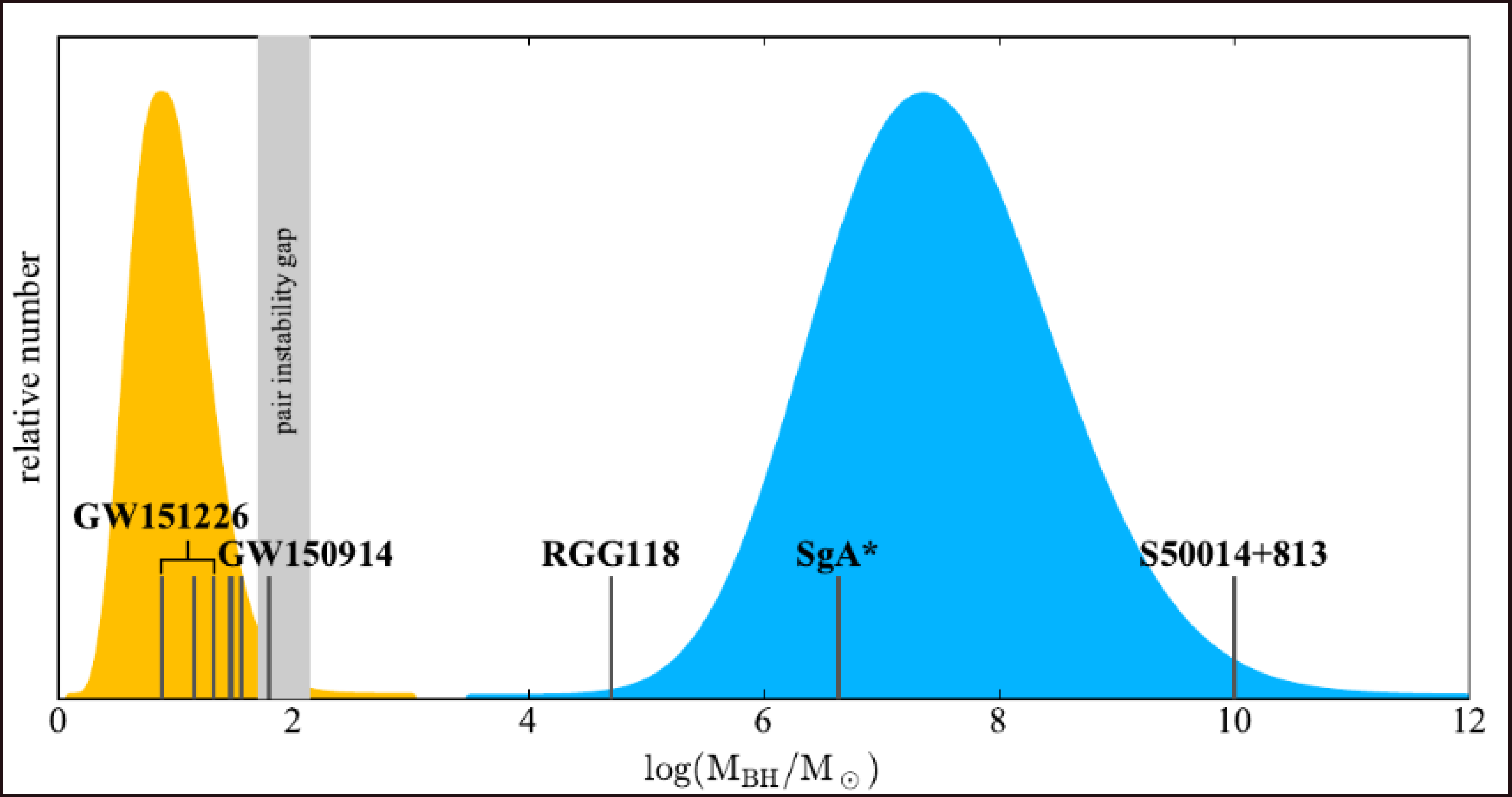
Supermassive black holes

Black hole masses



1807.11489

Plan of the lecture

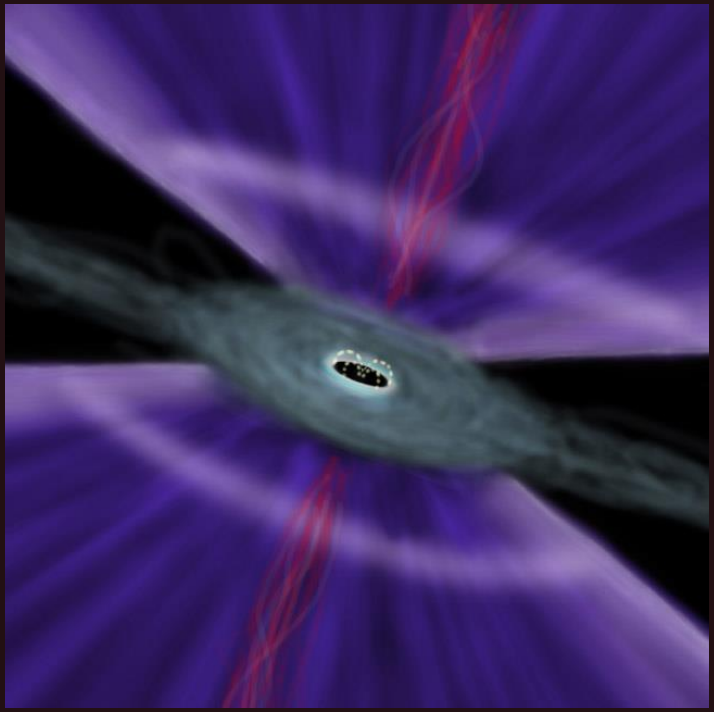
1. General information about SMBHs.
2. “Our” certain black hole: Sgr A*.
3. SMBHs: from radio to gamma. AGNs.
4. Mass measurements

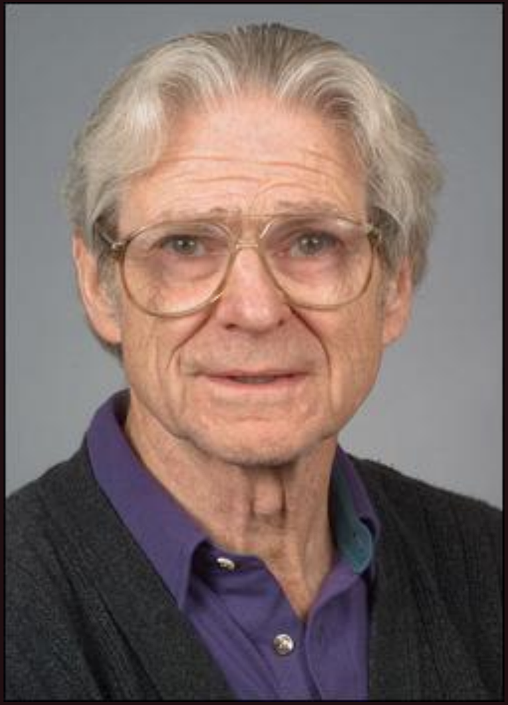
Main reviews

- arxiv: 1609.03562 **Observations of AGNs**
- 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, 2311.12118 **Intermediate-Mass Black Holes**
- arXiv: 1707.07134 **AGN**
- arXiv: 1911.12176 **Unification model**
- arXiv: 2302.02431 **Sgr A***
- arXiv: 1906.00873, 2108.03966 **Black hole shadow**

Some history

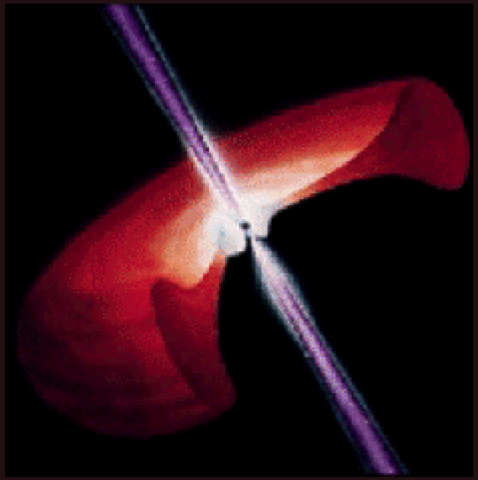
The story starts in 60-s when the first quasars have been identified (Schmidt 1963). Immediately the hypothesis about accretion onto supermassive BHs was formulated (Salpeter, Zeldovich, Novikov, Linden-Bell).



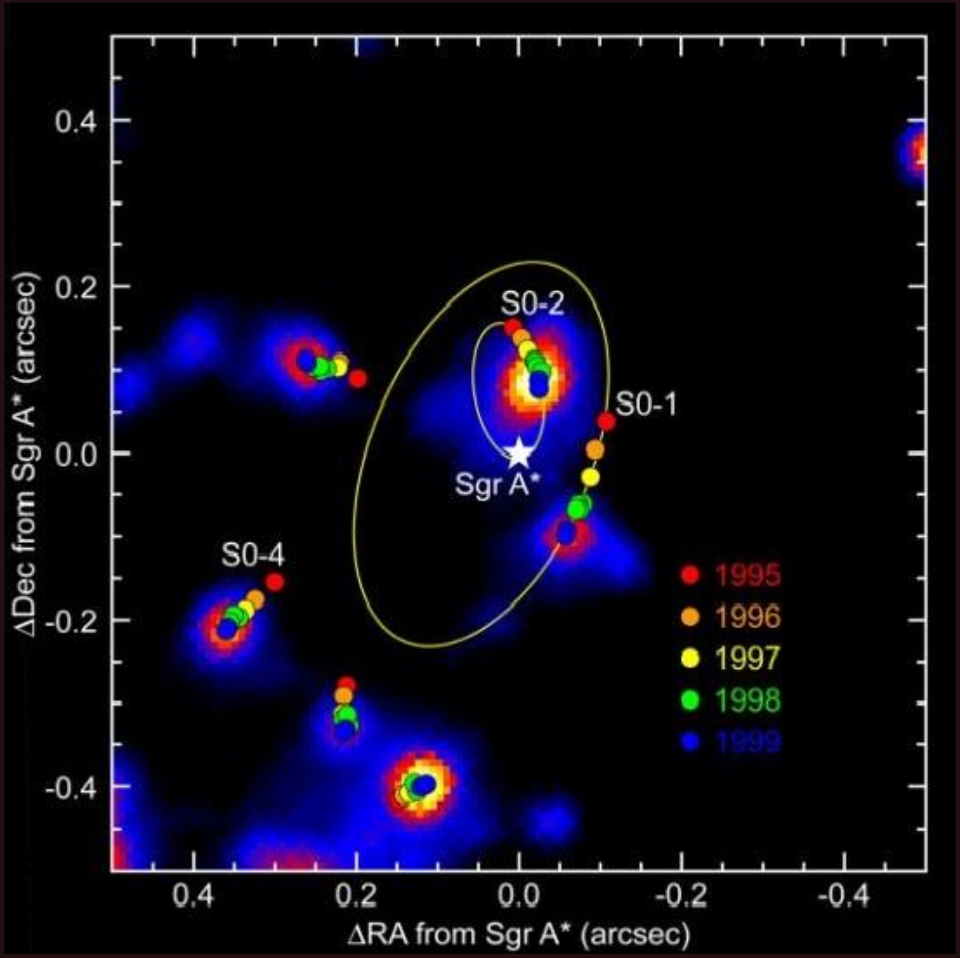


General info

• All galaxies with significant bulges should have a SMBH in the center.
• SMBH are observed already at redshifts z ~ 10 and even further
• Several percent of galaxies have active nuclei
• Now we know tens of thousands of quasars and AGNs,
all of them can be considered objects with SMBHs
• Measured masses of SMBHs are in the range ~10^6 – 10^{10} solar masses.
• Masses are well-measured for many tens of objects.
• The most clear case of an 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.

A review: arXiv: 1501.02171 **The Galactic Center Black Hole Laboratory**

The region around Sgr A*

(Park et al.; Chandra data)
astro-ph/0311460

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 (approximatelly 40 to 40 pc).

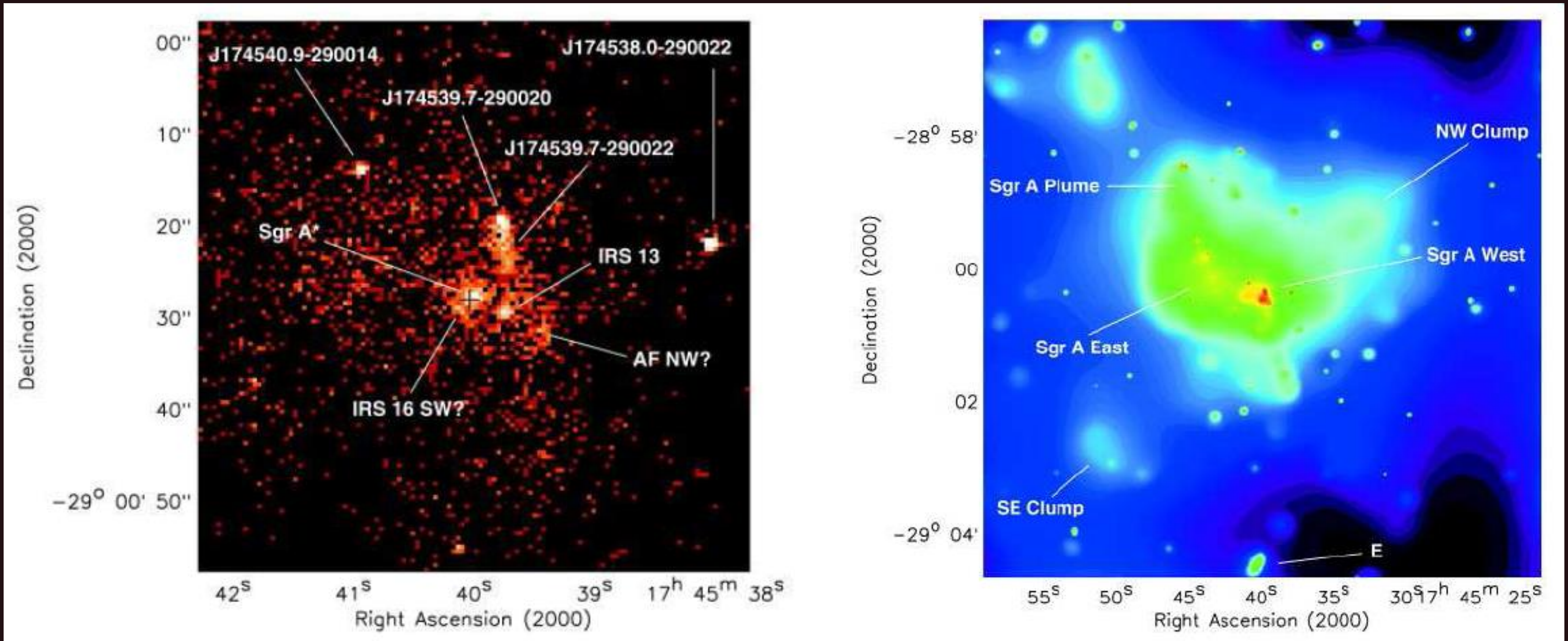
Multiwavelength observations of Sgr A* are summarized in 1501.02164.

A review: arxiv:1311.1841 **Towards the event horizon – the supermassive black hole in the Galactic Center**

A closer look

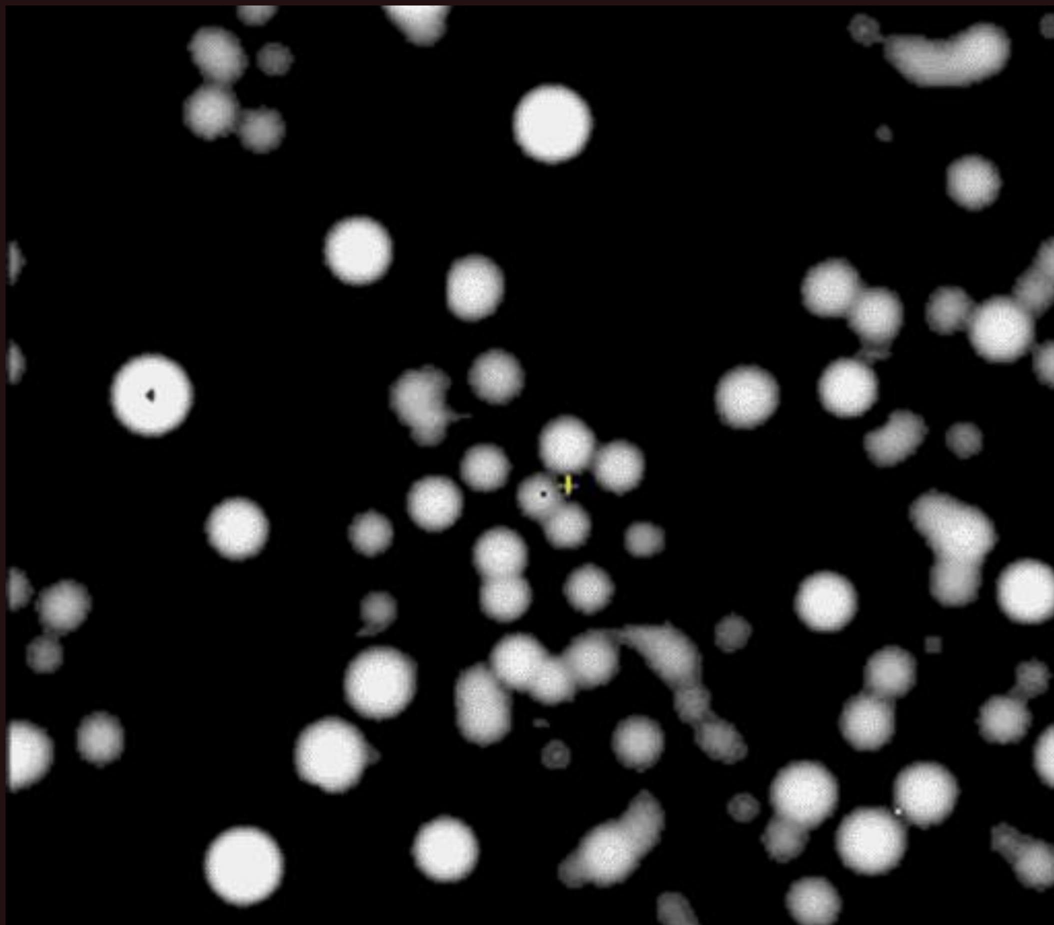
Chandra. 2-10 keV

2.4 pc   20 pc



1007.4174

Stellar dynamics around Sgr A*

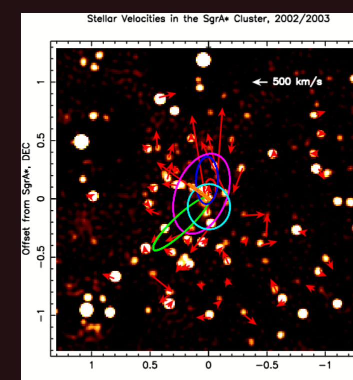


(APOD A. Eckart & R. Genzel)

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

The BH mass estimate is ~4 10^6 M_0

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



See more data in 0810.4674

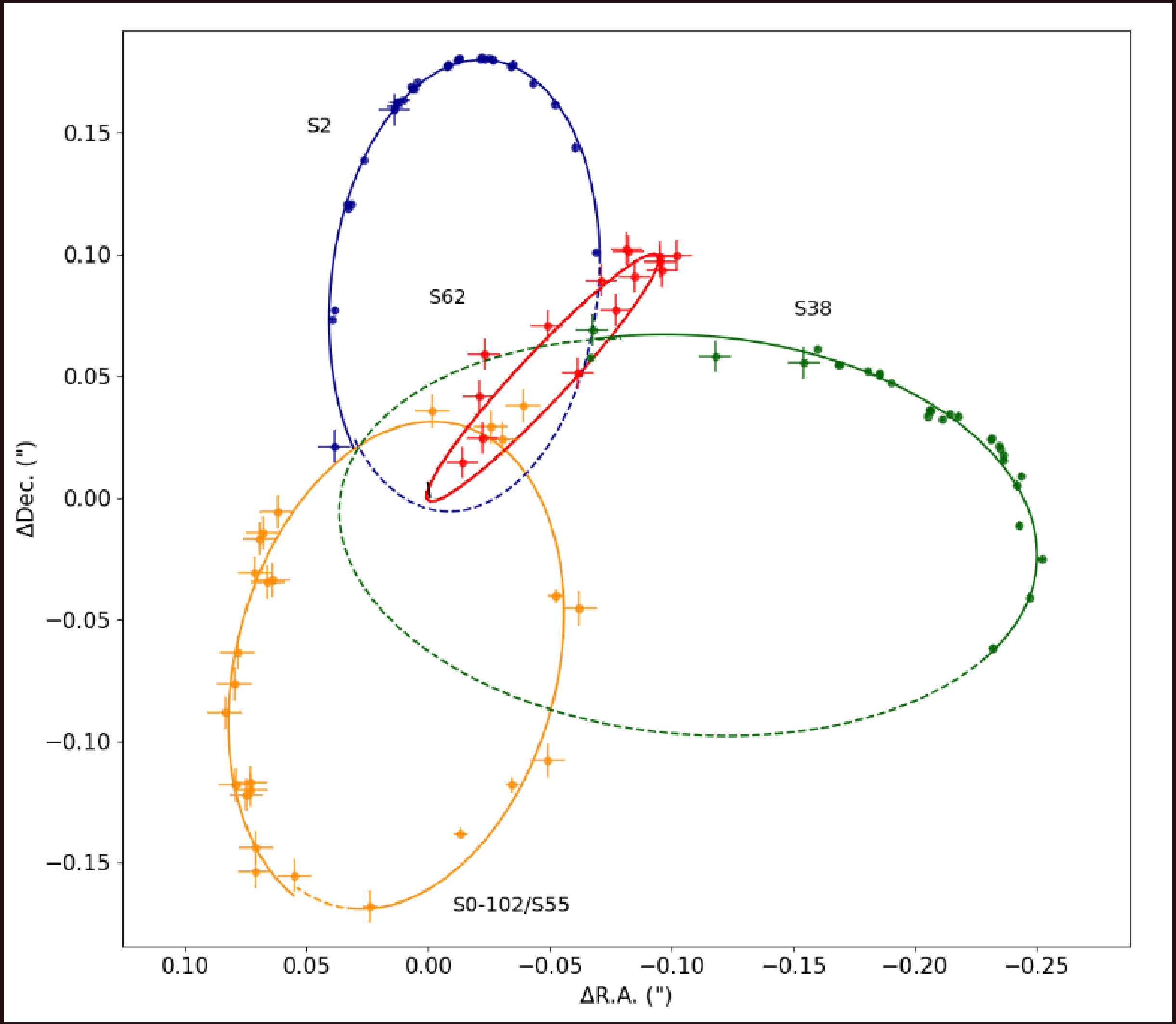
Stars-star interactions can be important: arXiv 0911.4718

S62. Just ten years.

2 solar masses.

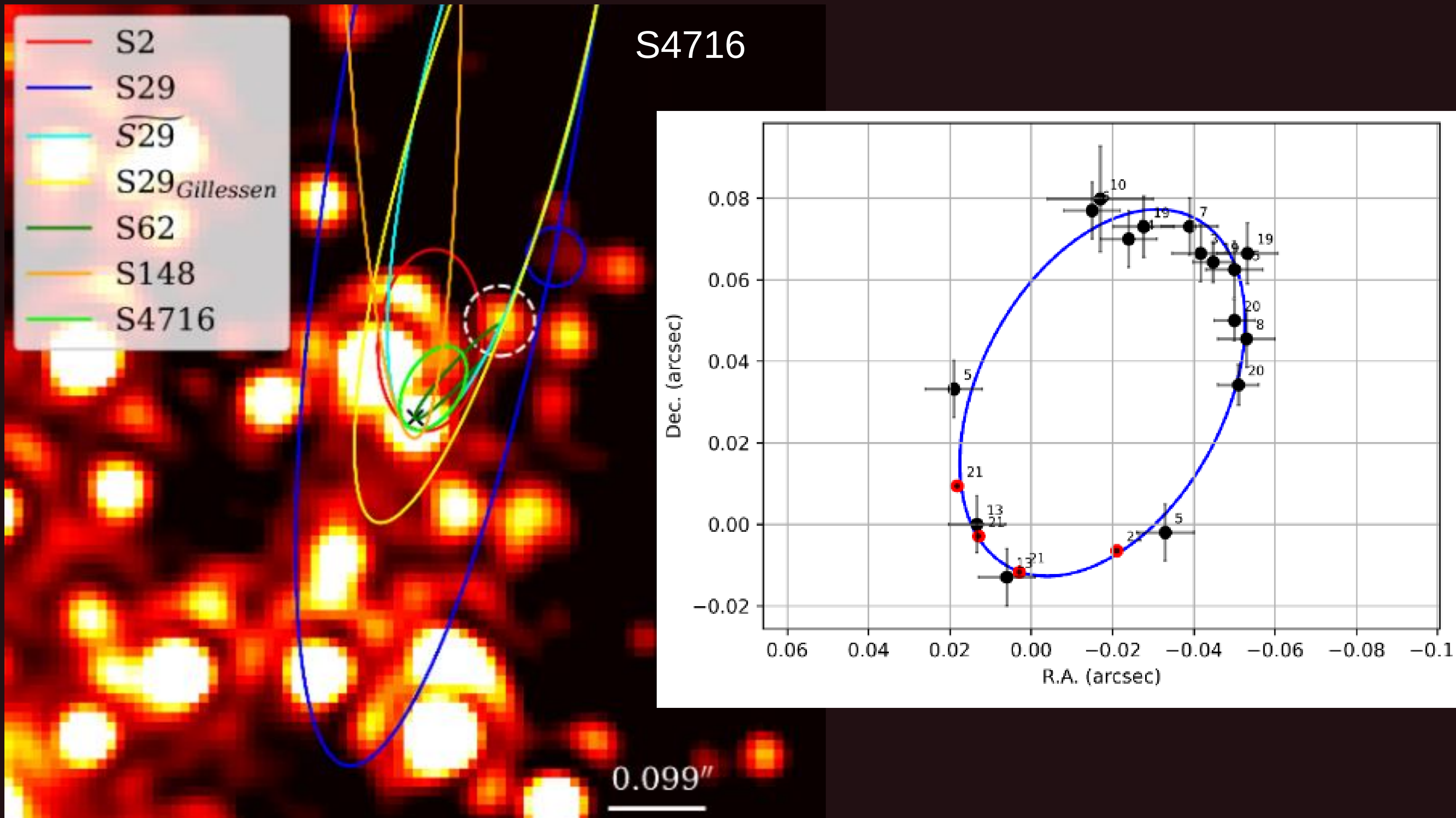
Porb=9.9 years
e=0.976

a_p=215 Rsh



2002.02341

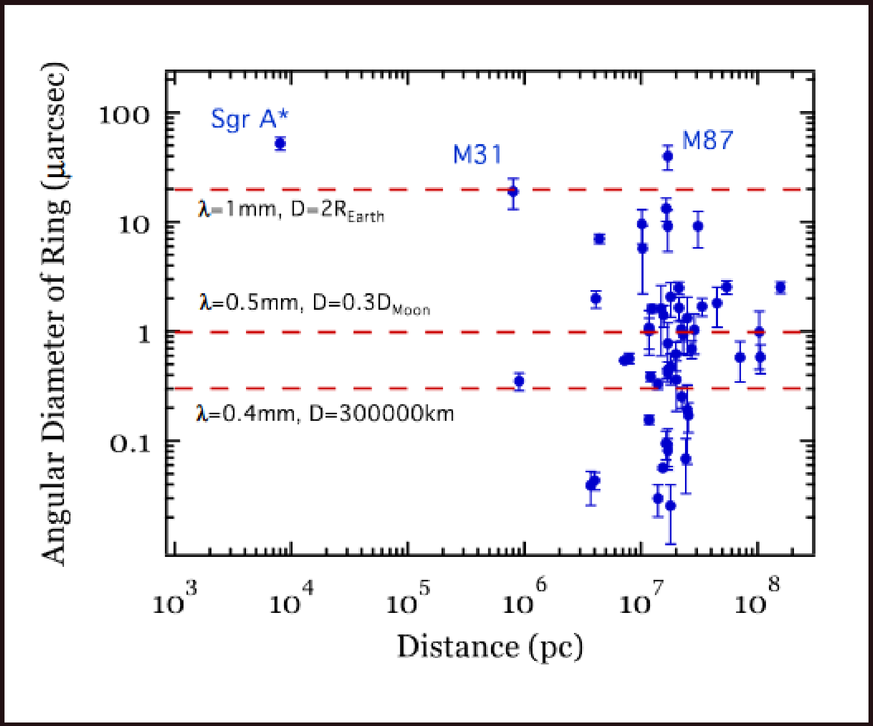
4-year orbit

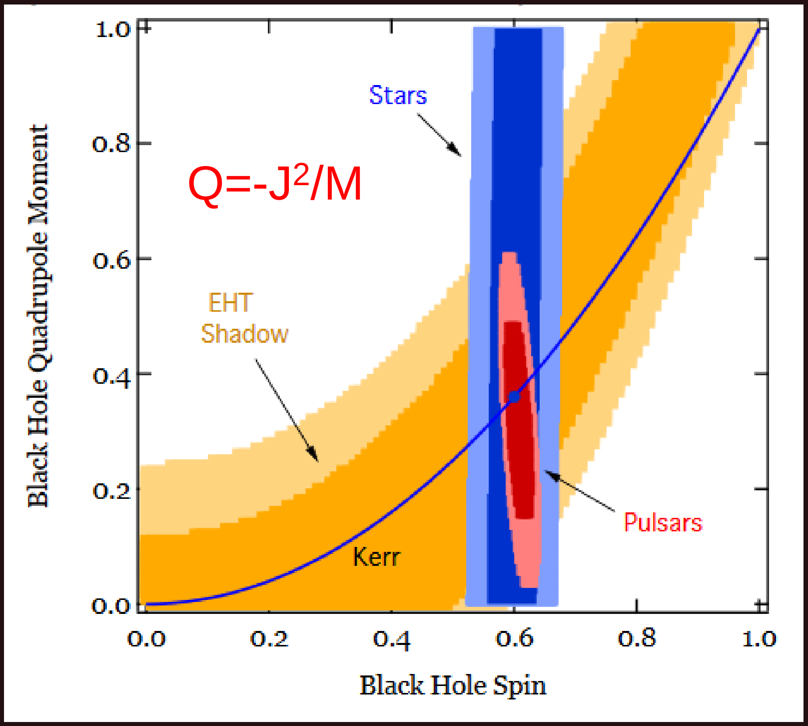


2207.02142

General relativity test, EHT, etc.

1512.03818



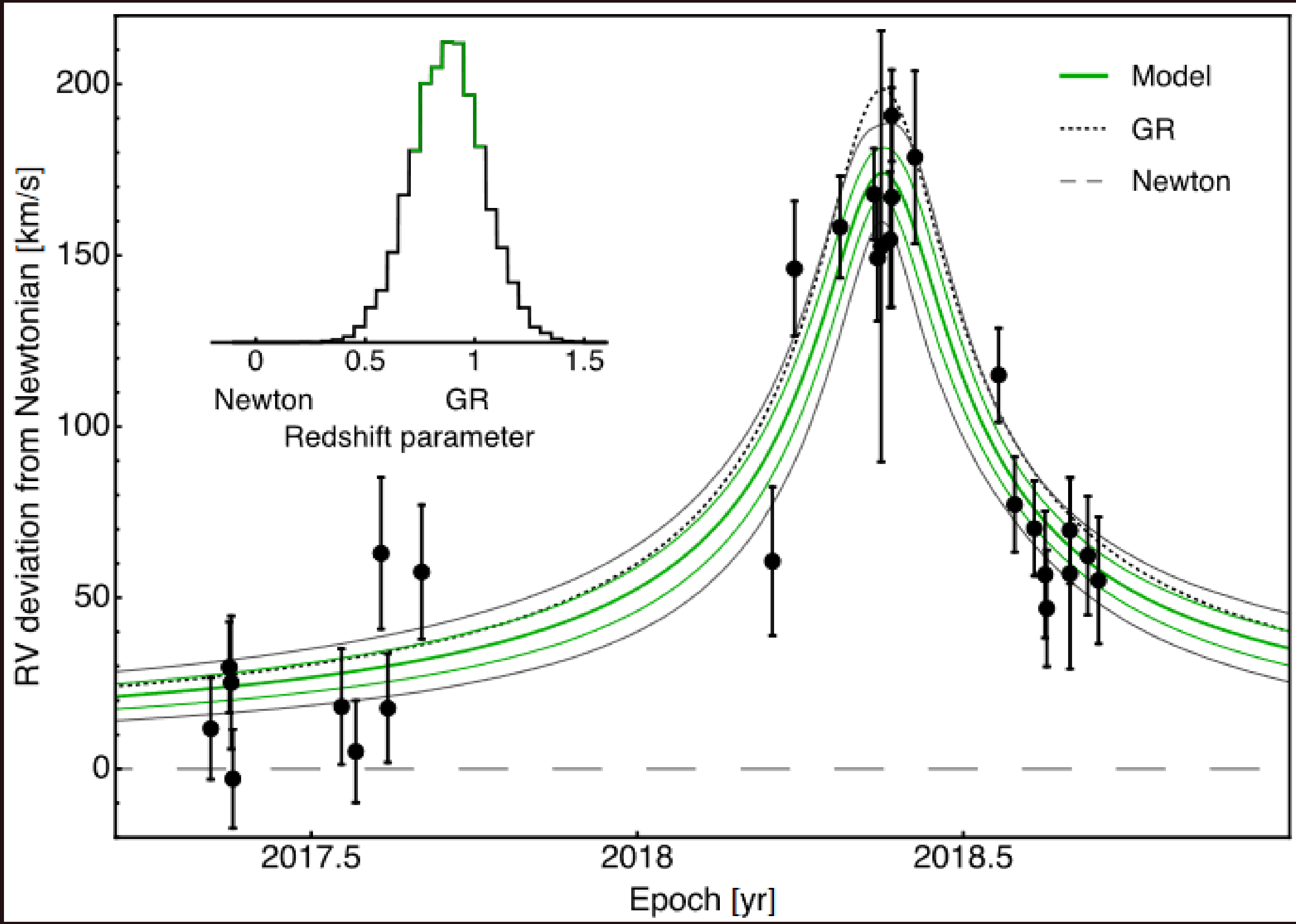


1510.00394

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.

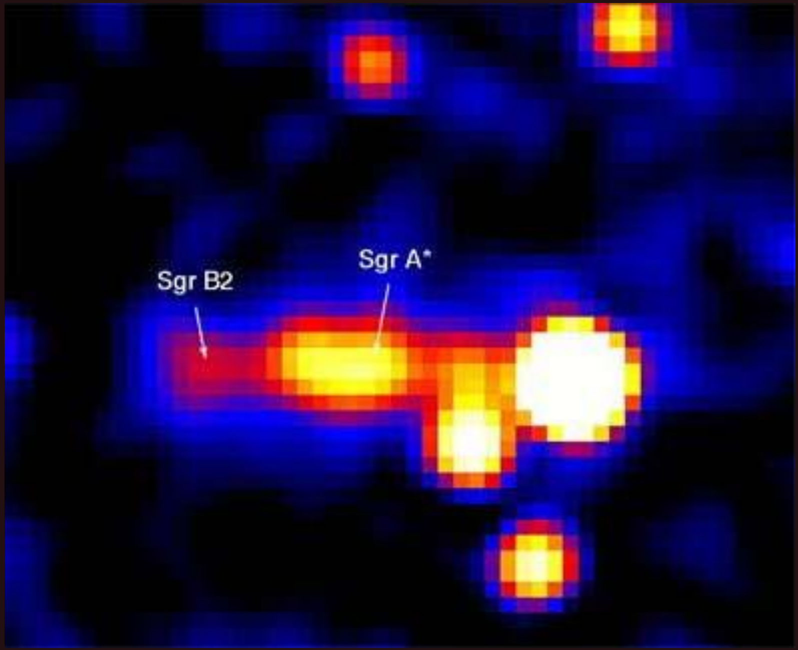
About EHT see 1410.2899

S02 orbit and tests of gravity



2302.02431

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.

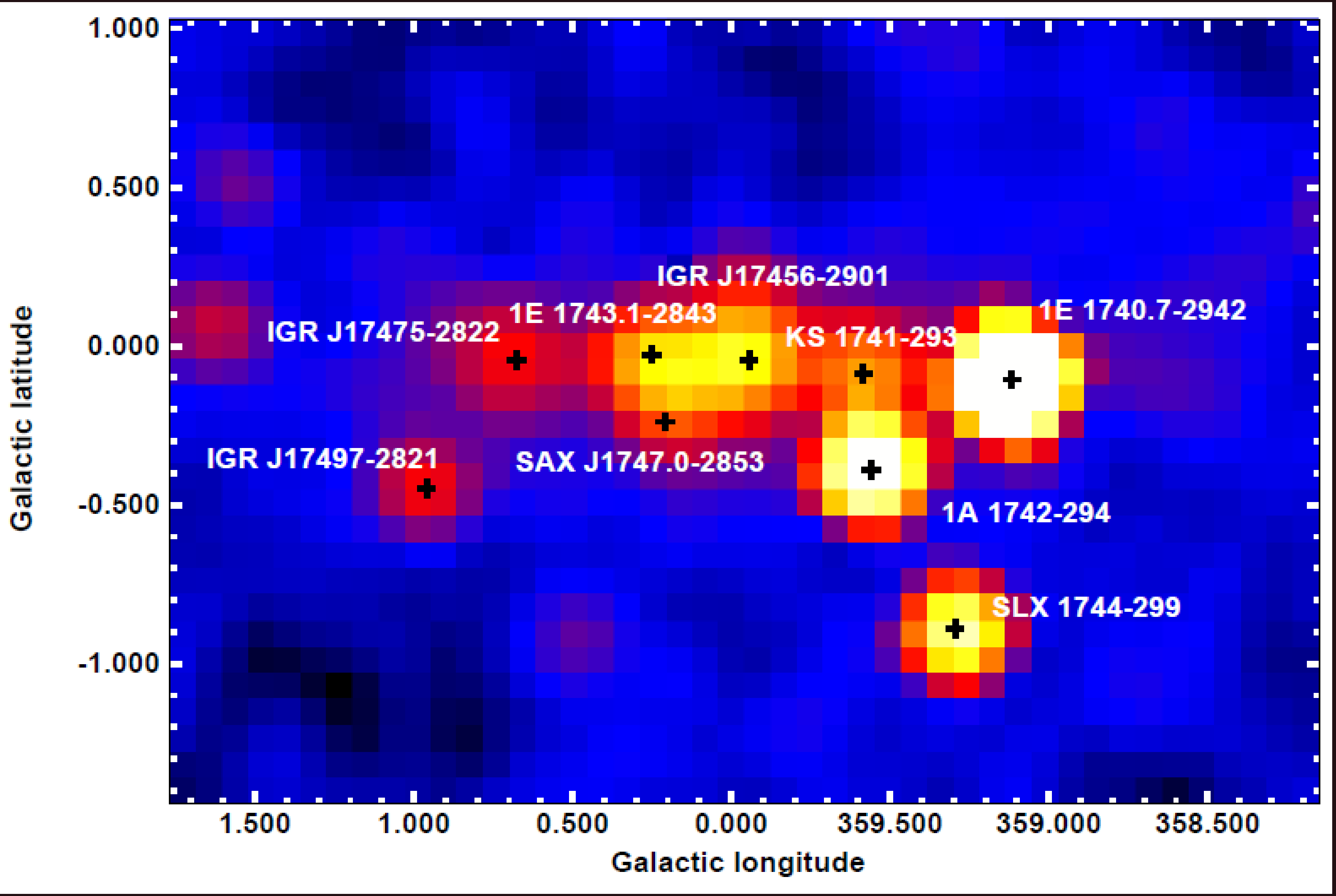
It is suspected that about 350 years ago
Sgr A* was in a "high state".
Now the hard emission generated by Sgr A*
at this time reached Sgr B2.
Sgr B2 is visible due to fluorescence
of iron.

See more data in 1211.4529, 1612.00180.

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

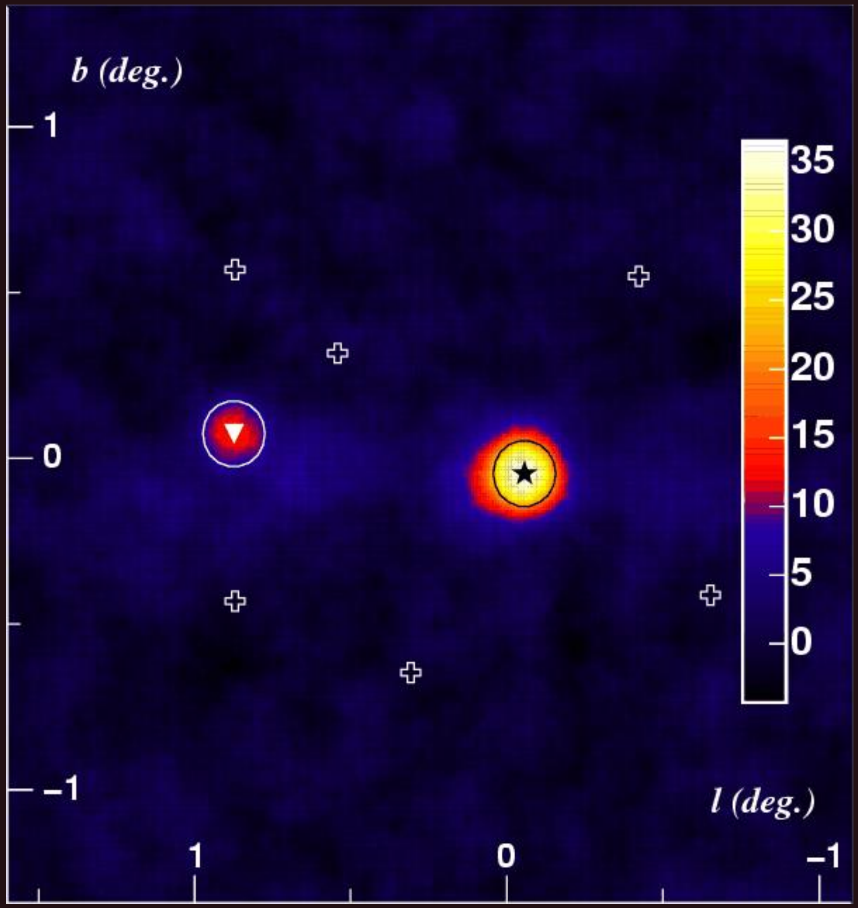
Confirmed by polarization measurements: 2304.06967

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.

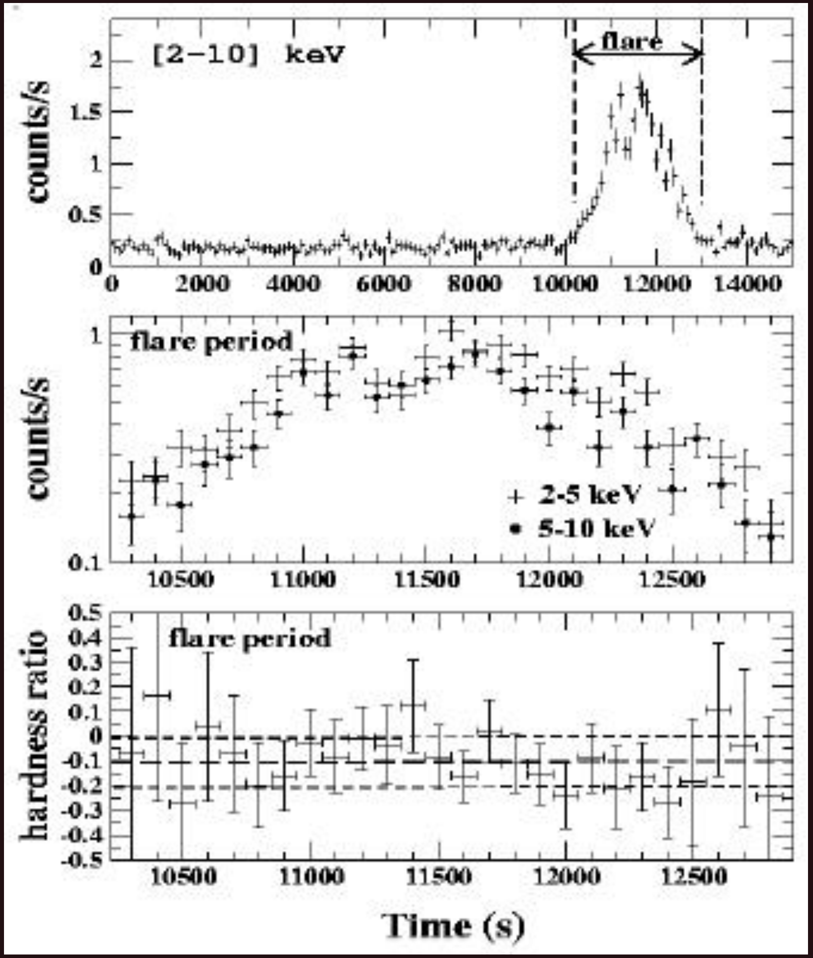
(Aharonian et al. 2005)

X-ray bursts from Sgr A*

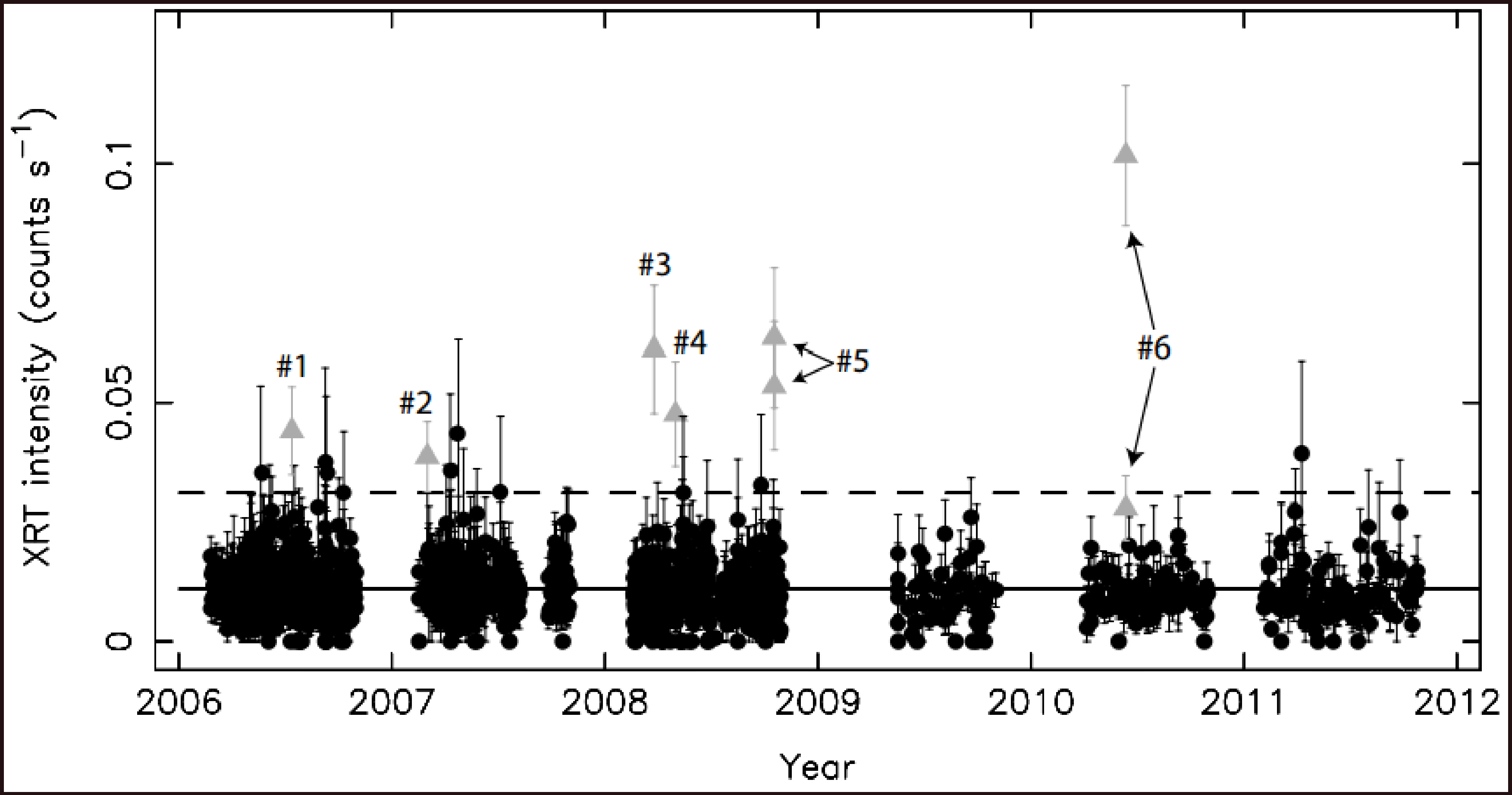
Bursts can happen about once in a day.
The flux is increased by a factor of a few
(sometimes even stronger).

A bright burst was observed on Oct. 3, 2002
(D. Porquet et al. astro-ph/0307110).
Duration: 2.7 ksec.
The fluxed increased by a factor ~160.
Luminosity: 3.6 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.



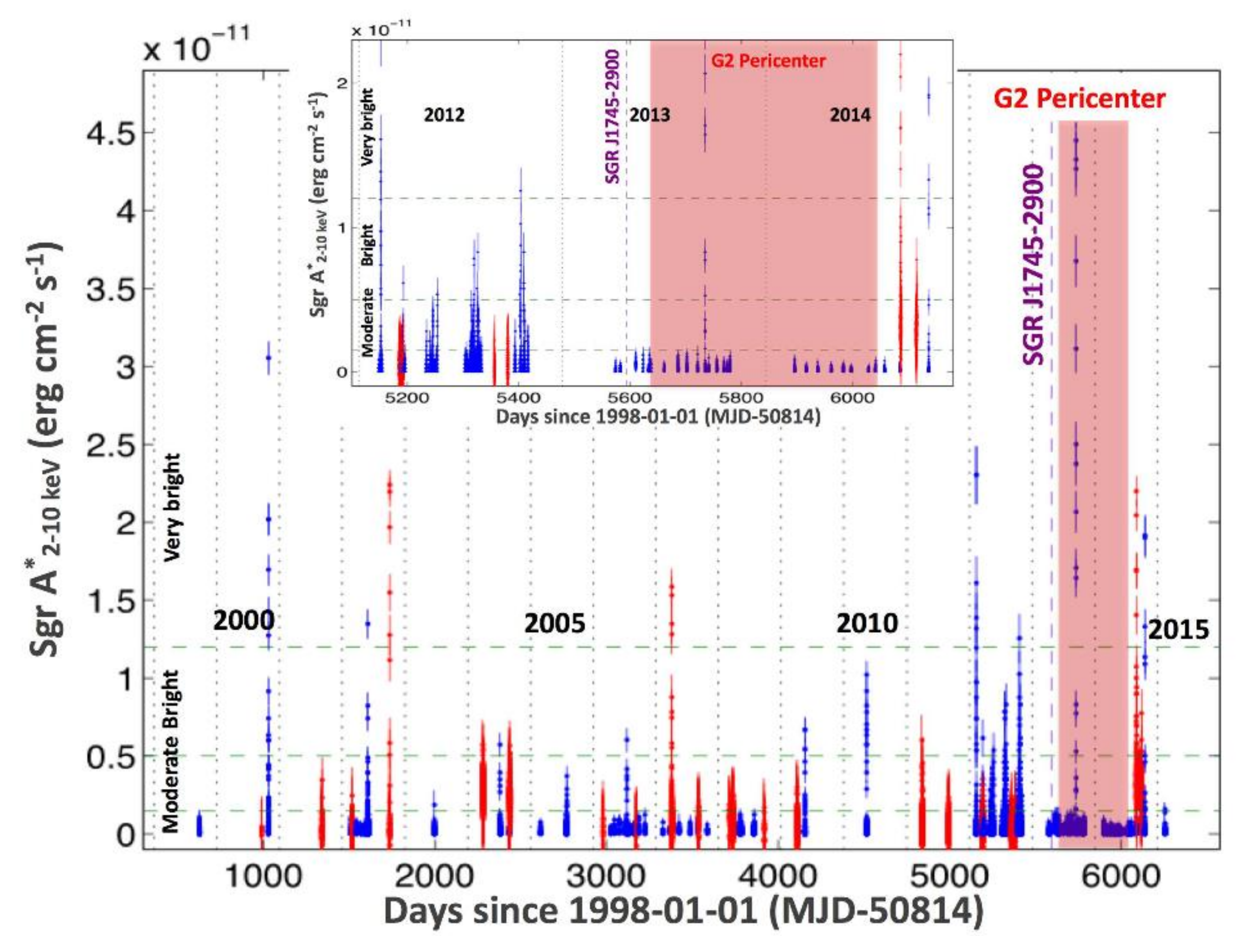
SWIFT monitoring of Sgr A*



1210.7237, see more recent results on long-term variability in 2111.10451

See 1501.02171 about accretion physics around Sgr A*

XMM-Newton and Chandra monitoring of Sgr A*



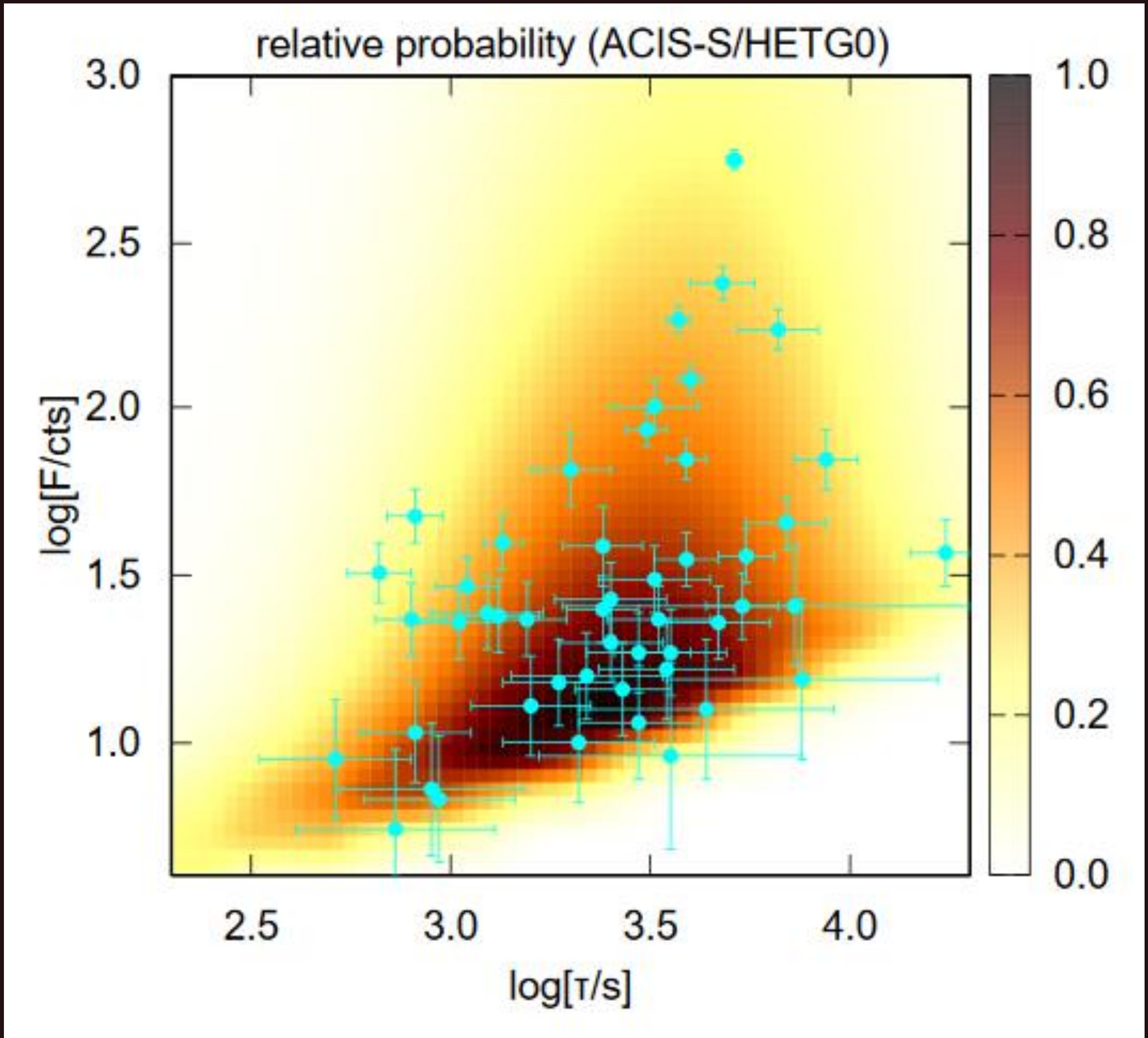
Plenty of data during all time of Chandra and XMM-Newton observations.

Very detailed statistics.

1507.02690

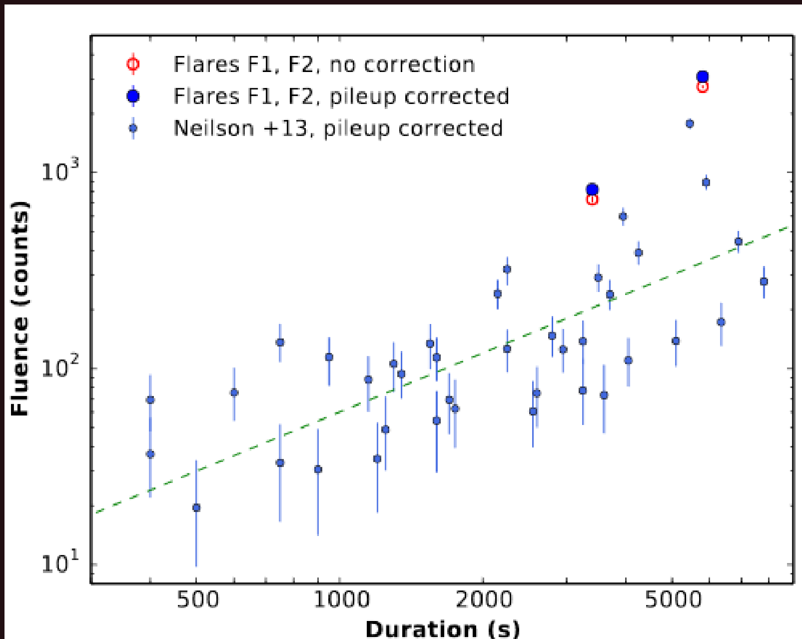
Chandra monitoring

1999-2012

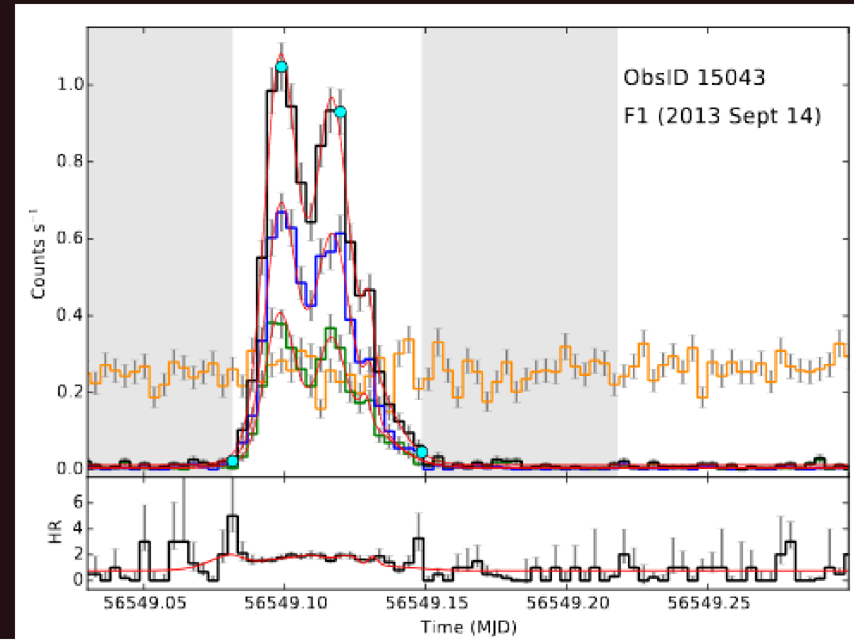


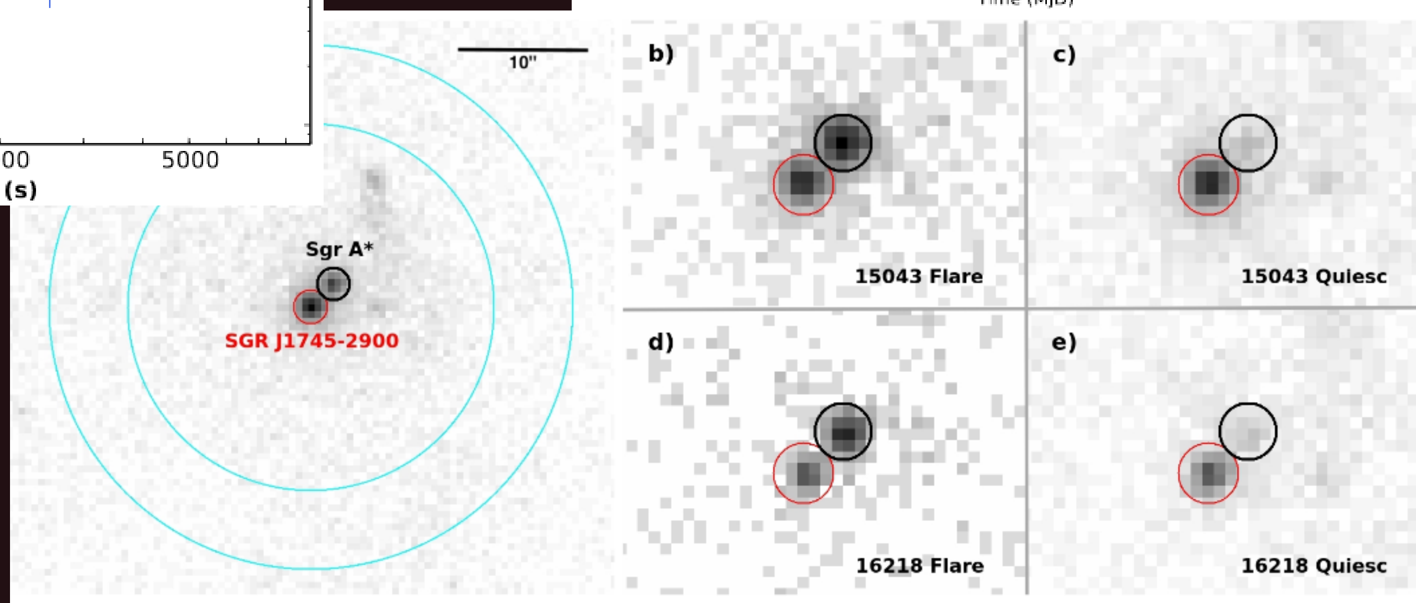
1709.03709

Brightest X-ray flares



1908.01781

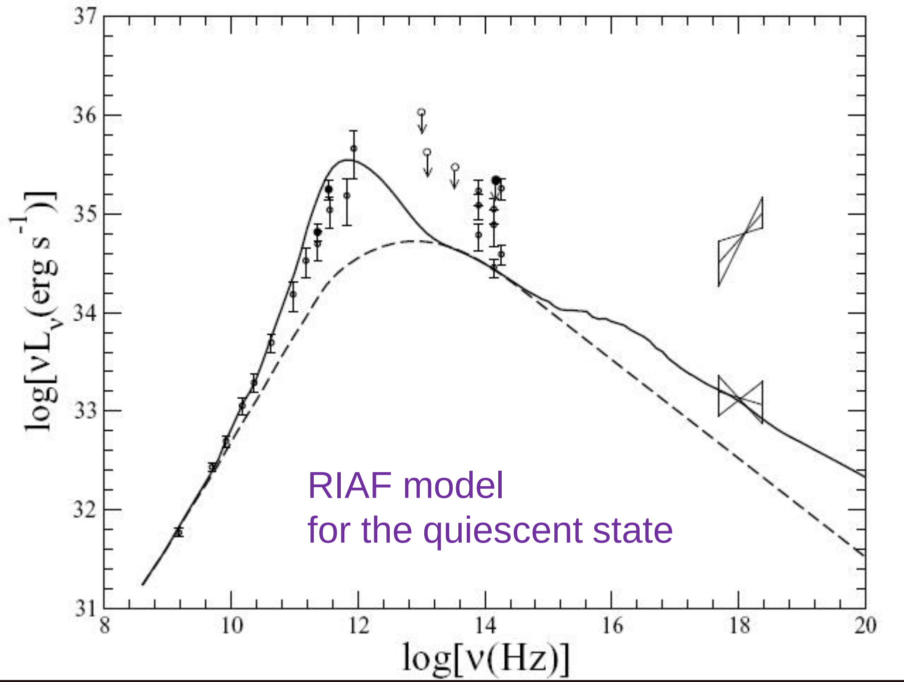


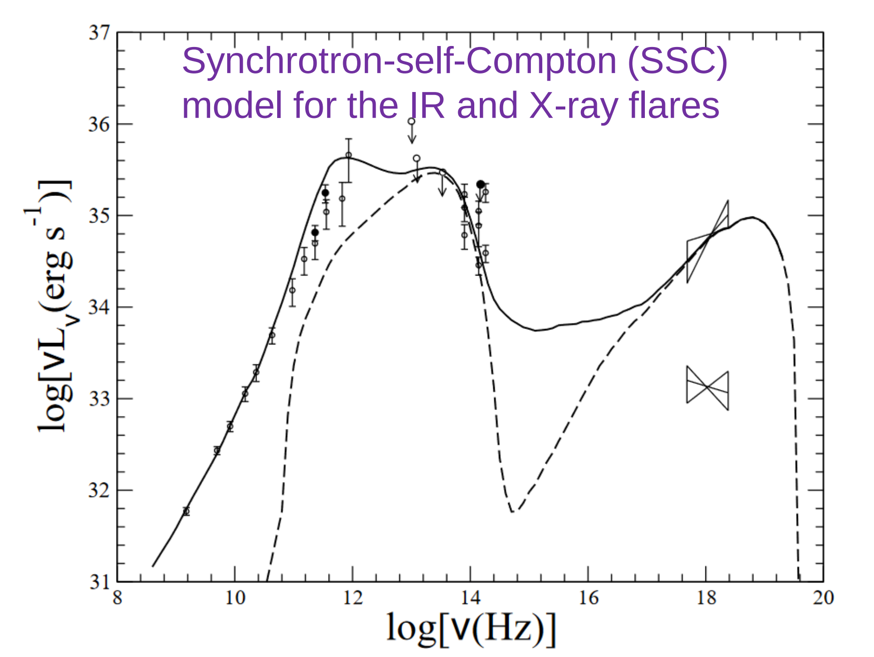


Since 2014 the rate of very bright flares increased (2003.06191)

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.

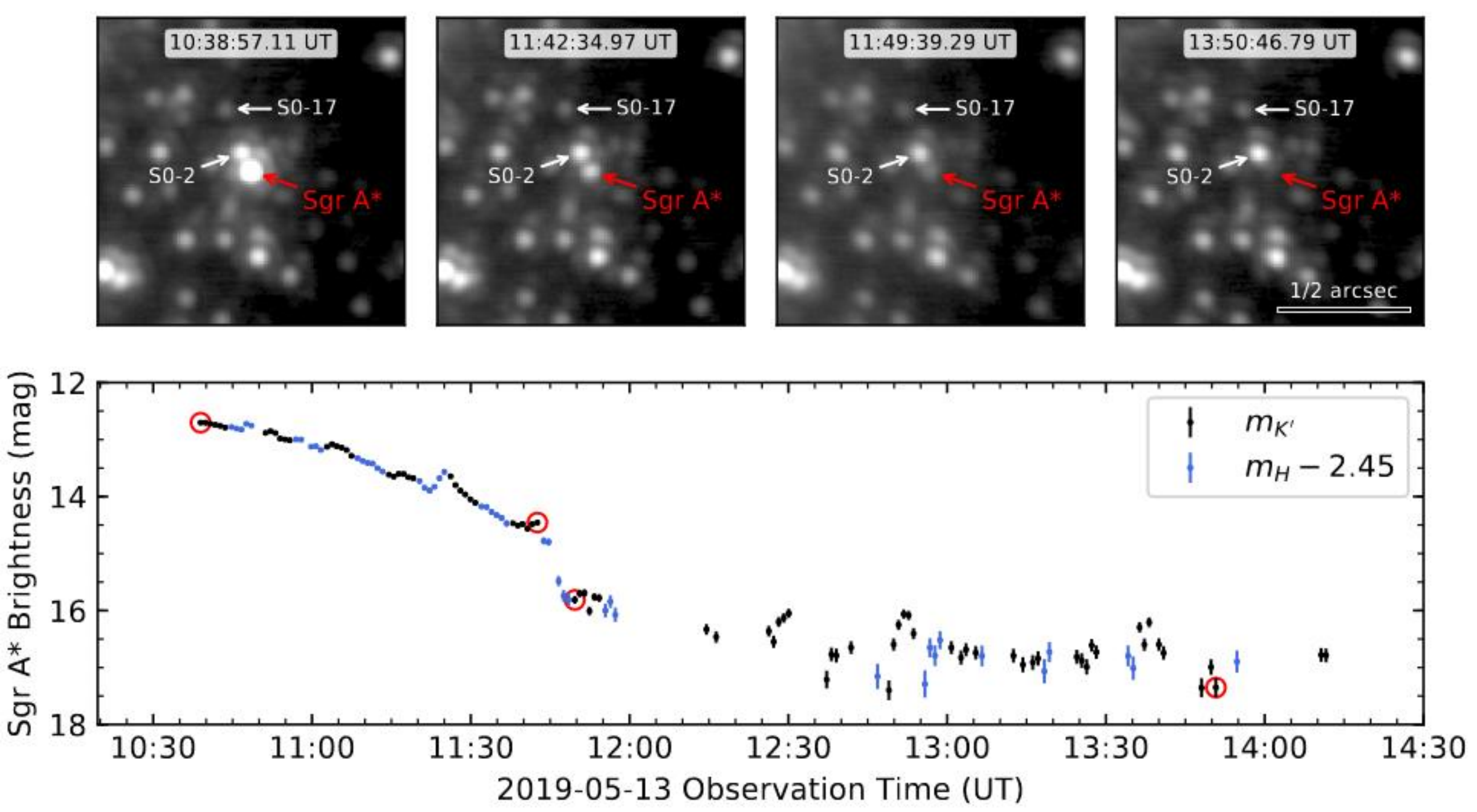




Non-thermal synchrotron?

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

Record: high NIR flux in 2019

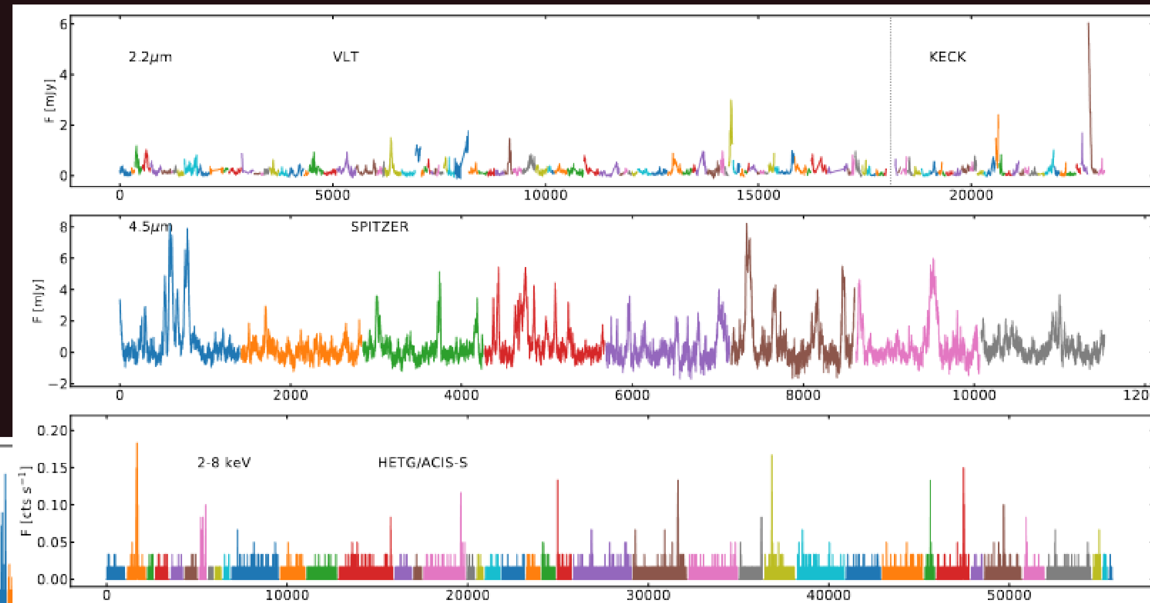


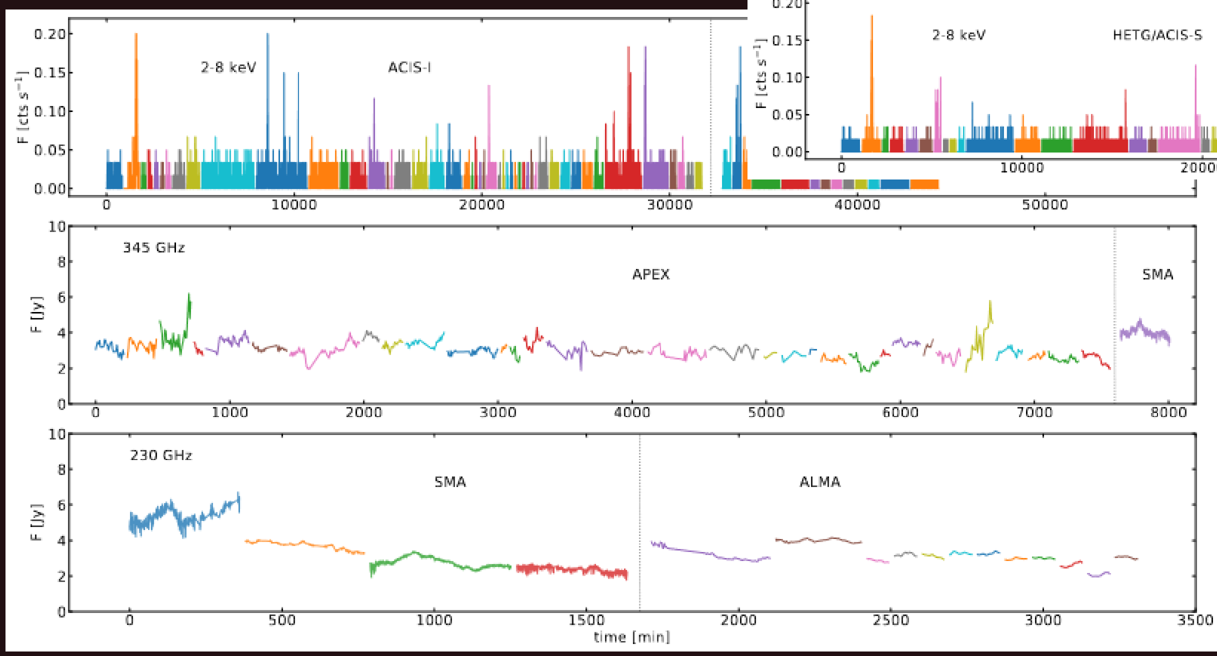
Twice higher than the previous record.

1908.01777

Multiwavelength data

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

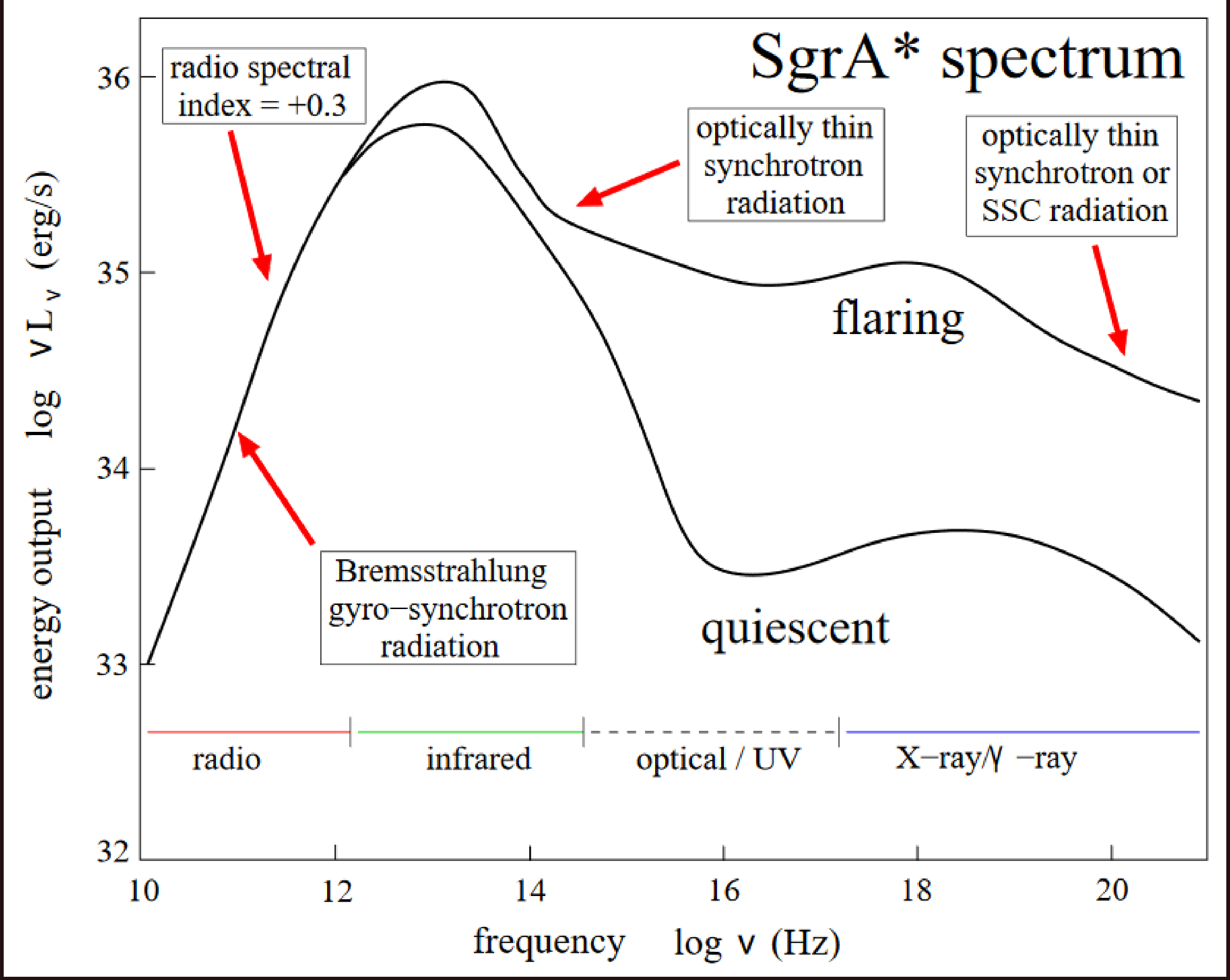




Less power at short timescales in the X-rays than in the NIR.

2011.09582

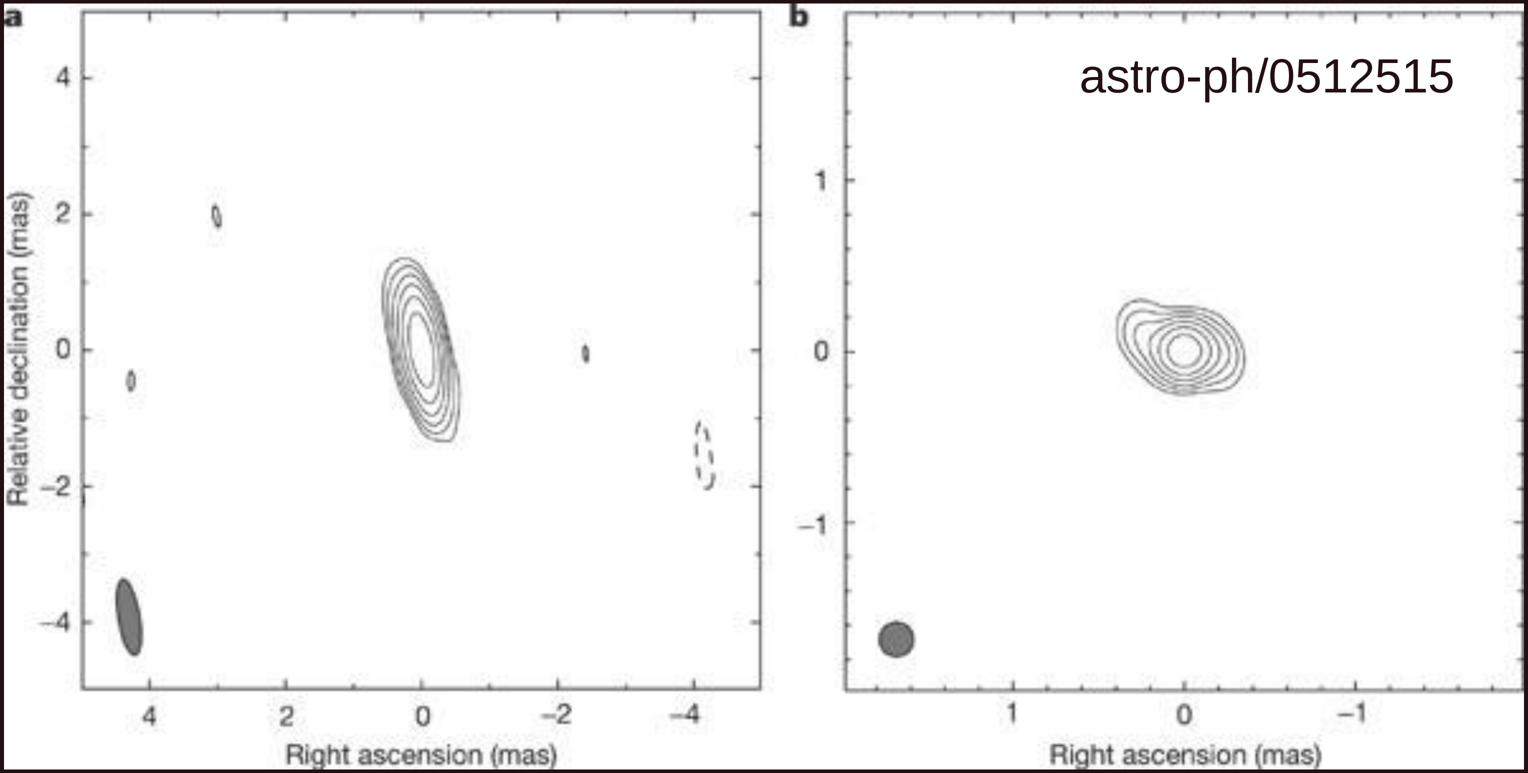
Sgr A* spectrum



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.

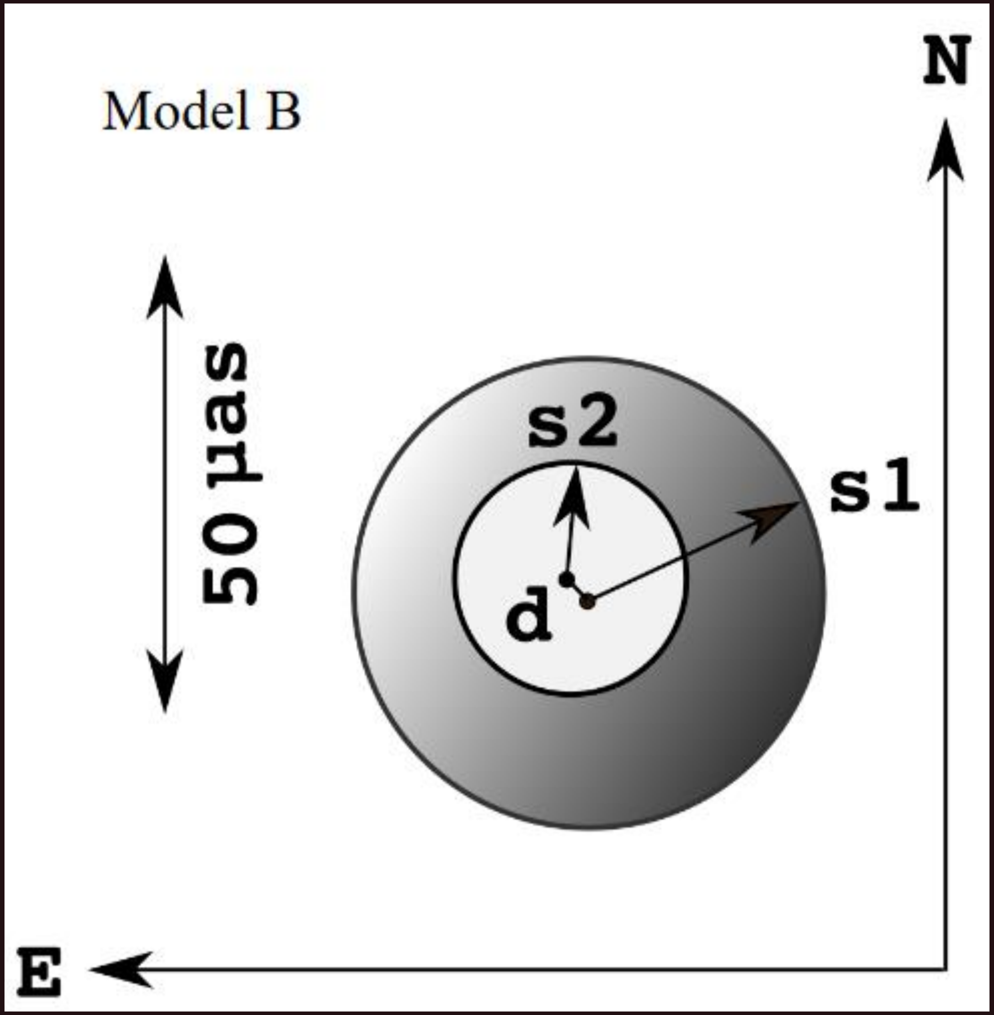


VLBI observations demonstrate variability at 1.3mm from the region about few Schwarzschild radii. arXiv: 1011.2472

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

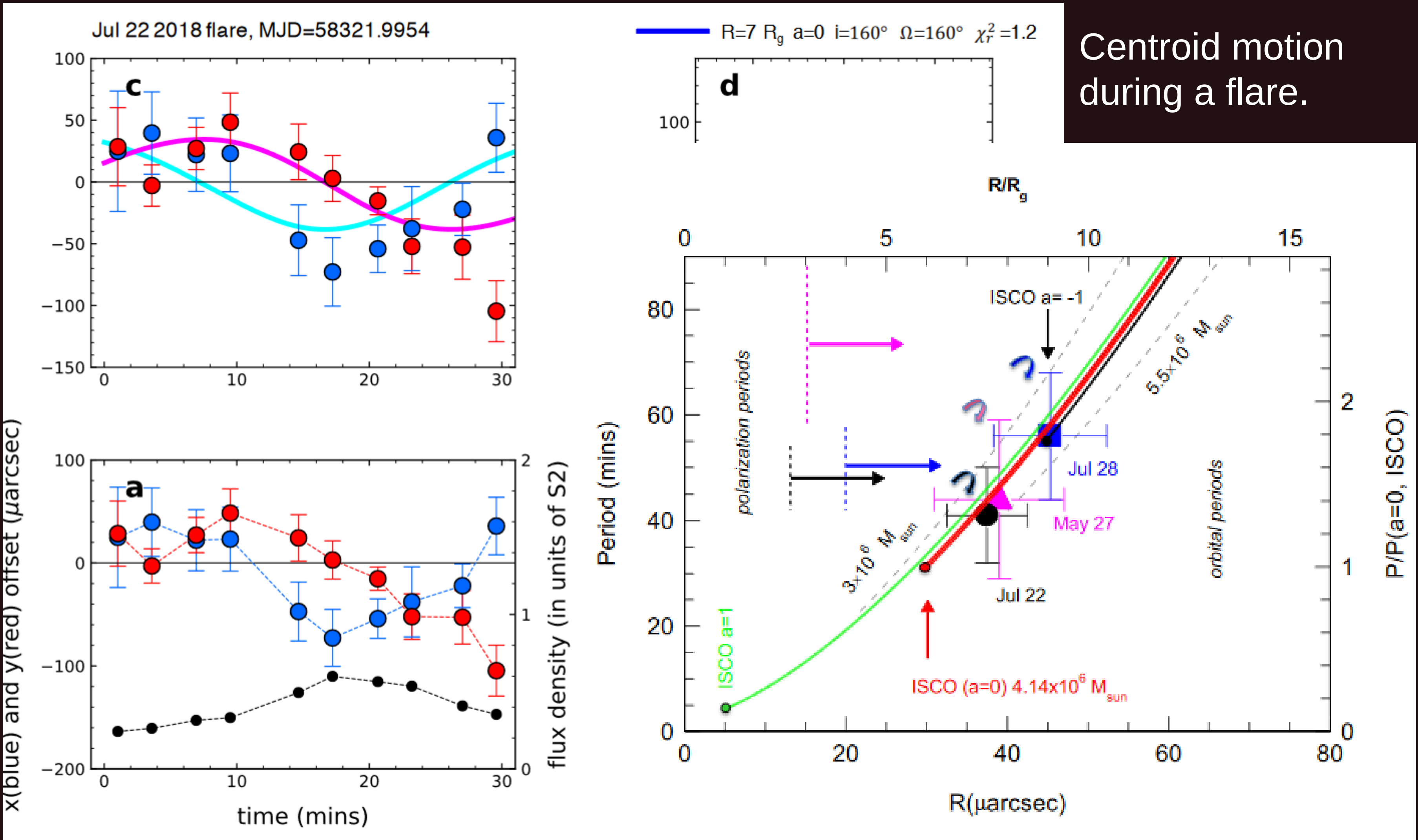
Structure at 3 Rg in Sgr A*

EHT 2013
VLBI 1.3 mm
30 μarcsec



1805.09223

Orbital motion near ISCO in Sgr A*

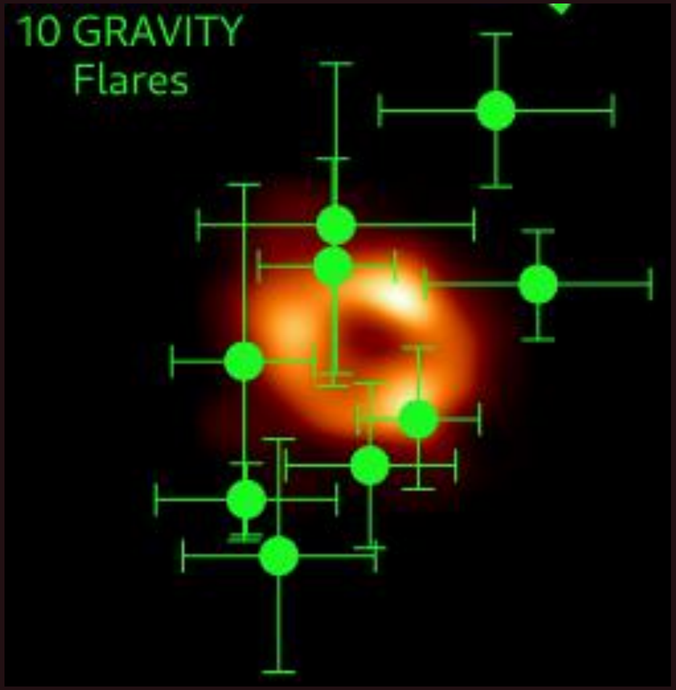


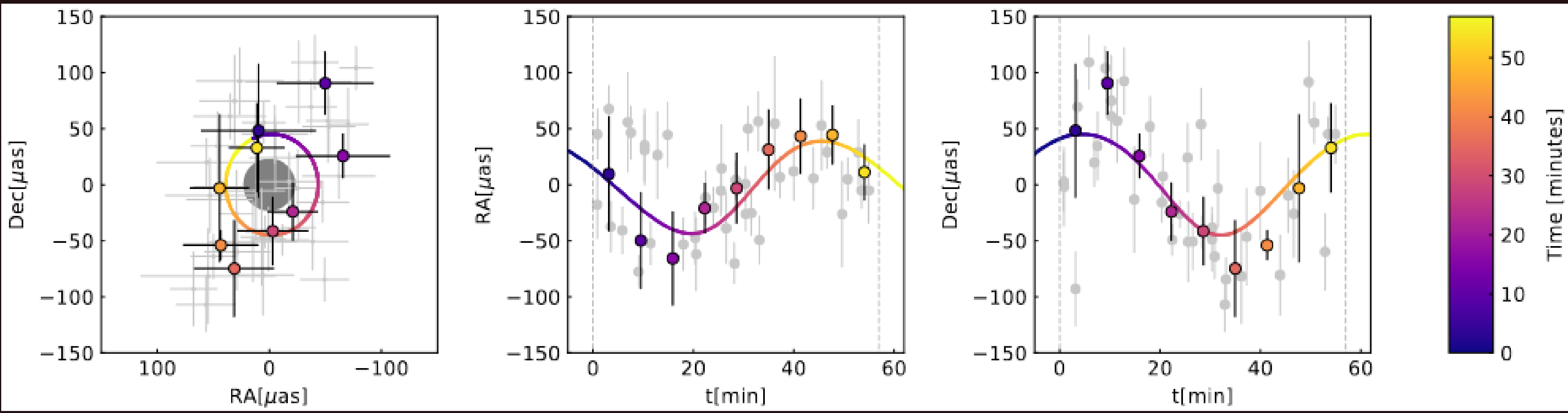
Centroid motion during a flare.

1810.12641

Flares from 9 R_g

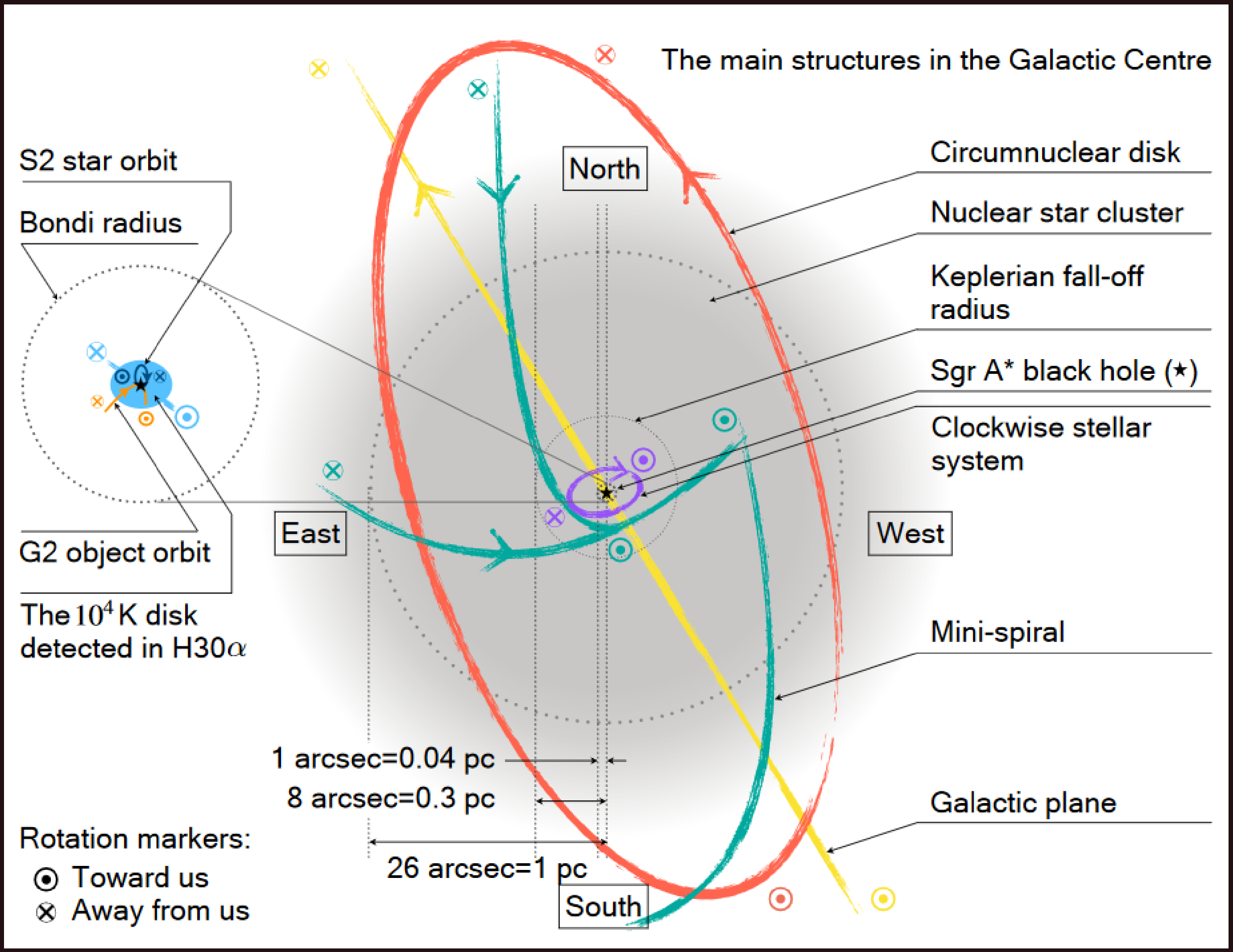
NIR+polarimetric data
VLTI+GRAVITY





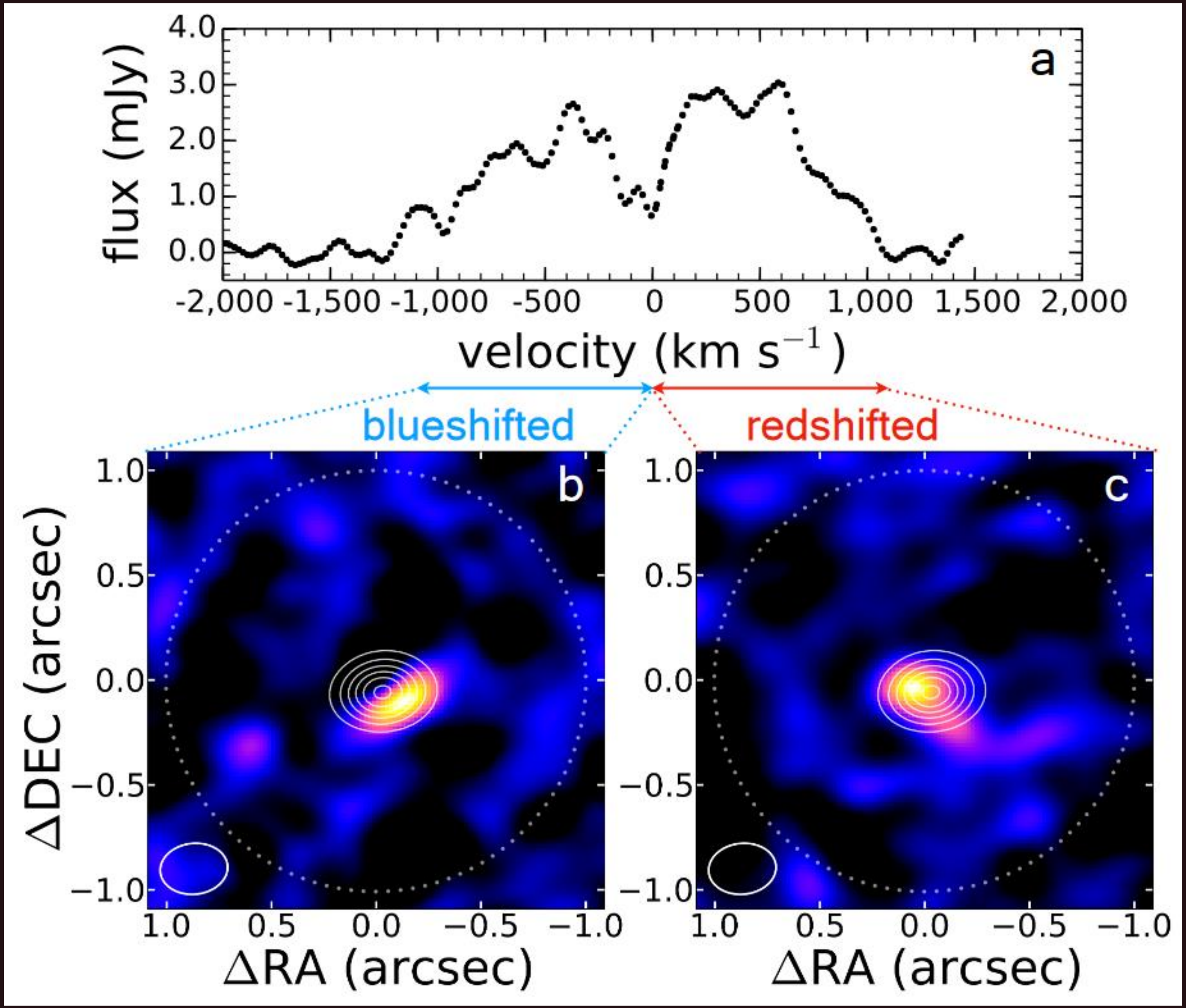
2307.11821

Cool disc in Sgr A*



1906.08289

Cool disc in Sgr A*



ALMA observations.

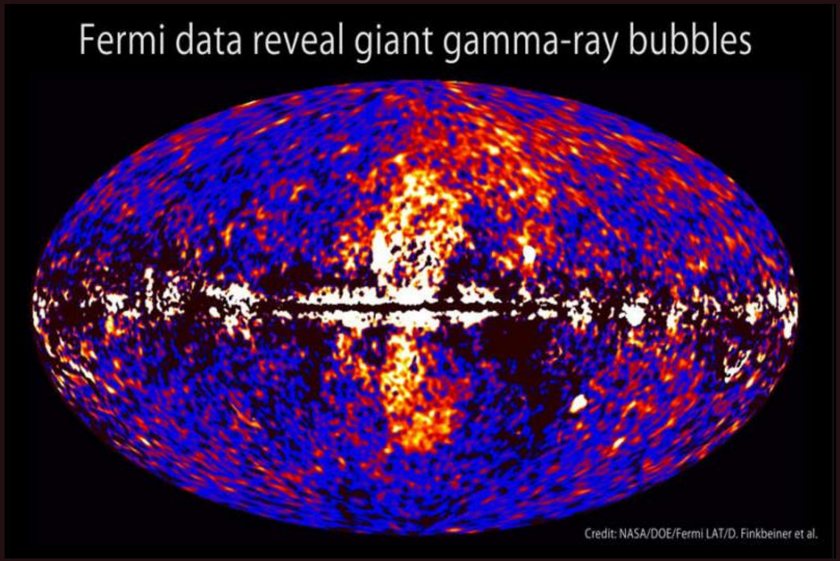
H30α line

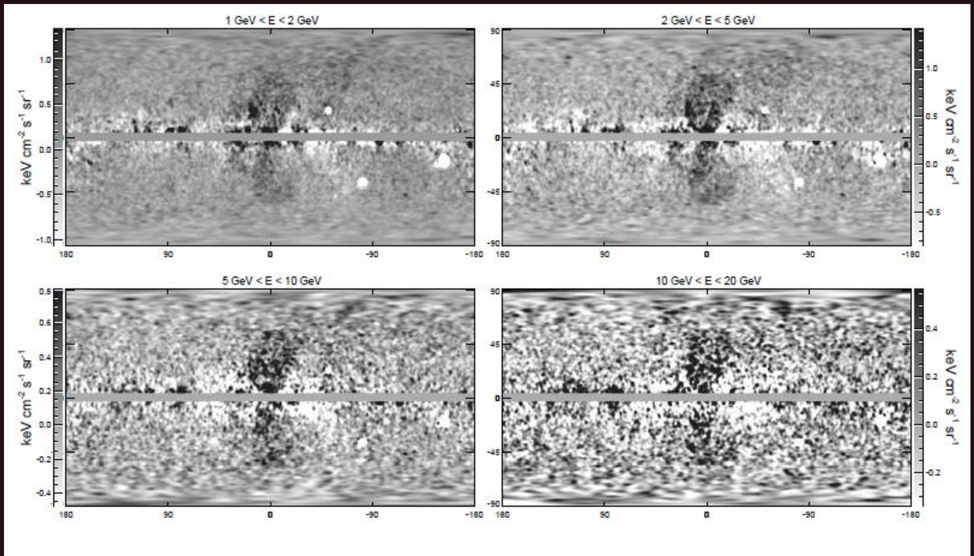
10^4 K disc at ~10^4 R_{sh}

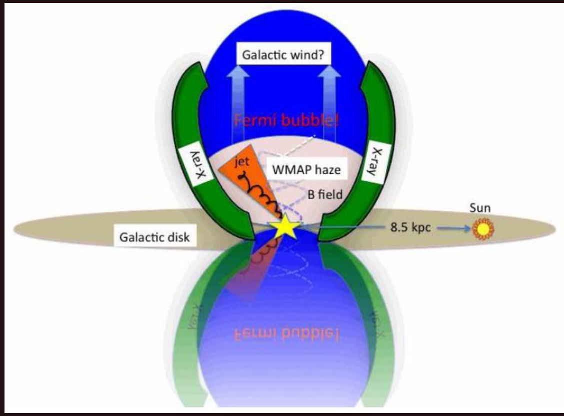
Off-set between
red and blue shifted
components respect to
the continuum Sgr A*
postion is:
0.11 arcsec = 0.004 pc

1906.08289

Bubbles in the center of the Galaxy



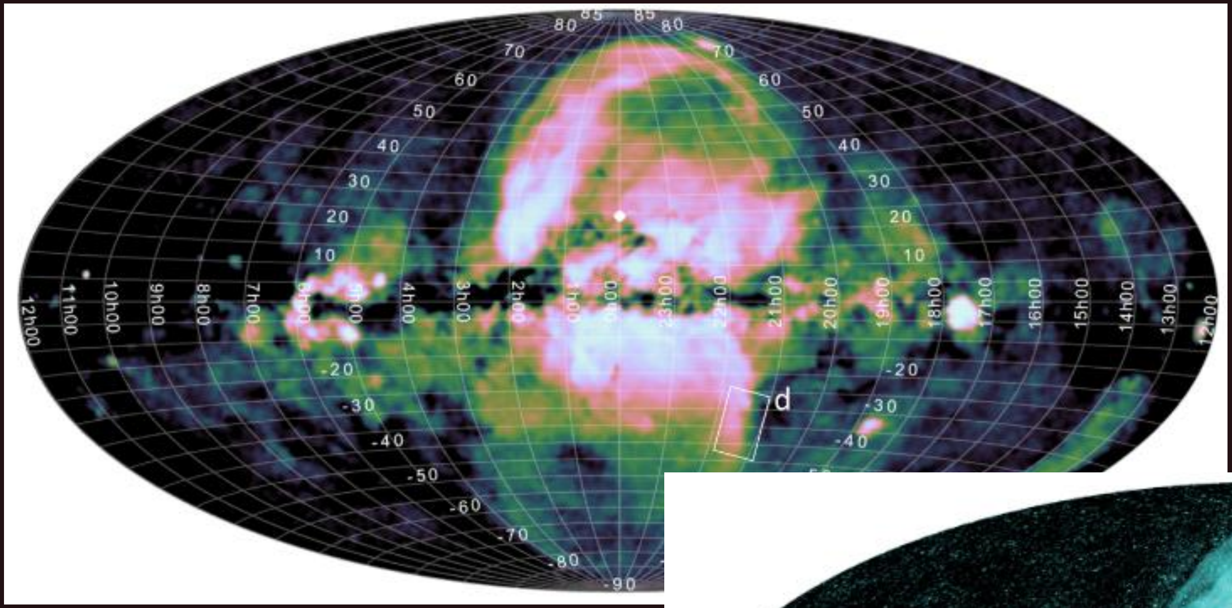


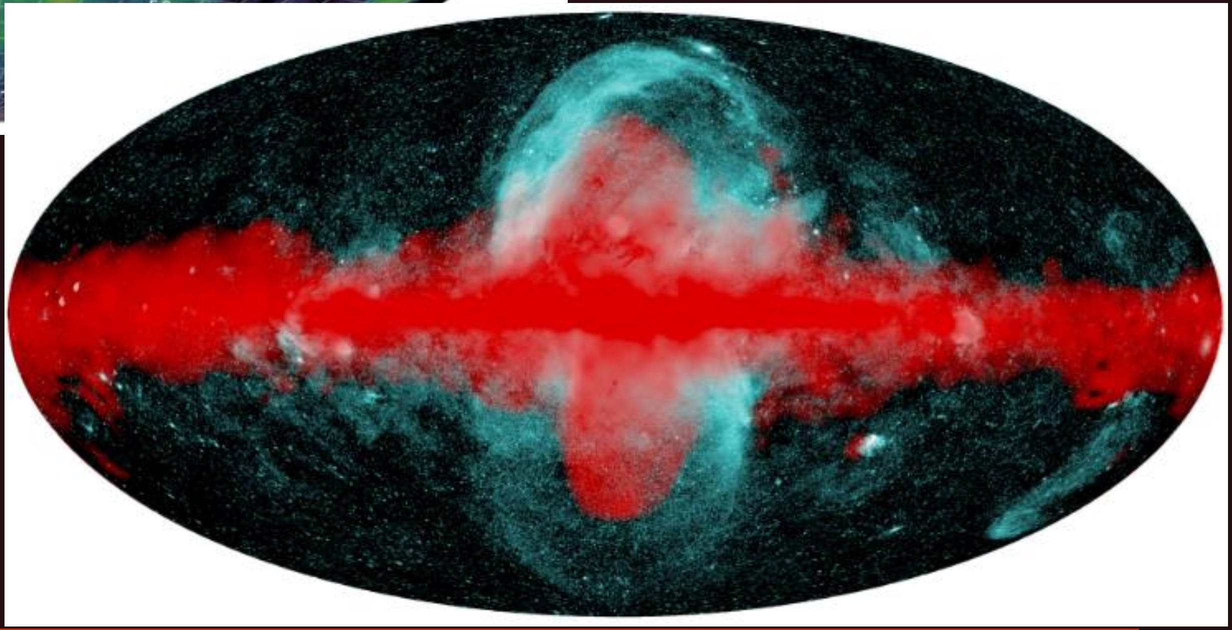


Structures have been already detected in microwaves (WMAP) and in soft X-rays (ROSAT)

arXiv: 1005.5480

Detailed structure of Fermi bubbles

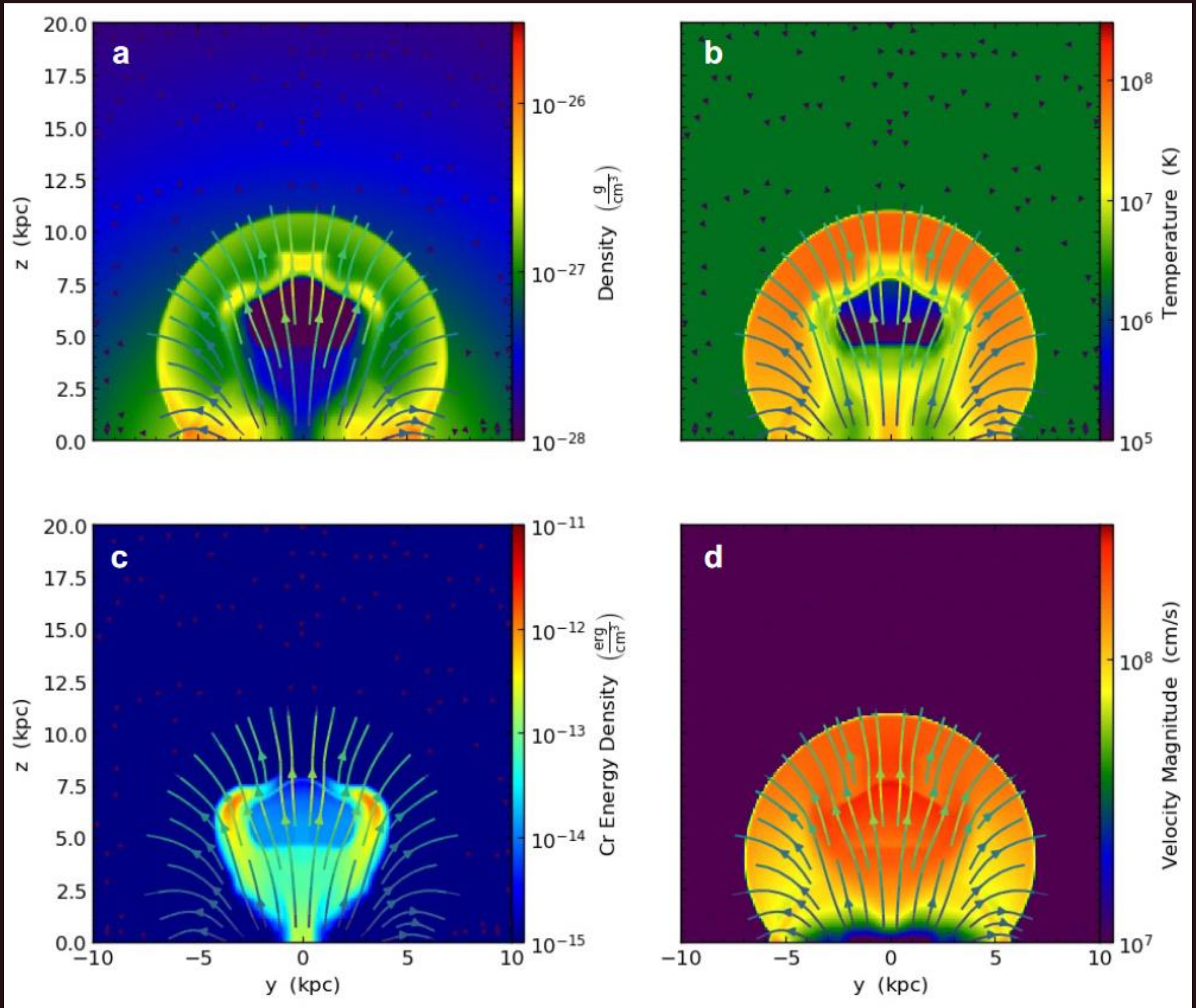




Red - Fermi,
Cyan - eRosita

2012.05840

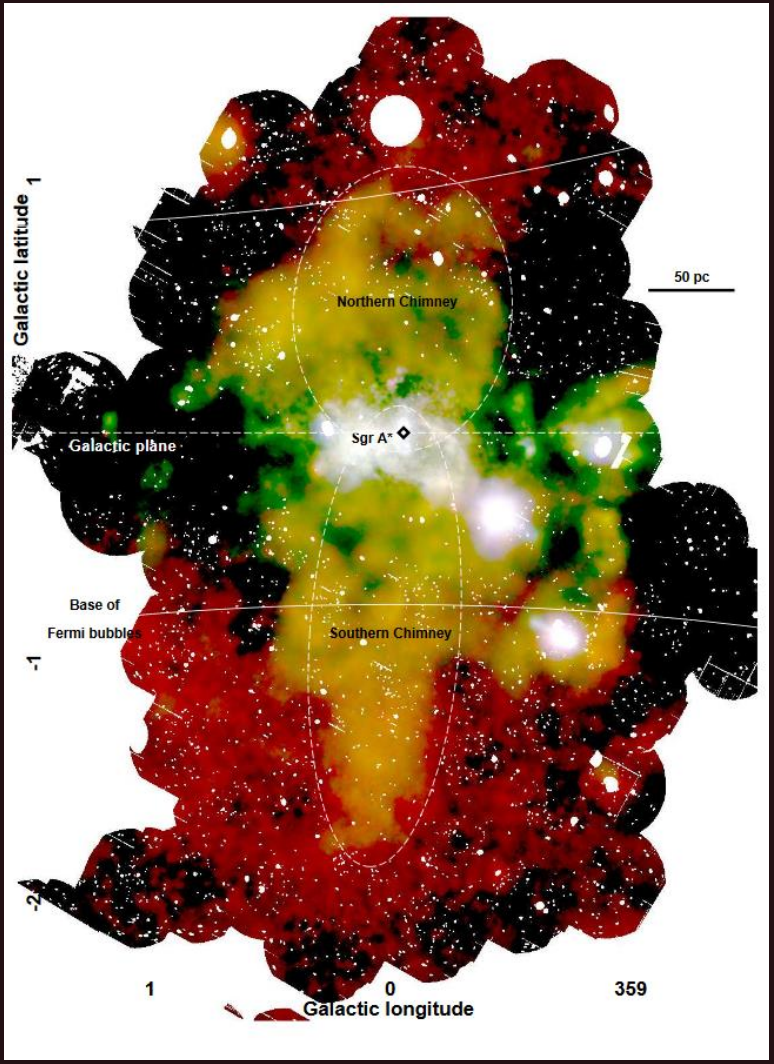
Simulations of the Fermi bubbles



The central SMBH was active ~ 2.6 Myr ago, injecting a pair of bipolar jets in mostly kinetic forms for a duration of ~ 0.1 Myr. After taking into account uncertainties in the initial conditions, the Sgr A* was estimated to be accreting at ~ 0.1 − 1 the Eddington rate during the active phase, corresponding to a consumption of ~ $10^3 - 10^4$ solar masses within ~ 0.1 Myr.

2203.02526

New structures: galactic chimney



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

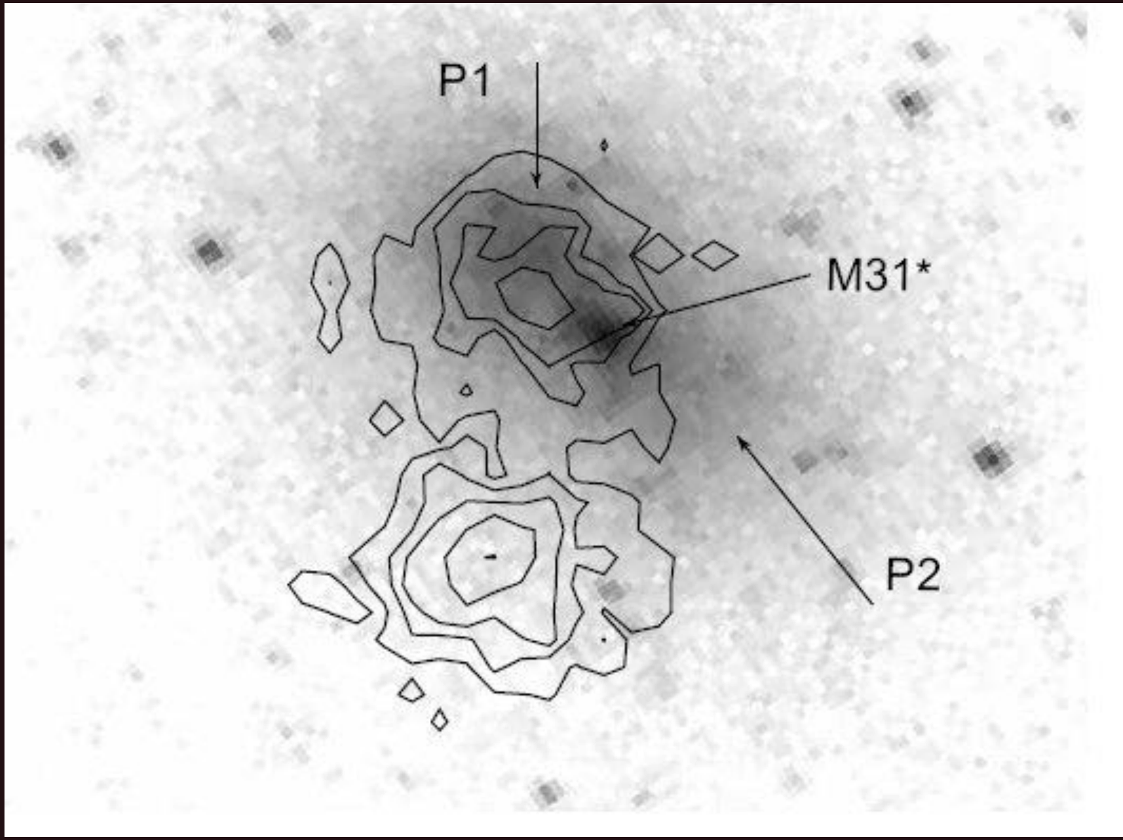
1904.05969

M31

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

M~(1-2) 10^8 M_{solar}
Lx ~ 10^{36} erg/s

See recent data in arXiv: 0907.4977

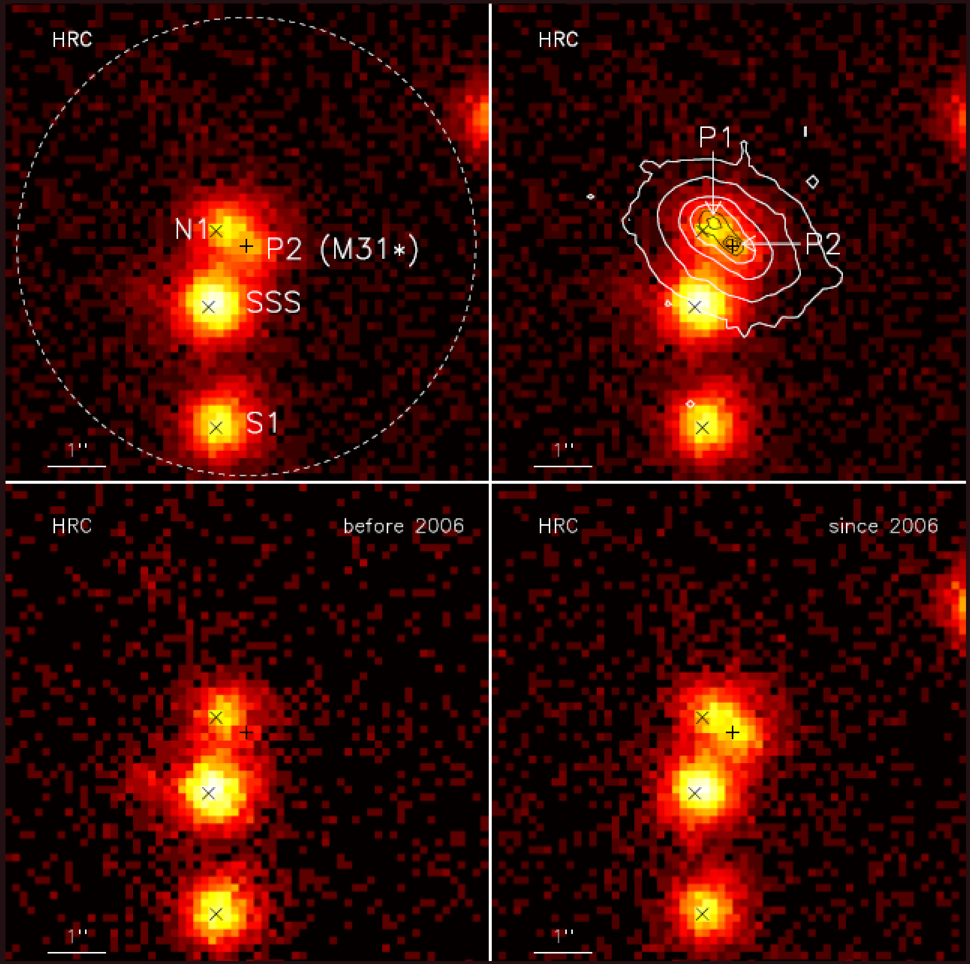


Activity of the M31 SMBH

SMBH with 100-200 million solar masses.

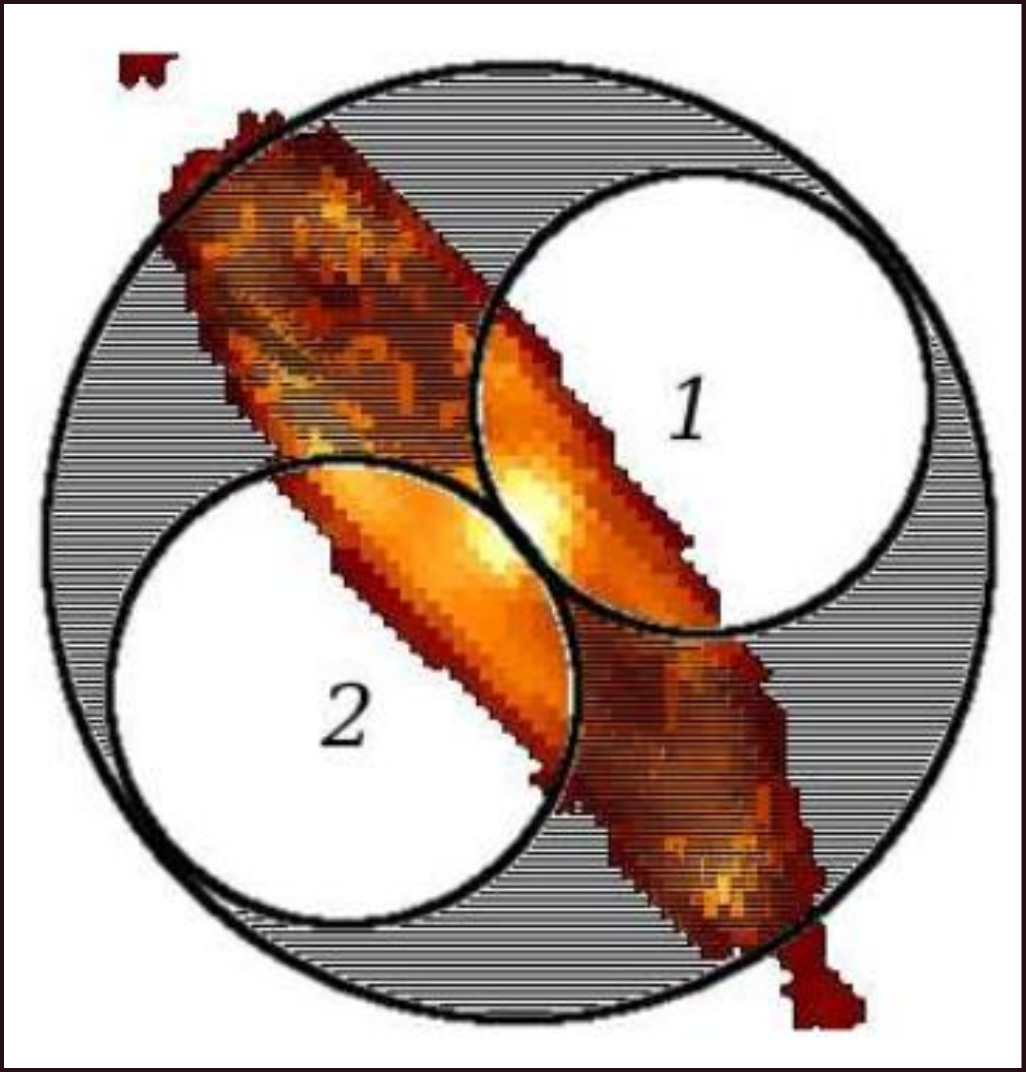
Mostly in the quiescent state.
Luminosity is billions of times less than the Eddington.

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



arXiv: 1011.1224

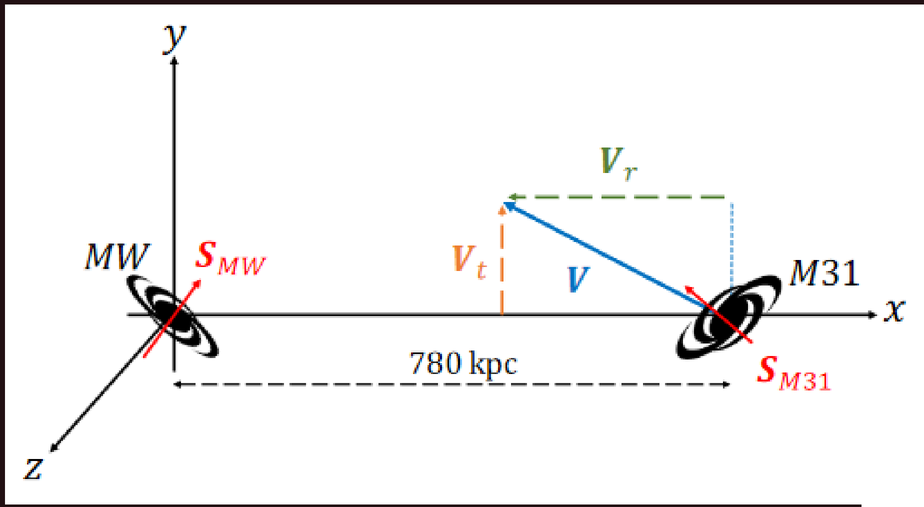
Fermi bubbles analogues in M31?

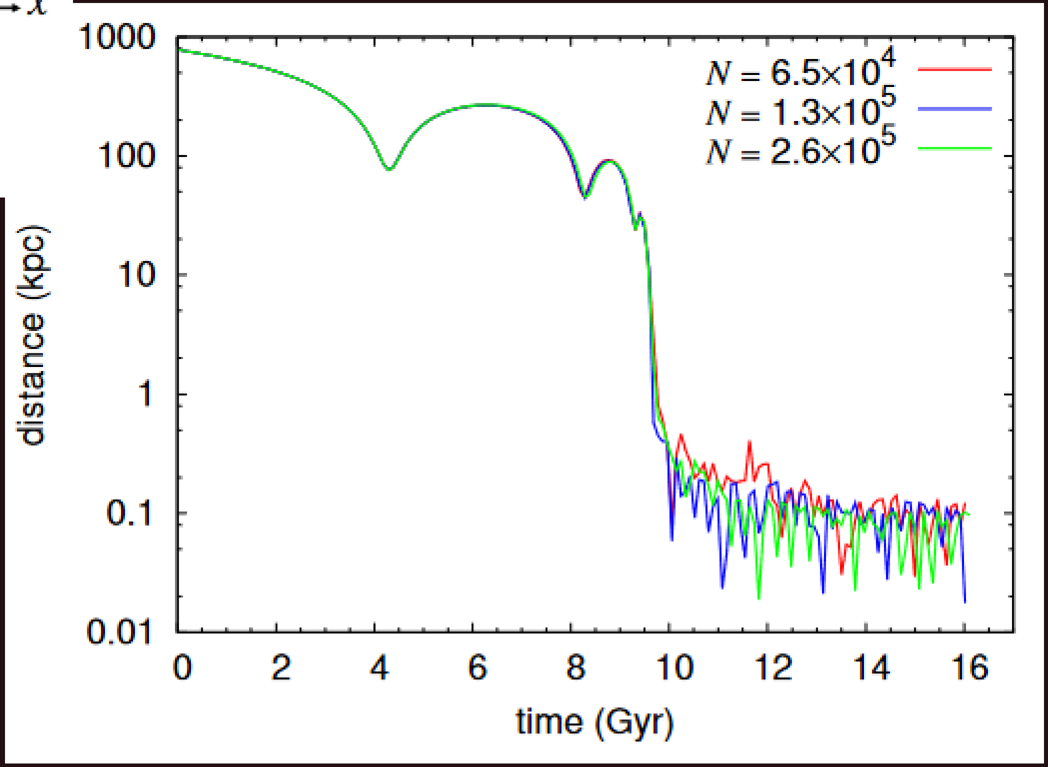


Using Fermi data
the authors demonstrated
that the shape of
gamma-ray image
is more consistent
with a structure
similar to Fermi bubbles
in our Galaxy.

1603.07245

Milky way and M31 SMBHs will coalesce

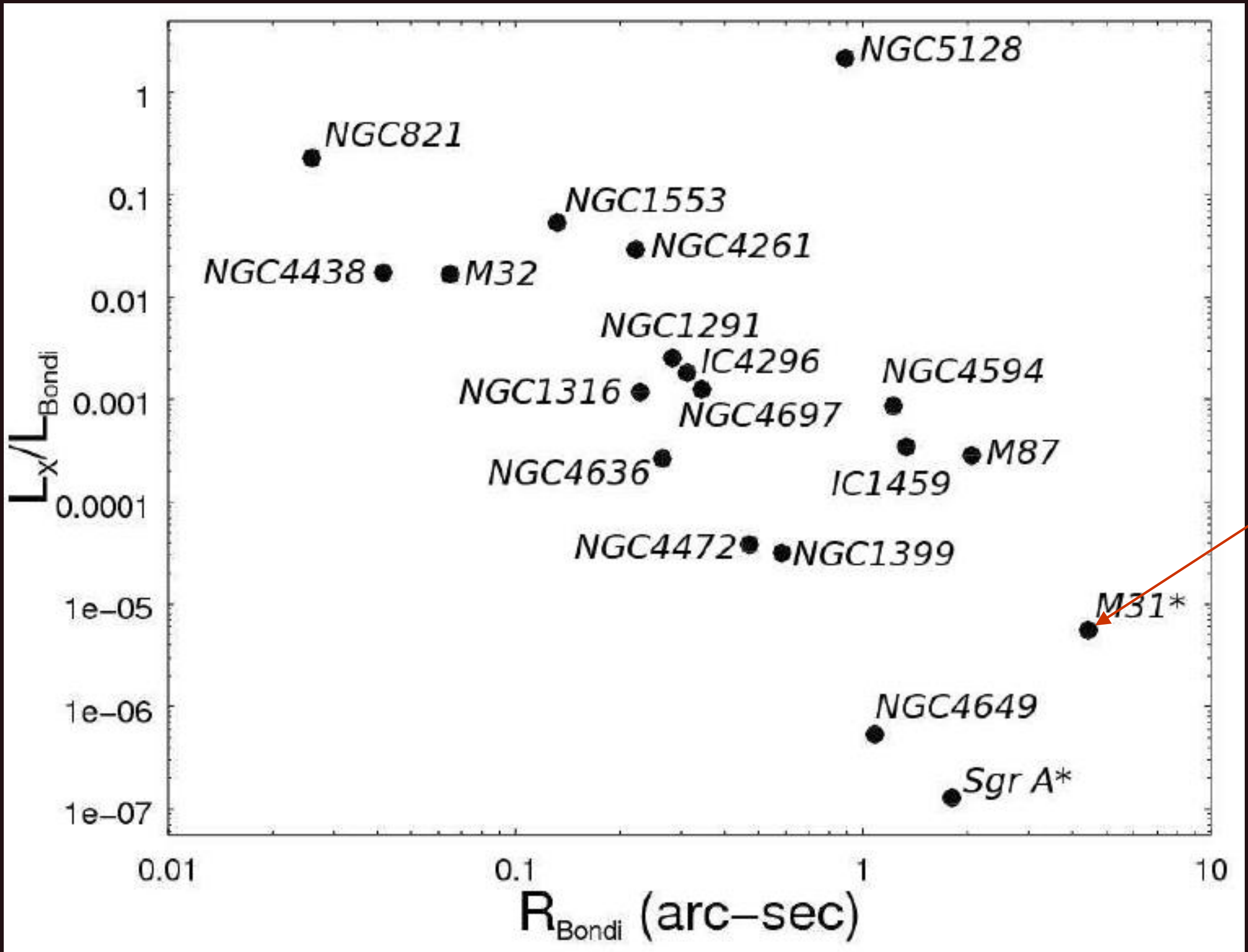




After the merging event is completed two SMBHs coalesce relatively rapidly: in <17 Myrs.

2102.10938

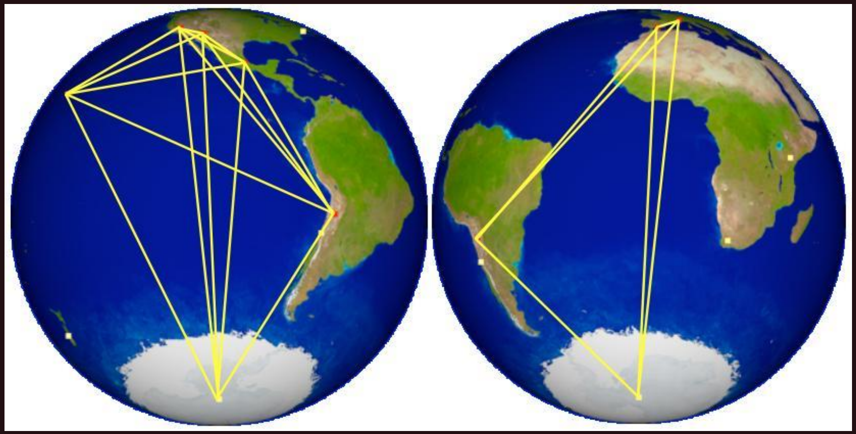
A “large” BH in M31



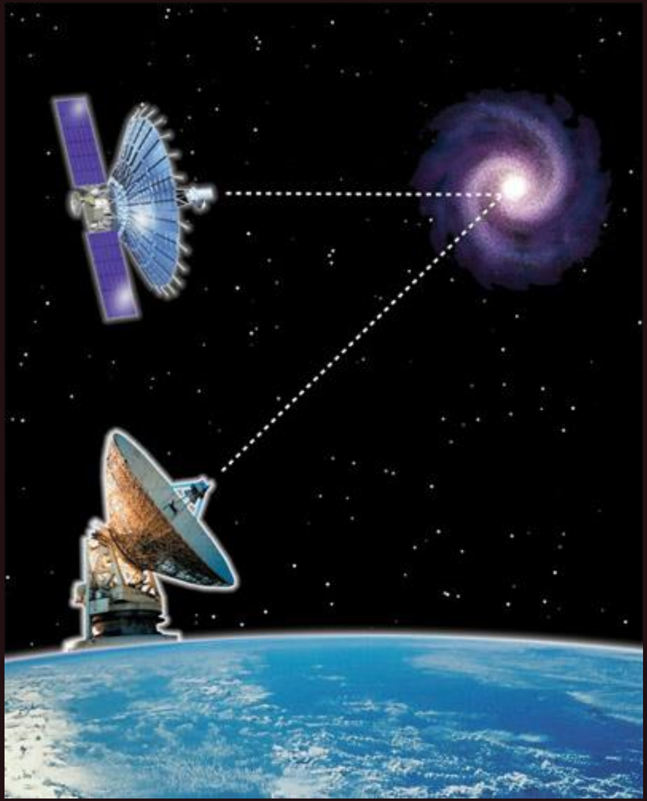
For M_{bh}=1.4 10^8 M_{sun}

0907.4977

Observational projects: horizon



Event Horizon telescope

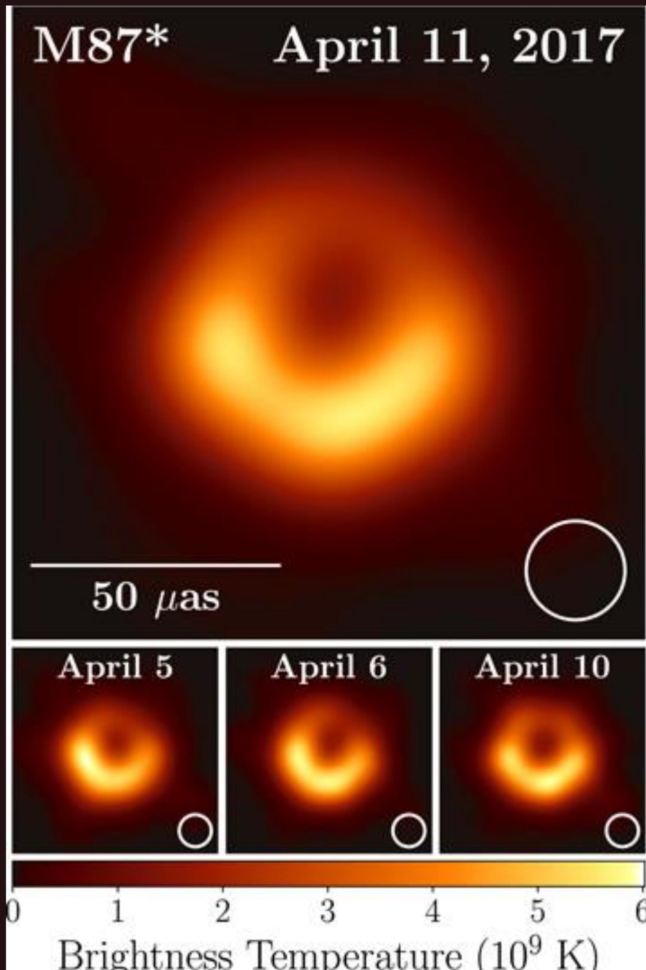


Radioastron

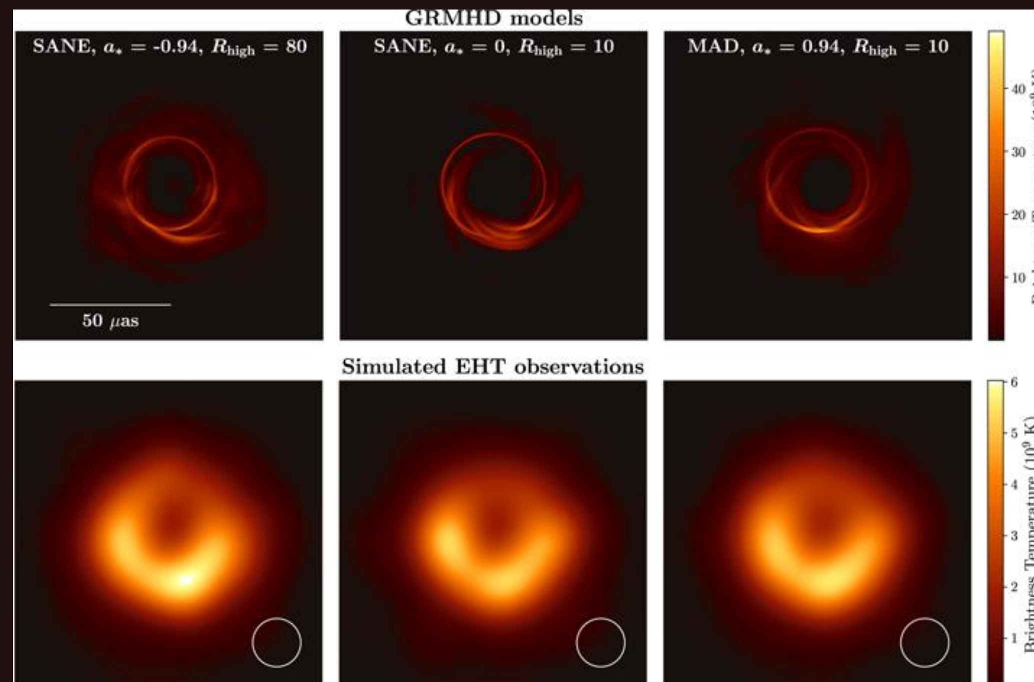
ALMA+mm-VLBI

About future plans and developments see 2304.11188
About interferometric observations of BHs: 2404.03522

SMBH in M87

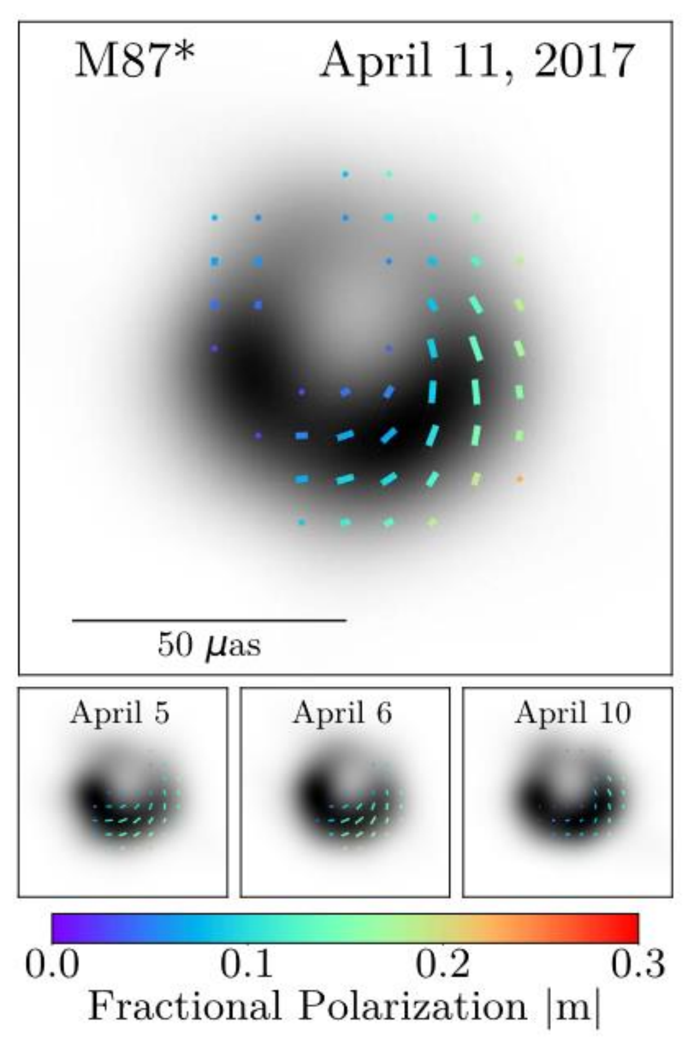


EHT 2017
Announced April 10, 2019
Structure, mass measurements, spin orientation

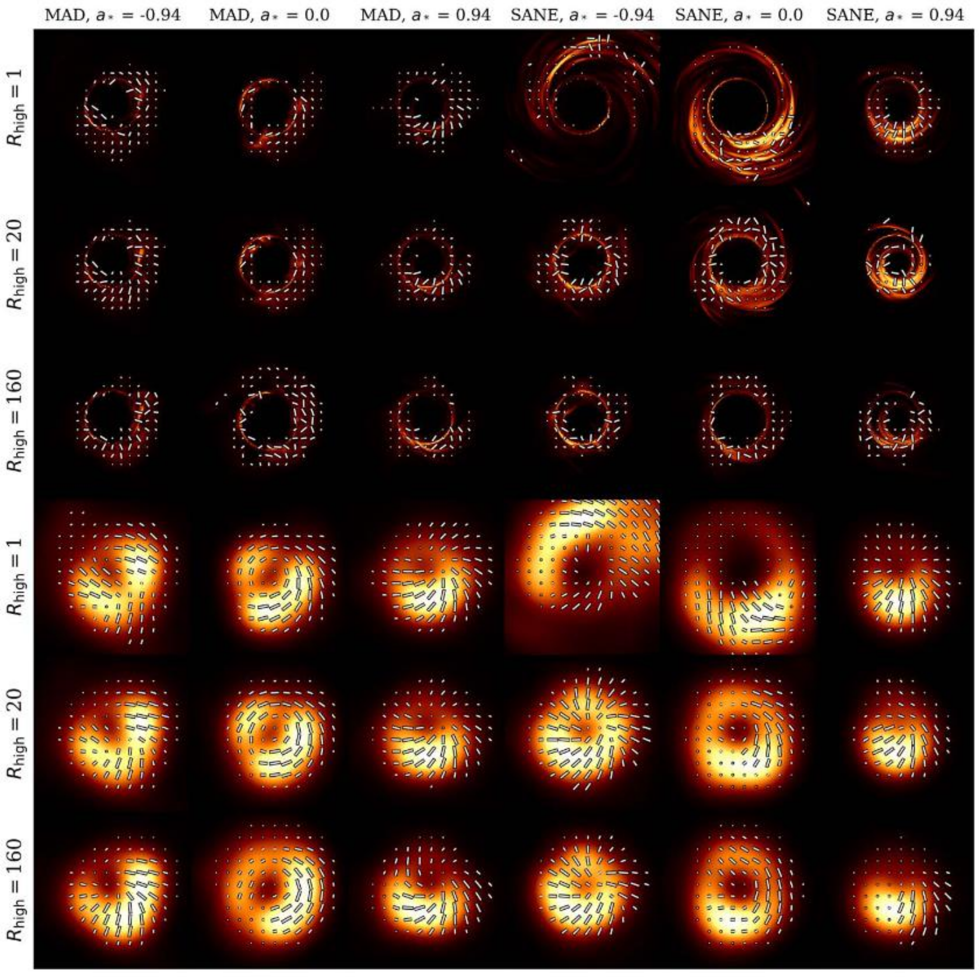


https://iopscience.iop.org/article/10.3847/2041-8213/ab0ec7

Magnetic field structure in M87

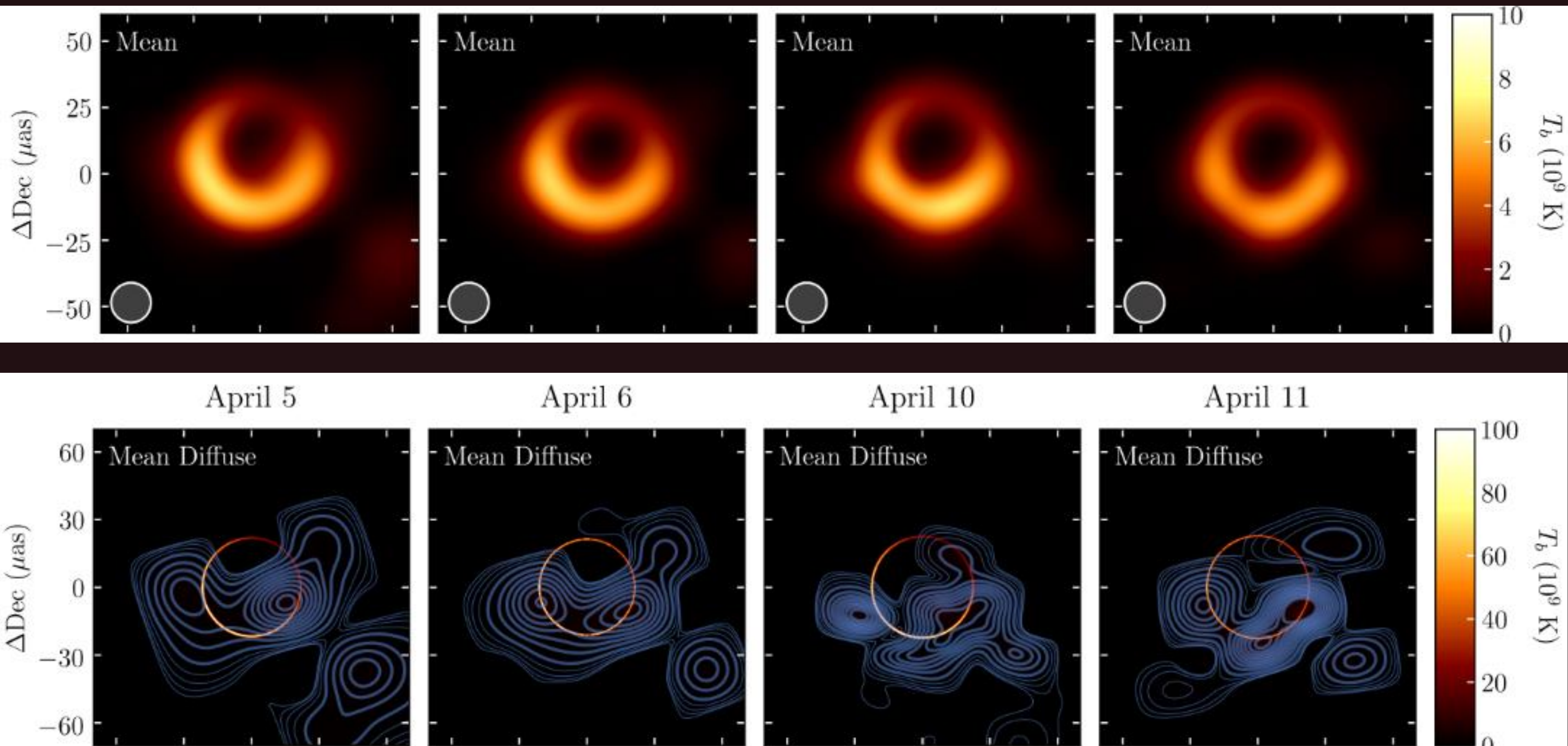


Polarization data strongly constrain GRMHD models.



2105.01173

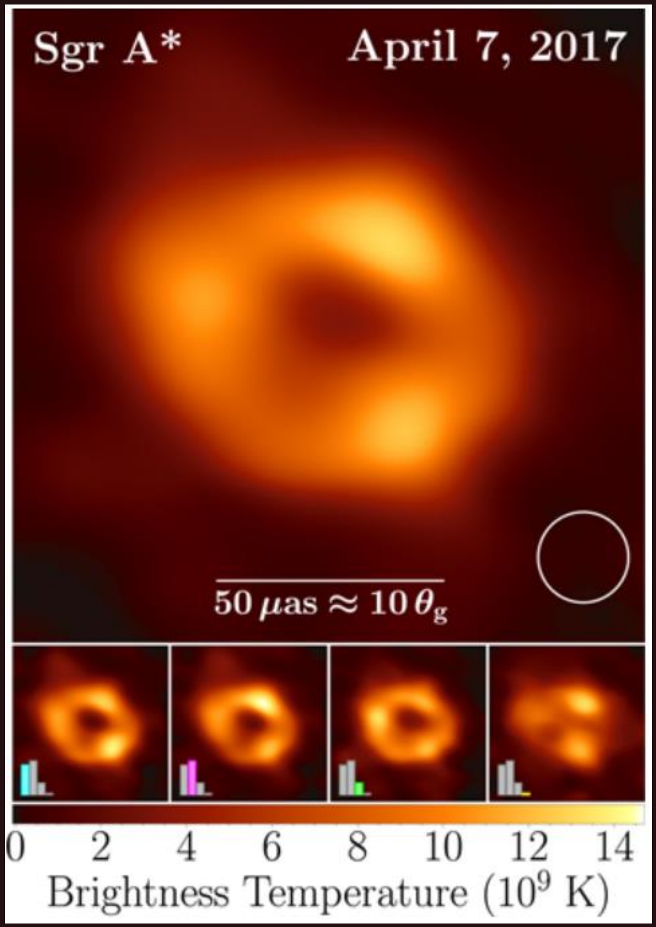
Photon ring in M87*

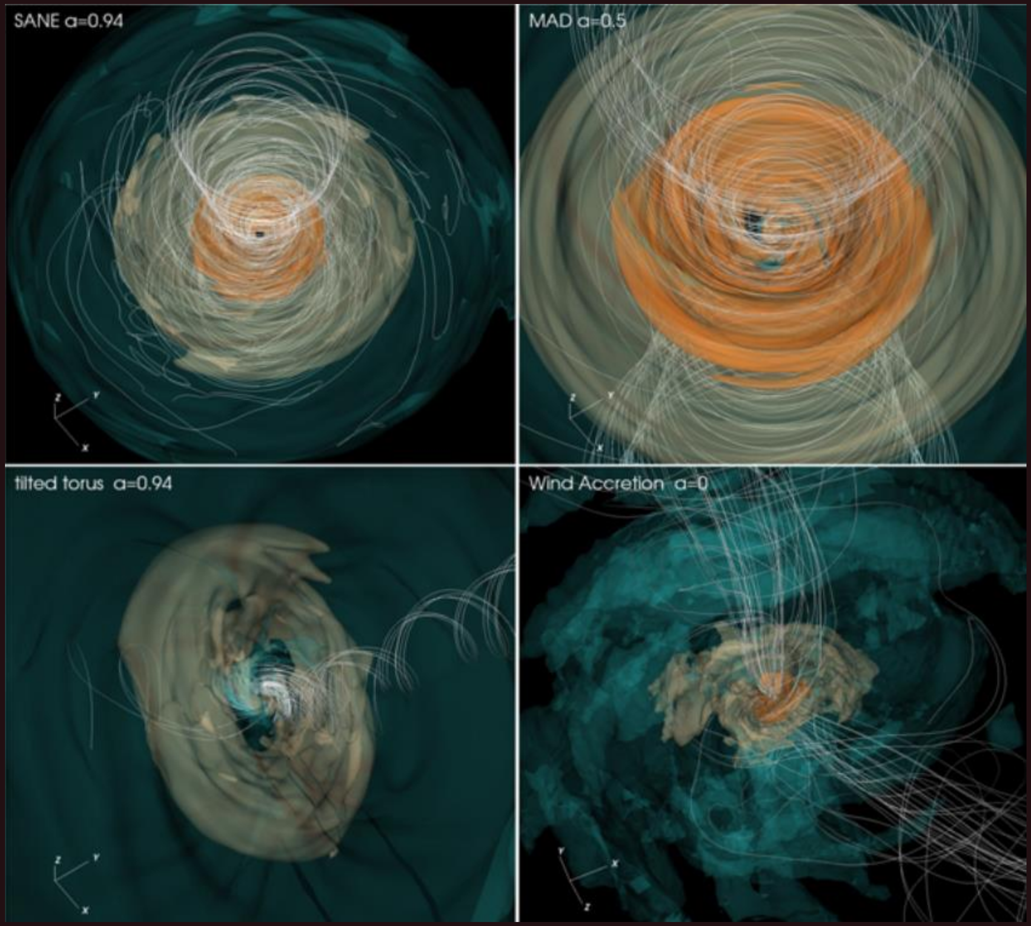


2208.09004

Photon ring in Sgr A*

https://iopscience.iop.org/article/10.3847/2041-8213/ac6674



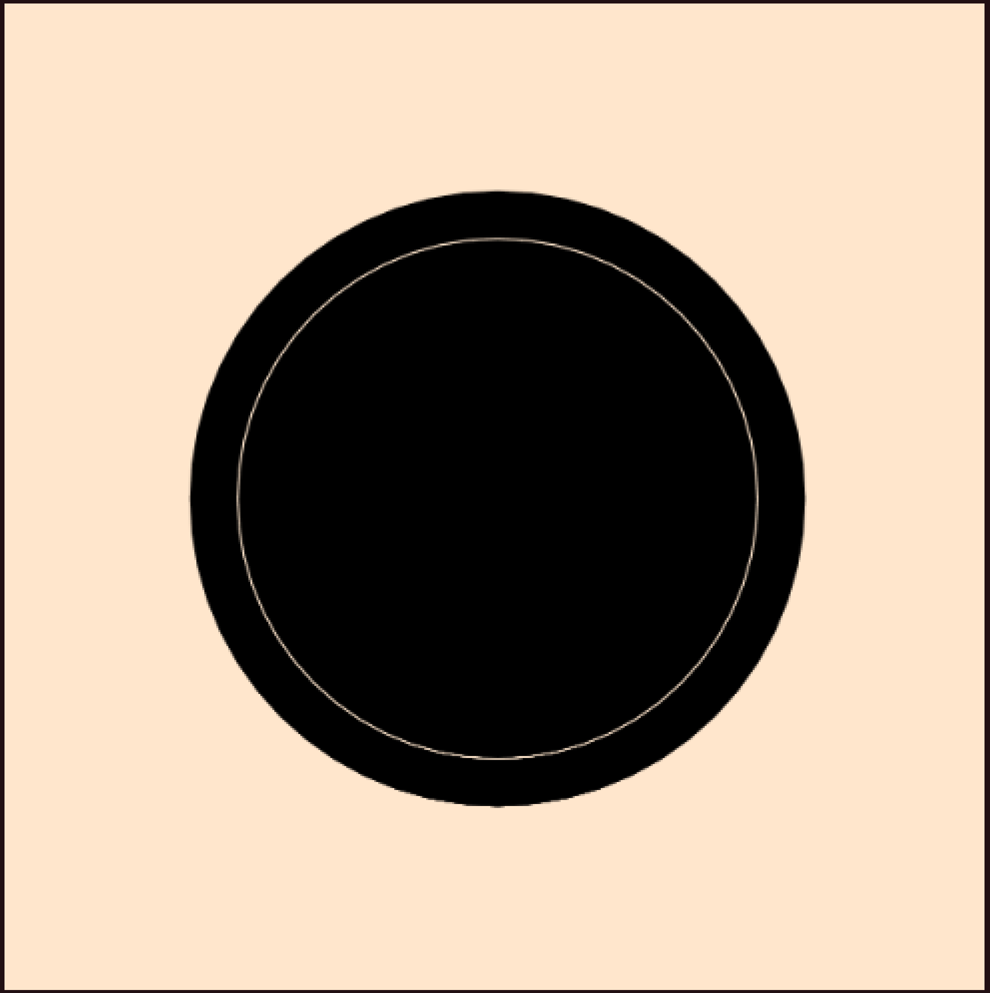


https://iopscience.iop.org/article/10.3847/2041-8213/ac6672

Flat uniform screen behind a BH

Observational appearance of a Schwarzschild black hole that is backlit by a large, distant screen of uniform, isotropic emission. The brightness (beige color) is uniform where it is non-zero.

The large dark area has radius 6.17M, and the thin ring has radius 5.20M and thickness 0.03M . Inside of this ring is an infinite sequence of tinier and tinier rings, which are far too thin to display in this figure.

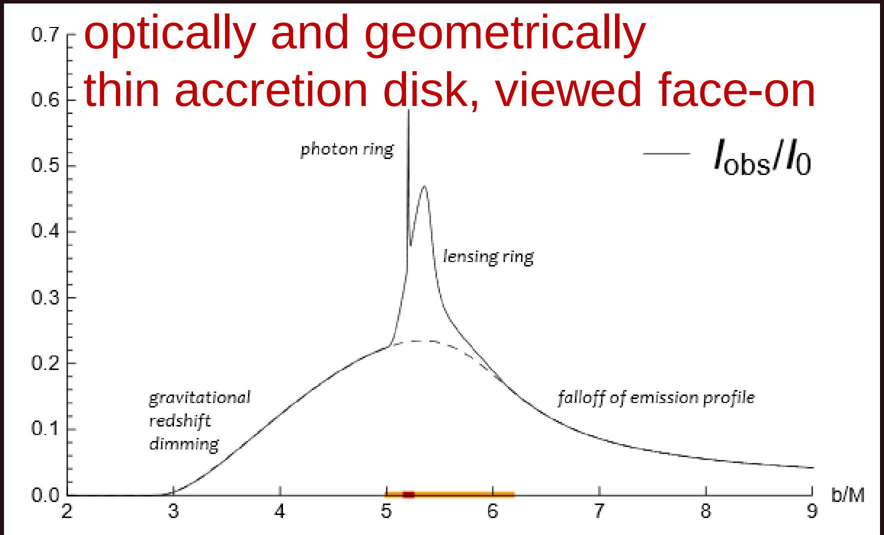


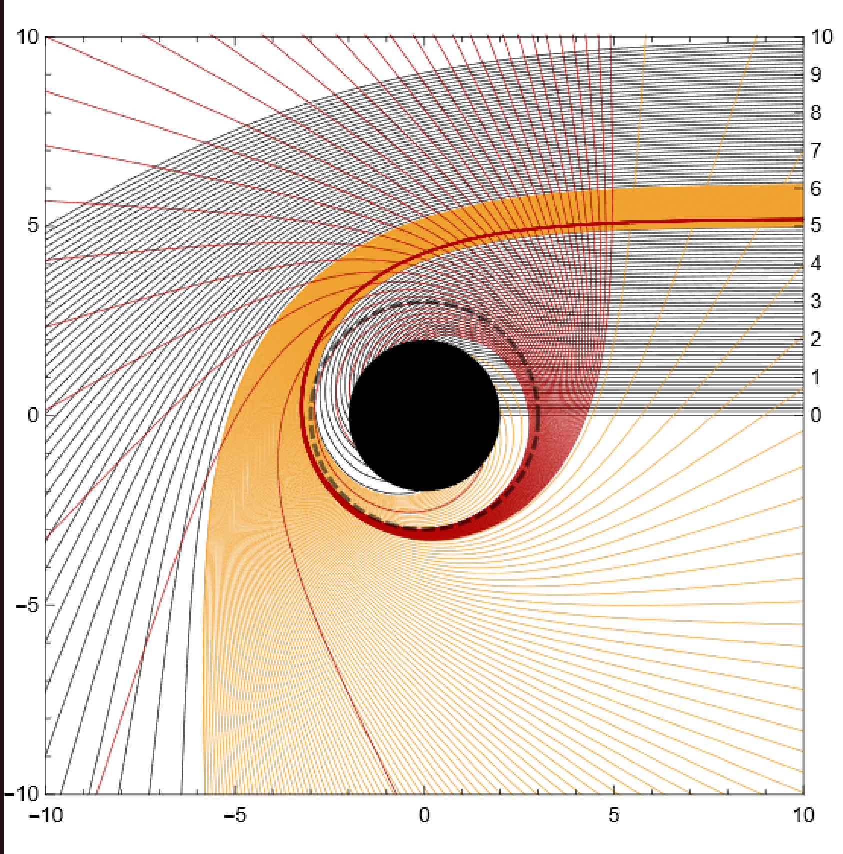
1906.00873

The shadow and the bright ring

$$R_\infty = R / \sqrt{1 - r_g / R}$$

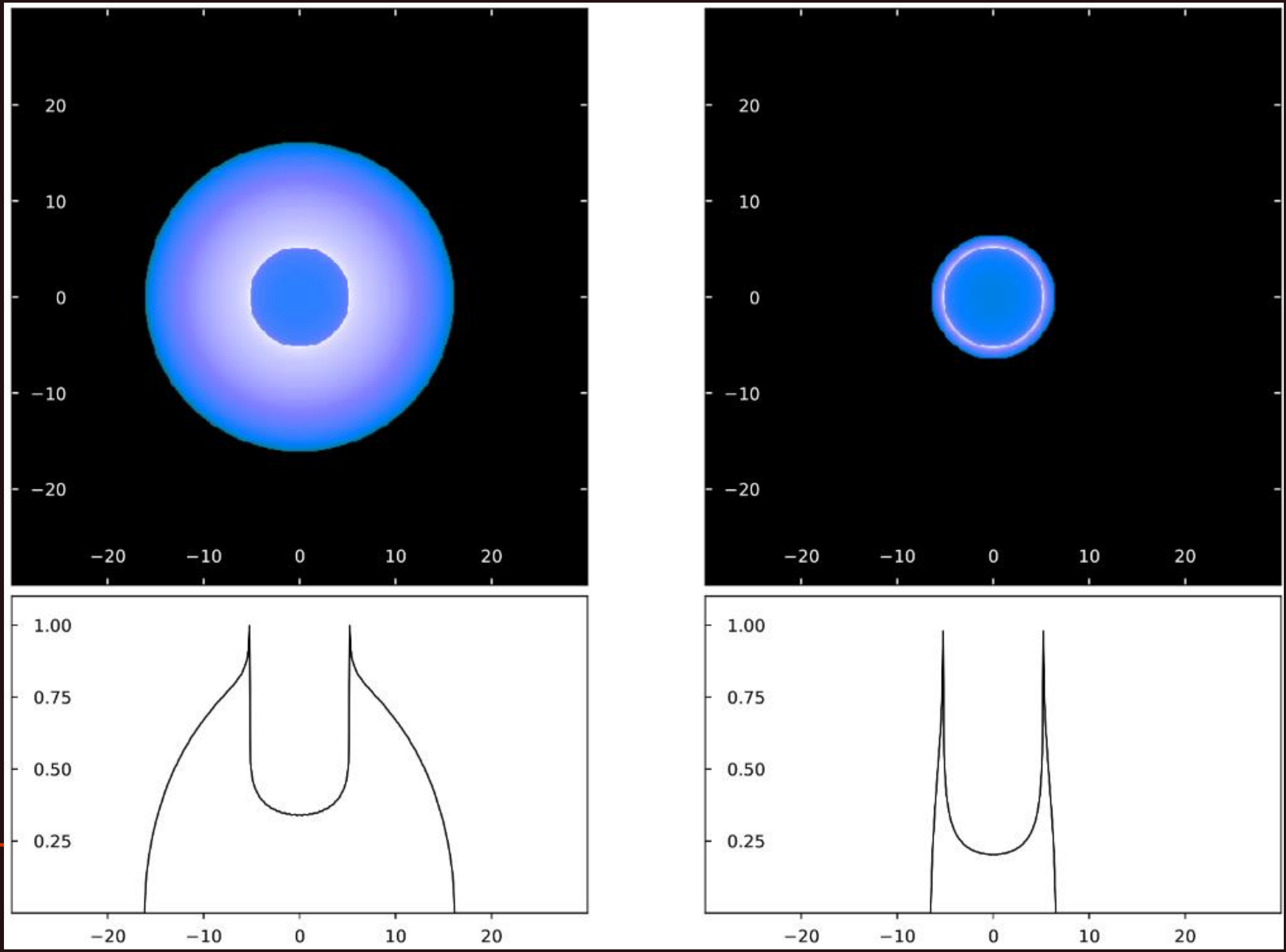
$$b_c = 3\sqrt{3}M$$





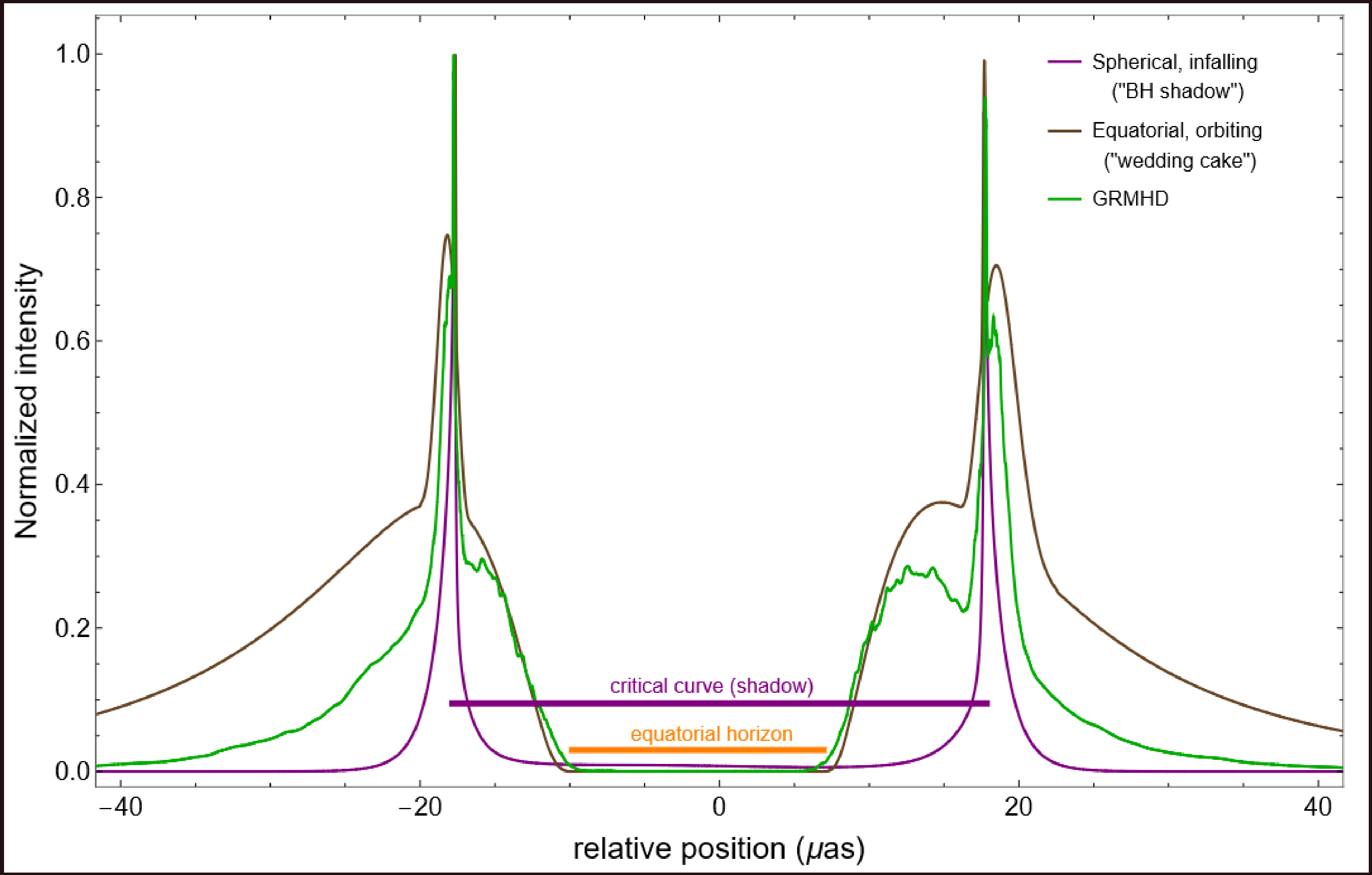
1906.00873

Shadow in the case of optically thin but geometrically thick emitters



2108.03966

What do we see: ring or disc, or …?



2206.12066

Active galactic nuclei and quasars

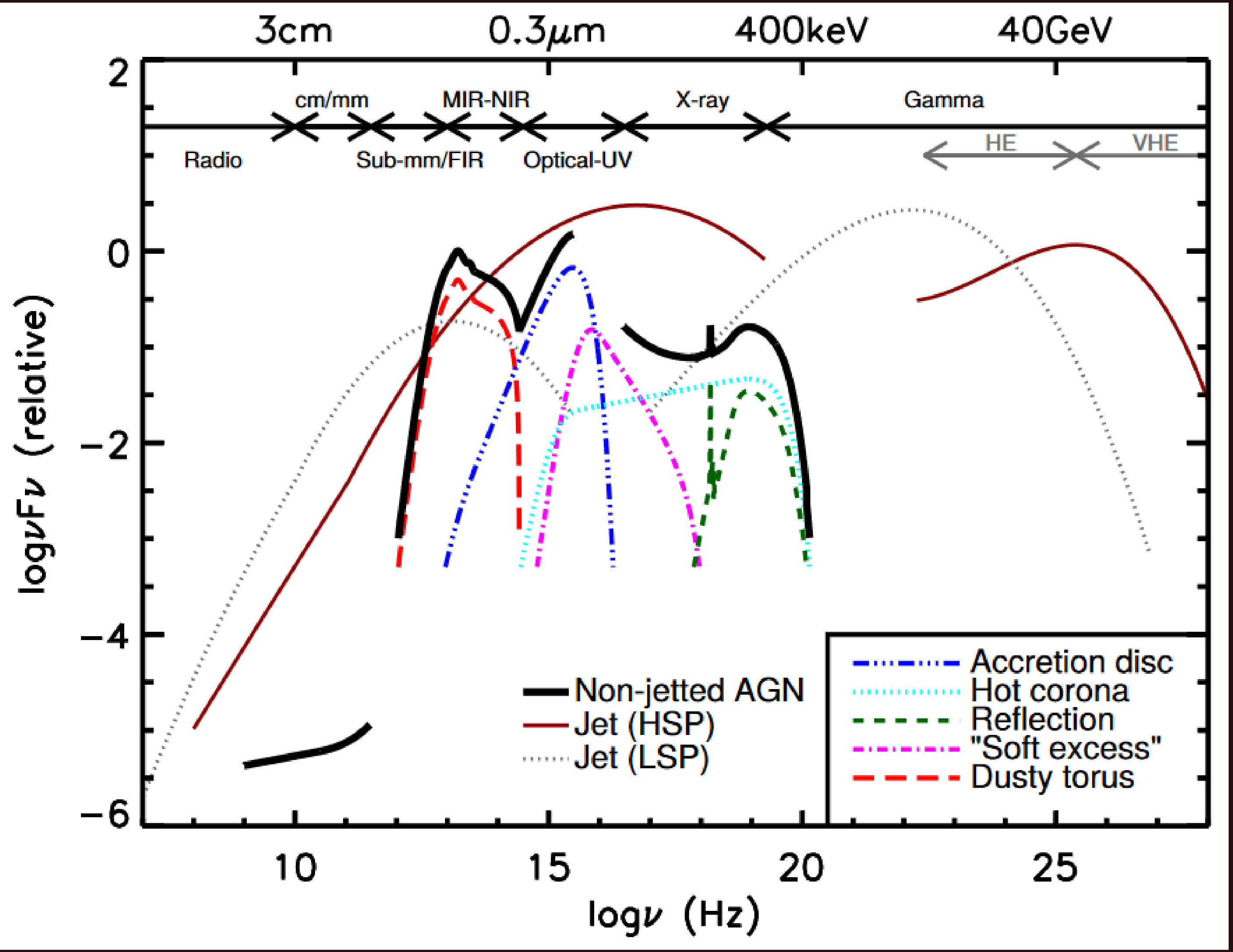
The classification is not very clear

- 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)

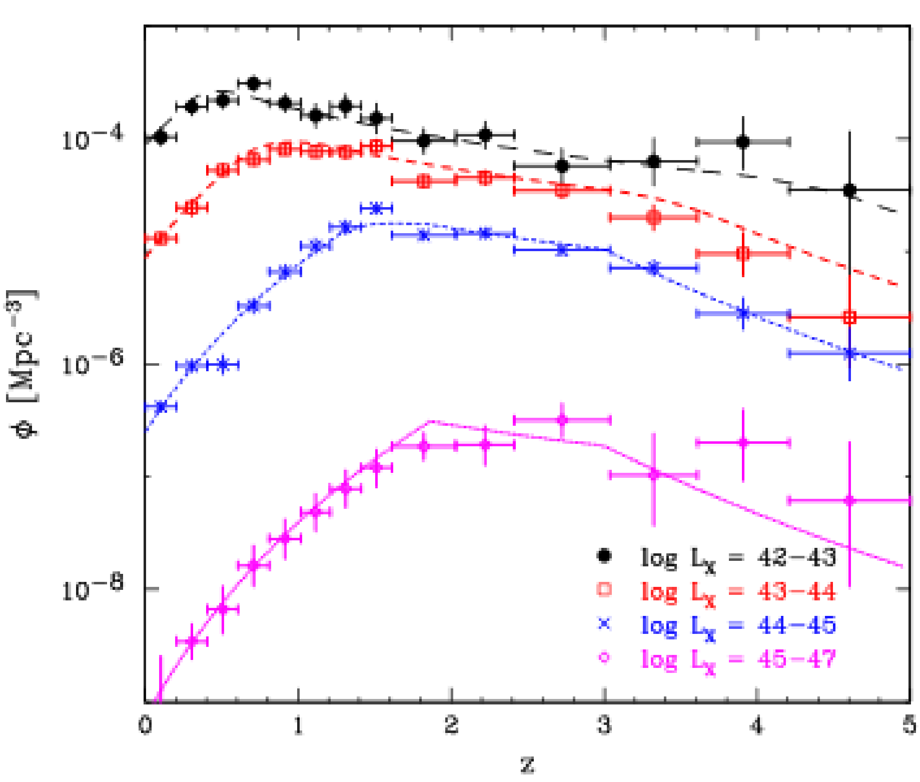
(see, for example, astro-ph/0312545)
A popular review can be found in arXiv: 0906.2119

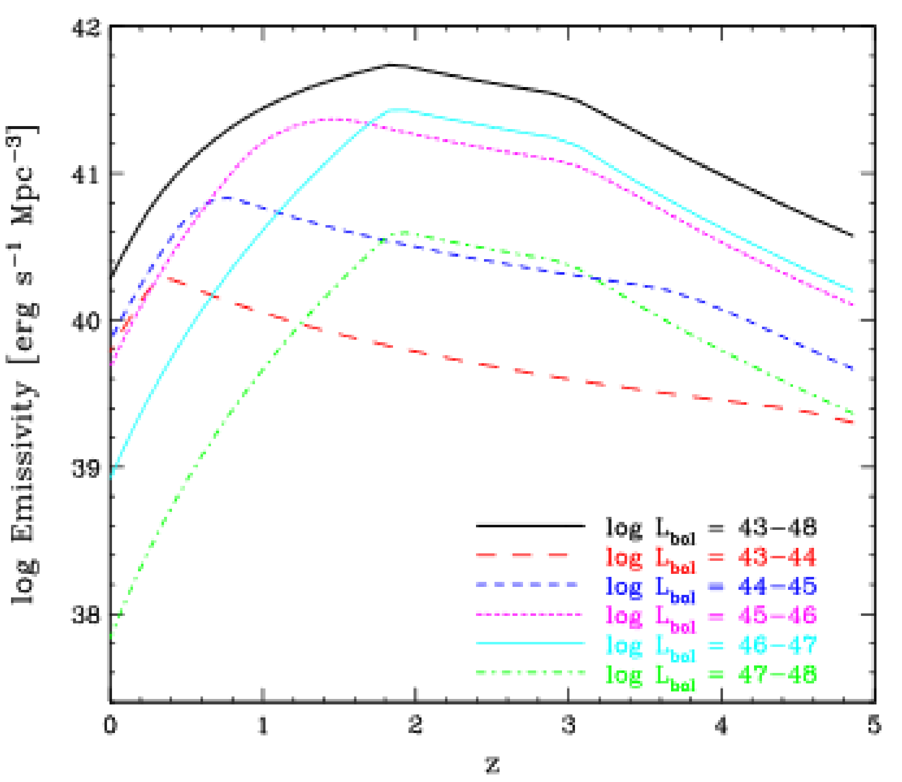
Spectra of AGNs



1707.07134 – detailed review on different types of AGNs

X-ray observations of AGNs



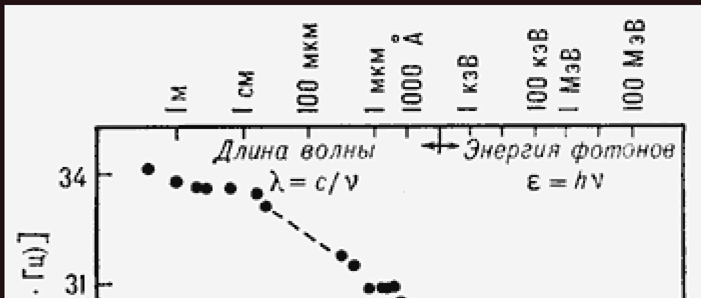


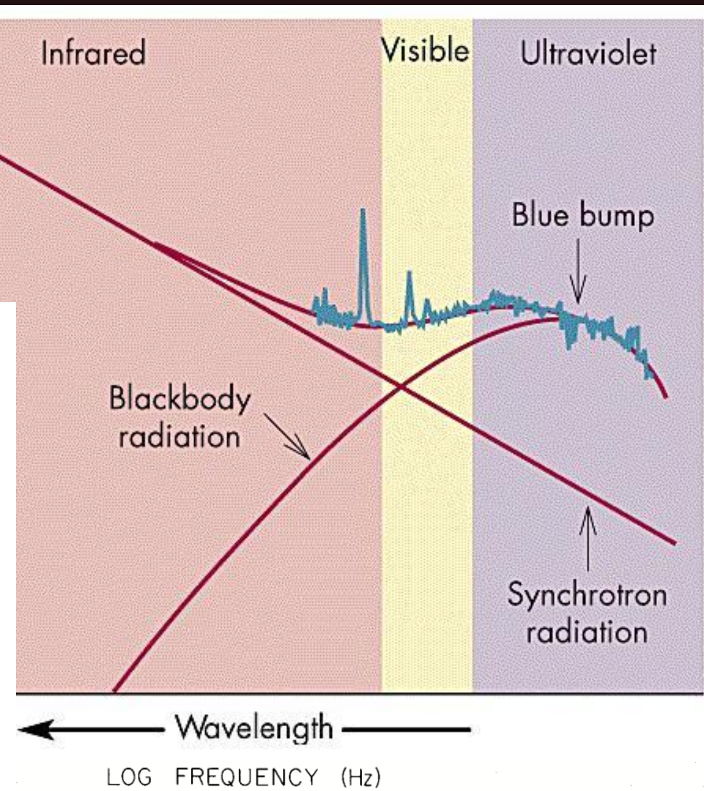
Comoving number density vs. redshift for AGNs, selected from multiple X-ray surveys, in four rest-frame 2–10 keV luminosity classes.

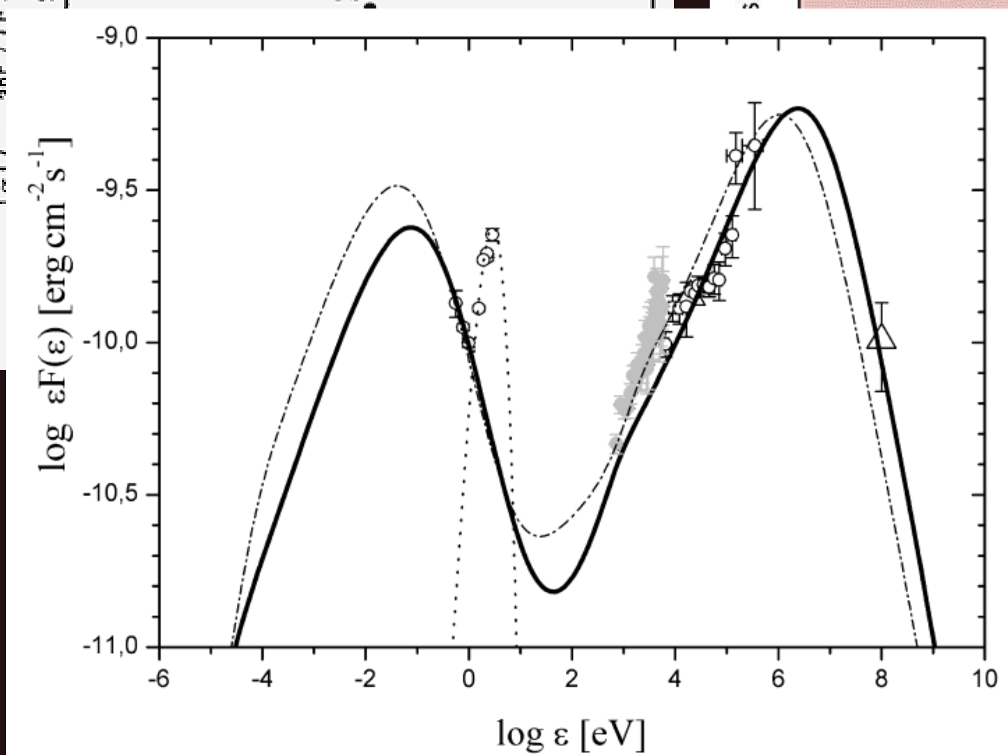
Comoving bolometric luminosity density vs. redshift for the same AGN sample in six bolometric luminosity classes.

1501.01982

Quasars spectra

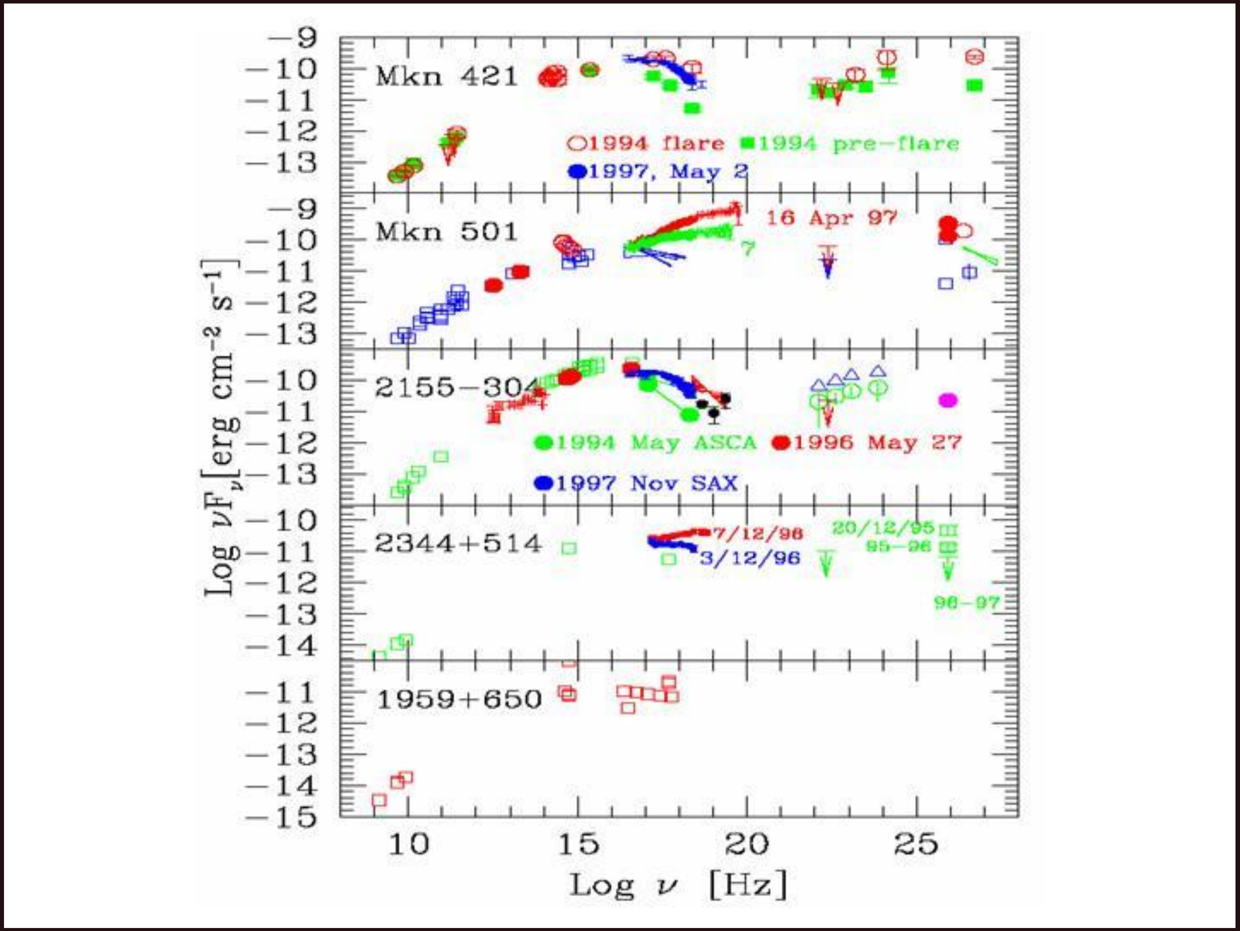






1102.4428

Spectra of BL Lacs



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

Ghisellini (1998)

Fermi observations of blazars: Huge set of data

In the third Fermi catalogue
(1501.02003)
>1100 AGNs

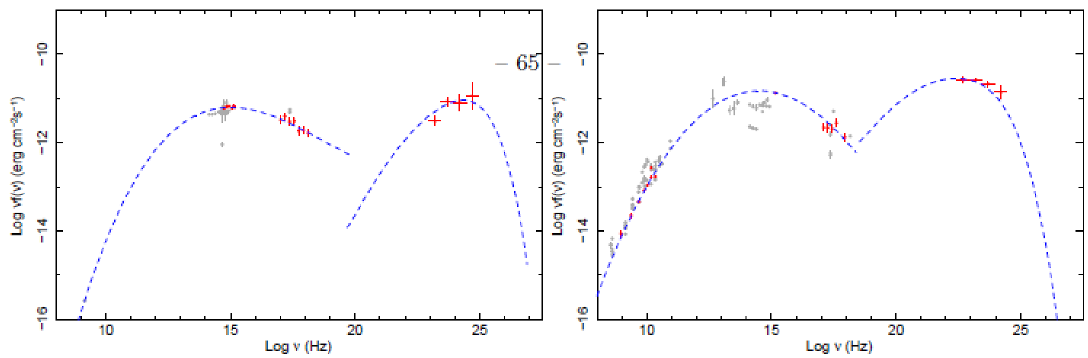
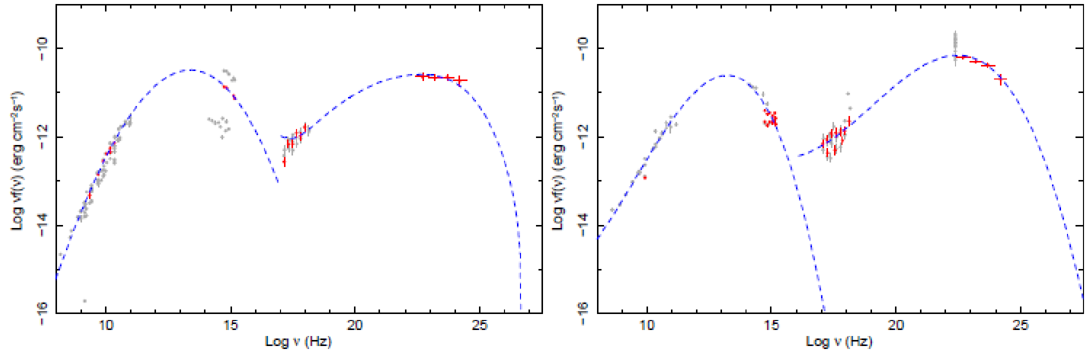


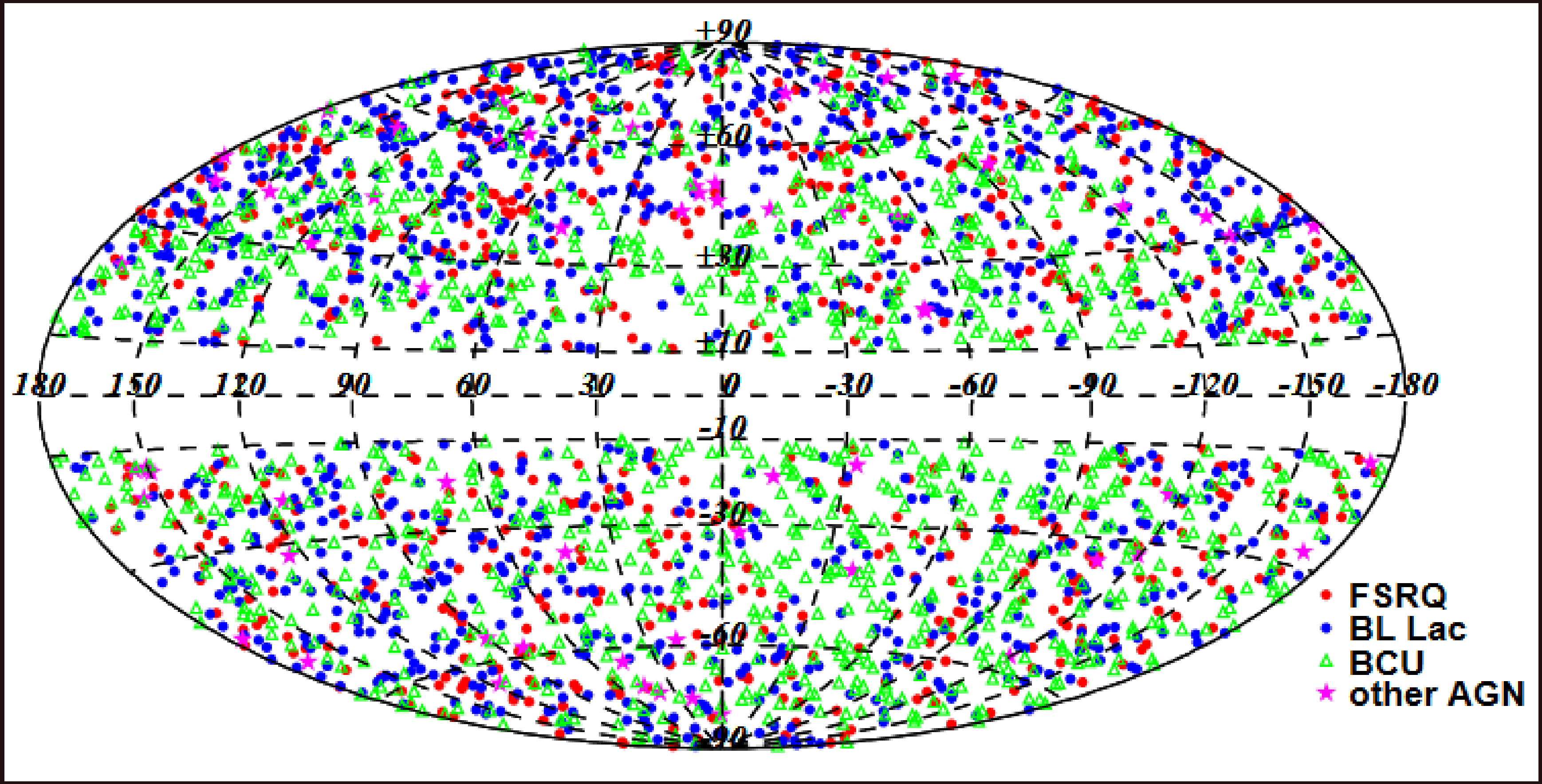
Fig. 1.— The SED of 0FGL J0033.6-1921 = 1RXS J003334.6-192130 = SHBL J003334.2-192133 (left) and of 0FGL J0050.5-0928 = PKS0048-09 (right). The quasi-simultaneous data appear as large filled red symbols, while non-simultaneous archival measurements are shown as small open grey points. The dashed lines represent the best fits to the Synchrotron and Inverse Compton part of the quasi-simultaneous SEDs (see text for detail).



0912.2040

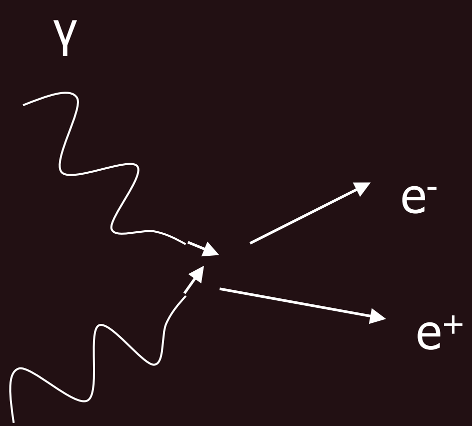
AGN in the forth Fermi catalogue

>2000 AGN

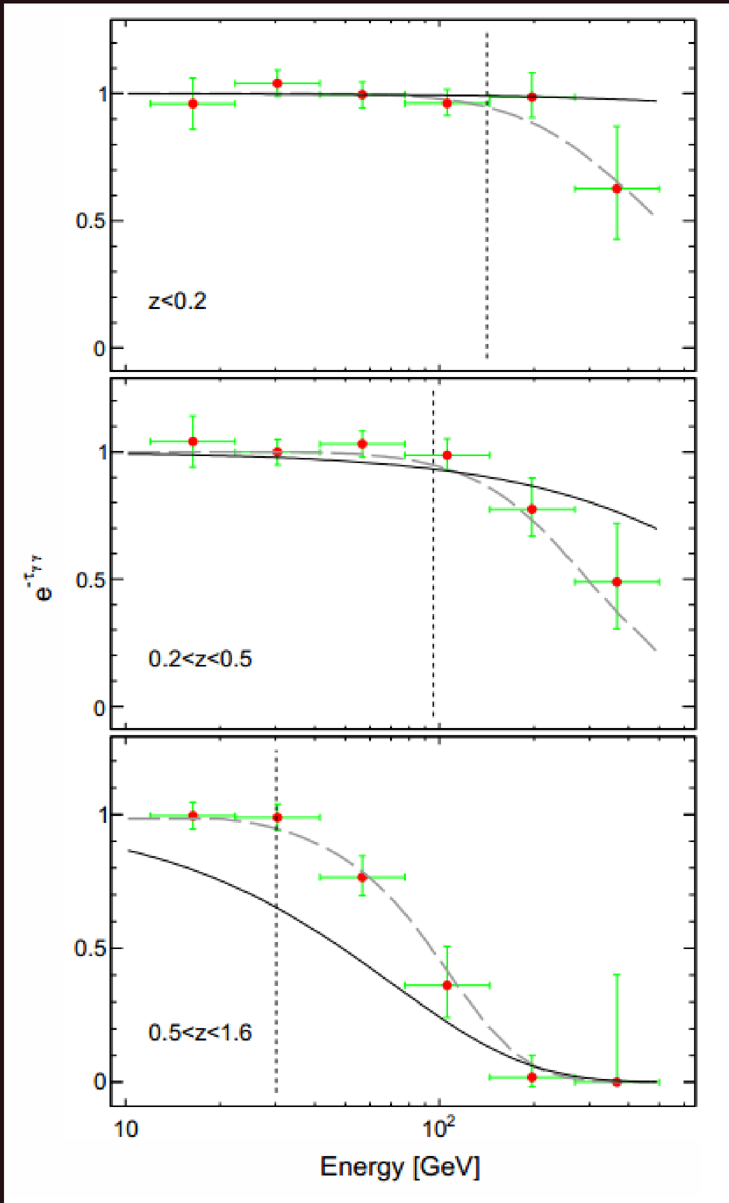


1905.10771

Background radiation

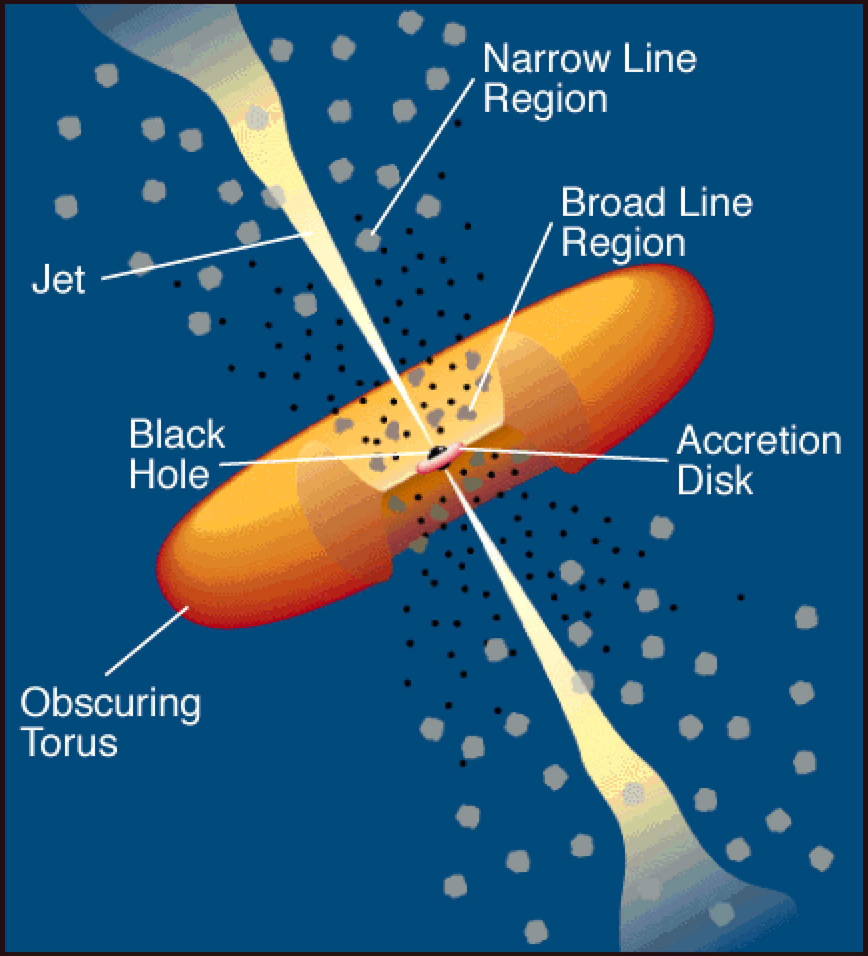


Photons from a distant source of gamma-emission can interact on their way with background UV and optical photons producing e^+-e^- pairs.
As a result, we observe a deficit of gamma photons in the spectrum.
It is challenging to detect it in the case of a single source.
The authors used Fermi data on ~150 blazars to identify a joint effect.



1211.1671

Unified model

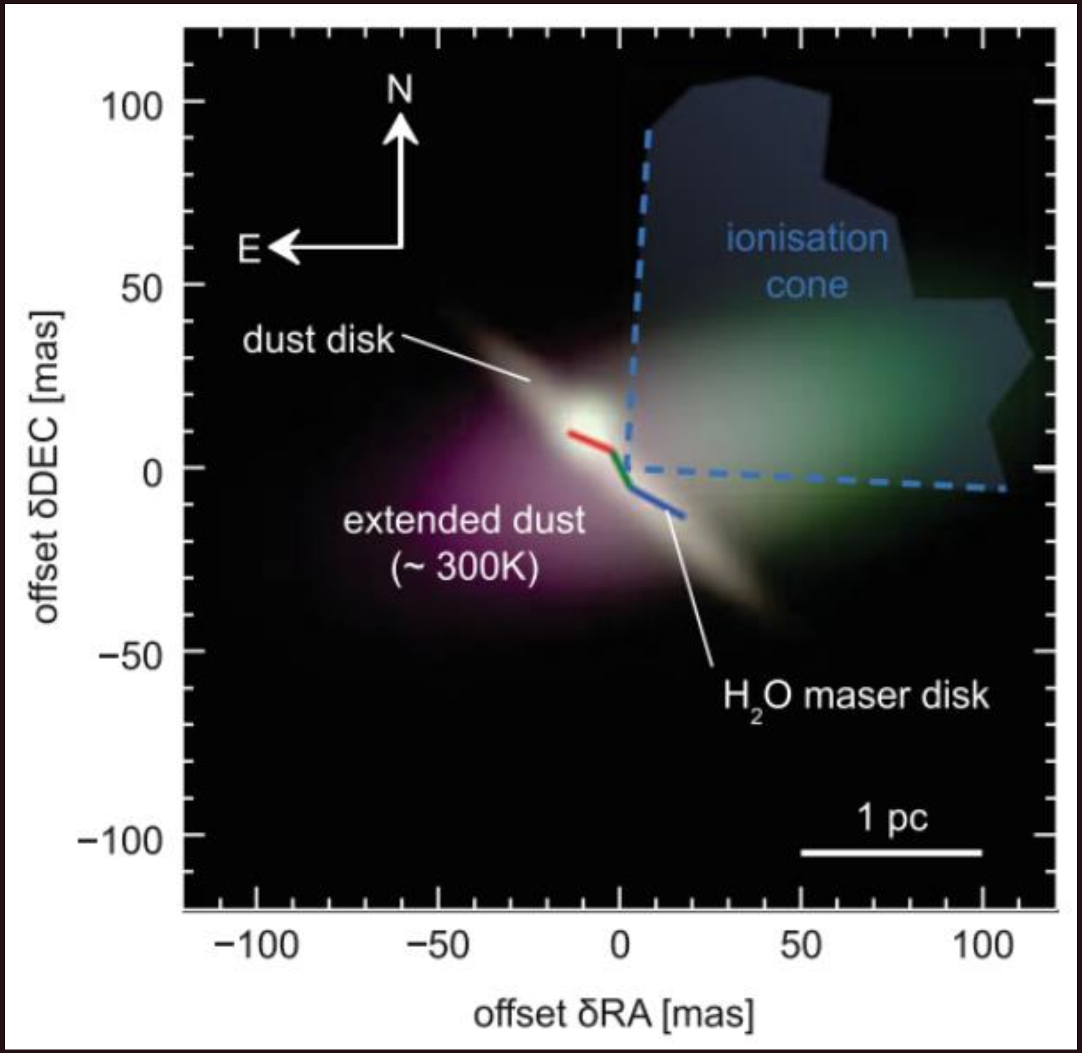


In the framework of the unified model properties of different types of AGNs are explained by properties of a torus around a BH and its orientation with respect to the line of sight.

Antonucci 1993 ARAA 31, 473

The model can be unapplicable to merging systems, see 1505.00811

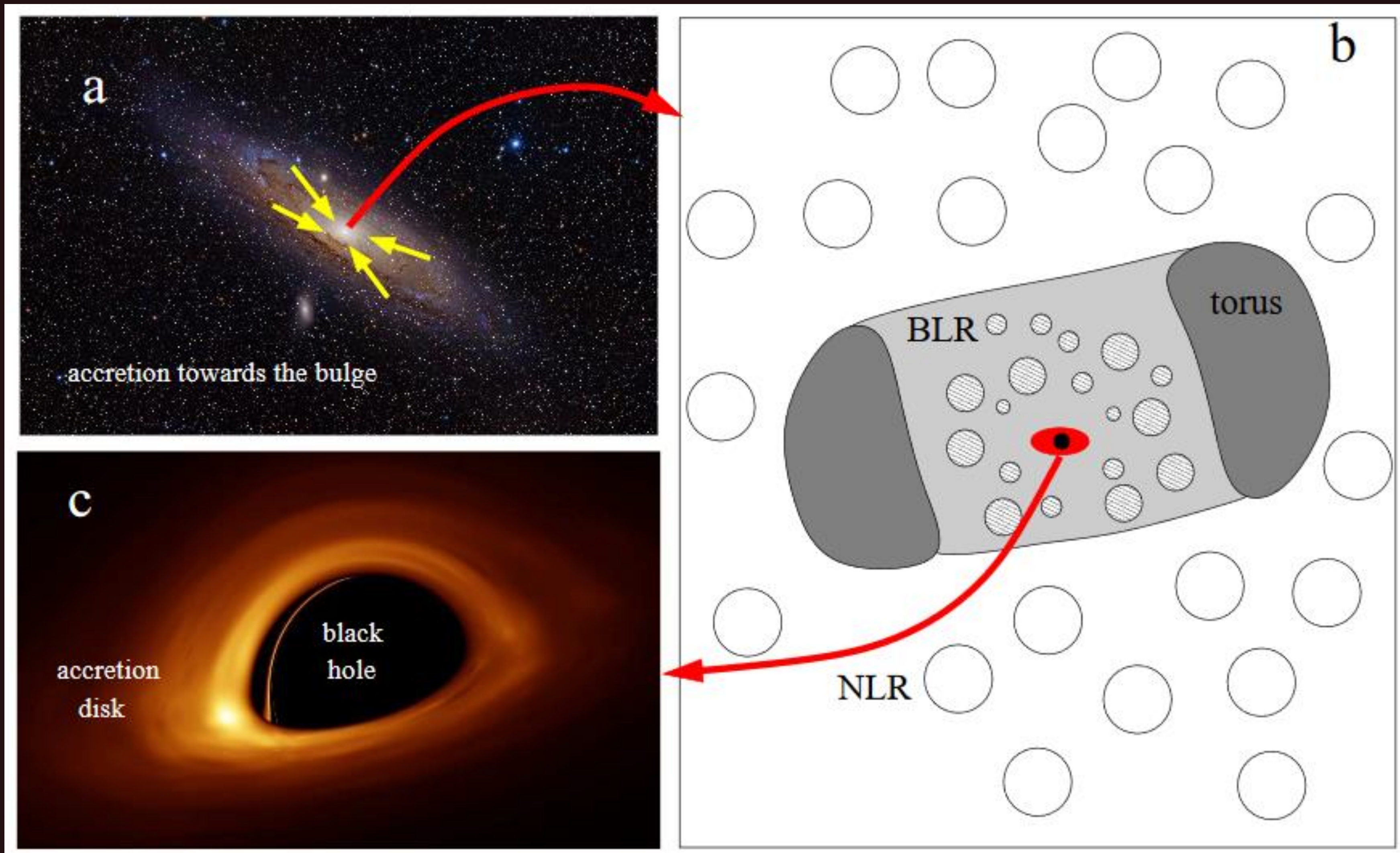
IR data for unification



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

1911.12176

Accretion on different scales

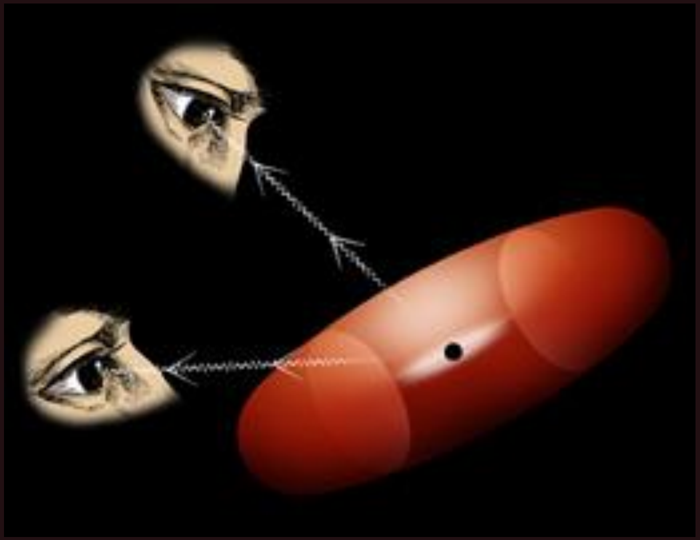


1712.06915

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

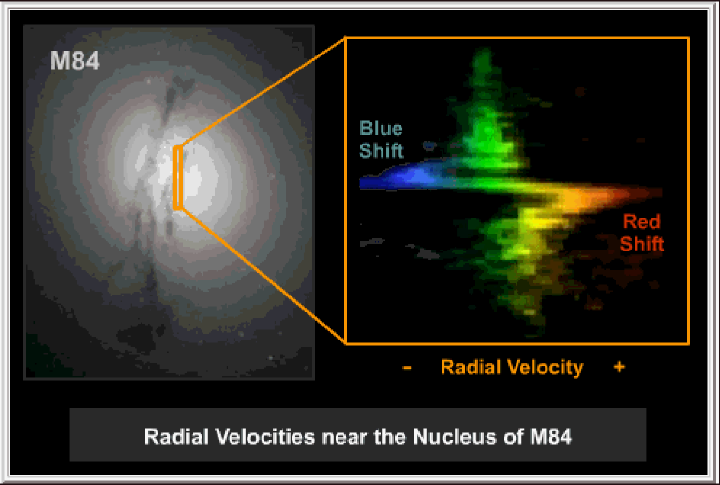
- Relative fracton of nuclei obscured by toruses
- Luminosity distribution of nuclei
- Spectral energy distribution
- Evolution of all these parameters

Mass determination in the case of SMBHs

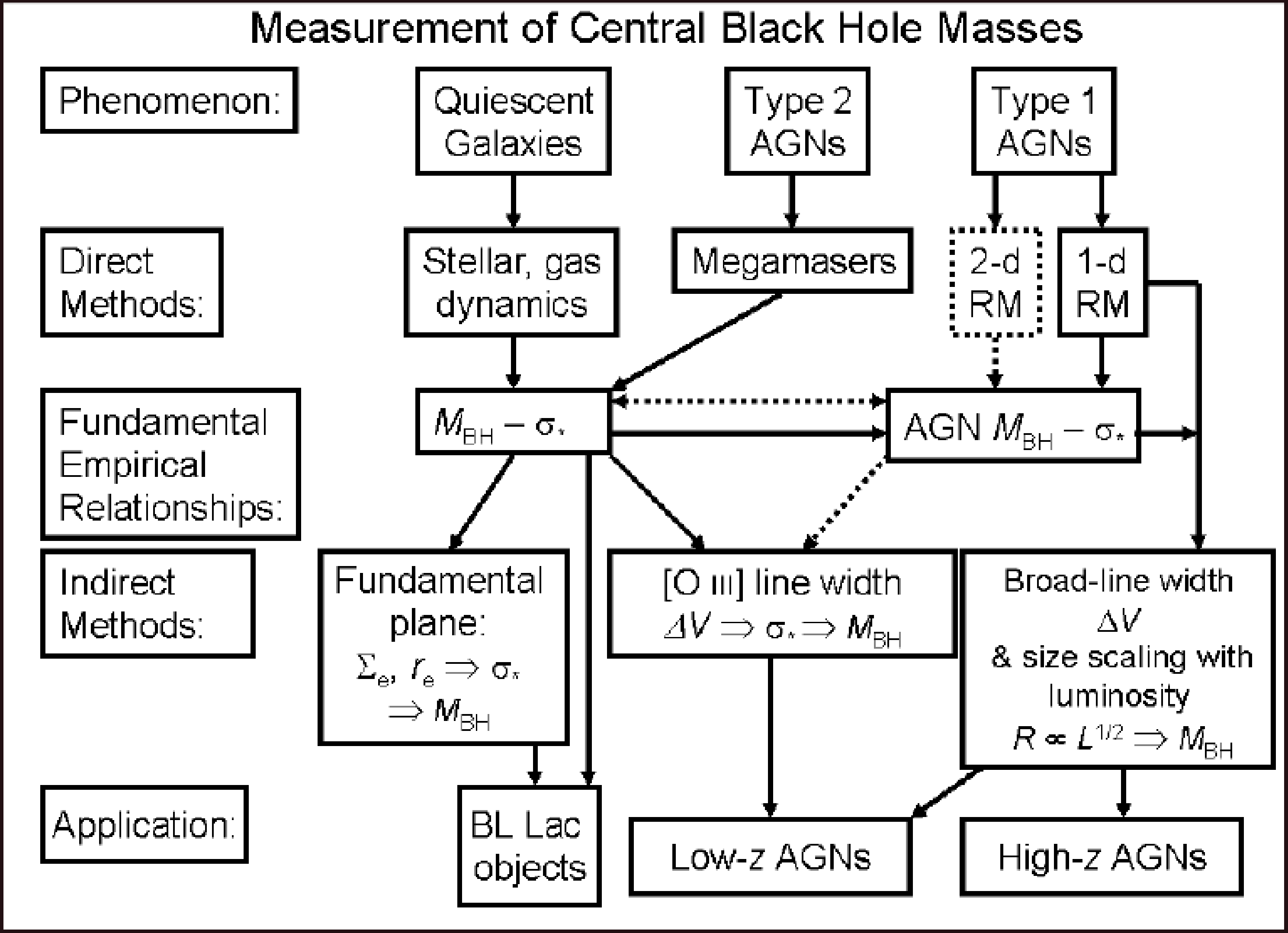
- Measurements of orbits of stars and masers around a BH.
- Gas kinematics.
- Stellar density profile.
- Reverberation mapping.
- Relation between a BH mass and a bulge mass (velocity dispersion).

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 also reviews in 0904.2615, and 1001.3675



Different methods



1001.3675

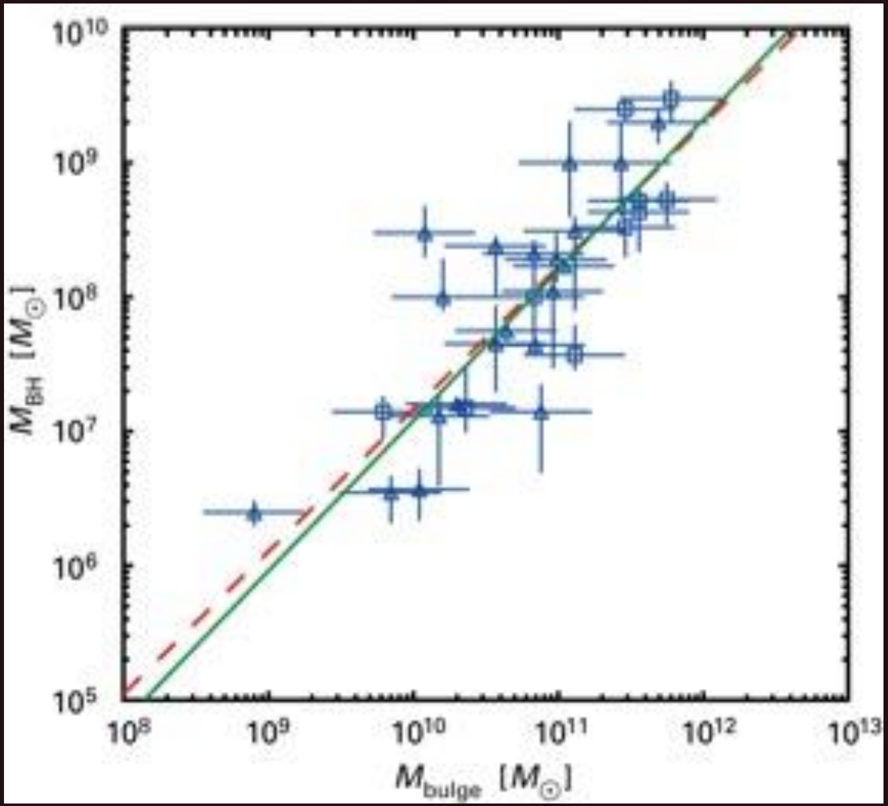
Comparison

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

1001.3675

BH mass vs. bulge mass

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

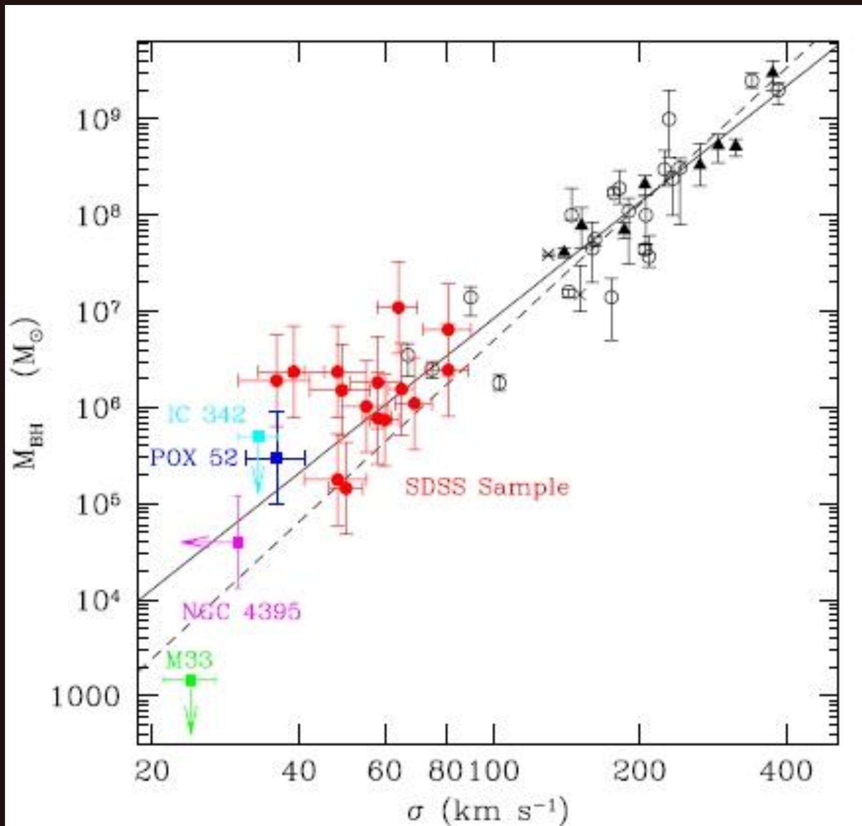


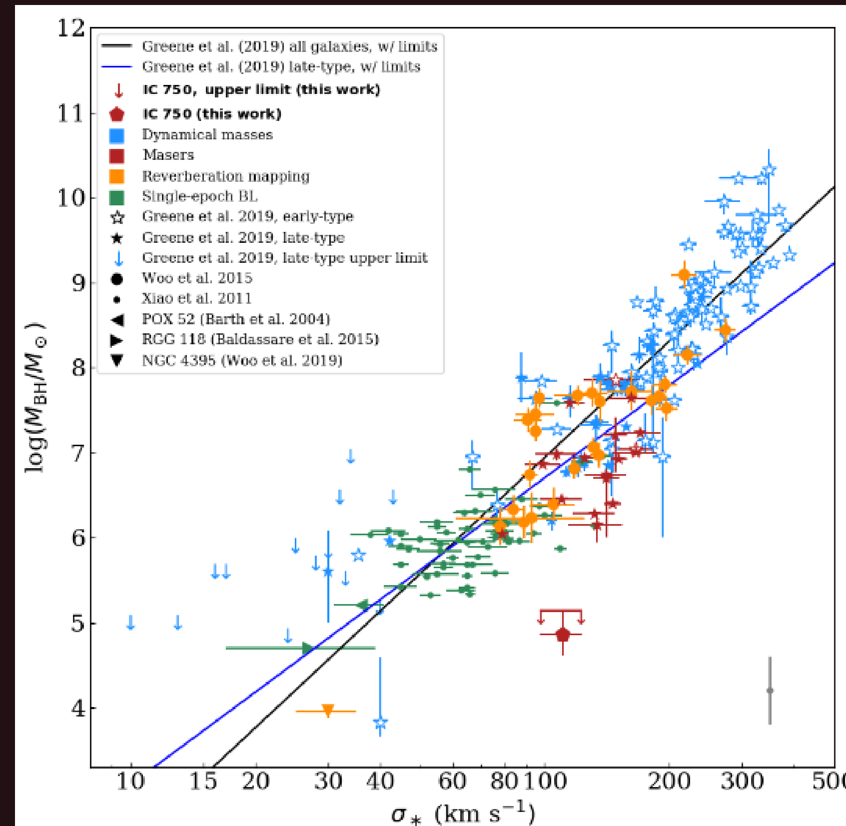
$M_{BH} \sim M_{bulge}^{1.12+/-0.06}$
(Haering, Rix astro-ph/0402376)

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





2006.01114

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

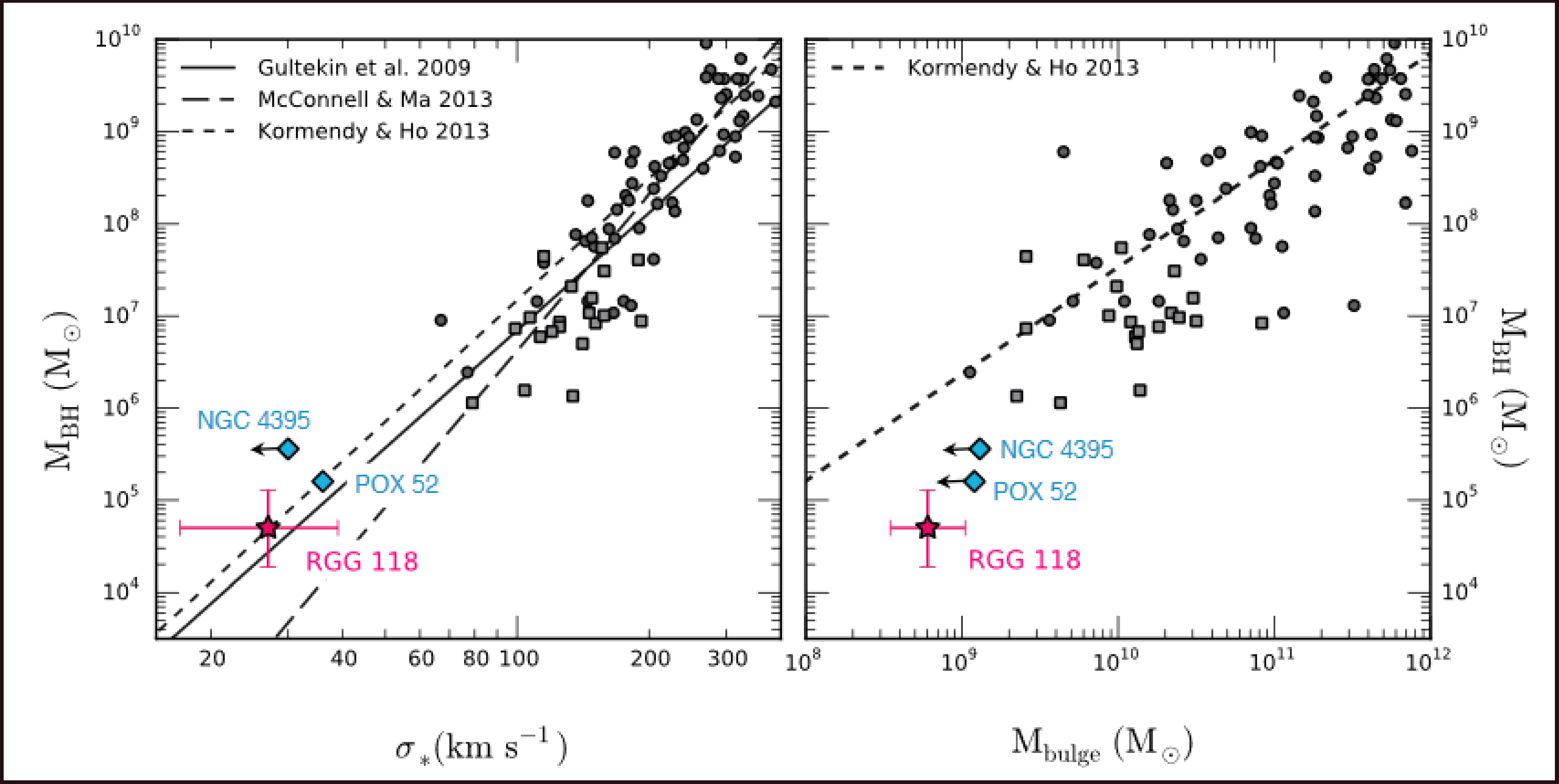
IC 750
Accreting SMBHs in a galaxy with a massive buldge.

Combes astro-ph/0505463

Light SMBH

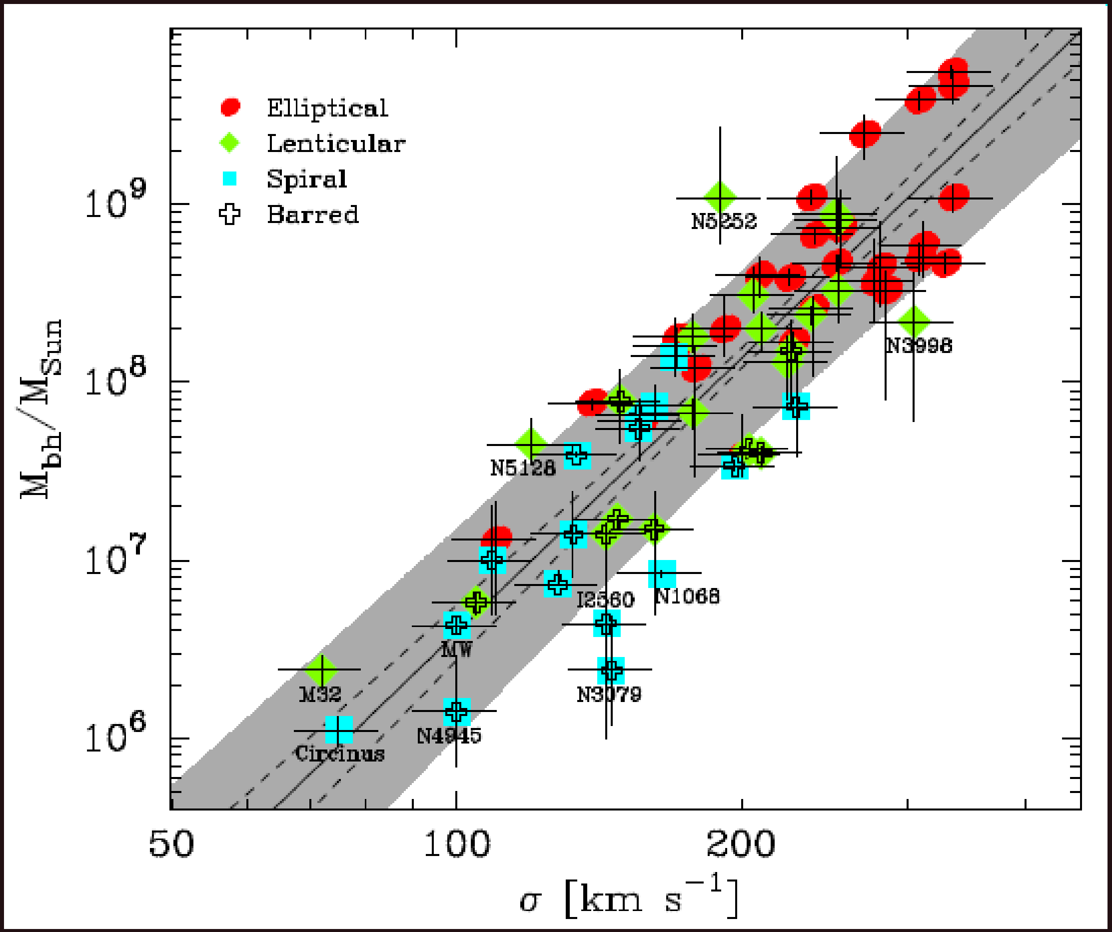
dwarf galaxy RGG 118

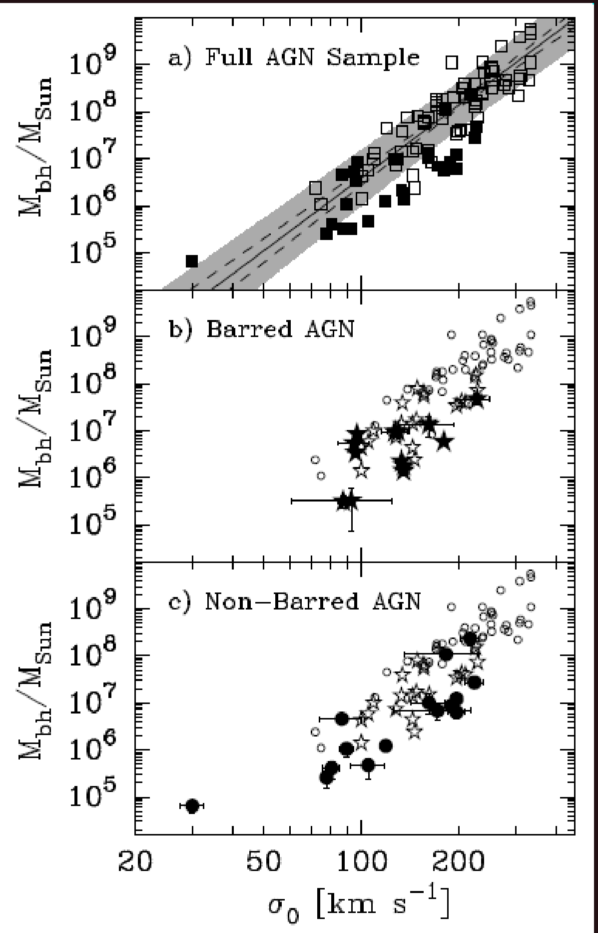
BH 50 000 solar masses



1506.07531

More data. Various galaxies.

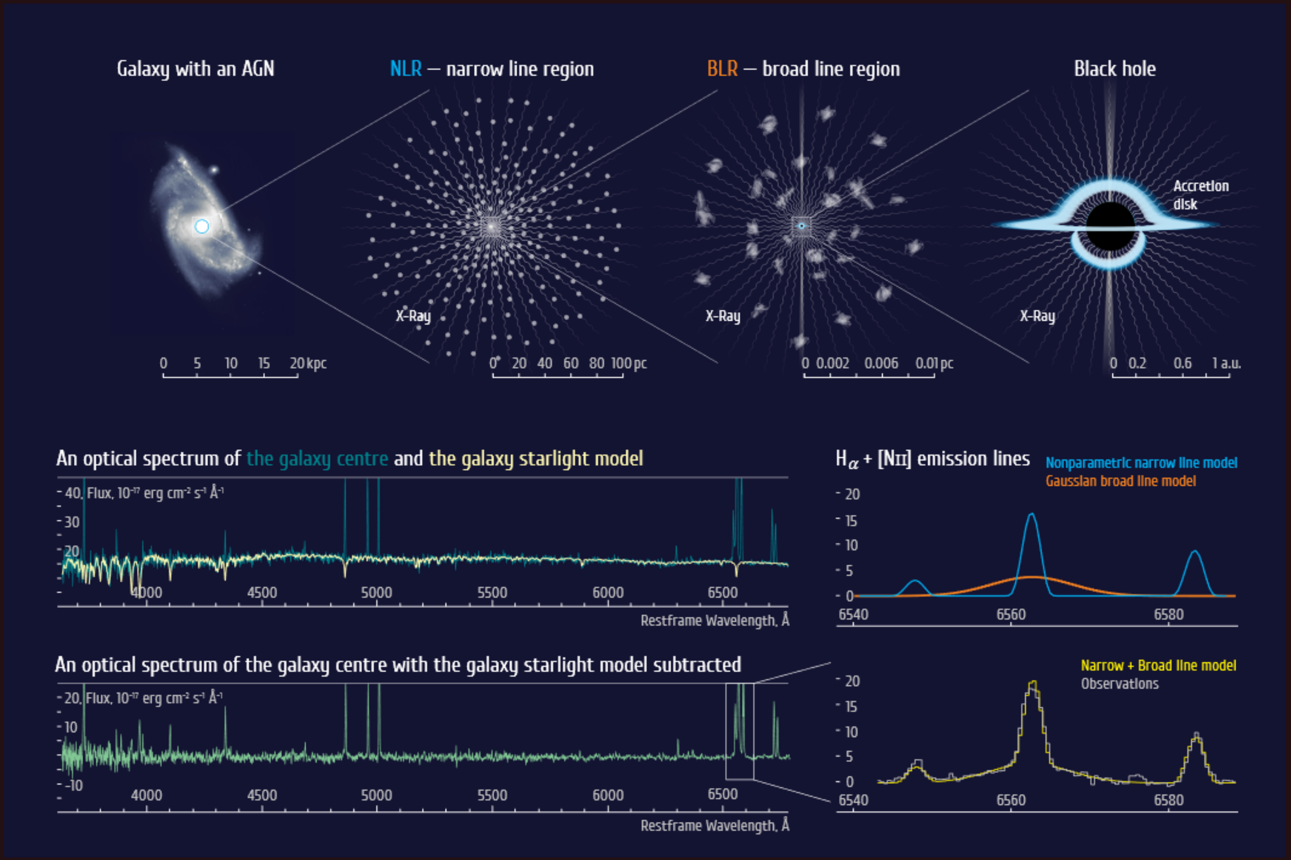




1007.3834

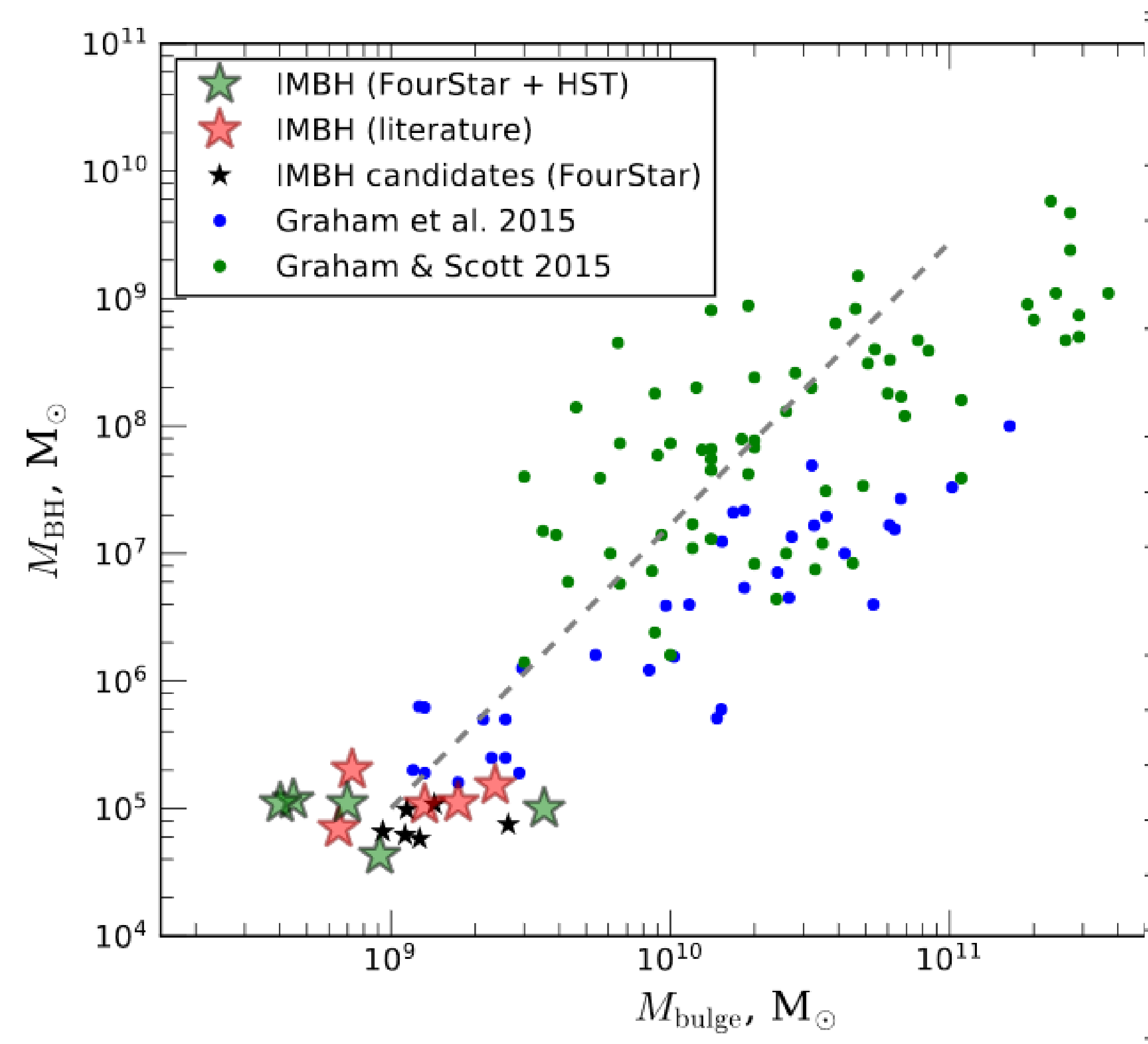
IMBHs in low luminosity AGNs

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



1805.01467

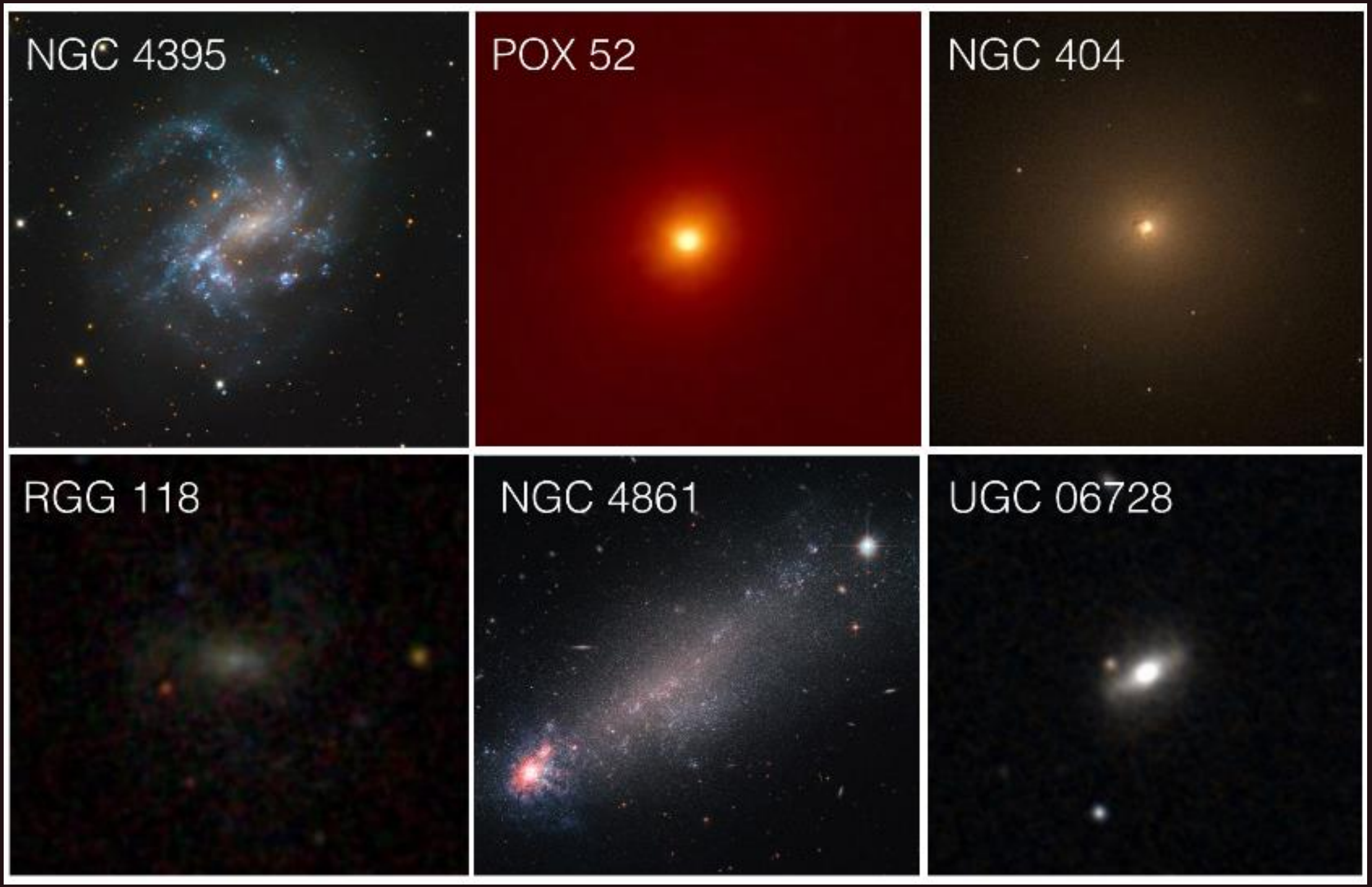
IMBHs in low luminosity AGNs



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]

1805.01467

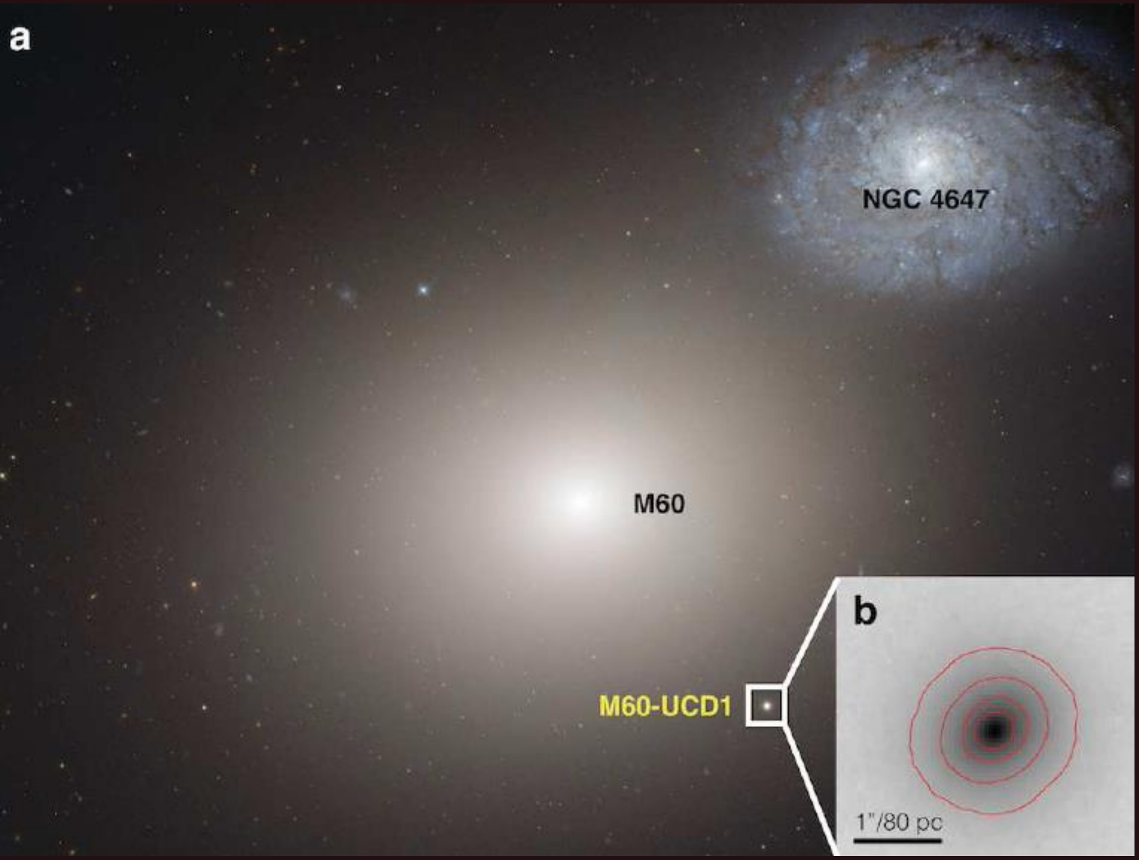
Dwarf galaxies with IMBHs

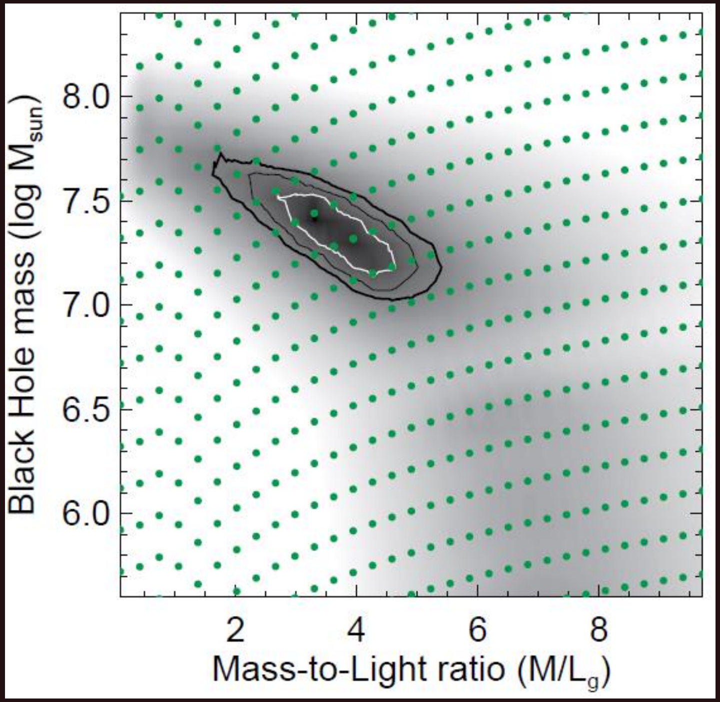


1705.09667 - review

A SMBH in a compact dwarf galaxy

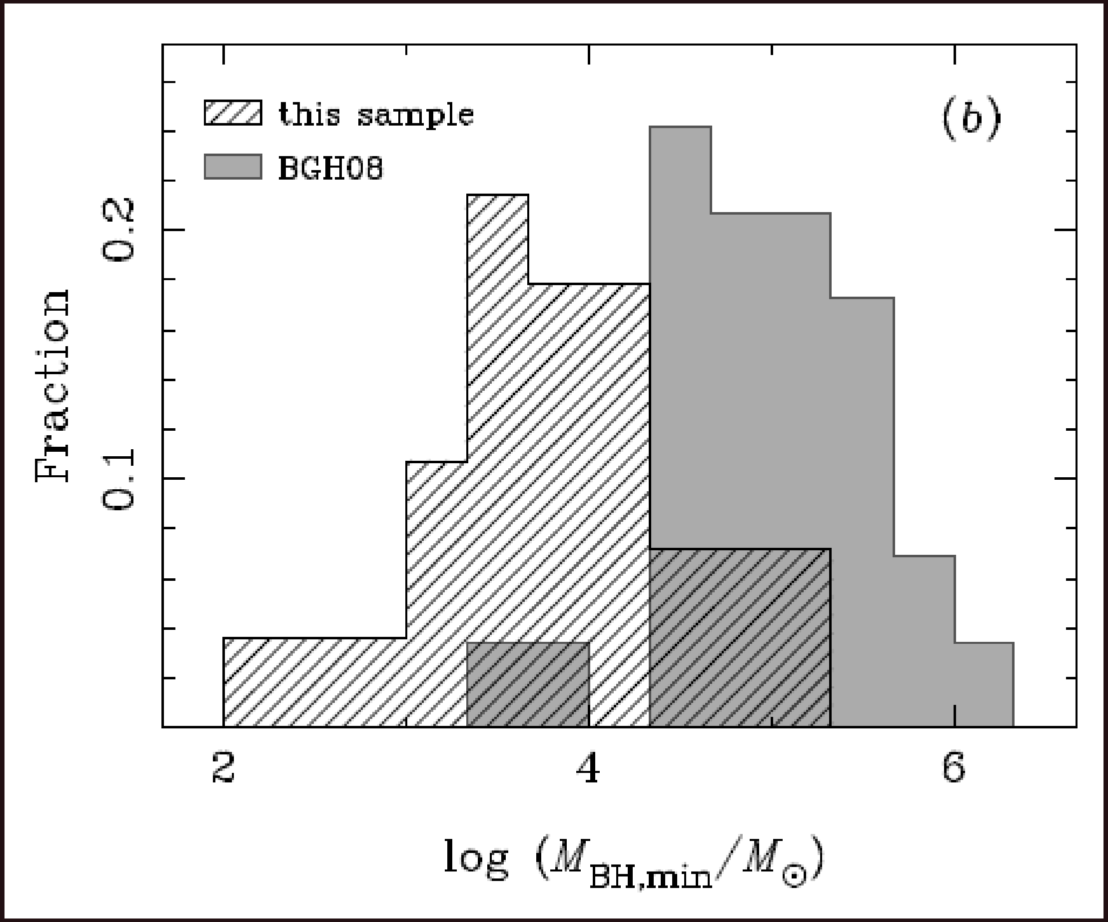
The lightest galaxy with a BH





1409.4769

Black holes in dwarf galaxies

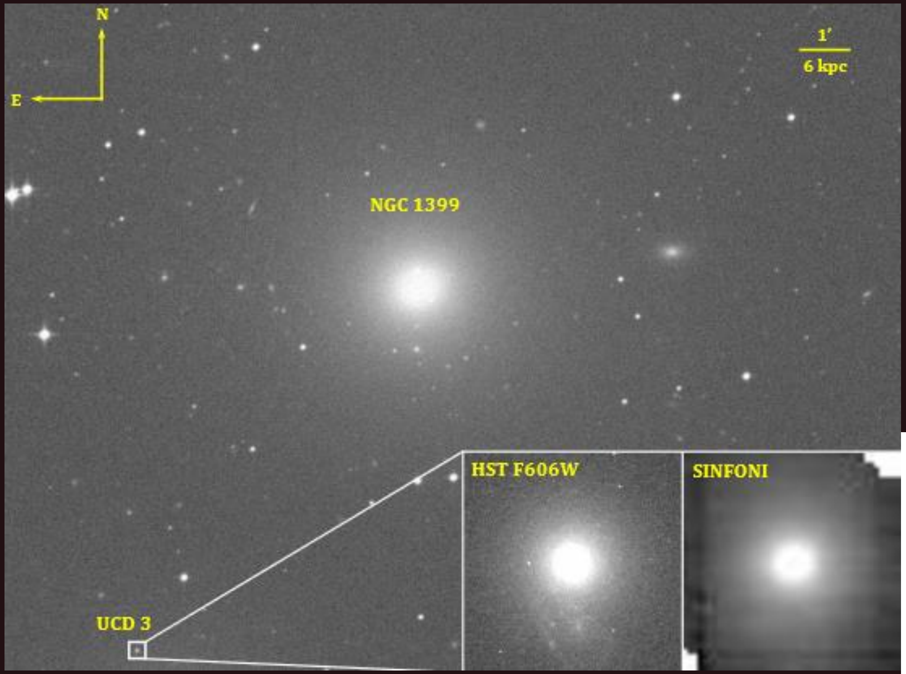


Galaxies have masses
About a few billion solar masses.
Their sizes are about a few kpc.

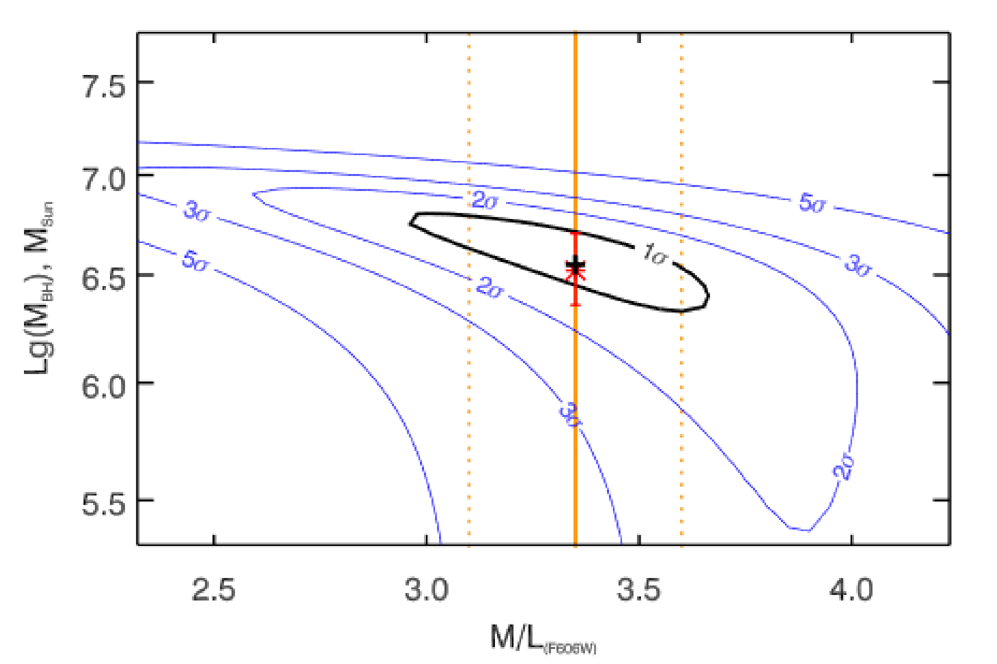
AGNs

1408.4451

SMBH in Fornax UCD3

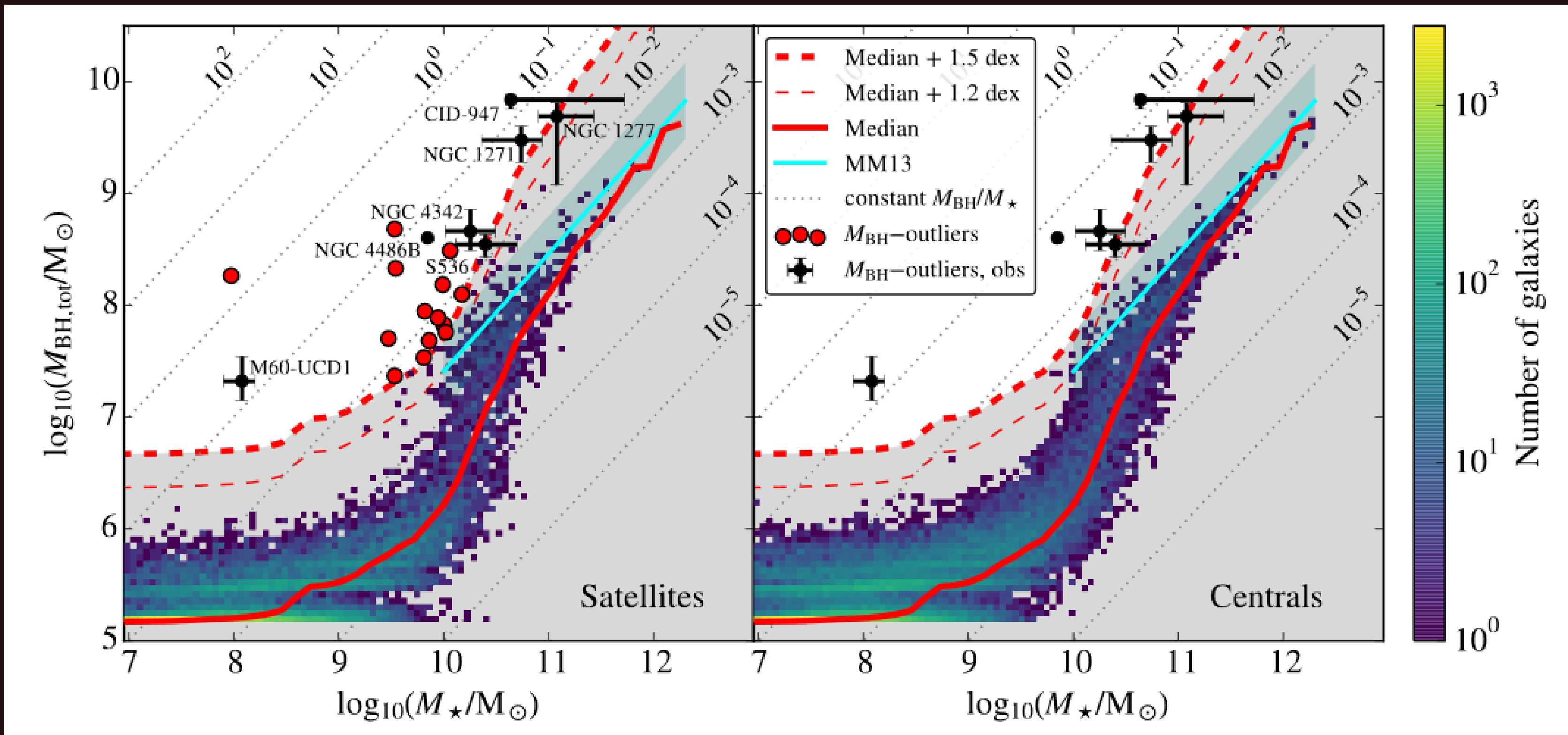


3.5 million M_{solar}



1804.02938

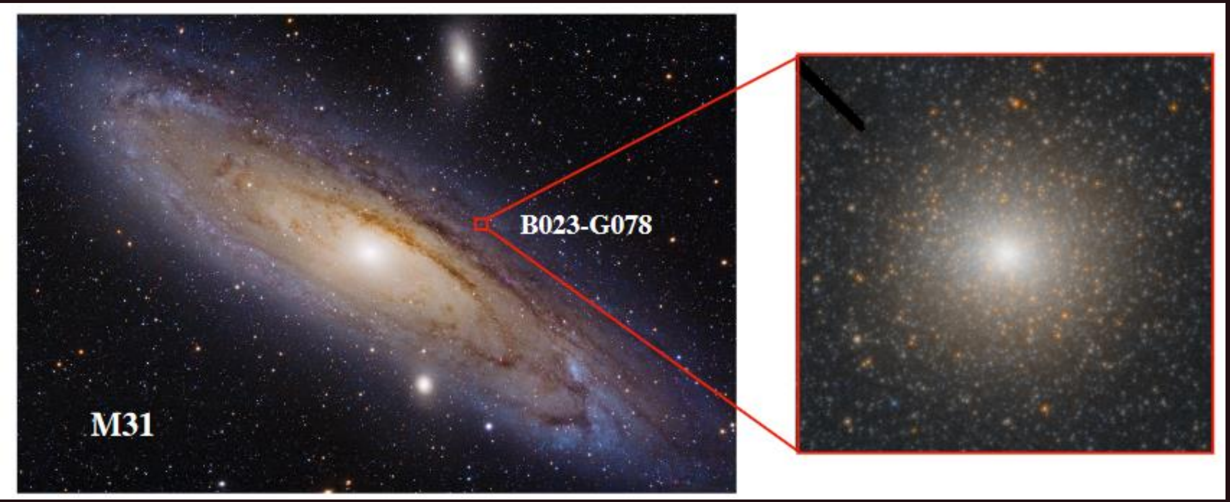
Massive BHs is small galaxies



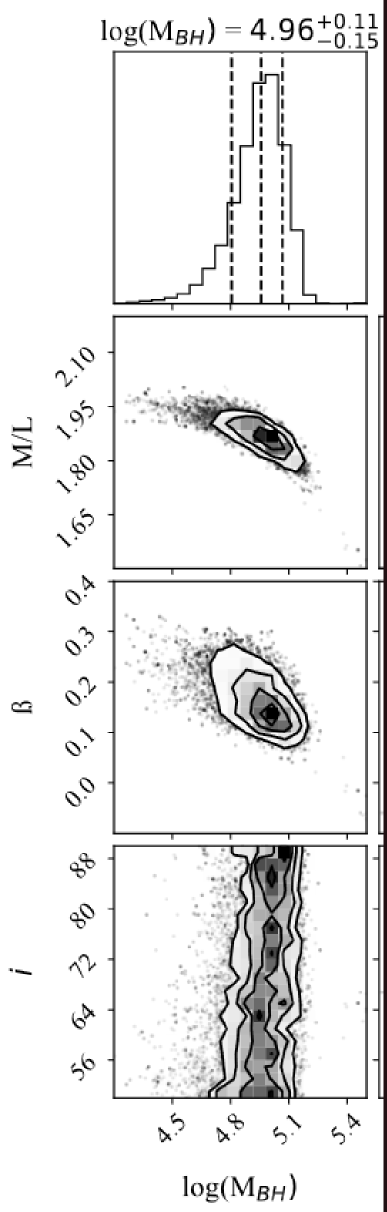
EAGLE modeling vs. observations.
Outliers are mainly due to tidal stripping.

1602.04819

A SMBH in a GC in M31?



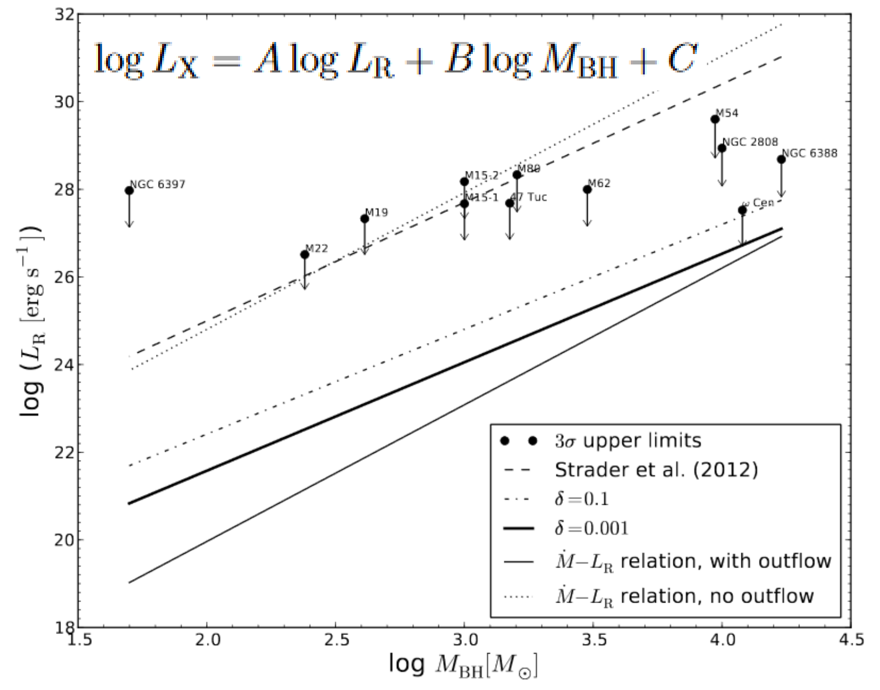
B023-G078 cluster properties	
Central V_{RMS}	37.2±0.6 km/s
V/σ	0.8
Cluster mass	$6.22^{+0.03}_{-0.02}\times10^6 M_\odot$
BH Mass	$9.1^{+2.6}_{-2.8}\times10^4$ $M_\odot$
BH mass fraction	1.5%
Half-mass relaxation time	14 Gyr
$[Fe/H]$	-0.65 (center) to -0.80 (at 1")
Age	10.5±0.5 Gyr
Assumed E(B-V)	0.23



2111.08720

BHs in globular clusters

1308.2869



Radio luminosity limits cannot exclude proposed IMBHs in GCs

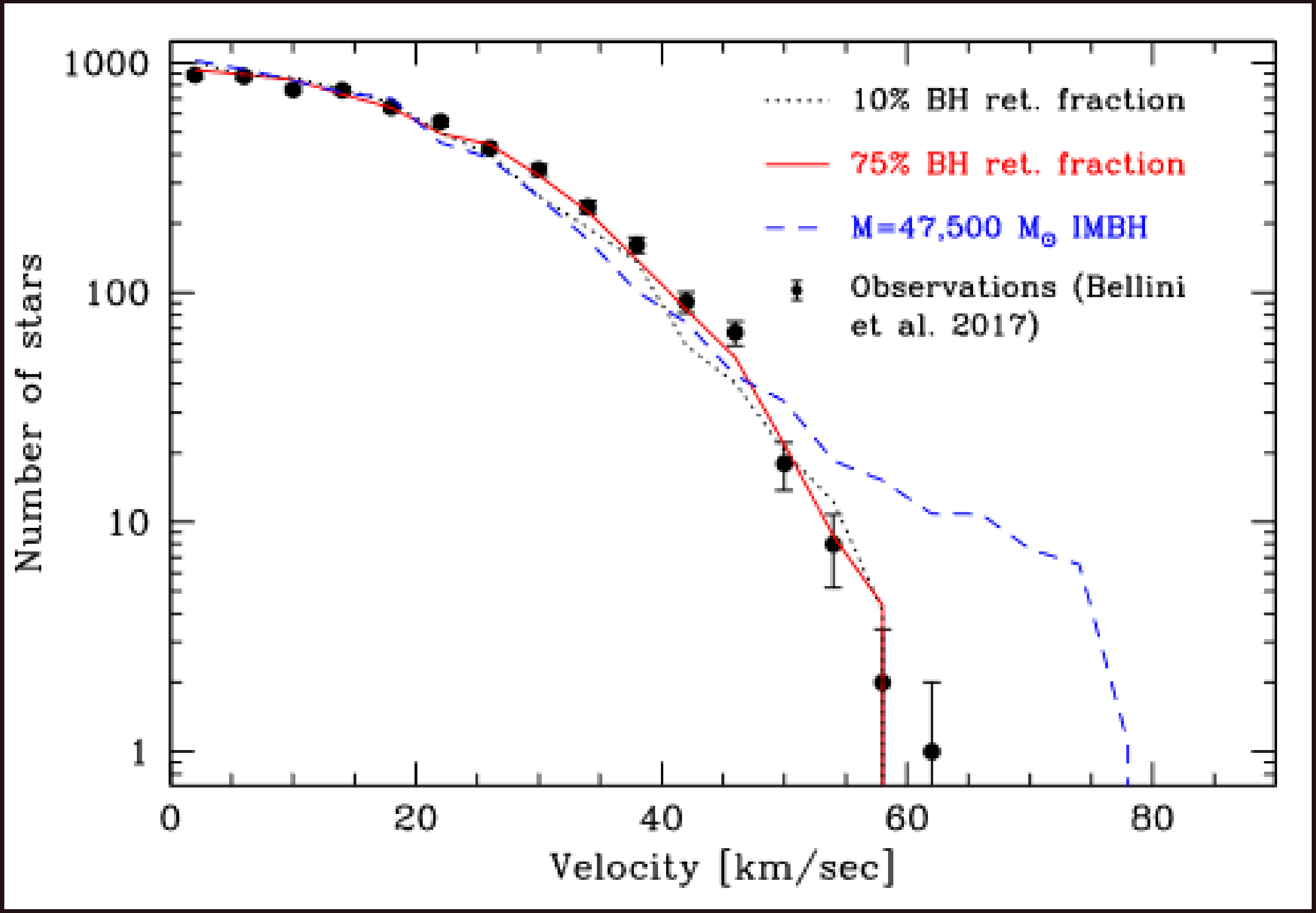
Limits from dynamics: 1404.2781

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).

~15 candidates (see 1705.09667)

No BHs in GCs???

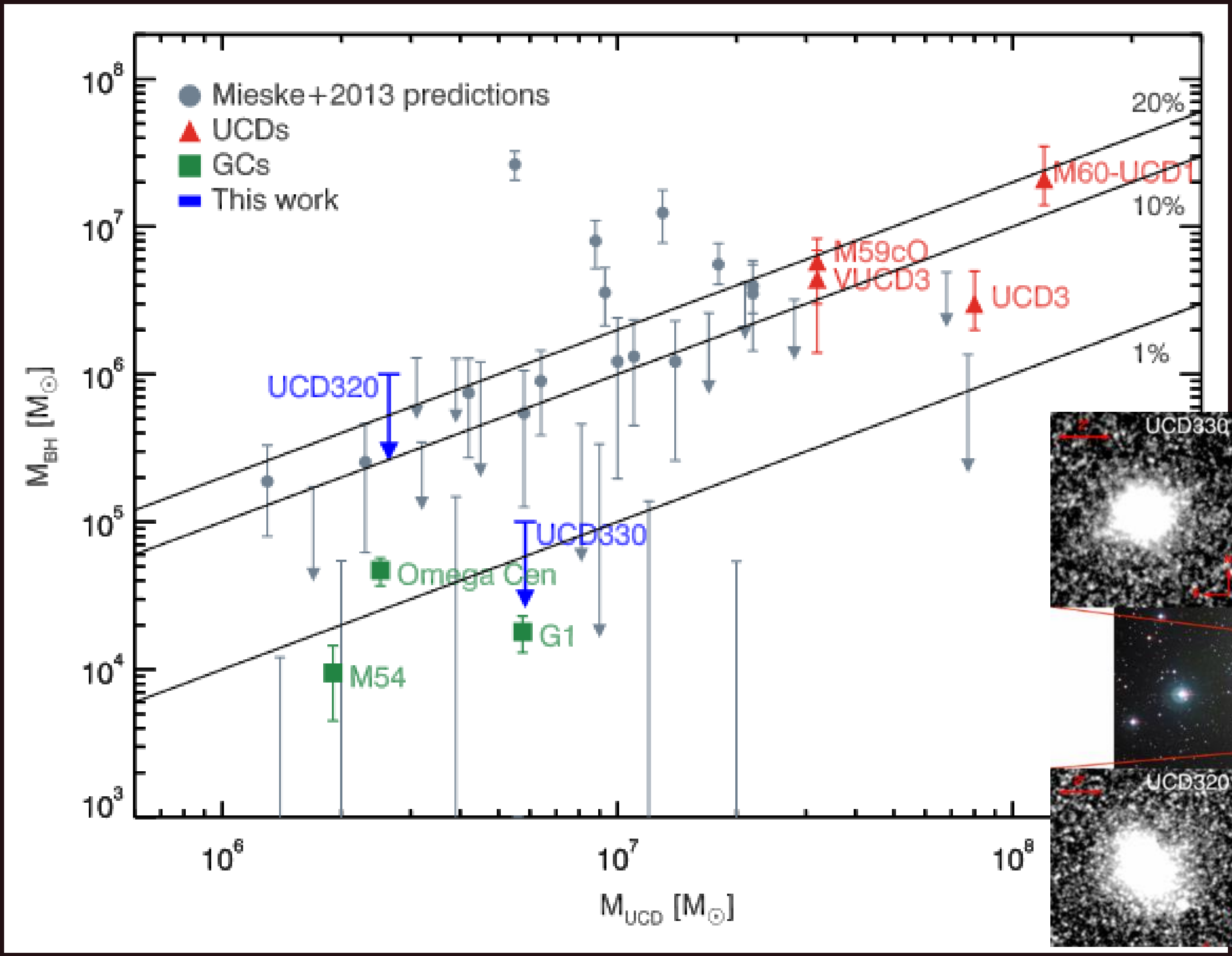


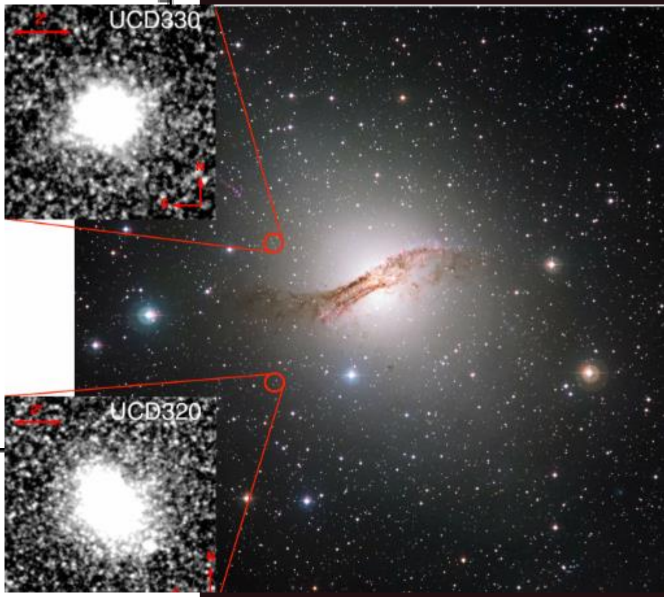
NGC 6624 is also in doubt.

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



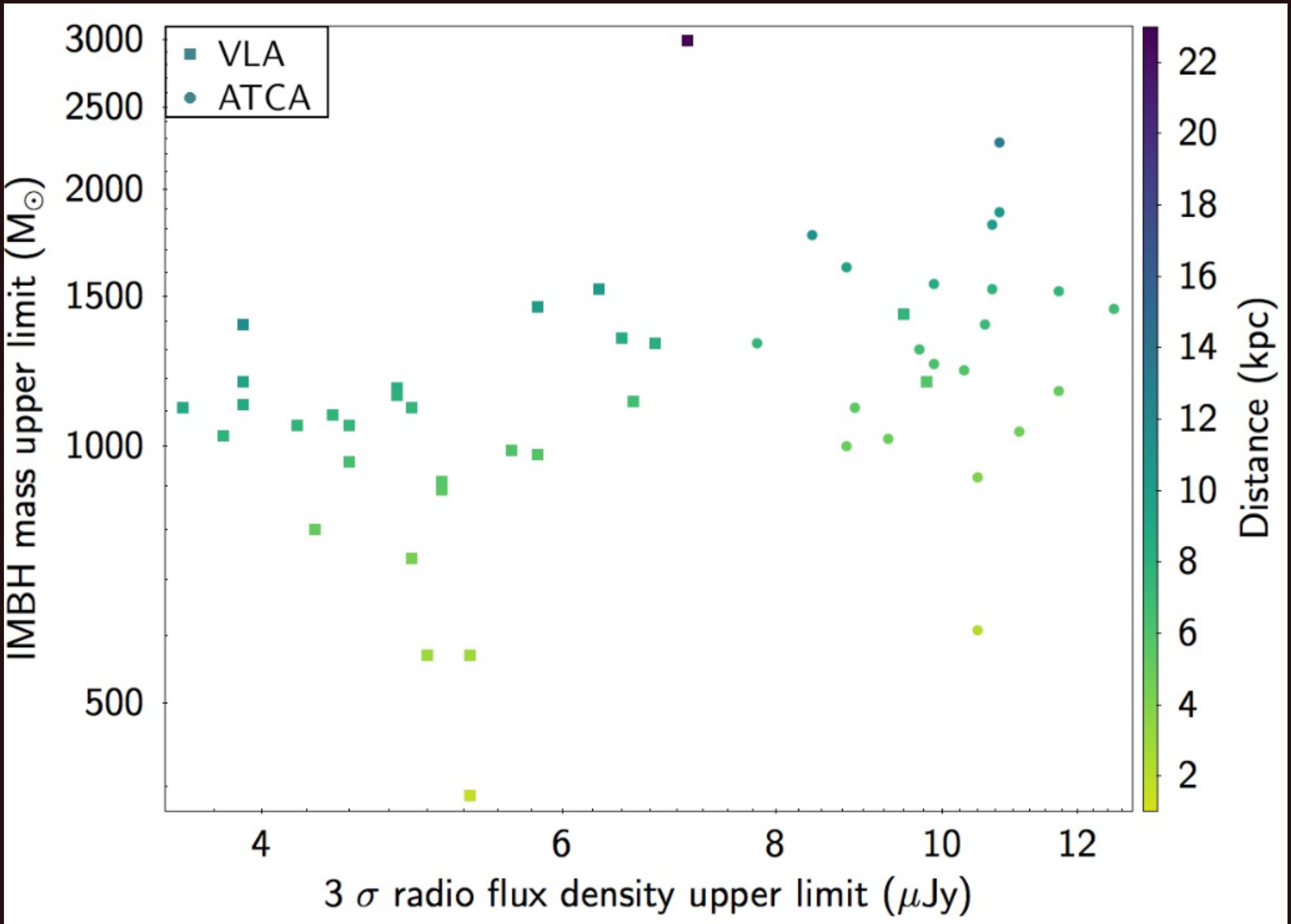


1803.09750,
see a large review on IMBHs in GC and dwarf galaxies in 2311.12118

Maveric survey: no accreting IMBHs in GCs

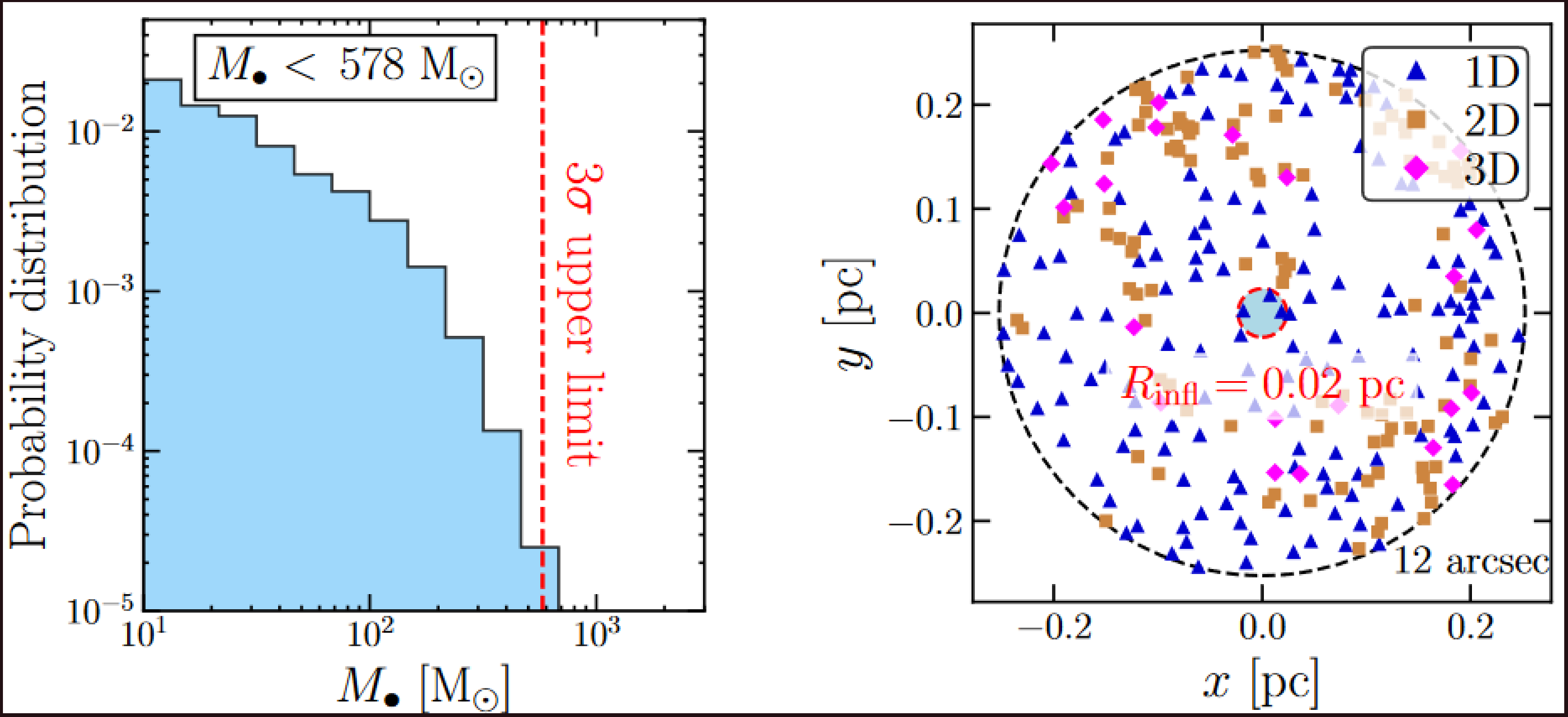
VLA + ATCA
50 globular clusters
No detections.

$$\log M_{BH} = 0.743 \log d + 0.372 \log S + 2.134$$



1806.00259

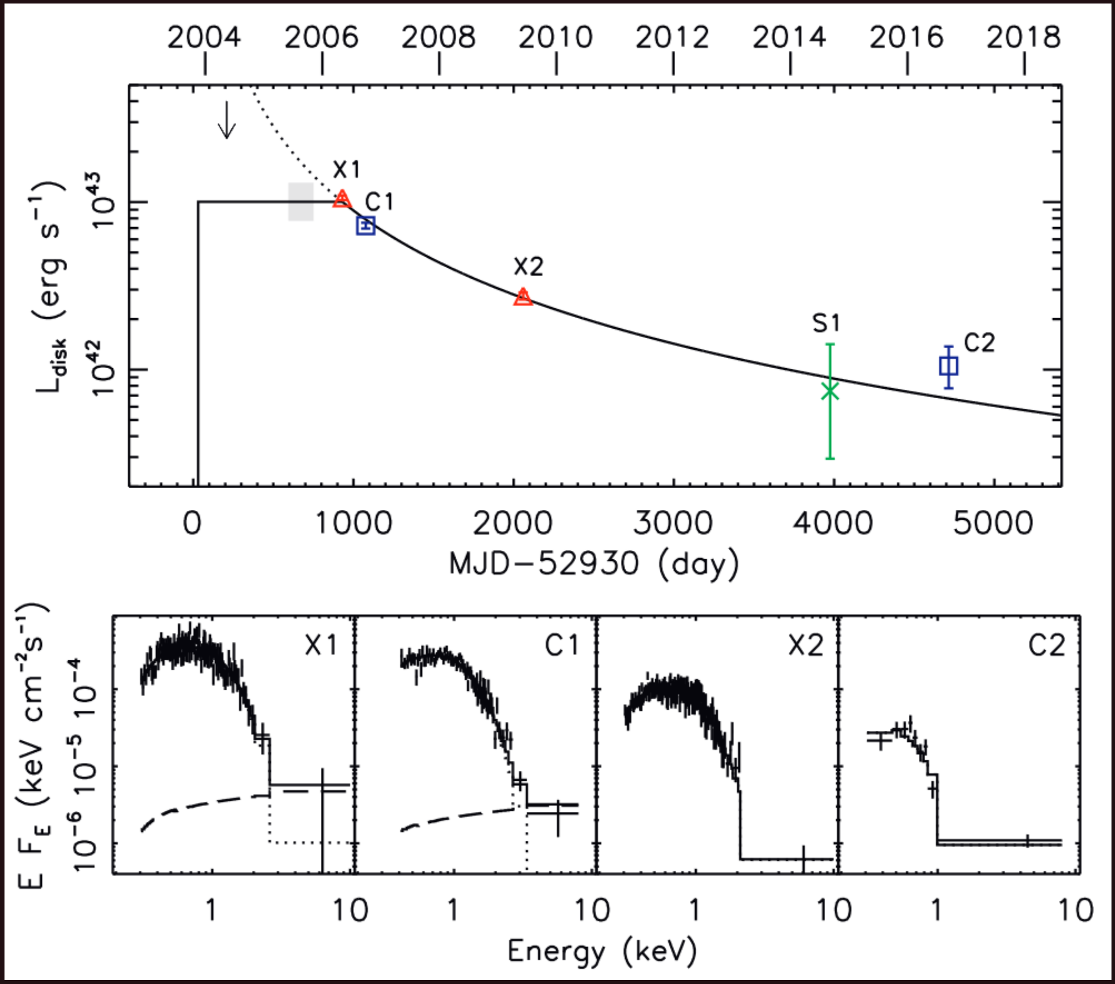
Limits for a BH in 47 Tucanae

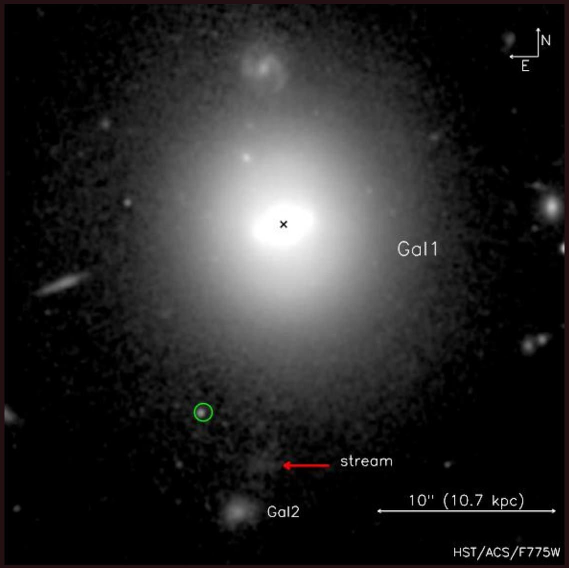


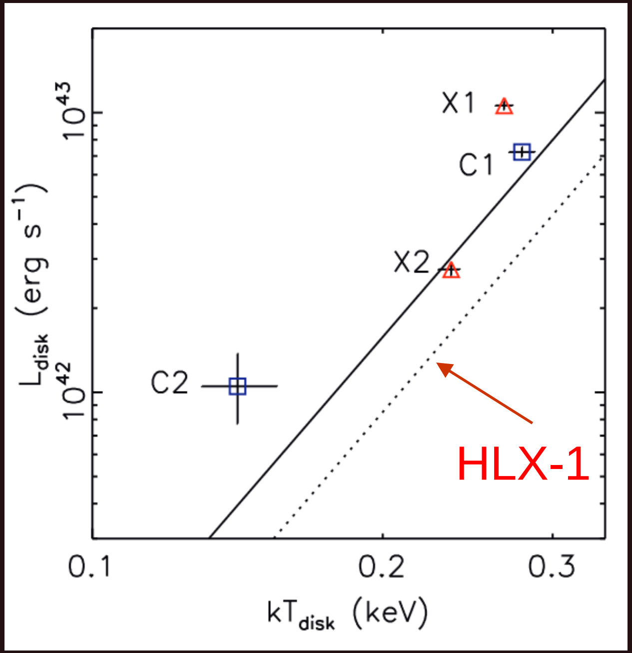
A central X-ray source was found recently: 2401.09692.
Potentially, it can be an IMBH consistent with the limits shown in the figure.

2310.15221

TDE in an extragalactic GC





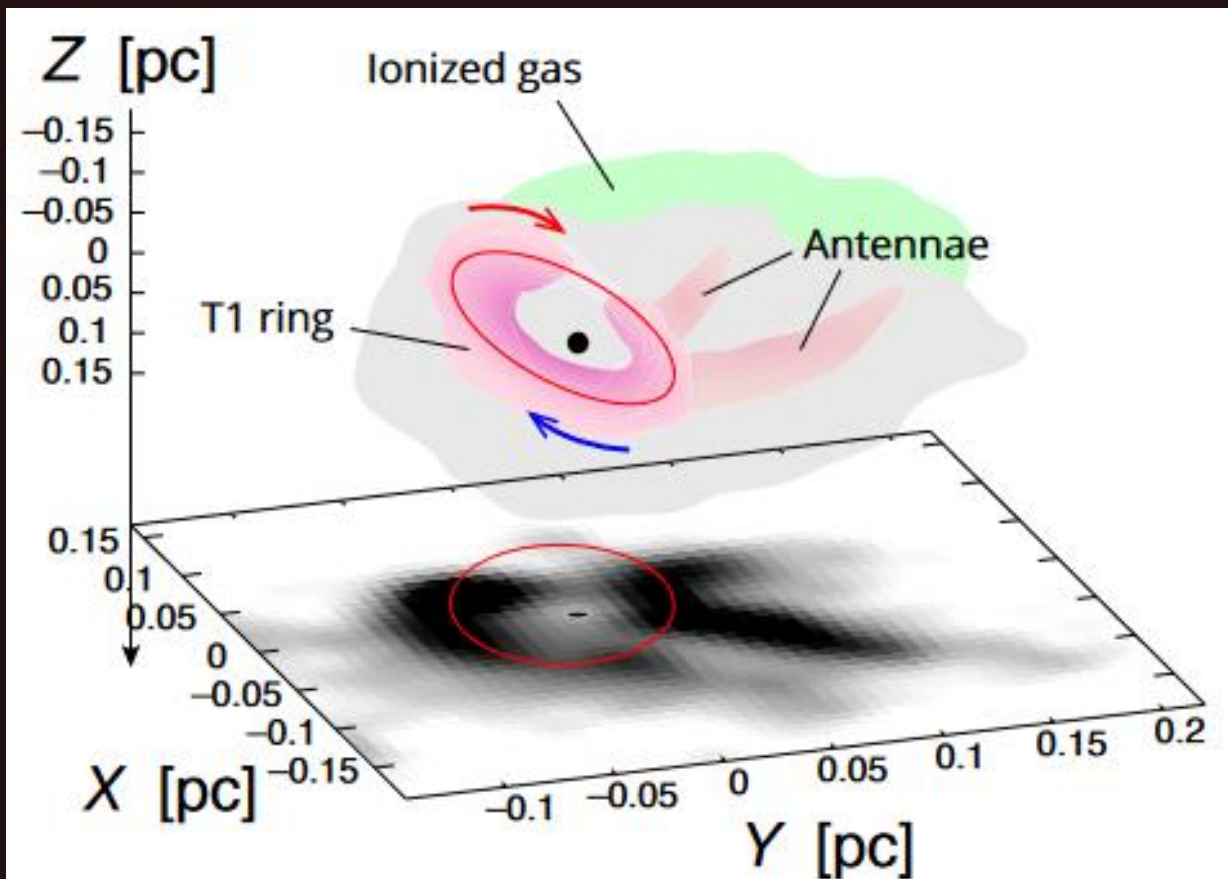


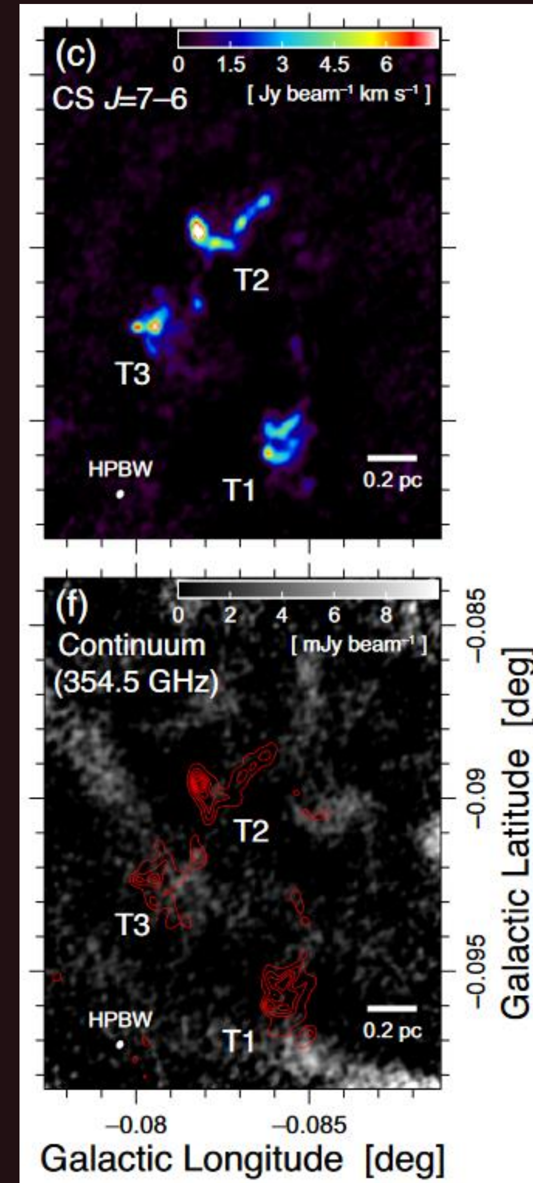
BH mass ~few 10^4 solar masses

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.



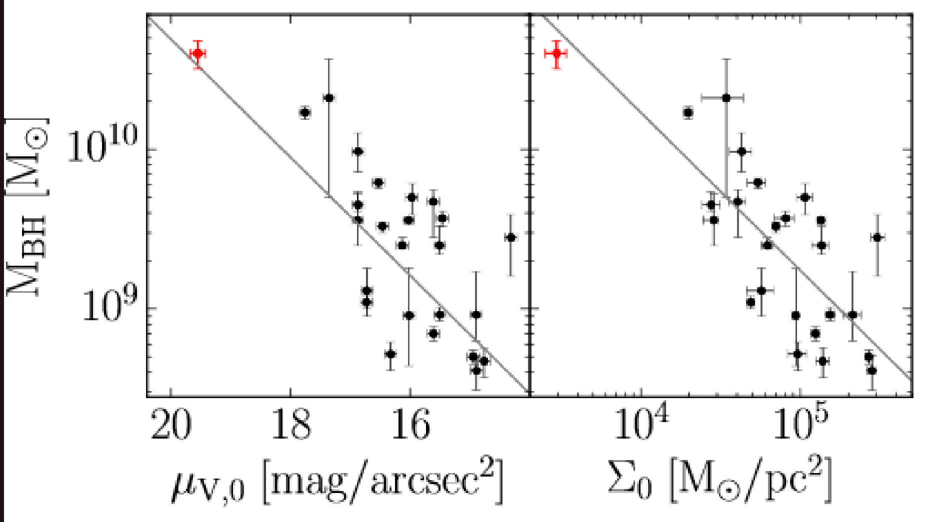


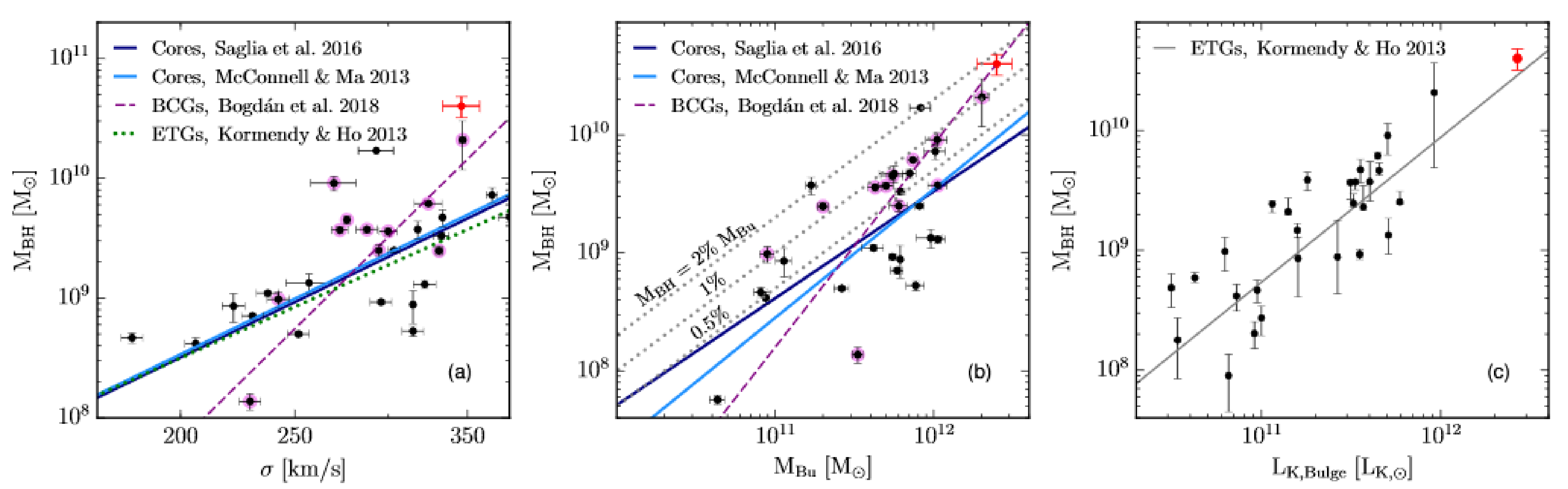
2002.05173, see however 2303.04067 for limits on IMBHs from S02 orbit

40-billion solar mass SMBH

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

Stellar kinematics used.

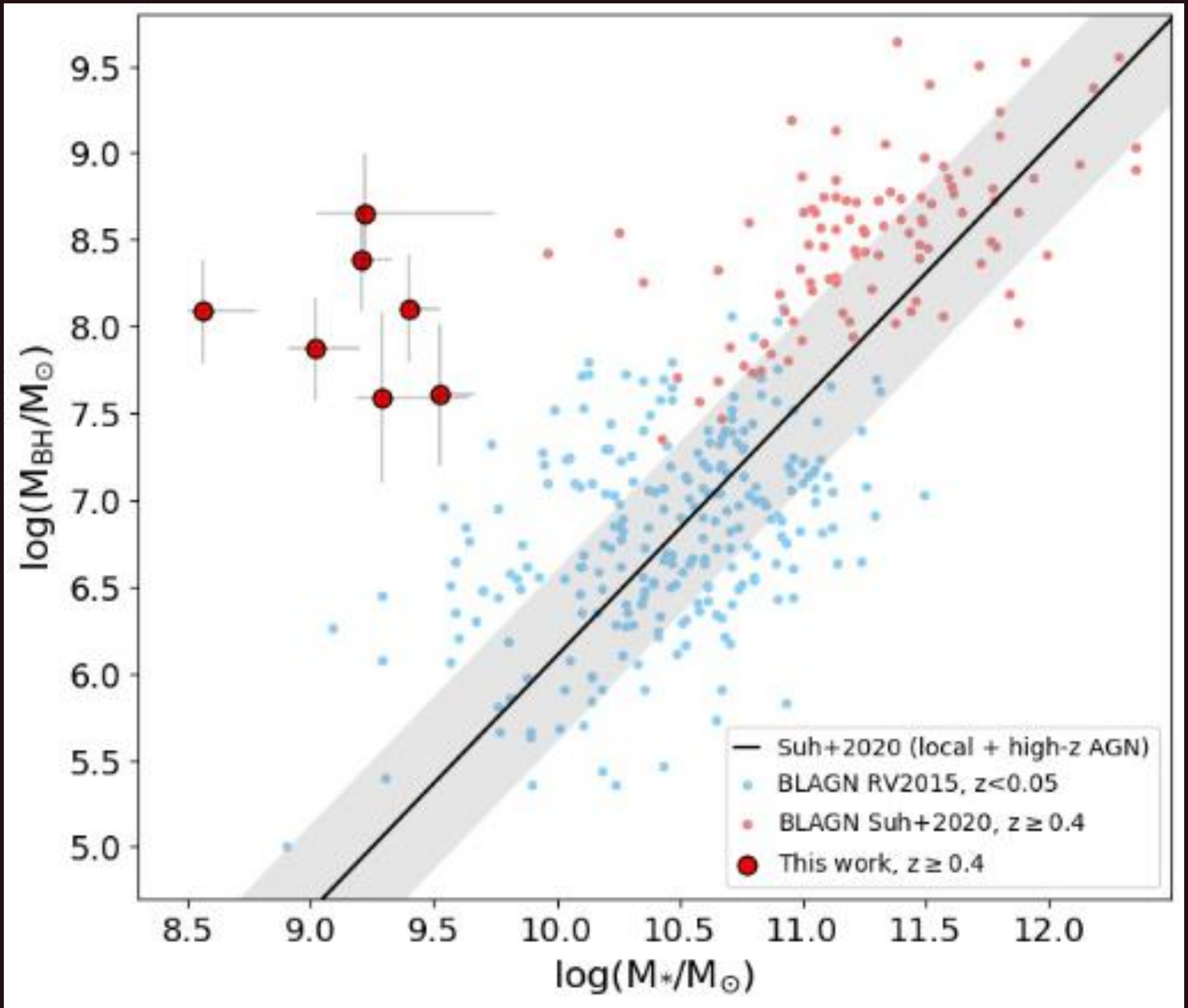




1907.10608

Overmassive black holes in dwarf galaxies

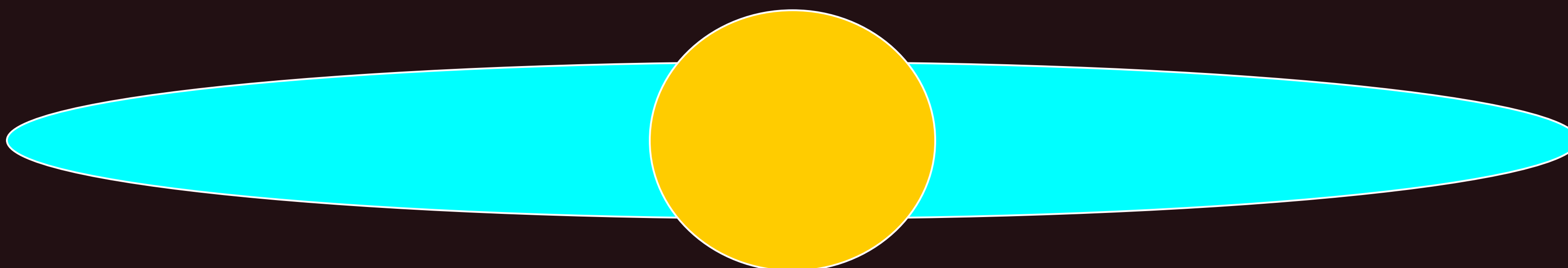
z=0.35 – 0.93
broad-line AGNs



2212.14057

A SMBH where it should not be

Observations of the galaxy NGC 4561 with XMM-Newton demonstrated that there is an AGN, i.e. there is an accreting SMBH.
However, this galaxy is bulgeless

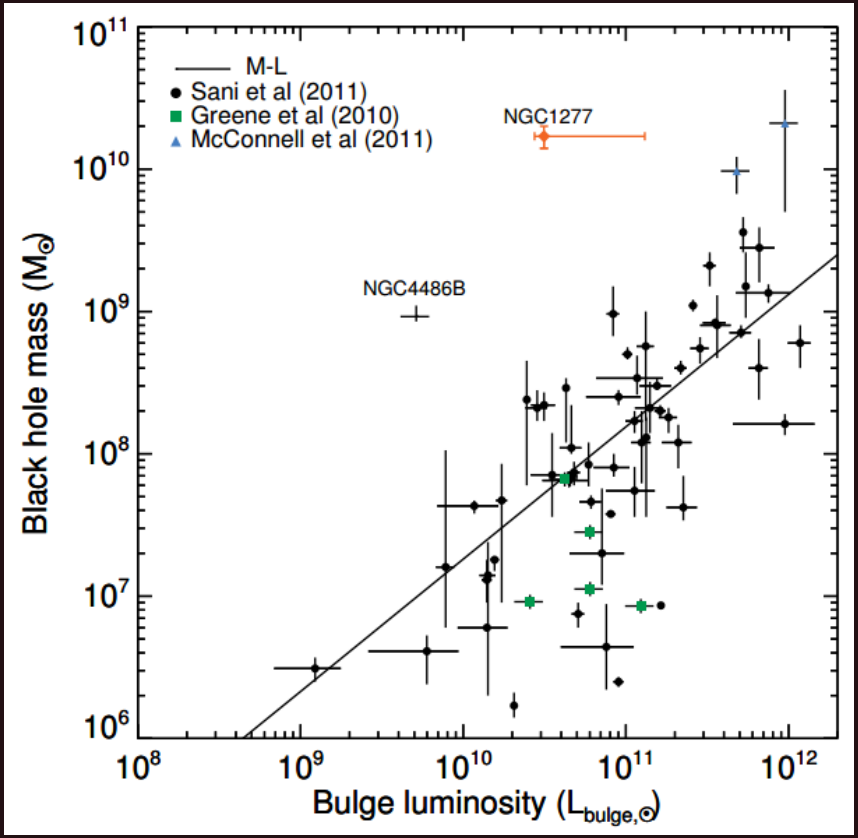


Black hole mass >20000 M_O

1209.1354

A too massive black hole

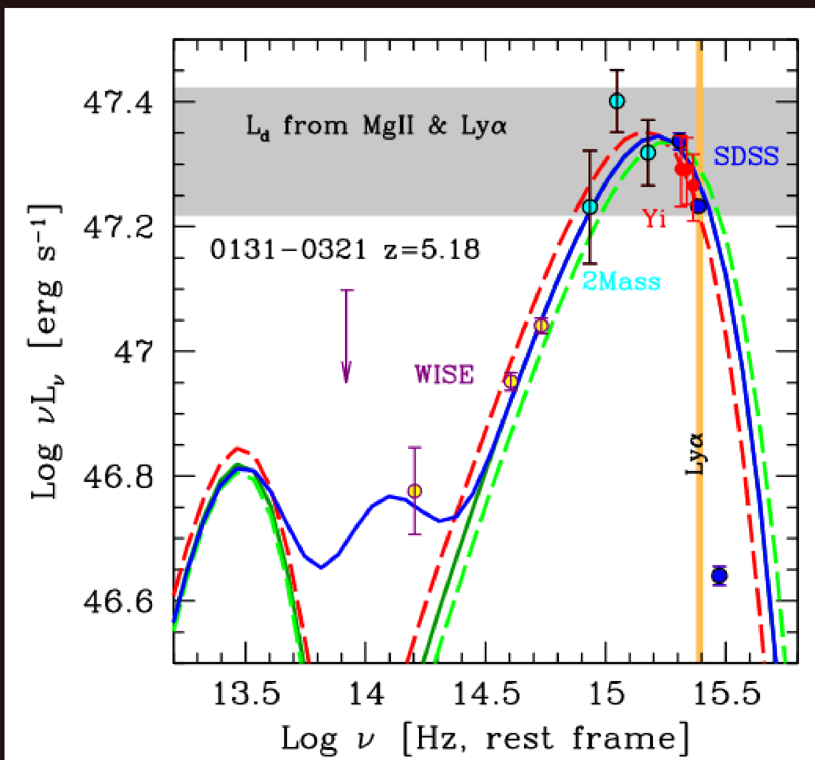
A compact lenticular galaxy.
It `must' have a BH with M~ 10^8 M_O
However, it has a BH with M >10^{10} M_O!

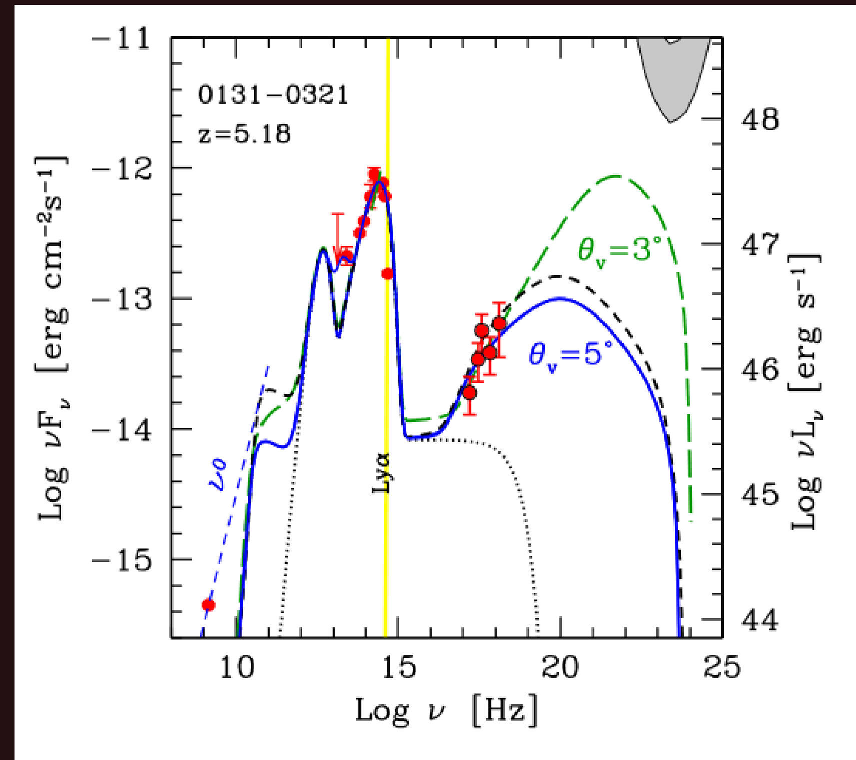


1211.6429

11 billion solar masses BH at z>5

SDSS J013127.34–032100.1
Mass determined via spectral fitting.



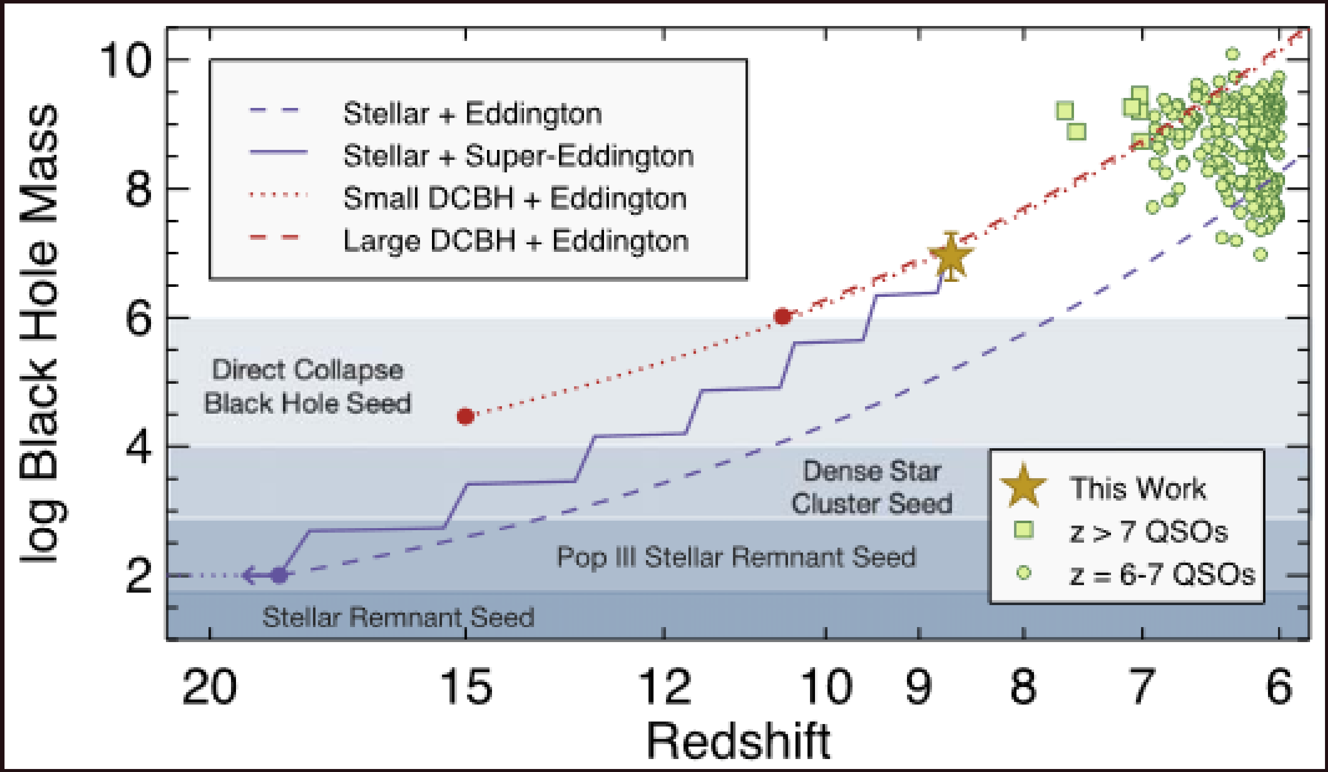


More recently, a 34-billion solar mass SMBH in the most luminous quasar at z=4.7 has been reported in 2005.06868.

1501.07269

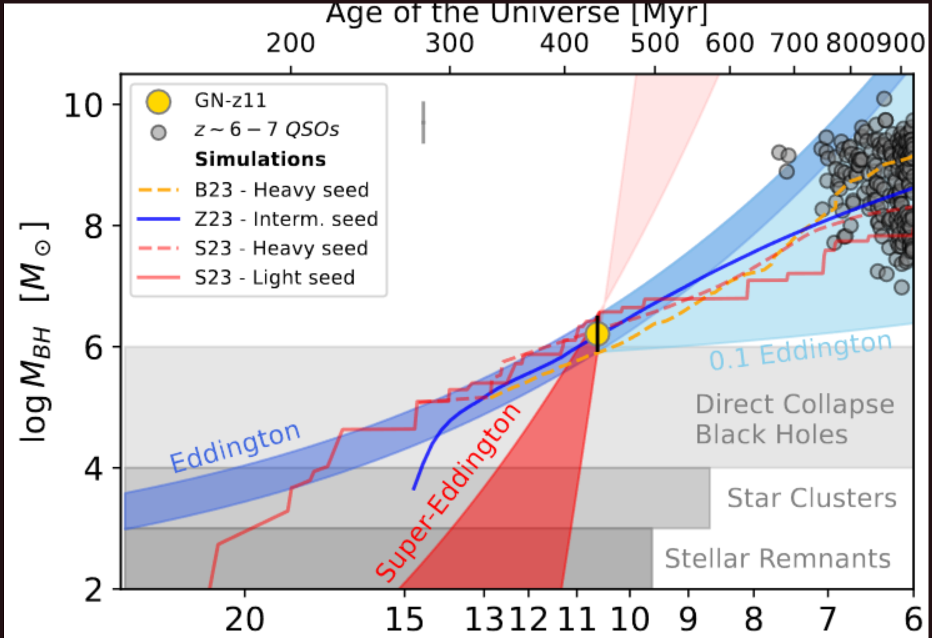
Very distant AGN

CEERS_1019
z = 8.679
log (M_{BH}/M_{sun}) = 6.95 ± 0.37
~Eddington accretion rate
galaxy: log M/M_{sun} ~9.5
SFR ~ 30 M_{sun} yr^{-1}



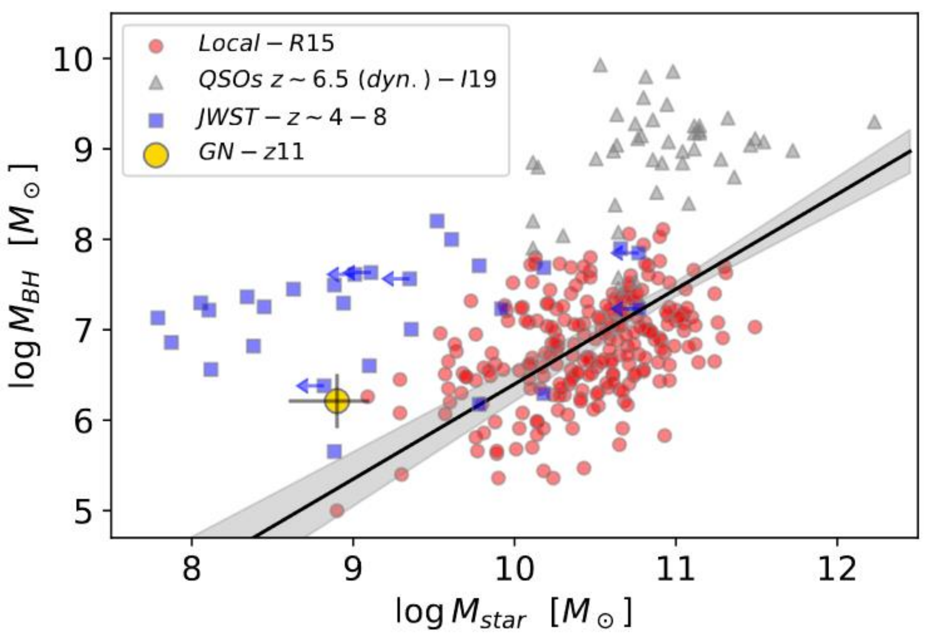
2303.08918

Even more distant!



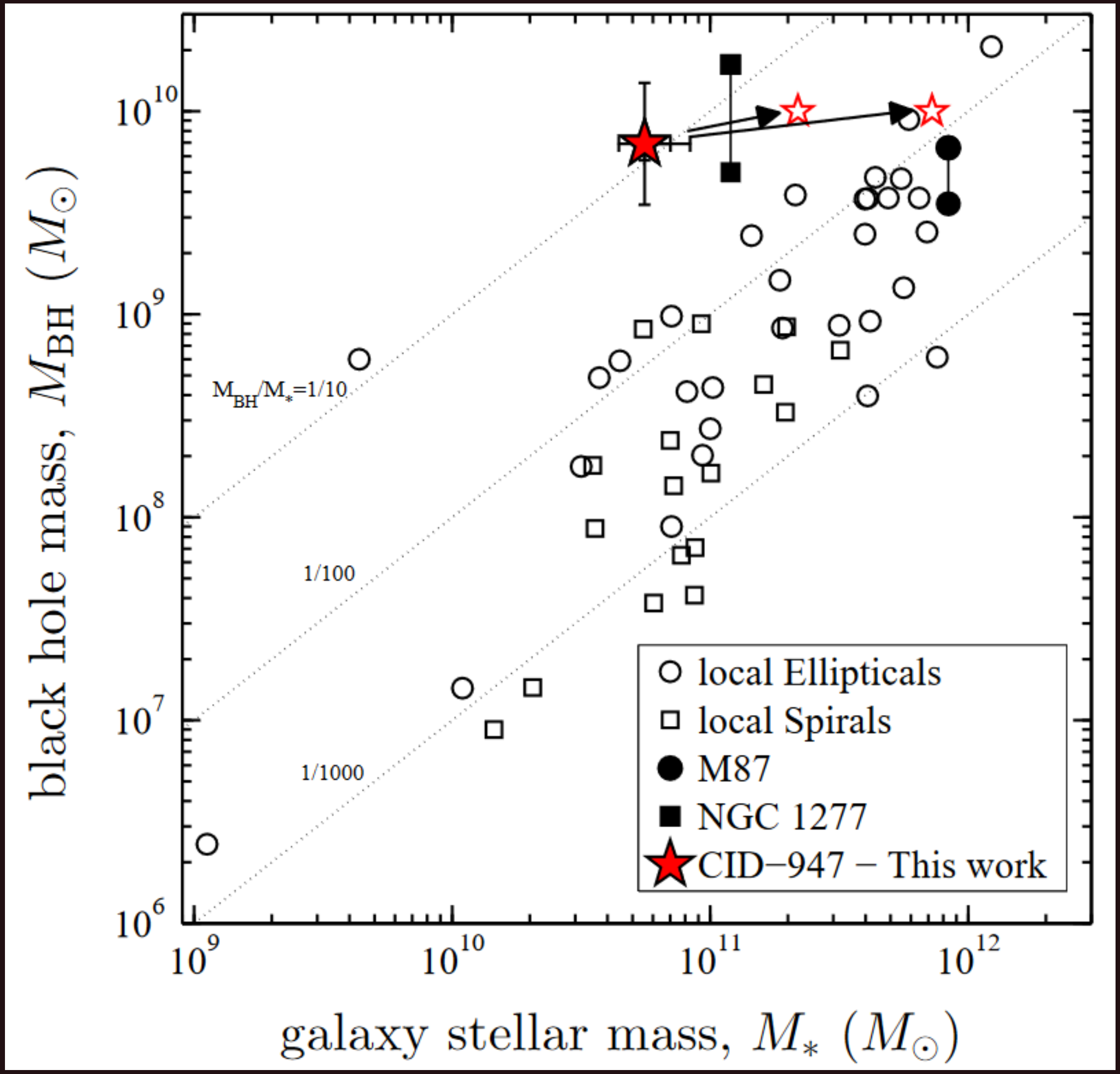
z=10.6

5 Eddington luminosities



2305.12492

Too massive BH in a starforming galaxy

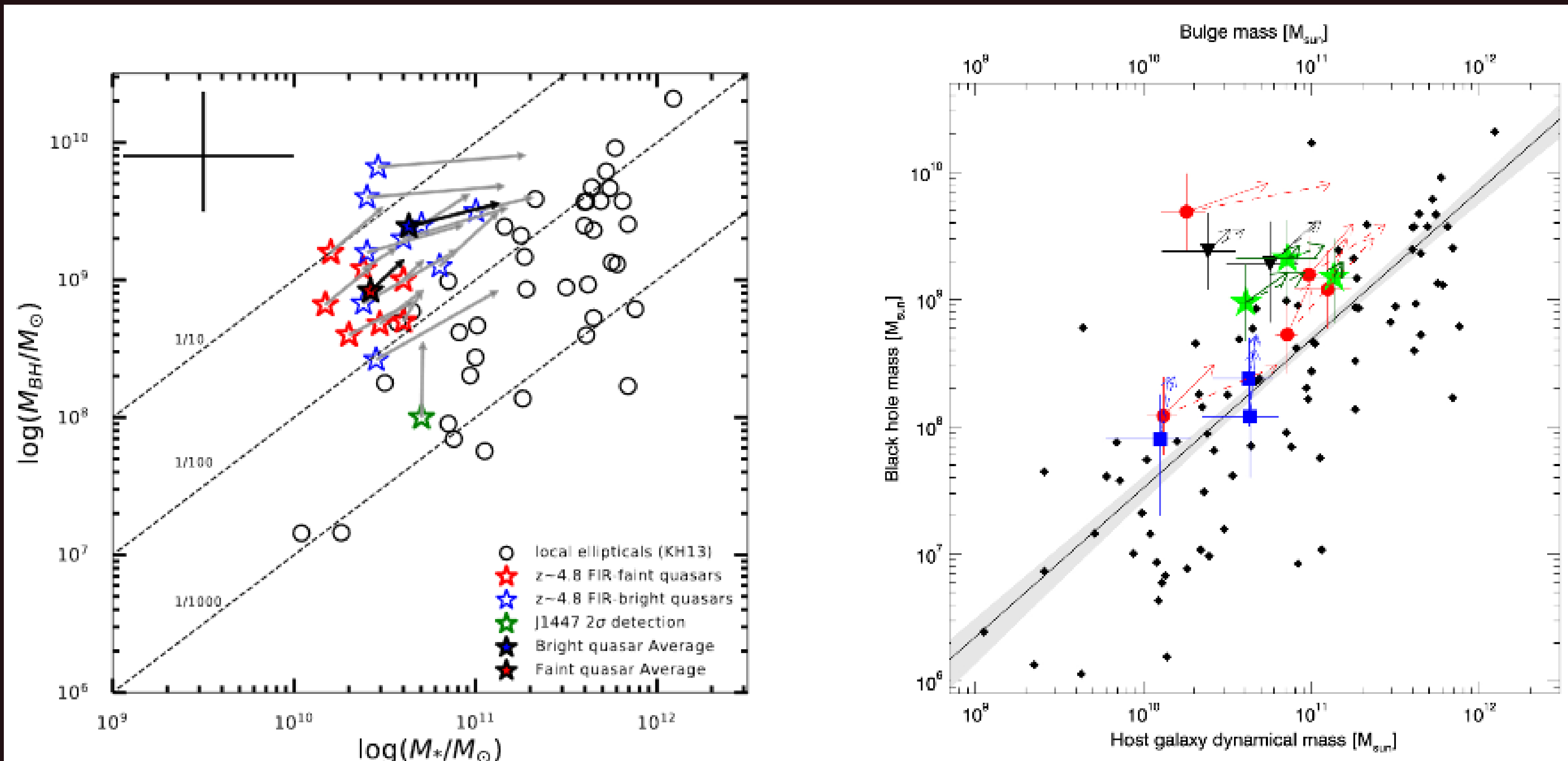


z=3.3

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

1507.02290

Expected mass growth for high-z SMBHs

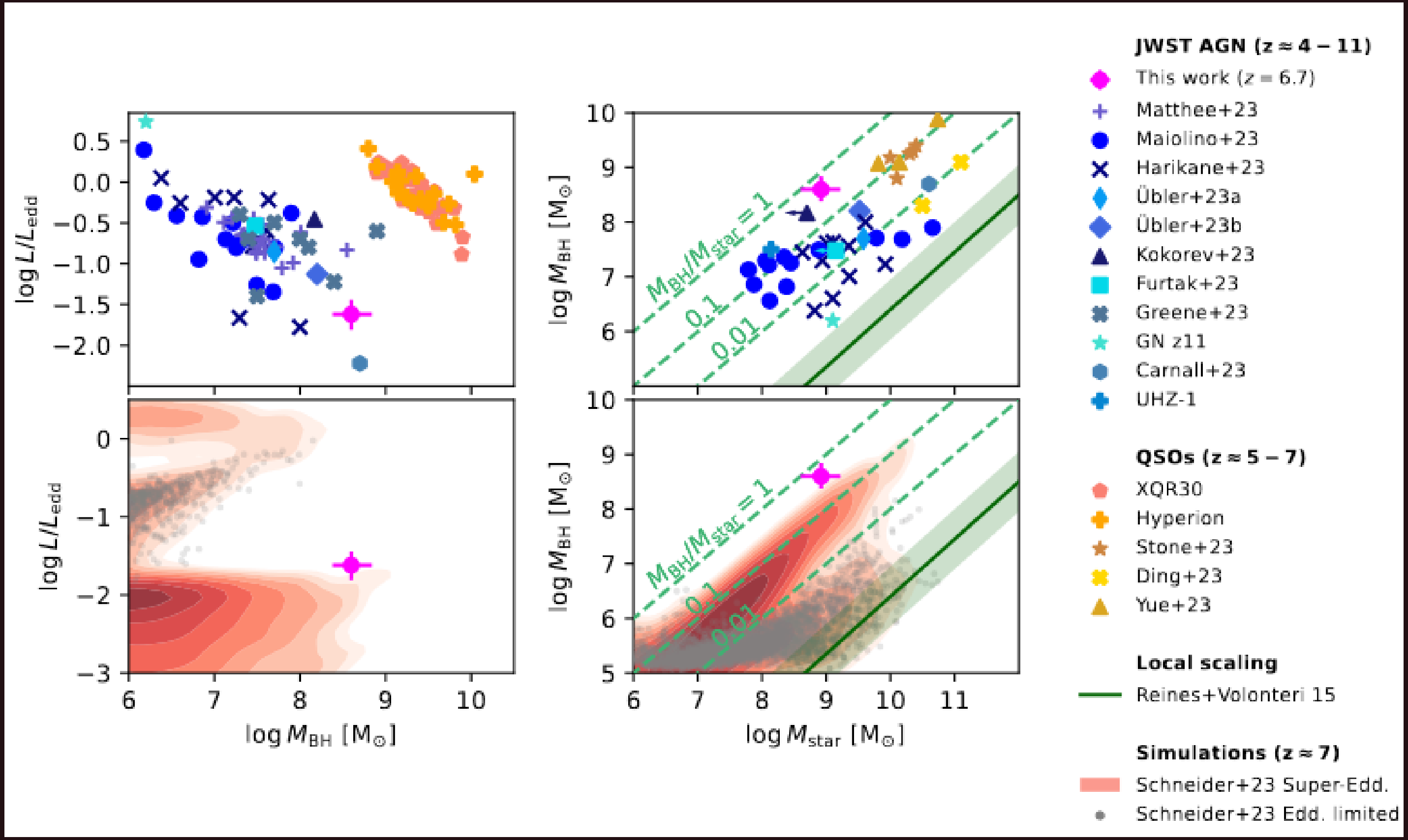


New ALMA data help to establish the growth rate expectations.

2002.00972

Overmassive BH at z~7

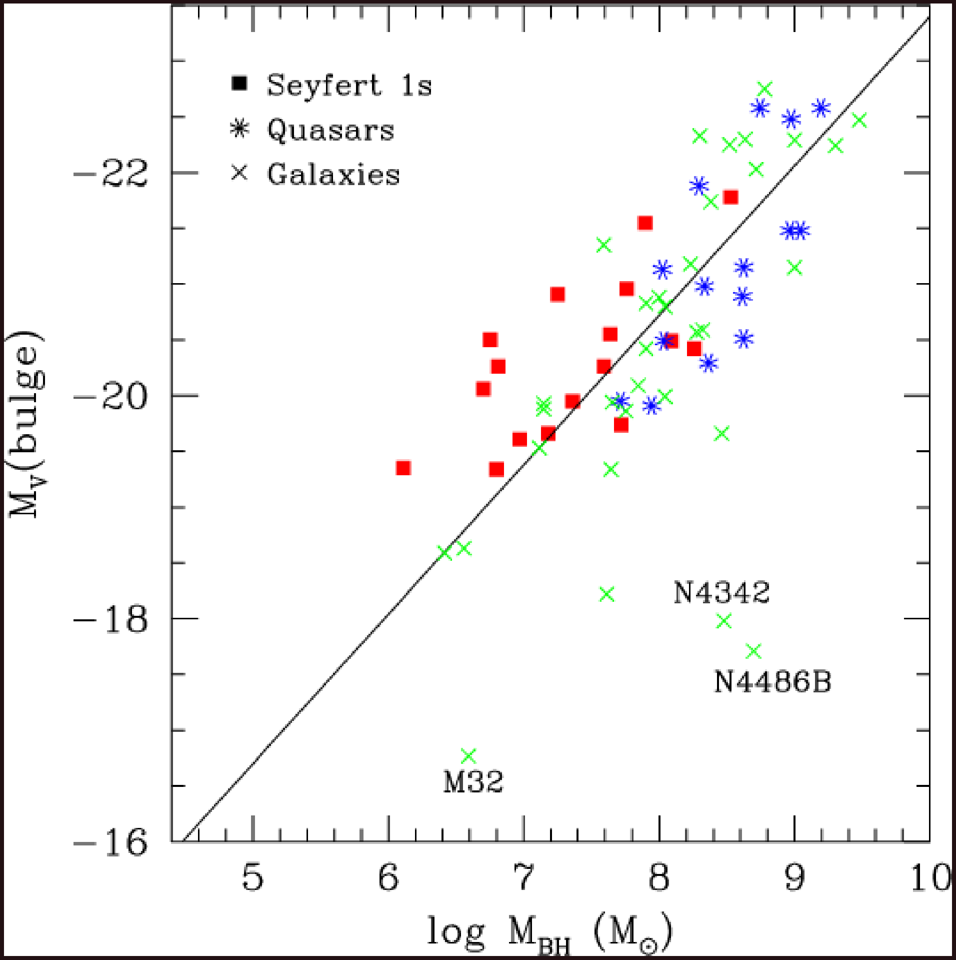
z=6.68
M_{BH}~3 10^8 M_{sun}
L~0.02L_{Edd}
SFR~1M_{sun}/yr
M_{BH}/M_{star}~0.4 !!!!



Can be the first representative of a larger population. Intensive episodes of super-Eddington accretion can increase the BH mass.

2403.03872

There are other correlations

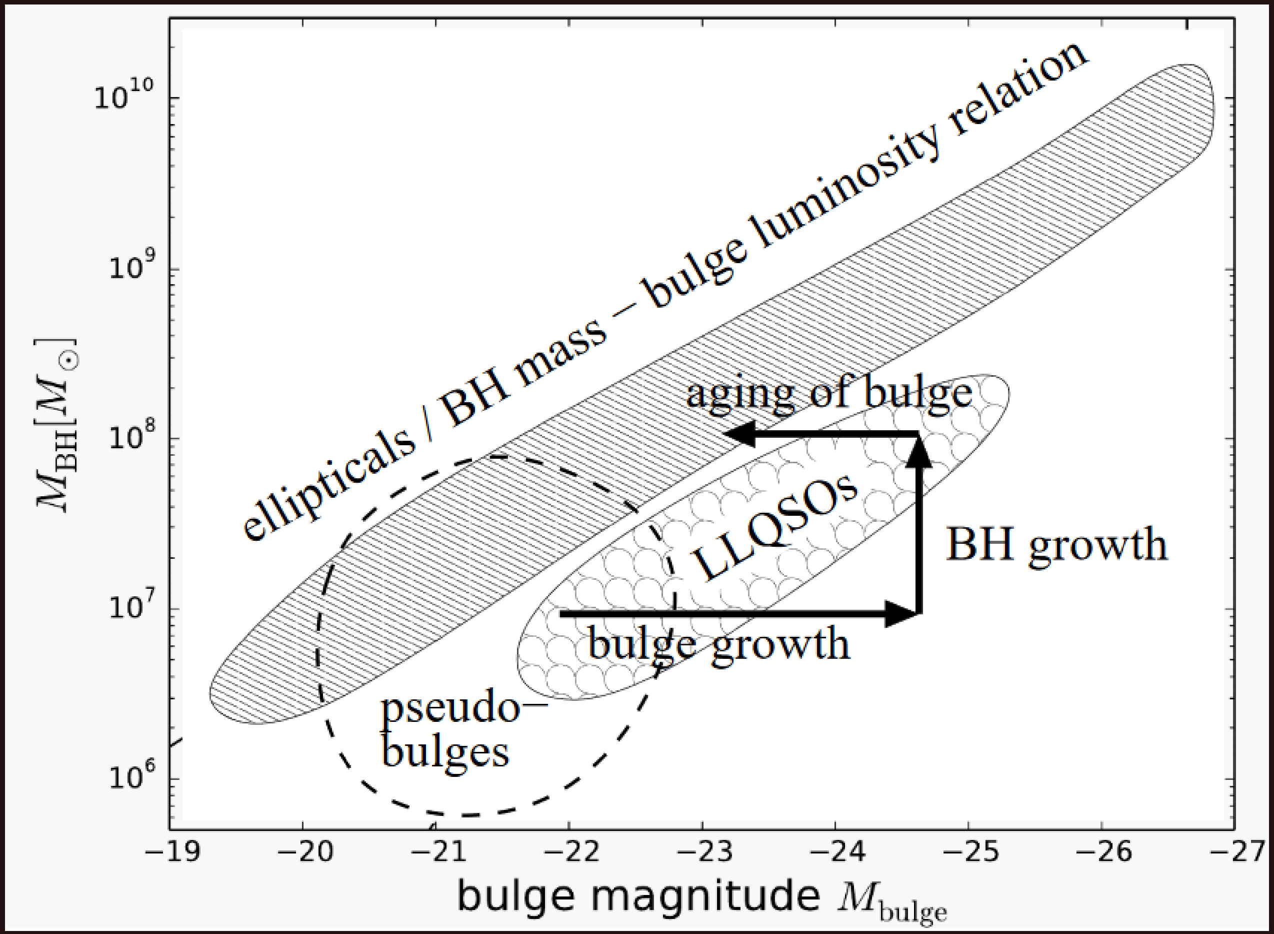


In the figure the following correlation is shown: absolute magnitude of the bulge (in V filter) vs. BH mass.
BH masses are obtained by reverberation mapping.

Other correlations are discussed in the literature.

Wu, Han A&A 380, 31-39, 2001

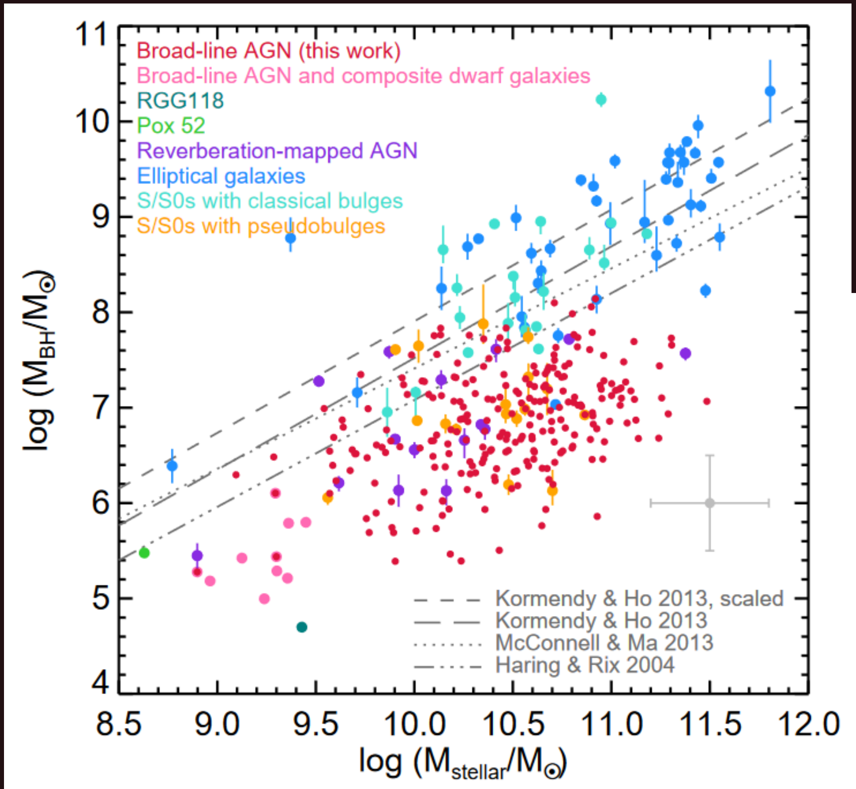
Origin of black hole mass – bulge magnitude correlation

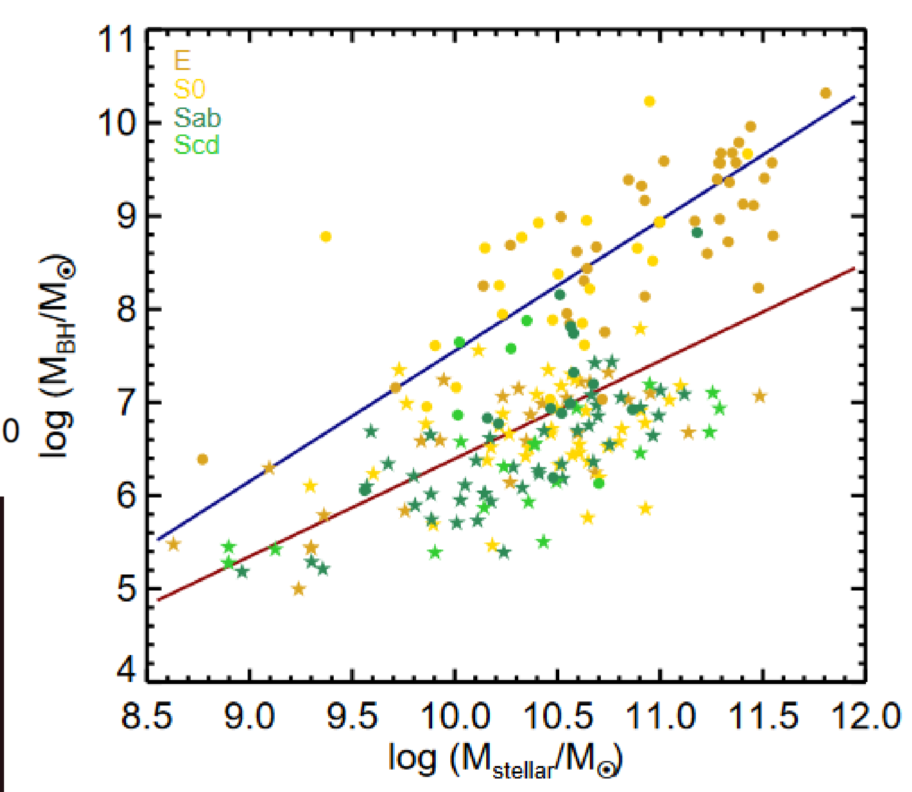


A possible evolutionary scenario in the BH mass - bulge luminosity diagram. Accretion of matter onto the central region results into enhanced star formation and BH growth. Young stellar populations cause overluminous bulges compared to inactive galaxies on the relation. BH growth and aging of the stellar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

1712.06915

BH mass vs stellar mass



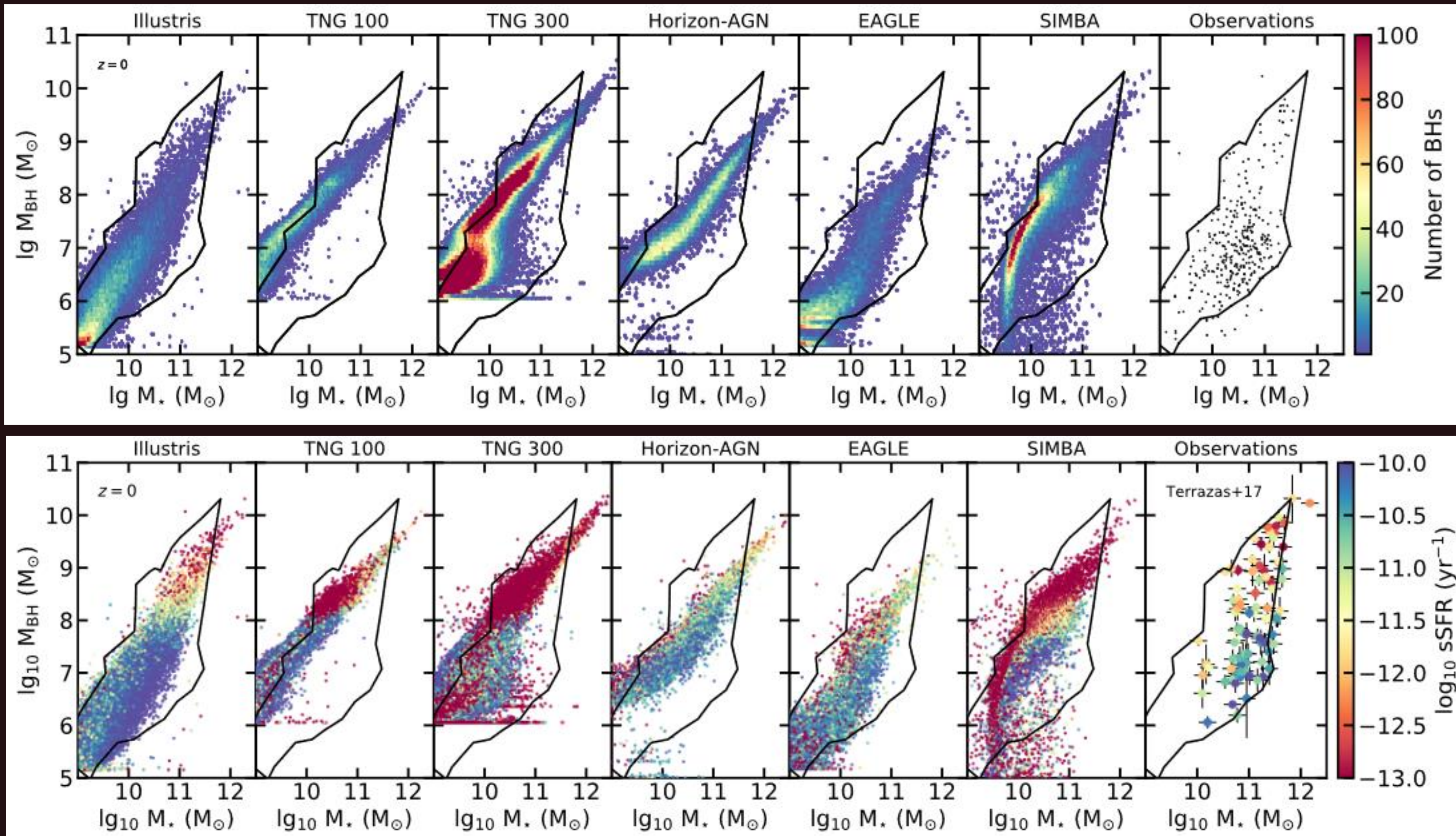


Red points – 244 AGNs.

1508.06274

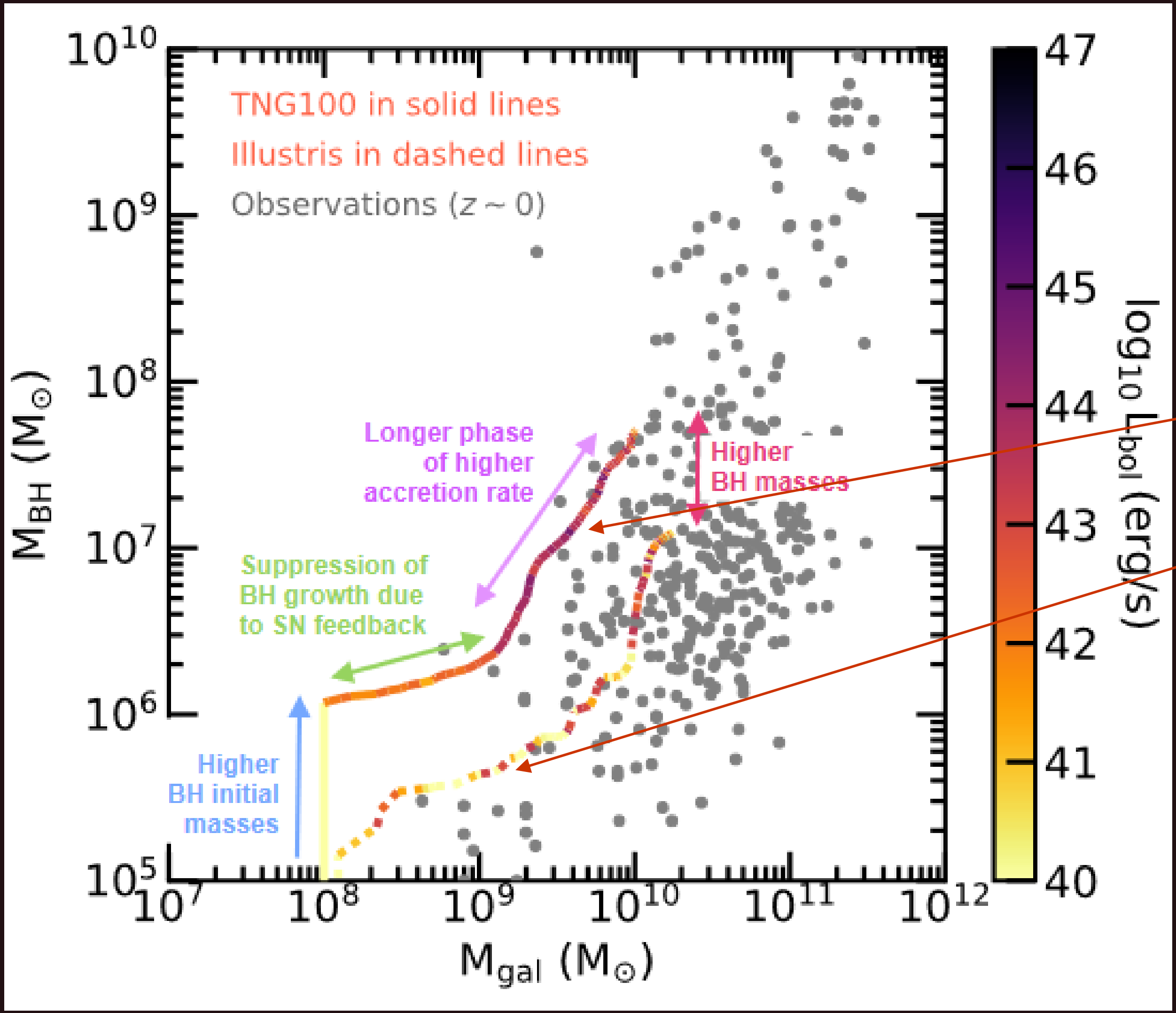
Numerical modeling

z=0



2006.10094

Different mass growth of SMBHs



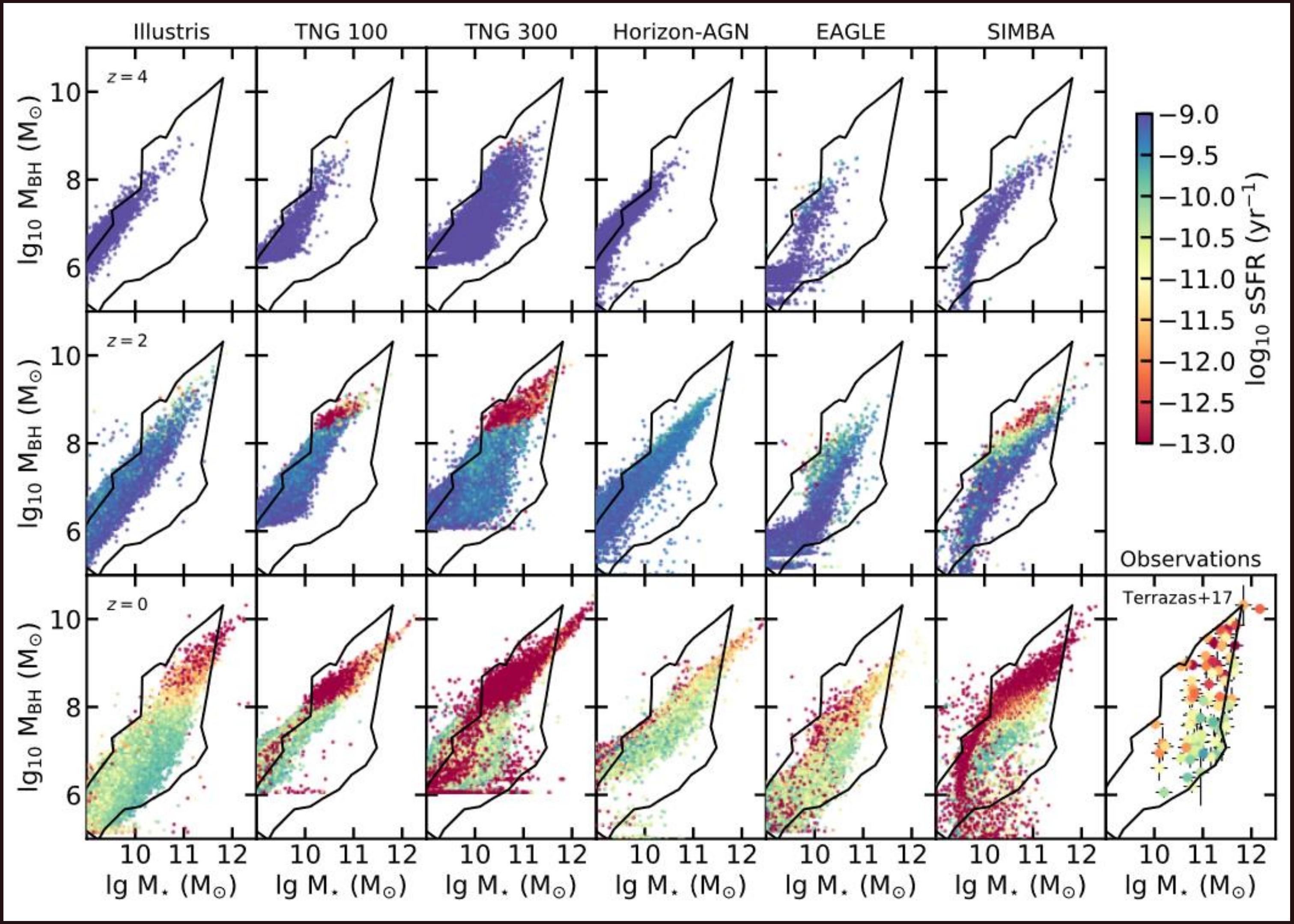
TNG

Illustris

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

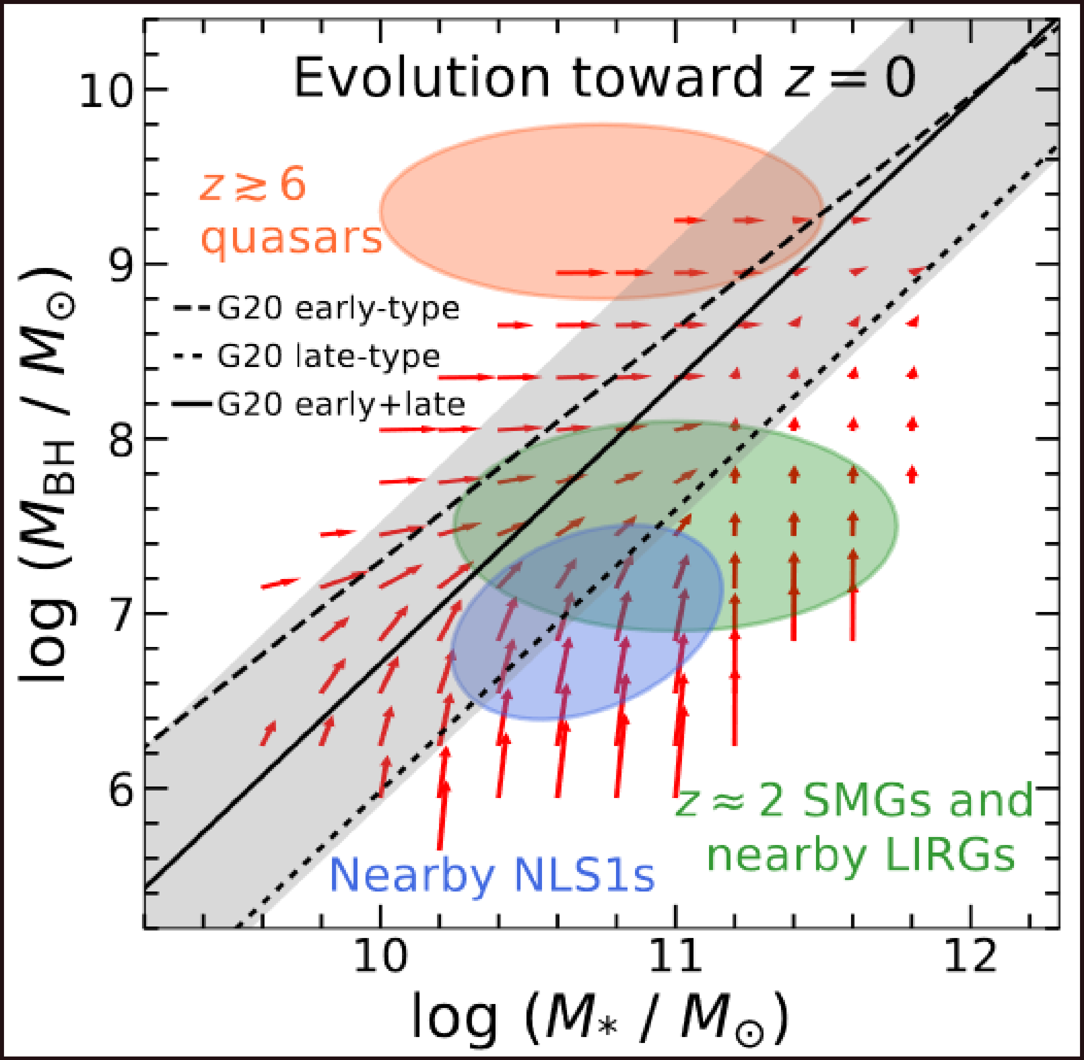
2006.10094

Evolution in different models



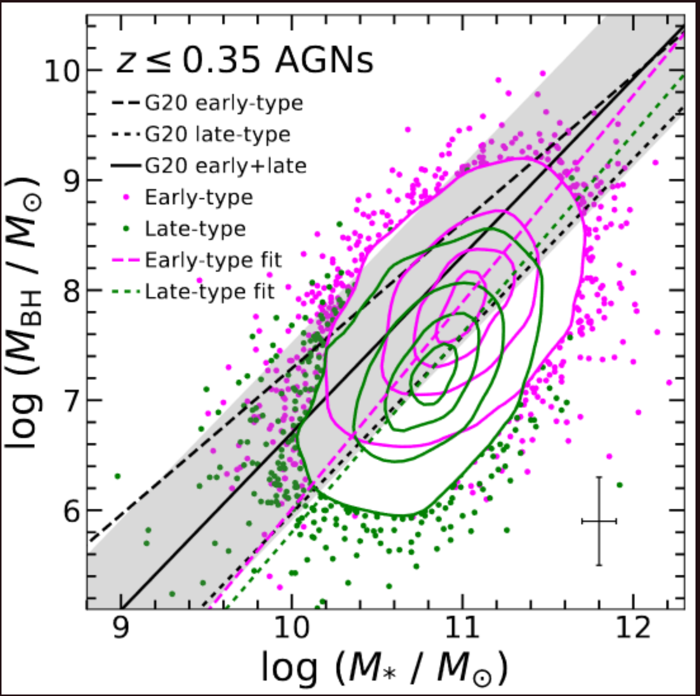
2006.10094

BH and stellar mass growth



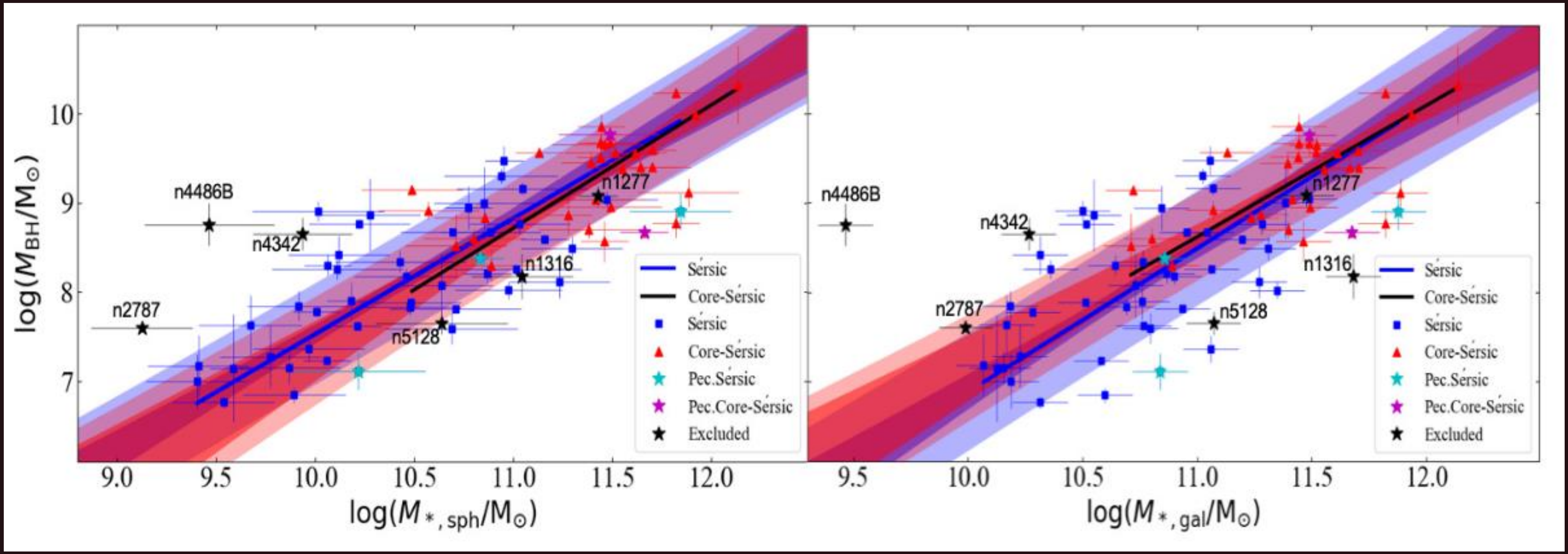
The authors studied 11500 AGNs at z<0.35.

The authors suggest that feedback from an AGN does not expel the gas preventing starformation.



2308.08603

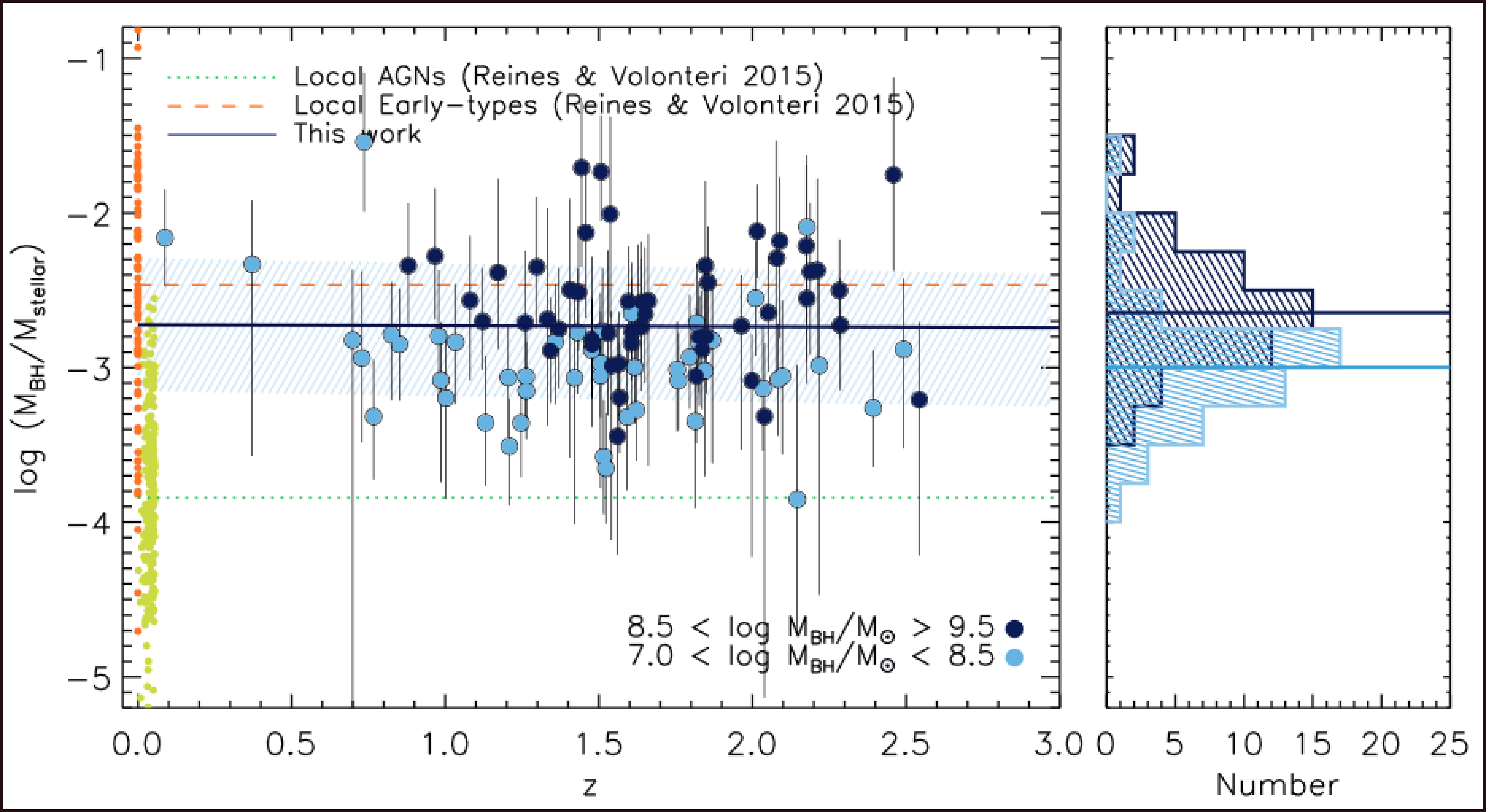
Scaling relations for early type galaxies



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

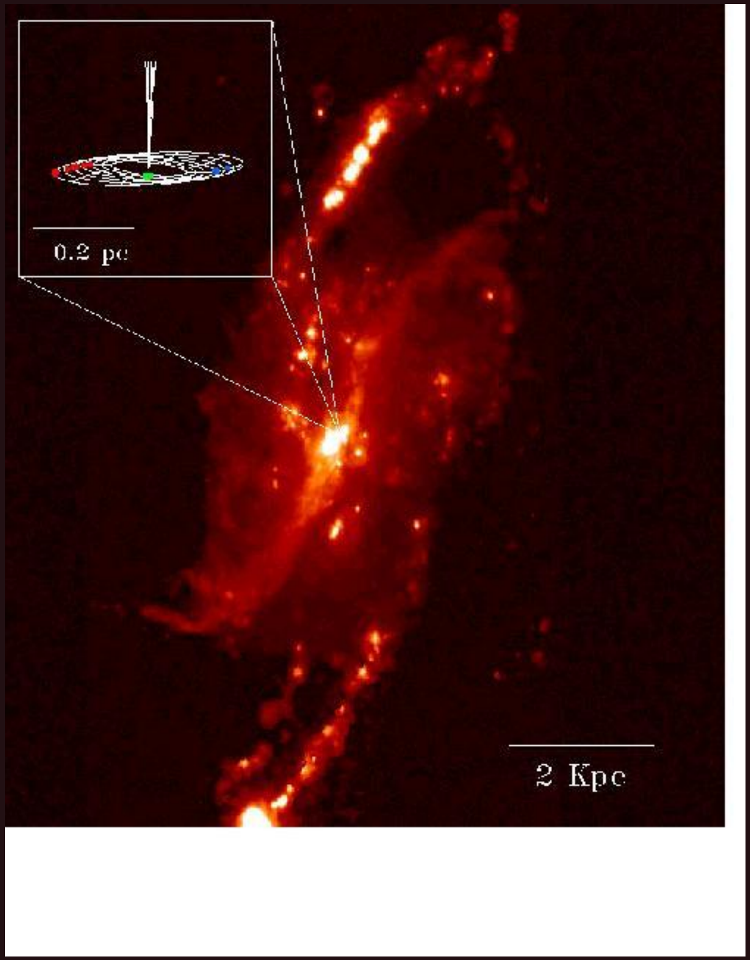
1903.04738

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



1912.02824

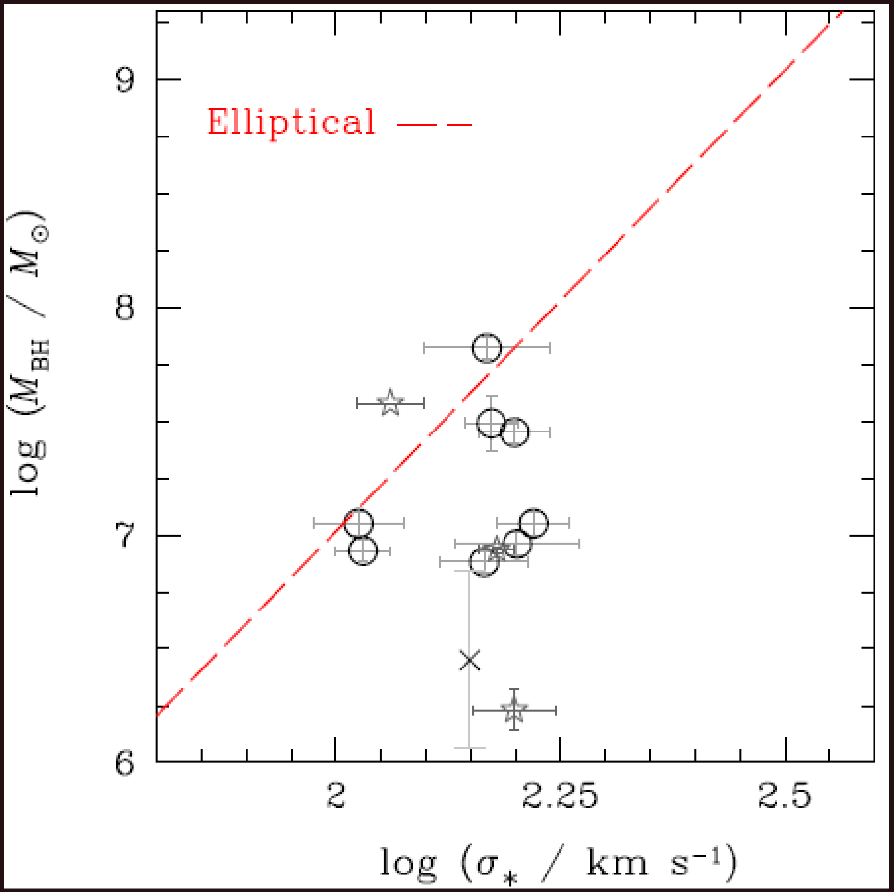
Masers

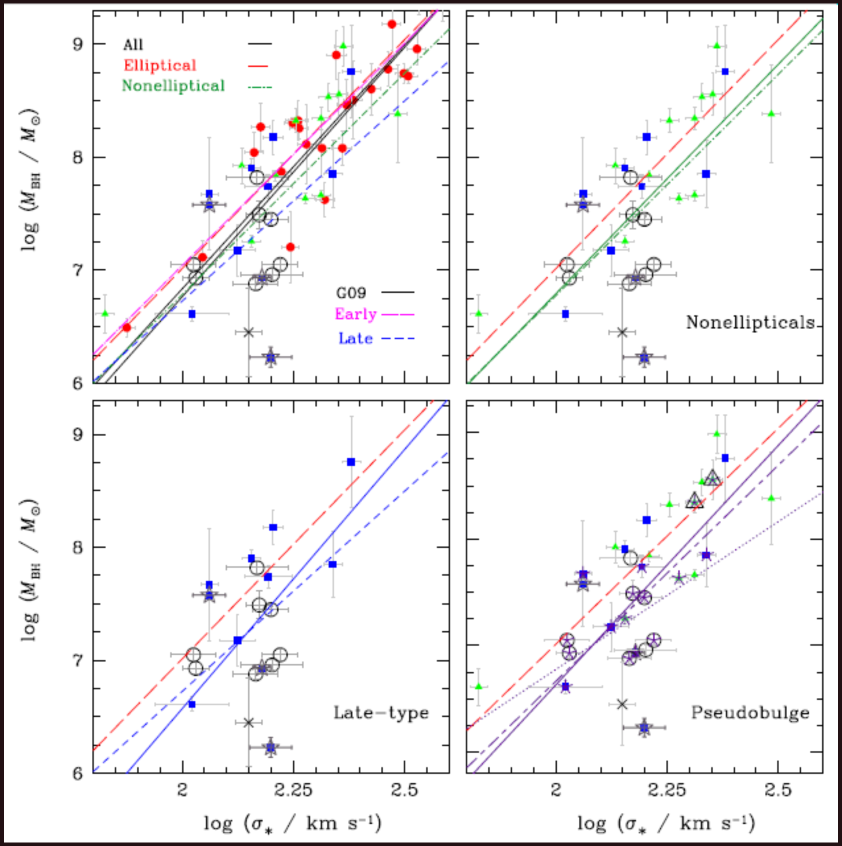


Observing movements of masers in **NGC 4258** it became possible to determine the mass inside 0.2 pc.
The obtained value is 35-40 million solar masses.

This is the most precise method of mass determination.

Several more megamaser measurements

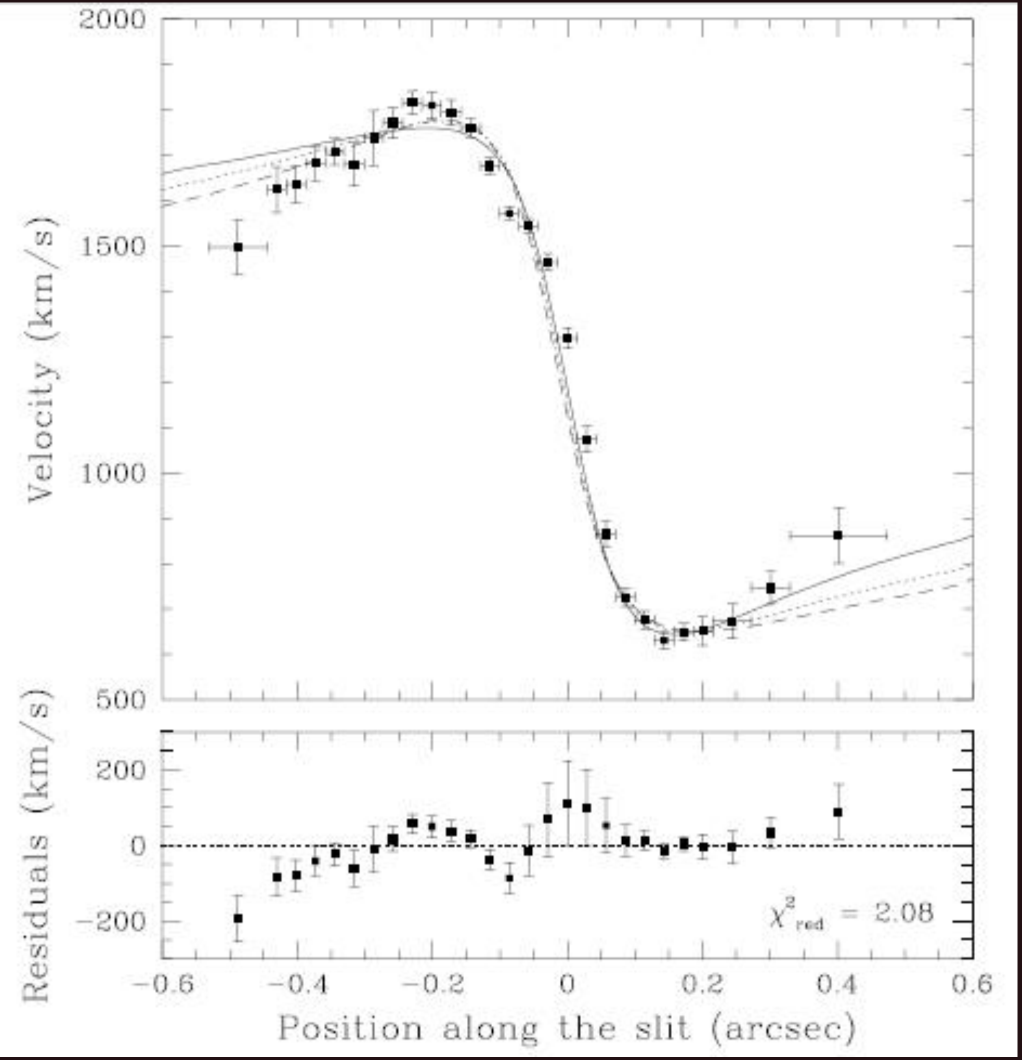




Circles – new measurements,
stars – from the literature.

1007.2851

Gas kinematics



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

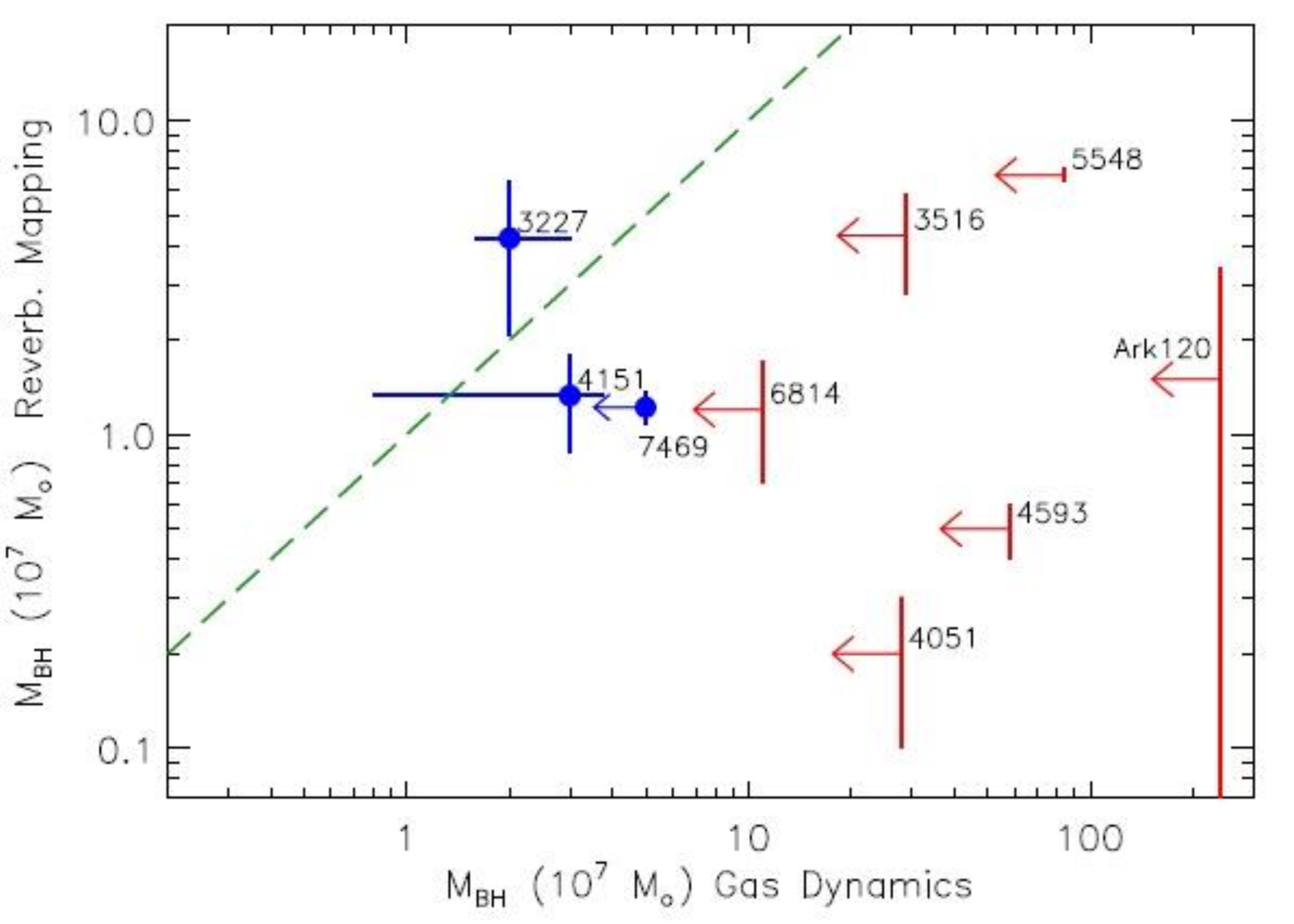
The mass is 3 10^9 M_0.

It is one of the heaviest BHs.

New measurements (2304.11264) suggest the disc inclination 25 degrees rather than 42 degrees and higher mass ~6 10^9 M_0.

(Macchetto et al. astro-ph/9706252)

Masses determined by gas kinematics

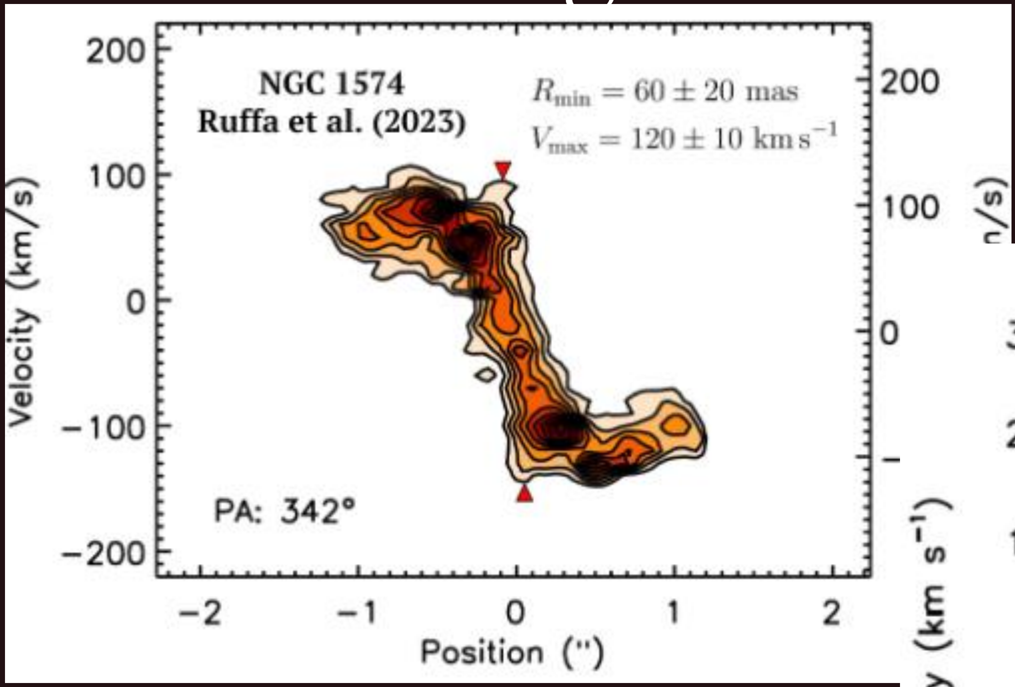


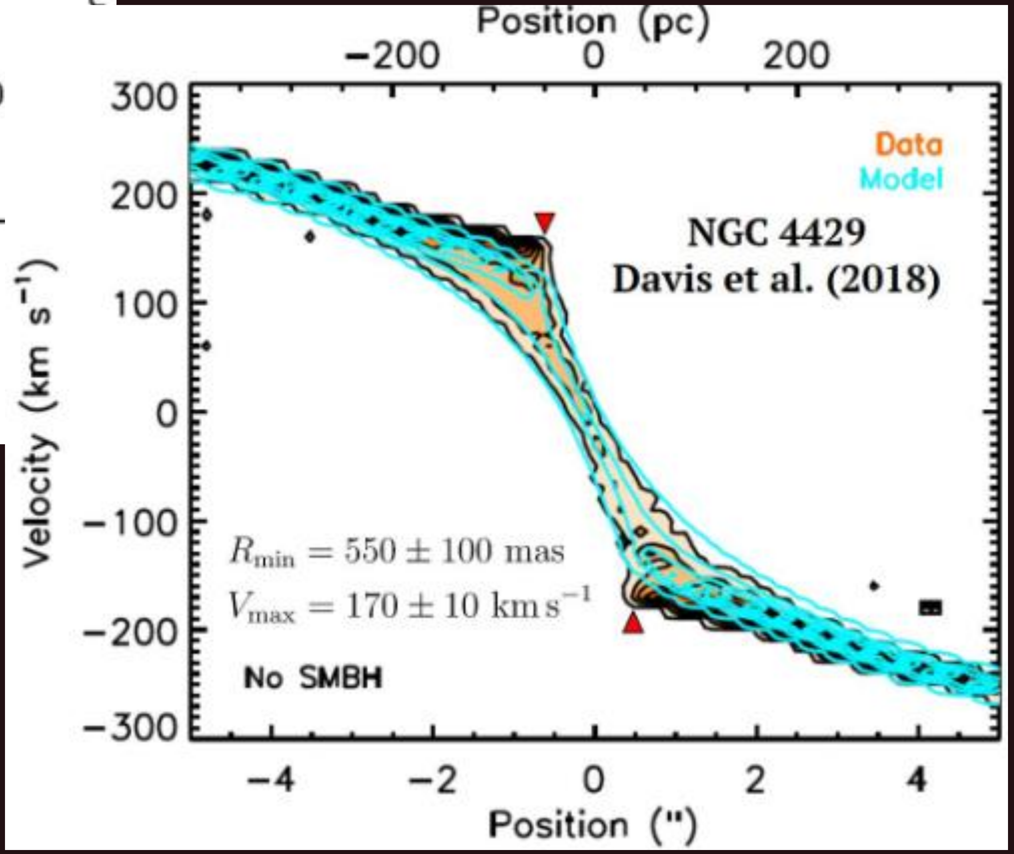
Masses determined by observing gas kinematics are in good correspondence with value obtained by reverberation mapping technique.

arXiv: 0707.0611

See a review in 1406.2555

Molecular gas measurements





SMBH is responsible for the rapid growth of velocity at the very center.

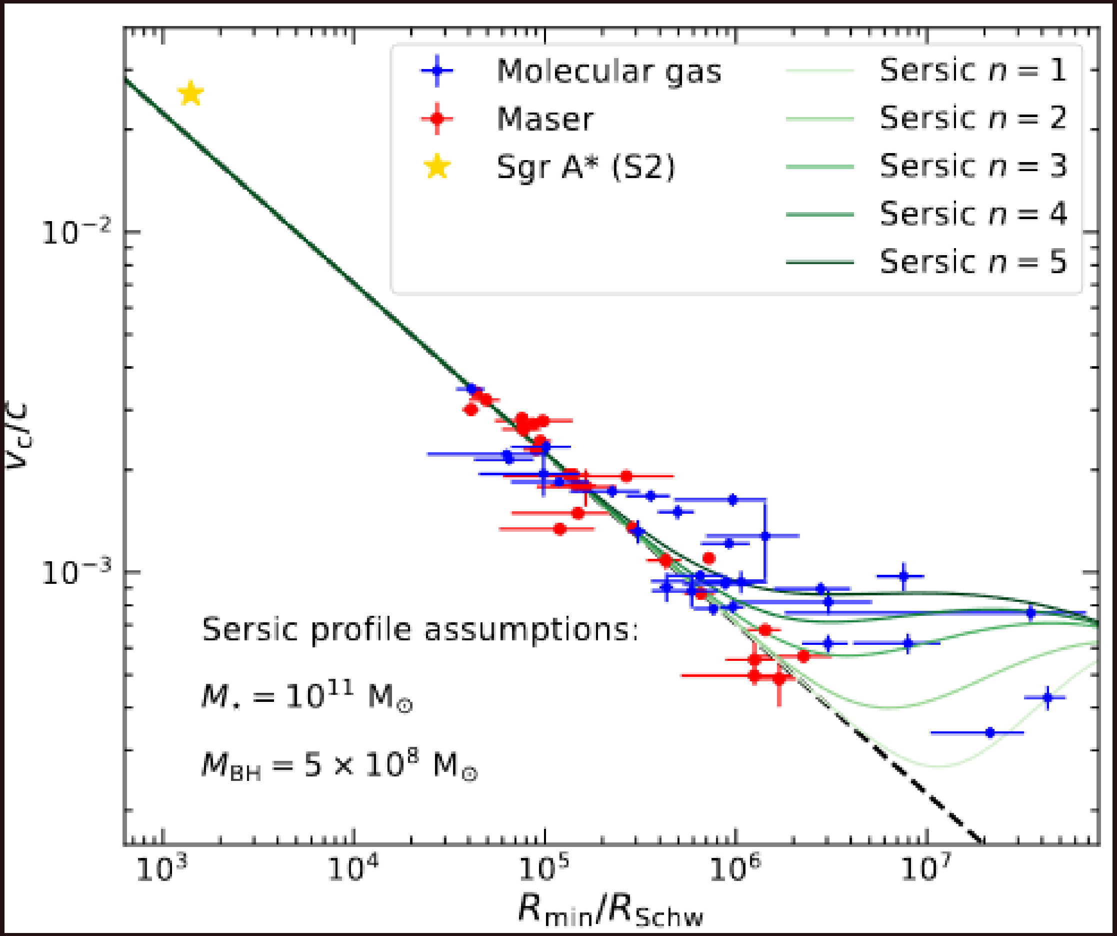
2404.16345

Comparison of the two methods

Masers vs. molecular gas

Masers provide a "gold standard" but in a narrow range of masses $M_{bh} \sim 10^7\ M_{sun}$ (as they usually are related to a particular type of galaxies)

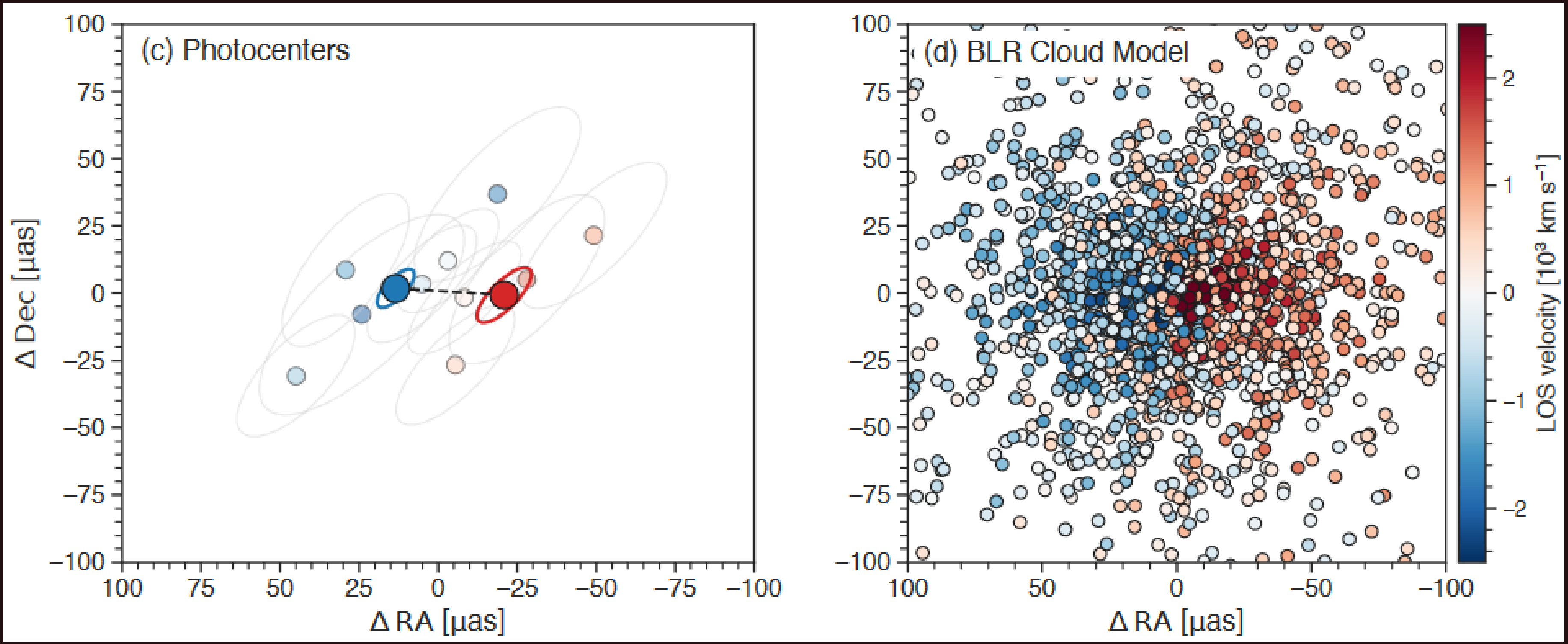
In some cases (nearby galaxies with massive BHs) molecular gas measurements can as precise as masers.



2404.16345

Broad line region kinematics at z~2

SDSS J092034.17+065718.0
VLTI+GRAVITY
Spatially resolved broad line region.
Shift between red and blue in Halpha.
M_{bh}~3.2 10^8 M_{sun}

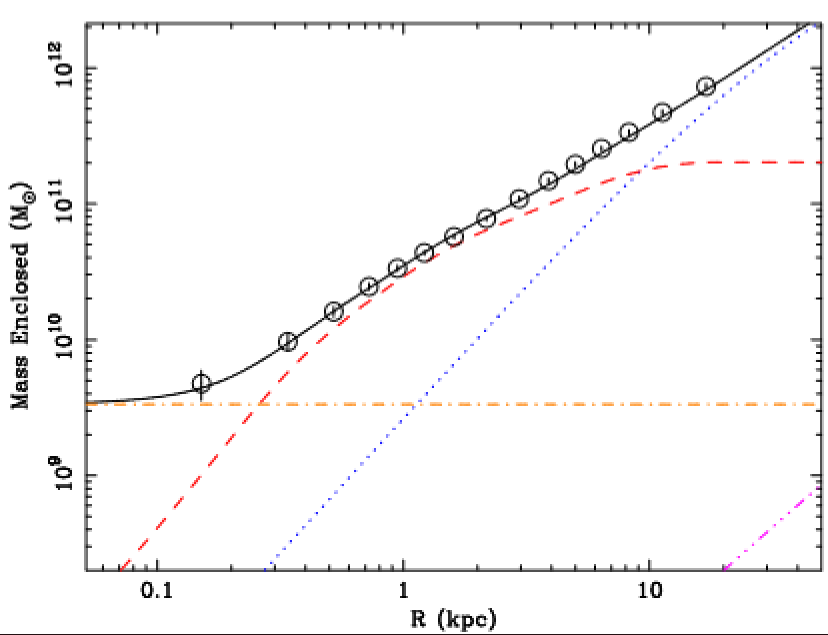


2401.14567

Mass via hot gas observations

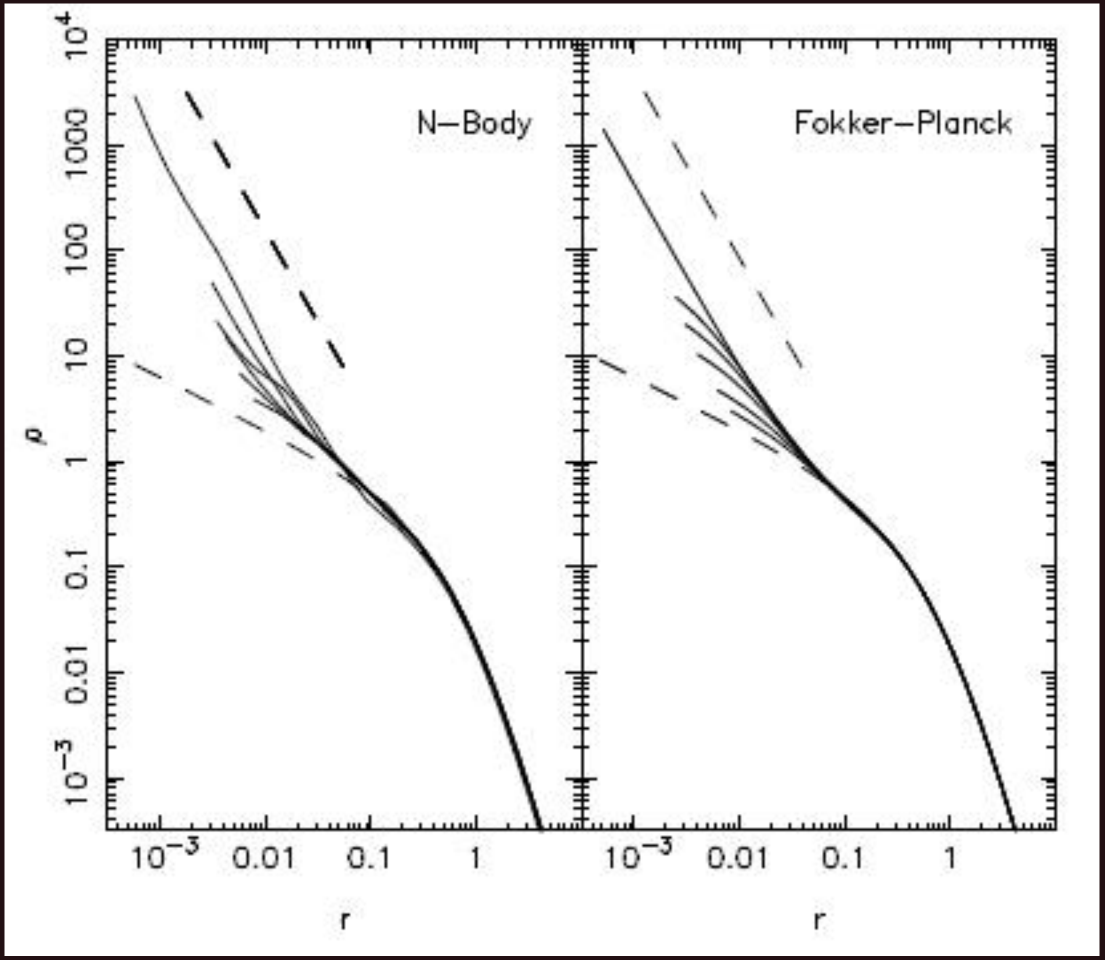
Giant elliptical galaxy NGC4649.
Chandra observations.
Temperature peaks at ~1.1keV within the innermost 200pc.

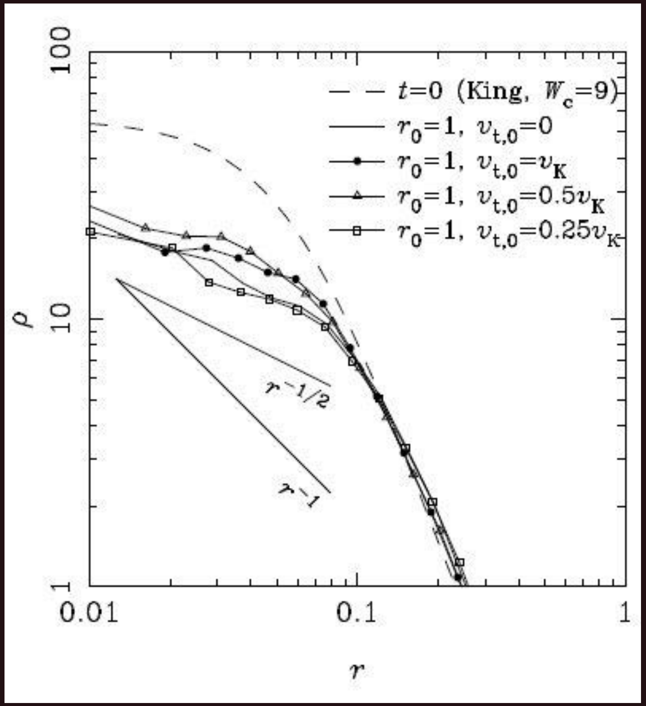
Under the assumption of hydrostatic equilibrium it is demonstrate that the central temperature spike arises due to the gravitational influence of a quiescent central super-massive black hole.



arXiv: 0801.3461

Stellar density profiles

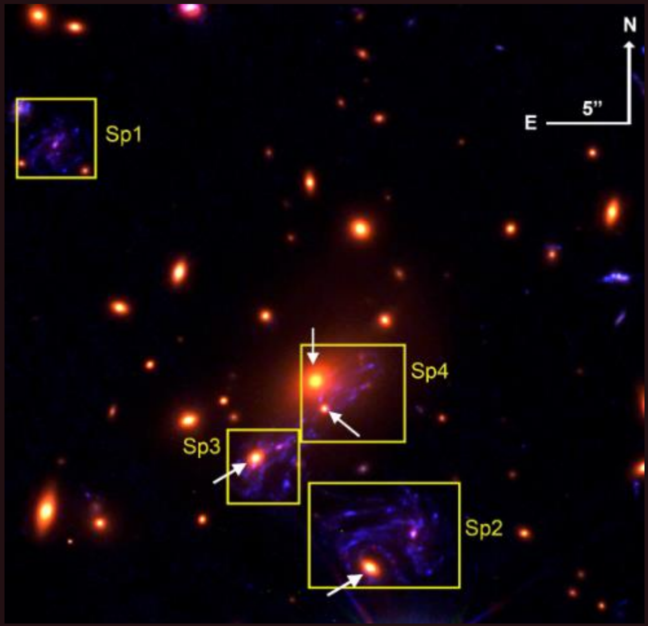


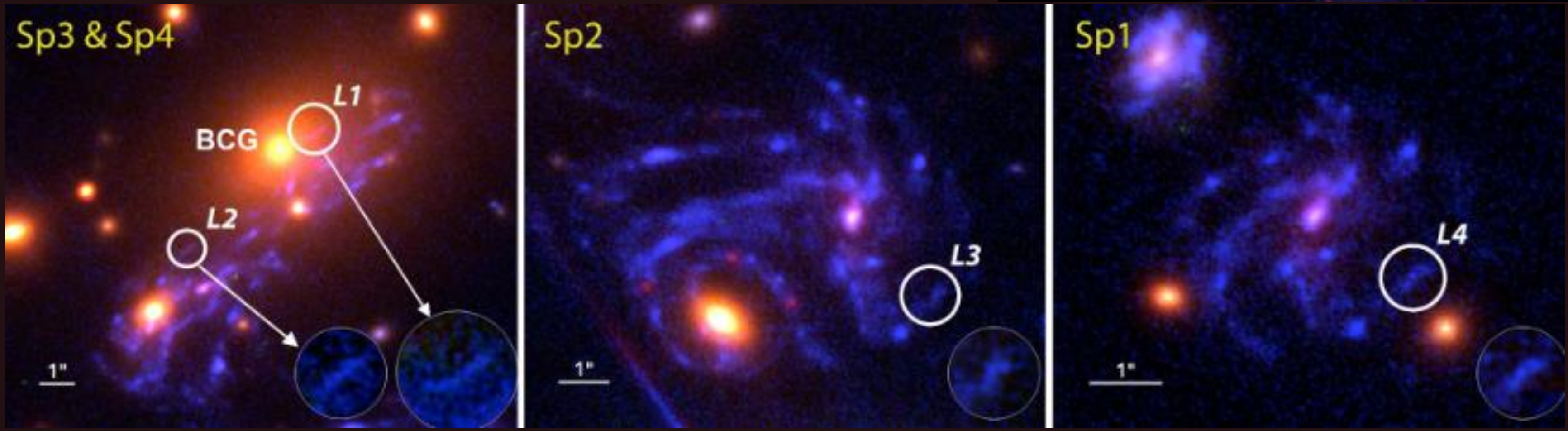


Combes astro-ph/0505463

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 ~7-12 billion solar masses.





1805.05051

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.

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

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

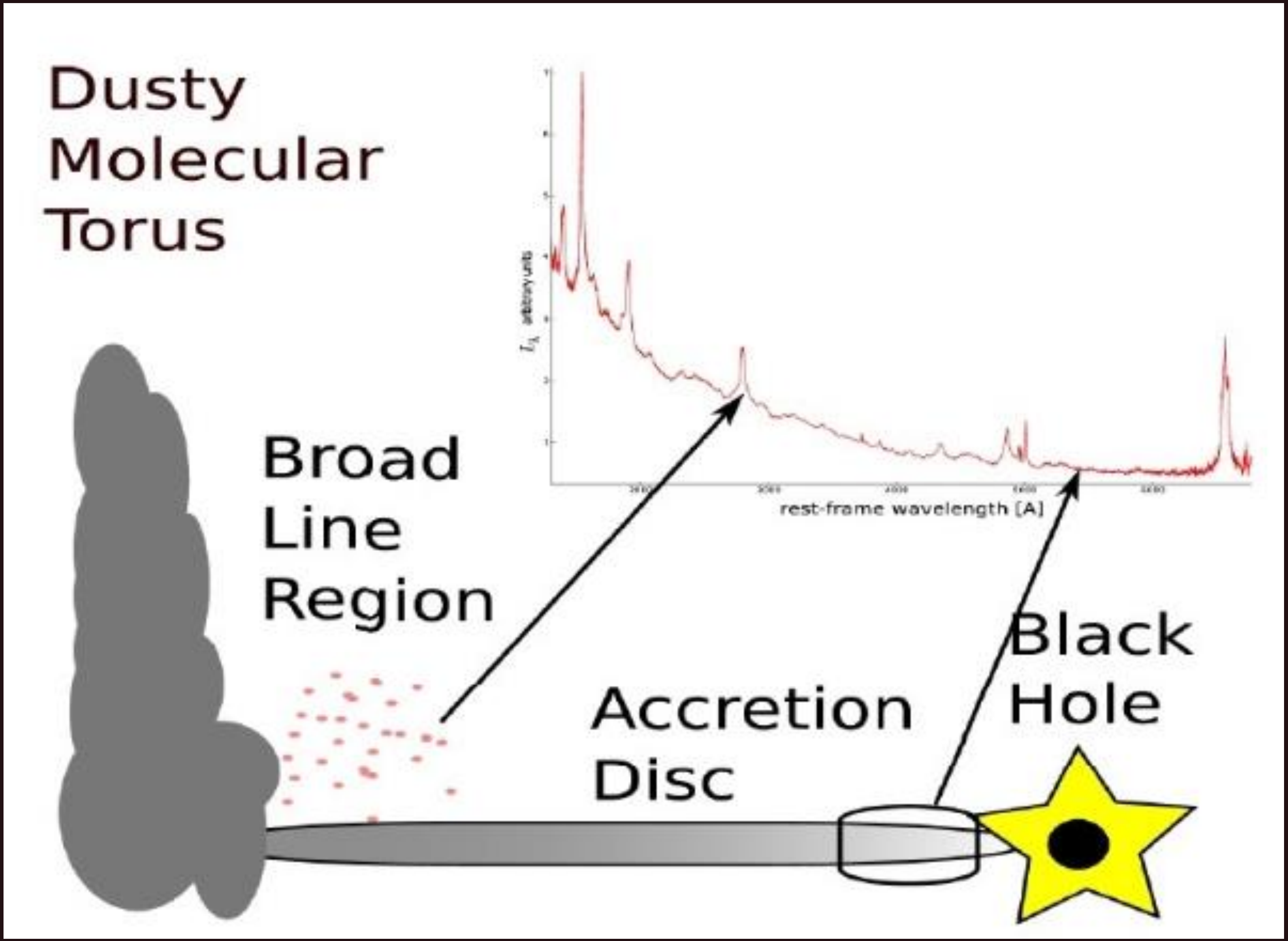
clouds velocities in BLR

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

(For details see arxiv:0705.1722)

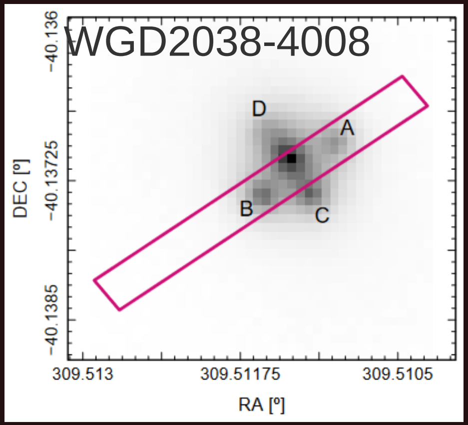
See a detailed recent example in 1104.4794

General scheme



1811.04326 – this paper is a review on AGN accretion

SMBH mass measurement with lensing



Two images, three lines used.
BH mass is measure with the reverberation mapping technique

$$M_{\rm BH} = f\, R_{BLR}\, (\Delta v)^2\, G^{-1}$$

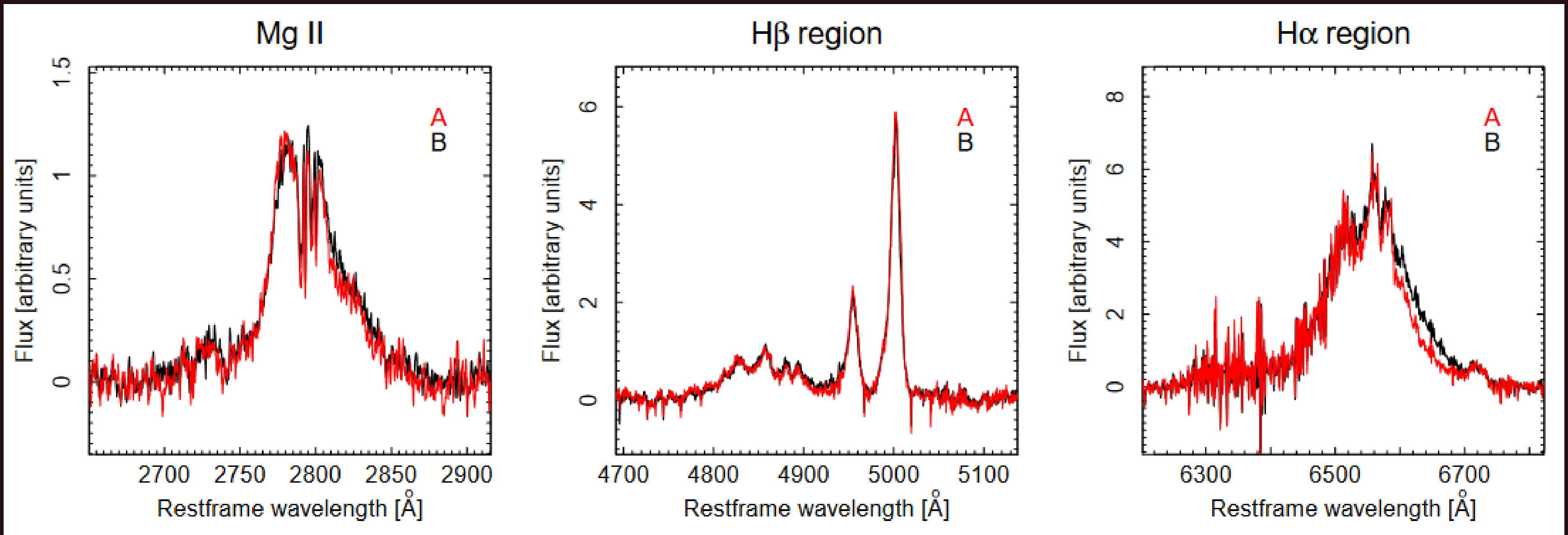
$$R_{BLR} \sim (\lambda L_\lambda)^\alpha$$

$$\log(M_{\rm BH}) = \log(K) + \alpha \log\left(\frac{\lambda L_\lambda}{10^{44}\ {\rm erg/s}}\right) + 2.0 \log\left(\frac{\rm FWHM}{1000\ {\rm km/s}}\right),$$

$$\log_{10}(M_{\rm BH}/M_\odot) = 8.37 \pm 0.40$$

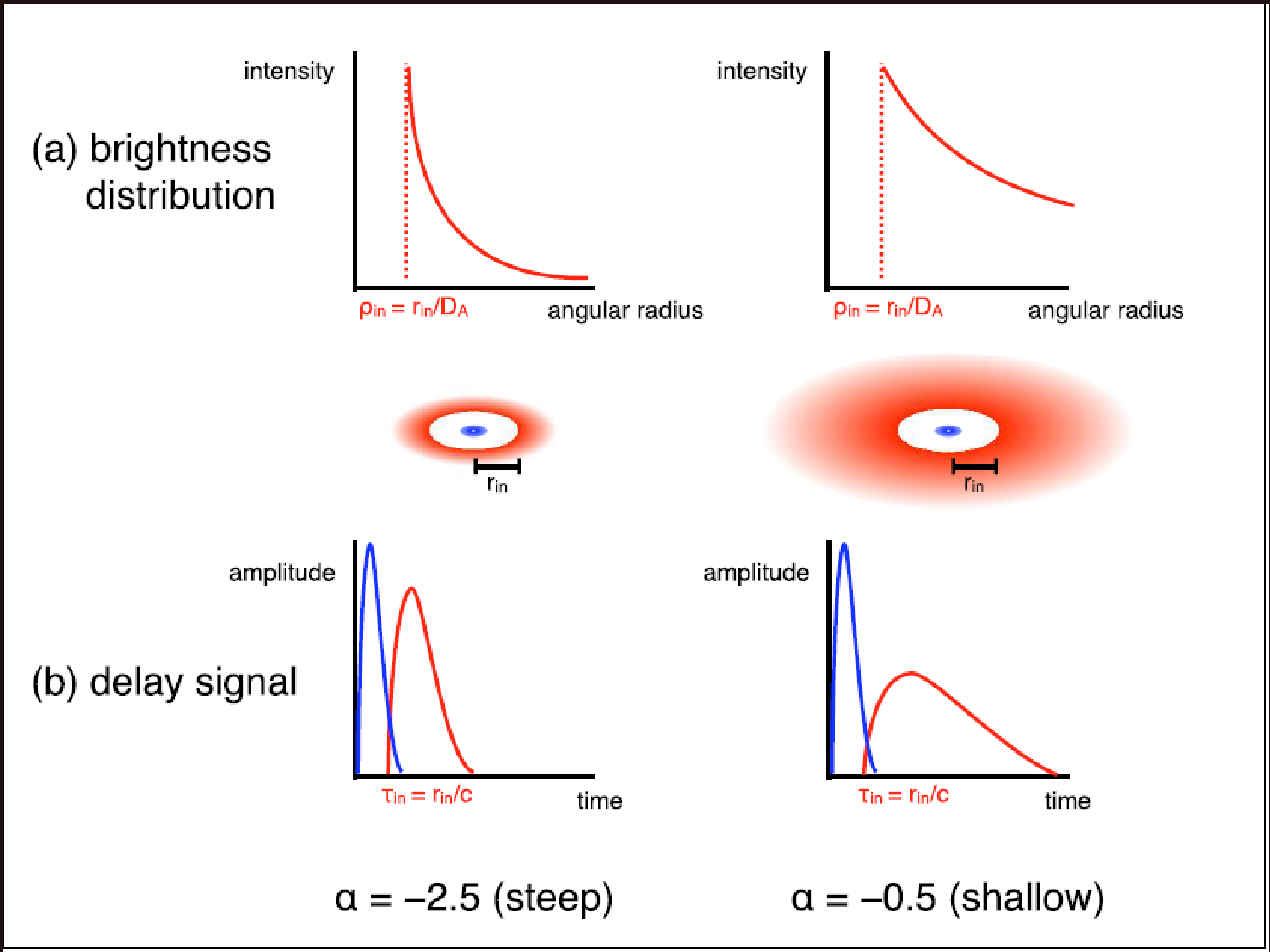
Accretion disc size:

$$\log_{10}(r_s/{\rm cm}) = 15.28 \pm 0.63$$



2110.01575

Why distances are important for mass measurements



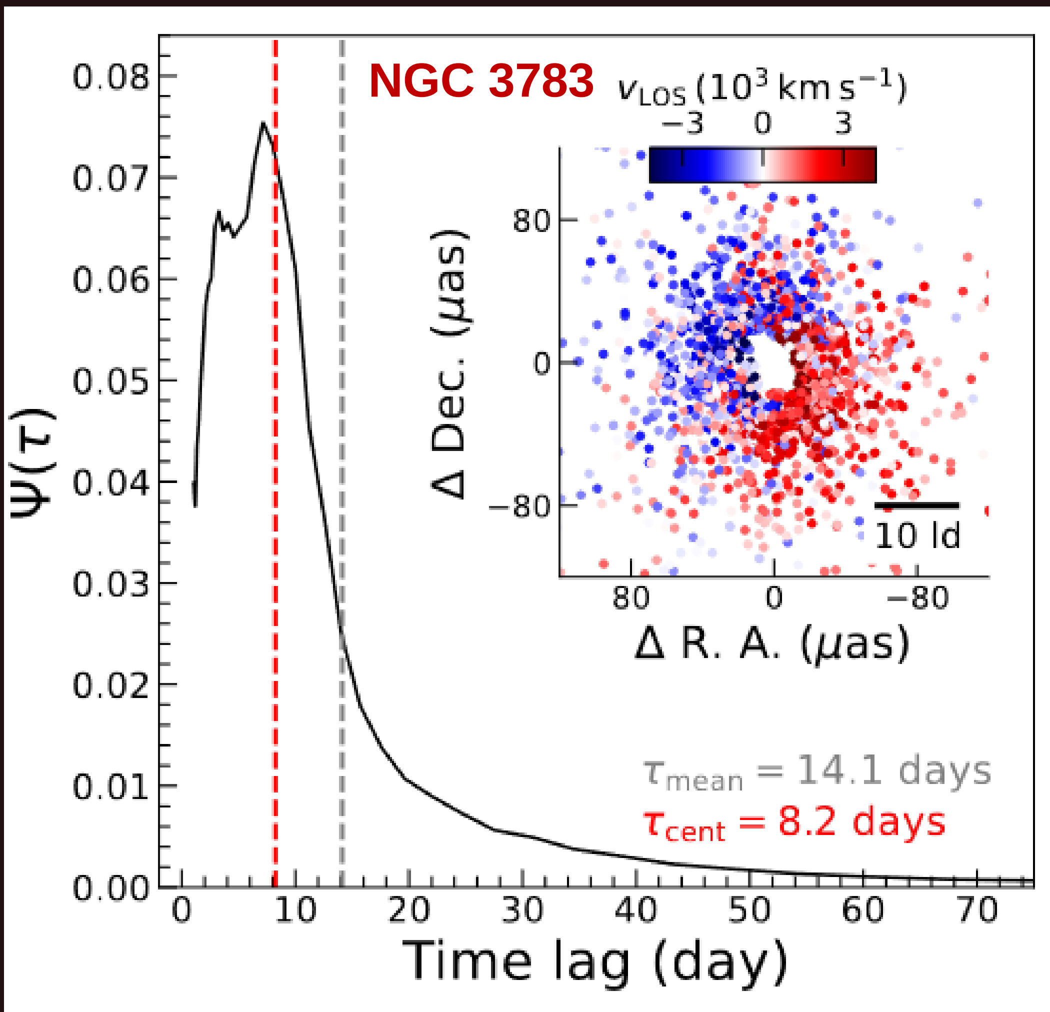
Galaxy NGC 4151 is used for calibration of SMBH masses as the mass is measured by several methods (reverberation mapping, stellar and gas dynamics.).

Re-determination of its distance resulted in re-determination of the mass.

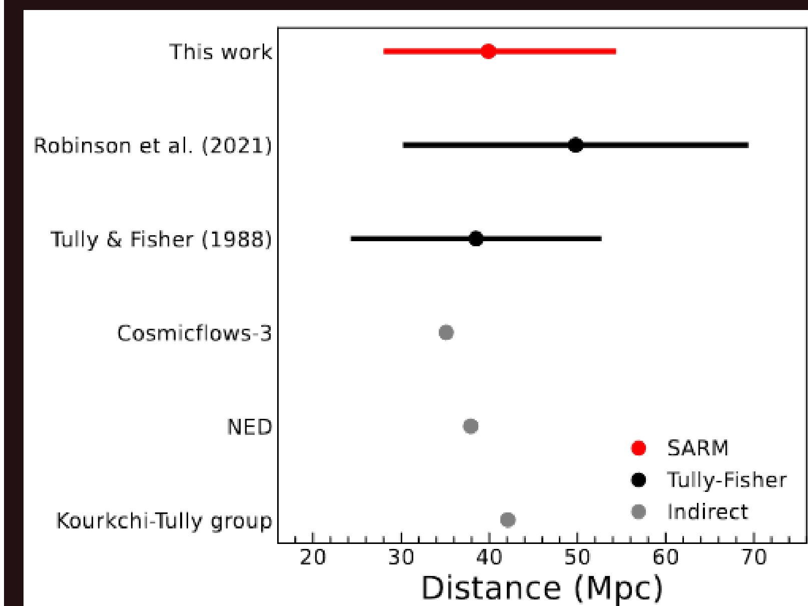
Thus, for many SMBHs mass measurements are enhanced by the factor ~1.4.

1411.7032

Mass and distance measurement



Distance (Mpc)	Method description
$39.9^{+14.5}_{-11.9}$	SARM (this work)
49.8 ± 19.6	Tully-Fisher relation (Robinson et al. 2021)
38.5 ± 14.2	Tully-Fisher relation (Tully & Fisher 1988)
35.1	Cosmicflows-3 (EDD; Kourkchi et al. 2020)
37.9	NED (Virgo + GA + Shapley)
42.1	Galaxy group (Kourkchi & Tully 2017)



2107.14262 VLTI/GRAVITY

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.

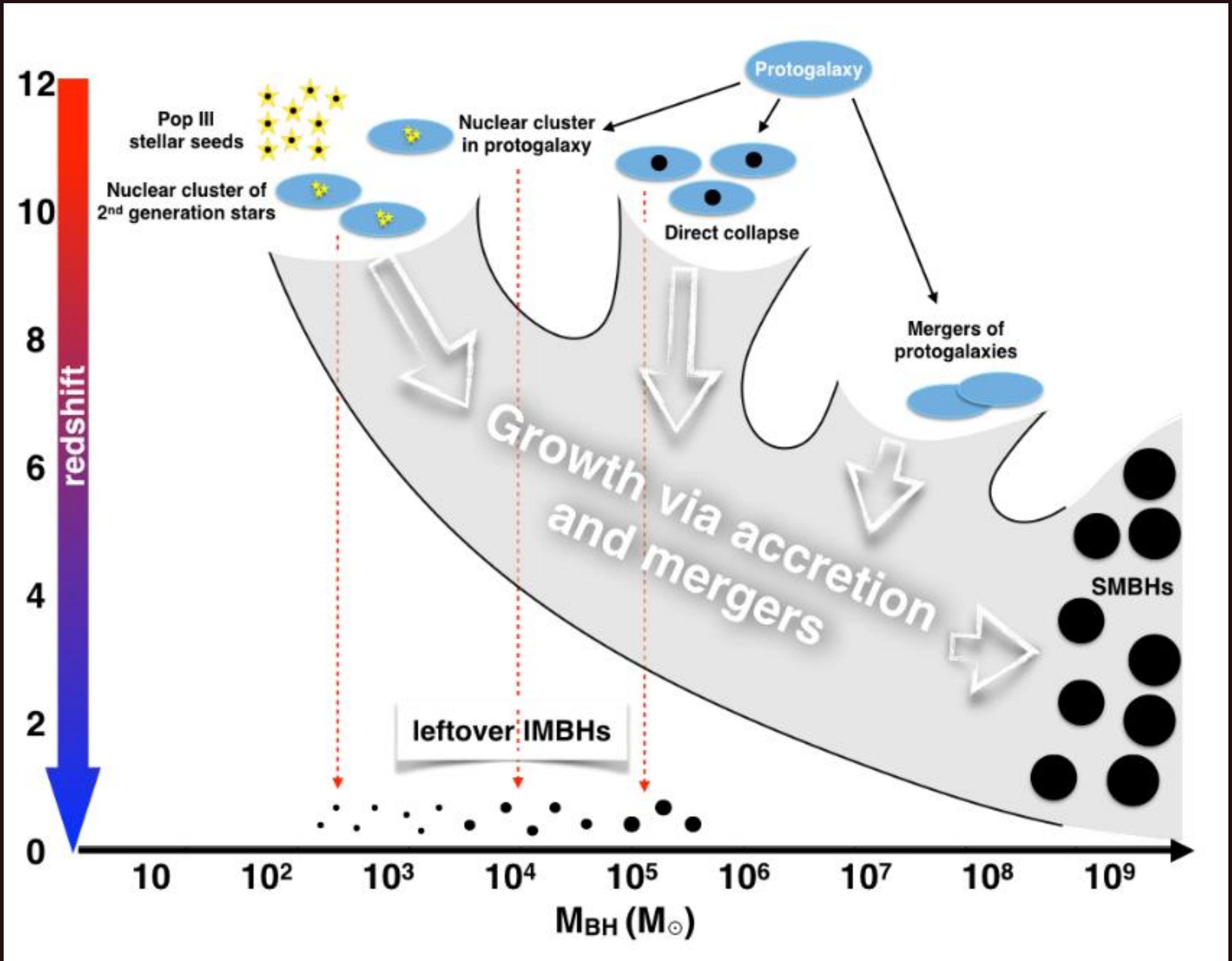
(see astro-ph/0411792)

Two variants

Evolutionary and Empirical

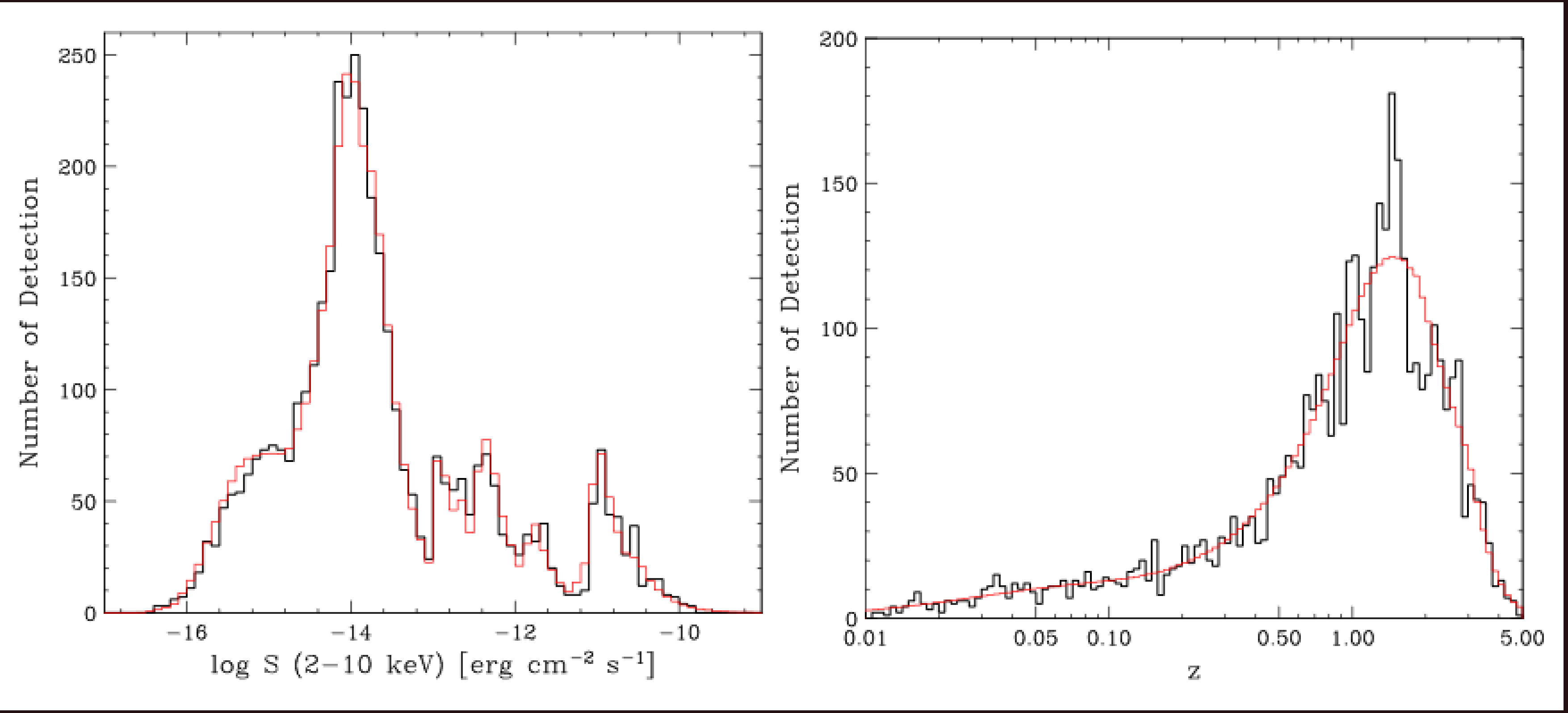
1. Evolutionary PS.
   The evolution is followed from some early stage.
   Typically, an artificial population is formed
   (especially, in Monte Carlo simulations)
2. Empirical PS.
   It is used, for example, to study integral properties
   (spectra) of unresolved populations.
   A library of spectra is used to predict integral properties.

Origin of SMBHs



1705.09667

X-ray background and pop. synthesis



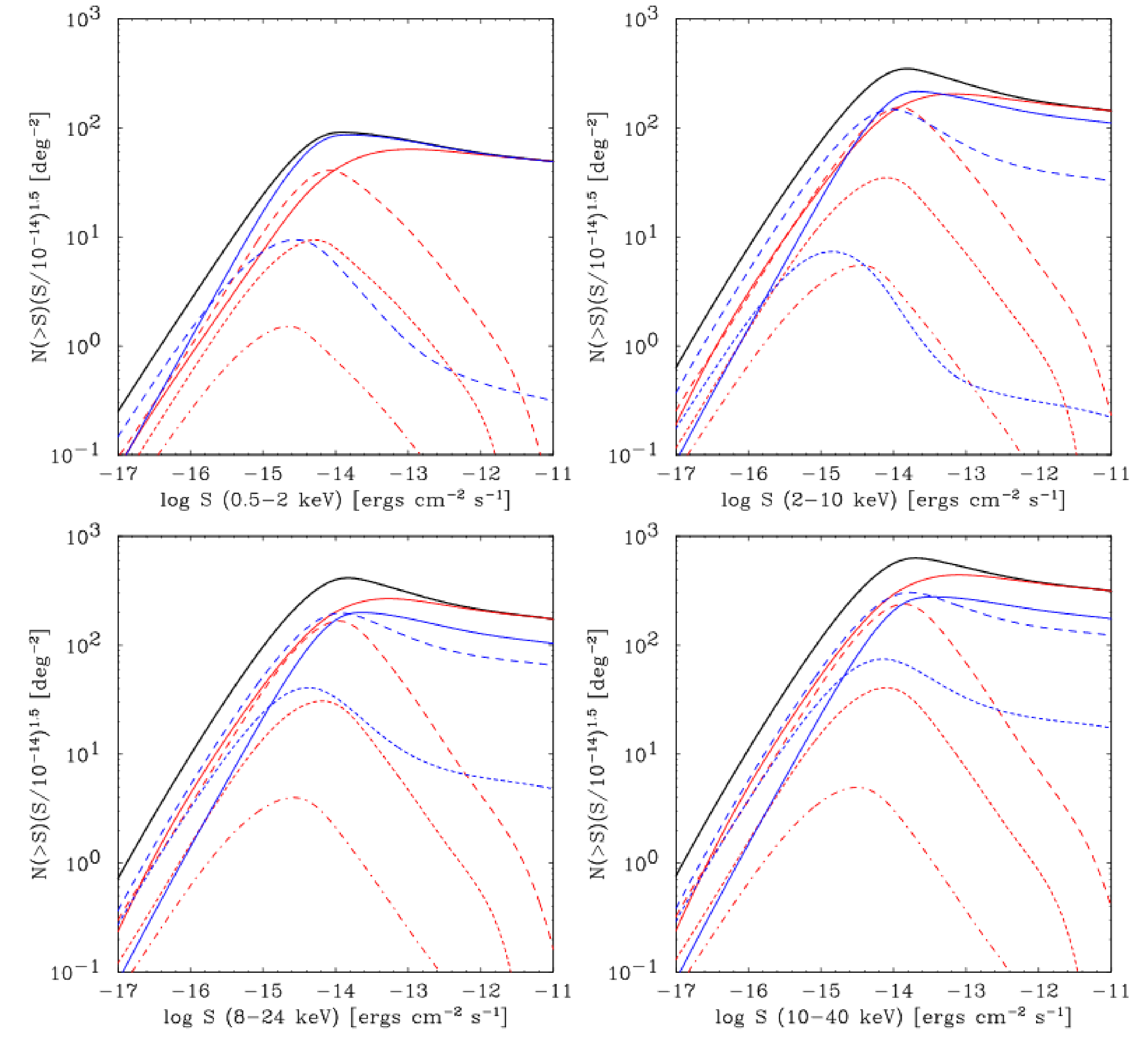
Observed histograms (thick, black) of flux (left) and redshift (right) of the authors sample compared with model predictions (thin, red).

1402.1836

Predicted
Log N – Log S
distributions.

Red: different z:

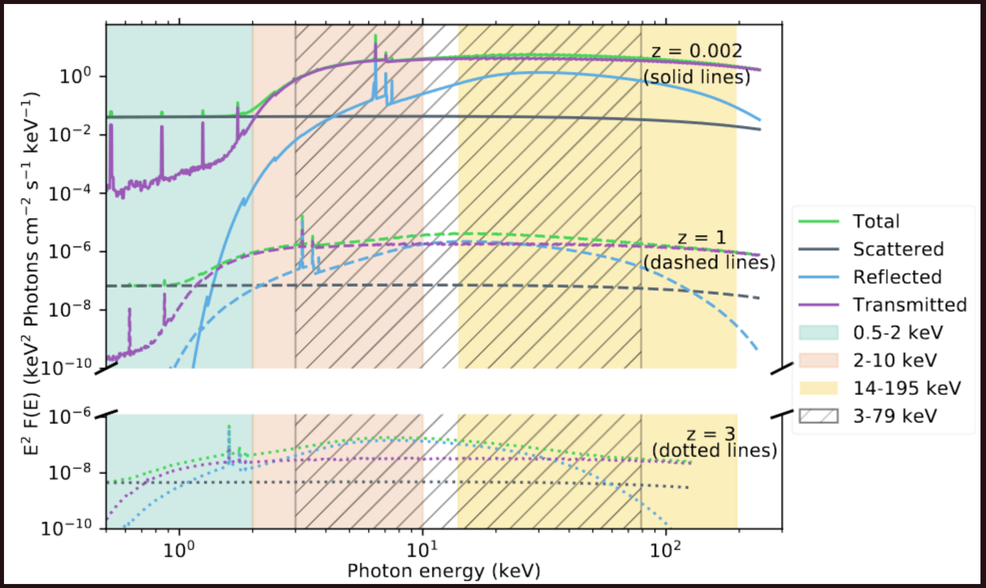
solid: z<1,
long-dashed:
z=1−2,
short-dashed:
z=2−3,
dot-dashed
z=3−5

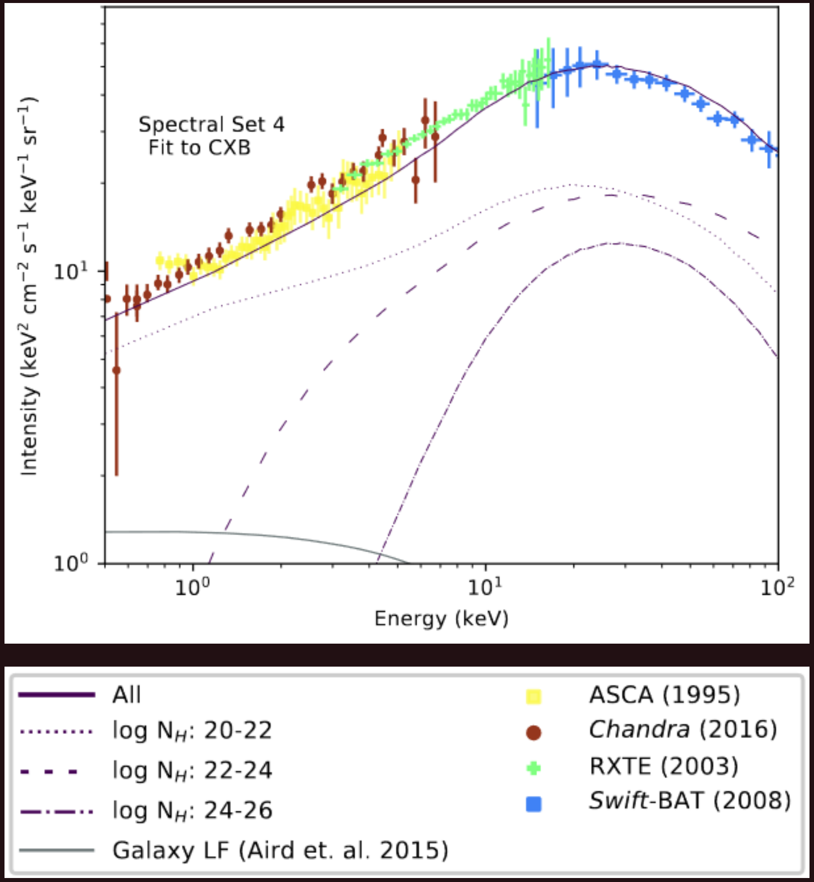


1402.1836

X-ray spectra of AGNs

New population synthesis

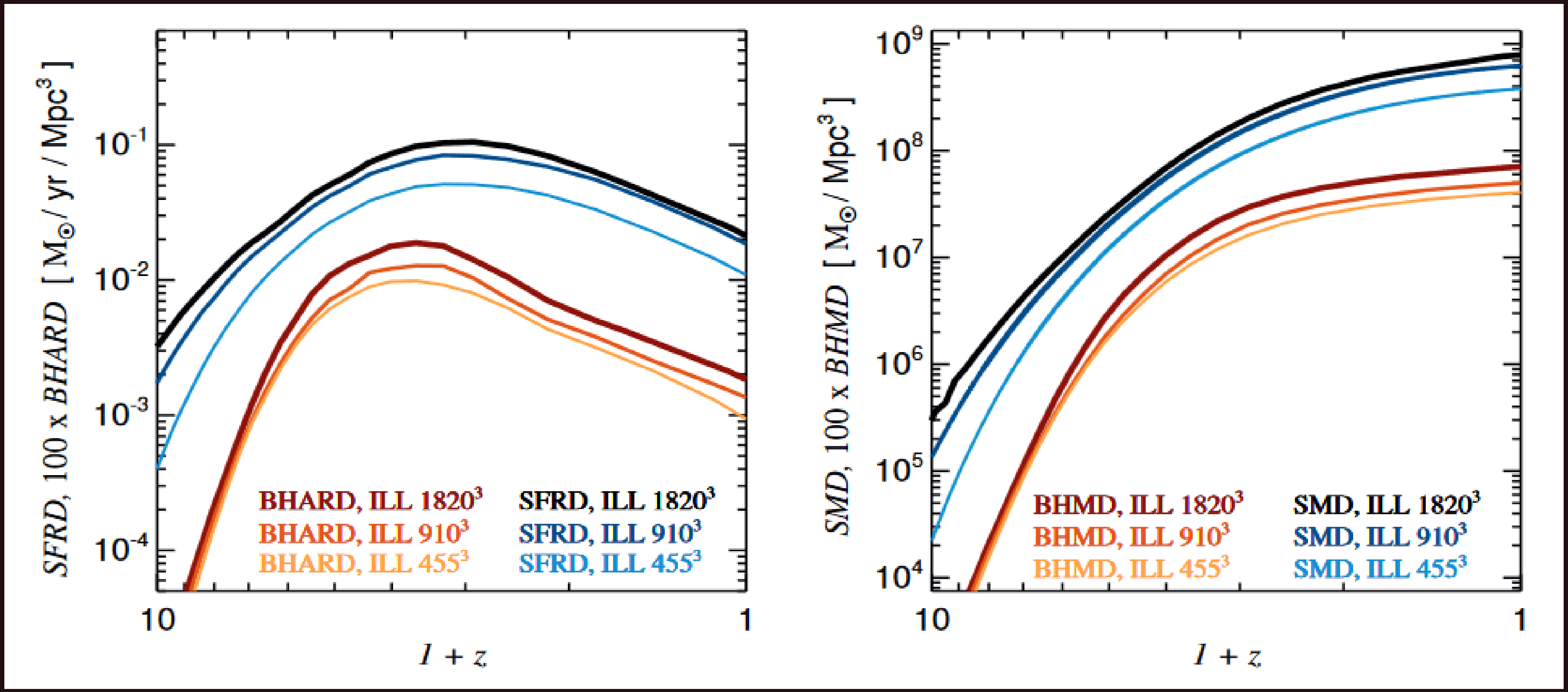




50±9% (56±7%) of all AGN
within z~0.1 (1.0) are Compton-thick.

1810.02298

Illustris calculations

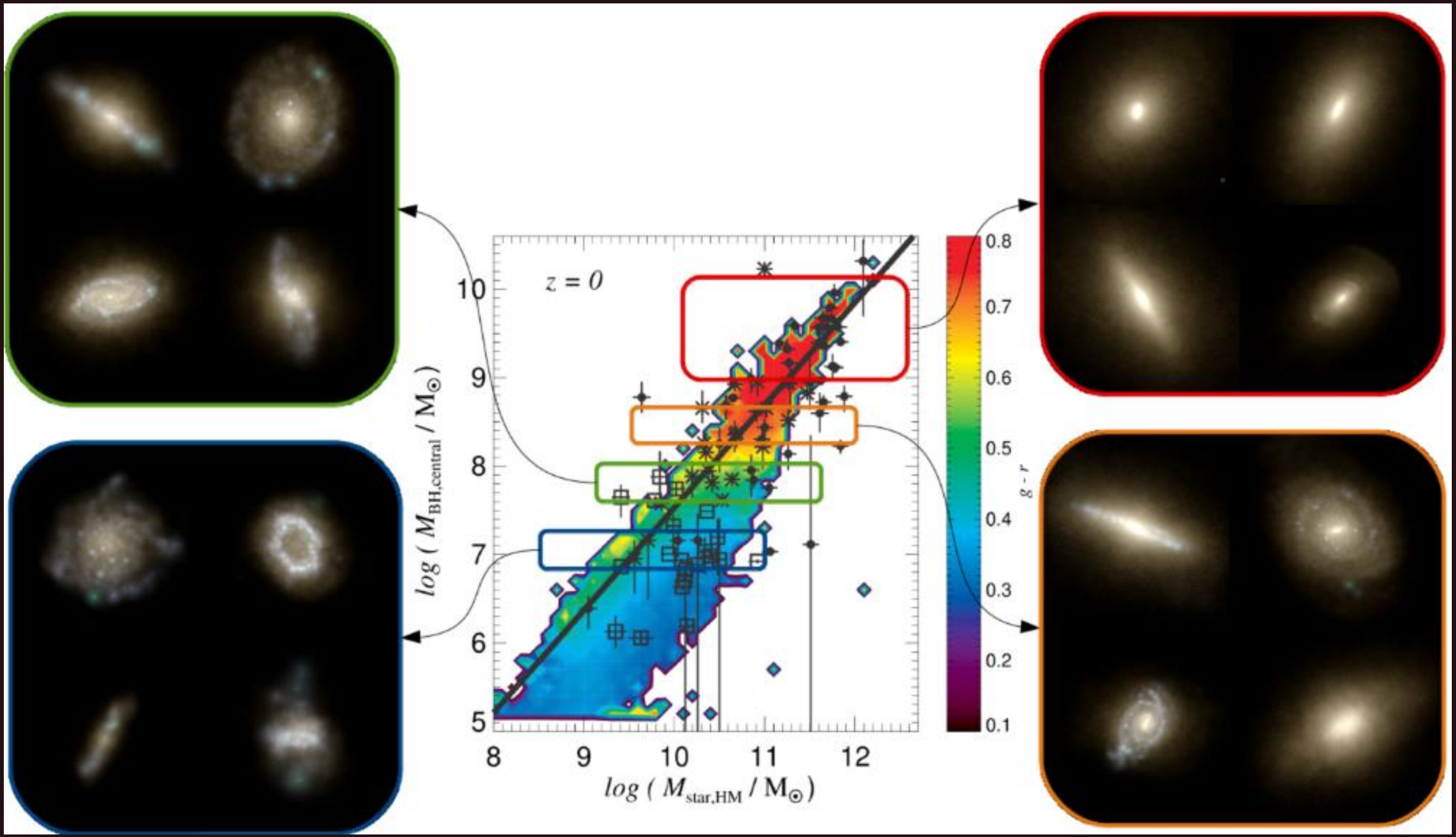


Time evolution of the star formation rate density (blue curves) and of the black hole accretion rate density (red curves; rescaled by a factor of a 100) for three different resolutions.

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

1408.6842

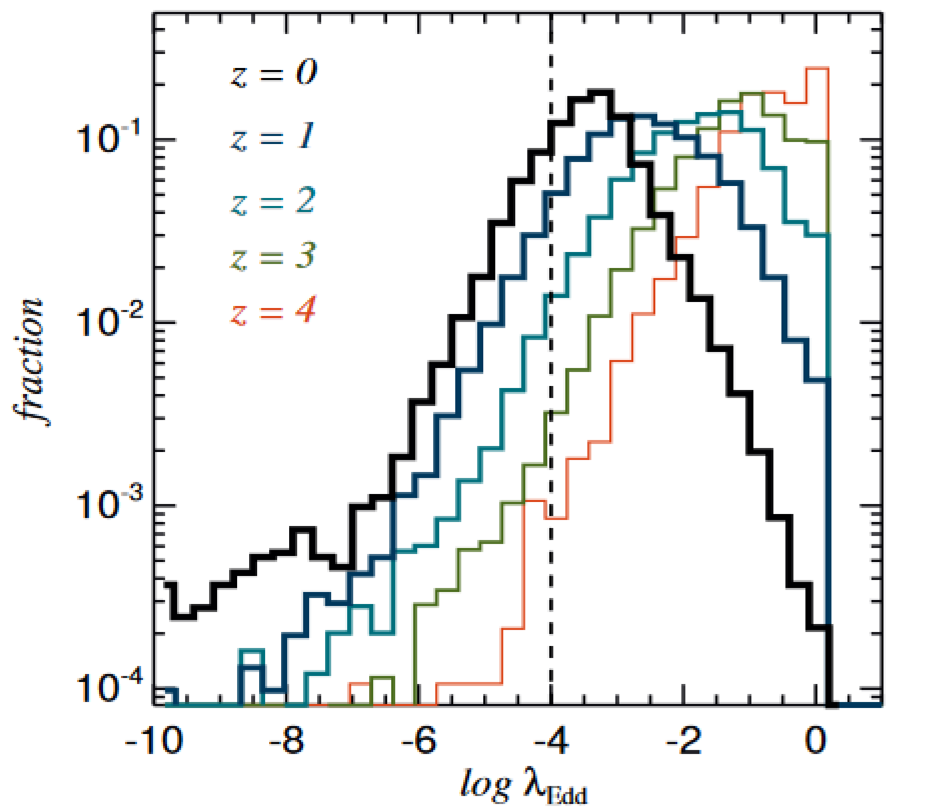
Illustris simulations

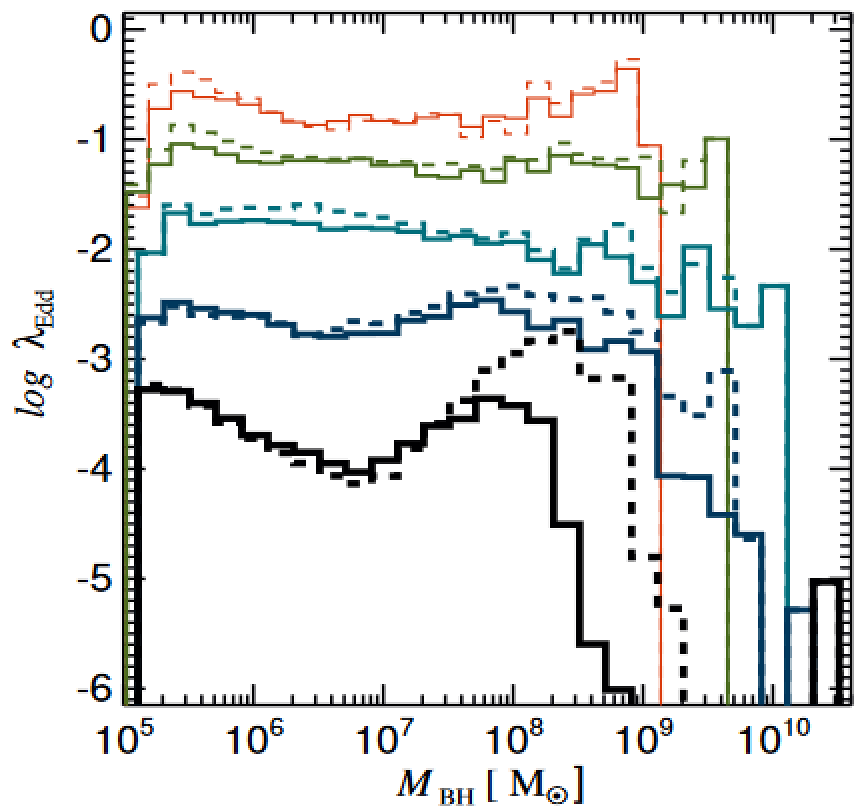


Stellar half-mass of all galaxies at z= 0 versus their central black hole mass

1408.6842

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.

1408.6842