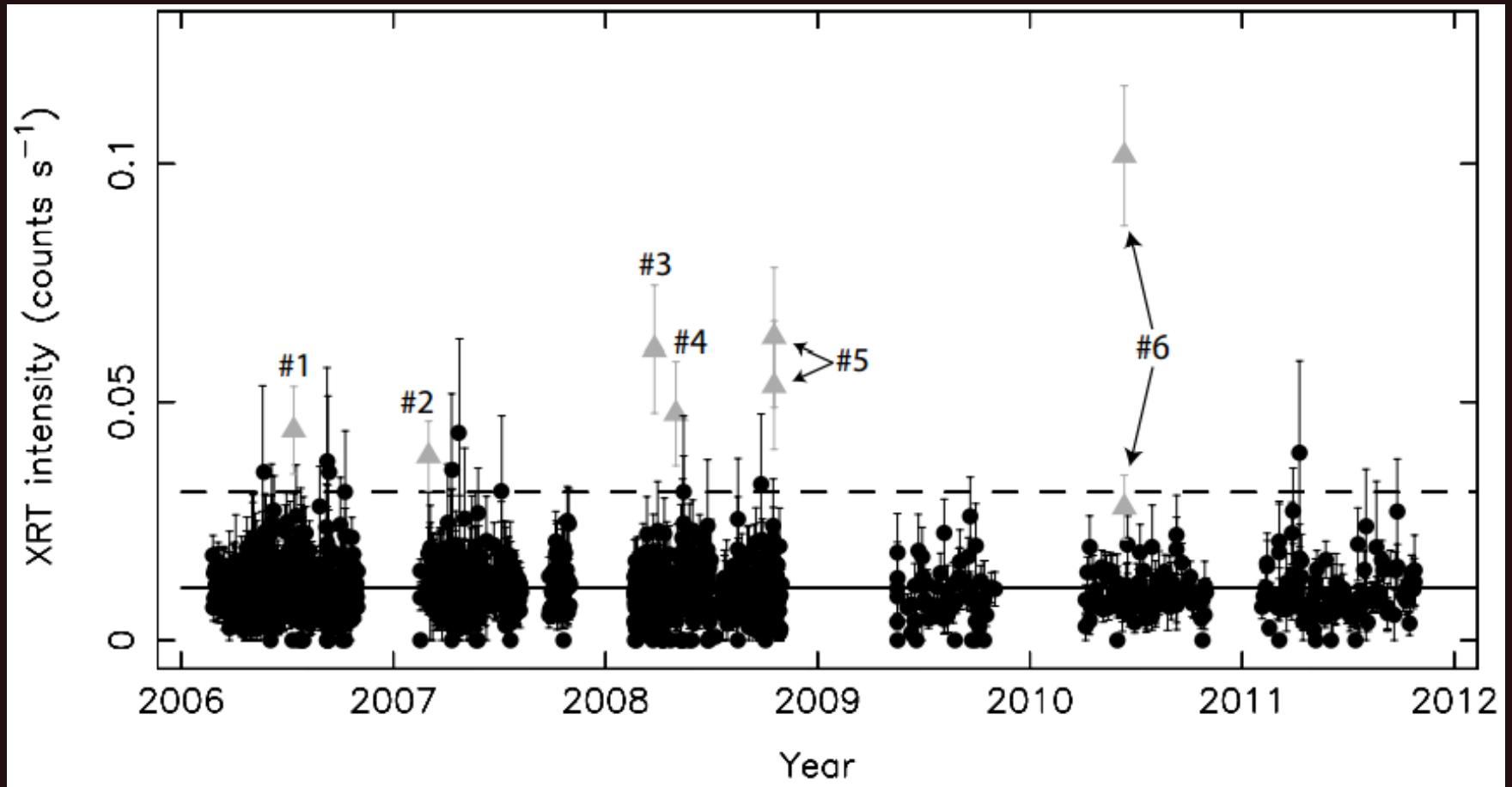
In one of the bursts, on Aug. 31, 2004,  
QPOs have been discovered.

The characteristic time: 22.2 minutes  
([astro-ph/0604337](#)).

In the framework of a simple model  
this means that  $a=0.22$ .



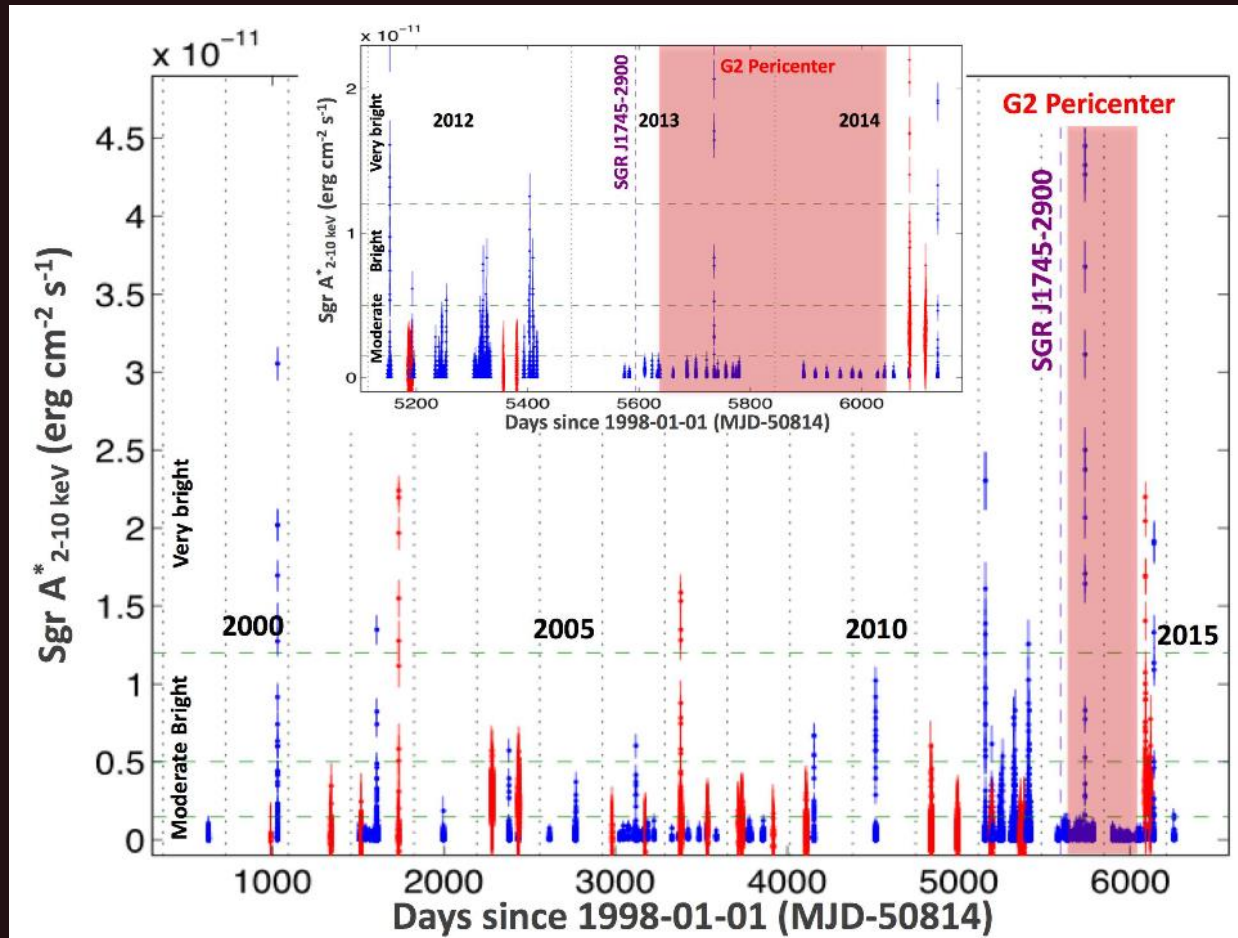
# SWIFT monitoring of Sgr A\*



1210.7237

See 1501.02171 about accretion physics around Sgr A\*

# XMM-Newton and Chandra monitoring of Sgr A\*

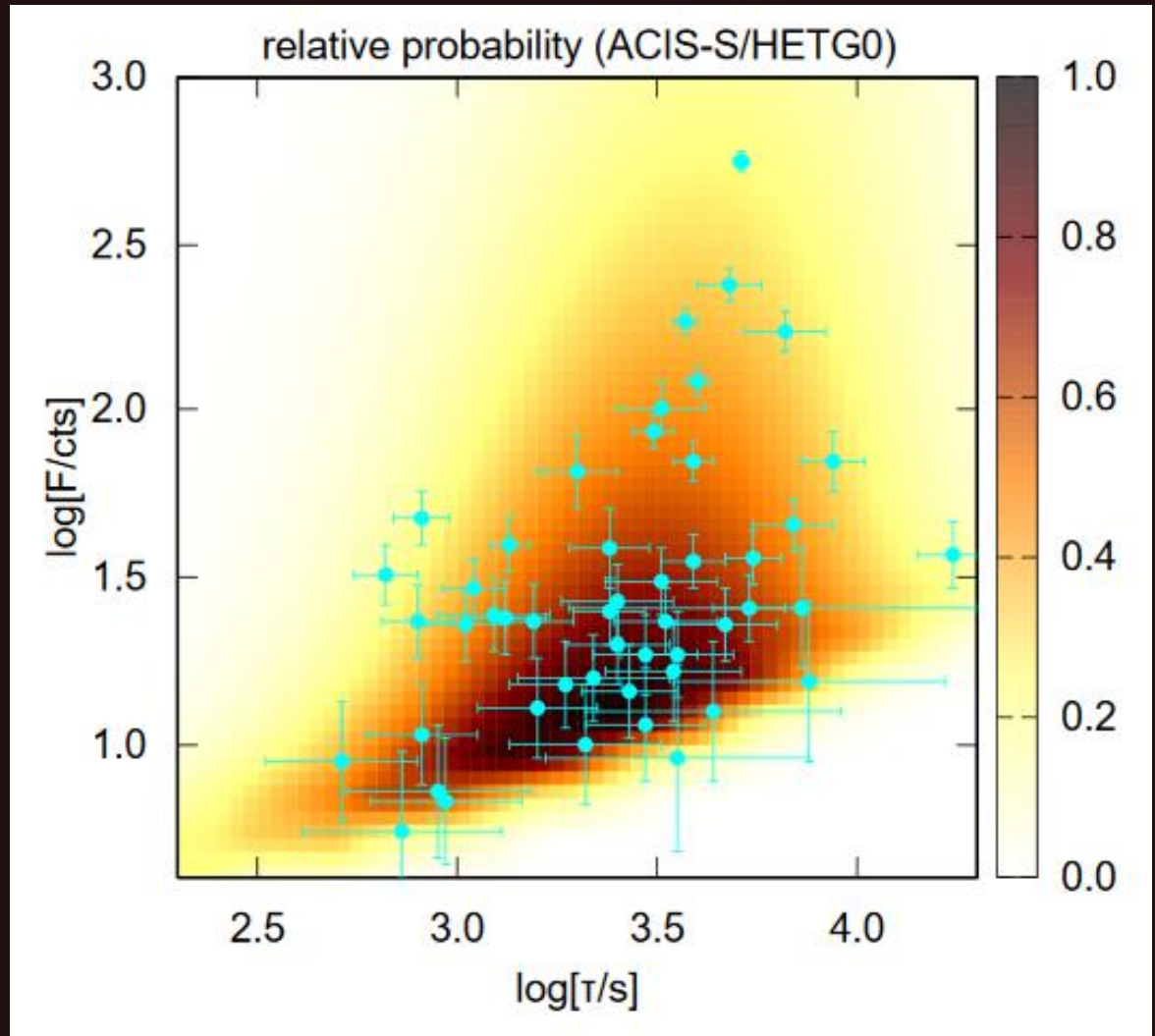


Plenty of data during all time of Chandra and XMM-Newton observations.

Very detailed statistics.

# Chandra monitoring

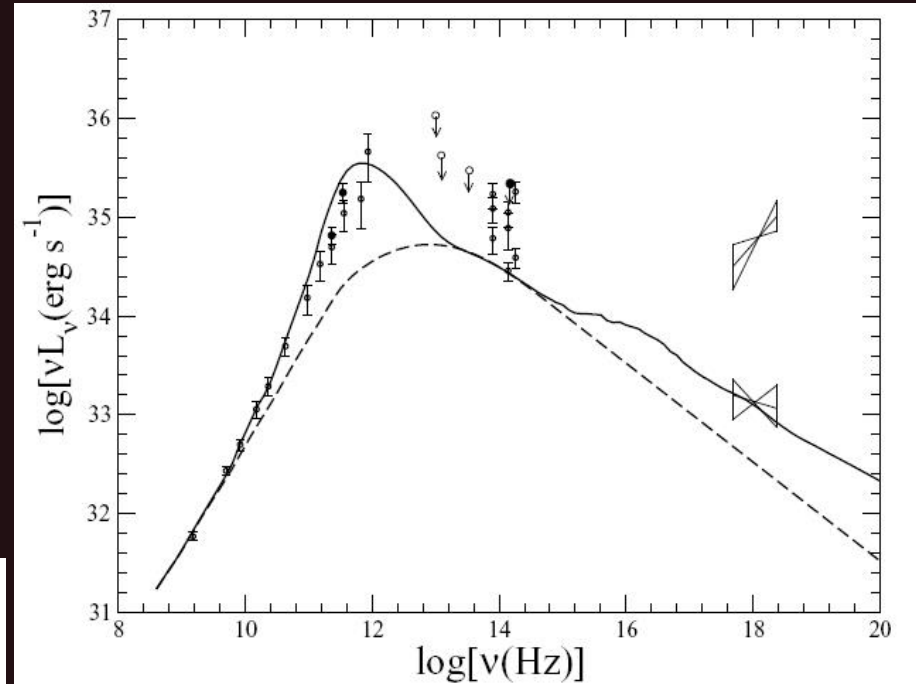
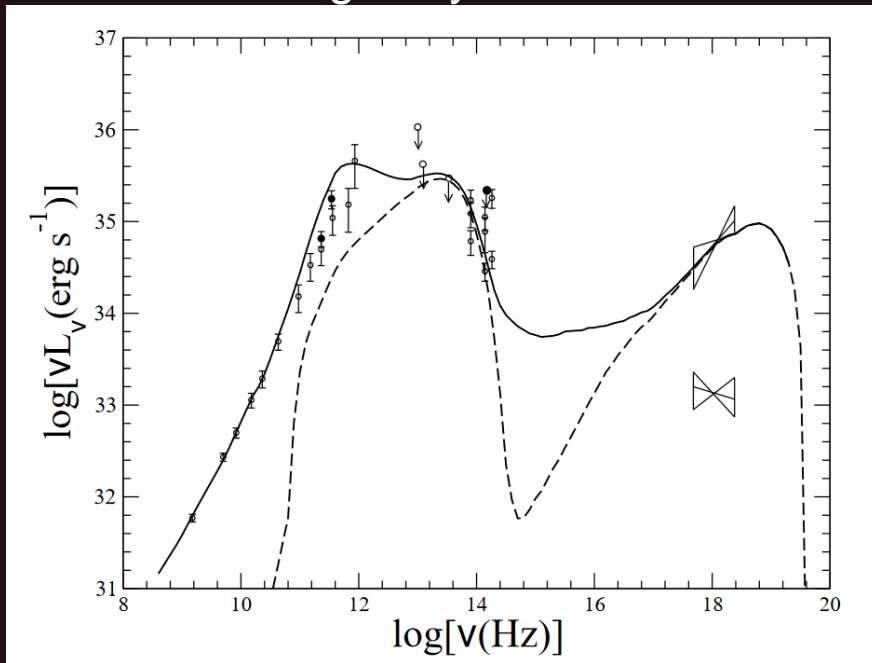
1999-2012



1709.03709

# IR burst of Sgr A\*

Observations on Keck, VLT.  
The scale of variability was  
about 30 minutes.  
This is similar to variability  
observed in X-rays.  
The flux changed by a factor 2-5.

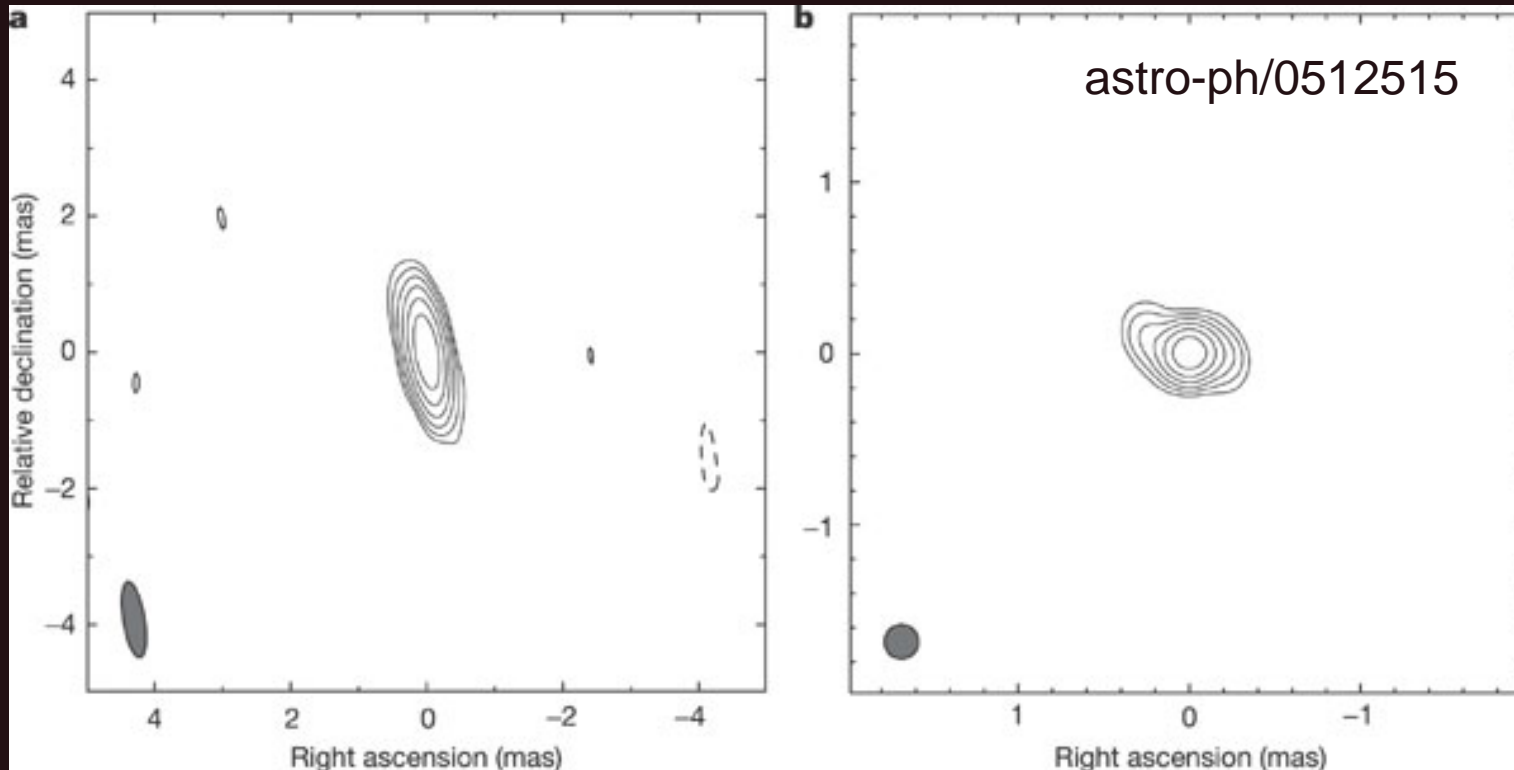


*Non-thermal synchrotron?*

([Feng Yuan](#), [Eliot Quataert](#), [Ramesh Narayan](#) astro-ph/0401429)

# Constraints on the size of Sgr A\*

Using VLBI observations a very strict limit was obtained for the size of the source Sgr A\*: 1. a.e.

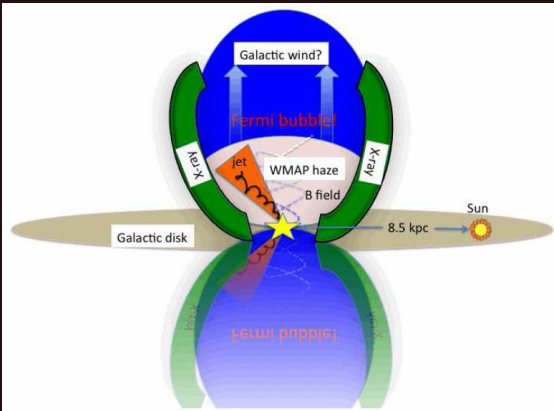
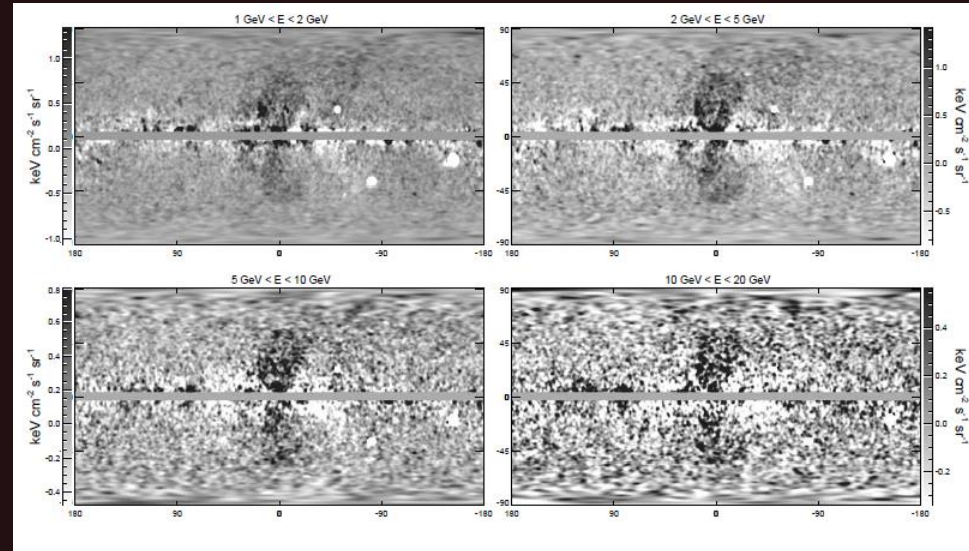
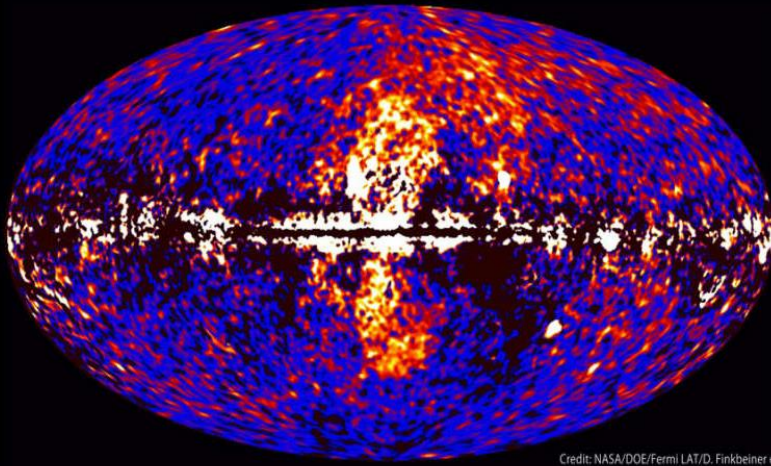


New VLBI observations demonstrate variability at 1.3mm from the region about few Schwarzschild radii. arXiv: 1011.2472

Strict limits on the size and luminosity with known accretion rate provides arguments in favor of BH interpretation (arXiv: 0903.1105)

# Bubbles in the center of the Galaxy

Fermi data reveal giant gamma-ray bubbles



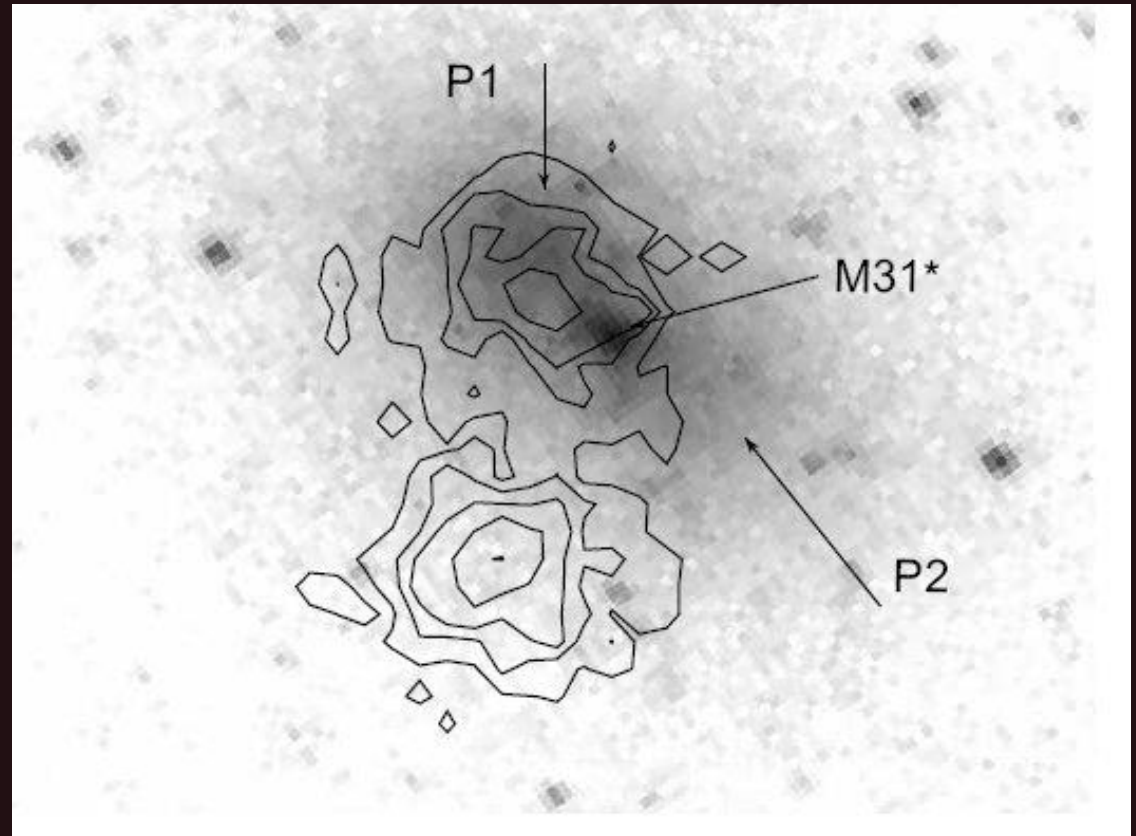
Structures have been already detected in  
microwaves (WMAP) and in soft X-rays (ROSAT)

# M31

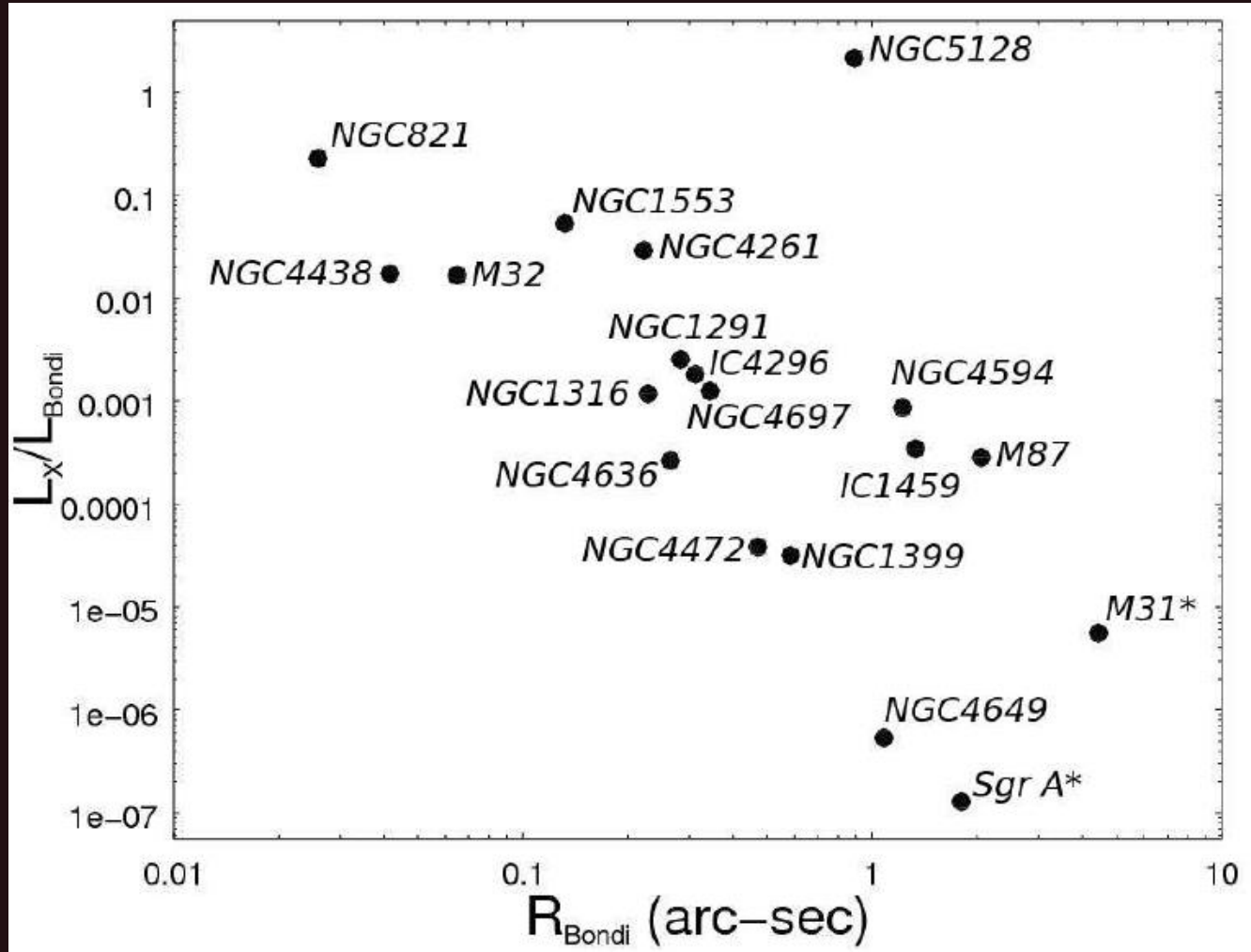
Probably, thanks to observations on Chandra and HST the central SMBH was discovered in M31 (astro-ph/0412350).

$M \sim (1-2) \cdot 10^8 M_{\text{solar}}$   
 $L_x \sim 10^{36} \text{ erg/s}$

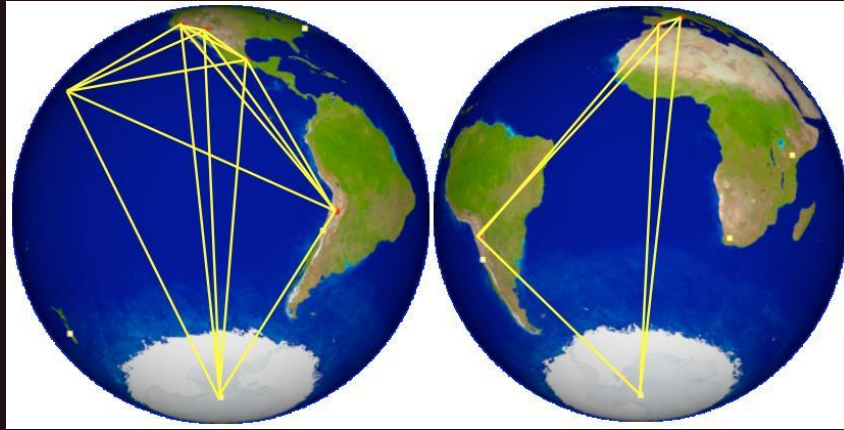
See recent data in  
arXiv: 0907.4977



# A “large” BH in M31



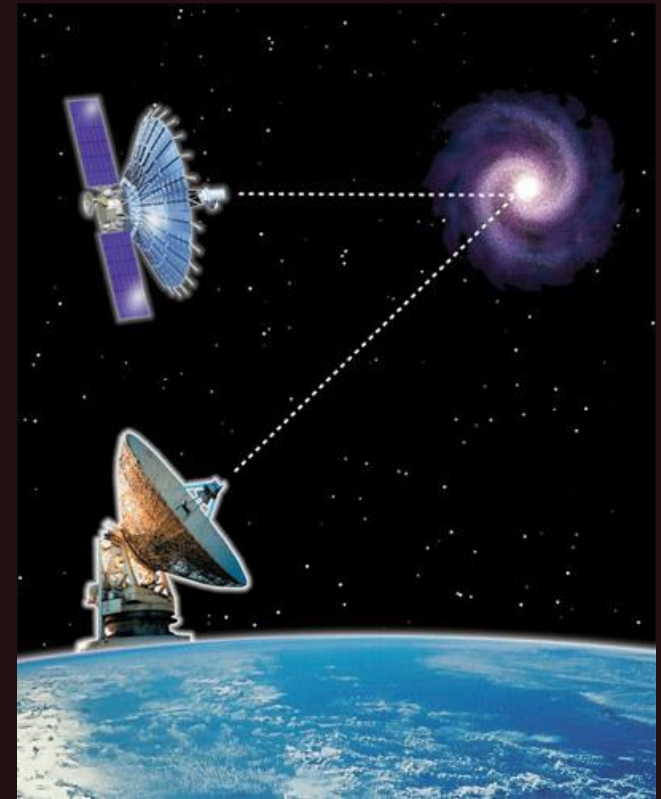
# Observational projects: horizon



Event Horizon telescope



ALMA+mm-VLBI



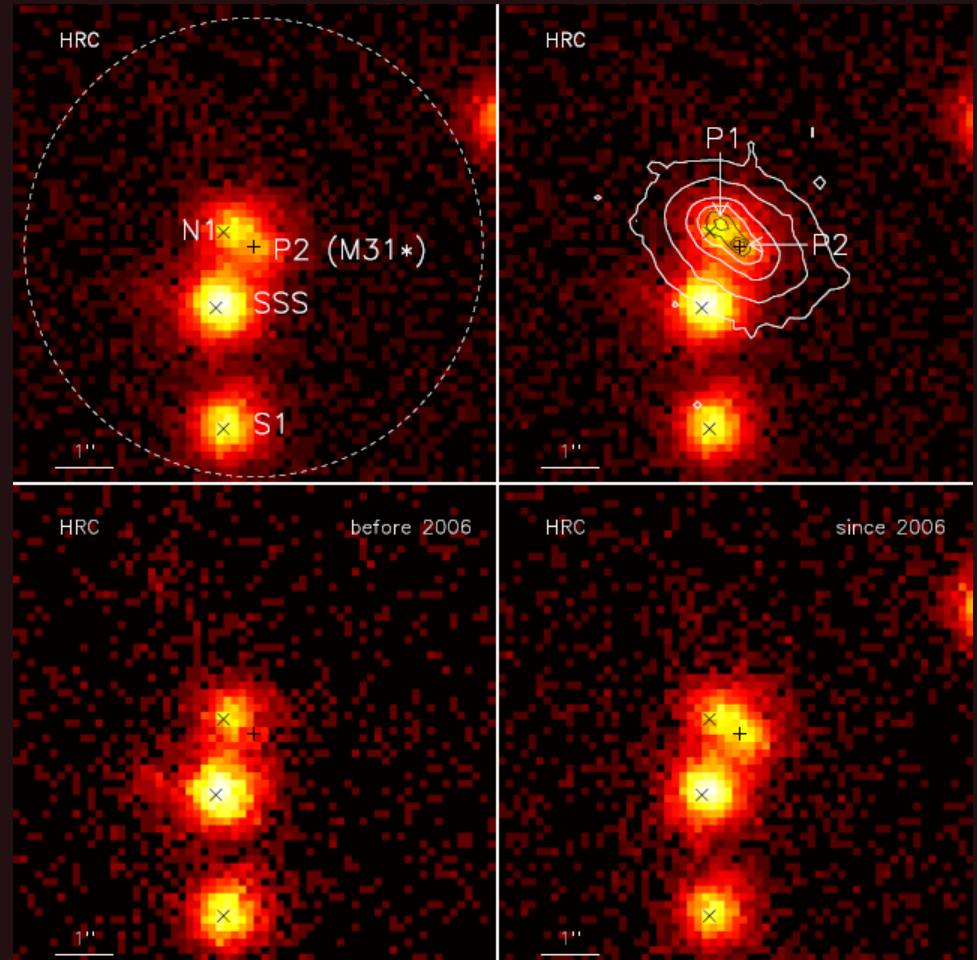
Radioastron

# Activity of the M31 SMBH

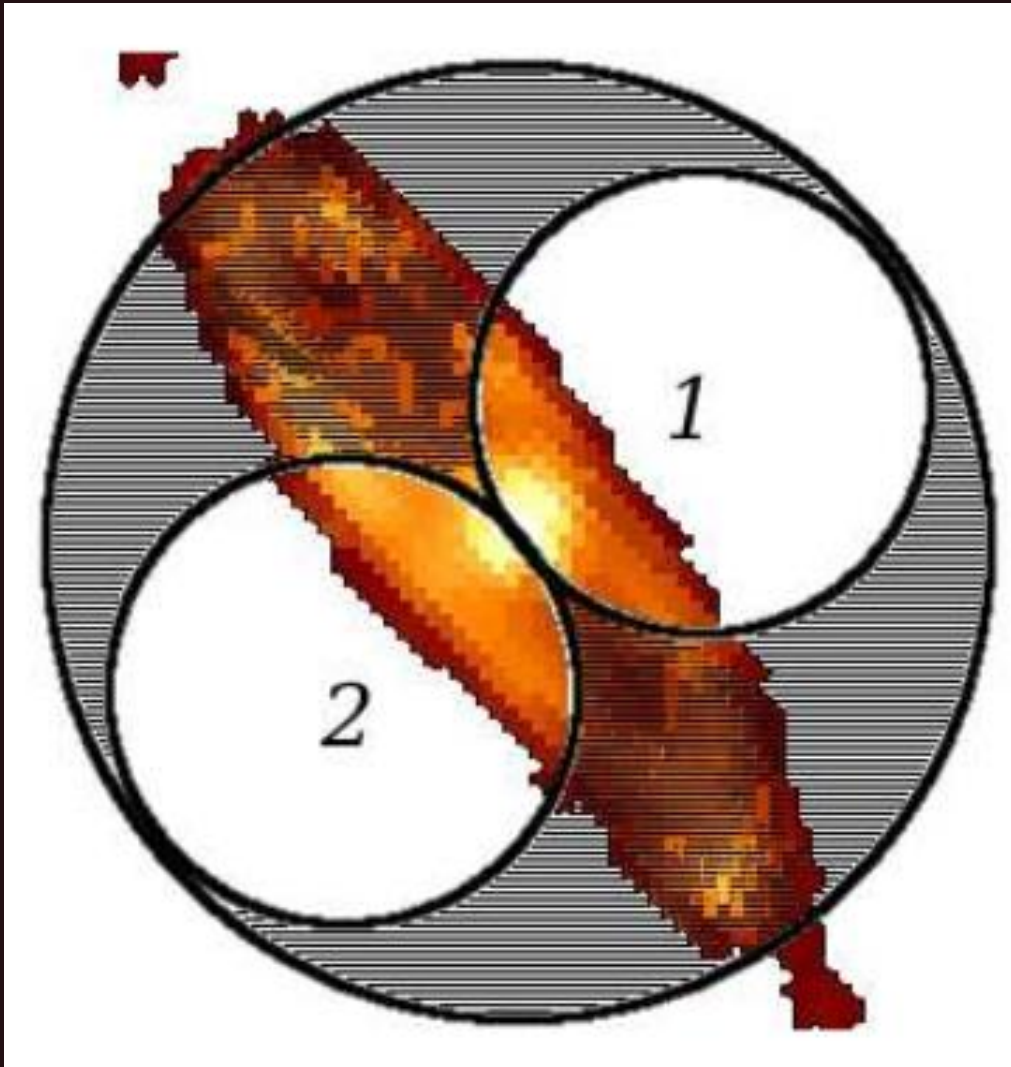
SMBH with 100-200 solar masses.

Mostly in the quiescent state.  
Luminosity is billions of times less than the Eddington.

Recently, bursts similar to the activity of Sgr A\* have been detected from the SMBH in M31.



# Fermi bubbles analogues in M31?



Using Fermi data the authors demonstrated that the shape of gamma-ray image is more consistent with a structure similar to Fermi bubbles in our Galaxy.

# Active galactic nuclei and quasars

*The classification is not very clear*

- Quasars
  - a) radio quiet (two types are distinguished)
  - b) radio loud
  - c) OVV (Optically Violently Variable)
- Active galaxies
  - a) Seyfert galaxies (types 1 and 2)
  - b) radio galaxies
  - c) LINERs
  - d) BL Lac objects

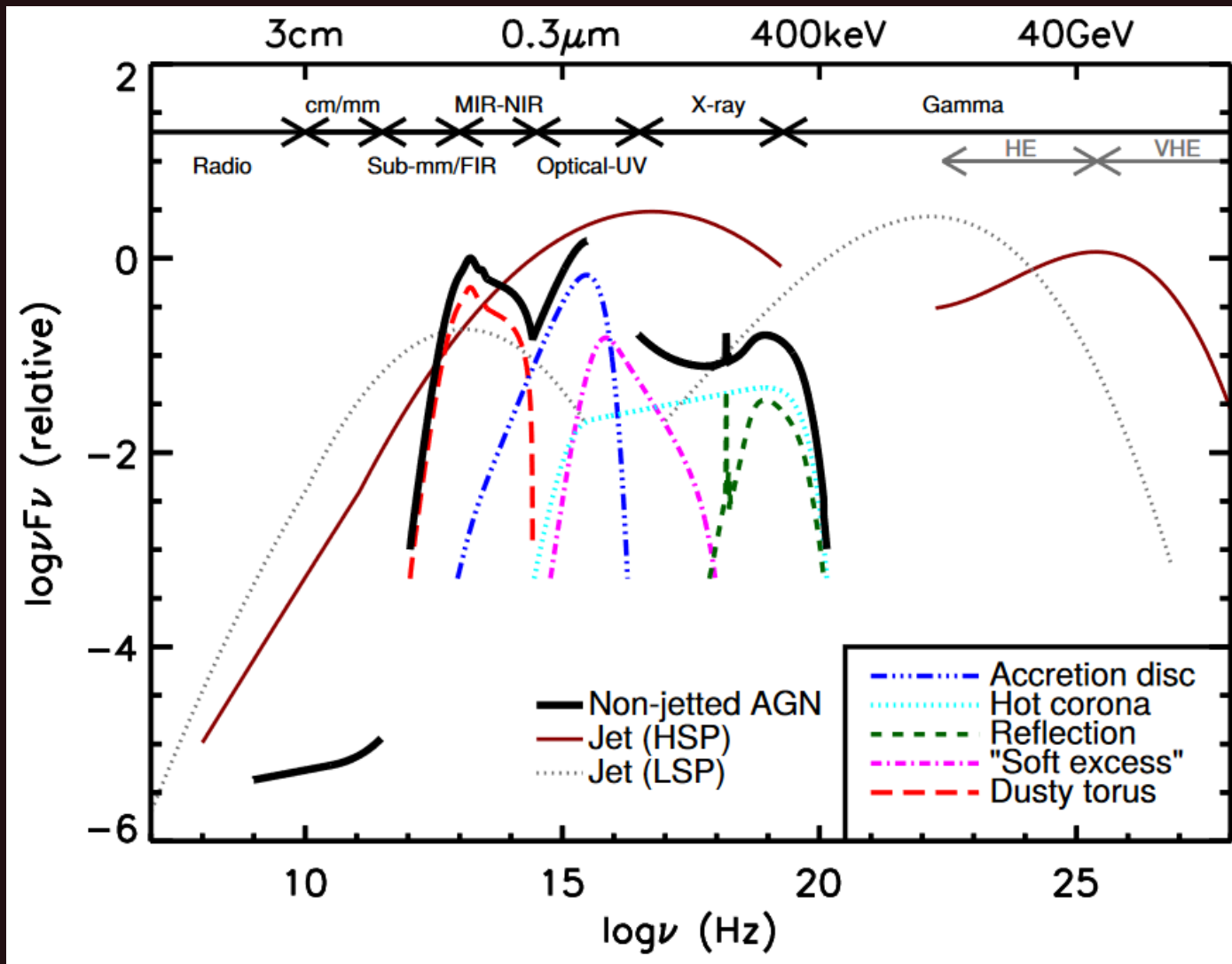


- Radio quiet
  - a) radio quiet quasars, i.e. QSO (types 1 and 2)
  - b) Seyfert galaxies
  - c) LINERs
- Radio loud
  - a) quasars
  - b) radio galaxies
  - c) blazars (BL Lacs и OVV)

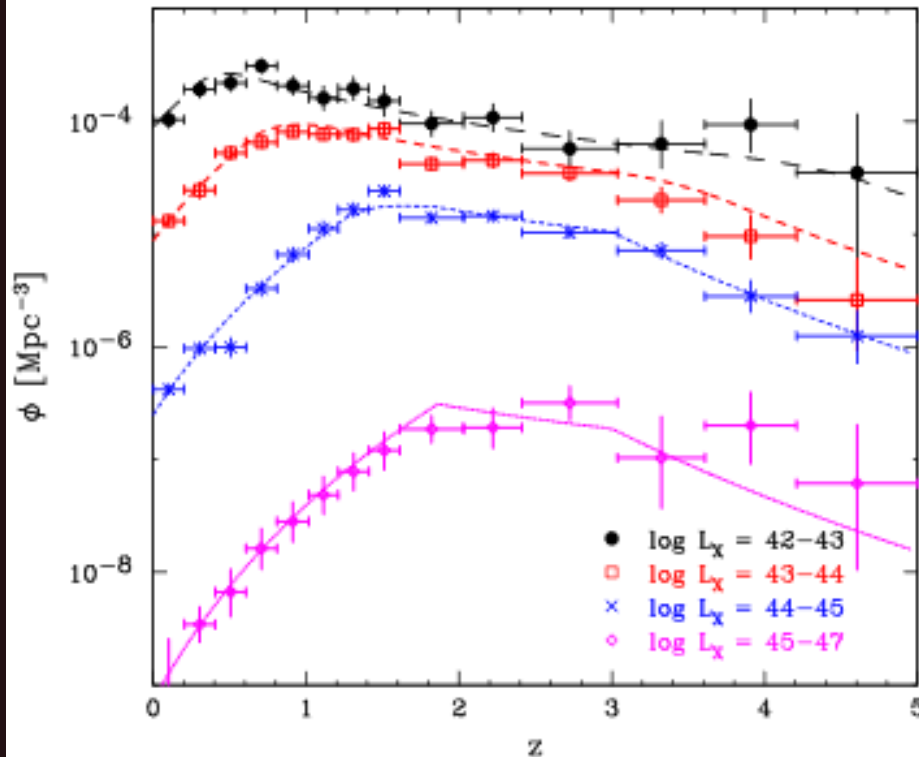
(see, for example, [astro-ph/0312545](https://arxiv.org/abs/astro-ph/0312545))

A popular review can be found in arXiv: 0906.2119

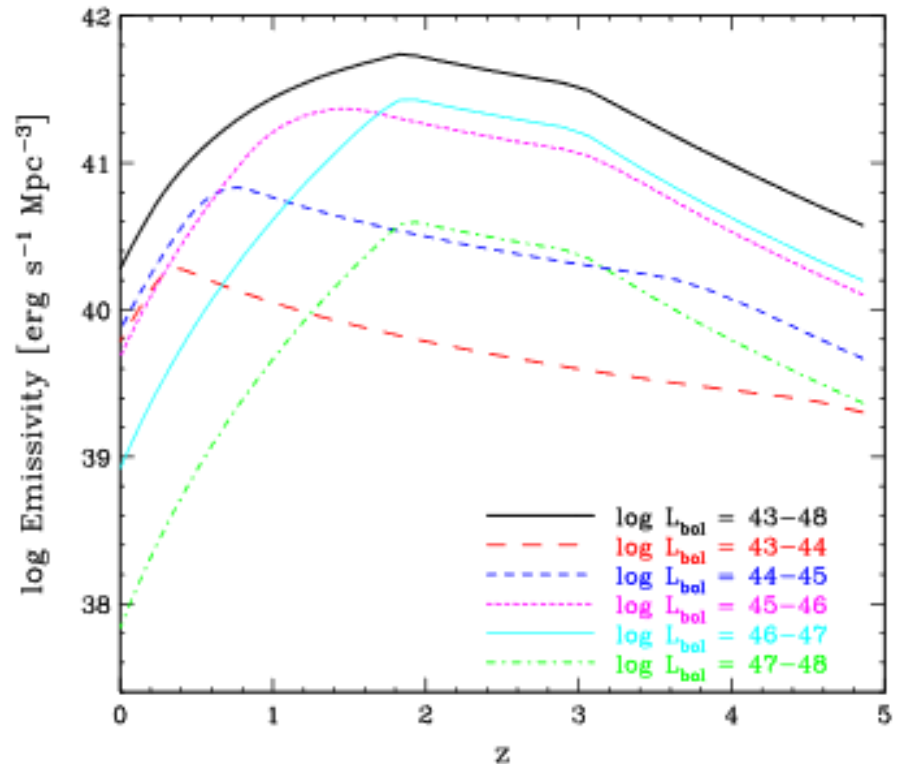
# Spectra of AGNs



# X-ray observations of AGNs

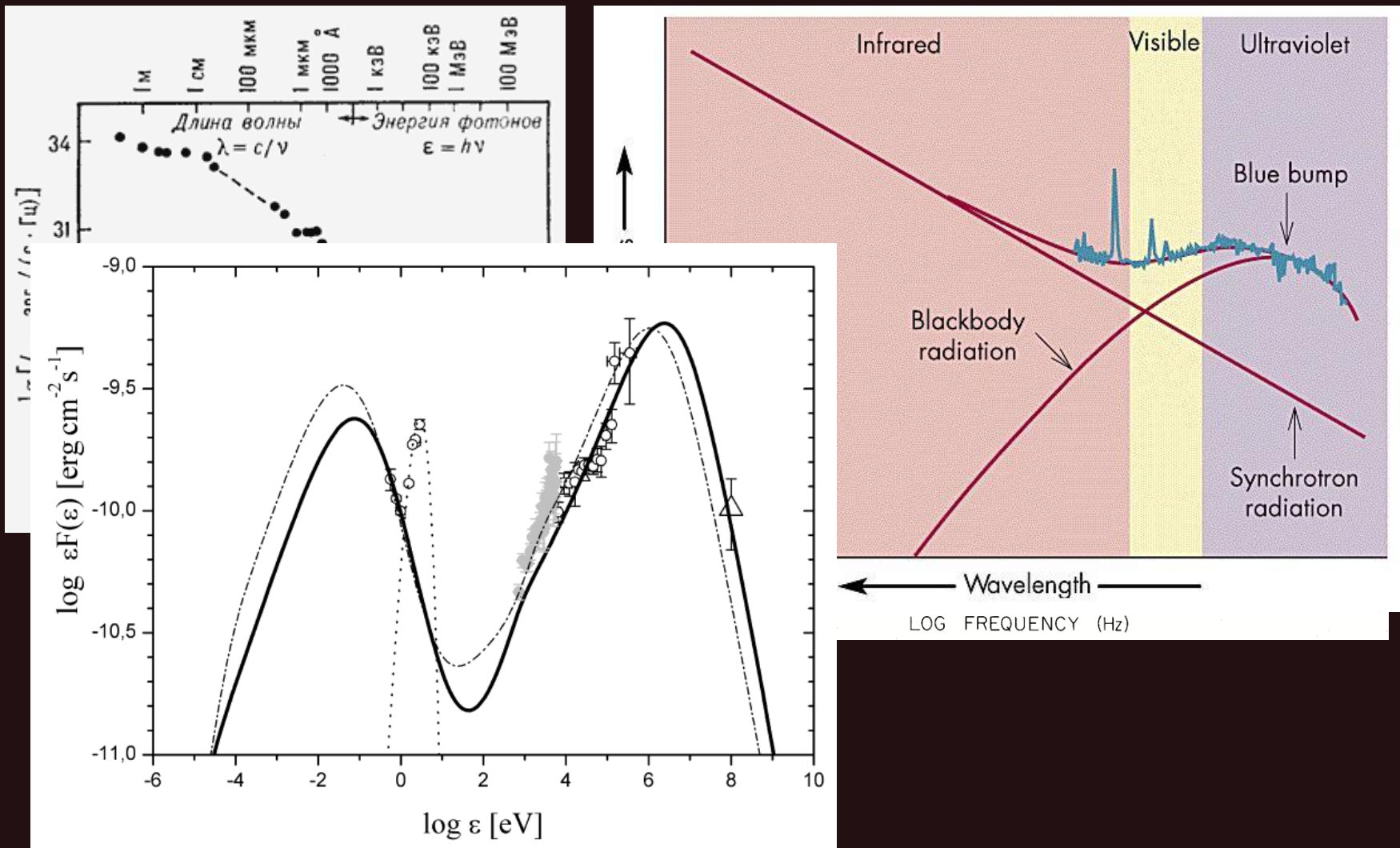


Comoving number density vs. redshift for AGNs, selected from multiple X-ray surveys, in four rest-frame 2–10 keV luminosity classes.

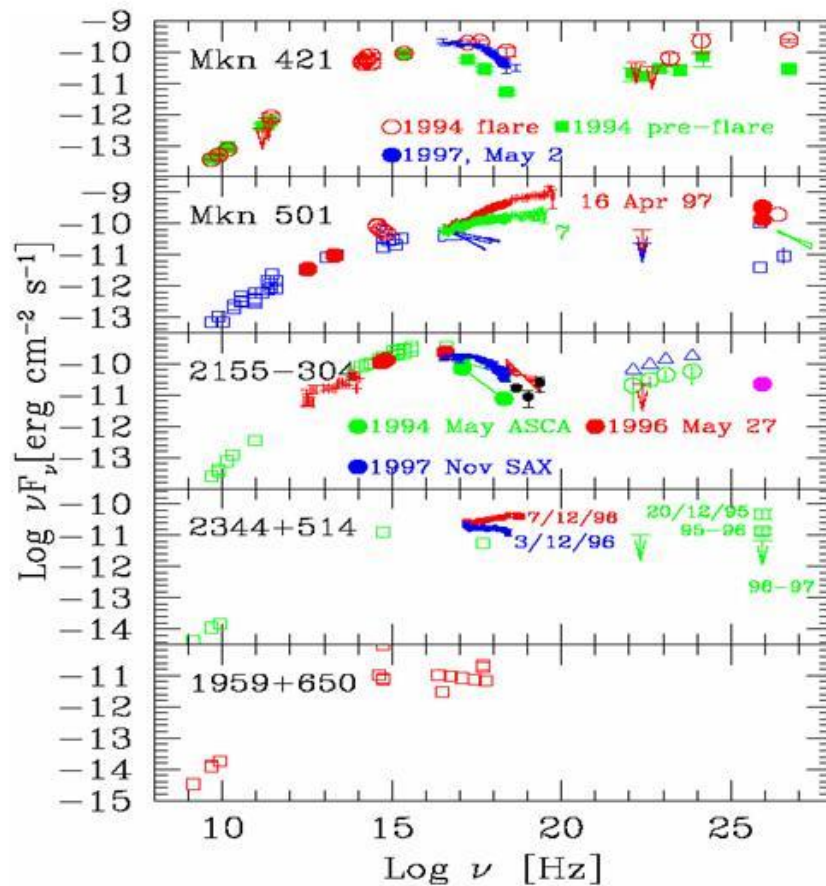


Comoving bolometric luminosity density vs. redshift for the same AGN sample in six bolometric luminosity classes.

# Quasars spectra



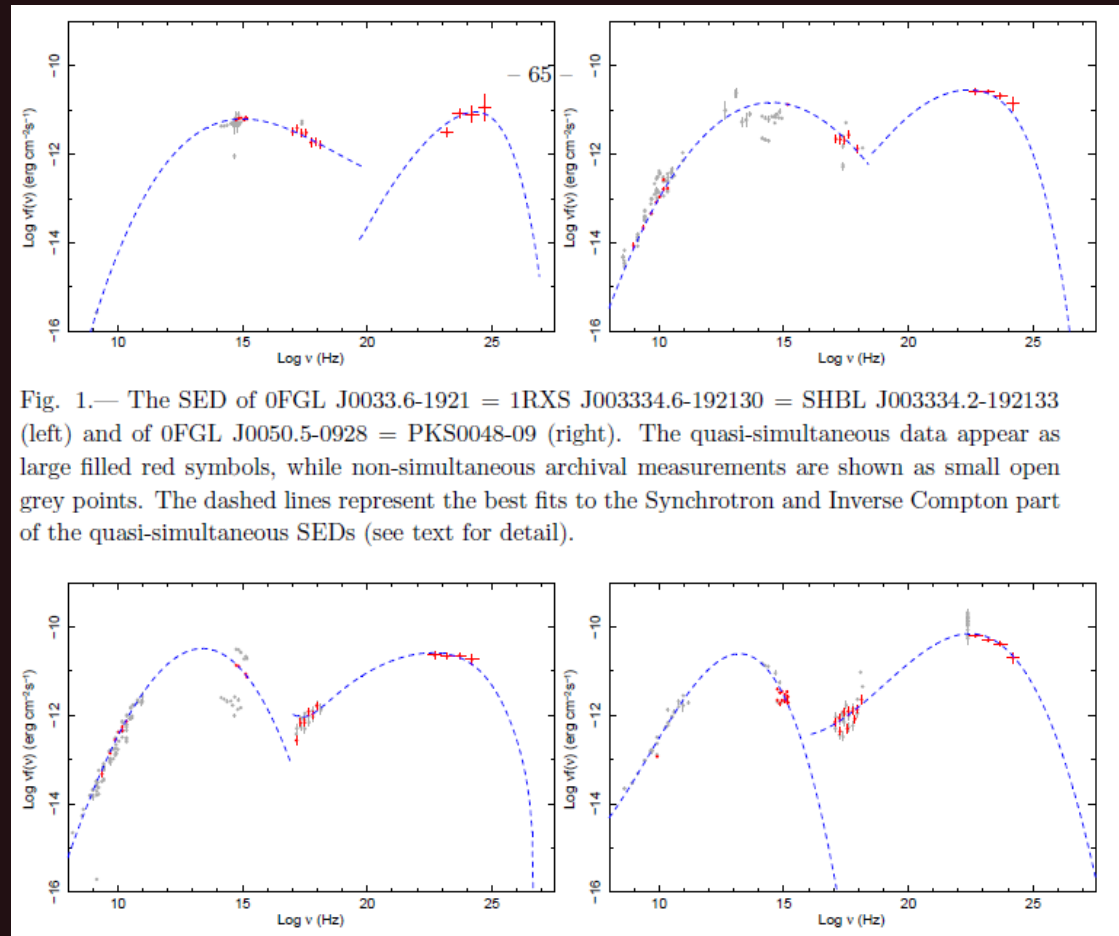
# Spectra of BL Lacs



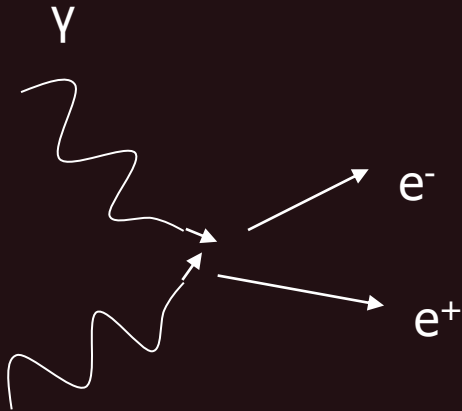
In the framework of the unified model BL Lacs (and blazars, in general) are explained as AGNs with jets pointing towards us.

# Fermi observations of blazars: Huge set of data

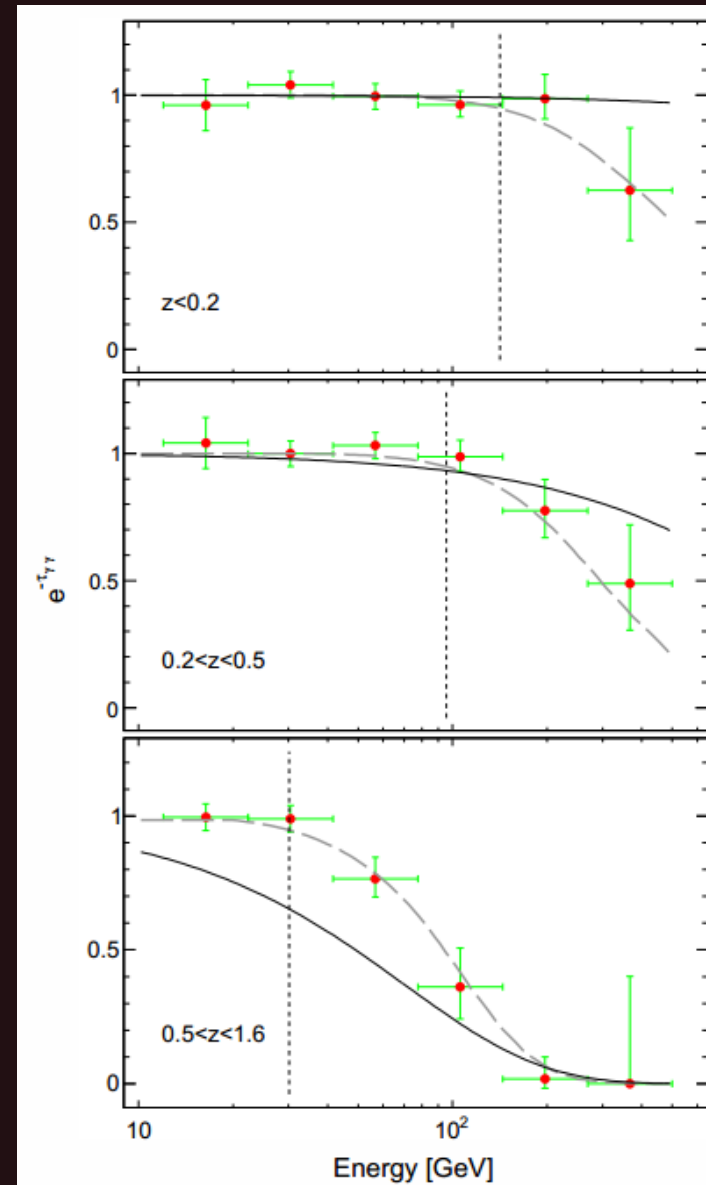
In the third Fermi catalogue  
(1501.02003)  
>1100 AGNs



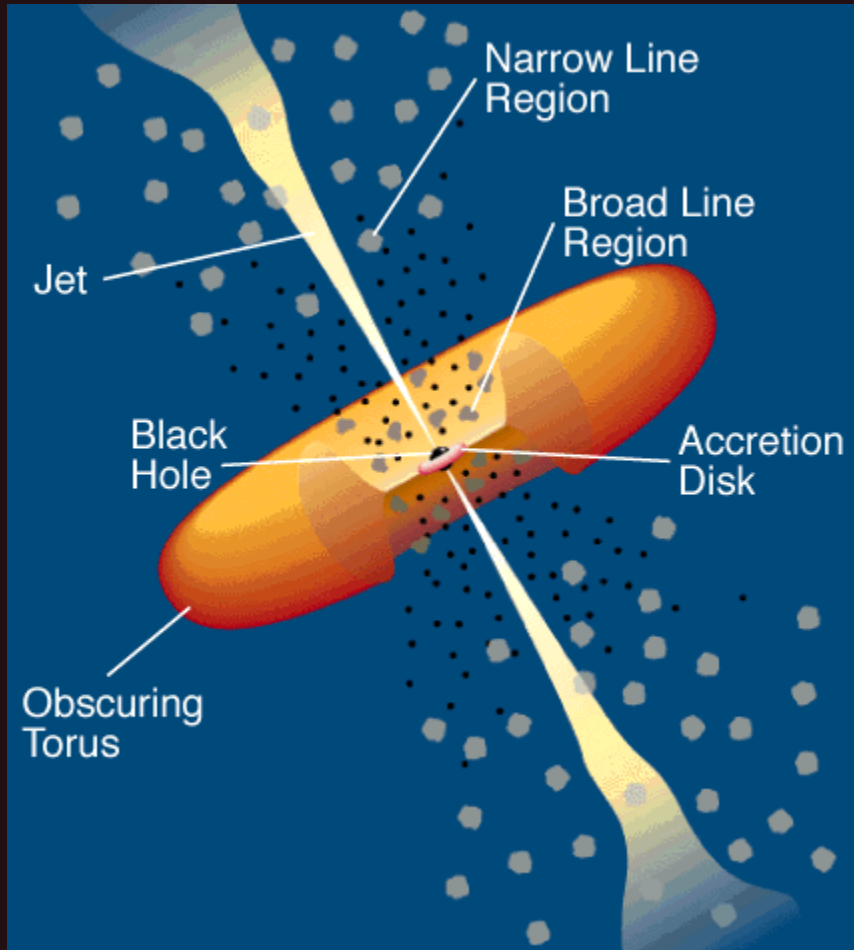
# Фоновое излучение



Если у вас есть далекий источник гамма-излучения, то гамма-фотоны по дороге к нам могут взаимодействовать с оптическим и УФ излучением фона, давая электрон-позитронные пары. Соответственно, в спектре далекого гамма-источника мы будем видеть депрессию. Для индивидуального источника увидеть это крайне тяжело. Авторы же использовали данные наблюдений на спутнике Ферми для полутора сотен блазаров, чтобы выделить суммарный эффект.



# Unified model

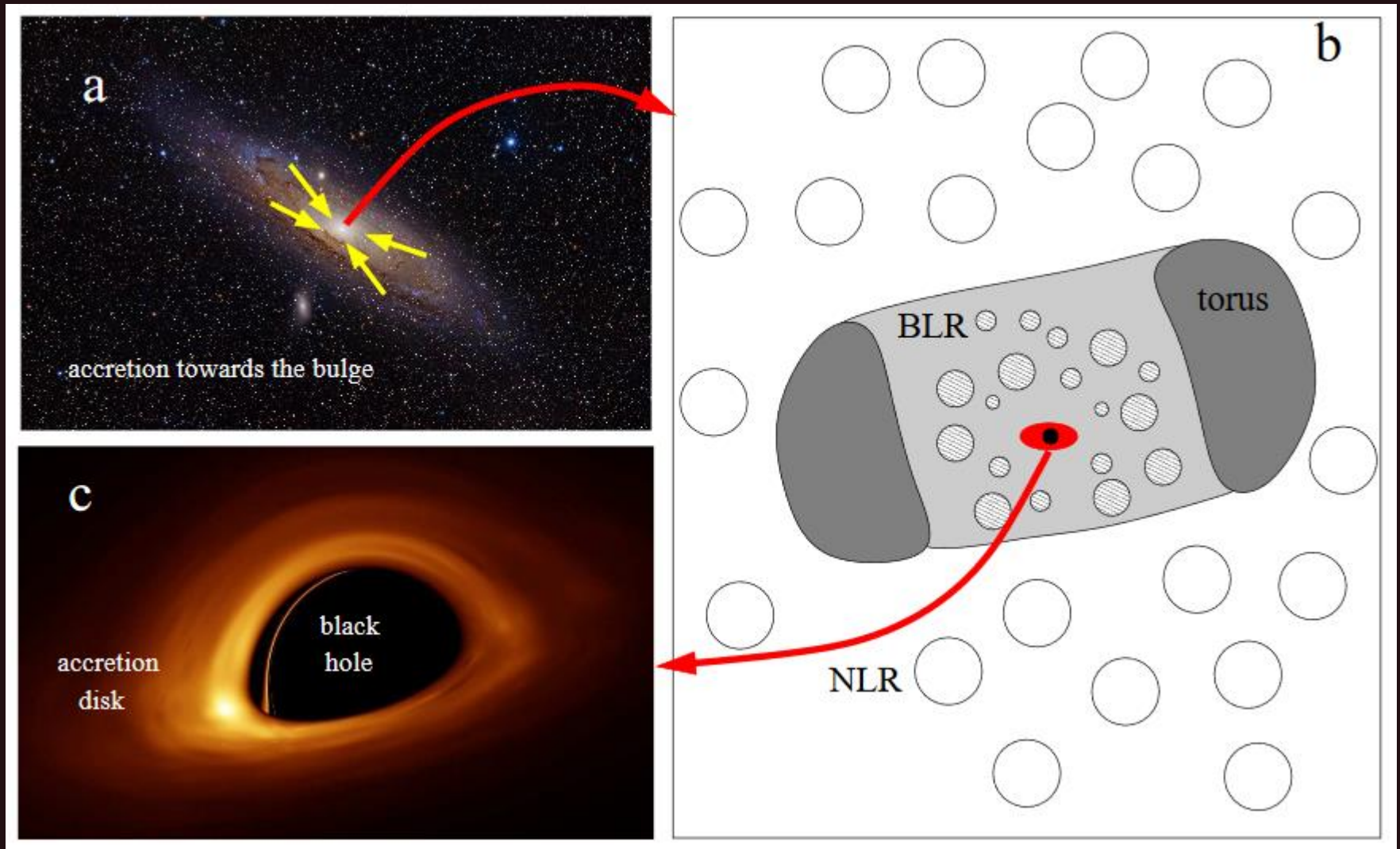


In the framework of the unified model properties of different types of AGNs are explained by properties of a torus around a BH and its orientation with respect to the line of sight.

Antonucci 1993 ARAA 31, 473

The model can be unapplicable to merging systems, see 1505.00811

# Accretion on different scales



# Unified model and population synthesis

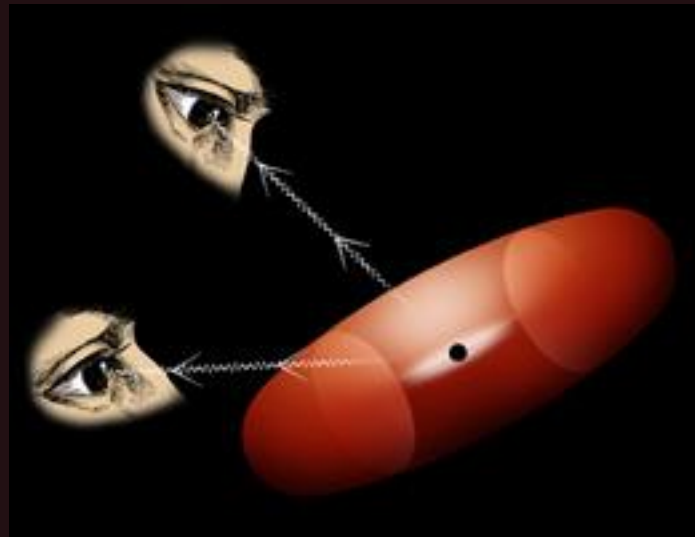
X-ray background is dominated by AGNs.

Discussion of the nature and properties of the background resulted in population synthesis studies of AGNs.

*Ueda et al.* [astro-ph/0308140](#)

*Franceschini et al.* [astro-ph/0205529](#)

*Ballantyne et al.* [astro-ph/0609002](#)



## What should be taken into account

- Relative fraction of nuclei obscured by toruses
- Luminosity distribution of nuclei
- Spectral energy distribution
- Evolution of all these parameters

# Mass determination in the case of SMBHs

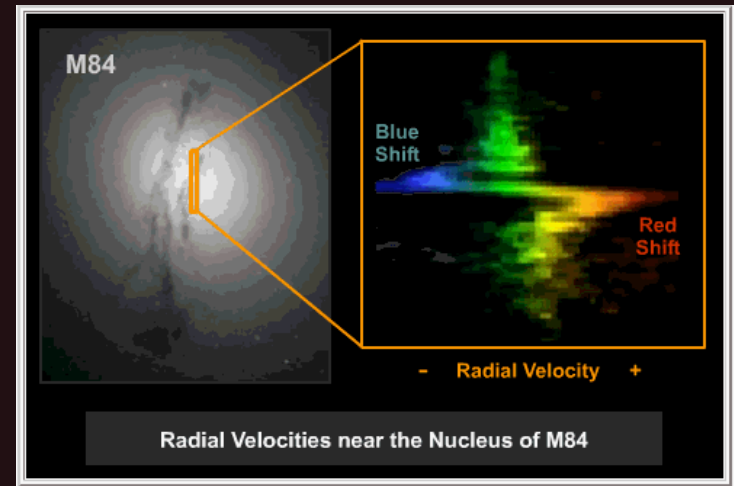
- Relation between a BH mass and a bulge mass (velocity dispersion).
- Measurements of orbits of stars and masers around a BH.
- Gas kinematics.
- Stellar density profile.
- Reverberation mapping.

Also, always a simple upper limit can be put based on the fact that the total luminosity cannot be higher than the Eddington value.

See a short review by [Vestergaard](#)  
in astro-ph/0401436

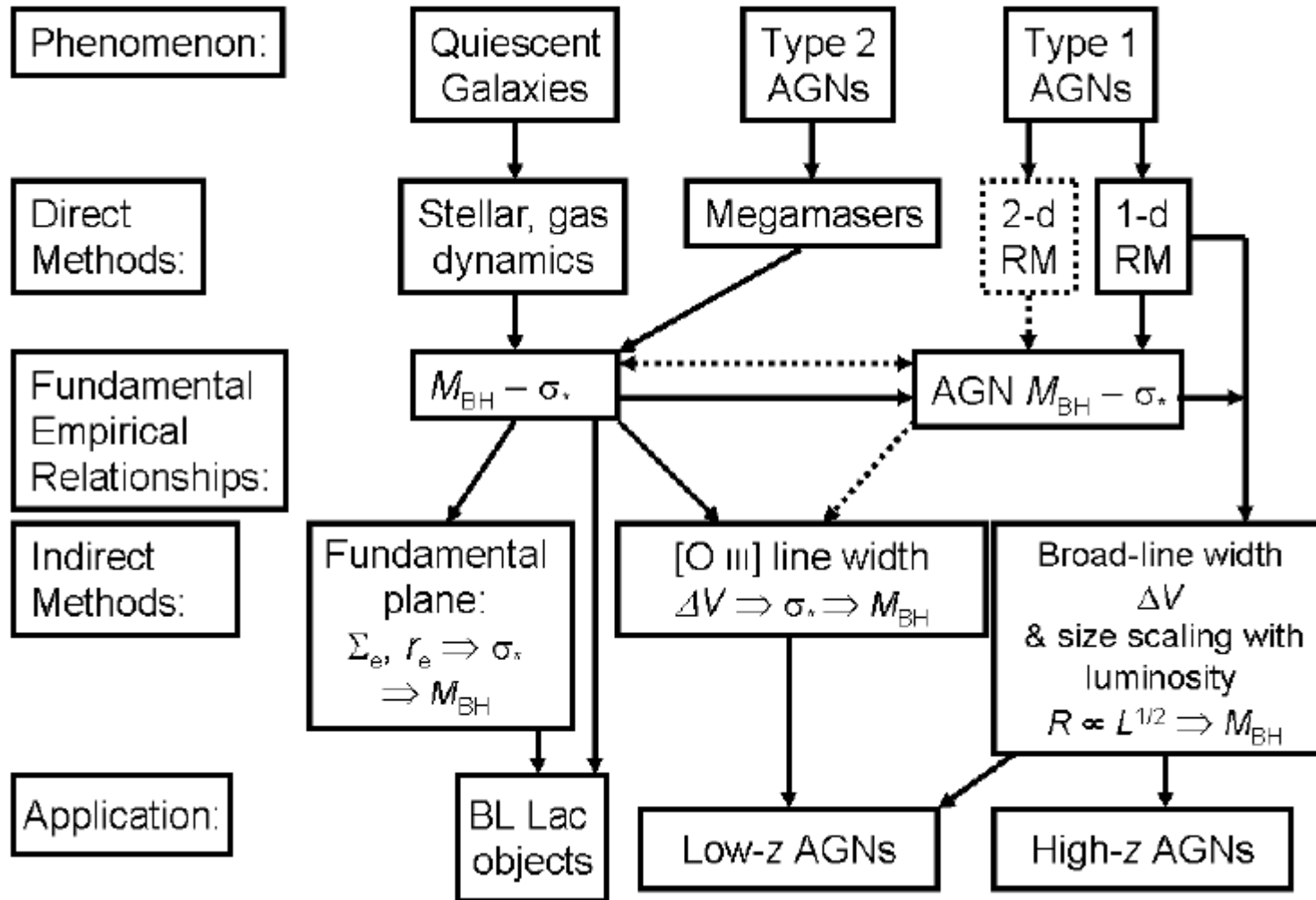
«**Black-Hole Mass Measurements**»

See a more recent reviews in [0904.2615](#),  
and [1001.3675](#)



# Different methods

## Measurement of Central Black Hole Masses

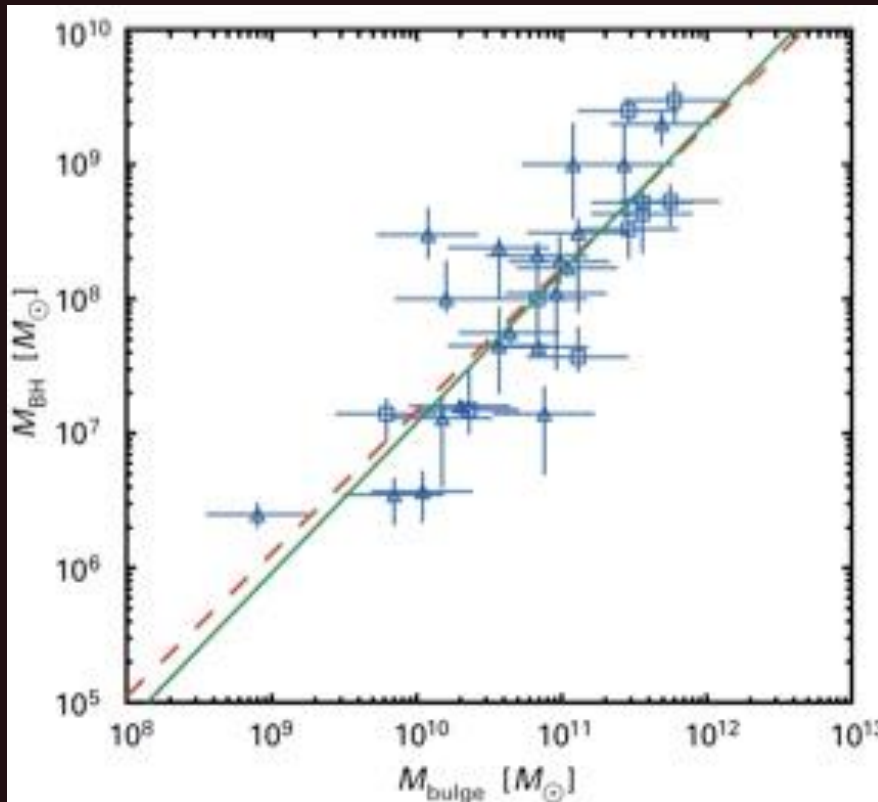


# Comparison

Method	NGC 4258	NGC 3227	NGC 4151
	(Units $10^6 M_\odot$ )		
<u>Direct methods:</u>			
Megamasers	$38.2 \pm 0.1^{[1]}$	N/A	N/A
Stellar dynamics	$33 \pm 2^{[2]}$	$7\text{--}20^{[3]}$	$\leq 70^{[4]}$
Gas dynamics	$25\text{--}260^{[5]}$	$20^{+10}_{-4} [6]$	$30^{+7.5}_{-22} [6]$
Reverberation	N/A	$7.63^{+1.62}_{-1.72} [7]$	$46 \pm 5^{[8]}$
<u>Indirect methods:</u>			
$M_{\text{BH}}\text{--}\sigma_*^{[9]}$	13	25	6.1
$R\text{--}L$ scaling <sup>[10]</sup>	N/A	15	29–120

# BH mass vs. bulge mass

According to the standard picture every galaxy with a significant bulge has a SMBH in the center.



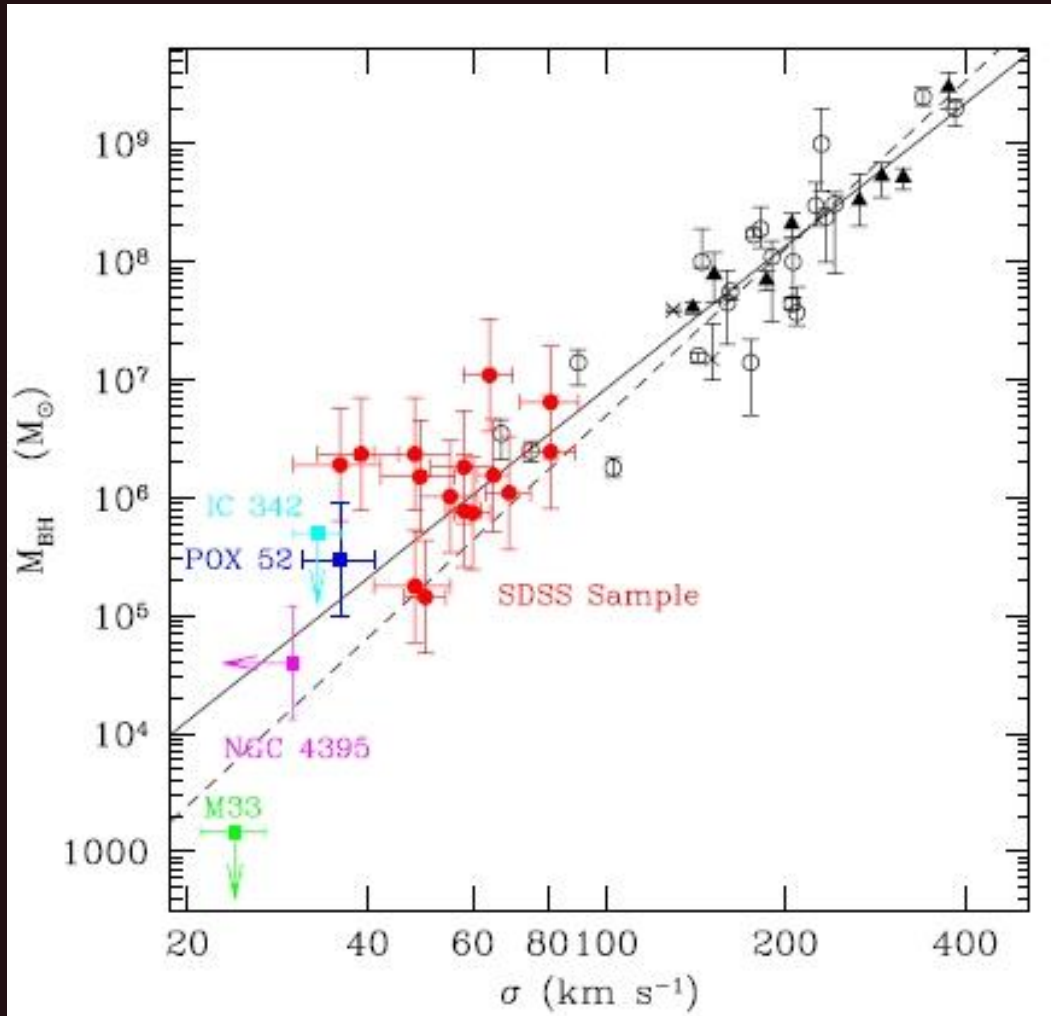
$$M_{\text{BH}} \sim M_{\text{bulge}}^{1.12 \pm 0.06}$$

([Haering](#), [Rix](#) astro-ph/0402376)

BH mass usually is about from 0.1% up to several tenth of percent of the bulge mass.

However, the situation is a little bit more complicated. BH mass correlates differently with different components of a galaxy (see 1304.7762 and 1308.6483).

# Exceptions: M33

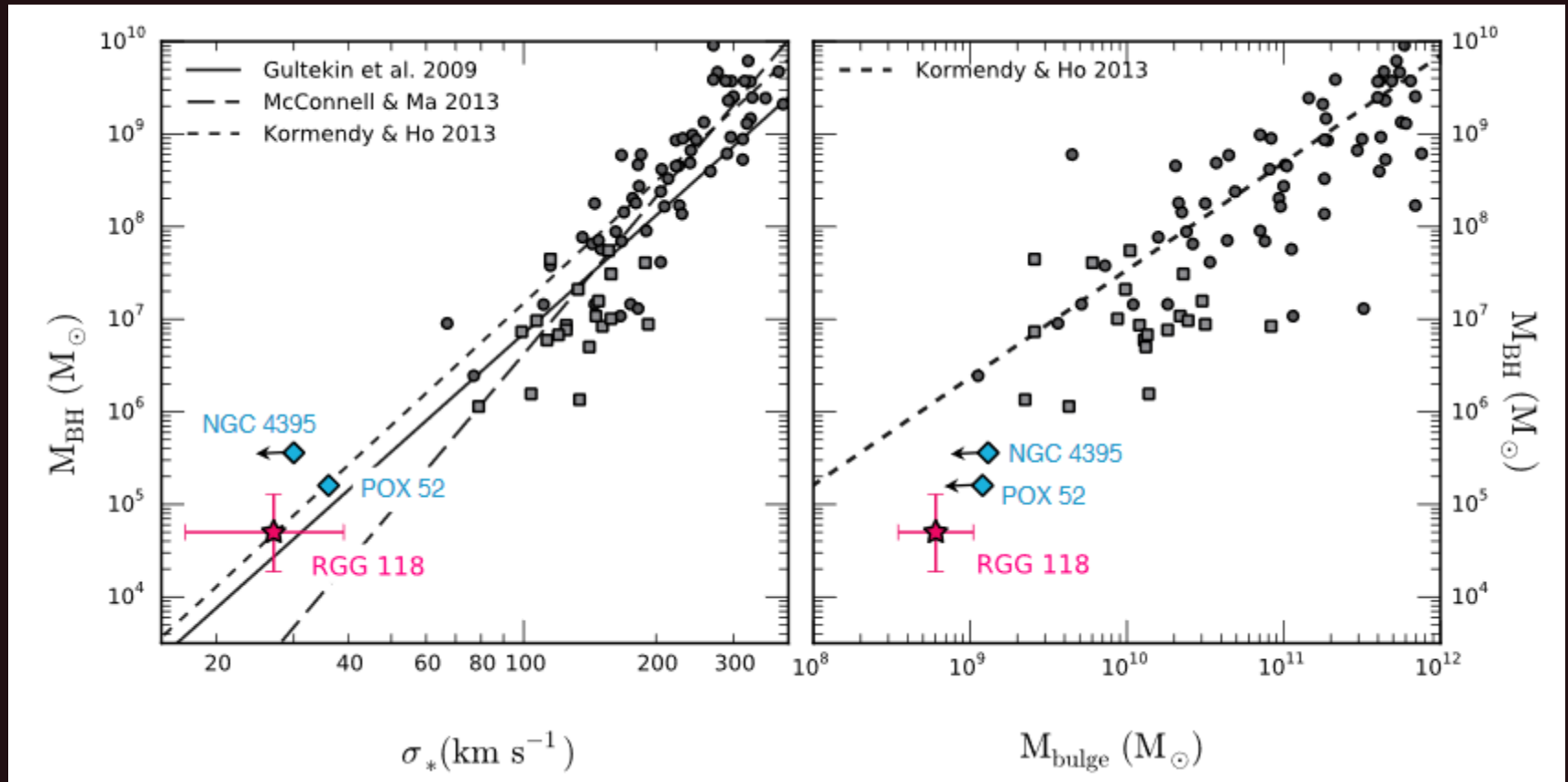


The upper limit on the BH mass in M33 is an order of magnitude lower than it should be according to the standard relation.

# Light SMBH

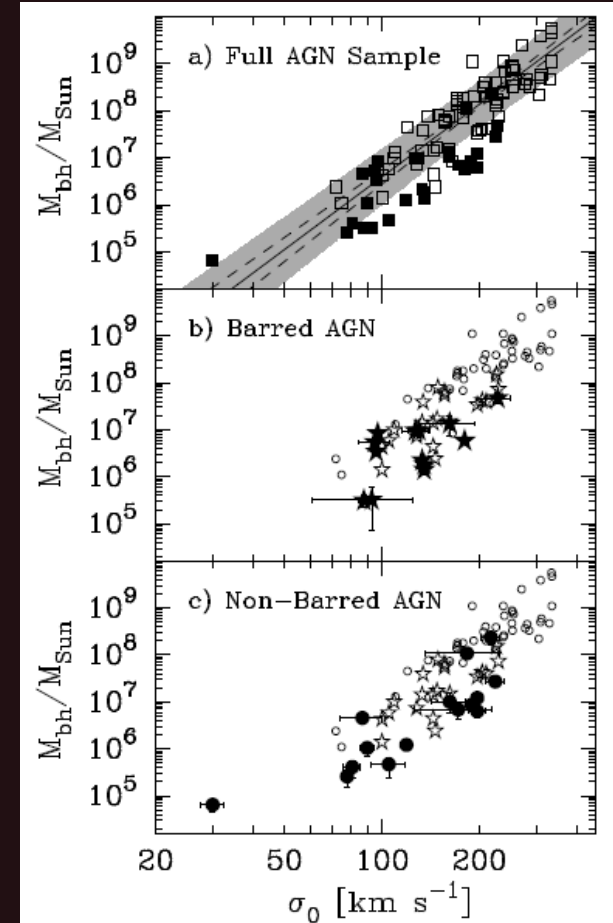
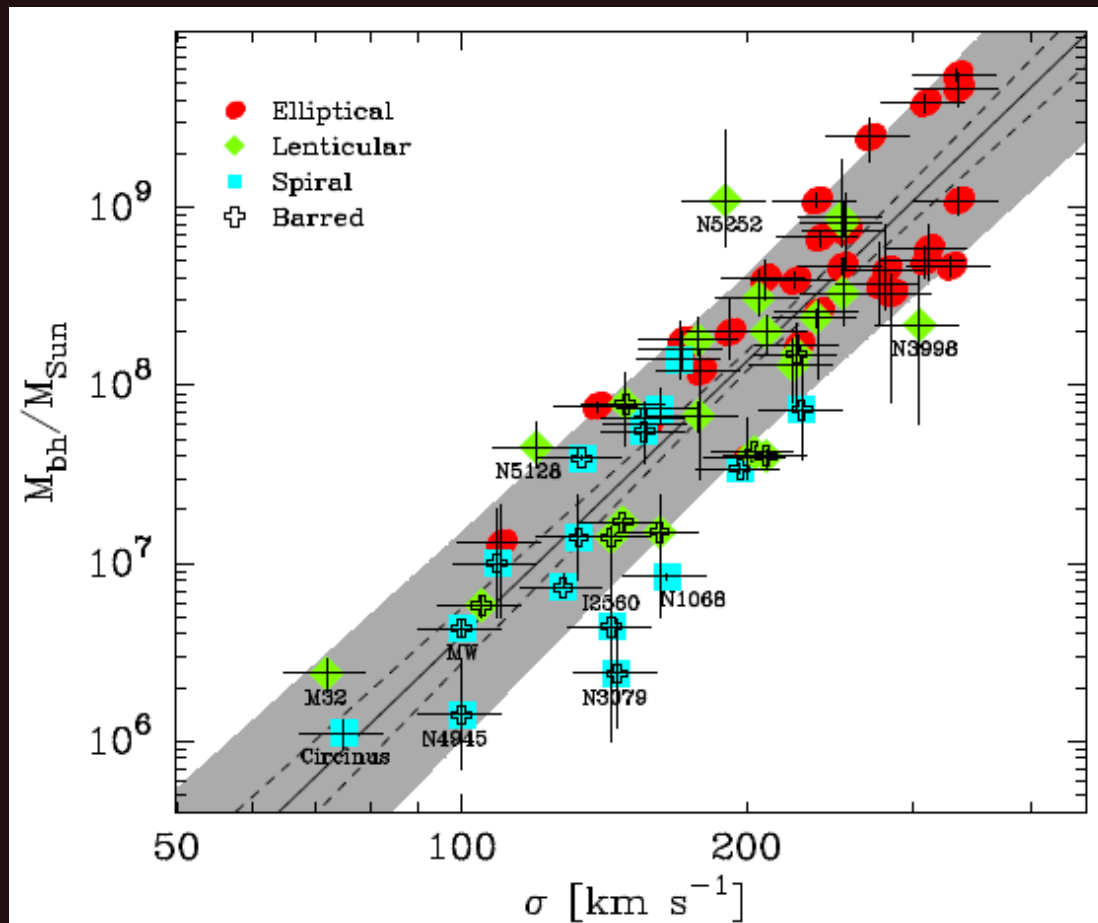
dwarf galaxy RGG 118

BH 50 000 solar masses



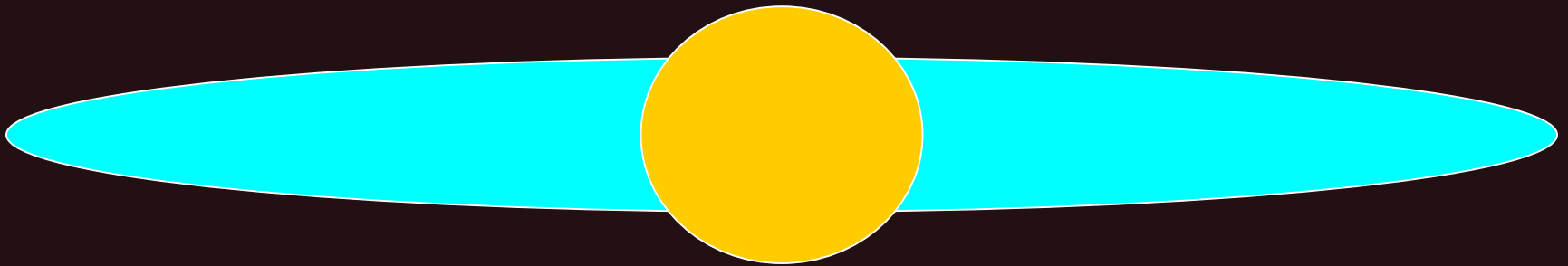
1506.07531

# More data



# Сверхмассивная черная дыра там, где ее не должно быть

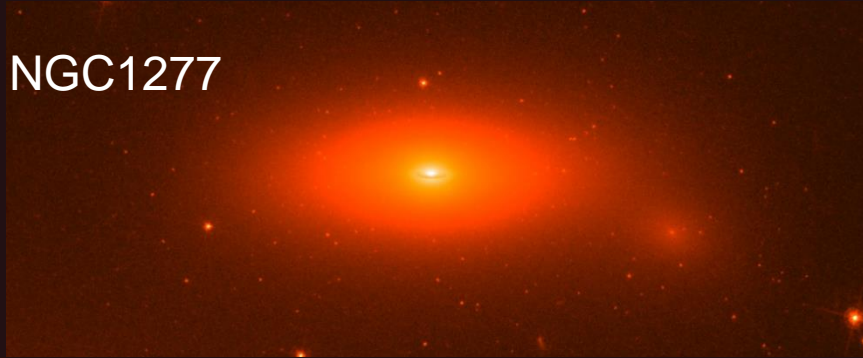
Наблюдения галактики NGC 4561 на спутнике XMM-Newton показали, что в ней есть активное ядро, т.е. – сверхмассивная черная дыра. Но при это быть там этой дыре не положено: у галактики нет балджа.



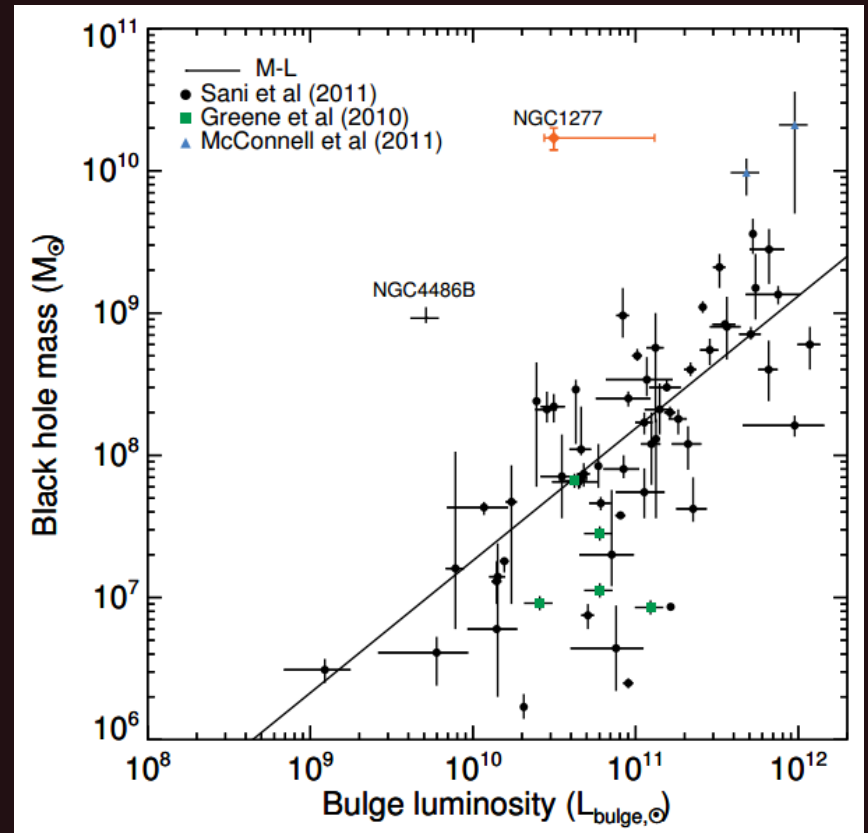
Масса черной дыры  $>20000 M_{\odot}$

# Слишком массивная черная дыра

NGC1277



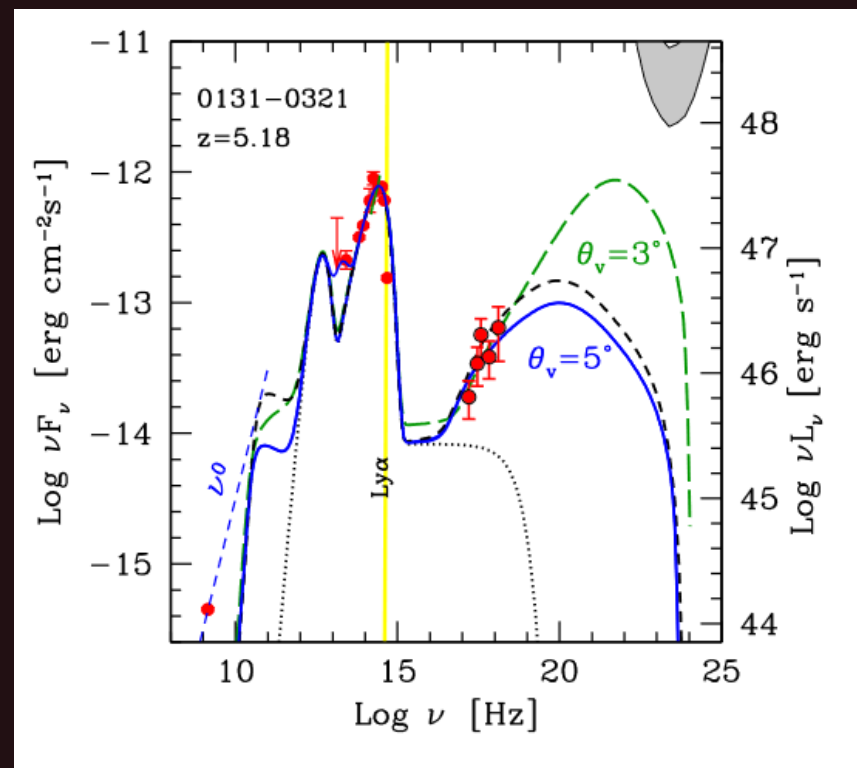
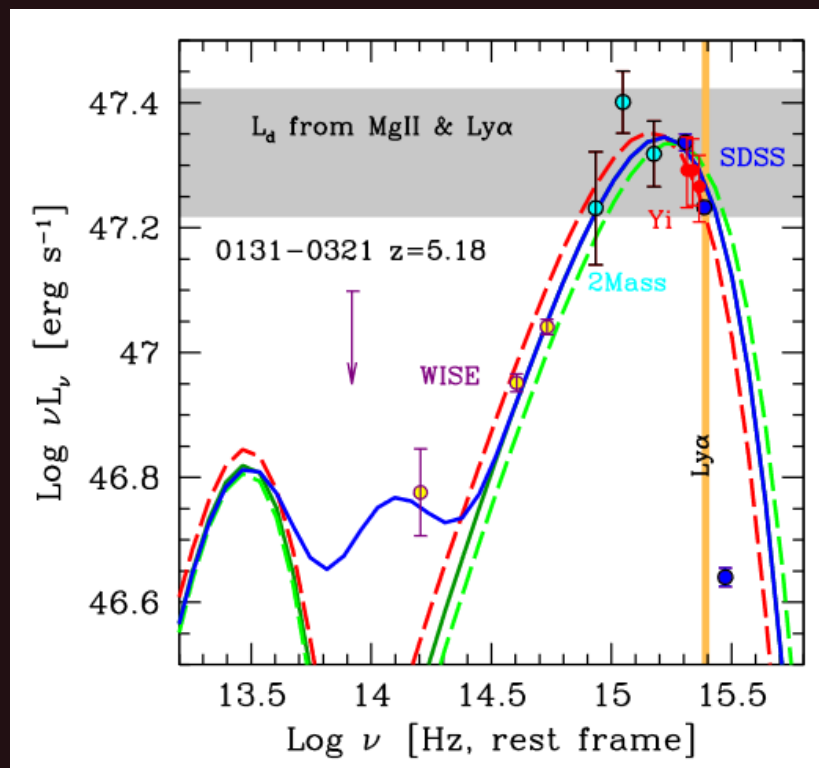
Компактная линзовидная галактика.  
«Положено» иметь черную дыру  $10^8 M_{\odot}$   
А присутствует  $>10^{10} M_{\odot}$ !



# 11 billion solar masses BH at $z > 5$

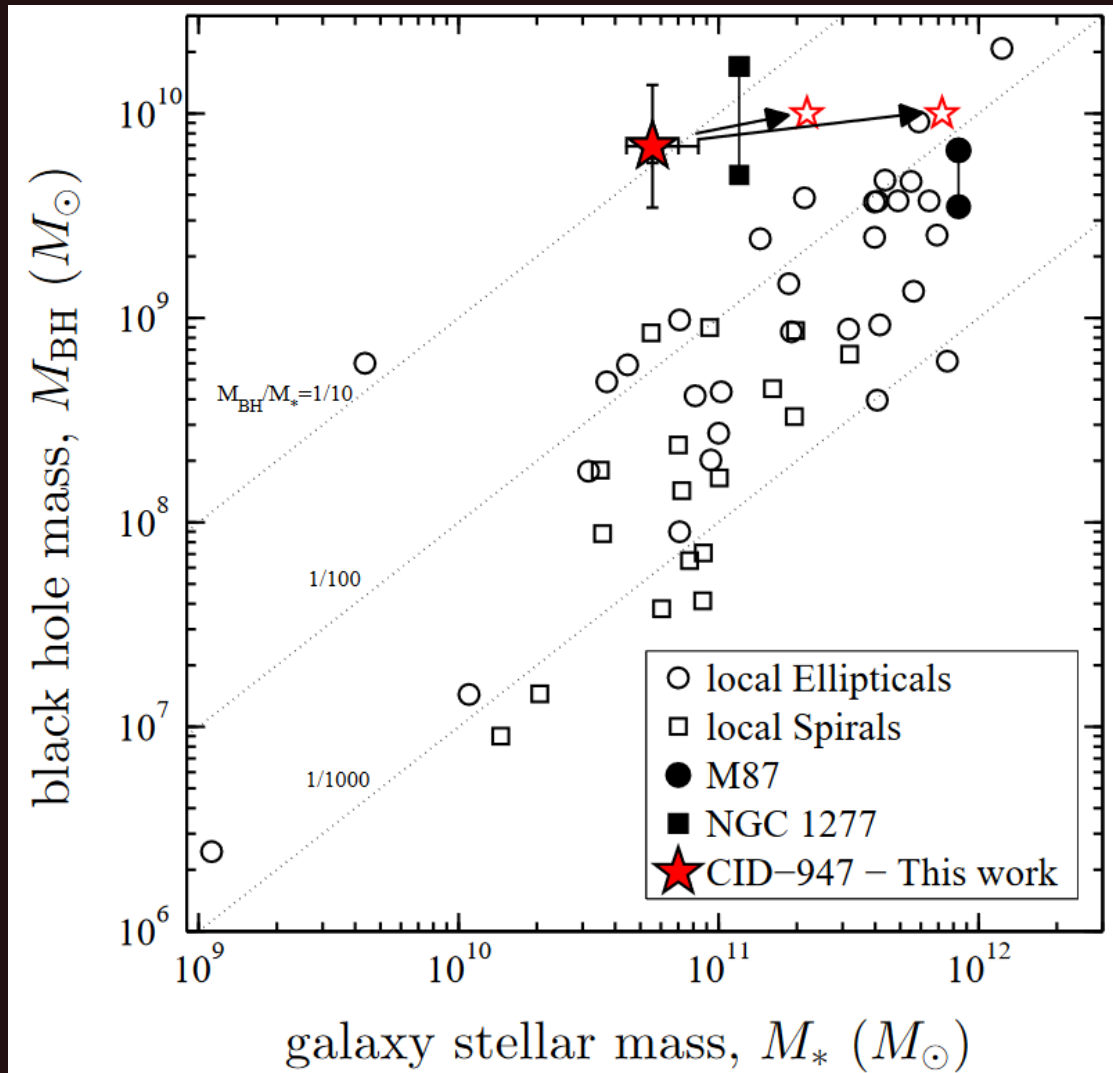
SDSS J013127.34–032100.1

Mass determined via spectral fitting.



1501.07269

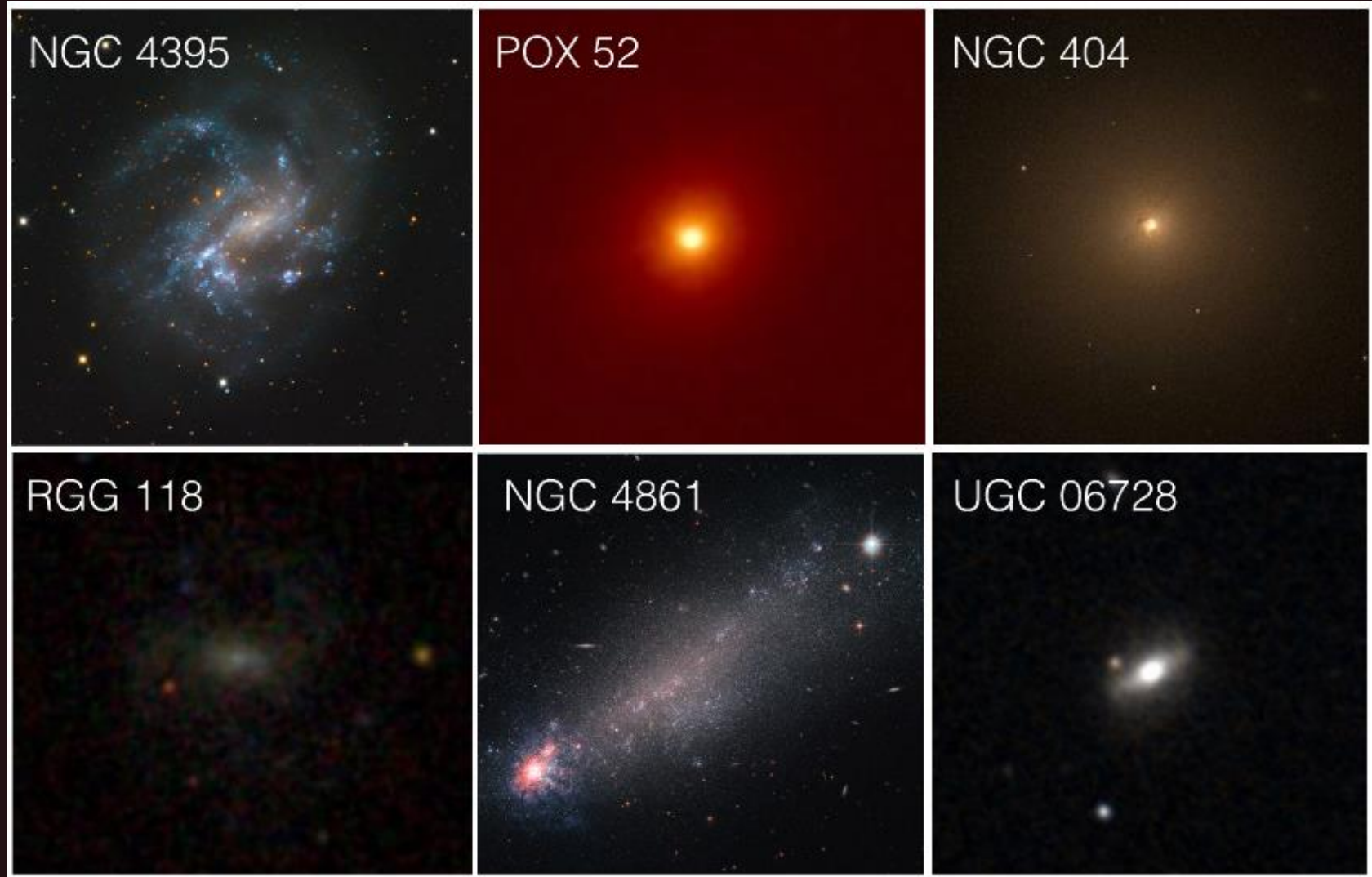
# Too massive BH in a starforming galaxy



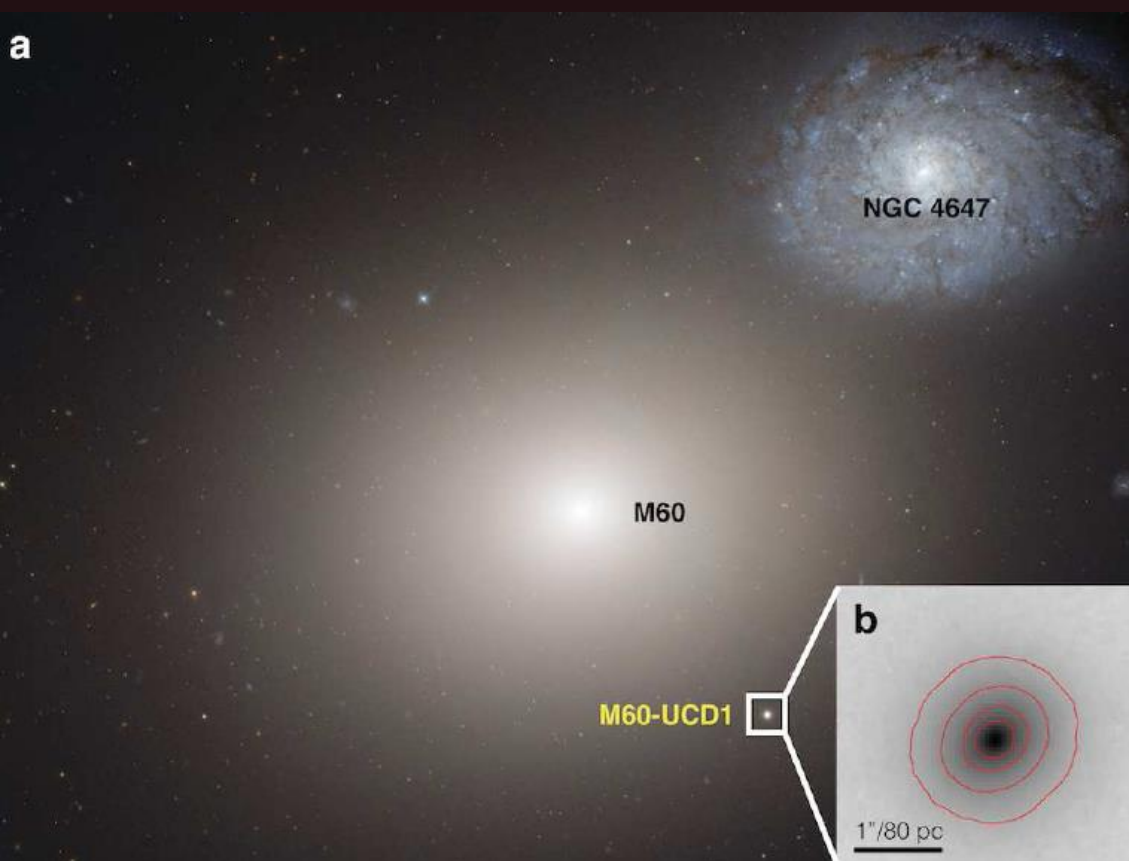
$z=3.3$

Due to large SFR  
in a time the BH  
might become  
“more typical”  
respect to the galaxy.

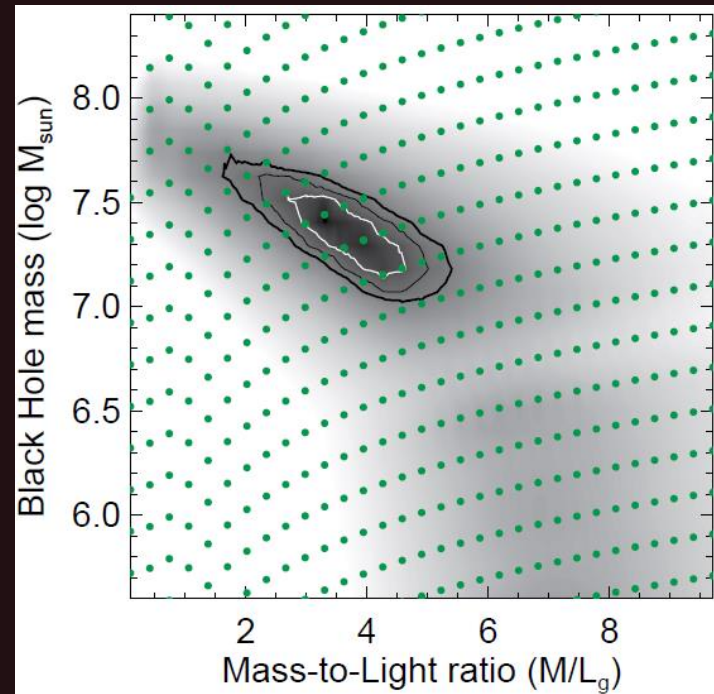
# Dwarf galaxies with IMBHs



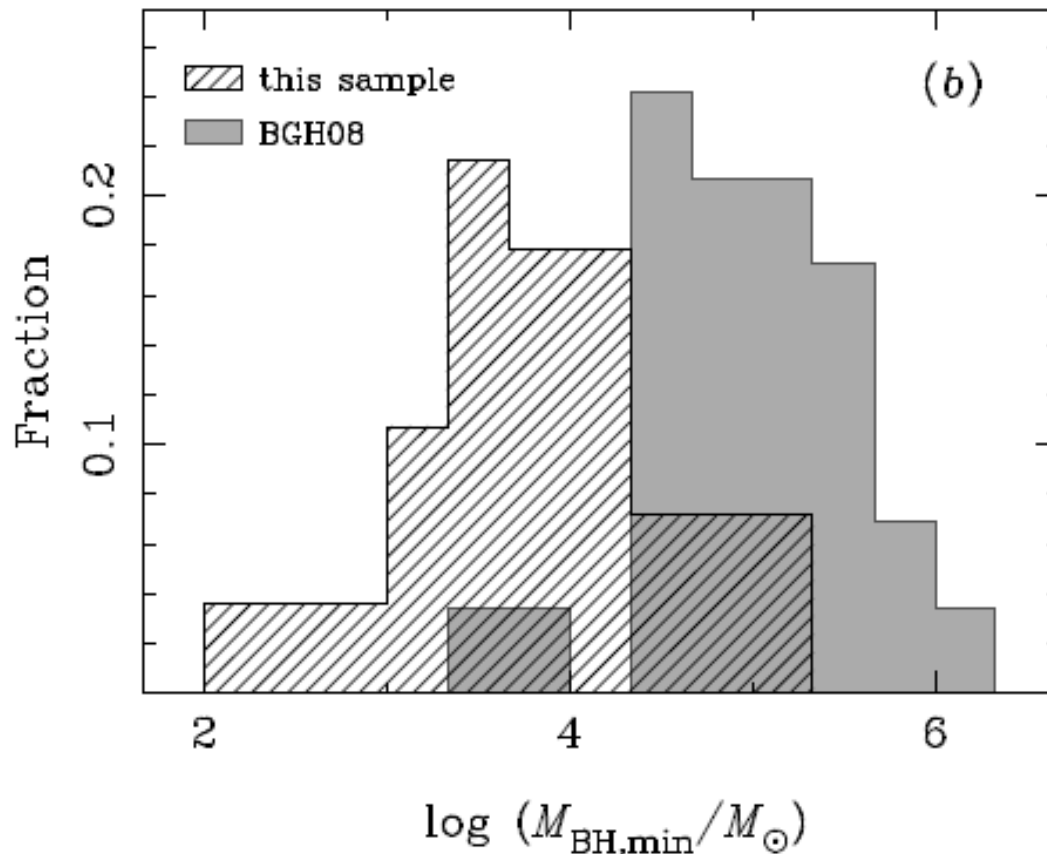
# Сверхмассивная черная дыра в карликовой компактной галактике



**Самая легкая  
галактика с  
черной дырой**

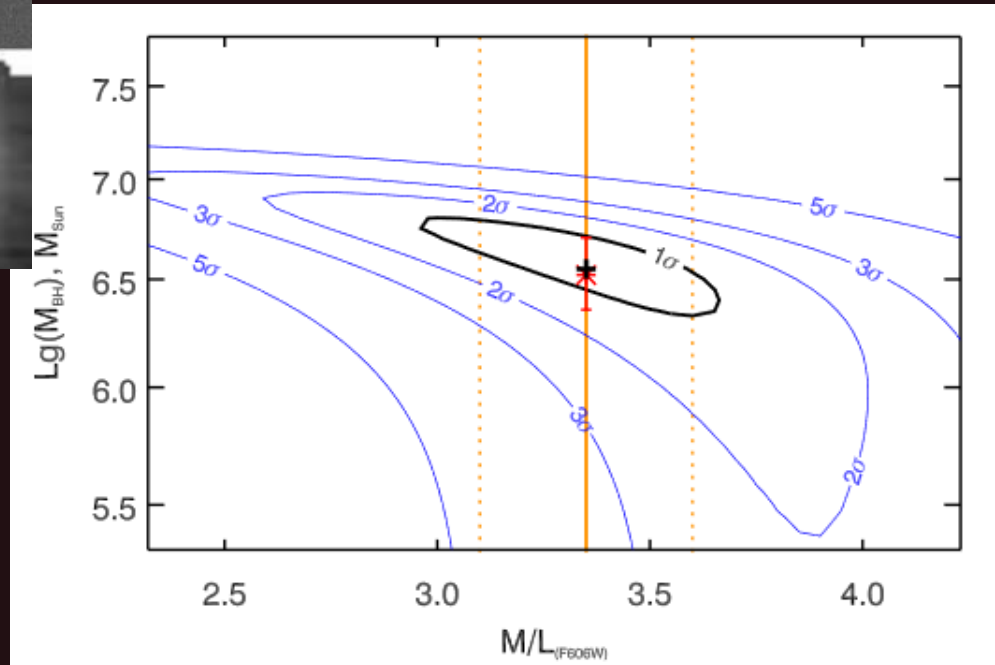
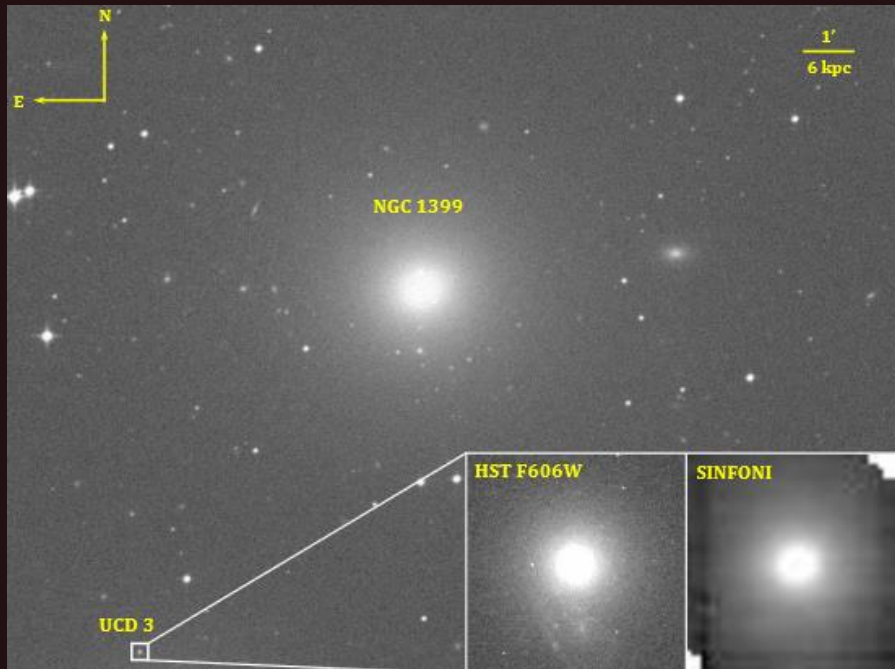


# Черные дыры в карликовых галактиках



**Сами галактики имеют массы порядка нескольких миллиардов масс Солнца, а размеры порядка нескольких килопарсек.**

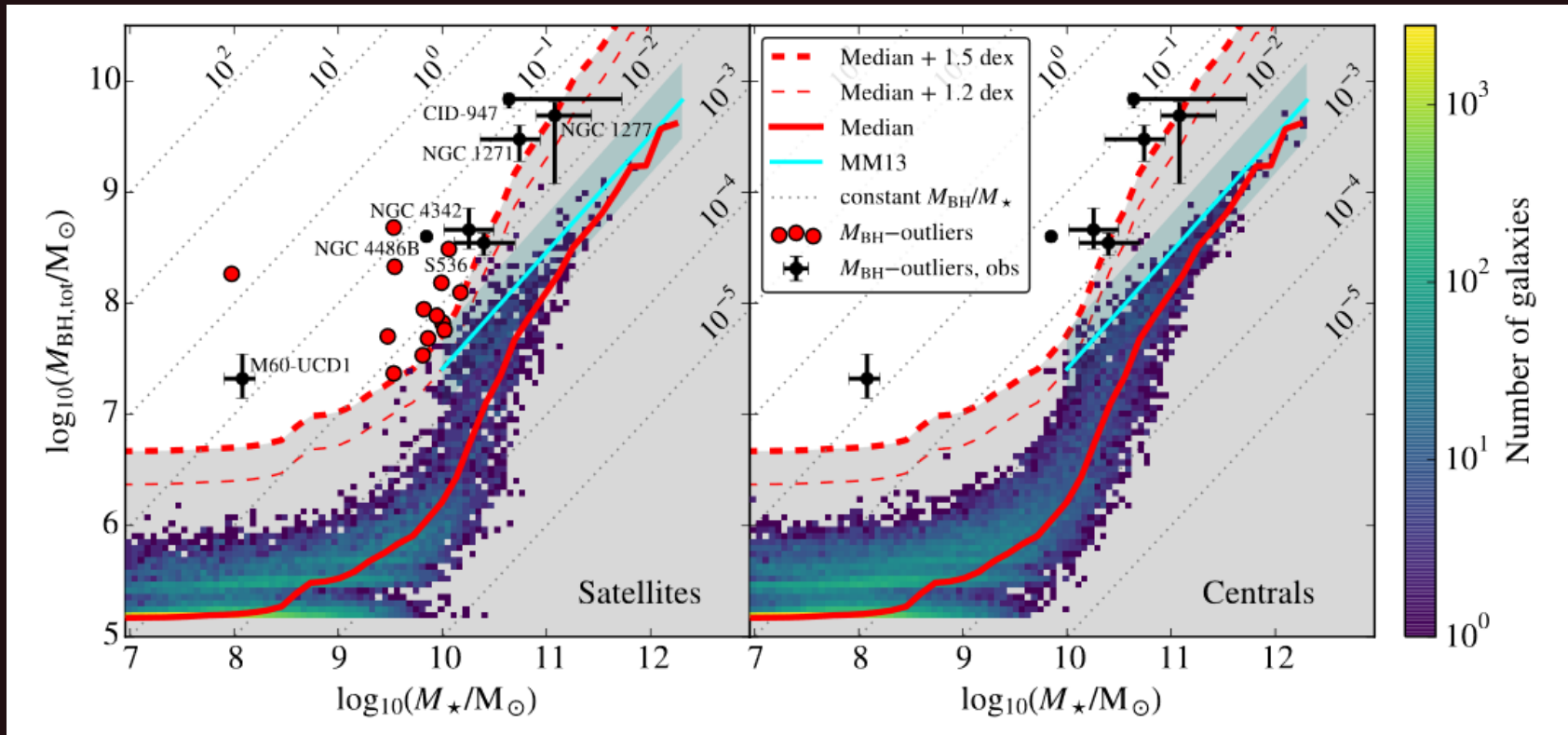
# SMBH in Fornax UCD3



3.5 million  $M_{\text{Solar}}$

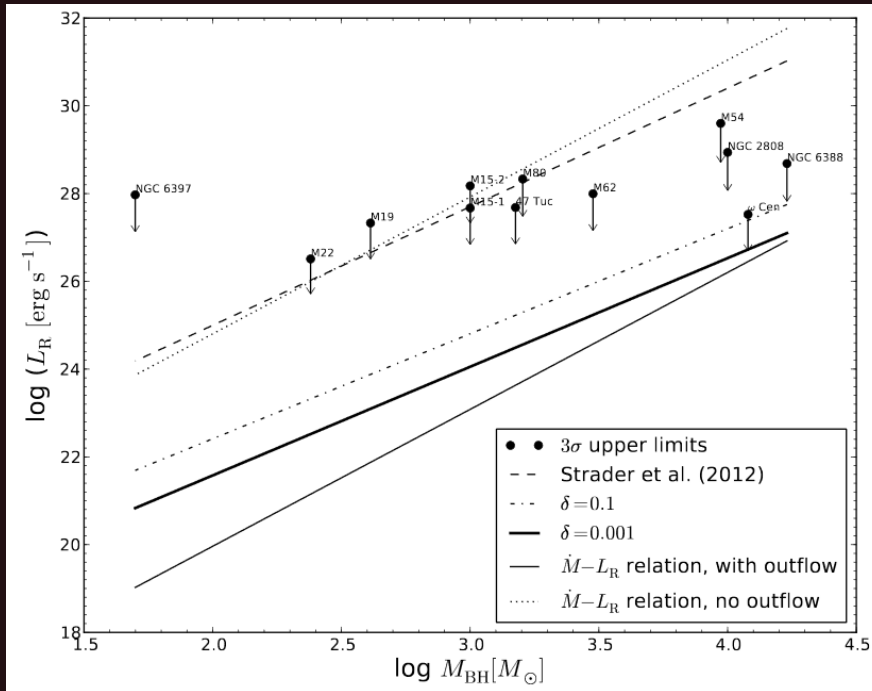
1804.02938

# Massive BHs in small galaxies



EAGLE modeling vs. observations.  
Outliers are mainly due to tidal stripping.

# BHs in globular clusters



Radio pulsar observations in NGC 6624 suggest that there is an IMBH with  $M > 7500$  solar masses.

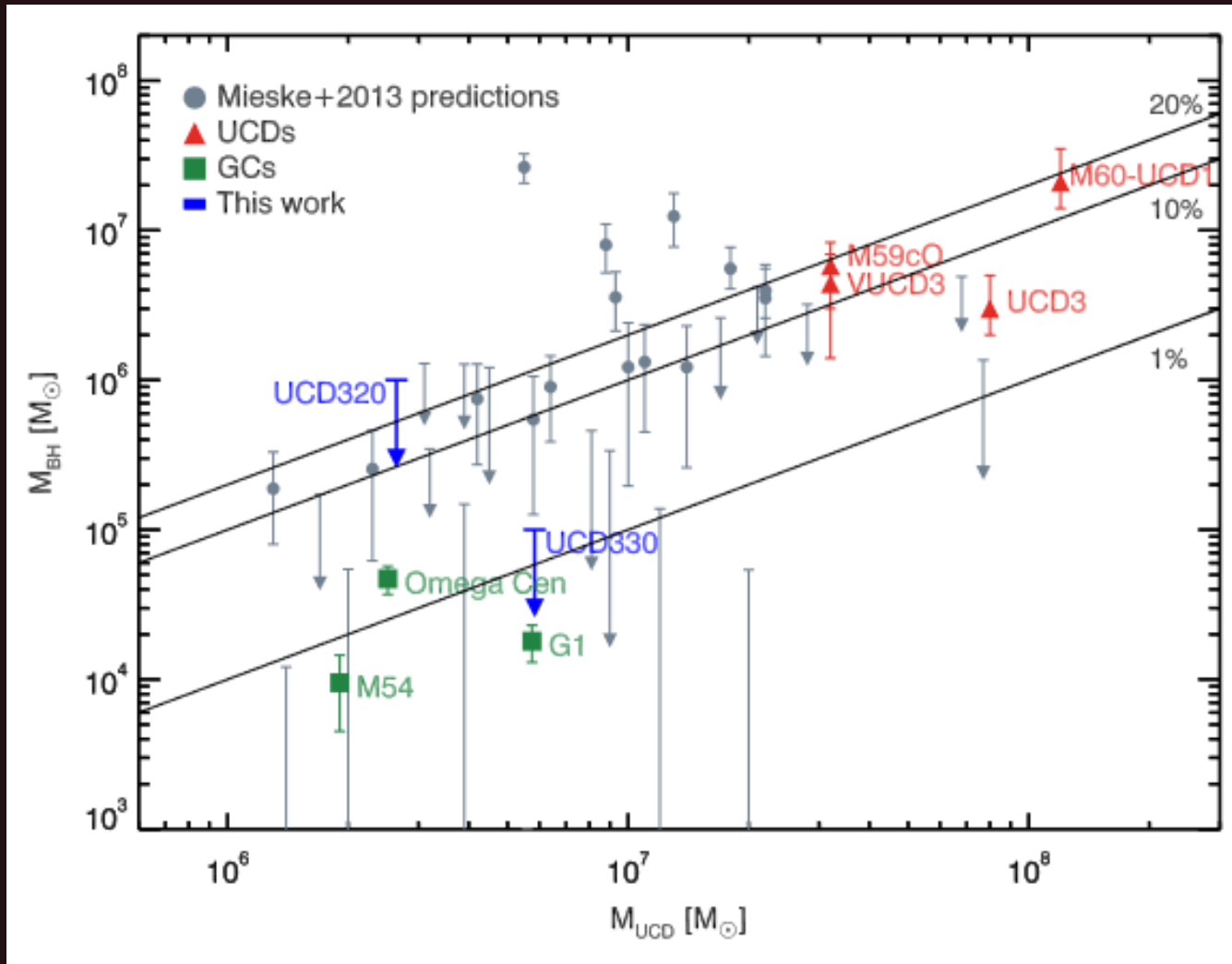
1705.01612

Radio luminosity limits cannot exclude proposed IMBHs in GCs

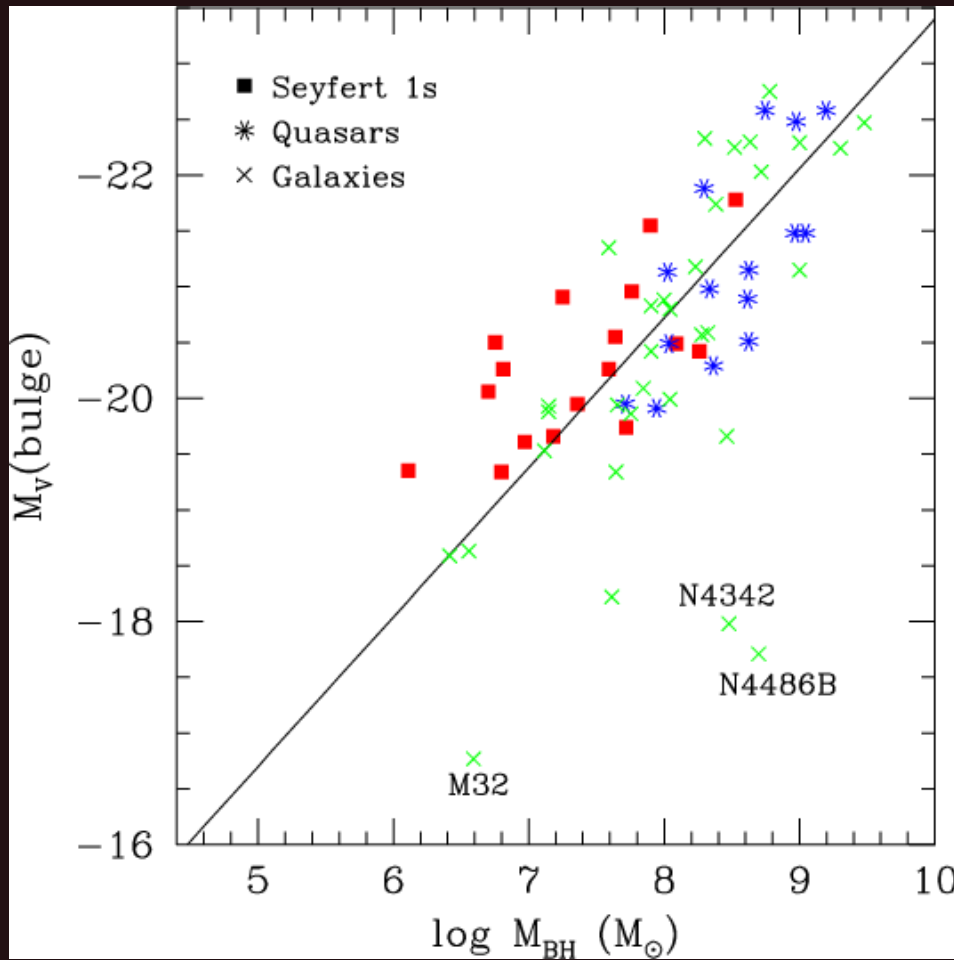
~15 candidates now (see 1705.09667)

Limits from dynamics: 1404.2781

# Ultra compact galaxies vs. globular clusters



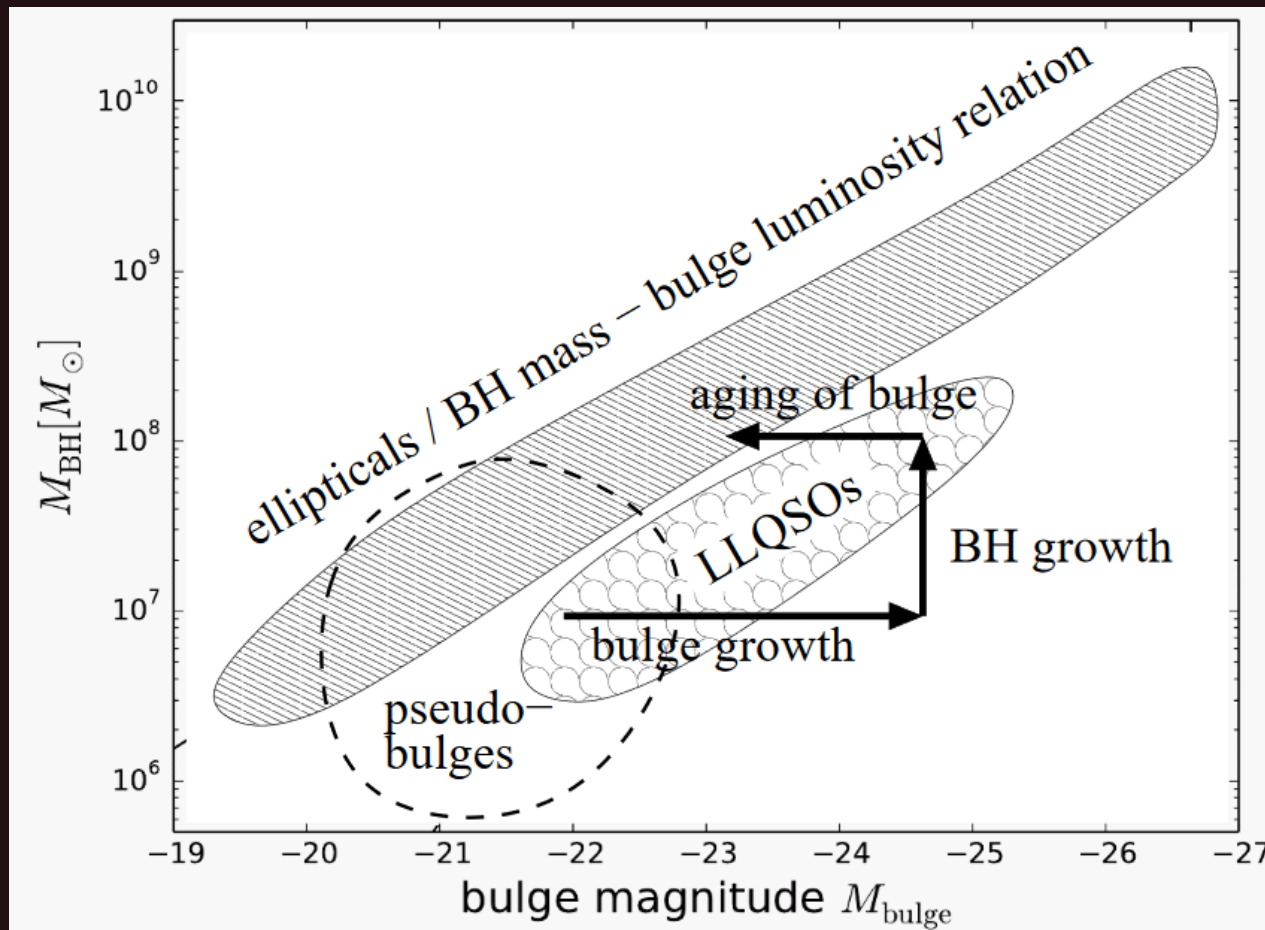
# There are other correlations



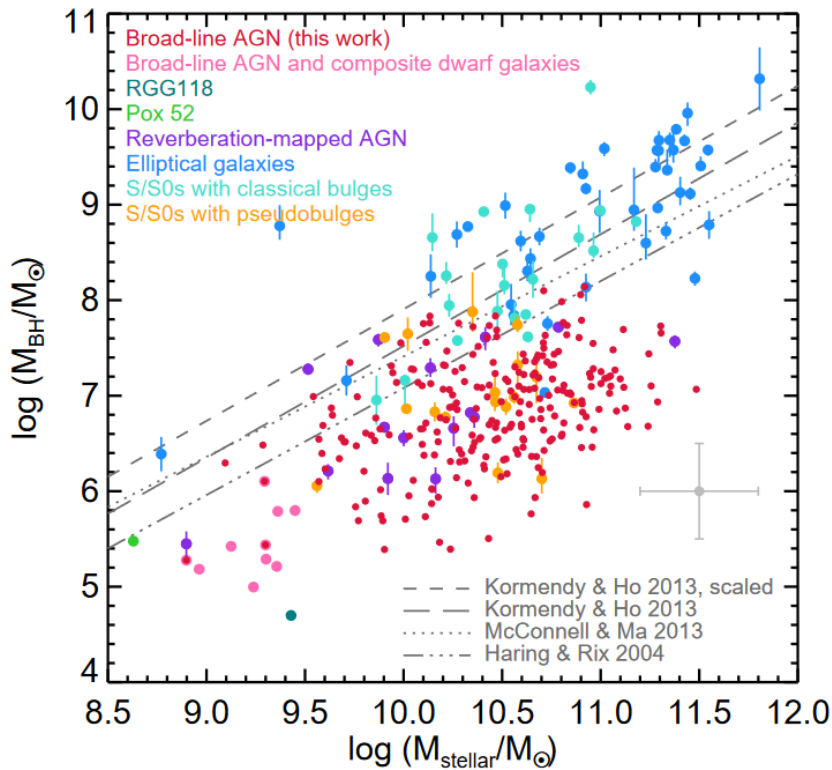
In the figure the following correlation is shown: absolute magnitude of the bulge (in V filter) vs. BH mass. BH masses are obtained by reverberation mapping.

Other correlations are discussed in the literature.

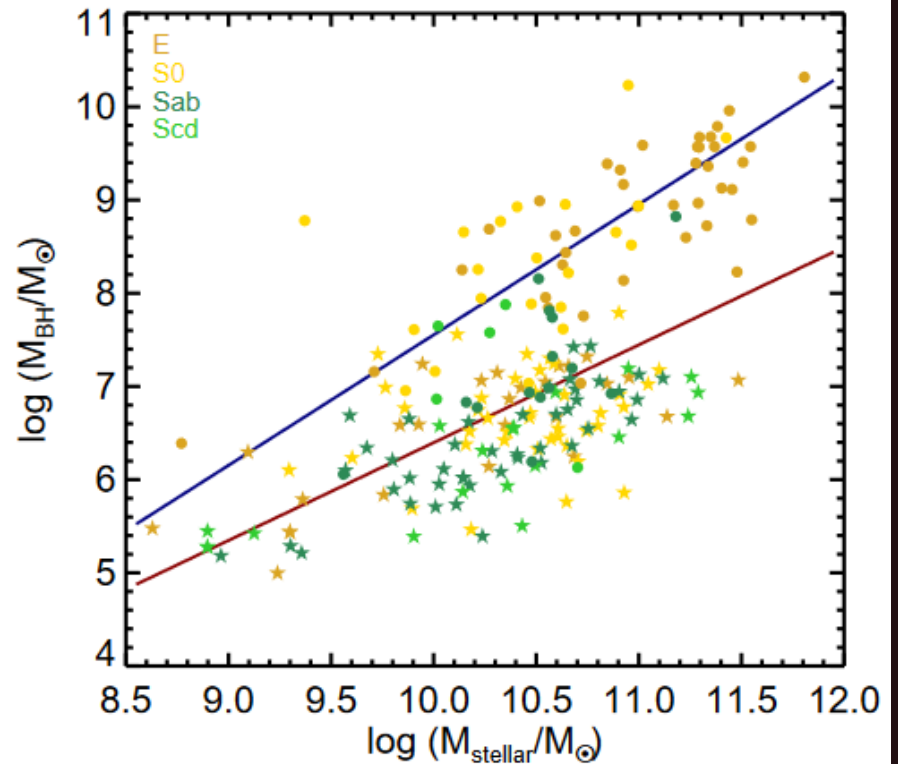
# Origin of black hole mass – bulge magnitude correlation



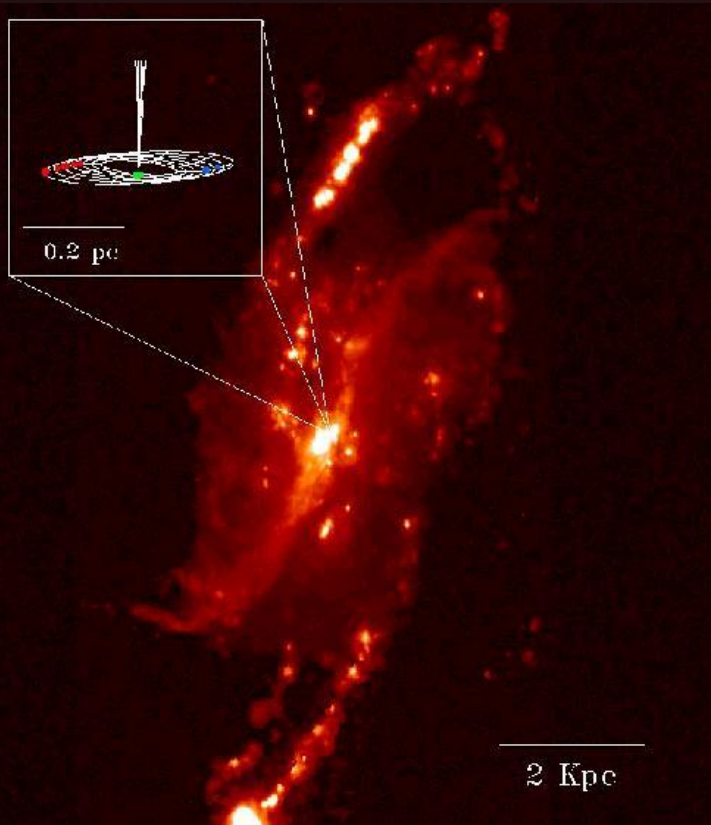
# BH mass vs stellar mass



Red points – 244 AGNs.



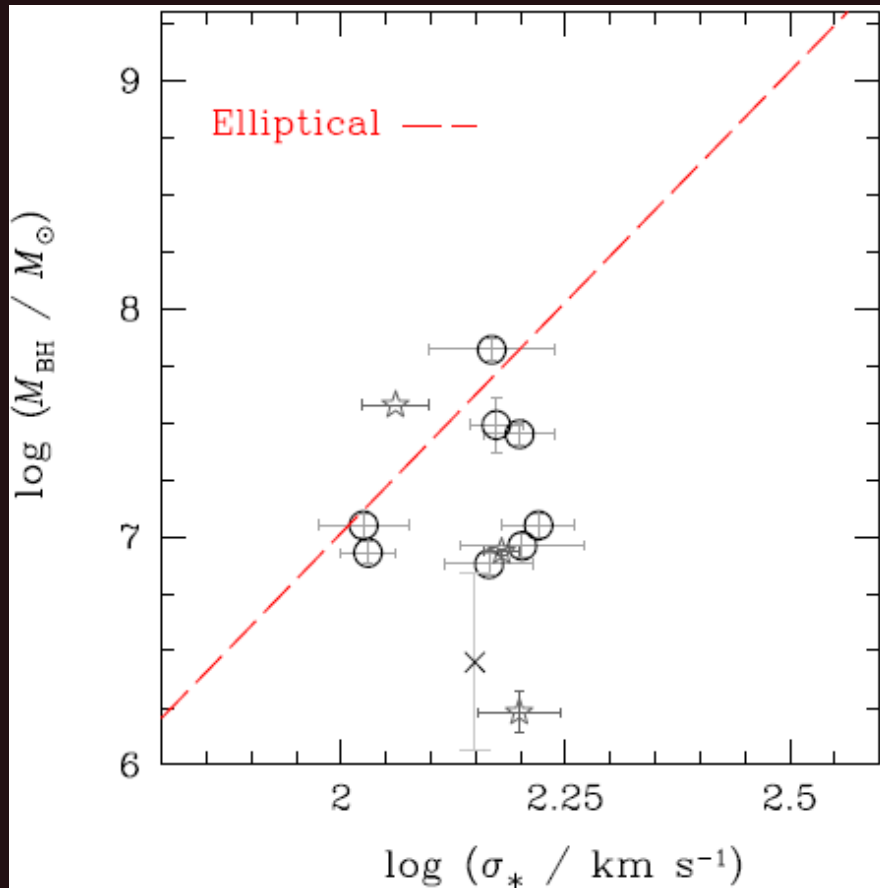
# Masers



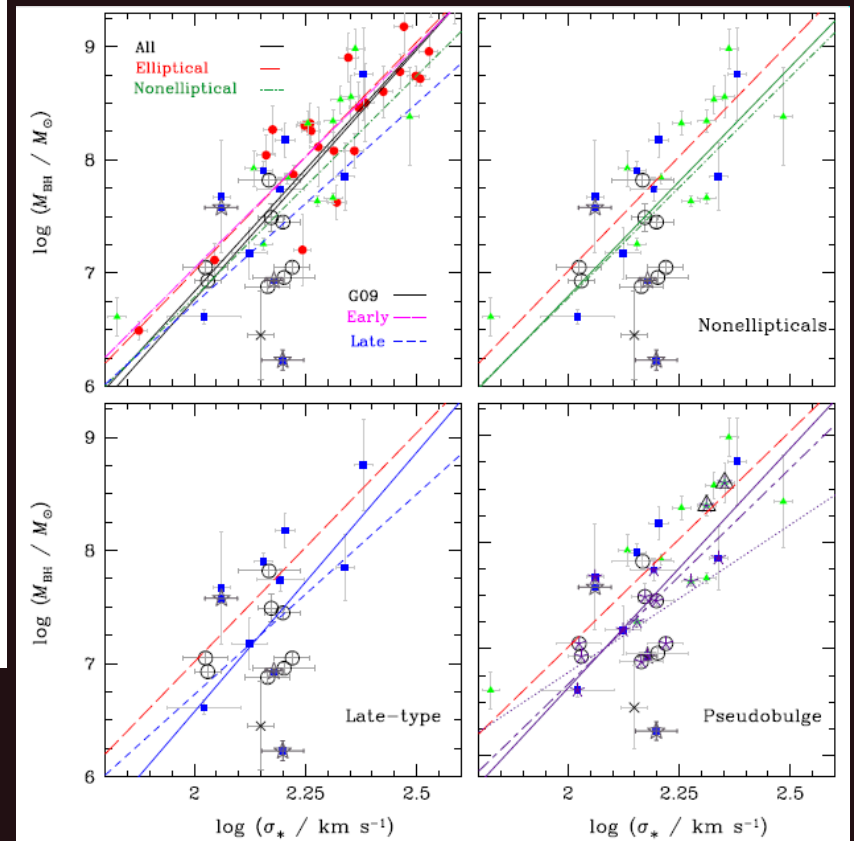
Observing movements of masers in **NGC 4258** it became possible to determine the mass inside 0.2 pc.  
The obtained value is 35-40 million solar masses.

This is the most precise method of mass determination.

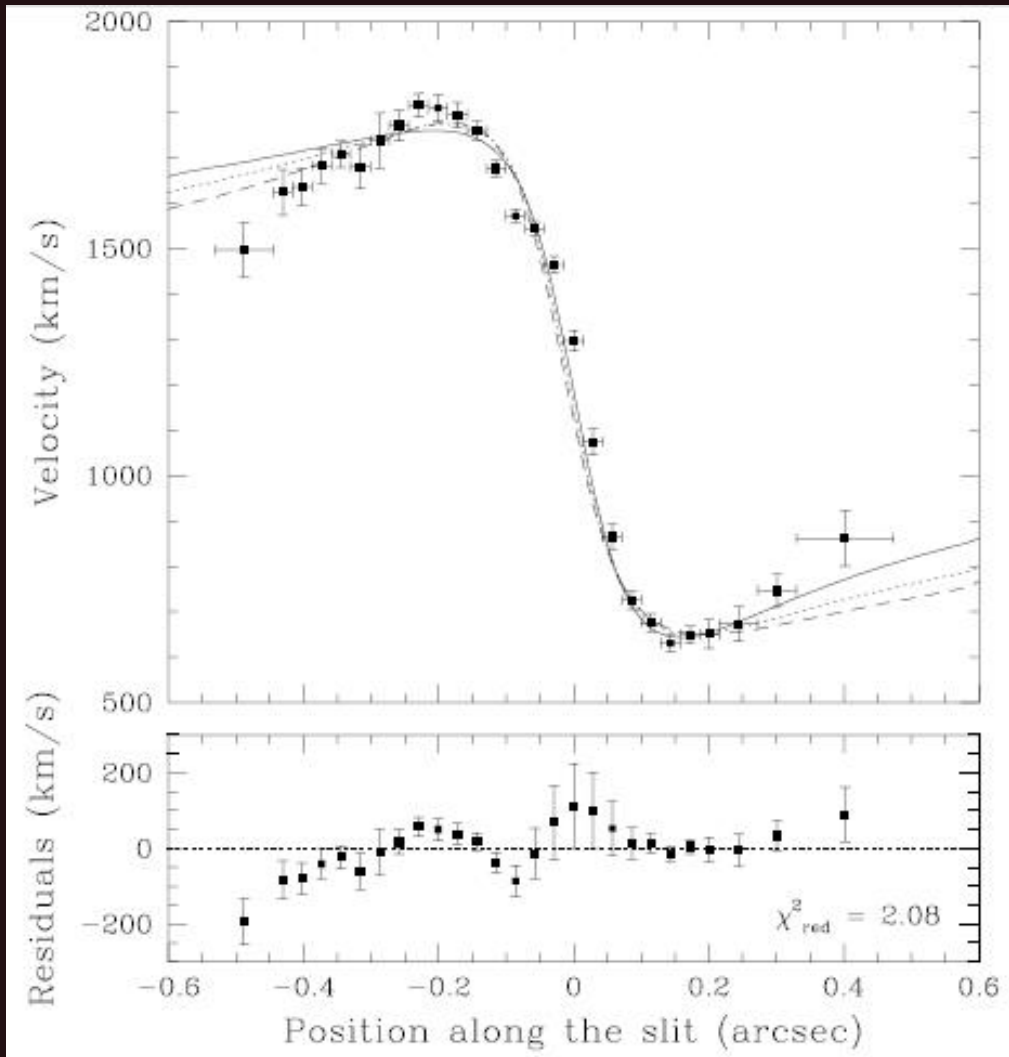
# Several more megamaser measurements



Circles – new measurements,  
stars – from the literature.



# Gas kinematics



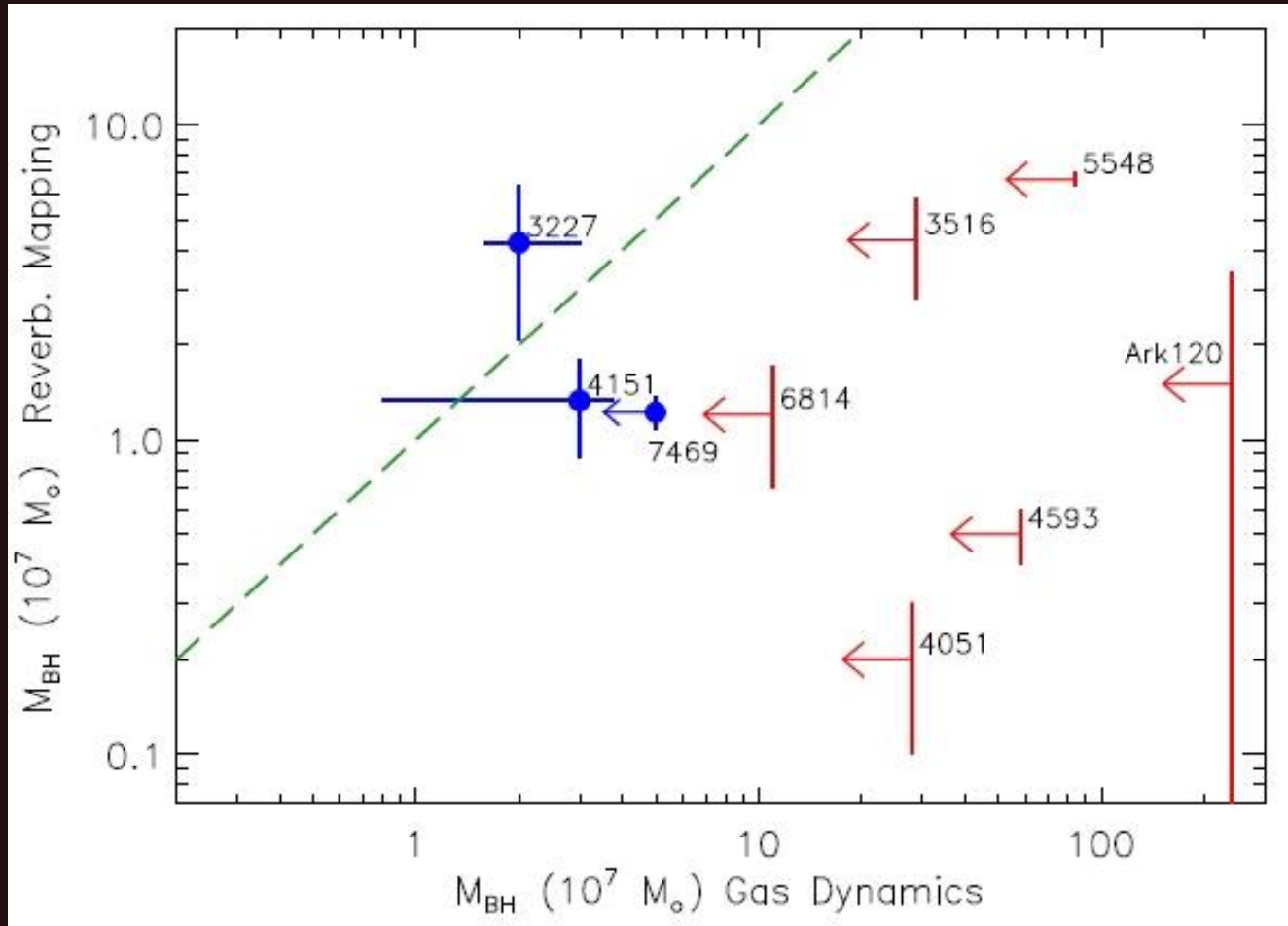
For M87 gas velocities were measured inside one milliarcsecond (5pc).

The mass is  $3 \times 10^9 M_{\odot}$ .

It is one of the heaviest BHs.

(Macchetto et al. astro-ph/9706252)

# Masses determined by gas kinematics



Masses determined by observing gas kinematics are in good correspondence with value obtained by reverberation mapping technique.

arXiv: 0707.0611

See a review in 1406.2555

# Mass via hot gas observations

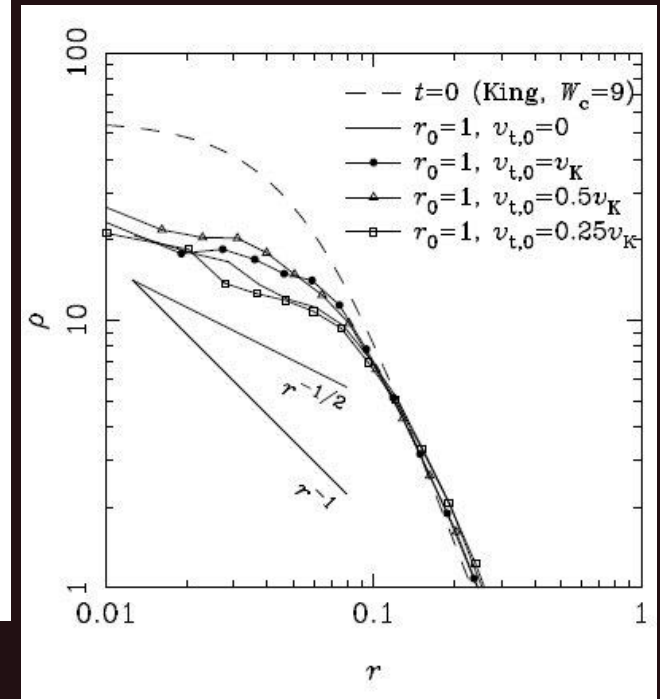
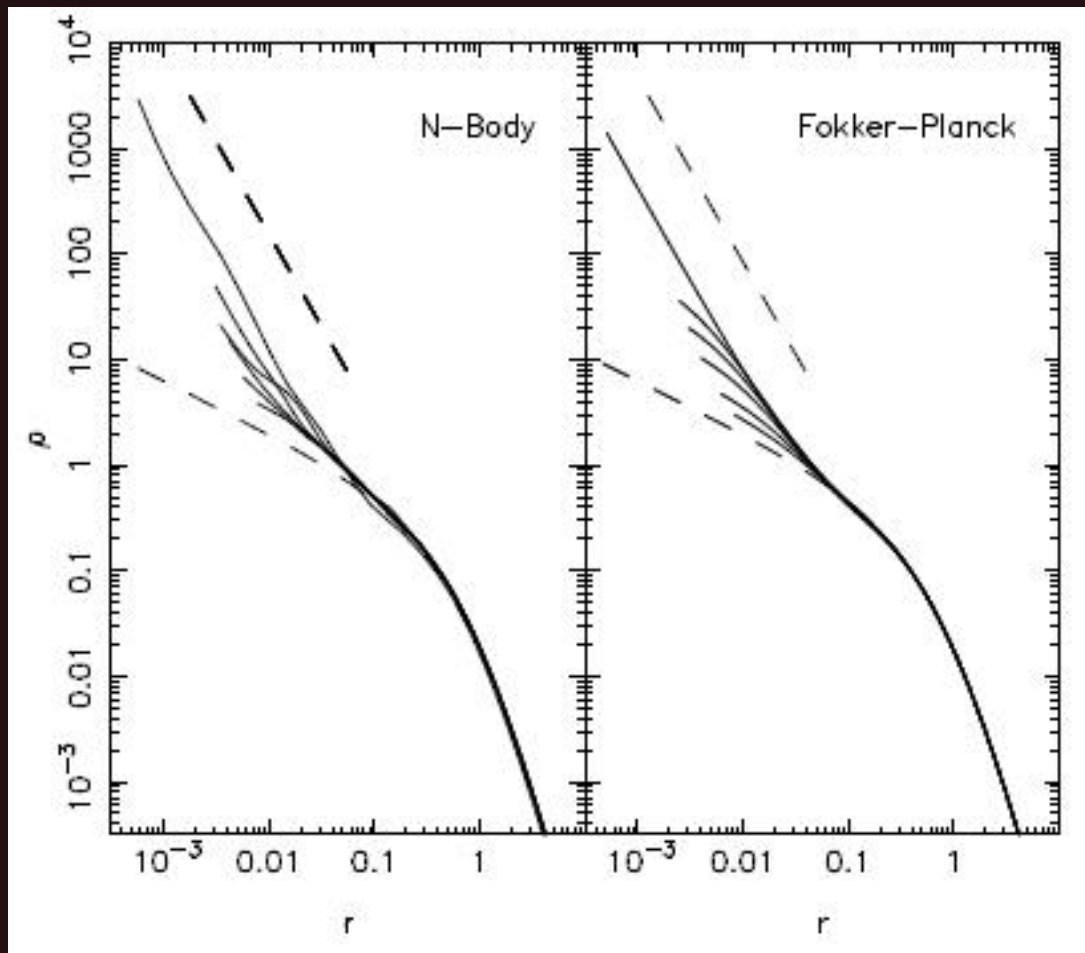
Giant elliptical galaxy NGC4649.

Chandra observations.

Temperature peaks at  $\sim 1.1\text{keV}$  within the innermost 200pc.

Under the assumption of hydrostatic equilibrium it is demonstrate that the central temperature spike arises due to the gravitational influence of a quiescent central super-massive black hole.

# Stellar density profiles



# Reverberation mapping

The method is based on measuring the response of irradiated gas to changes in the luminosity of a central sources emitting is continuum.

Initially, the method was proposed and used to study novae and SN Ia.

In the field of AGN was used for the first time in 1972 (Bahcall et al.)

An important early paper: Blandford, McKee 1982.

What is measured is the delay between changes in the light curve in continuum and in spectral lines. From this delay the size of BLR is determined.

To apply this method it is necessary to monitor a source.

$$M_{BH} = f G^{-1} R_{BLR} V^2,$$

dimensionless factor,  
depending on the geometry of BLR  
and kinematics in BLR

clouds velocities in BLR

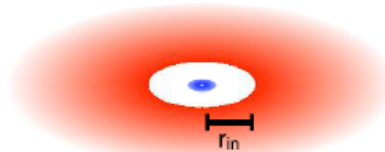
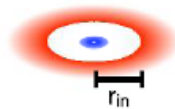
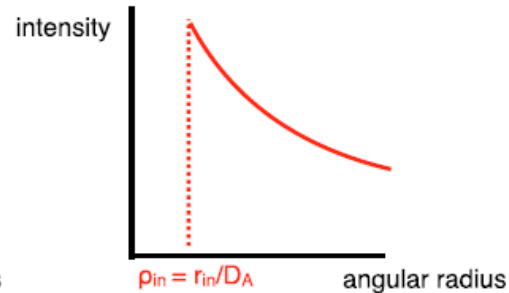
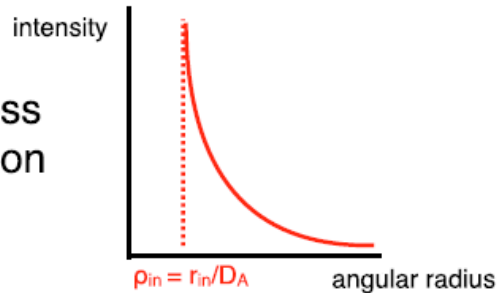
The method is not good for very bright and very weak AGNs.

( For details see [arxiv:0705.1722](https://arxiv.org/abs/0705.1722))

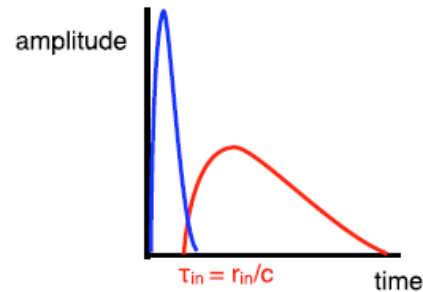
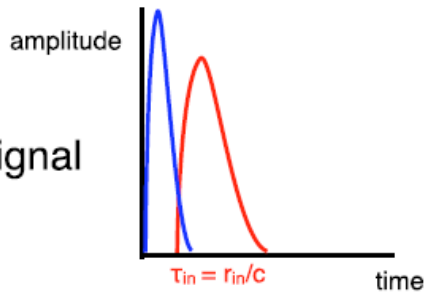
See a detailed recent example in [1104.4794](https://arxiv.org/abs/1104.4794)

# Как расстояние помогает массу измерить

(a) brightness distribution



(b) delay signal



**Удалось уточнить расстояние до важной галактики NGC 4151 с черной дырой. По ней калибруют массы других черных дыр. В итоге – массы возросли почти в полтора раза.**

# Population synthesis in astrophysics

A population synthesis is a method of a direct modeling of relatively large populations of weakly interacting objects with non-trivial evolution.

As a rule, the evolution of the objects is followed from their birth up to the present moment.

(see [astro-ph/0411792](#))

# Two variants

## Evolutionary and Empirical

1. Evolutionary PS.

The evolution is followed from some early stage.

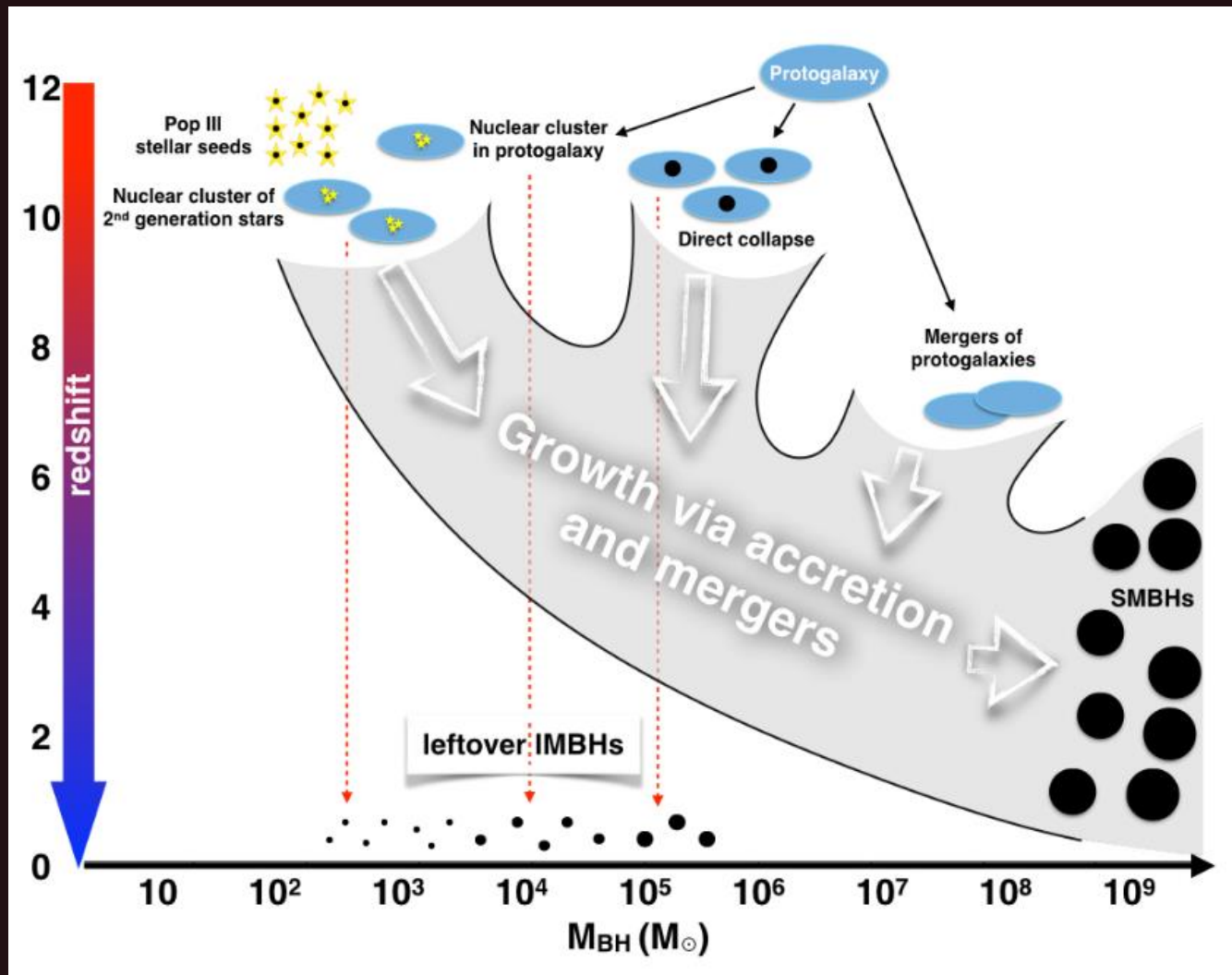
Typically, an artificial population is formed  
(especially, in Monte Carlo simulations)

2. Empirical PS.

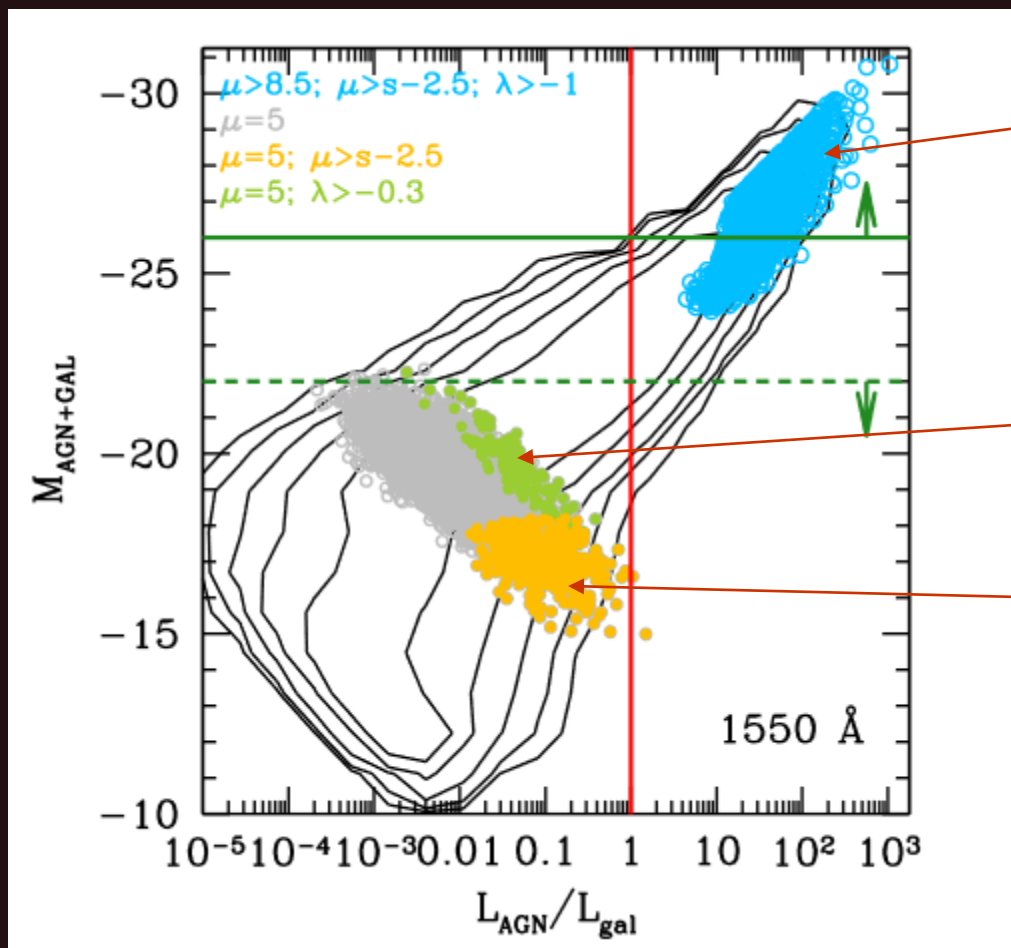
It is used, for example, to study integral properties  
(spectra) of unresolved populations.

A library of spectra is used to predict integral properties.

# Origin of SMBHs



# Population synthesis of SMBHs



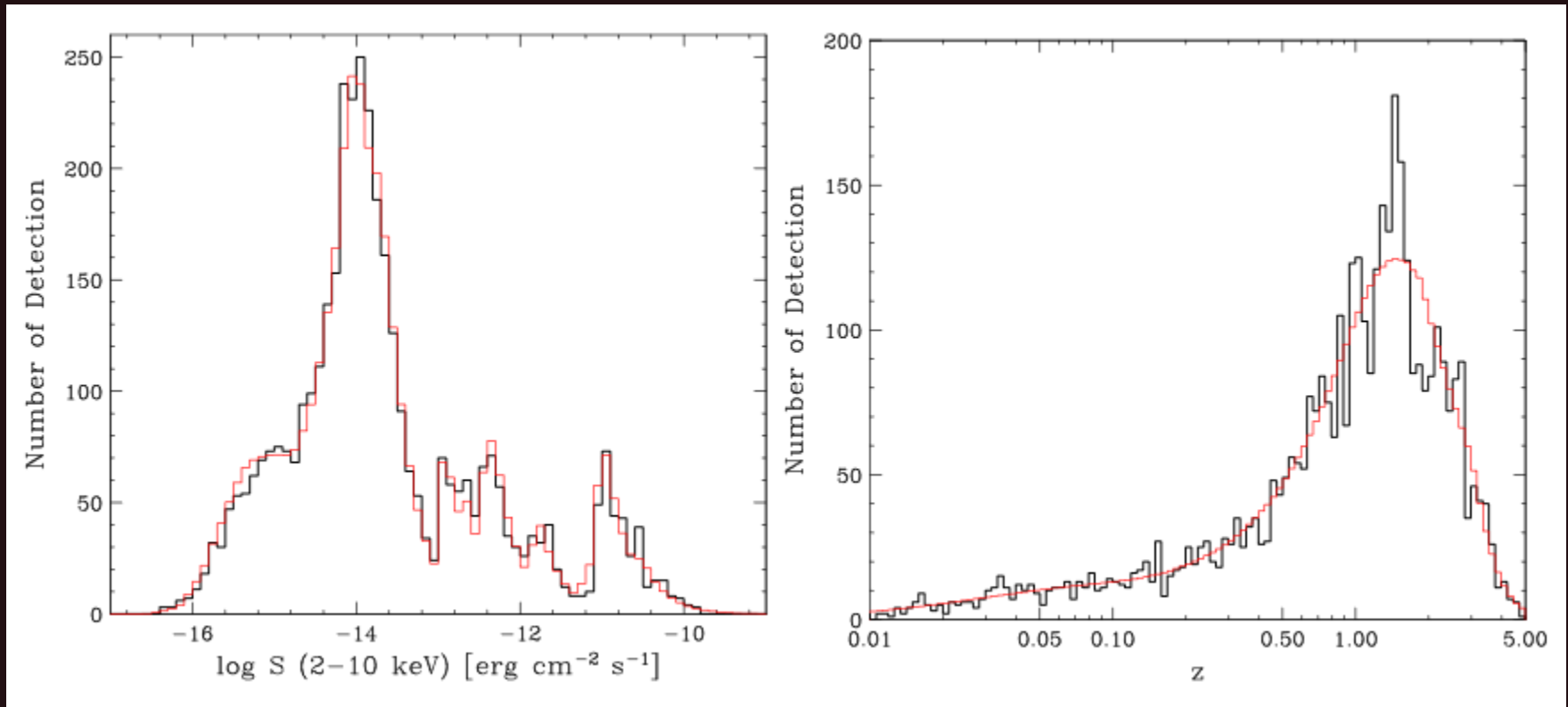
QSOs

High accretion rate

Massive BH (relative to the galaxy mass)

Predictions for JWST

# X-ray background and pop. synthesis

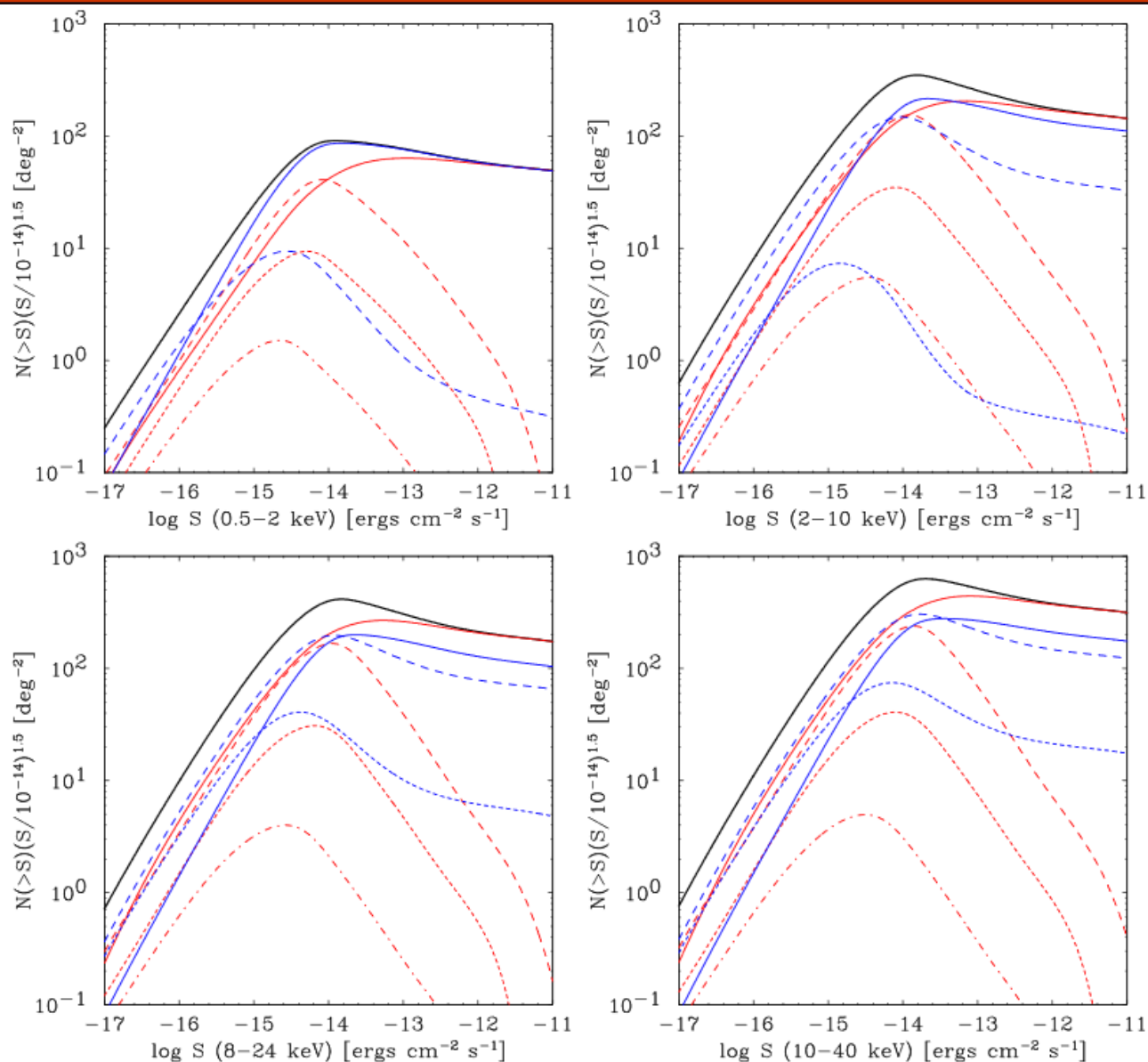


Observed histograms (thick, black) of flux (left) and redshift (right) of the authors sample compared with model predictions (thin, red).

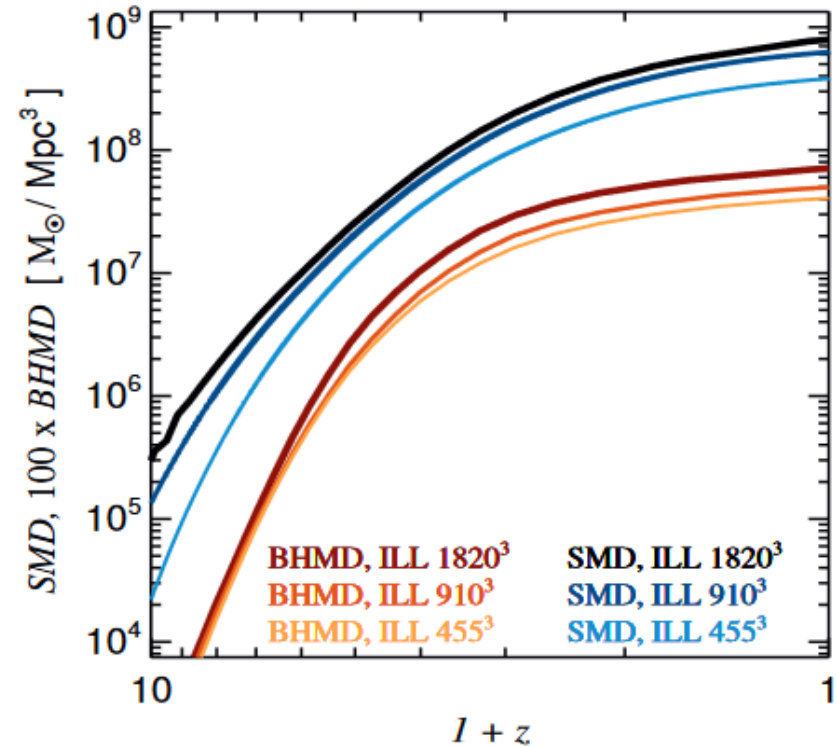
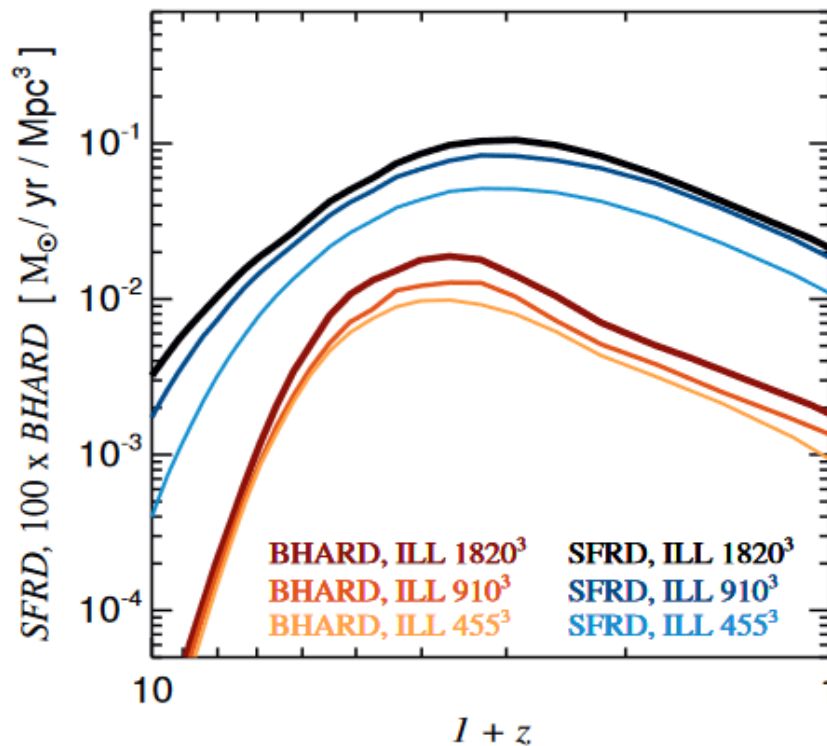
Predicted  
Log N – Log S  
distributions.

Red: different z:

solid:  $z < 1$ ,  
long-dashed:  $z = 1-2$ ,  
short-dashed:  $z = 2-3$ ,  
dot-dashed:  $z = 3-5$



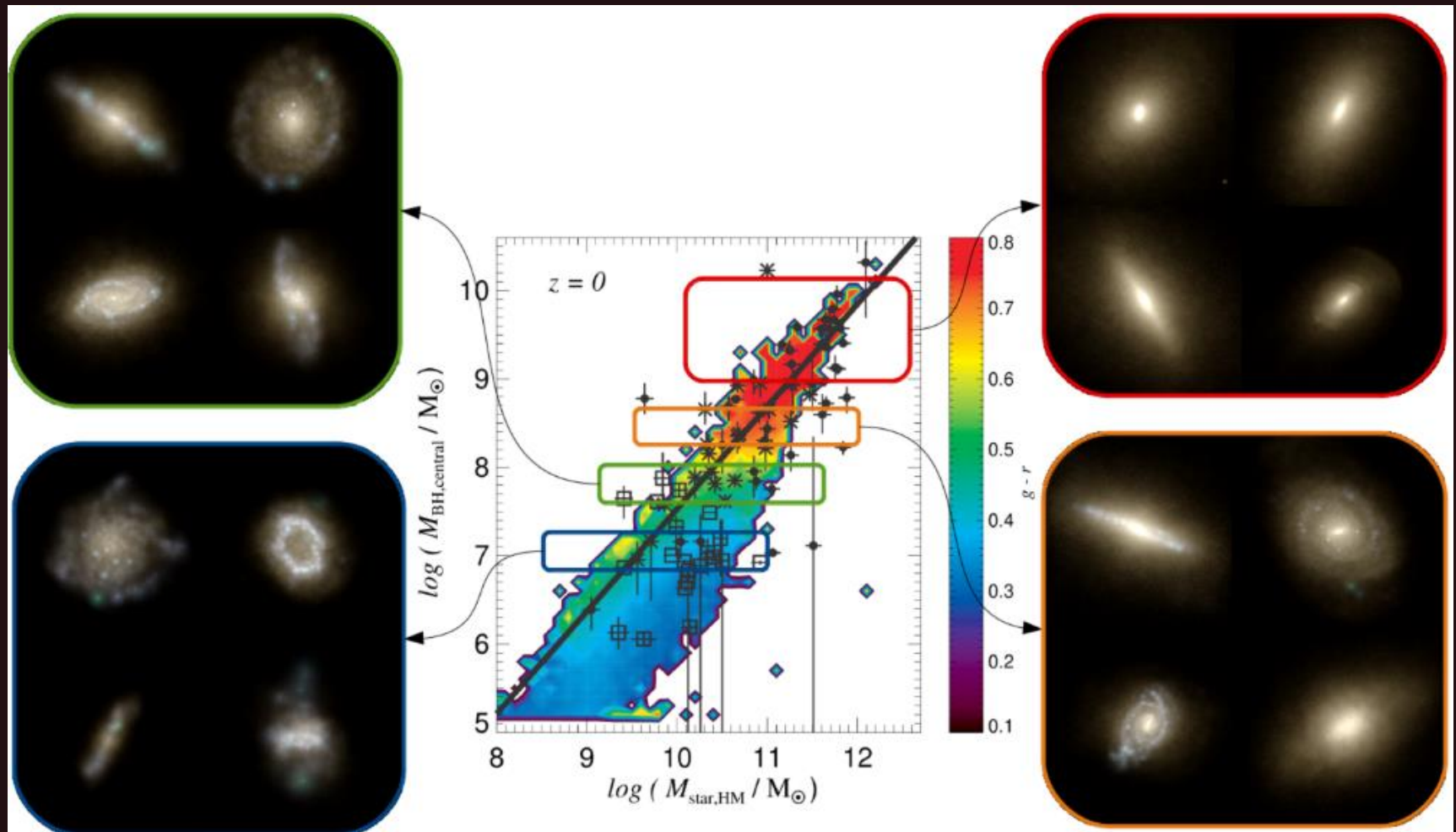
# Illustris calculations



Time evolution of the star formation rate density (blue curves) and of the black hole accretion rate density (red curves; rescaled by a factor of a 100) for three different resolutions.

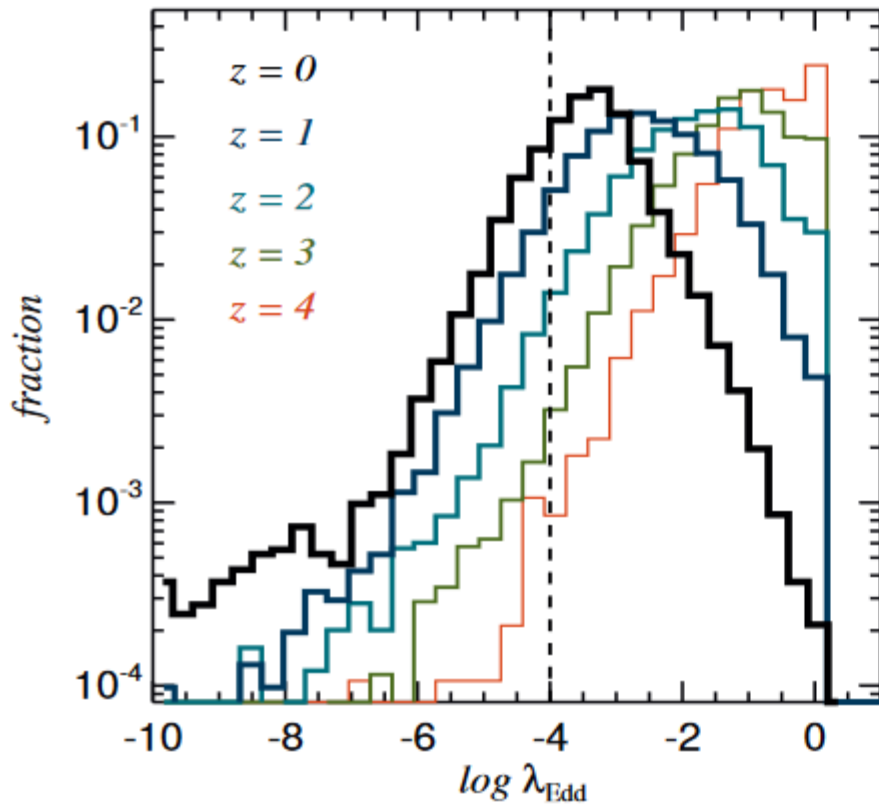
Stellar mass density and black hole mass density as a function of cosmic time

# Illustris simulations

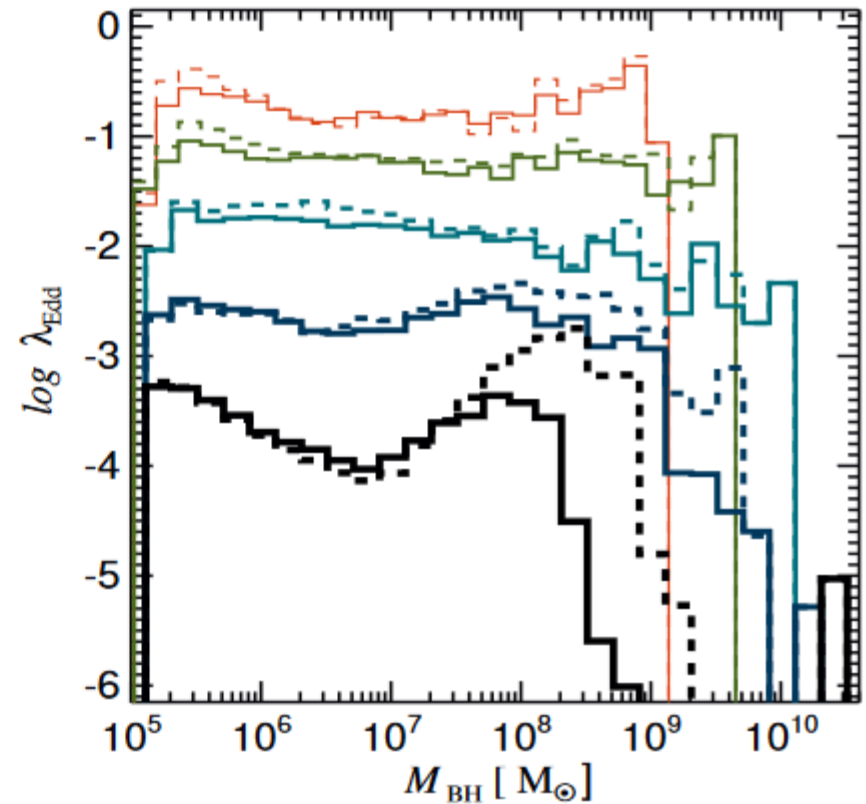


Stellar half-mass of all galaxies at  $z=0$  versus their central black hole mass

# BH accretion rate evolution



Distribution of black hole Eddington ratios at  $z=4, 3, 2, 1$  and 0.



Eddington ratios as a function of black hole mass at  $z=4, 3, 2, 1$  and 0.

# High redshift AGNs

Future observations might reveal many AGNs with moderate luminosities at high  $z$ .

This will allow to probe early evolution of SMBHs.

