# SMBH mass growth and BH coalescence

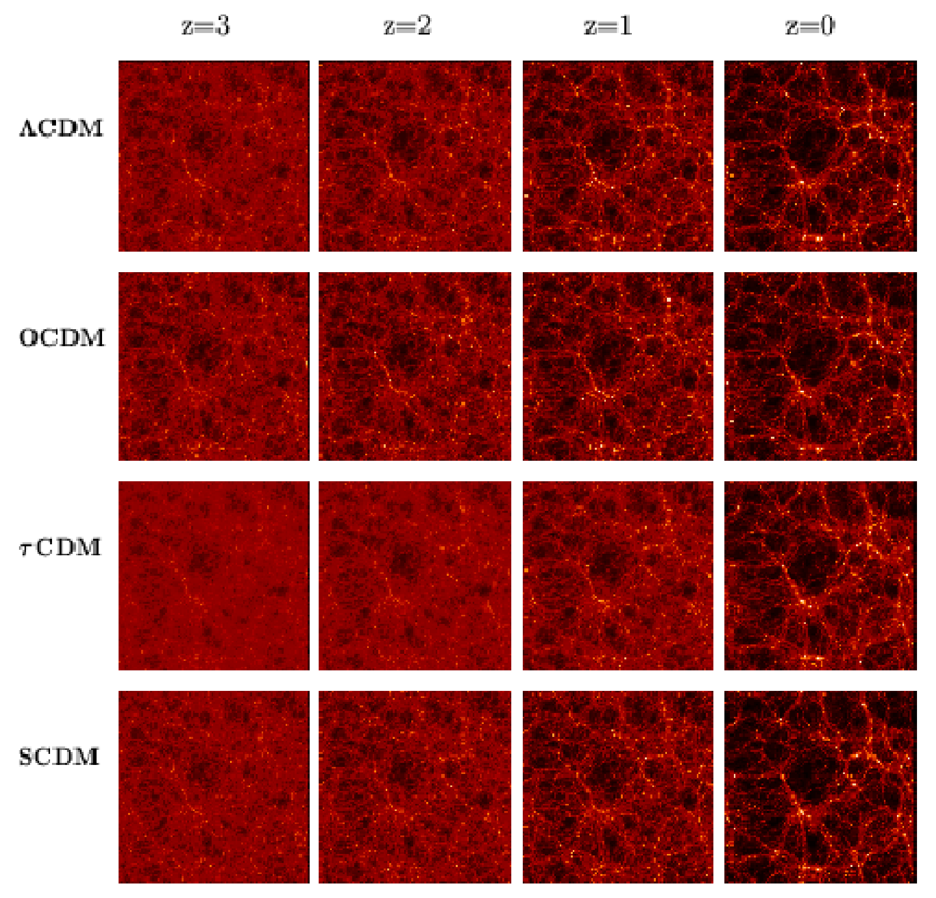
# Plan of the lecture

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**
**astro-ph/0609741 Supermassive black hole mergers and cosmological structure formation**
**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: 1307.4086 **Gravitational wave emission from binary SMBHs**
**arXiv: 2110.10175** The origins of massive black holes

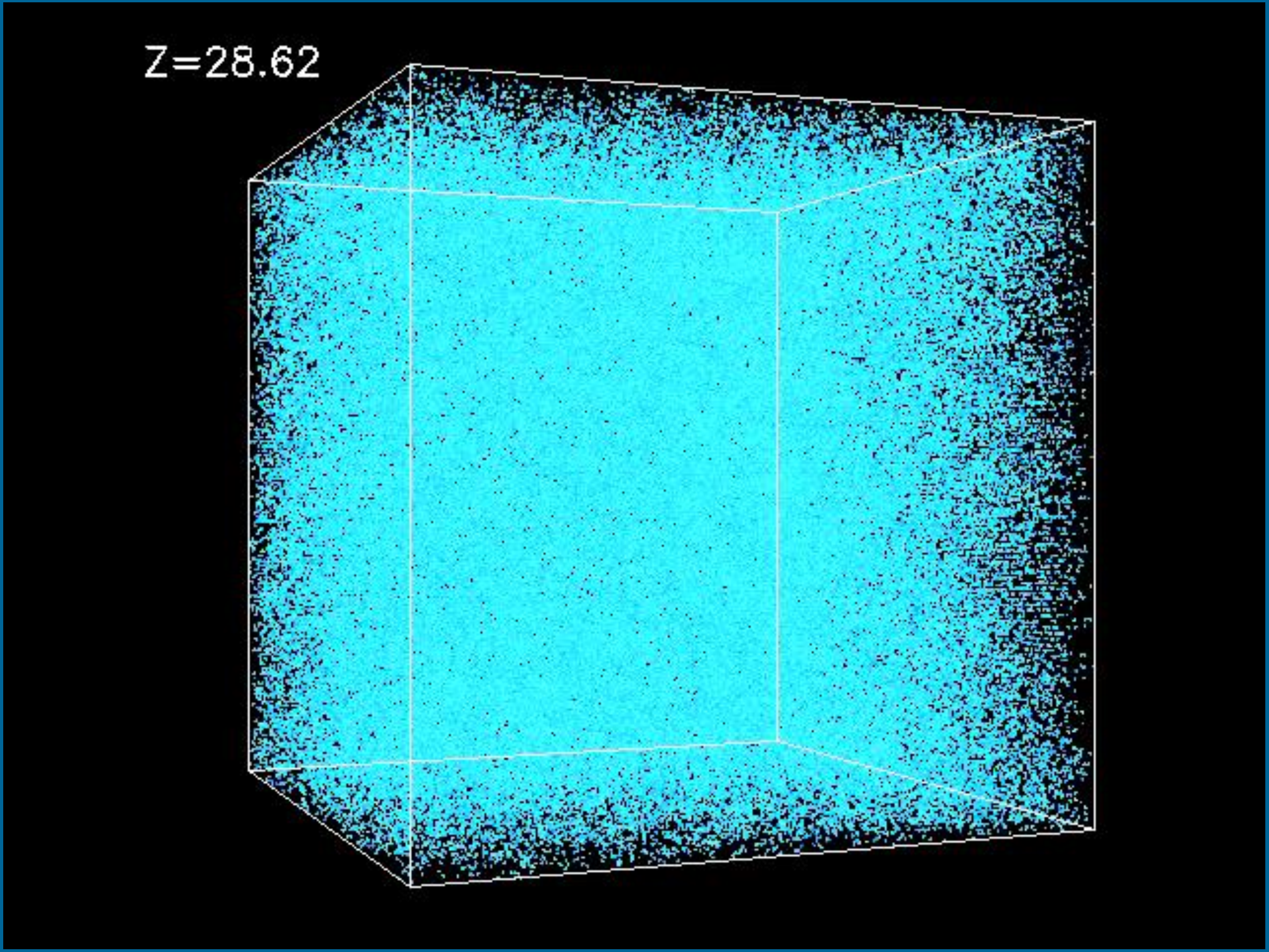
# Structure growth in the universe



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

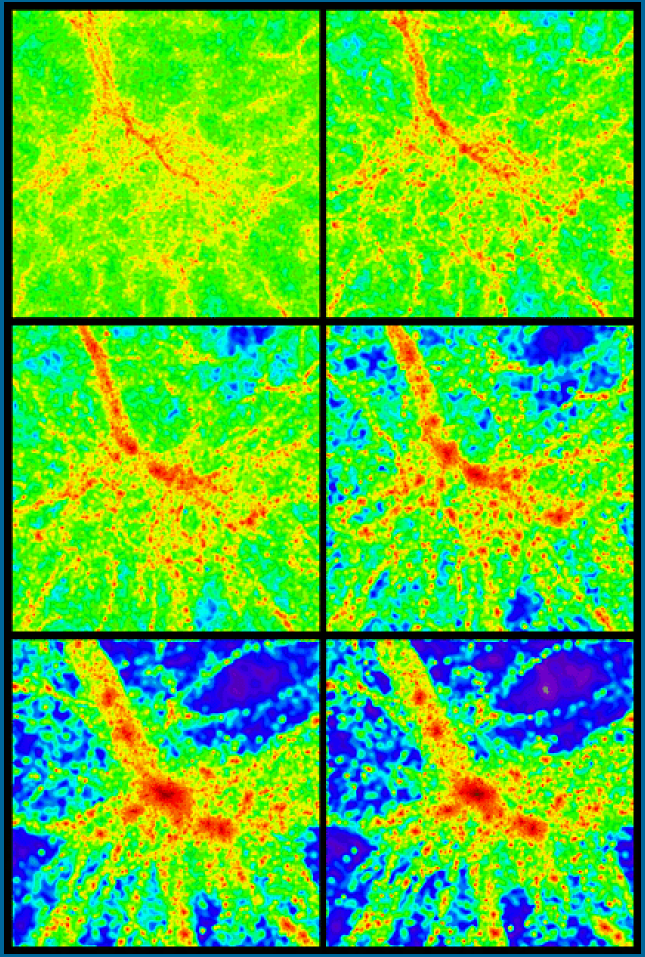
Numerical calculations of the evolution of the large-scale structure and single “blocks” reached a very high level of precision (arxiv:0706.1270).

# Large scale structure



**Kravtsov et al.**

# Formation of clusters of galaxies



tCDM
21x21 (Mpc/h)$^3$

LCDM
35x35 (Mpc/h)$^3$

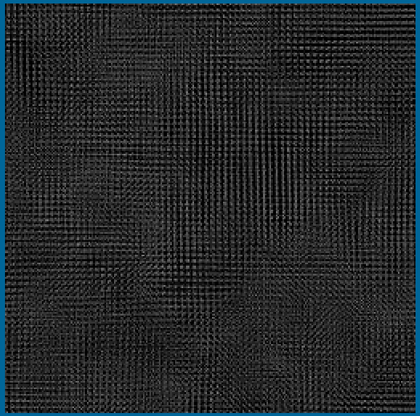
In the process of structure growth numerous coalescence of “building blocks” happen, each of these blocks can contain a BH.

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

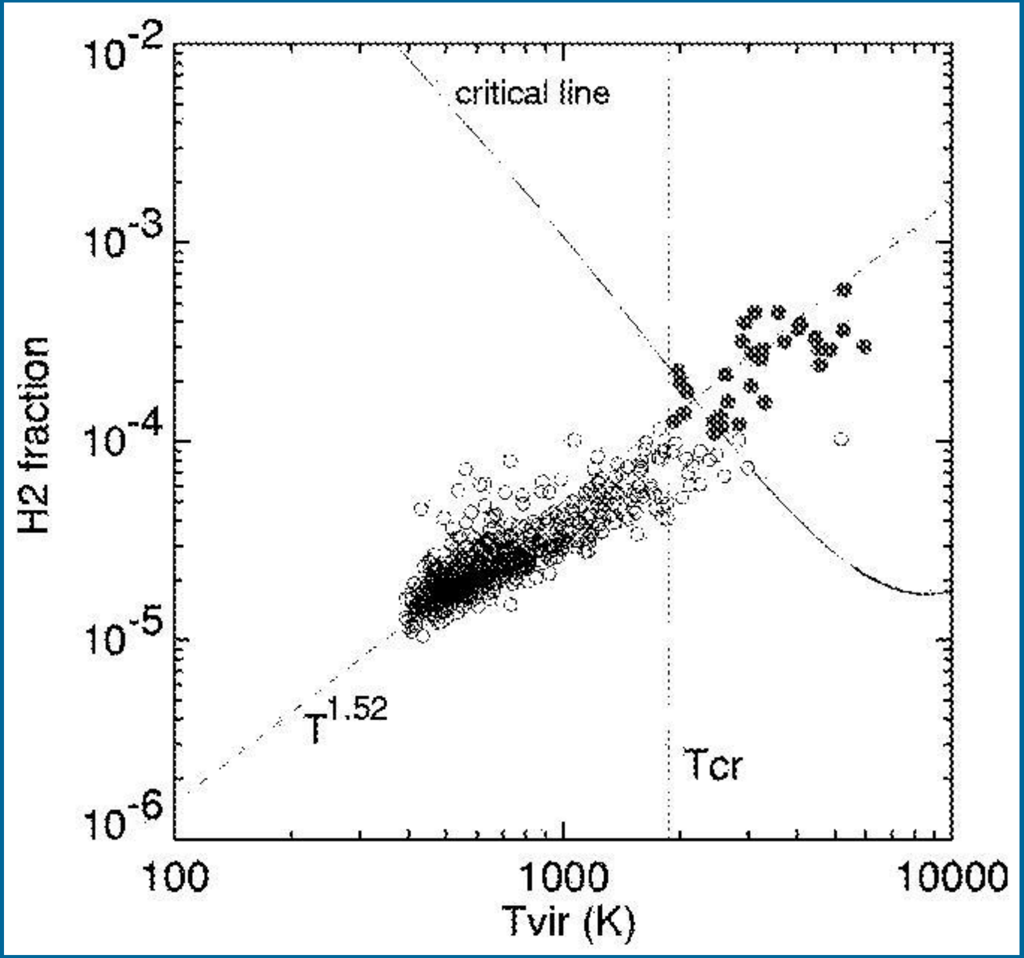
Formation of large galaxies is finished as z~2, after this no major mergers happen, only small satellites are captured by big galaxies.

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 $10^5$ $M_O$.

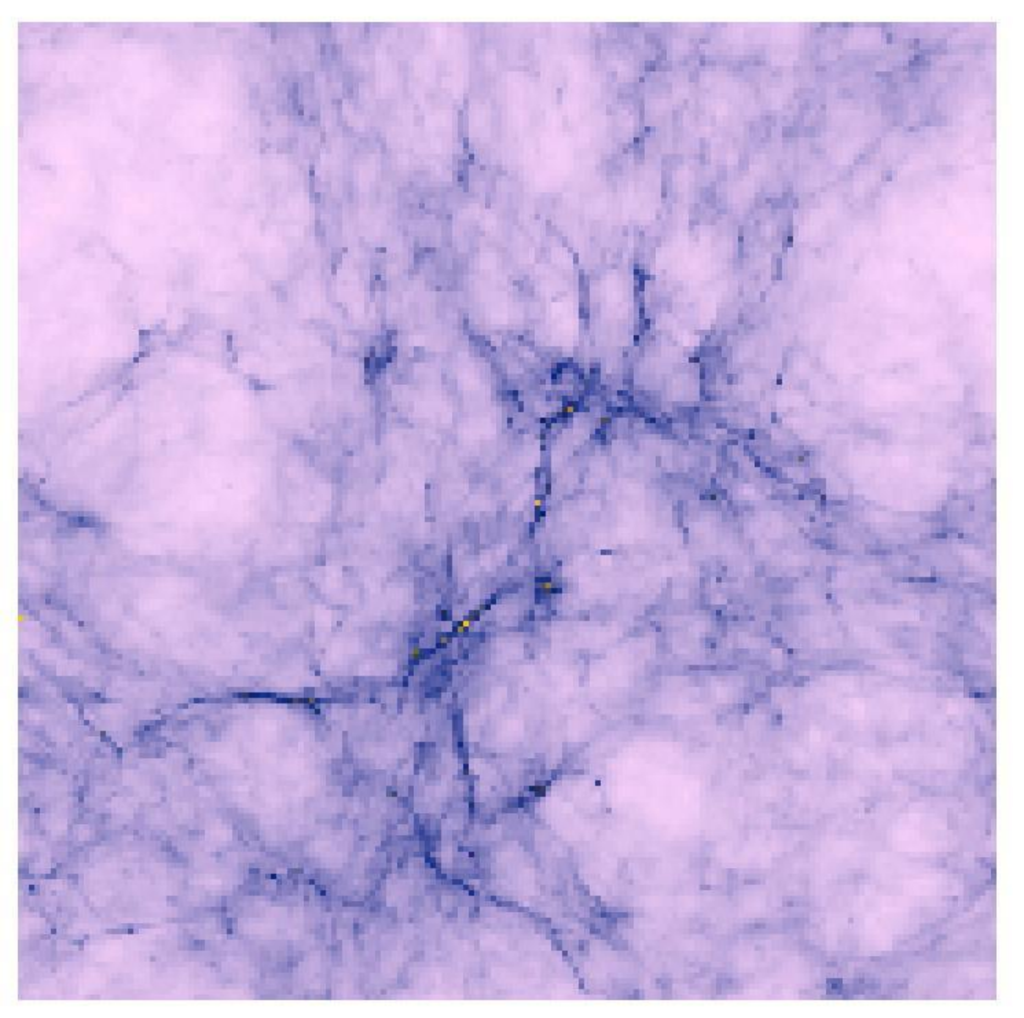
These BHs produce the first miniquasars, which contribute to the reionization at z~10-12.

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

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

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.

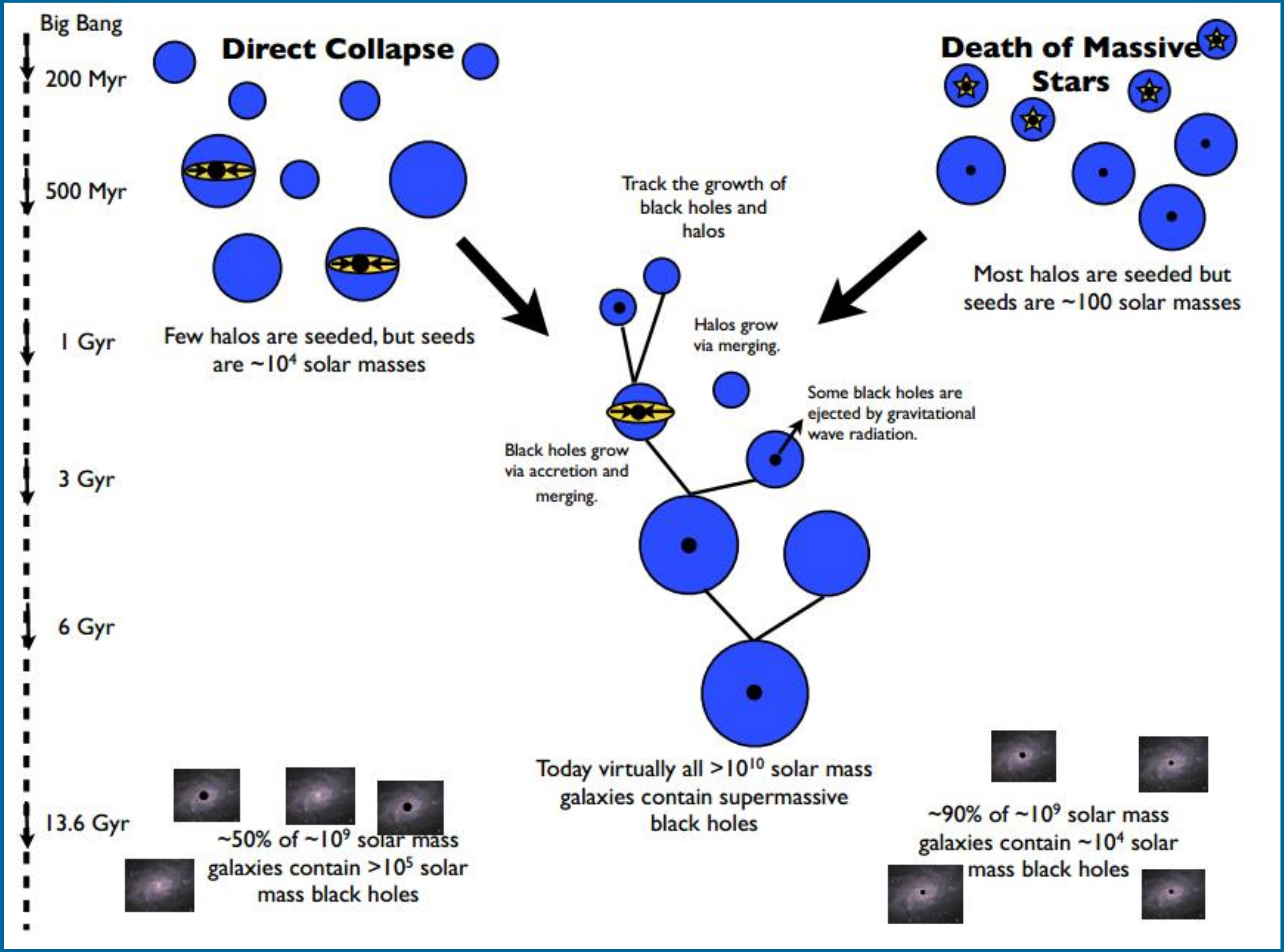
The picture is plotted for $z=17$.

The size is 50 kpc.

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

Yoshida et al. astro-ph/0301645

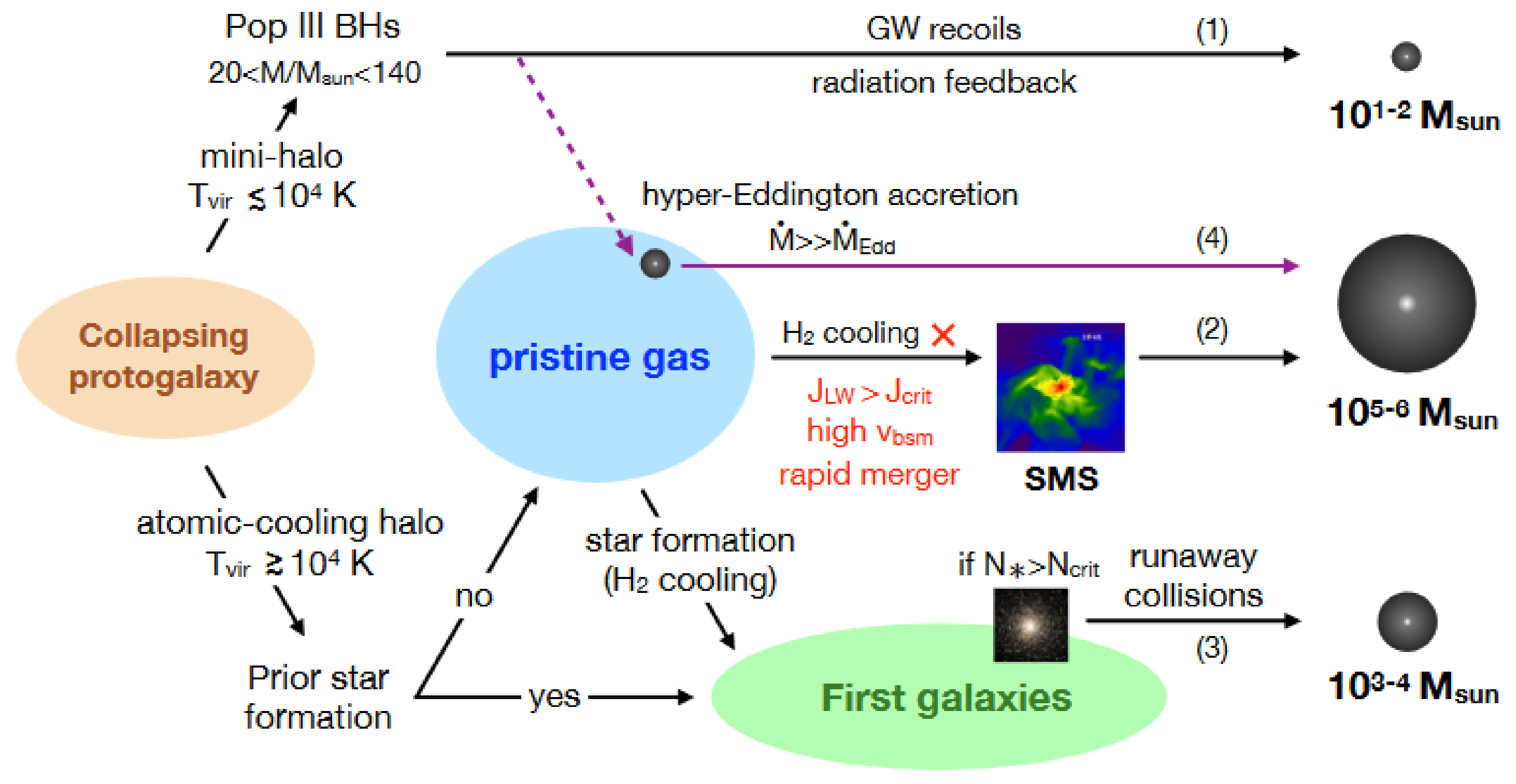
# A scheme for SMBH formation



1211.7082

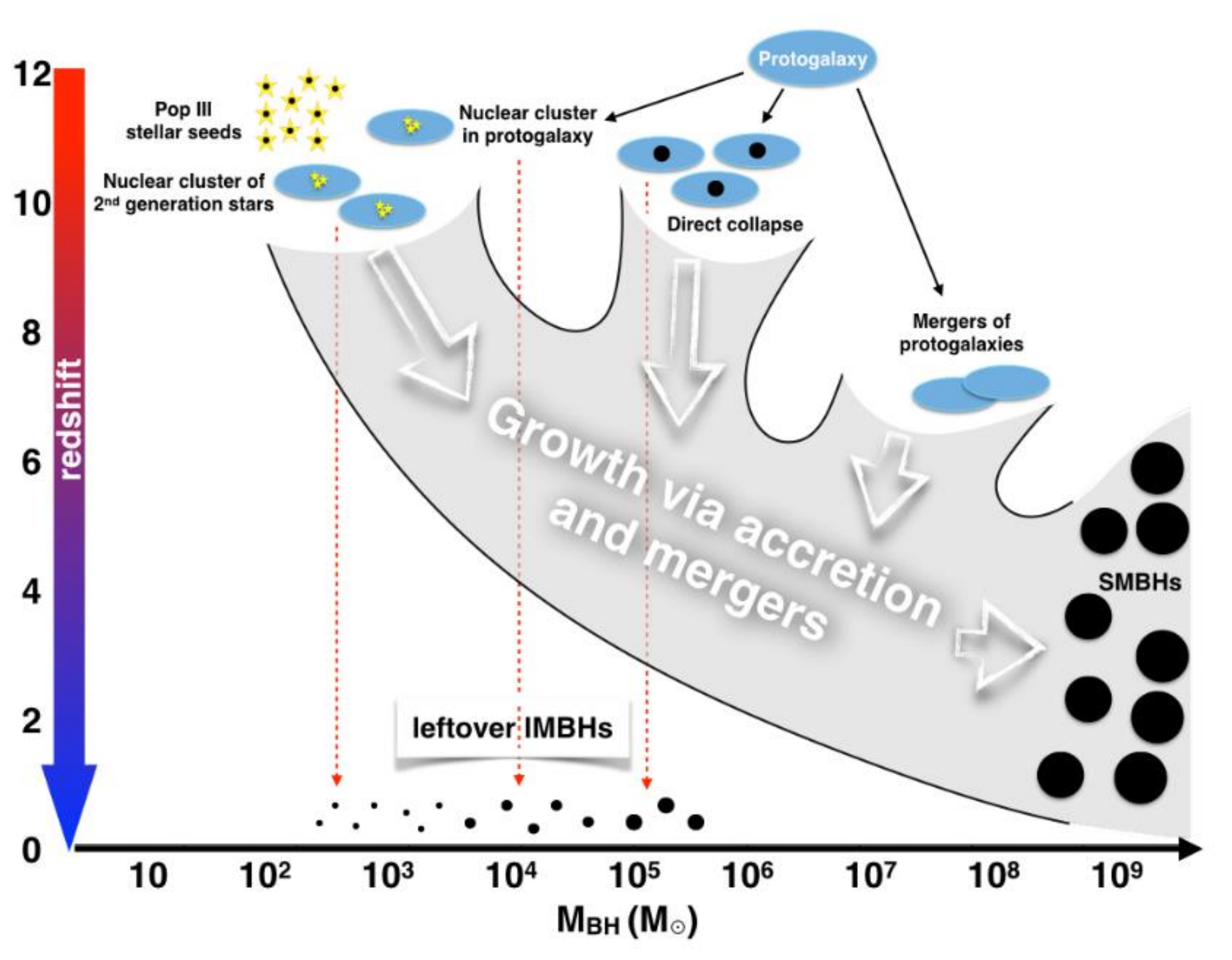
See a recent brief review in 2110.10175

# … and with more details



1911.05791

# Origin of SMBHs and IMBHs

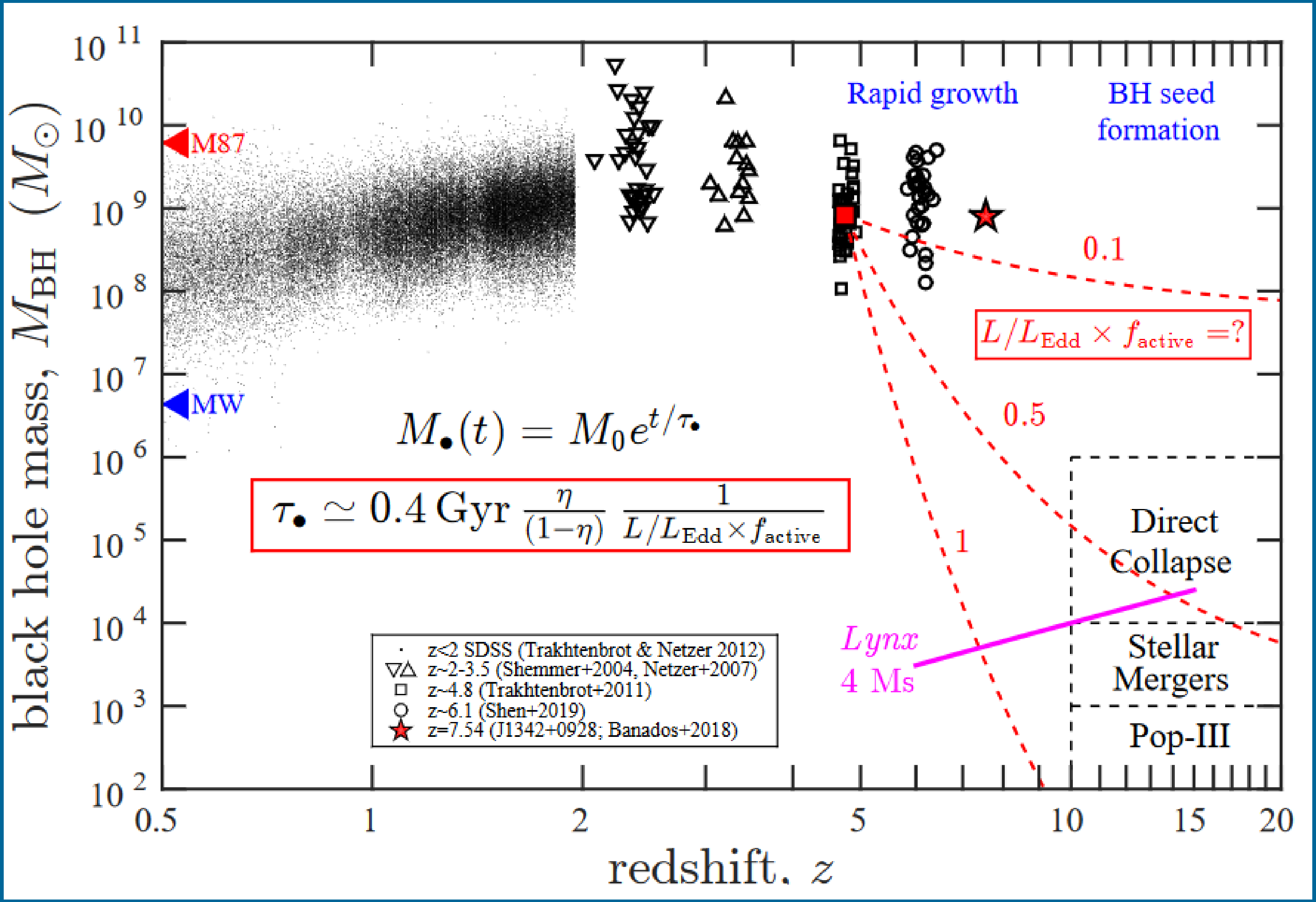


IMBHs:

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

1705.09667

# Some are too massive



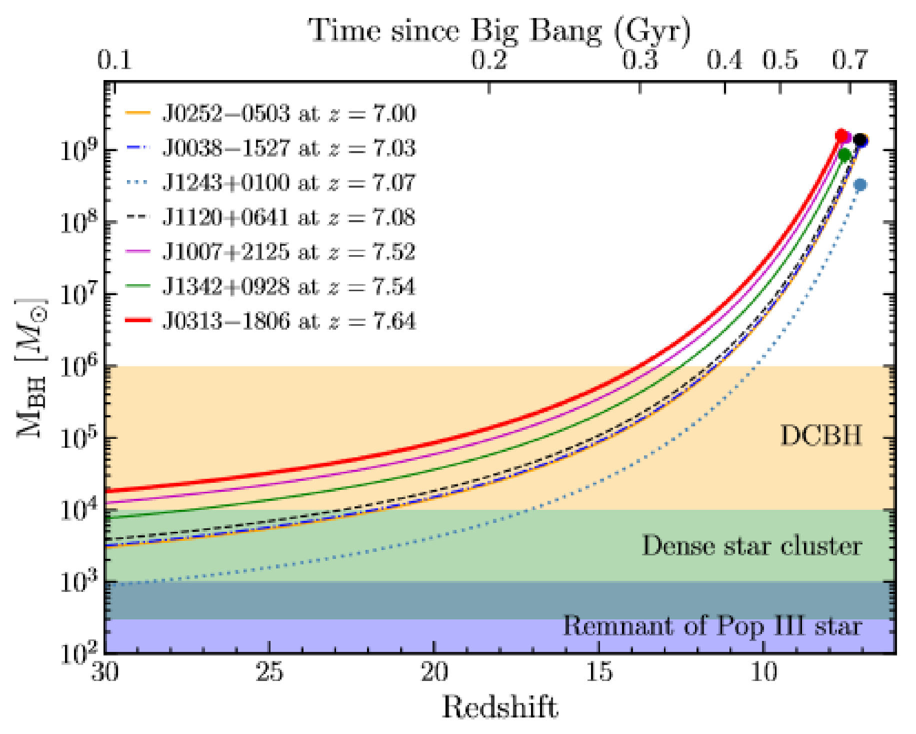
2002.00972

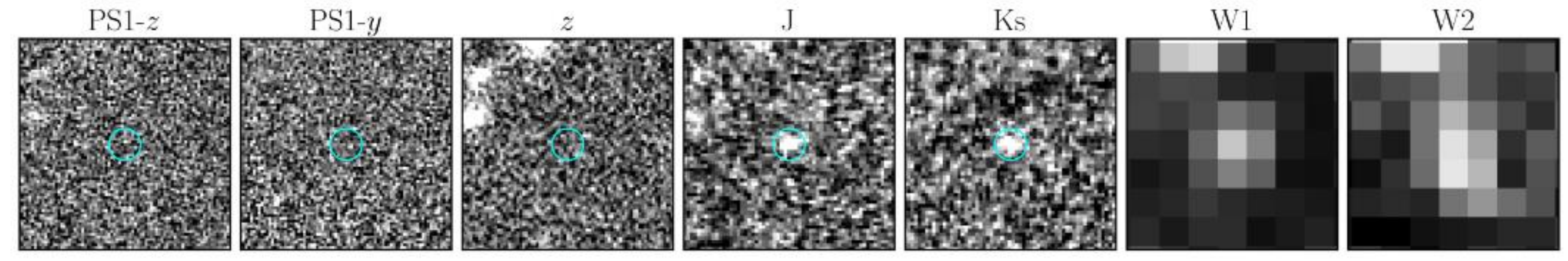
# Some form too early

The most distant quasar 0313–1806: z= 7.642

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

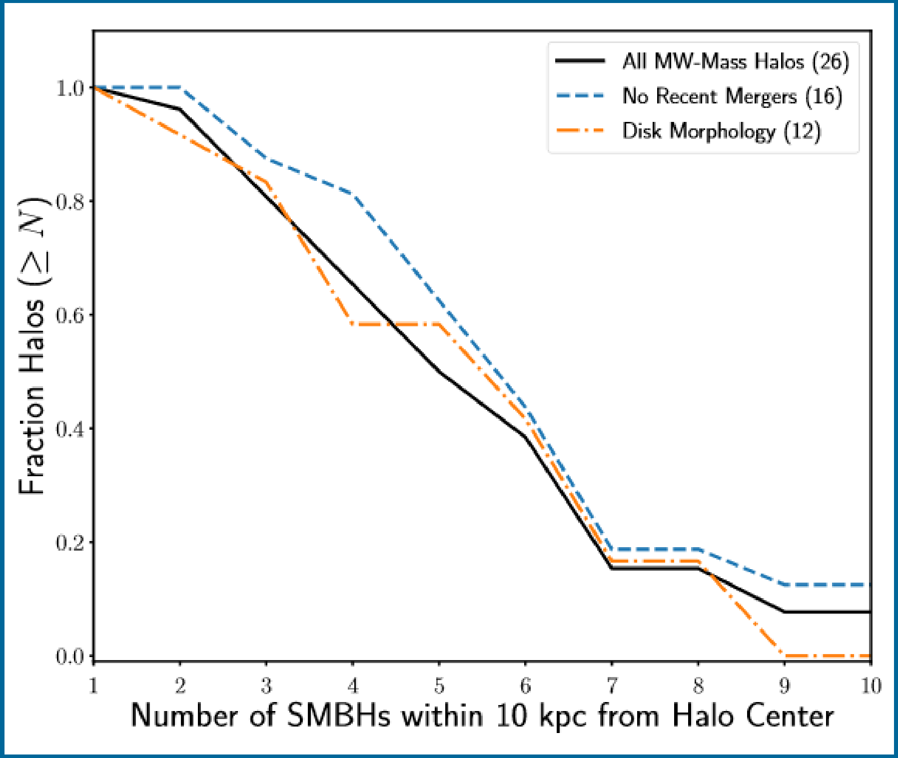
$$3.6 \times 10^{13} L_\odot$$



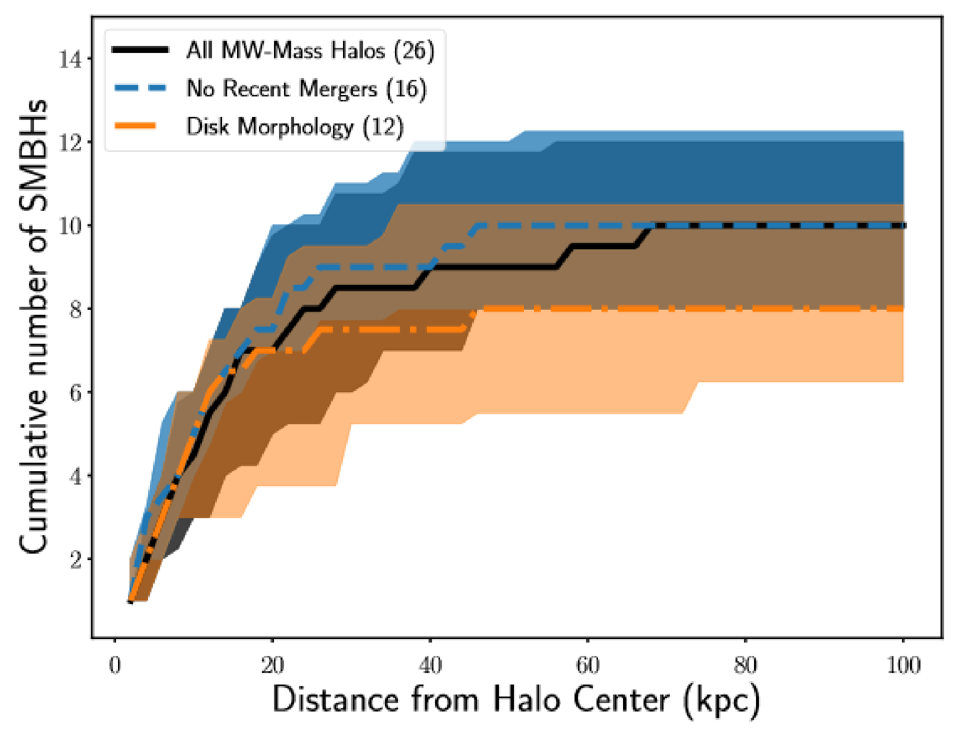


2101.03179

# Wandering BHs

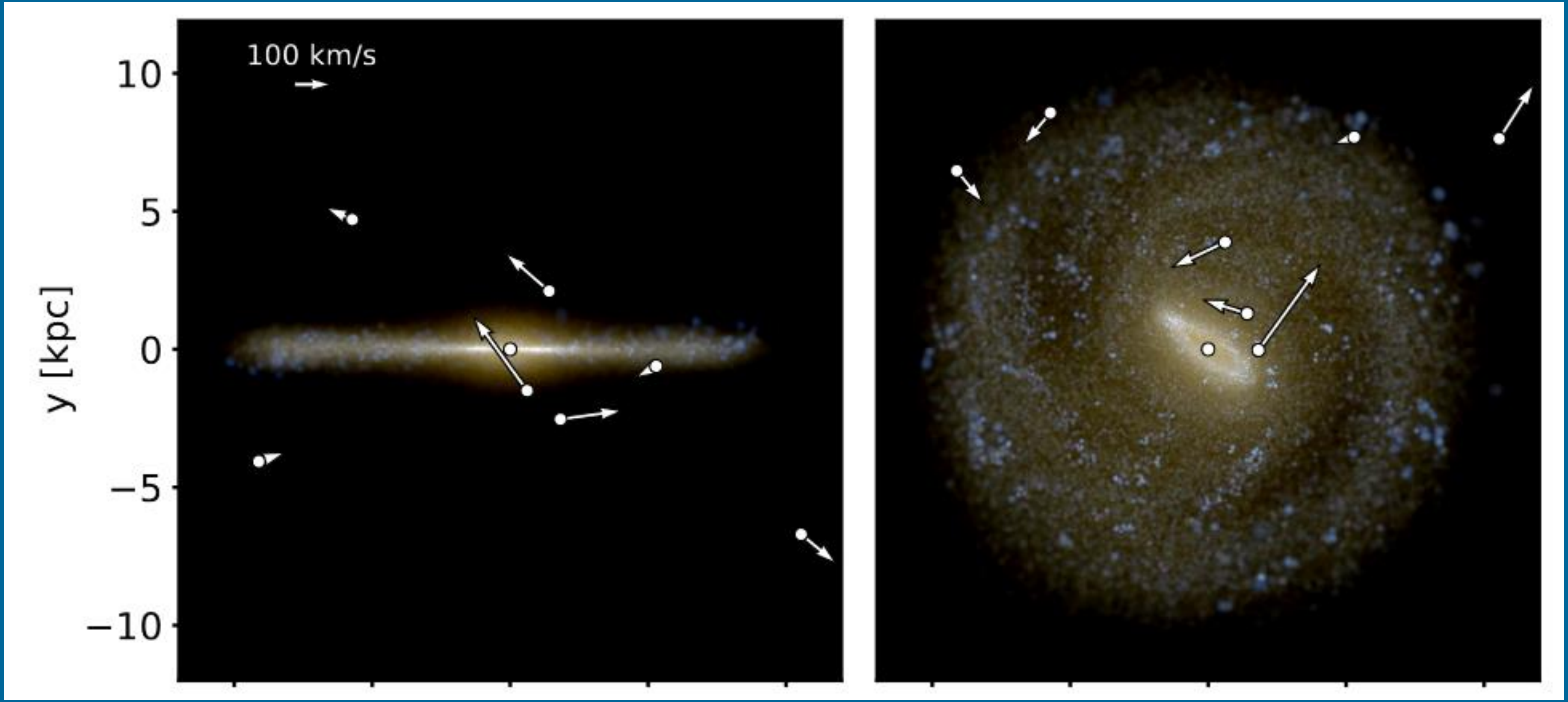


Only masses >$10^6$ solar are considered.
Usually 2-8 inside 10 kpc,
and up to ~20 inside the virial radius.



1802.06783

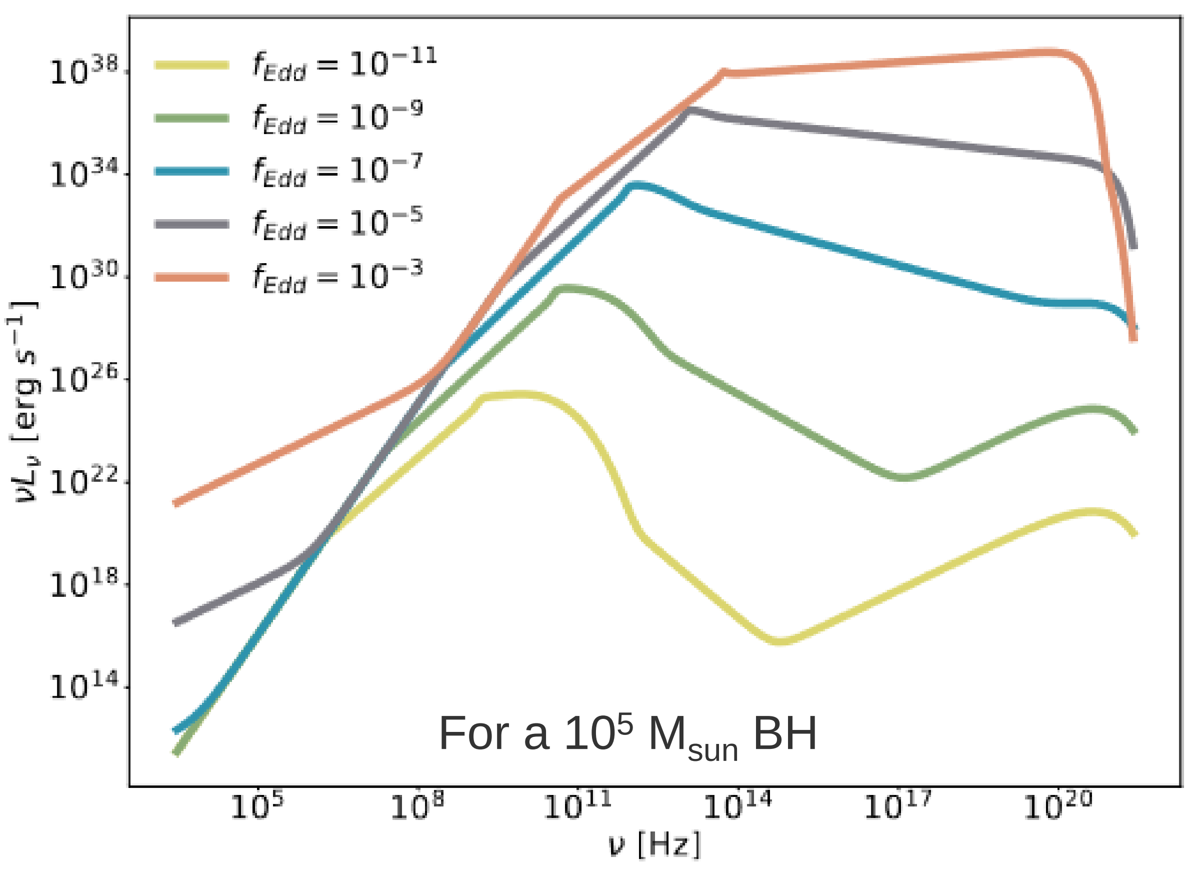
# Examples from simulations



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

1802.06783, see new calculations in 2103.12124

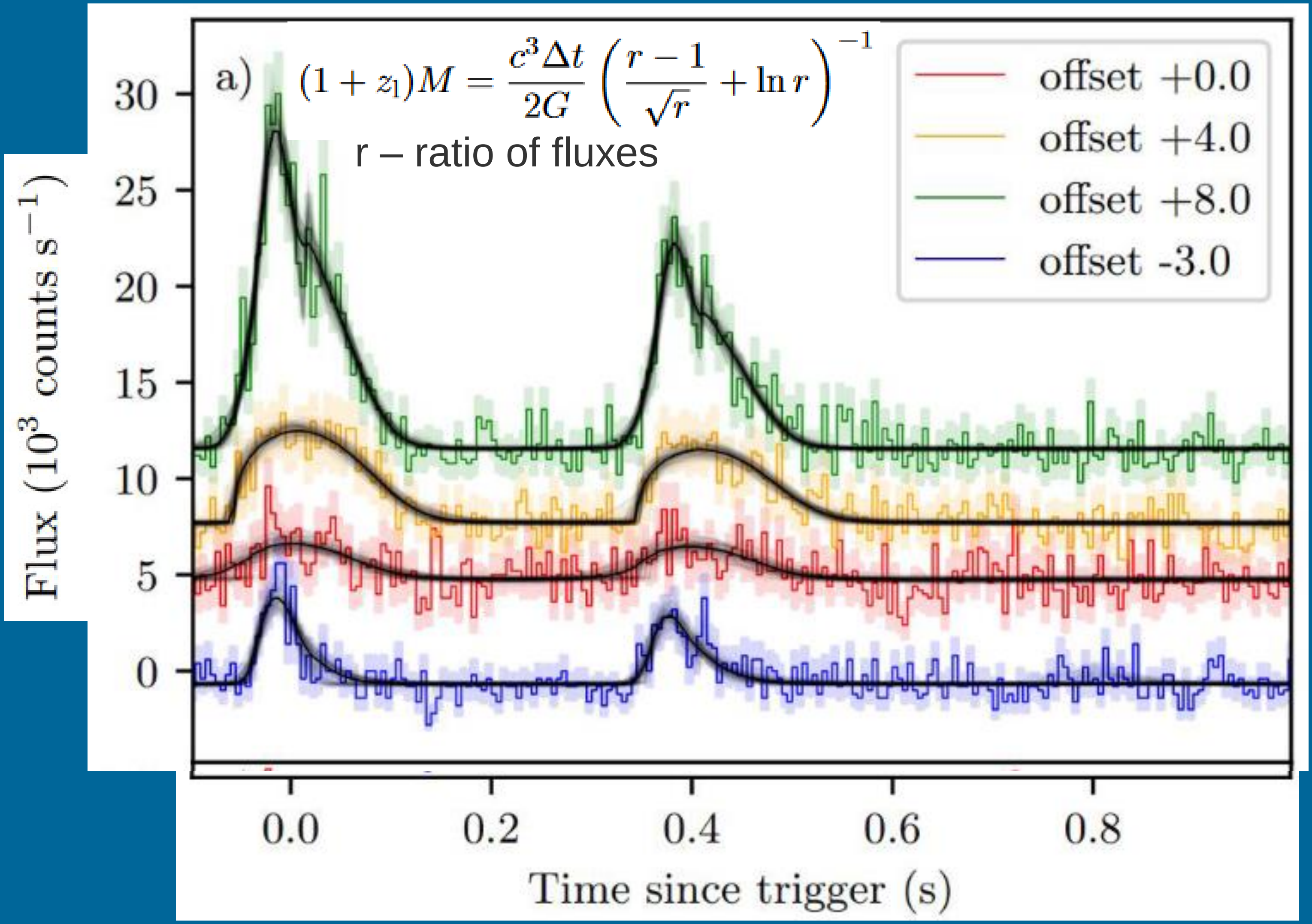
# Detectability of wandering IMBHs



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

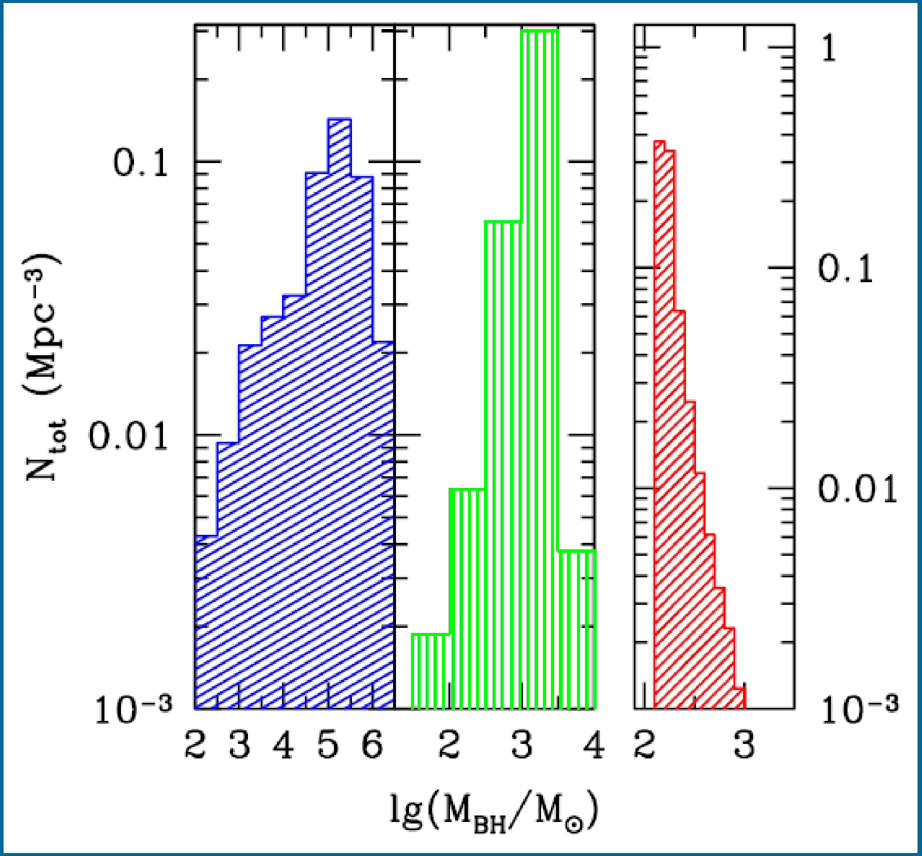
BATSE data

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).

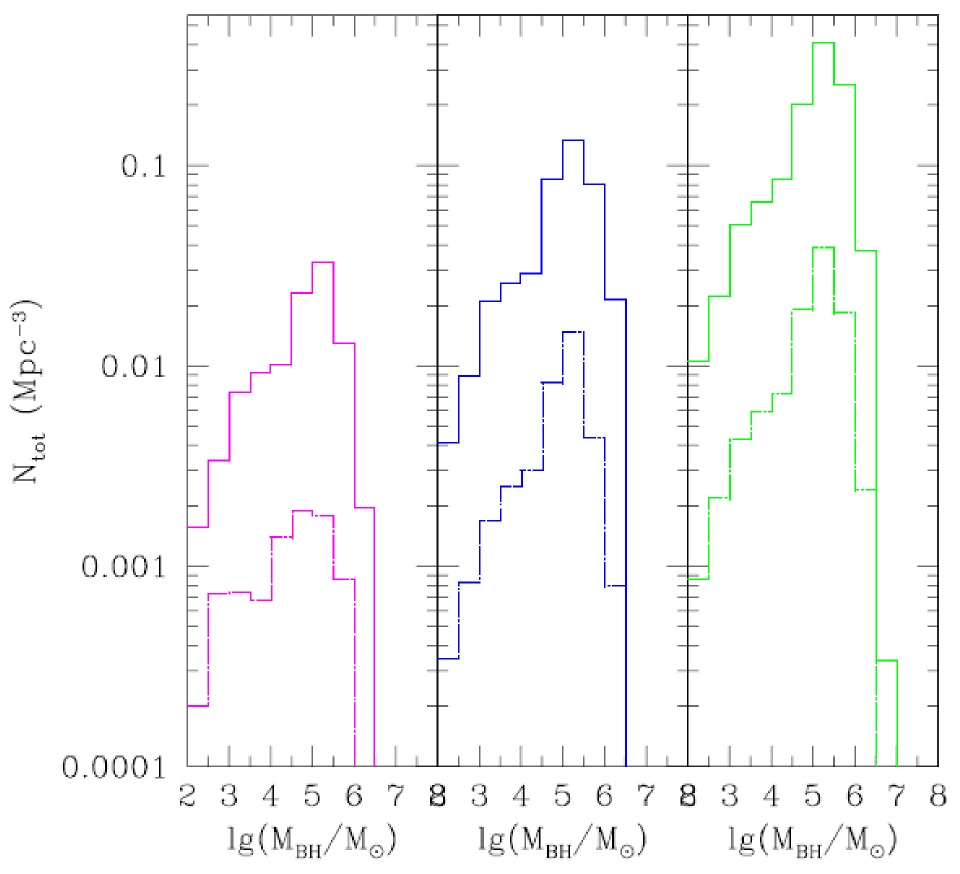
See a brief review of different scenarios of seed formation
in arXiv: 0912.0525.

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).

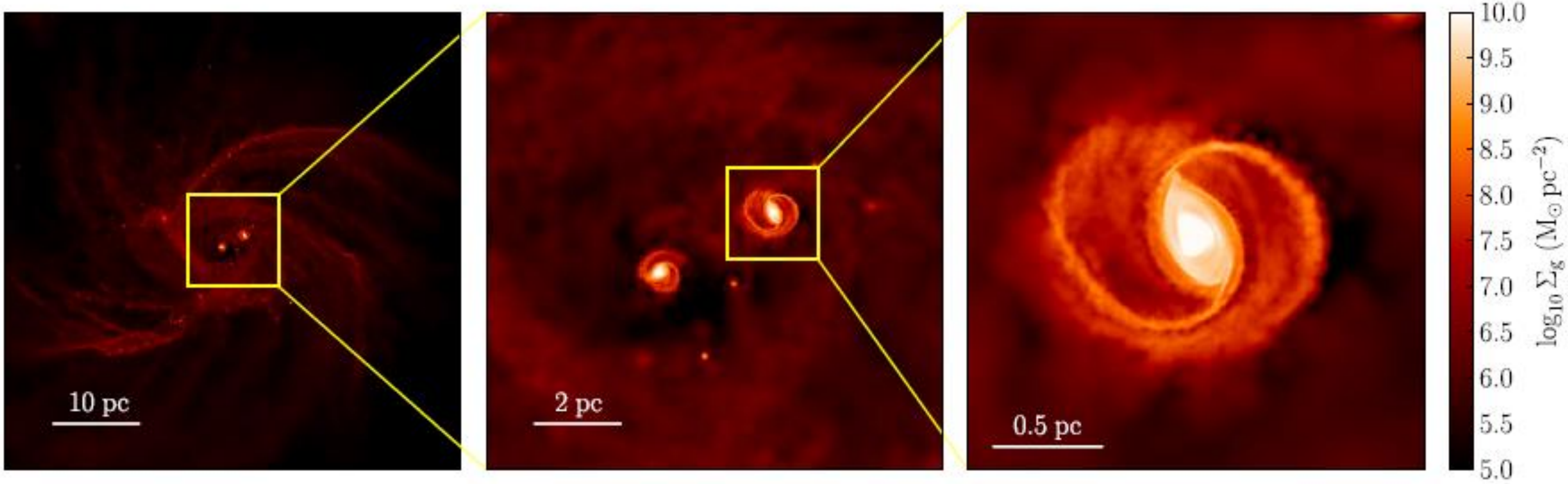
In low-mass halos and in rapidly rotating halos (later on, probably, bulgeless galaxies) there are no SMBHs in this scenario.

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

# Образование массивных черных дыр

**Сверхмассивные черные дыры можно образовать в результате слияния крупных галактик на z=8-10. После слияния образуется плотный ядерный диск, который затем может сколлапсировать в черную дыру с массой $10^8$-$10^9$ солнечных.**

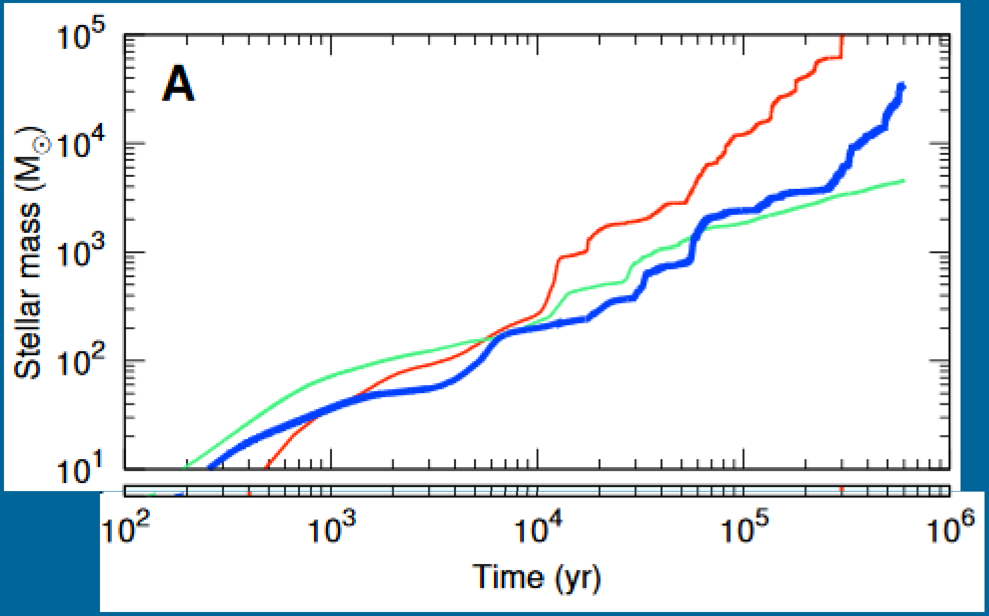


**1411.5683**

# Formation via a supermassive star

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

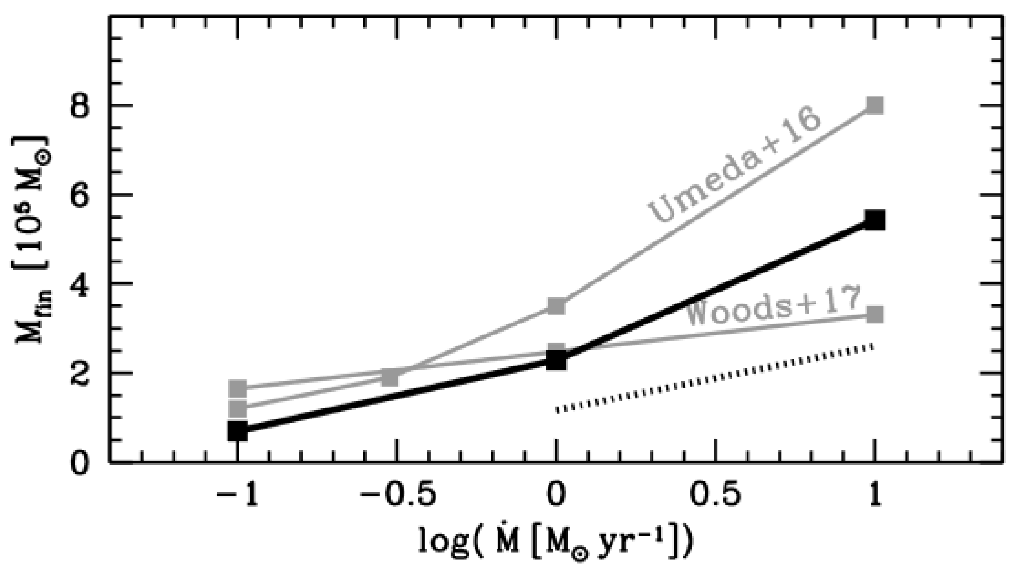
In regions with a large streaming velocity, gas condensation – and hence star formation – is suppressed until a deep gravitational potential is generated by a clump of dark matter with mass $10^7$ solar masses.

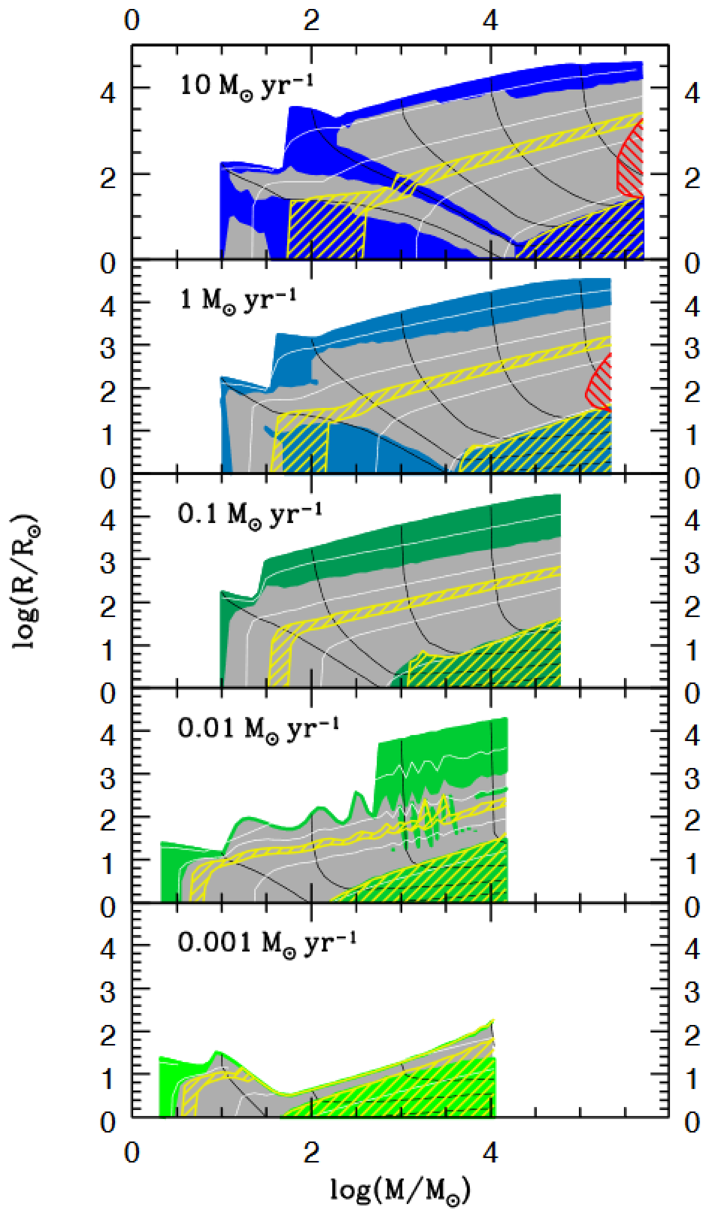


1709.09863, see more recent calculations in 1901.07563

# Supermassive primordial stars

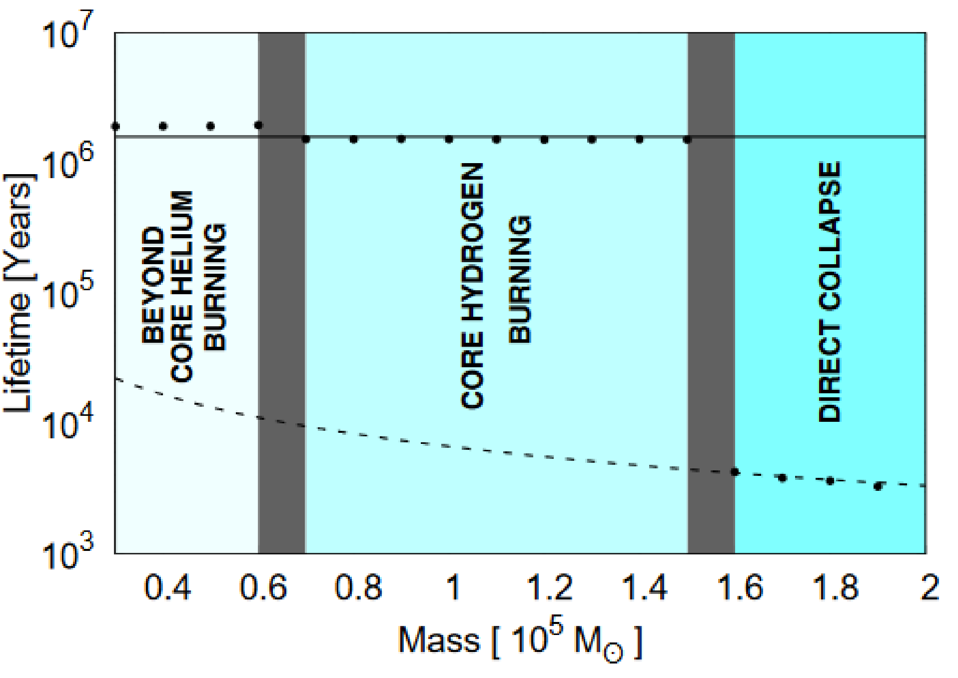
Internal structures of the models for the indicated accretion rates. On each panel, the upper curve is the stellar radius, the blue and green areas indicate convective zones, and the grey areas indicate radiative transport. The yellow hatched areas correspond to D- and H-burning, and the red hatched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





1705.09301

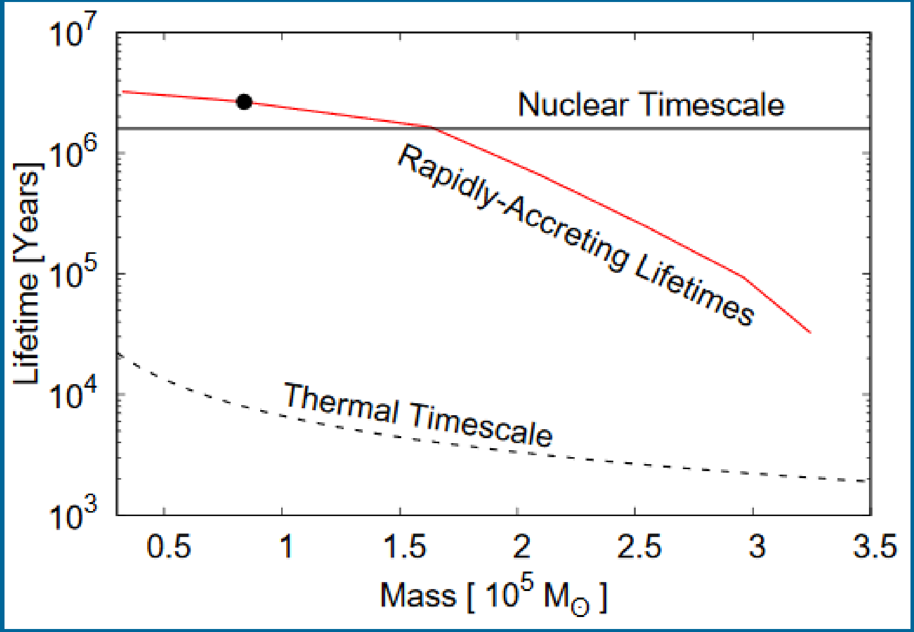
# Monolithic Supermassive Stars



1D stellar evolution code Kepler

Stars born with masses between ~60 k$M_\odot$ and ~150 k$M_\odot$ collapse at the end of the main sequence, burning stably for~1.5 Myr.

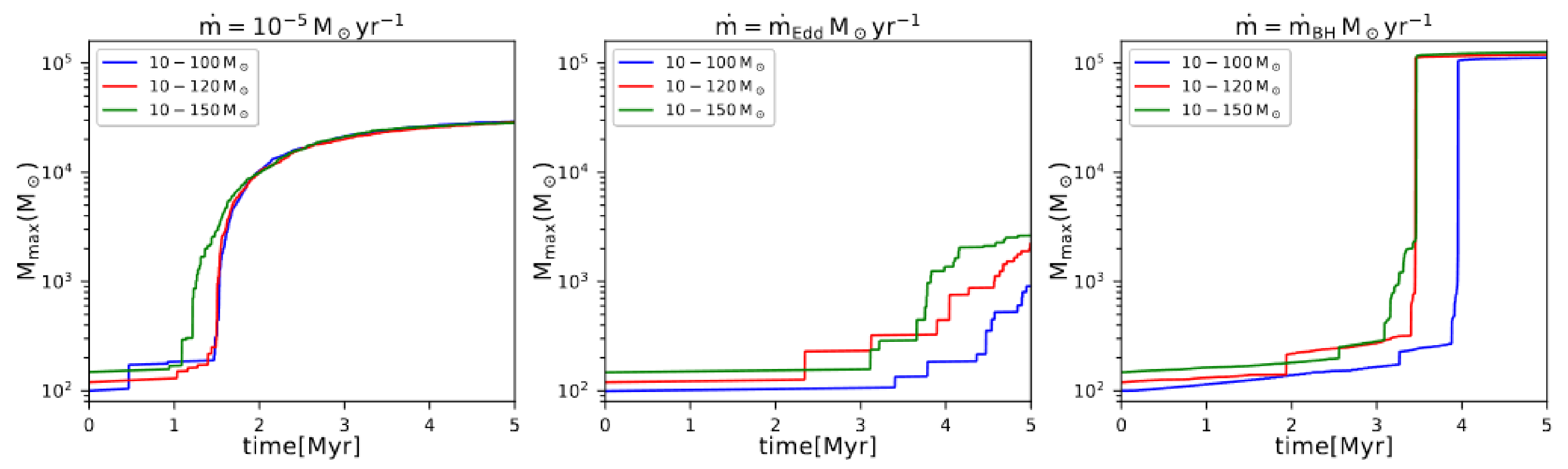
More massive stars collapse directly due to the general relativistic instability after a thermal timescale of ~3 kyr – 4 kyr.



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

2003.10467

# Stellar coalescence in clusters

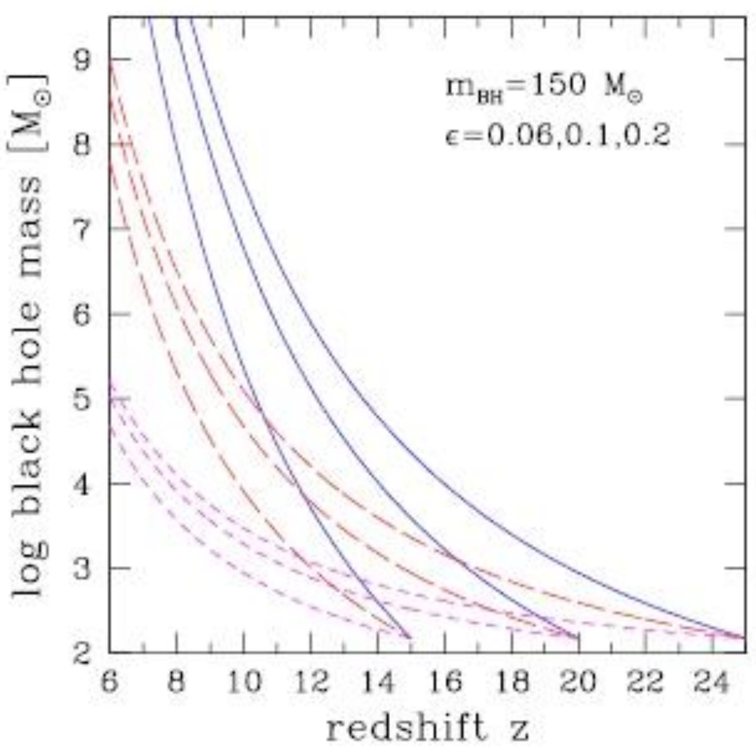


In dense nuclear stellar clusters in the young galaxies stars can coalesce and grow by accretion.

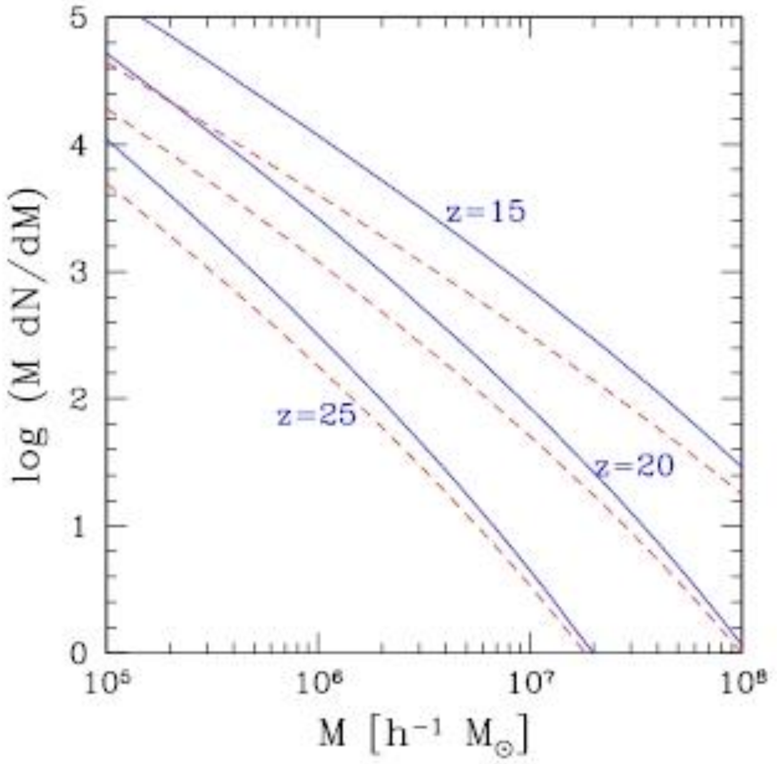
Depending on many uncertain parameters (accretion rate, mass function, etc.) this can result in formation of seed BHs with masses $10^3$-$10^5$ solar masses,

2012.01456

# BH mass growth



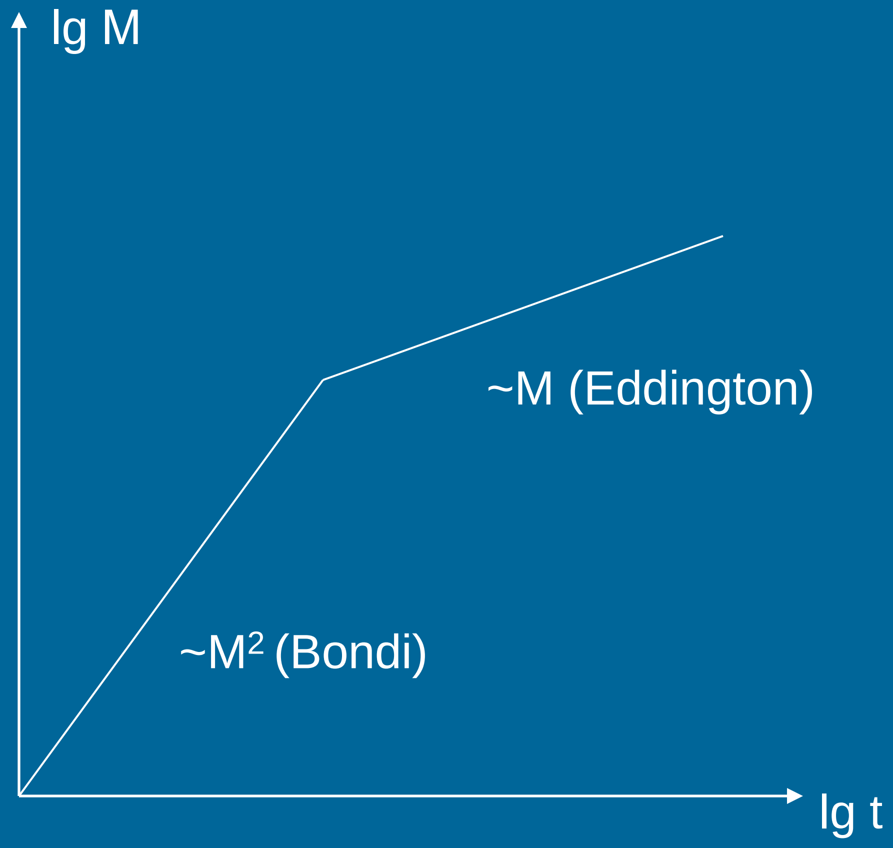
BH mass growth for different accretion efficiency.



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



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

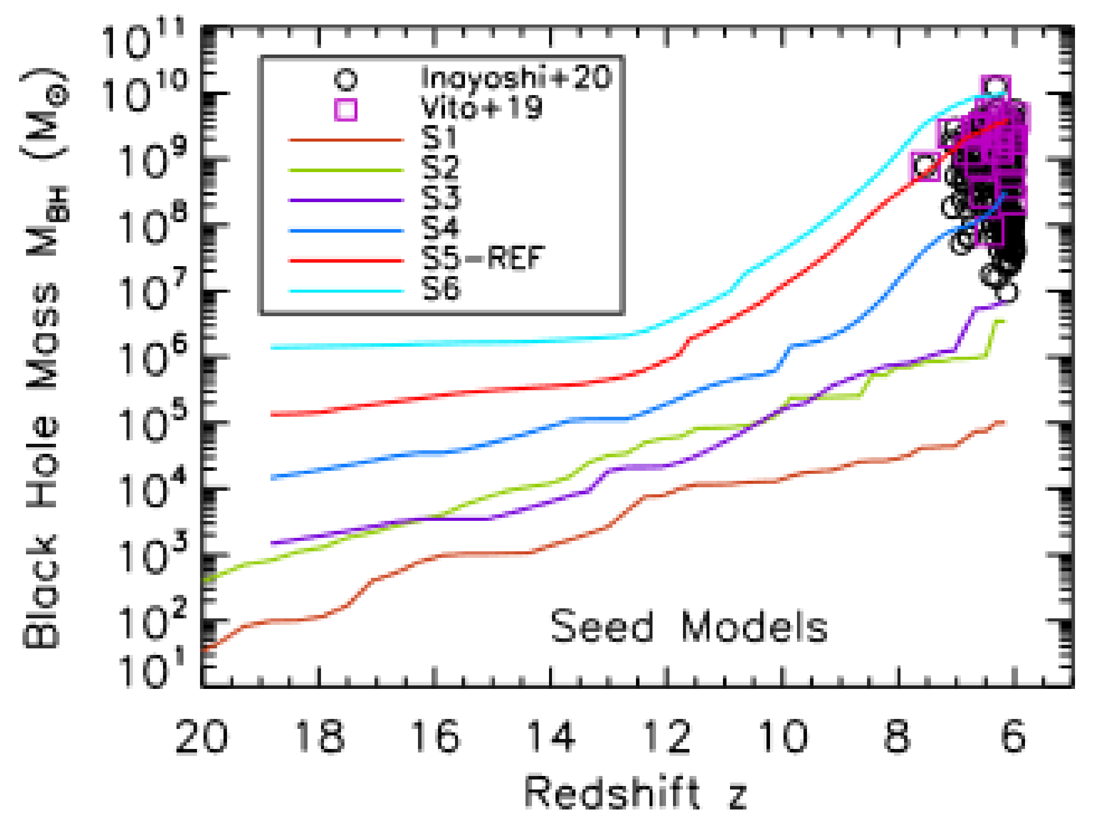
The so-called Salpeter time:
the time in which the mass is doubled.

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

# Light seeds cannot grow fast enough?



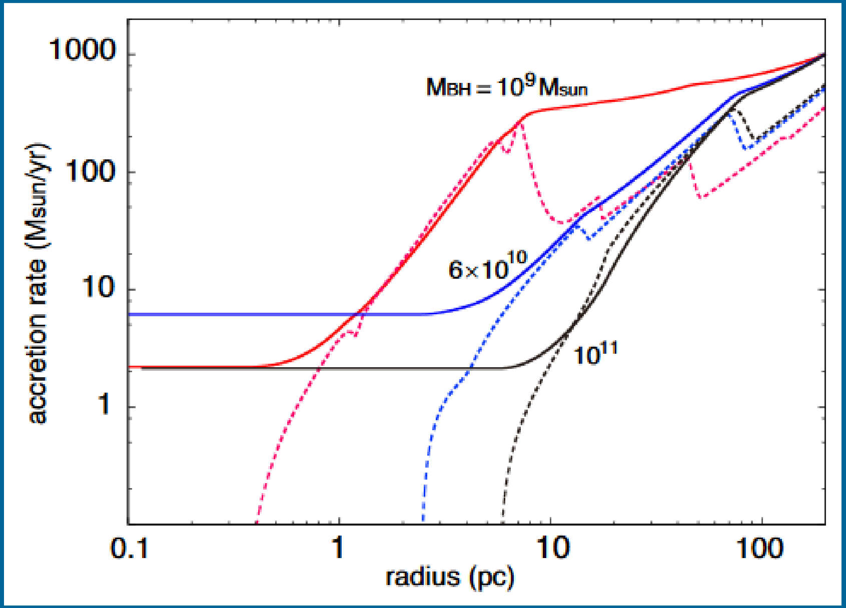
Starting with $10^5$ solar masses it is possible to obtain a massive BH at z=6.

However, still there are many uncertainties.

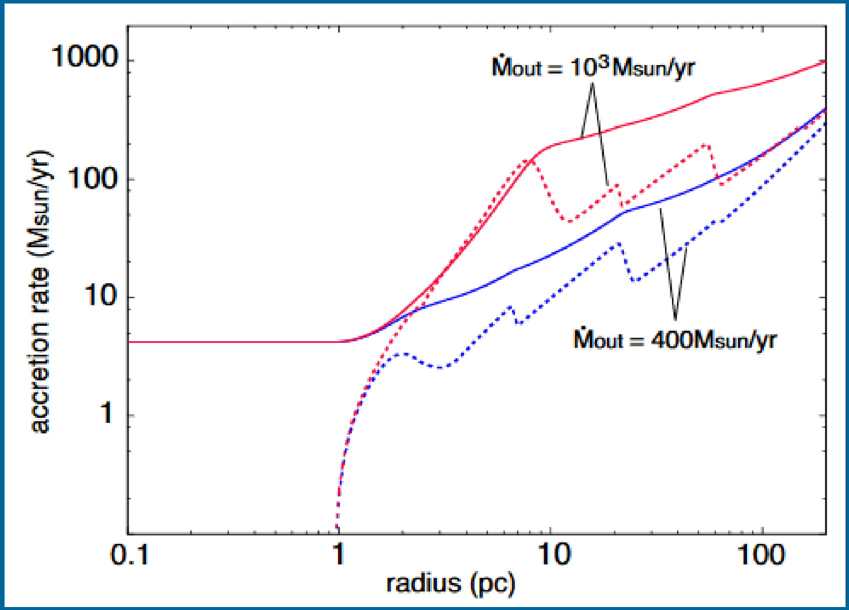
2012.01458

# 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.

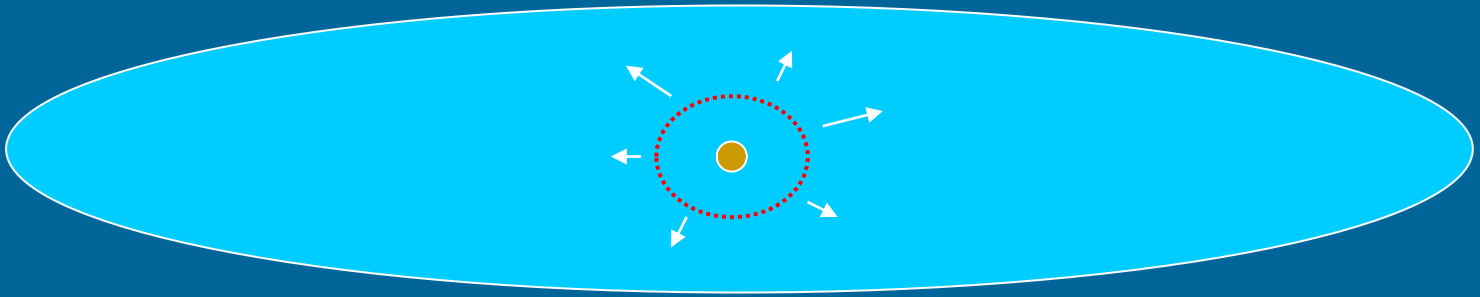


$M_{BH}=10^{10}$

1601.02611

# Квазар «задувает» галактику

Активность квазара может привести к мощному оттоку вещества. Этот поток может выметать газ из галактики, что приведет к выключению звездообразования в ней.

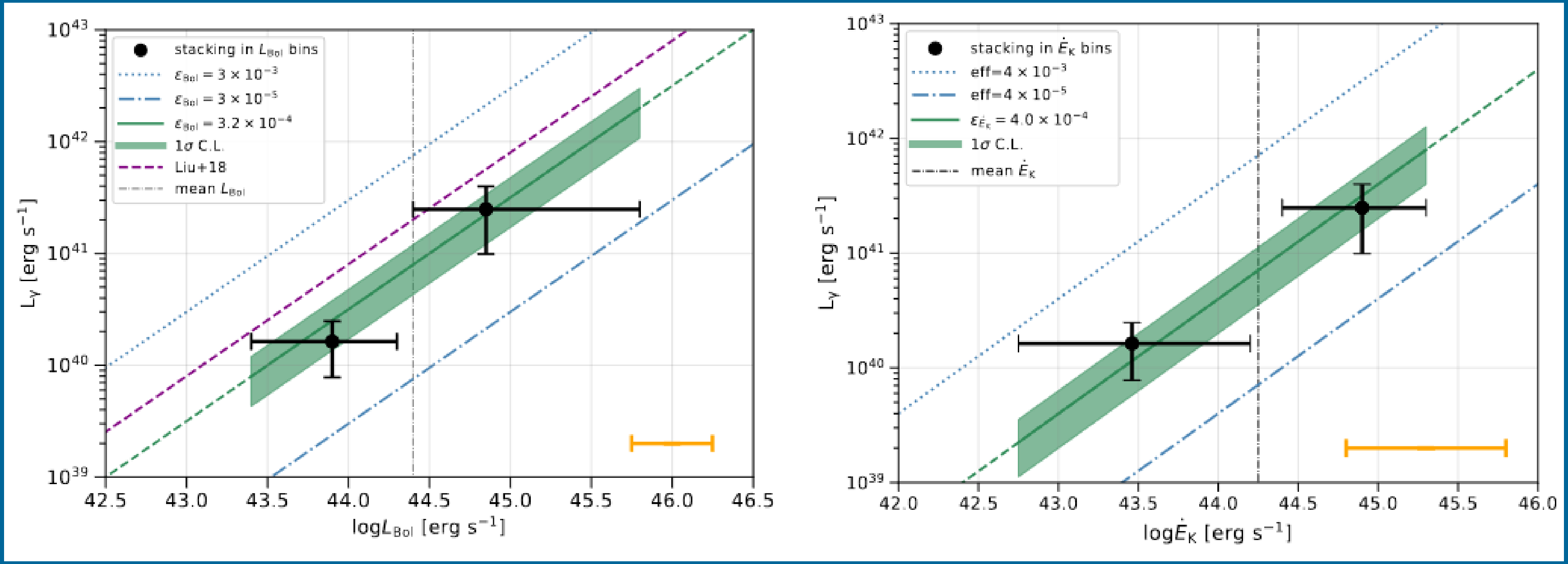


Обнаружен квазар на z=6.4
В нем отток вещества составляет 3500 масс Солнца в год.
Этого достаточно, чтобы воздействовать на всю галактику.

1204.2904

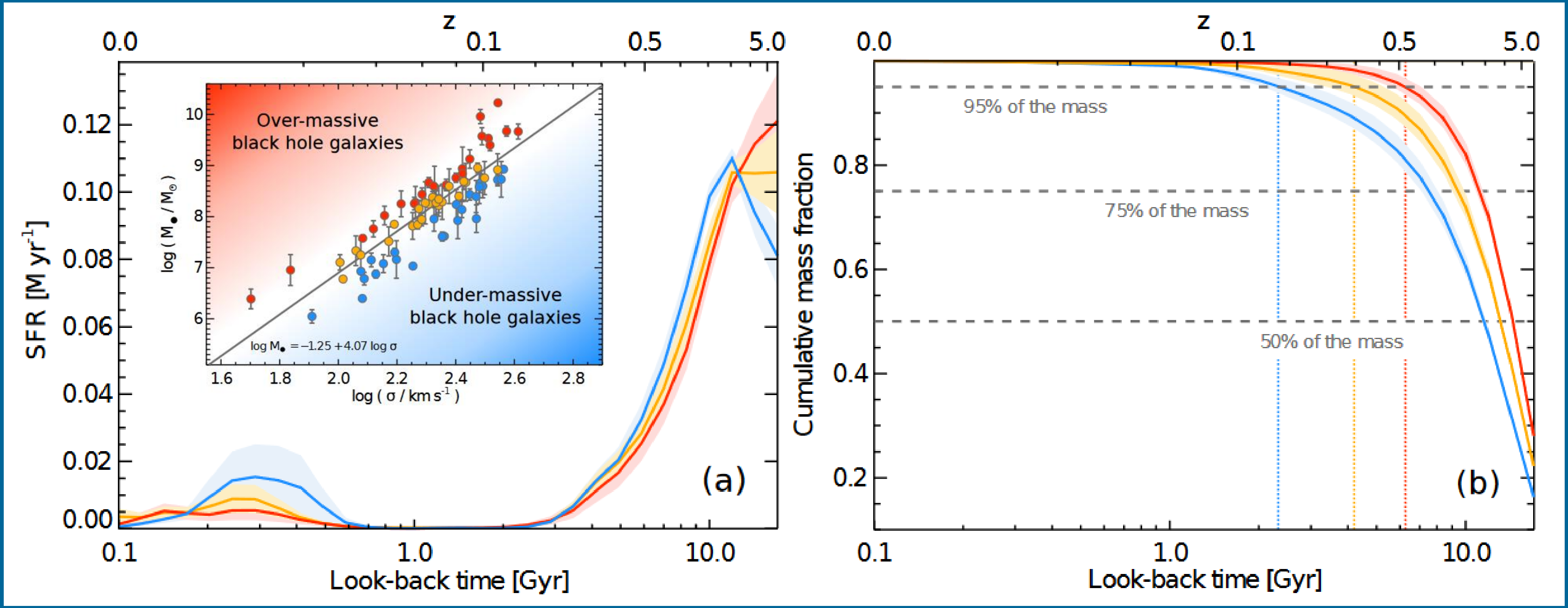
# Ultra-fast outflows visible in gamma

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

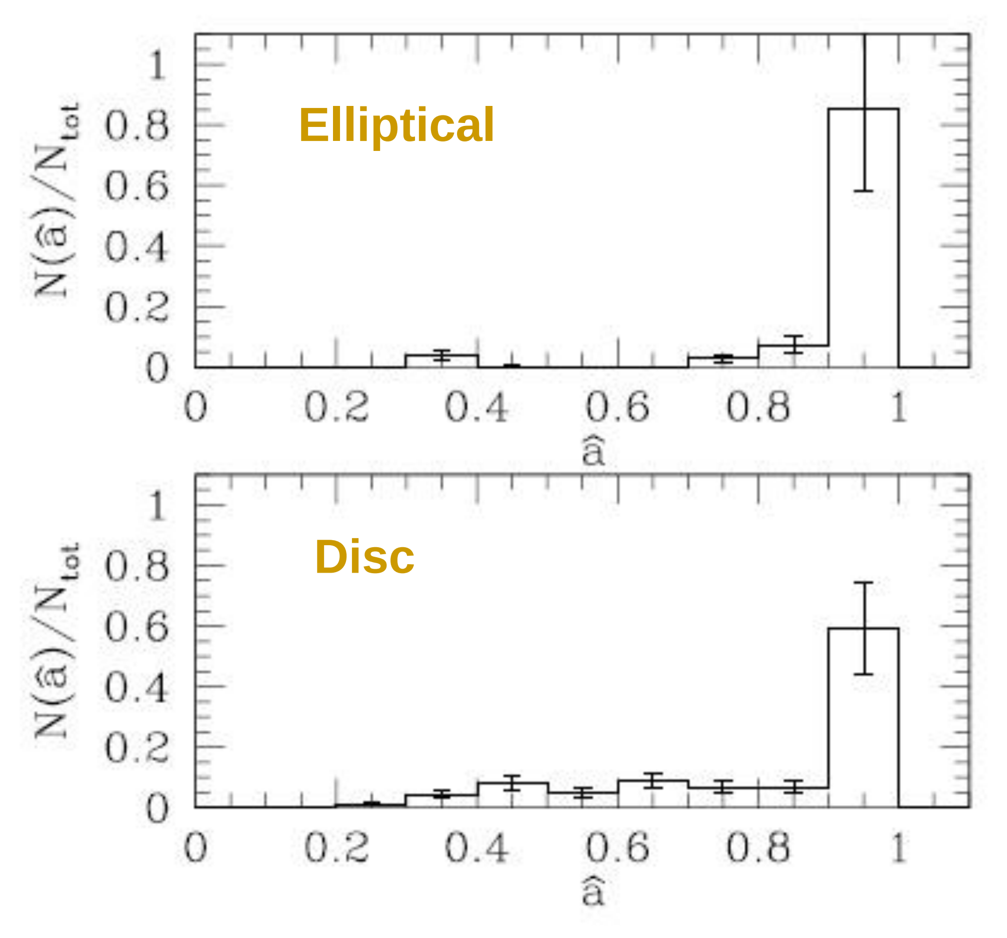
# Starformation rate and black hole mass



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



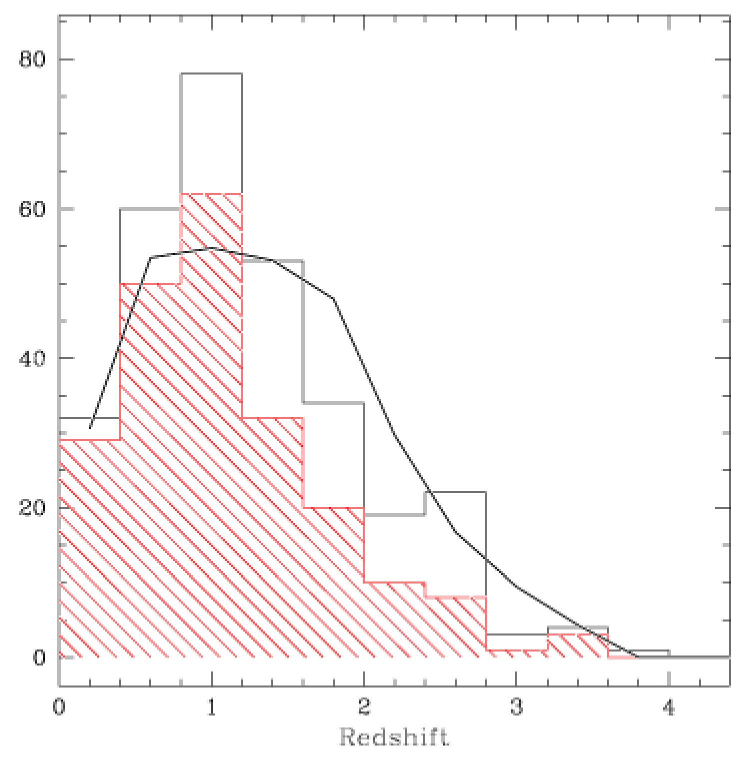
Some time ago it was noticed, that radio emission from elliptical galaxies is stronger, than from disc galaxies.

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

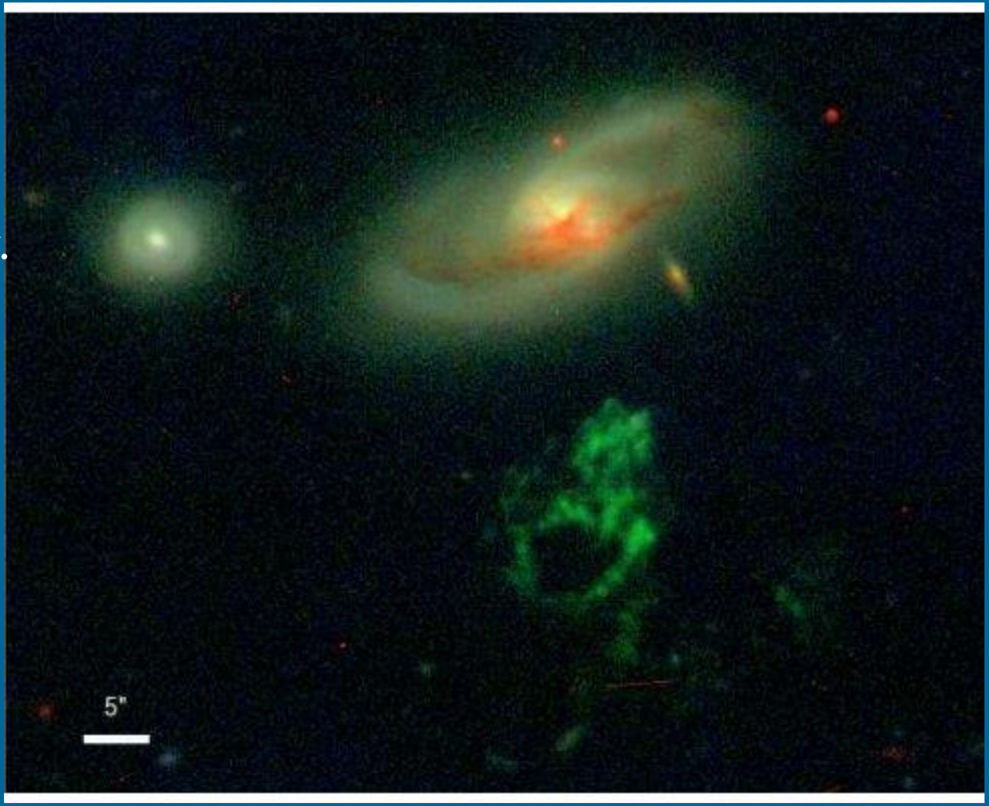
# Light echo from a dead quasar

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.

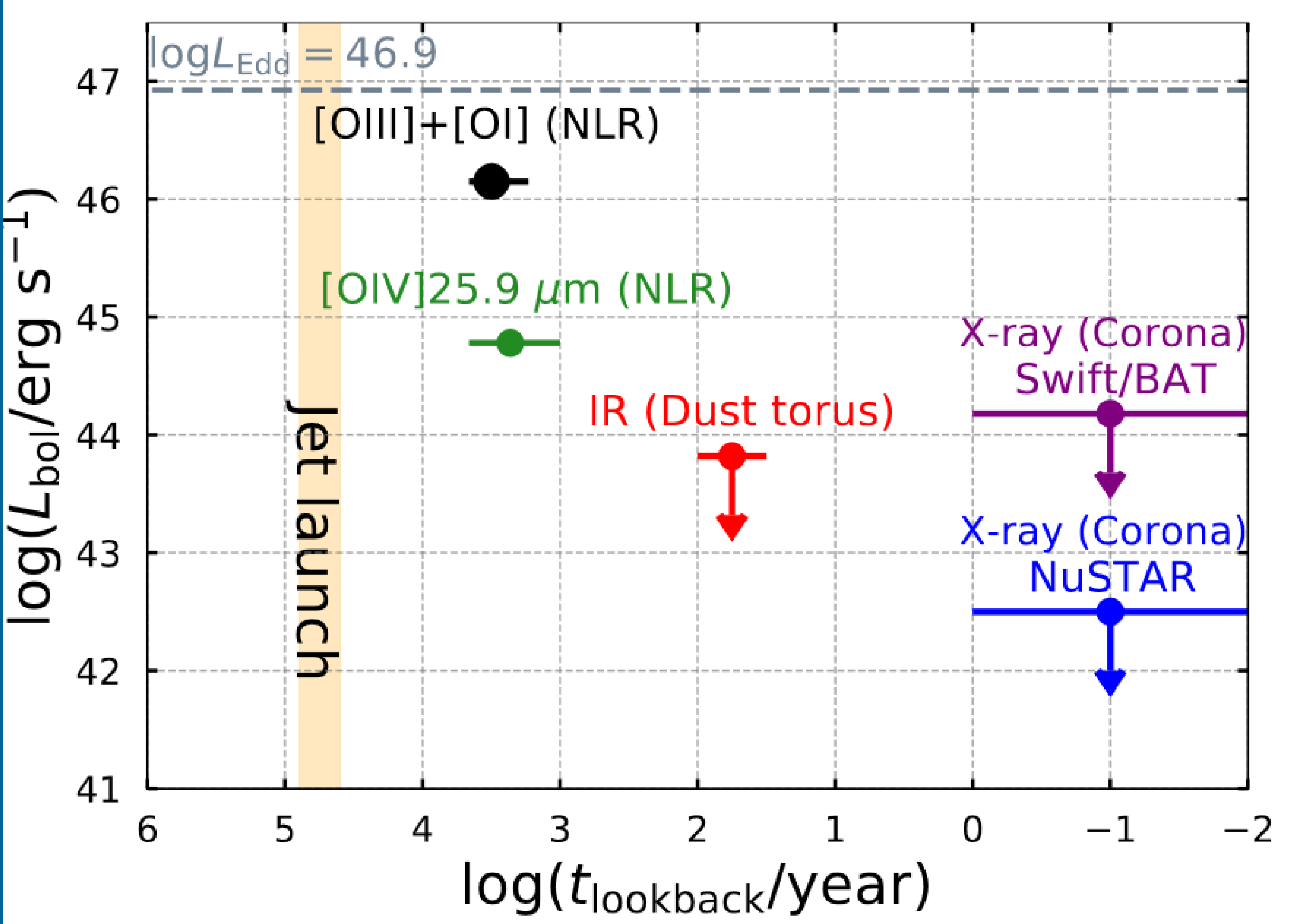
The alternative explanation
(a radiogalaxy with a jet and huge
absorbtion in the nuclei) was proposed
in arXiv: 1101.2784



This was the closest QSO!

arXiv: 1011.0427

# Another light echo



Arp 187

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

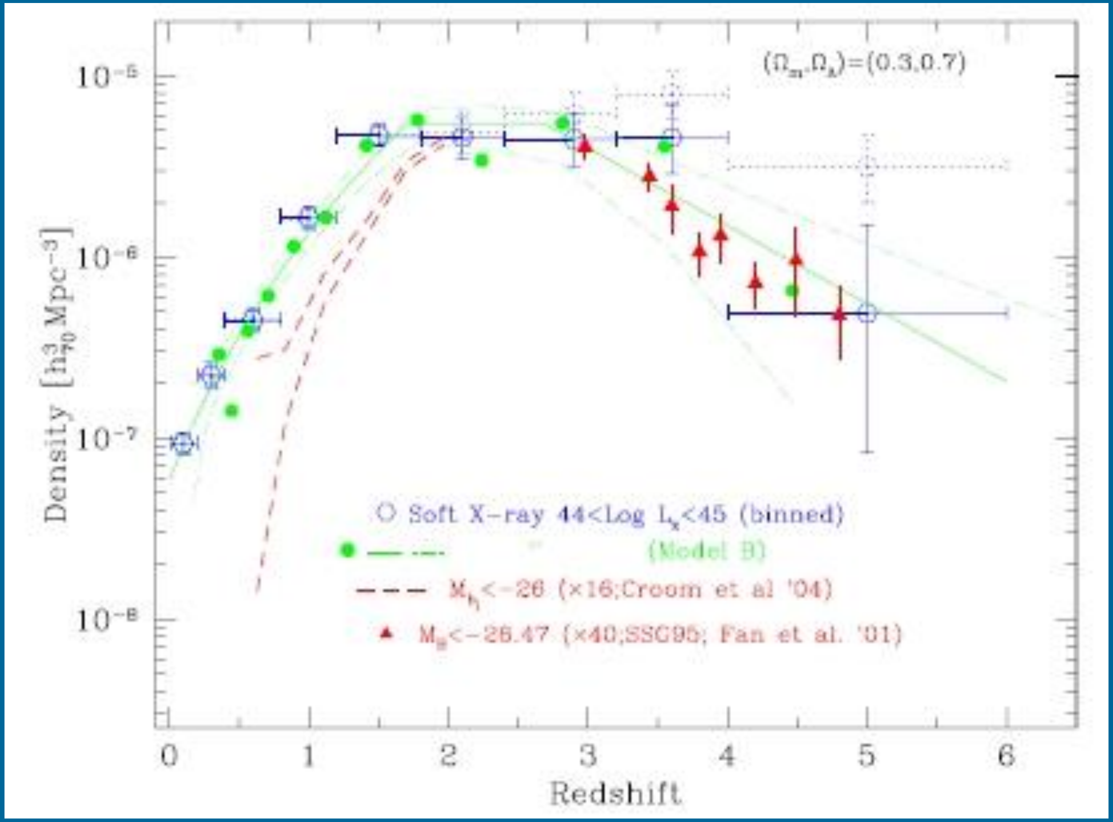
Kinematic age of the jet ~8 $10^4$ yrs.

Size of narrow line region ~1 kpc.

TDE of a molecular cloud

1908.10864

# Evolution of quasars number



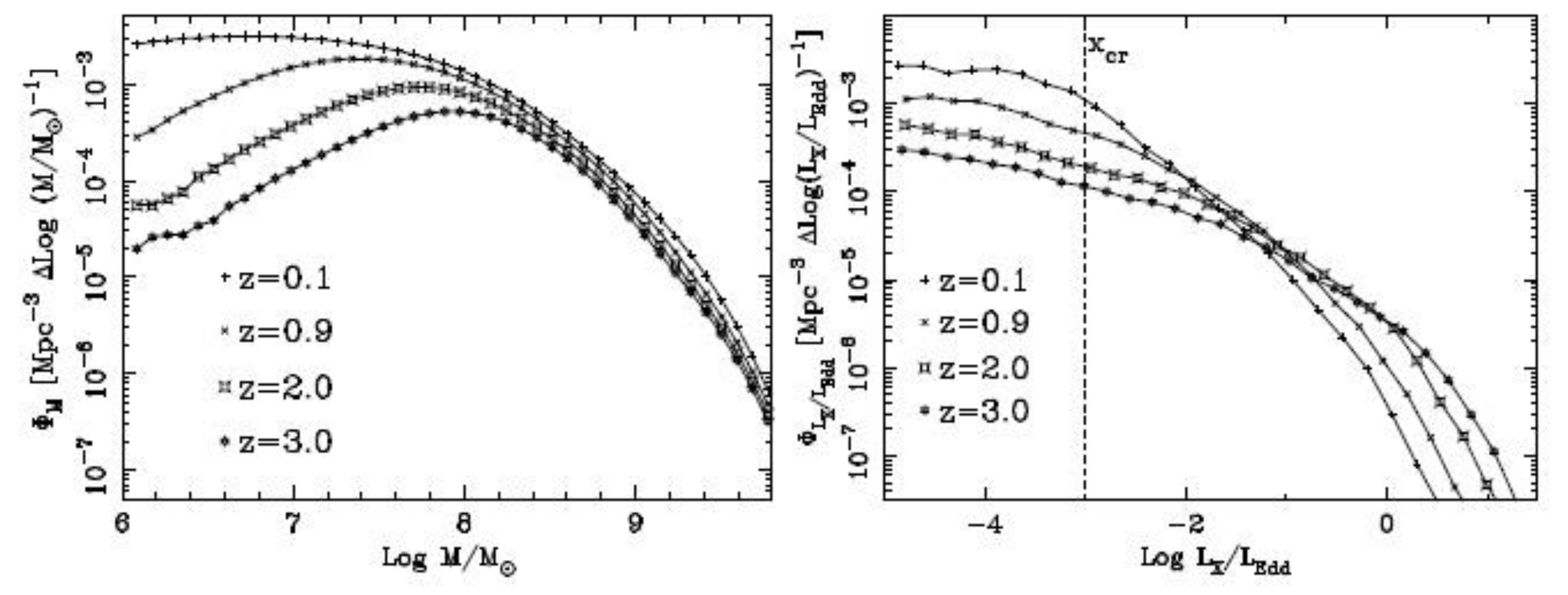
Very bright quasars are formed very early, and then their number is decreasing.

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.

Combes astro-ph/0505463

# Mass and luminosity evolution



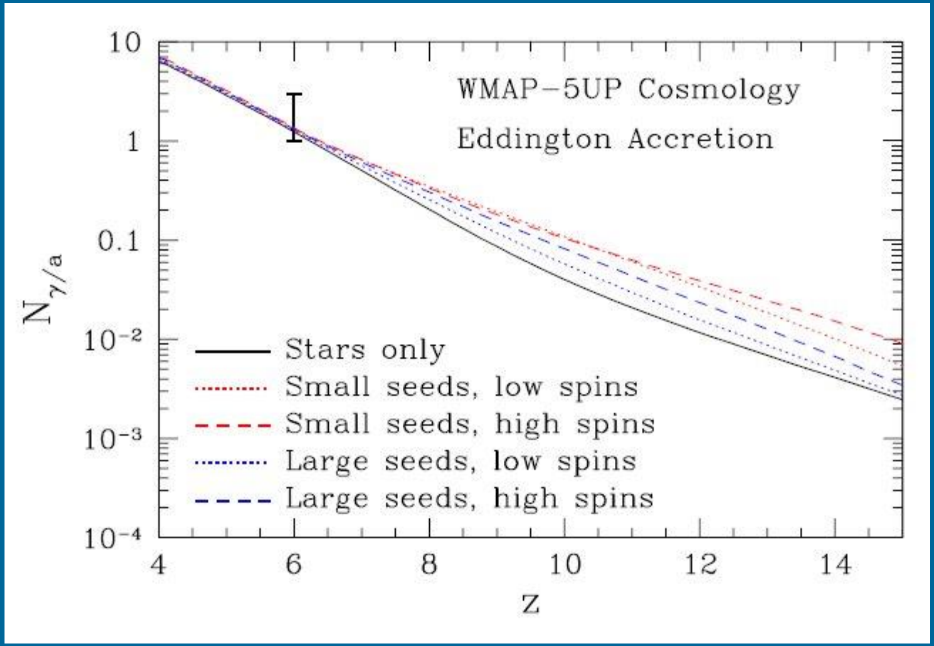
Results of numerical simulations are shown (Merloni 2004).
Lifetime grows with decreasing z.

see Combes astro-ph/0505463

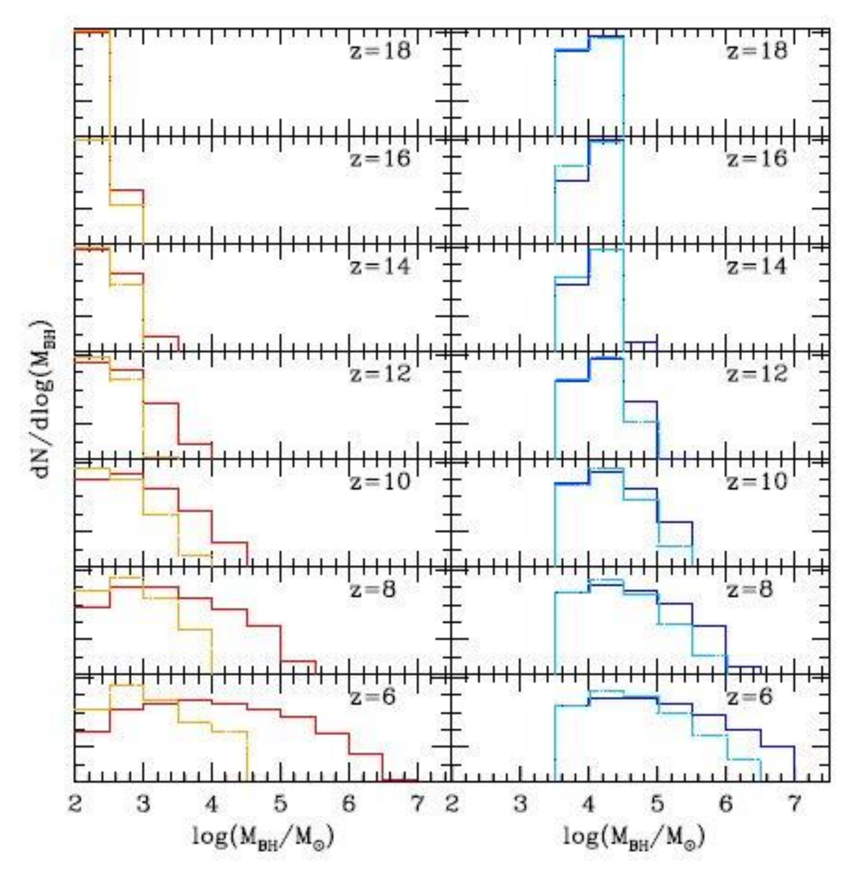
# Quasars and reionization

It is important that quasars
have harder spectrum.

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



Mass function of MBHs
at different cosmic times

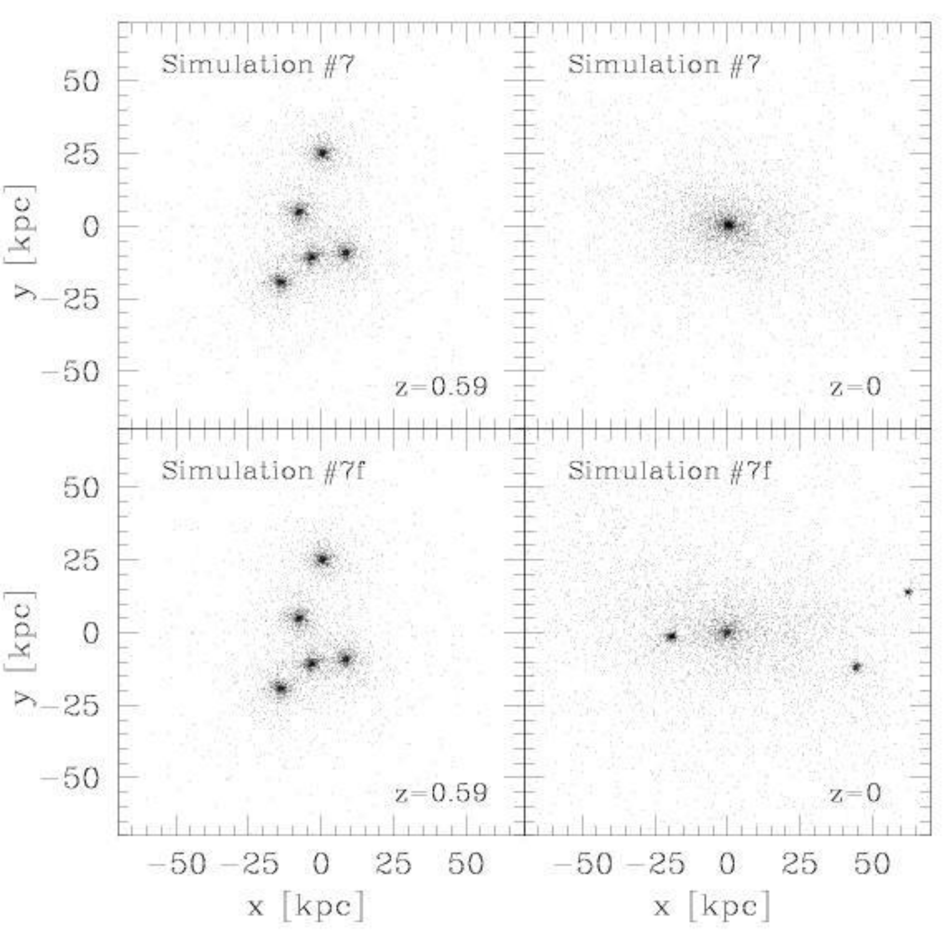


Small seeds

Large seeds

arxiv:0905.0144

# Galactic cannibalism



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

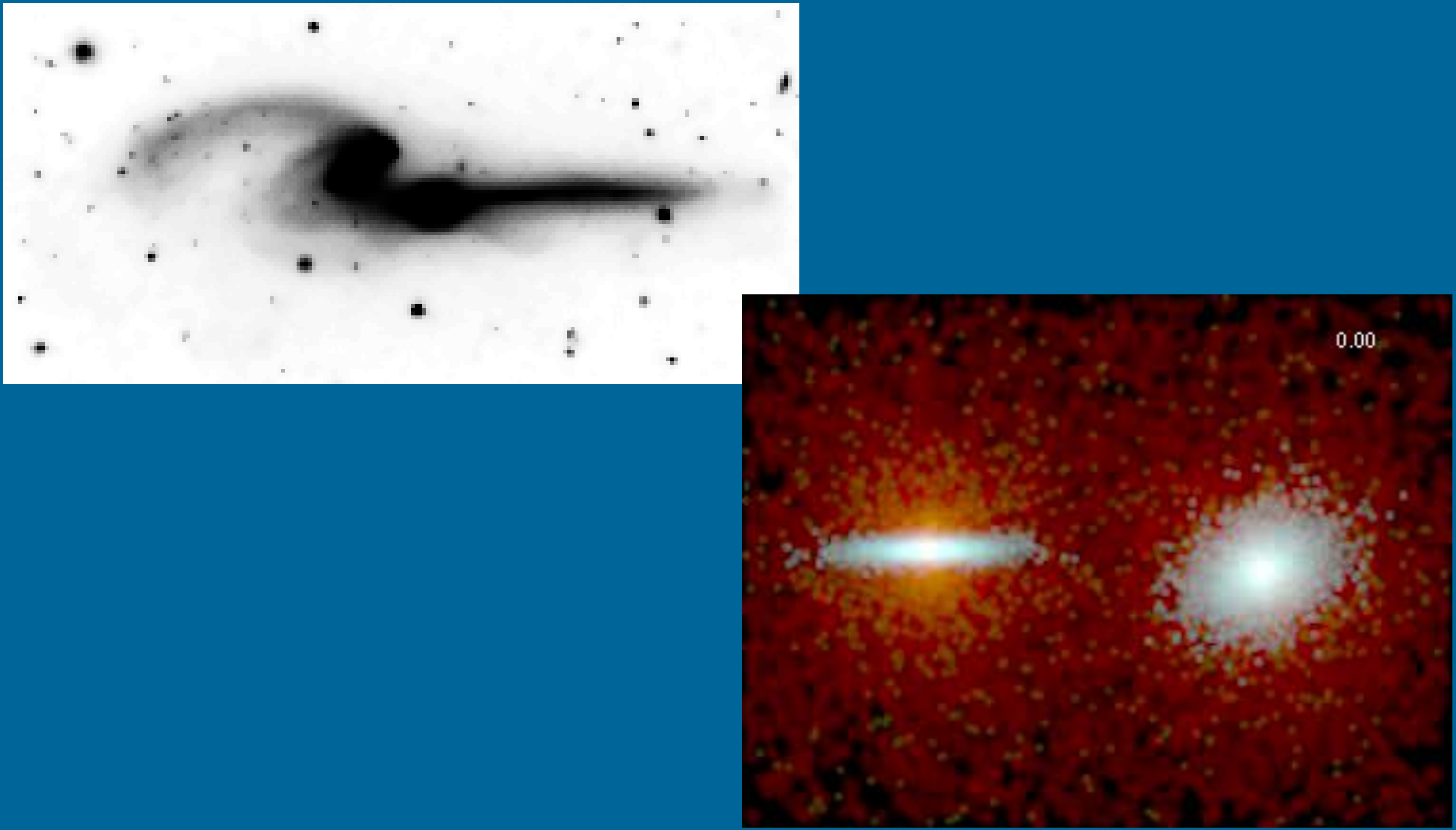
**On the left the present day (observed) configuration is shown.**

**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.

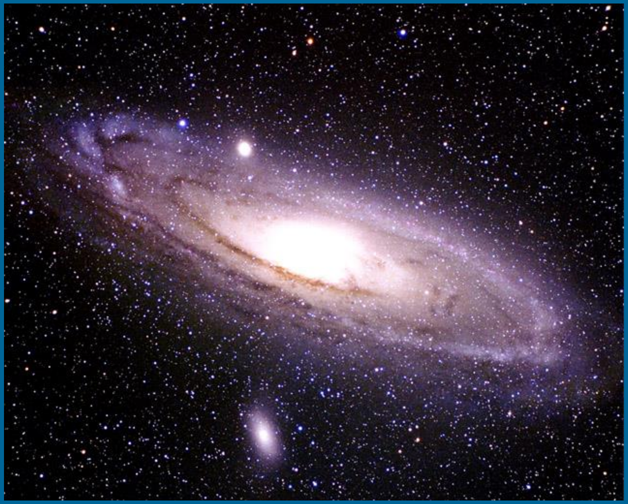
C.Nipoti et al. astro-ph/0306082

# Interacting galaxies

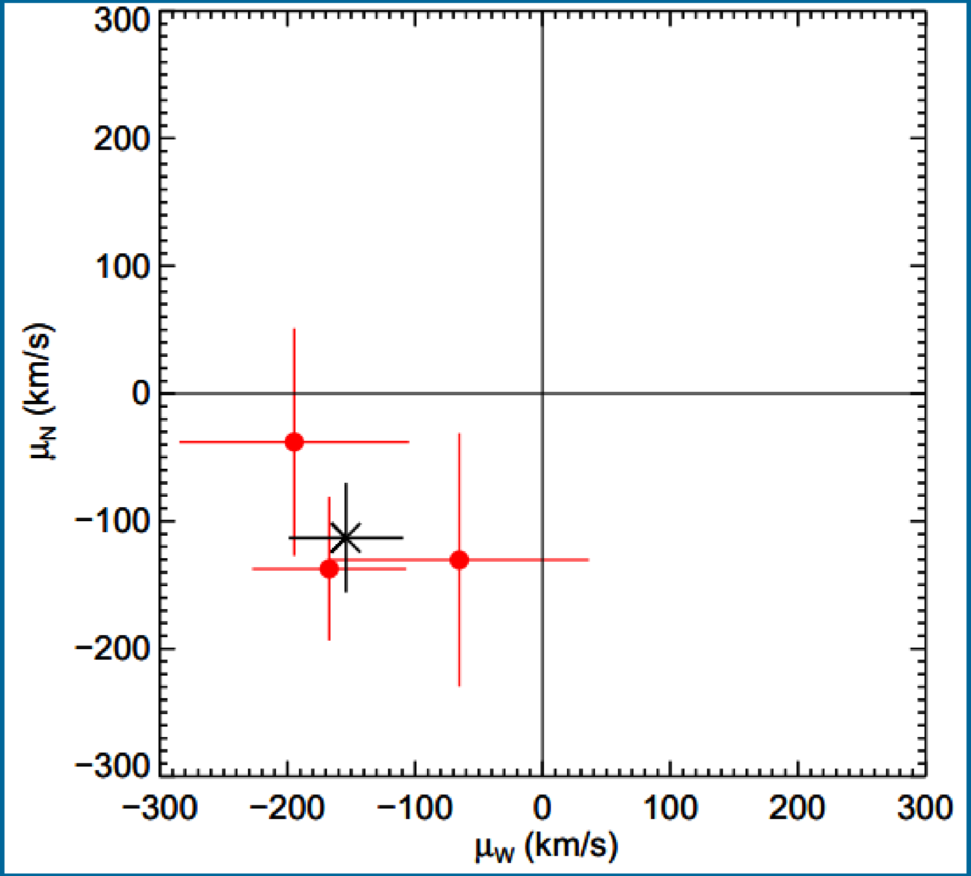


**(Hibbard, Barnes)**

# Куда движется туманность Андромеды?

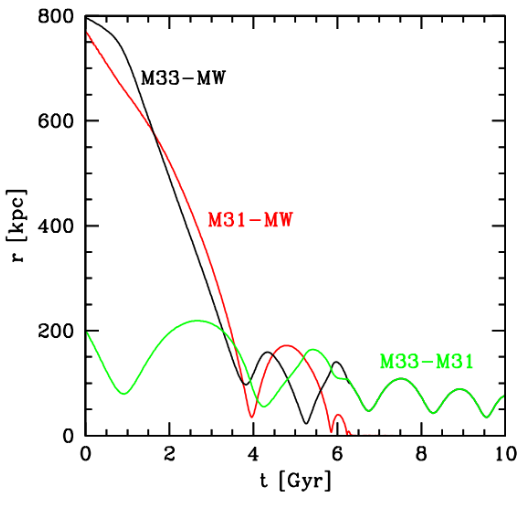


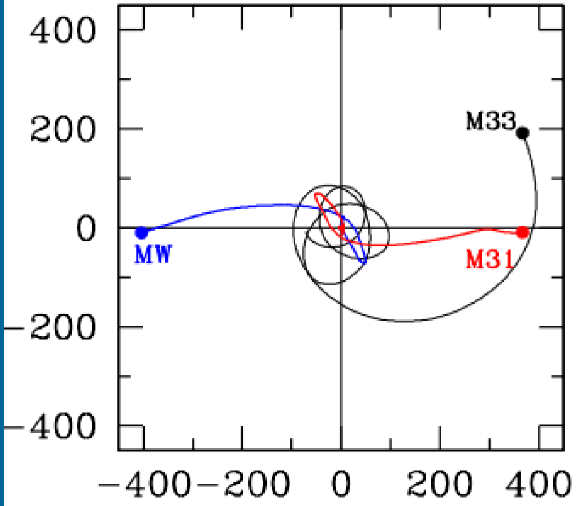
Впервые удалось измерить собственное движение ближайшей крупной галактики – M31.
Это позволяет определить ее трехмерную скорость.

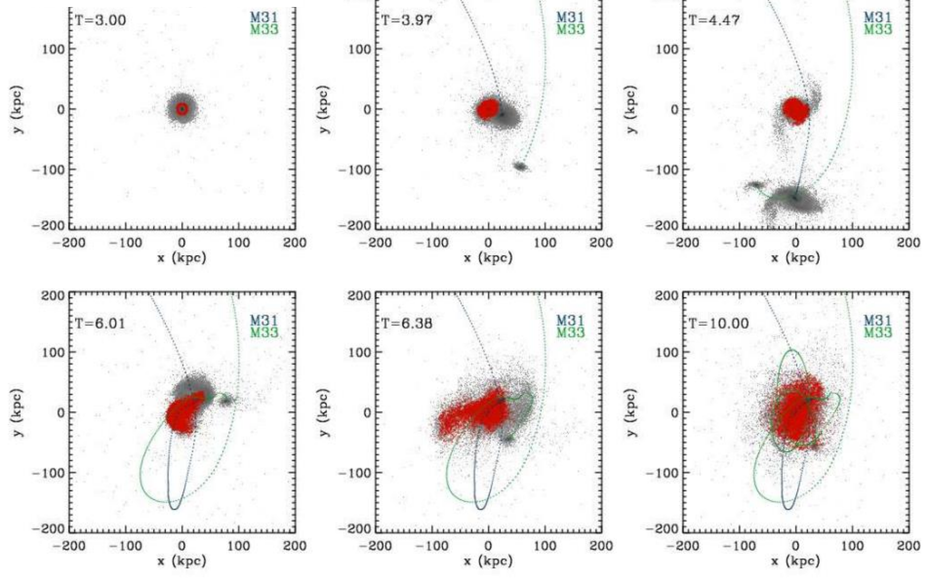


1205.6863

# Как все сольется



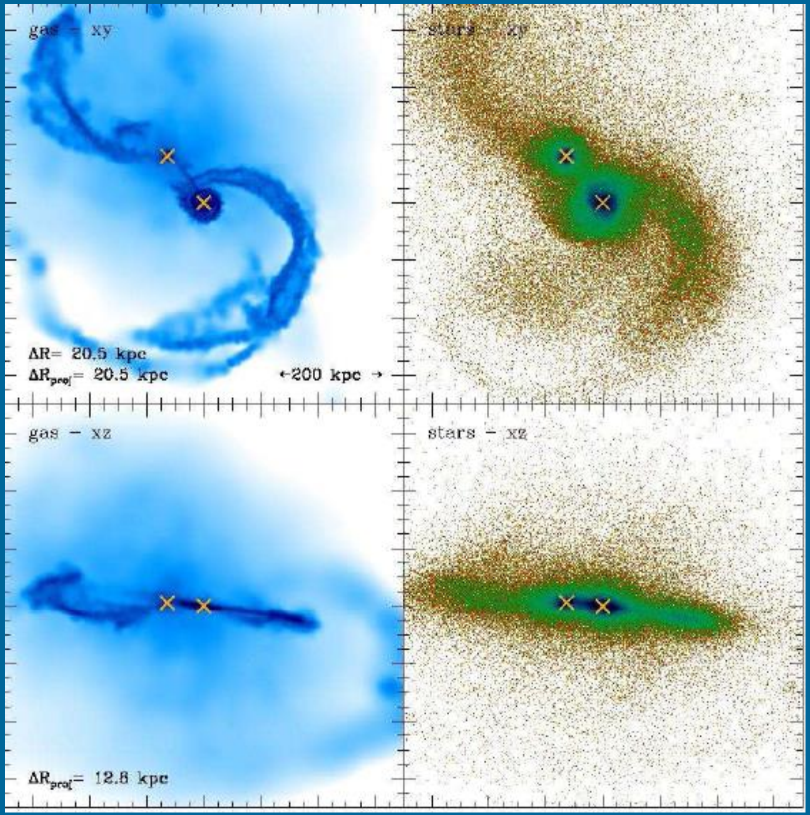


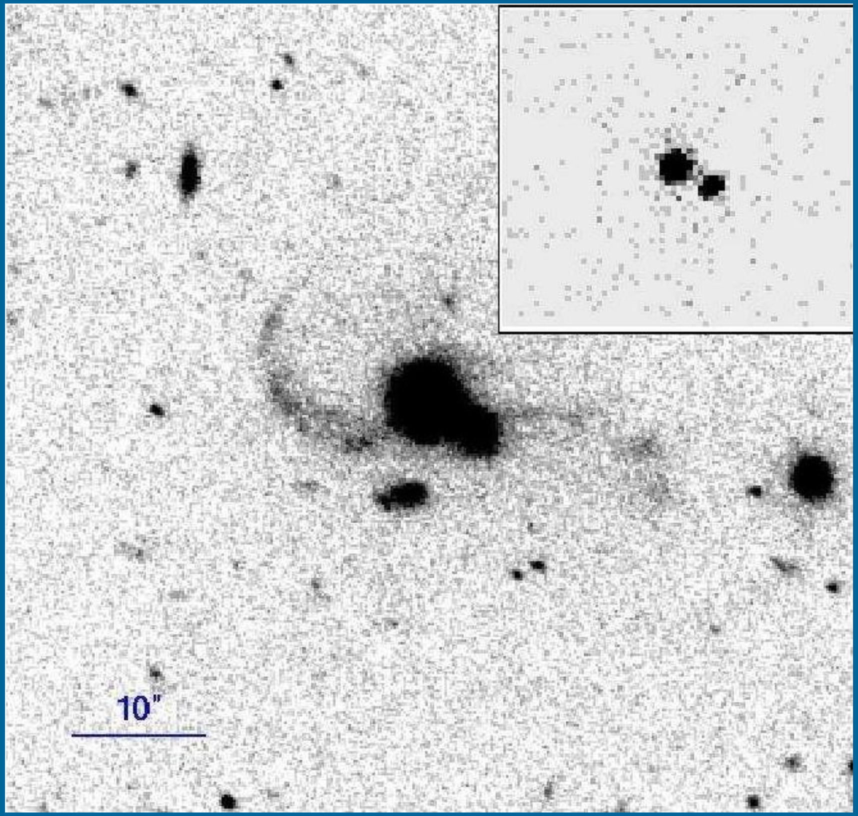


Наша Галактика и M31 сольются через 5-7 млрд. лет. Первое сближение произойдет через 3.5-4 млрд. Скорее всего, M33 также сольется с Милкомедой.

# Double quasar in a merger

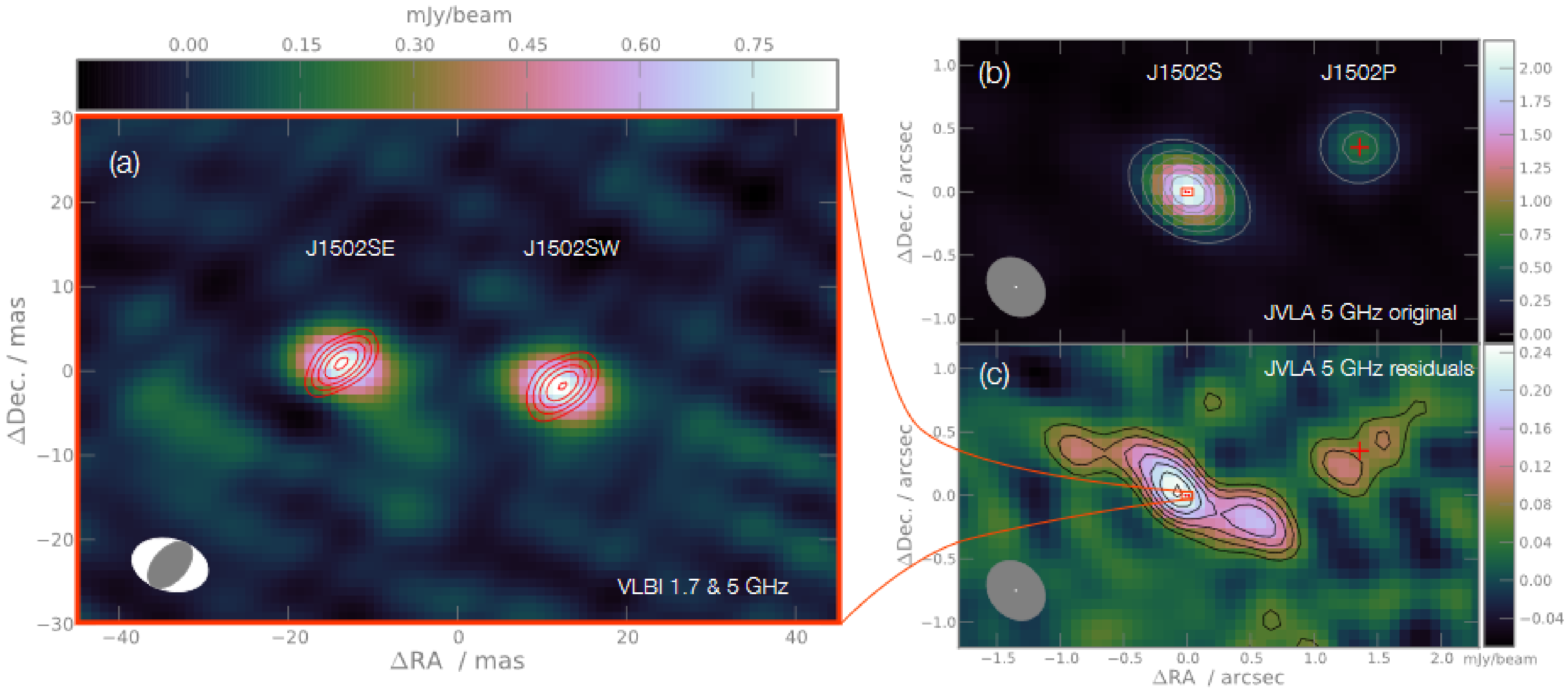
For the first time a bright binary QSO is found in a clearly merging pair of galaxies.
Both QSOs are radioquiet. They form a physically bounded system at z=0.44.
In projection the separation is 21 kpc.





arXiv: 1001.1783

# Triple BH system

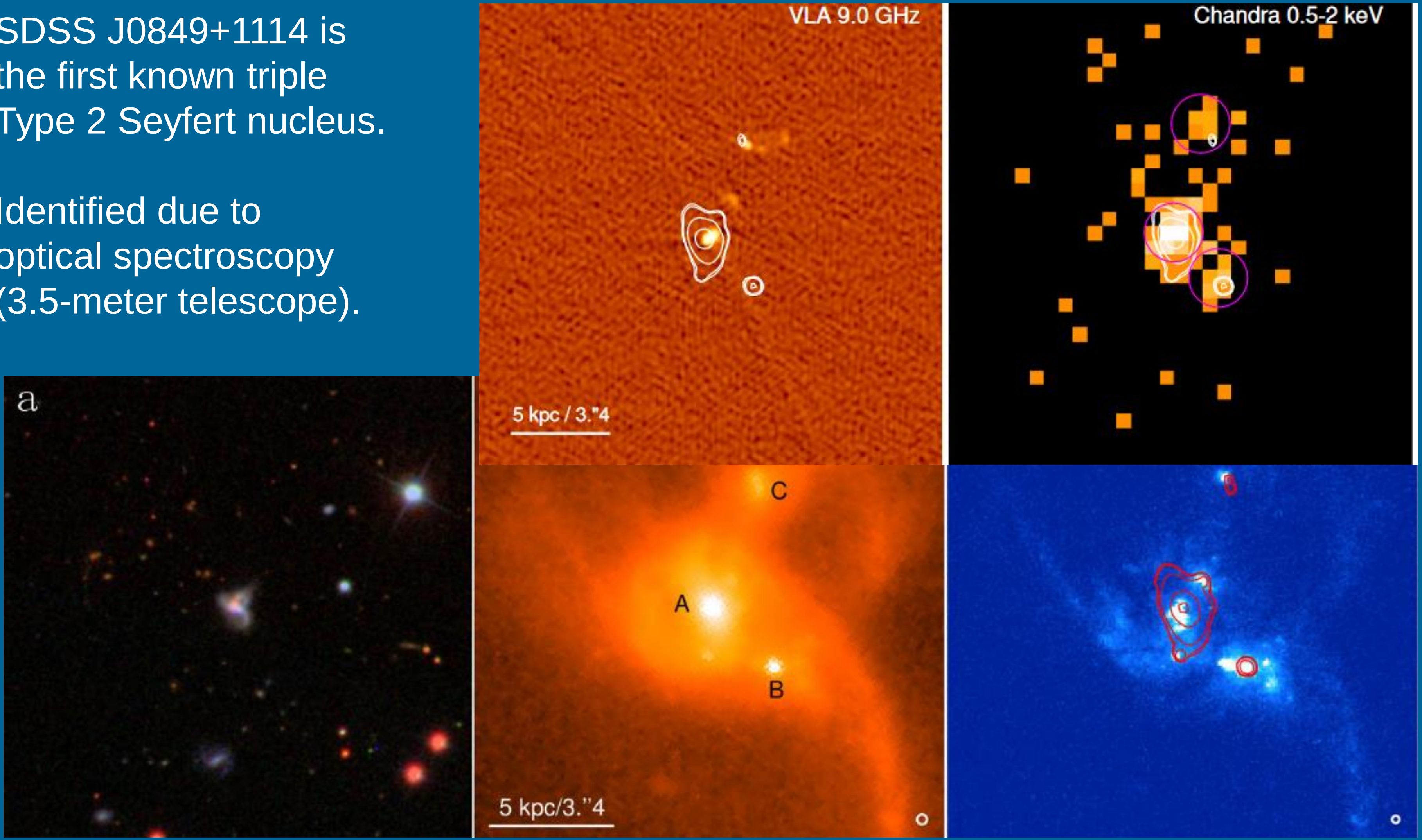


1406.6365

# Triple SMBH in a Seyfert galaxy

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

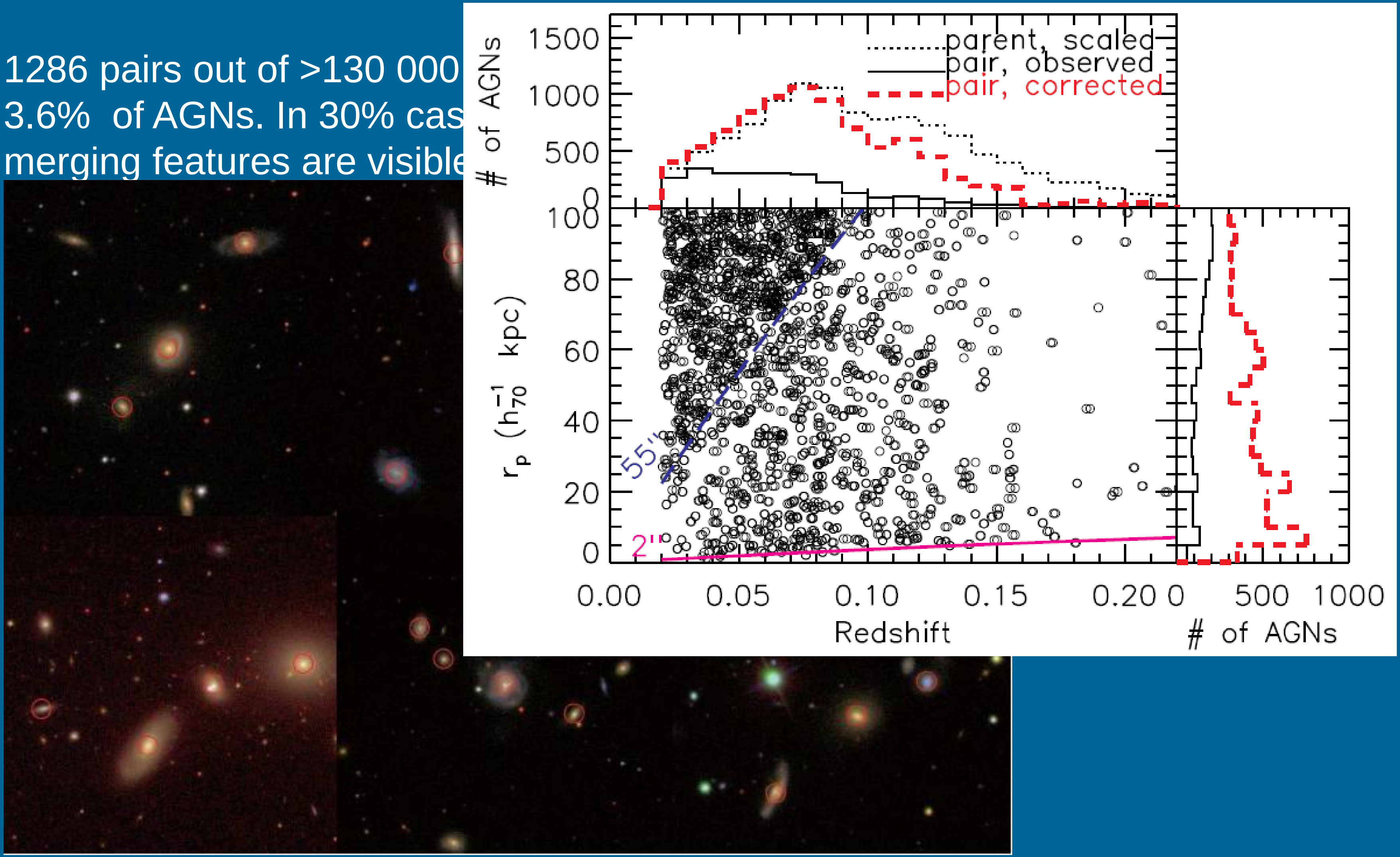
Identified due to optical spectroscopy (3.5-meter telescope).



1907.10639, see new results in 2012.00769

# AGN pairs in SDSS

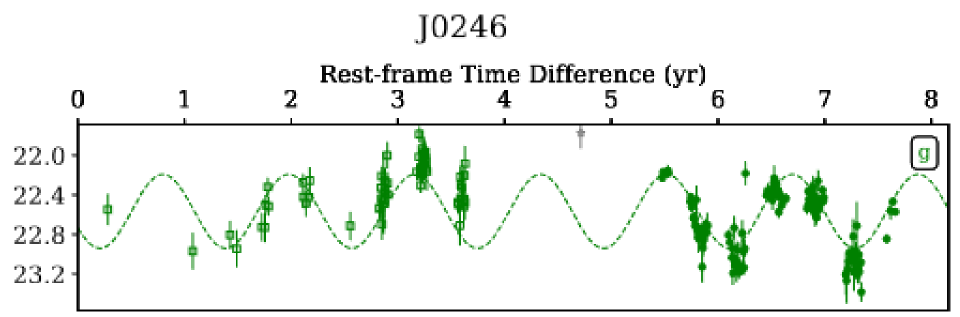
1286 pairs out of >130 000
3.6% of AGNs. In 30% cas
merging features are visible

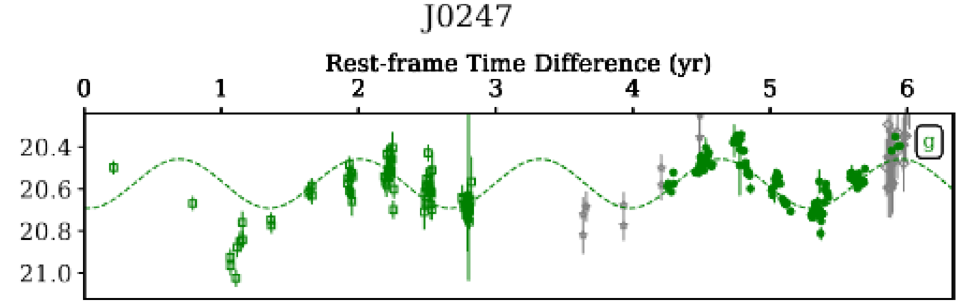


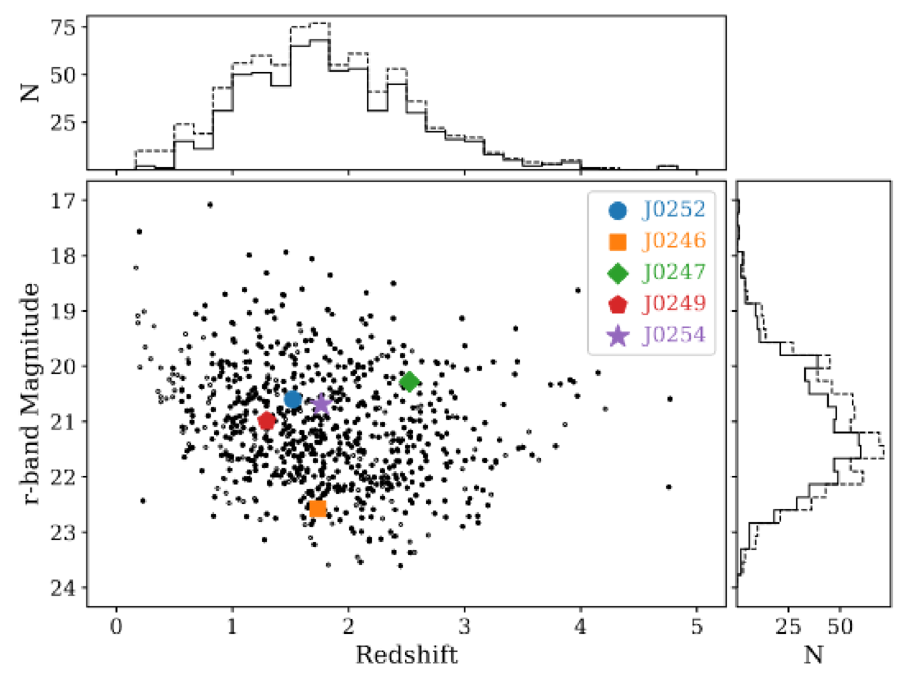
1104.0950, 1104.0951

# Periodic variability in QSOs

5 candidates among ~700 sources







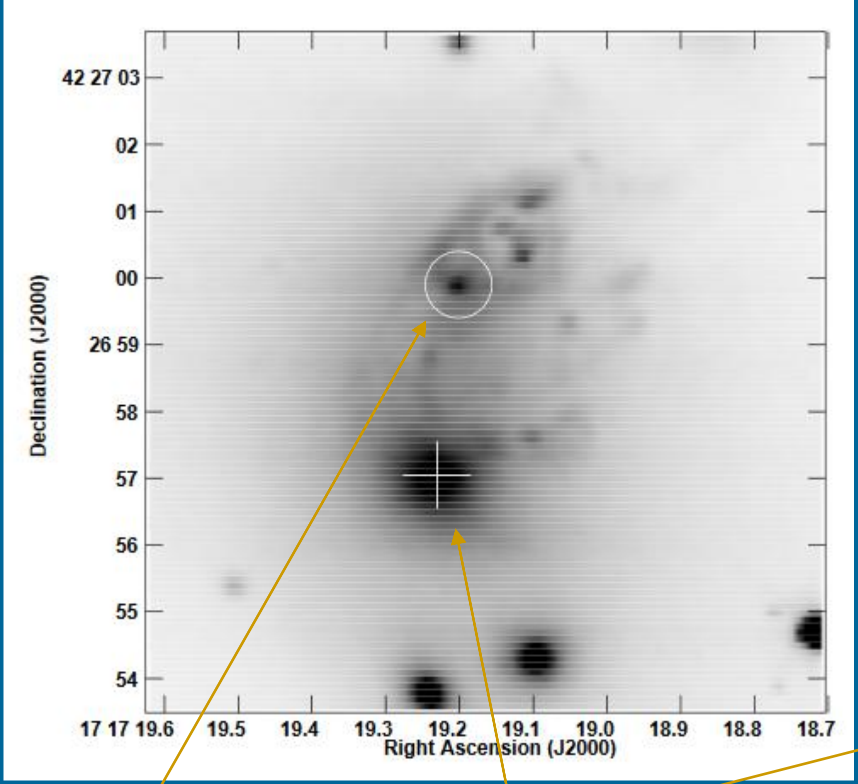
LSST might find many periodically variable AGNs, see e.g. 2110.07465

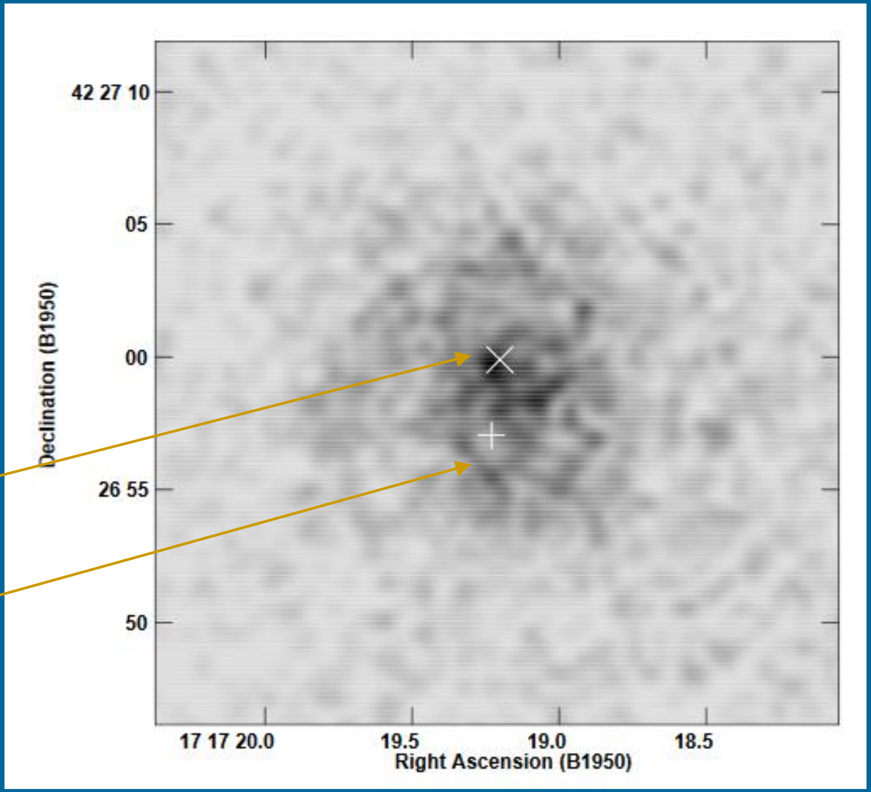
2008.12329

# 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

# 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:

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

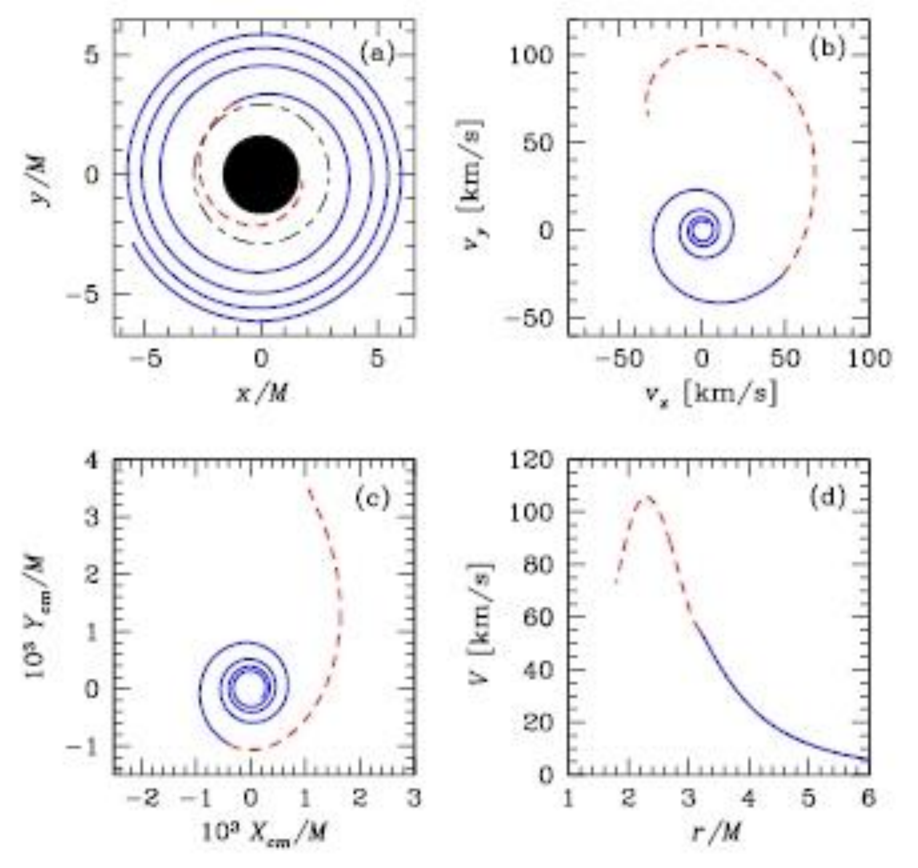
$f(q)=q^2(1-q)/(1+q)^5$, $f_{max}=0.38$

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.

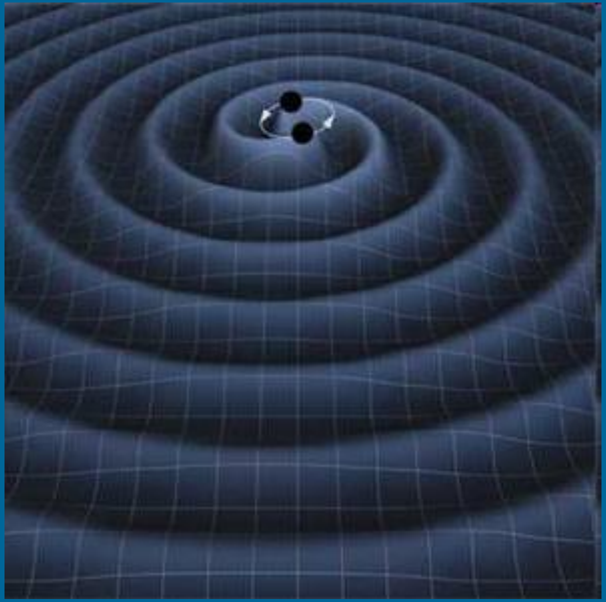
**astro-ph/0402056** “How black holes get their kicks?”

# Favata et al. (2004)

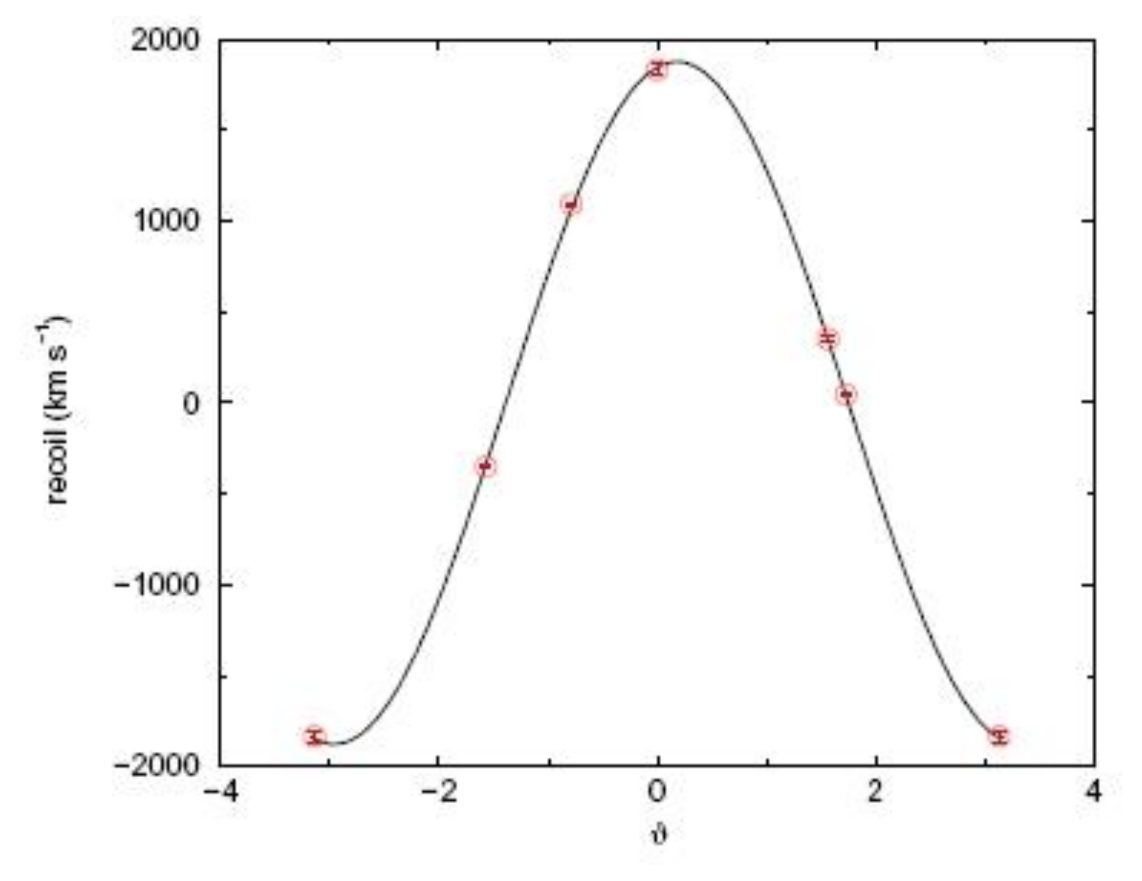


a/M=0.8, q=0.127
(rotation of the smaller BH
is neglected)

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



# Maximum kick



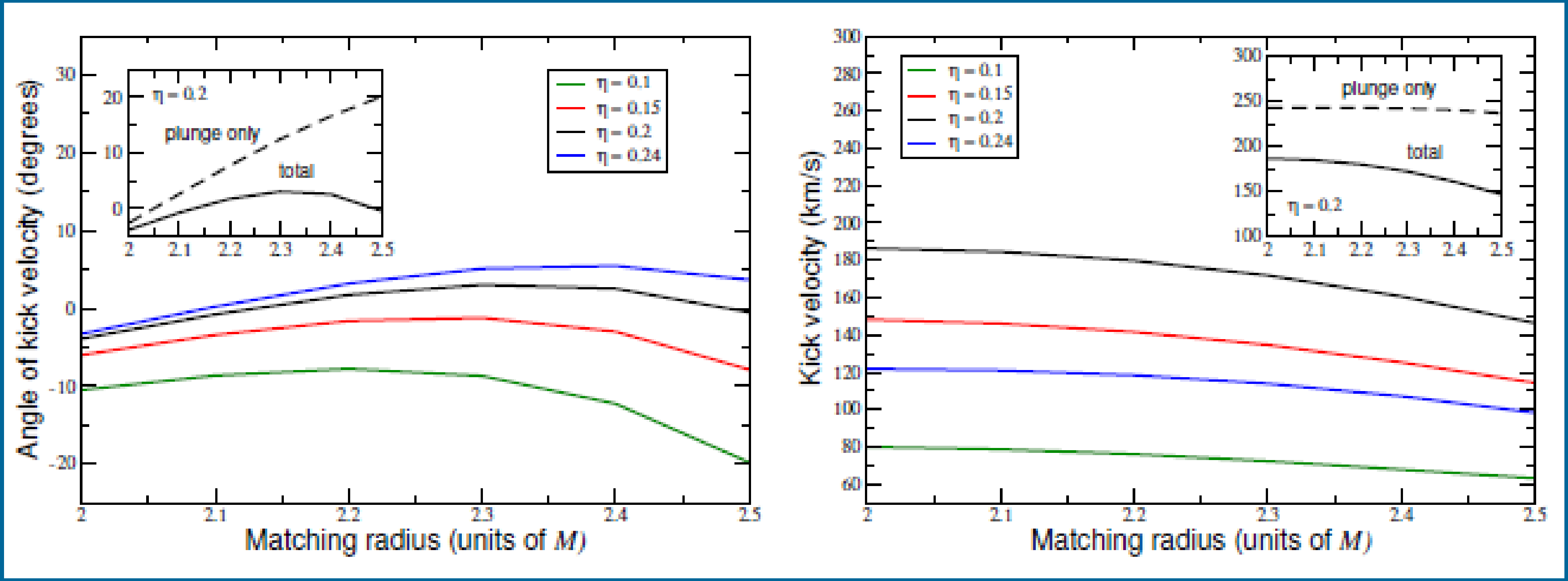
The velocity is strongly dependent on the relative orientation of BHs spins prior to coalescence.

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

Campanelli et al. gr-qc/0702133

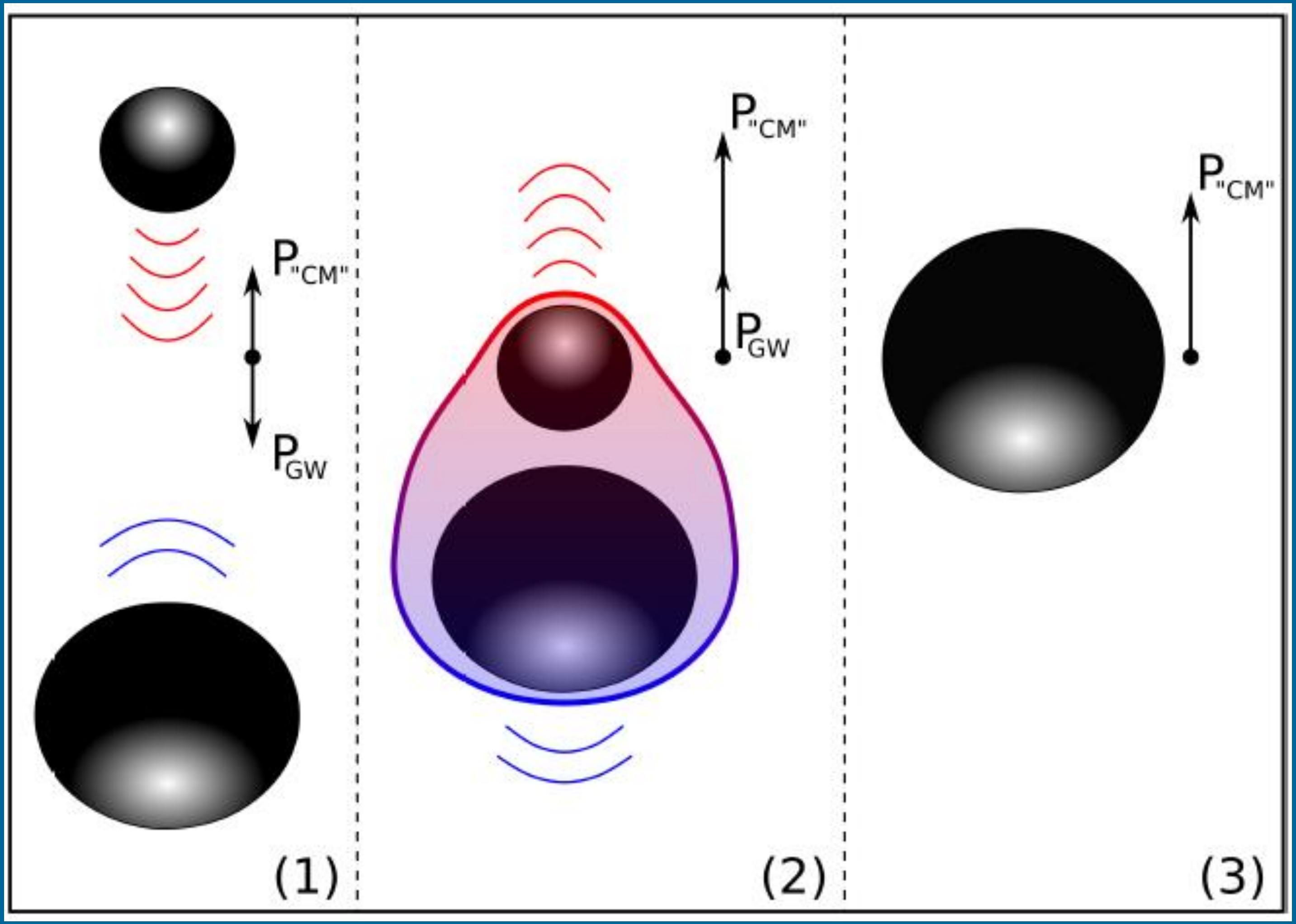
# Antikick

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 significant “anti-kick".



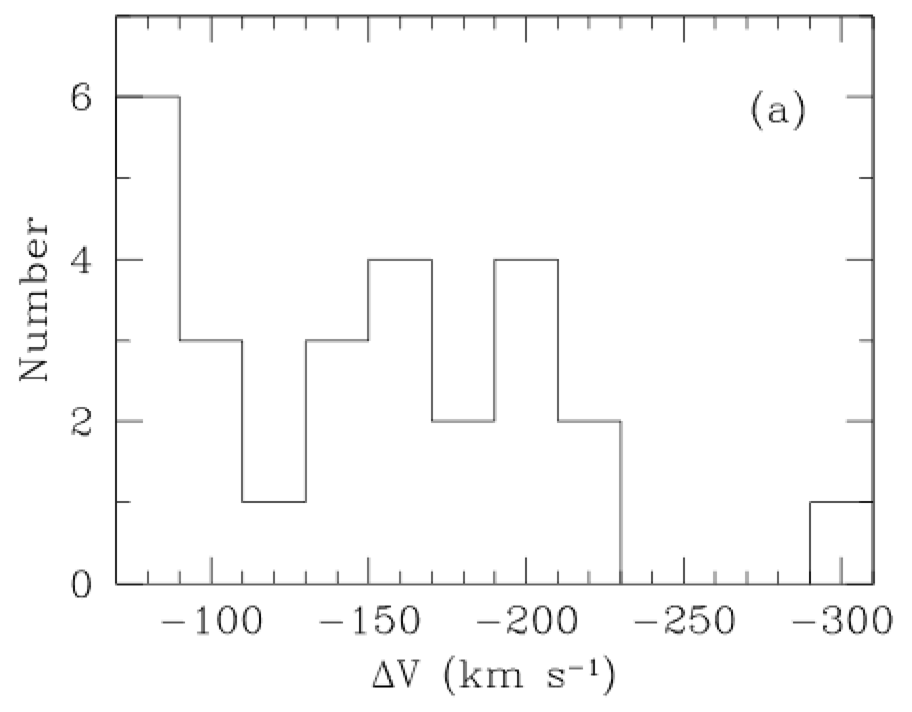
0910.4594

# Antikick



1003.0873

# Recoiling BH



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

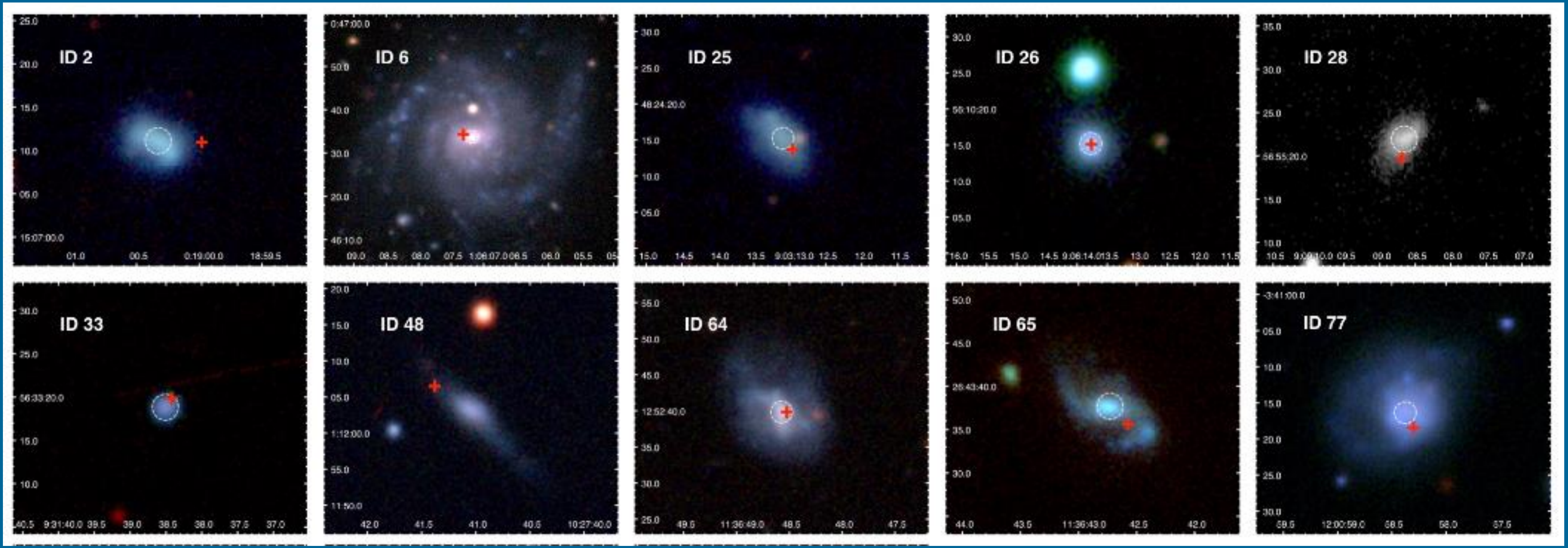
Average velocity ~265 km/s.

See also 1409.3976

1604.05604

# Wandering BHs in Dwarf Galaxies

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

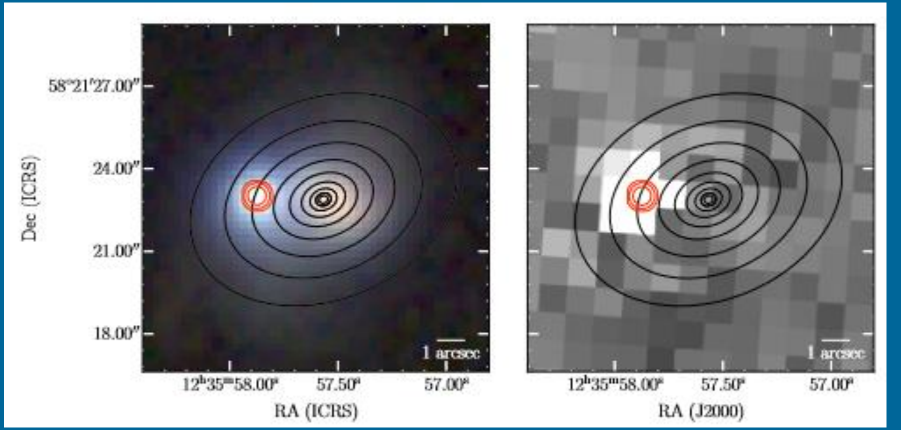


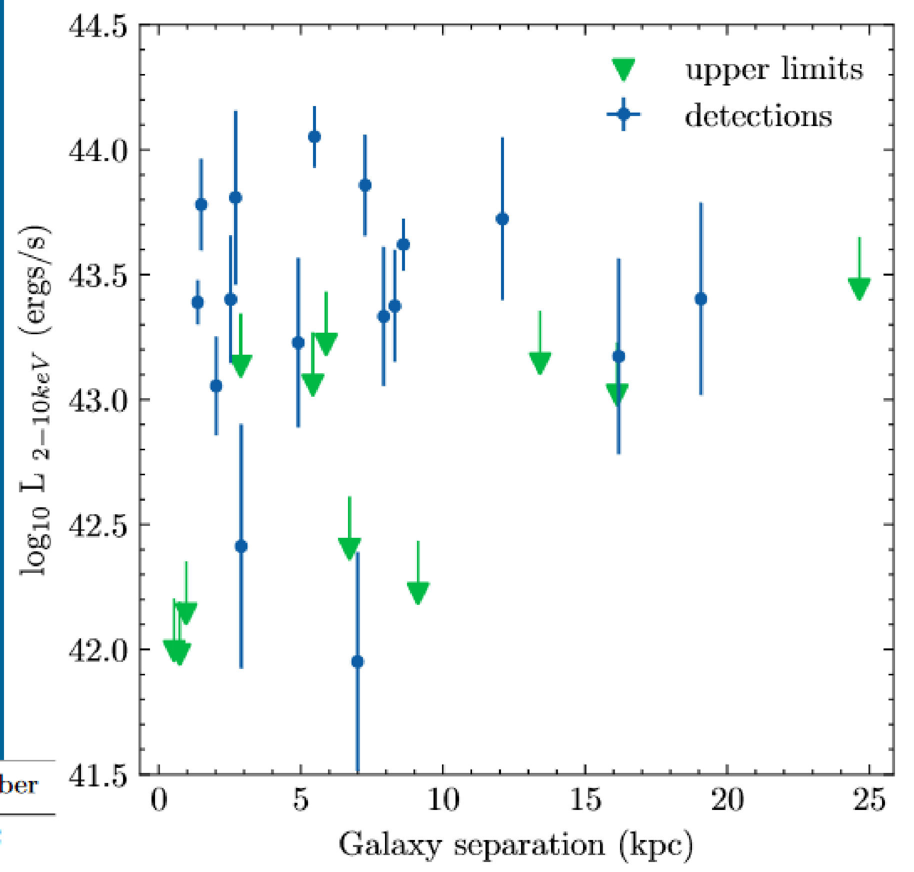
Off-center BHs in dwarf galaxies can be also due to mergers, see 2102.09566

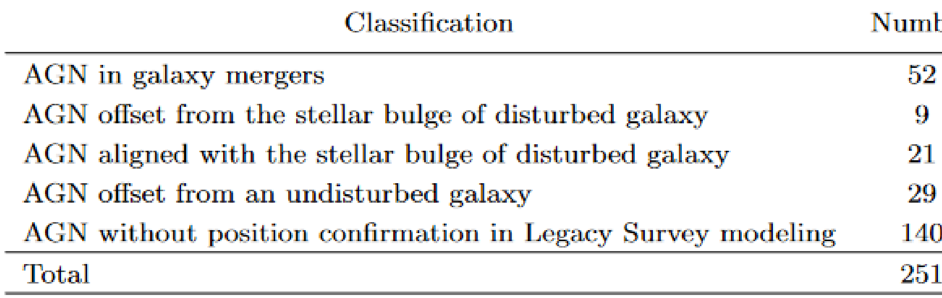
1909.04670

# Offcenter optical sources

ZTF
~10 recoiling SMBHs and
~50 merging galaxies







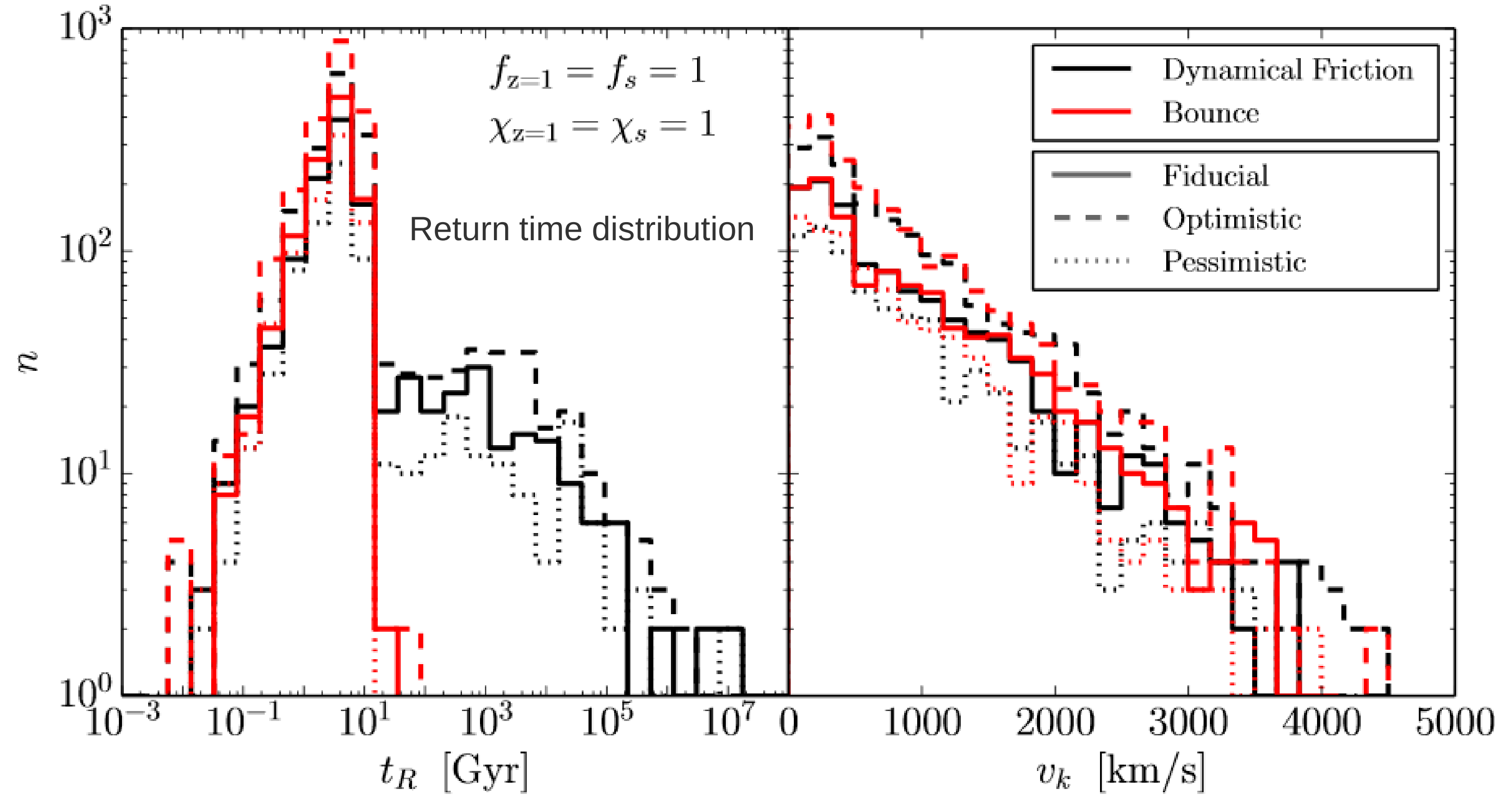
| Classification | Number |
|---|---|
| AGN in galaxy mergers | 52 |
| AGN offset from the stellar bulge of disturbed galaxy | 9 |
| AGN aligned with the stellar bulge of disturbed galaxy | 21 |
| AGN offset from an undisturbed galaxy | 29 |
| AGN without position confirmation in Legacy Survey modeling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

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

2011.11656

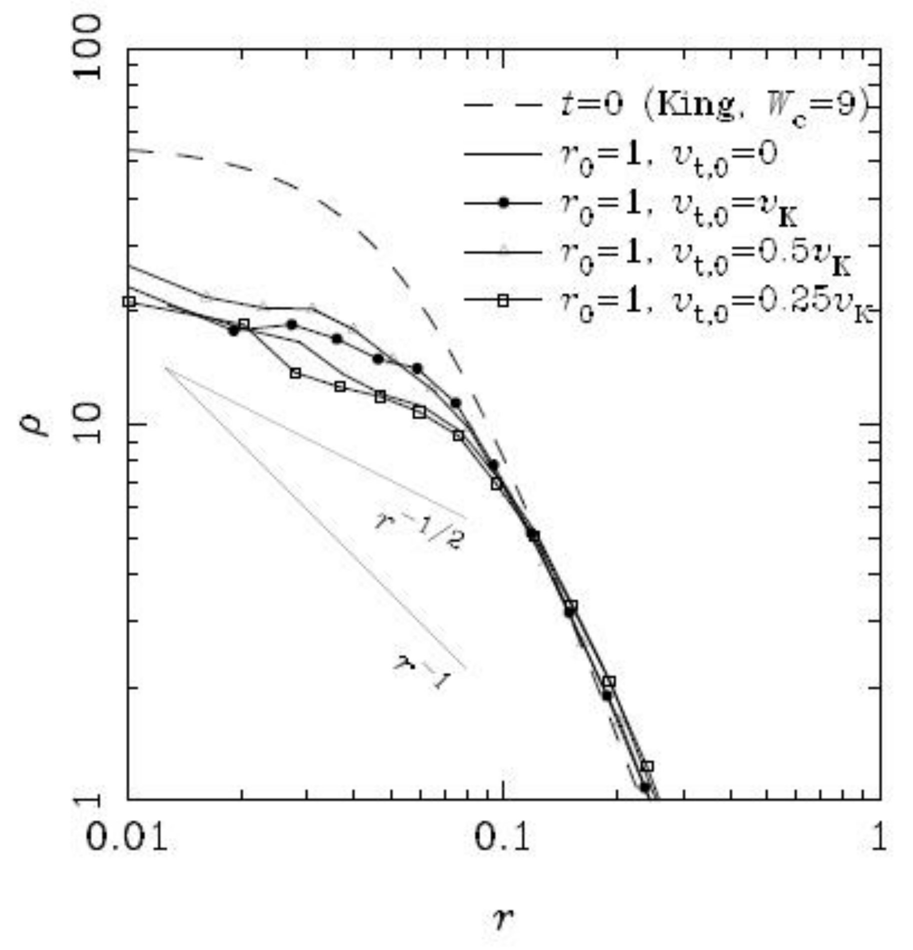
# Superkicks?

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

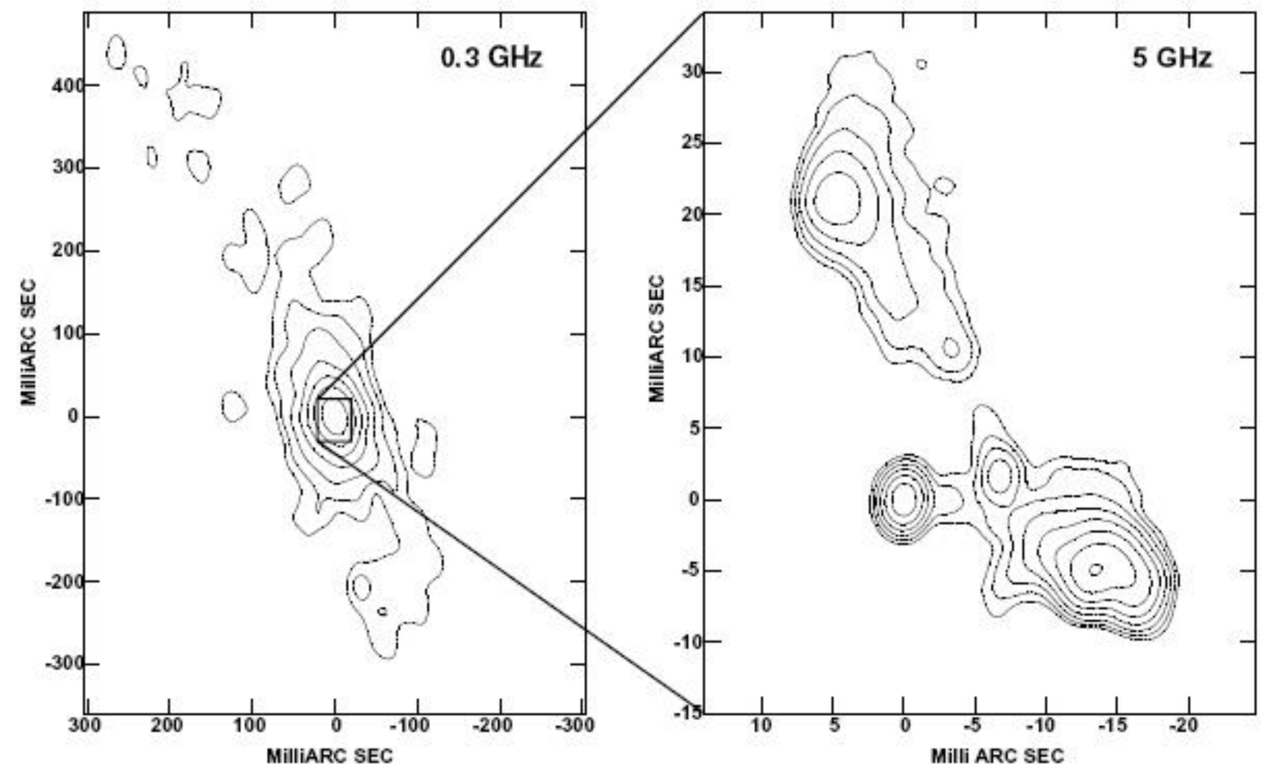
# Stellar density profile evolution in the case of two BHs



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

Combes astro-ph/0505463

# Binary supermassive BHs



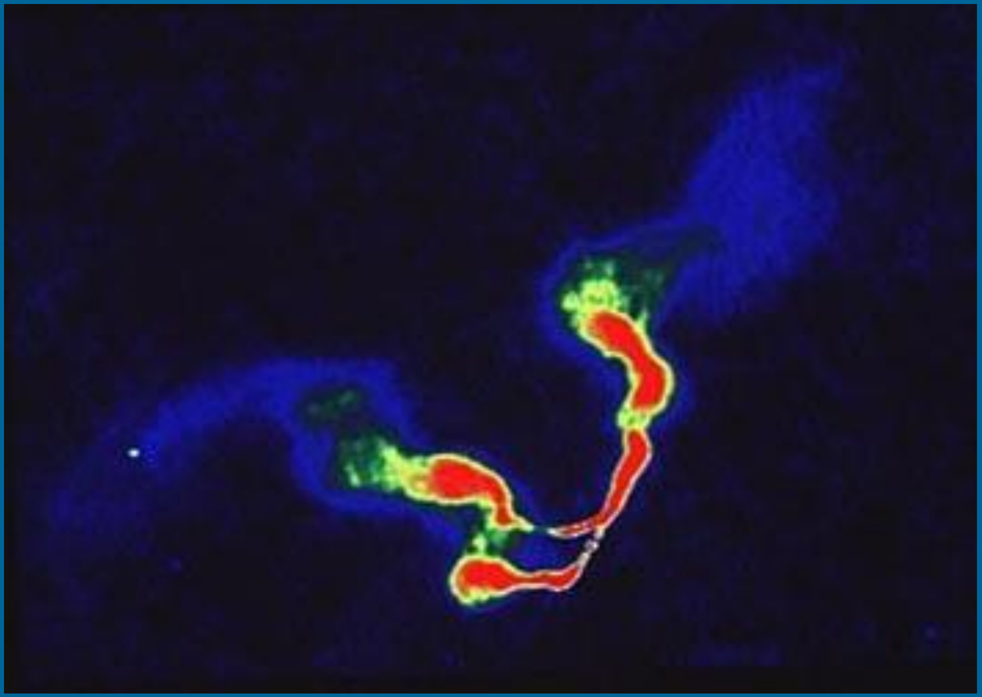
Galaxy 0402+379

Total mass: 1.5 $10^8$ $M_0$

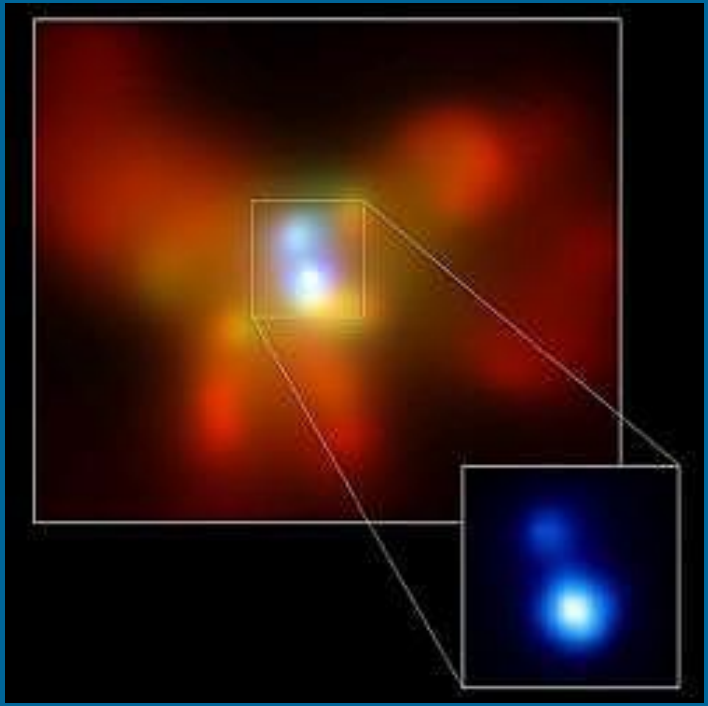
Distance between two BHs is 7.3 pc.

Rodriguez et al. astro-ph/0604042

# Examples of binary SMBHs



3C75

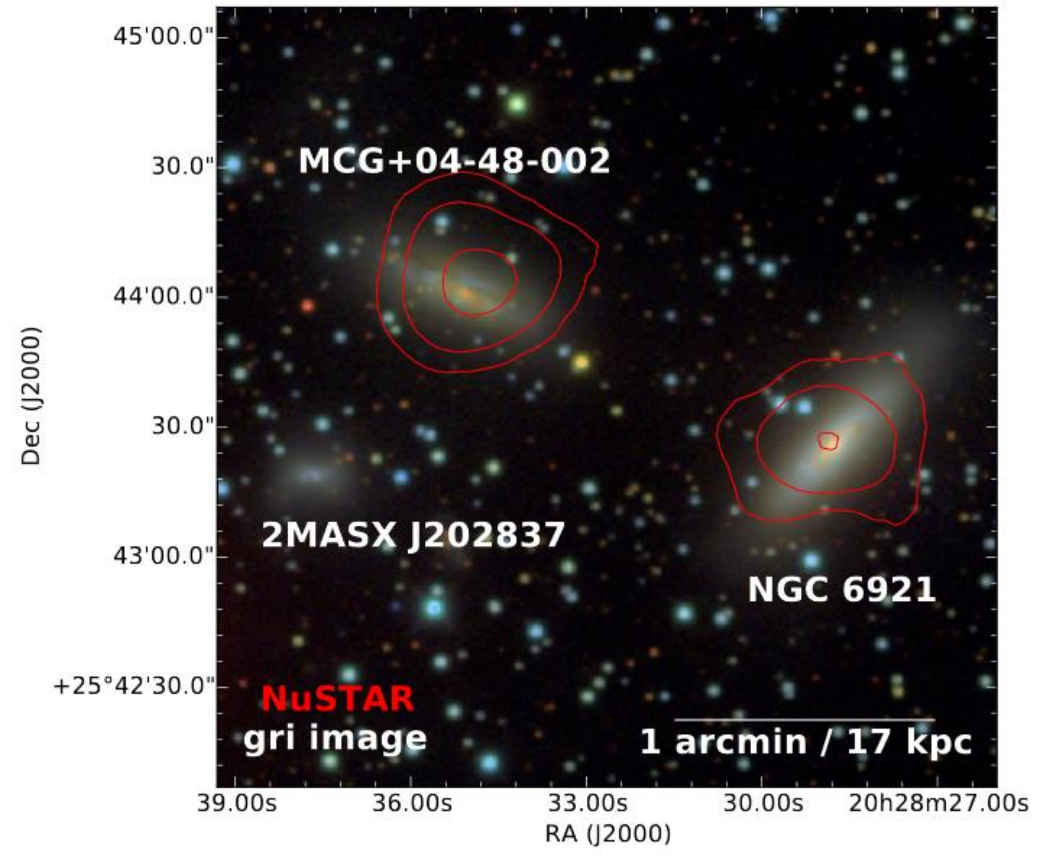


Abell 400

astro-ph/0410364

# Dual AGN observed by NuStar

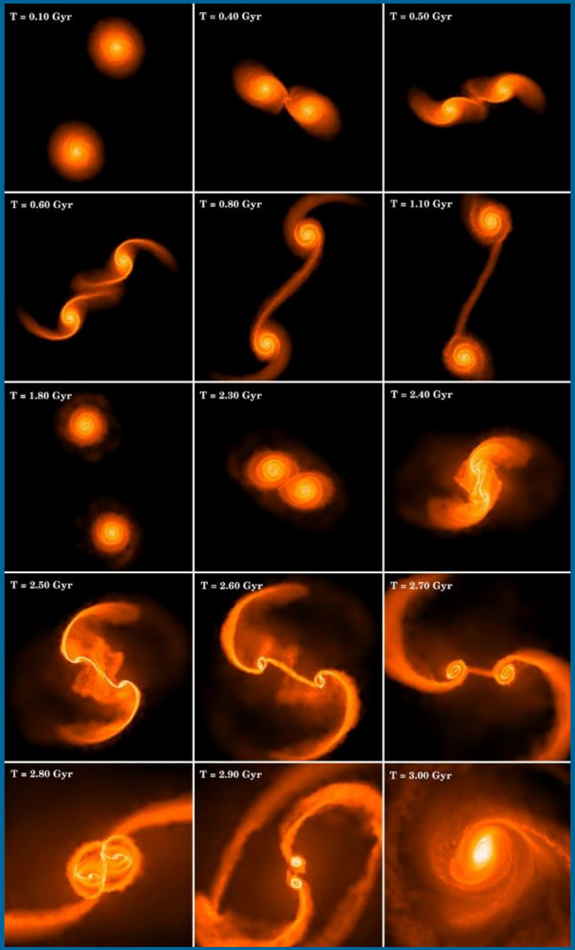
SWIFT J2028.5+2543
NGC 6921 and MCG+04-48-00
First observations at E>10 keV

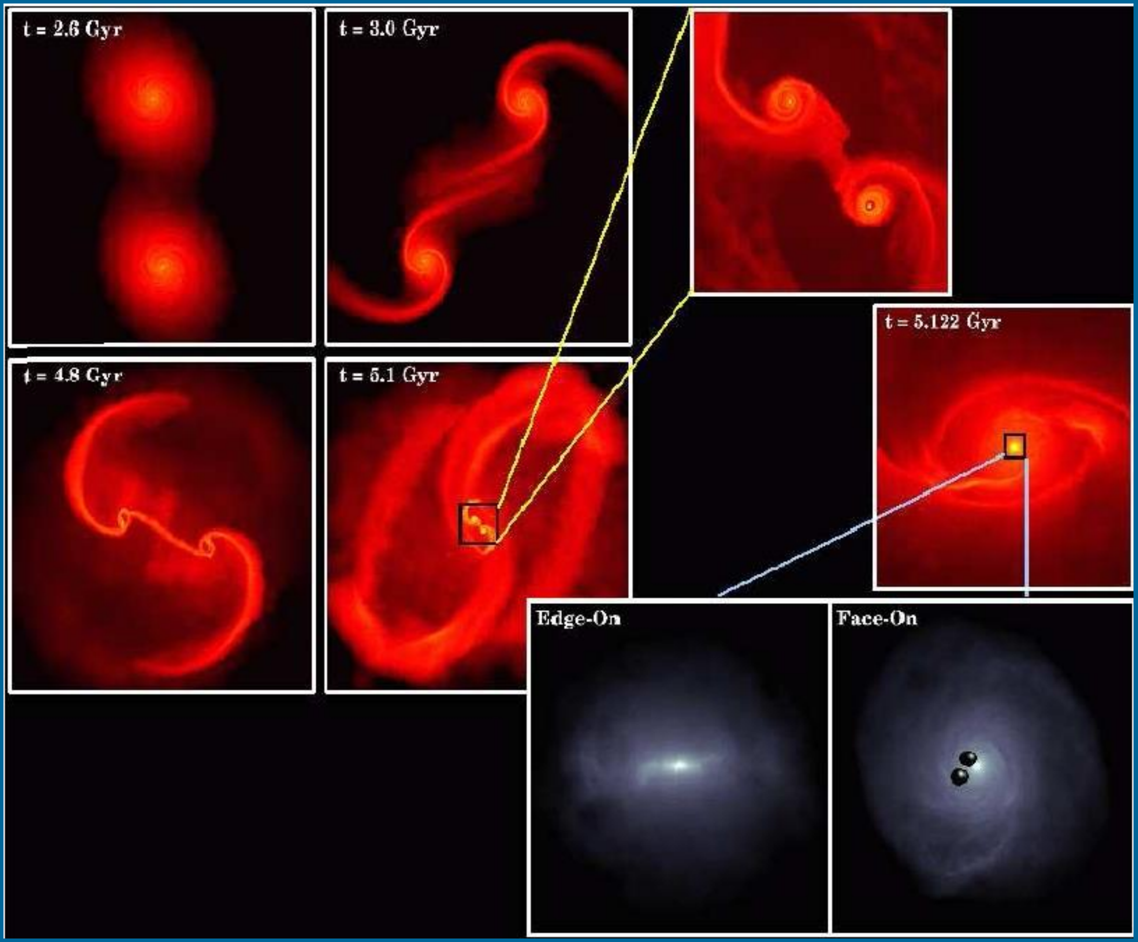


Galaxy merger triggers AGN activity.
Separation ~25 kpc
$4 \times 10^8$ and $7 \times 10^7$ $M_{solar}$

1708.06762

# Merging of galaxies with BHs



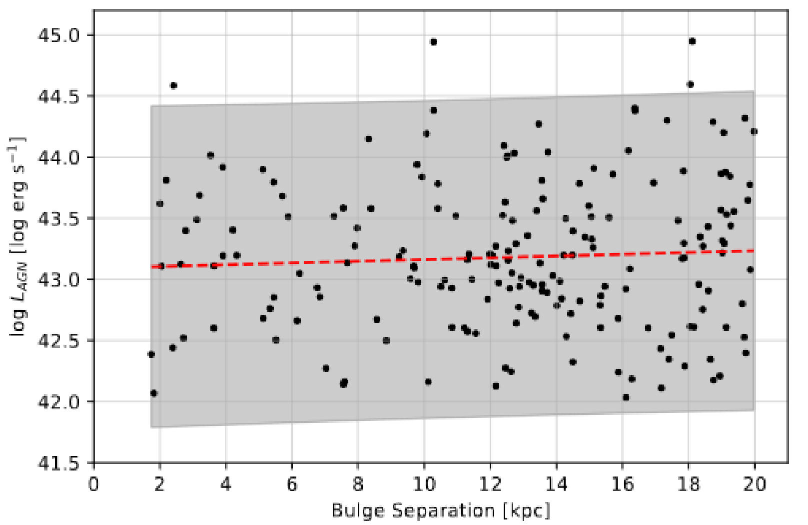


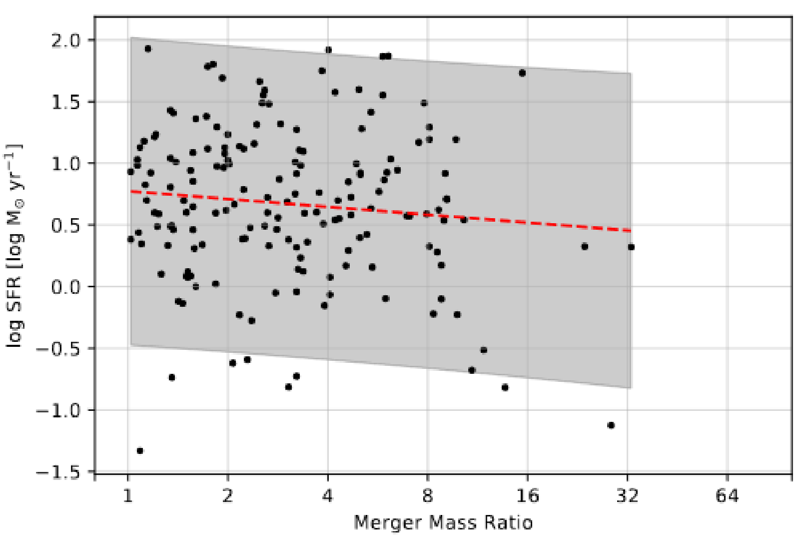
arXiv:0706.1562

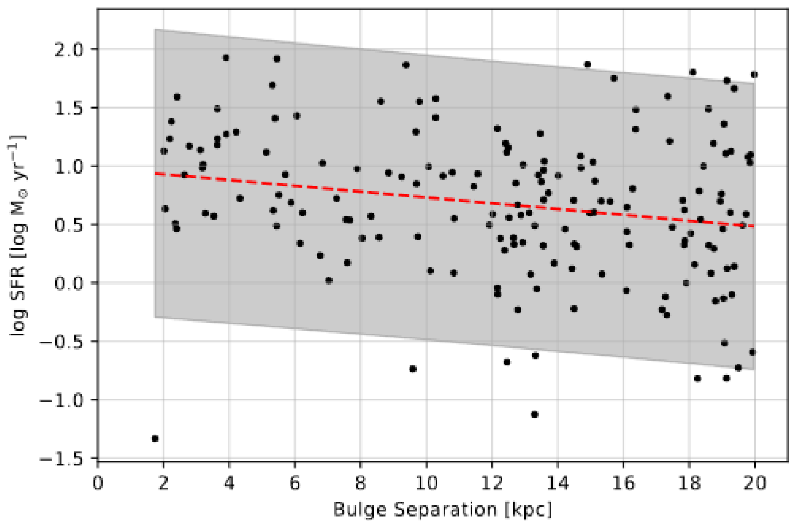
See more about the role of recoil after merging in 1001.1743, 1103.0272, 1103.3701

# 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.

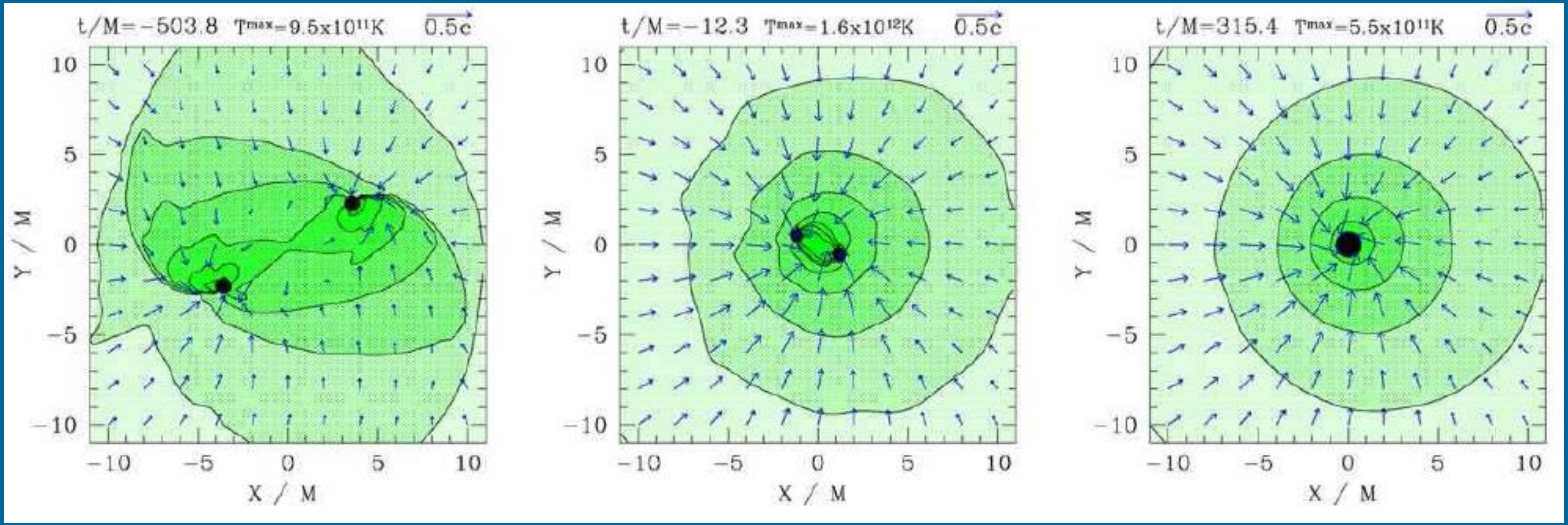






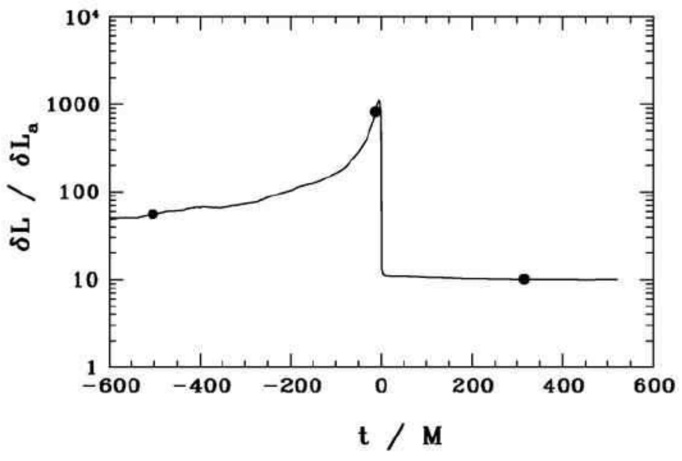
2011.10051

# EM signal during coalescence



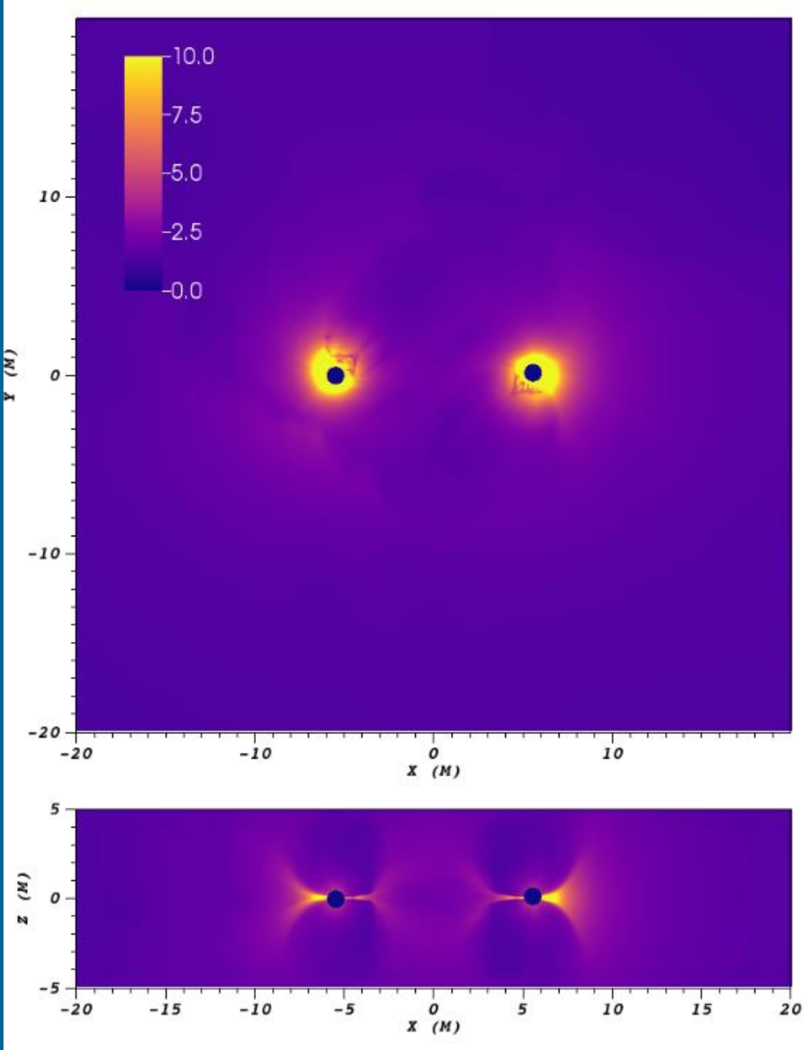
For M=$10^6$ solar mass binary in n=10 $cm^{-3}$ gas
$\Delta L \sim 3\ 10^{43}$ erg/s
Detectable by LSST from z~1

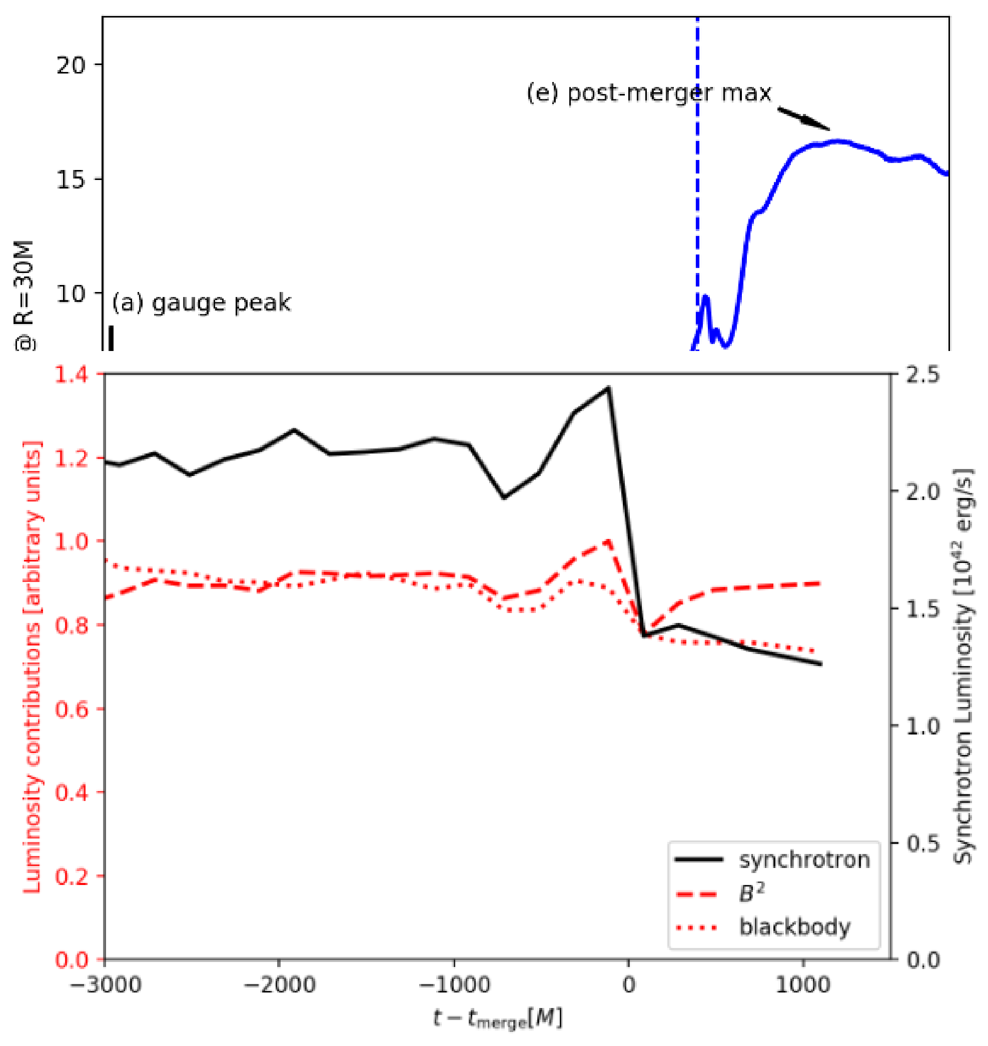
Stirring, shock heating and accretion of the gas may produce variability and enhancements in the electromagnetic flux.



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.

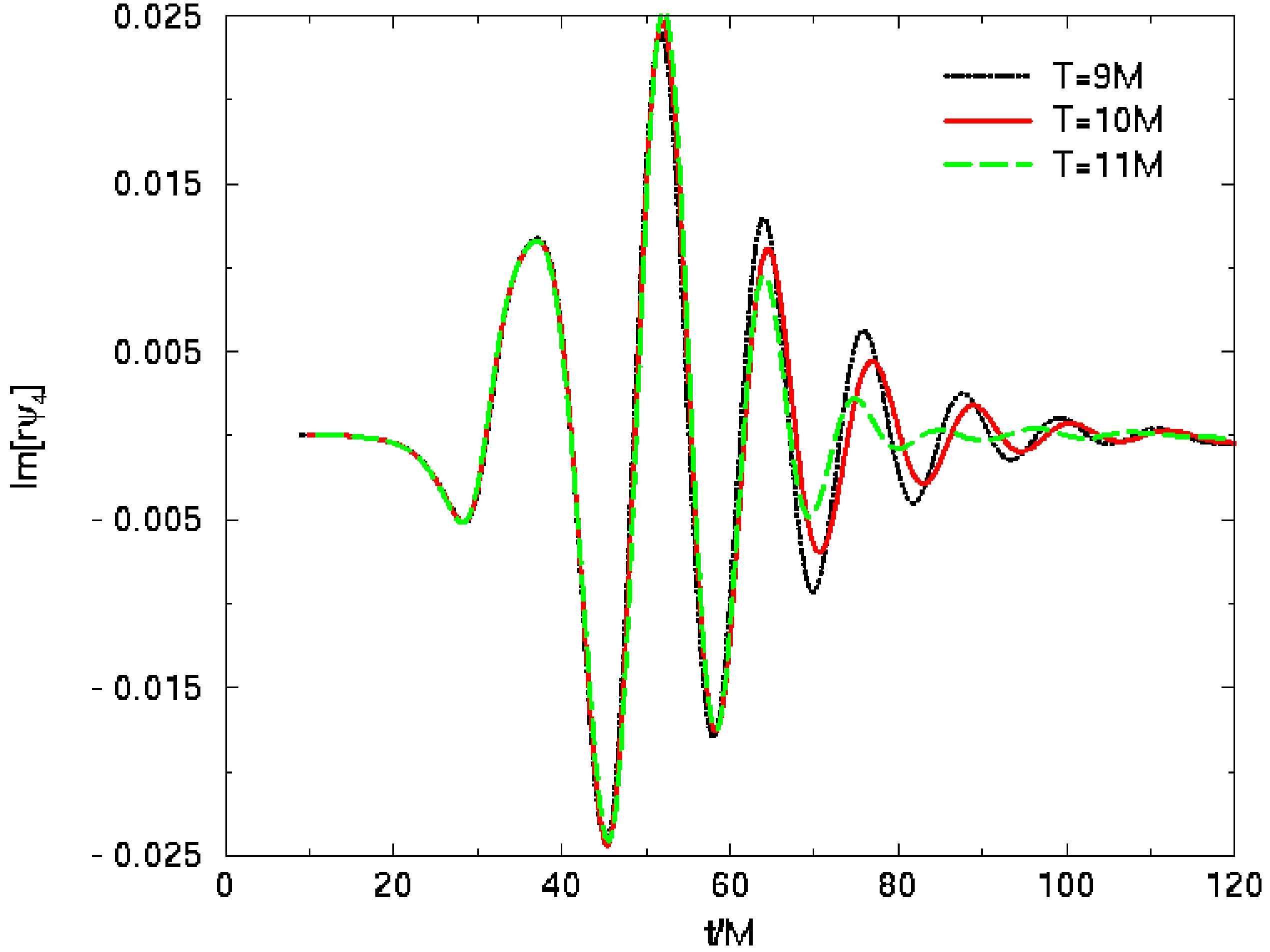
Also, systems BH+NS can exist.

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



astro-ph/0305287

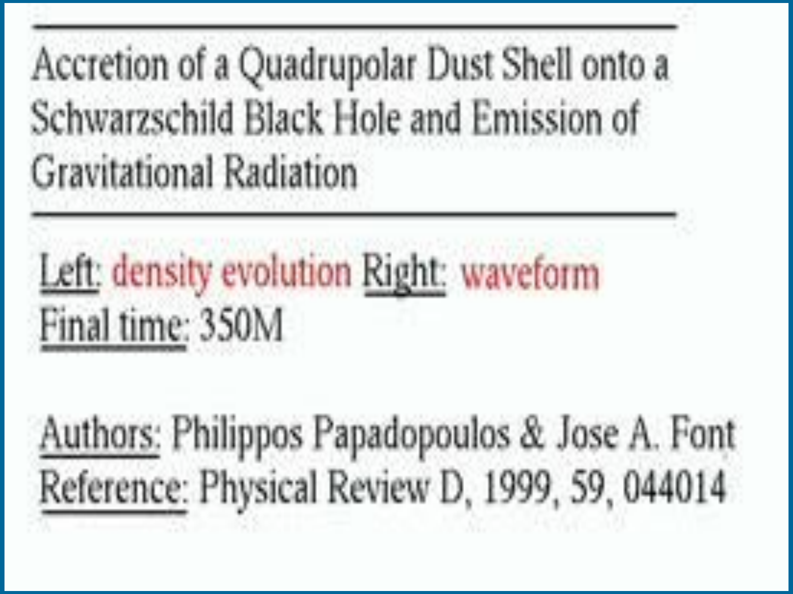
It is important to calculate in advance so-called waveforms.

Otherwise, it is very difficult to identify the signal.

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

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

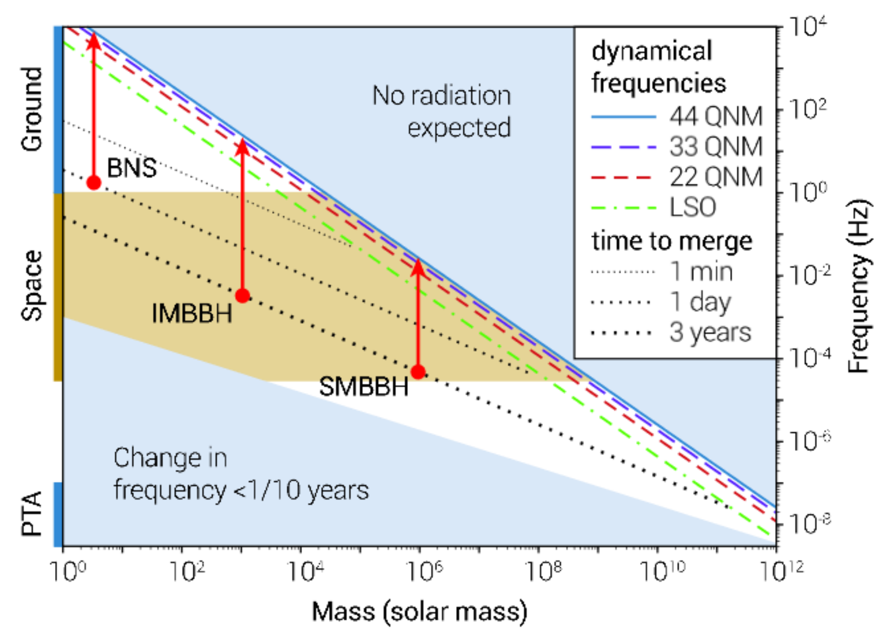
Left: density evolution Right: waveform
Final time: 350M

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

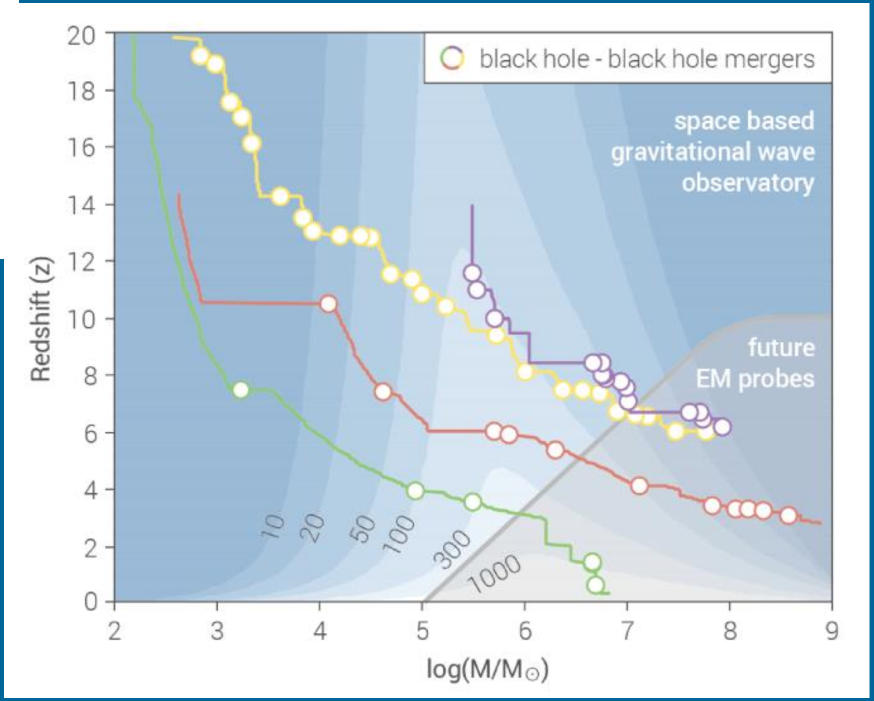
See also gr-qc/0306082 **An Effective Search Method for Gravitational Ringing of Black Holes**

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

# Frequency ranges and instruments

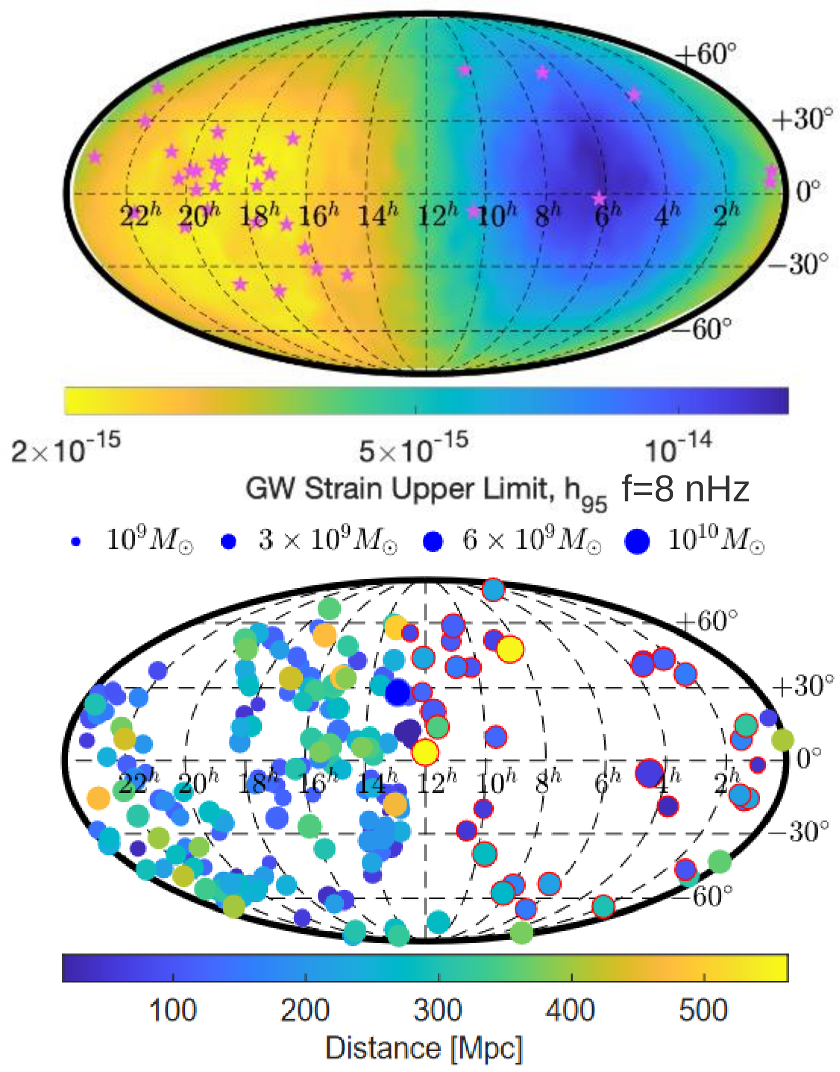


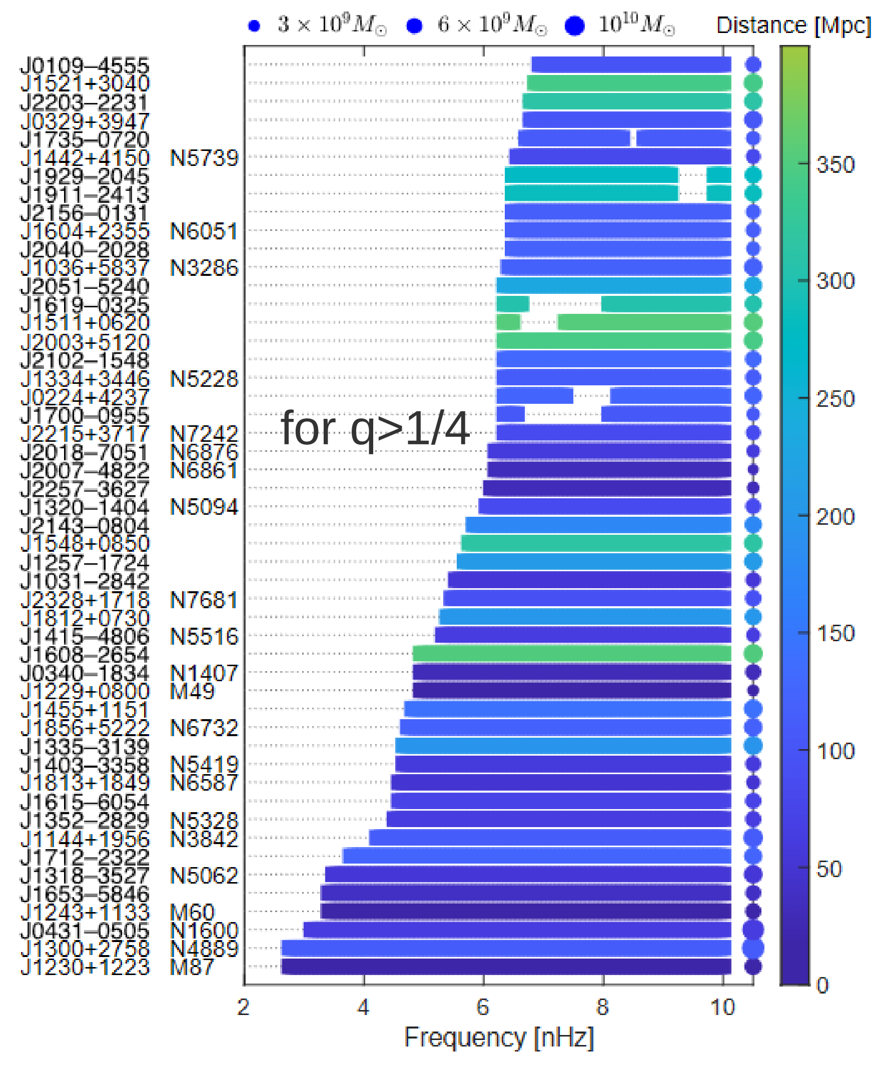
Blue (massive seed) and yellow (PopIII seed): BH powering a z≈6 quasar.
Red: typical elliptical.
Green: Milky way-like



1307.4086

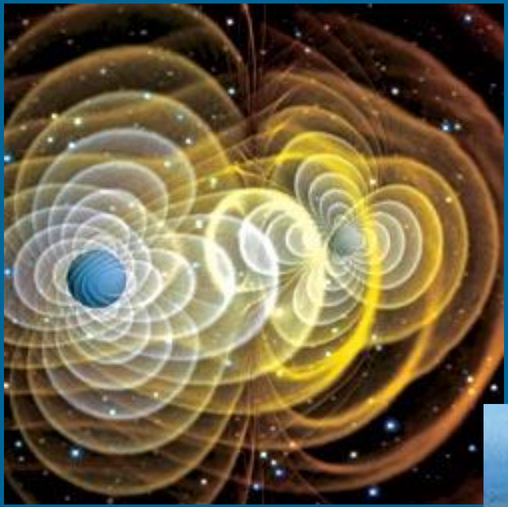
# NANOGrav 11-year data





2101.02716, see 2101.10081 about PTAs

# Registration of GW

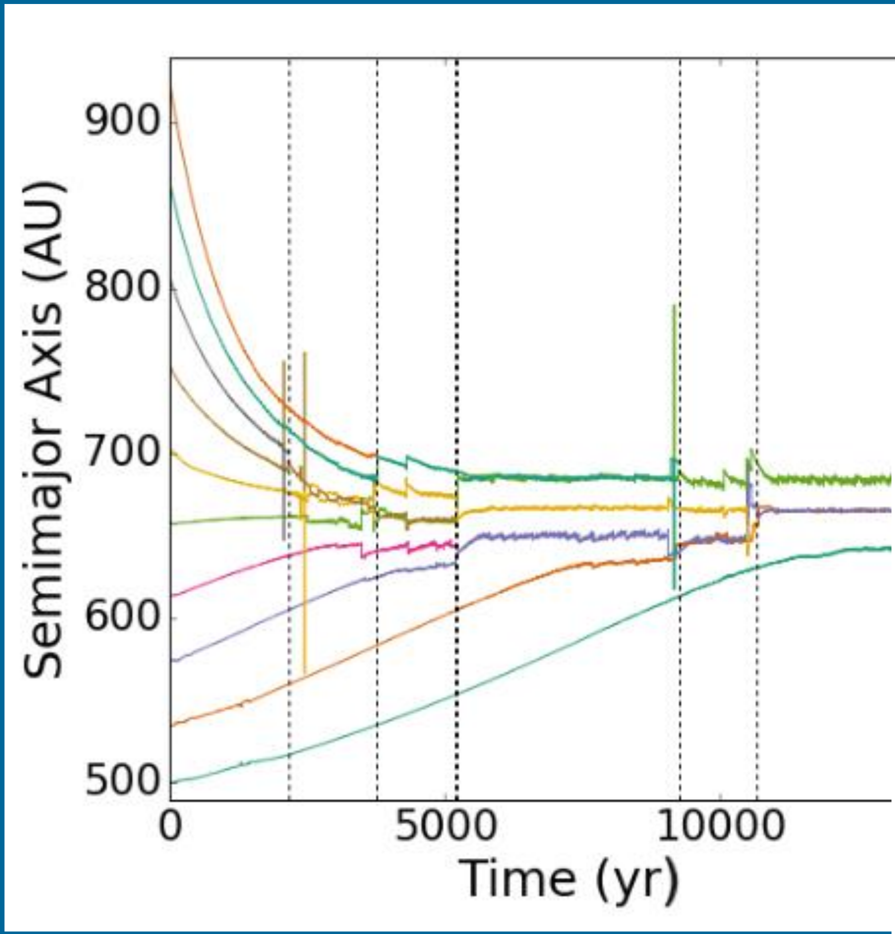


Since 2015 LIGO and VIRGO detect signals from coalescing compact objects.

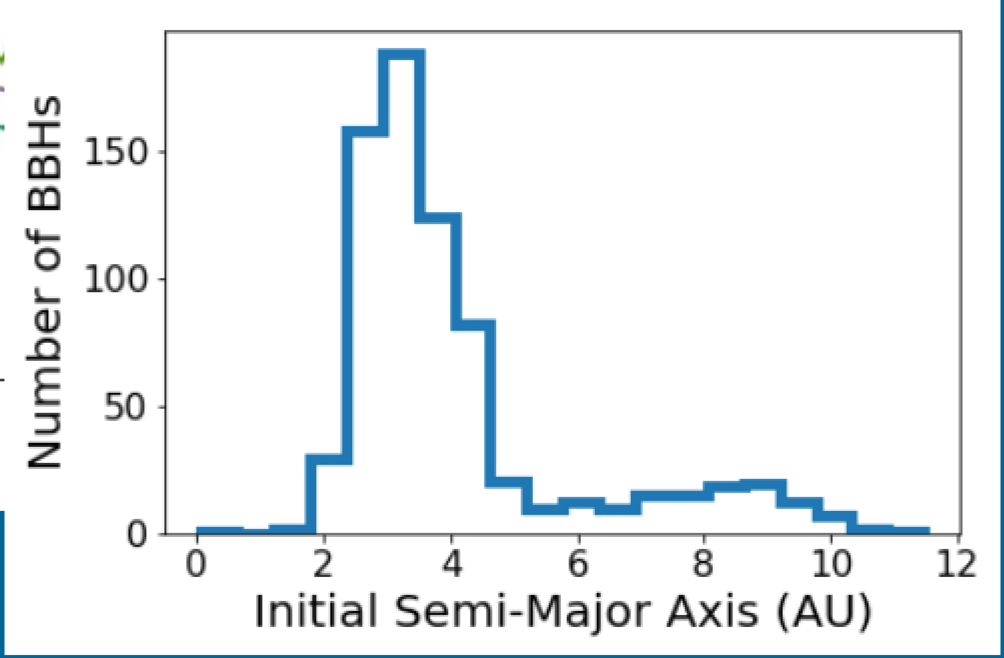
See https://gracedb.ligo.org/
https://stellarcollapse.org/

VIRGO

# BH coalescence in discs around SMBHs

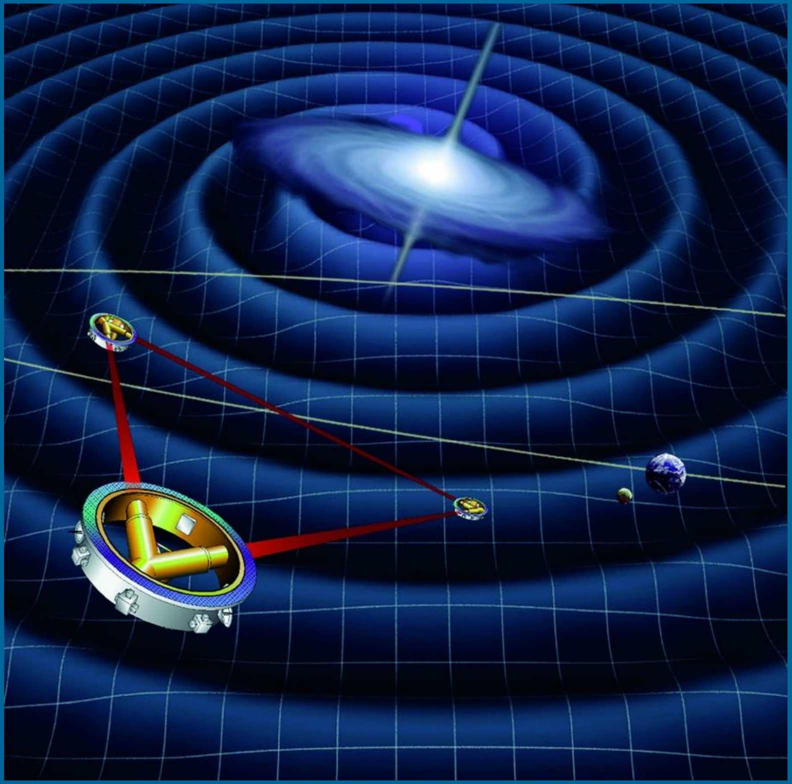


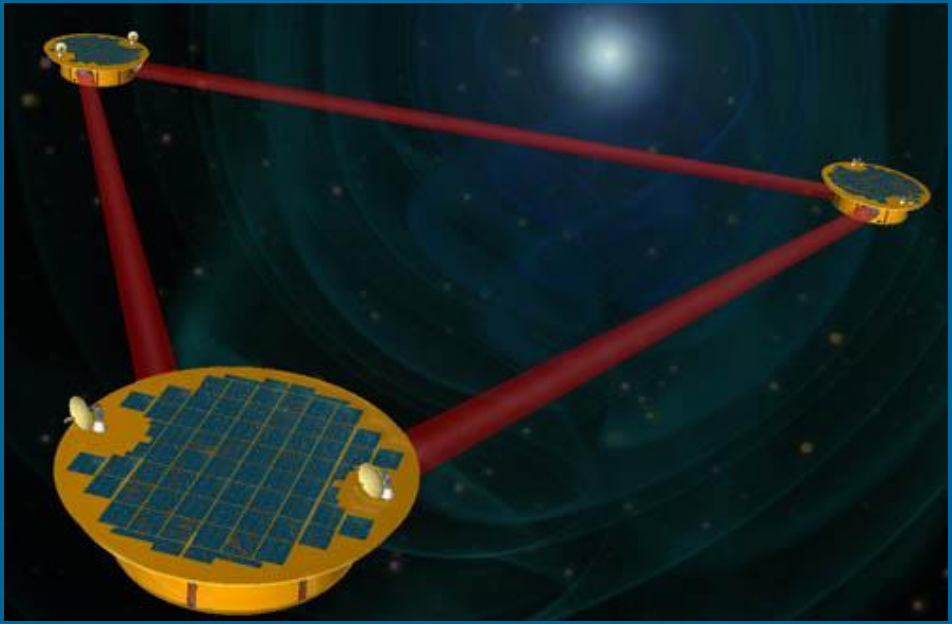
BHs migrate in
the accretion disc
towards a trapping zone.
There they form pairs.
Prograde and retrograde
rotation is possible.

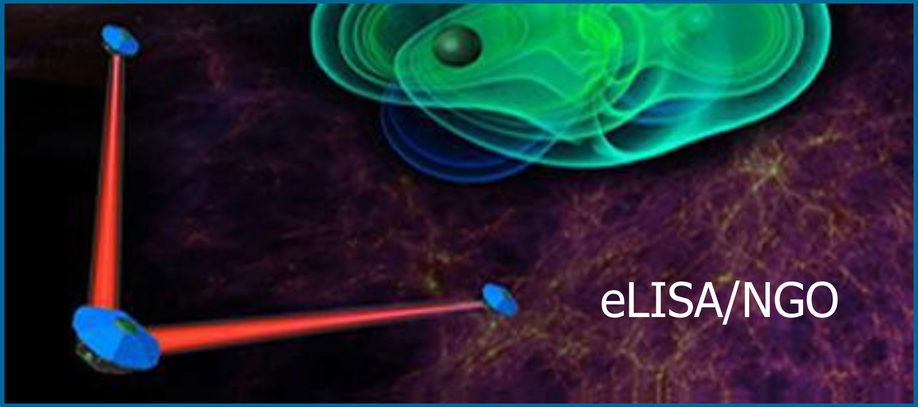


2004.11936

# Космический проект LISA

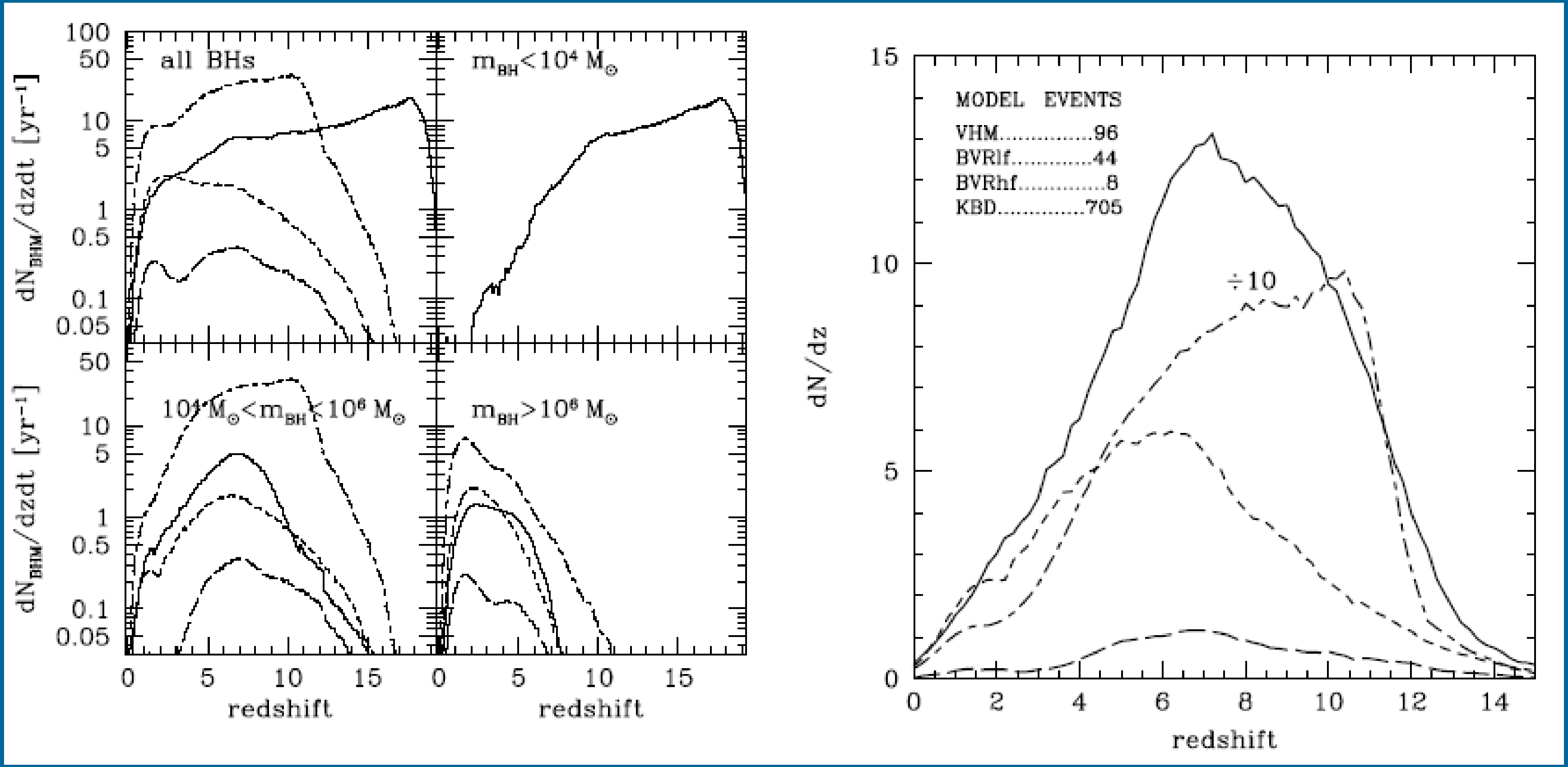






NASA сняла свое финансирование.
Европа в начале не одобрила
даже сокращенный вариант.
Но теперь он поддержан: >2032 г.
Правда, в урезанном виде ….

# 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 ~$10^9$ $M_O$.
- 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).