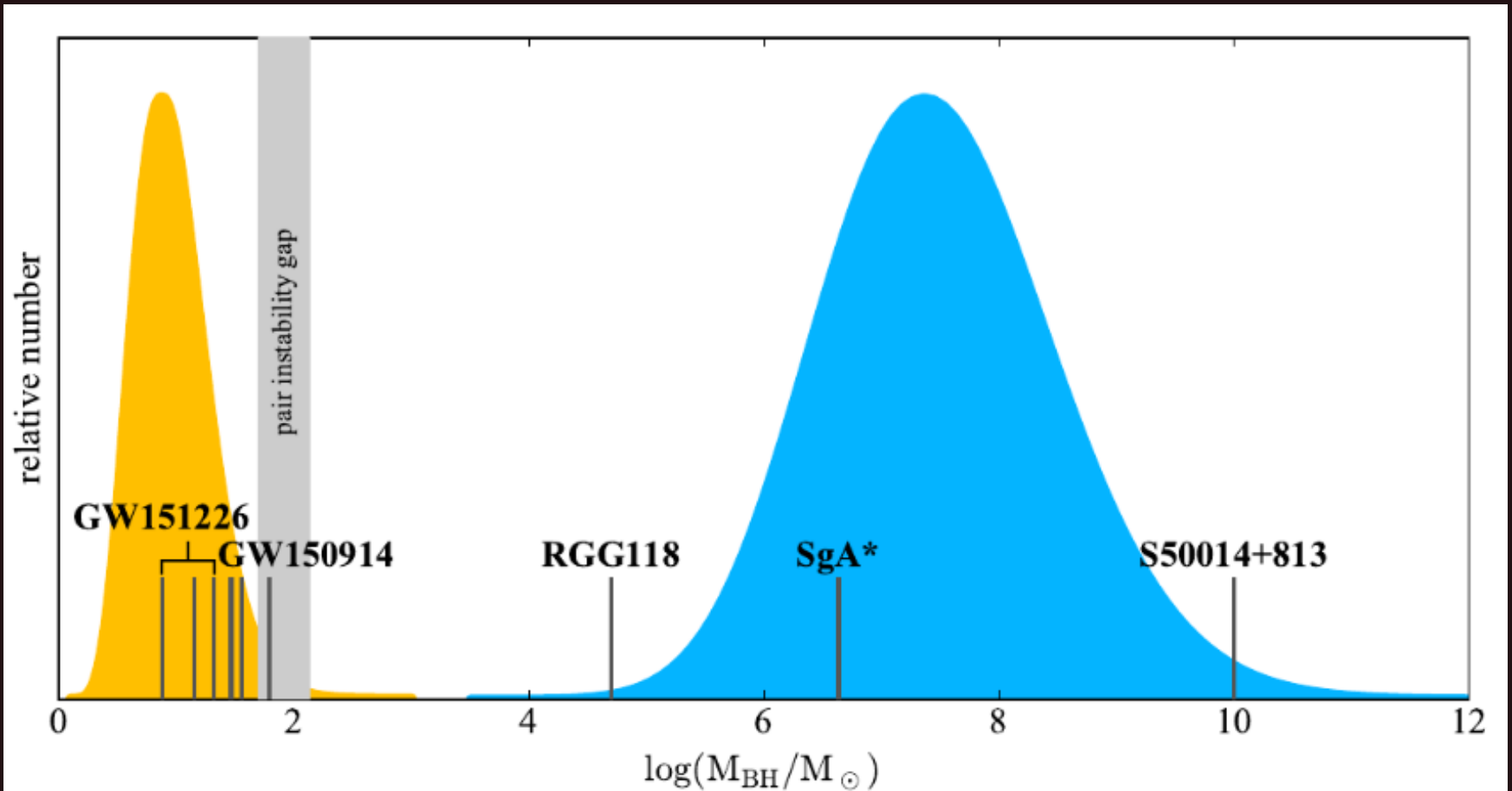




Supermassive black holes



Black hole masses



Plan of the lecture

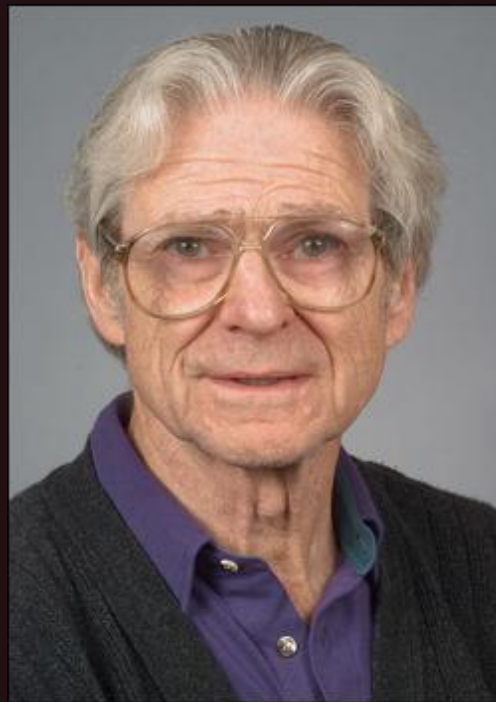
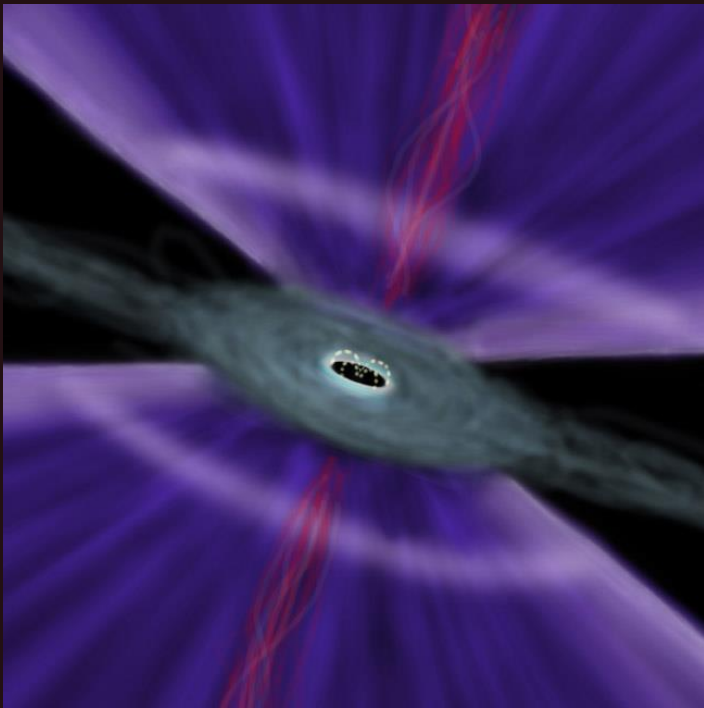
1. General information about SMBHs.
2. “Our” certain black hole: Sgr A*.
3. SMBHs: from radio to gamma. AGNs.
4. Mass measurements

Main reviews

- [arxiv: 1609.03562, 0907.5213](#) **Supermassive Black Holes**
- [astro-ph/0512194](#) **Constraints on Alternatives to Supermassive Black Holes**
- 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**
- arXiv: 1911.09678 **Intermediate-Mass Black Holes**
- arXiv: 1707.07134 **AGN**
- arXiv: 1911.12176 **Unification model**

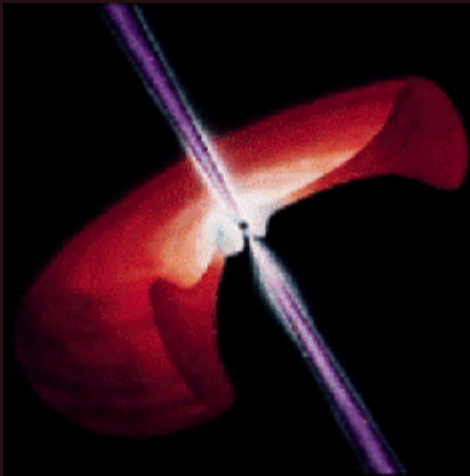
Some history

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).

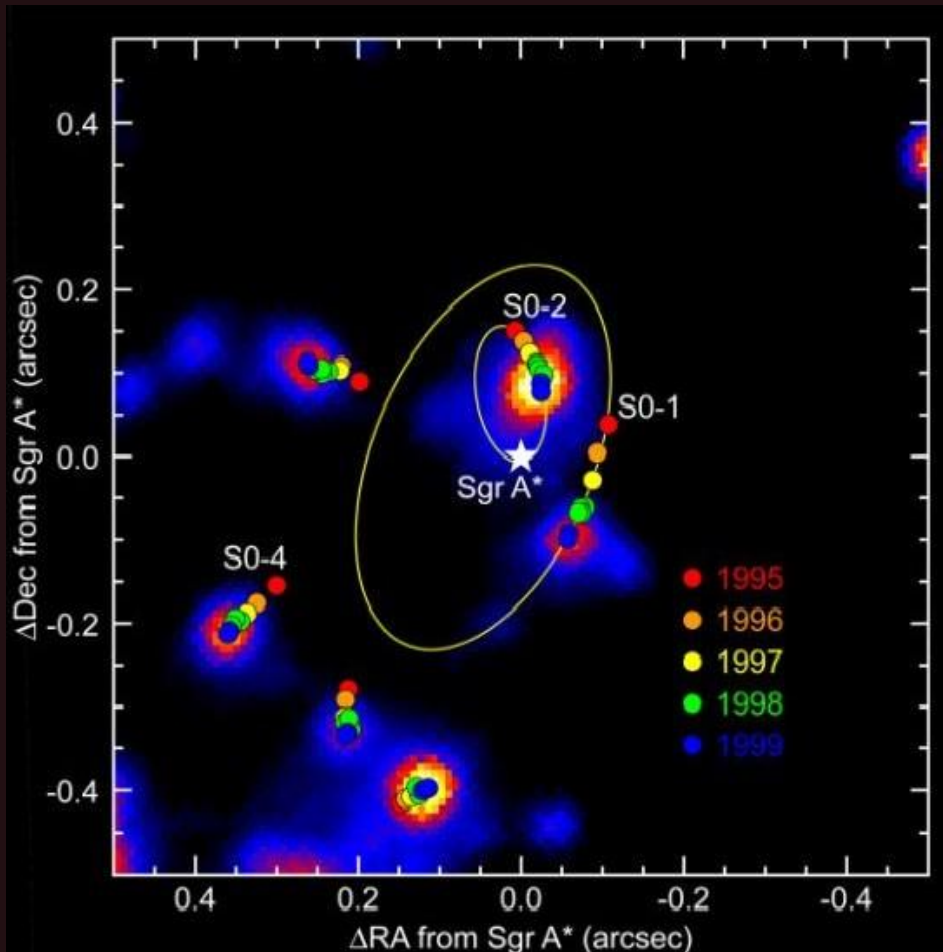


General info

- All galaxies with significant bulges should have a SMBH in the center.
- SMBH are observed already at redshifts $z \sim 7$ 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.

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)

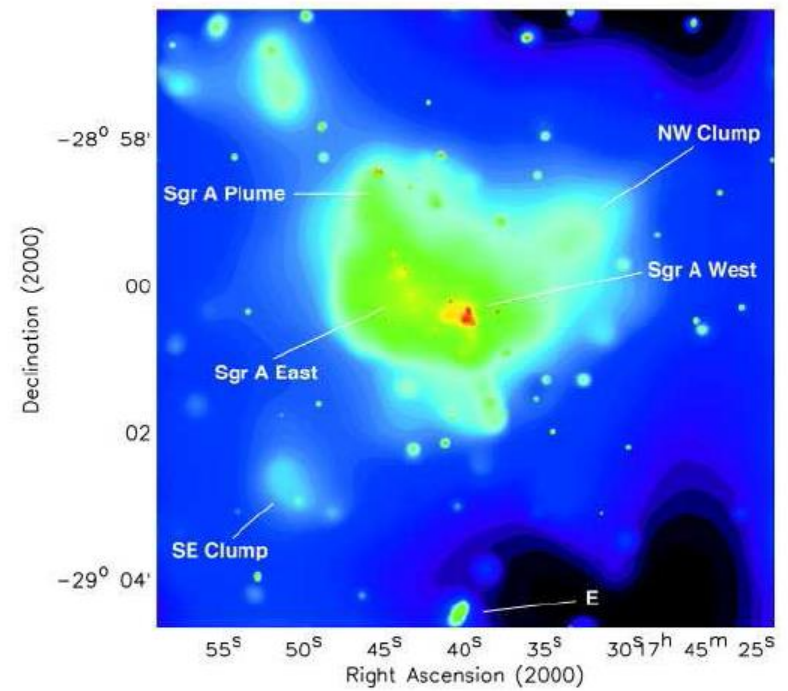
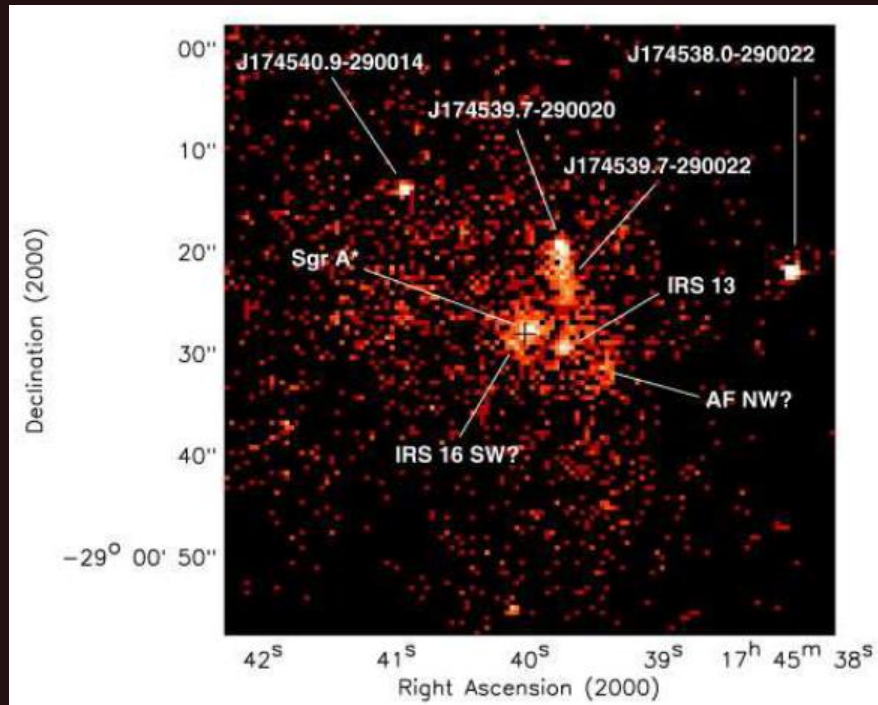
A review: [arxiv:1311.1841](https://arxiv.org/abs/1311.1841) **Towards the event horizon –
the supermassive black hole in the Galactic Center** ⁷

A closer look

Chandra. 2-10 keV

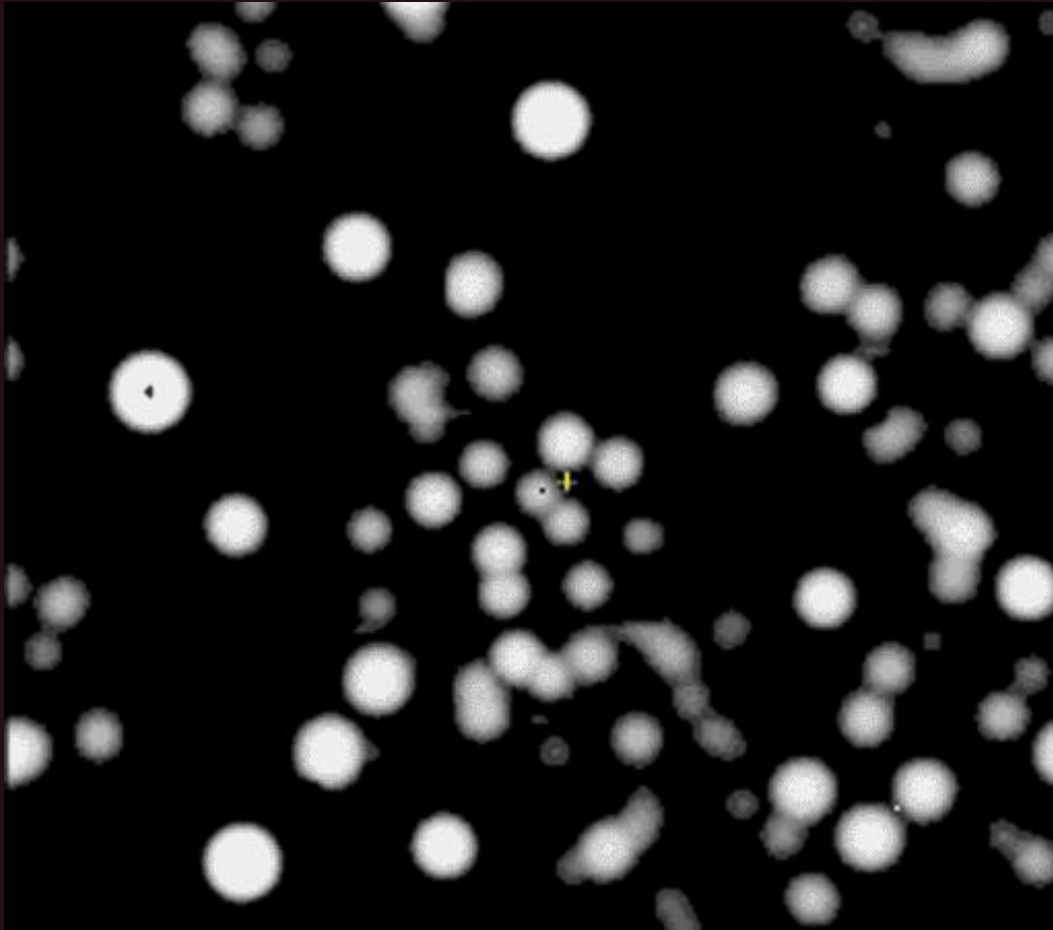
2.4 pc

20 pc



1007.4174

Stellar dynamics around Sgr A*

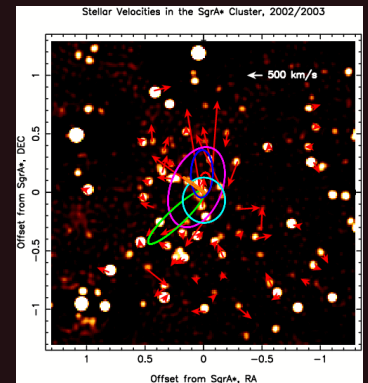


With high precision we know stellar dynamics inside the central arcsecond ([astro-ph/0306214](#))

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

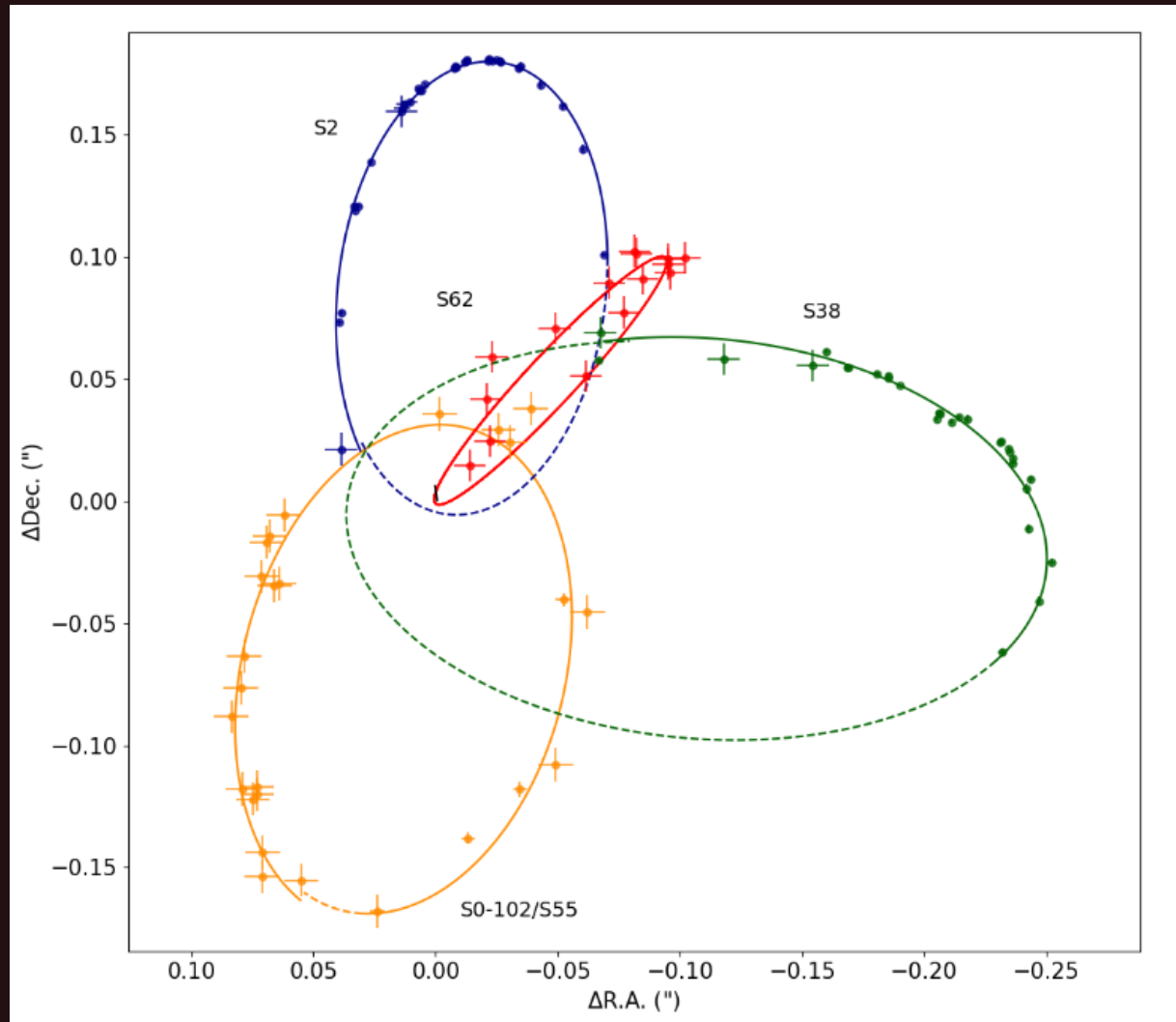
Stars-star interactions can be important: arXiv 0911.4718

S62. Just ten years.

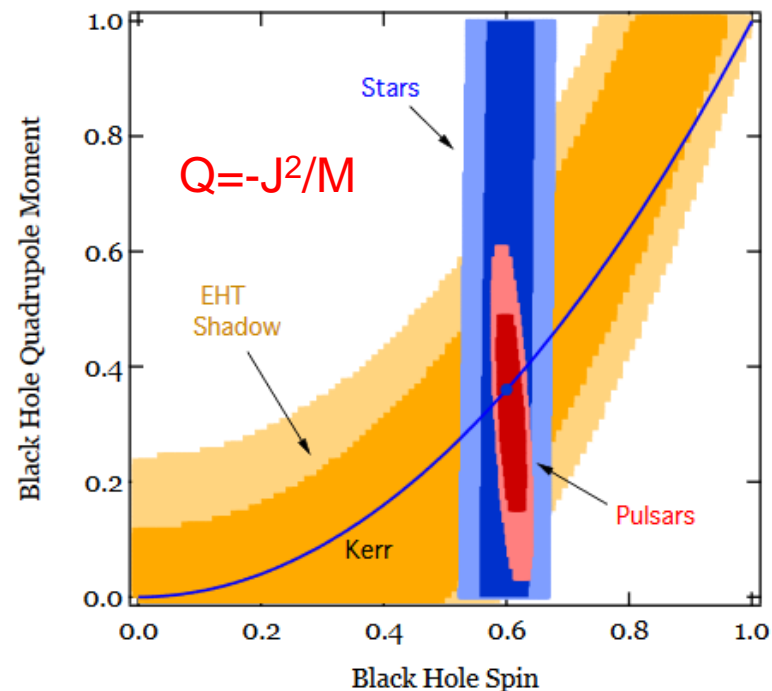
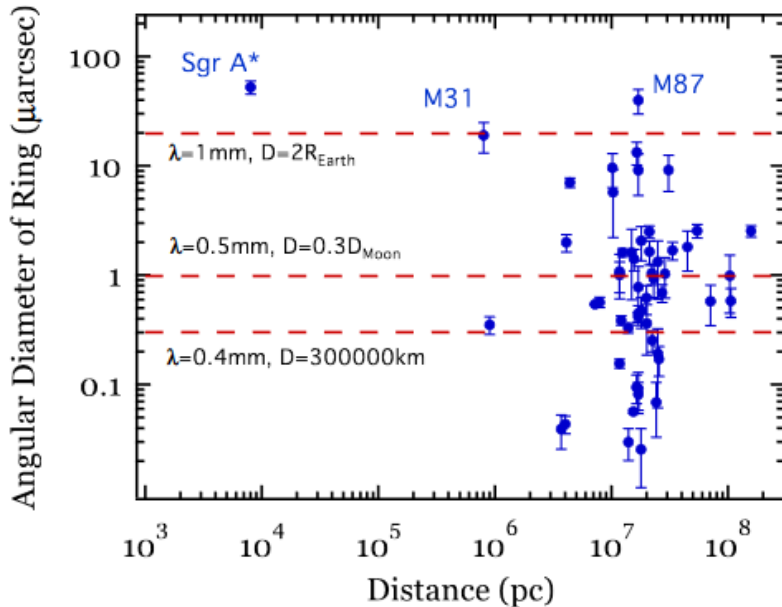
2 solar masses.

$P_{\text{orb}}=9.9$ years
 $e=0.976$

$a_p=215 R_{\text{sh}}$

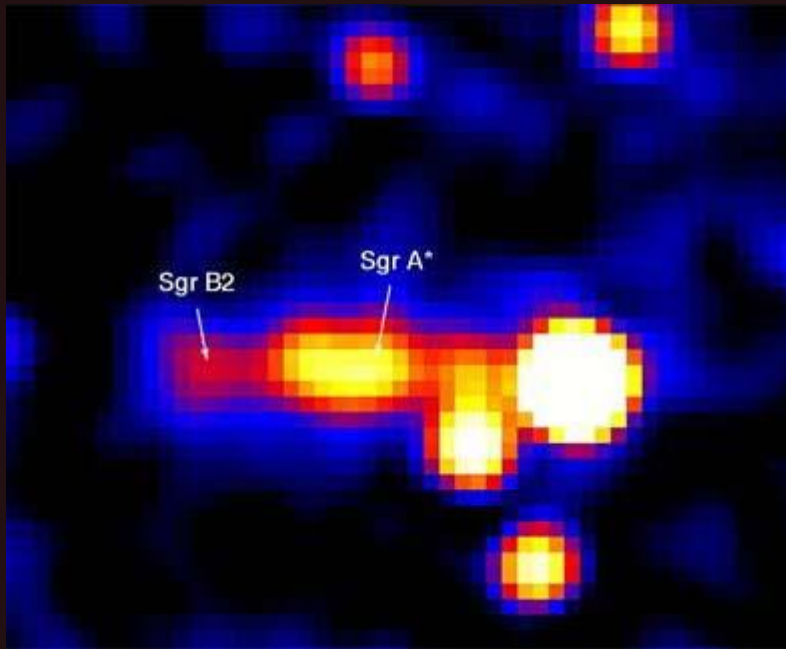


General relativity test, EHT, etc.



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.**

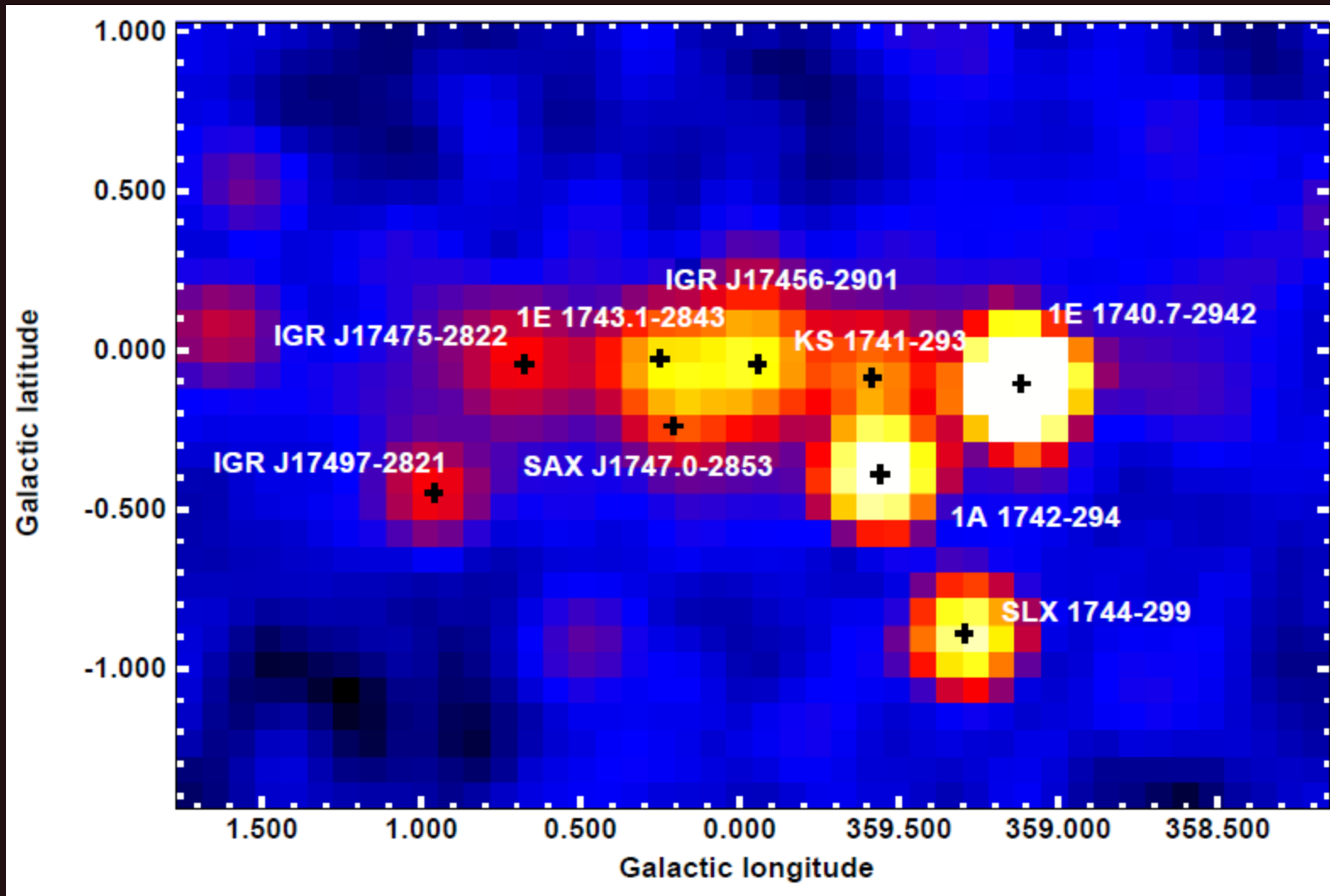
At present “our” black hole is not active.
However, it was not so in the past.

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.

See more data in 1211.4529, 1612.00180.

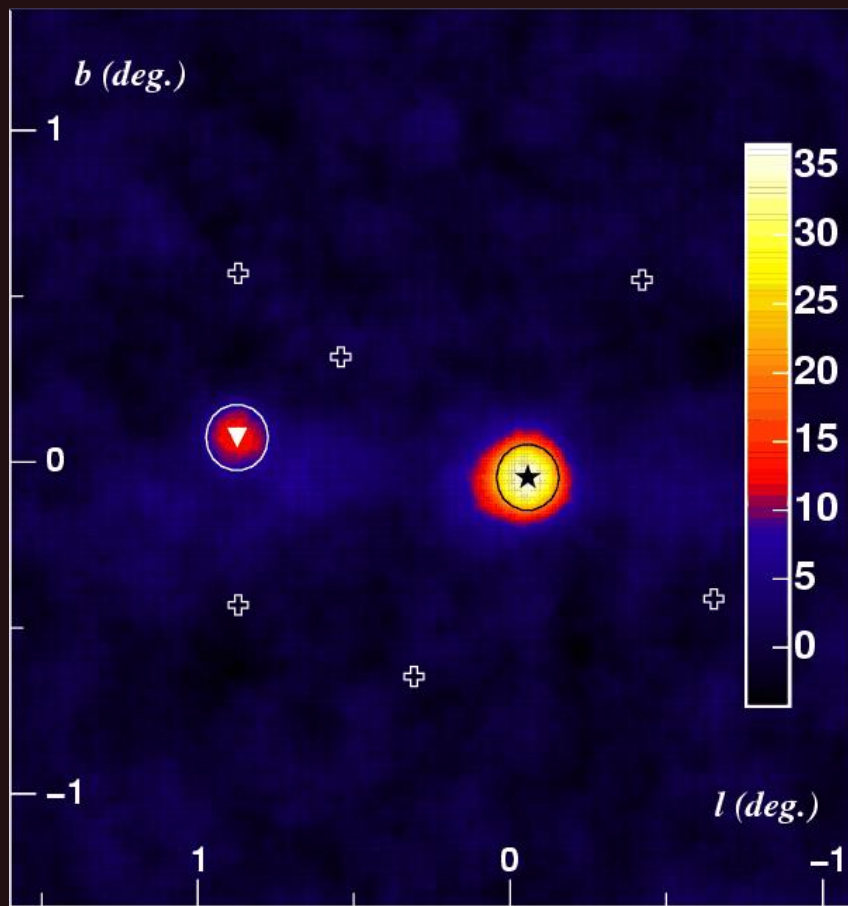
Probably, there have been several strong
flares in the past 1307.3954.

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.

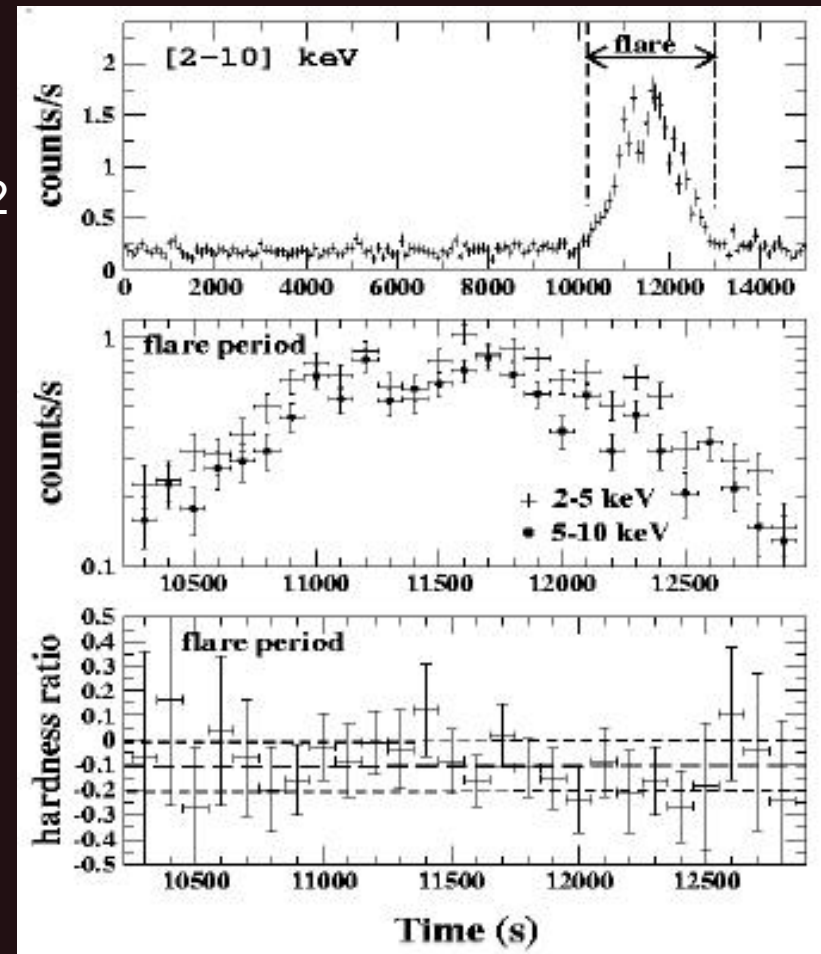
The flux increased by a factor ~ 160 .

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

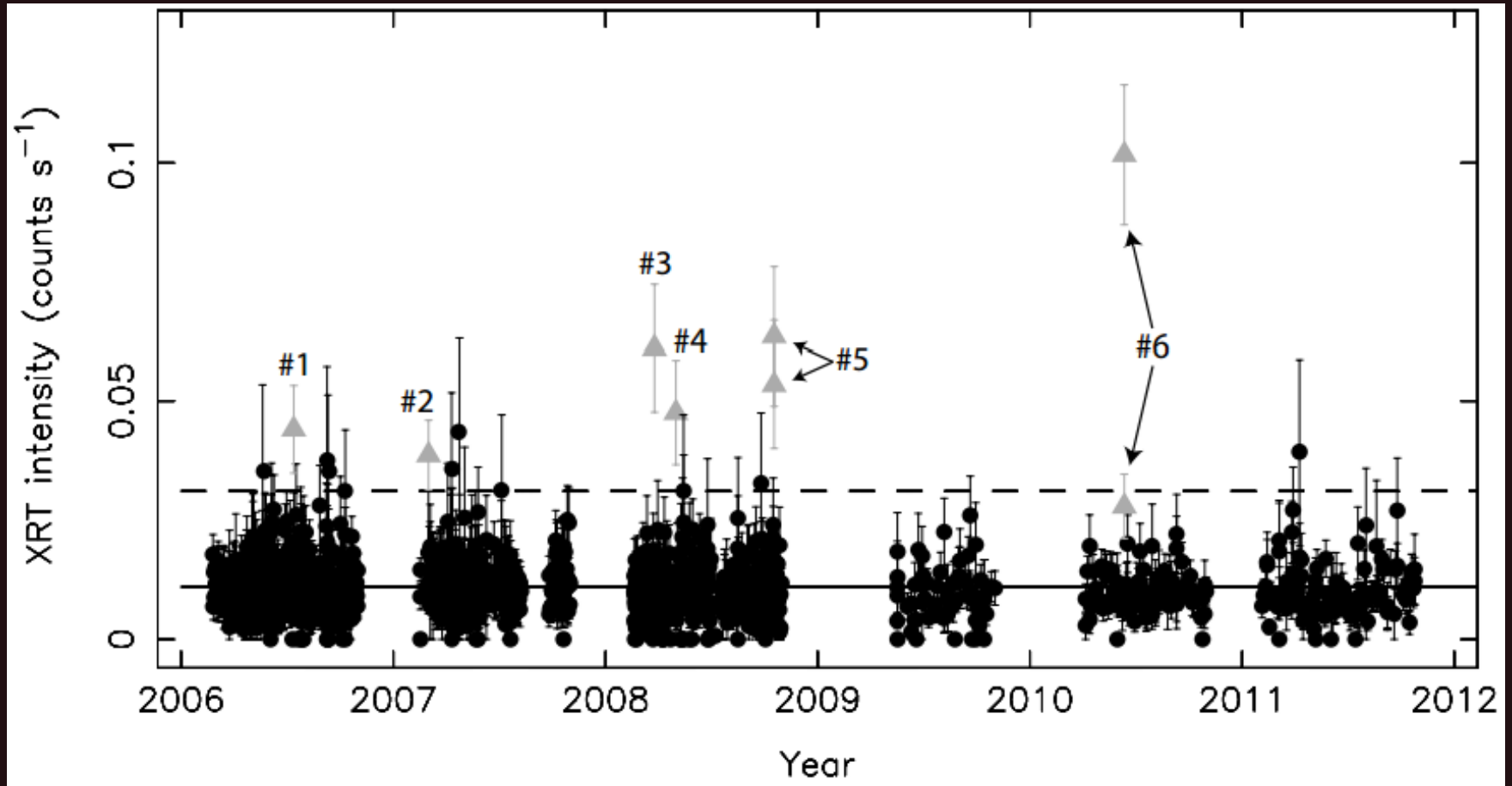
In one of the bursts, on Aug. 31, 2004,
QPOs have been discovered.

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

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



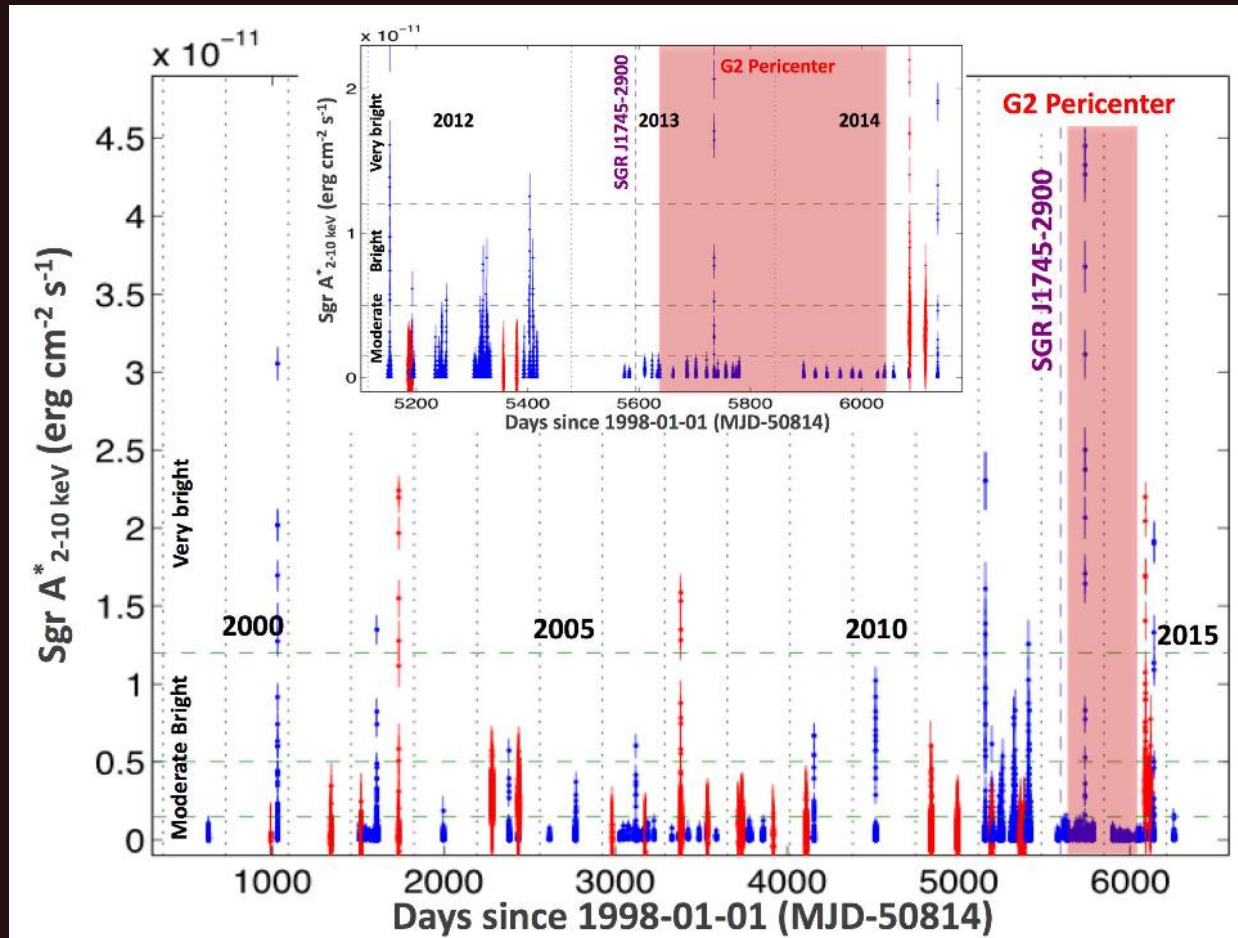
SWIFT monitoring of Sgr A*



1210.7237

See 1501.02171 about accretion physics around Sgr A*

XMM-Newton and Chandra monitoring of Sgr A*

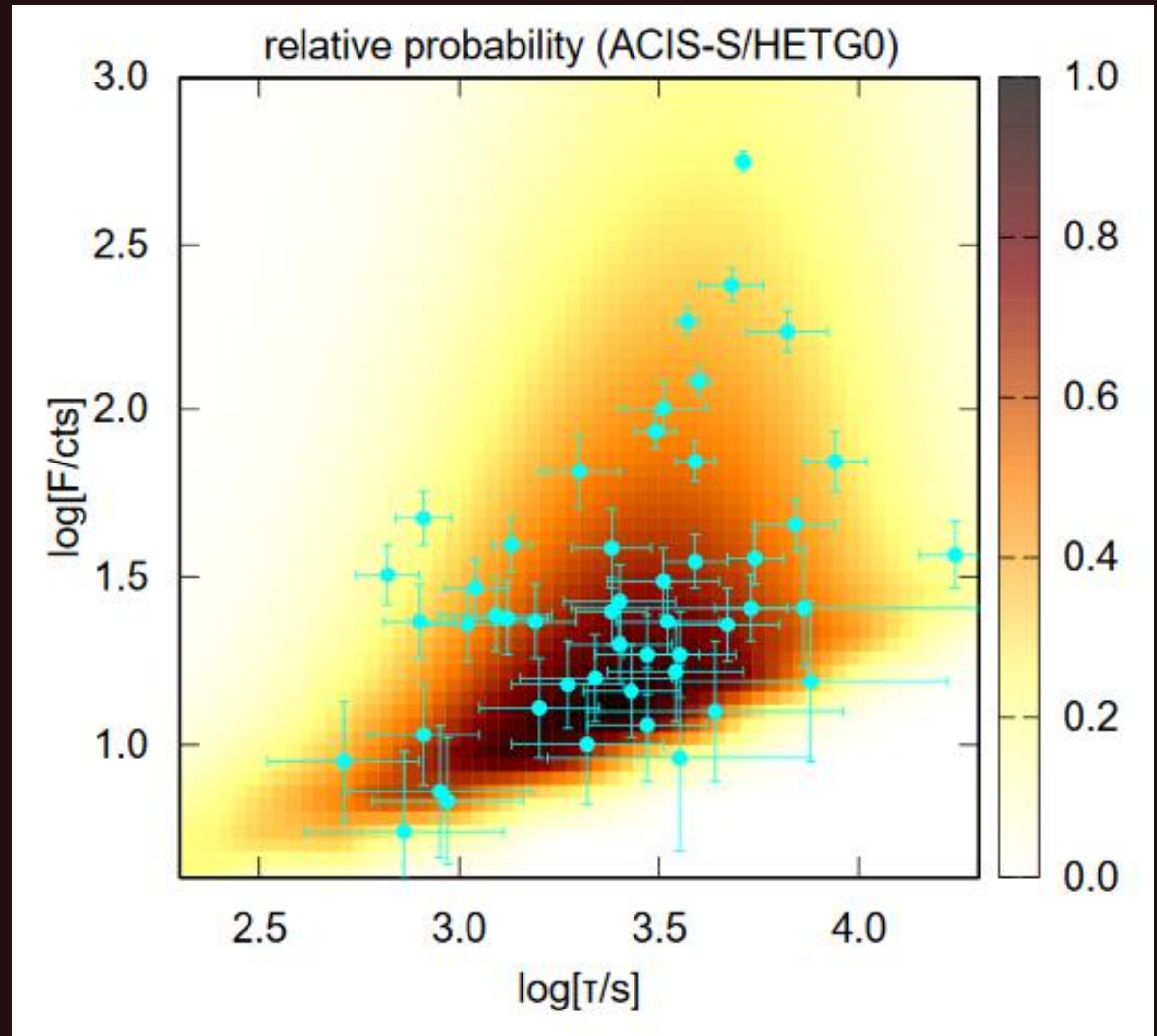


Plenty of data during all time of Chandra and XMM-Newton observations.

Very detailed statistics.

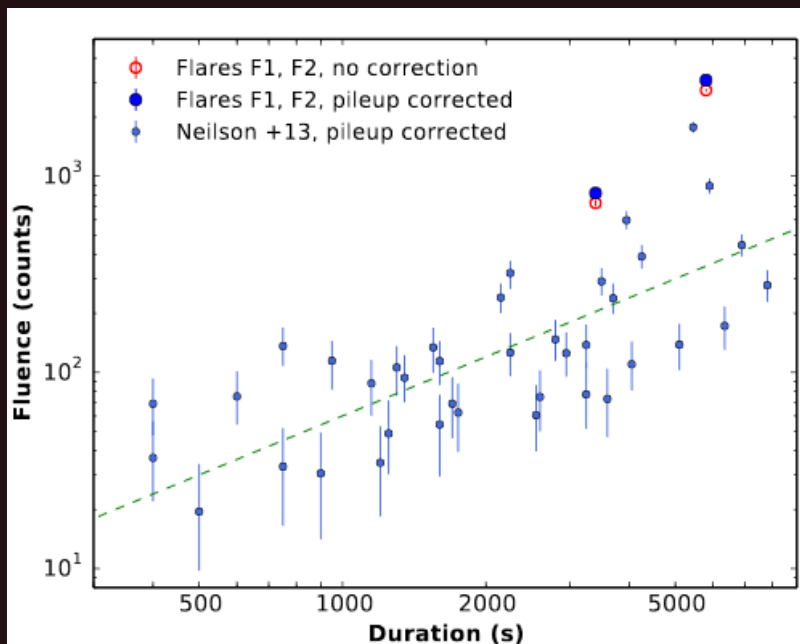
Chandra monitoring

1999-2012

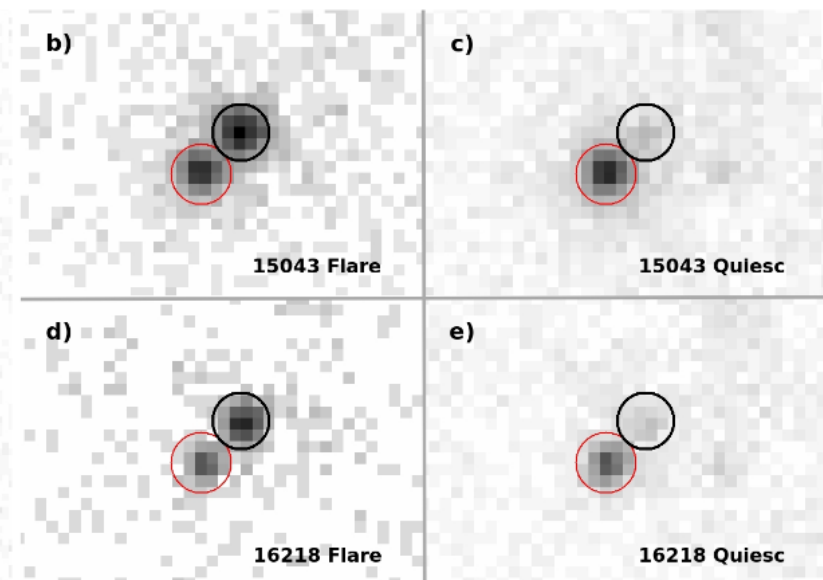
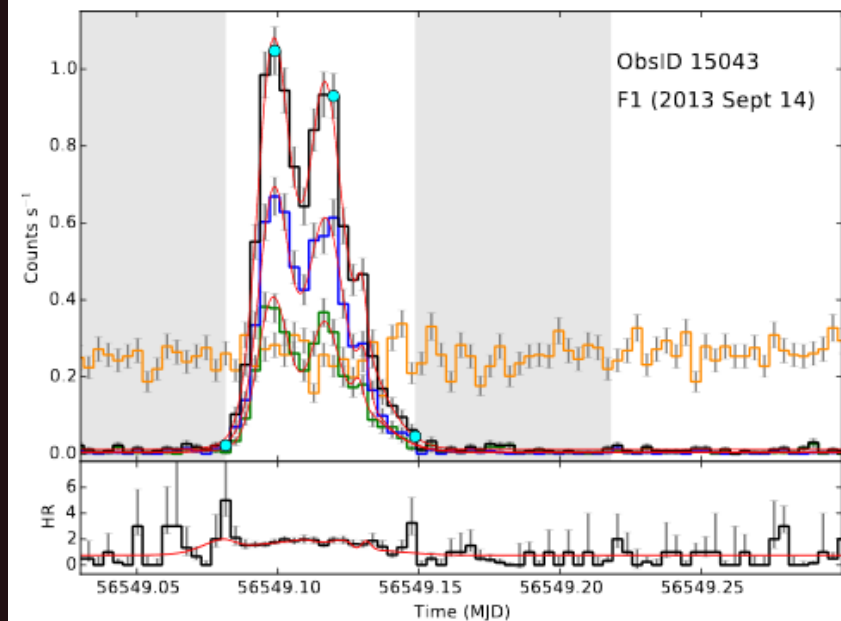
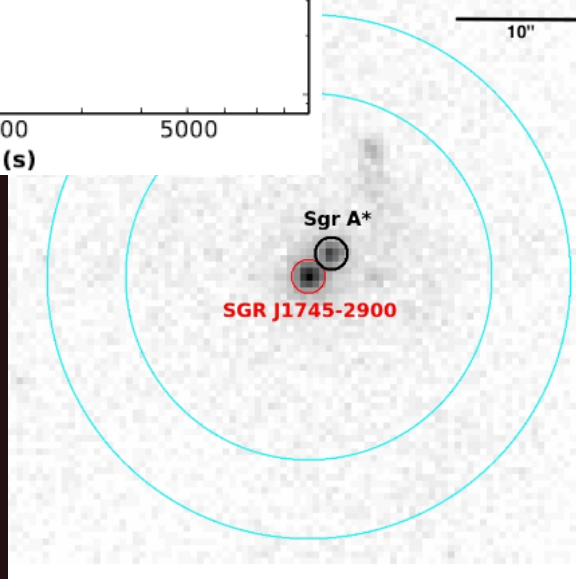


1709.03709

Brightest X-ray flares



1908.01781



Since 2014 the rate of very bright flares increased (2003.06191)

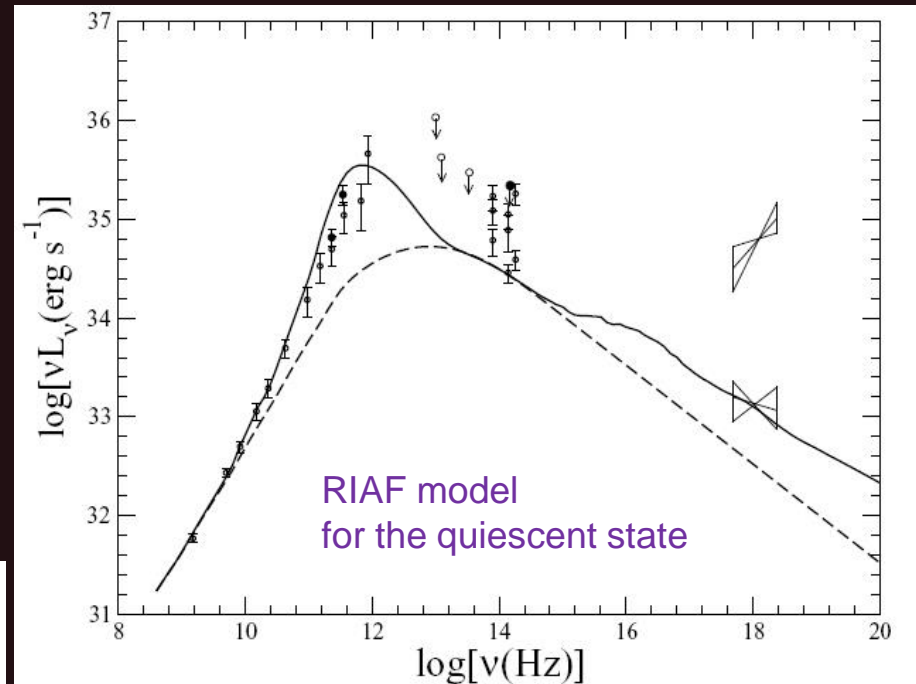
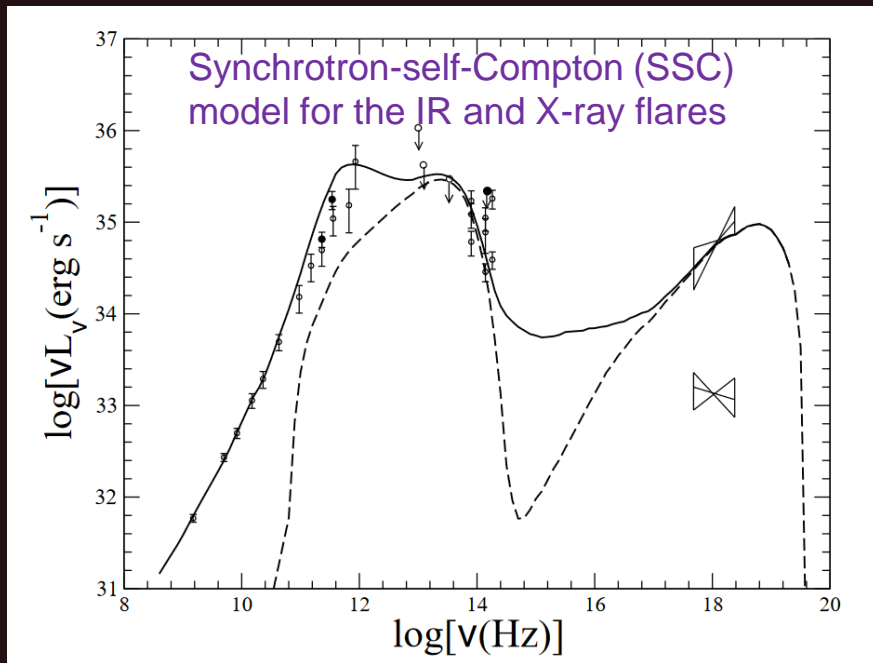
IR burst of Sgr A*

Observations on Keck, VLT.

The scale of variability was about 30 minutes.

This is similar to variability observed in X-rays.

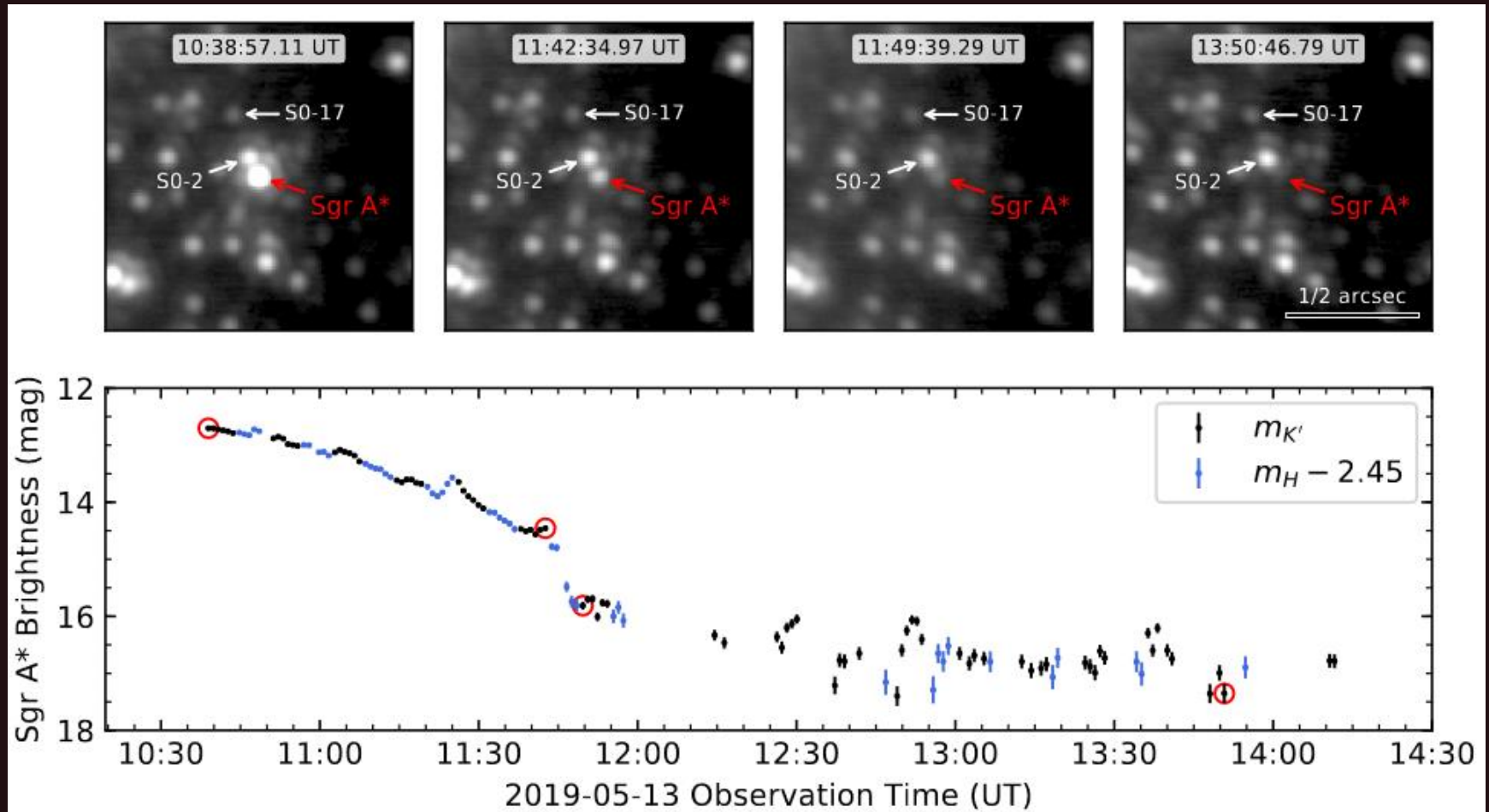
The flux changed by a factor 2-5.



Non-thermal synchrotron?

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

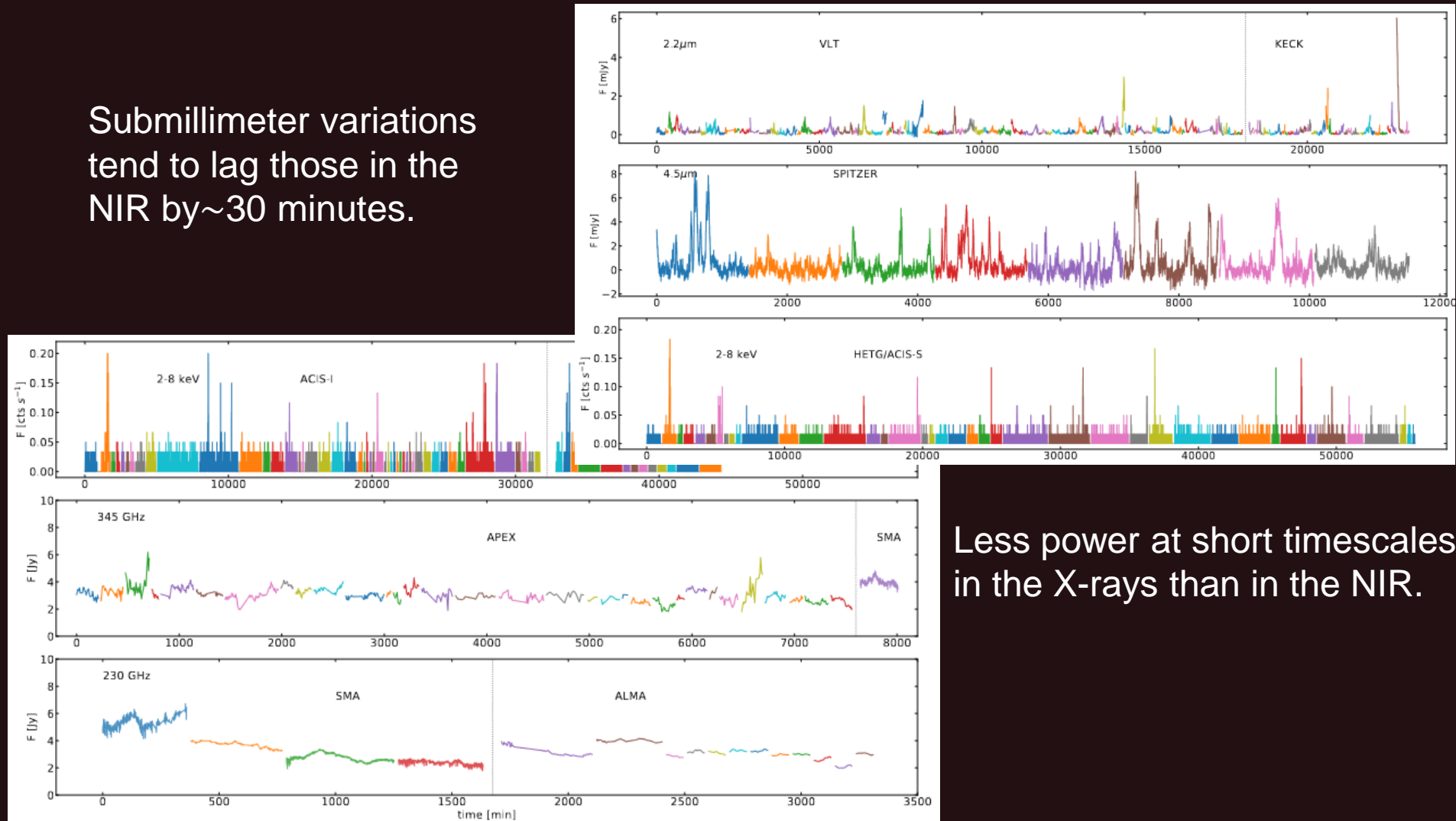
Record: high NIR flux in 2019



Twice higher than the previous record.

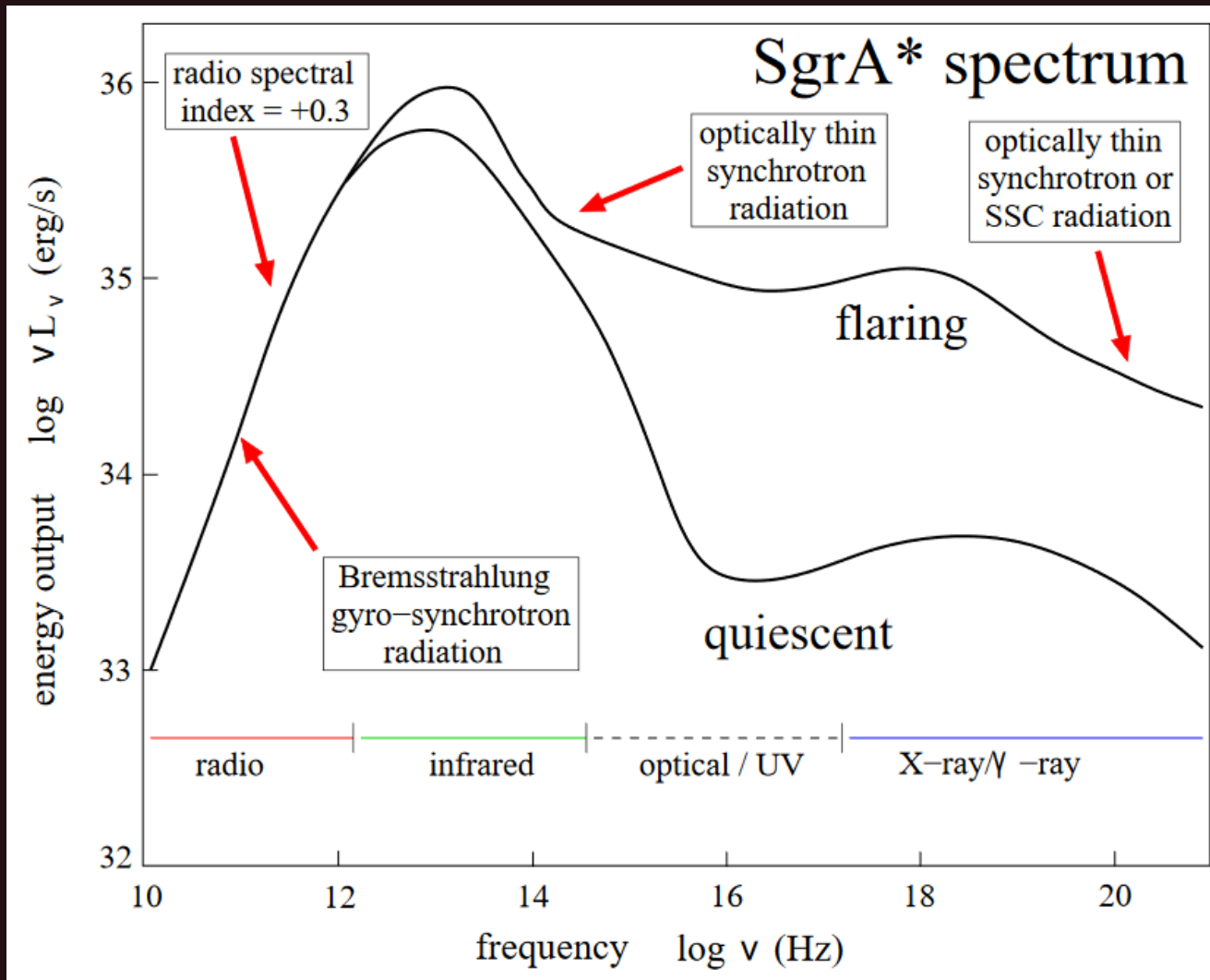
Multiwavelength data

Submillimeter variations tend to lag those in the NIR by ~ 30 minutes.



Less power at short timescales in the X-rays than in the NIR.

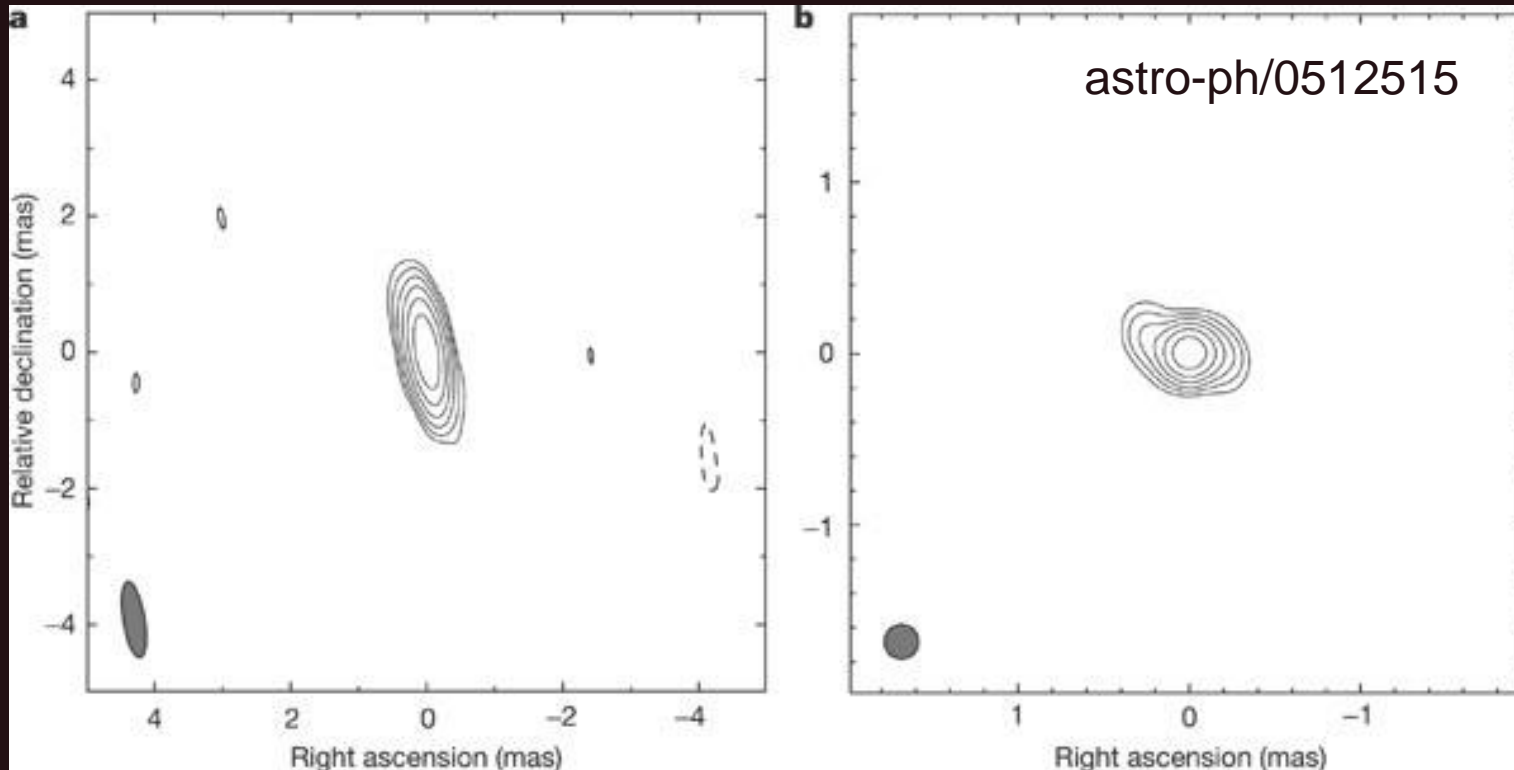
Sgr A* spectrum



See a review in 1806.00284 and 2004.07185

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.

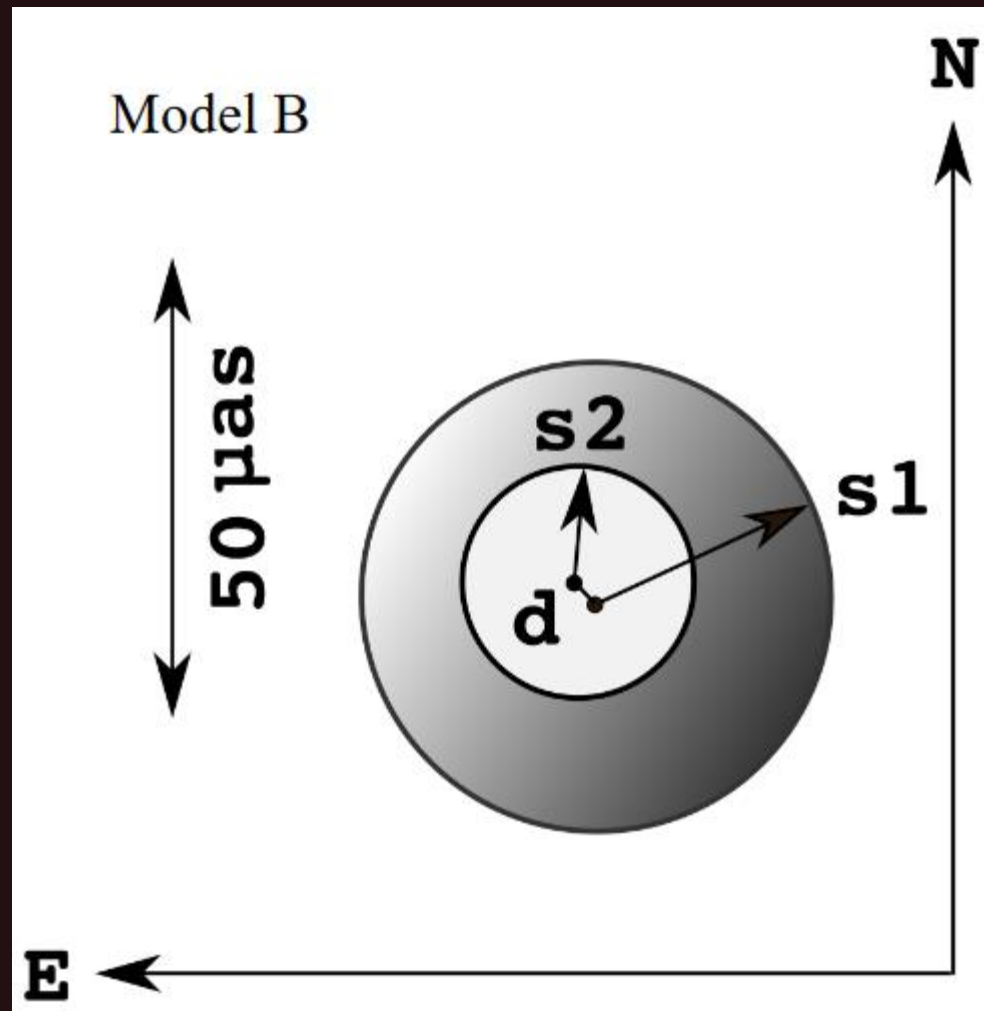


New VLBI observations demonstrate variability at 1.3mm from the region about few Schwarzschild radii. arXiv: 1011.2472

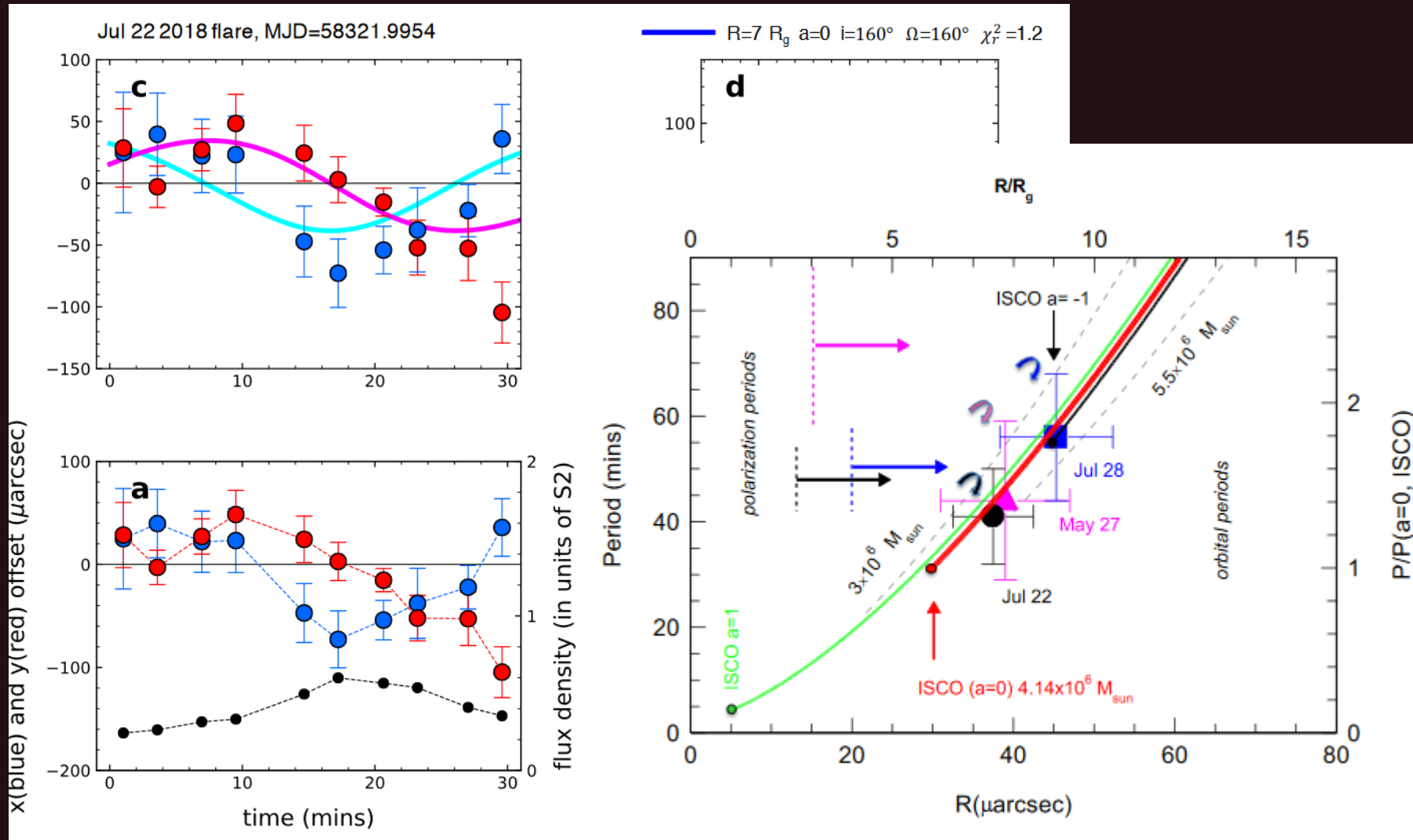
Strict limits on the size and luminosity with known accretion rate provides arguments in favor of BH interpretation (arXiv: 0903.1105)

Structure at 3 R_g in Sgr A*

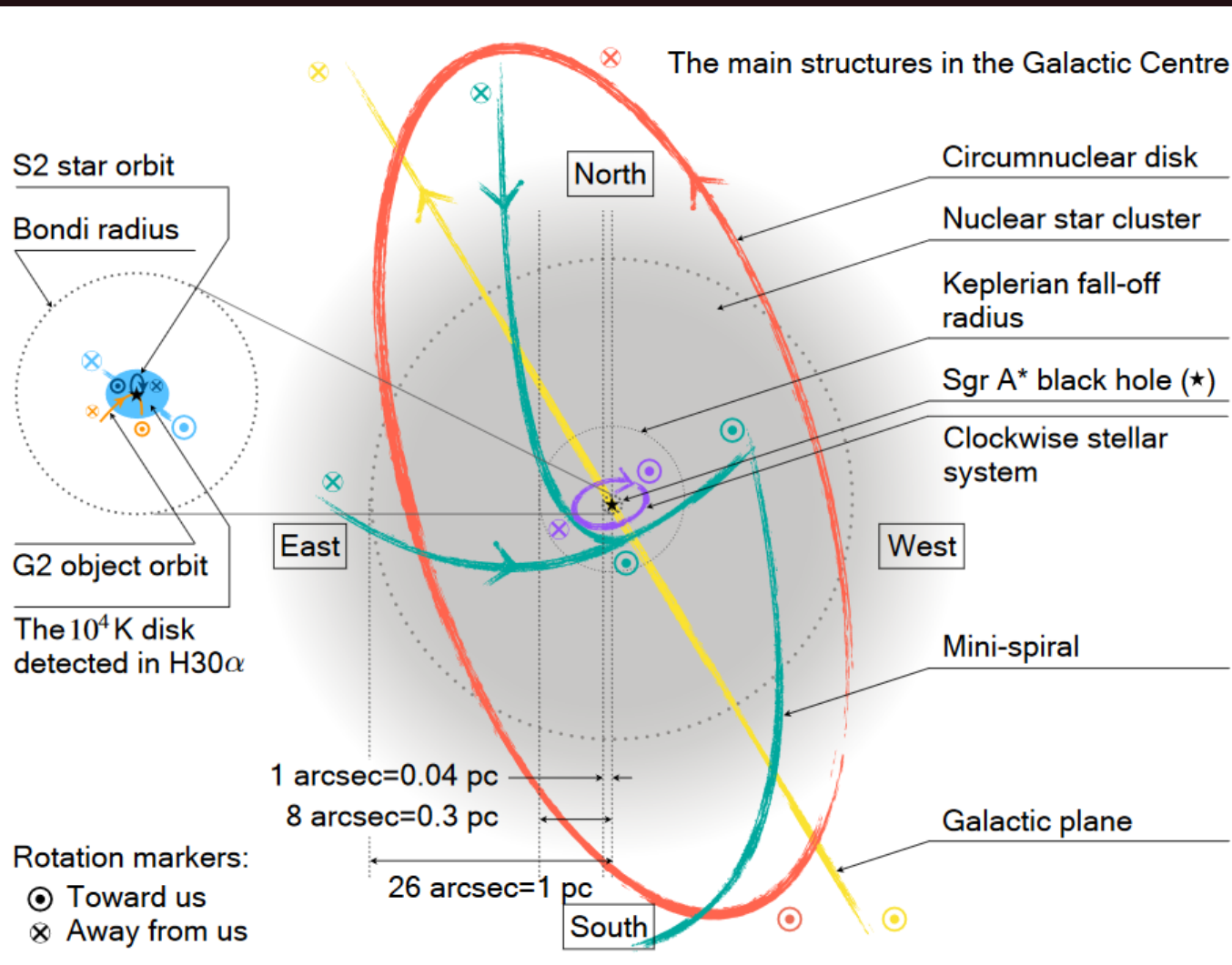
EHT 2013
VLBI 1.3 mm
30 μ arcsec



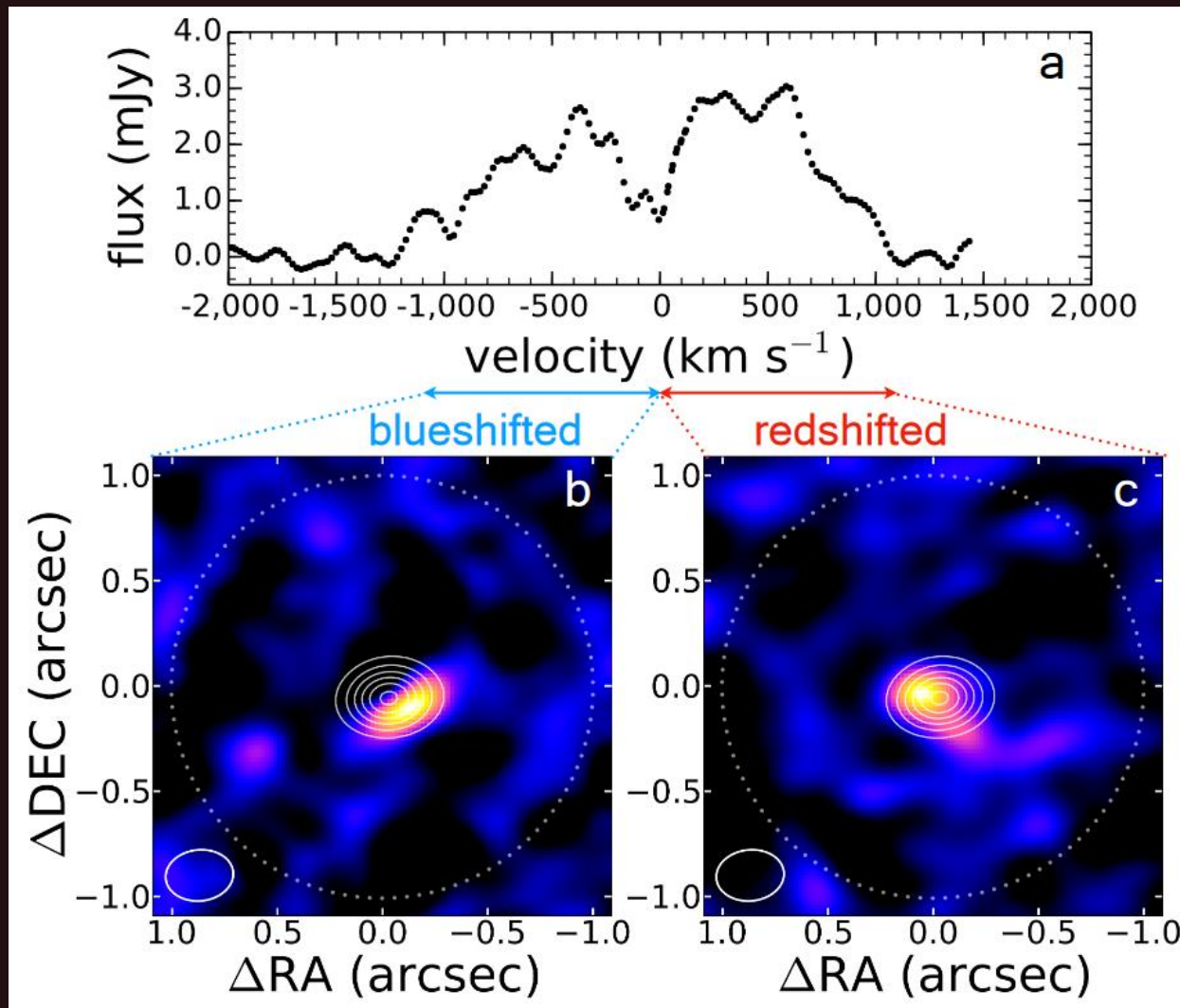
Orbital motion near ISCO in Sgr A*



Cool disc in Sgr A*



Cool disc in Sgr A*



ALMA observations.

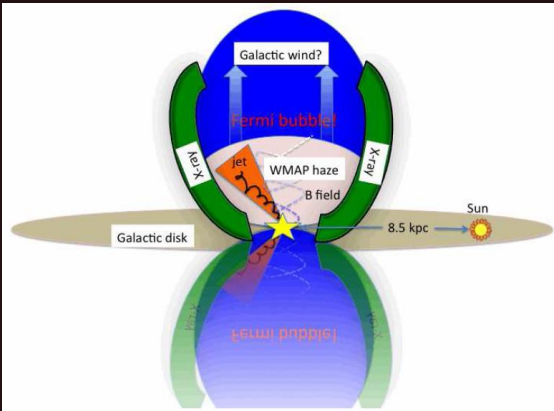
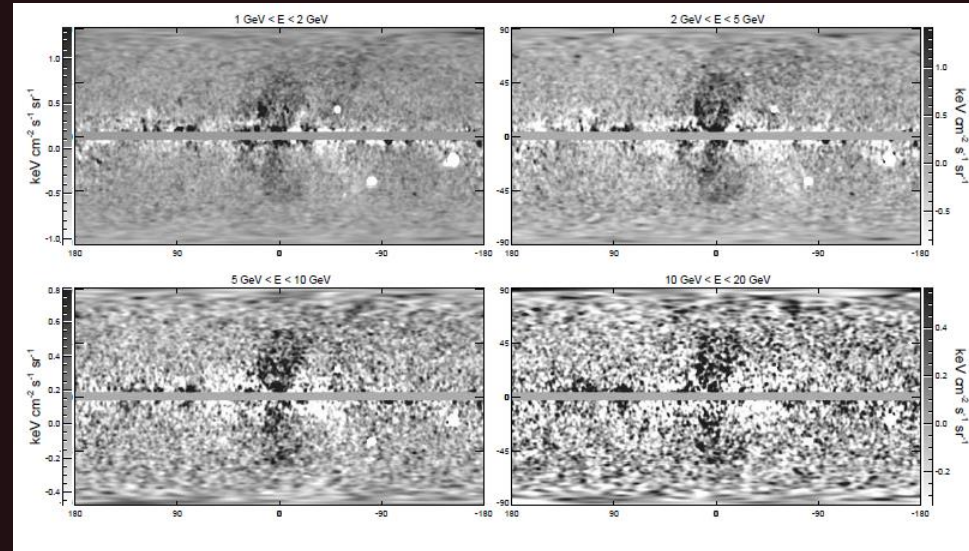
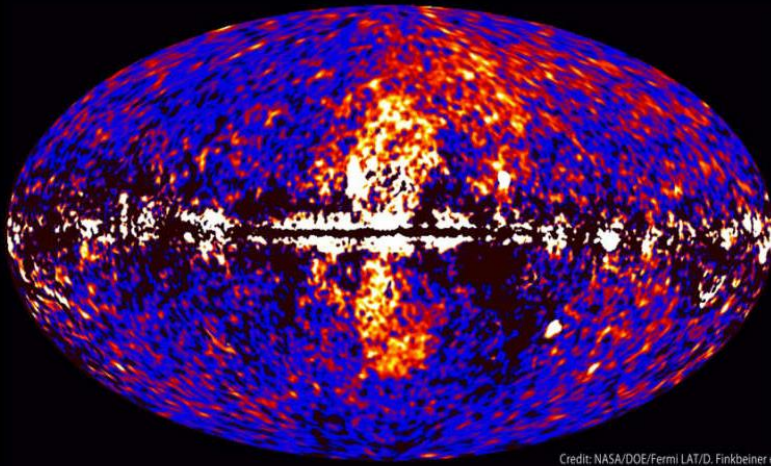
H30 α line

10⁴ K disc at $\sim 10^4 R_{\text{sh}}$

Off-set between red and blue shifted components respect to the continuum Sgr A* position is:
0.11 arcsec = 0.004 pc

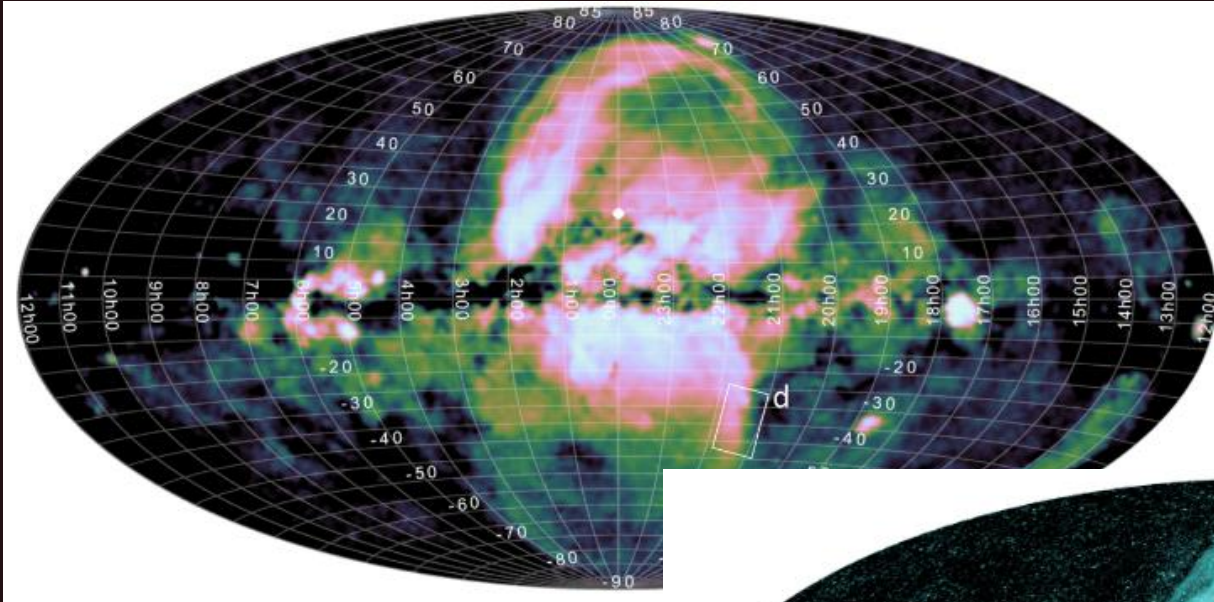
Bubbles in the center of the Galaxy

Fermi data reveal giant gamma-ray bubbles

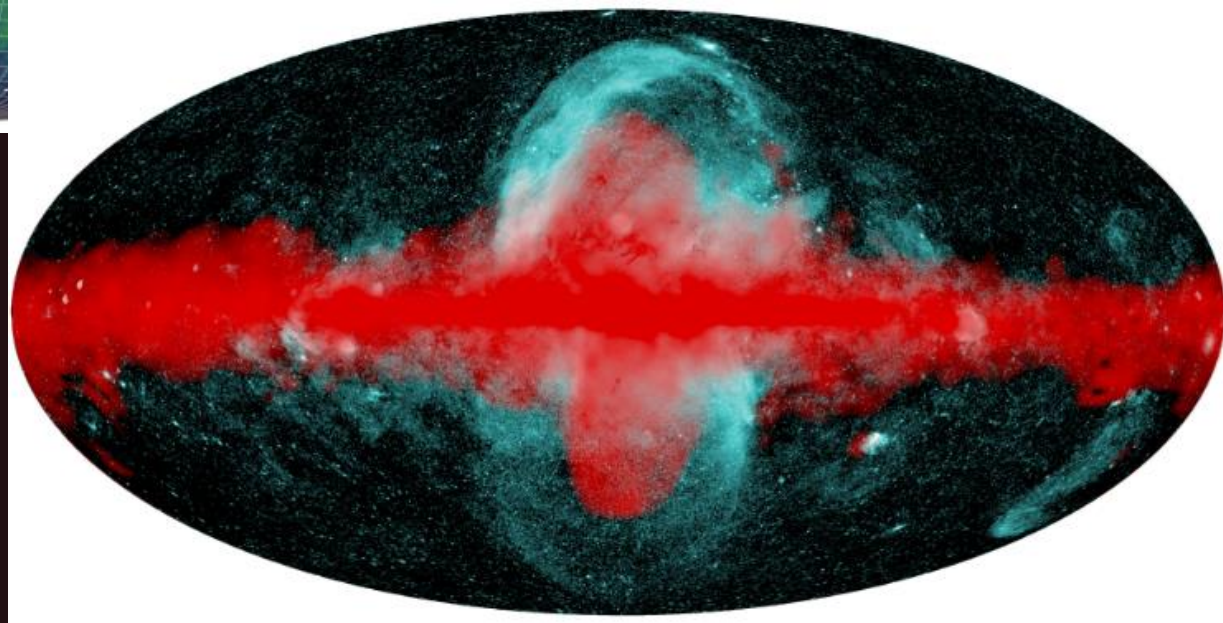


Structures have been already detected in
microwaves (WMAP) and in soft X-rays (ROSAT)

Detailed structure of Fermi bubbles

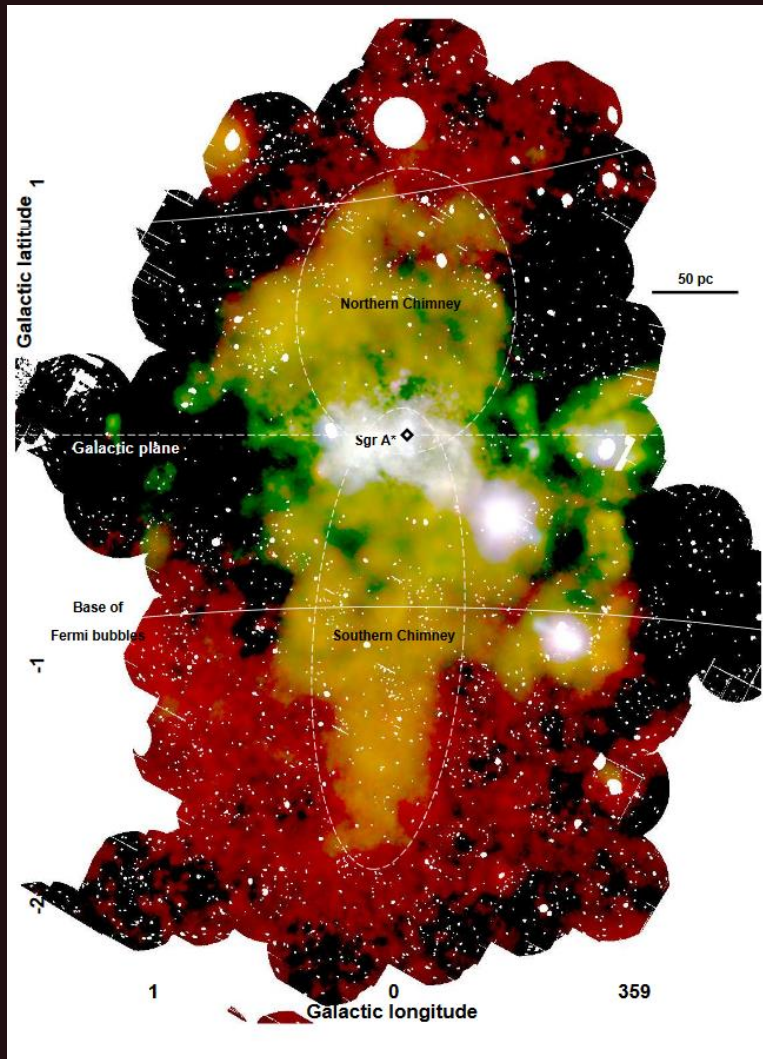


Red - Fermi,
Cyan - eRosita



New structures: galactic chimney

Through these “chimneys” energy from episodically active central engine is channeled to Fermi Bubbles.

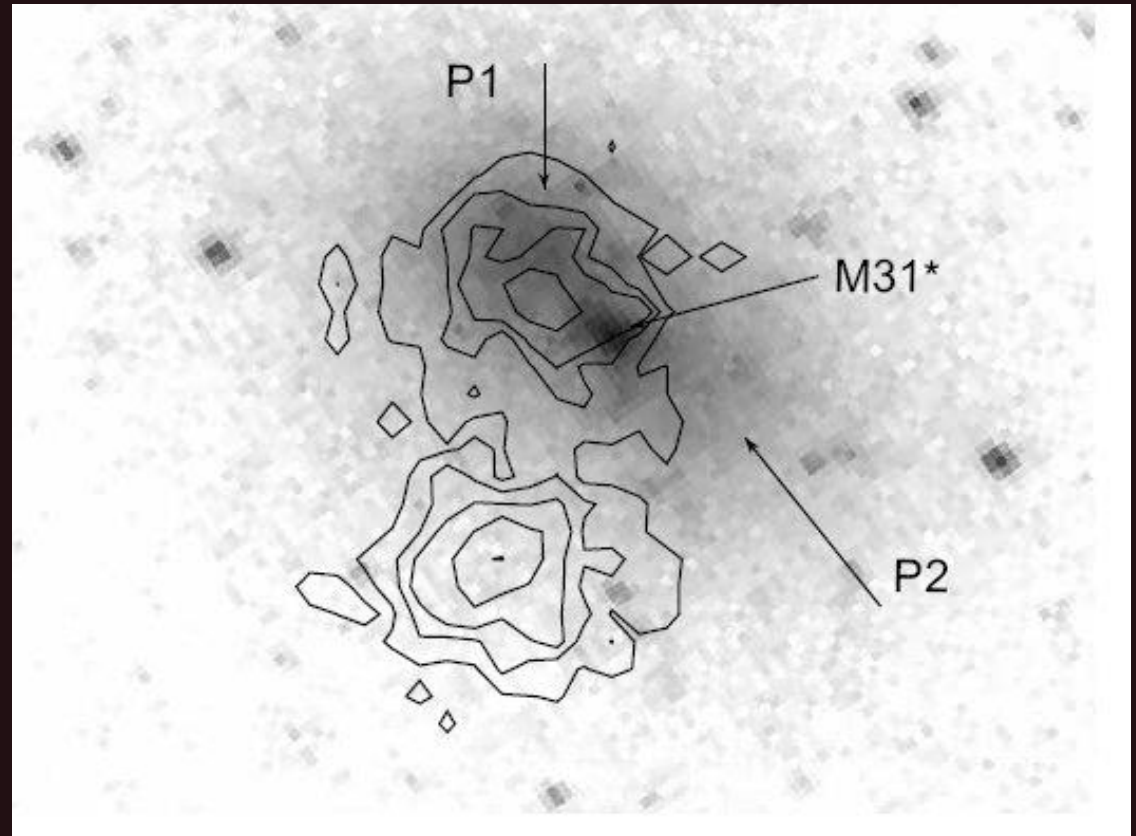


M31

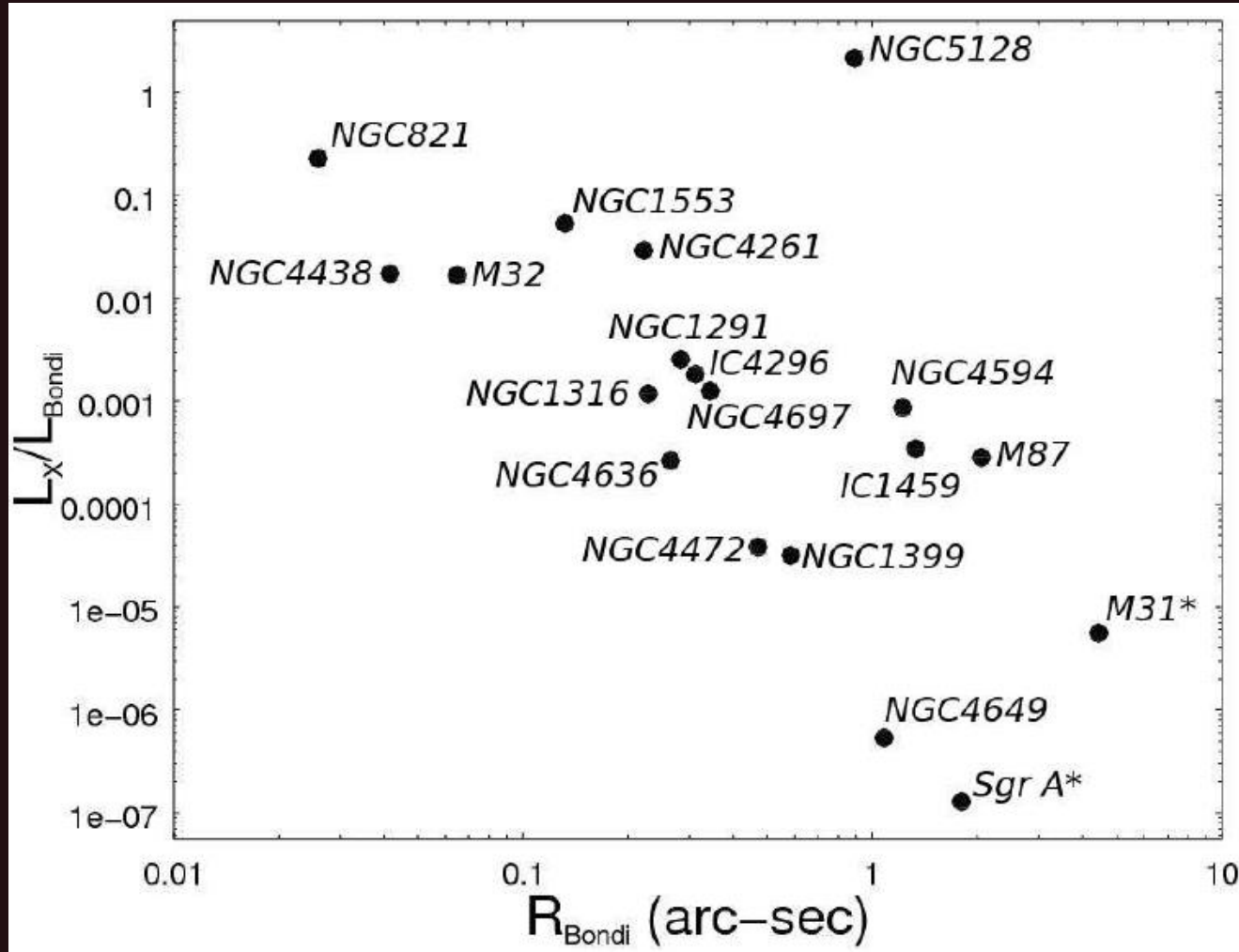
Probably, thanks to observations on Chandra and HST the central SMBH was discovered in M31 (astro-ph/0412350).

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

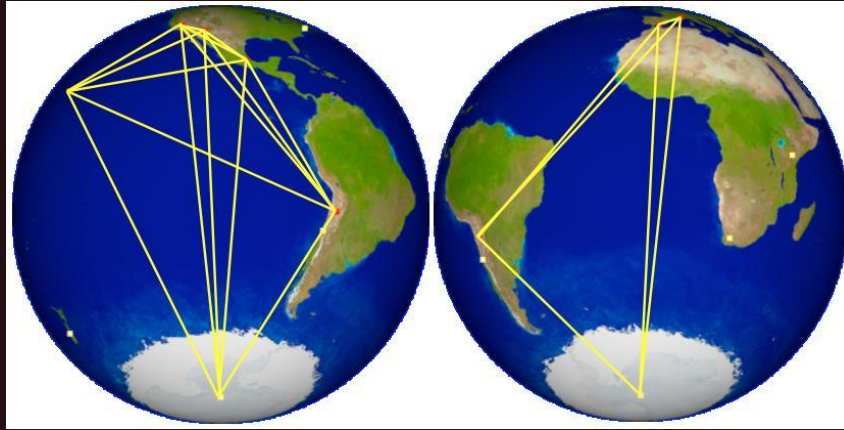
See recent data in
arXiv: 0907.4977



A “large” BH in M31



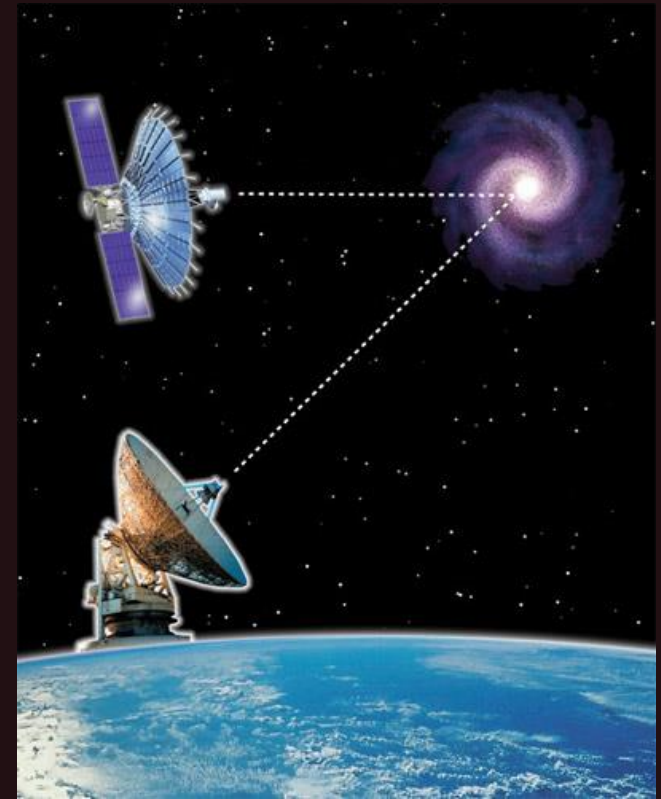
Observational projects: horizon



Event Horizon telescope

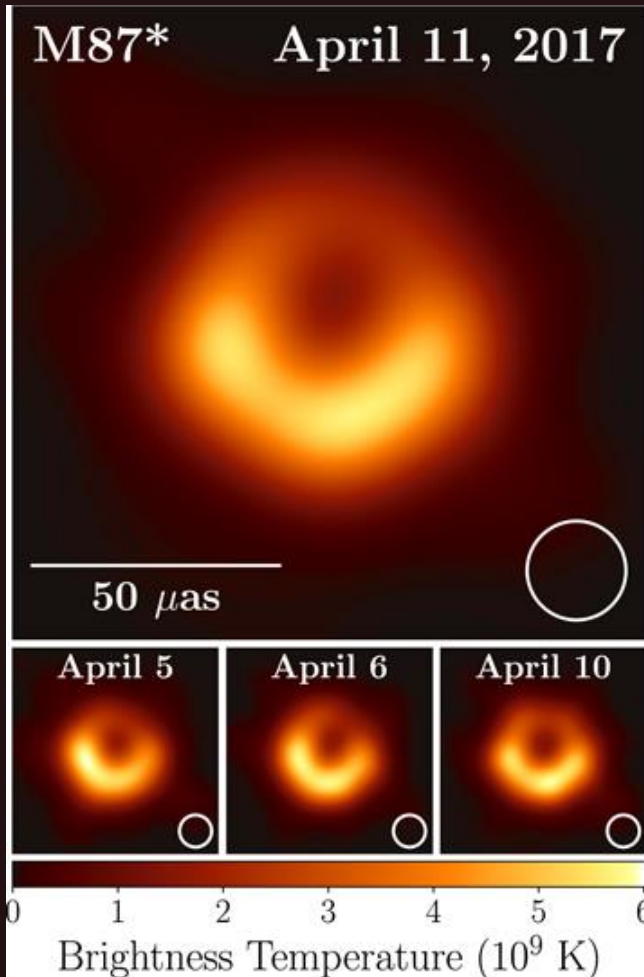


ALMA+mm-VLBI



Radioastron

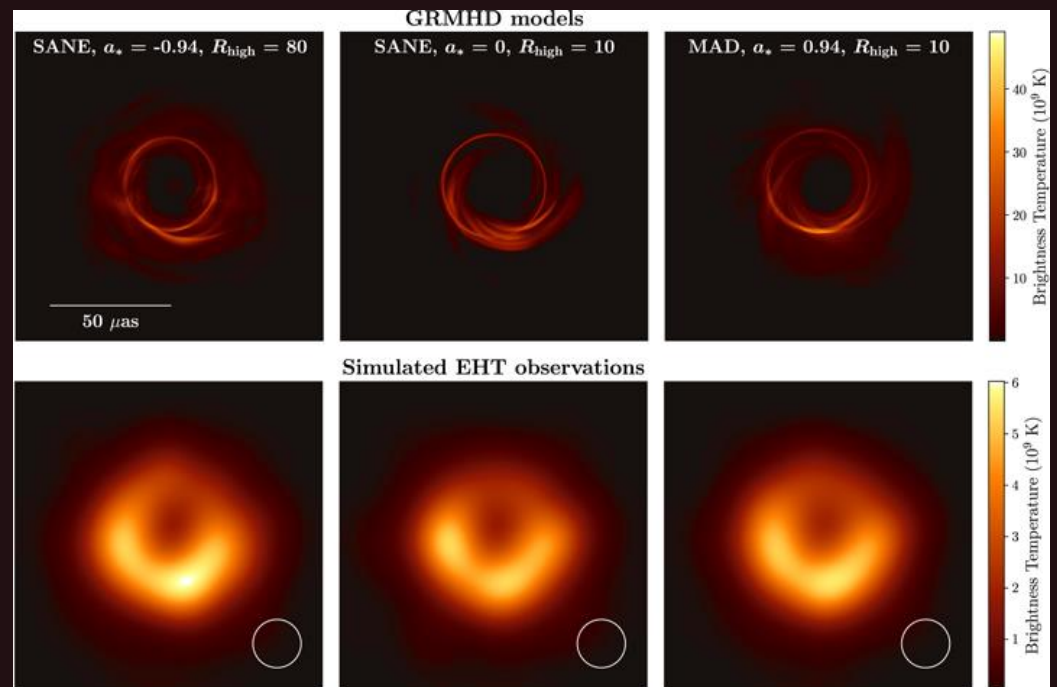
SMBH in M87



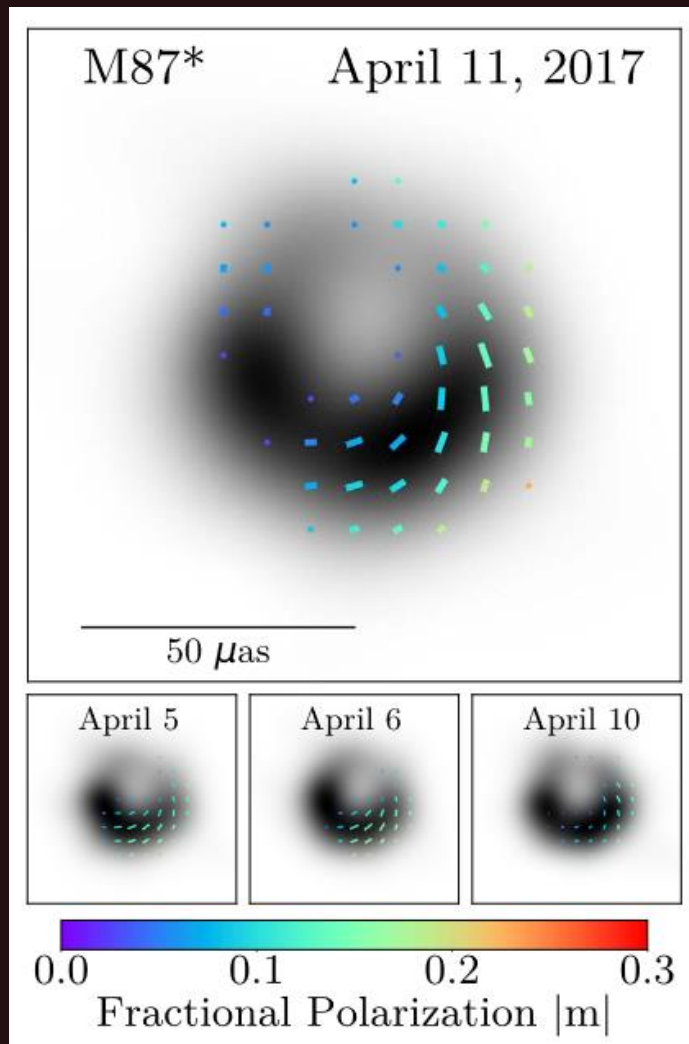
EHT 2017

Announced April 10, 2019

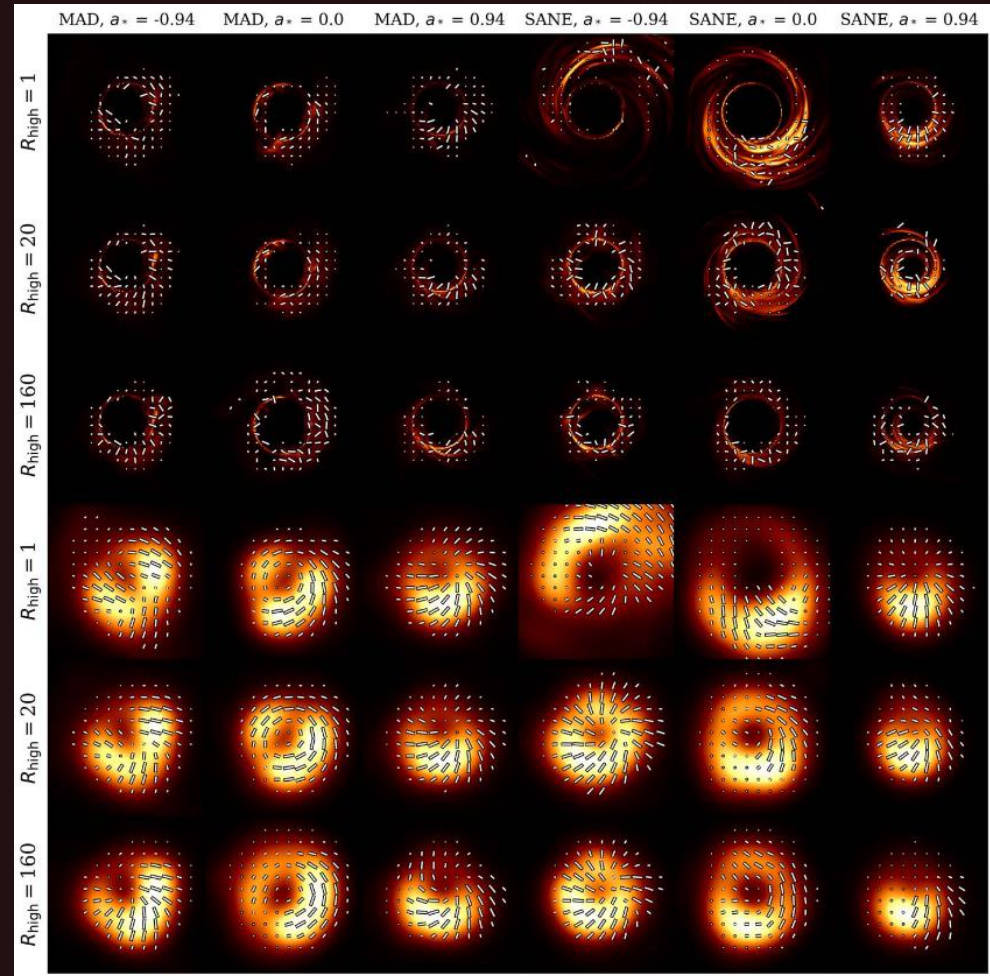
Structure, mass measurements,
spin orientation



Magnetic field structure in M87



Polarization data strongly constrain GRMHD models.

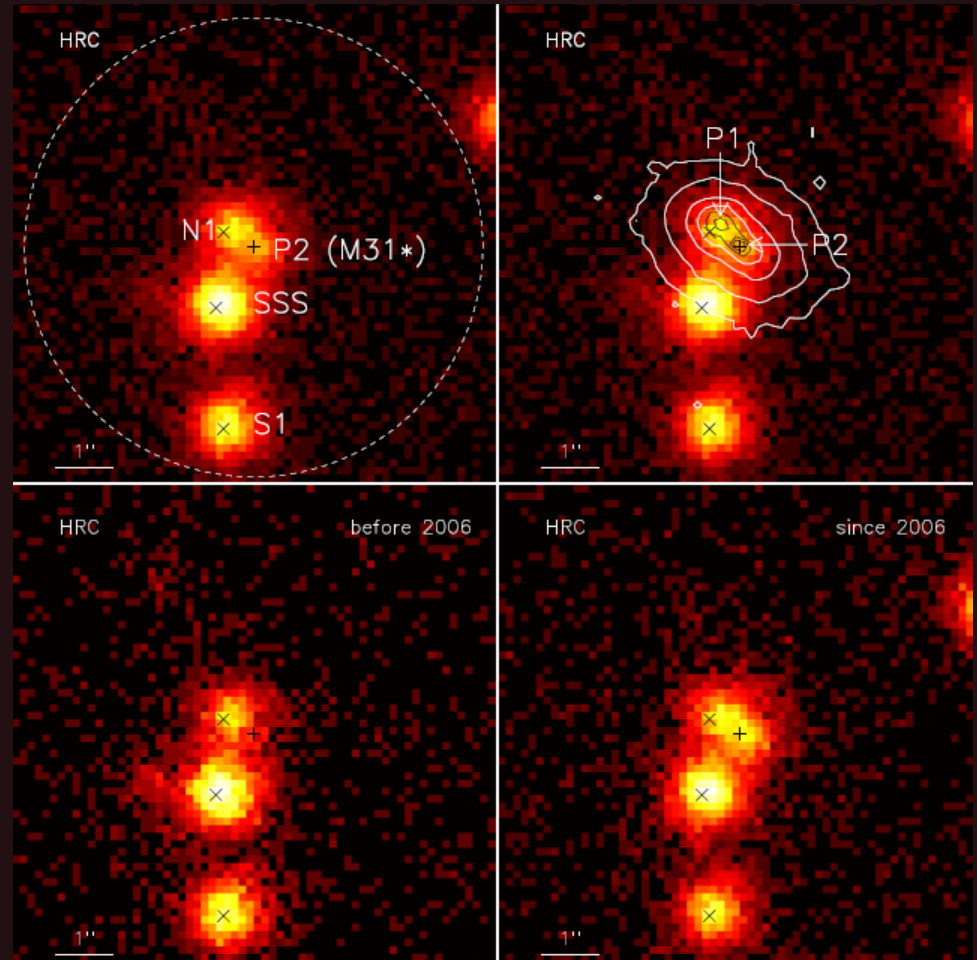


Activity of the M31 SMBH

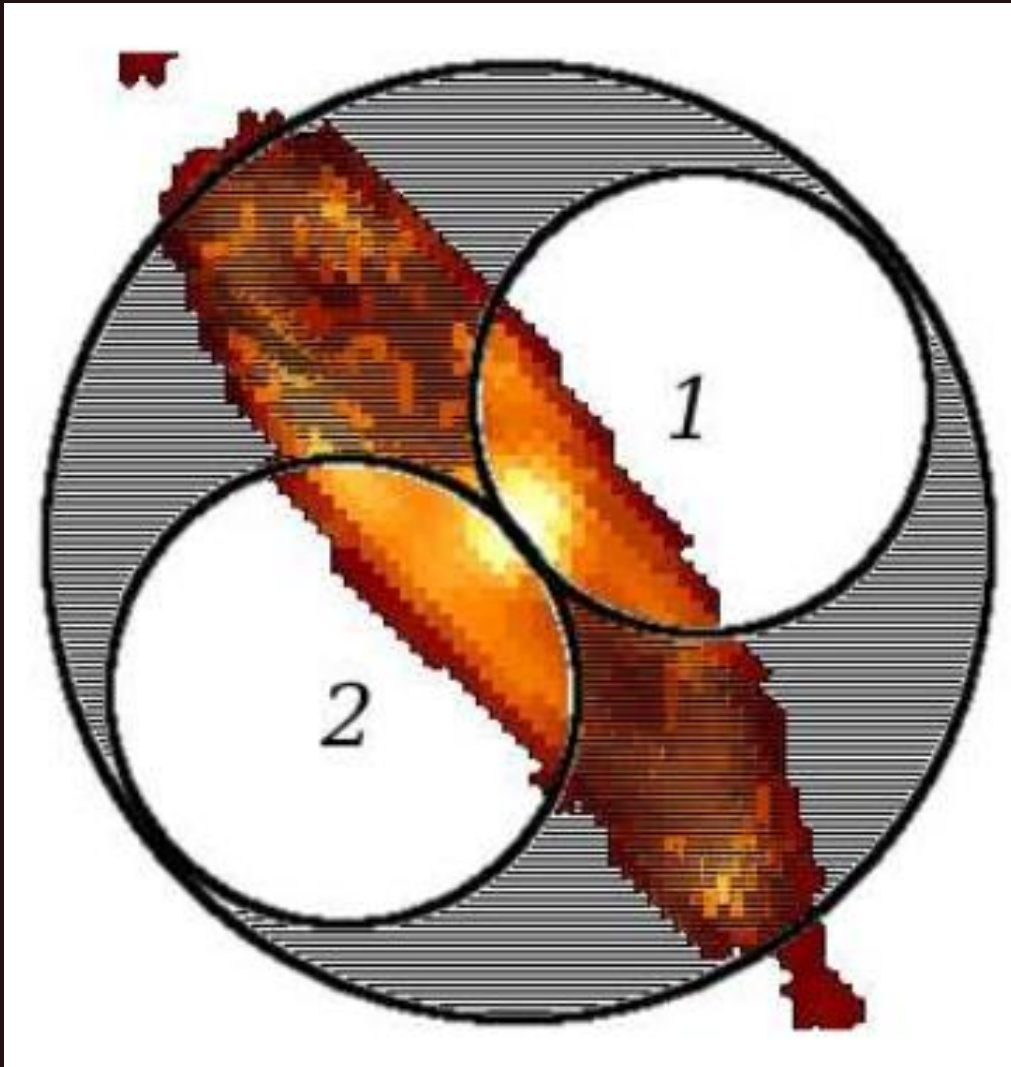
SMBH with 100-200 solar masses.

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.

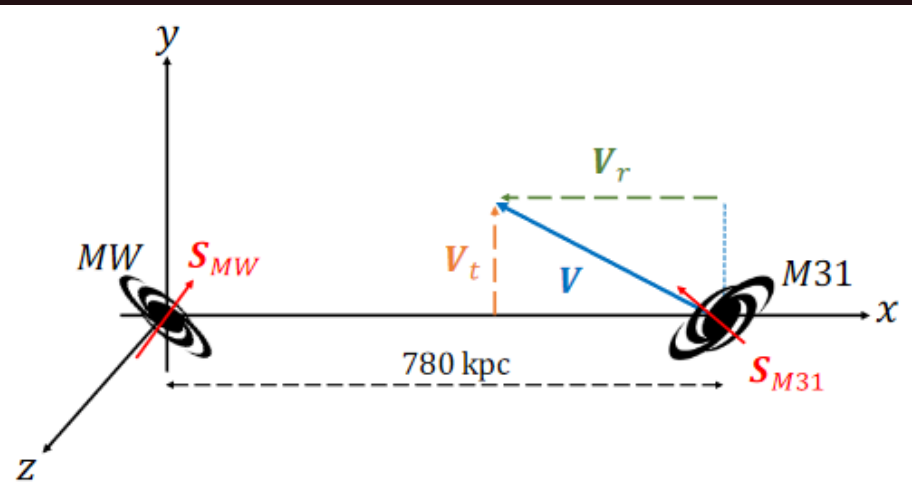


Fermi bubbles analogues in M31?

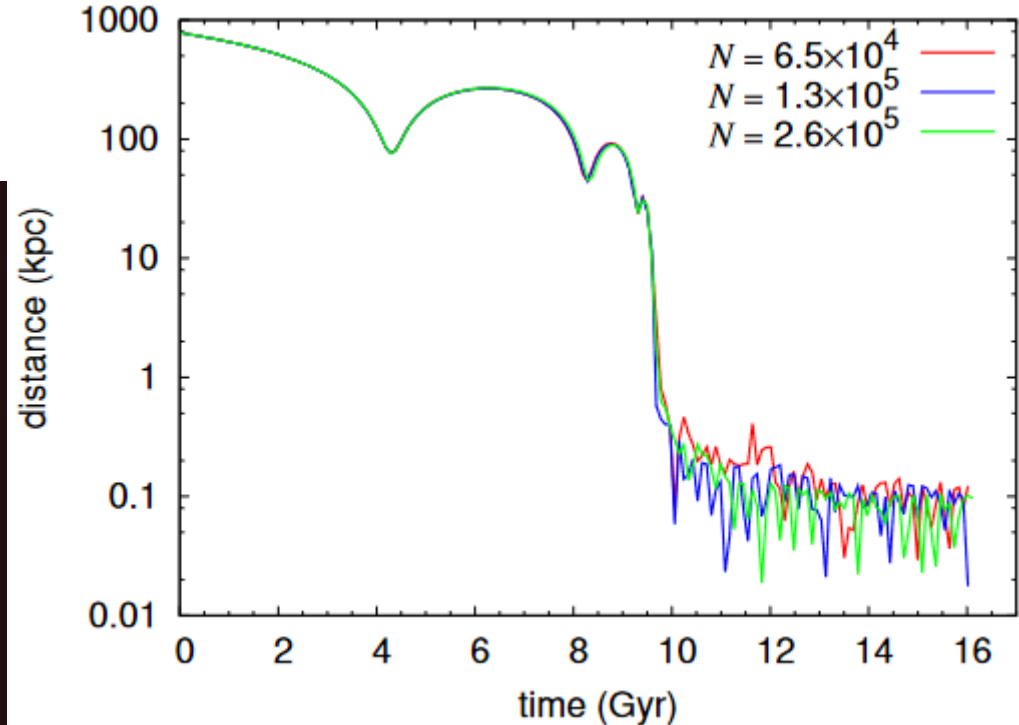


Using Fermi data the authors demonstrated that the shape of gamma-ray image is more consistent with a structure similar to Fermi bubbles in our Galaxy.

Milky way and M31 SMBHs will coalesce



After the merging event is completed two SMBHs coalesce relatively rapidly: in <17 Myrs.



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

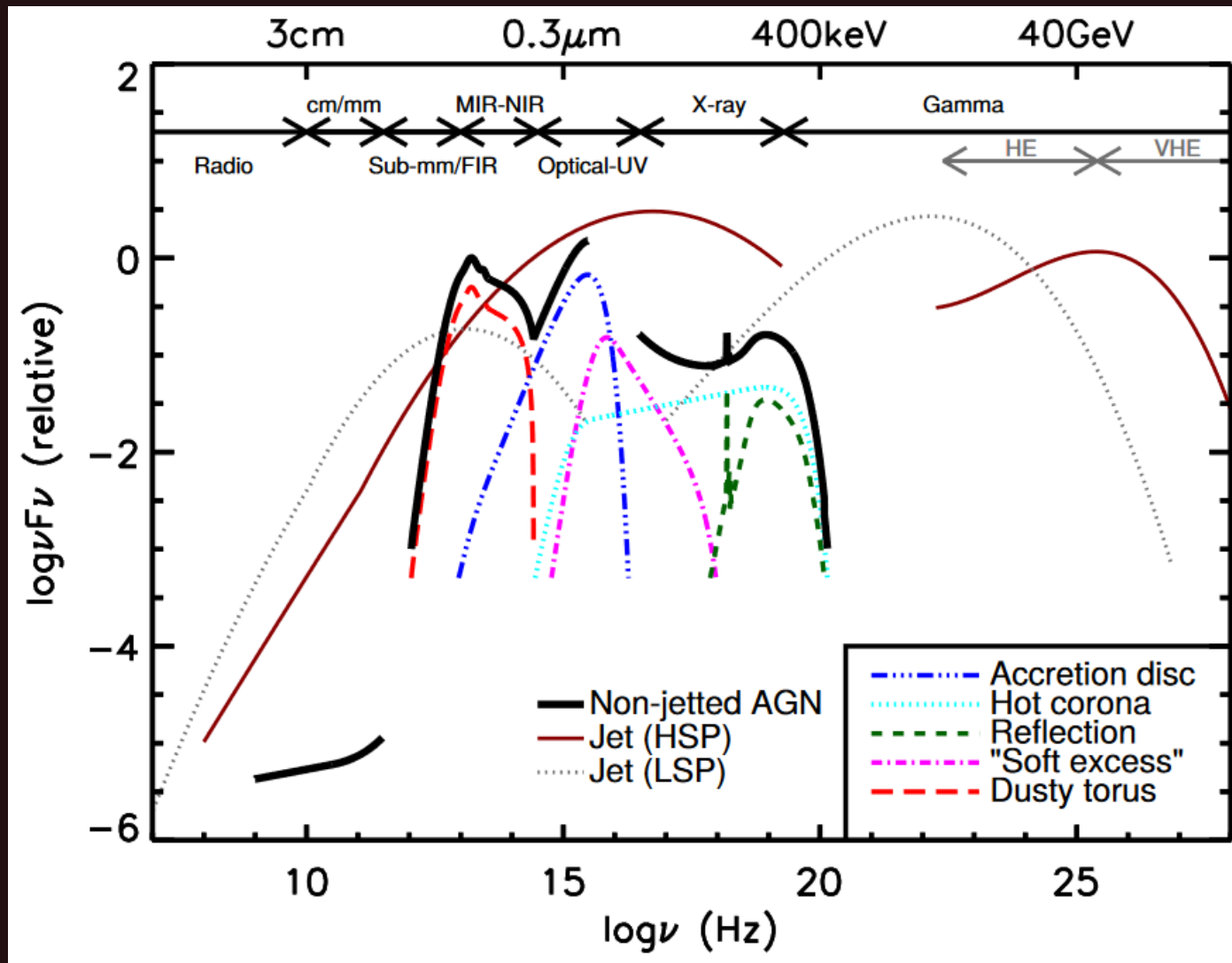


- Radio quiet
 - a) radio quiet quasars, i.e. QSO (types 1 and 2)
 - b) Seyfert galaxies
 - c) LINERs
- Radio loud
 - a) quasars
 - b) radio galaxies
 - c) blazars (BL Lacs и OVV)

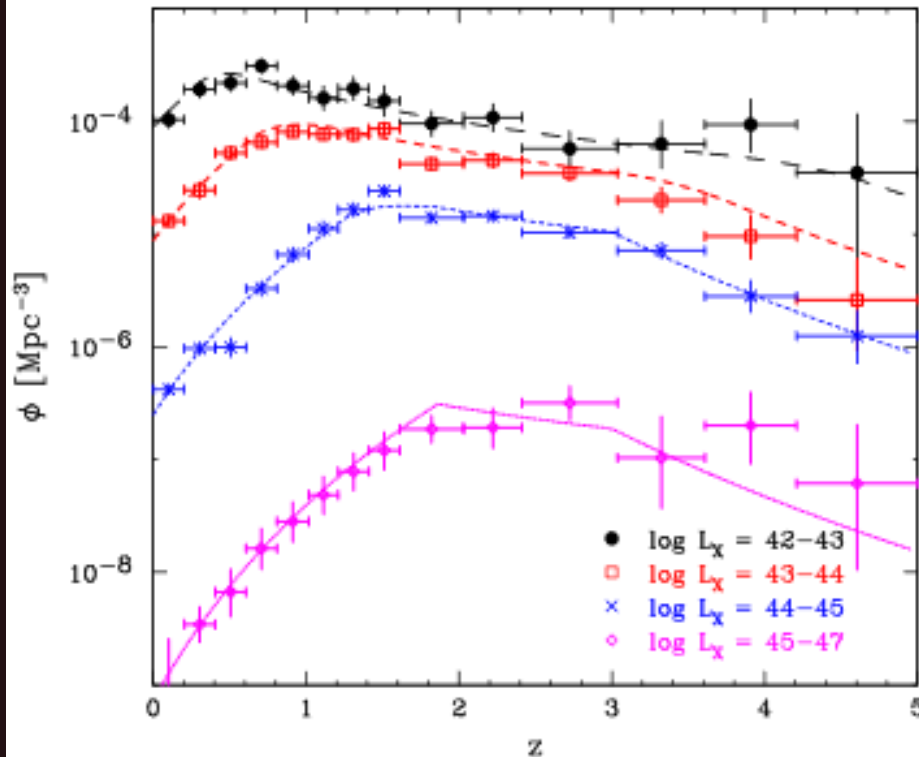
(see, for example, [astro-ph/0312545](https://arxiv.org/abs/astro-ph/0312545))

A popular review can be found in arXiv: 0906.2119

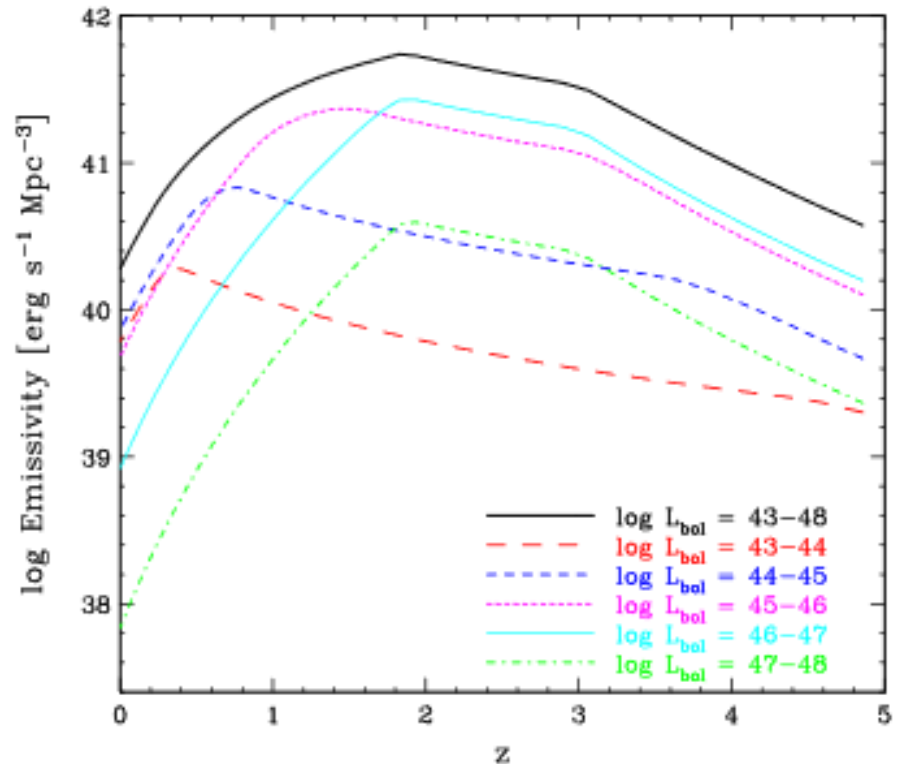
Spectra of AGNs



X-ray observations of AGNs

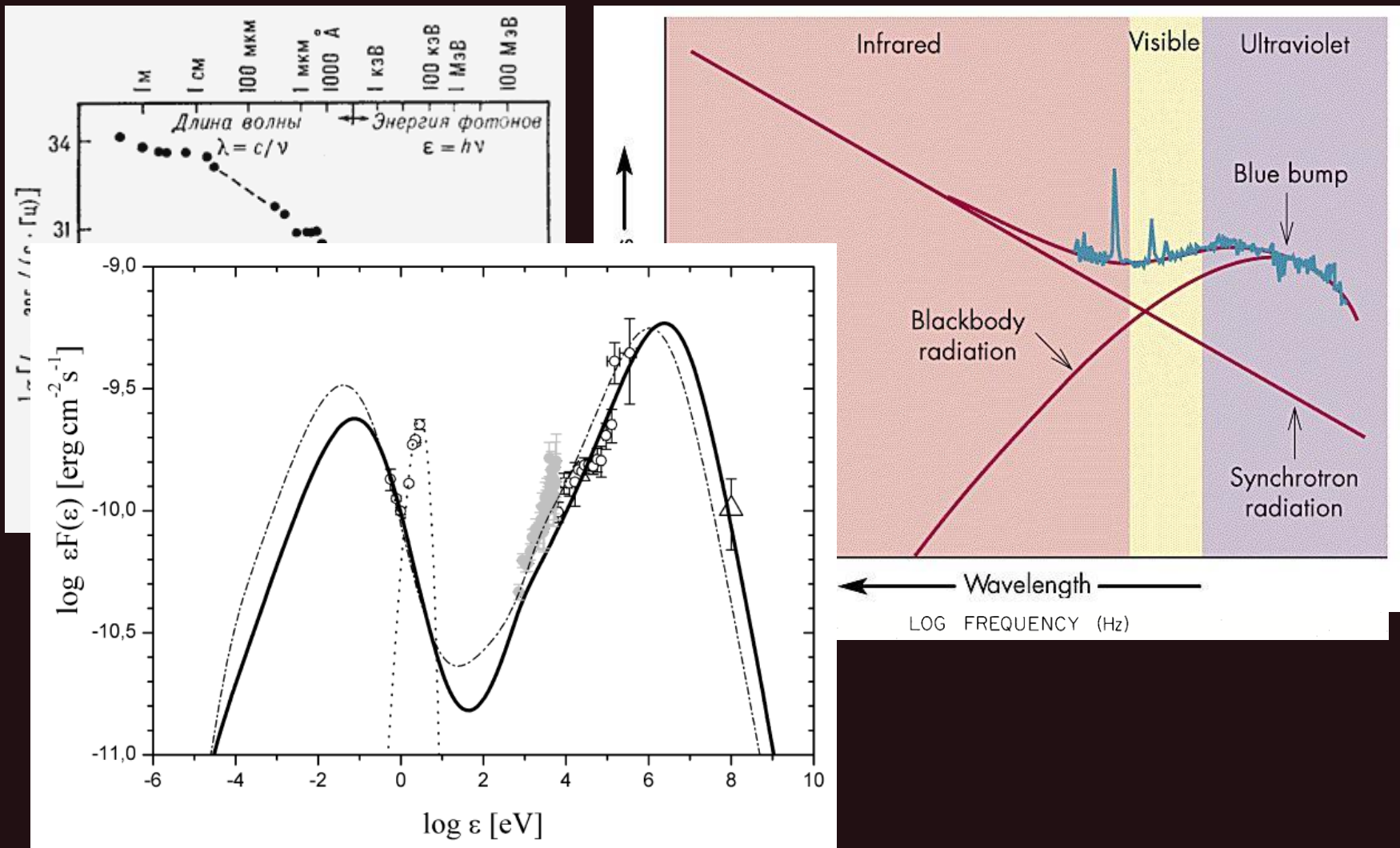


Comoving number density vs. redshift for AGNs, selected from multiple X-ray surveys, in four rest-frame 2–10 keV luminosity classes.

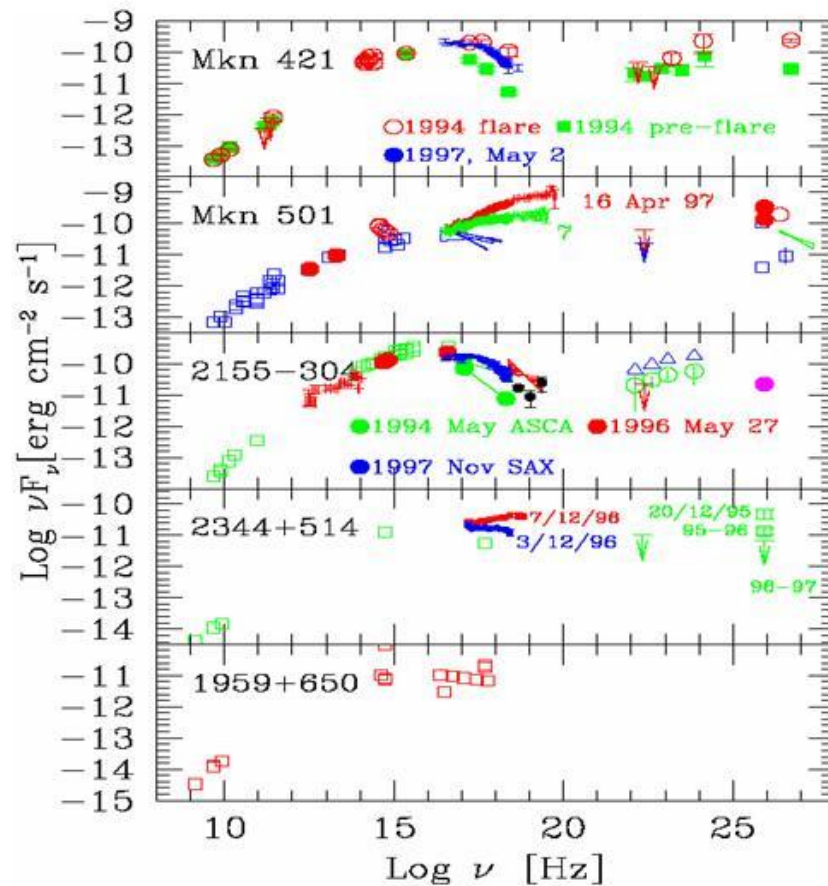


Comoving bolometric luminosity density vs. redshift for the same AGN sample in six bolometric luminosity classes.

Quasars spectra



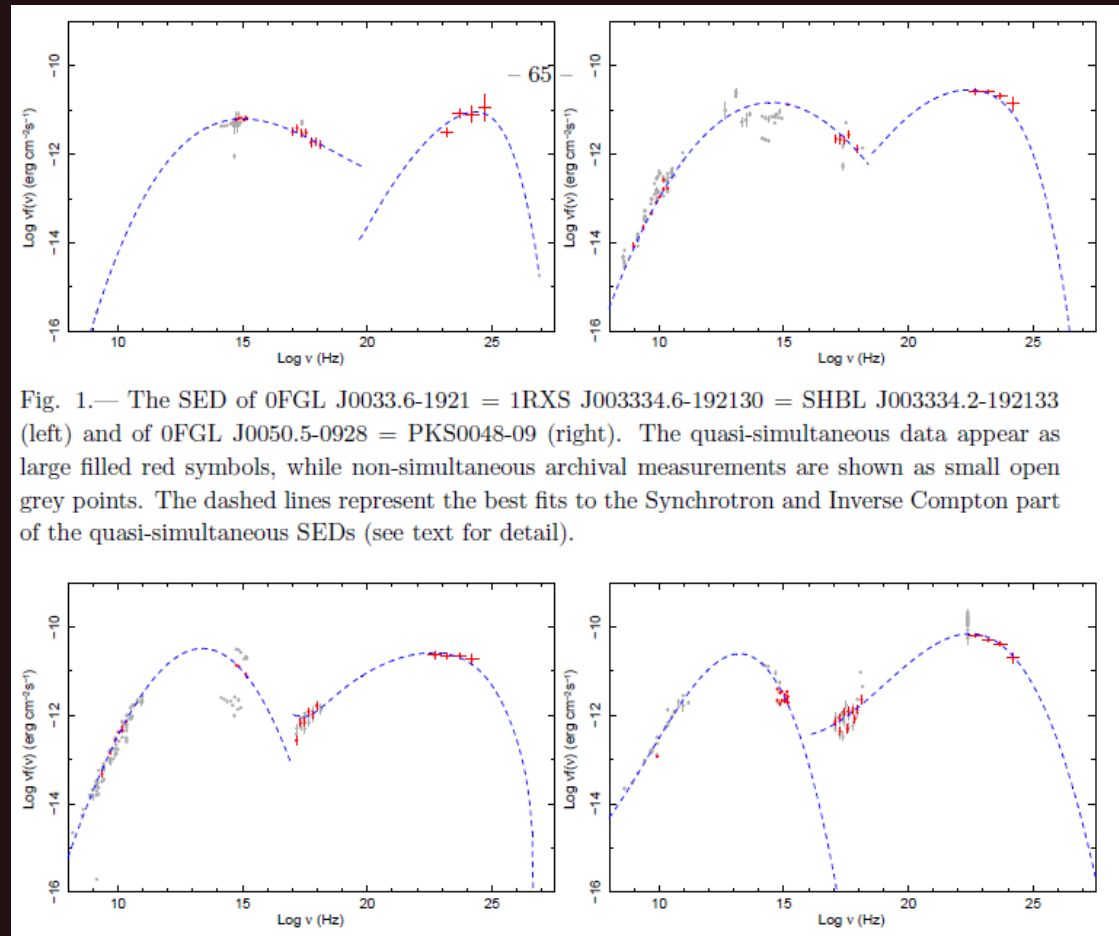
Spectra of BL Lacs



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

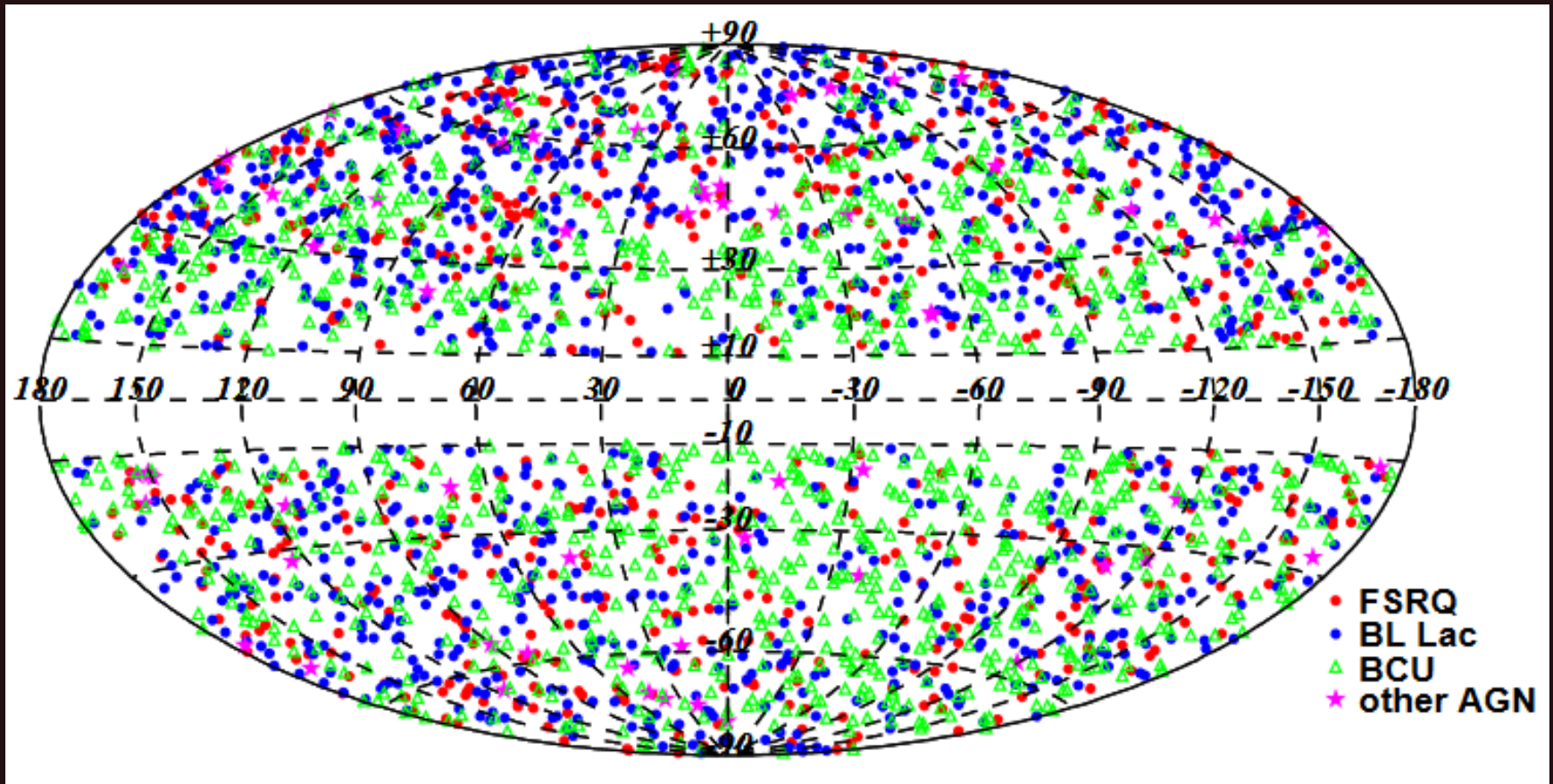
Fermi observations of blazars: Huge set of data

In the third Fermi catalogue
(1501.02003)
>1100 AGNs

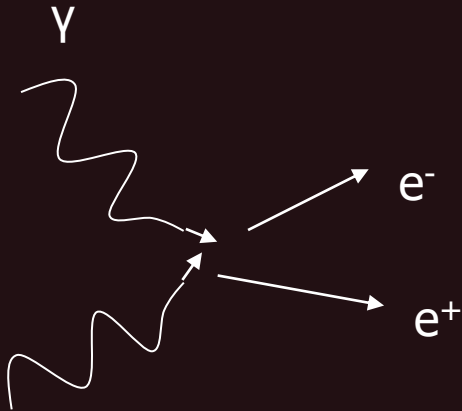


AGN in the forth Fermi catalogue

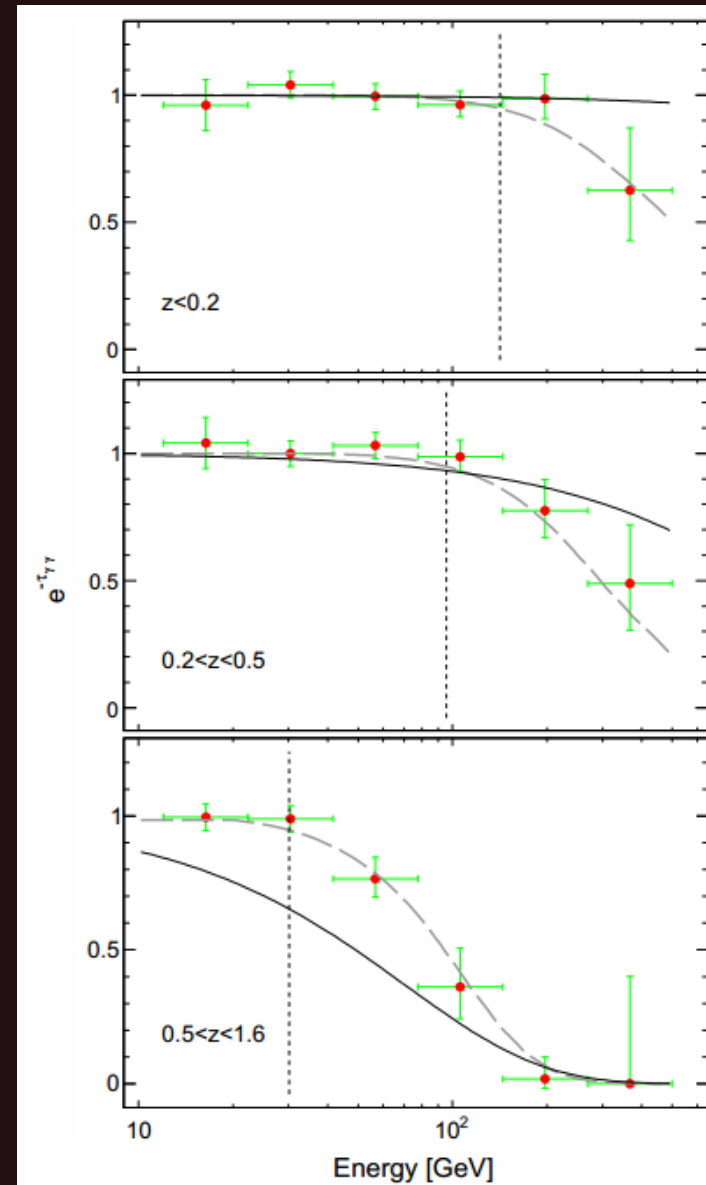
>2000 AGN



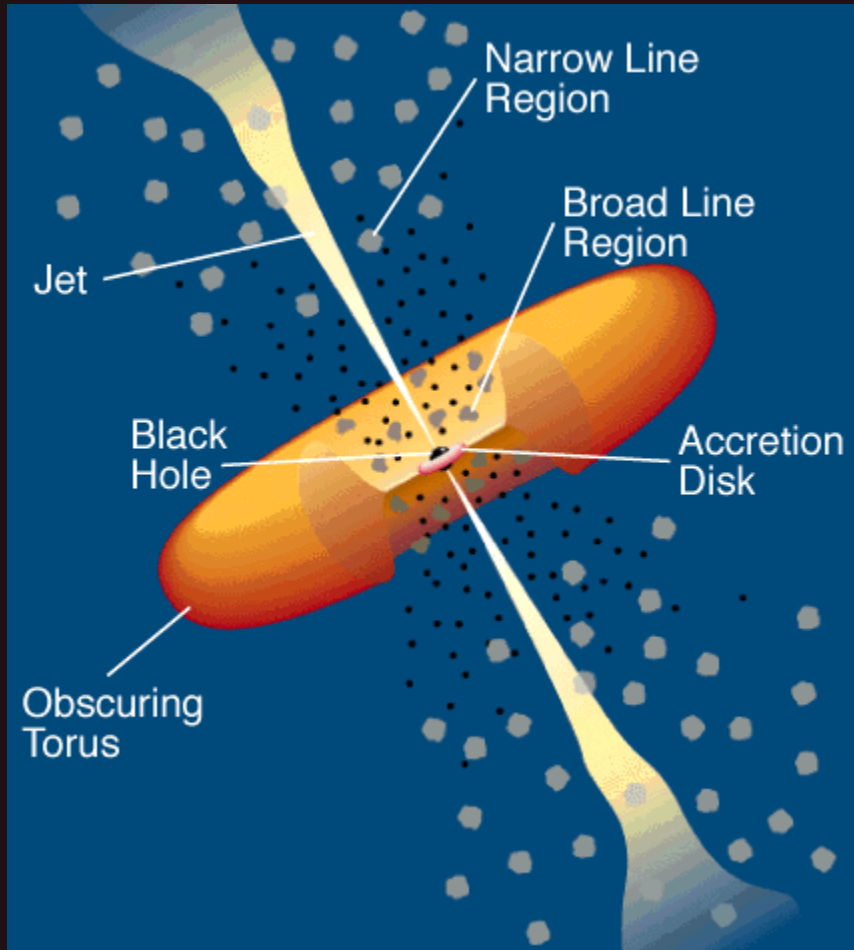
Фоновое излучение



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

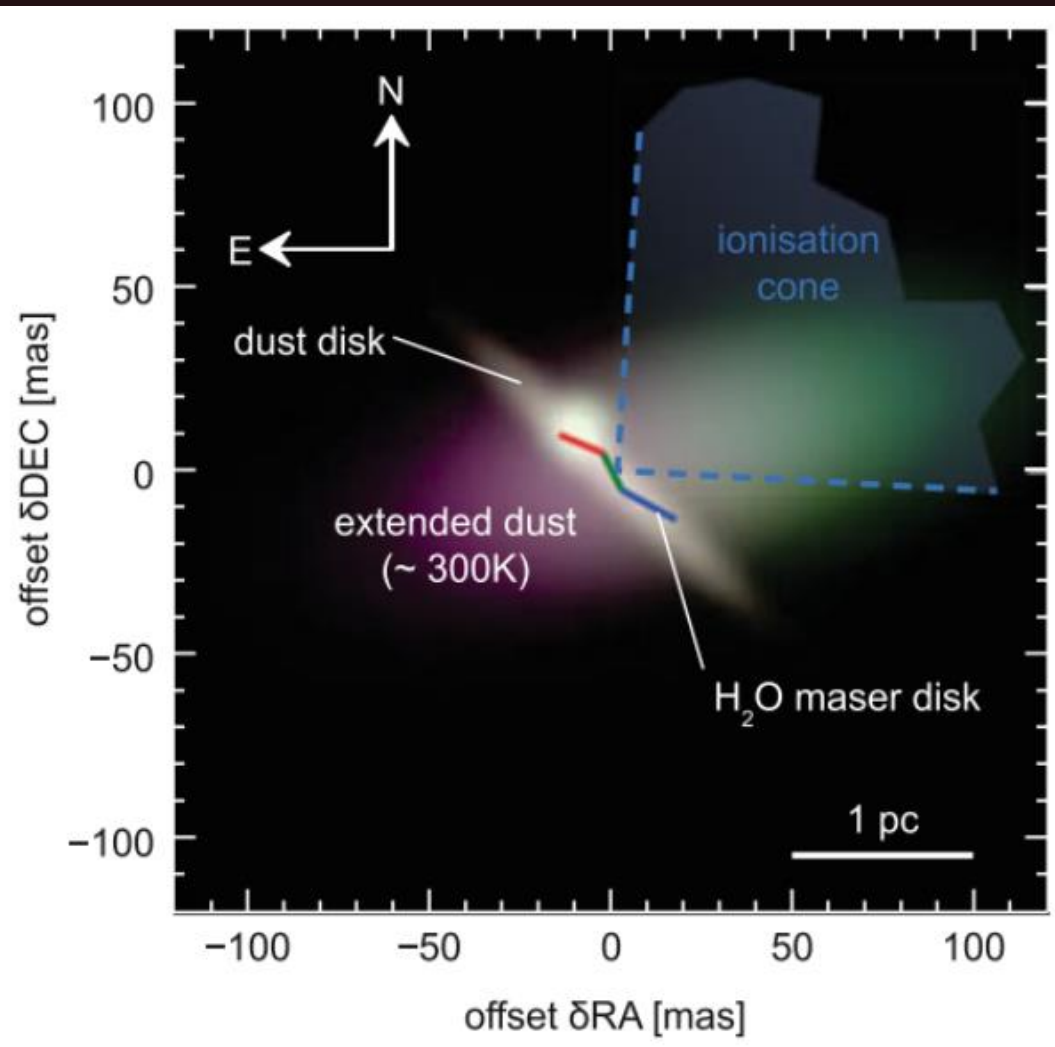


In the framework of the unified model properties of different types of AGNs are explained by properties of a torus around a BH and its orientation with respect to the line of sight.

Antonucci 1993 ARAA 31, 473

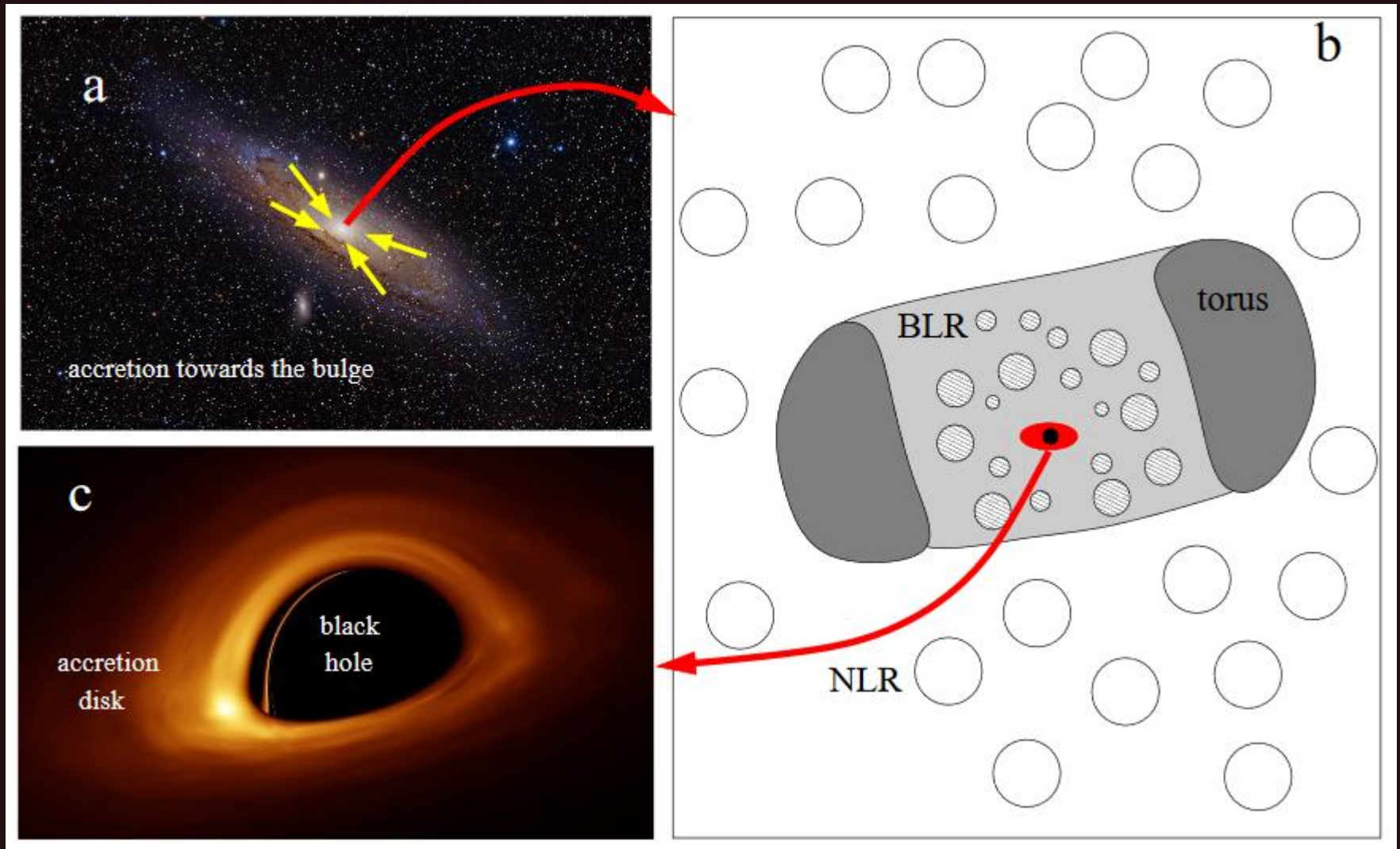
The model can be unapplicable to merging systems, see 1505.00811

IR data for unification



Seyfert type 2 galaxy
Circinus (~4 Mpc)
VLT data, mid-IR

Accretion on different scales



Unified model and population synthesis

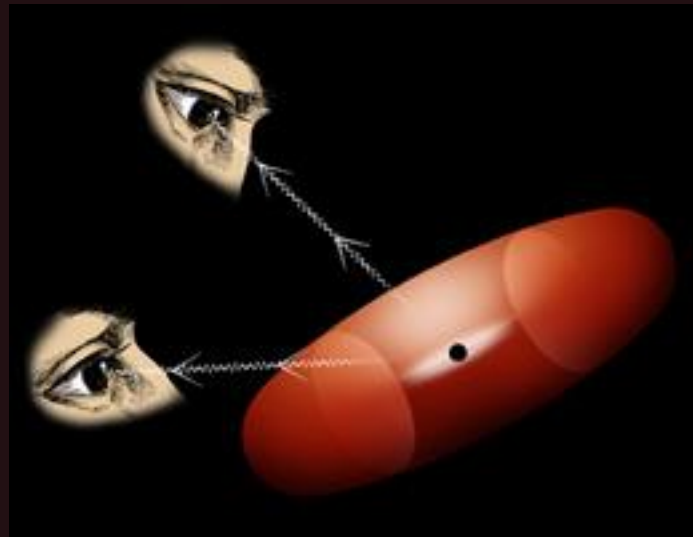
X-ray background is dominated by AGNs.

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

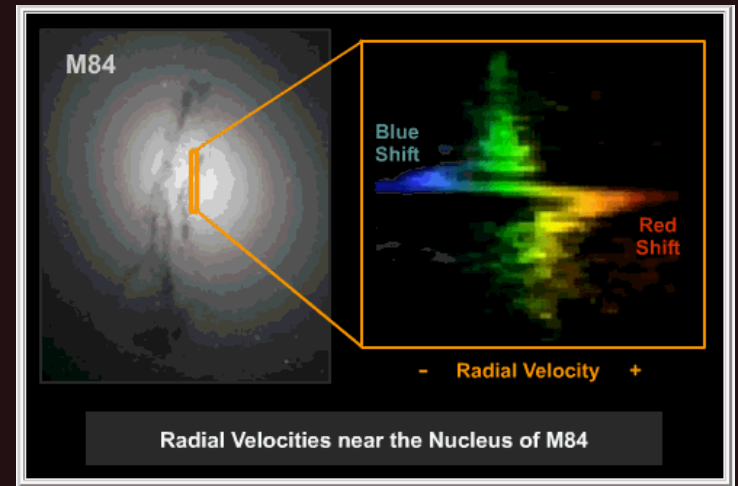
- Relation between a BH mass and a bulge mass (velocity dispersion).
- Measurements of orbits of stars and masers around a BH.
- Gas kinematics.
- Stellar density profile.
- Reverberation mapping.

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

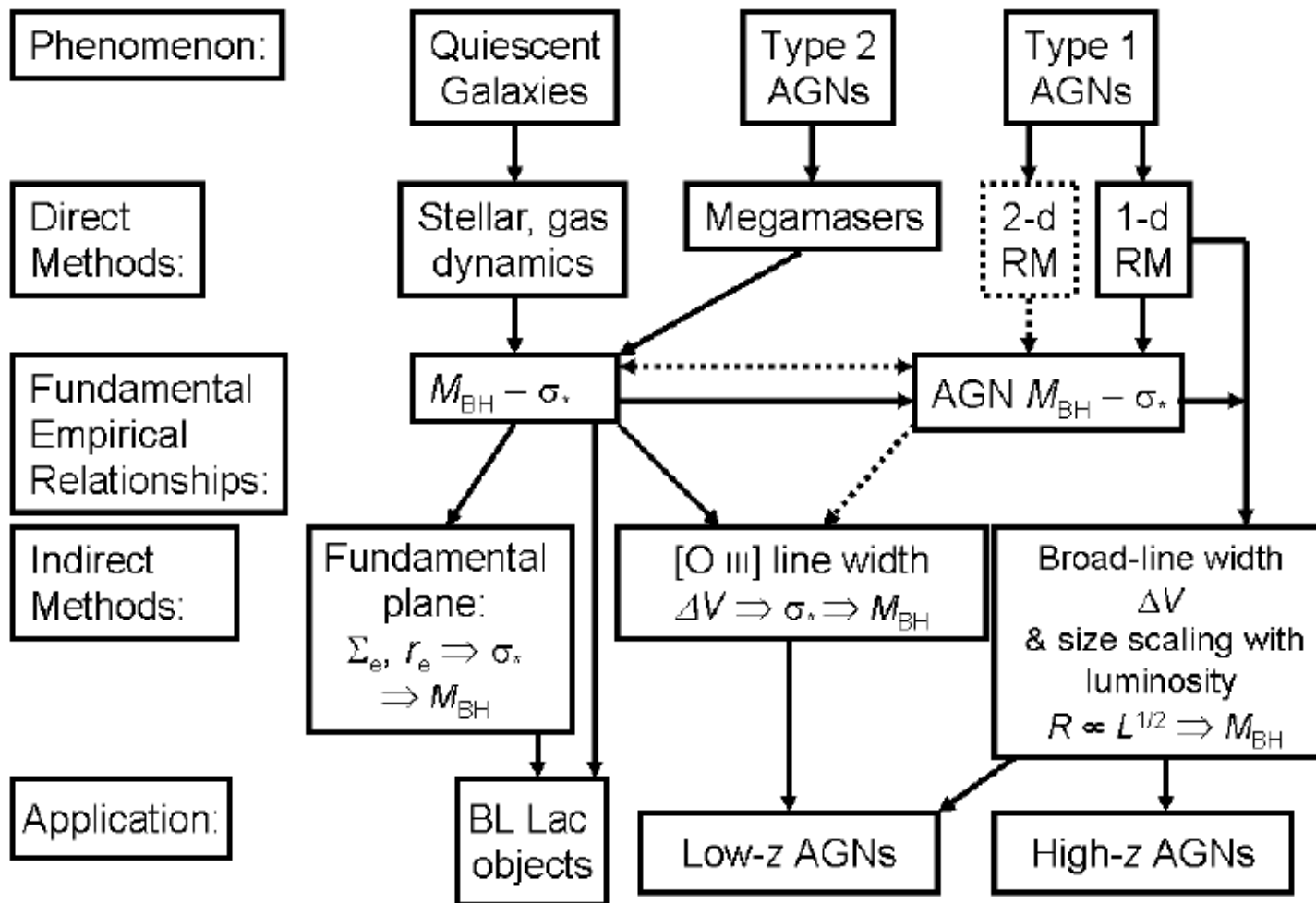
«**Black-Hole Mass Measurements**»

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



Different methods

Measurement of Central Black Hole Masses

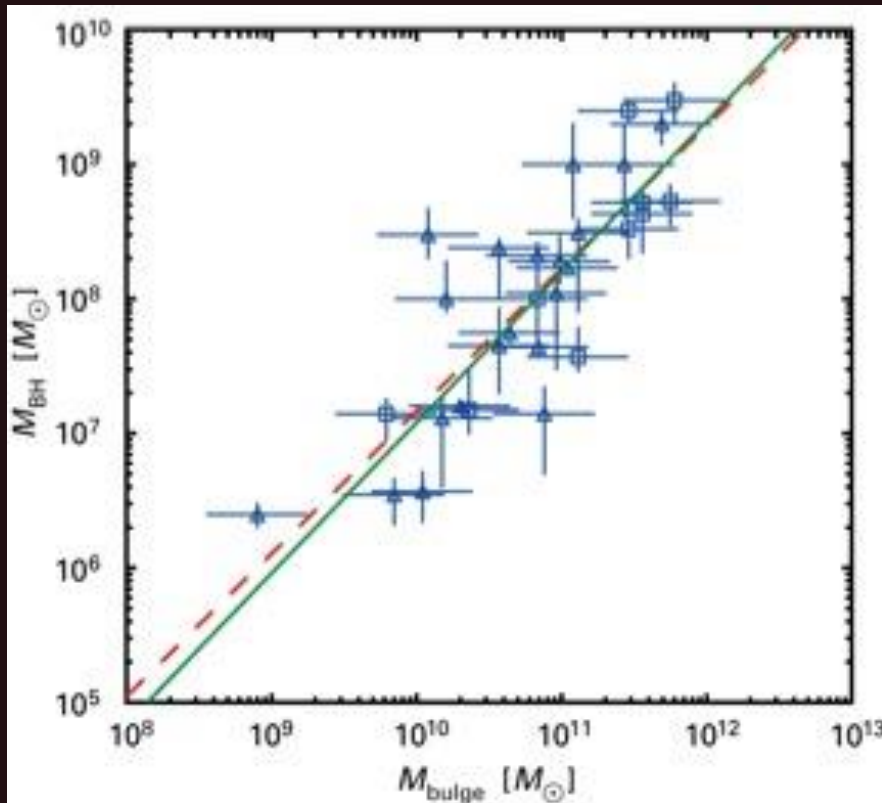


Comparison

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	$25\text{--}260^{[5]}$	$20^{+10}_{-4} \text{ [6]}$	$30^{+7.5}_{-22} \text{ [6]}$
Reverberation	N/A	$7.63^{+1.62}_{-1.72} \text{ [7]}$	$46 \pm 5^{[8]}$
<u>Indirect methods:</u>			
$M_{\text{BH}}\text{--}\sigma_*^{[9]}$	13	25	6.1
$R\text{--}L$ scaling ^[10]	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.



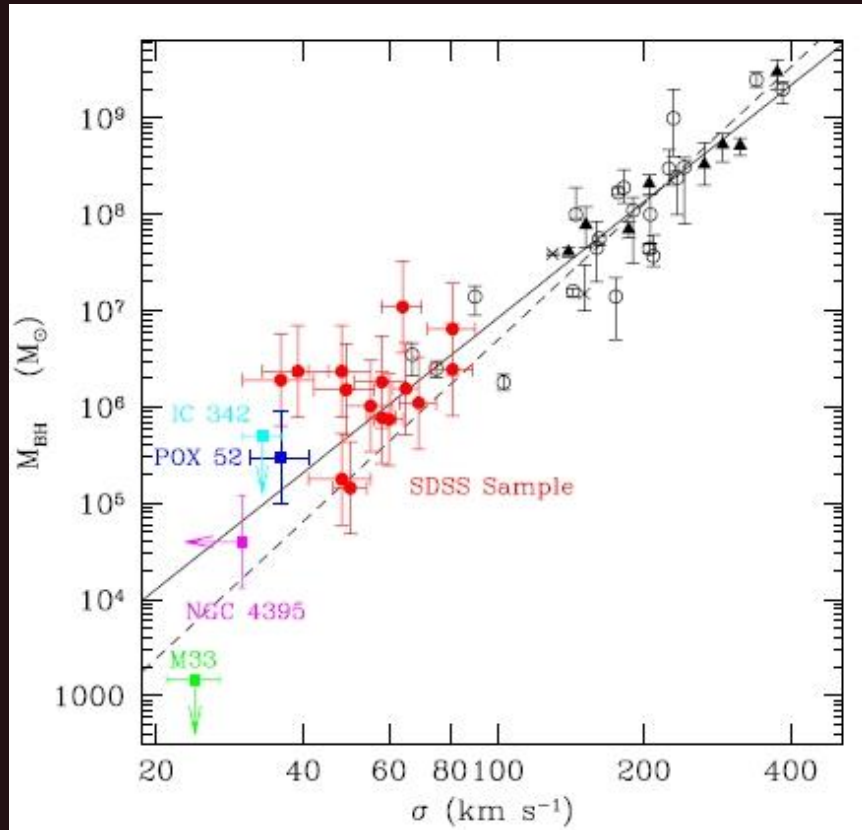
$$M_{\text{BH}} \sim M_{\text{bulge}}^{1.12 \pm 0.06}$$

(Haering, Rix astro-ph/0402376)

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

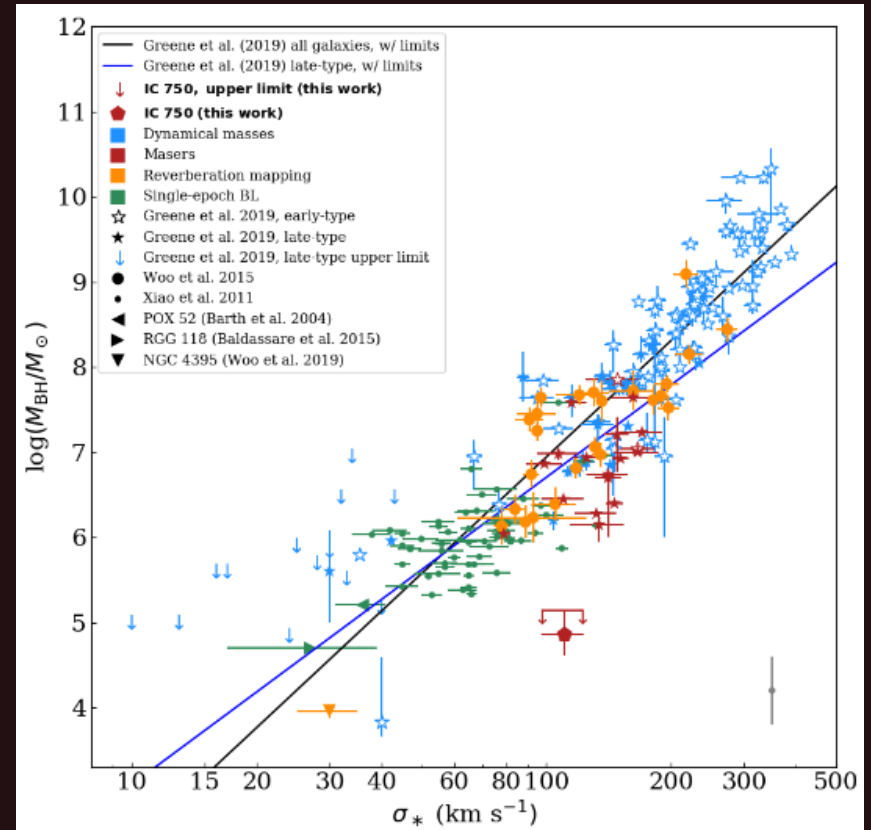
However, the situation is a little bit more complicated. BH mass correlates differently with different components of a galaxy (see 1304.7762 and 1308.6483).

Exceptions: M33 and others



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

Combes astro-ph/0505463



IC 750

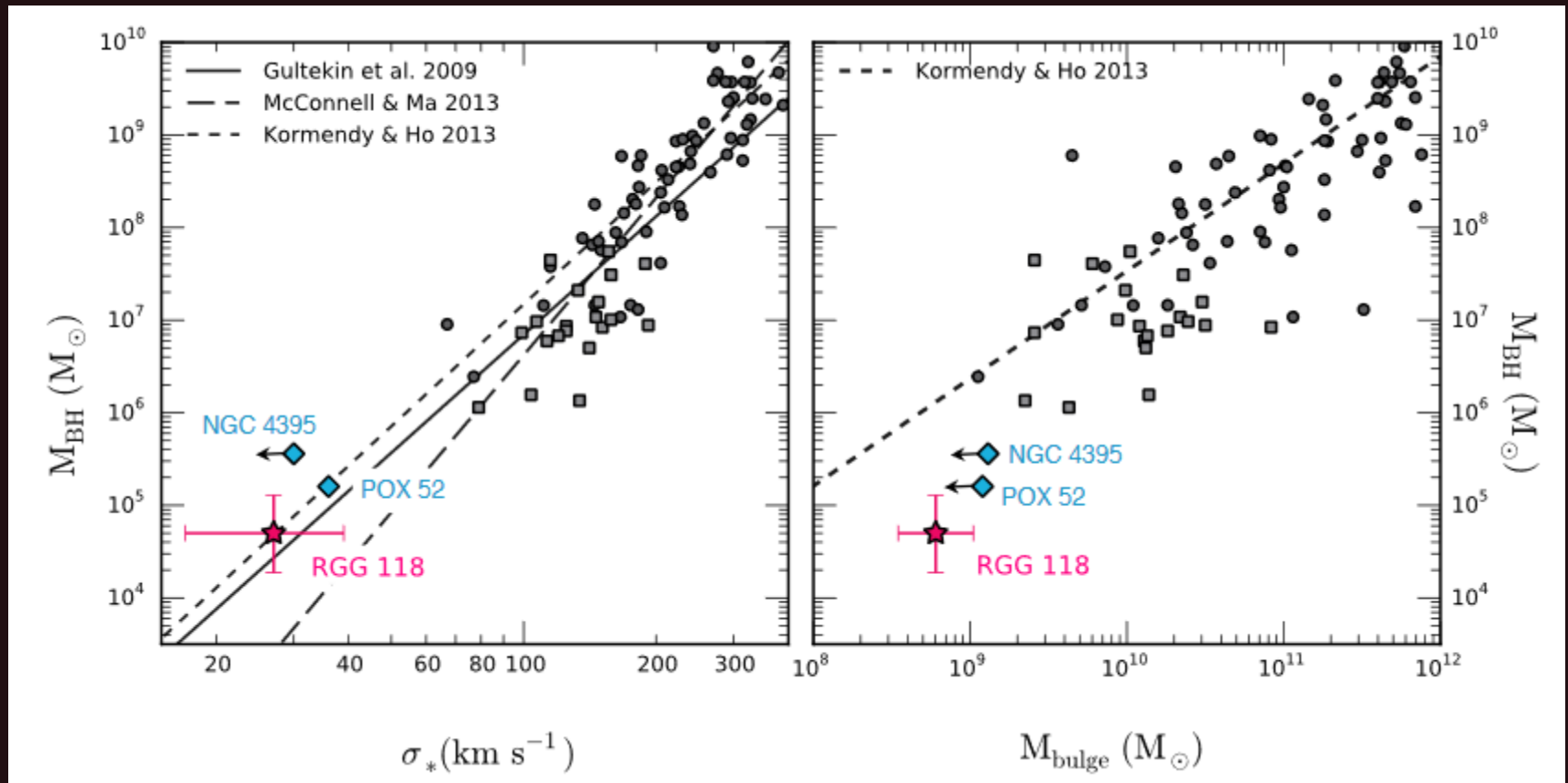
Accreting SMBHs in a galaxy with a massive buldge.

2006.01114

Light SMBH

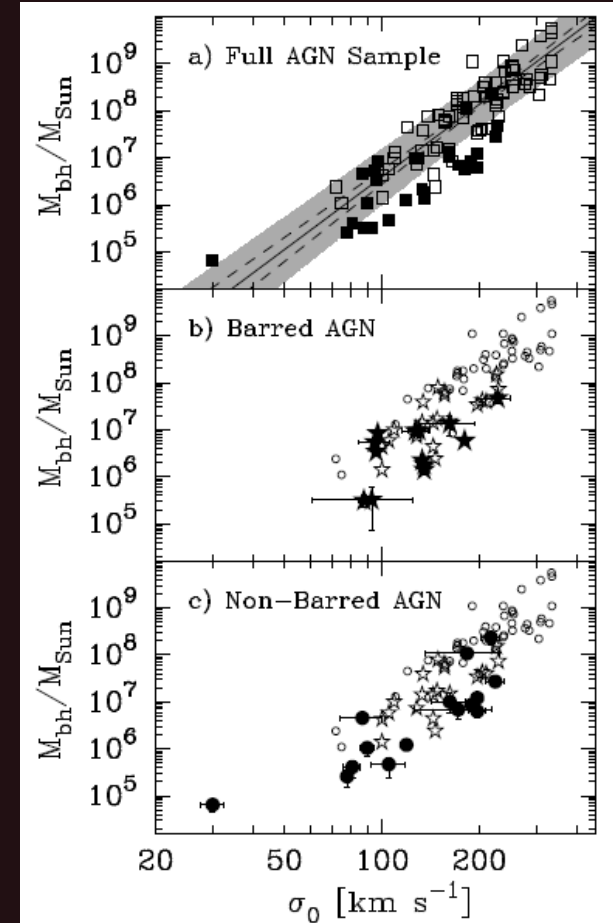
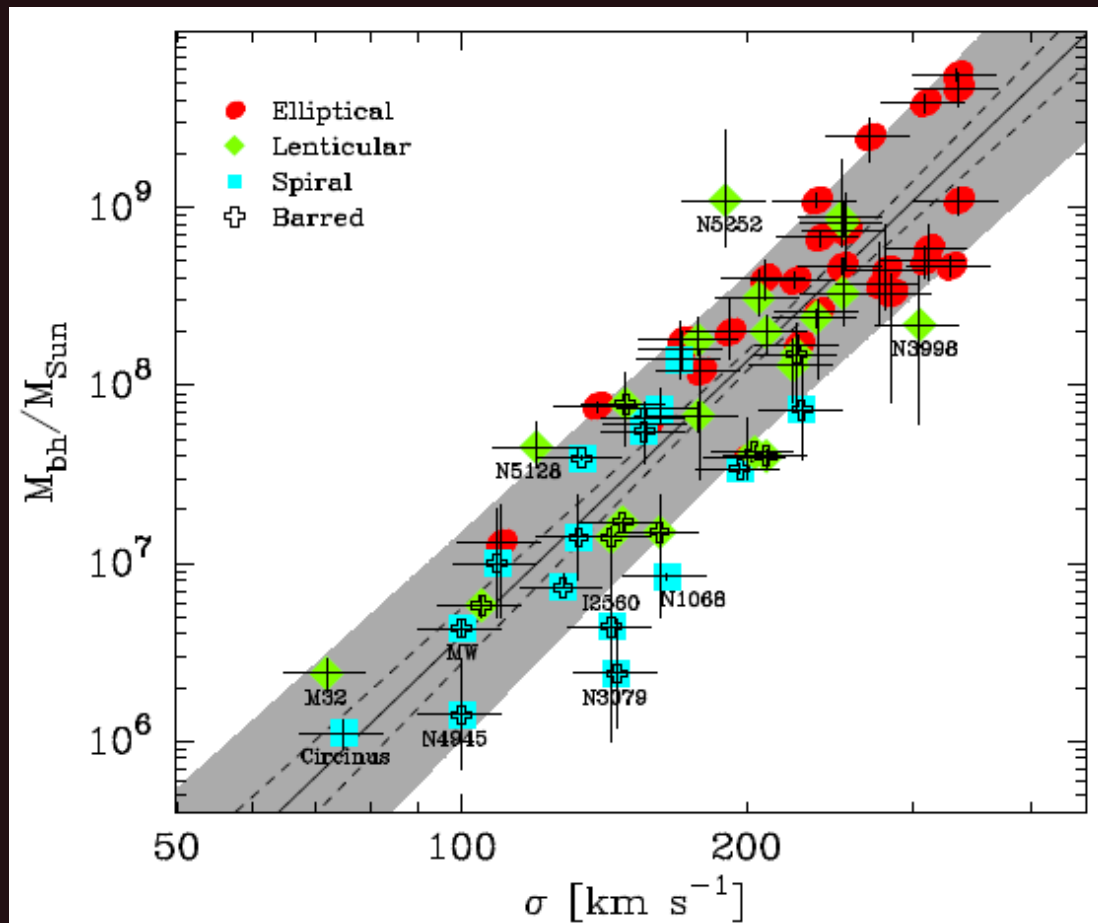
dwarf galaxy RGG 118

BH 50 000 solar masses



1506.07531

More data



$M_{\text{BH}}-\sigma$ relation

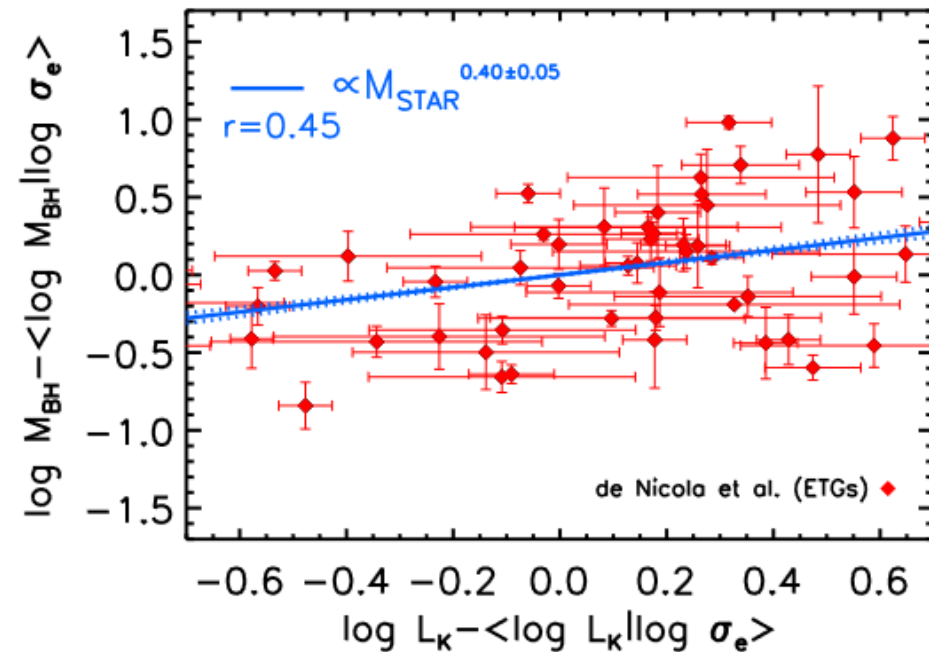
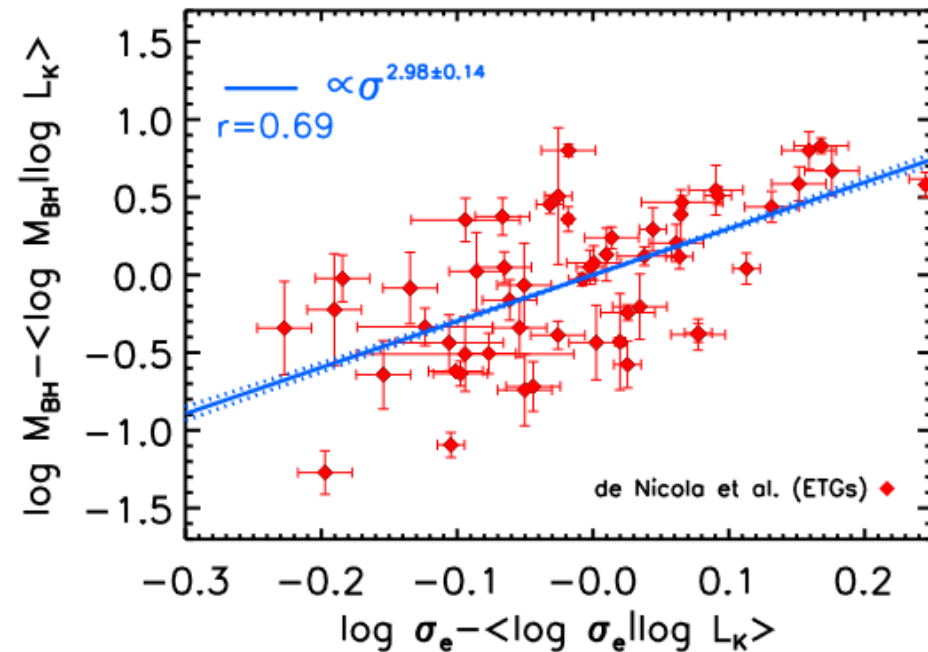
$$M_{\text{BH}} \propto \sigma^\beta M_*^\alpha \propto \sigma^{\beta+\alpha\gamma}$$

$$M_* \propto \sigma^\gamma \quad \gamma \approx 2.2$$

$$\beta \sim 3 \quad \alpha \sim 0.4$$

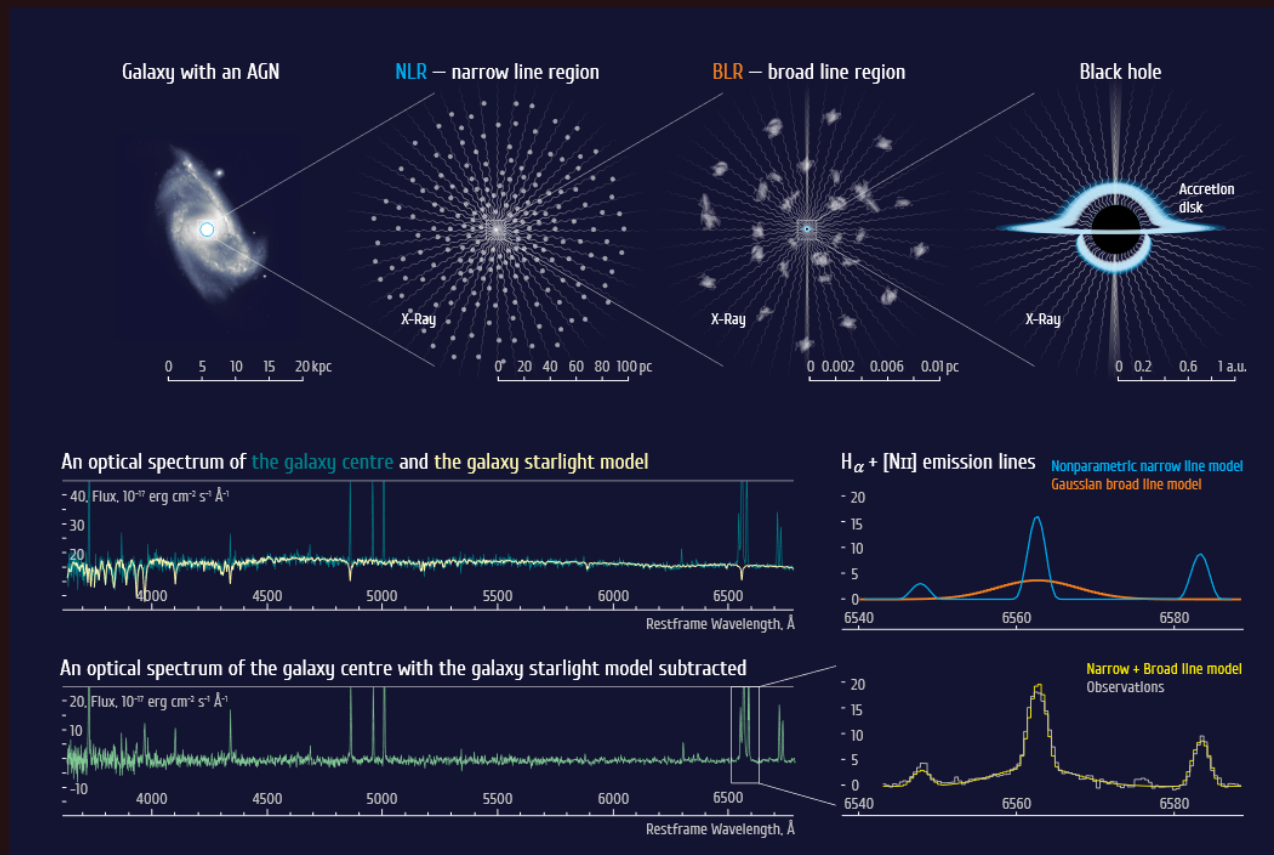
$$M_{\text{BH}} \propto \sigma_e^5$$

In the plot only early type galaxies are shown

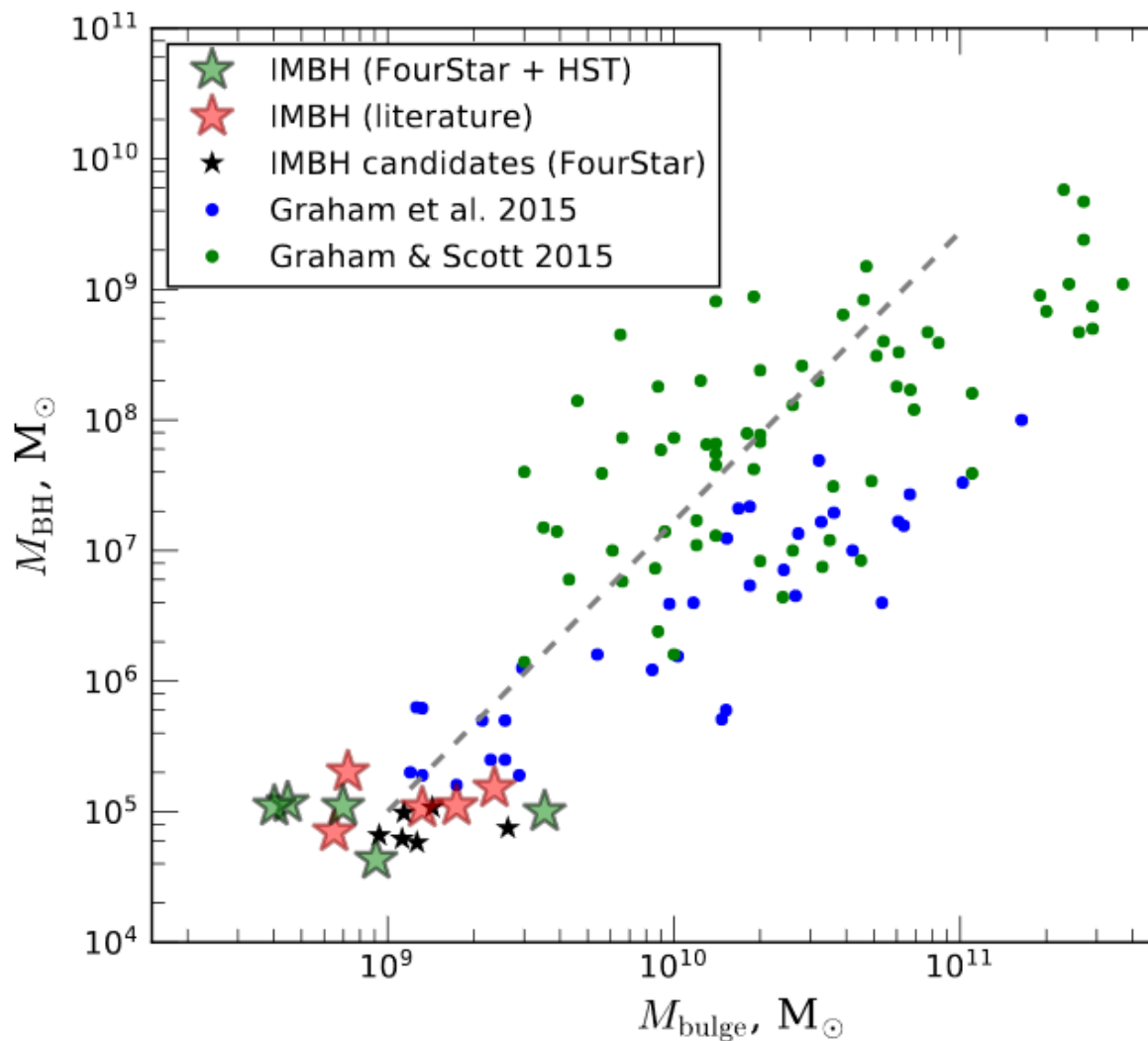


IMBHs in low luminosity AGNs

$$M_{\text{BH}} = 3.72 \times 10^6 (\text{FWHM}_{\text{H}\alpha} / 10^3 \text{ km s}^{-1})^{2.06} \times (L_{\text{H}\alpha} / 10^{42} \text{ erg s}^{-1})^{0.47} M_{\odot}$$

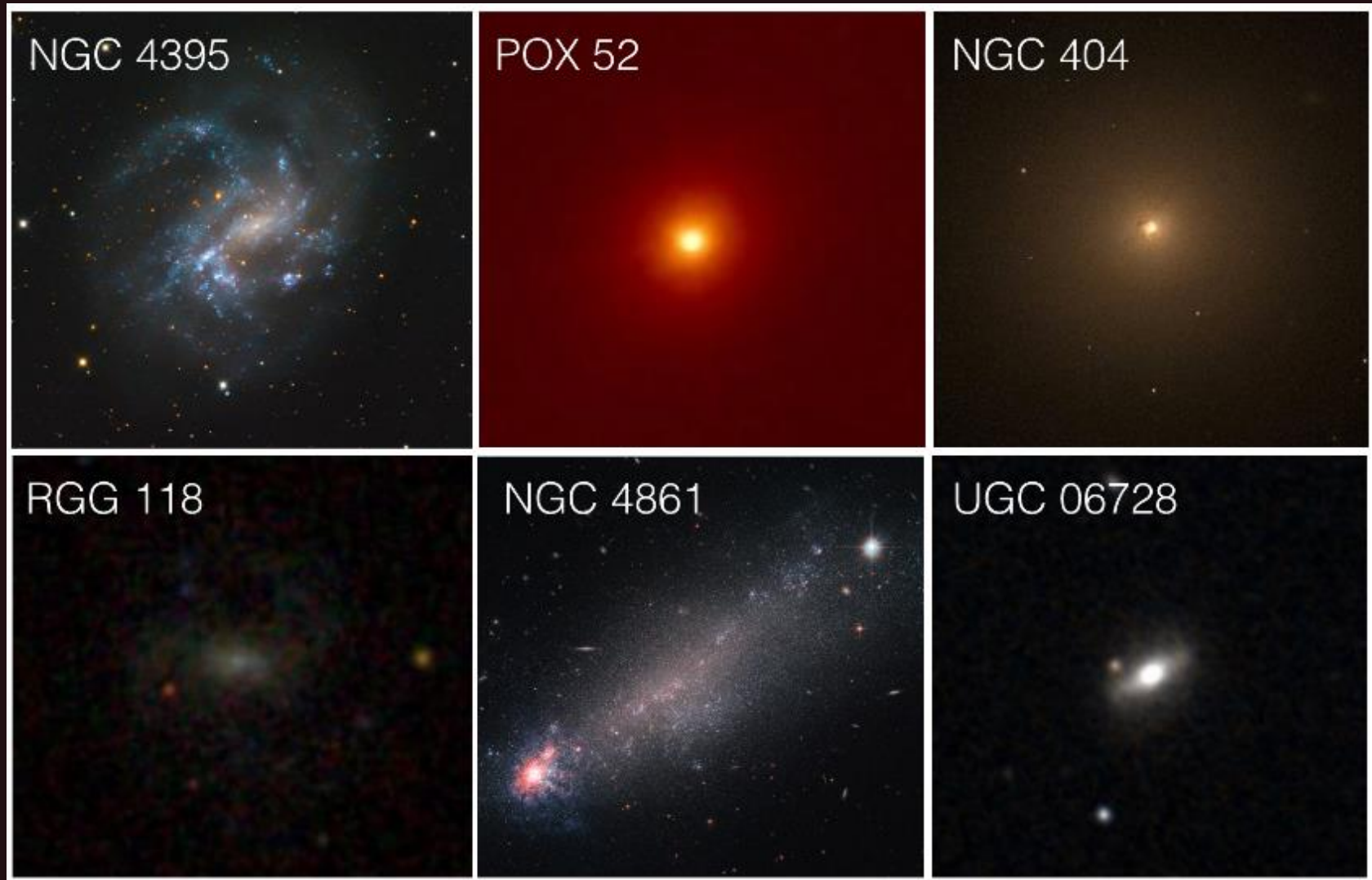


IMBHs in low luminosity AGNs

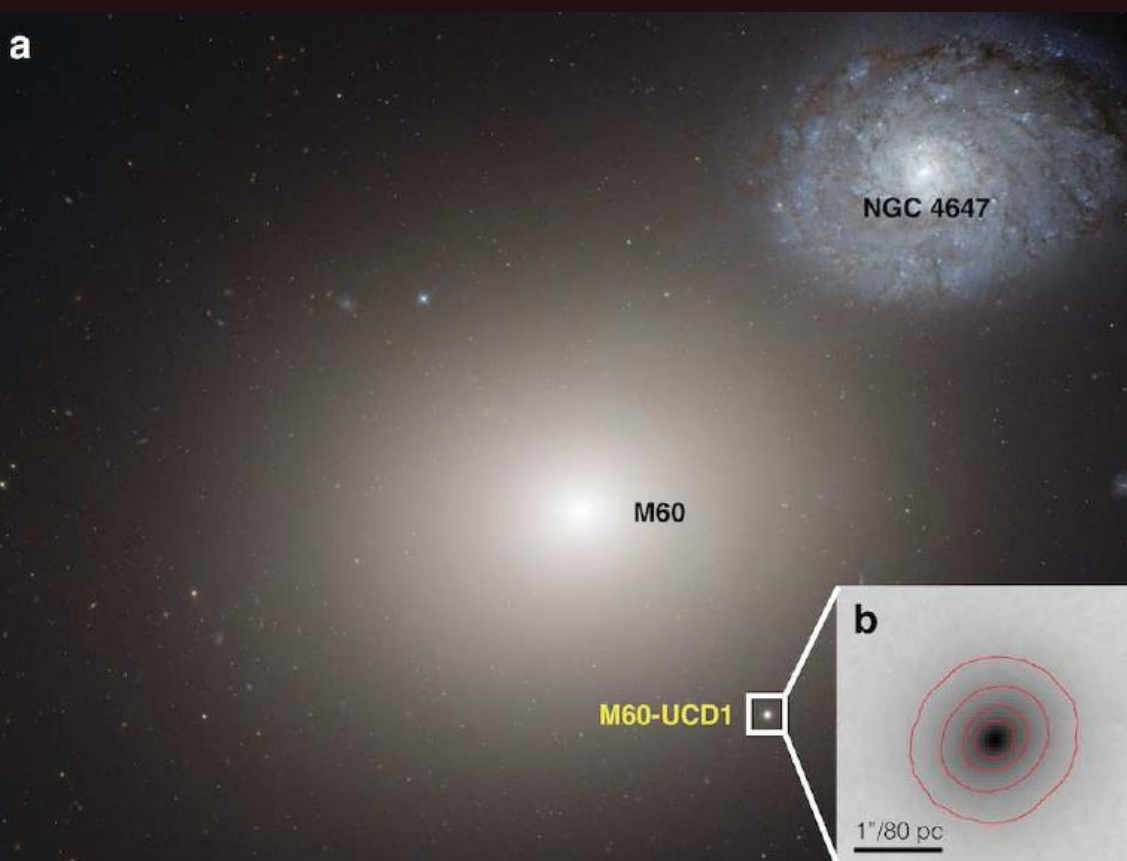


Object	M_{BH} ($10^3 M_{\odot}$)
J122732.18+075747.7	43 ± 10^1 36 ± 7^2
J134244.41+053056.1	65 ± 7^1 96 ± 13^2
J171409.04+584906.2	115 ± 24^1
J111552.01-000436.1	115 ± 38^1
J110731.23+134712.8	122 ± 18^1 71 ± 10^2
J152304.97+114553.6 ^a	70 ± 20^1
J153425.58+040806.7 ^b	111 ± 7^1
J160531.84+174826.1 ^b	116 ± 11^1
J112333.56+671109.9 ^c	157 ± 36^1
J022849.51-090153.8 ^c	202 ± 13^1 367 ± 27^2

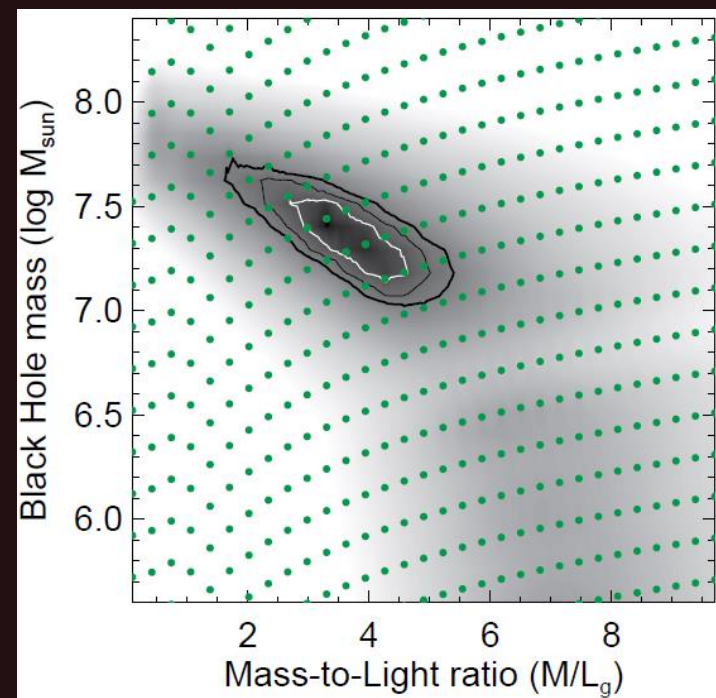
Dwarf galaxies with IMBHs



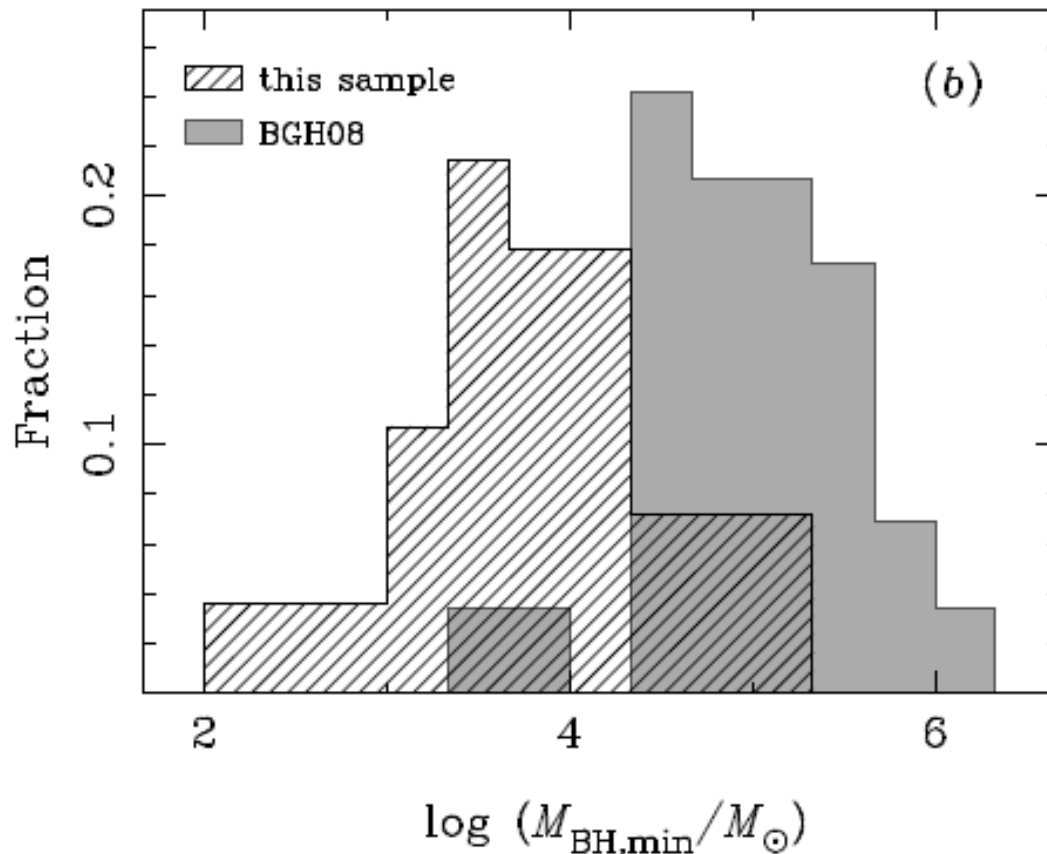
Сверхмассивная черная дыра в карликовой компактной галактике



**Самая легкая
галактика с
черной дырой**

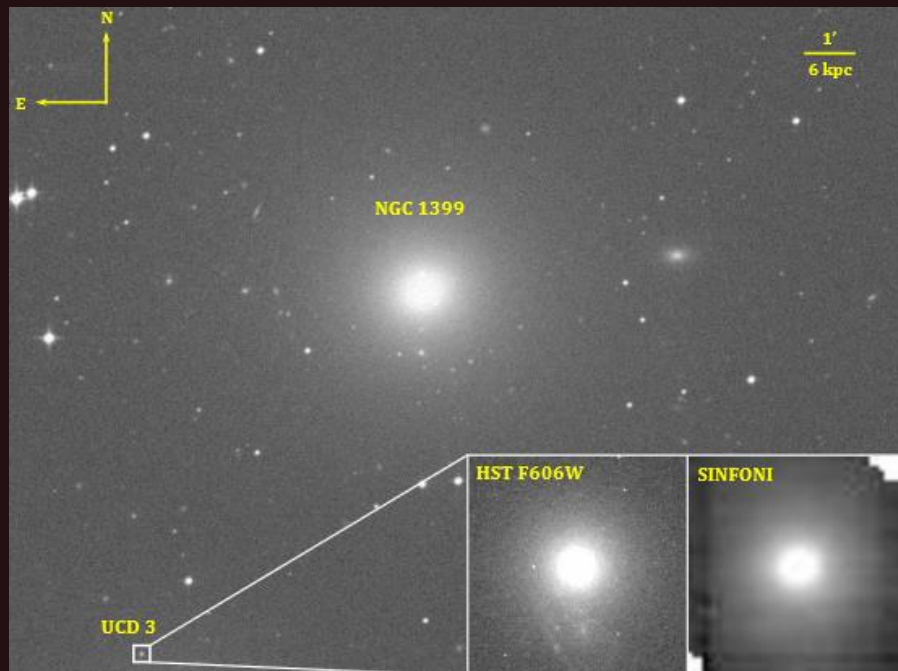


Черные дыры в карликовых галактиках



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

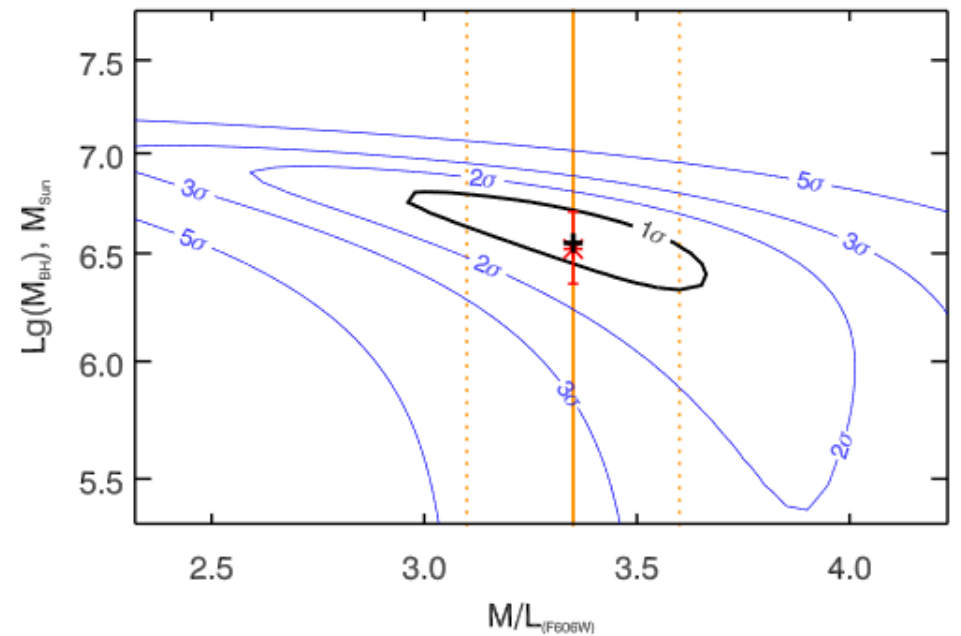
SMBH in Fornax UCD3



HST F606W

SINFONI

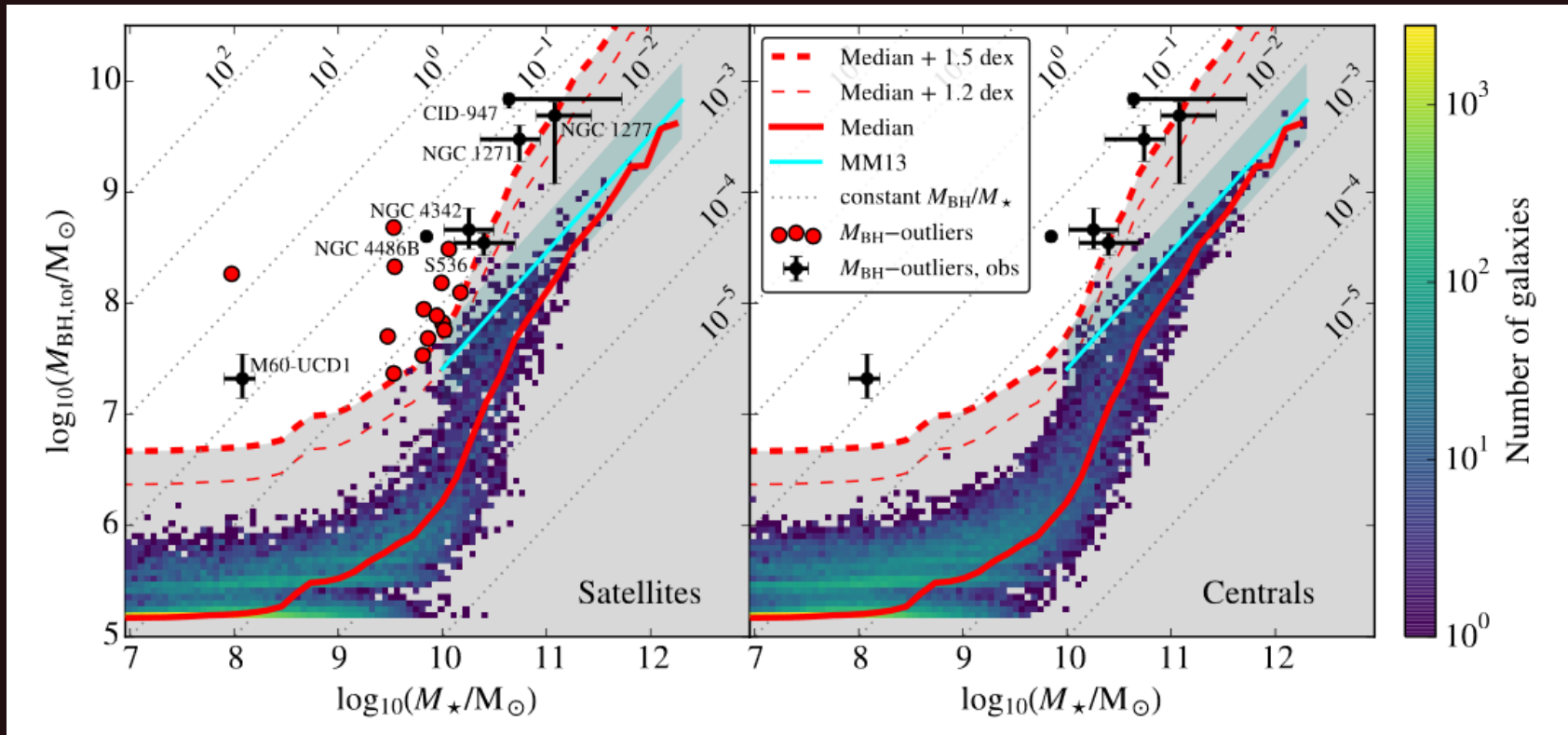
UCD 3



3.5 million M_{solar}

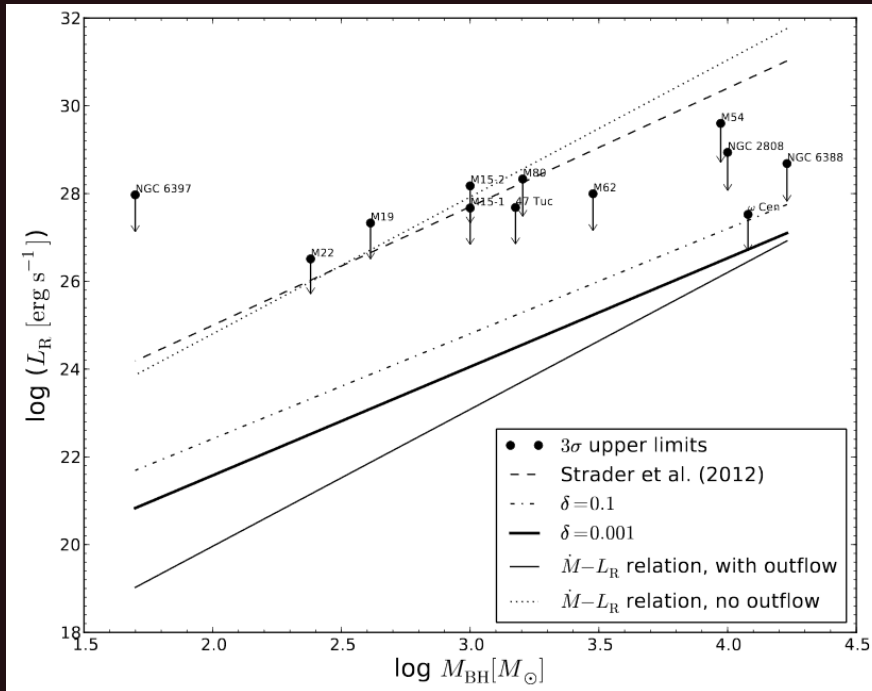
1804.02938

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

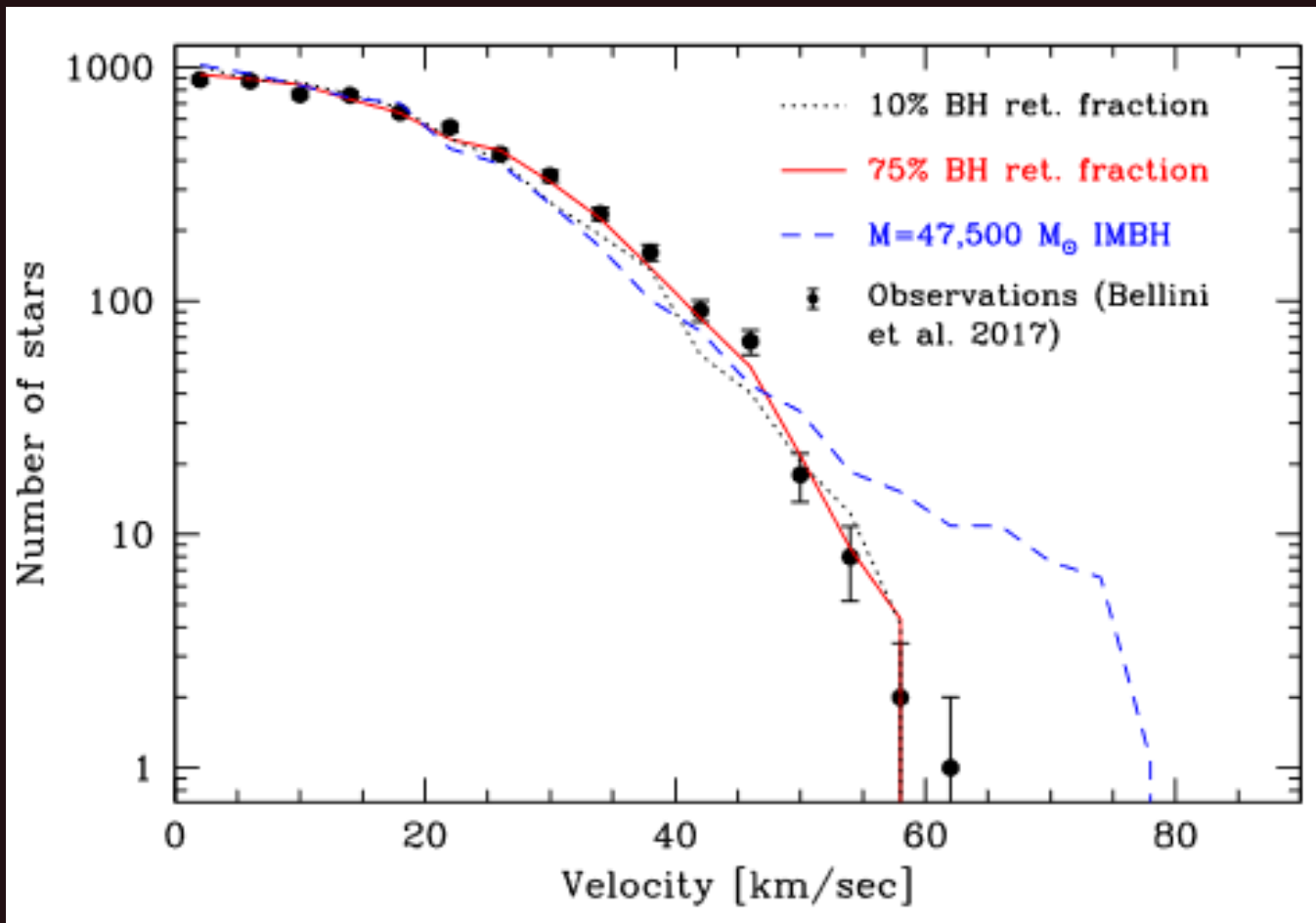
Also radio pulsar data favours an IMBH in the globular cluster M62 (1909.11091).

Radio luminosity limits cannot exclude proposed IMBHs in GCs

~15 candidates now (see 1705.09667)

Limits from dynamics: 1404.2781

No BHs in GCs???

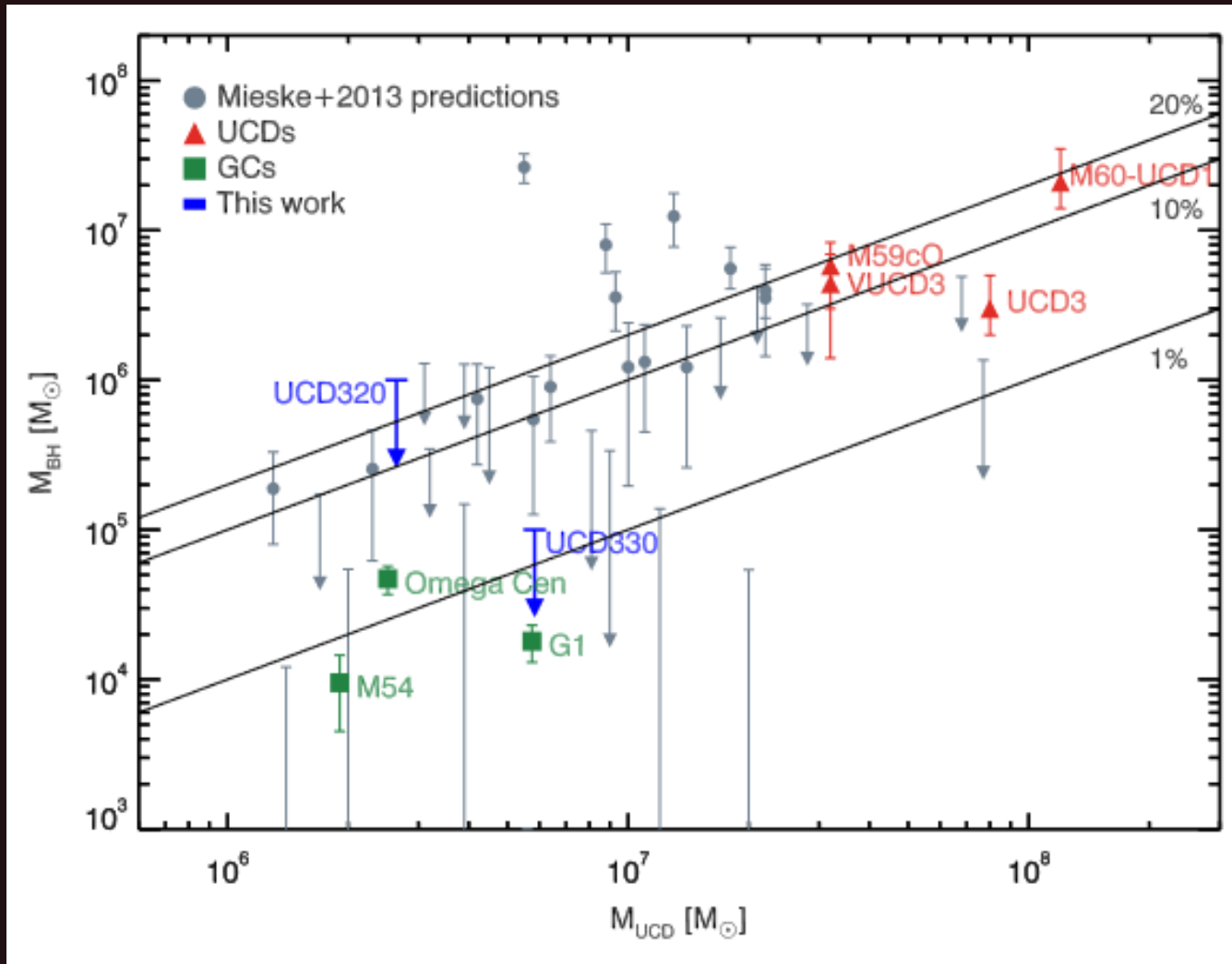


NGC 6624
is also
in doubt.

In ω Cen for an IMBH model it is predicted that many high-velocity low-mass stars might be observed. However, none are found.

1907.10845

Ultra compact galaxies vs. globular clusters

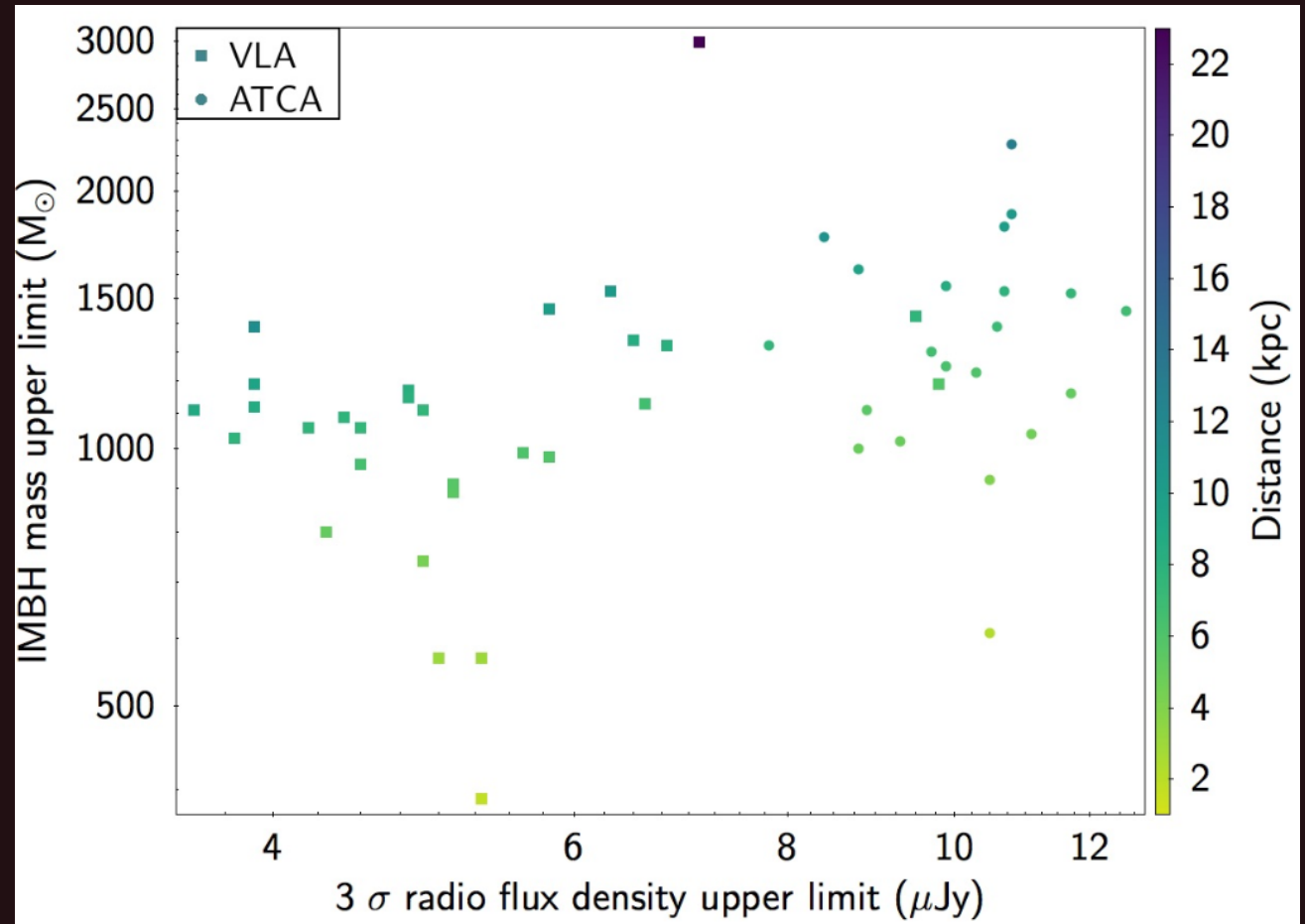


Maveric survey: no accreting IMBHs in GCs

VLA + ATCA

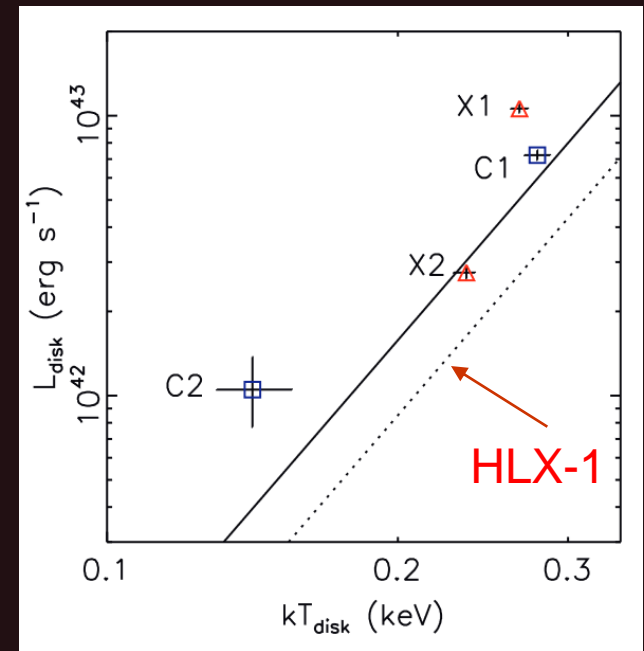
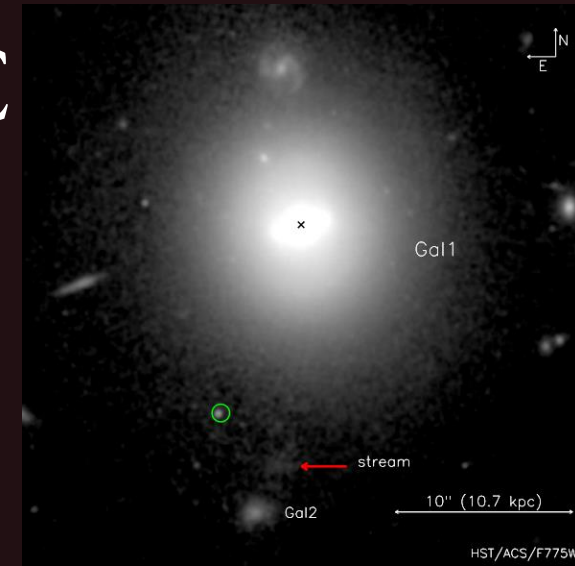
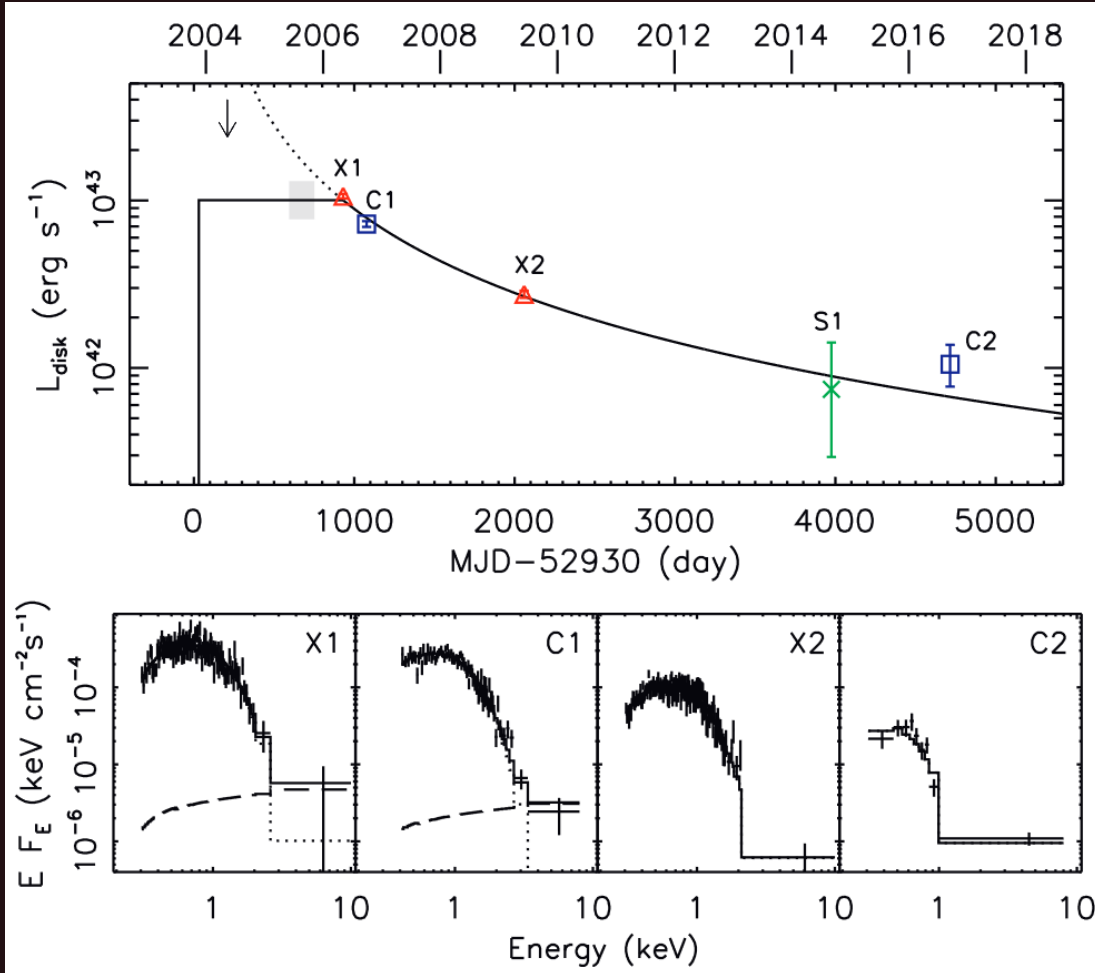
50 globular clusters

No detections.



1806.00259

TDE in an extragalactic GC

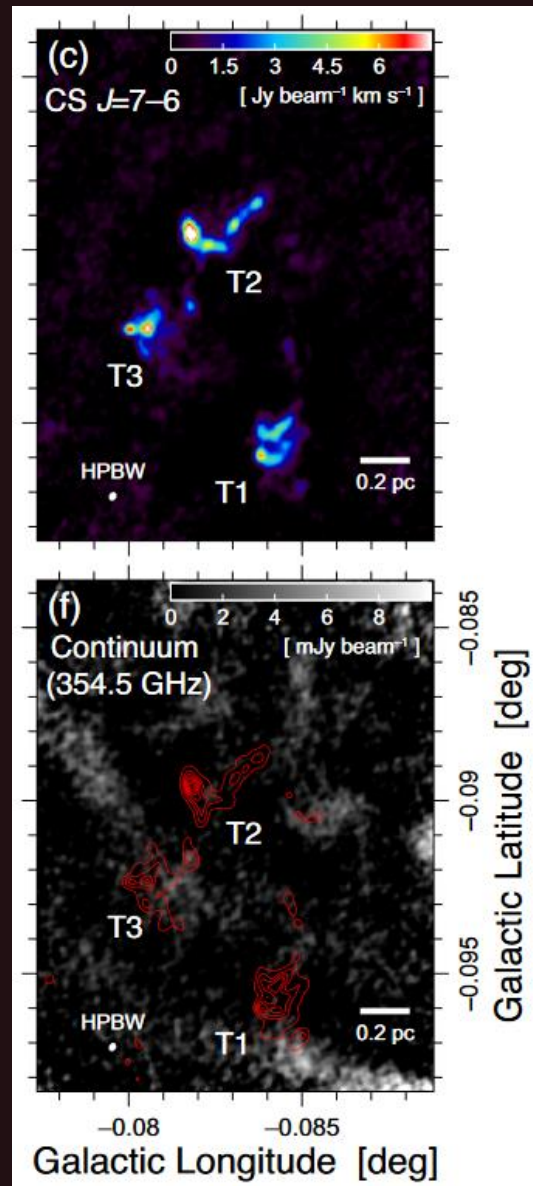
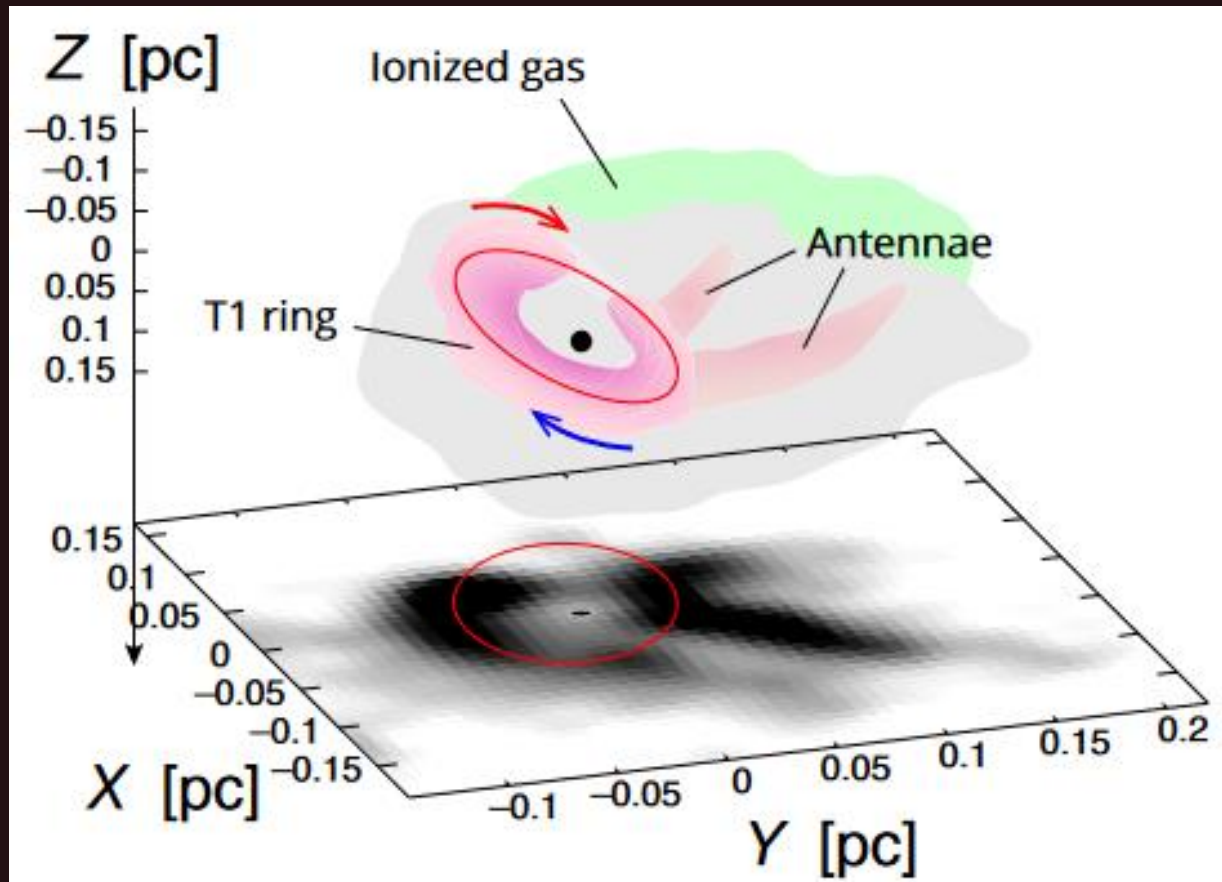


BH mass ~few 10^4 solar masses

1806.05692, see modeling of such events in 1904.06353

IMBHs around Sgr A* ?

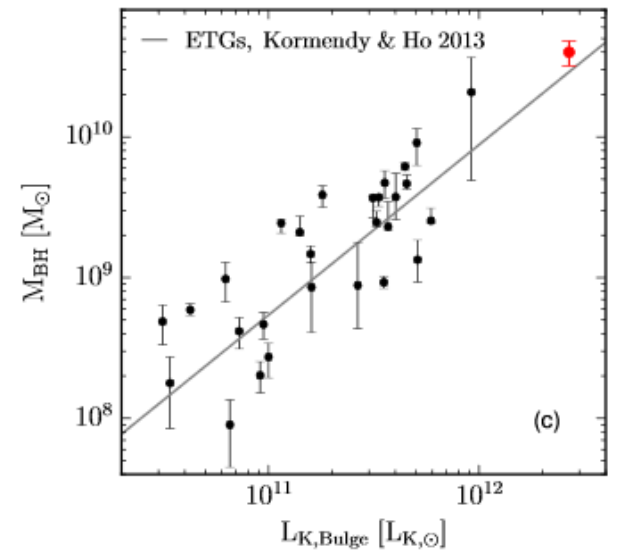
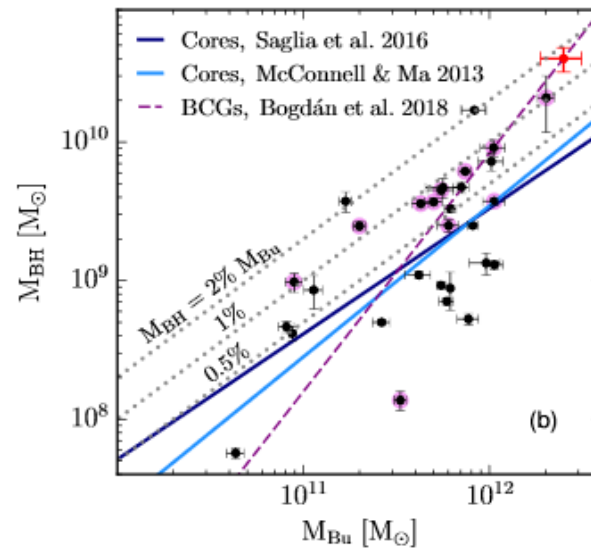
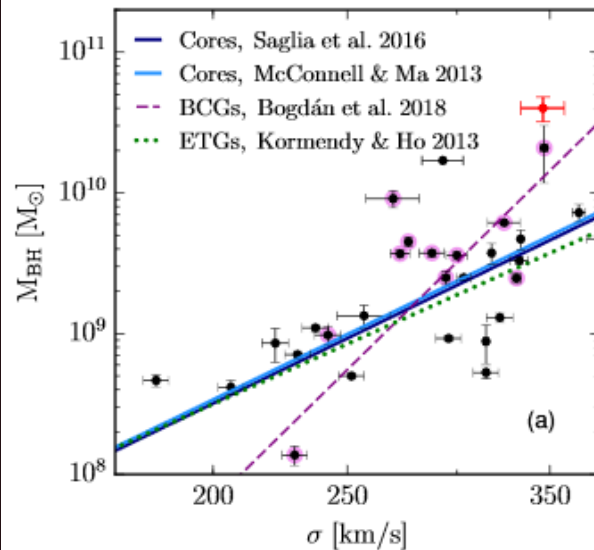
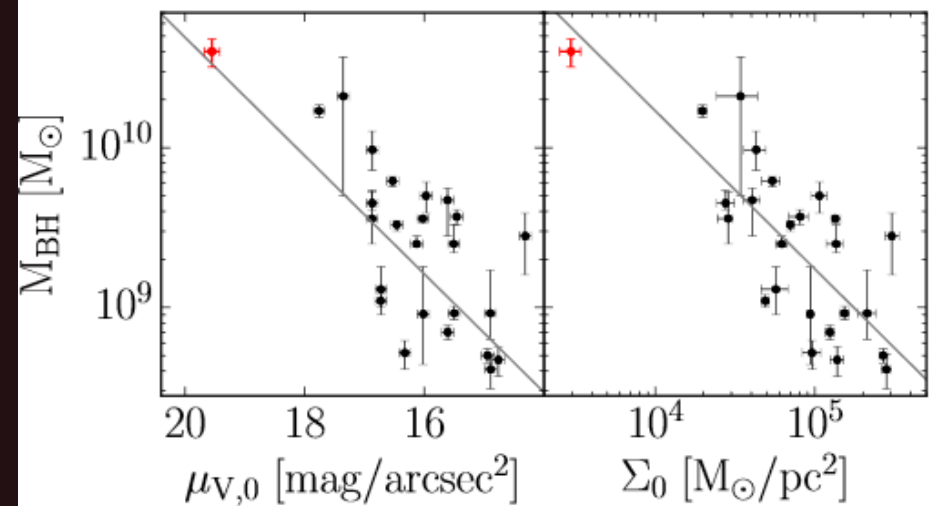
Hypothesis: some of high-velocity compact clouds (HVCC) can contain IMBHs.



40-billion solar mass SMBH

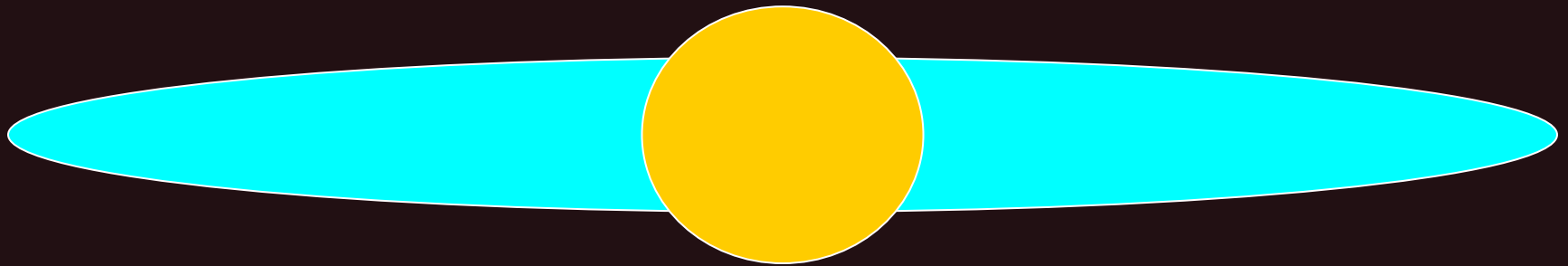
Holm 15A is
the brightest cluster galaxy (BCG)
of the galaxy cluster Abell 85.

Stellar kinematics used.



Сверхмассивная черная дыра там, где ее не должно быть

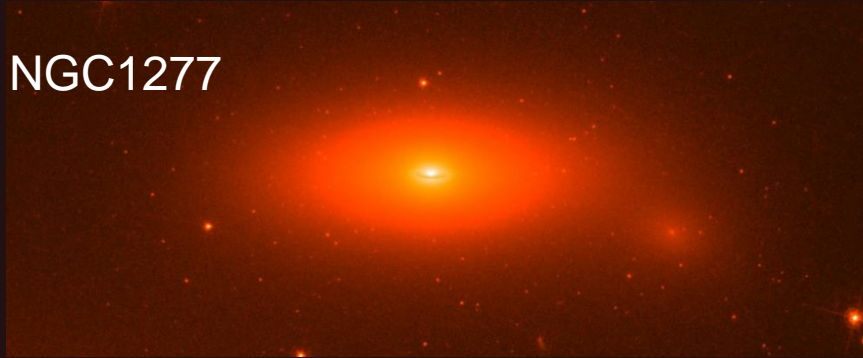
Наблюдения галактики NGC 4561 на спутнике XMM-Newton показали, что в ней есть активное ядро, т.е. – сверхмассивная черная дыра. Но при это быть там этой дыре не положено: у галактики нет балджа.



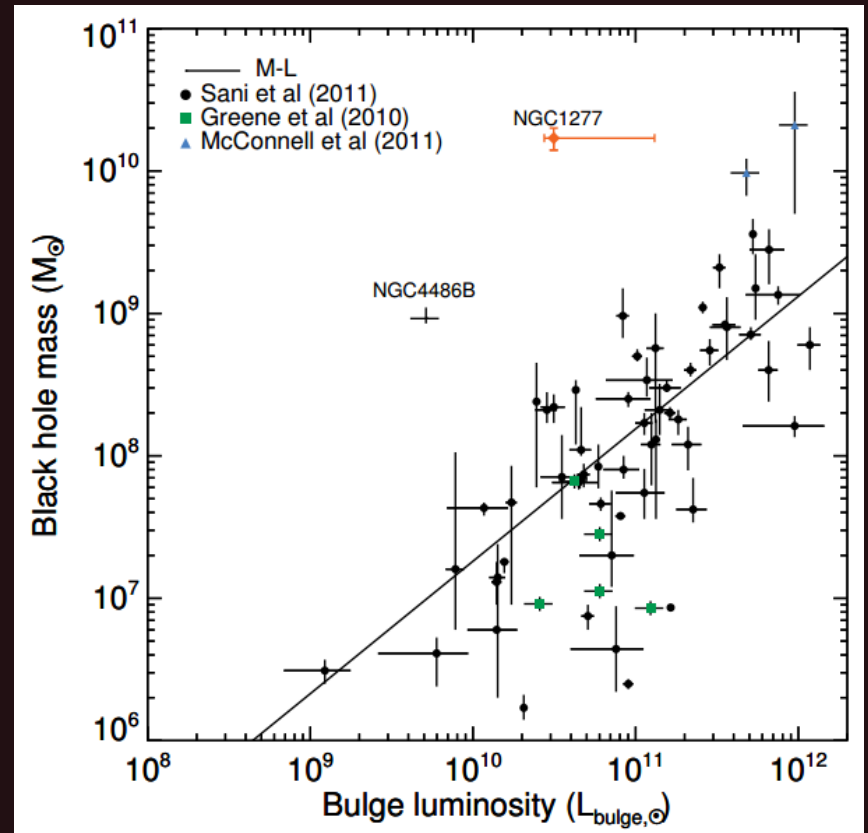
Масса черной дыры $>20000 M_{\odot}$

Слишком массивная черная дыра

NGC1277



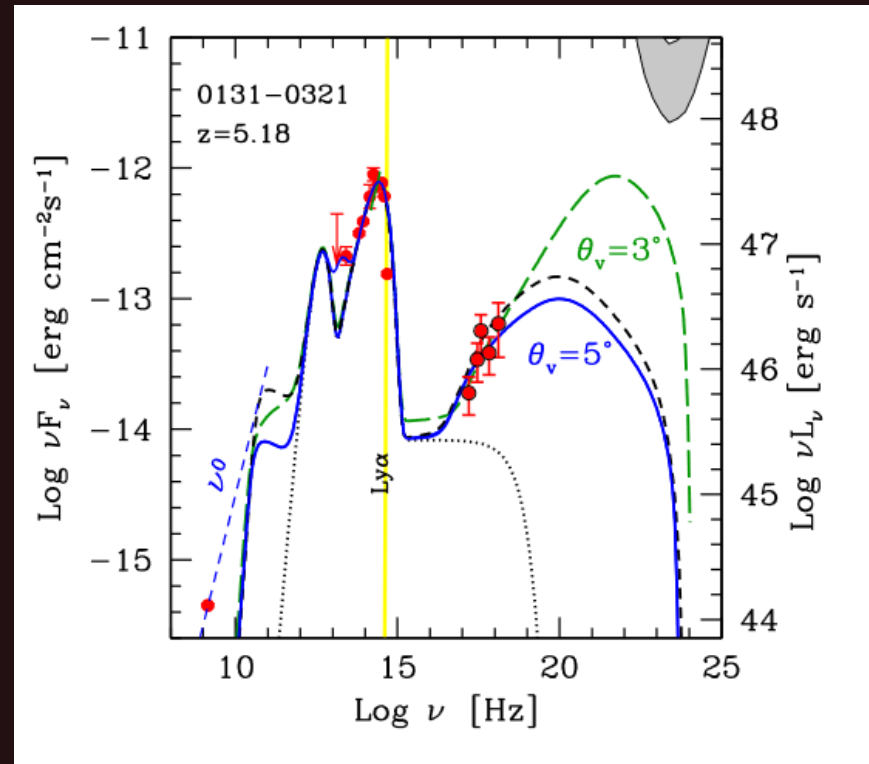
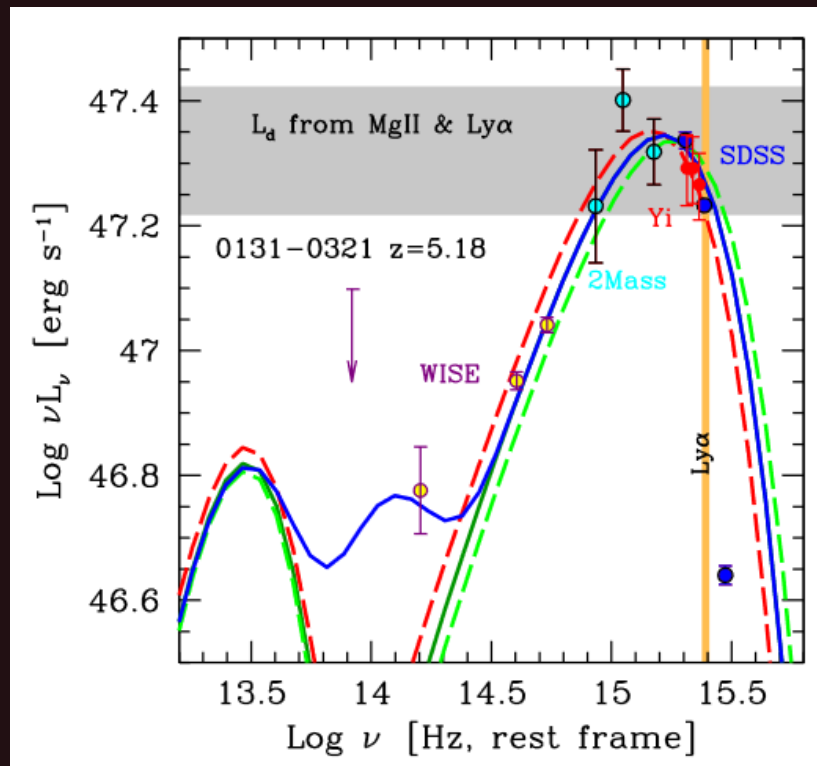
Компактная линзовидная галактика.
«Положено» иметь черную дыру $10^8 M_{\odot}$
А присутствует $>10^{10} M_{\odot}$!



11 billion solar masses BH at $z>5$

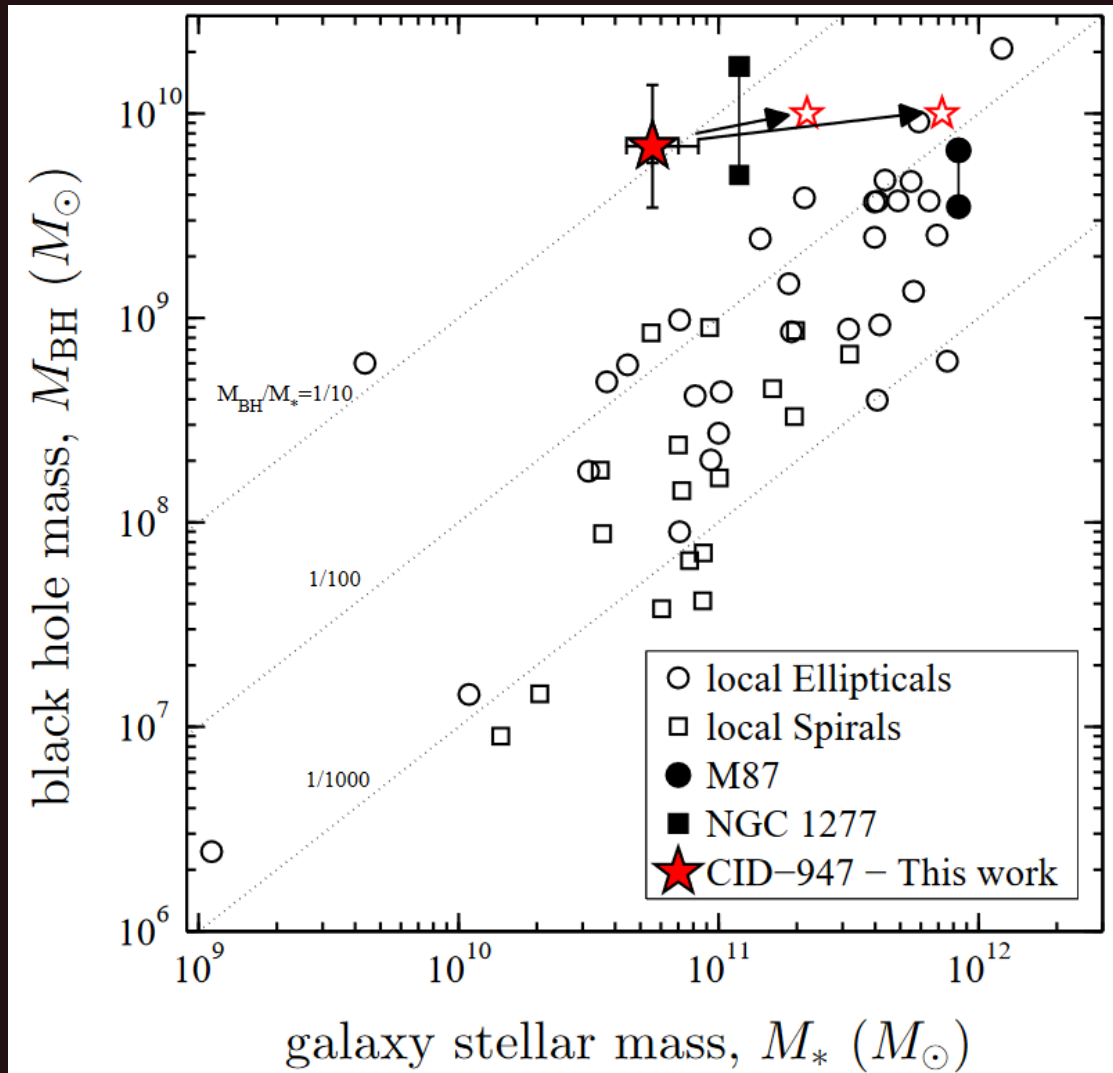
SDSS J013127.34-032100.1

Mass determined via spectral fitting.



Recently, a 34-billion solar mass SMBH in the most luminous quasar at $z=4.7$ has been reported in 2005.06868.

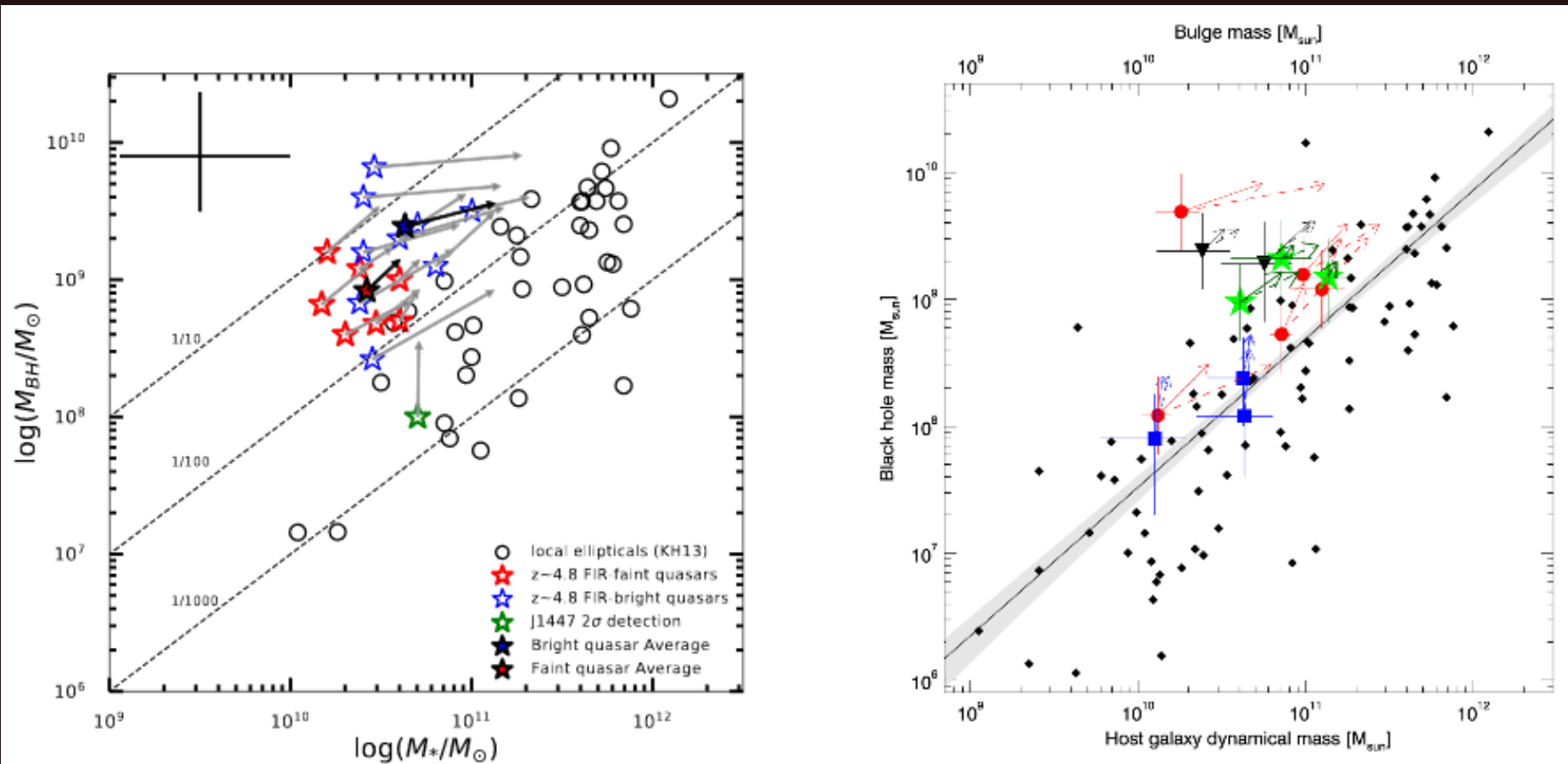
Too massive BH in a starforming galaxy



$z=3.3$

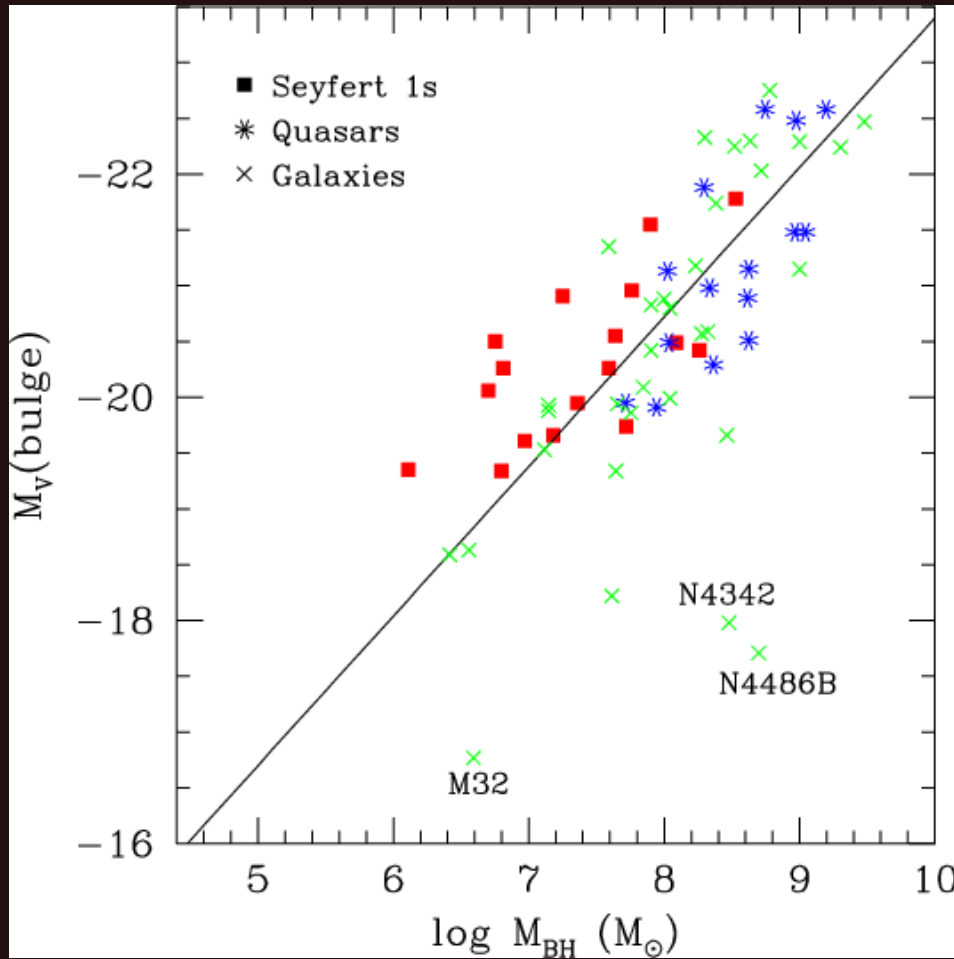
Due to large SFR
in a time the BH
might become
“more typical”
respect to the galaxy.

Expected mass growth for high- z SMBHs



New ALMA data help to establish the growth rate expectations.

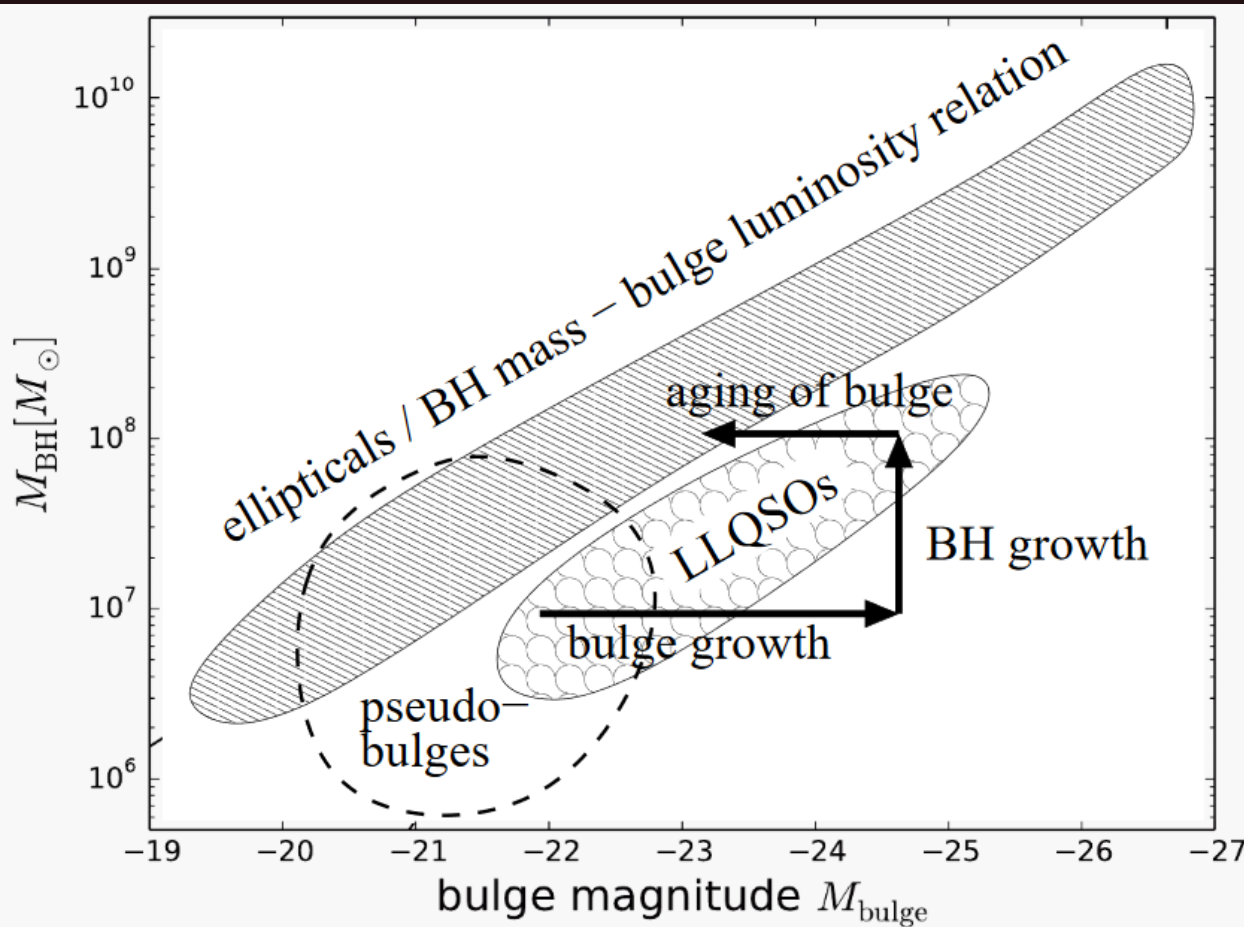
There are other correlations



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.

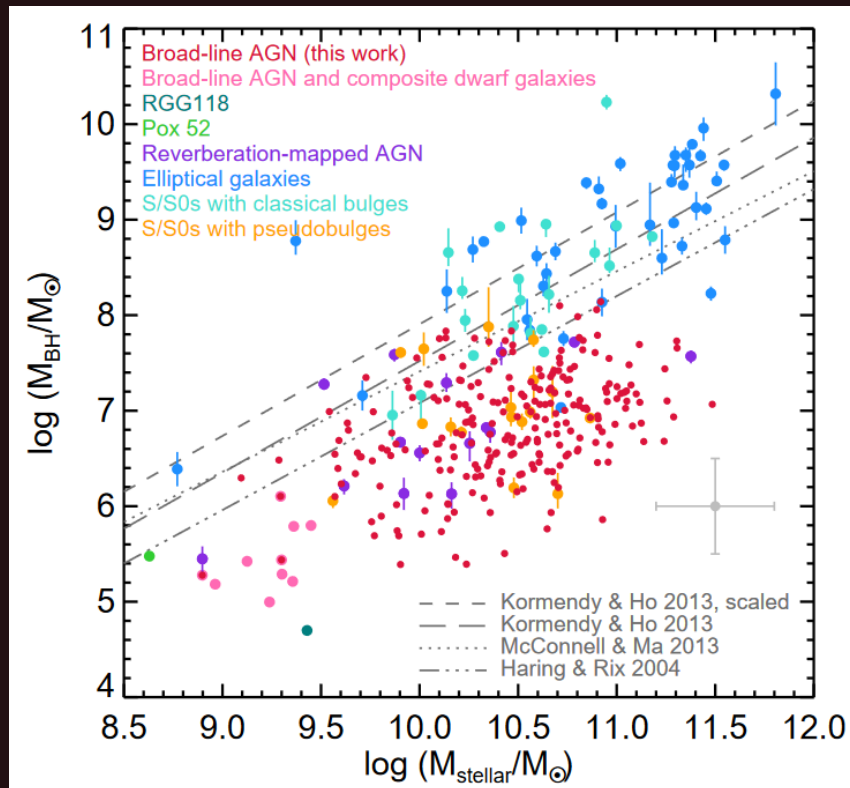
Other correlations are discussed in the literature.

Origin of black hole mass – bulge magnitude correlation

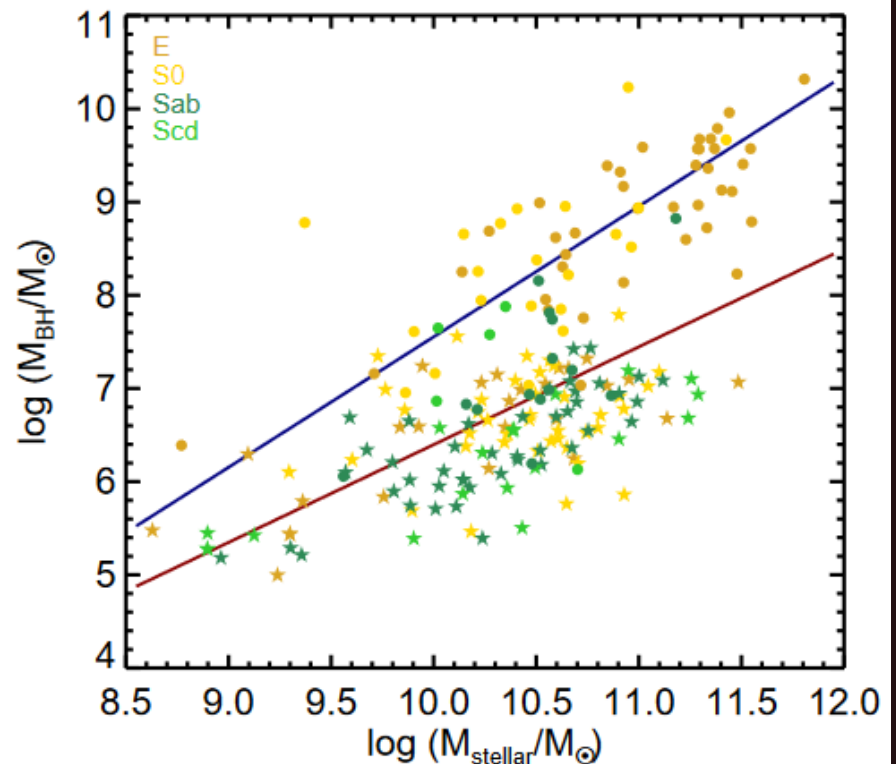


A possible evolutionary scenario in the BH mass - bulge luminosity diagram. Accretion of matter onto the central region results into enhanced star formation and BH growth. Young stellar populations cause overluminous bulges compared to inactive galaxies on the relation. BH growth and aging of the stellar populations then move the objects back onto the relation.

BH mass vs stellar mass

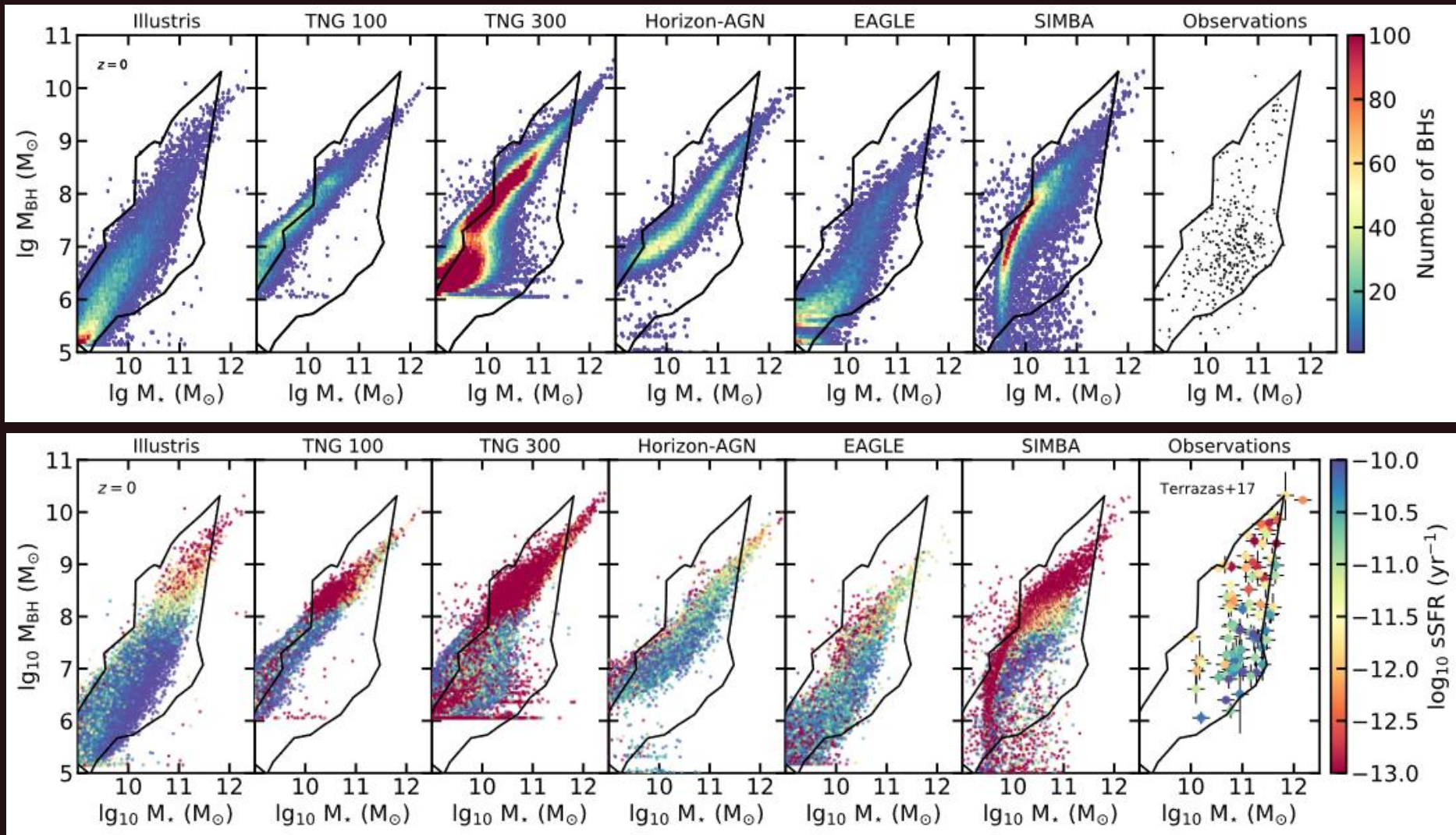


Red points – 244 AGNs.



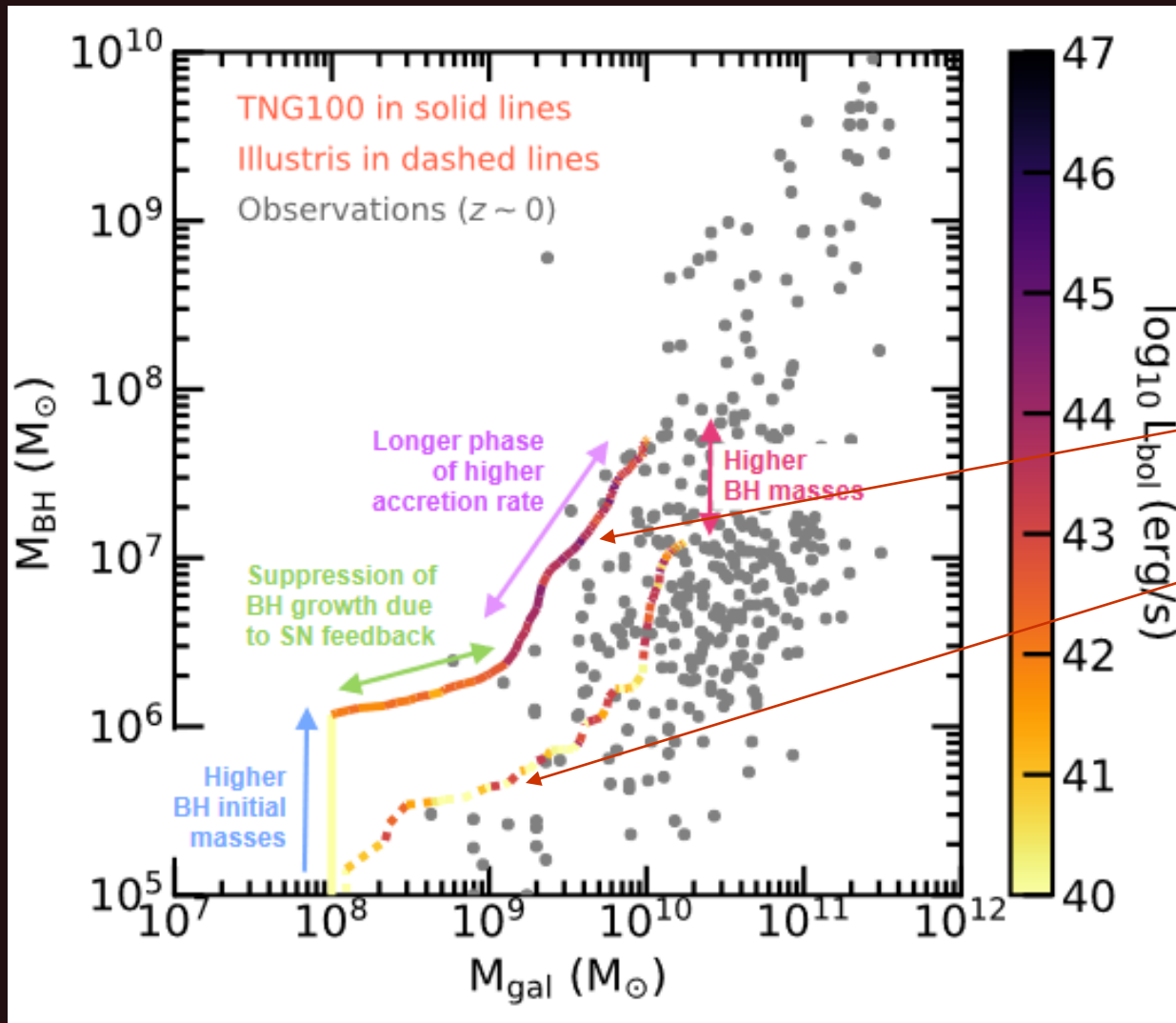
Numerical modeling

$z=0$



2006.10094

Different mass growth of SMBHs

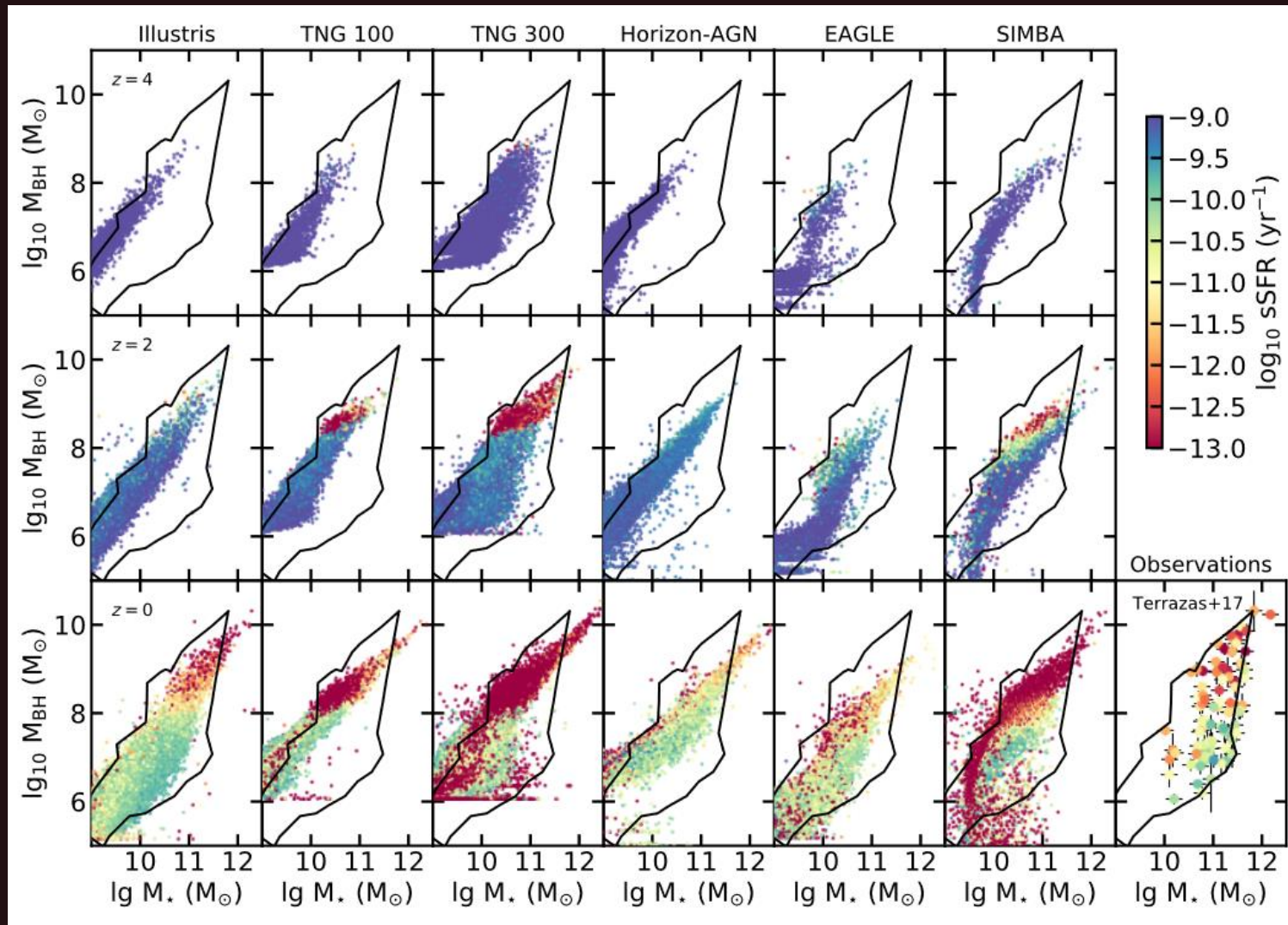


TNG

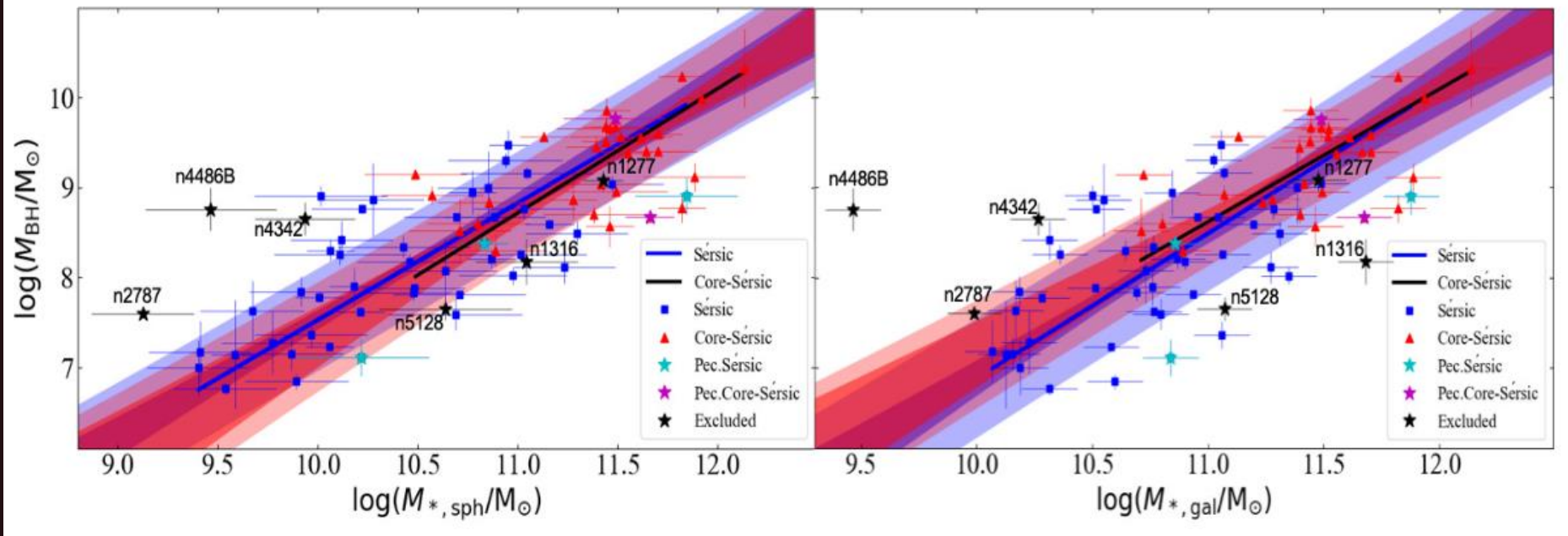
Illustris

In TNG initial mass of a BH is larger, and SN feedback is stronger.

Evolution in different models

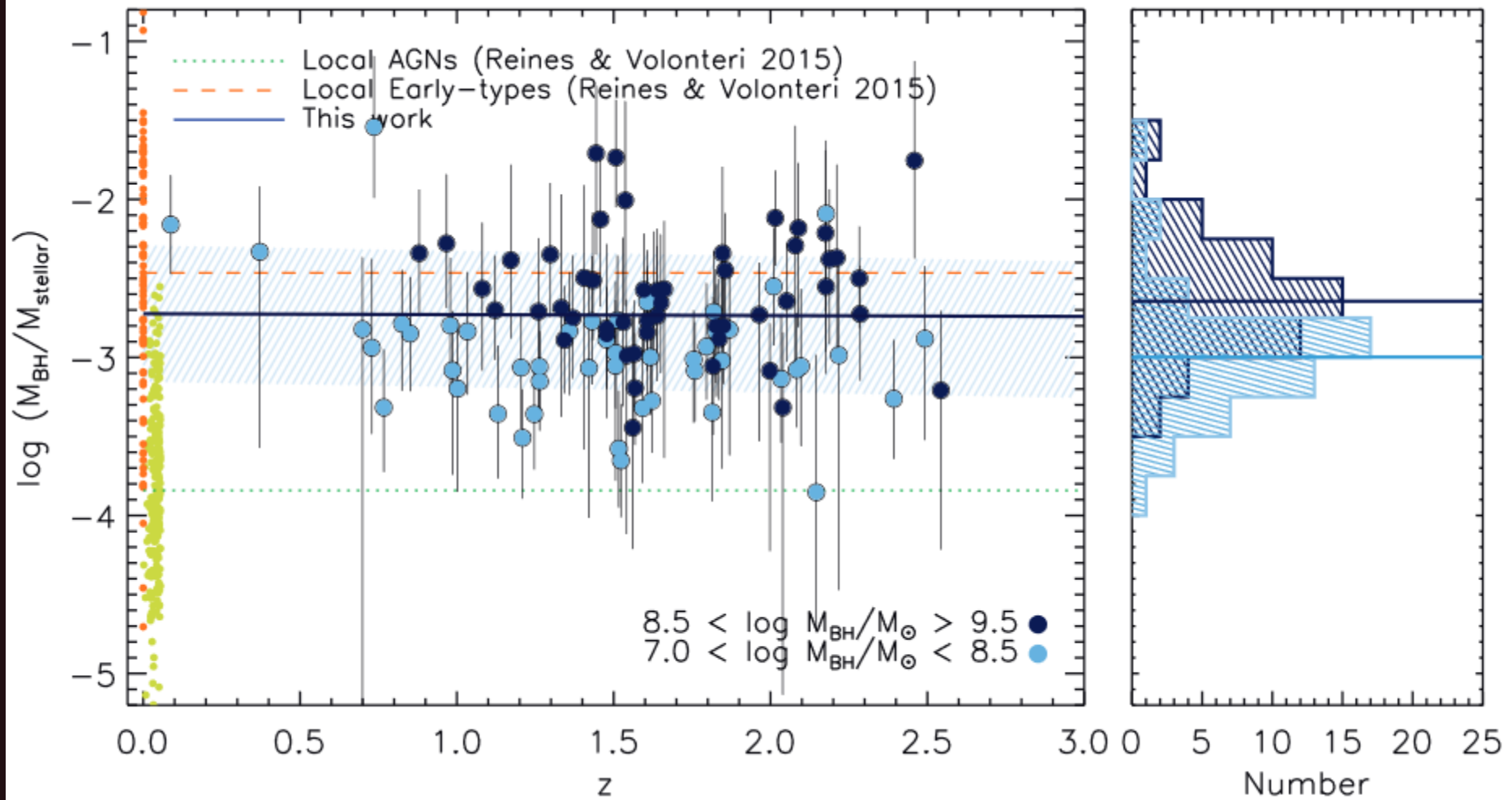


Scaling relations for early type galaxies

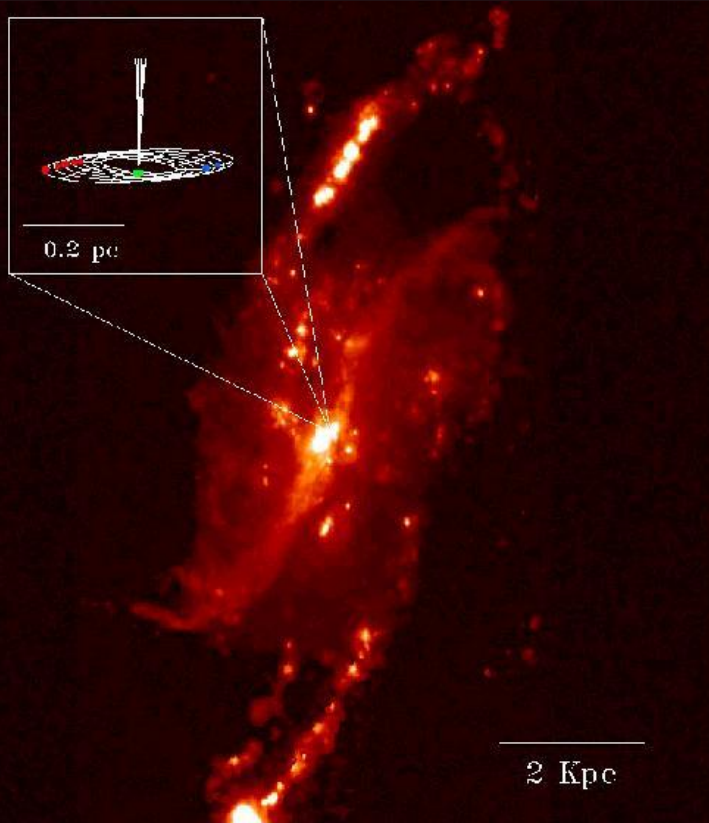


The authors studies correlations for different subsamples of early type galaxies.

$M_{\text{bh}} - M_{\text{stellar}}$ vs. redshift



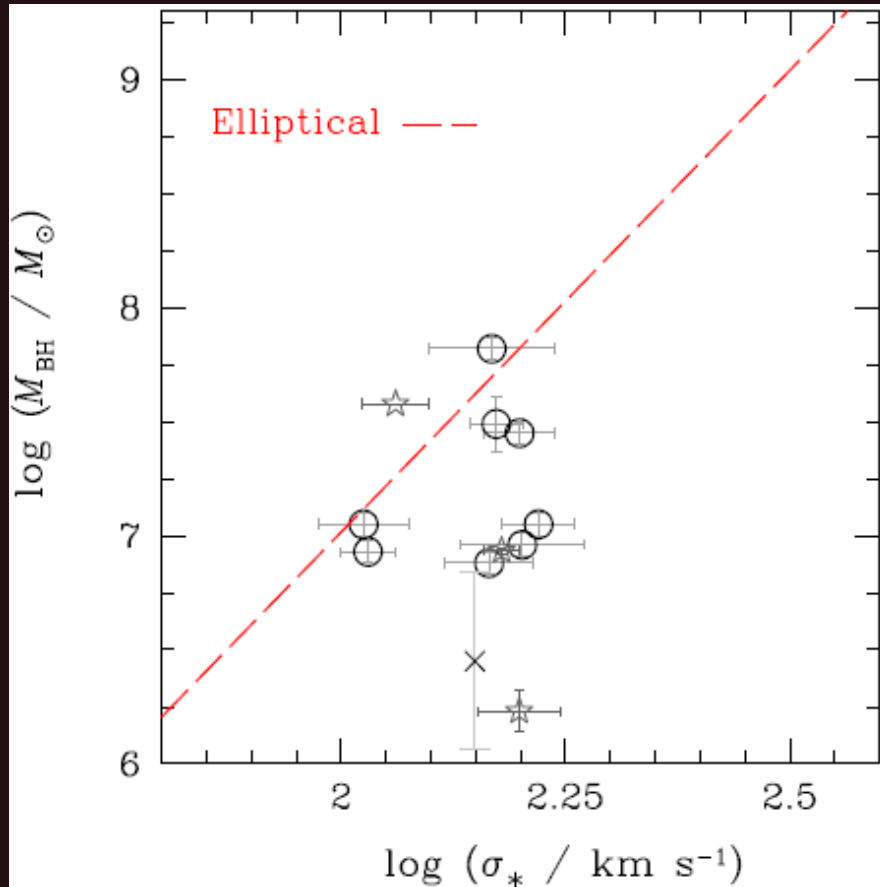
Masers



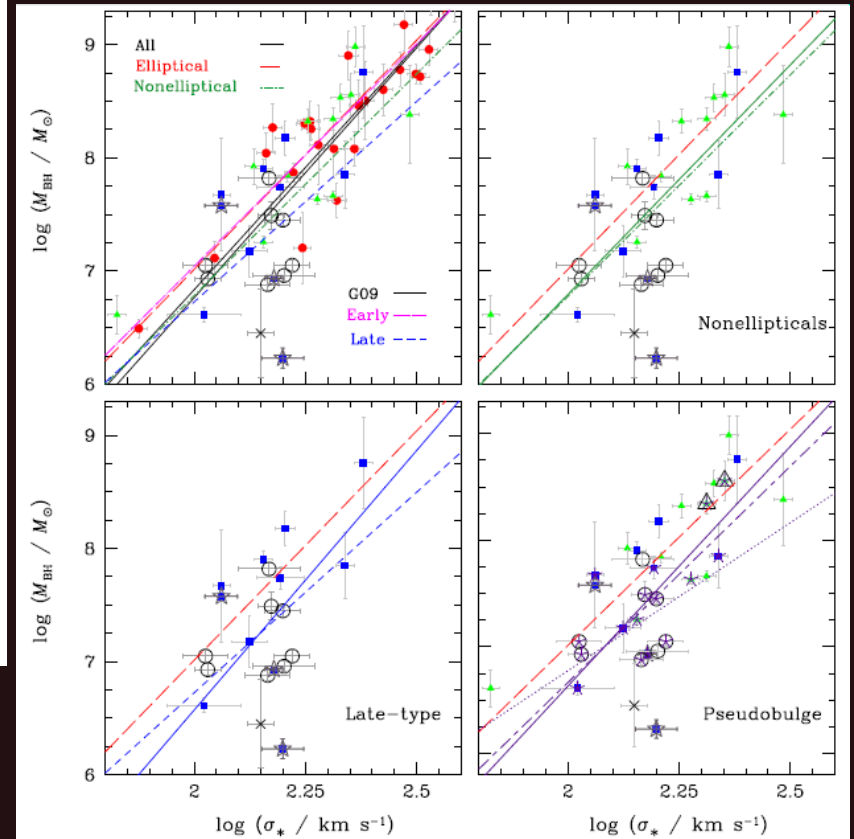
Observing movements of masers in **NGC 4258** it became possible to determine the mass inside 0.2 pc.
The obtained value is 35-40 million solar masses.

This is the most precise method of mass determination.

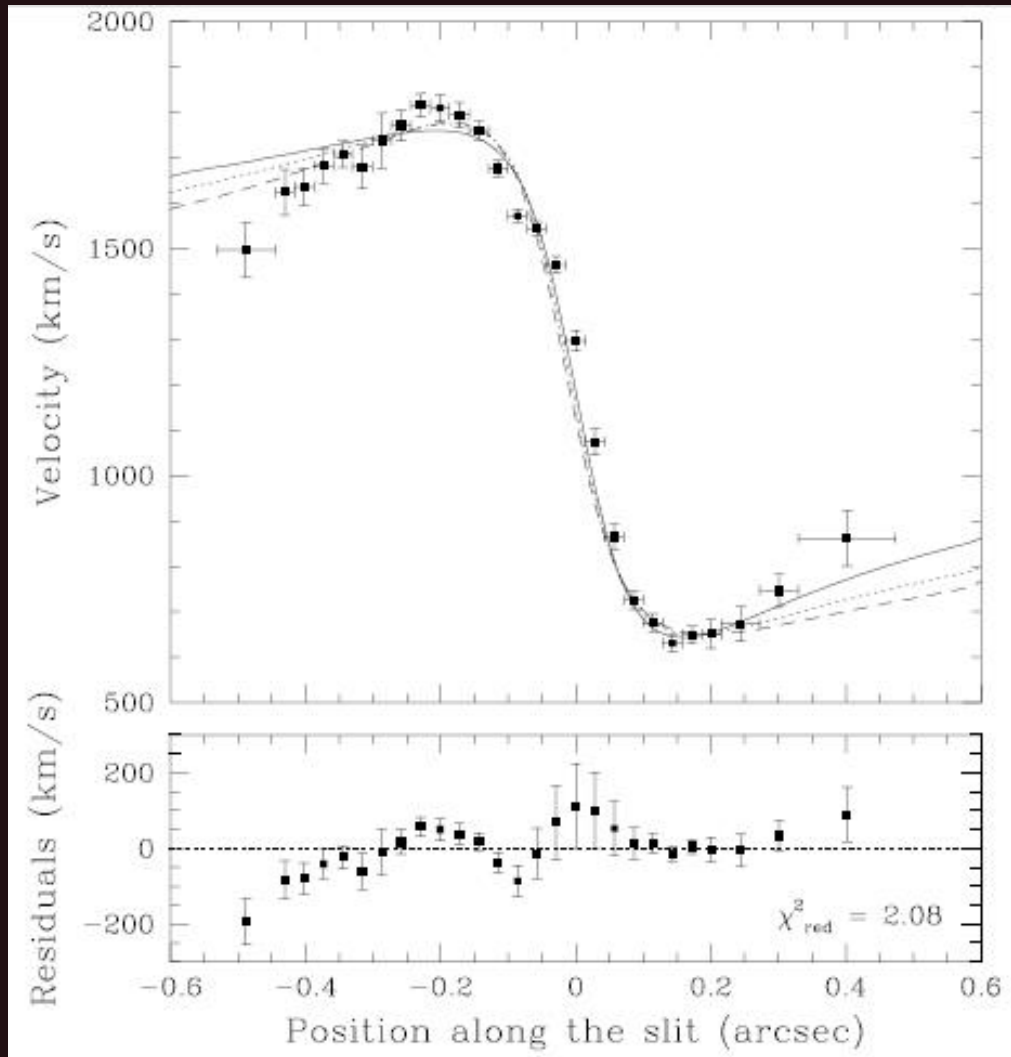
Several more megamaser measurements



Circles – new measurements,
stars – from the literature.



Gas kinematics



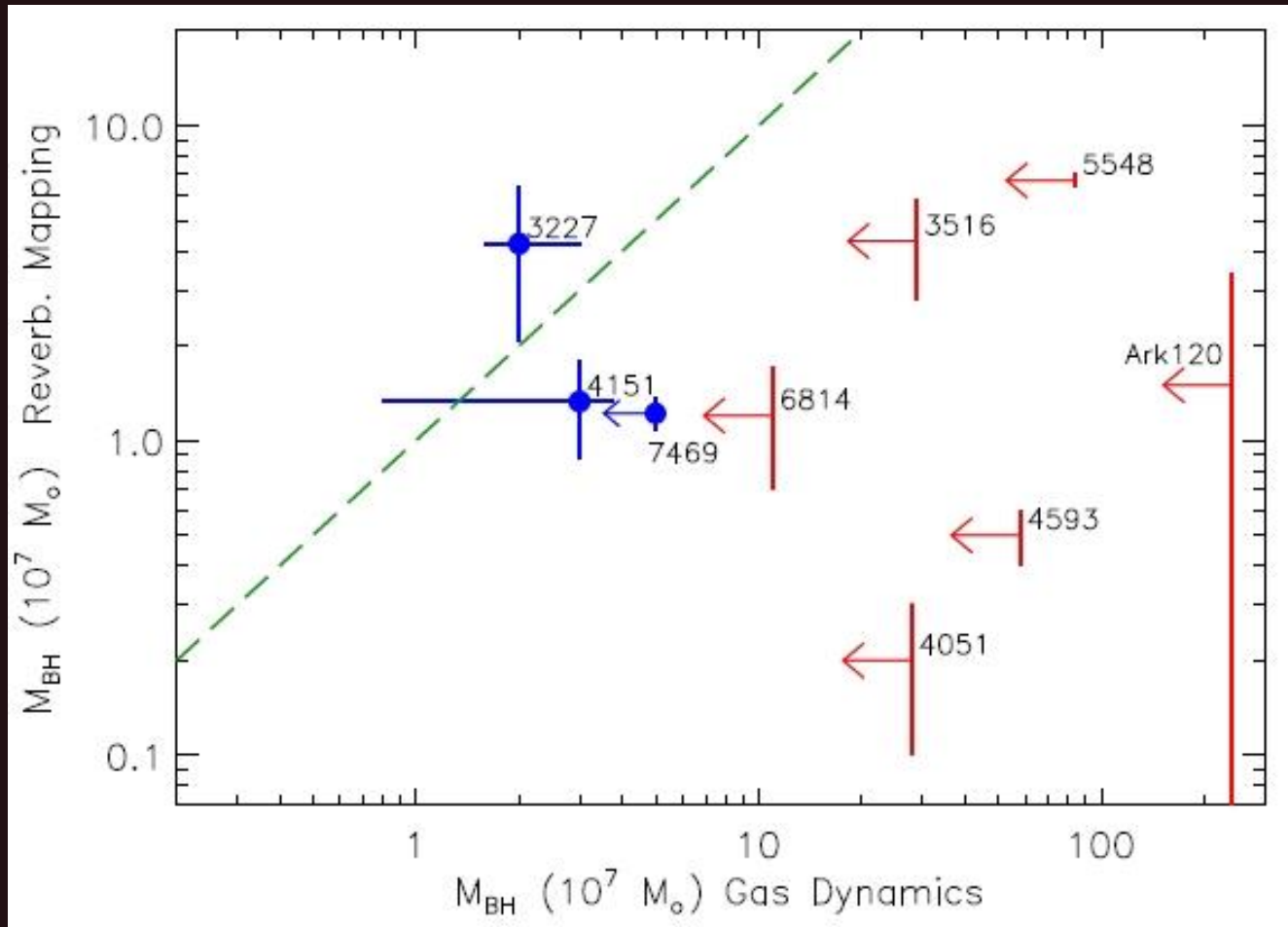
For M87 gas velocities were measured inside one milliarcsecond (5pc).

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

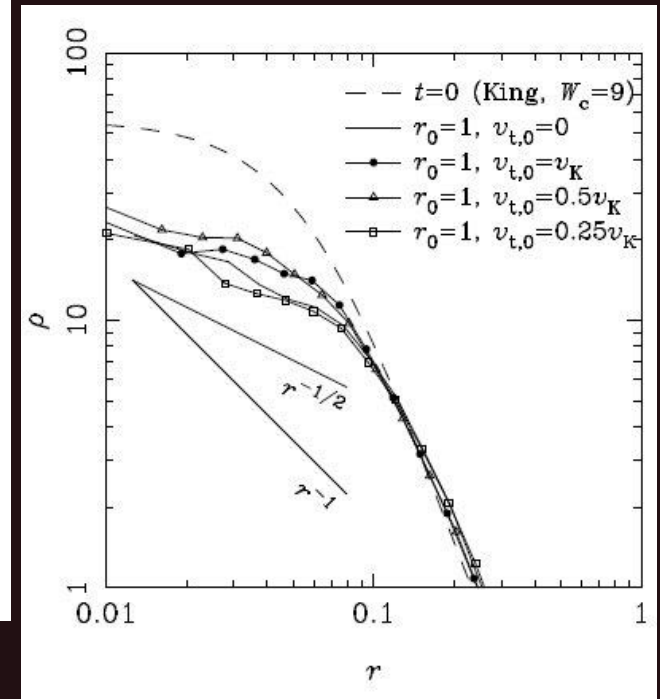
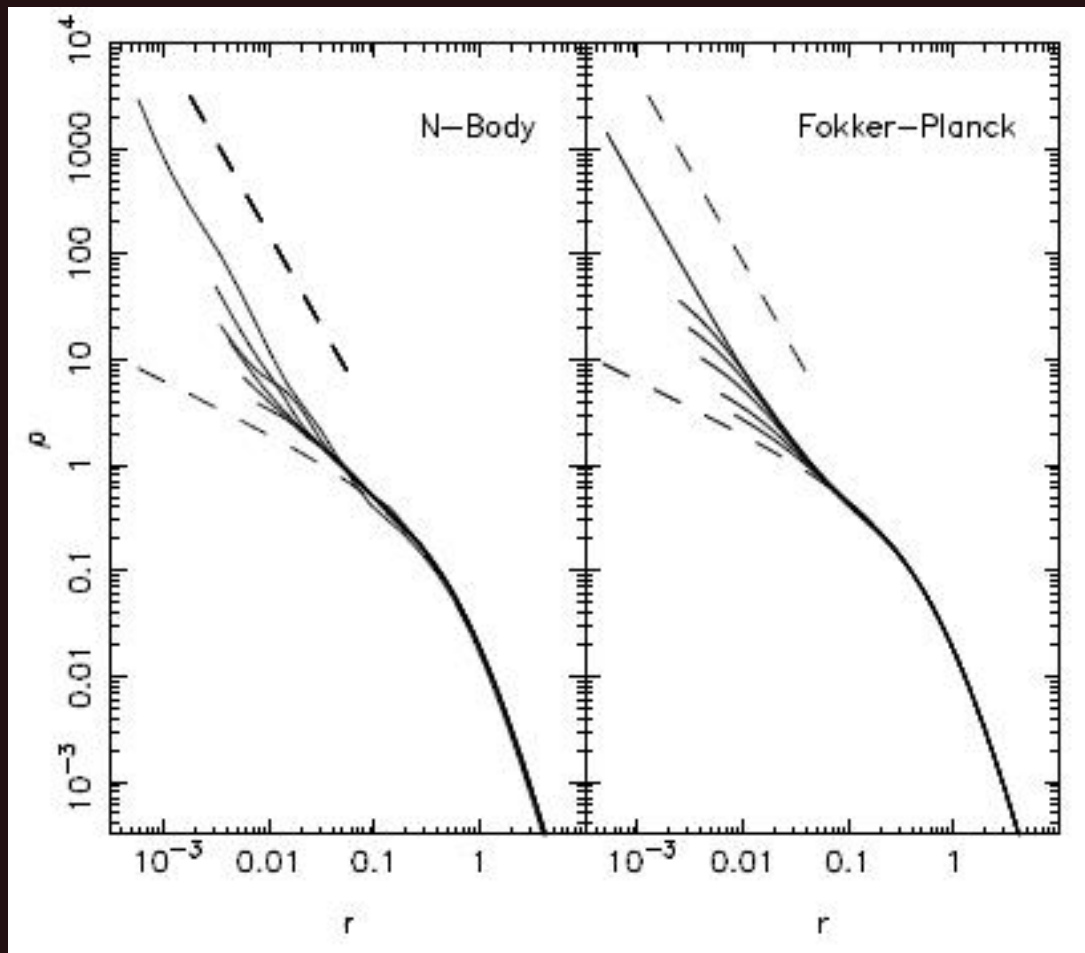
Giant elliptical galaxy NGC4649.

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



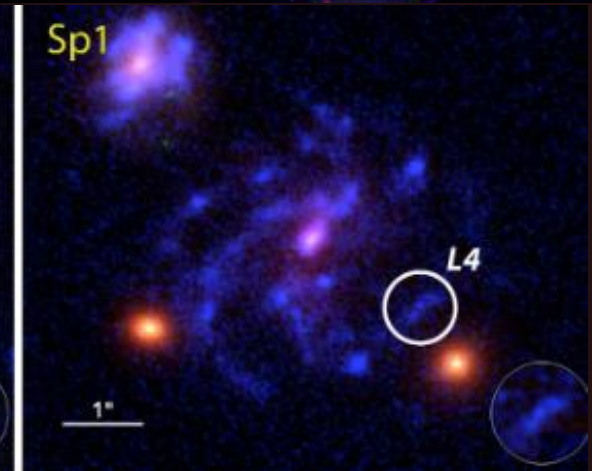
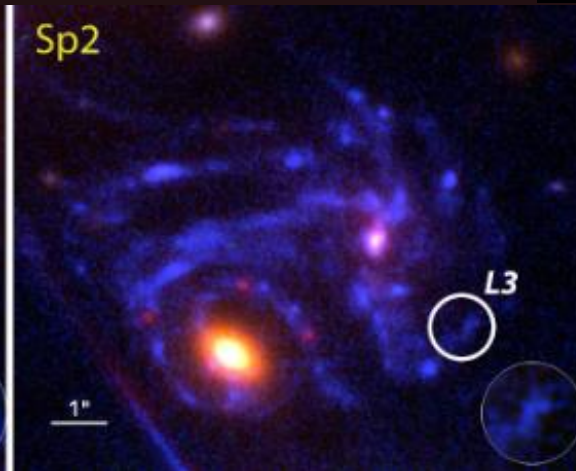
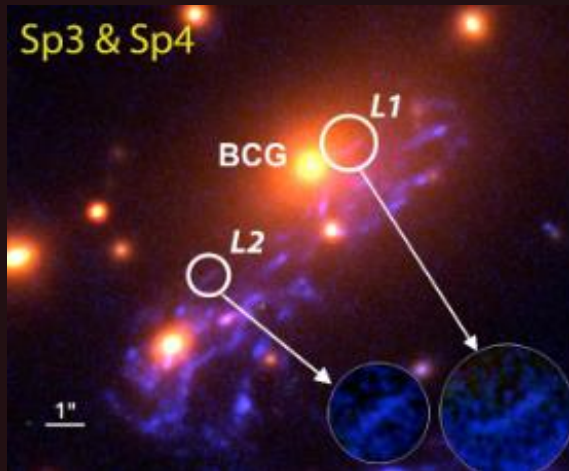
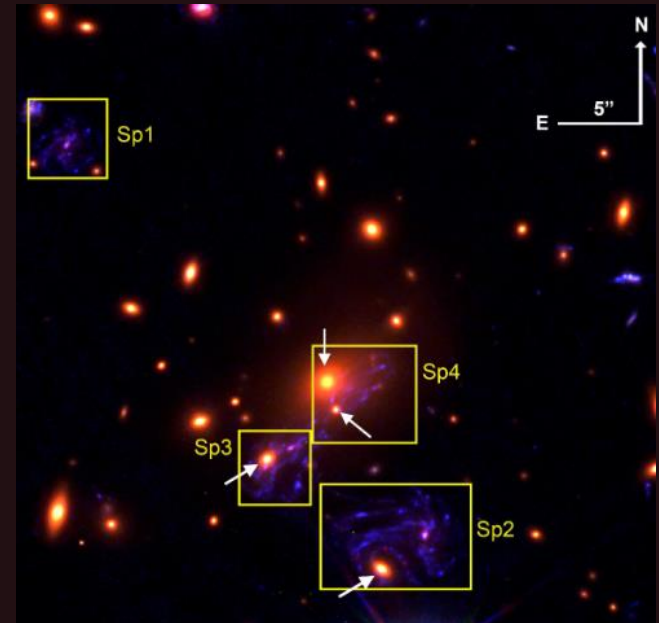
Gravitational lensing on a SMBH

A background galaxy is lensed by a massive galaxy. Analysis of images suggests that some features are generated by a point mass.

Fits with an off-center SMBHs are the best.

Other explanations (a compact galaxy) are still possible.

SMBH mass estimate is $\sim 7\text{-}12$ billion solar masses.



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

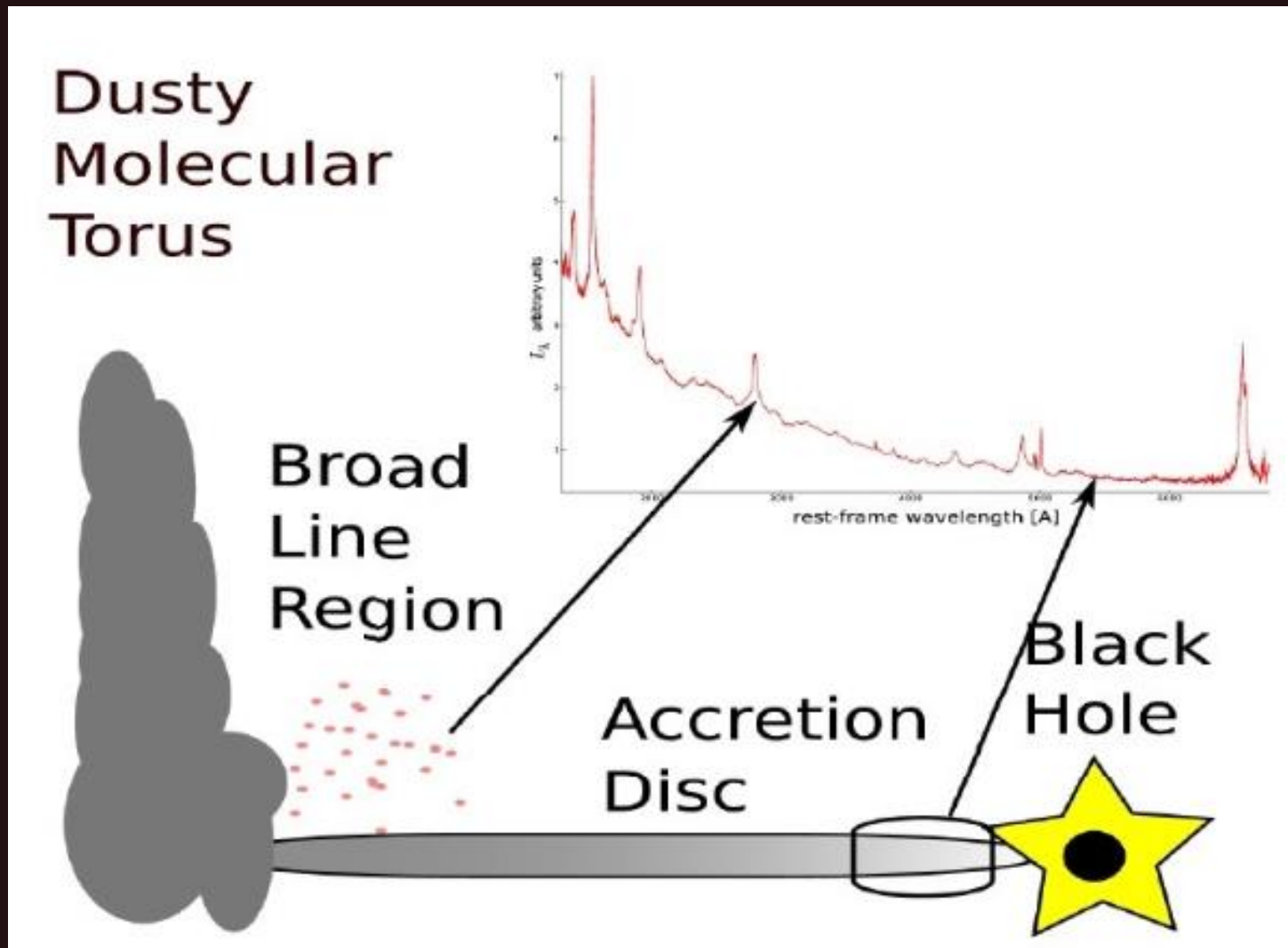
clouds velocities in BLR

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

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

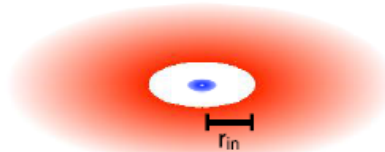
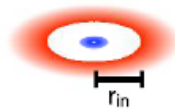
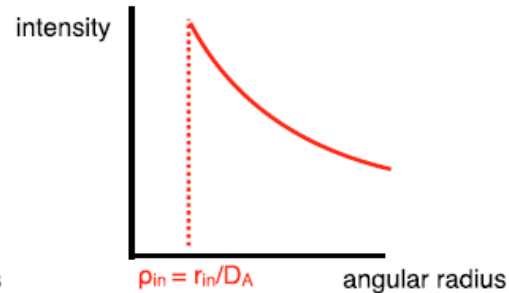
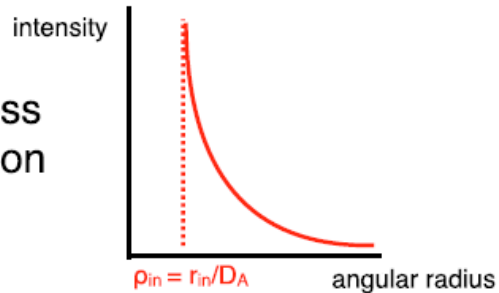
See a detailed recent example in [1104.4794](https://arxiv.org/abs/1104.4794)

General scheme

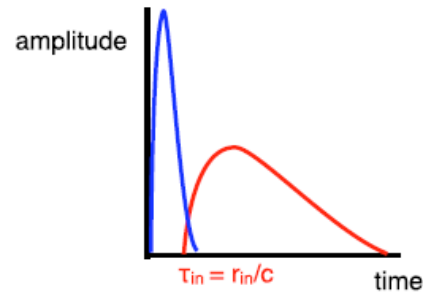
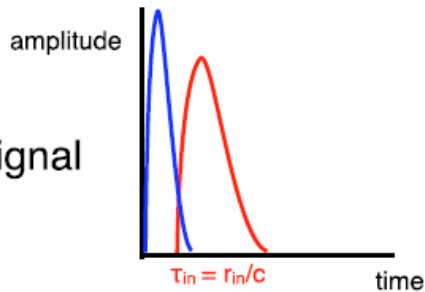


Как расстояние помогает массу измерить

(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.

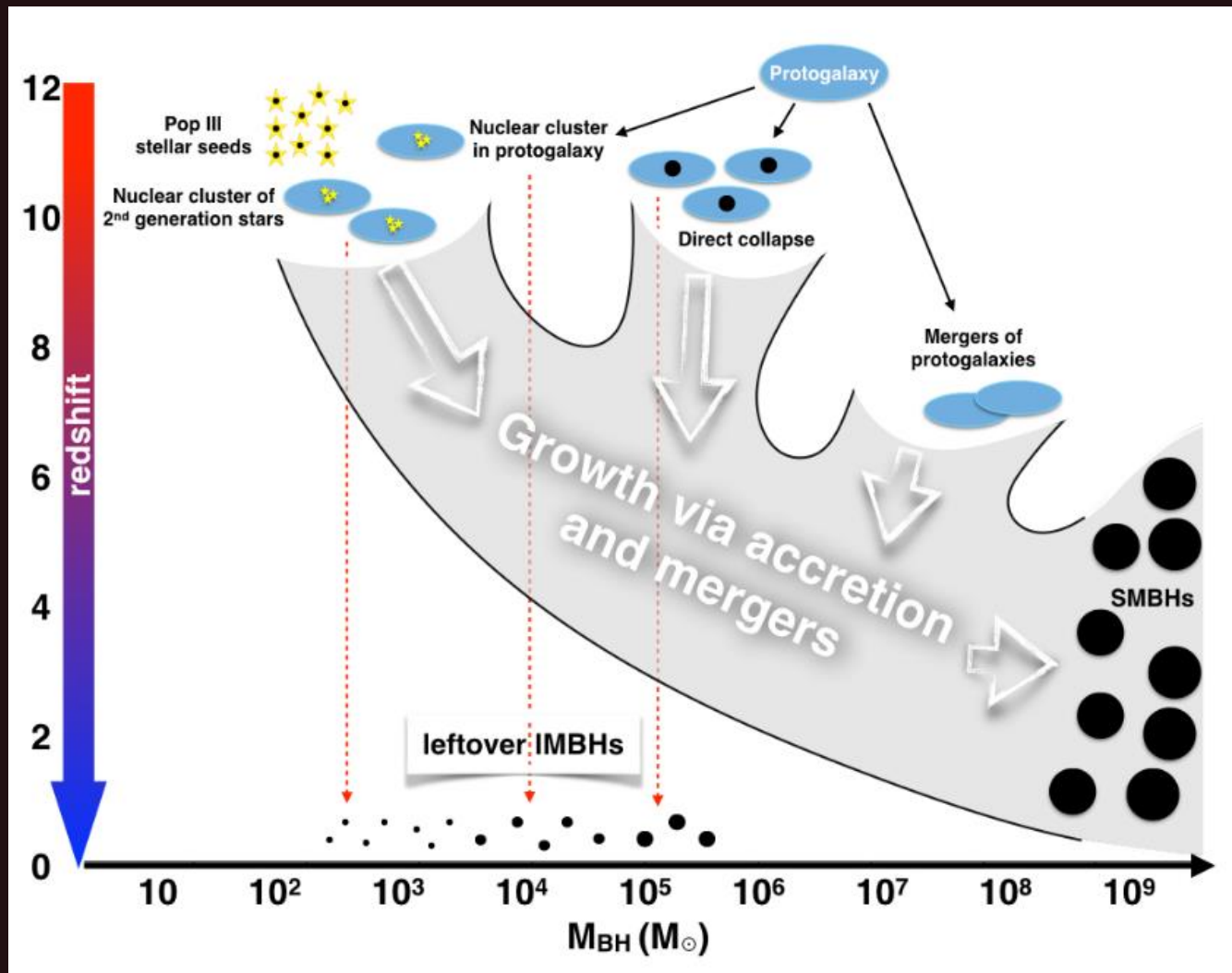
Typically, an artificial population is formed
(especially, in Monte Carlo simulations)

2. Empirical PS.

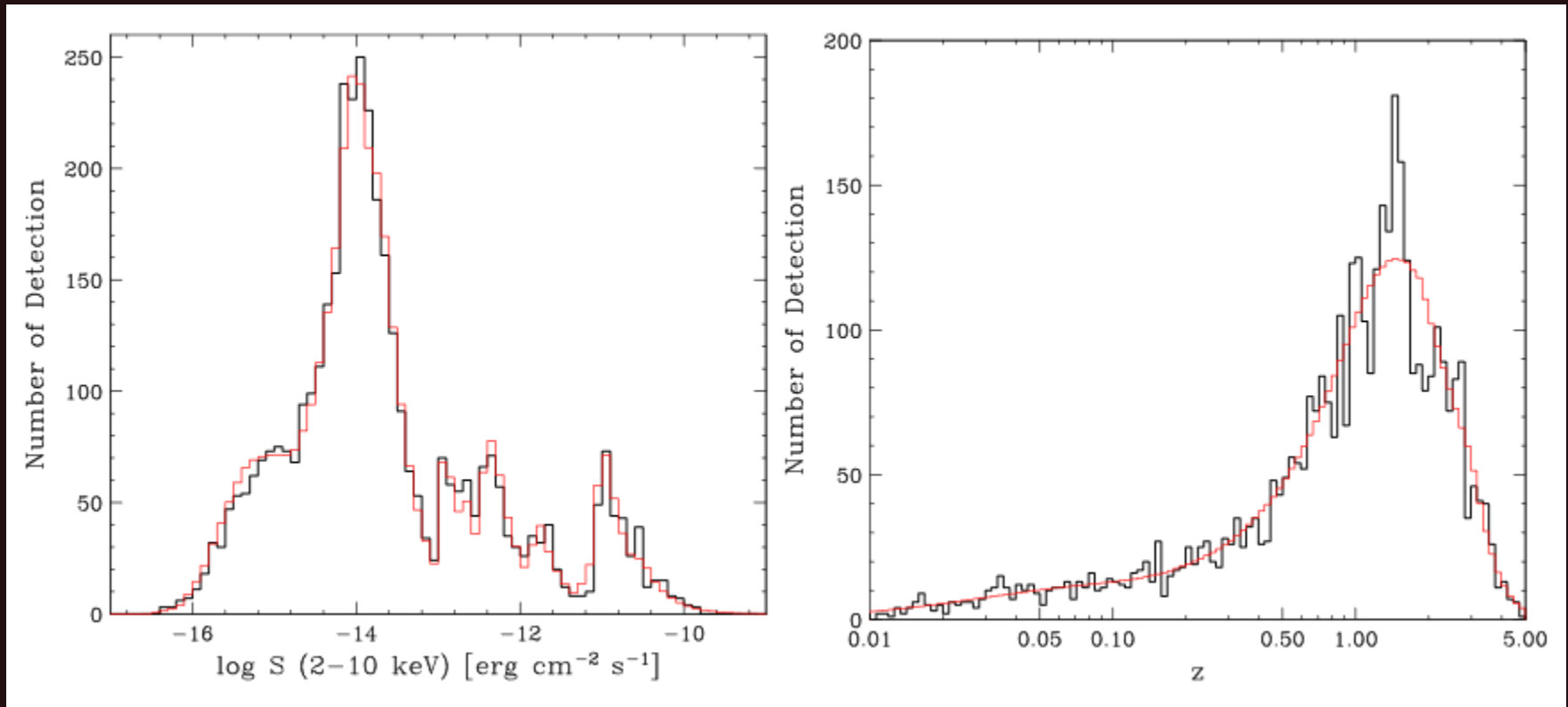
It is used, for example, to study integral properties
(spectra) of unresolved populations.

A library of spectra is used to predict integral properties.

Origin of SMBHs



X-ray background and pop. synthesis

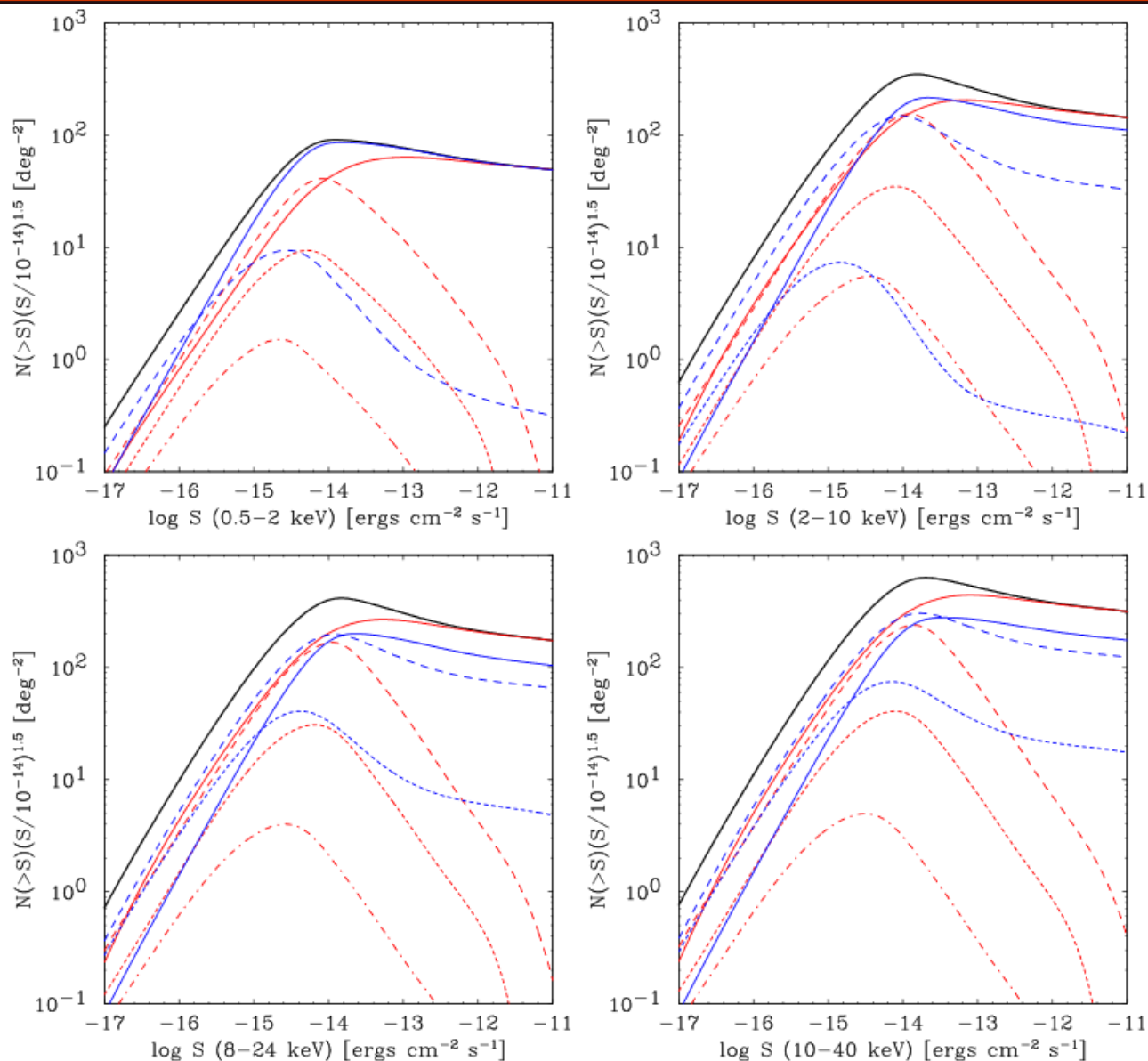


Observed histograms (thick, black) of flux (left) and redshift (right) of the authors sample compared with model predictions (thin, red).

Predicted
Log N – Log S
distributions.

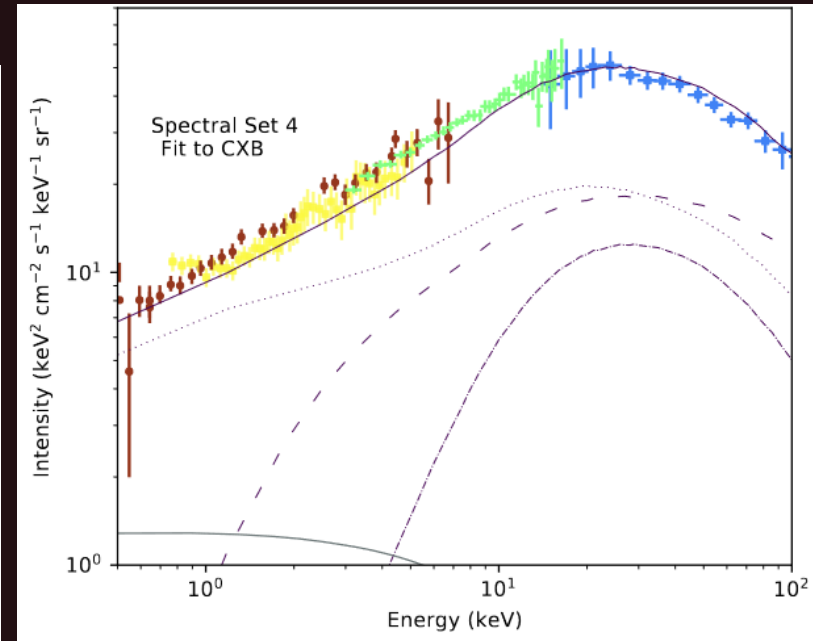
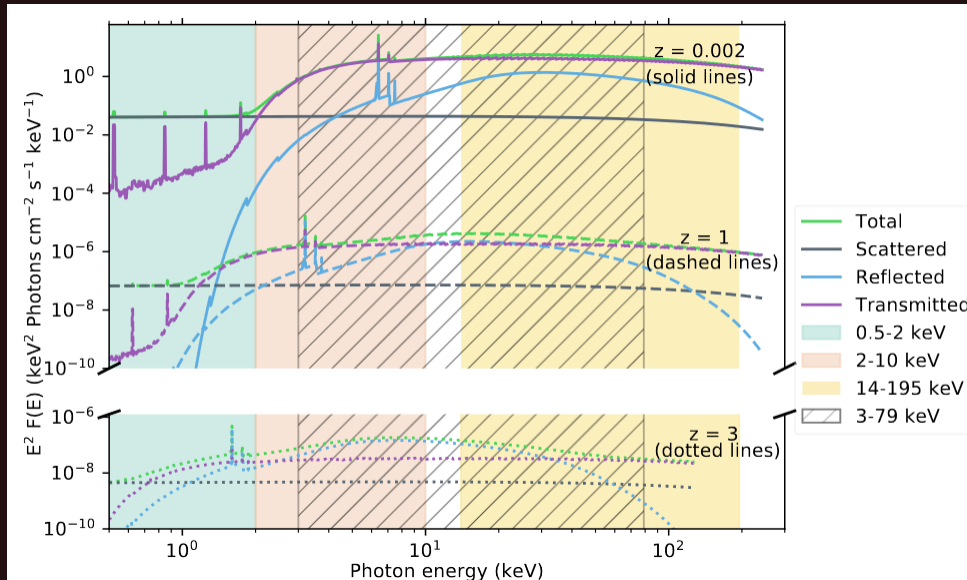
Red: different z:

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

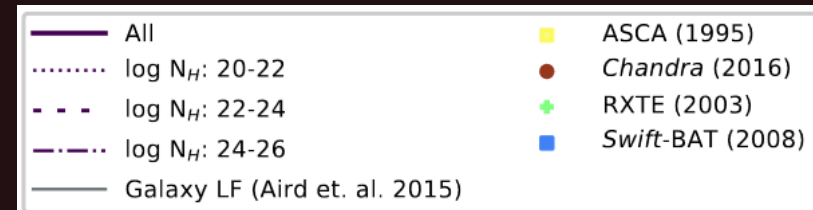


X-ray spectra of AGNs

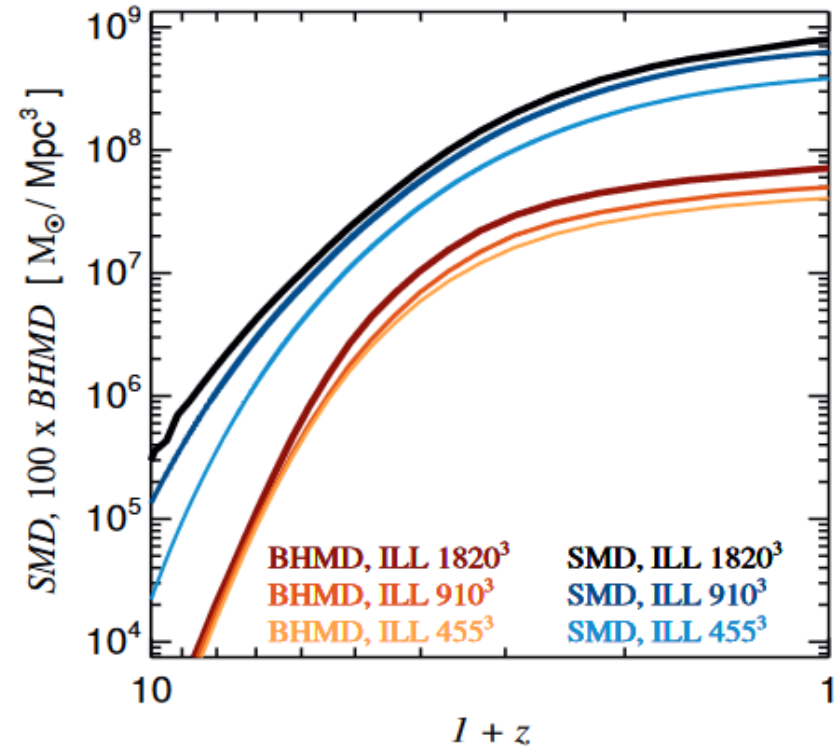
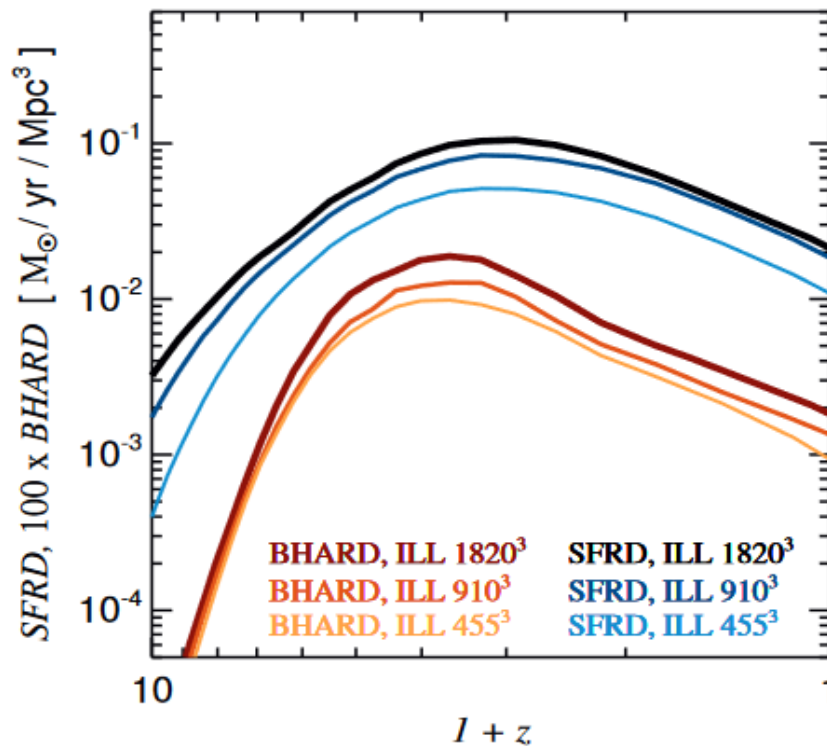
New population synthesis



50±9% (56±7%) of all AGN within $z \sim 0.1$ (1.0) are Compton-thick.



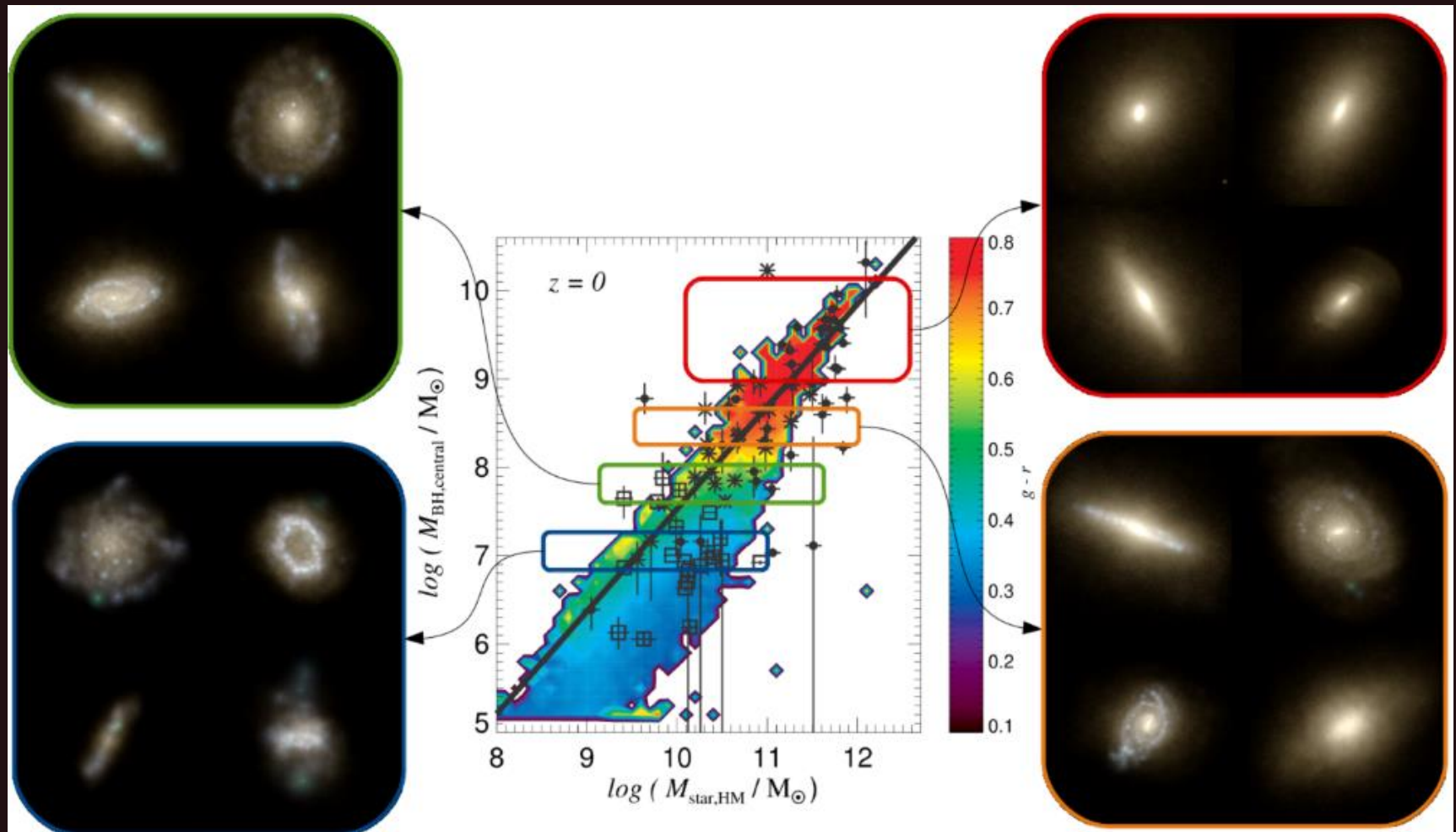
Illustris calculations



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.

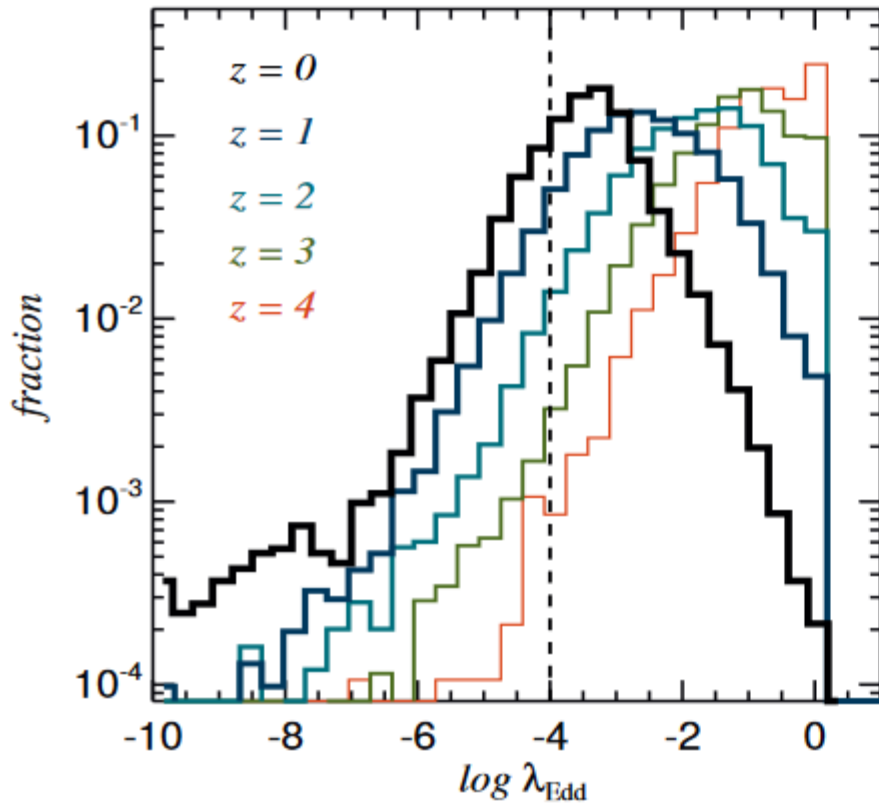
Stellar mass density and black hole mass density as a function of cosmic time

Illustris simulations

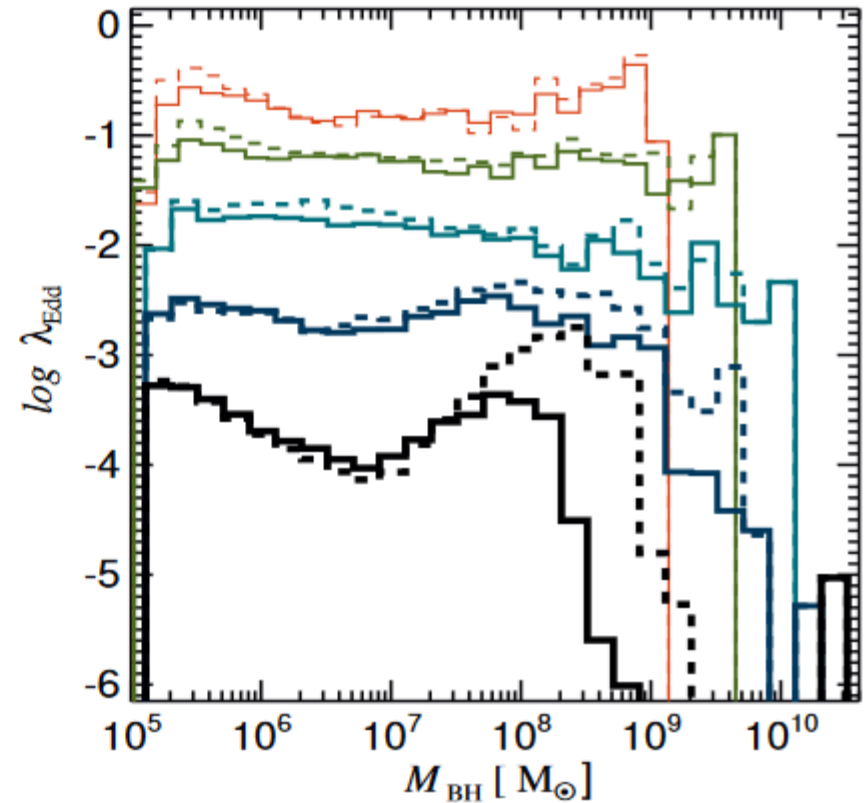


Stellar half-mass of all galaxies at $z=0$ versus their central black hole mass

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.

