SMBH mass growth and BH coalescence

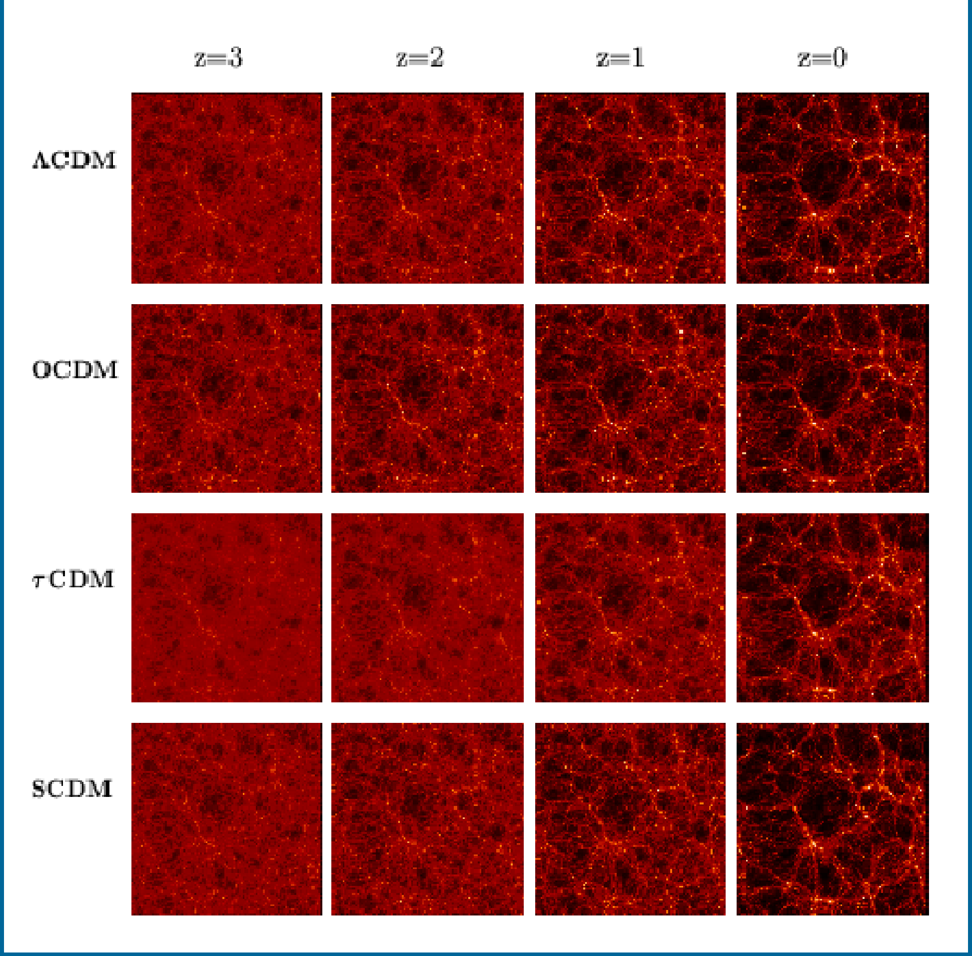
Plan of the lecture

1. Hierarchical model of galaxy formation.
2. Gravitational wave rocket.
3. Black holes at large redshifts.
4. Coalescence of SMBHs.
5. BH coalescence in binaries.

Reviews

arXiv: 1911.05791 **The Assembly of the First Massive Black Holes**
arXiv: 1307.3542 **Astrophysics of Super-massive Black Hole Mergers**
arXiv: 1110.6445 **A practical guide to the massive black hole cosmic history**
arXiv:1112.0320 **The Cosmic History of Black Hole Growth from Deep Multiwavelength Surveys**
arXiv: 1407.3102 **Massive binary black holes in galactic nuclei and their path to coalescence**
arXiv: 2310.16896 **Observational signatures of binary SMBH within the final pc**
arXiv: 1307.4086 **Gravitational wave emission from binary SMBHs**
arXiv: 2110.10175 **The origins of massive black holes**
arXiv: 2304.11541 **Modeling of SMBHs properties and evolution**

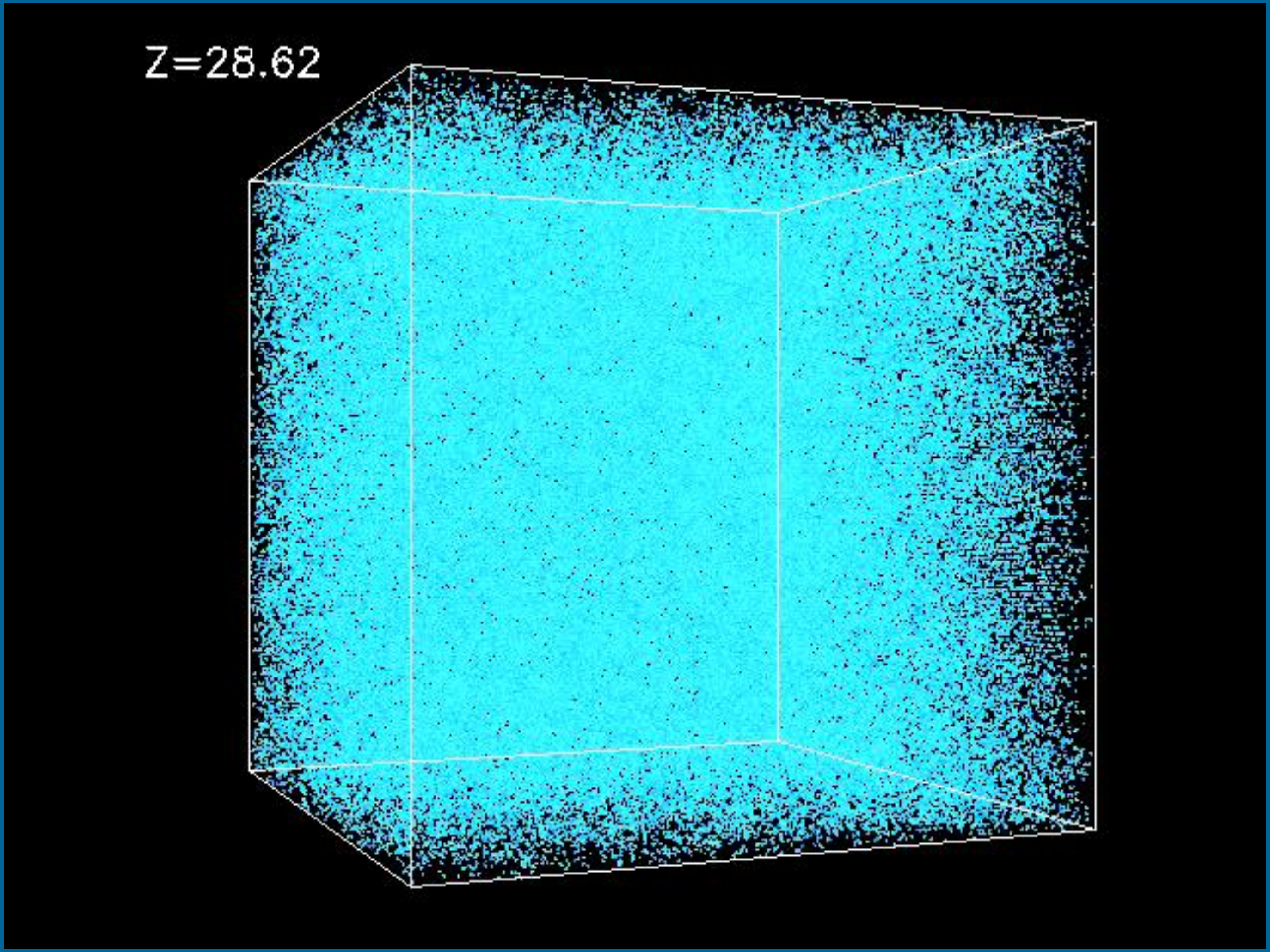
Structure growth in the universe



Today the standard model of the structure formation is the *hierarchical* one.

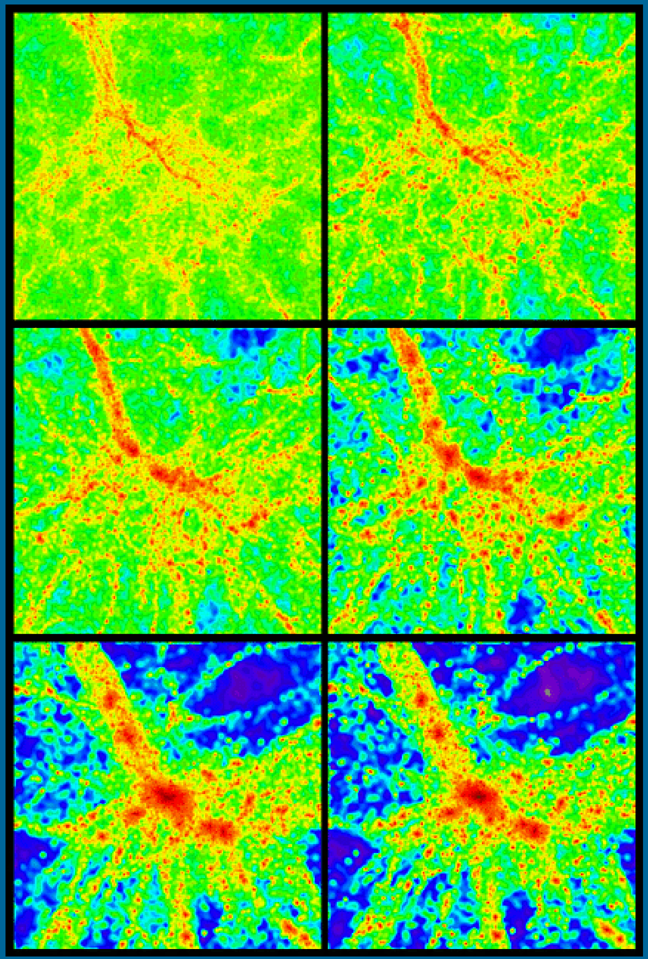
Numerical calculations of the evolution of the large-scale structure and single “blocks” reached a very high level of precision (arxiv:0706.1270).

Large scale structure



Kravtsov et al.

Formation of clusters of galaxies



tCDM 21x21 $(Mpc/h)^3$ LCDM 35x35 $(Mpc/h)^3$

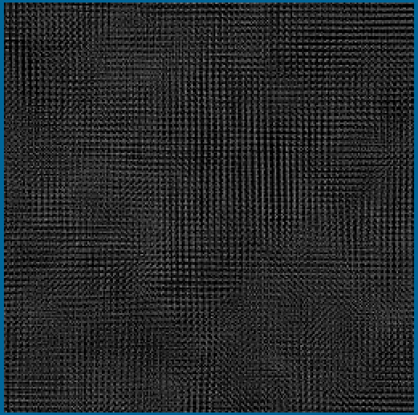
In the process of structure growth numerous coalescence of “building blocks” happen, each of these blocks can contain a BH.

After a coalescence a new-formed BH slowly, due to dynamical friction, moves towards the center of the resulting structure.

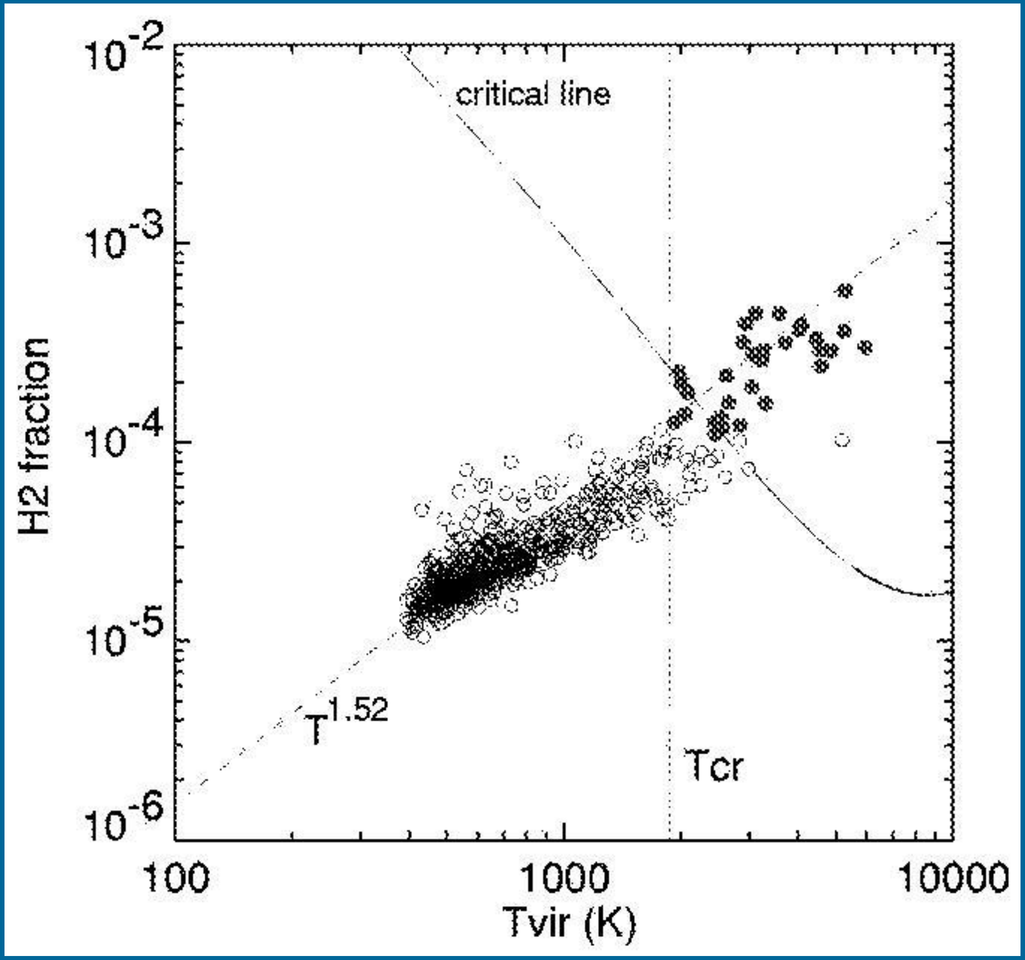
Formation of large galaxies is finished as z~2, after this no major mergers happen, only small satellites are captured by big galaxies.

Kauffmann, Colberg, Diaferio, and White

Growth of clusters of galaxies



Minihalos and the first stars



Symbols indicate minihalos.

Open symbols –
Cooling is not effective enough.

The critical line corresponds to equality between the cooling time and dynamical evolution time scale of a minihalo (free-fall time).

This line separates dark halos and halos that can produce stars.

In each minihalo a very small number of stars in formed.

Volker Bromm astro-ph/0311292

The first stars and minihalos

In the standard λCDM model the first massive BHs are formed at z>15 in minihalos with M> 5 10^5 M_O.

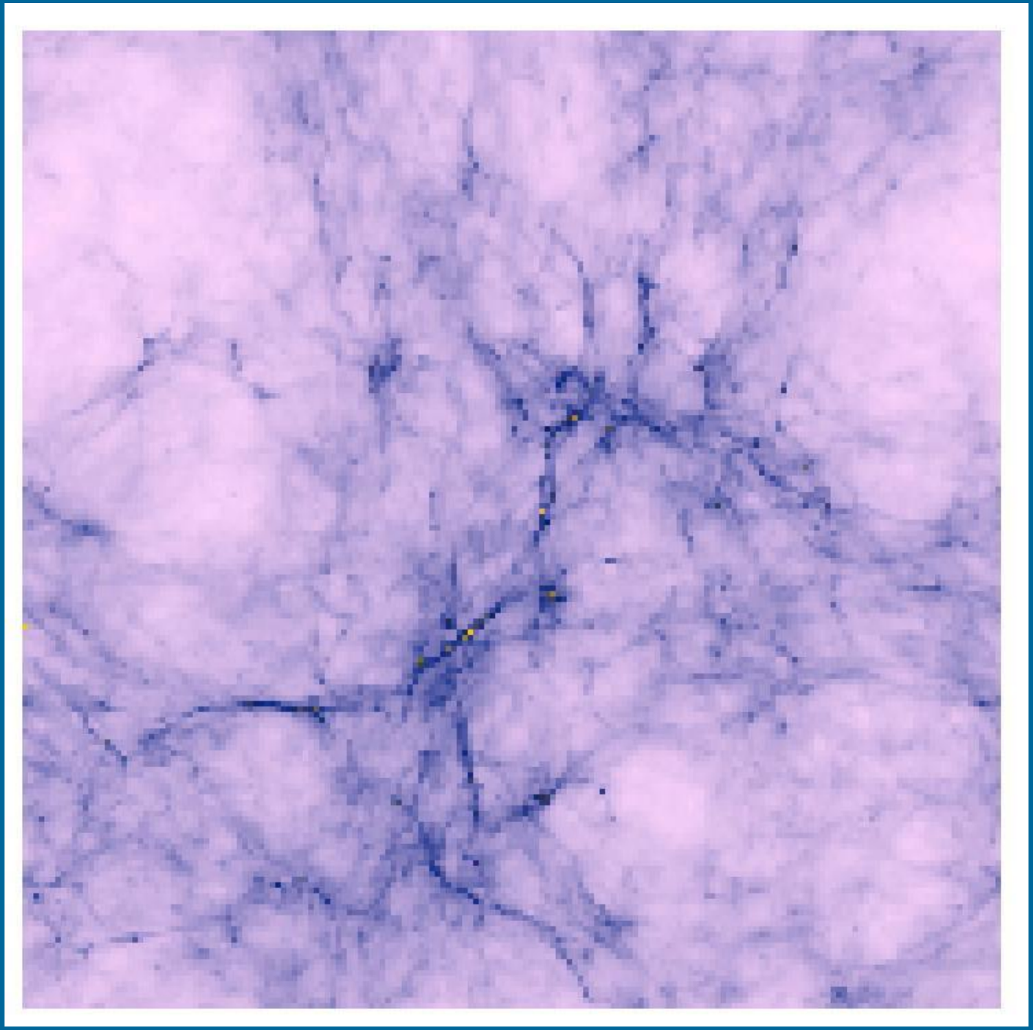
These BHs produce the first miniquasars, which contribute to the reionization at z~10-12.

Such low mass of minihalos is explained by the role of molecular hydrogene (Tegmark et al. 1997).

$$5 \times 10^5 \, [(1+z)/10]^{-3/2} \, \mathrm{M}_\odot$$

The first stars with masses 40-140 solar and >260 solar masses produce BHs. A BH mass (in the case of the first stars) is typically >0.5 of the mass of a star.

The first stars



Calculations have been done in the ΛCDM model.

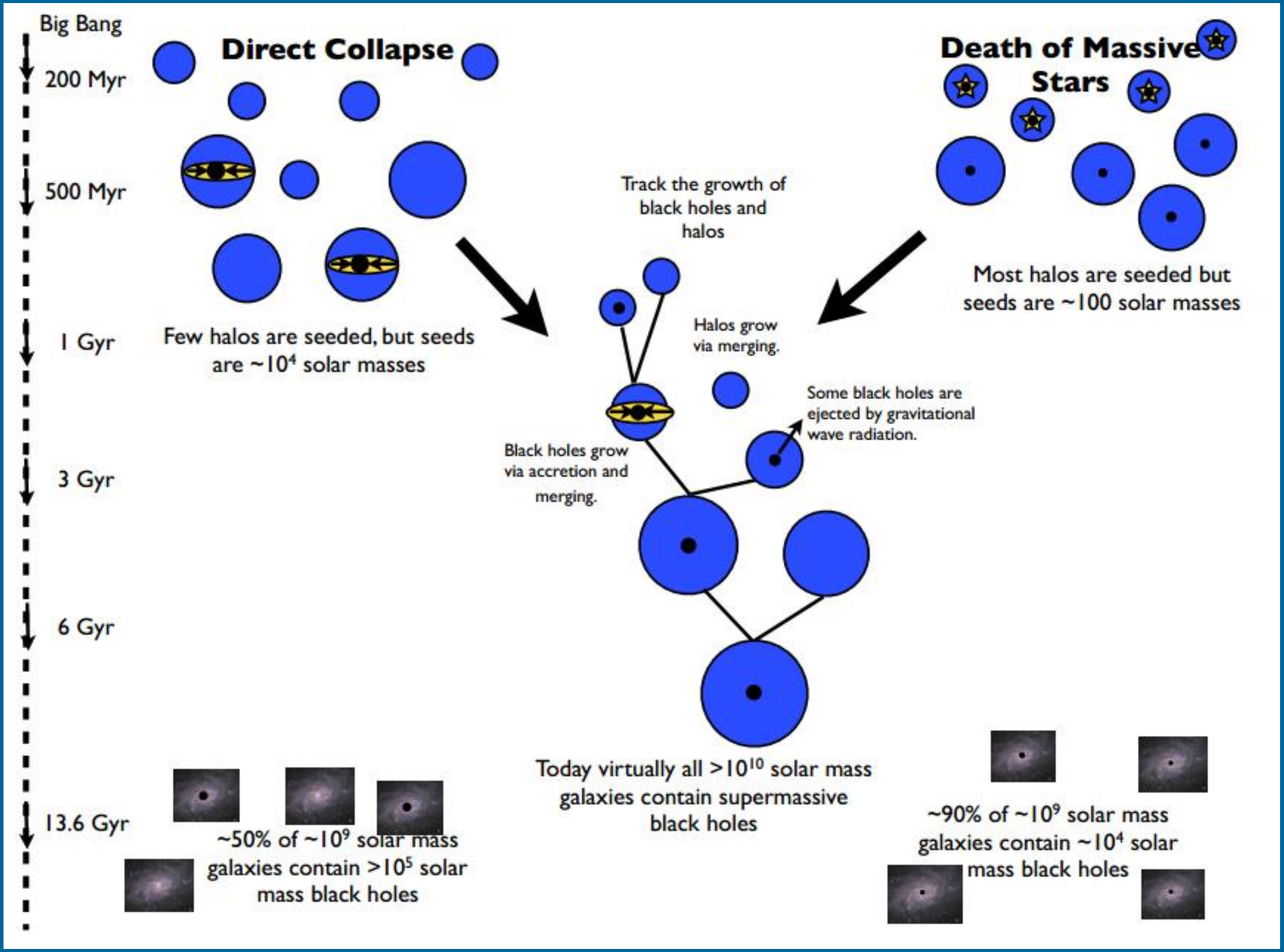
The picture is plotted for *z*=17.

The size is 50 kpc.

Stars are formed on the cross-sections of filaments (bright dots).

Yoshida et al. astro-ph/0301645

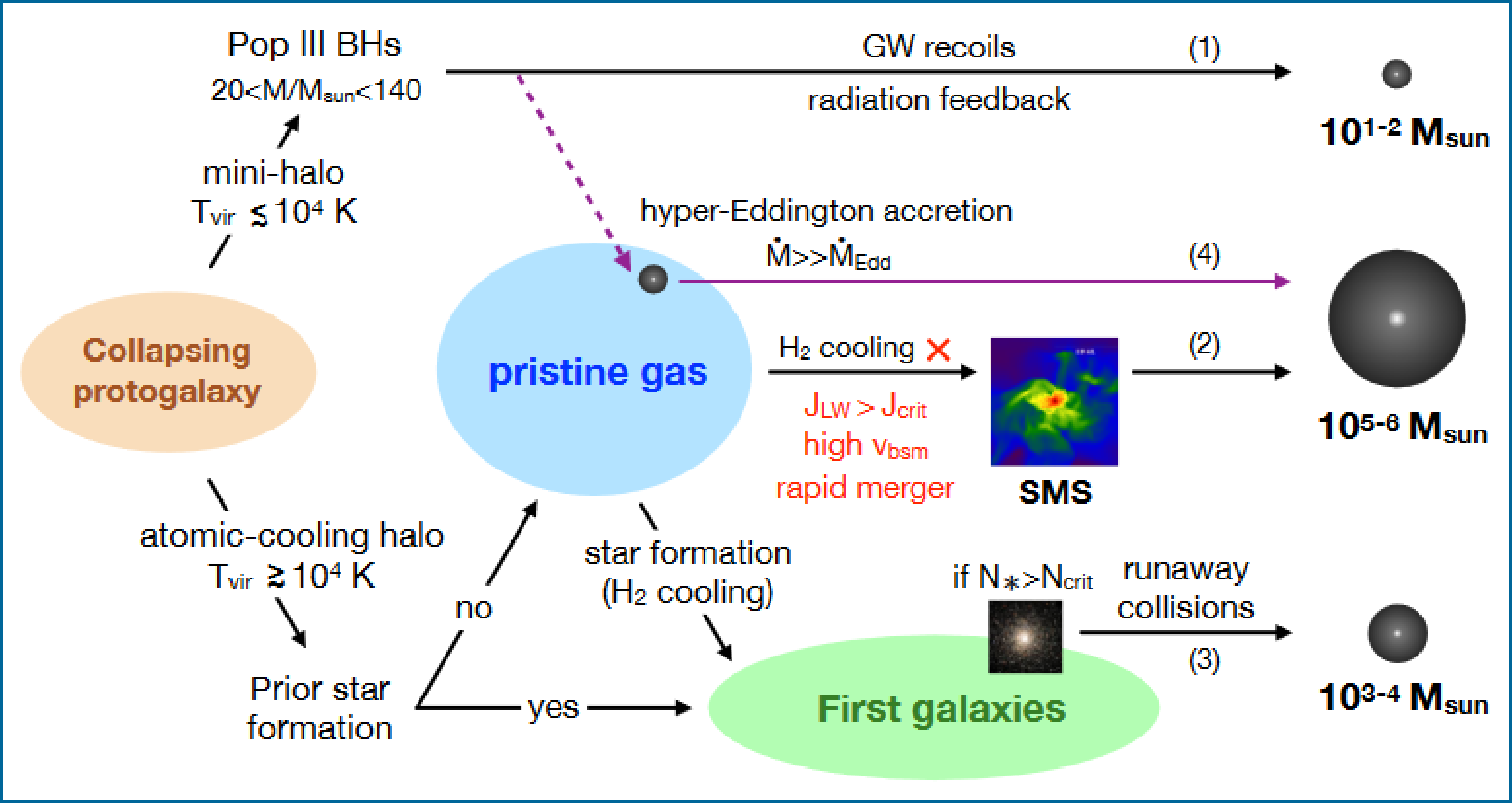
A scheme for SMBH formation



1211.7082

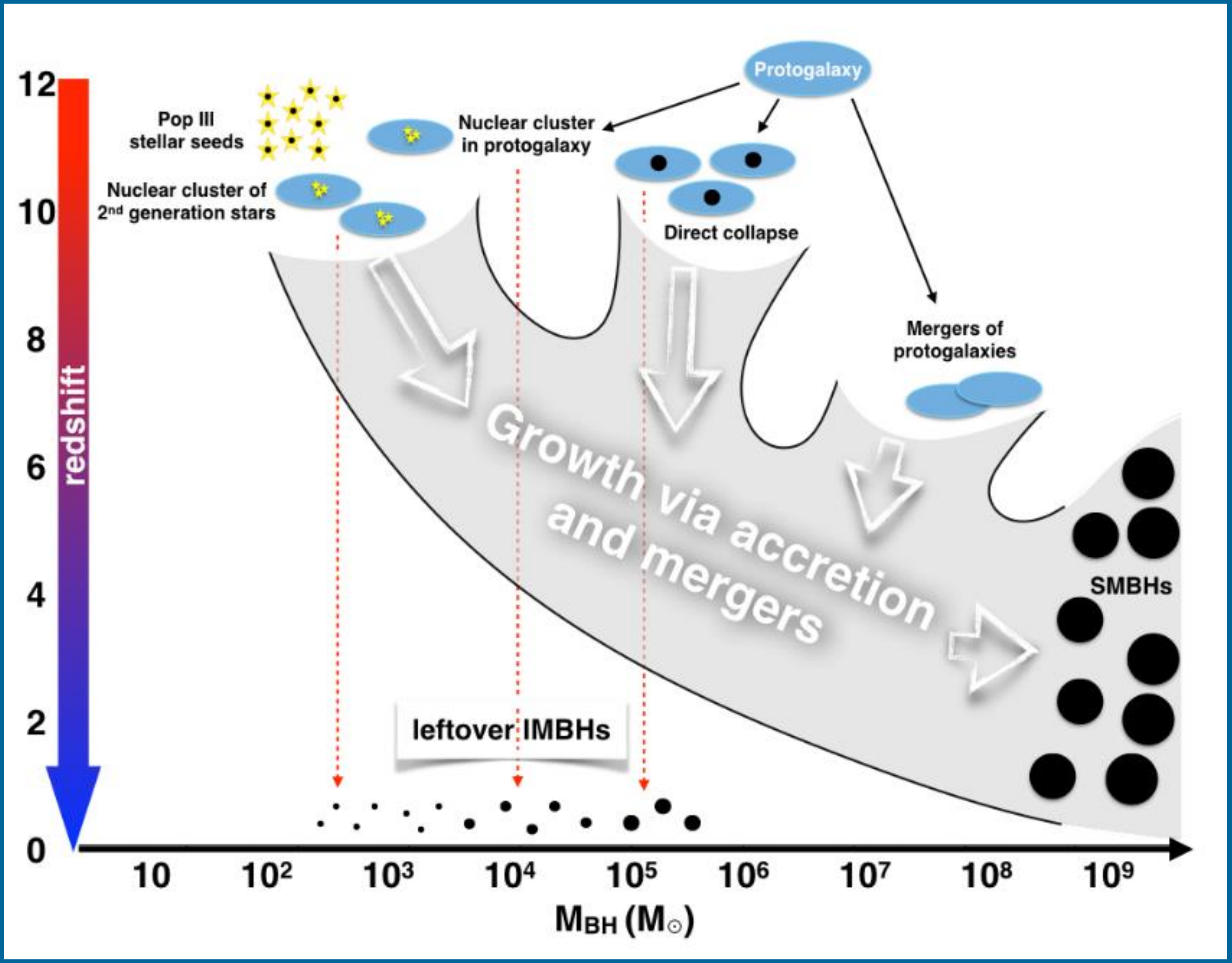
See a recent brief review in 2110.10175

… and with more details



1911.05791

Origin of SMBHs and IMBHs

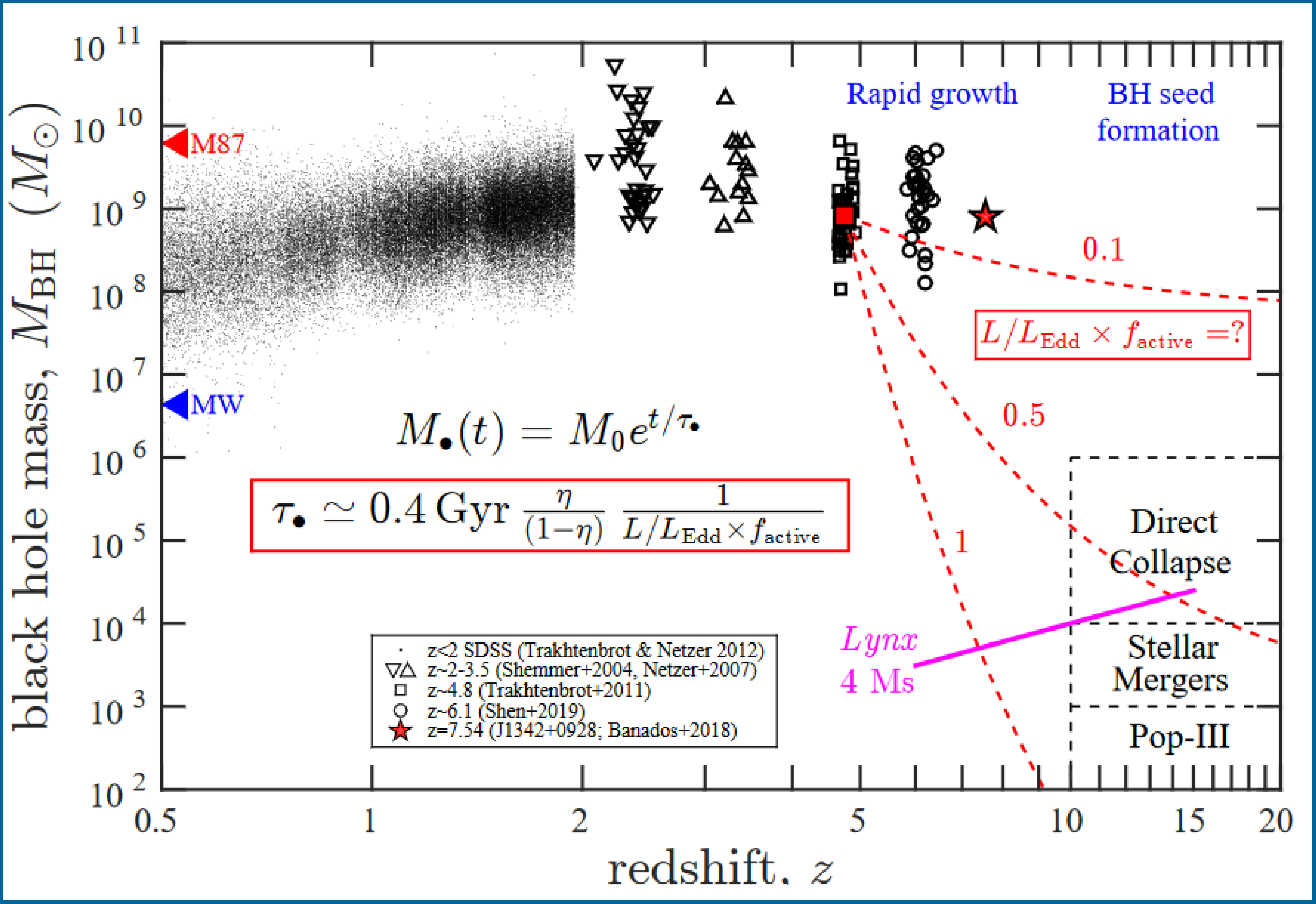


<u>IMBHs</u>:

- Globular clusters
- ULXs
- Dwarf galaxies
- Remaining seed BHs

1705.09667

Some are too massive



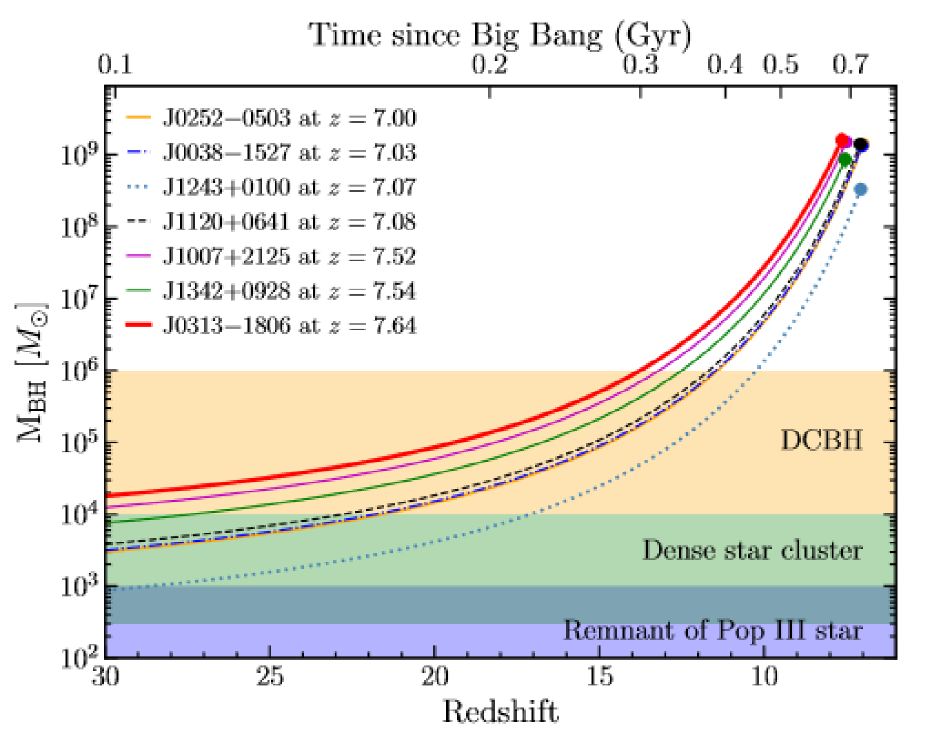
2002.00972

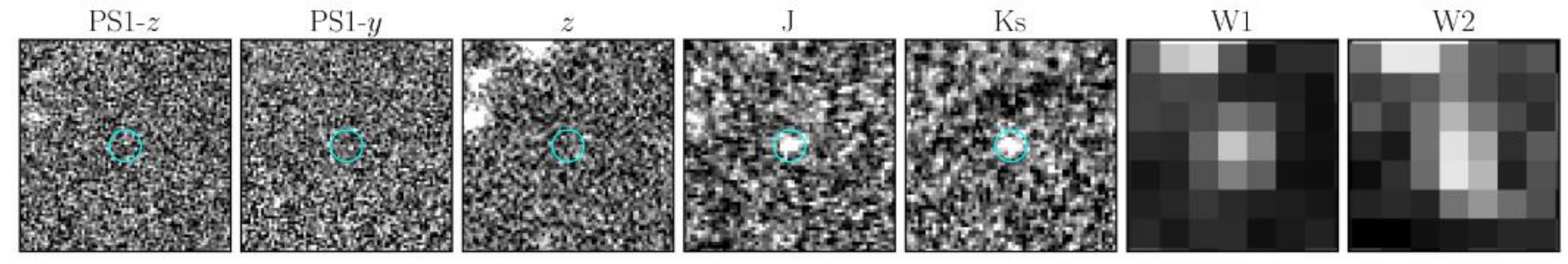
Some form too early

The most distant quasar 0313–1806: z= 7.642

$(1.6 \pm 0.4) \times 10^9 M_\odot$

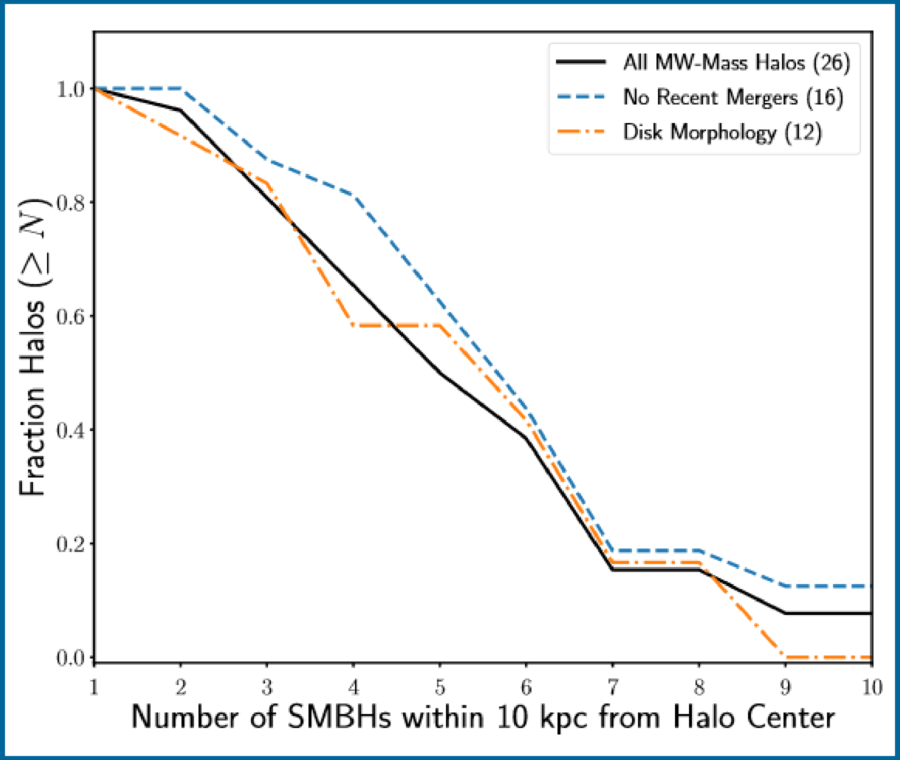
$3.6 \times 10^{13} L_\odot$



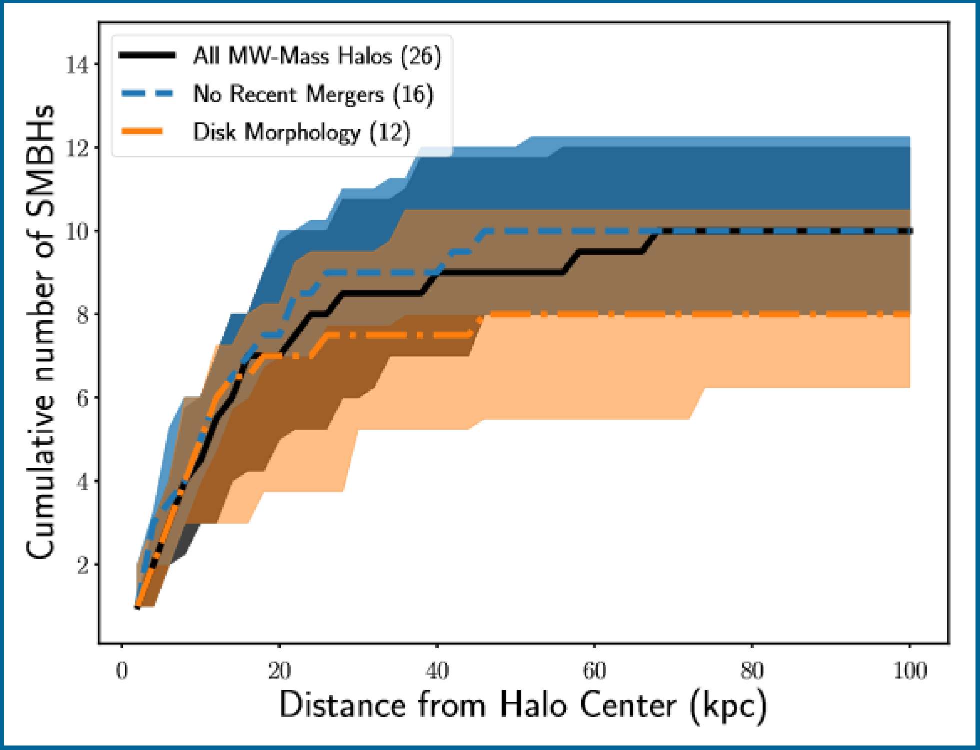


2101.03179

Wandering BHs

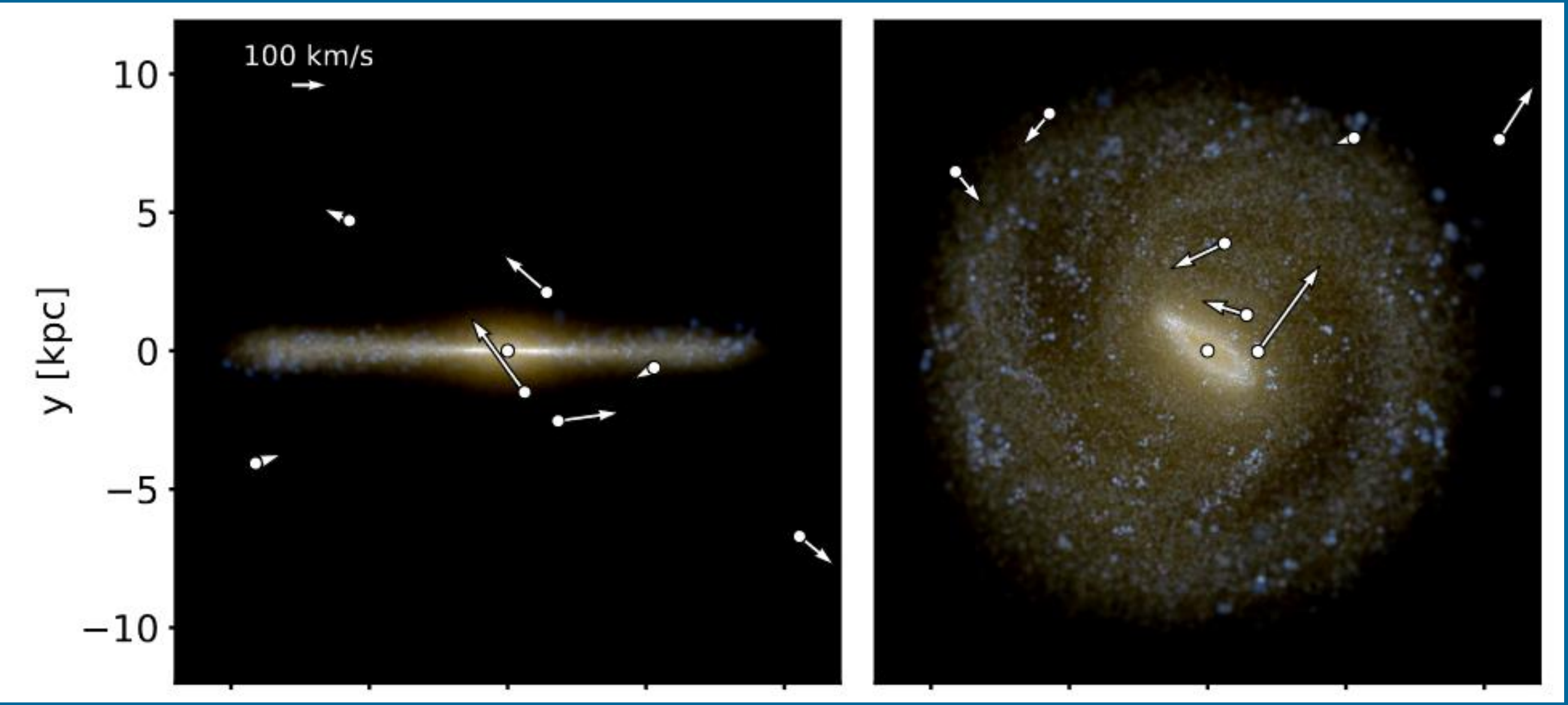


Only masses >10^6 solar are considered.
Usually 2-8 inside 10 kpc,
and up to ~20 inside the virial radius.



1802.06783

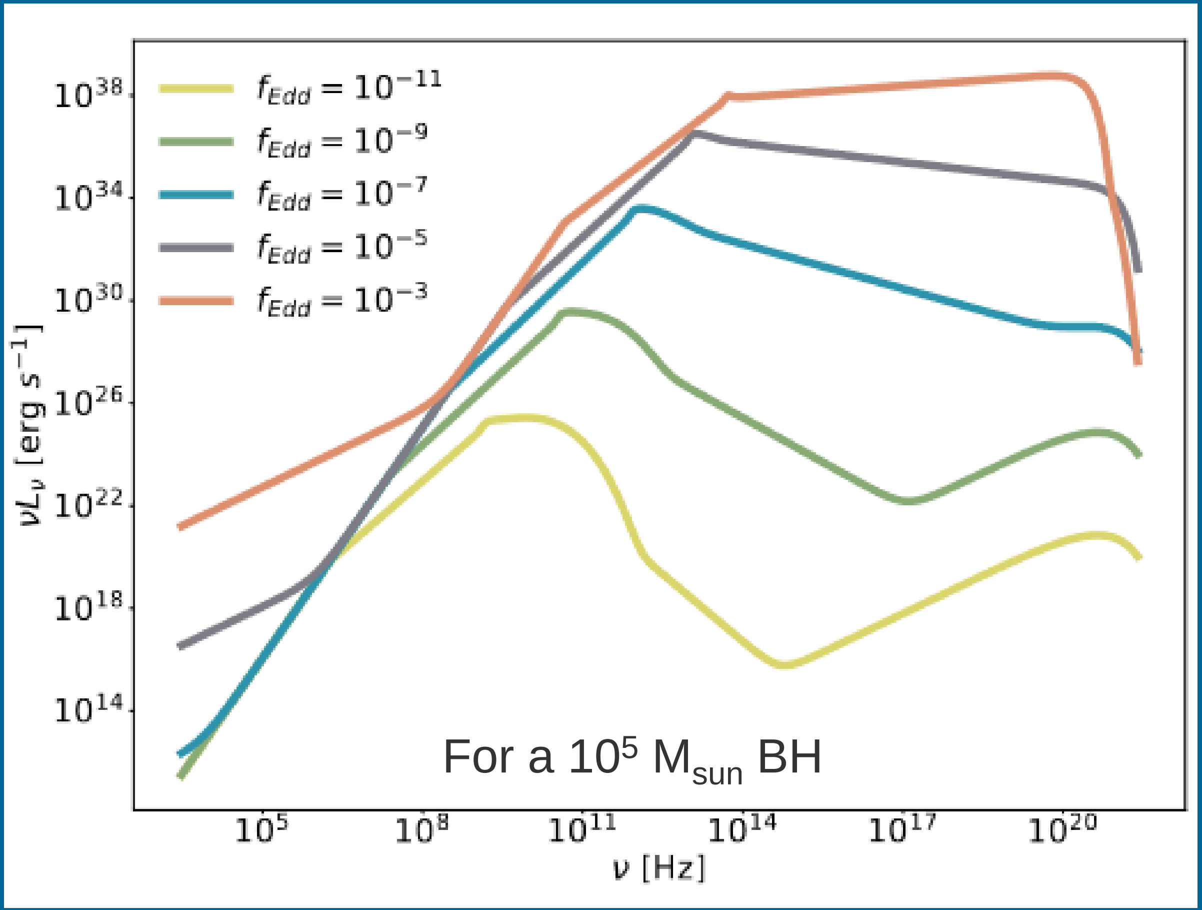
Examples from simulations



May be they can be detectable via their accretion luminosity? 2006.08203

1802.06783, see new calculations in 2103.12124 and critics in 2404.15404

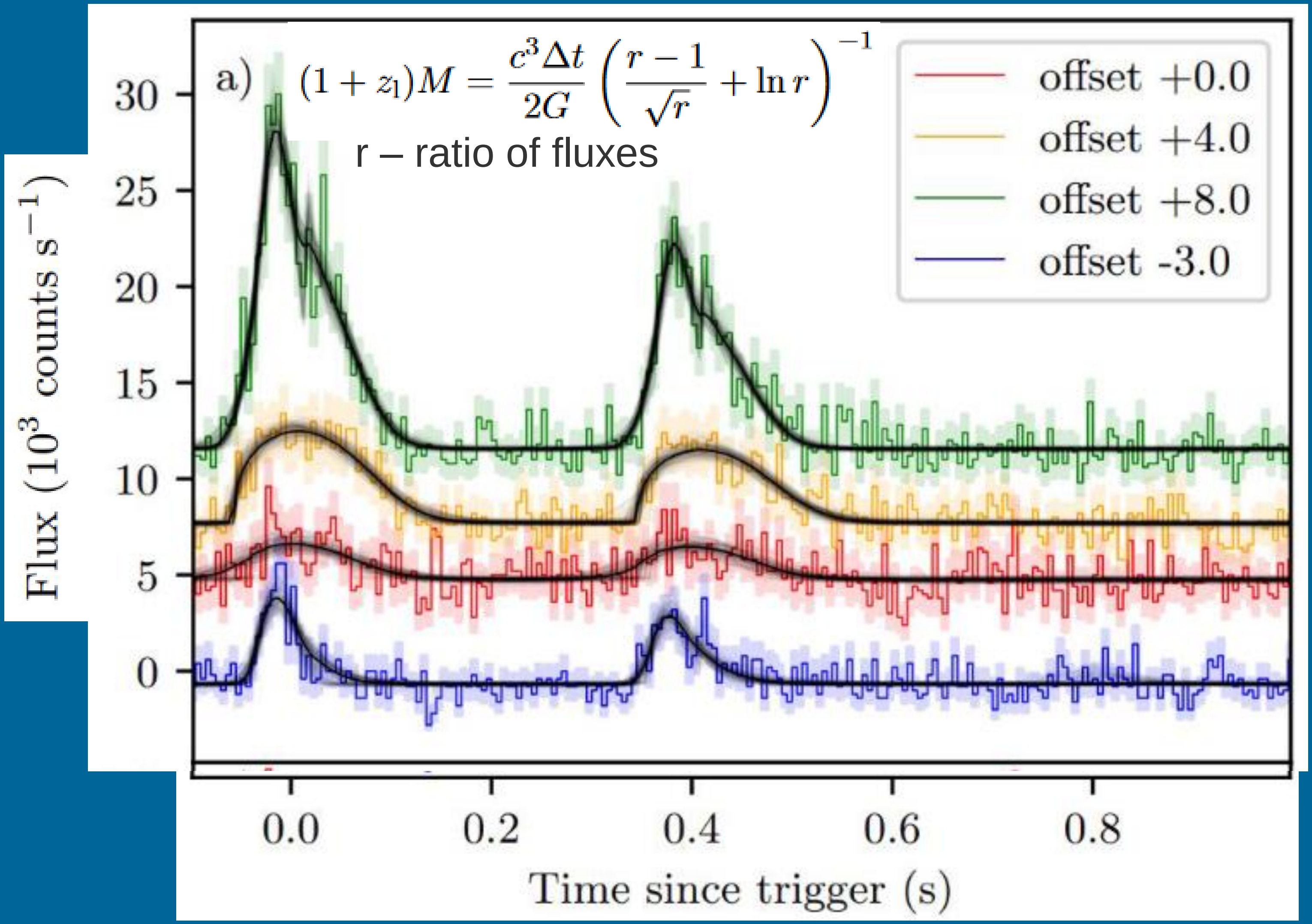
Detectability of wandering IMBHs



Roman Space Telescope, CMB-S4 and ngVLA might contribute in identifying ~50% of wandering IMBHs in our Galaxy.

2204.12498

GRB lensing on an IMBH?



GRB 950830

a short GRB

M~(5-7)10^4 M_{sun}

z~1

BATSE data

Can be also
a globular cluster.

2103.15414

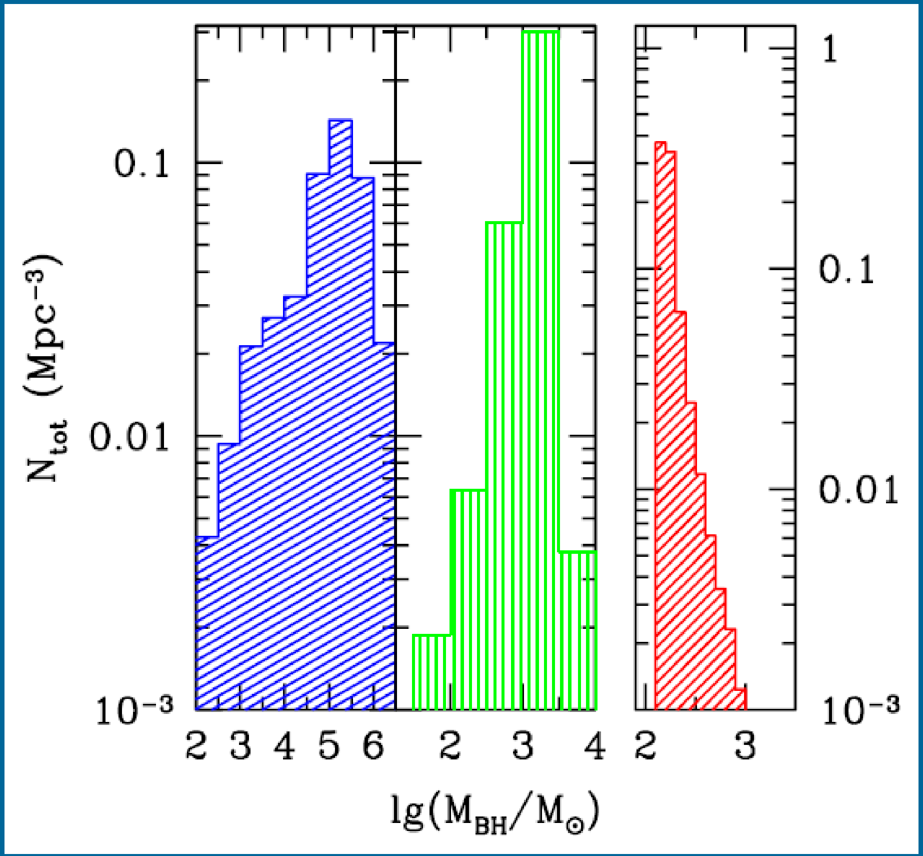
The problem of the existence of very massive BHs at high redshifts

At redshifts ~7 already there are SMBHs with masses ~10^9 M_0.
These redshifts correspond to the age of the universe <10^9 yrs.

It is necessary to have seed BHs already at z>15 and to provide their rapid growth
(note, that the accretion rate is limited by the Eddington rate).

See a brief review of different scenarios of seed formation in arXiv: 0912.0525.

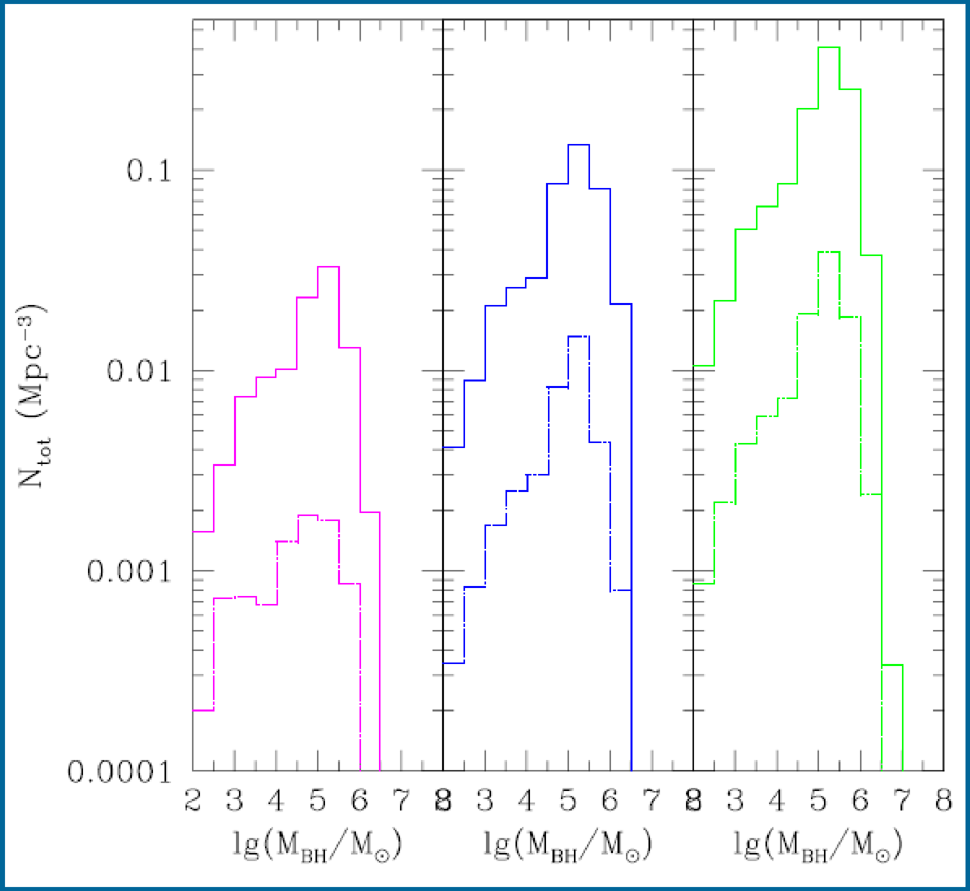
In the figure: seeds mass function for three scenarios. Direct collapse, runaway stellar mergers, Pop III



0912.0525

Direct collapse of gas discs

Direct collapse of pre-galactic gas discs.
Seeds are already massive at formation:
$M>10^5$ Msolar (at z>15)



Plots are done for different efficiencies and for two values of the redshift: z=18 (dashed and z=15 (solid).

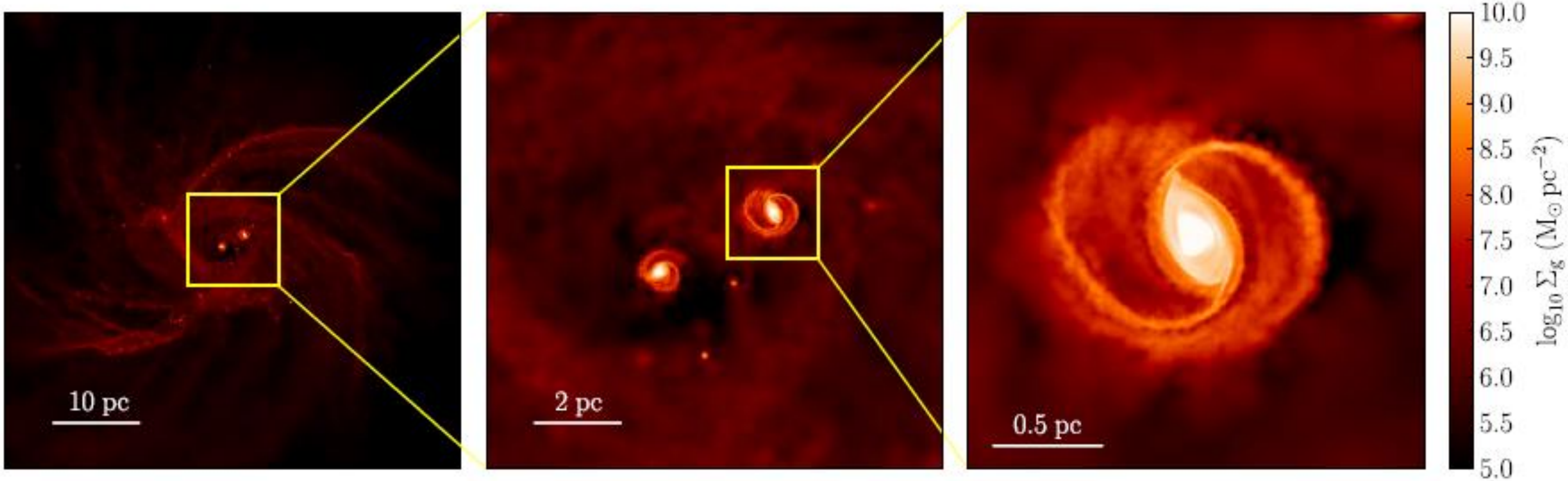
In low-mass halos and in rapidly rotating halos (later on, probably, bulgeless galaxies) there are no SMBHs in this scenario.

In this model it is possible to explain lack of correlation between dark matter halo mass and SMBH mass for galaxies with small bulges (1103.1644).

1104.4797

Formation of supermassive BHs

SMBHs can be formed after galaxy mergers at z~8-10.
After a merger, a dense nuclear disc can be formed.
Later the disc can collapse to form a BH with a mass ~10^8-10^9 Msun.

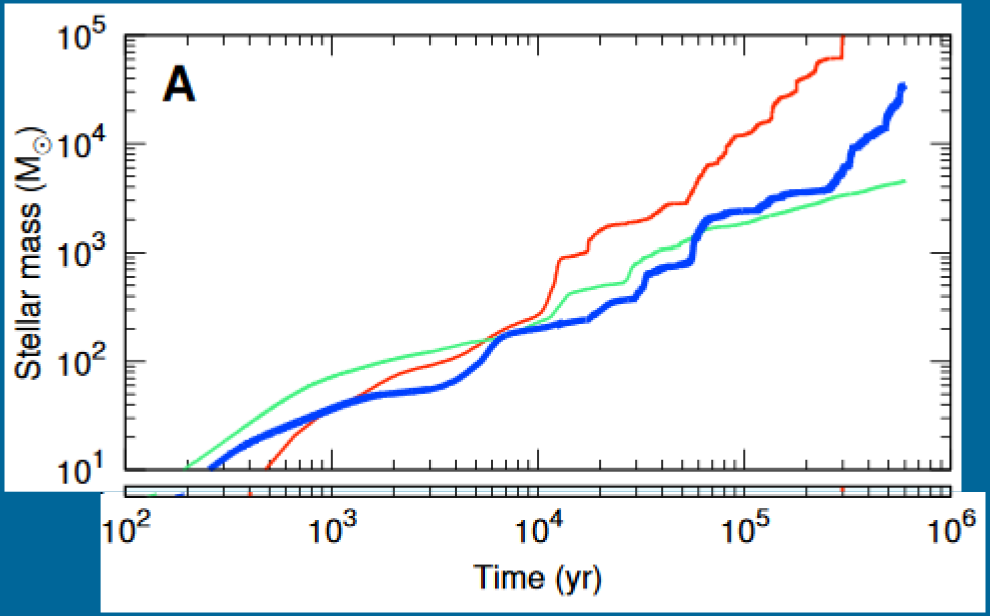


1411.5683

Formation via a supermassive star

34000 solar mass star → 34000 solar mass BH at z~30

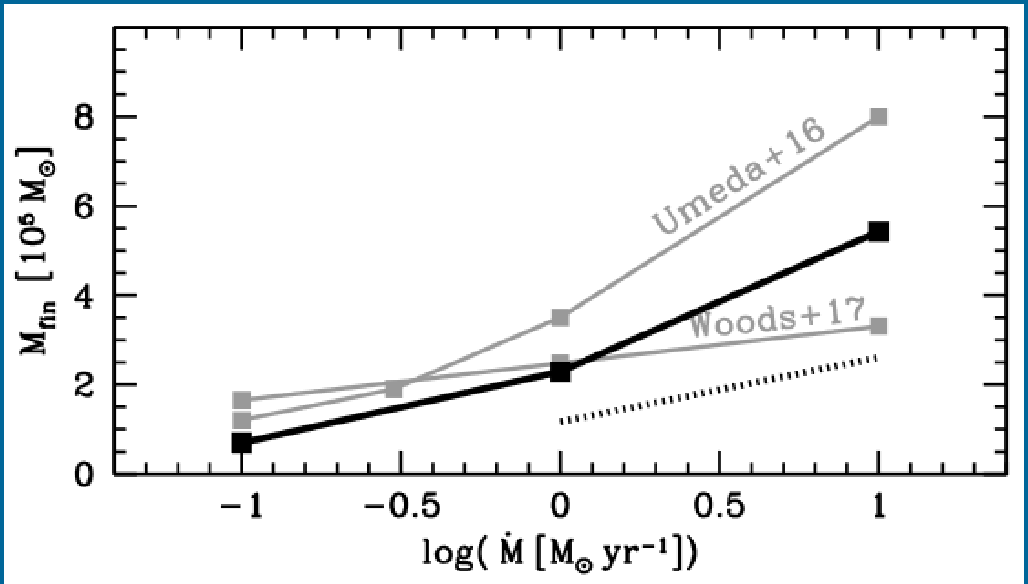
In regions with a large streaming velocity, gas condensation – and hence star formation – is suppressed until a deep gravitational potential is generated by a clump of dark matter with mass 10^7 solar masses.

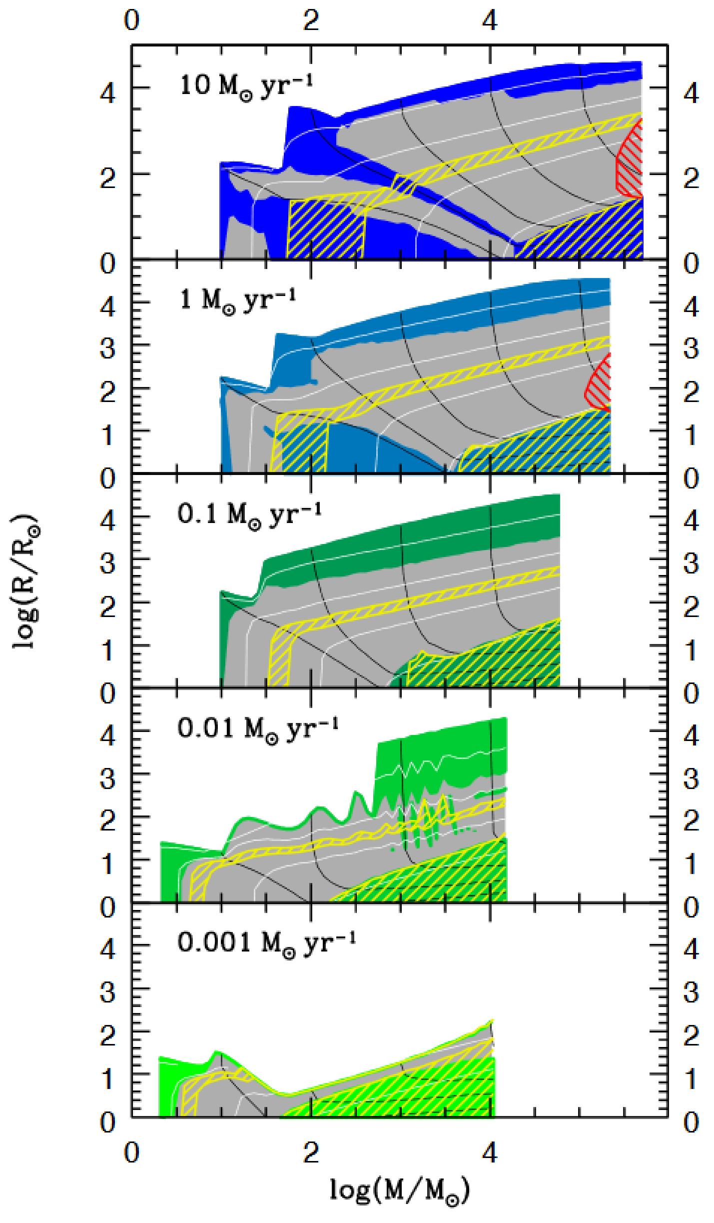


1709.09863, see more recent calculations in 1901.07563

Supermassive primordial stars

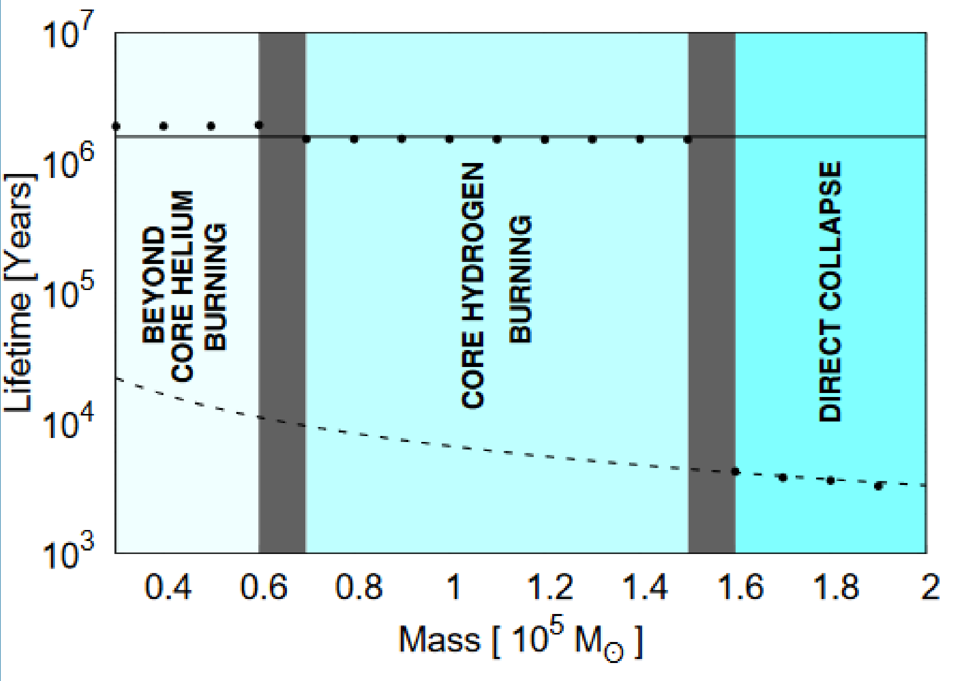
Internal structures of the models for the indicated accretion rates. On each panel, the upper curve is the stellar radius, the blue and green areas indicate convective zones, and the grey areas indicate radiative transport. The yellow hatched areas correspond to D- and H-burning, and the red hatched areas indicate the GR instability according to the polytropic criterion with n=3.





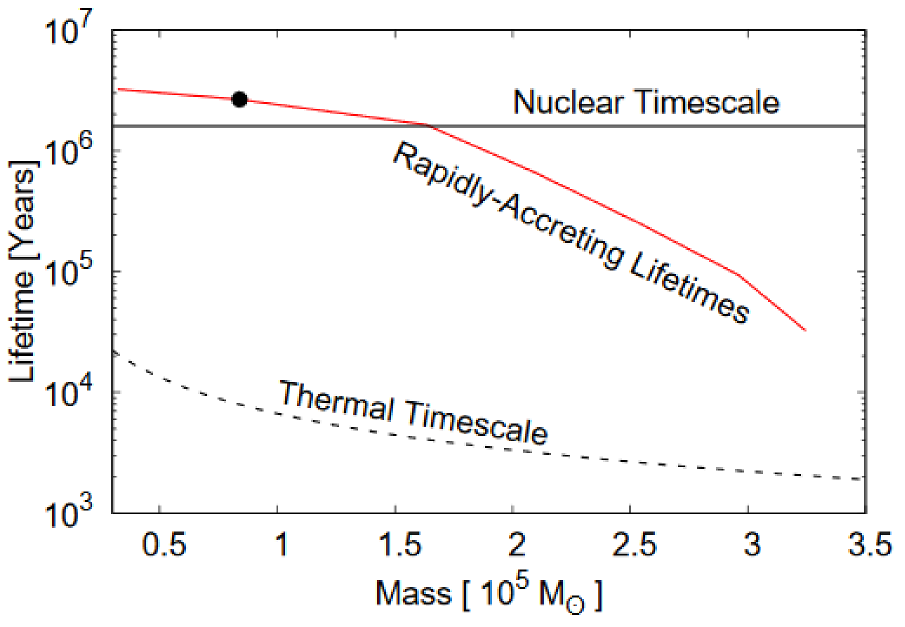
1705.09301

Monolithic Supermassive Stars



1D stellar evolution code Kepler

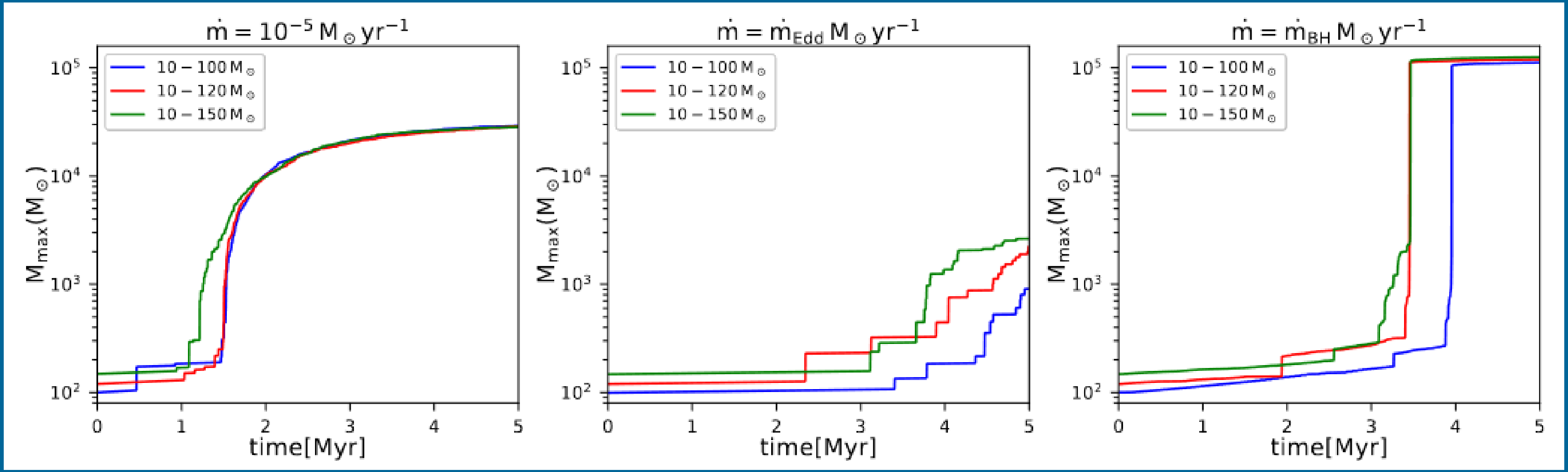
Stars born with masses between ~60 $kM_\odot$ and ~150 $kM_\odot$ collapse at the end of the main sequence, burning stably for~1.5 Myr.
More massive stars collapse directly due to the general relativistic instability after a thermal timescale of ~3 kyr – 4 kyr.



2003.10467

A review on physics of supermassive stars and black hole seed formation can be found in 2003.10533.

Stellar coalescence in nuclear clusters



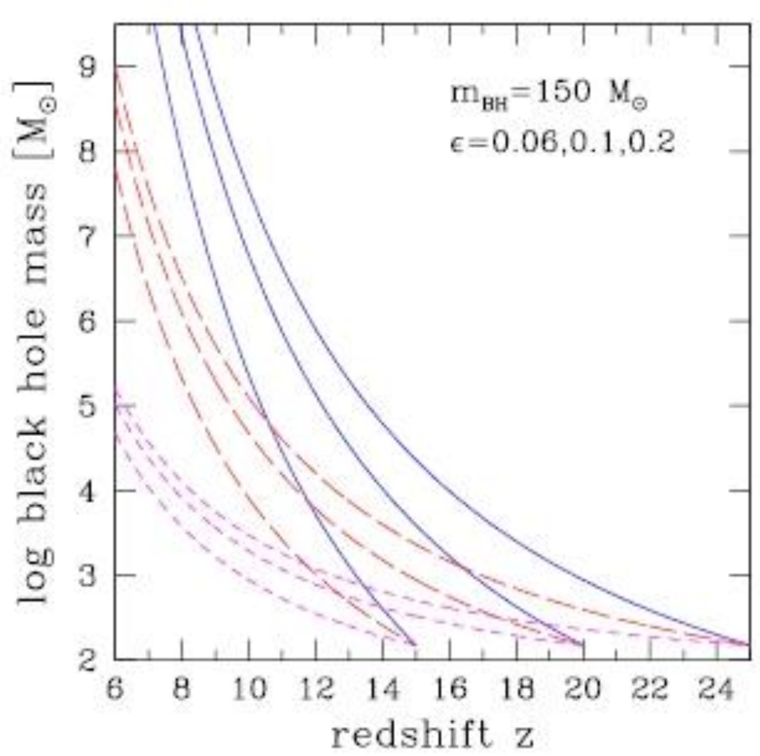
In dense nuclear stellar clusters in the young galaxies
stars can coalesce and grow by accretion.

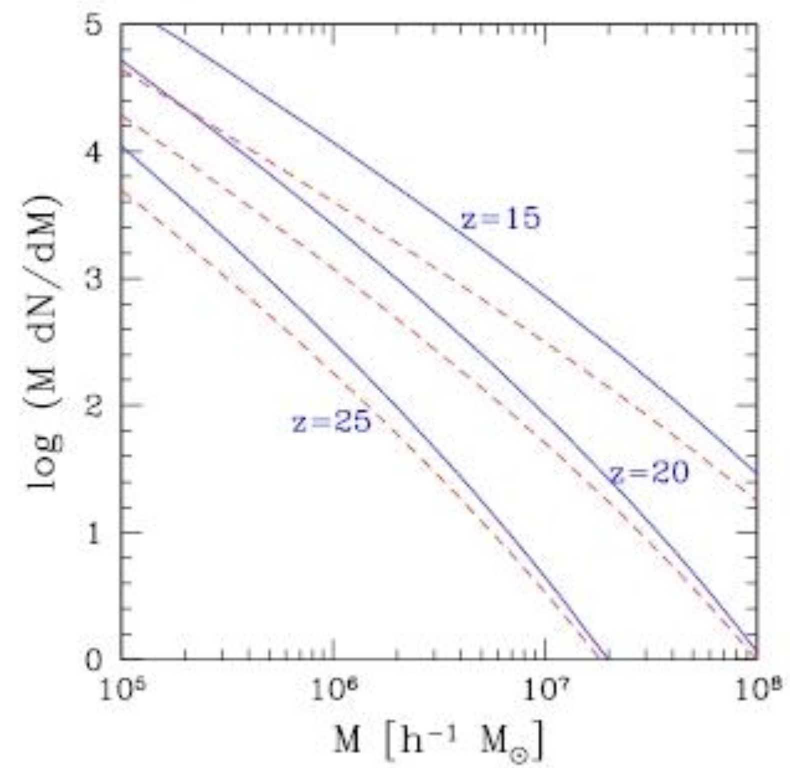
Depending on many uncertain parameters (accretion rate, mass function, etc.)
this can result in formation of seed BHs with masses 10^3-10^5 solar masses,

Three scenarios are presented:
constant accretion rate, Eddington-limited, and Bondi-Hoyle.

2012.01456

BH mass growth





BH mass growth for different radiation efficiency.

$$t_{\rm grow} \approx \frac{0.45\ \epsilon}{(1-\epsilon) f_{\rm duty}} \ \ln\left(\frac{M_\bullet}{M_{\rm seed}}\right) \ {\rm Gyr} \approx 0.81 \ {\rm Gyr}.$$

$\epsilon = 0.1$, $f_{\rm duty} = 1$, $M_{\rm seed} = 100\ {\rm M}_\odot$, and $M_\bullet = 10^9\ {\rm M}_\odot$.

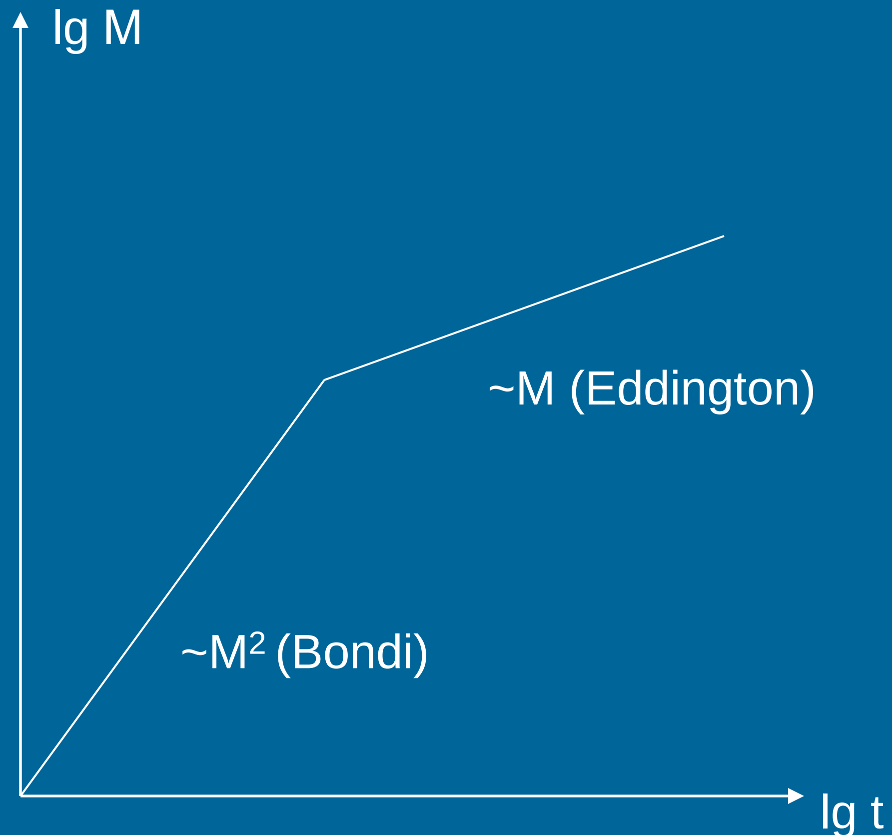
Halo mass functions at different z.
These galaxies due to coalescence produce at z_0=0.8 a Milky Way-like galaxy (10^{12} solar masses, solid curves), or a slightly smaller one at z_0=3.5 (2 10^{11}, dashed curves).

Madau astro-ph/0701394.
See new calculations for various seed masses in 2106.08330.

Mass growth

$$t_{\rm grow} \approx \frac{0.45\,\epsilon}{(1-\epsilon)f_{\rm duty}}\ \ln\left(\frac{M_\bullet}{M_{\rm seed}}\right)\ {\rm Gyr} \approx 0.81\ {\rm Gyr}.$$

$\epsilon = 0.1,\ f_{\rm duty} = 1,\ M_{\rm seed} = 100\ {\rm M}_\odot$, and $M_\bullet = 10^9\ {\rm M}_\odot$.



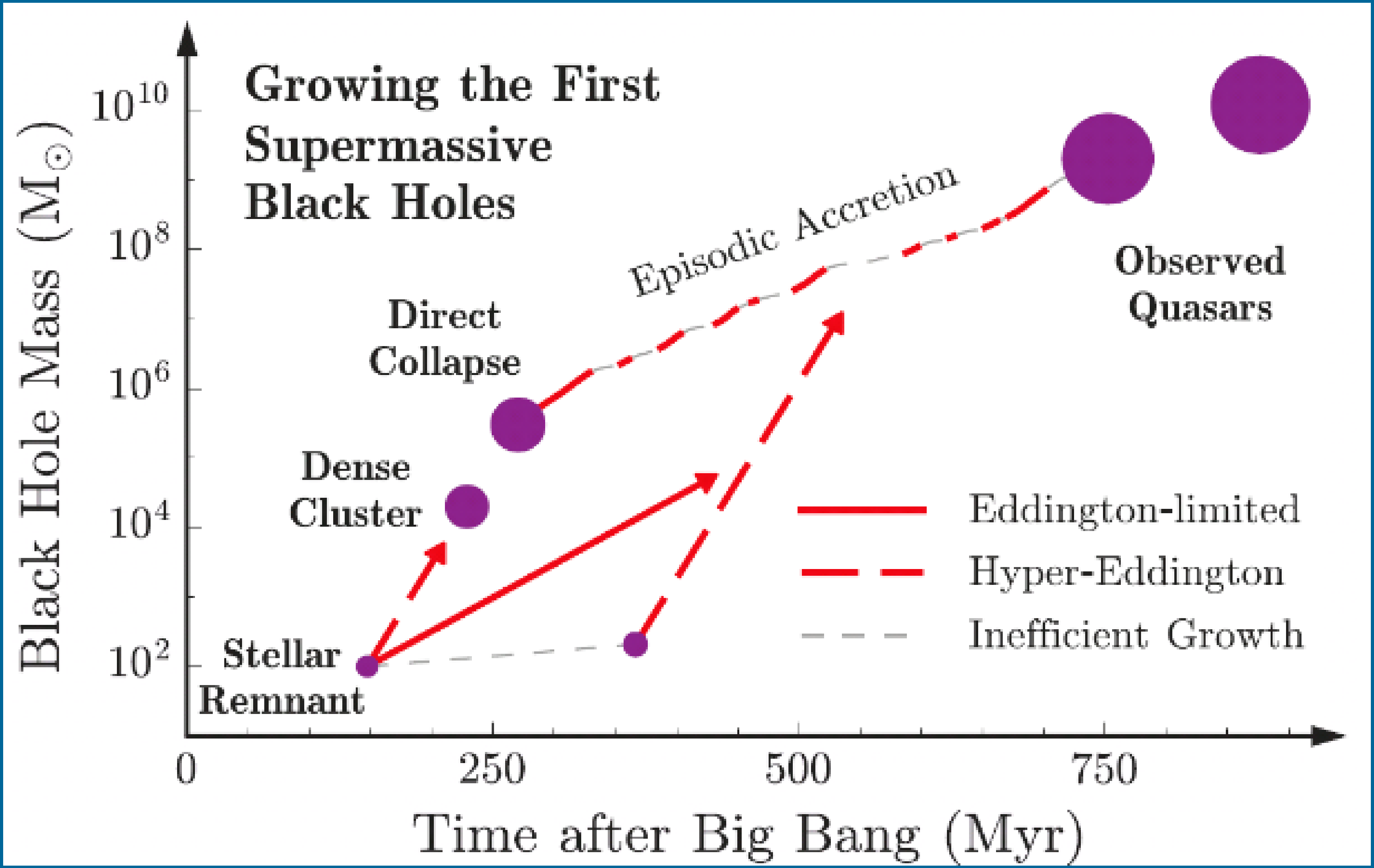
At first the mass is growing rapidly according to the Bondi formula.
Then, when the Eddington limit is reached, the growth slows down.

The so-called Salpeter time:
the time in which the mass is doubled.

Accretion and coalescence are both important for the mass growth.

Now SMBHs in giant elliptical galaxies increase their masses mostly due to coalescence with satellites.

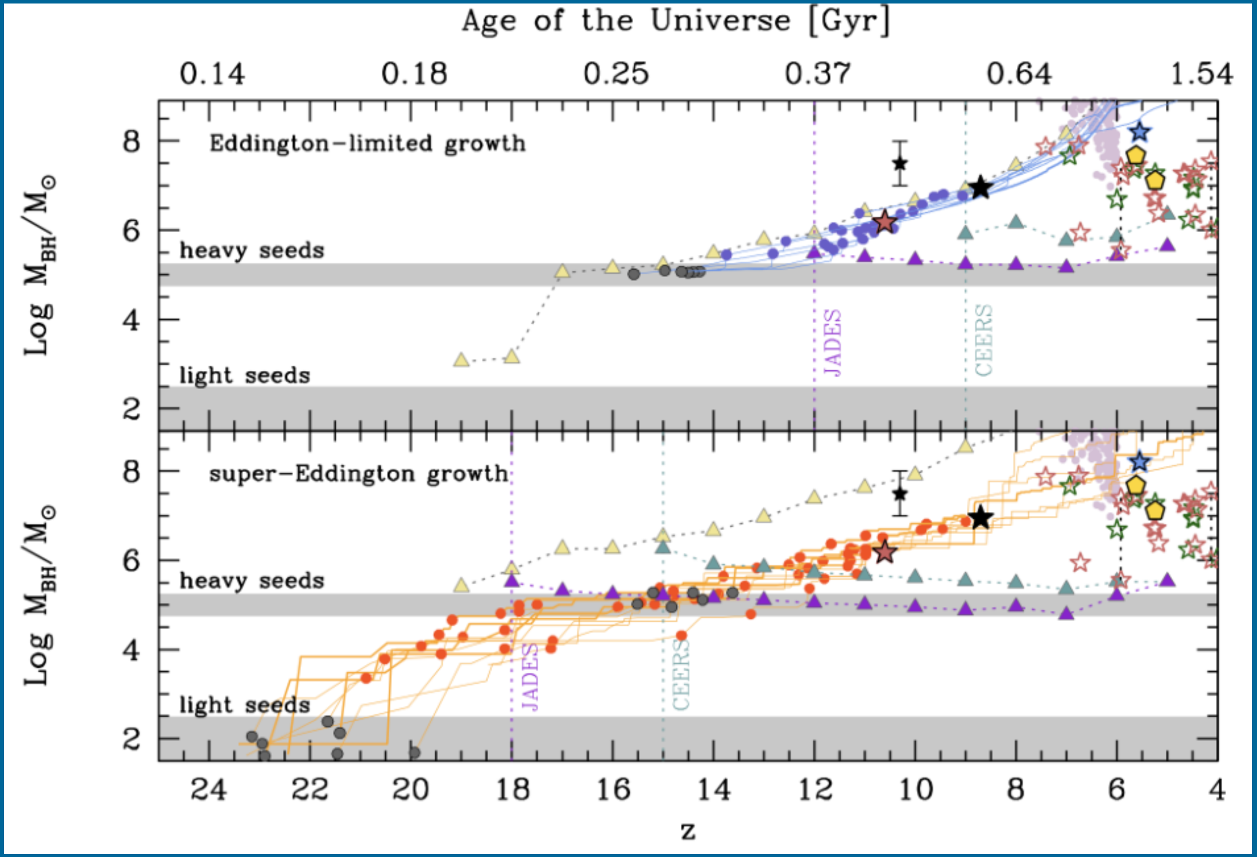
Mass growth was recently reviewed in arXiv:1304.7762 and 1601.05473


Growing the First Supermassive Black Holes
Black Hole Mass ($M_\odot$)
10^{10}
10^8
10^6
10^4
10^2
Observed Quasars
Episodic Accretion
Direct Collapse
Dense Cluster
Stellar Remnant
Eddington-limited
Hyper-Eddington
Inefficient Growth
0
250
500
750
Time after Big Bang (Myr)

2304.09311

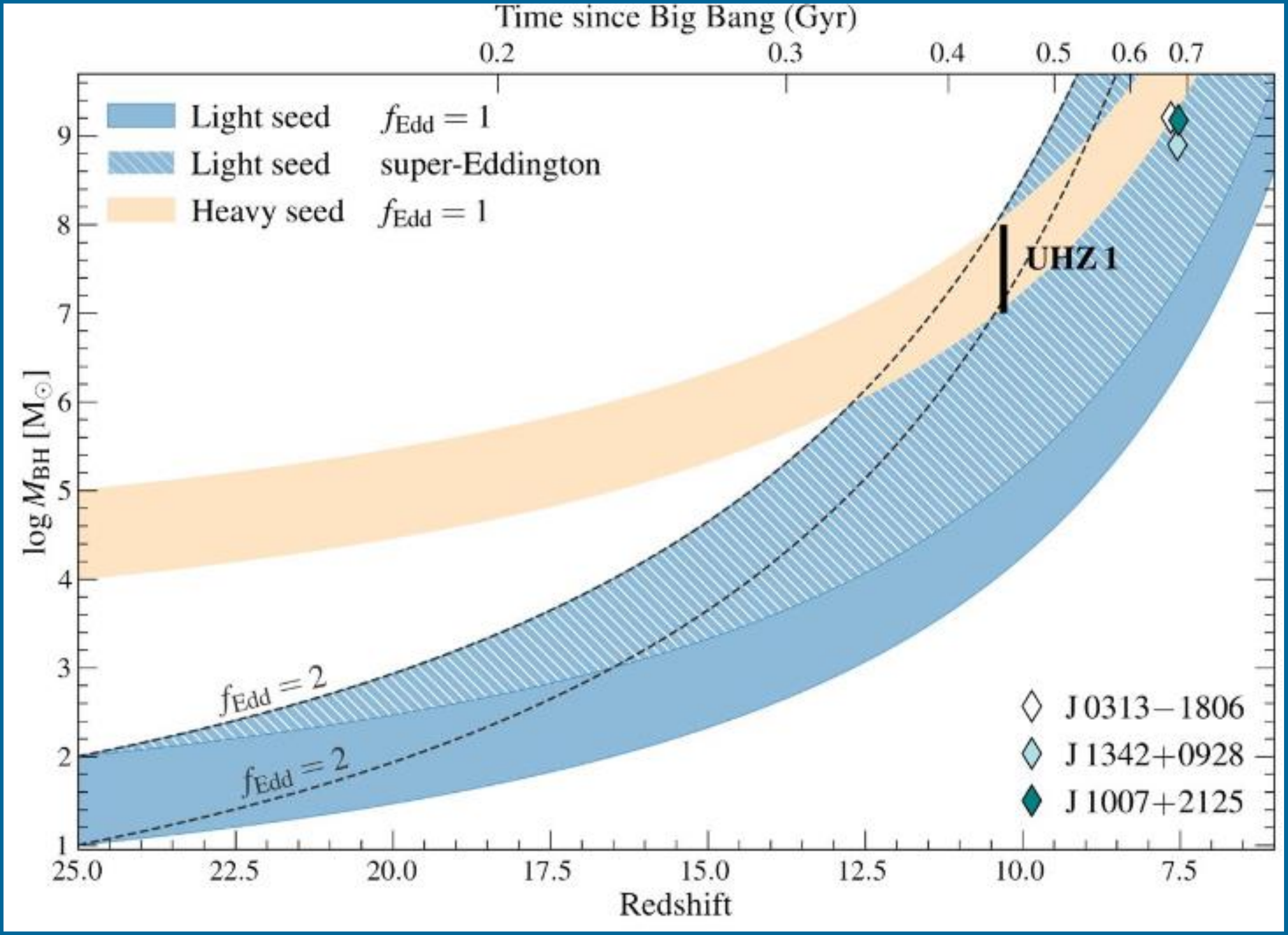
SMBH growth

Cosmic Archaeology Tool: semi-analytical model.
SE growth is followed in a simplified approach.
Still, it is favored in some cases.



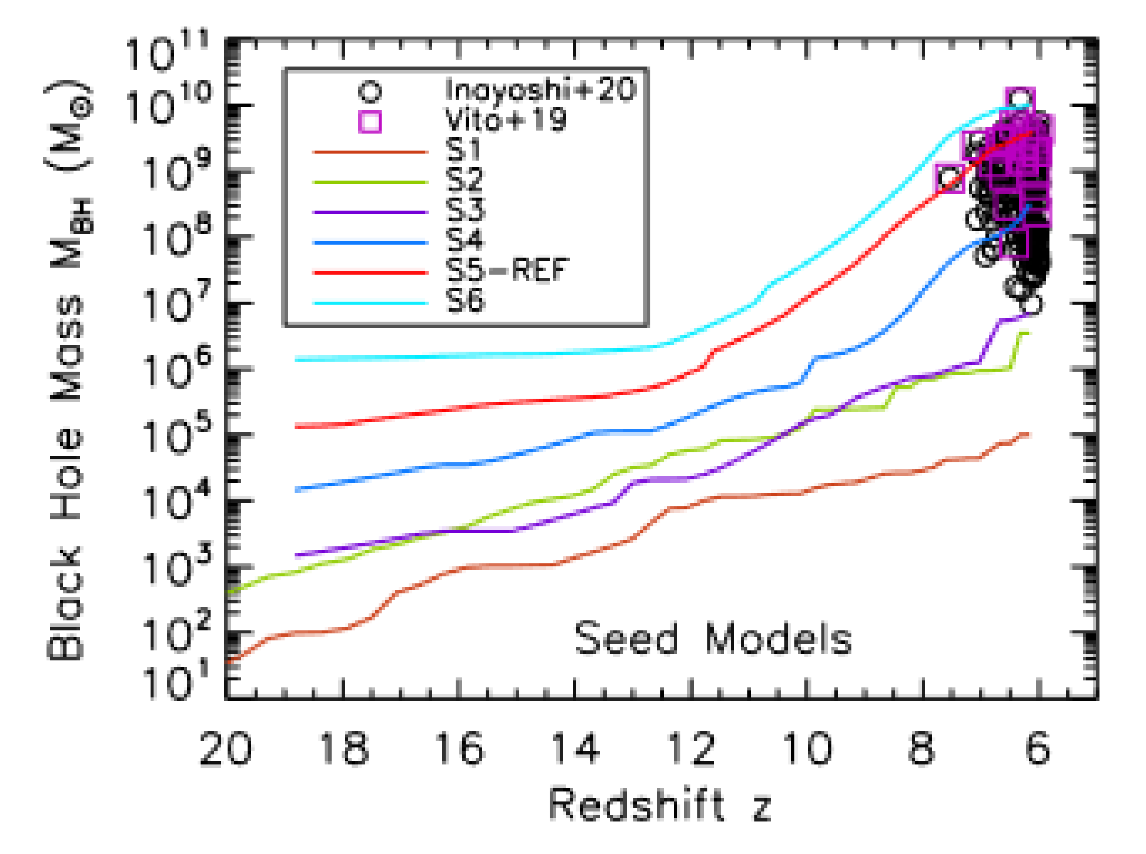
2305.12504

A heavy seed for UHZ1



2305.15458, see also 2308.02654

Light seeds cannot grow fast enough?

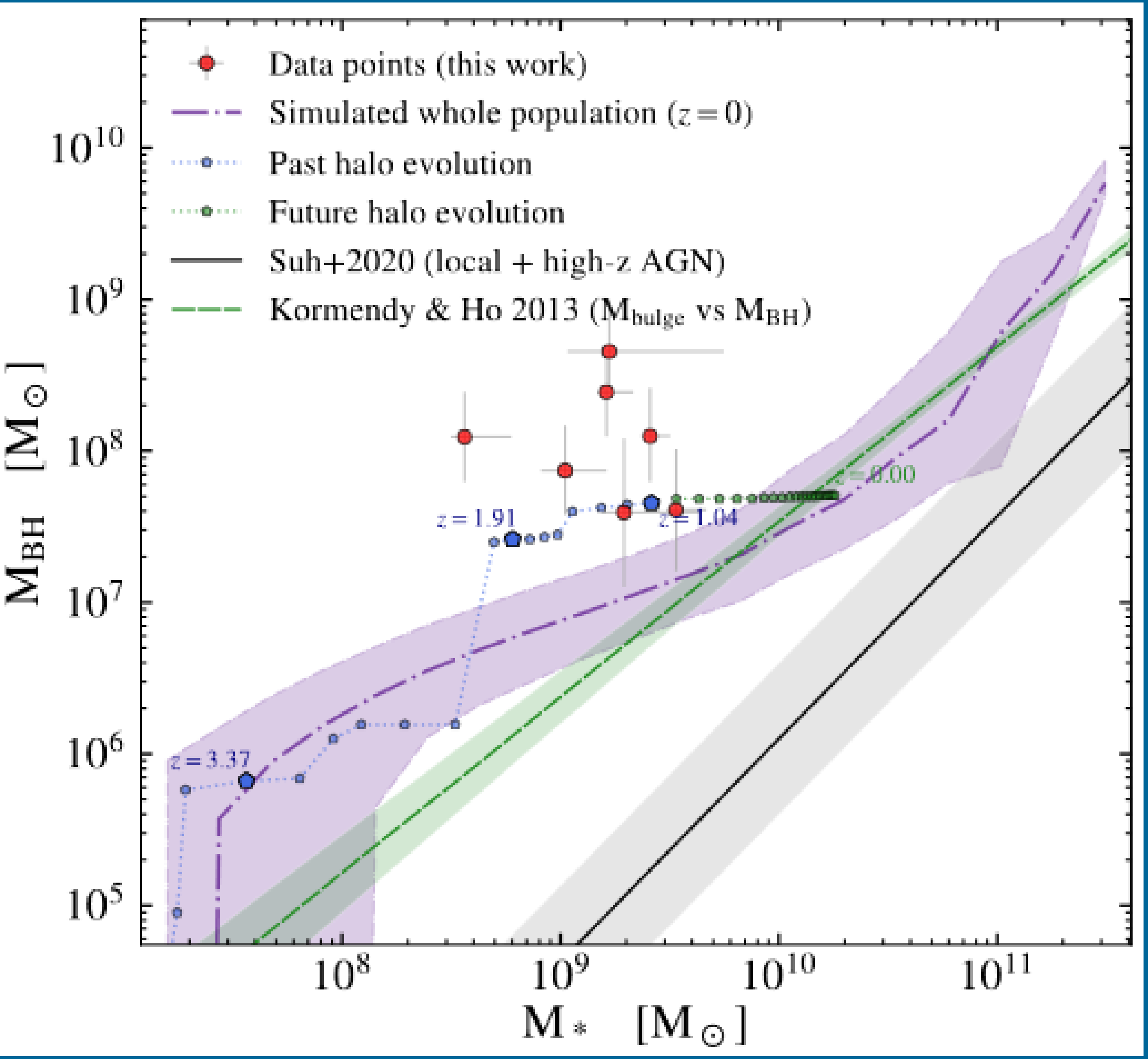


Starting with 10^5 solar masses it is possible to obtain a massive BH at z=6.

However, still there are many uncertainties.

2012.01458

Evolution of overmassive black holes

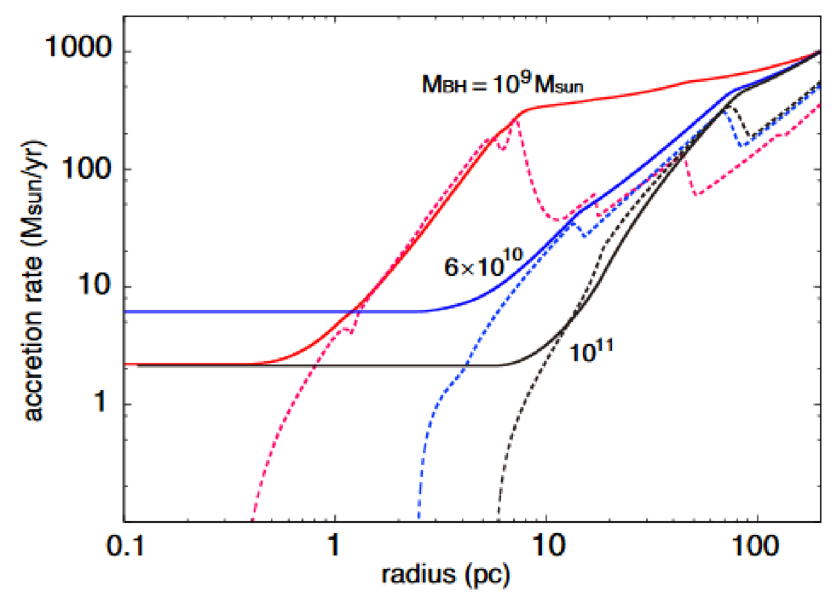


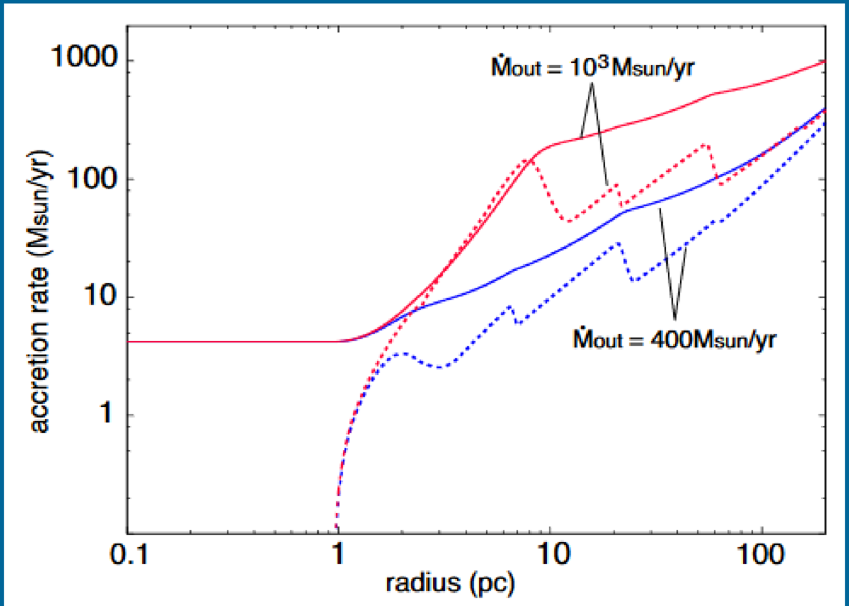
The detected SMBHs are likely overmassive with respect to their hosts since early times (z>4), independently of whether they formed as heavy ($\sim 10^5$ Msun) or light ($\sim$ 100 Msun) seed black holes. In the simulations, these objects tend to grow faster than their host galaxies, contradicting models of synchronized growth.

2212.14057

Maximum mass

The most massive BHs are ~10^{10} solar masses.
The authors suggest that higher masses require very large accretion rate.
Such a rate requires massive dense accretion discs, and under such conditions most of the gas is transformed into stars.
In addition, outflows can take away matter around very massive BHs.





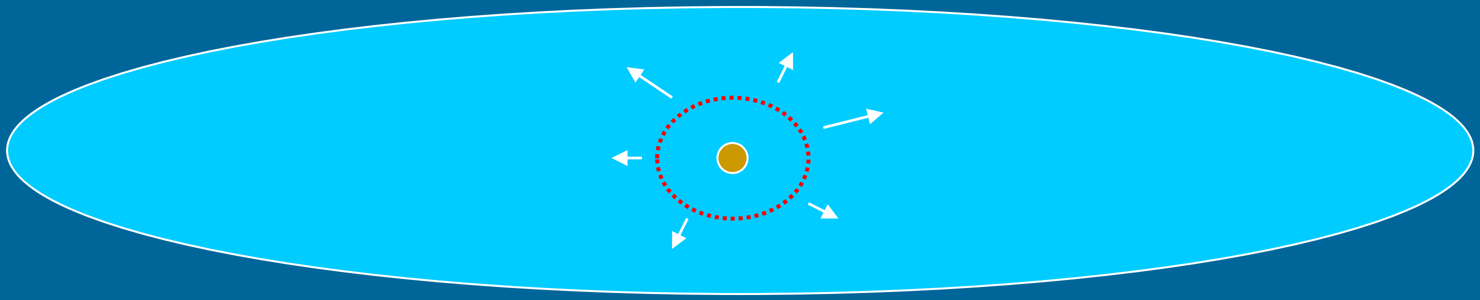
Solid – accretion rate.
Dashed – star formation rate.

$M_{BH}=10^{10}$

1601.02611

A quasar `puffes out' a galaxy

Quasar activity can result in a powerful outflow of matter.
This outflow can expel gas from the galaxy.
This results in quenching the galactic star formation.

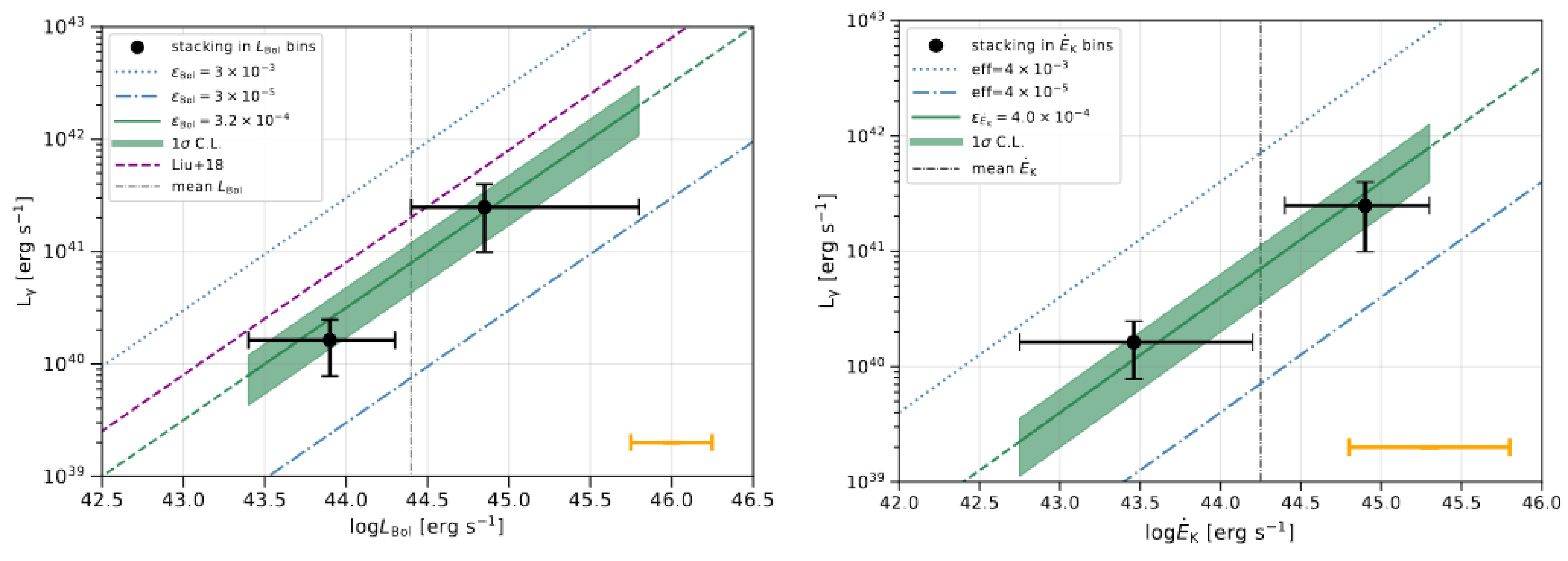


A quasar at z=6.4.
An outflow with the rate 3500 Msun/year.
It is enough to influence the whole galaxy.

1204.2904

Ultra-fast outflows visible in gamma

AGN activity launches an ultra-fast outflow.
The outflow interacts with the ISM. A shock is formed.
Particles can be accelerated on the shock,
so gamma-ray emission is produced.
Emission is found, and it is shown, that it scales
as the bolometric luminosity and kinetic power.



2105.11469

Supereddington SMBH in a dwarf galaxy at the transitional stage

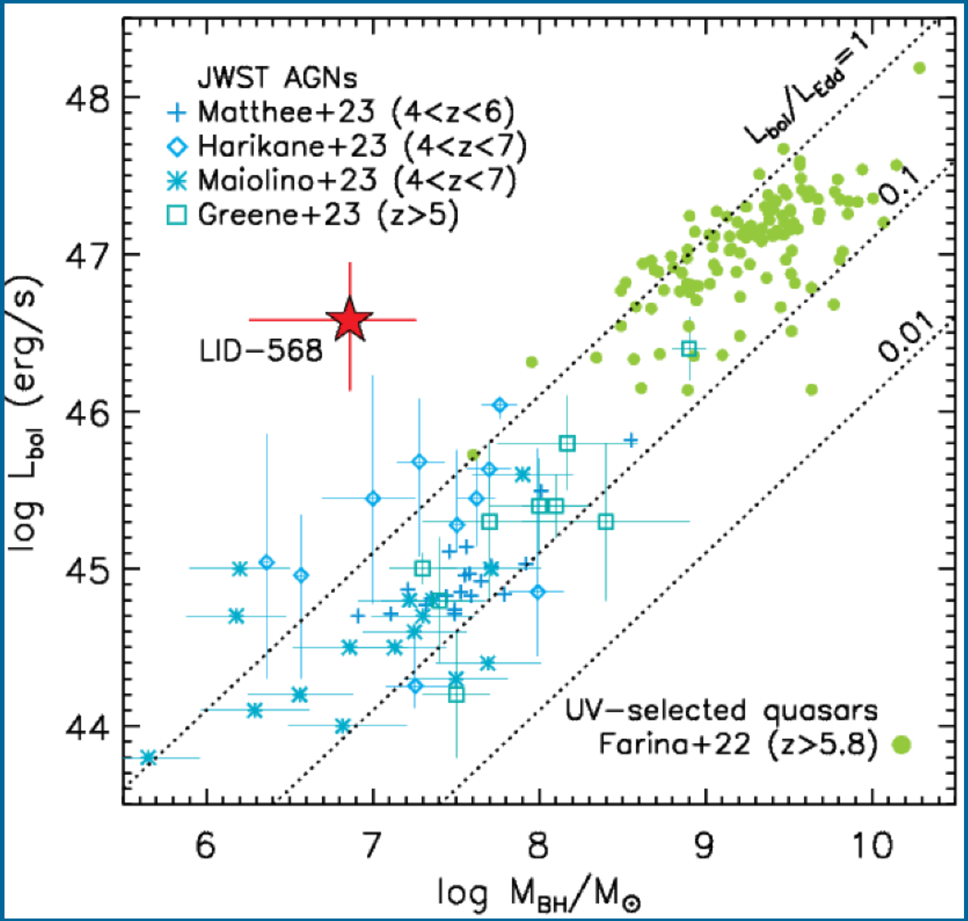
AGN at z~4.

Detected by Chandra and JWST

M_{bh}~ few 10^6 M_{sun}

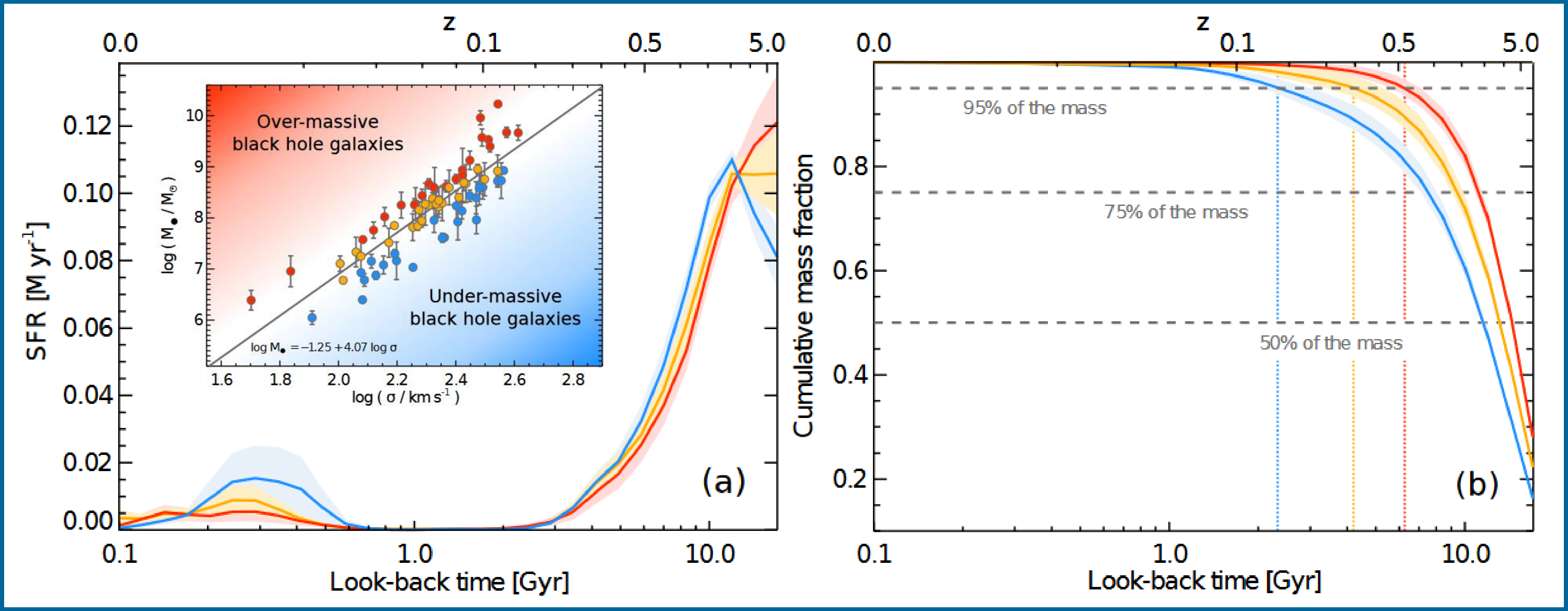
Powerful outflow.
Supereddington accretion.

The starformation is not quenched, yet. But, probably, the outflow will do it soon.



2405.05333

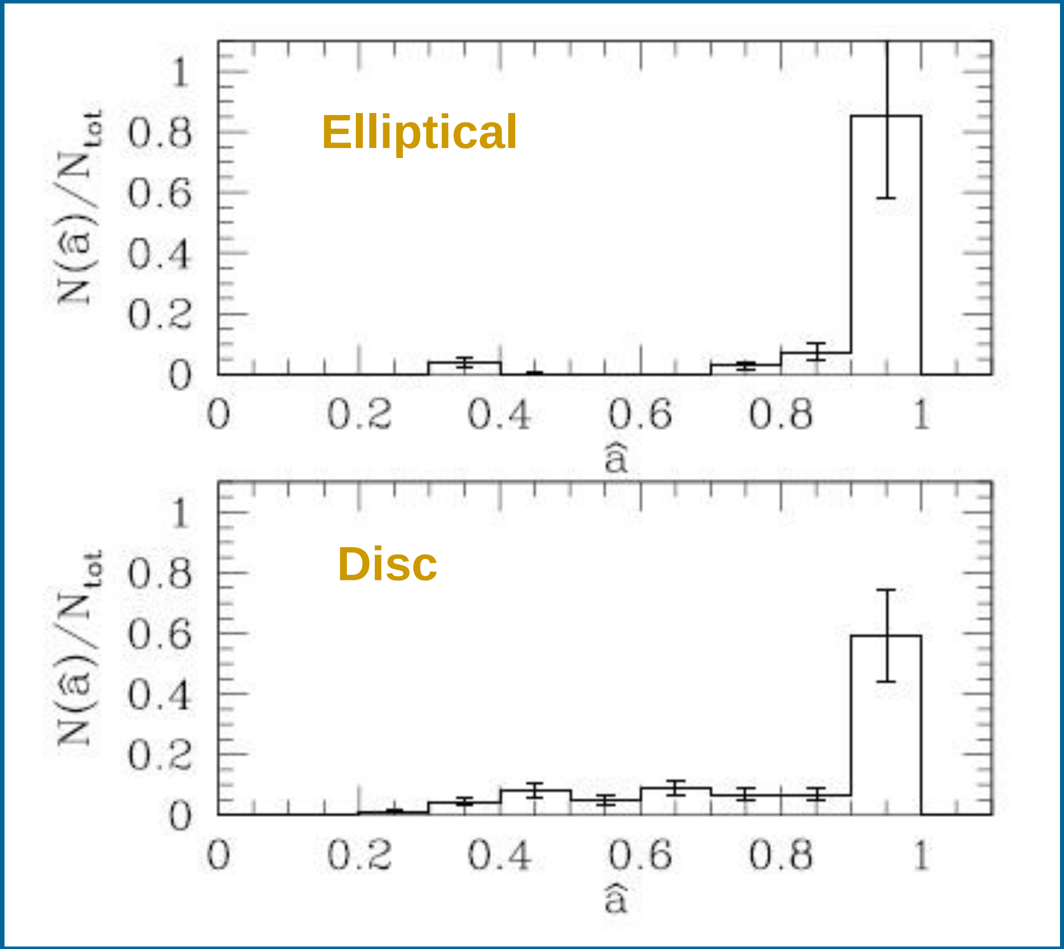
Starformation rate and black hole mass



Galaxies with different BH mass have different star formation histories.
Not the absolute BH mass is important, but if it is more or less massive than might be.
The authors suggest that more massive BHs form and evolve faster, and then quickly quench star formation in their galaxies.

1801.00807

Mass growth, spin and activity



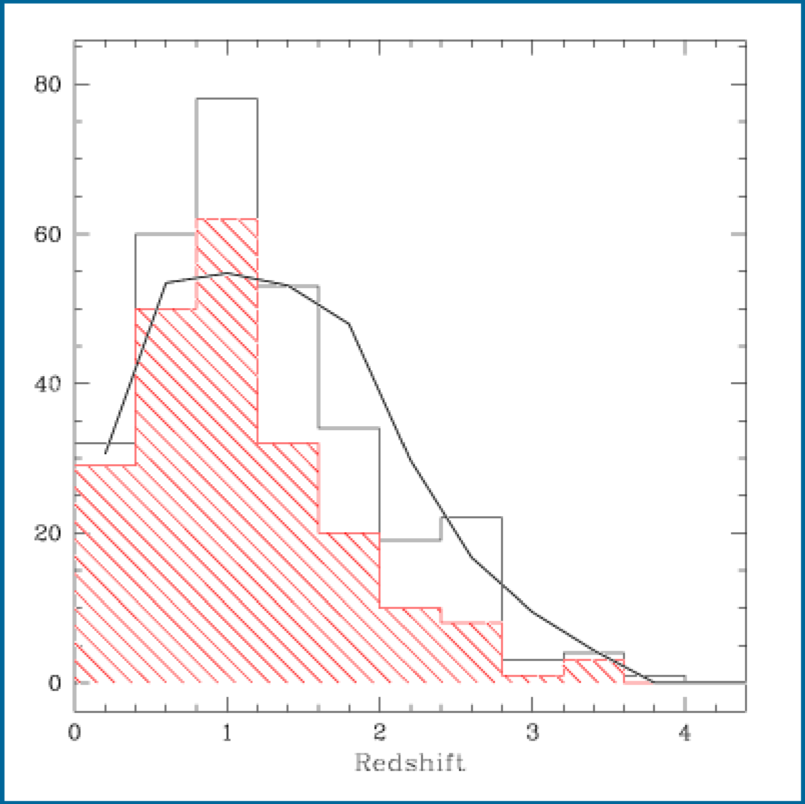
Some time ago it was noticed, that radio emission from elliptical galaxies is stronger, than from disc galaxies.

It was proposed that this can be related to faster rotation of central BHs in elliptical galaxies.

Recent calculations (see the plot) demonstrated that it can be true. The reason is that the mass growth of BHs in ellipticals happen via more powerful episodes of accretion.

arXiv: 0706.3900

Evolution of SMBHs activity



The plot shows the redshift distribution of AGNs detected by Chandra and XMM-Newton.

The top histogram: all sources from the joint sample of Chandra and XMM.

Red hatched region:
sources identified in optics.

Solid curve: results of modeling.

The “cutoff” at high redshifts is not an artifact.

Comastri astro-ph/0307426

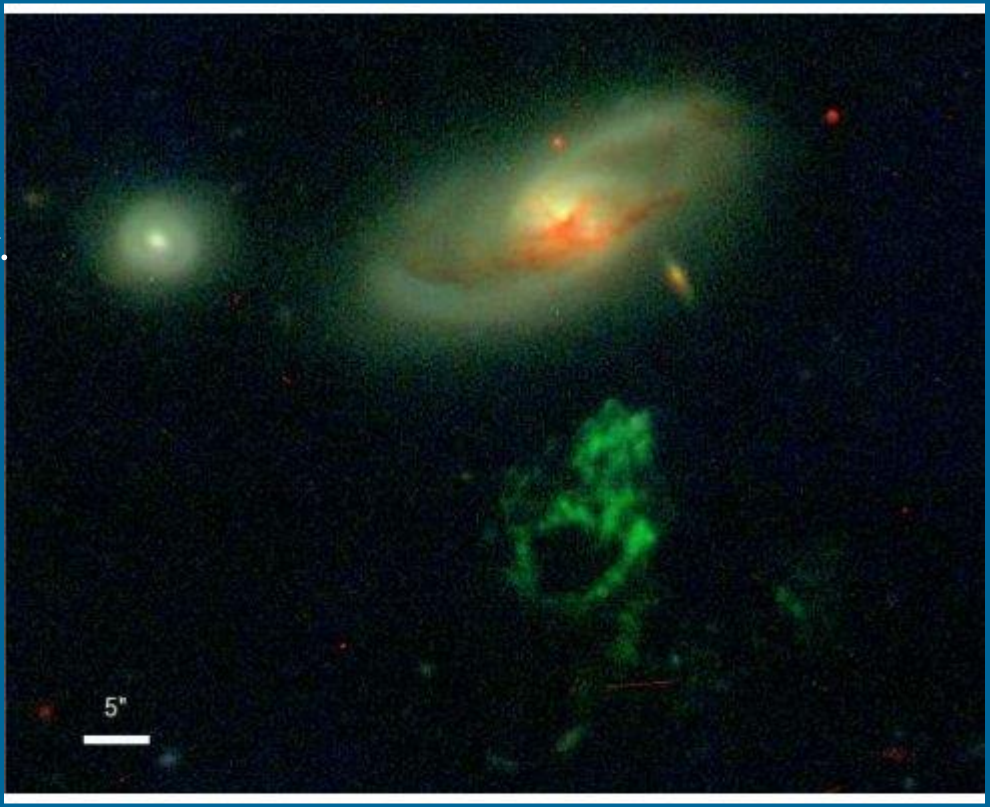
Light echo from a dead quasar

Hanny's Voorwerp.
The source was discovered
by the Galaxy Zoo Project.

This is a gas cloud in 45-70 thousand l.y.
from the galaxy IC 2497

The galaxy is not active now,
but probably <70 000 years ago it was
and powered the gas cloud.

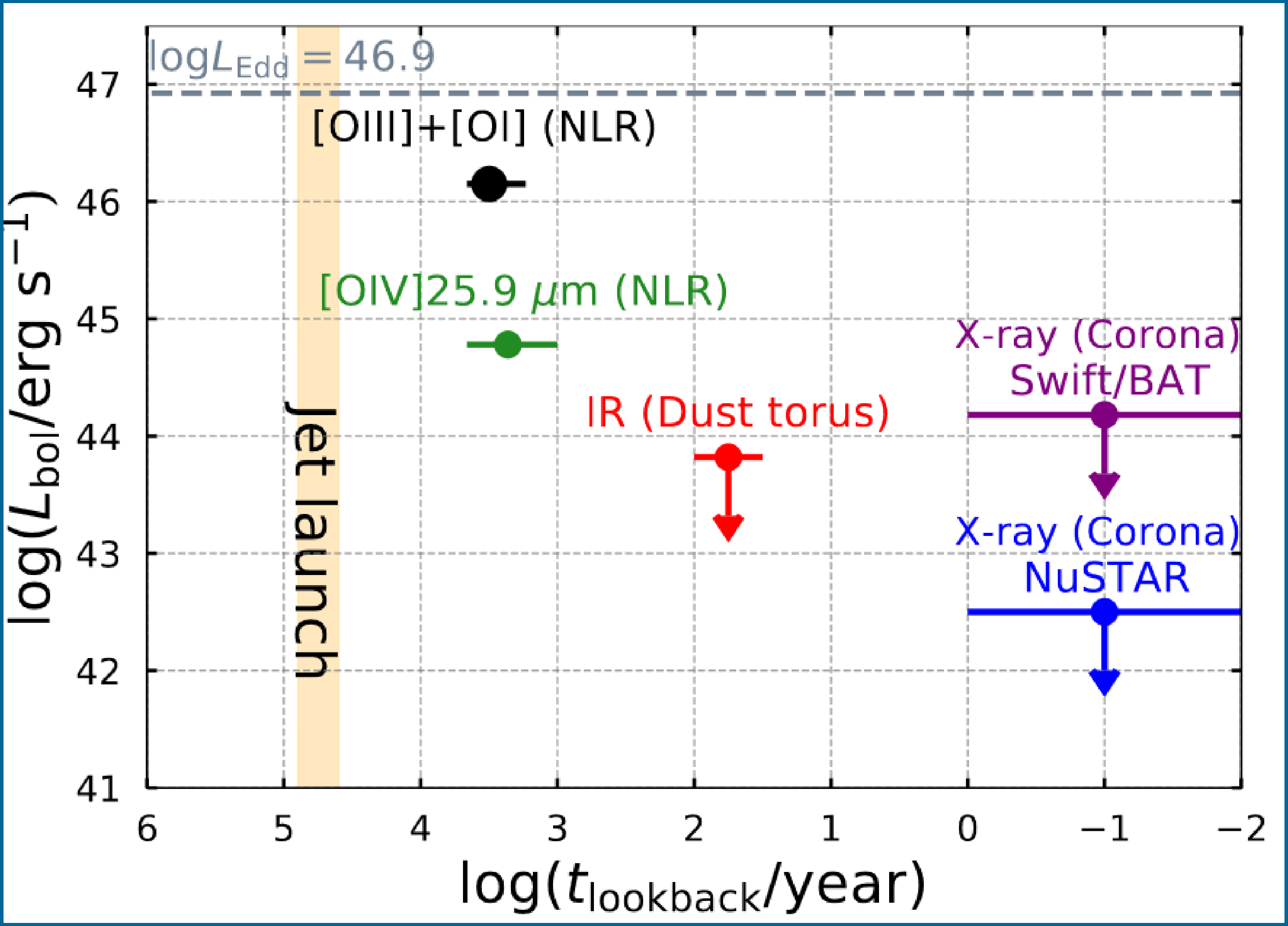
The alternative explanation
(a radiogalaxy with a jet and huge
absorption in the nuclei) was proposed
in arXiv: 1101.2784



This was the closest QSO!

arXiv: 1011.0427

Another light echo



Arp 187

Luminosity decline on the time scale ~10^4 yrs.

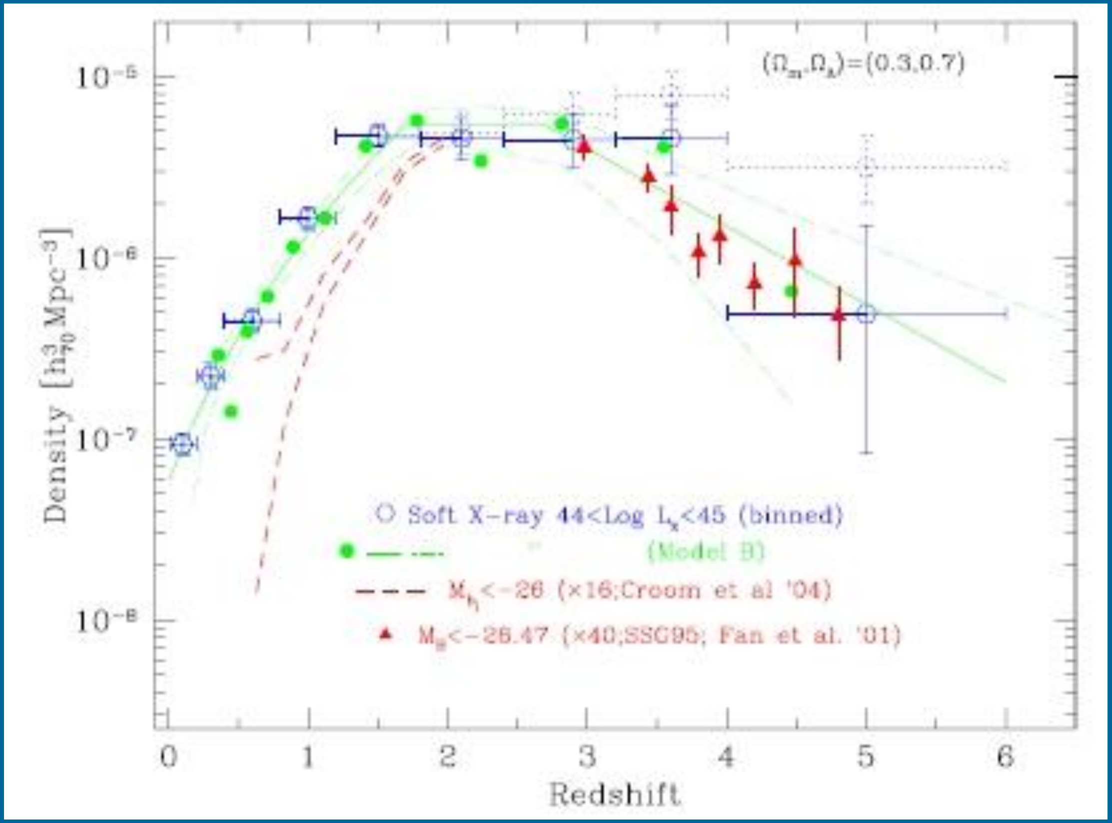
Kinematic age of the jet ~8 10^4 yrs.

Size of narrow line region ~1 kpc.

TDE of a molecular cloud

1908.10864

Evolution of quasars number



Very bright quasars are formed very early, and then their number is decreasing.

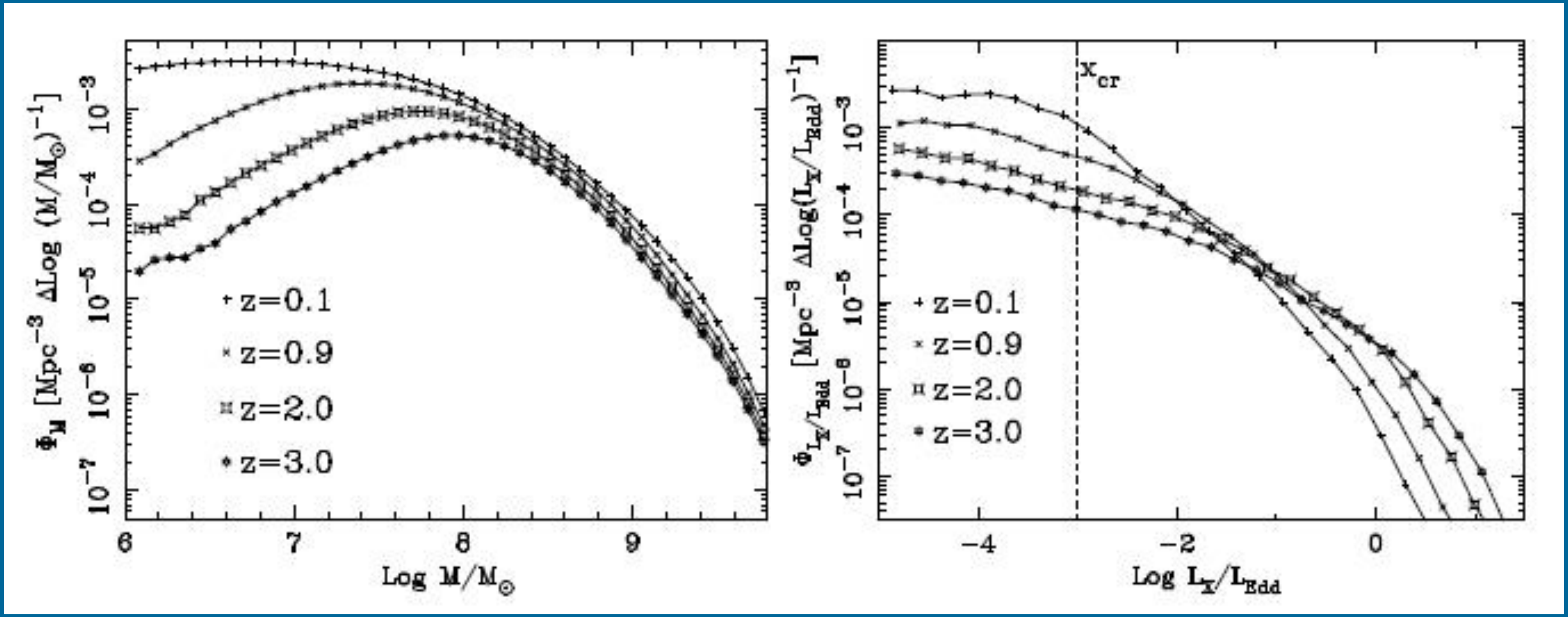
For AGNs with low luminosities the evolution is not so pronounced, but anyway it is evident.

For luminosities 10^{42}-10^{43} erg/s the maximum is at z~0.5-0.7, for 10^{45}-10^{46} erg/s – at z~2.

z=3 corresponds to 11.55 bl yrs ago.

Combes astro-ph/0505463

Mass and luminosity evolution of AGNs



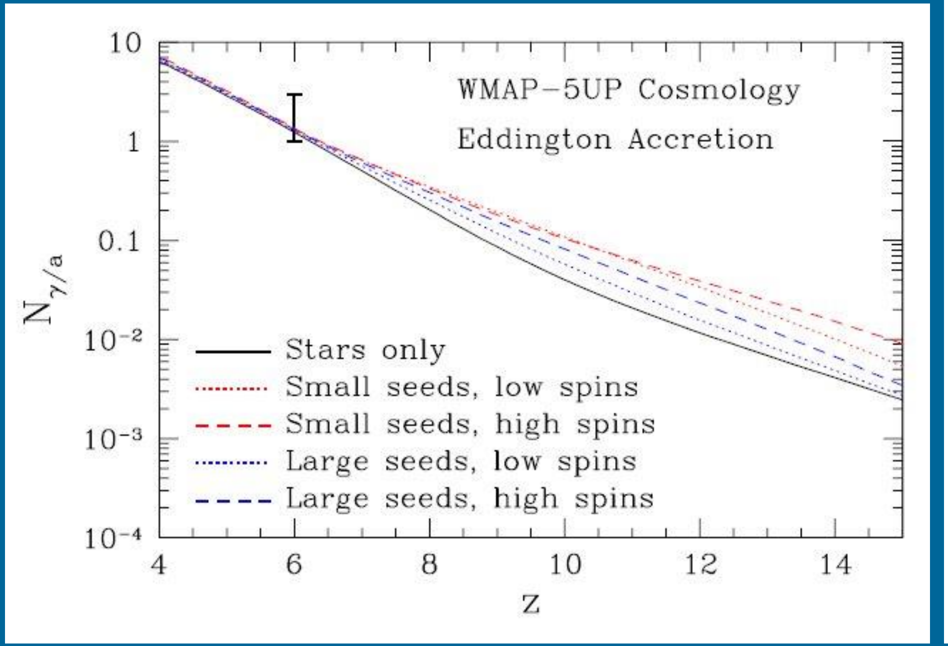
Results of numerical simulations are shown (Merloni 2004).
Lifetime grows with decreasing z.

see Combes astro-ph/0505463

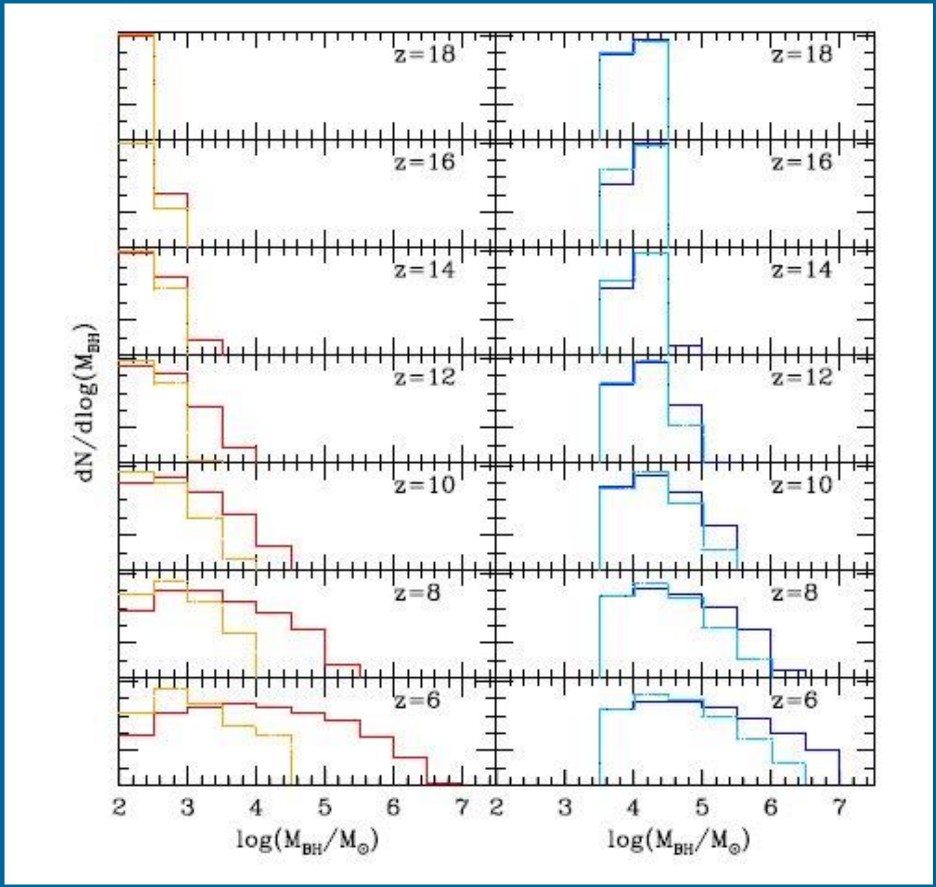
Quasars and reionization

It is important that quasars have a harder spectrum.

Quasars dominate till z~8.
After – starforming galaxies dominate.



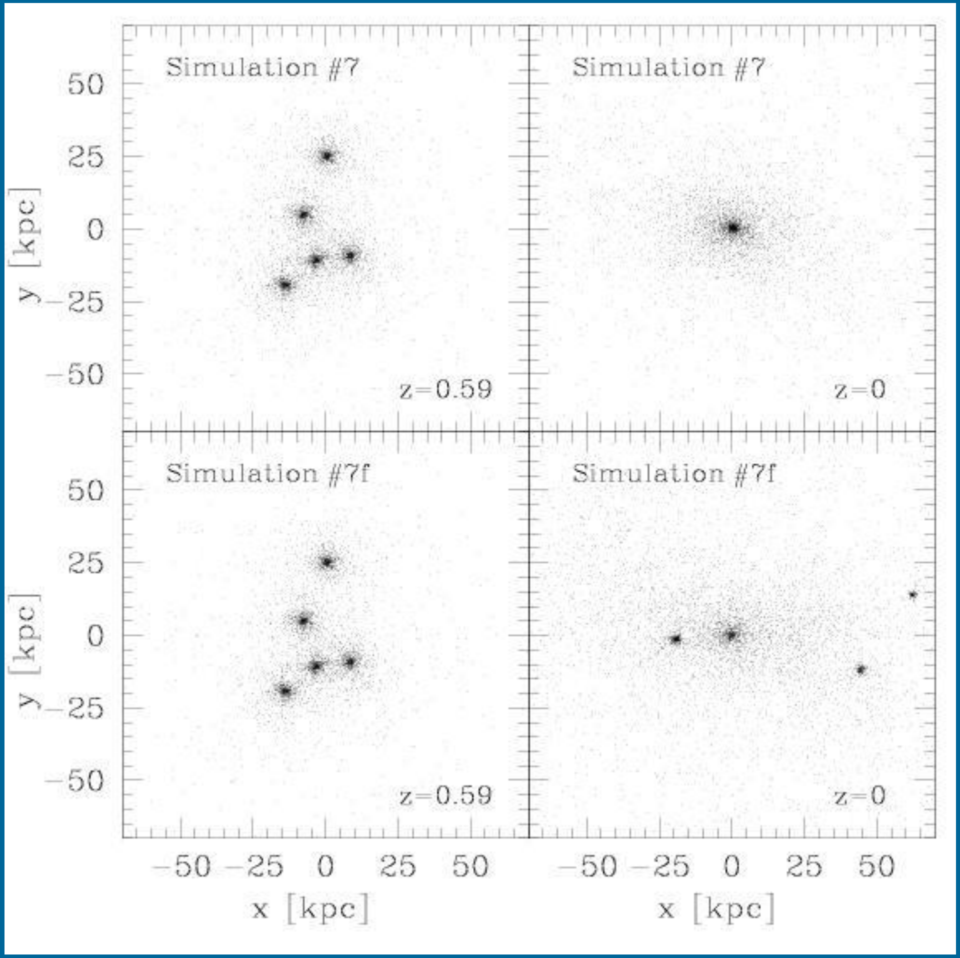
Mass function of MBHs at different cosmic times



Small seeds Large seeds

arxiv:0905.0144

Galactic cannibalism



Results of calculations for the evolution of galaxies in the center of the cluster C0337-2522.

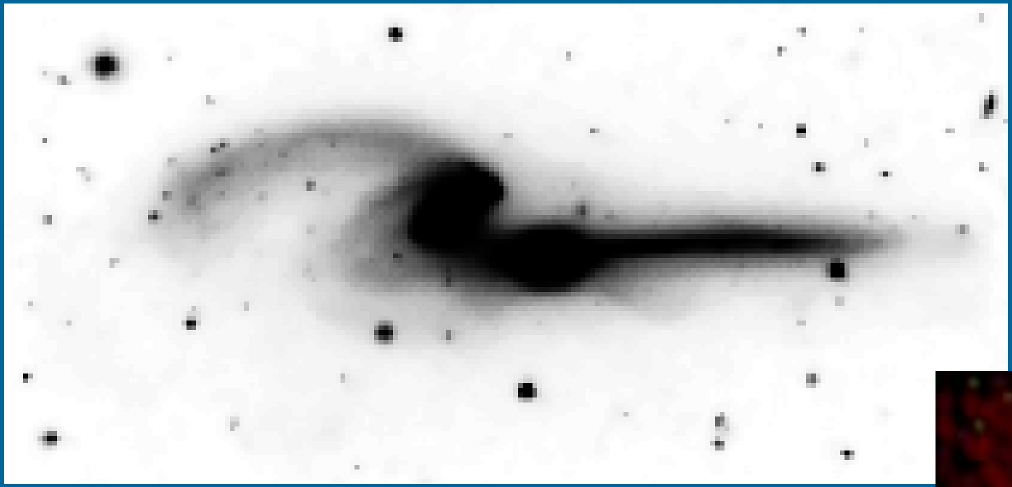
On the left the present day (observed) configuration is shown.

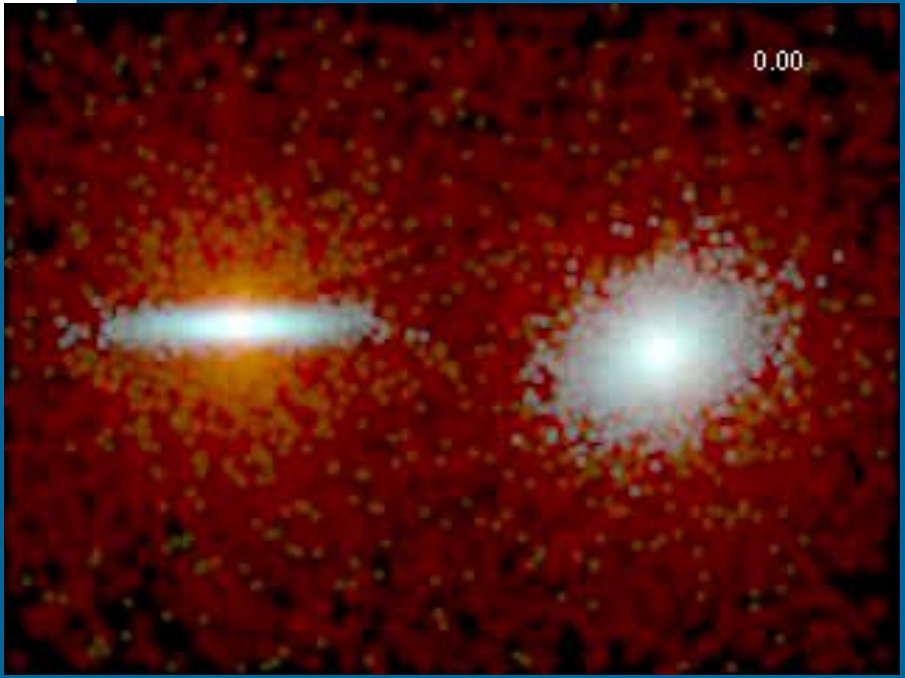
On the right – results of calculations for two models.

Two variants of calcualtions differ by the way the DM particles are treated. The upper one seems to be more realistic.
Dynamical friction is important.

C.Nipoti et al. astro-ph/0306082

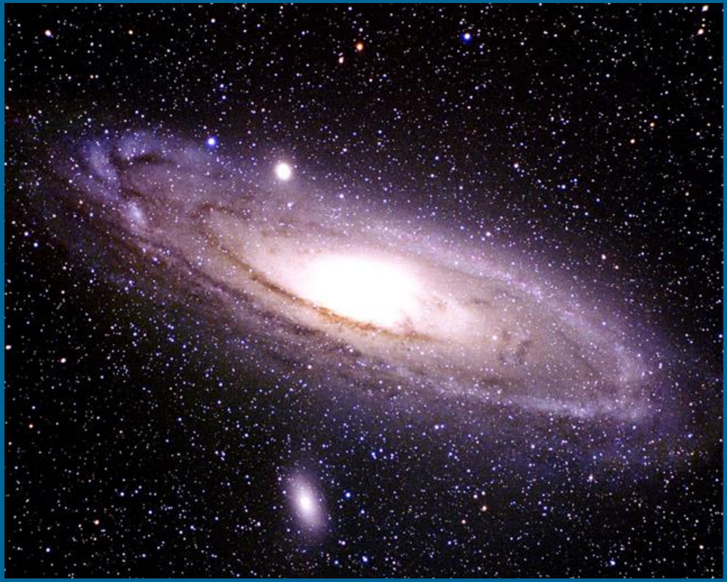
Interacting galaxies





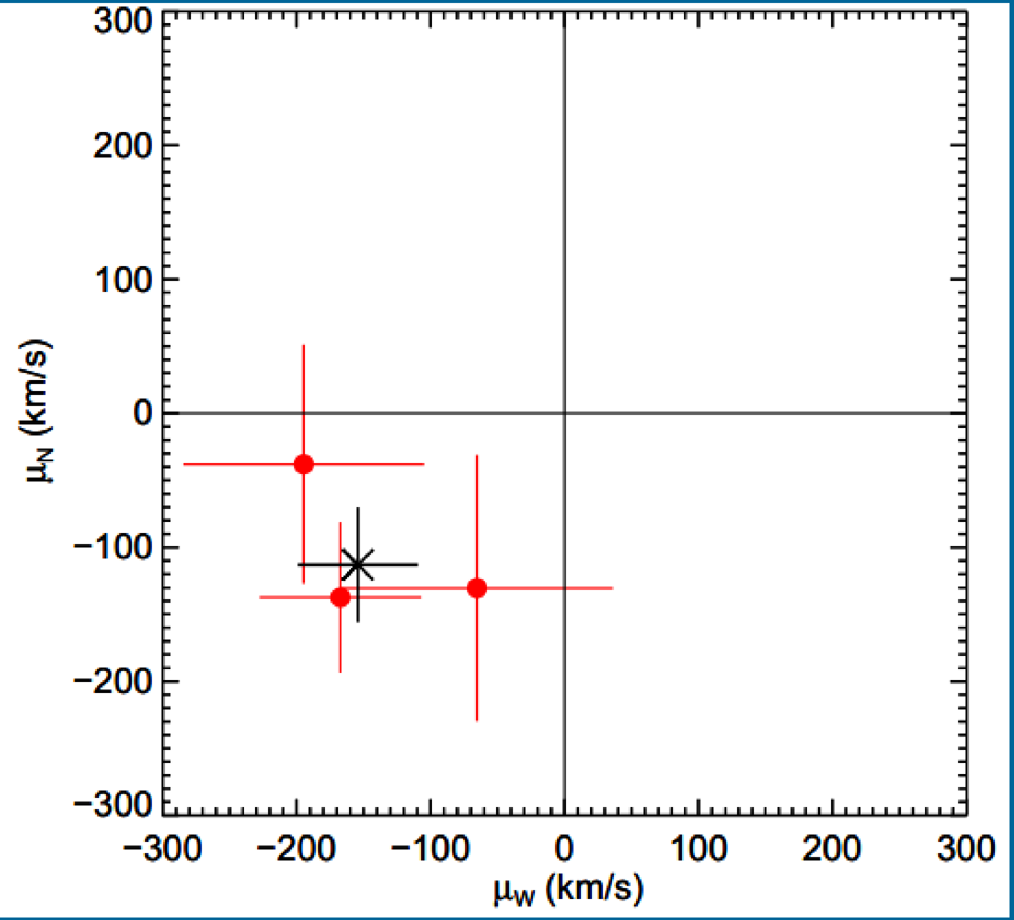
(Hibbard, Barnes)

Where does the Andromeda galaxy move?



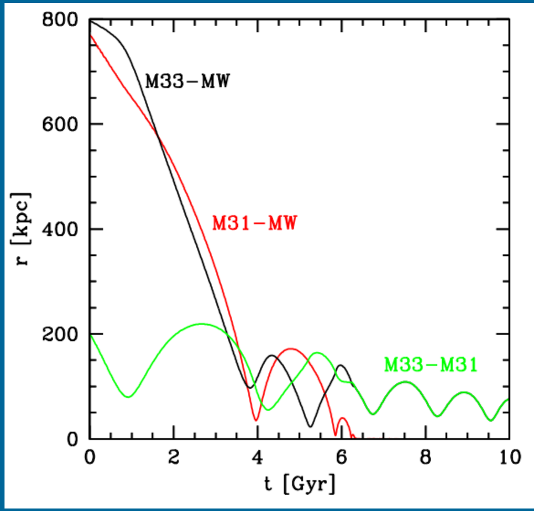
HST observations

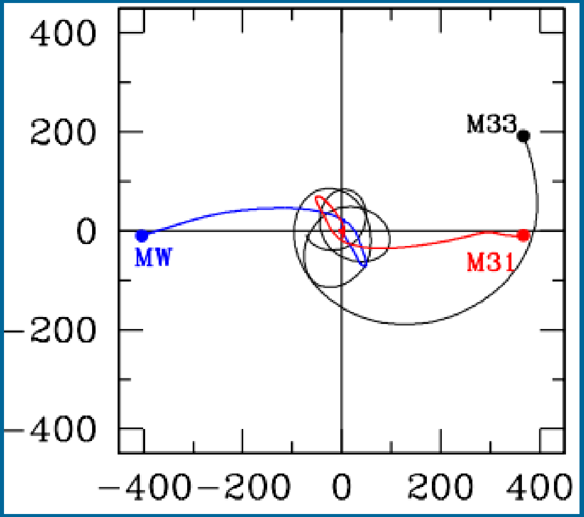
The first proper motion measurements.
This allows measuring the 3D velocity.



1205.6863

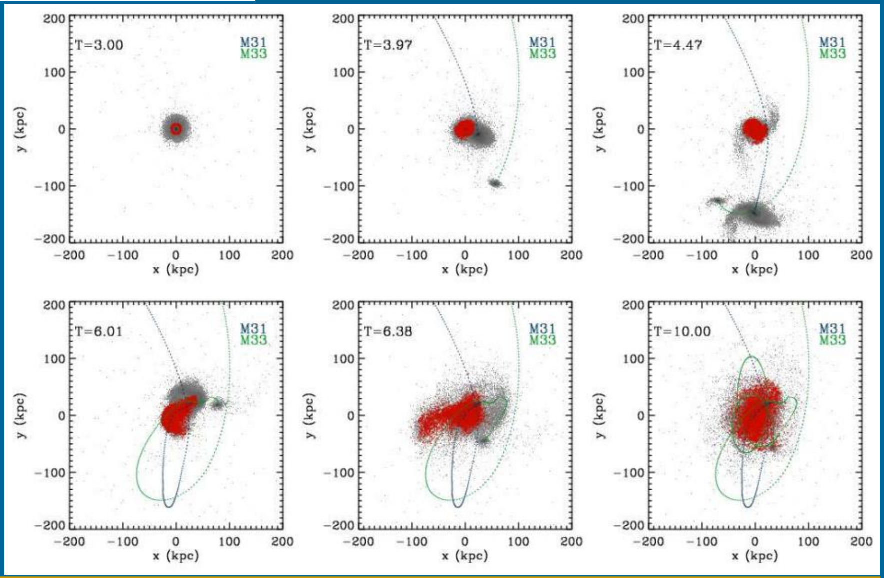
Milky way + Andromeda + M33



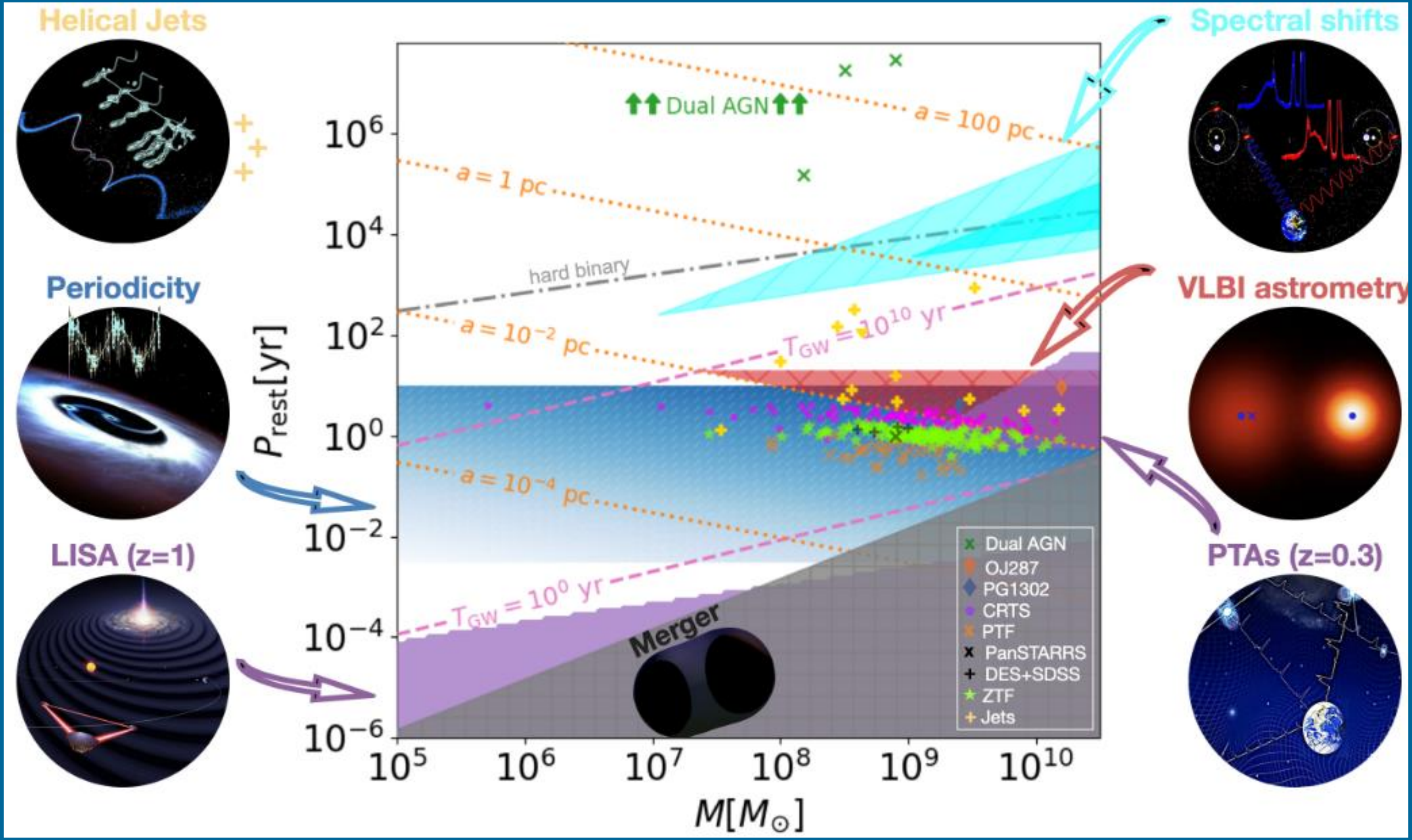


Our Galaxy and M31 will merge
in 5-7 billion years.
The first close approach
will happen in 3.5-4 billion years.

Later on, the M33 galaxy will join.



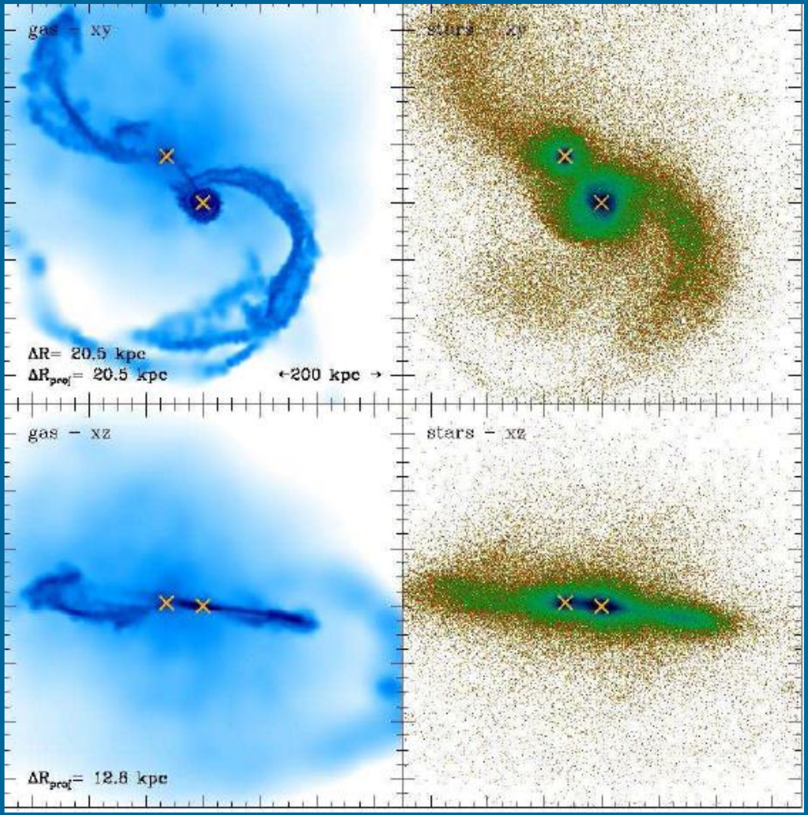
Observational signatures of SMBHBs

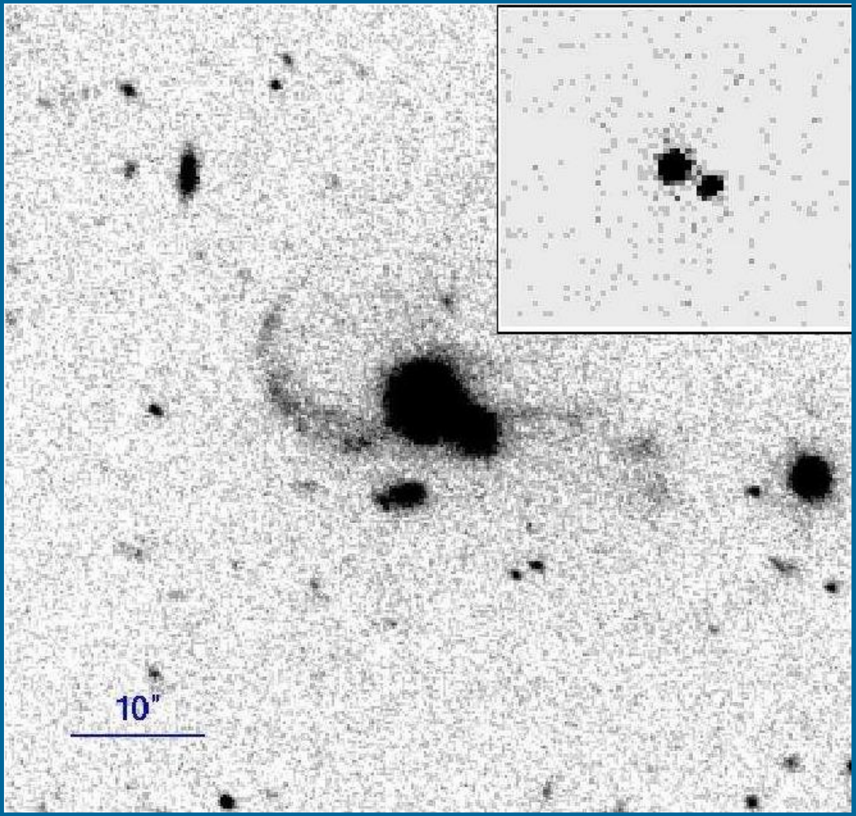


2310.16896

Double quasar in a merger

For the first time a bright binary QSO is found in a clearly merging pair of galaxies.
Both QSOs are radioquiet. They form a physically bounded system at z=0.44.
In projection the separation is 21 kpc.

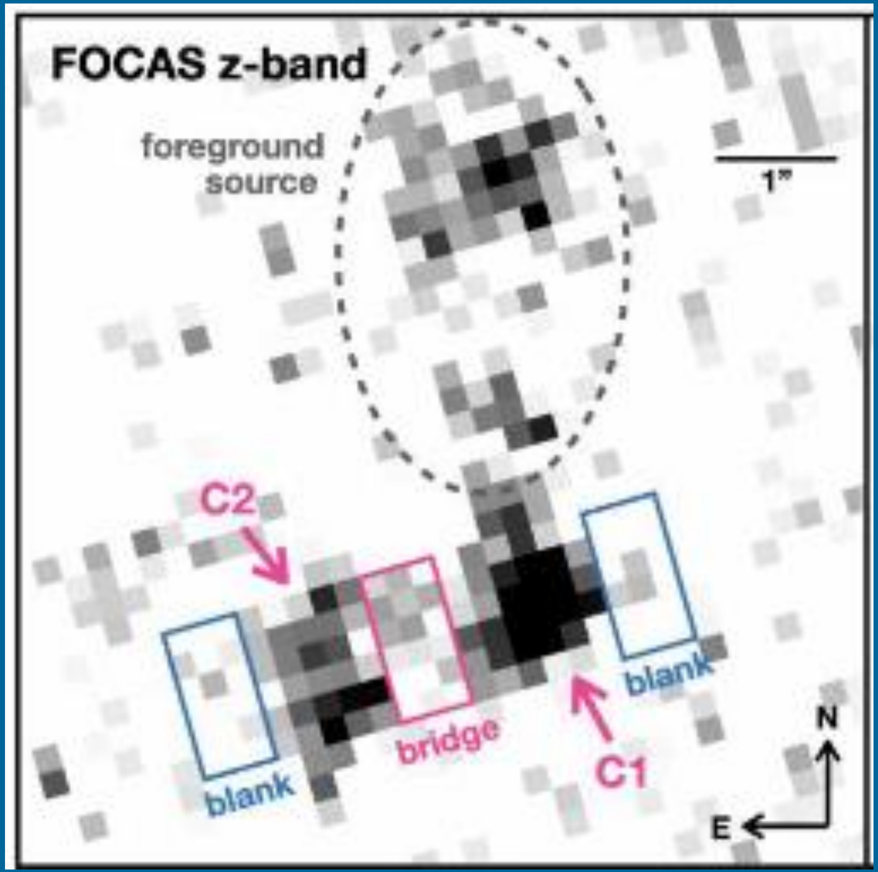


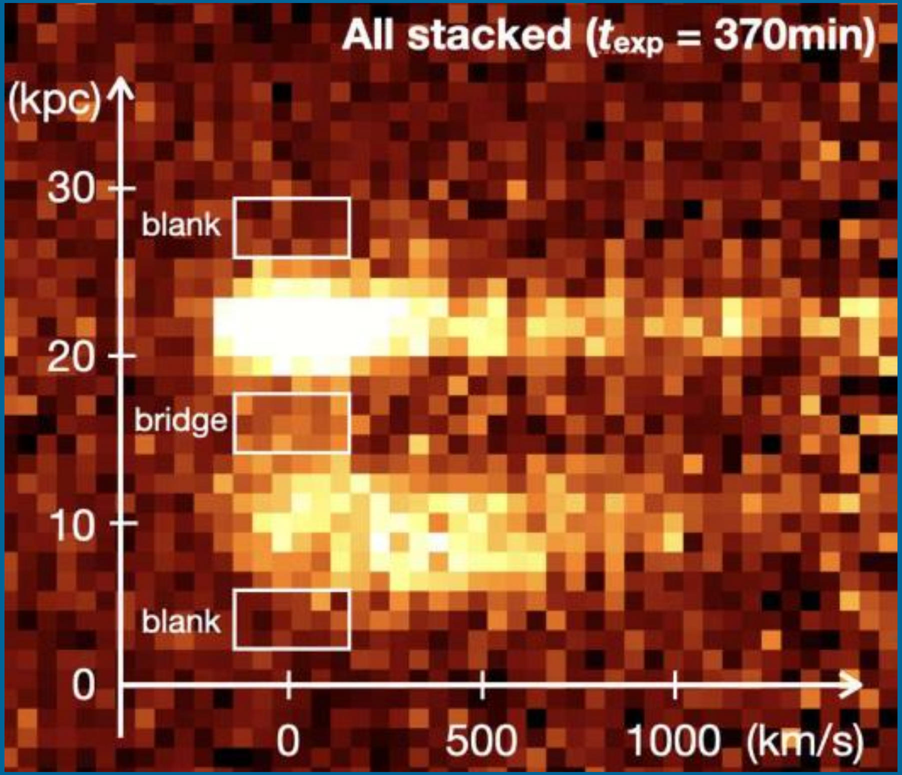


arXiv: 1001.1783. See a review about binary SMBHs in arXiv: 2310.16896

Merging quasars at z>6

z = 6.05
$\log(M_{BH}/M_{\odot}) = 8.1 \pm 0.3$
12 kpc - projected distance

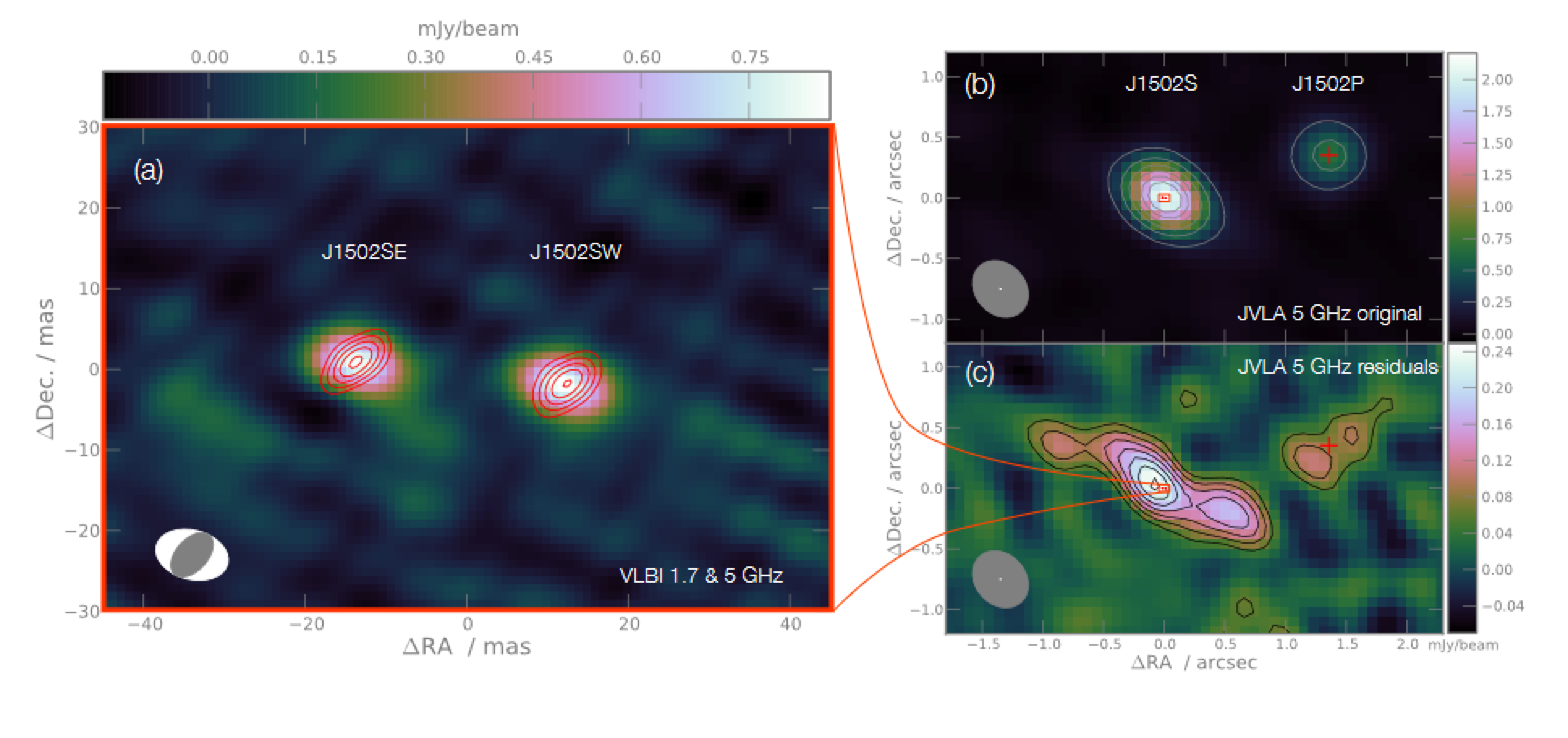




Lyα spectra

2405.02465, see also 2405.02468 about the host galaxies

Triple BH system



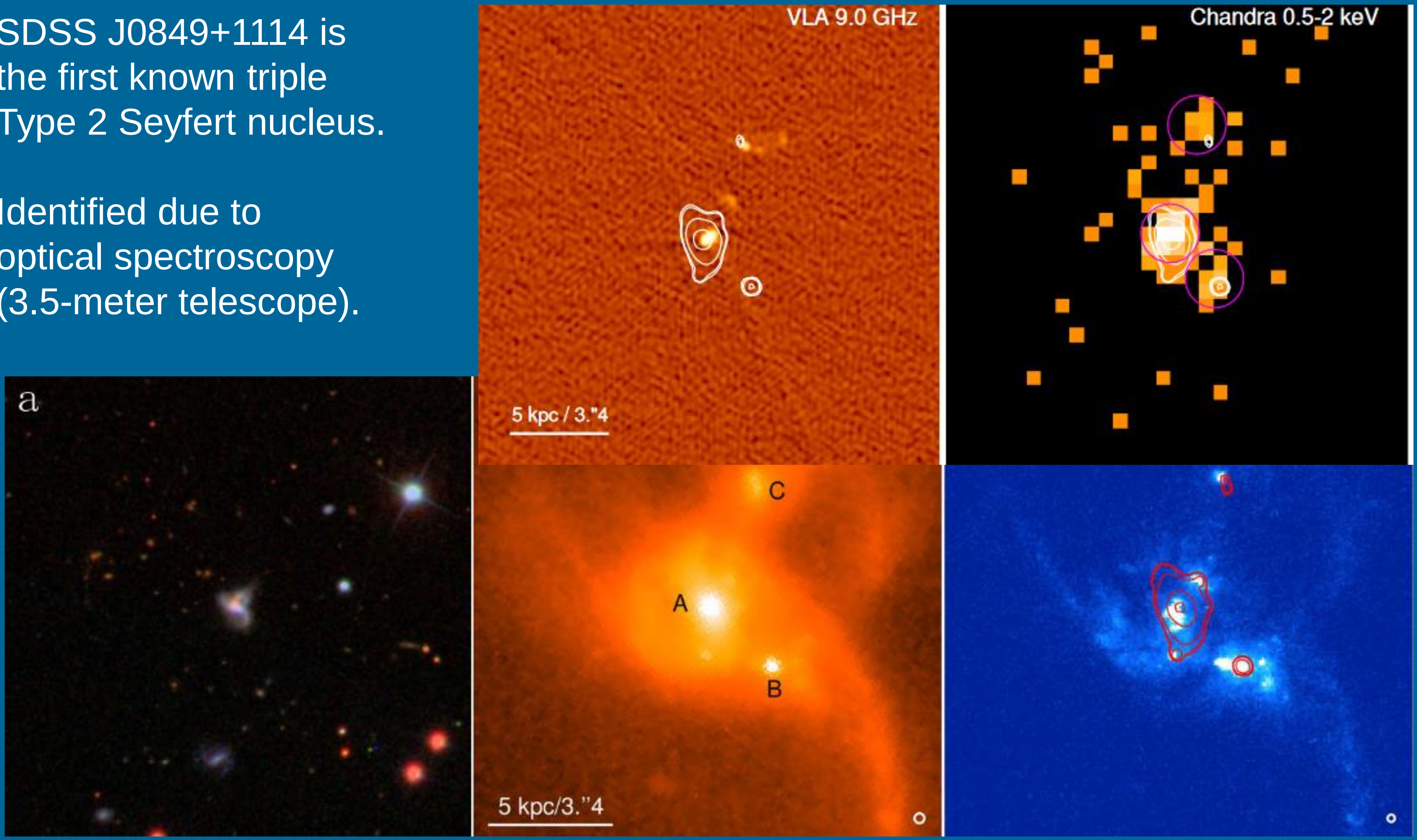
z=0.39
The closest pair separation ~140 pc
The third at ~7.4 kpc

1406.6365

Triple SMBH in a Seyfert galaxy

SDSS J0849+1114 is the first known triple Type 2 Seyfert nucleus.

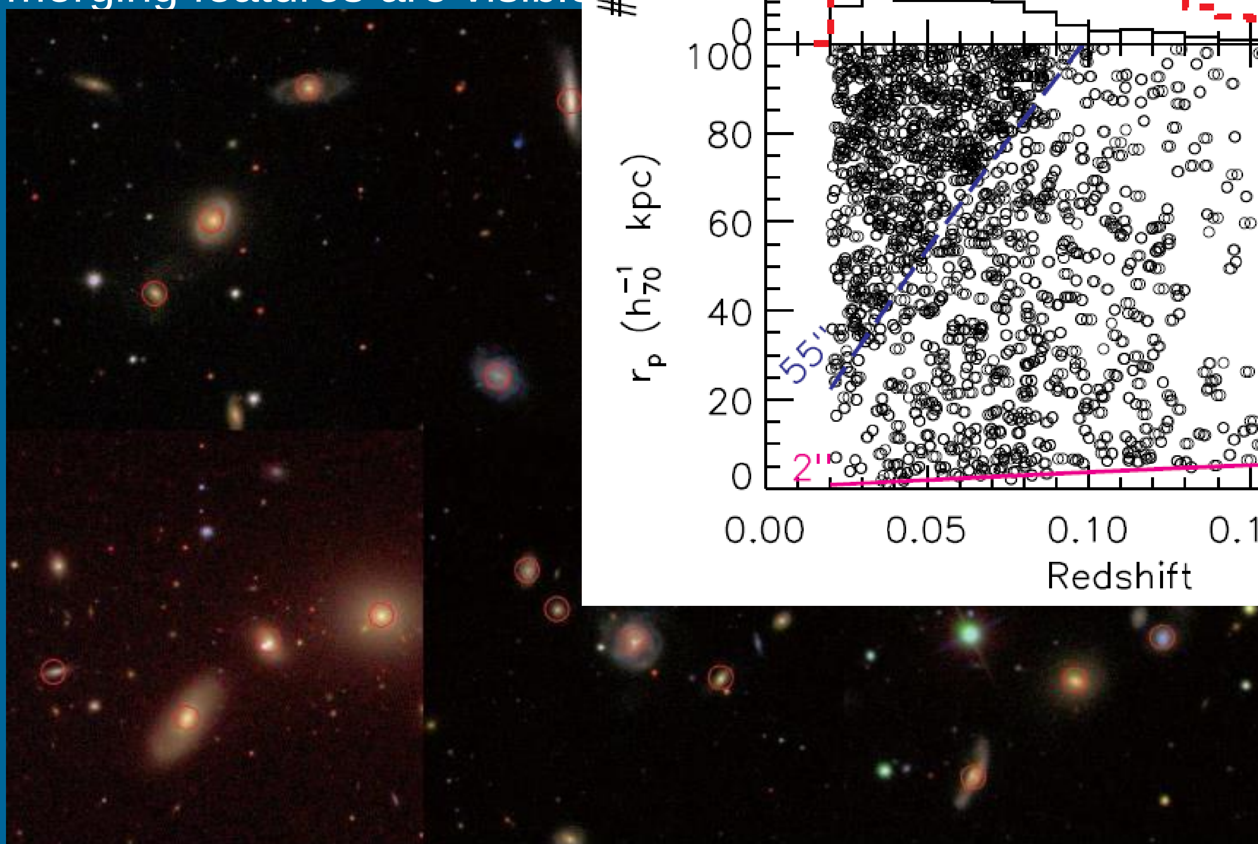
Identified due to optical spectroscopy (3.5-meter telescope).

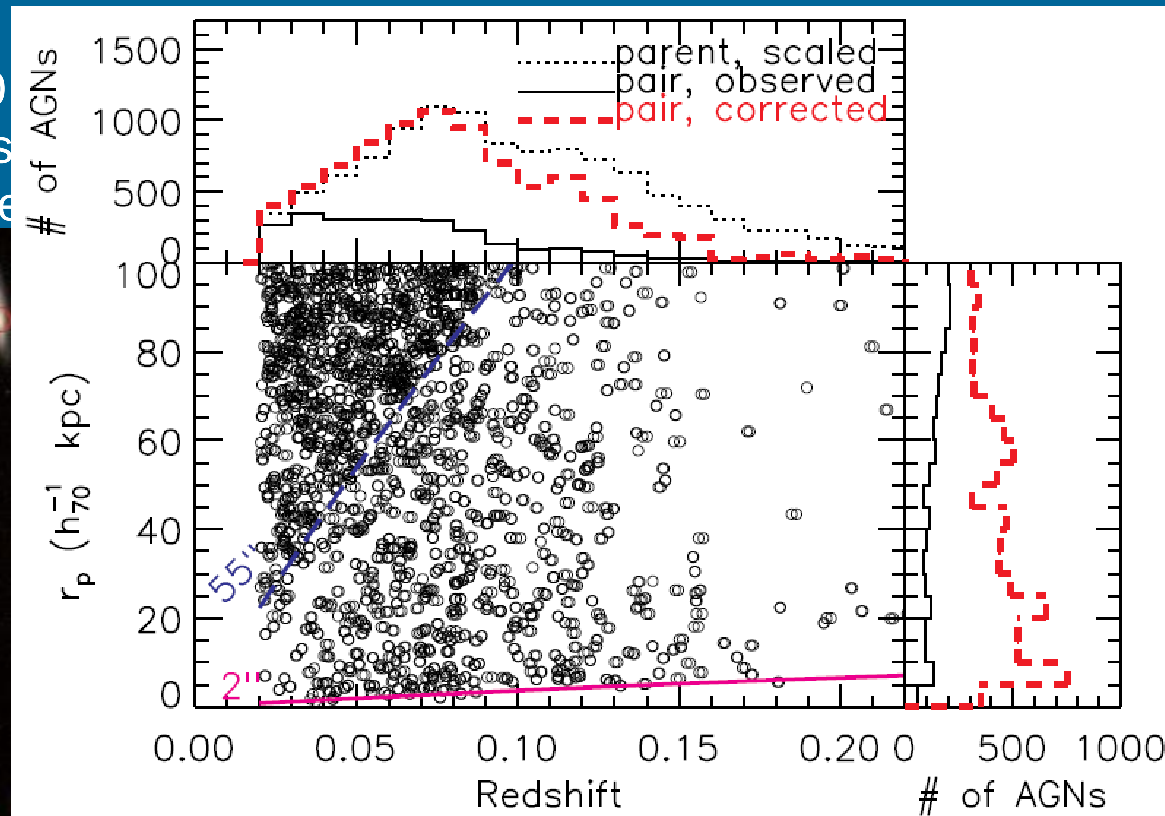


1907.10639, see new results in 2012.00769

AGN pairs in SDSS

1286 pairs out of >130 000
3.6% of AGNs. In 30% cas
merging features are visible

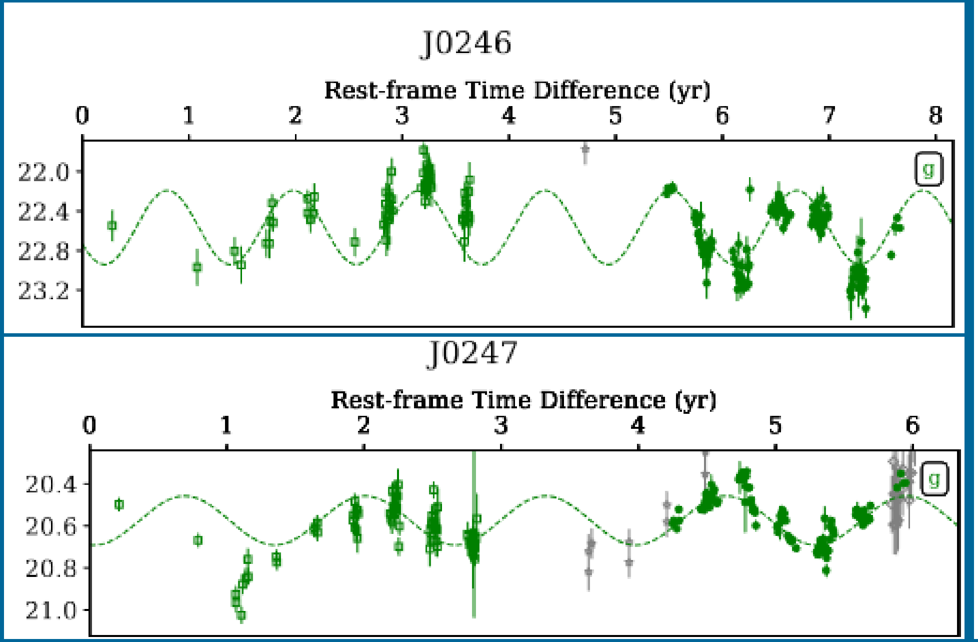


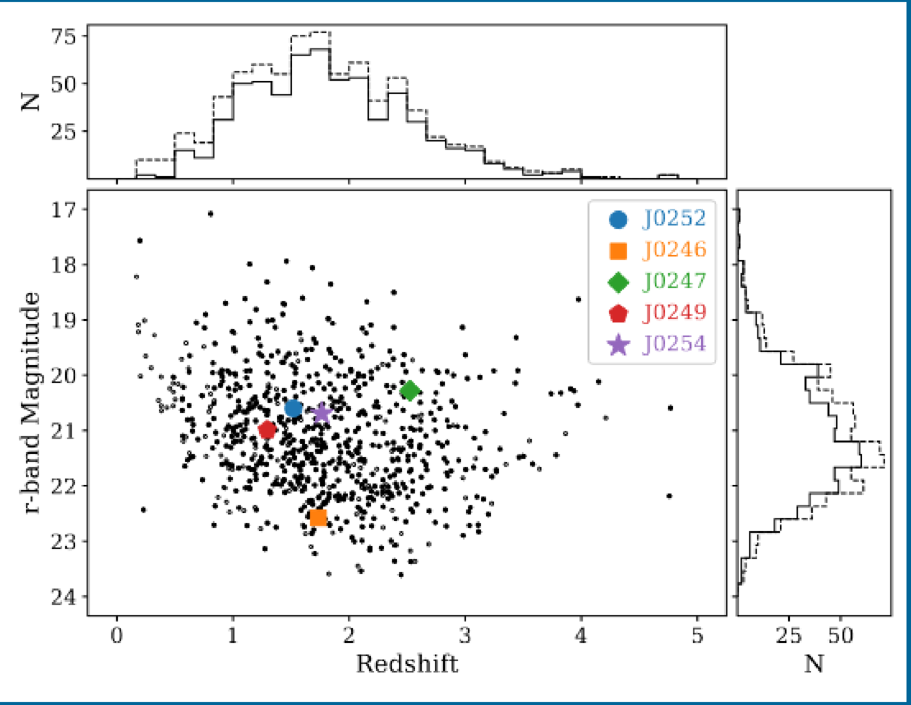


1104.0950, 1104.0951

Periodic variability in QSOs

5 candidates among ~700 sources





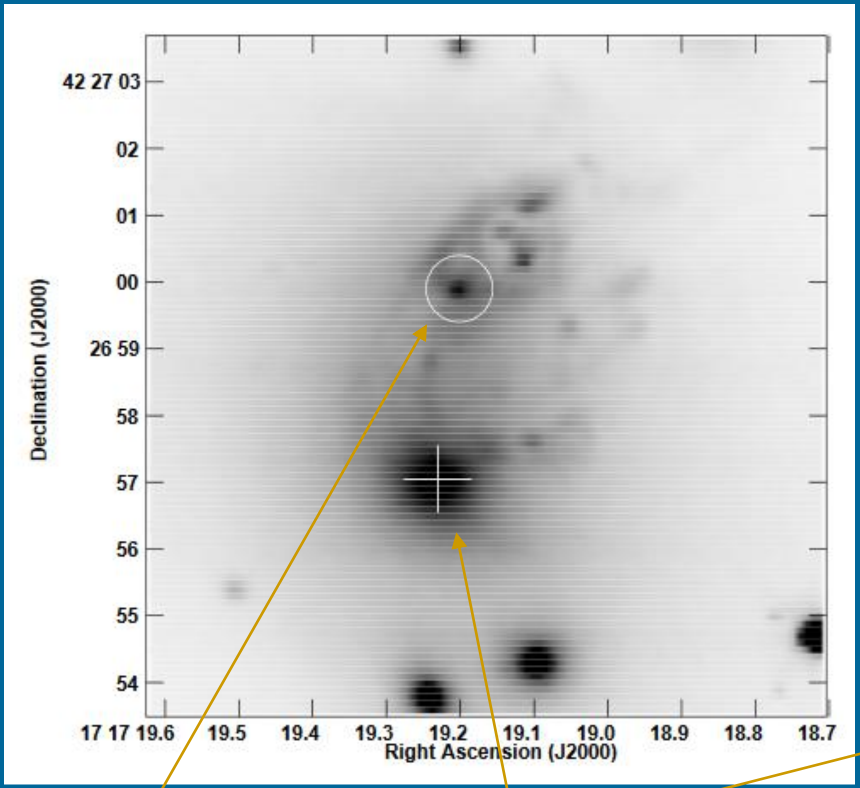
LSST might find many periodically variable AGNs, see e.g. 2110.07465

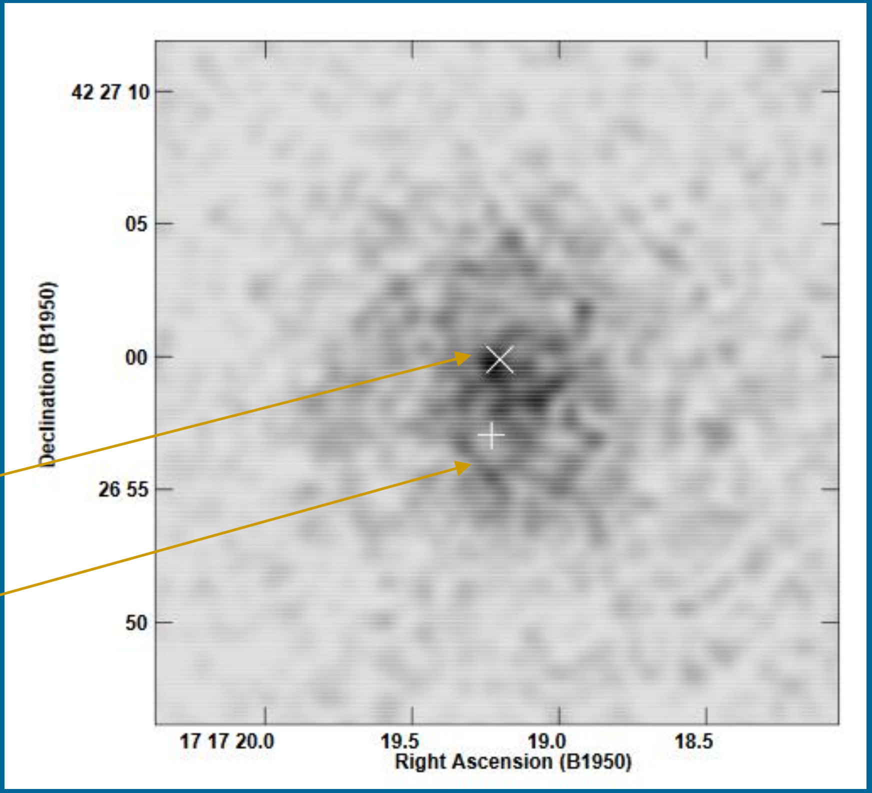
2008.12329

Nearly naked SMBH

Strong radio source 8.5 kpc from the BCG. Likely an AGN in a small stripped galaxy. Traces of interaction.

HST





VLBA

Radio source

BCG

1606.04067

Coalescence

$$a_{GW} \approx 0.049 \text{ pc} \left(\frac{q/(1+q)^2}{0.25}\right)^{1/4} \left(\frac{T}{1.3\times 10^{10}\text{yr}}\right)^{1/4} \left(\frac{M}{10^8 M_\odot}\right)^{3/4}$$

$$P_{GW} \approx 100.5 \text{ yr} \left(\frac{q/(1+q)^2}{0.25}\right)^{3/8} \left(\frac{T}{1.3\times 10^{10}\text{yr}}\right)^{3/8} \left(\frac{M}{10^8 M_\odot}\right)^{5/8}$$

Time before coalescence smaller than the age of the Universe.

Dynamical friction can bring two SMBHs down to ~a few pc distance.

Final-parsec problem (Milosavljevi´c & Merritt 2003)
Solutions:
- stars;
- gas;
- massive perturbers.

$$\theta_{\rm orb} = \frac{a}{D_A(z)} \approx 7.8\mu\text{as} \left(\frac{P}{5.1\text{yr}}\right)^{2/3} \left(\frac{M}{10^9 M_\odot}\right)^{1/3} \left(\frac{D_A}{200\text{Mpc}}\right)$$

2310.16896

Gravitational wave rocket

In addition to energy and angular moment, gravitational waves also take away the linear momentum. So, the object formed via a coalescence gets a kick.
The first estimate of the effect in the case of binaries was obtained in 1983 by Fitchett:

$$V_F \simeq 1480\,\mathrm{km/s}\,\frac{f(q)}{f_{\mathrm{max}}}\left(\frac{2GM/c^2}{r_{\mathrm{term}}}\right)^4$$

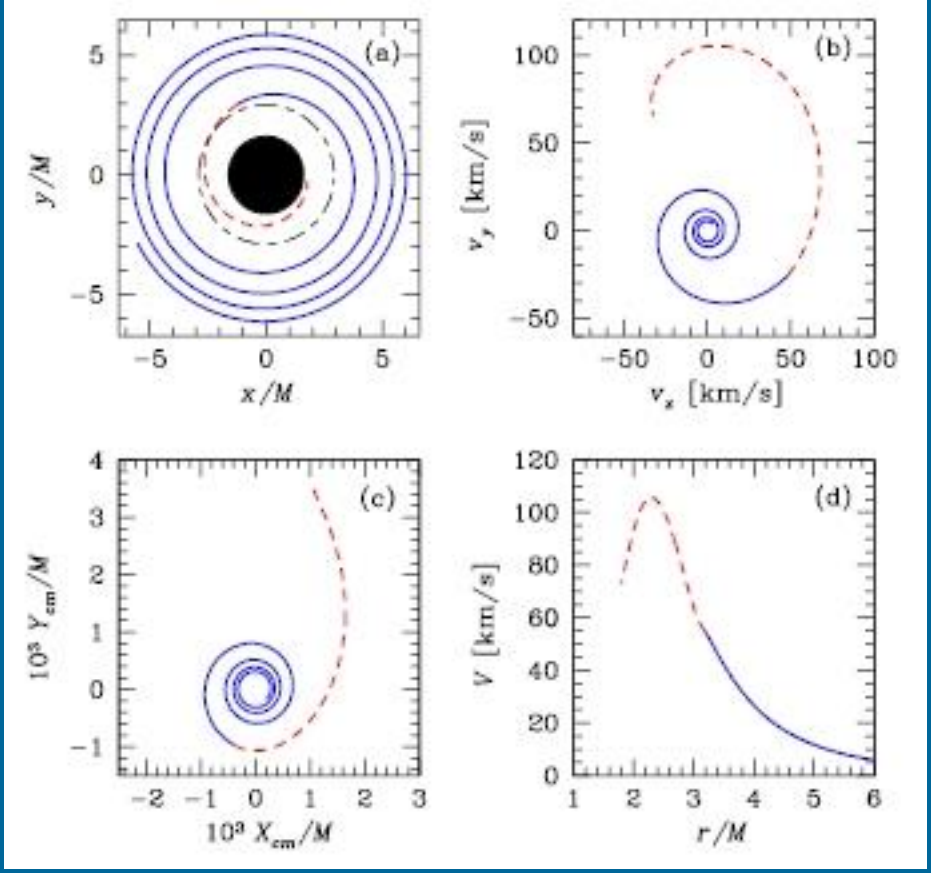
$f(q)=q^2(1-q)/(1+q)^5$, $f_{max}=0.38$

Recently, this topic became very hot due to calculations in the framework of the hierarchical model. Continuosly new results appear to improve the formula above

One of the first articles in the "new wave" was the paper by Favata et al.

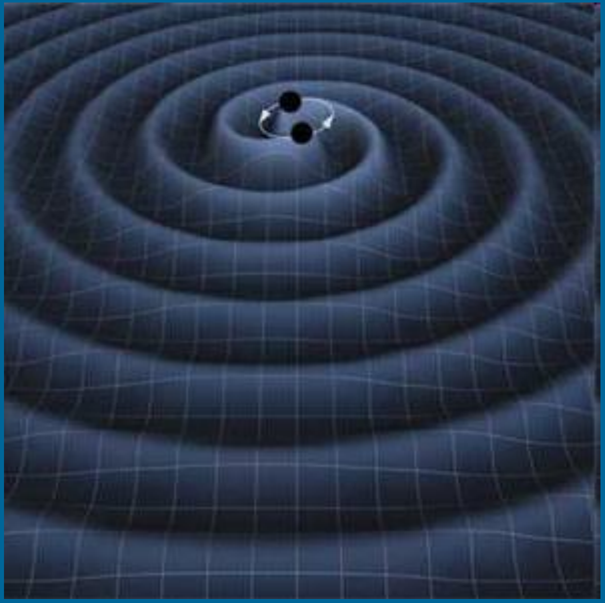
astro-ph/0402056 "How black holes get their kicks?"

Favata et al. (2004)

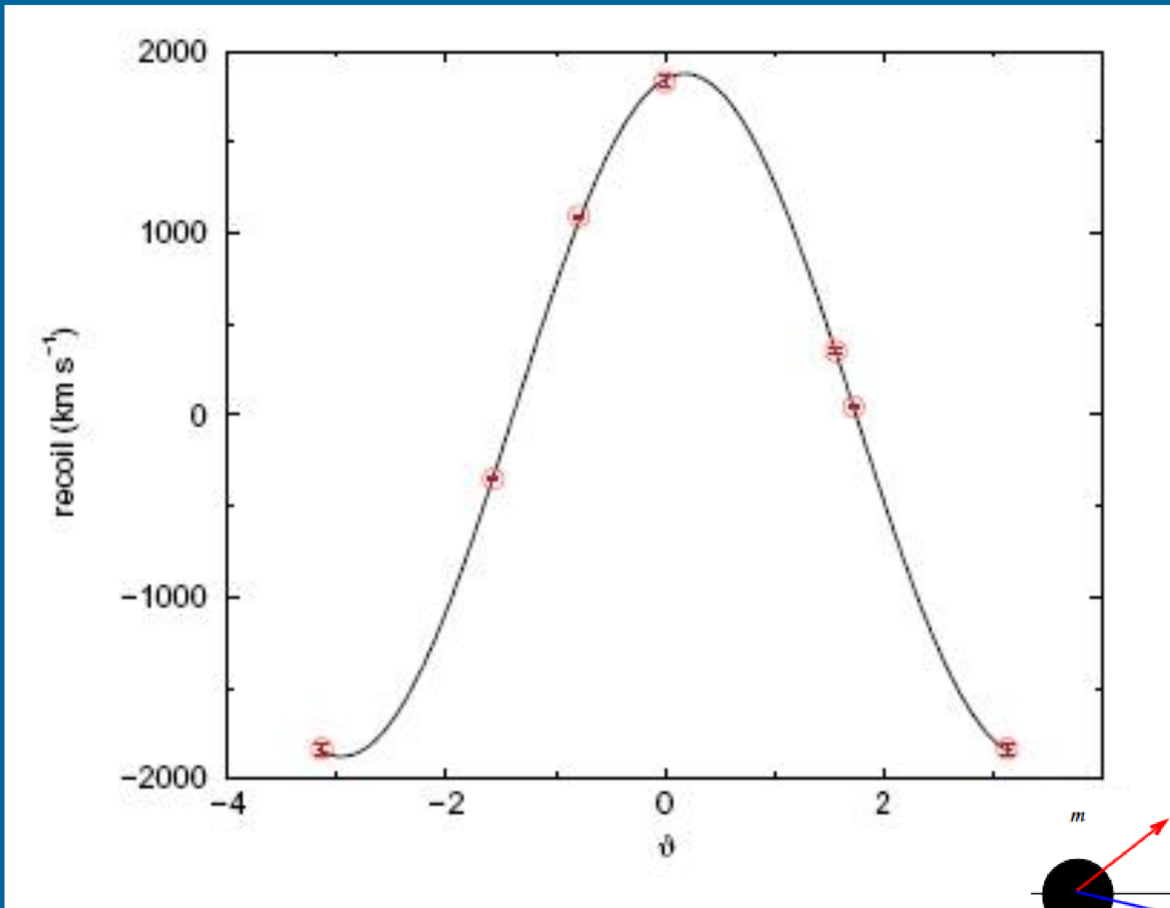


a/M=0.8, q=0.127
(rotation of the smaller BH
is neglected)

The velocity is high enough to escape from a not very massive halo, or to “shake” a central SMBH.



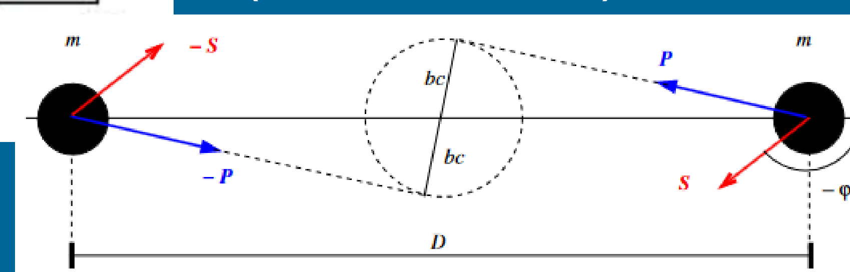
Maximum kick



The velocity is strongly dependent on the relative orientation of BHs spins prior to coalescence.

GW200129 could have a large kick ~1000 km/s, see 2201.01302.

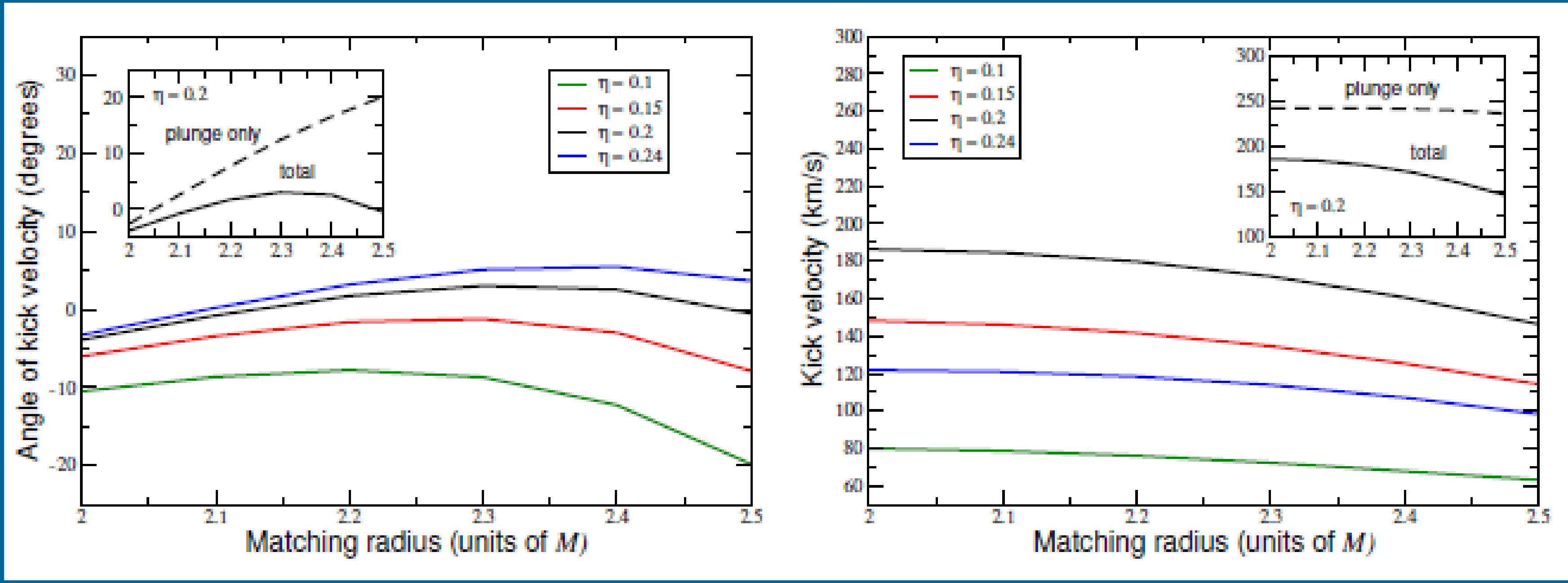
High-energy collisions (unrealistic in the case of usual BHs) can produce kick velocities up to 10% of the velocity of light, (see 2301.00018).



Campanelli et al. gr-qc/0702133

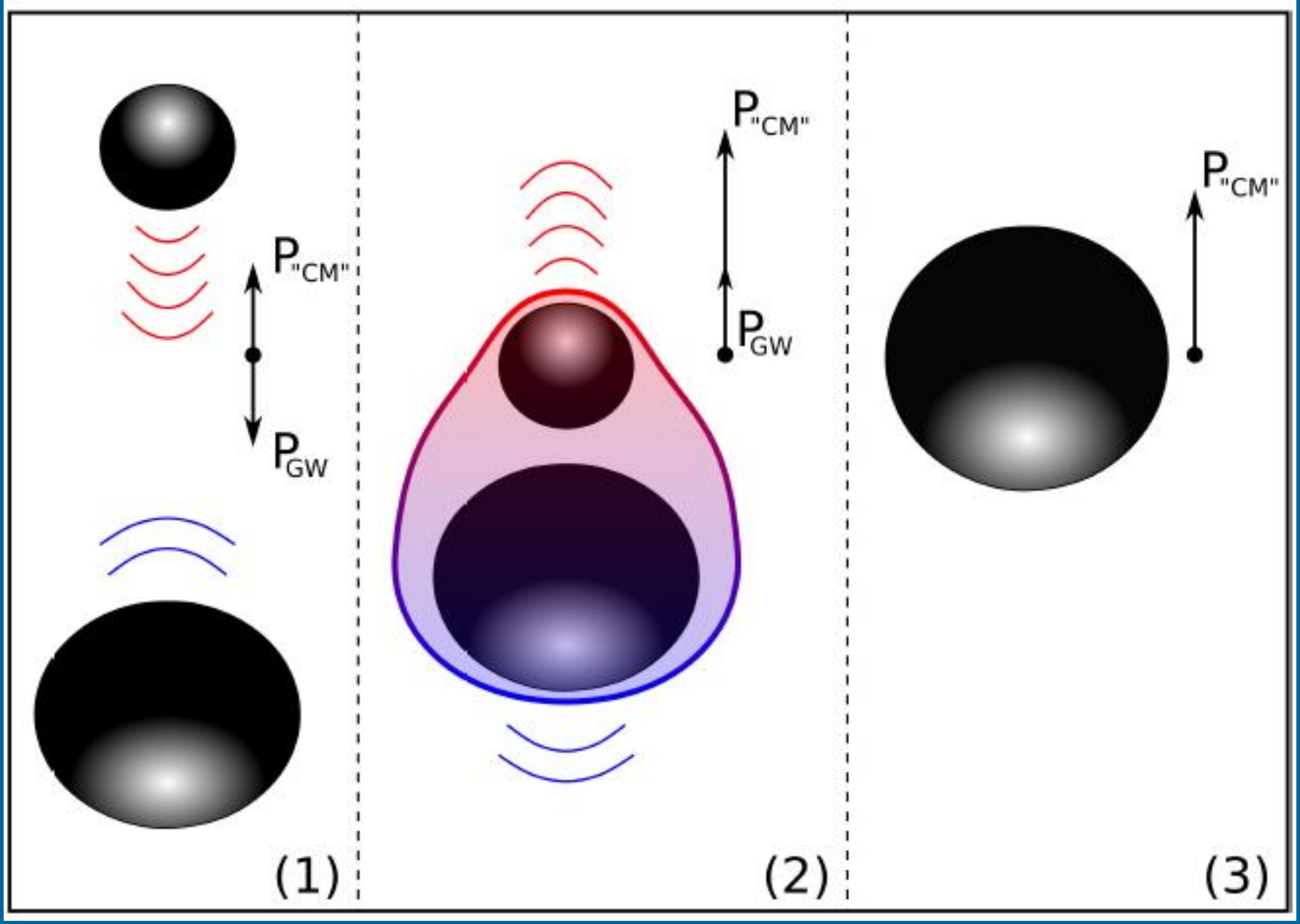
Antikick

In all cases we found that the direction of the ringdown kick is approximately opposite to that of the accumulated inspiral plus plunge kick.
I.e., ringdown radiation produces a signicant “anti-kick".



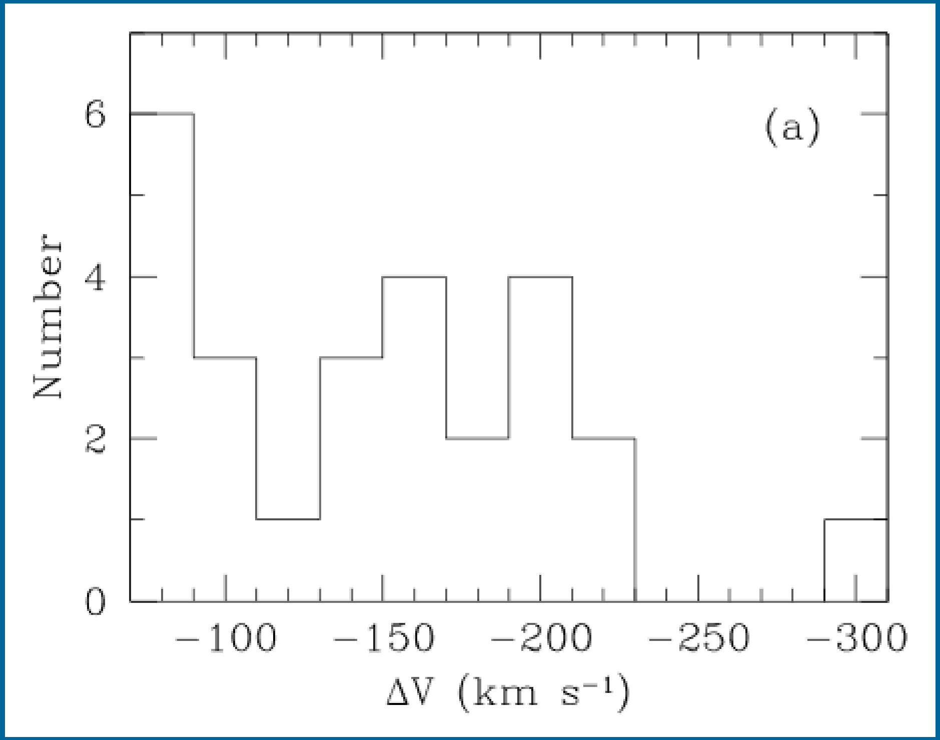
0910.4594

Antikick



1003.0873

Recoiling BH



Among 1271 SDSS QSOs at z<0.25 the authors selected 26 recoiling SMBH candidates.

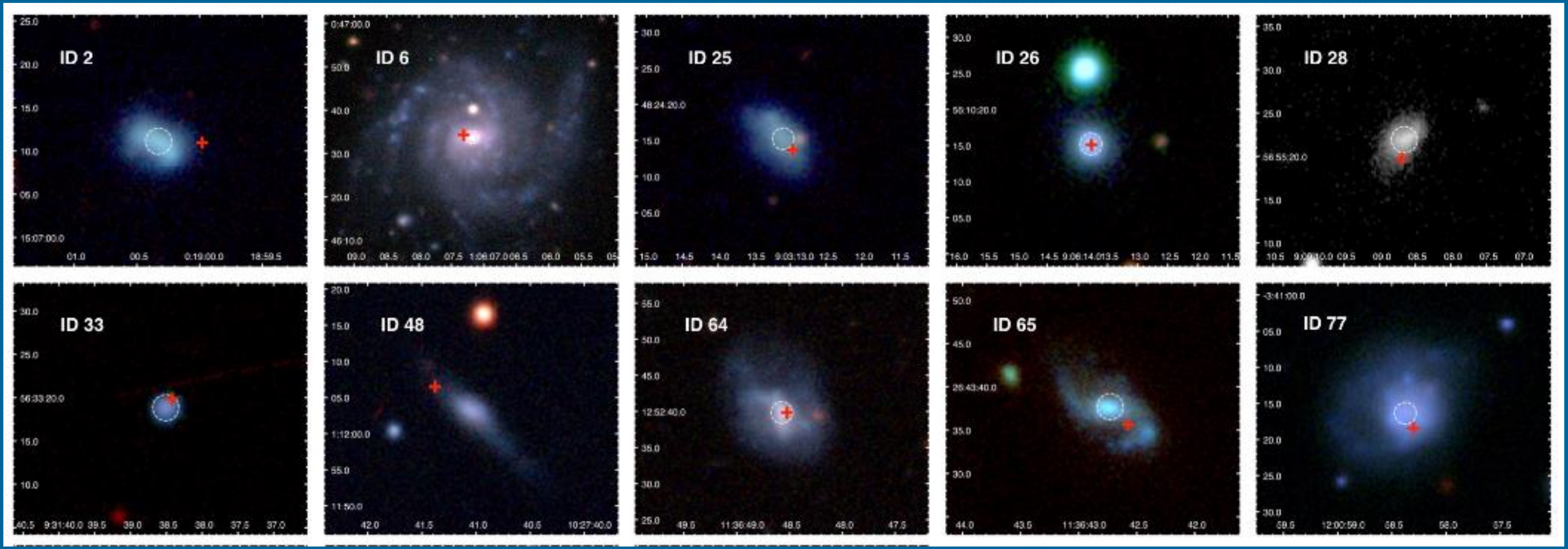
Average velocity ~265 km/s.

See also 1409.3976

1604.05604

Wandering BHs in Dwarf Galaxies

The authors observed off-center compact radio sources in dwarf galaxies.

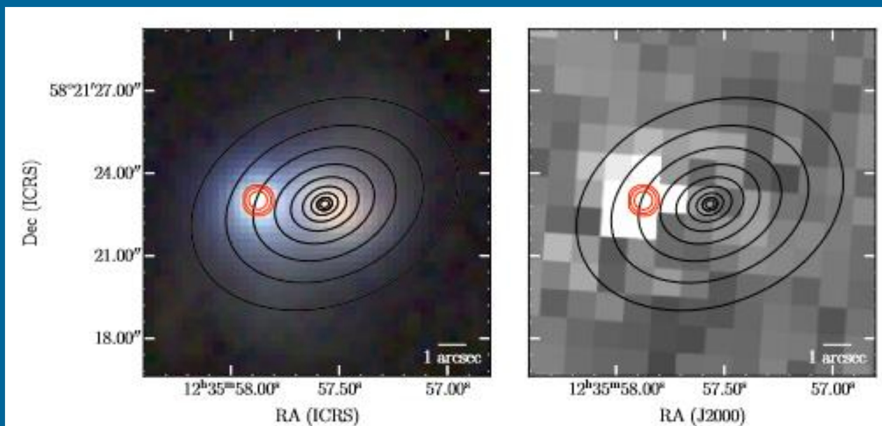


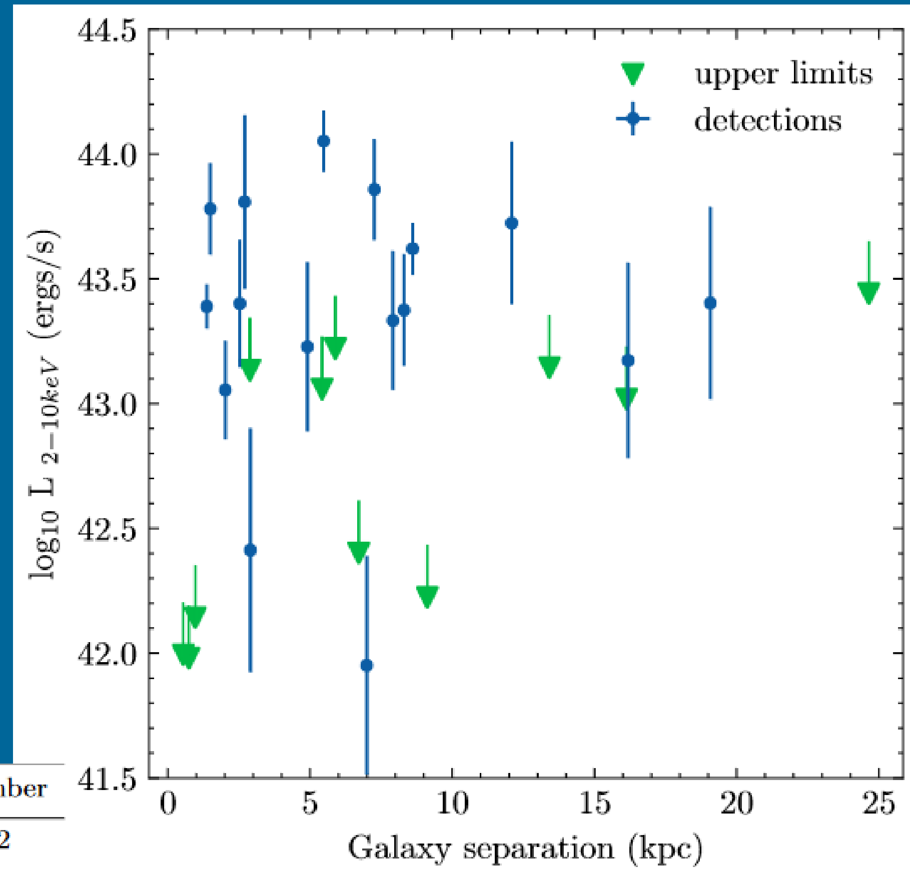
Off-center BHs in dwarf galaxies can be also due to mergers, see 2102.09566

1909.04670

Offcenter optical sources

ZTF
~10 recoiling SMBHs and
~50 merging galaxies



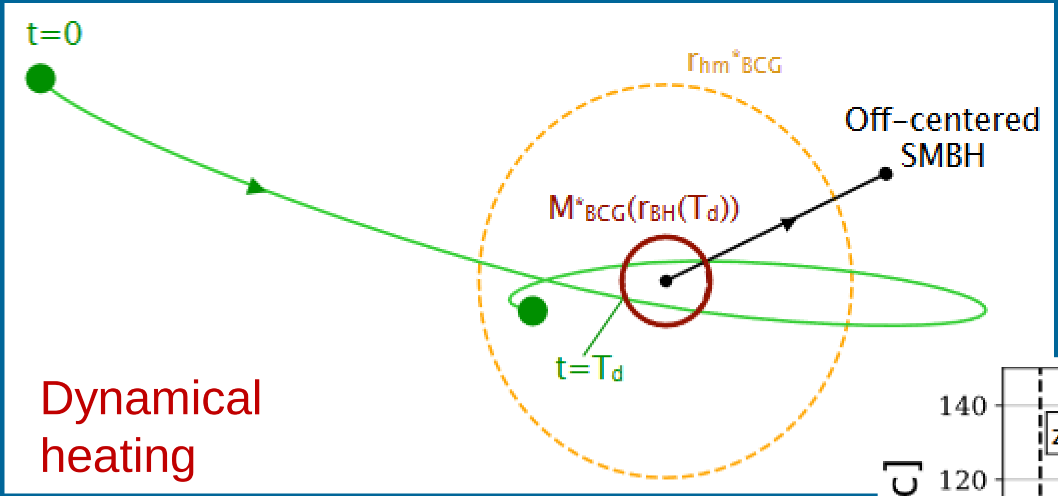


Classification	Number
AGN in galaxy mergers	52
AGN offset from the stellar bulge of disturbed galaxy	9
AGN aligned with the stellar bulge of disturbed galaxy	21
AGN offset from an undisturbed galaxy	29
AGN without position confirmation in Legacy Survey modeling	140
Total	251

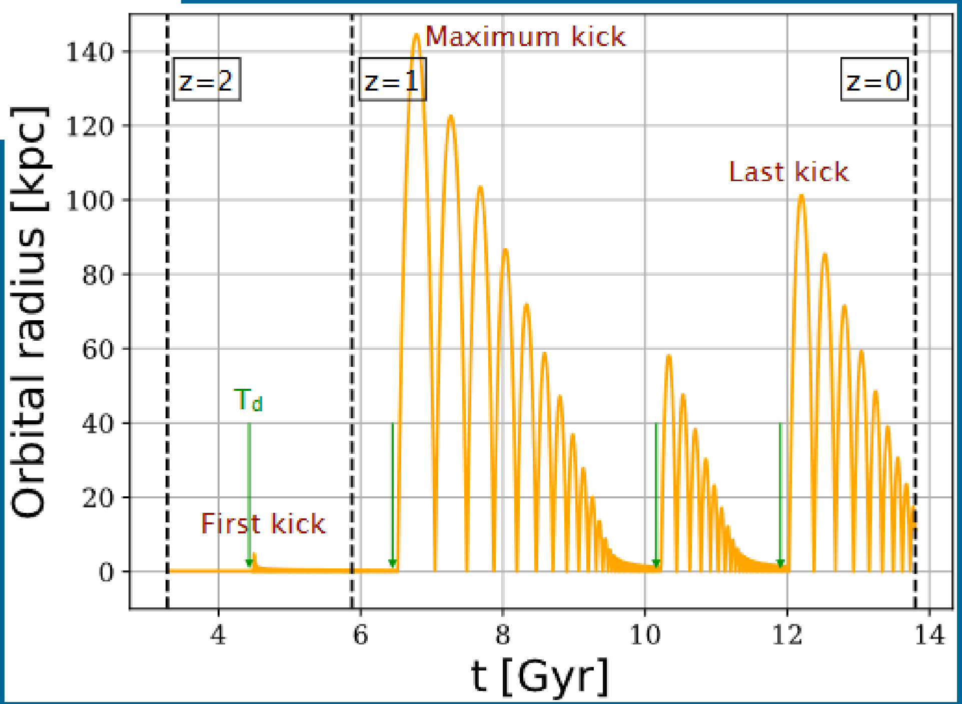
X-ray properties for 27 AGNs with well-measure redshifts.

2011.11656

Galactic mergers and offset SMBHs

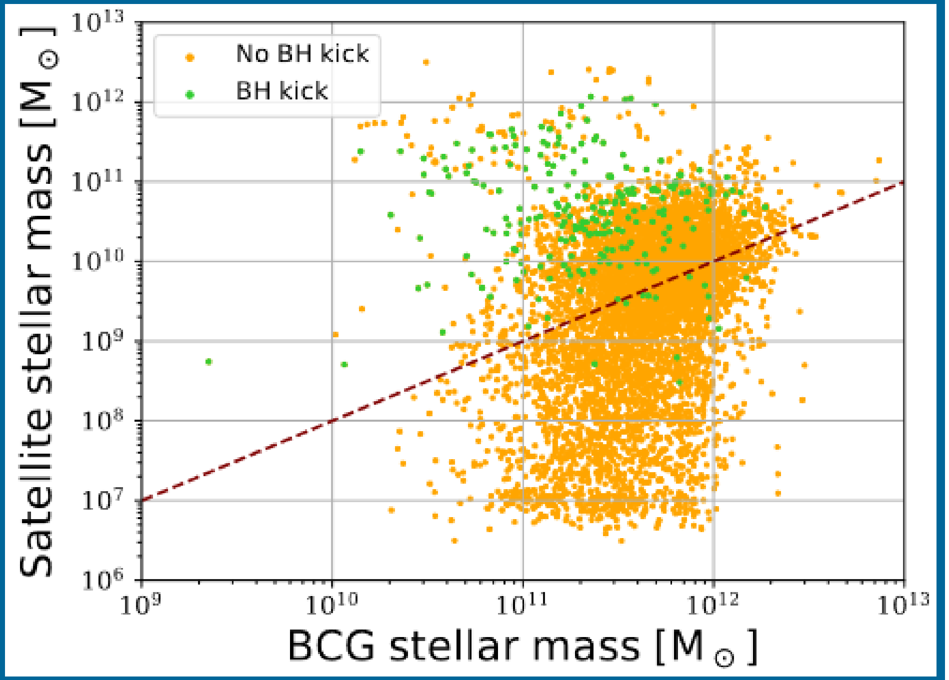


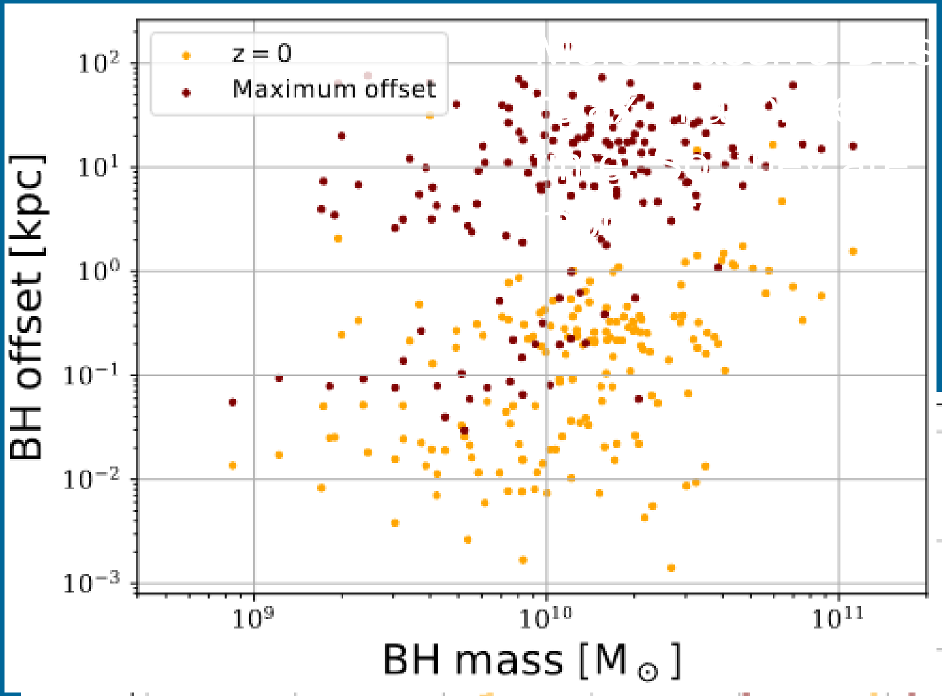
17 mergers,
4 produced a significant kick

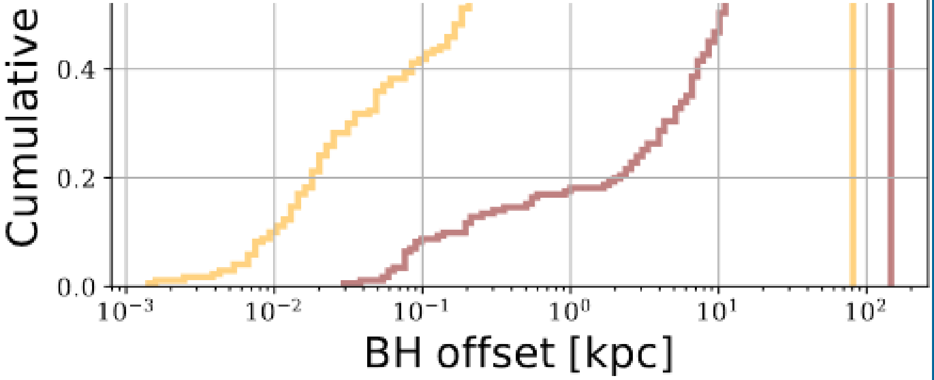


2212.13277

TNG300 modeling of 370 clusters





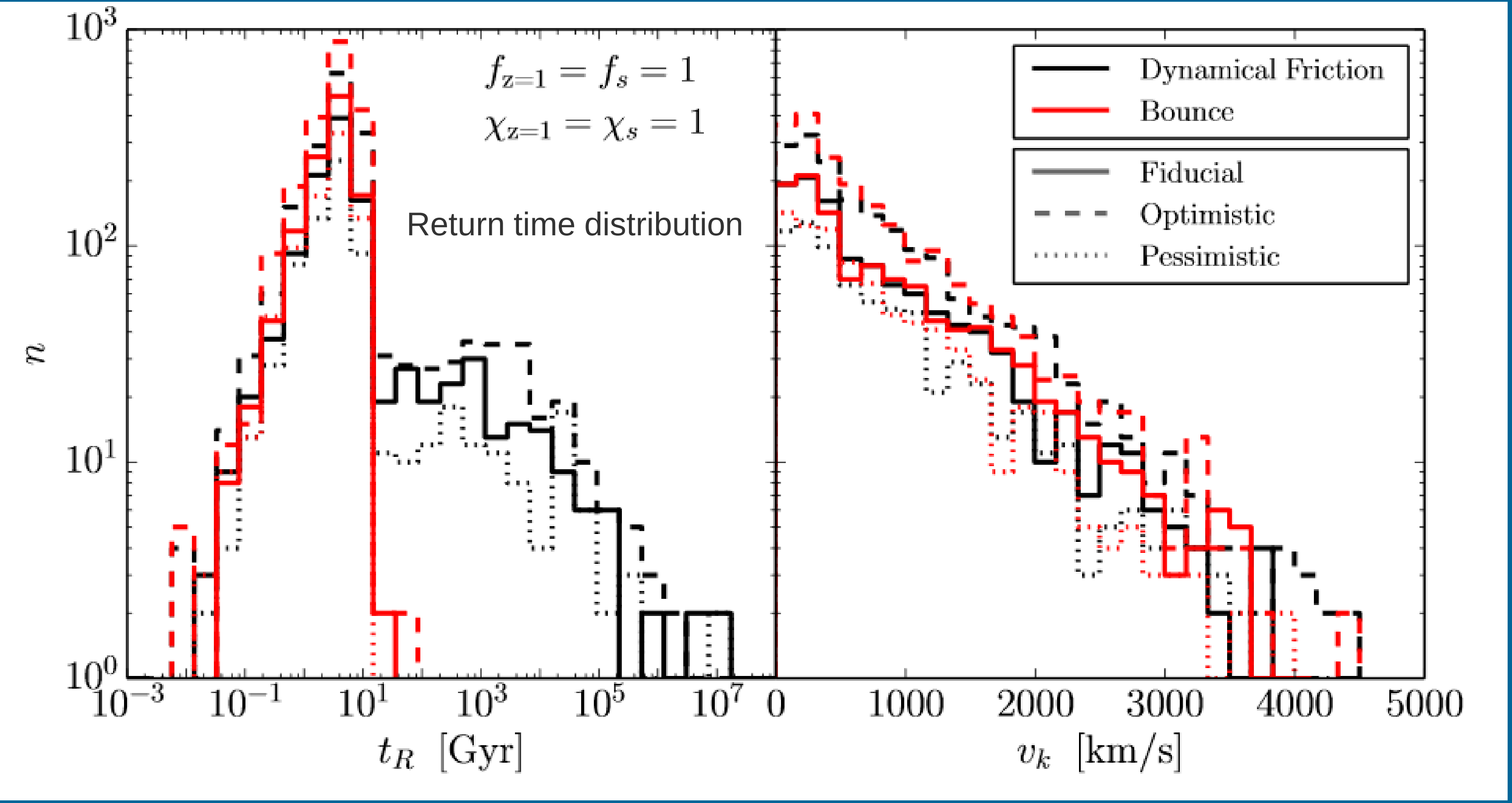


85% (60%) of the BCGs exhibit a SMBH with an offset of 10 pc (100 pc) for more than 6 Gyr since z = 2.
I.e., SMBHs in BCGs spent more than half of their lifetime off-centered.
However, BHs spend <3 Gyr above 1 kpc.

2212.13277

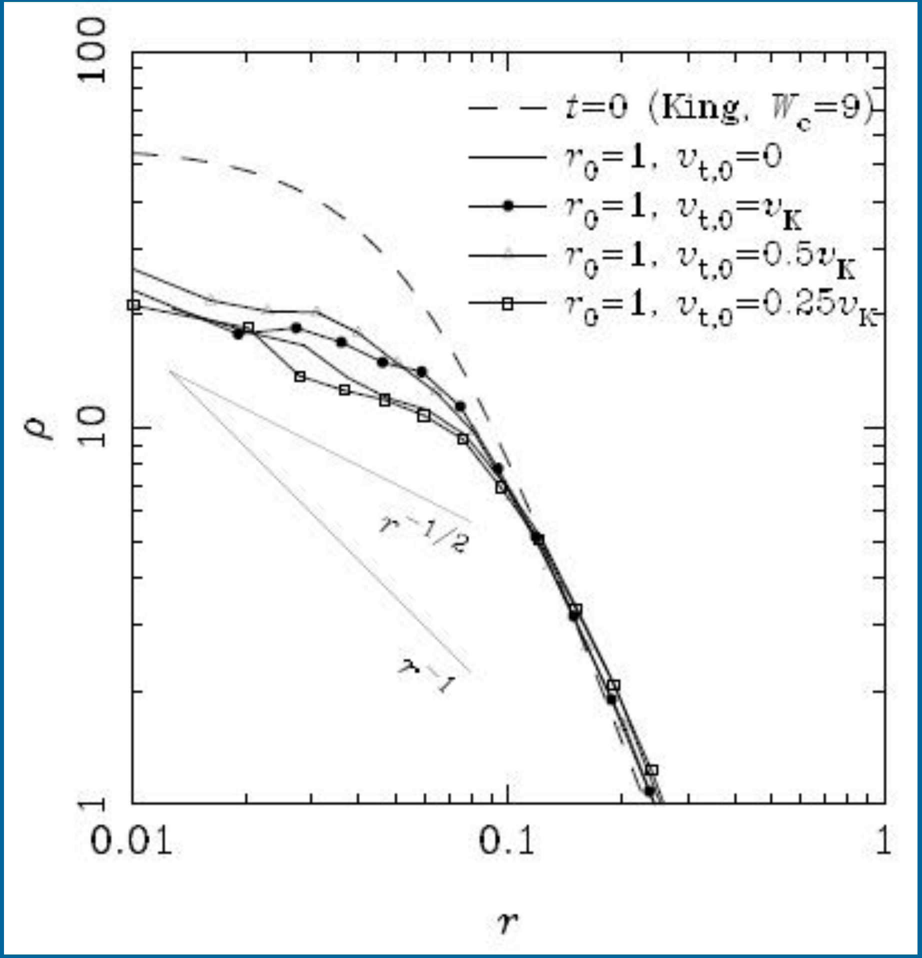
Superkicks?

Large kicks (>2000 km/s) can eject SMBHs even from BCG.
As these galaxies have rich merging history, their SMBHs can be at least significantly shifted, due to long returning time.



1405.2072

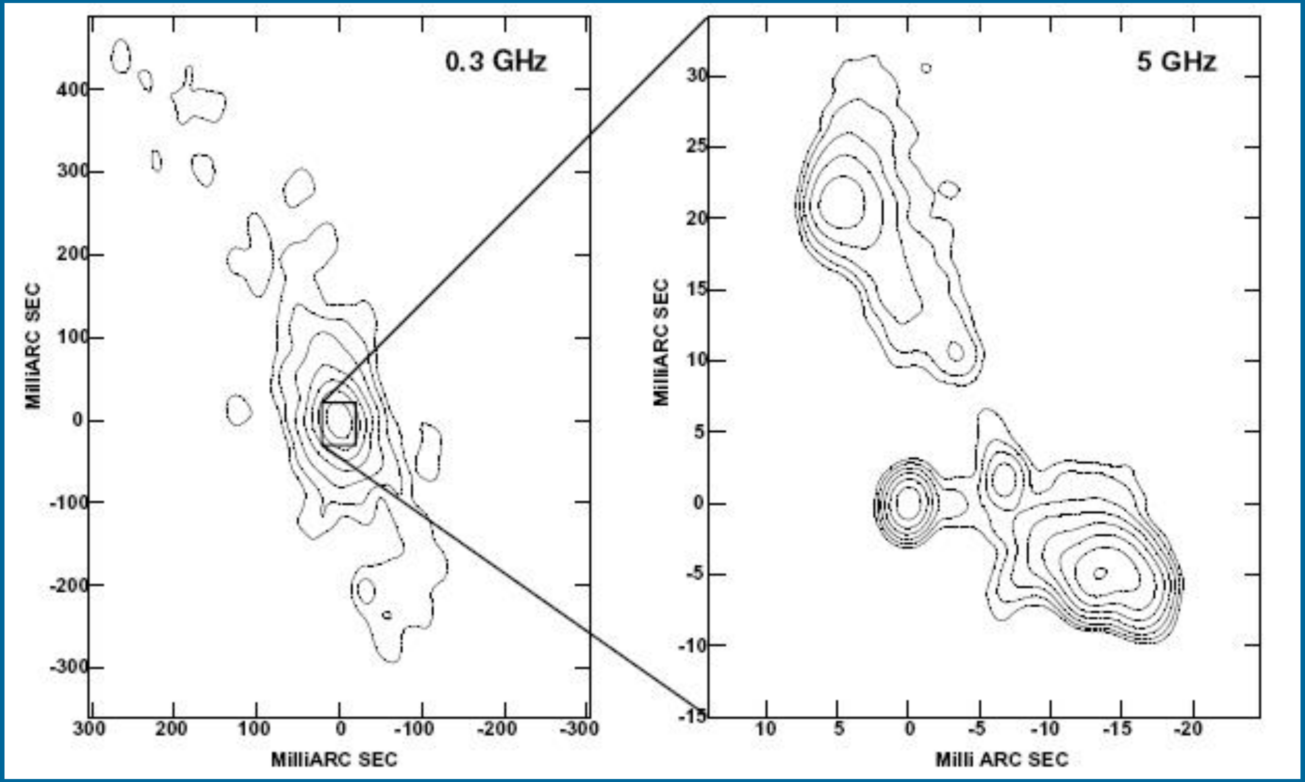
Stellar density profile evolution in the case of two BHs



Flat profiles can be explained by an existence of the second BH.

Combes astro-ph/0505463

Binary supermassive BHs



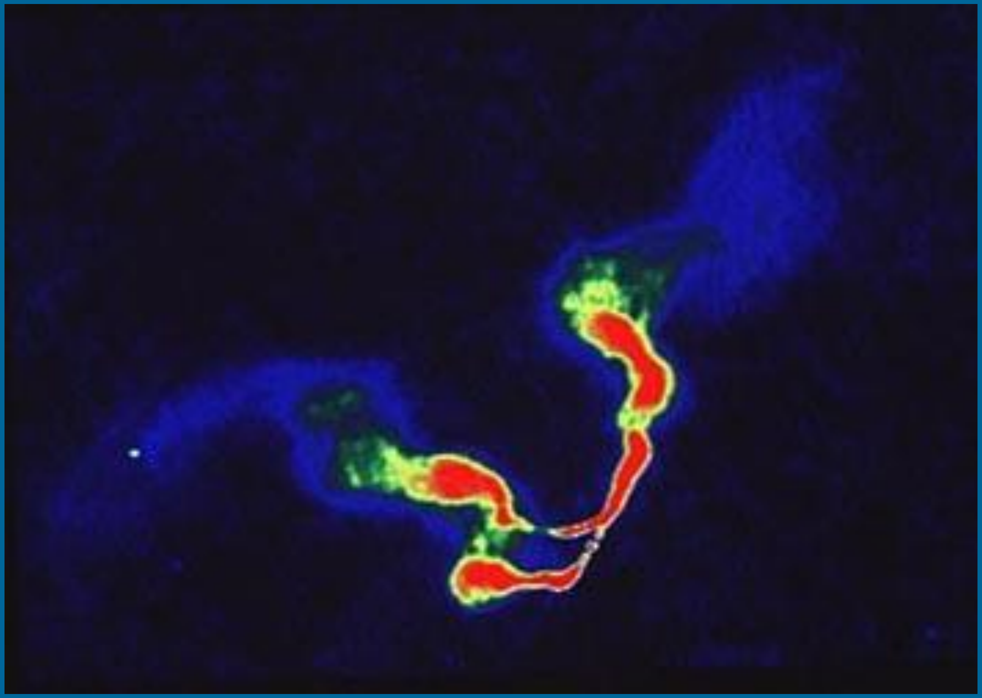
Galaxy 0402+379

Total mass: 1.5 10^8 M_0

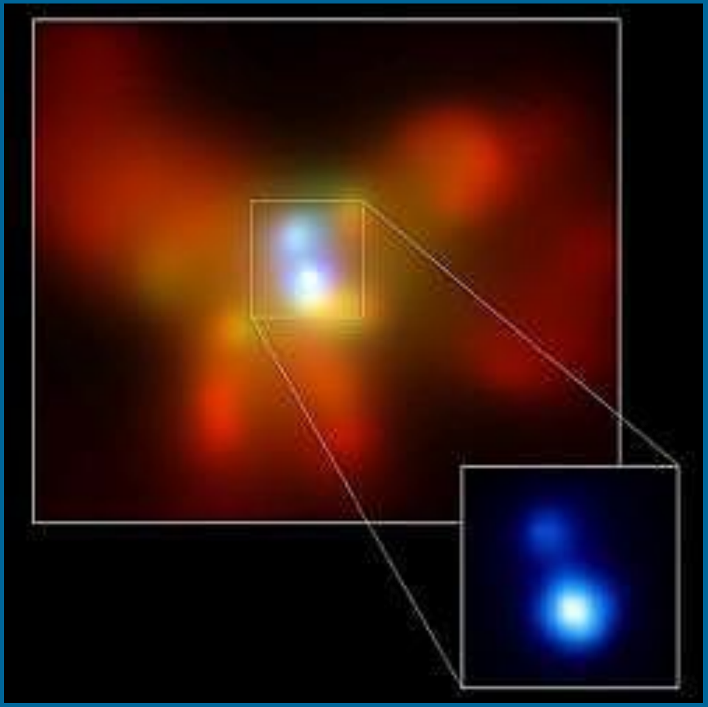
Distance between two BHs is 7.3 pc.

Rodriguez et al. astro-ph/0604042

Examples of binary SMBHs



3C75



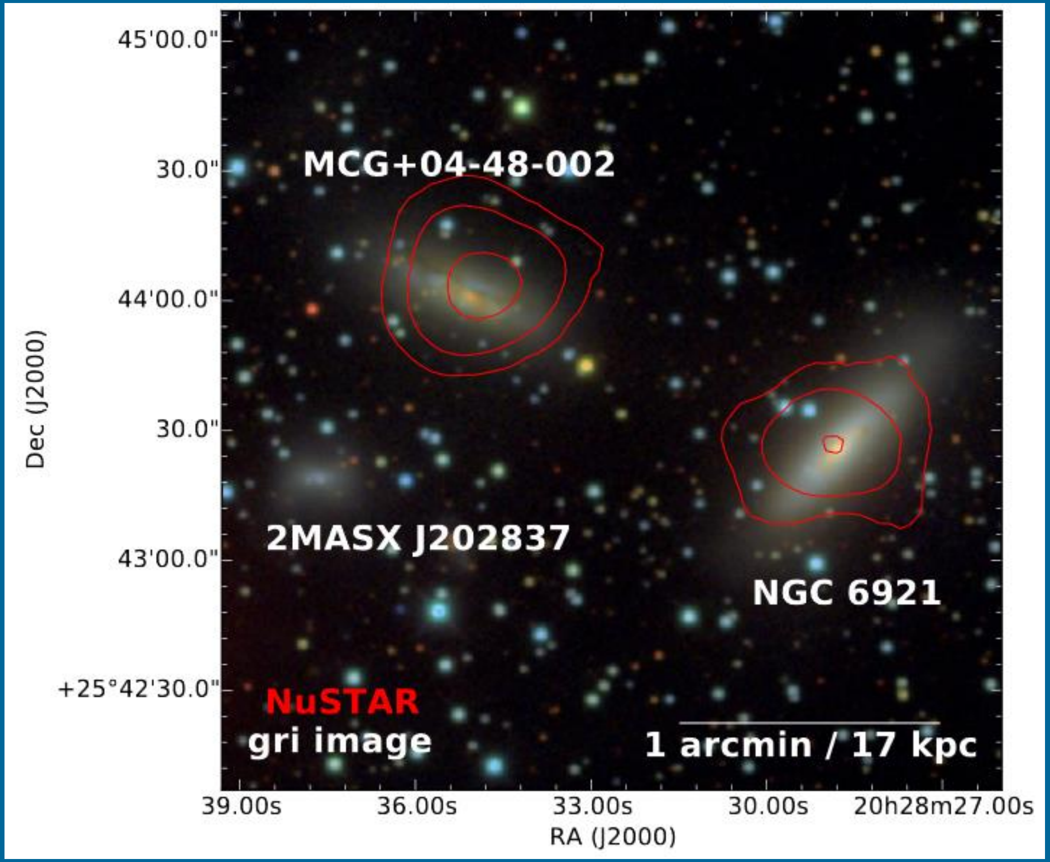
Abell 400

astro-ph/0410364

See a review about binary SMBHs in arXiv: 2310.16896

Dual AGN observed by NuStar

SWIFT J2028.5+2543
NGC 6921 and MCG+04-48-00
First observations at E>10 keV

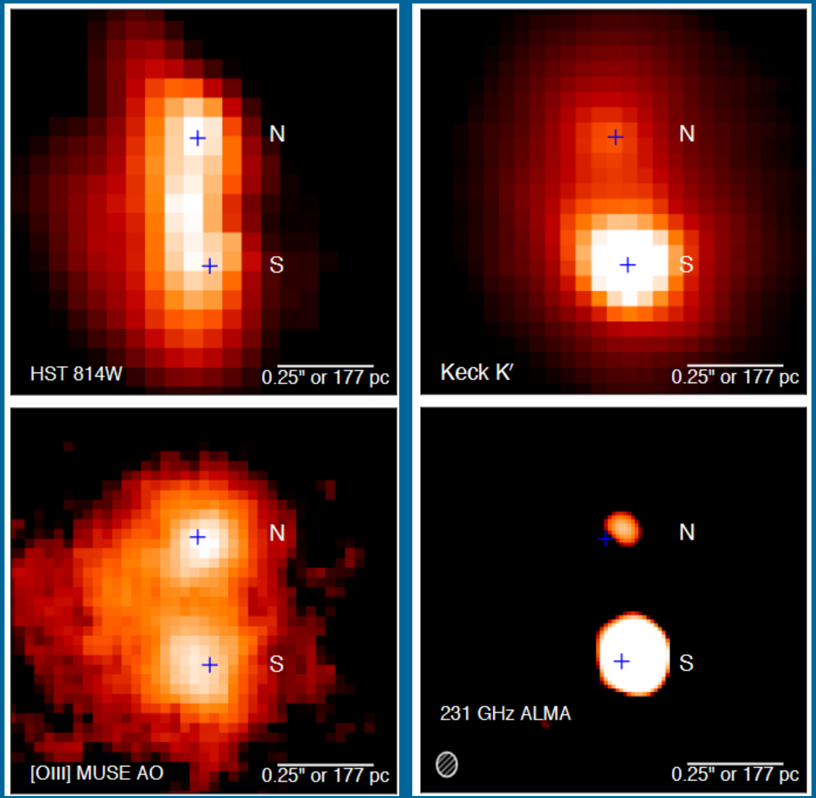


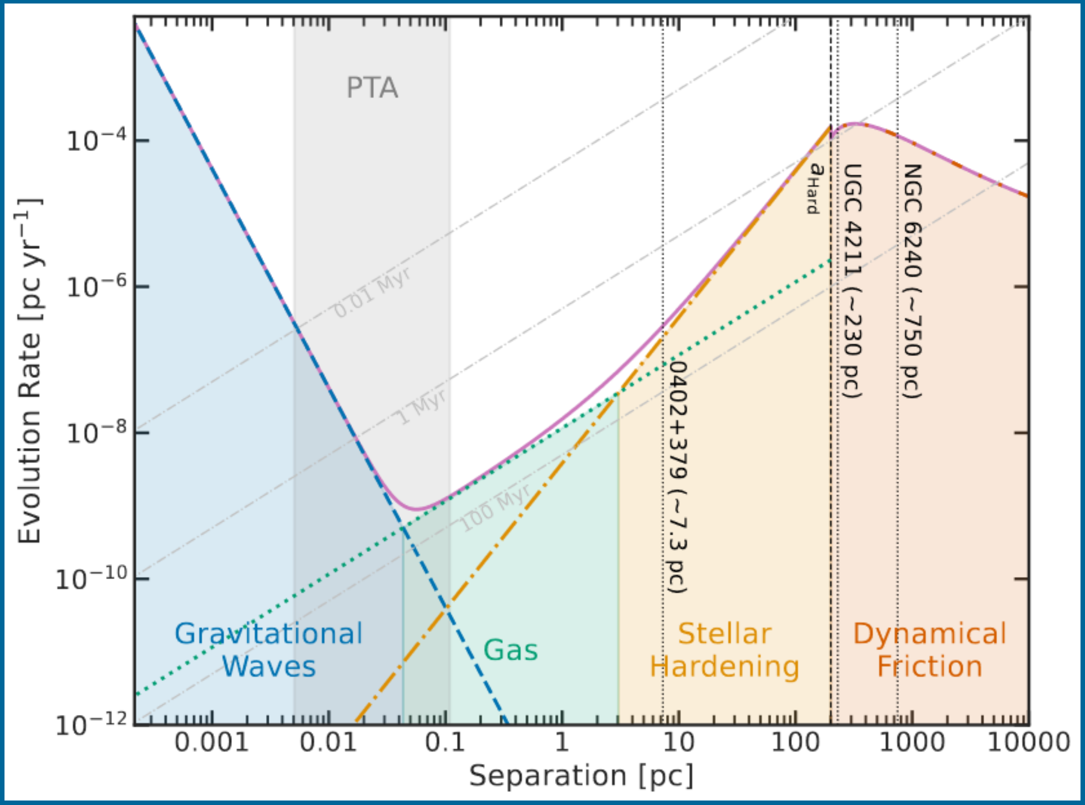
Galaxy merger triggers AGN activity.
Separation ~25 kpc
4×10^{8} and 7×10^{7} M_{solar}

1708.06762

Just 230 pc between two SMBHs

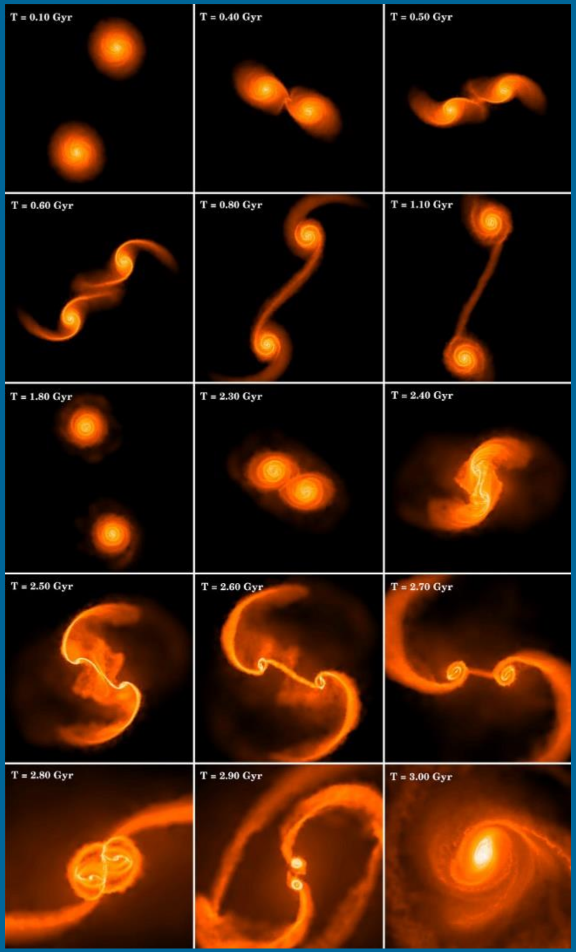
AGN: UGC 4211
z=0.35 merger
BH masses >~10^8 M_{sun}
Multiwavelength observations

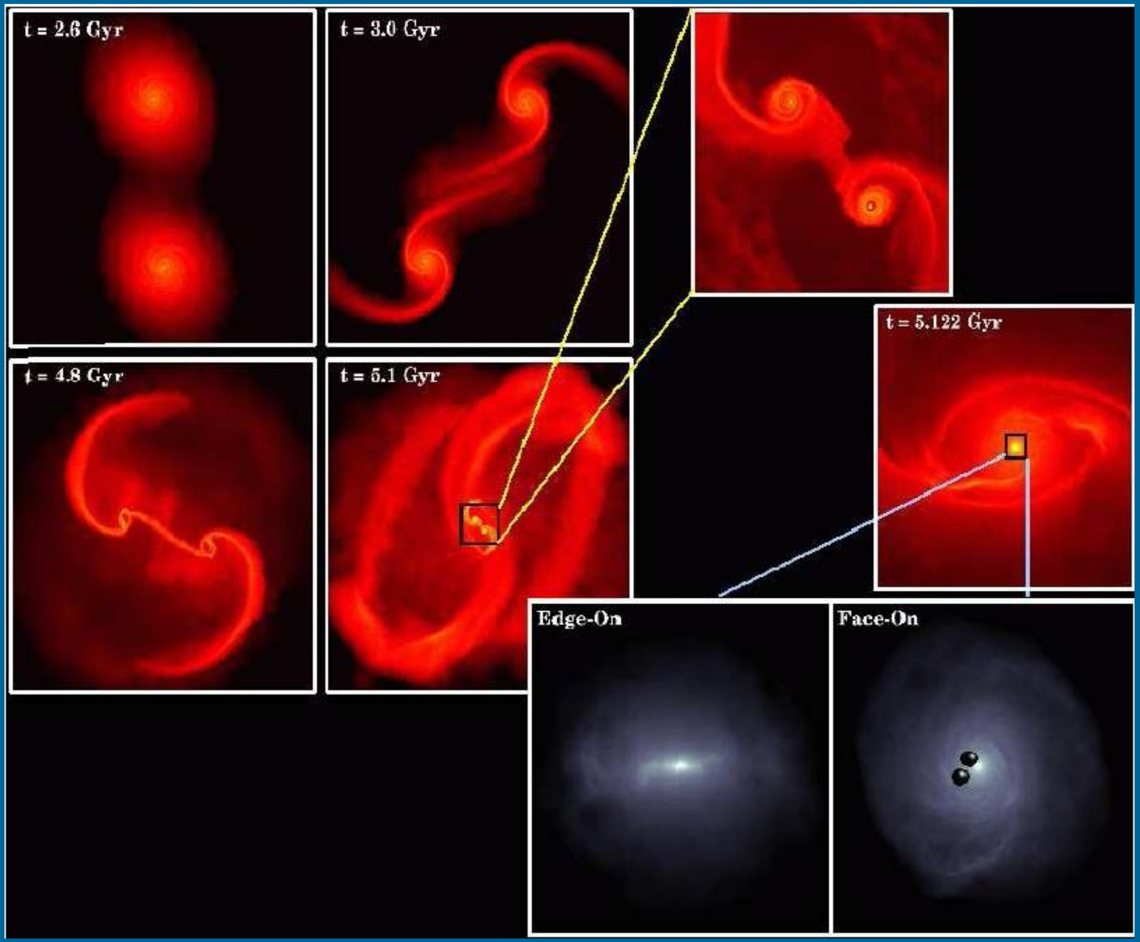




2301.03609

Merging of galaxies with BHs



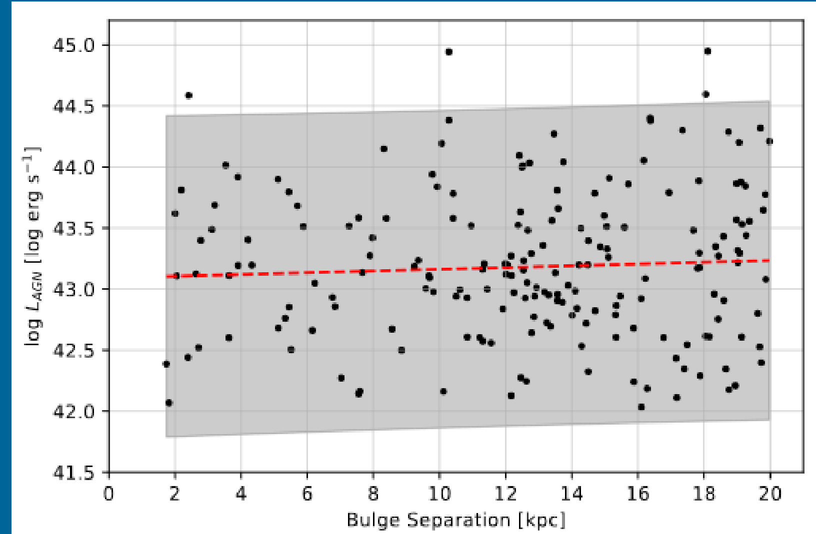


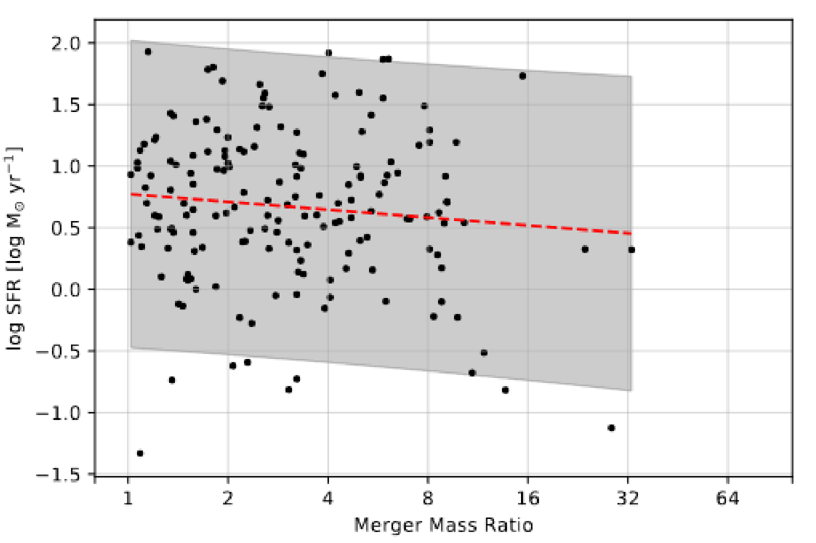
arXiv:0706.1562

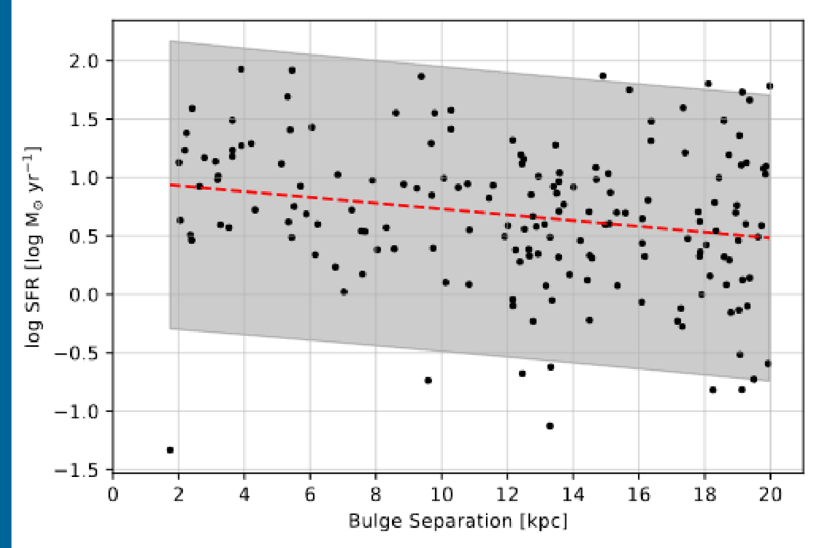
See more about the role of recoil after merging in 1001.1743, 1103.0272, 1103.3701

Catalog of 220 Offset and Dual AGNs

0.2< z <2.5
<20 kpc between bulges
HST observations
The authors looked for pairs among 2585 AGN host galaxies in HST data.

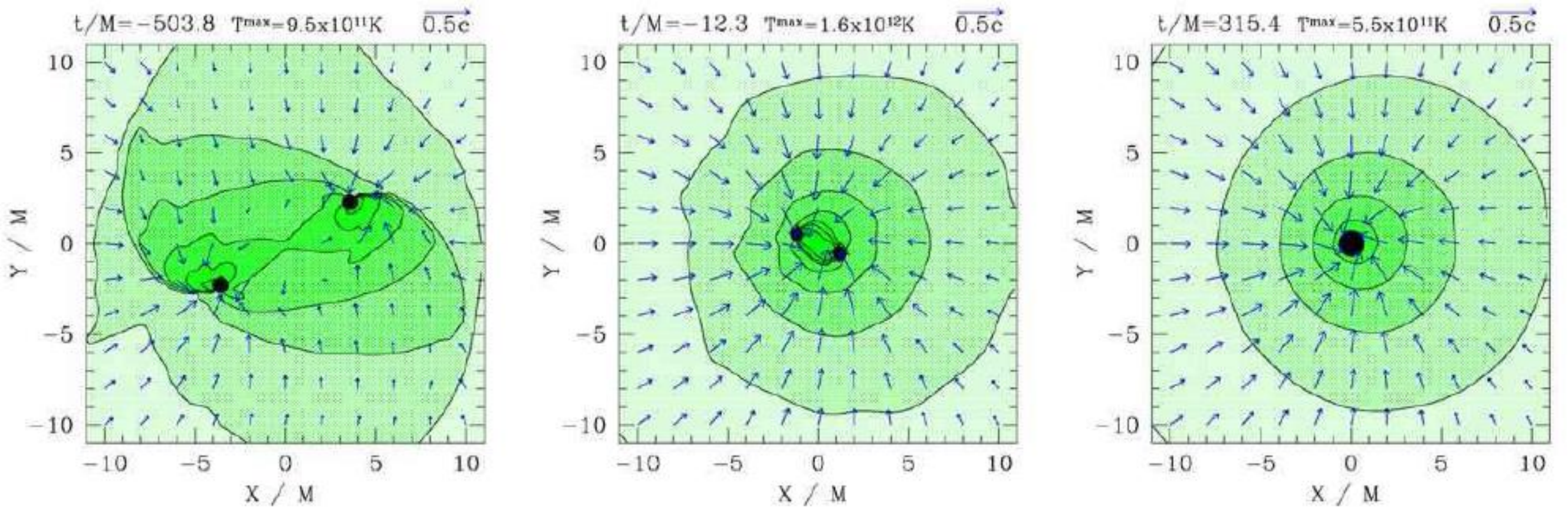






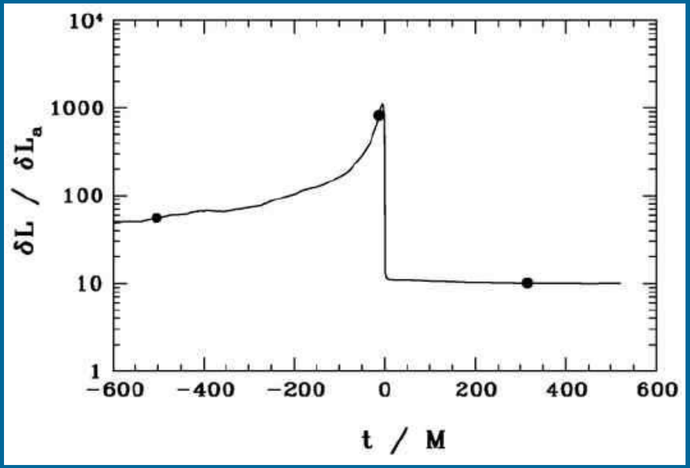
2011.10051

EM signal during coalescence



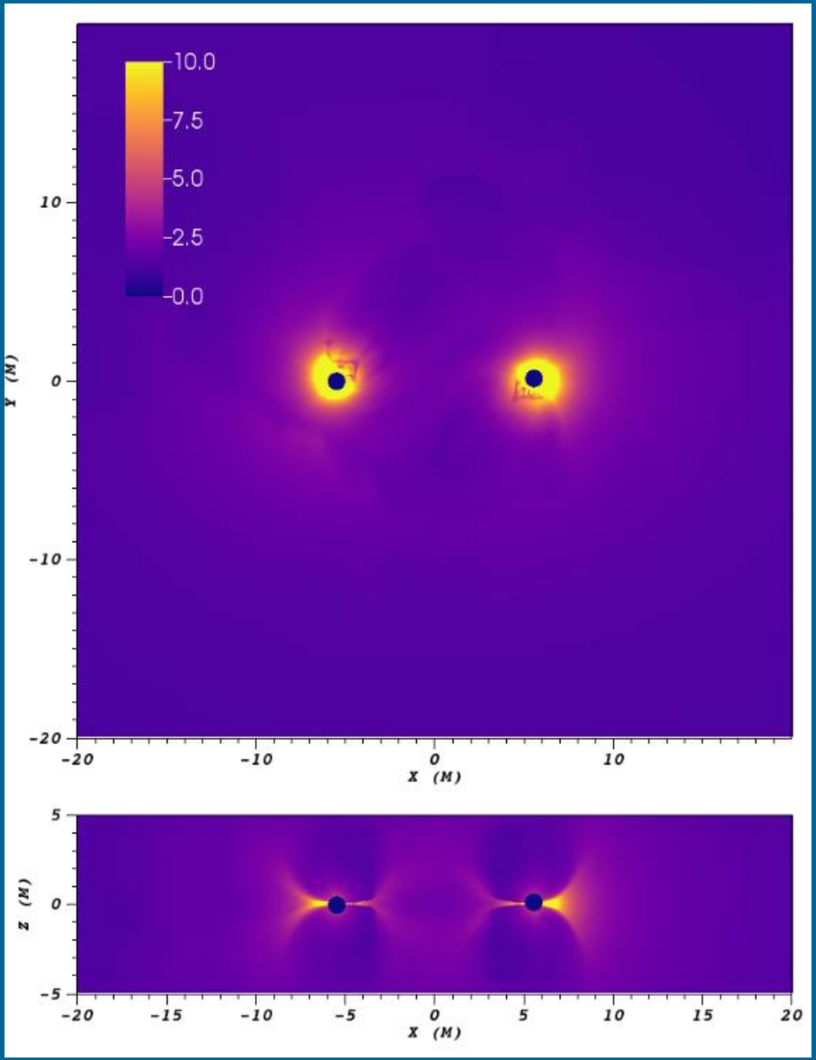
For M=10^6 solar mass binary in n=10 cm^{-3} gas
ΔL~ 3 10^{43} erg/s
Detectable by LSST from z~1

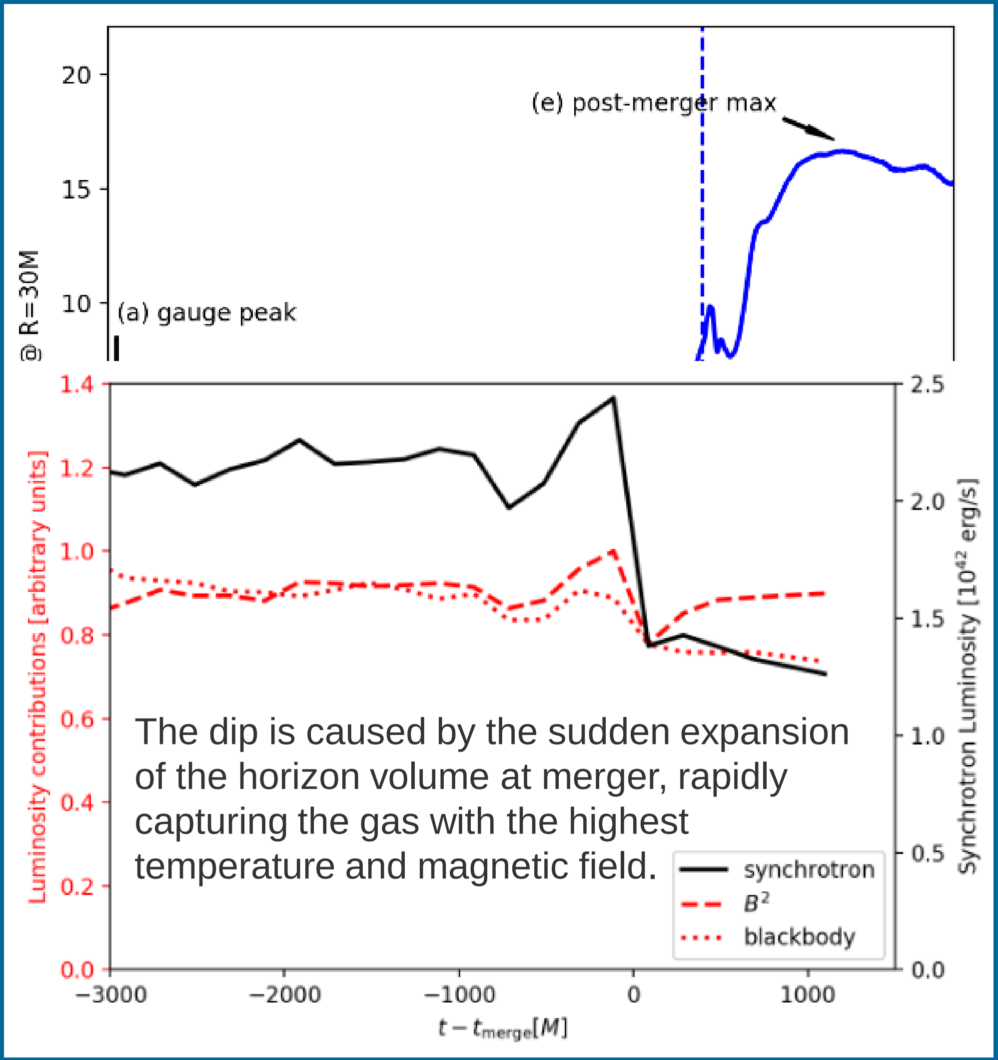
Stirring, shock heating and accretion of the gas may produce variability and enhancements in the electromagnetic flux.



0912.2096

Electromagnetic signals





1710.02132, see new calculations in 1806.05697

Coalescence of BHs in binary systems

Unfortunately, at the moment we do not know
any systems with two compact objects, one of which is a BH.

It is very difficult to identify a system with two BHs.
However, models of the stellar evolution show, that such systems
are quite natural result of binary evolution.

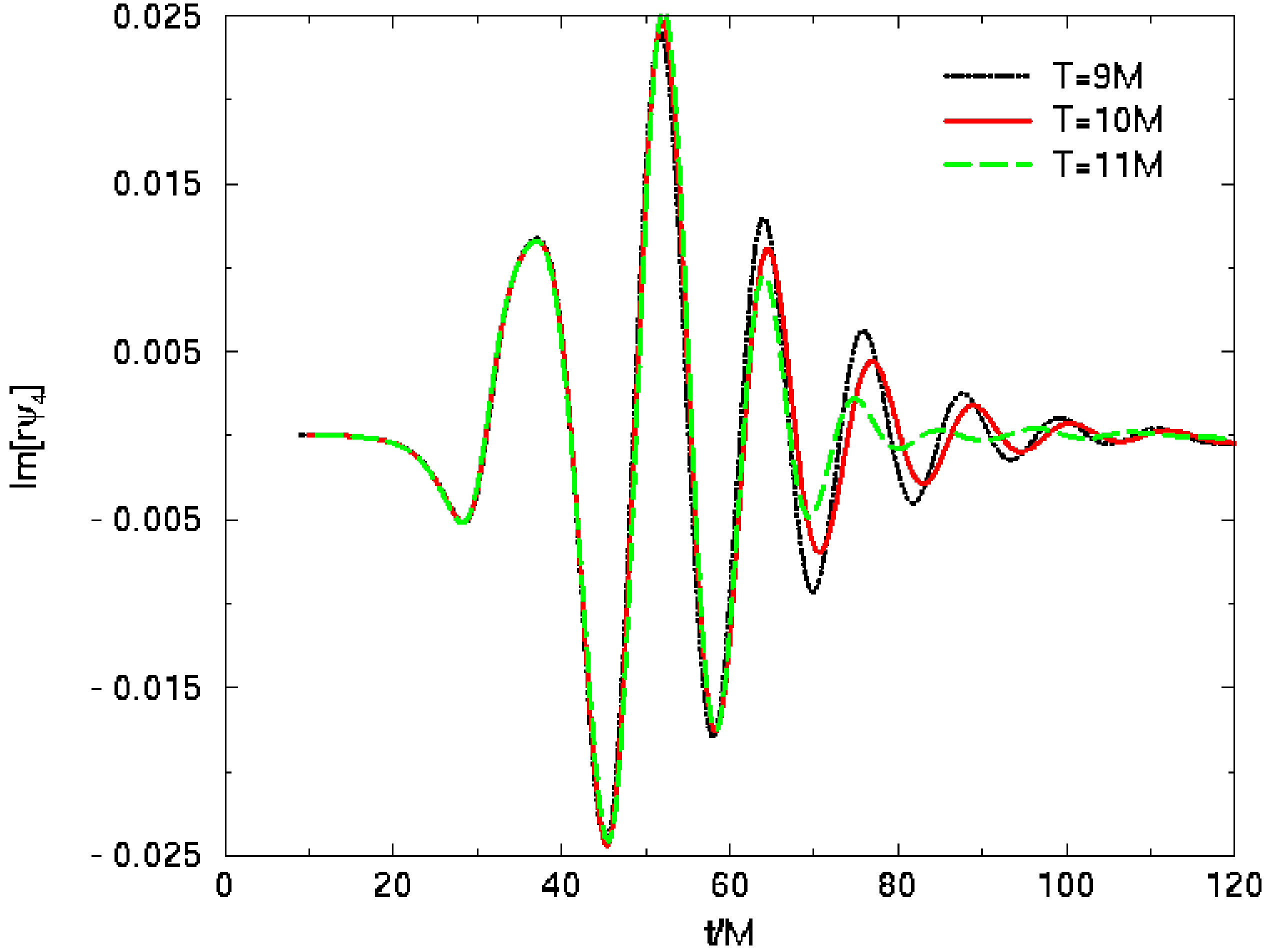
Also, systems BH+NS can exist.

Calculations show that systems BH+PSR should be relatively abundant
(one system per several thousand PSRs).

On one hand, systems with BHs are more rare than NS+NS systems,
on the other hand, due to larger masses GW signal is much more powerful.
So, coalescence of BHs can be observed from much larger distances.

See 1010.5260 for a review of BH-BH coalescence physics

Last orbits of BHs



It is important to calculate in advance so-called waveforms.

Otherwise, it is very difficult to identify the signal.

Waveforms in the case of BH coalescence should be different from NS+NS coalescence.

astro-ph/0305287

See 1010.5260 for a review

Fall-down of matter onto a BH and GW emission

Accretion of a Quadrupolar Dust Shell onto a Schwarzschild Black Hole and Emission of Gravitational Radiation

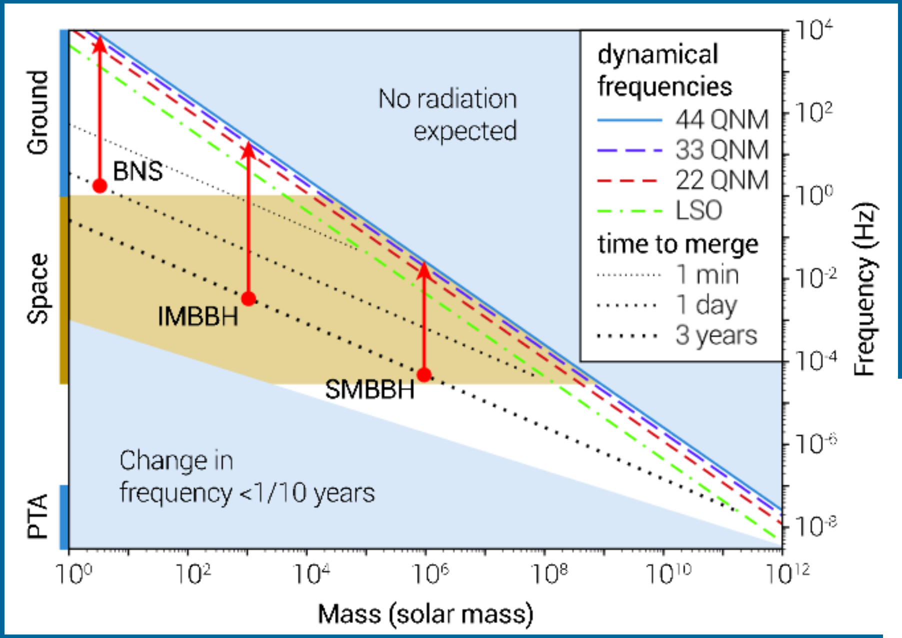
Left: density evolution Right: waveform
Final time: 350M

Authors: Philippos Papadopoulos & Jose A. Font
Reference: Physical Review D, 1999, 59, 044014

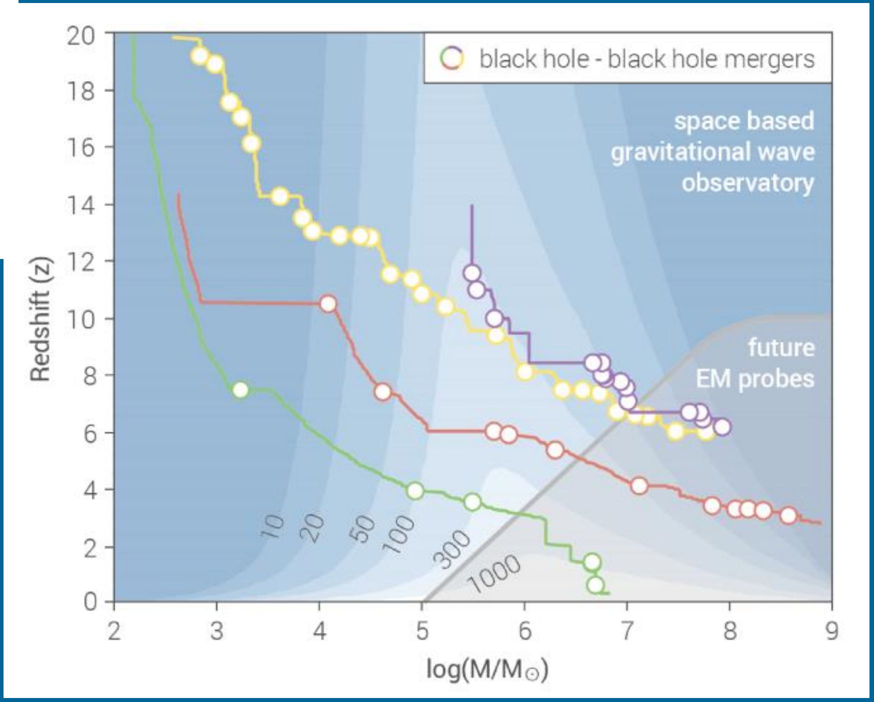
See also gr-qc/0306082 **An Effective Search Method for Gravitational Ringing of Black Holes**

In this paper the authors calculated a family of waveforms for effective search for gravitational ringing of BHs.

Frequency ranges and instruments

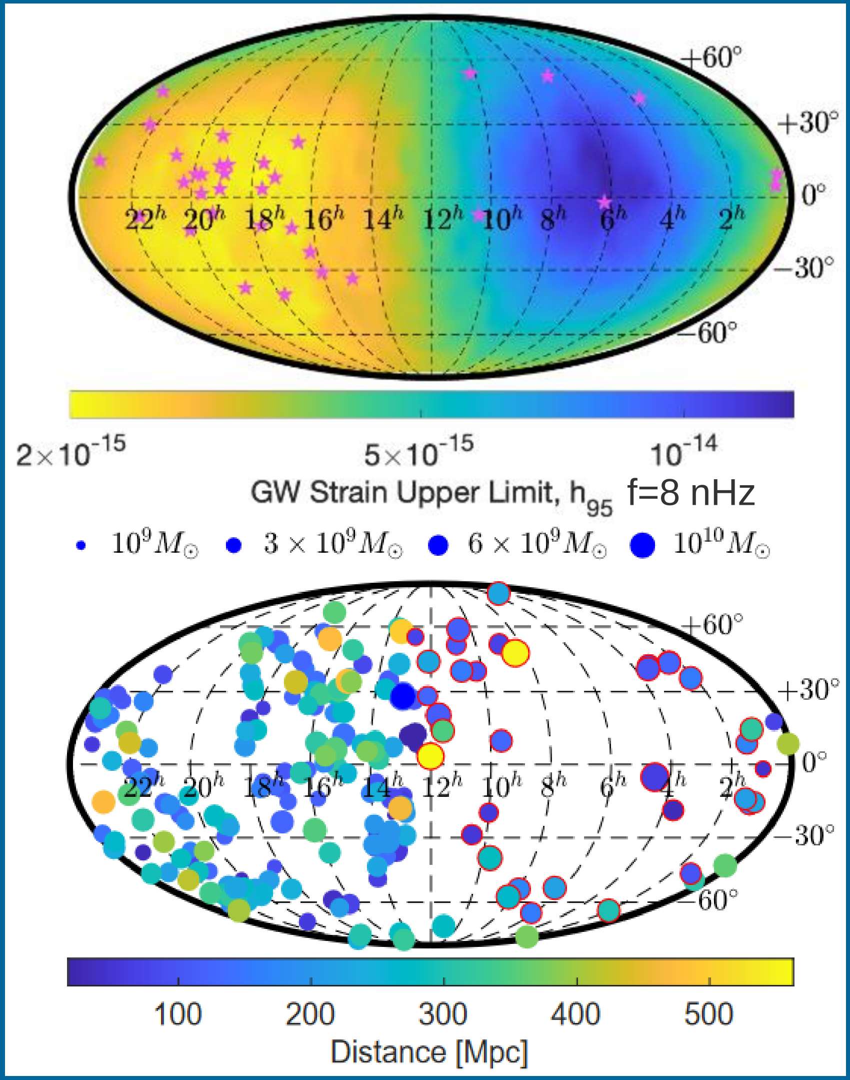


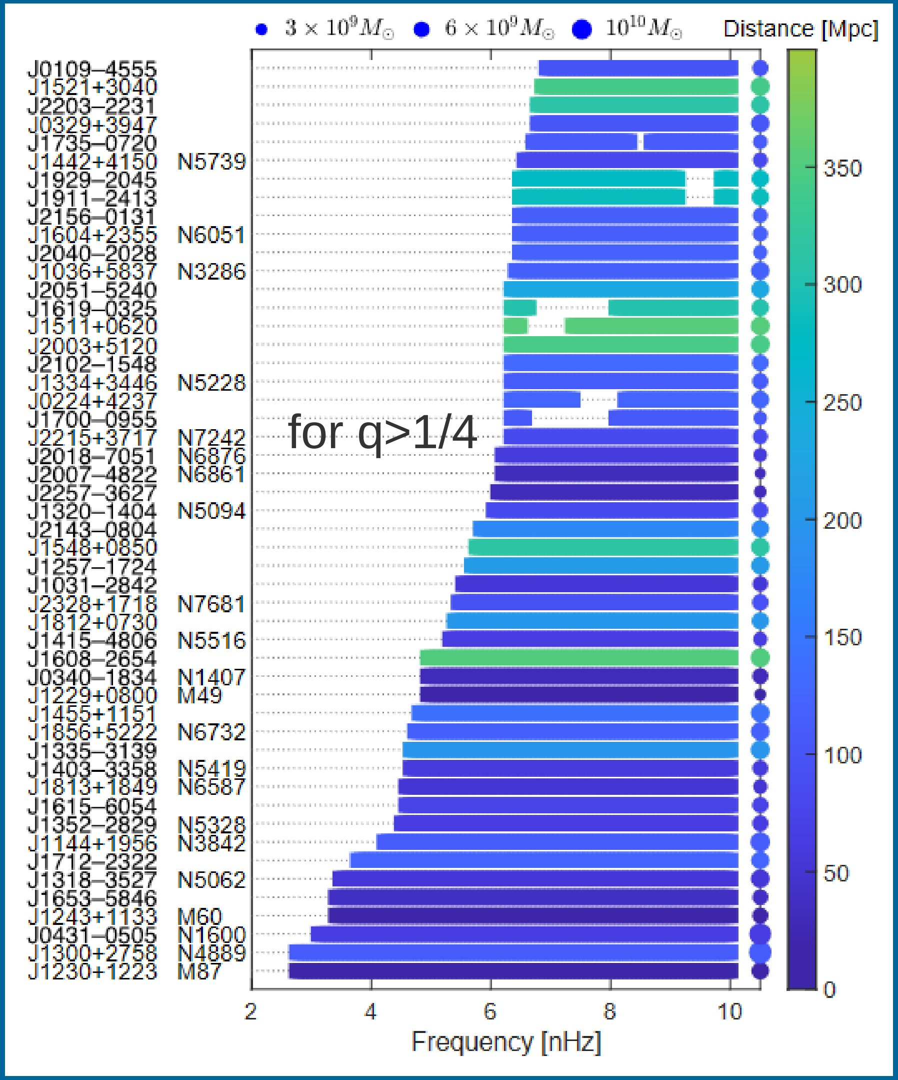
Blue (massive seed) and yellow (PopIII seed): BH powering a z≈6 quasar.
Red: typical elliptical.
Green: Milky way-like



1307.4086

NANOGrav 11-year data

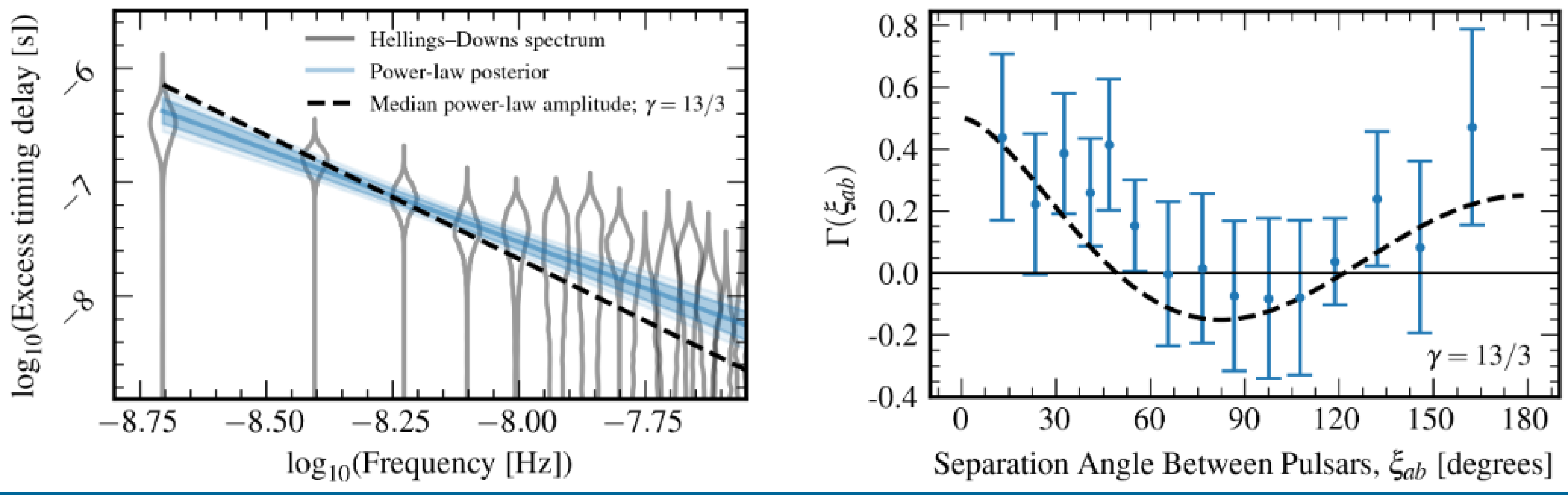




2101.02716, see 2101.10081 about PTAs

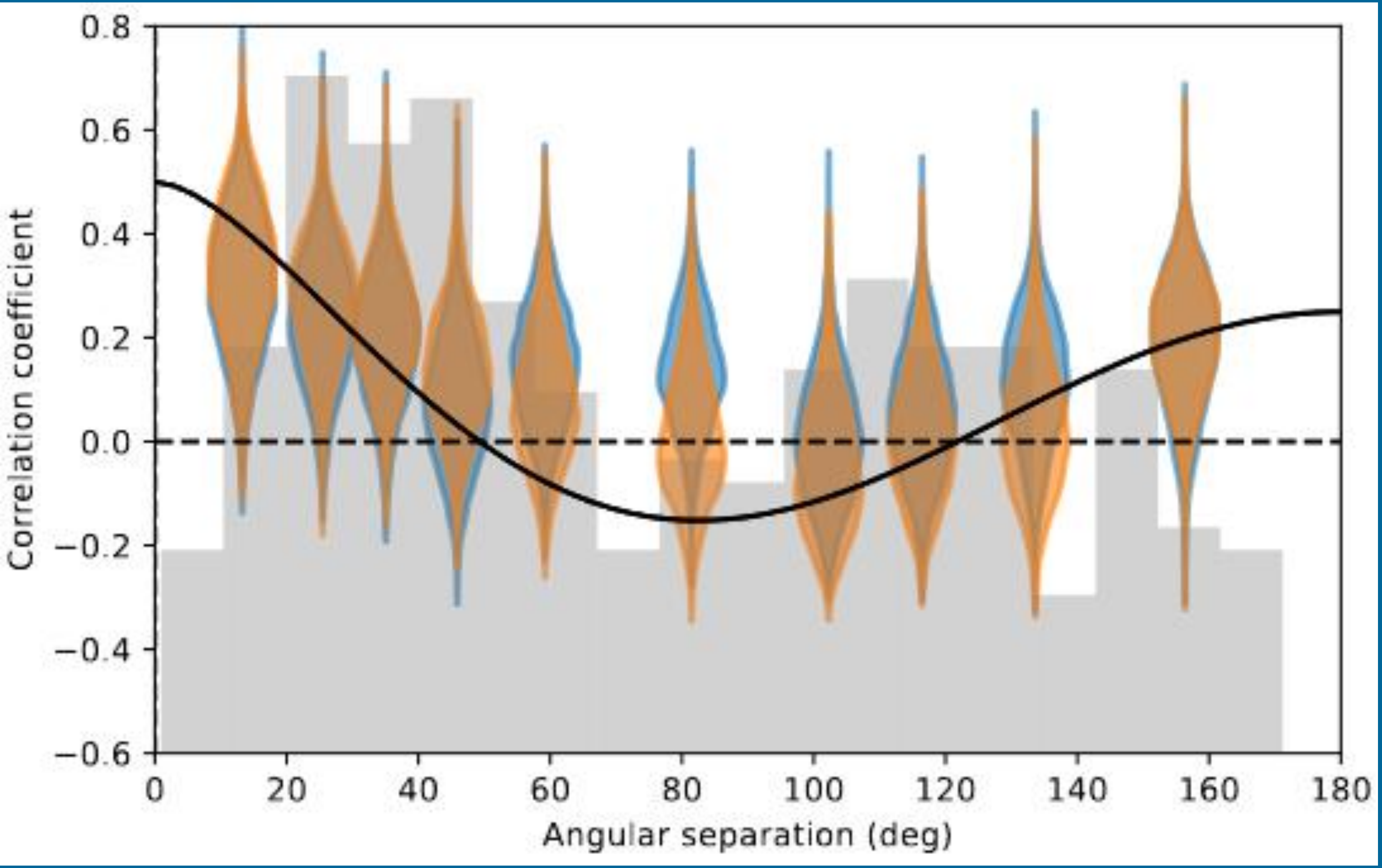
15 years data of NANOGrav

67 pulsars
~4-sigma



2306.16213

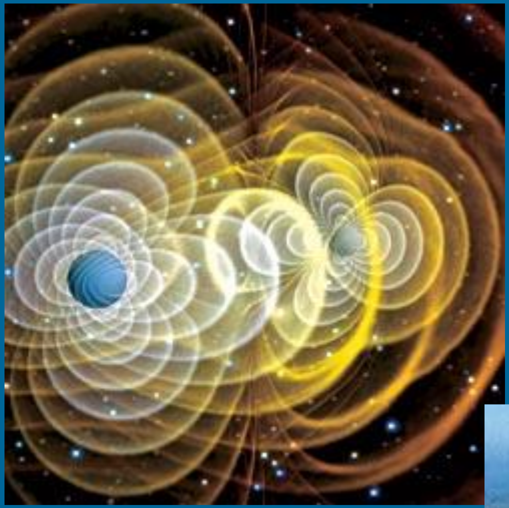
EPTA data: 25 years of observations



2306.16214

Parkes data: 2306.16215
Chinese PTA: 2306.16216

Registration of GW

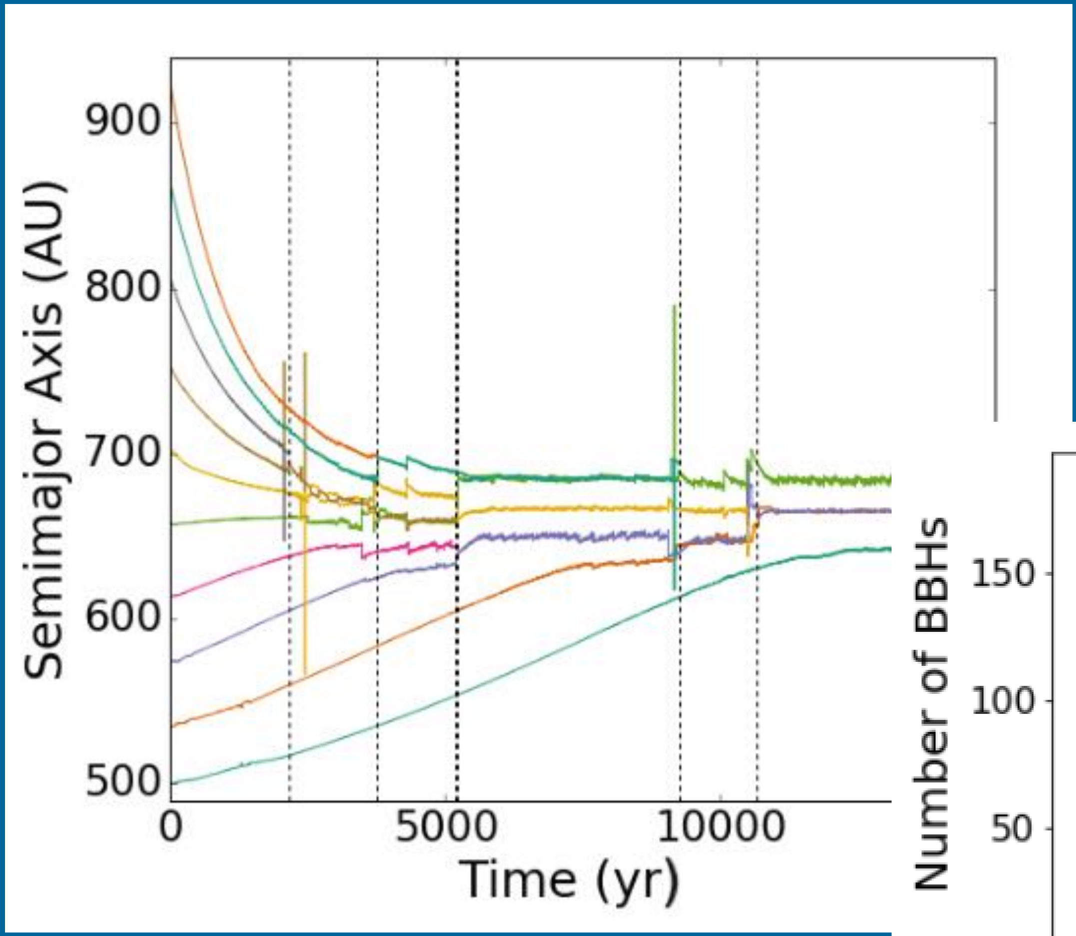


Since 2015 LIGO and VIRGO detect signals from coalescing compact objects.

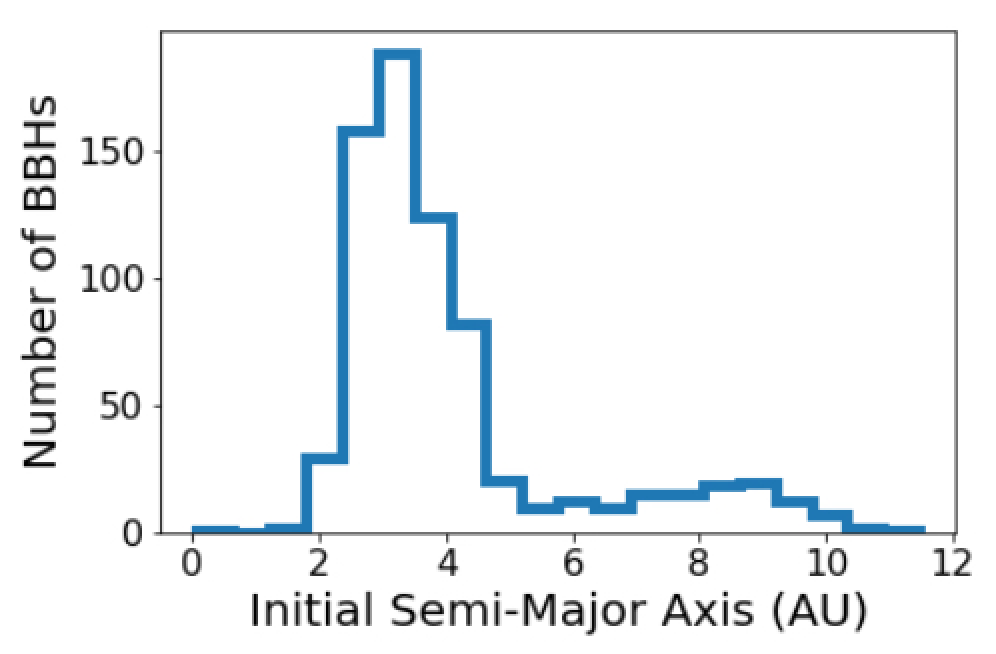
See https://gracedb.ligo.org/
https://stellarcollapse.org/

VIRGO

BH coalescence in discs around SMBHs

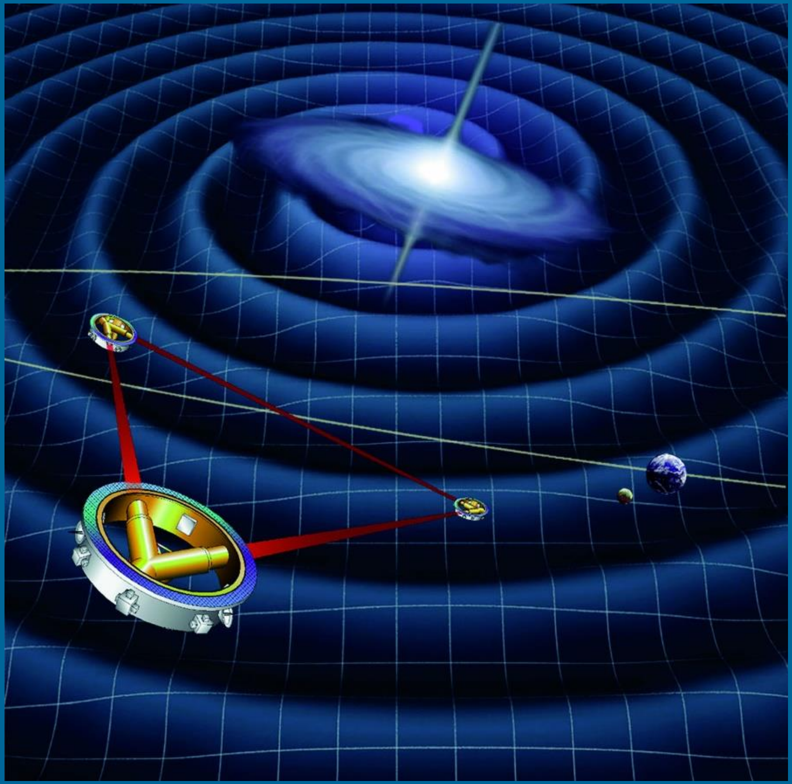


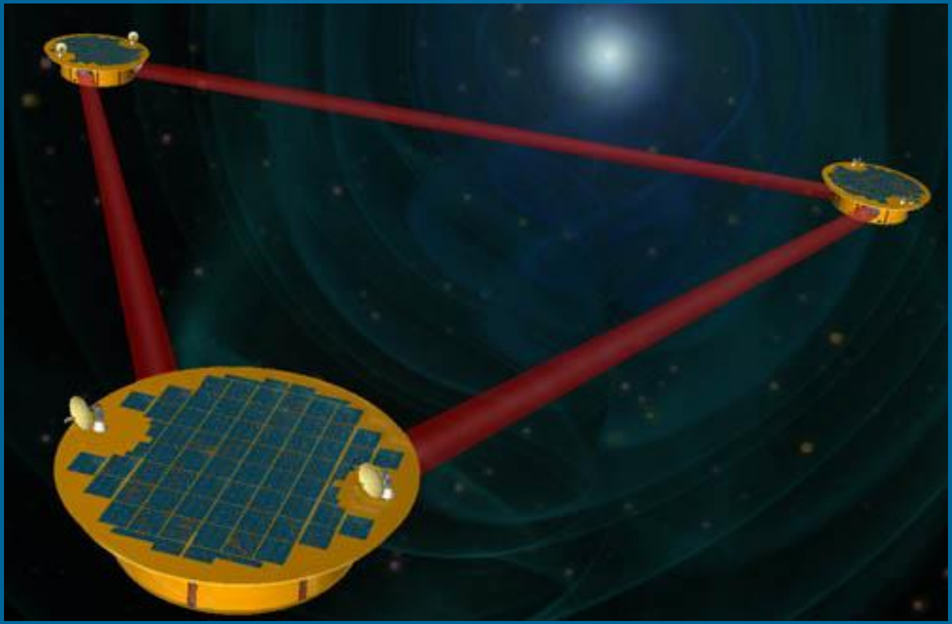
BHs migrate in
the accretion disc
towards a trapping zone.
There they form pairs.
Prograde and retrograde
rotation is possible.



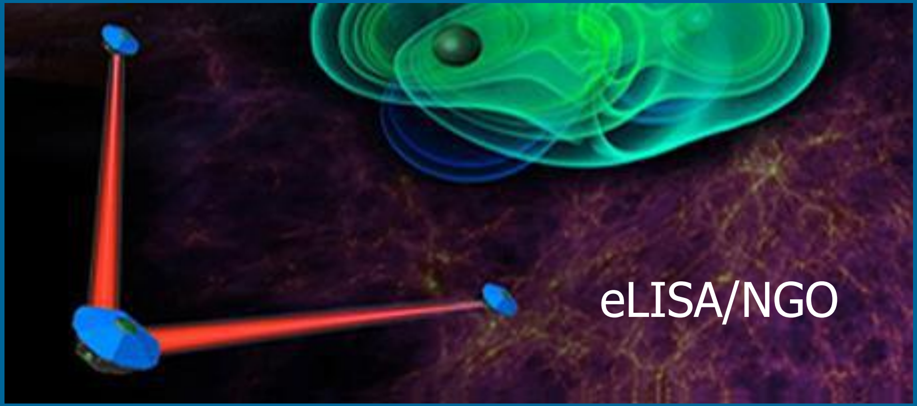
2004.11936

Space-bases interferometer LISA

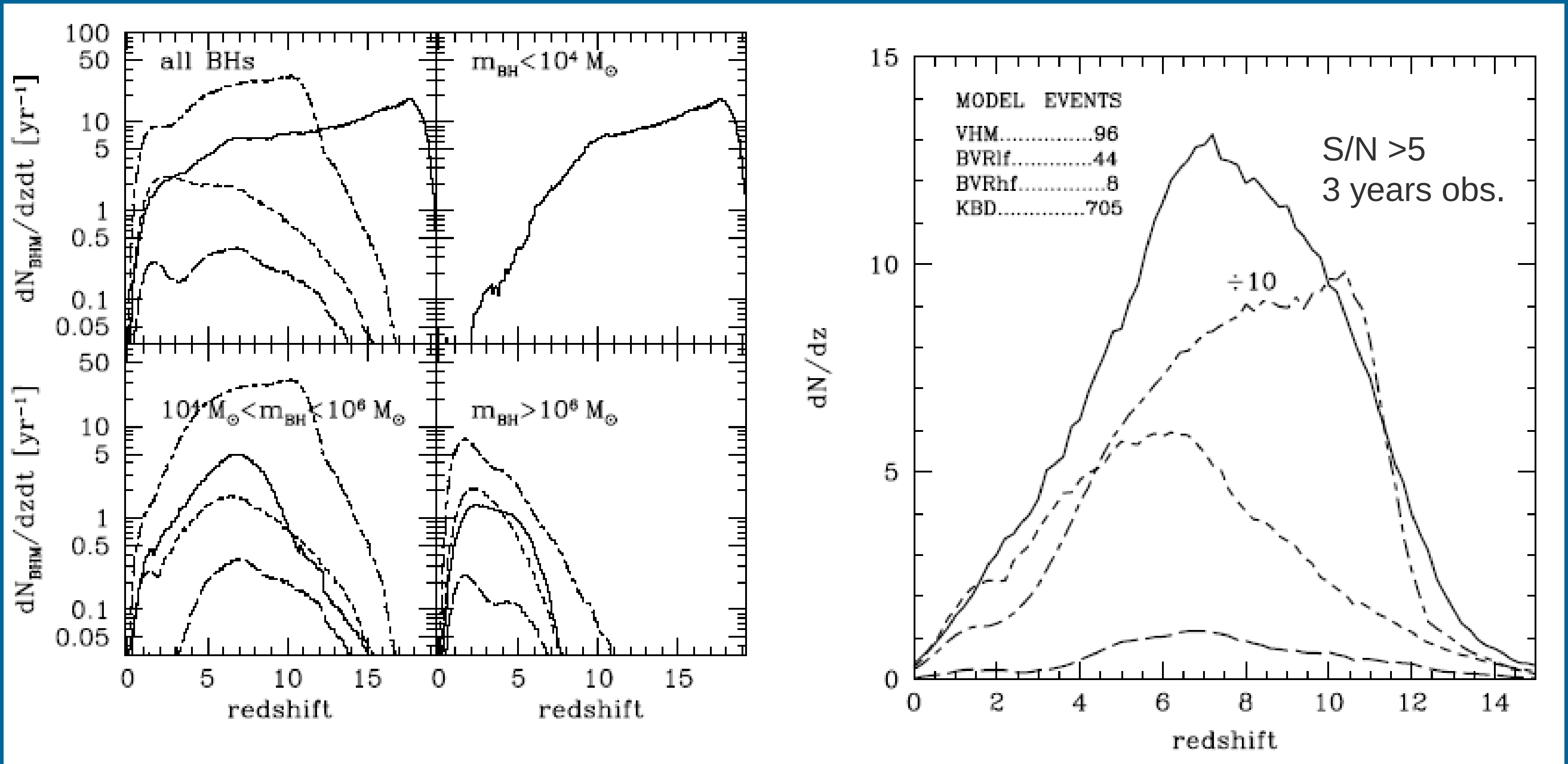




The project might be in orbit ~2035.



Coalescence rate and background



Calculations made aiming to fit the sensitivity of the original LISA proposal.
The authors predicted LISA detection rates spanning two order of magnitude, in the range 3-300 events per year,
depending on the detail of the assumed massive black hole seed model

0810.5554. Calculations continue to take into accounts more effects, see 2006.12513

Main conclusions

- The first massive BHs are formed from the first massive stars at redshifts >15 in minihalos with masses about 10^6 M_O.
- Halos (and BHs inside them) coalesce with each other in the process of hierarchical merging.
- Mass growth of BHs is due to accretion and coalescence.
- Already at $z>6$ there are SMBHs with masses $\sim 10^9$ M_O.
- The GW rocket effect is important, especially early in the merging history, as at that time potentials were not so deep.
- Observations of GW signals are possible with detectors like VIRGO and LIGO (for stellar mass objects), and with LISA (in the case of SMBHs).