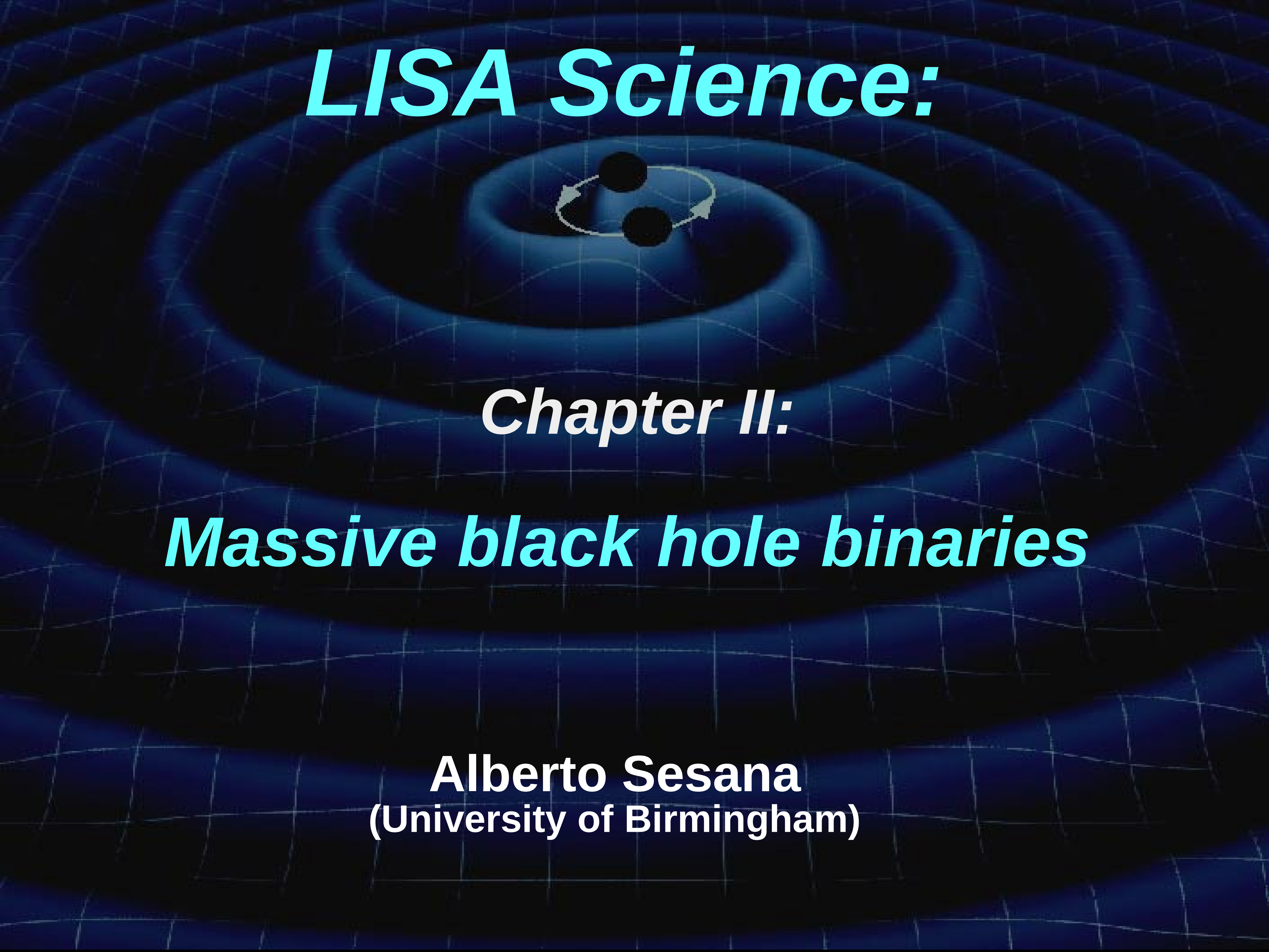
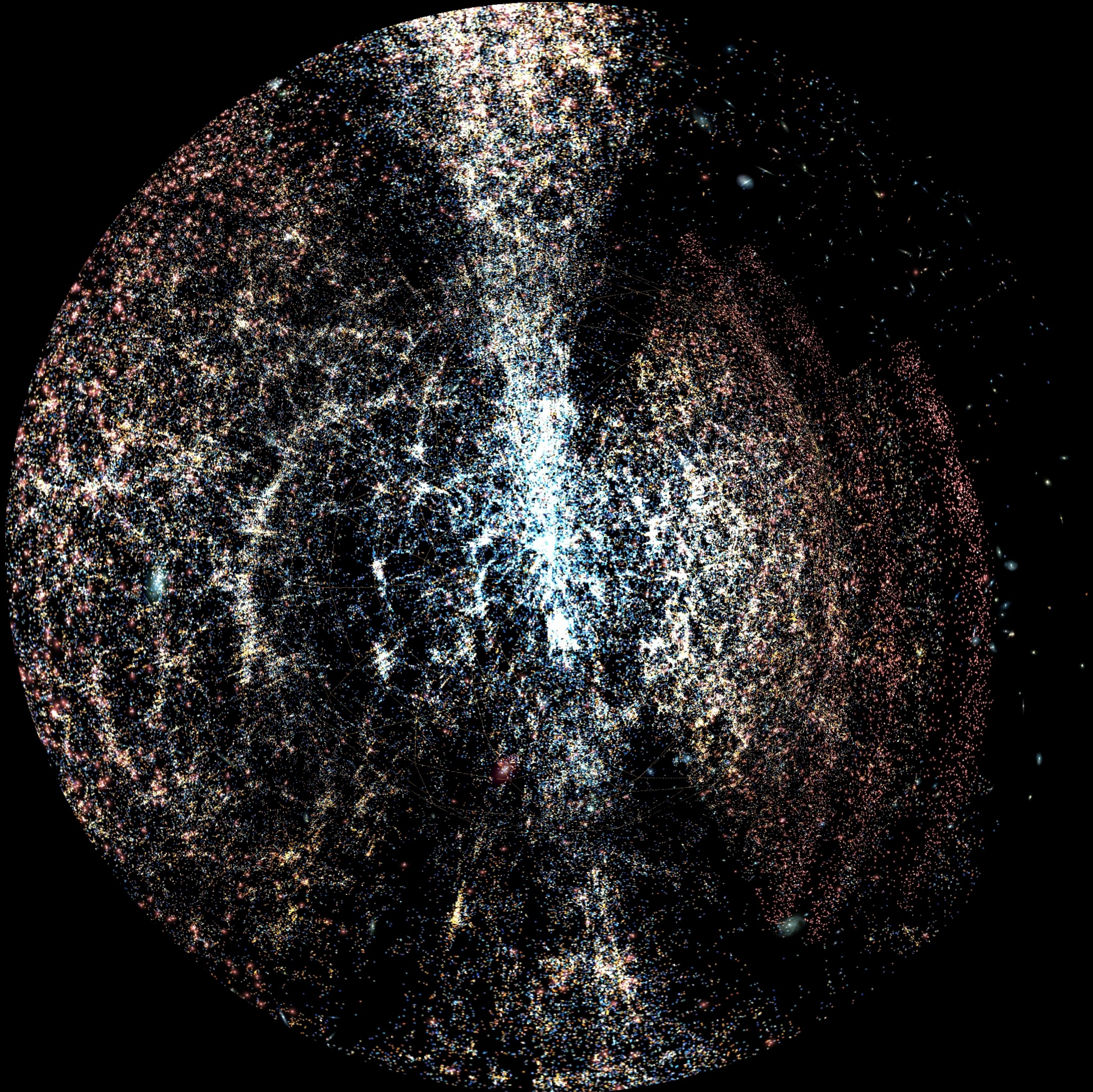


LISA Science:

Chapter II:

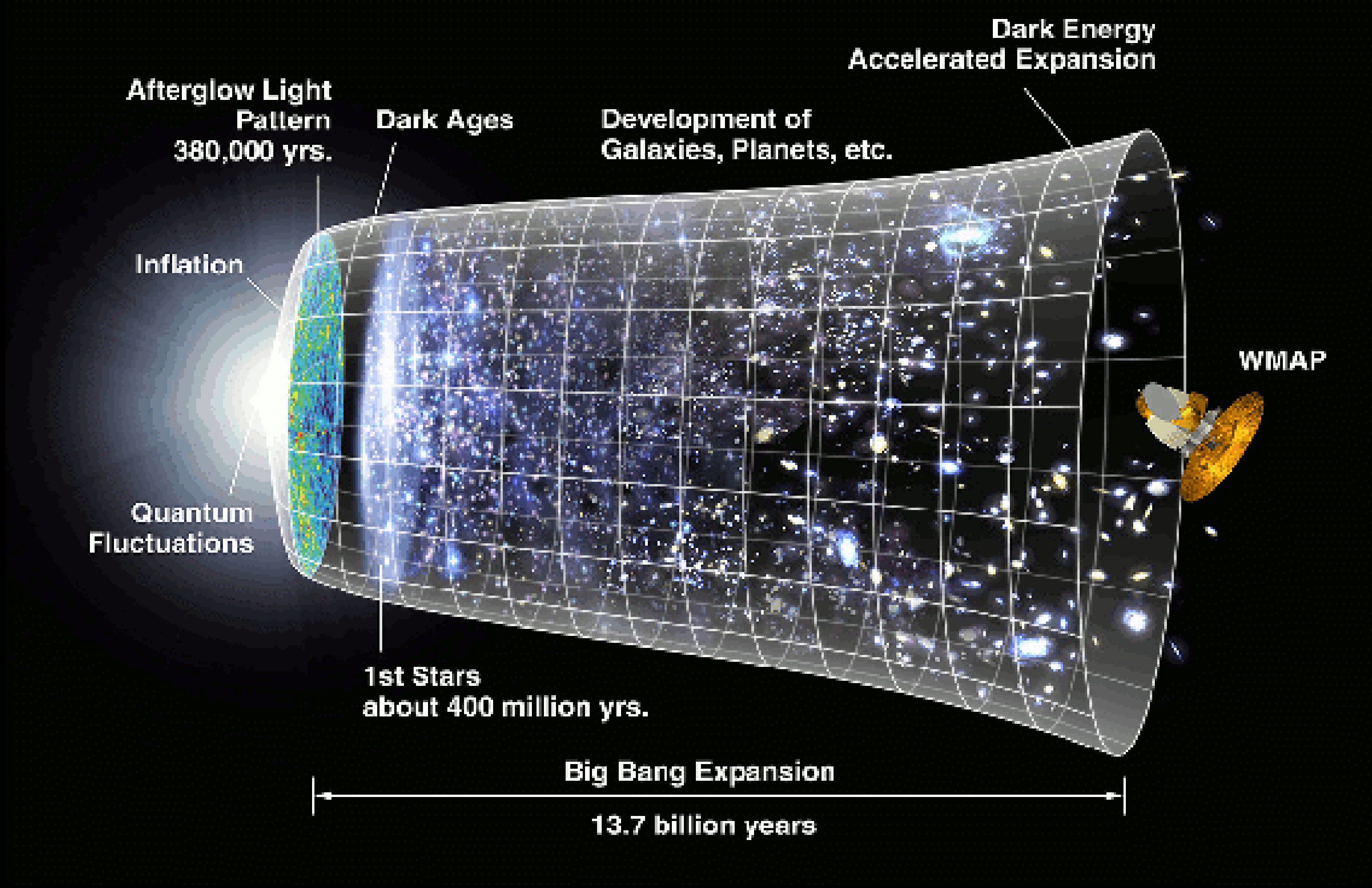
Massive black hole binaries

Alberto Sesana
(University of Birmingham)



Cosmology in two slides

According to our best cosmological models, we live in a ***ΛCDM Universe***. The energy content of the Universe is ***27%*** in the form of ***ordinary matter*** (~3% baryons, ~24% dark matter) and ***73%*** in the form of a ***cosmological constant*** (or Dark energy, or whatever), which would be responsible of the accelerated expansion.



The age of the Universe is ~14Gyr, during this time its size has expanded from a singularity to ~10^{28}cm.

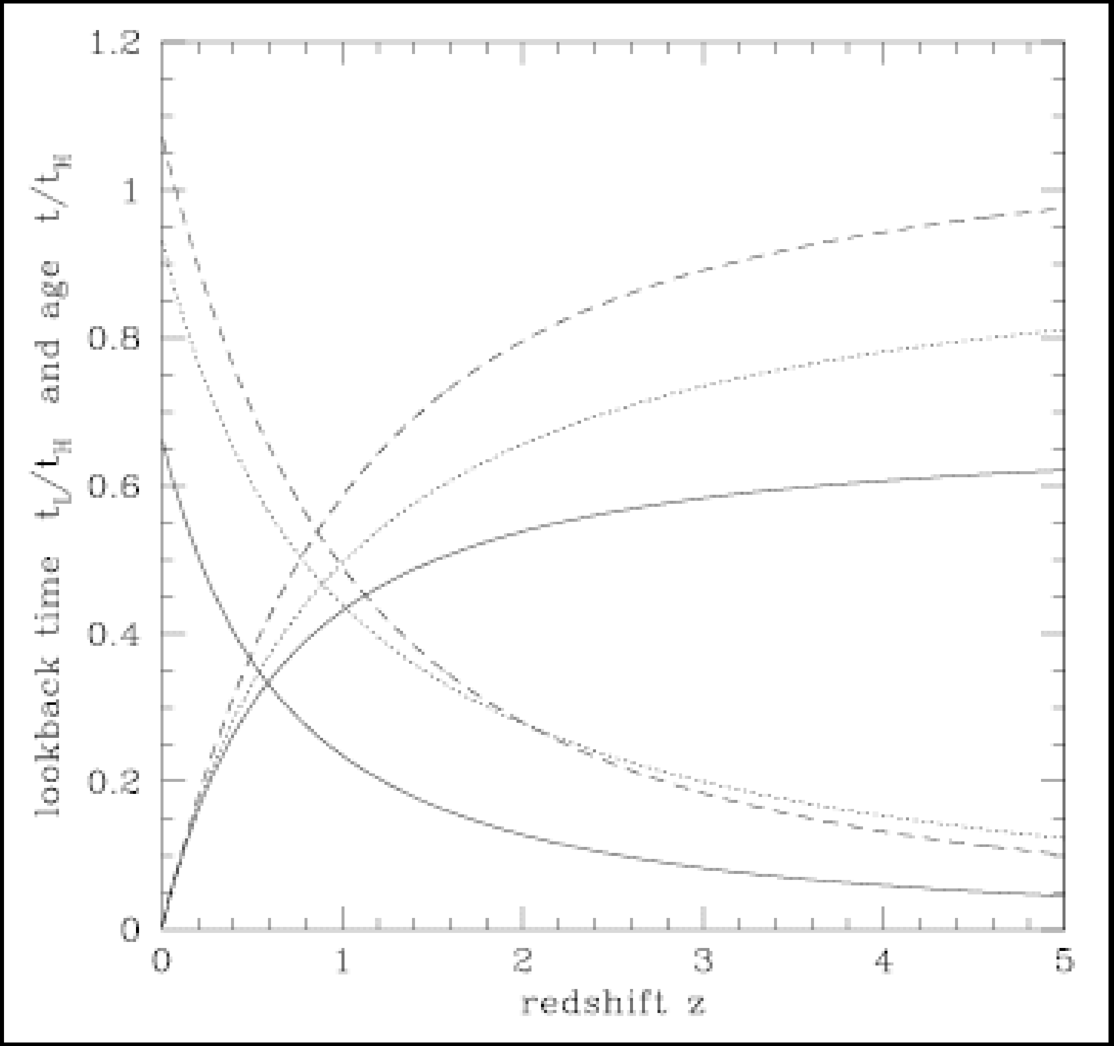
Usually cosmologists describe the epochs of the Universe in terms of ***redshift***:

$$z \equiv \frac{\nu_e}{\nu_o} - 1 = \frac{\lambda_o}{\lambda_e} - 1$$

which describe how much the photons emitted at a given time are redshifted, because of the expansion, when they arrive on the Earth.
The redshift of a photon is related to the size of the Universe at the moment of its emission through:

$$1 + z = \frac{a(t_o)}{a(t_e)}$$

A given redshift correspond to a specific time in the past:



z=0 today
z=1 ~8Gyr ago
z=6 ~13Gyr ago (age of the Universe <1Gyr!)

Observational facts

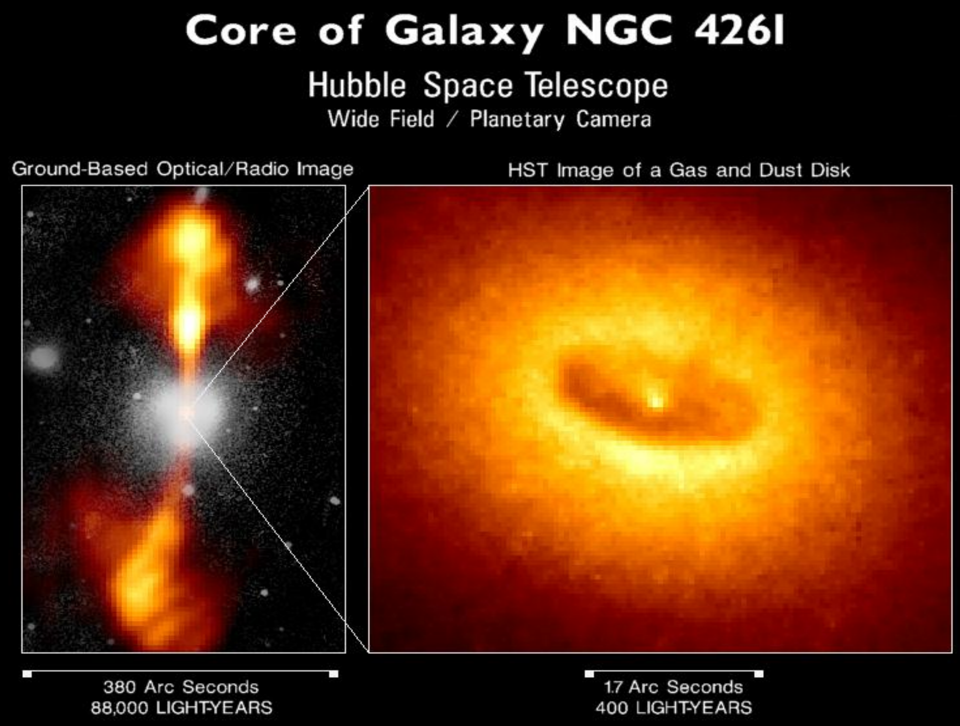
1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive black hole (MBH) has been found in the center.

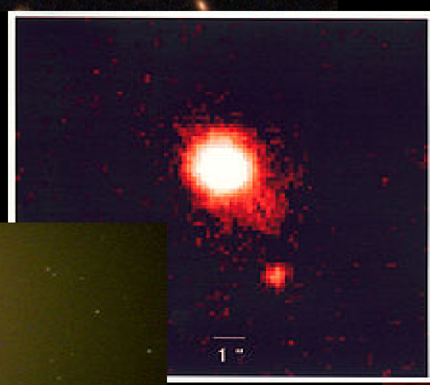
2- MBHs are believed to be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

3- Quasars have been discovered at z~7, their inferred masses are ~10^9 solar masses!

THERE WERE 10^9 SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

Our aim is to understand the MBH formation and evolution and to assess the consequences for GW astronomy


Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS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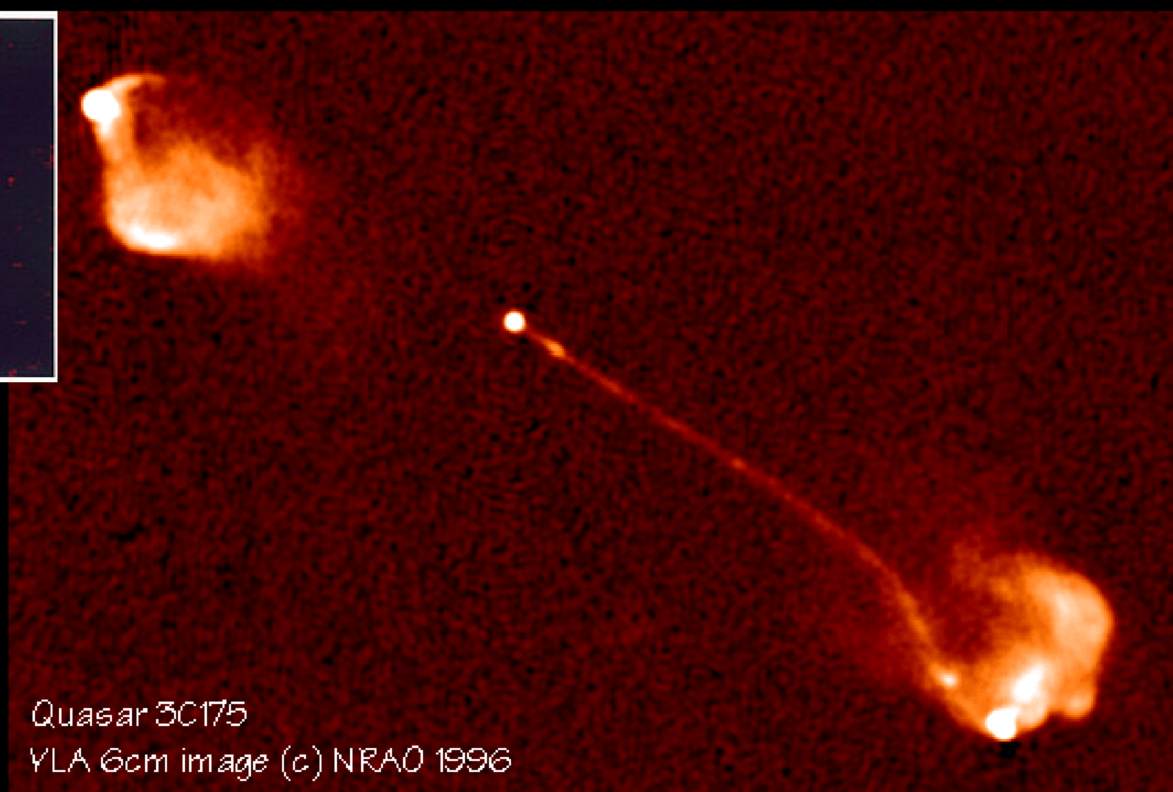
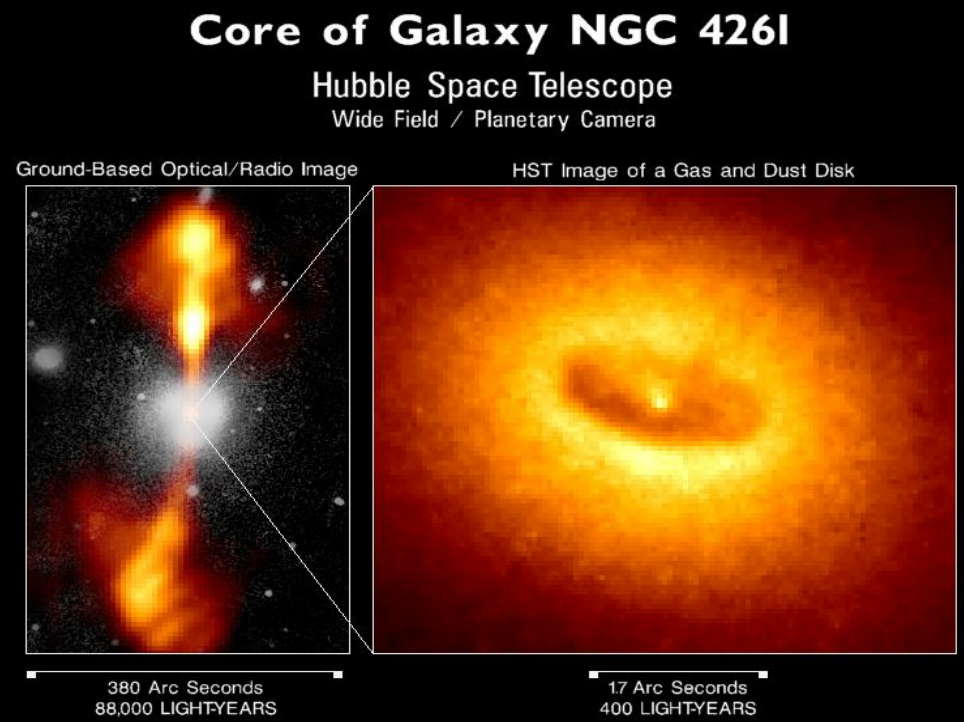

Quasar 3C175
VLA 6cm image (c) NRAO 1996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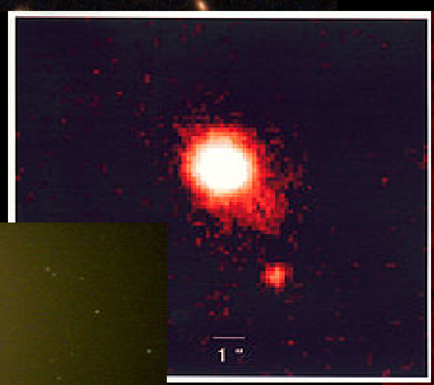
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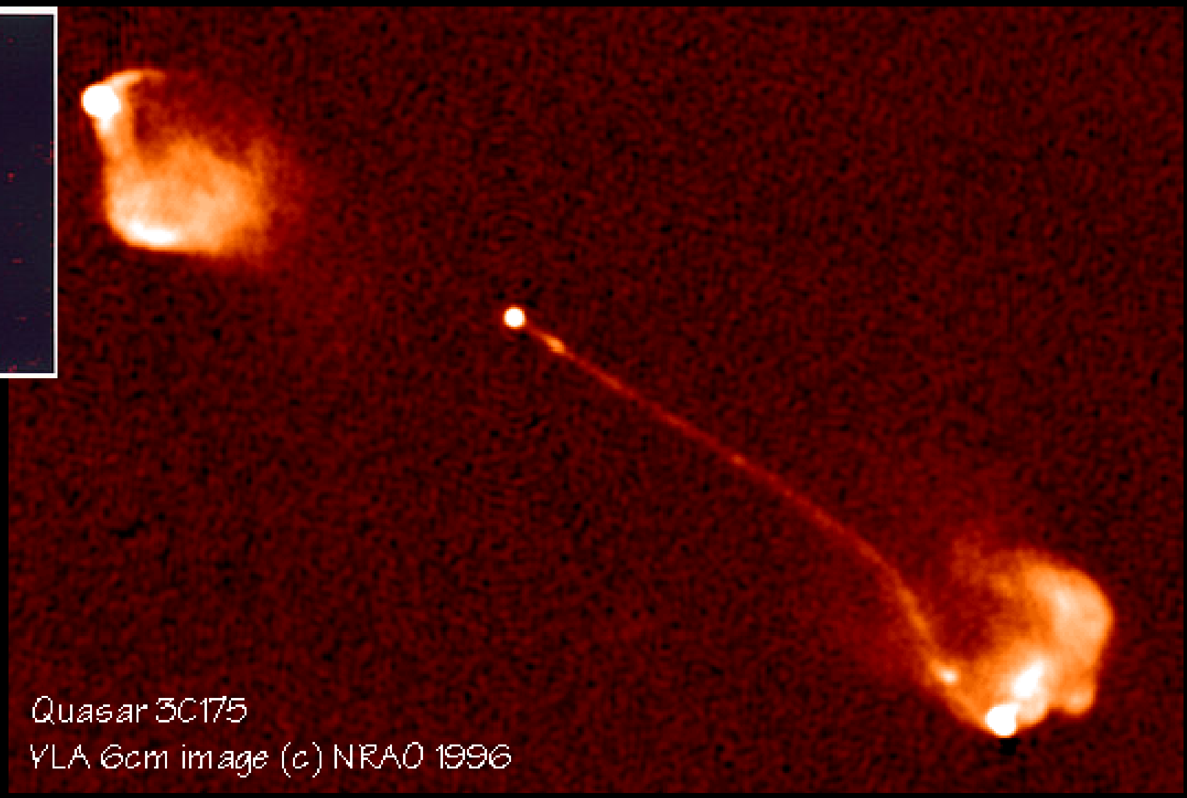
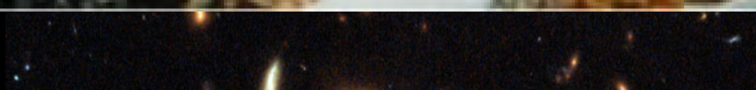
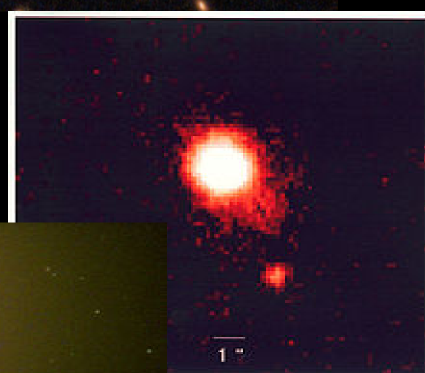
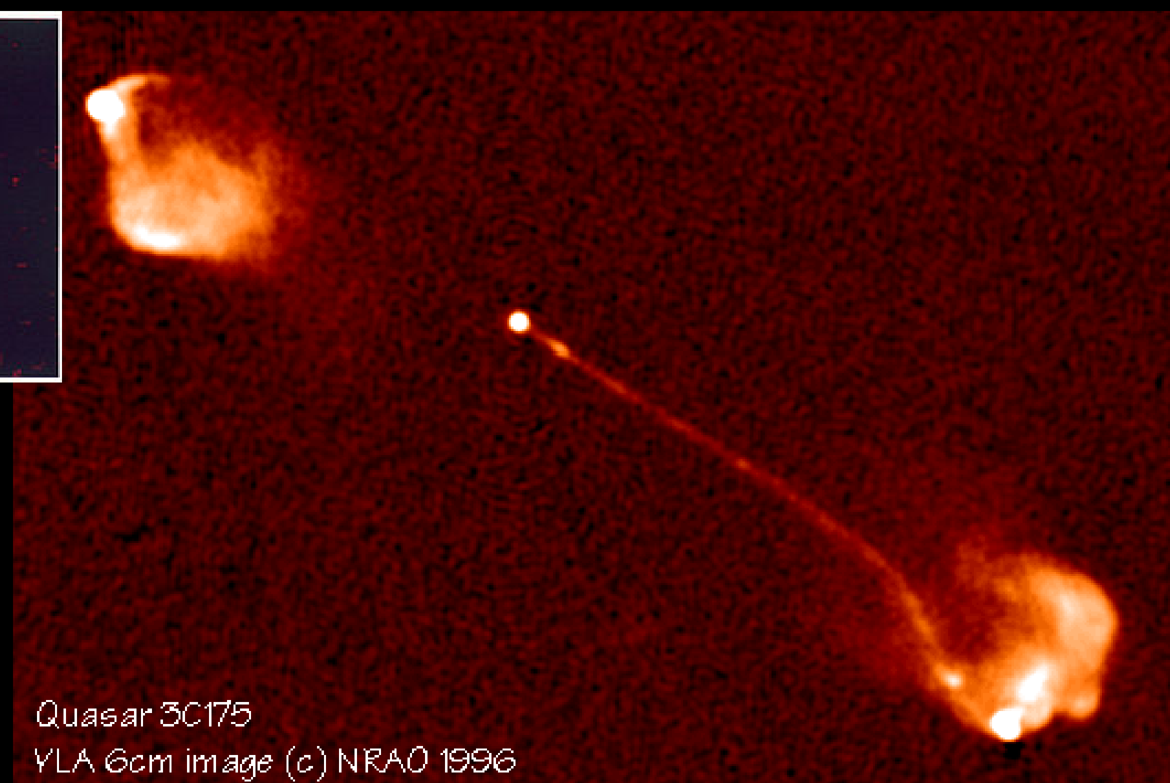

Quasar 3C175
VLA 6cm image (c) NRAO 1996




1''


Quasar 3C175
VLA 6cm image (c) NRAO 1996

Cosmological structure formation

(Binney & Tremaine, 1987, chapter 9)

The Universe after the Big Bang was not completely uniform

The matter content was (and is) dominated by dark matter. The *ratio dark matter/baryonic matter is ~10:1*

Gravitational instabilities due to non uniform matter distribution cause the matter to condense until small regions become gravitationally bound

These regions then decouple themselves from the global expansion of the universe and collapse, forming what we call the *first galactic minihalos*.

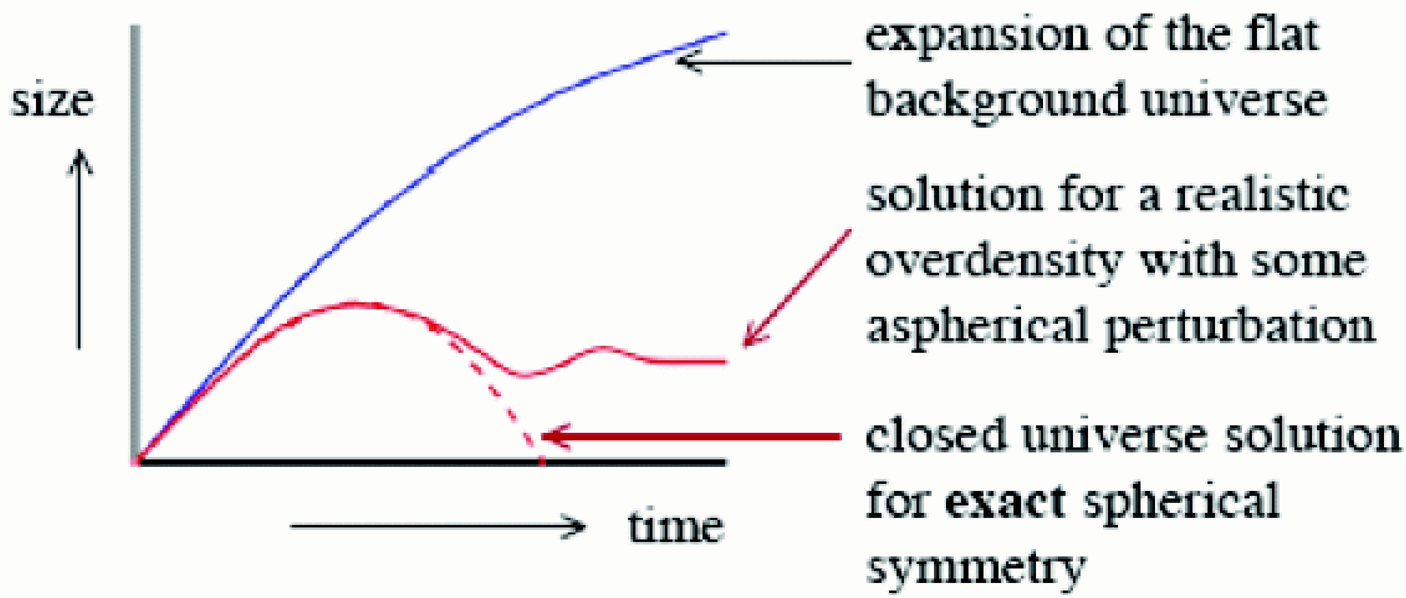
The baryonic matter feels the gravitational potential of these halos and falls at their center, forming the first protogalaxies

This *halos continuously form during the cosmic history and merge with each other* in what we call the *hierarchical scenario for galaxy formation*.

Halo formation: spherical collapse

Consider a flat, matter dominated Universe, and consider a region which is slightly denser than the mean density.

The self-gravitational force of the sphere depends only on the matter inside the sphere itself (Birkhoff's theorem), and the overdensity behaves like a small closed Universe.



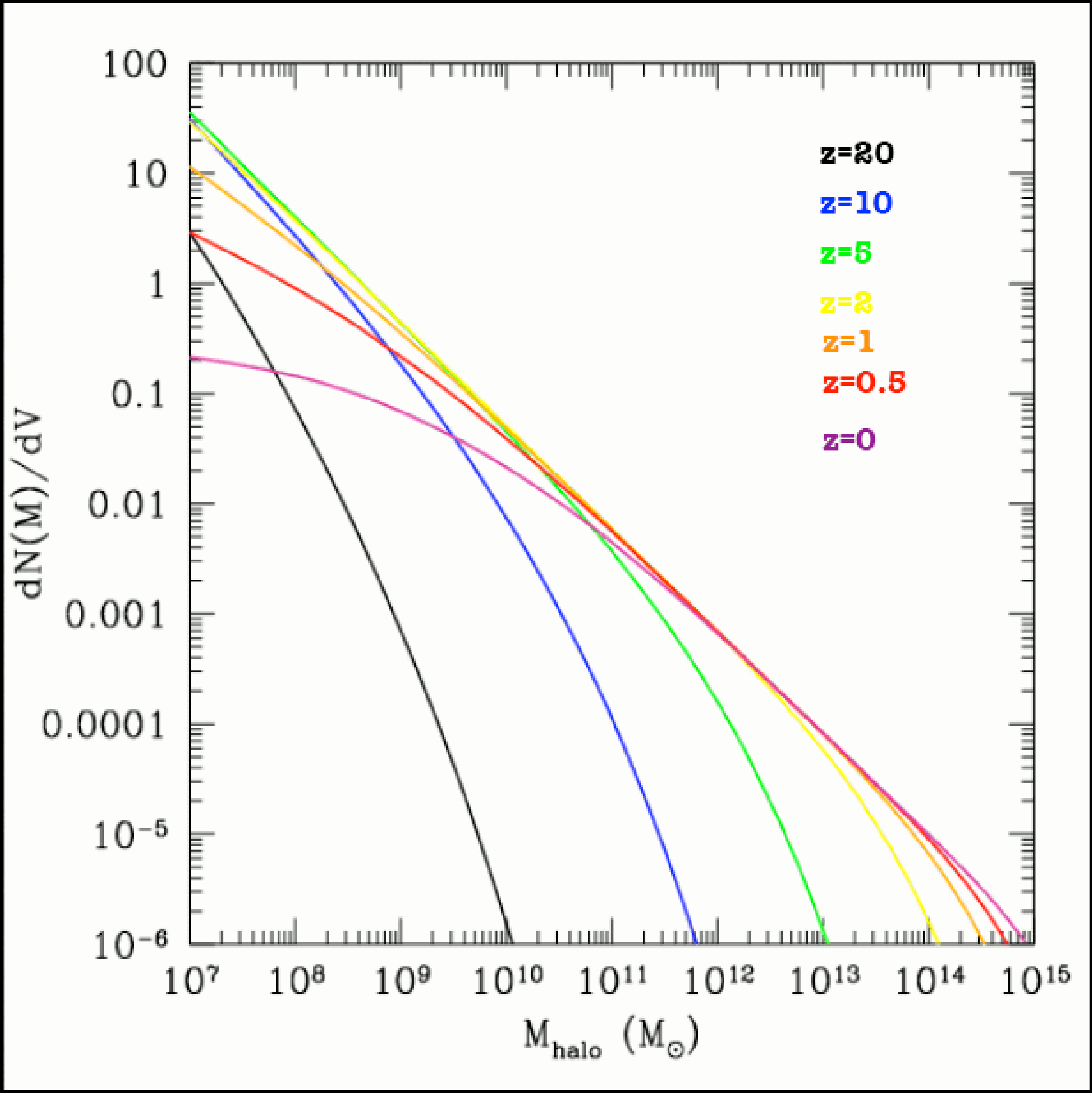
Schematic evolution:

- Density contrast grows as universe expands
- Perturbation "turns around" at $R = R_{turn}$, $t = t_{turn}$
- If exactly spherical, collapses to a point at $t = 2\ t_{turn}$
- Realistically, bounces and **virializes** at radius $R = R_{virial}$

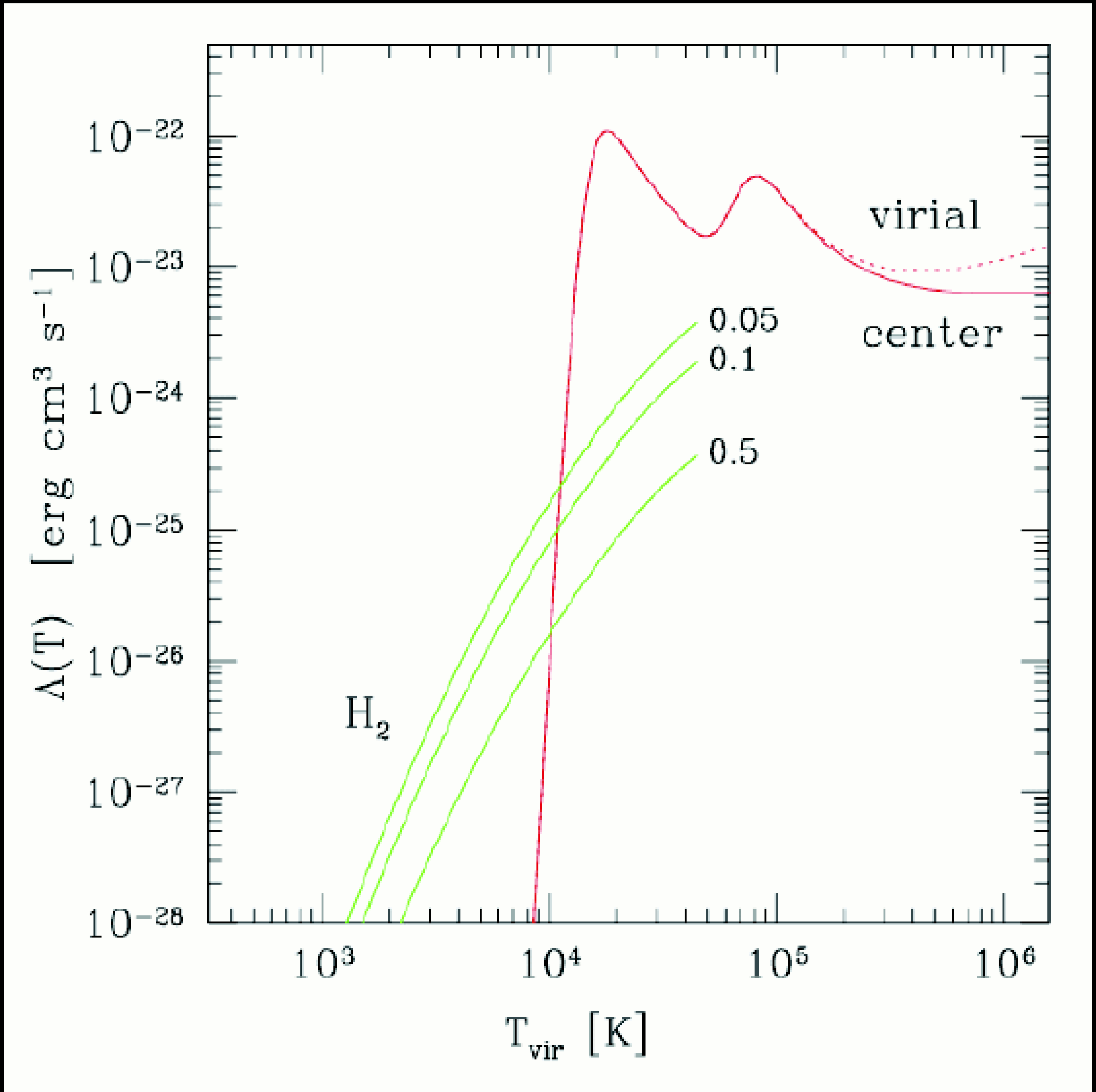
The typical halo mass is an increasing function of time: bottom-up or

HIERARCHICAL structure formation!

The halo mass function evolves in time (redshift) with larger halos forming at lower redshifts (later times).



What happens to the baryons? In the early Universe most of the baryonic matter is in form of hot *atomic (H) or molecular (H_2) Hydrogen*.



Baryons need to cool down (i.e. loose energy) in order to condense in dense structures and form stars.

The only way to cool down is through transition between different atomic or molecular levels.

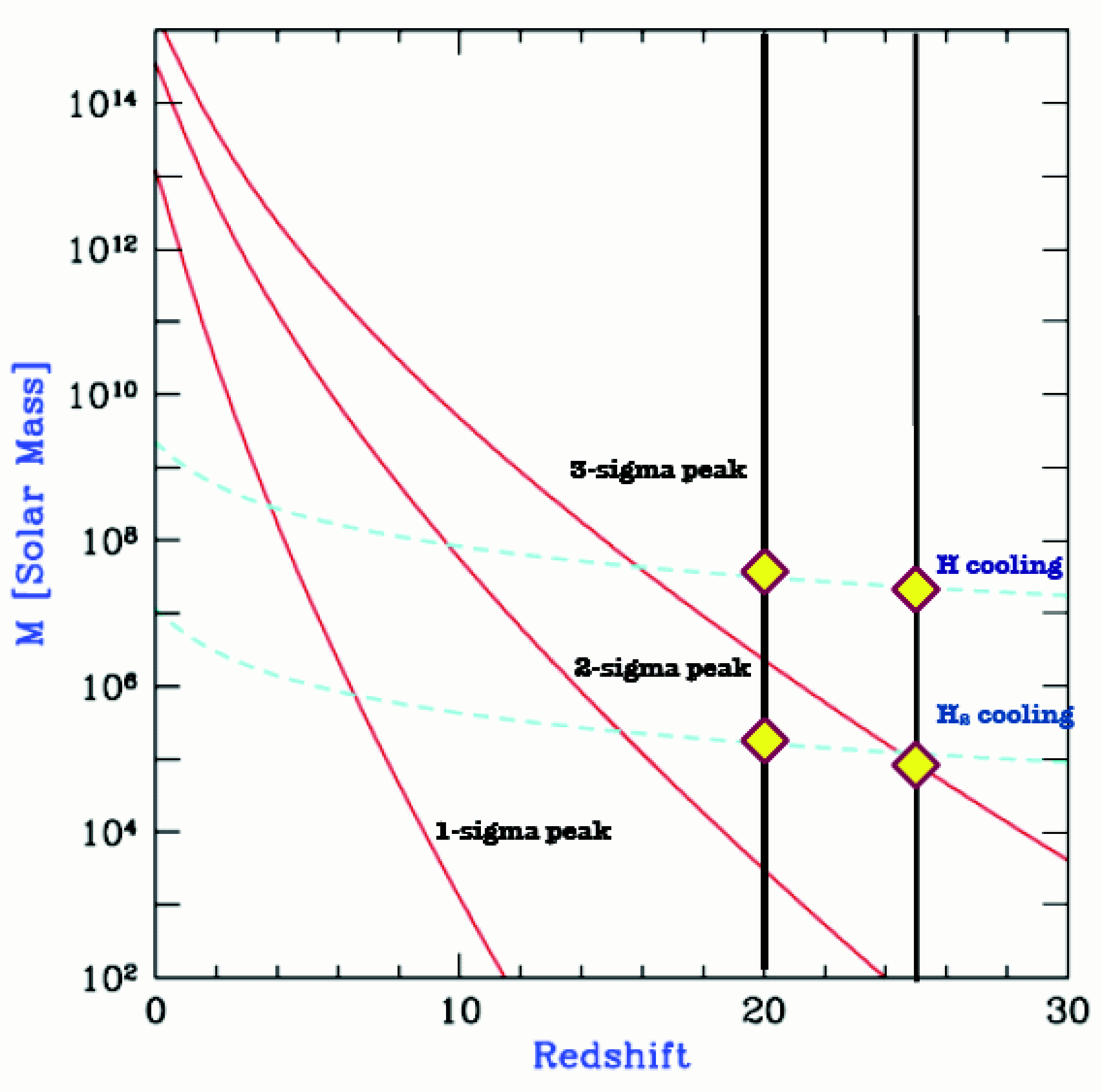
We need to excite high energy levels to radiate this energy away.

The only way is collisional excitation: *we need high temperatures!!!*

Atomic Hydrogen can cool only at temperatures>10^4K, while H_2 can cool already at 10^3K.

$$T_{\rm vir} = 1.98 \times 10^4 \left(\frac{\mu}{0.6}\right) \left(\frac{M}{10^8\ h^{-1}\ M_\odot}\right)^{2/3} \left[\frac{\Omega}{\Omega(z)}\ \frac{\Delta_c}{18\pi^2}\right]^{1/3} \left(\frac{1+z}{10}\right)\ \mathrm{K}$$

The *halo virial temperature is a function of the halo mass*. At high z, we need *M*>10^6 solar masses to cool H_2, and *M*>10^8 solar masses to cool H.



Such massive halos correspond to high sigma peaks of the density fluctuation field (nevermind). This means that are quite RARE!

BOTTOM LINE: BARION CONDENSATION IS POSSIBLE IN FAIRLY MASSIVE RARE HALOS AT REDSHIFT ~20.

Seed BH formation from POPIII stars

H_2 cooling → $T=10^3$ K → $z=30$ $M_{DM}=10^6 M_\odot$

↓

Subsonic collapse

↓

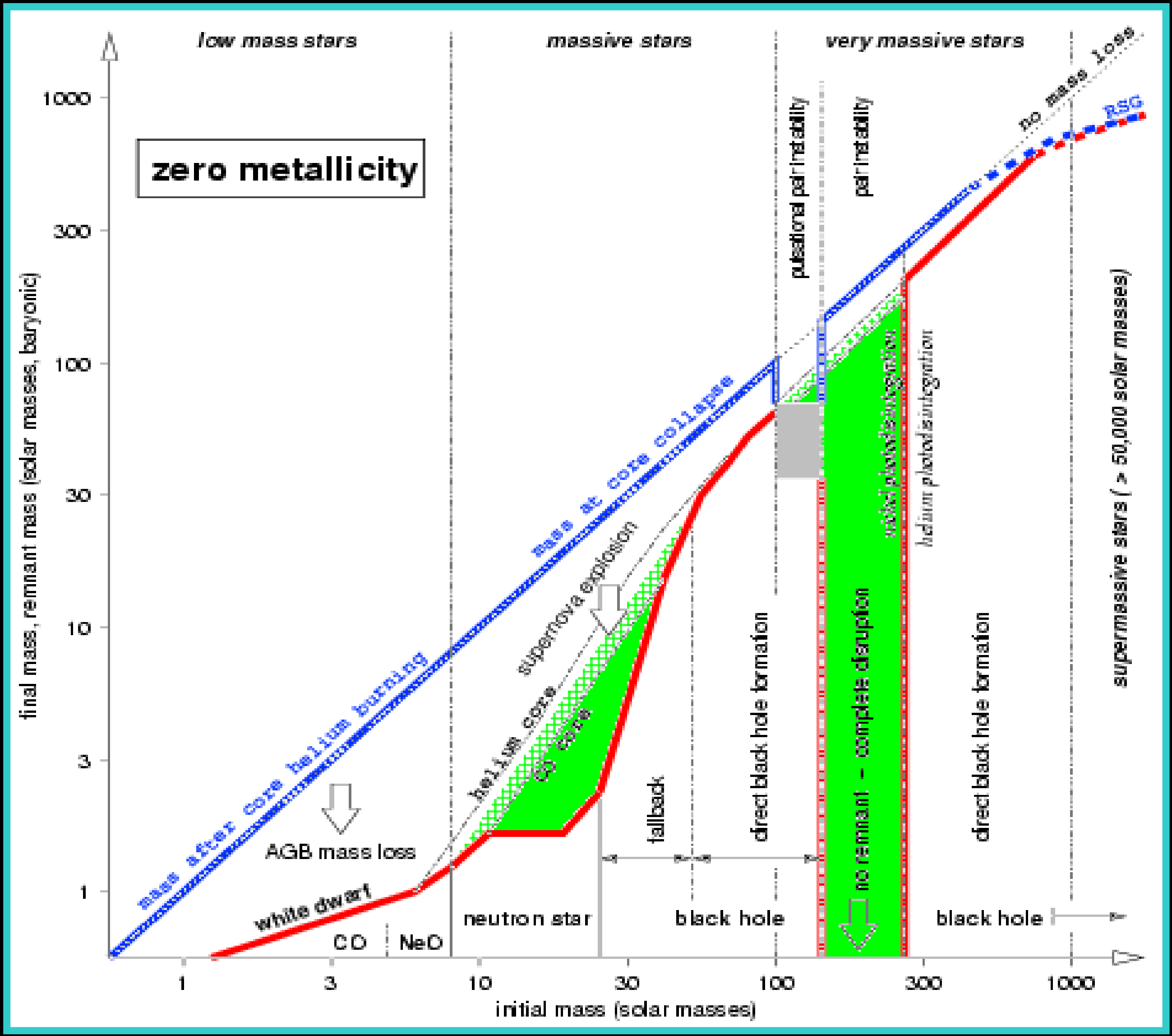
No fragmentation

↓

Formation of VMSs

↓

Intermediate mass seed BHs



Heger & Woosley 2002

Seed BH formation from direct collapse

A seed BH can directly form following the collapse of a giant gas cloud. Two problems:

1- ***you need to dissipate the angular momentum of the cloud***

$$\frac{GM^2}{R} \simeq Mc^2 \rightarrow R \simeq \frac{GM}{c^2} \qquad R_{\mathrm{Sch}} = 2\frac{GM}{c^2}$$

Angular momentum can halt the collapse when the rotational support equals the gravitational binding energy

$$\frac{J^2}{MR^2} \approx \frac{GM^2}{R} \rightarrow R \approx \frac{J^2}{GM^3} \approx \frac{GM}{v^2} \rightarrow \boxed{R_J \approx \left(\frac{c}{v}\right)^2 R_{\mathrm{Sch}}}$$

You need *J*~0, or an efficient way to dissipate *J*.

2- ***you need to avoid star formation***

a-if you form stars you have less gas to feed the BH

b-stars are collisionless: you don't dissipate *J* efficiently anymore

c-supernovae blow away gas.

It turns out that both scenarios are viable, and form BH seeds in relatively massive halos (10^7-10^9 solar masses) at high redshift.

POPIII SCENARIO:

-seed BH mass~10^2 solar masses

-at redshift 15-20

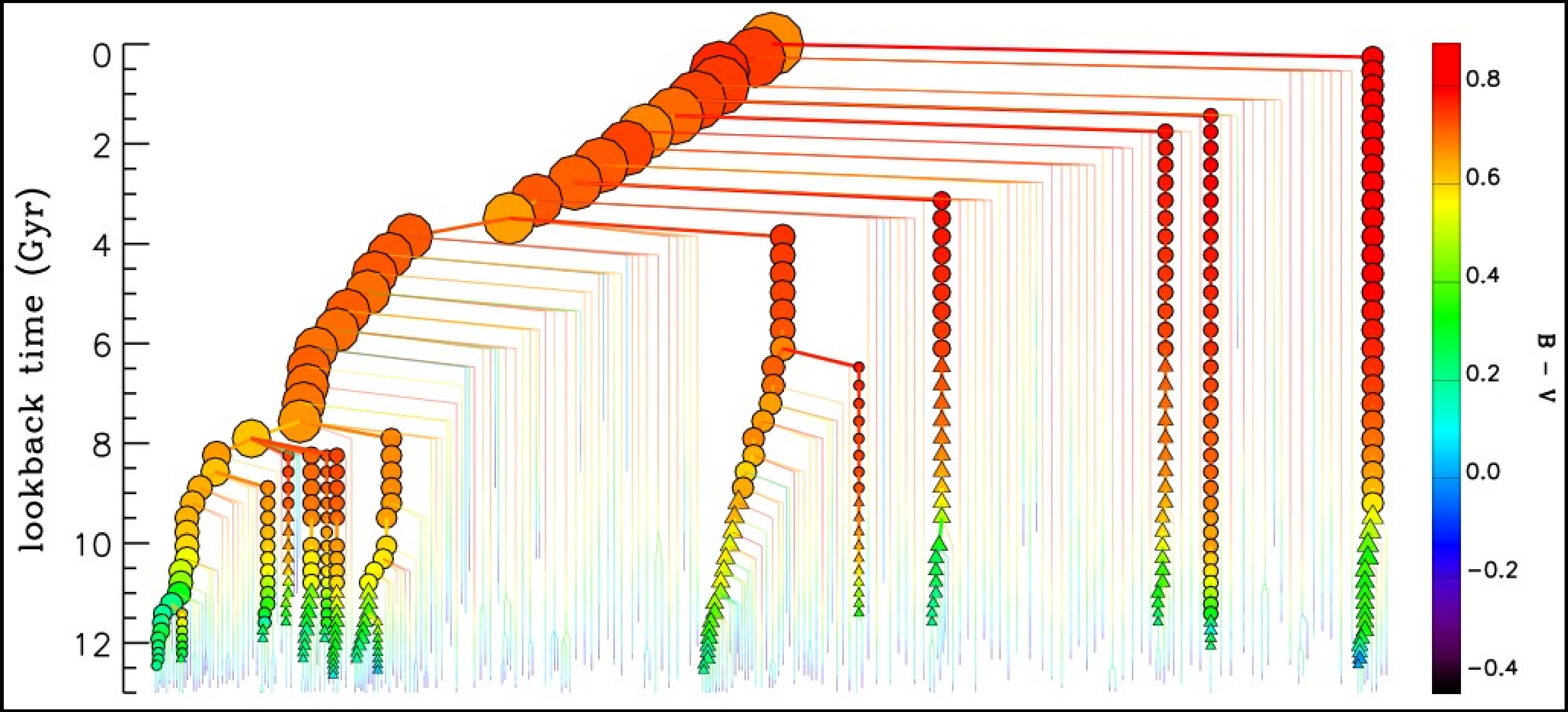
DIRECT COLLAPSE SCENARIO:

-seed BH mass~10^4-10^5 solar masses

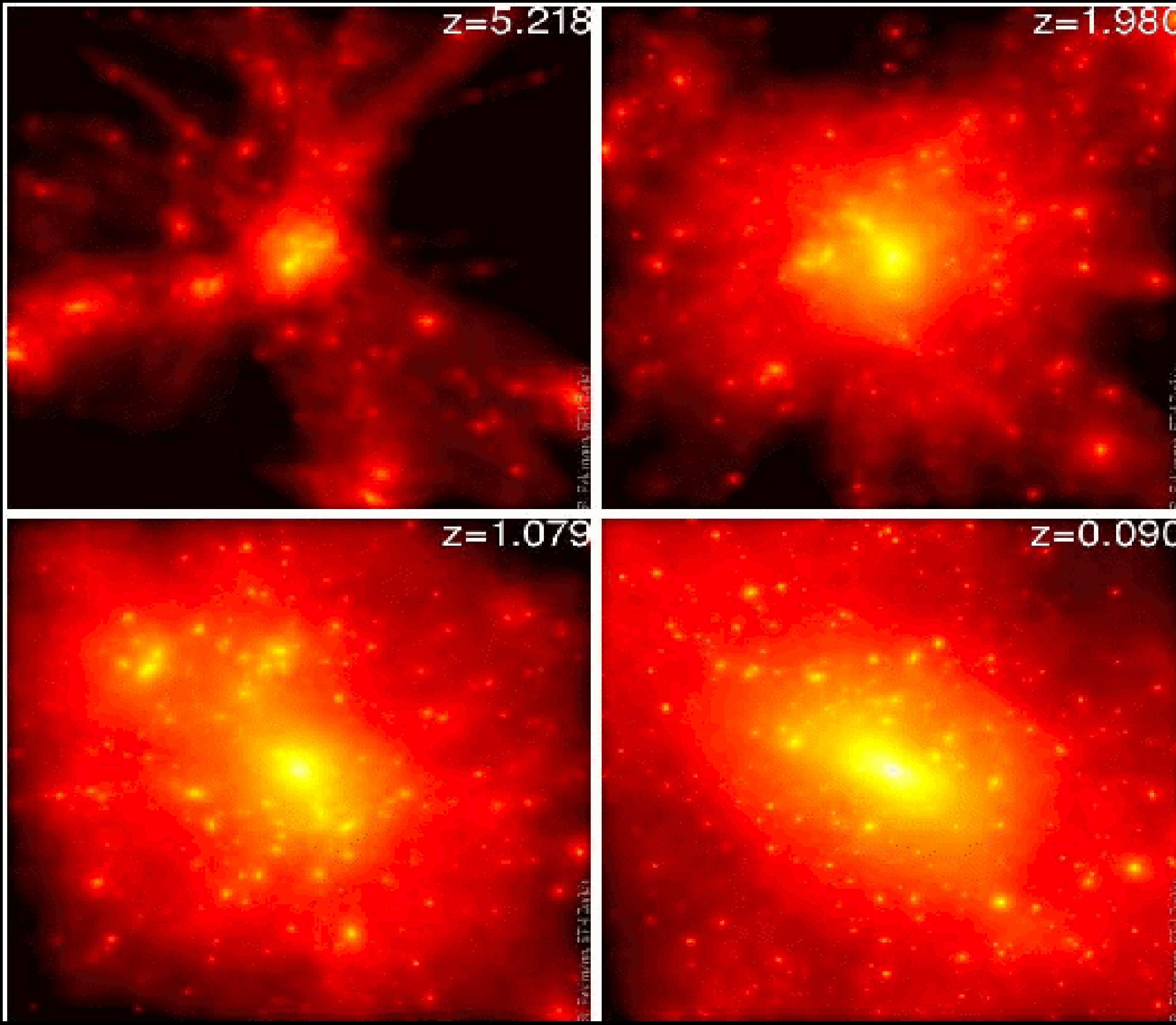
-at redshift 15-10

HIERARCHICAL GALAXY EVOLUTION…

According to the Hierarchical scenario, protogalaxies formed in the first halos at high redshift merge feel each other gravitational attraction and merge together to form the galaxies we see today in the local Universe



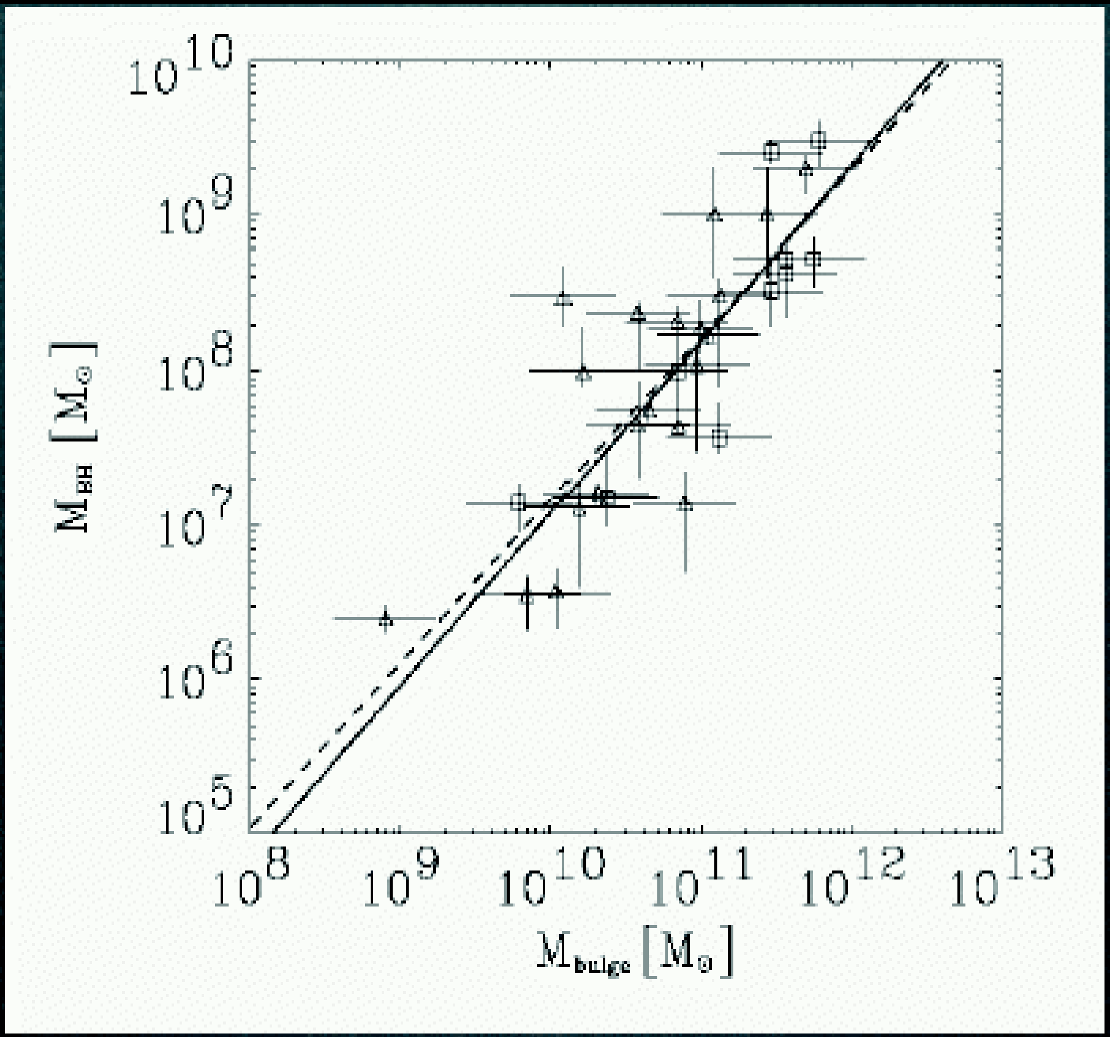
From De Lucia et al. 2006

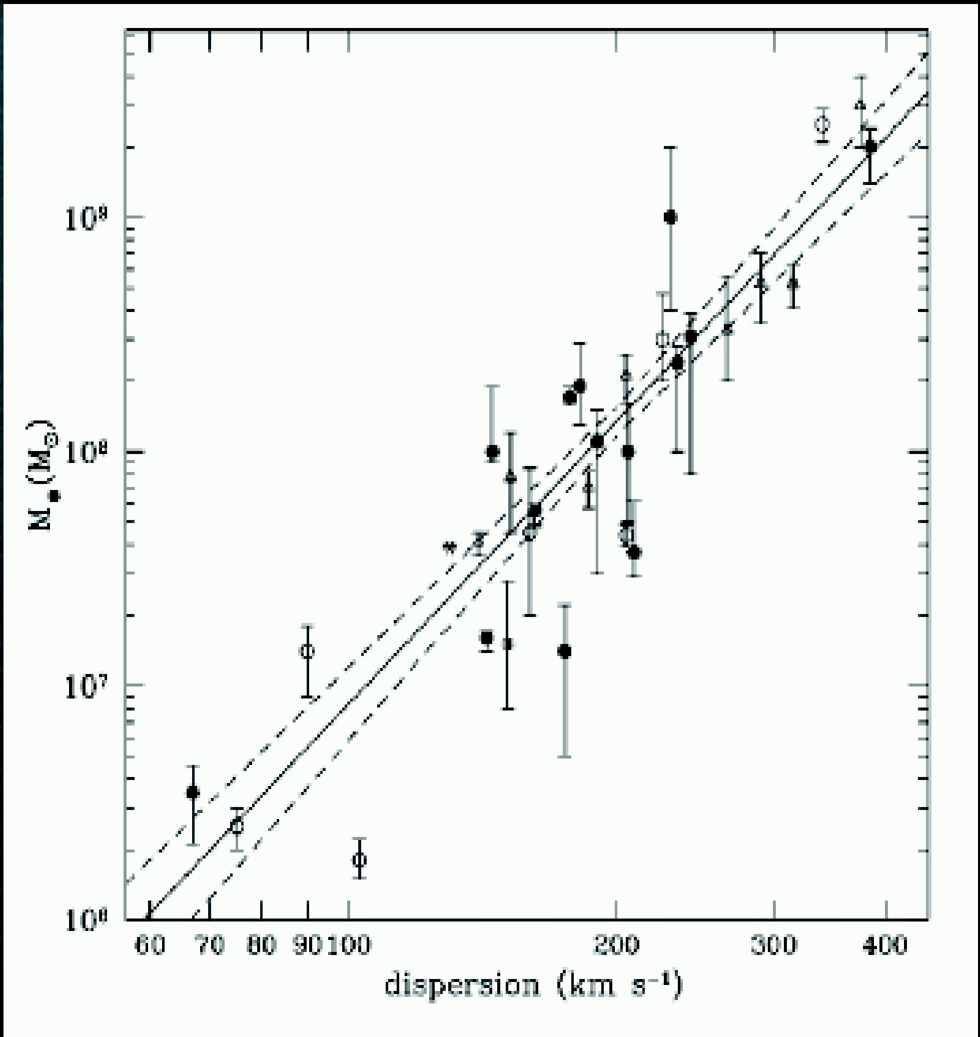

z=5.218
z=1.980
z=1.079
z=0.090

...+ M_{BH}- BULGE RELATIONS...

Massive black holes (MBHs) are ubiquitous in the galaxy centres.

In the last decade, tight relation have been discovered, correlating the MBH mass with the host galaxy bulge mass (Magorrian et al. 1998) **and with the host bulge velocity dispersion** (Gebhardt et al. 2000, Ferrarese & Merrit 2000)**. This relation are a clear hint of a *coevolution of MBHs and host galaxies.***





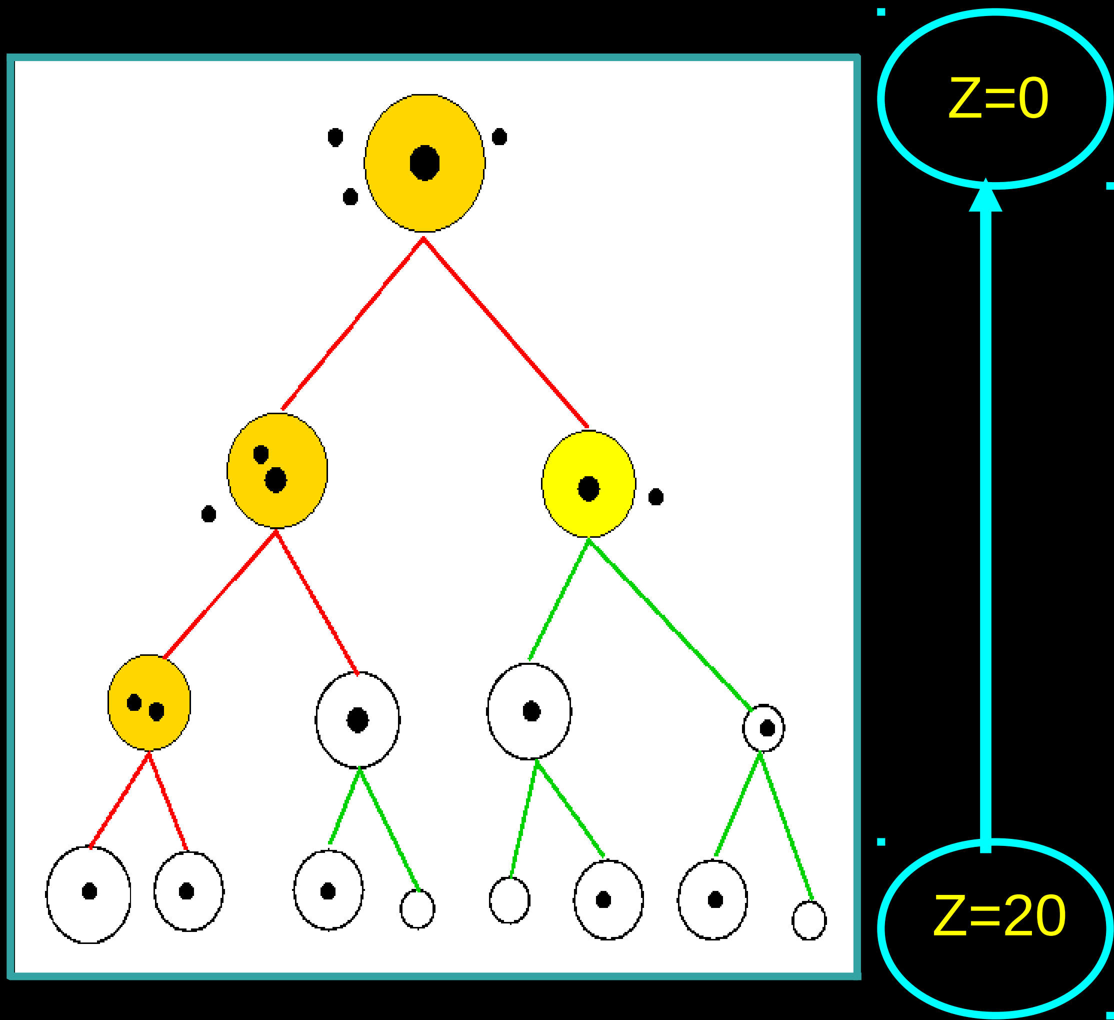
…= HIERARCHICAL MBH EVOLUTION

GENERAL FRAMEWORK: (Volonteri, Haardt & Madau 2003)

> The halo hierarchy can be traced backwards by means of EPS Monte-Carlo merger tree.

The semi-analytic code follows the accretion and the dynamical history of BHs in every single branch of the tree

The adopted threshold for density peaks hosting a seed ensures an occupation fraction of order unity today for halos more massive than $10^{11}M_{\odot}$



Binary merger trees starting at z=20
In a ΛCDM cosmology

Accretion

During mergers, gravitational instabilities drive cold gas toward the galactic nucleus, this gas can form a thin disk around the MBH, starting the accretion process.

Now consider a flux of proton with density ρ being accreted onto a BH of mass *M*. The accreting material emits radiation with a luminosity *L*. Equating the gravitational force (acting on the accreting material) to the force due to the radiation pressure (exerted by the outward radiation emitted by the accretion disk itself)

$$F_g = \frac{GMm}{r^2},$$

$$F_l = \frac{L\sigma_T}{4\pi r^2 c},$$

one found an equilibrium condition (in the spherical limit), which is commonly known as ***Eddington accretion limit***, described by the ***Eddington luminosity***:

$$L_{\mathrm{Edd}} = \frac{4\pi G M m_{\mathrm{p}} c}{\sigma_{\mathrm{T}}}$$

L_{EDD}=1.38x10^{38} erg/s for a solar mass BH and scales as the BH mass. A 10^9 solar mass MBH shines with a luminosity of about 10^{47} erg/s (10^{14} Suns or 1000 MWs)!!!!!

This imply an accretion in mass given by:

$$\frac{dM}{dt} = 2.5 \times 10^{-8} \left(\frac{M}{\mathrm{M}_\odot}\right) \mathrm{M}_\odot \mathrm{yr}^{-1}$$

MBHs CAN EFFICIENTLY INCREASE THEIR MASS!!!!!!

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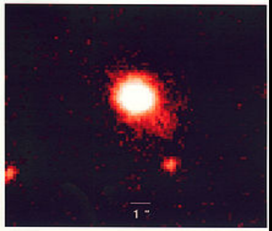

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MBHs CAN EFFICIENTLY INCREASE THEIR MASS!!!!!!

The natural timescale related to accretion is the Eddington timescale:

$$t_{\rm Edd} = \frac{Mc^2}{L_{\rm Edd}} = \frac{\sigma_T c}{4\pi G m_p} = 0.45{\rm Gyr}$$

$$\dot{M} = (1-\epsilon)\dot{M}_{\rm acc} = \frac{(1-\epsilon)}{\epsilon} f_{\rm Edd} \frac{M}{t_{\rm Edd}}$$

This defines the basic equation of mass growth via accretion

$$M(t) = M_0 e^{\frac{(1-\epsilon)}{\epsilon} f_{\rm Edd} \frac{(t-t_0)}{t_{\rm Edd}}}$$

Although often set to 0.1, *ε* is in fact an important parameter that depends on the spin. What is it?

$$\Delta E = -\frac{GmM}{2r_{\rm rim}} \Longrightarrow L = -\frac{dE}{dt} = \frac{G\dot{M}M}{2r_{\rm rim}},$$

$$L = \frac{1}{4\beta}\dot{M}c^2 = \epsilon \dot{M}c^2,$$

β=3 for a Sch. BH, ***β***=1 for a max spinning BH and prograde accretion. The GR calculation gives

$$a = 0 \rightarrow \epsilon \approx 0.06 \rightarrow M = M_0\ e^{\frac{t}{3\times 10^7 {\rm yr}}},$$

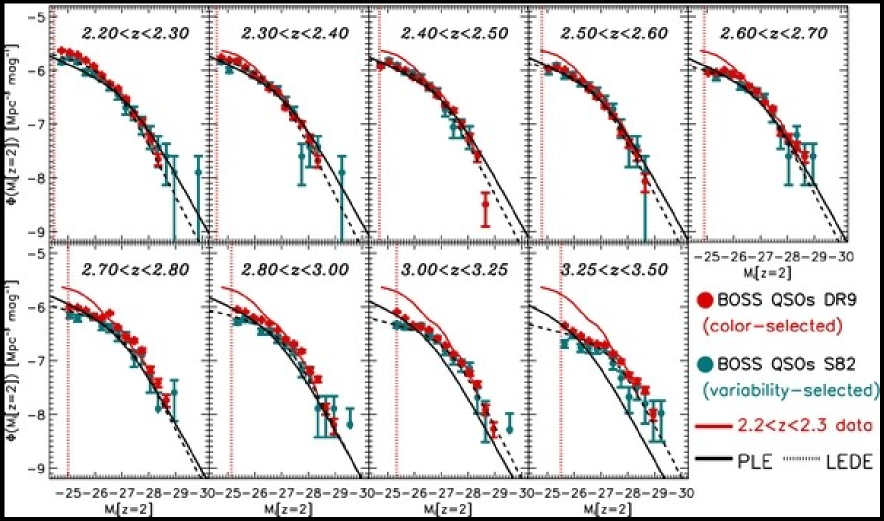
$$a = 0.998 \rightarrow \epsilon \approx 0.42 \rightarrow M = M_0\ e^{\frac{t}{3\times 10^8 {\rm yr}}}$$

No problem accreting MBHs to 10^9 solar masses by z=0, but what about z>7 QSOs?

Evidence that MBHs grow mostly via radiative efficient accretion comes from the Soltan argument (1982).

By measuring the luminosity function of quasars, one can compute the energy density due to the light emitted by accreting MBHs

$$e = \frac{4\pi}{c}\int_0^\infty (1+z)dz \int_0^\infty n(S,z)S\ dS,$$



An energy density corresponds to an accreted mass density via

$$\rho_{\rm acc} = \frac{1-\epsilon}{\epsilon}\frac{e}{c^2}$$

The luminosity function of quasars can be measured empirically so that the estimate of the accreted mass density can be compared to the current mass density in MBHs (which can be also measured):

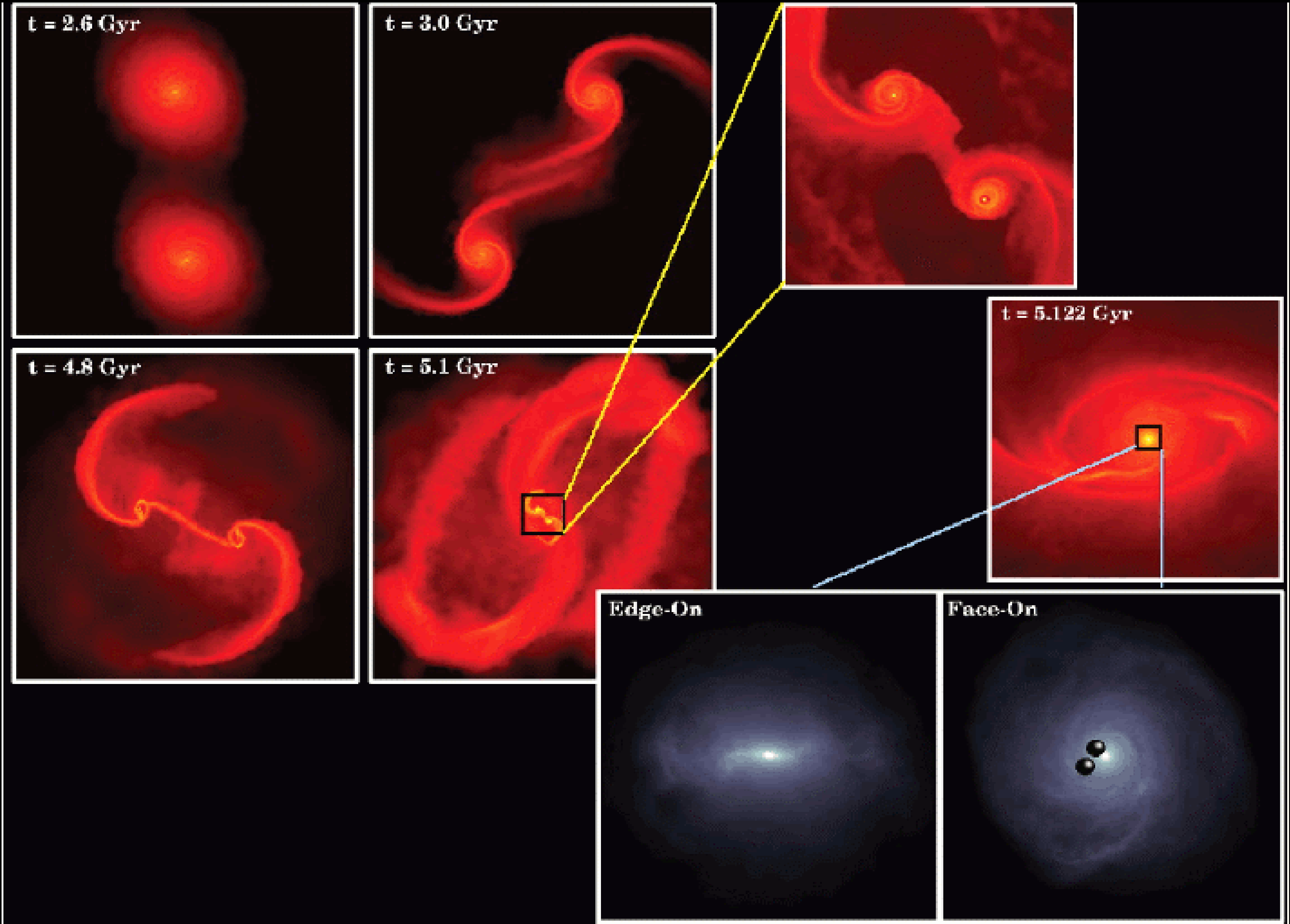
$$\rho_{\rm acc} \approx 2.2\times 10^5 \left(\frac{0.1}{\epsilon}\right)\frac{M_\odot}{Mpc^3}$$

$$\rho_{\rm BH} \approx 3-5\times 10^5 \frac{M_\odot}{Mpc^3}$$

About half quasars are obscured! Which brings the two estimates to match quite well.

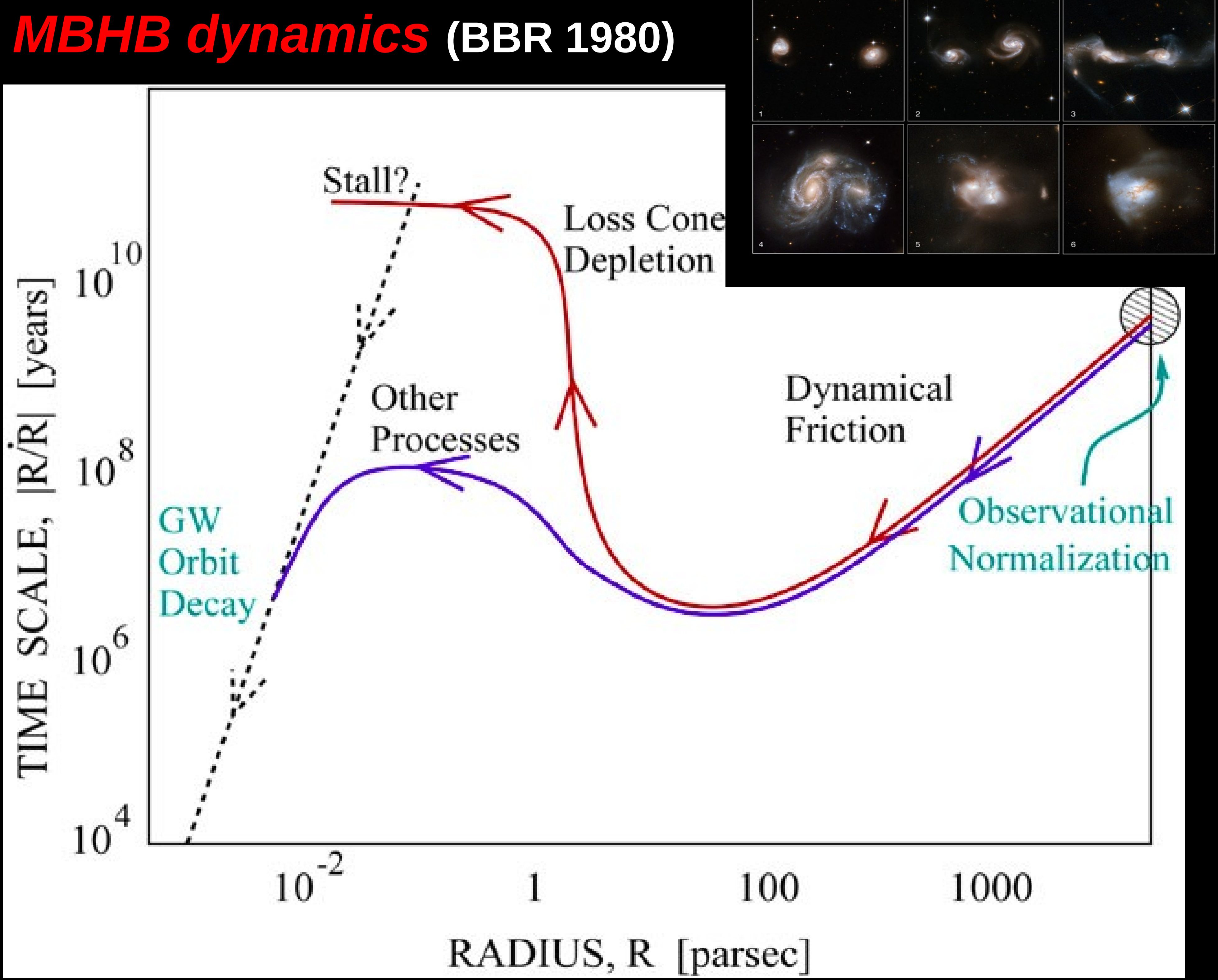
Mergers


1
2
3
4
5
6

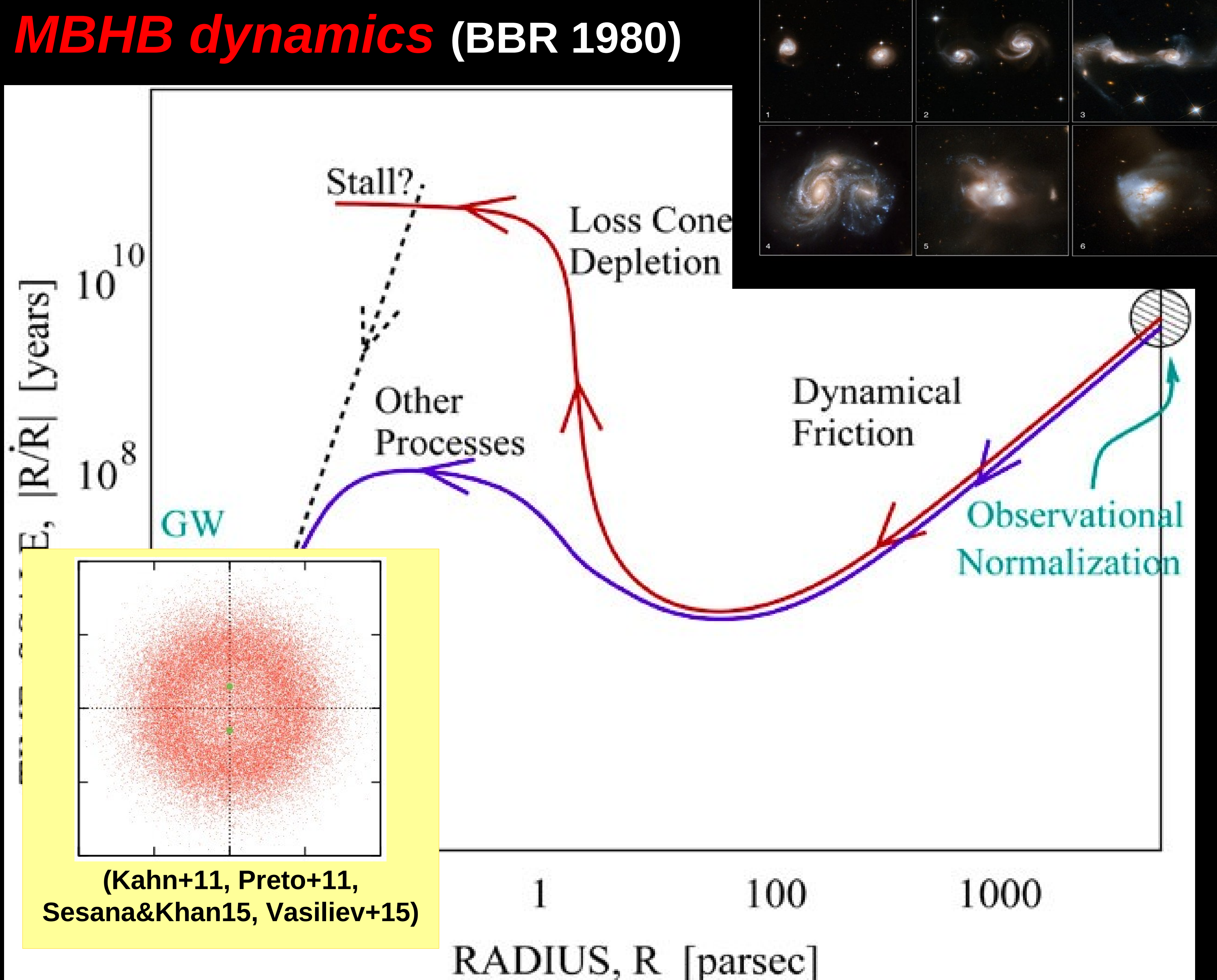


t = 2.6 Gyr
t = 3.0 Gyr
t = 4.8 Gyr
t = 5.1 Gyr
t = 5.122 Gyr
Edge-On
Face-On

MBHB dynamics (BBR 1980)

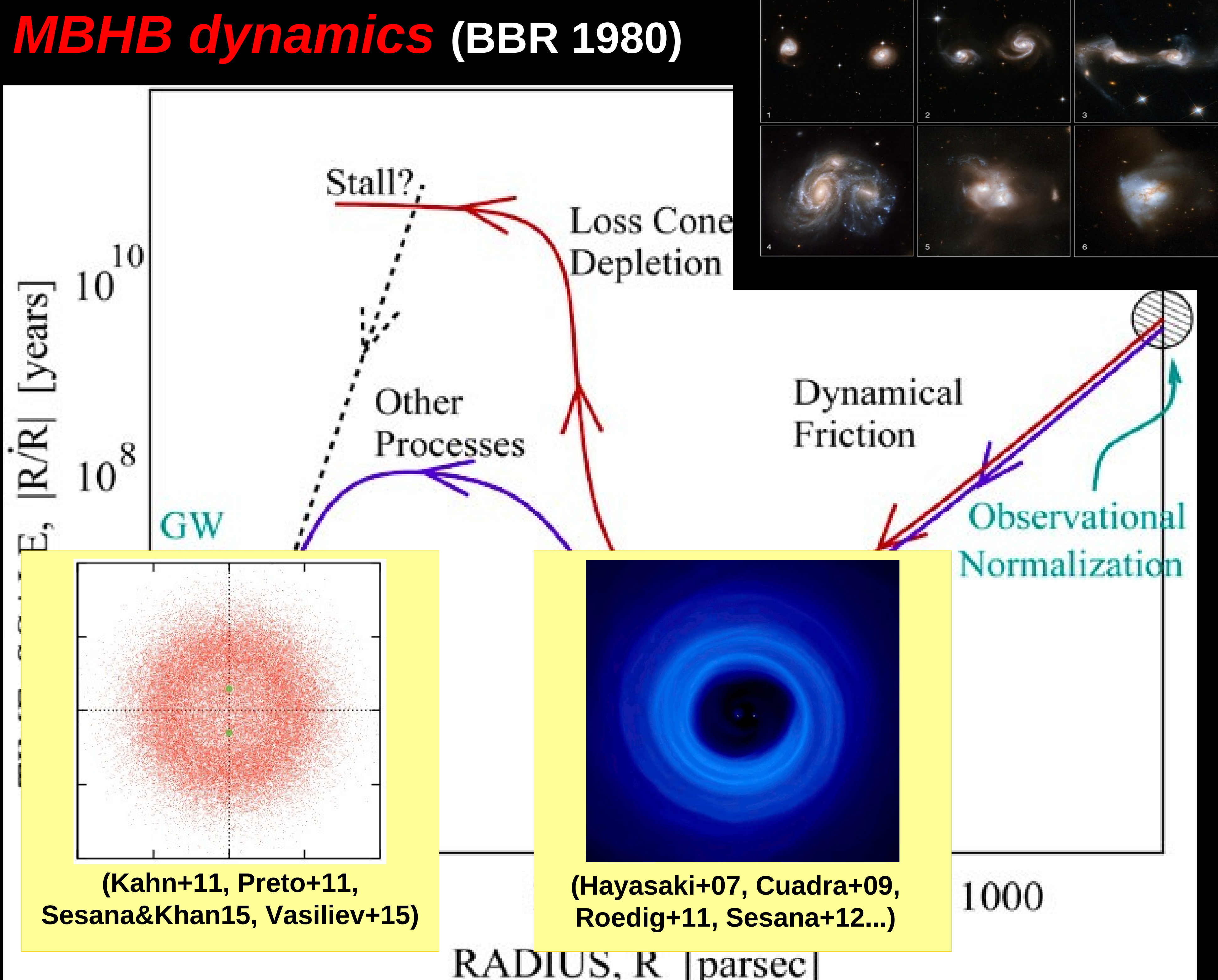


MBHB dynamics (BBR 1980)



(Kahn+11, Preto+11, Sesana&Khan15, Vasiliev+15)

MBHB dynamics (BBR 1980)



I-Dynamical friction: 10kpc-1pc

Consider a BH with mass M_{BH} moving with velocity *V* in a surrounding distribution of field star with a density ρ_* and a Maxwellian velocity distribution with dispersion σ. The drag exerted by the stars on the BH is given by:

$$\mathbf{F}_{\rm DF} = -4\pi \ln\Lambda G^2 M_{\rm BH}^2 \rho_* \left[\mathrm{erf}\left(\frac{V}{\sqrt{2}\sigma}\right) - \left(\sqrt{\frac{2}{\pi}}\frac{V}{\sigma}\right)\exp\left(-\frac{V^2}{2\sigma^2}\right)\right]\frac{\mathbf{V}}{V^3}$$

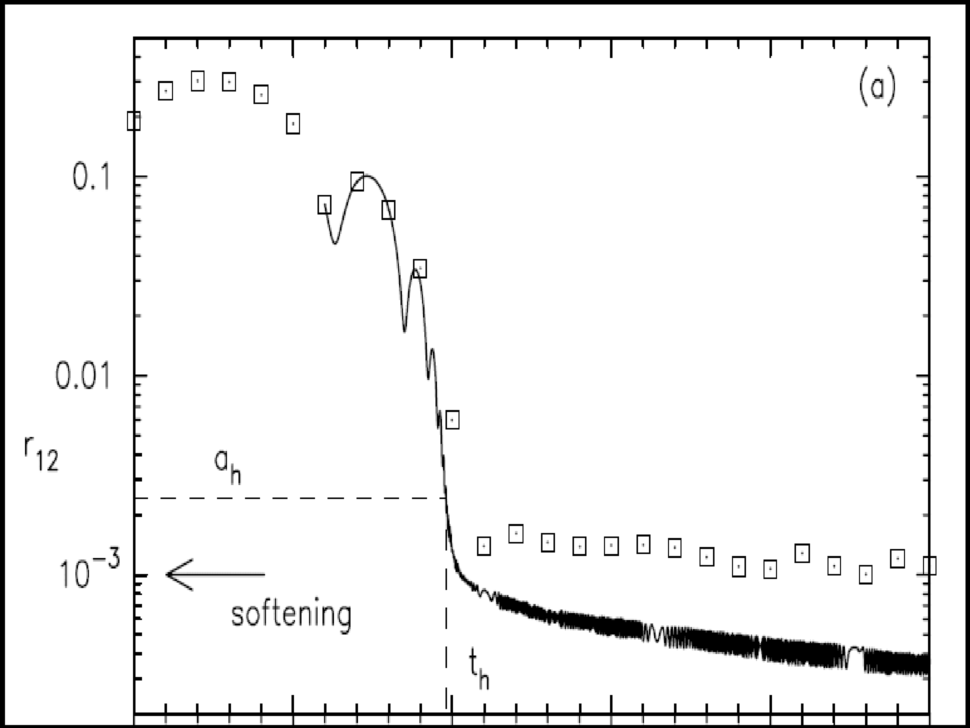
- in the limit *V*->0 this force is proportional to *V*
- in the limito of $V \gg \sigma$ this force is proportional to $1/V^2$
- the drag is maximum for $V=\sigma$

In a gaseous medium the formula is similar:

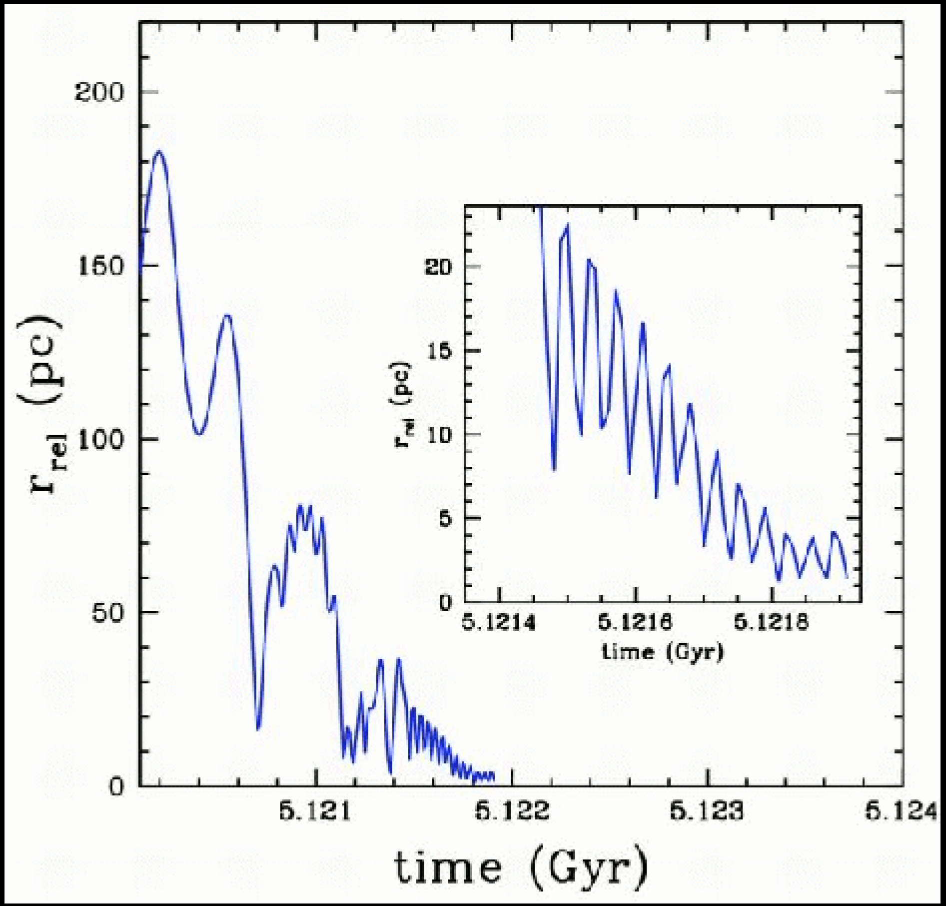
$$\mathbf{F}_{\rm DF}^{\rm gas} = -4\pi \ln\left[\frac{b_{\rm max}}{b_{\rm min}}\frac{(\mathcal{M}^2-1)^{1/2}}{\mathcal{M}}\right] G^2\, M_{\rm BH}^2 \rho_{\rm gas}\frac{\mathbf{V}}{V^3}, \quad \text{for} \quad \mathcal{M} > 1$$

$$\mathbf{F}_{\rm DF}^{\rm gas} = -(4/3)\pi G^2\, M_{\rm BH}^2 \rho_{\rm gas} \mathcal{M}^3 \mathbf{V}/V^3 \propto M_{\rm BH}^2 \rho_{\rm gas}\, \mathbf{V}/c_{\rm s}^3 \text{ for } \mathcal{M} \ll 1$$

but now $\mathcal{M} = V/c_{\rm s}$ is the gas speed of sound.
Again the drag is maximum when $V=c_s$, and is comparable to the stellar case.



From Milosavljevic & Merritt 2001



From Colpi & Dotti 2009

Dynamical friction is initially very efficient in shrinking the binary, but on parsec scales the mechanism is no longer efficient:

BINARY STALLING? (Probably not)

II-The hardening phase: "final parsec problem". 1pc-0.01pc

Dynamical friction **is efficient in driving the two BHs to a separation of the order**

$$a_h \simeq 0.31\,\mathrm{pc}\ M_{2,6}^{1/2}\sqrt{\frac{q}{1+q}}$$

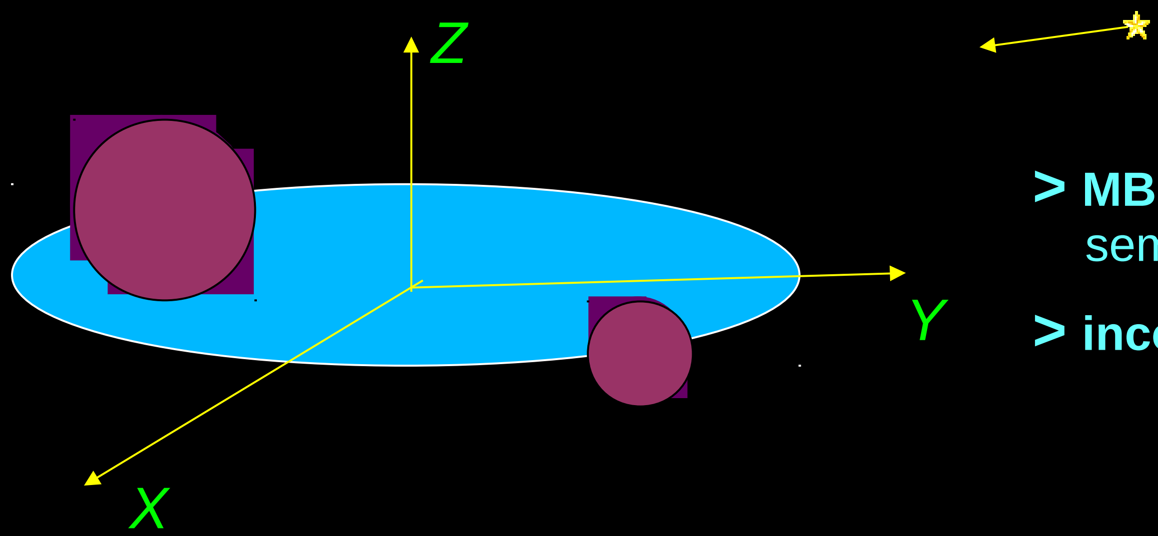
GW emission **takes over at separation of the order**

$$a_{GW} \approx 0.0014\,\mathrm{pc}\ \left(\frac{M M_1 M_2}{10^{18.3}\ \mathrm{M_\odot}^3}\right)^{1/4}\ F(e)^{1/4}\,t_9^{1/4}$$

The ratio can be written as

$$\frac{a_h}{a_{GW}} \approx 2.5\times 10^2\left(\frac{q}{1+q}\right)^{3/4}\ F(e)^{-1/4}\,M_6^{-1/4}\,t_9^{-1/4}$$

3-body interactions



> **MBHB** $M_1 > M_2$ on a keplerian orbit with semimajor axis a and eccentricity e

> **incoming star** with $m_* \ll M_2$ and velocity $\underline{\mathbf{v}}$

A star on a intersecting orbit receive a kick taking away from the binary an amount of energy of the order $(3/2)Gm_*\mu_{\rm BH}/a$

This energy, and the relative angular momentum carried away, can be used to define dimensionless rate that describe the evolution of the binary.

$$\frac{dN}{dt} = n\Sigma\sigma = \frac{2\pi G(M_1 + M_2 + m_3)na}{\sigma}$$

Hardening of the binary

Quinlan 1996

$$H = \frac{\sigma}{G\rho_0}\frac{d}{dt}\left(\frac{1}{a}\right)$$

HARDENING RATE

$$K = \frac{de}{d\ln(1/a)}$$

ECCENTRICITY GROWTH RATE

$$J = \frac{1}{M}\frac{dM_{\mathrm{ej}}}{d\ln(1/a)}$$

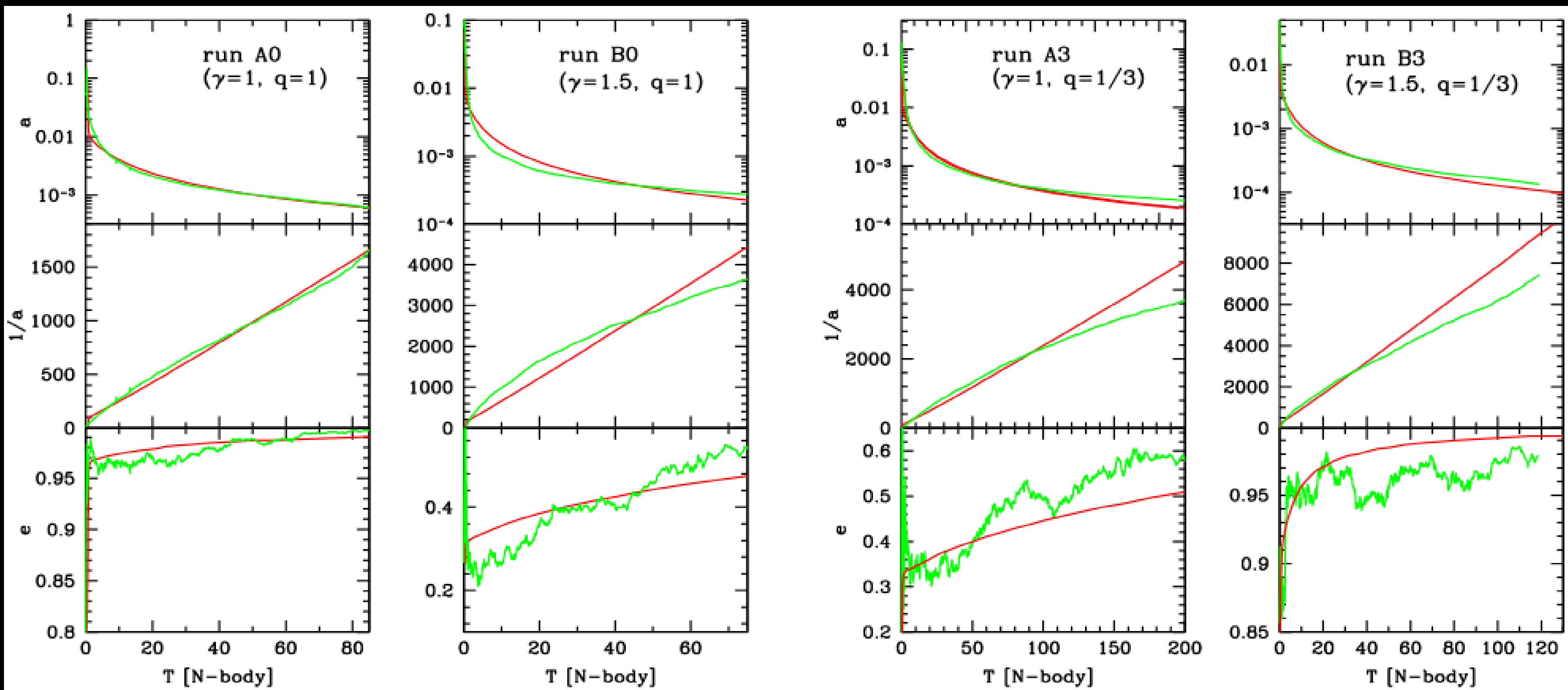
MASS EJECTION RATE

This equations are derived in the approximation that the stellar background DOES NOT CHANGE during the binary evolution!!!!

But 'loss cone depletion' is a potential problem ($t_{rlx} > T_H$)

AS & Khan 2015 (See also Vasiliev et al. 2015)

Compare:
-'realistic' mergers with N-body simulations
-semianalytic models including scattering of bound and unbound stars



Reasonable agreement if the evolution is rescaled with ρ and σ at the binary influence radius

$$\frac{d}{dt}\left(\frac{1}{a}\right) = \frac{G\rho}{\sigma} H_{3b}$$

$$\frac{da}{dt} = \frac{da}{dt}\bigg|_{3b} + \frac{da}{dt}\bigg|_{\rm gw} = -Aa^2 - \frac{B}{a^3},$$

$$A = \frac{GH\rho_{\rm inf}}{\sigma_{\rm inf}}, \quad B = \frac{64G^3M_1M_2MF(e)}{5c^5},$$

$$a_{*/\rm gw} = \left[\frac{64G^2\sigma_{\rm inf}M_1M_2MF(e)}{5c^5H\rho_{\rm inf}}\right]^{1/5}$$

Triaxiality of the merger remnant keeps the 'loss cone full' and the hardening rate ~constant

The evolution of the binary can be simply obtained by combining stellar and GW hardening

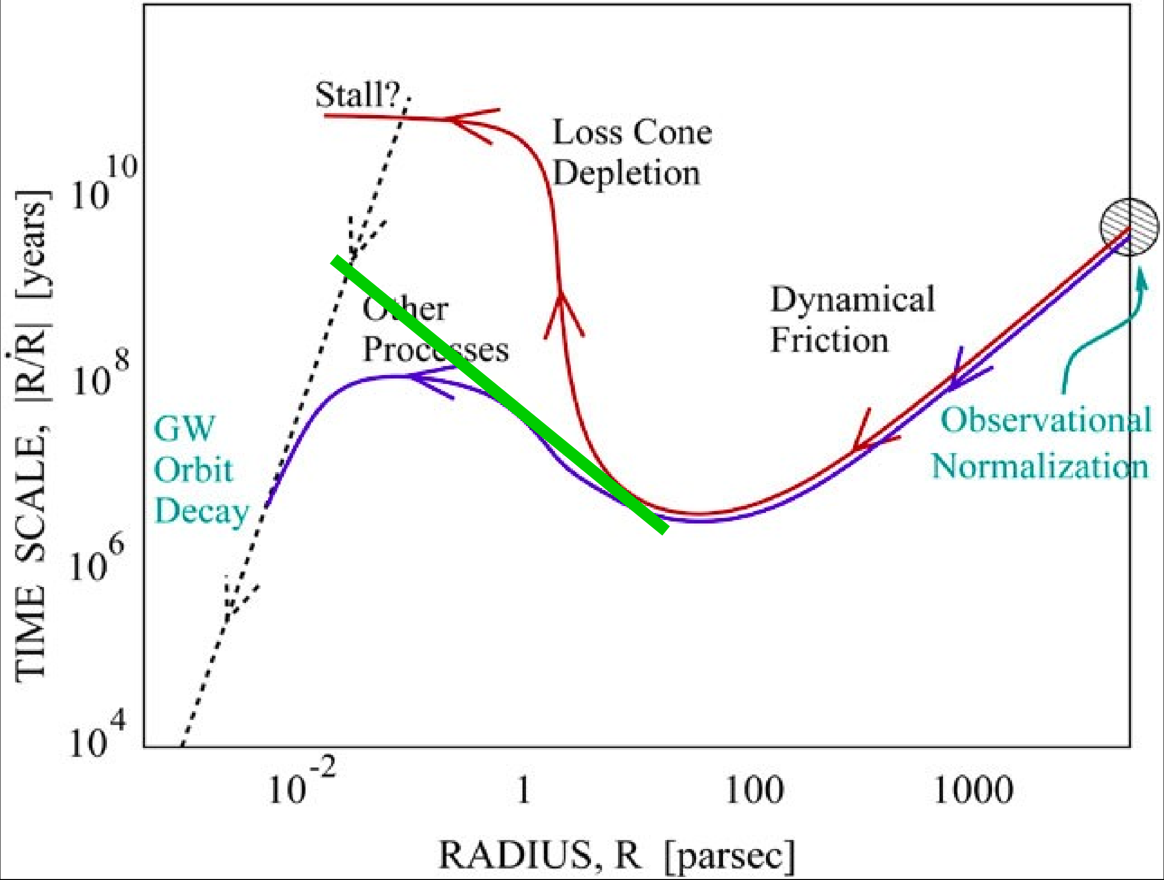
The binary spends most of its time at the transition separation

$$t(a_{*/\rm gw}) = \frac{\sigma_{\rm inf}}{GH\rho_{\rm inf}a_{*/\rm gw}}.$$

Assuming an isothermal sphere and a simple M-sigma relation

$$a_{*/\rm gw} \approx 0.01\,{\rm pc}\left(\frac{M}{10^8{\rm M}_\odot}\right)^{3/4}$$

$$t(a_{*/\rm gw}) \approx 10^8{\rm yr}.$$

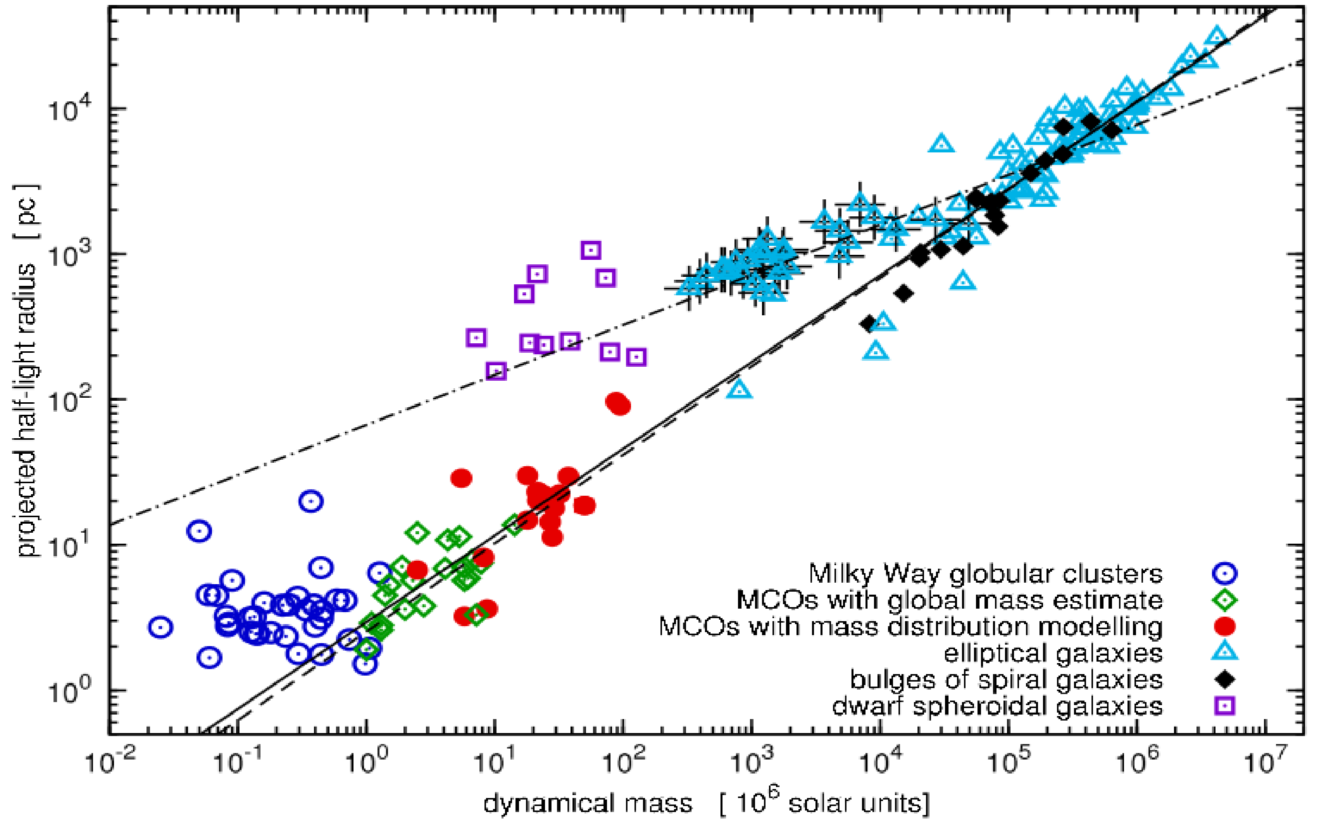


A MBHB In a merger remnant evolve as if it was immersed in an homogeneous background of stars with with ρ and σ taken at the influence radius of the merger remnant

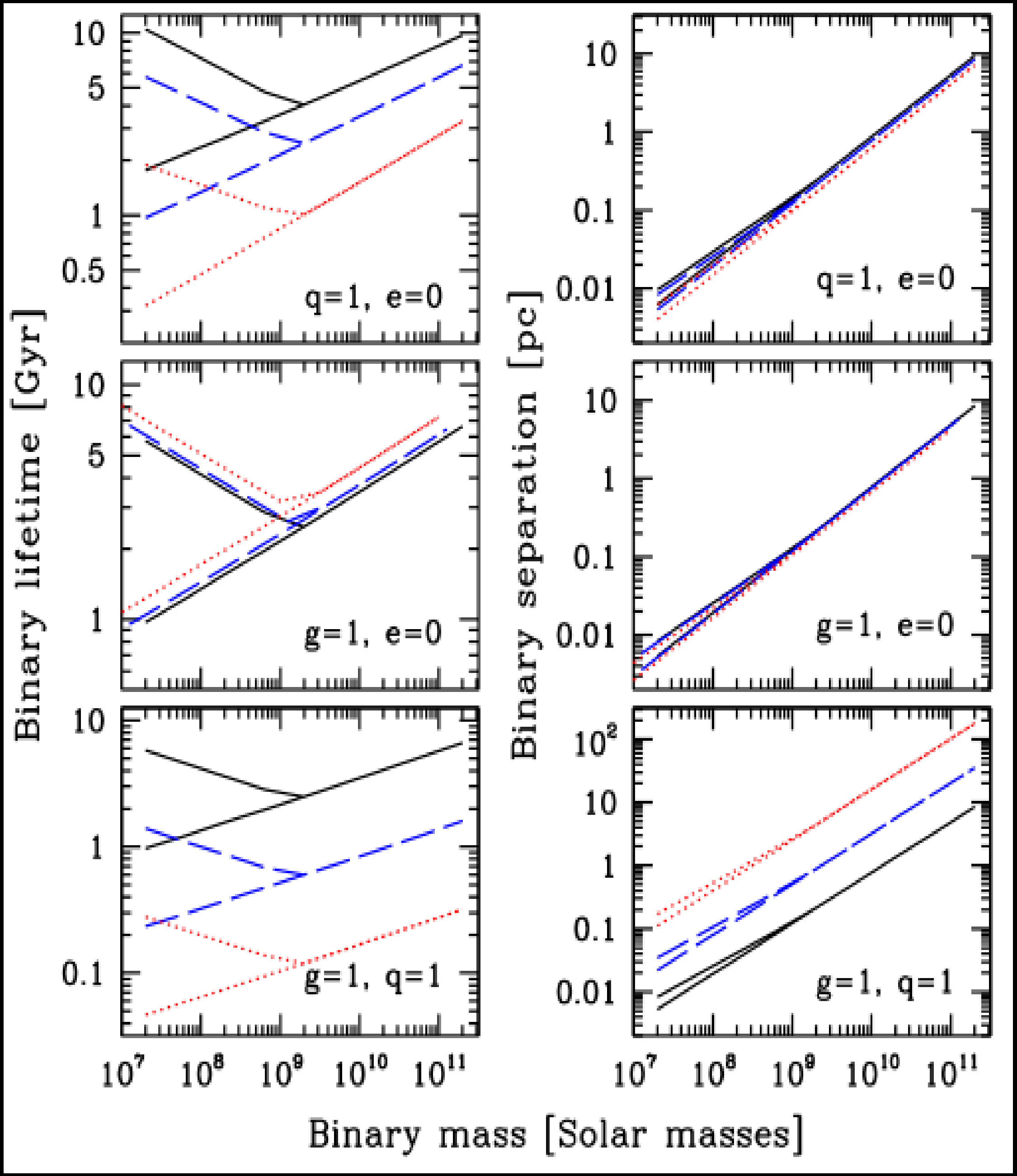
We can then assume a Dehnen density profile

$$\rho(r) = \frac{(3-\gamma)M_*}{4\pi}\frac{r_0}{r^\gamma(r+r_0)^{4-\gamma}}$$

Connect the MBHB mass to the stellar mass via standard M-galaxy relations; get the scale radius from observations



...and compute the coalescence timescale for typical galaxy properties as a function of the MBHB mass

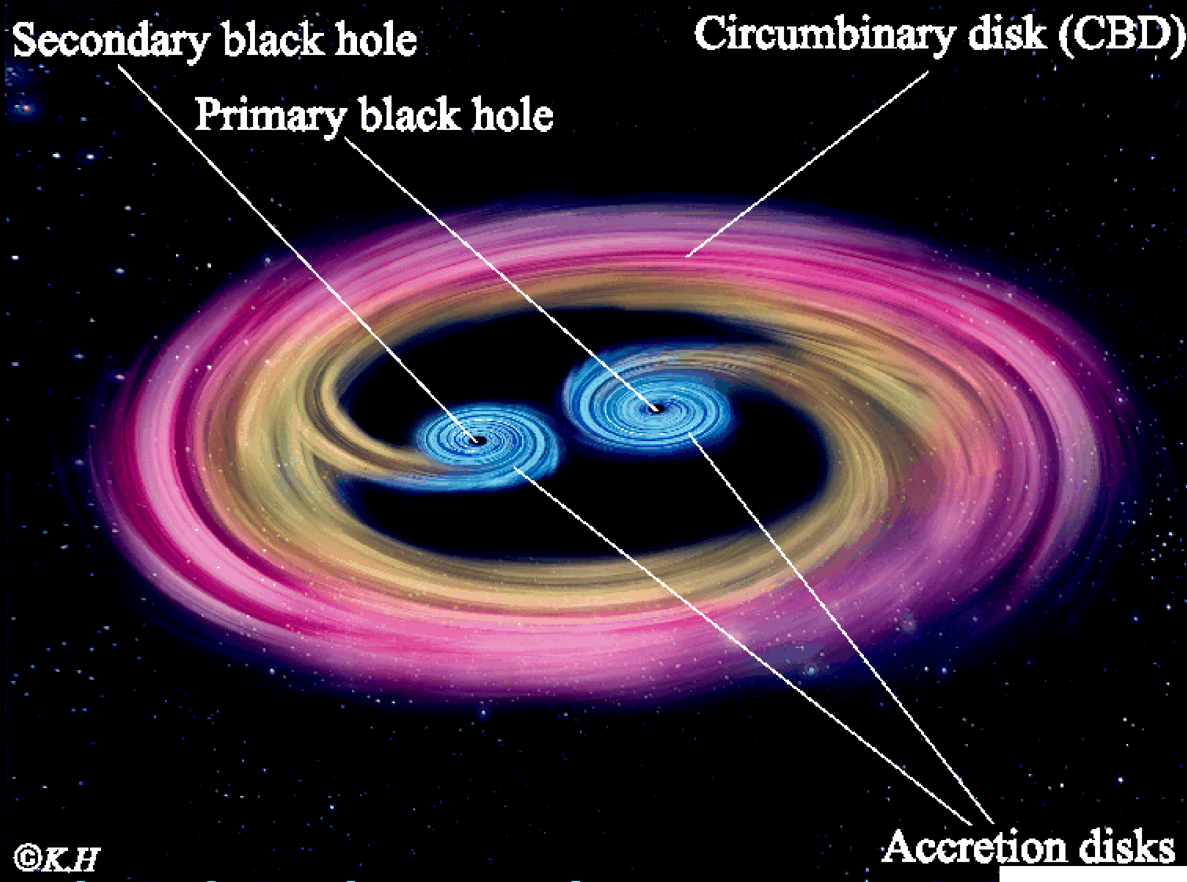


Coalescence timescales are fairly long:

***bending of GW spectrum in the PTA band might not be an issue unless binaries gets very eccentric (might be likely)**

***Gyr coalescence timescale open interesting scenarios like triple interactions**

Circumbinary disk-driven binaries



Gas inflows with a constant accretion rate. Its change in angular momentum is

$$\frac{dL}{dt} == -\dot{m}\sqrt{GMr_{\rm gap}}$$

The binary acts as a dam holding the gas at r_{gap} .

Therefore is injecting in the disk an angular momentum equal and opposite to the above

Therefore the angular momentum of the binary also evolve as

$$\frac{dL}{dt} == -\dot{m}\sqrt{GMr_{\rm gap}}$$

Using $L = \mu\sqrt{GMa}$ and assuming that the mass ratio does not change one get the equation

$$\frac{da}{a} = -2\sqrt{2}\frac{dM}{\mu}$$

The binary makes ~3 e-folds by accreting a mass equal to mu. Assuming Eddington limited accretion this happens in ~4 x 10^7 yrs. (Dotti+15)

Supermassive black hole triplets

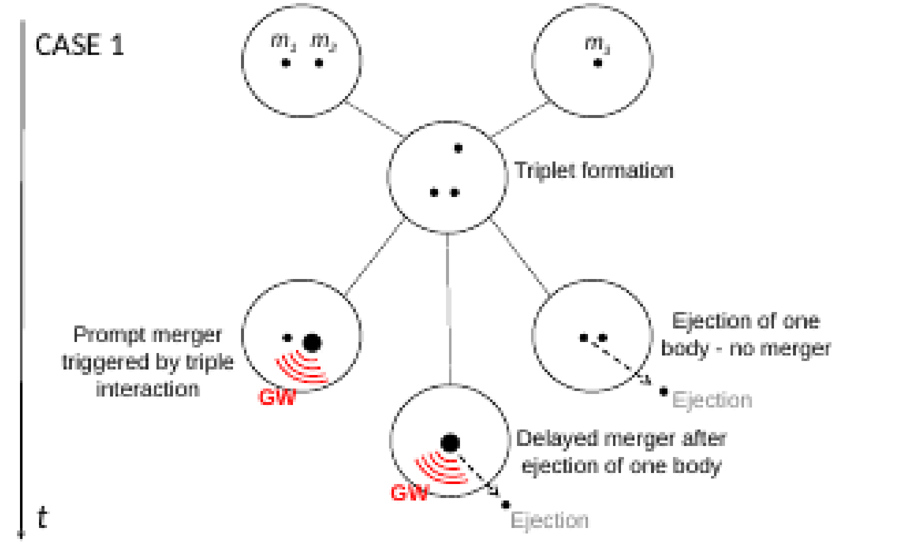


Figure 1. Cartoon representation of how triple MBH interactions are treated in the semianalytic model described in Section 2.

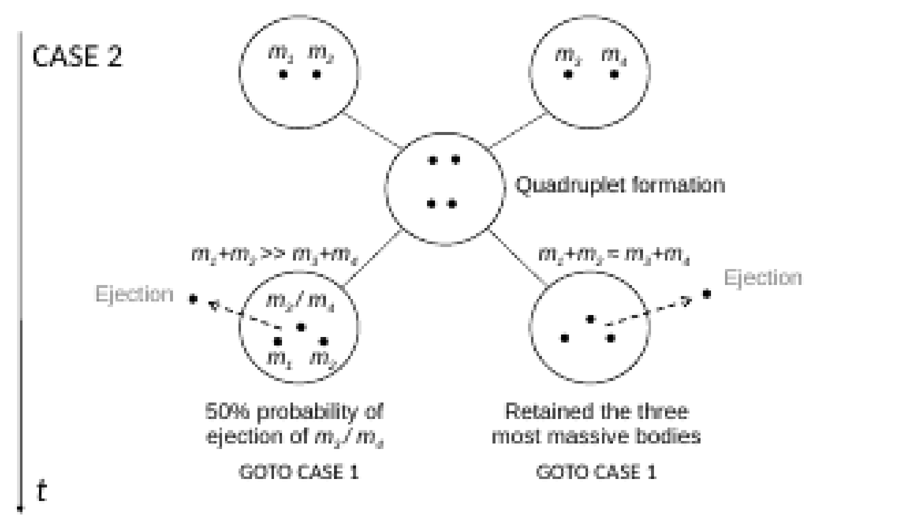
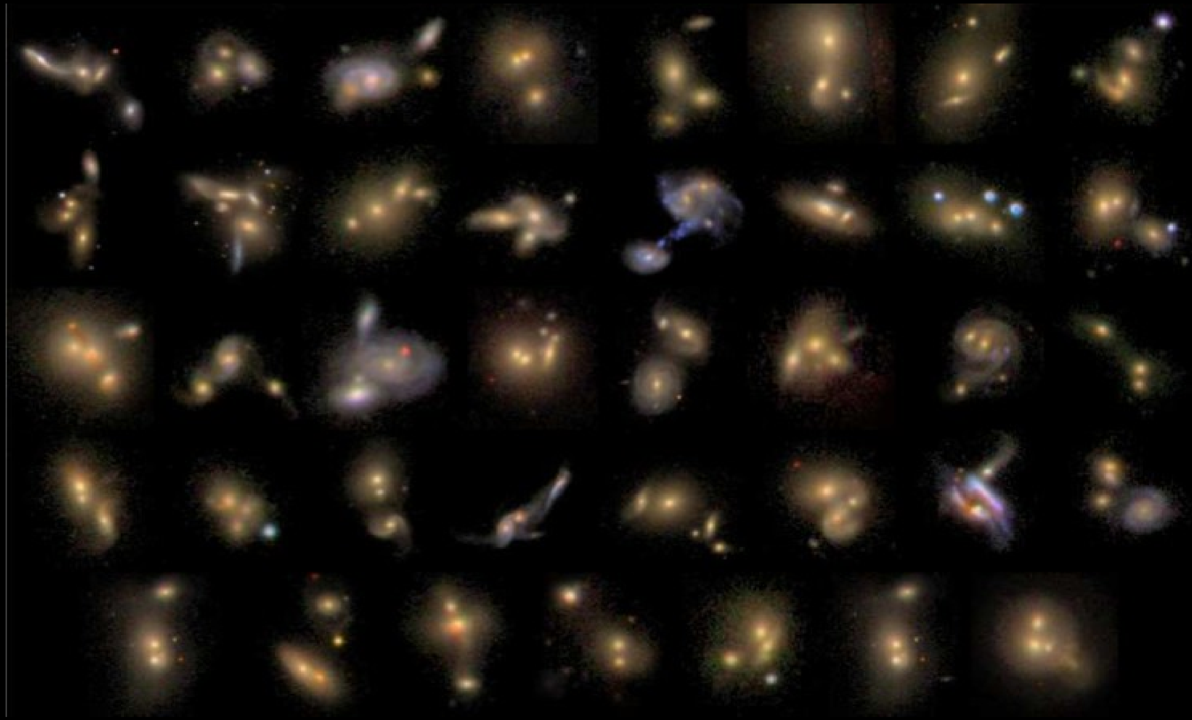


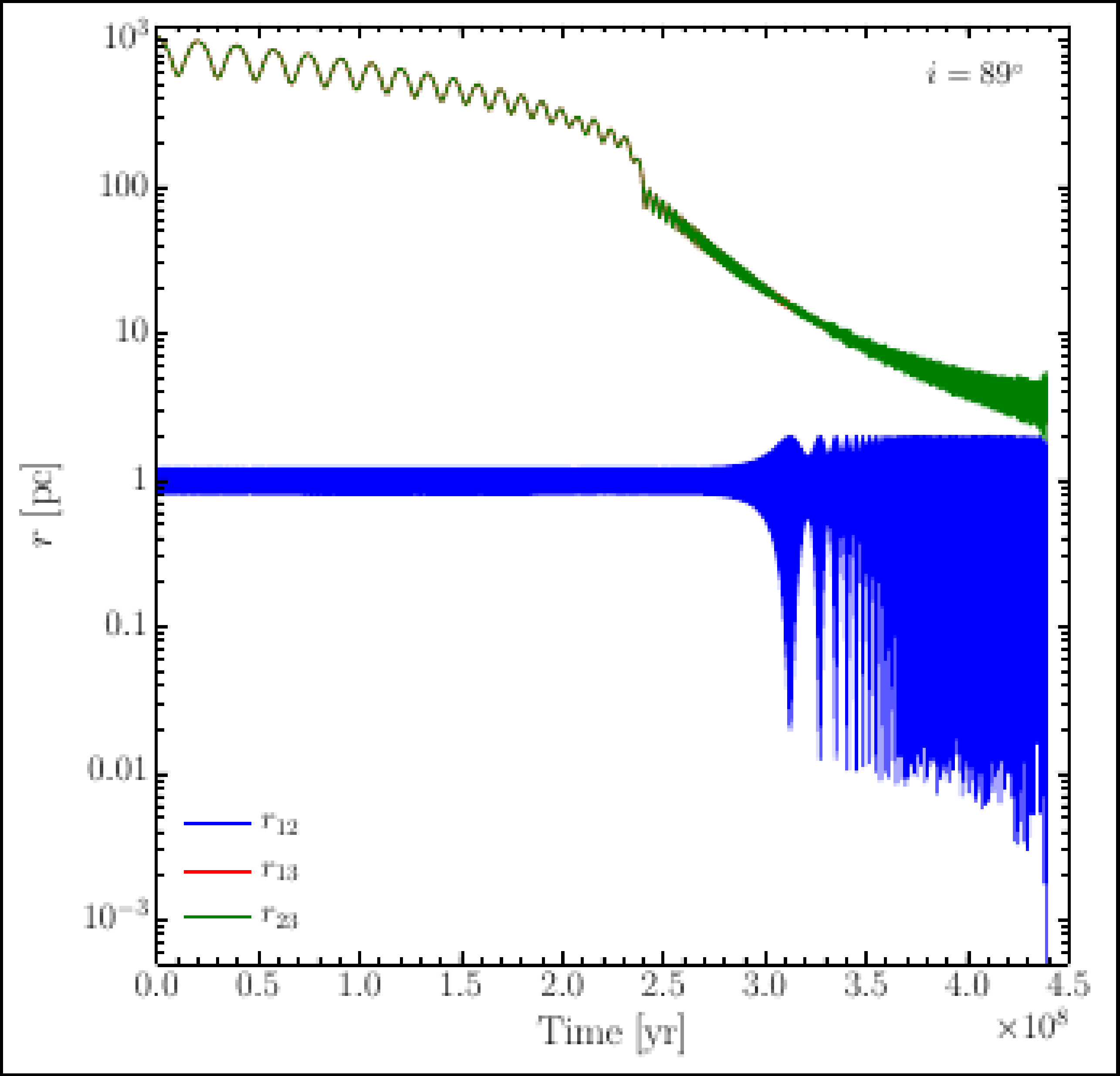
Figure 2. Same as figure 1, but for quadruple interactions.



merger timescales comparable with galaxy subsequent merger timescale

There is a concrete possibility of injecting a third MBH in the system when the binary is still 'slowly hardening'
(Hoffmann & Loeb 2007; Amaro-Seoane, AS, et al. 2010; Bonetti+16; Bonetti+17a,b; Ryu+17)

Integration of the 3-body dynamics



We designed a code for evolving MBHB triplets including

-PN dynamics up to 2.5 order, including all terms consistently derived from the 3-body Hamiltonian

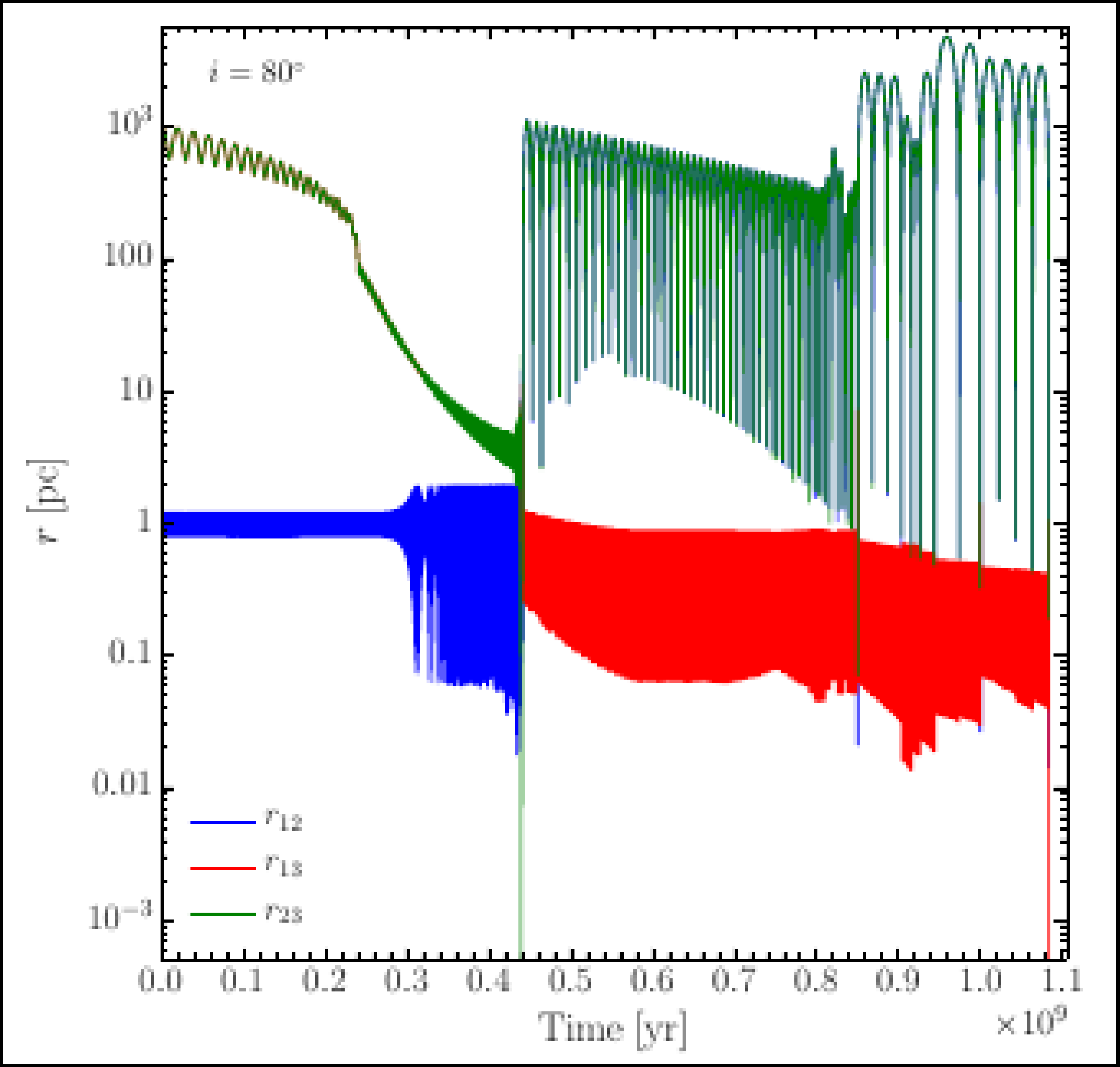
-Dynamical friction (Chandrasekhar 1943)

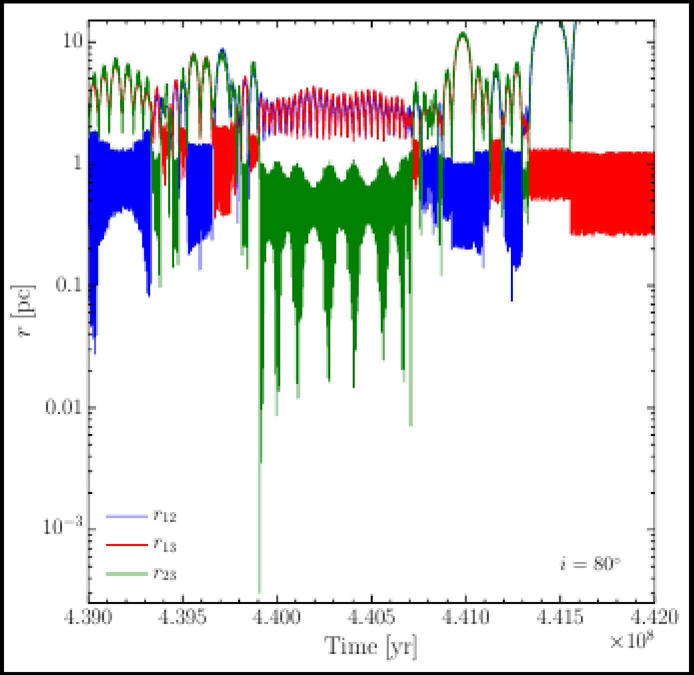
-Stellar hardening (Sesana 2006)

-Spherical external potential

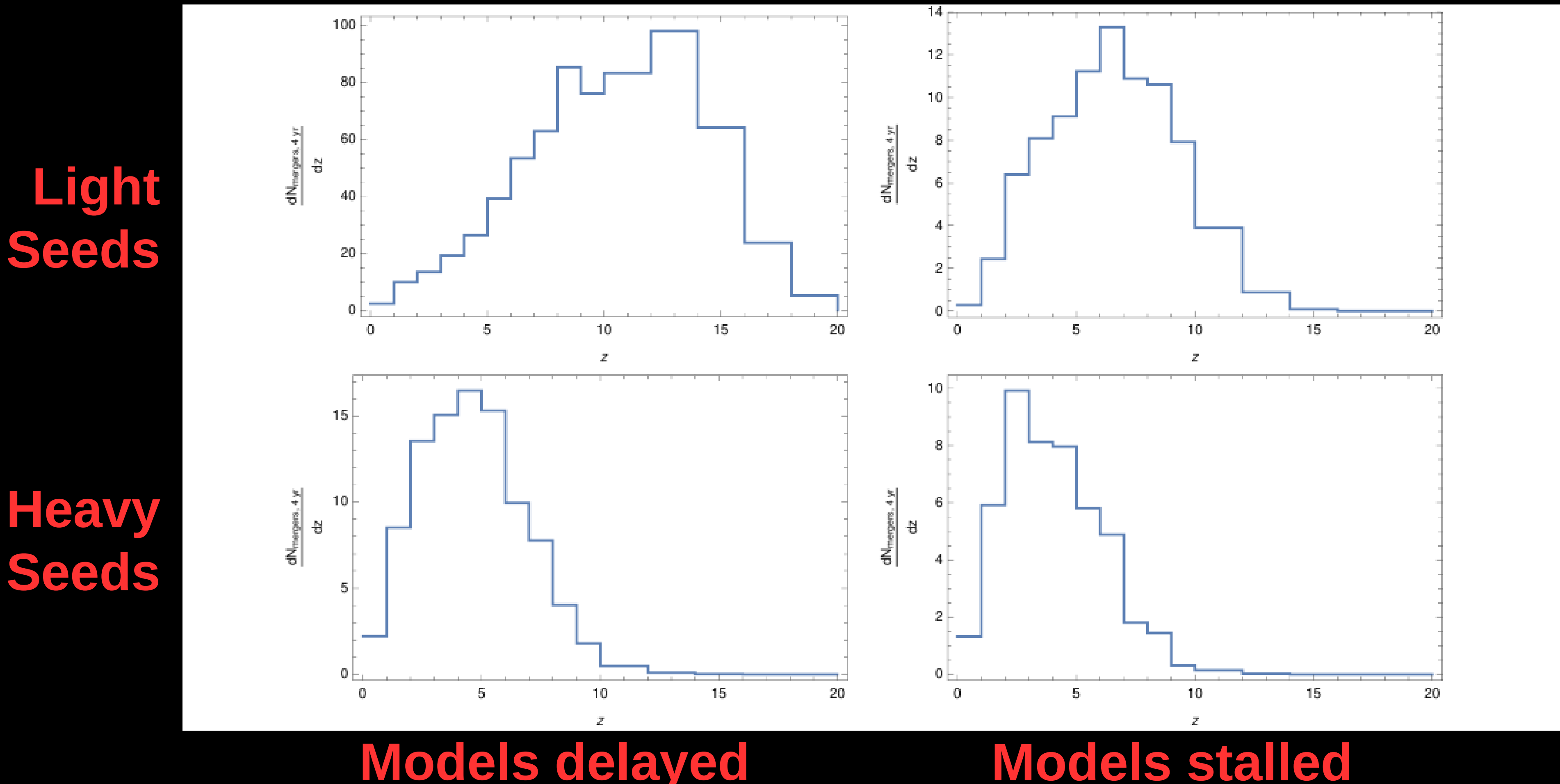
The code has been extensively tested reproducing results from the literature.

It can handle complex chaotic dynamics





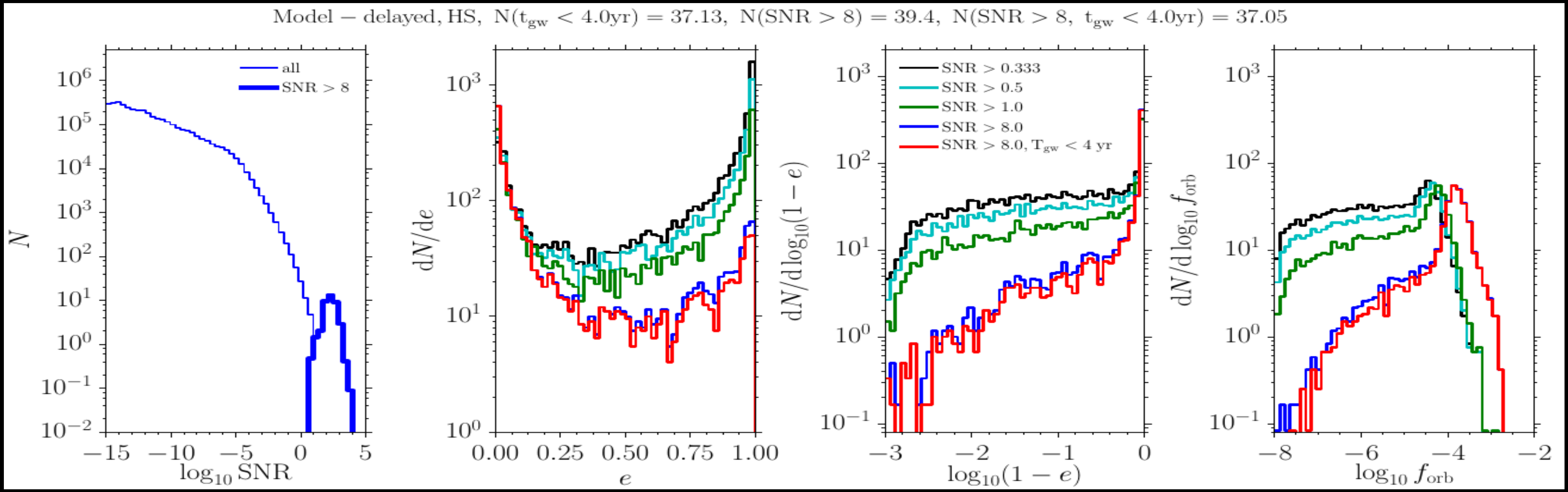
Results I: Merger rates

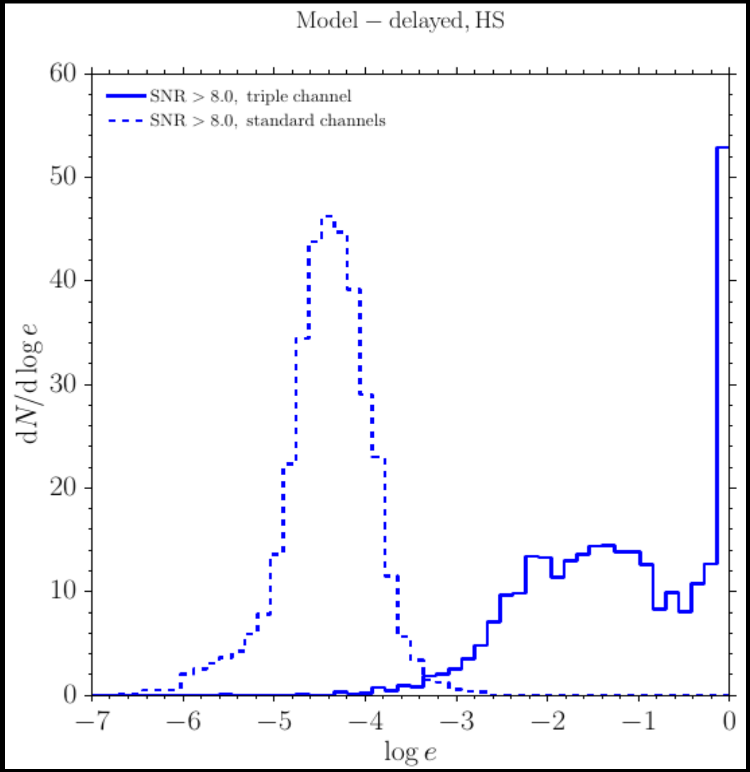


4 yr mergers	HS-stalled	LS-stalled	HS-delayed	LS-delayed
Triple	~42	~86	~36	~15
Total	~42	~86	~90	~894

Triplets provide a ‘safety net’ for the MBHB merger rates

Results II: eccentricity



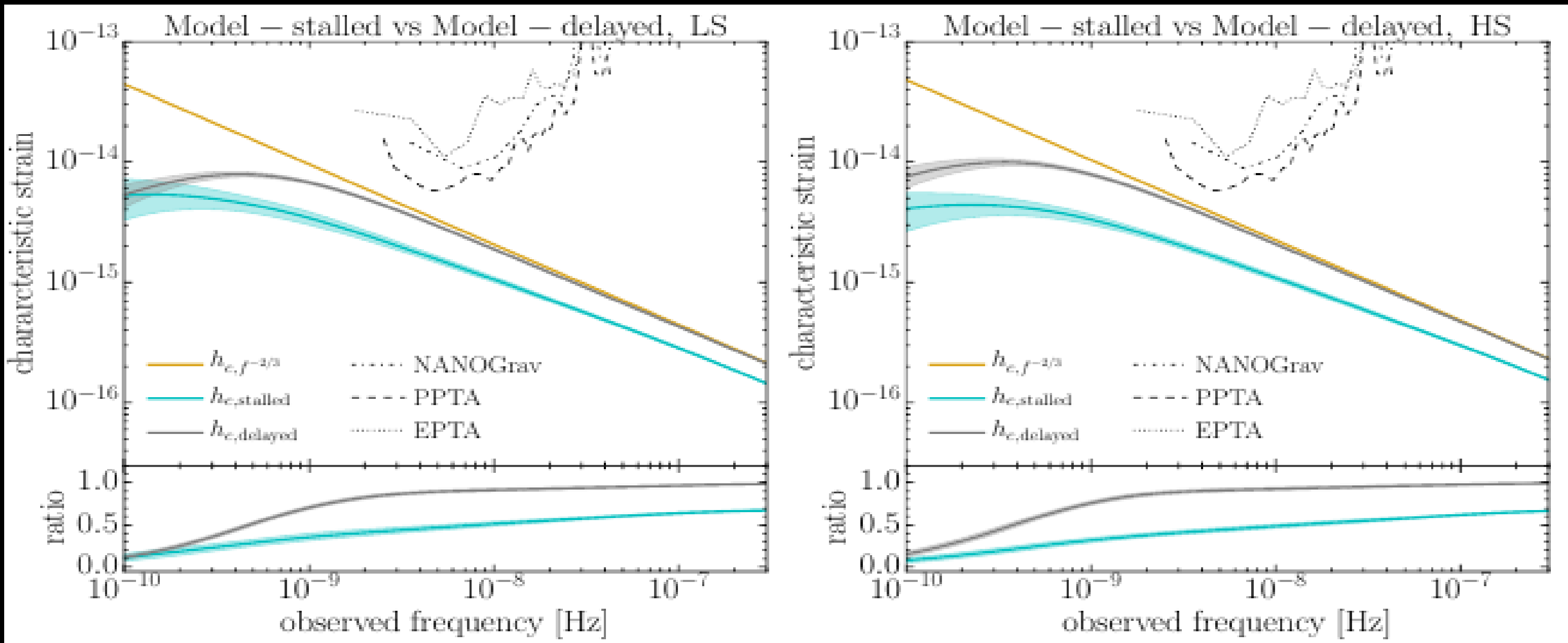


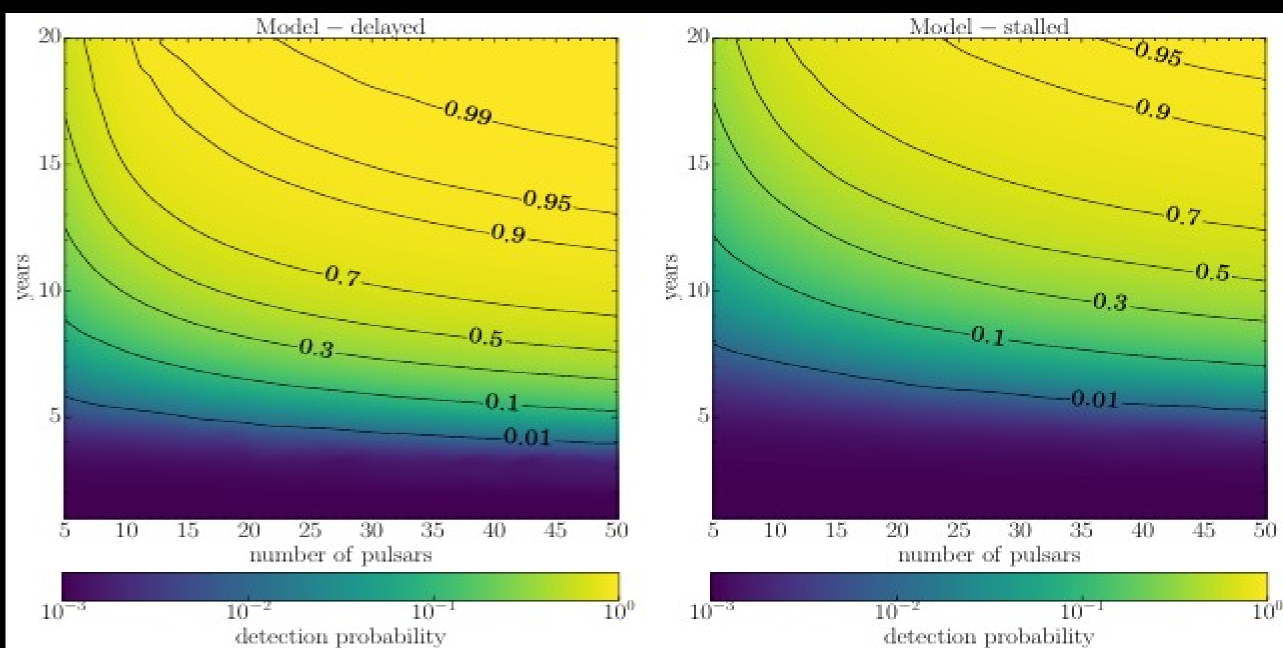
Eccentricity distribution carries the fingerprint of 3-body interaction

- *e* can be >0.9 as the source builds up an S/N=8 in the LISA band
- Decisive probe of the formation channel
- Requires very accurate very eccentric waveforms

Further consequences being explored (e.g. stochastic GWB, eccentric bursts)

Results III: consequences for PTAs

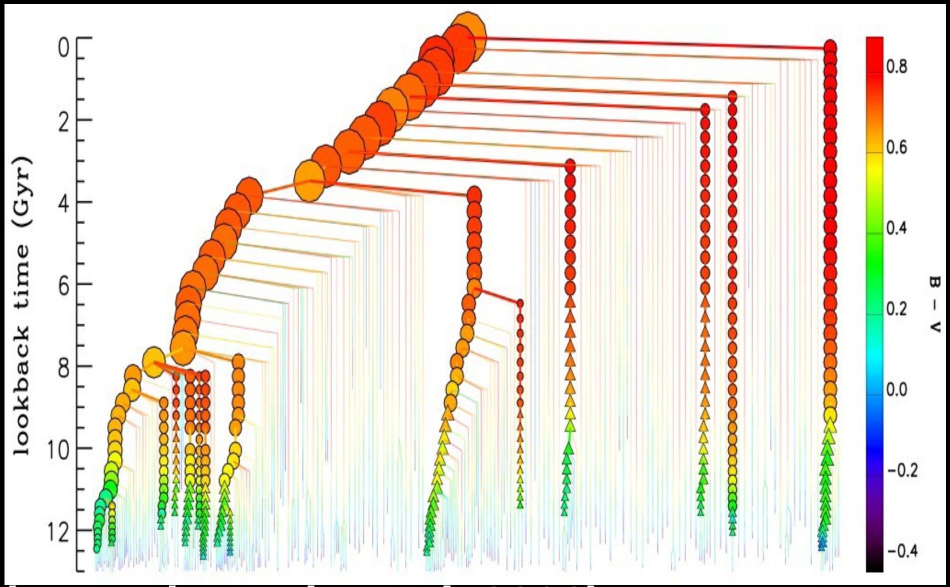




The GW signal in the PTA band is at most reduced by a factor 2-3

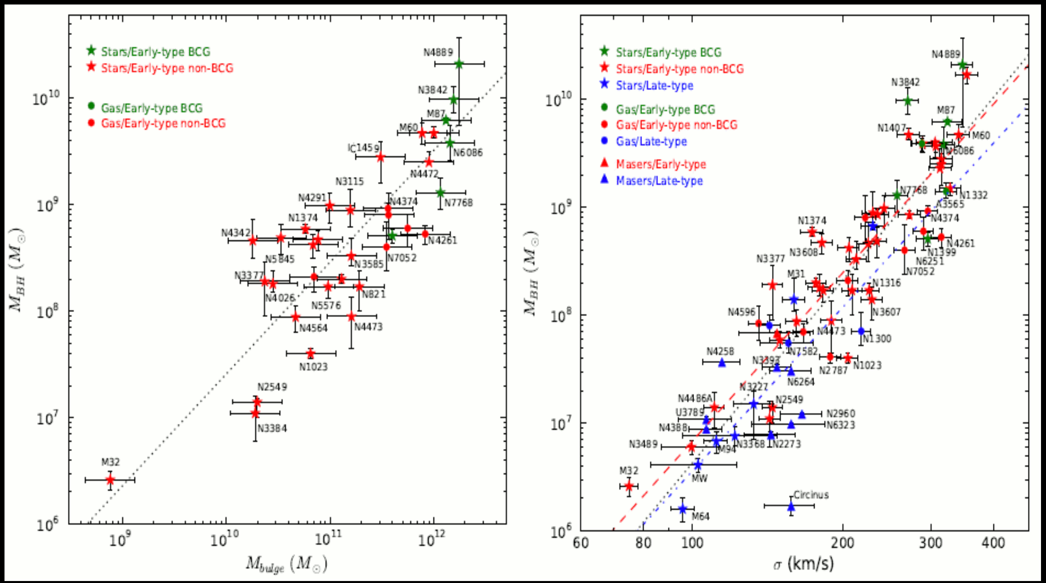
PTA detection is delayed by few years only.

In a nutshell



(From de Lucia et al. 2006)

+



(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

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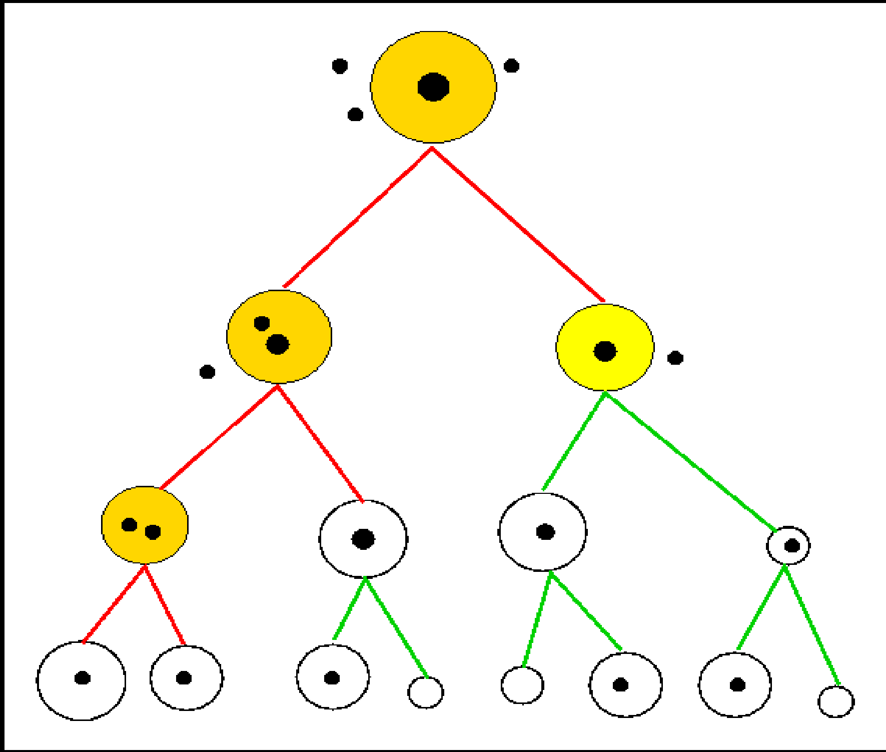
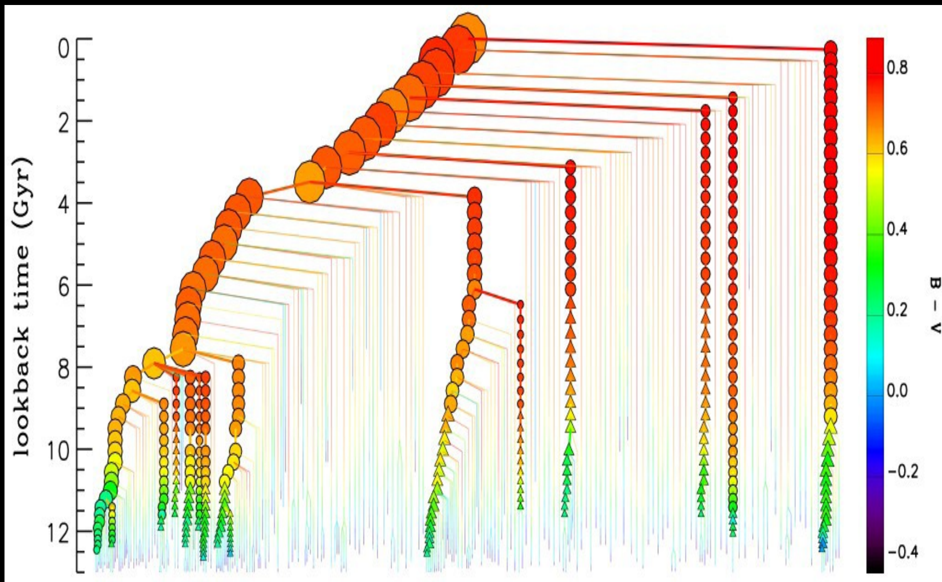


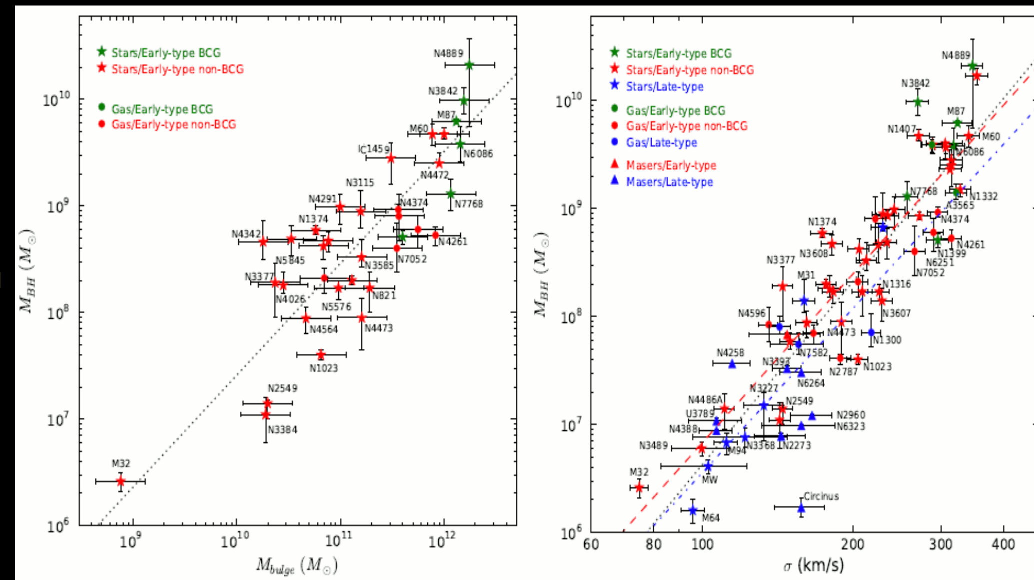
(Menou et al 2001, Volonteri et al. 2003)

In a nutshell



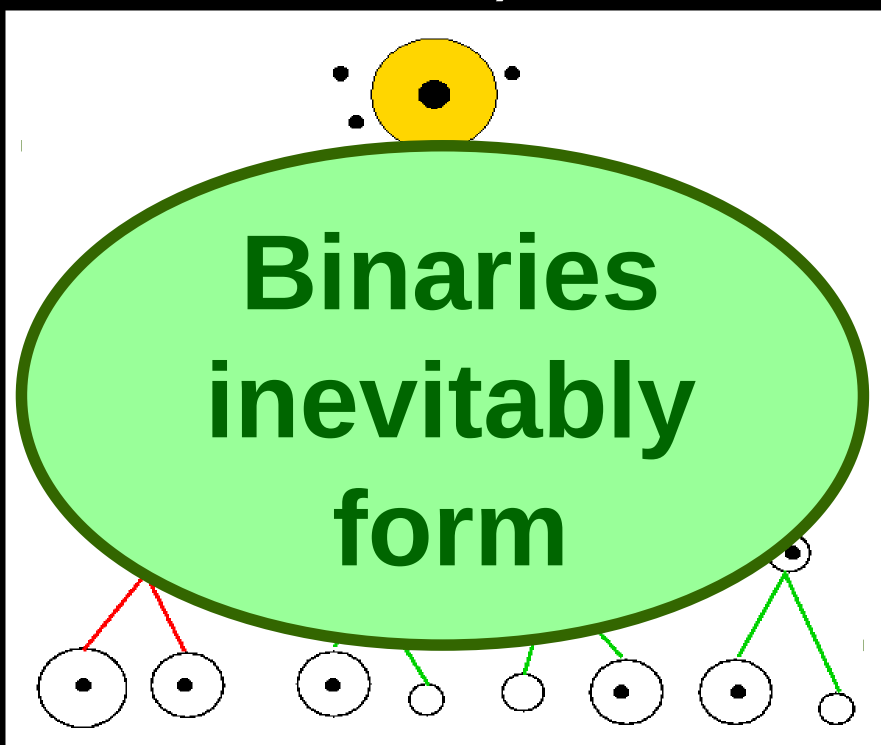
(From de Lucia et al. 2006)

+



(Ferrarese & Merritt 2000, Gebhardt et al. 2000)

=



(Menou et al 2001, Volonteri et al. 2003)

*Where and when do the first MBH seeds form?

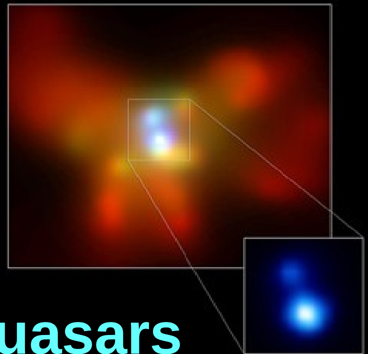
*How do they grow along the cosmic history?

*What is their role in galaxy evolution?

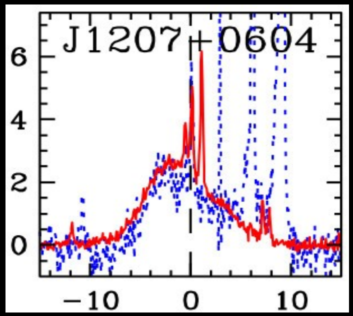
*What is their merger rate?

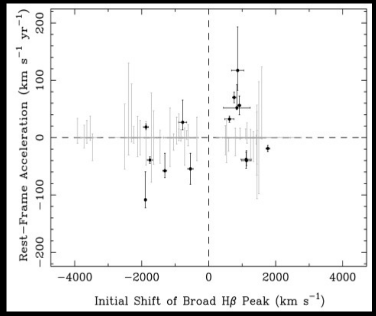
*How do they pair together and dynamically evolve?

But do we see them?

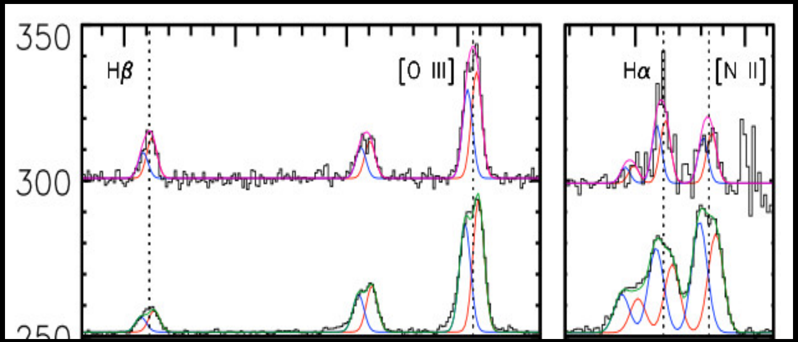



10 kpc: double quasars
(Komossa 2003)

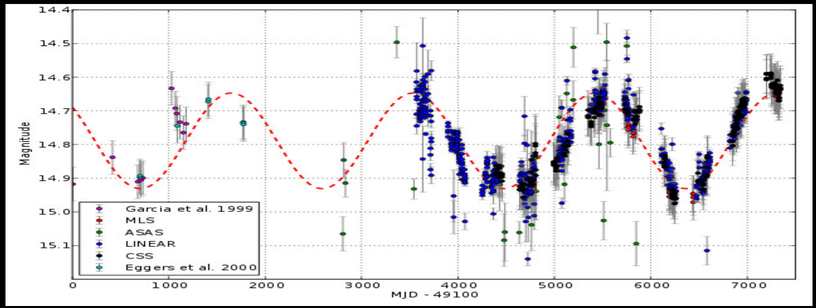




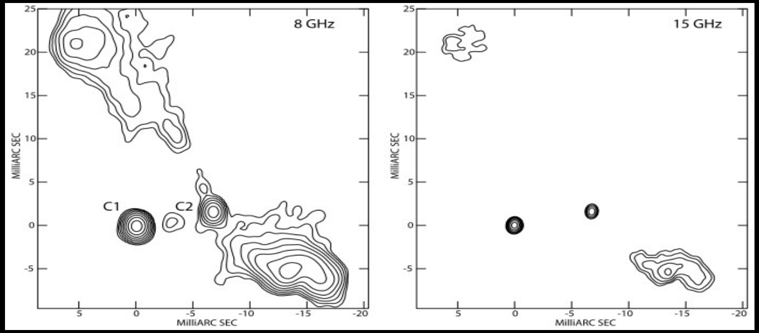
1 pc: -shifted BL (Tsalmatzsa 2011)
-accelerating BL (Eracleous 2012)



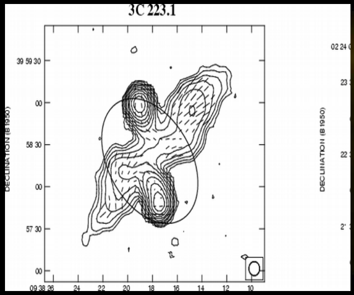
1 kpc: double peaked NL
(Comerford 2013)



0.01 pc: periodicity (Graham 2015)



10 pc: double radio cores
(Rodriguez 2006)



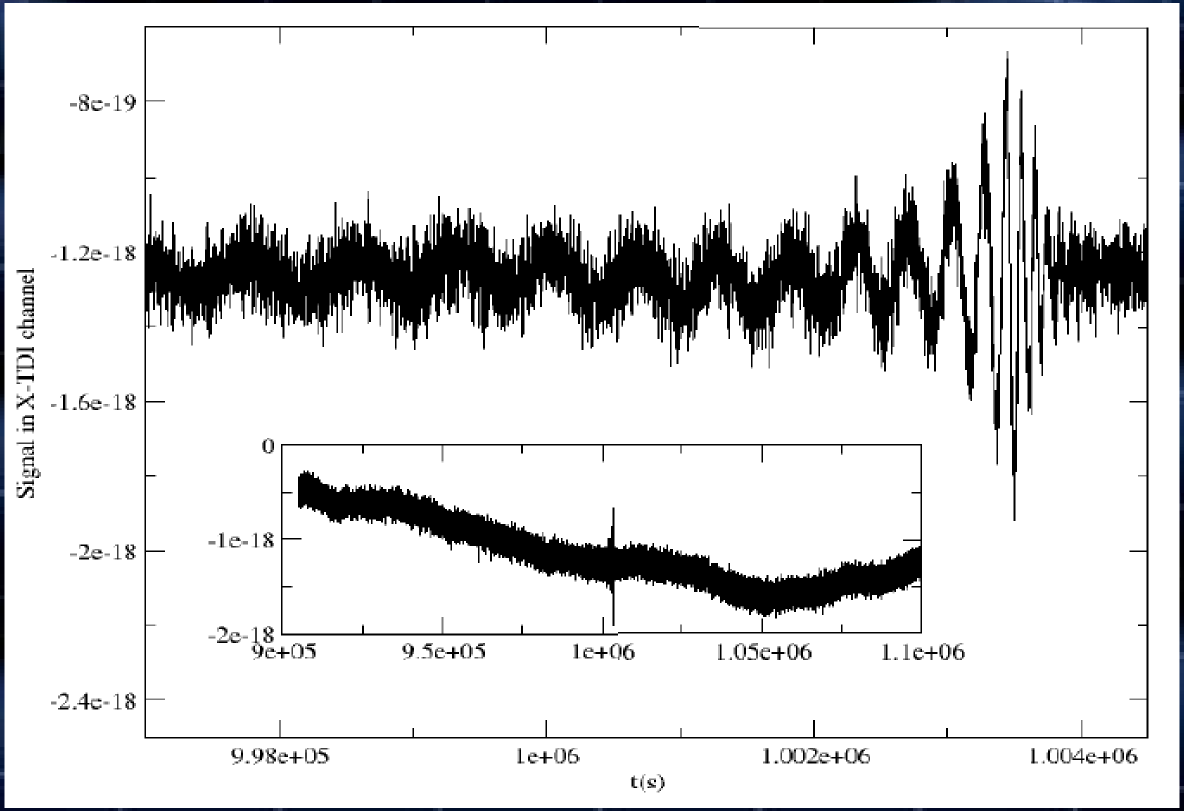
0.0pc:-X-shaped sources (Capetti 2001)
-displaced AGNs (Civano 2009)

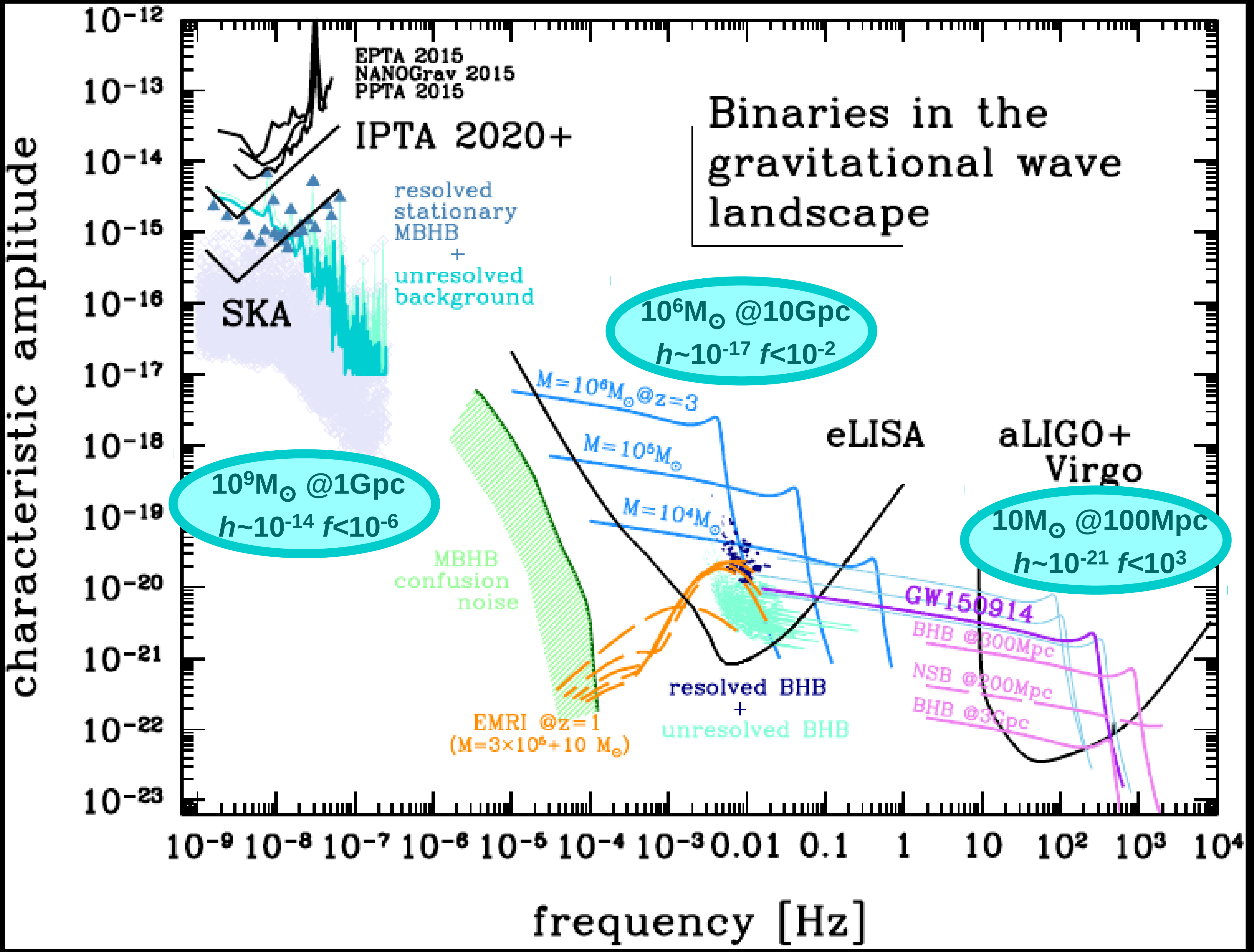
III-Gravitational wave emission
0.01pc-coalescence

If the binary overcome the final parsec problem then it coalesces on a timescale given by:

$$t_{\rm GW} = \frac{5c^5}{256G^3}\frac{a^4}{M_1 M_2 M F(e)} \approx 0.25\,{\rm Gyr}\left(\frac{M M_1 M_2}{10^{18.3}\ {\rm M}_\odot{}^3}\right)^{-1} F(e)^{-1}\left(\frac{a}{0.001{\rm pc}}\right)^4$$

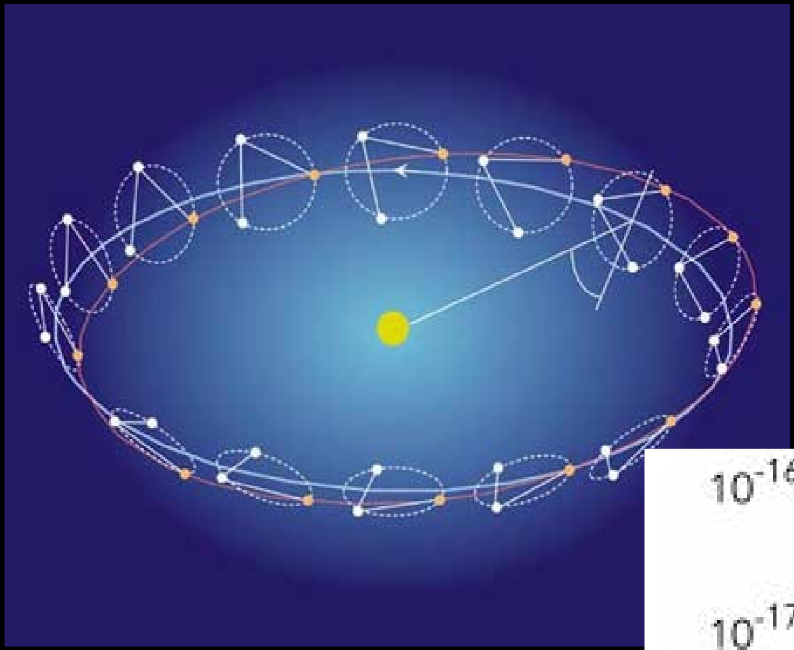
producing the ***loudest gravitational wave signals in the Universe!***





Binaries in the gravitational wave landscape
characteristic amplitude
frequency [Hz]
EPTA 2015
NANOGrav 2015
PPTA 2015
IPTA 2020+
SKA
resolved stationary MBHB
+
unresolved background
$10^6 M_\odot$ @10Gpc
$h \sim 10^{-17}$ $f < 10^{-2}$
$10^9 M_\odot$ @1Gpc
$h \sim 10^{-14}$ $f < 10^{-6}$
$10 M_\odot$ @100Mpc
$h \sim 10^{-21}$ $f < 10^3$
$M=10^6 M_\odot$@z=3
$M=10^5 M_\odot$
$M=10^4 M_\odot$
eLISA
aLIGO+ Virgo
MBHB confusion noise
GW150914
BHB @300Mpc
NSB @200Mpc
BHB @3Gpc
resolved BHB
+
unresolved BHB
EMRI @z=1
($M=3\times10^5+10$ $M_\odot$)

The Laser Interferometer Space Antenna

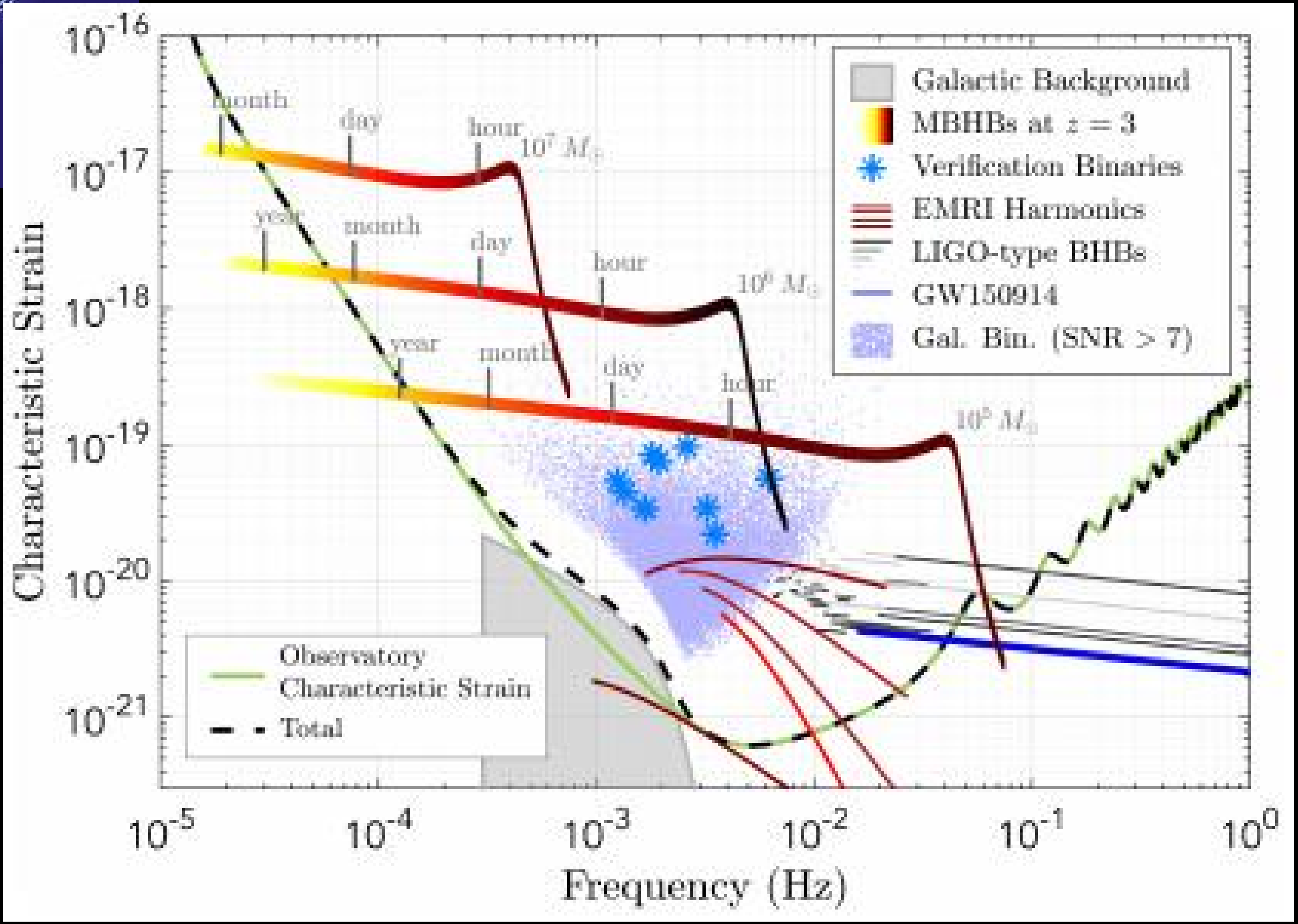


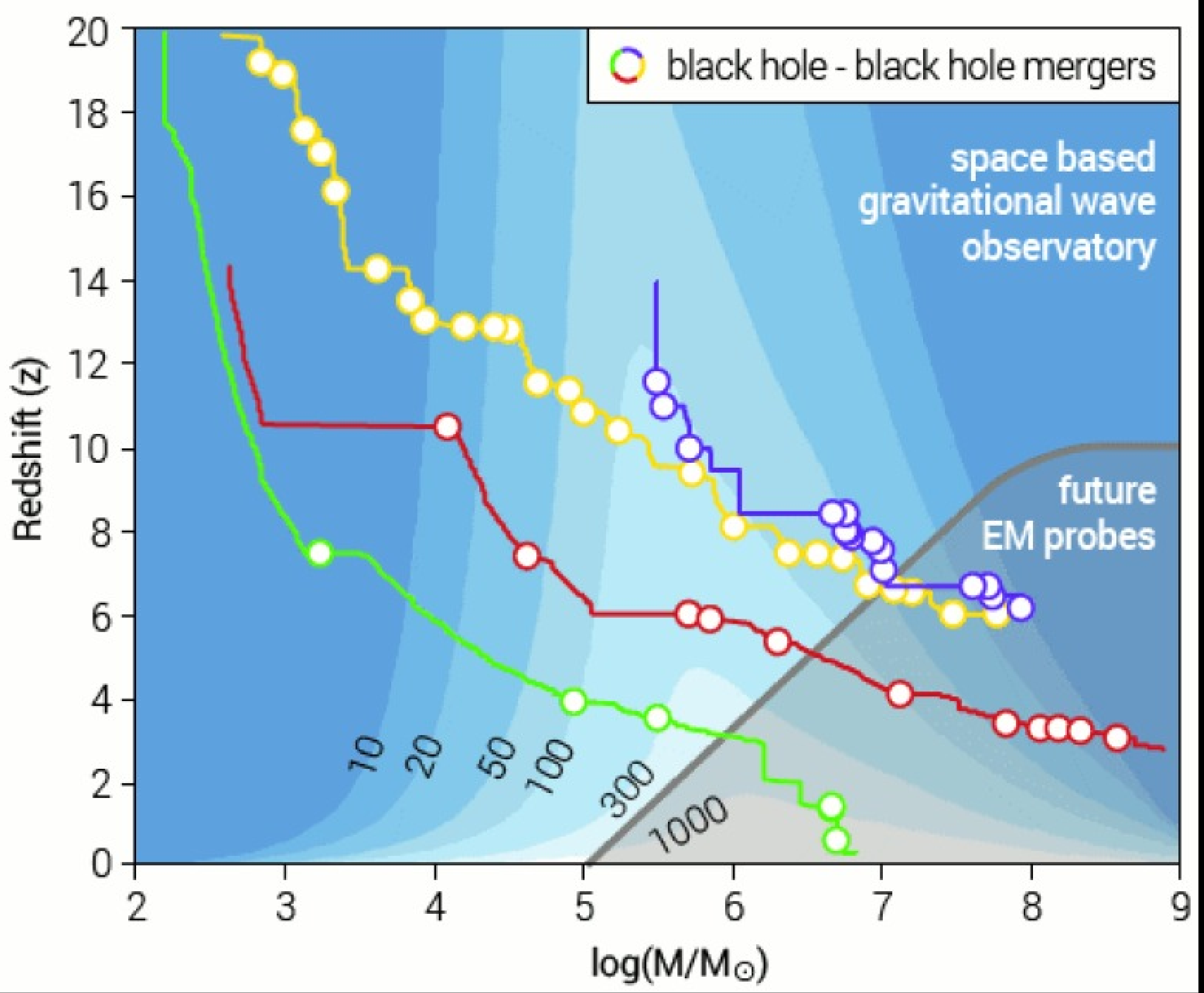
Sensitive in the mHz frequency range where MBH binary evolution is fast (chirp)

Observes the full inspiral/merger/ringdown

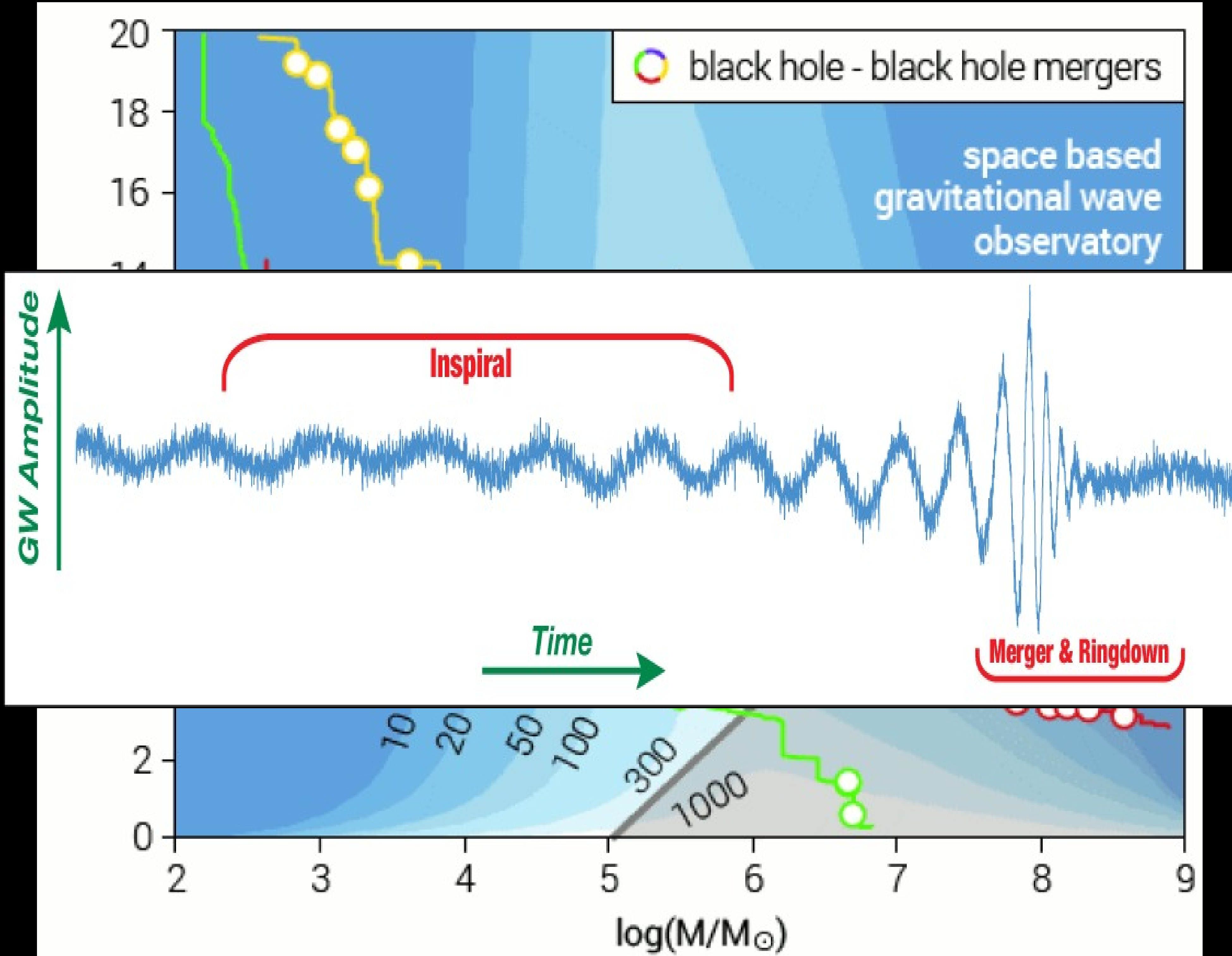
3 satellites trailing the Earth connected through laser links

Proposed baseline:
2.5M km armlength
6 laser links
4 yr lifetime (10 yr goal)





black hole - black hole mergers
space based gravitational wave observatory
future EM probes
10
20
50
100
300
1000
Redshift (z)
log(M/M⊙)
0
2
4
6
8
10
12
14
16
18
20
2
3
4
5
6
7
8
9



black hole - black hole mergers
space based gravitational wave observatory
GW Amplitude
Inspiral
Time
Merger & Ringdown
20
18
16
2
0
10
20
50
100
300
1000
2
3
4
5
6
7
8
9
log(M/M⊙)

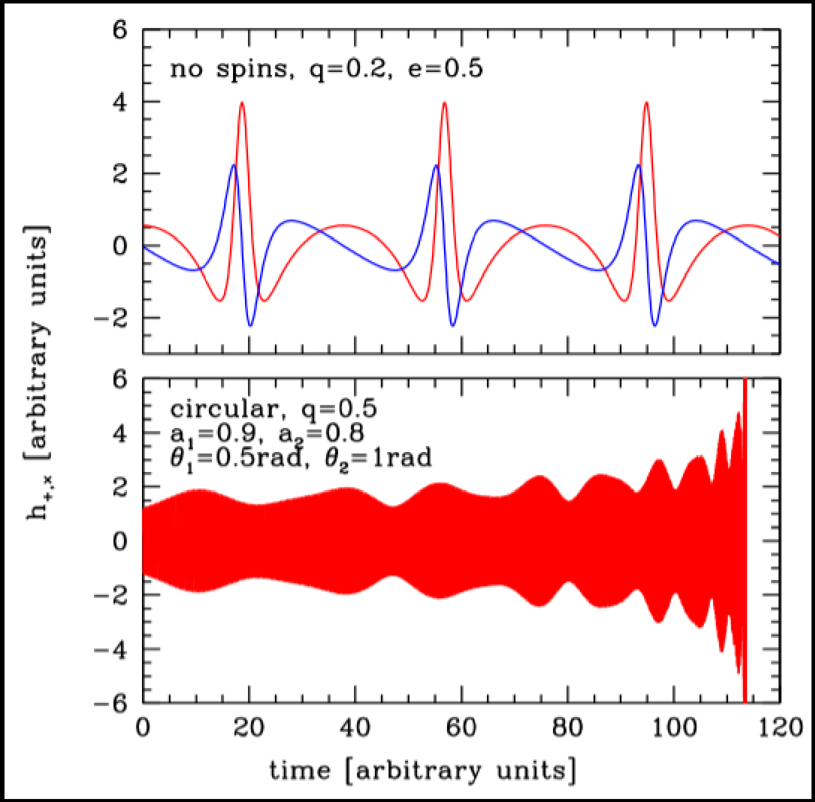
Parameter imprint in the waveform

>Redshifted masses have the largest impact on the phase modulation

>Eccentricity impacts the waveform and the phase modulation

>Spins impact the waveform and the phase modulation (but weaker effect)

Depend on the number of cycles and SNR, can be easily measured with high precision

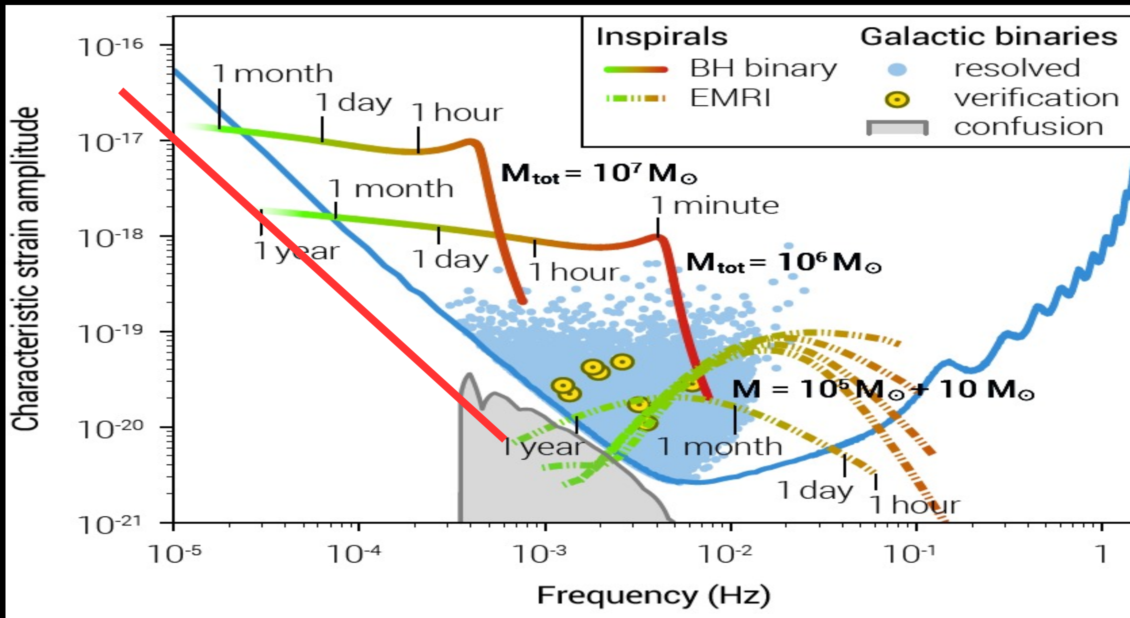


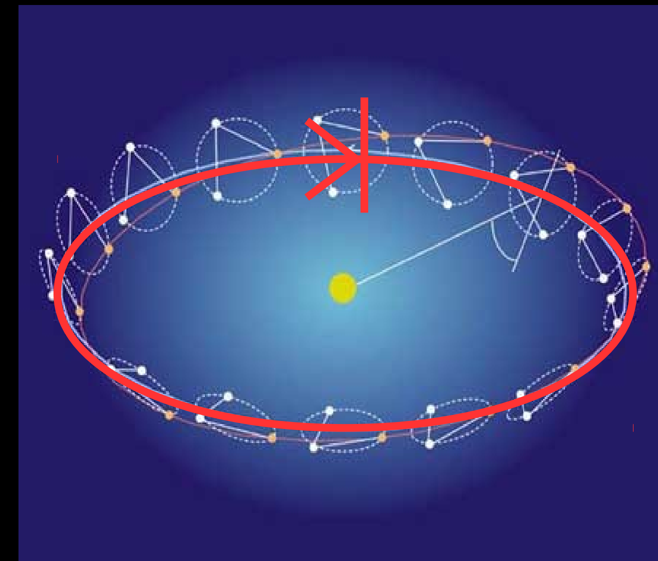
>Sky location impacts the waveform modulation over time through antenna beam pattern

>Distance impacts the waveform amplitude (degenerate with masses, and sky location, inclination)

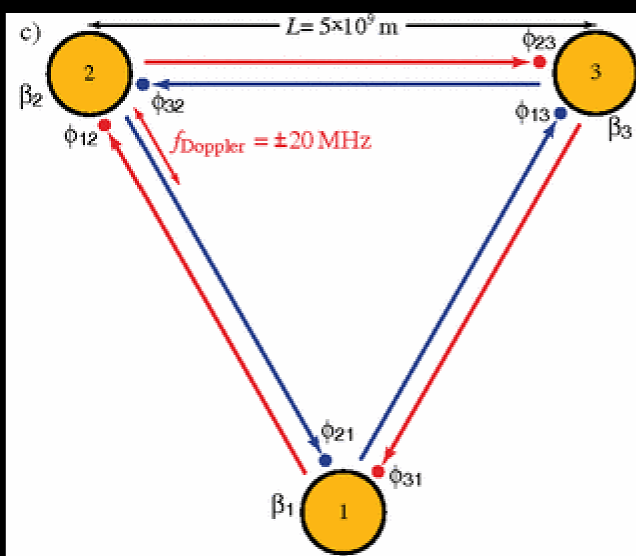
Depend on the time in band, polarization disentanglement, SNR.
Measurement is more difficult.
For MBH binaries, strong impact of having: 1) longer baseline
2) 6 laser links

Baseline

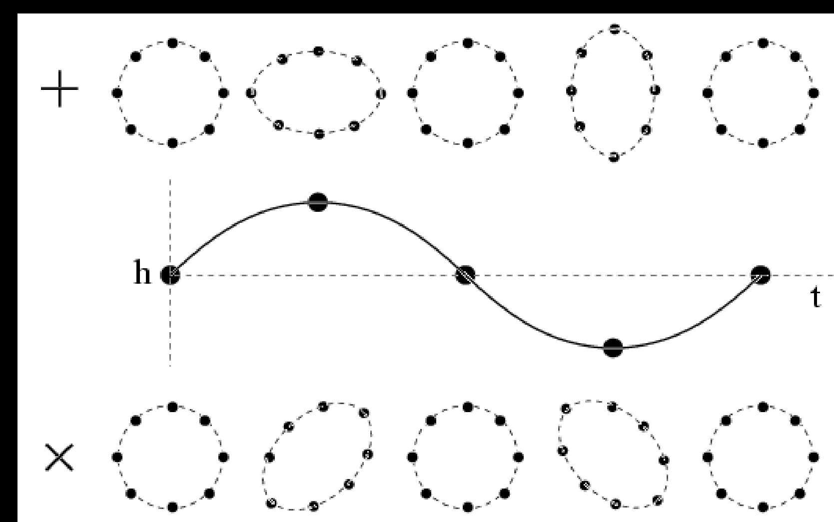




Number of laser links



$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1+h_+^{TT} & h_\times^{TT} \\ 0 & 0 & h_\times^{TT} & 1-h_+^{TT} \end{pmatrix}$$



General considerations

WD-WD binaries and EMRIs stay in band for >1yr: the polarization degeneracy is broken by orbital motion of the detector, and the improvement in having 6 links is basically related to the improvement in SNR only. In fact, as such we have:

-Increase in number of EMRIs ~2.8 (=$2^{3/2}$)

-Improvement in parameter estimation accuracy ~1.4 (=$2^{1/2}$)

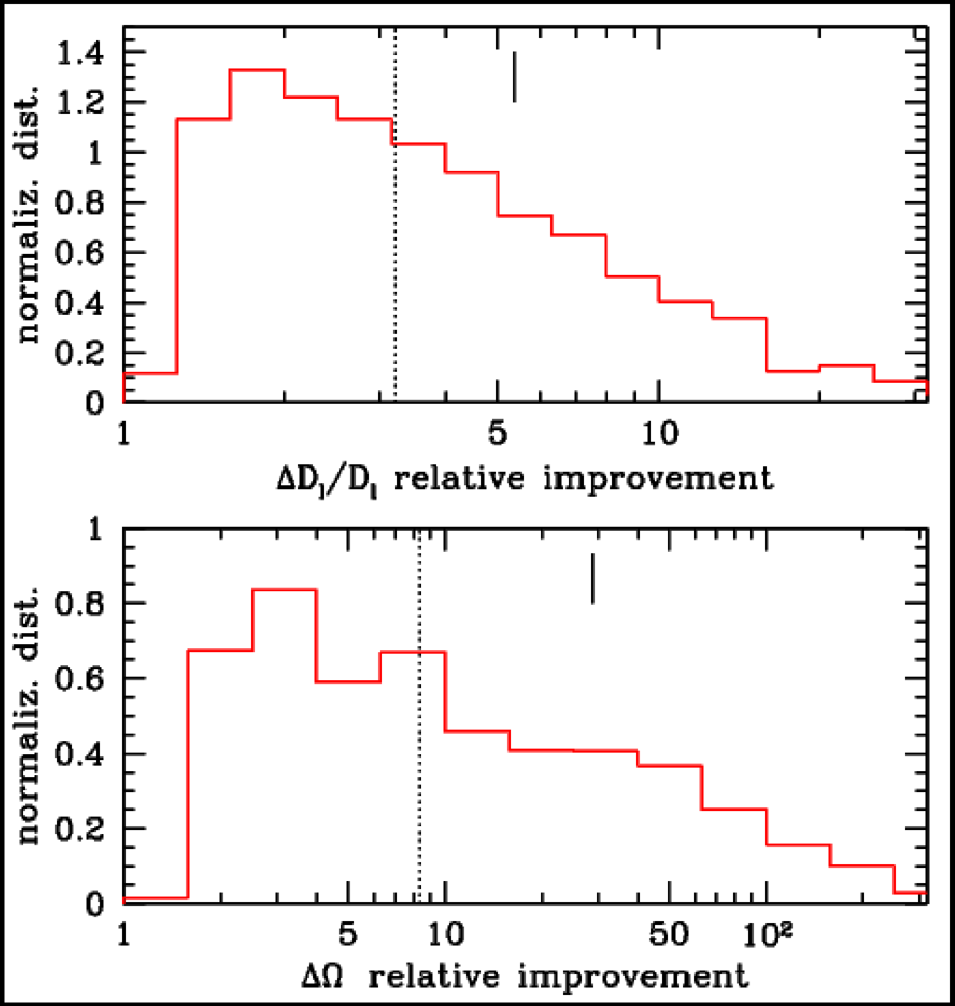
-Increase in number of resolvable WD-WD binaries ~2

-Improvement in parameter estimation accuracy ~2

6-links allow to search for stochastic backgrounds through the so called Sagnac channel!

Massive black hole binaries
Model independent results: relative improvements

Results based on inspiral PN waveforms including spin precession and higher harmonics



Mass and spin measurements have an improvement consistent with the increase in SNR going from 1 to 2 interferometer, i.e. ~1.4

Mean D_l improvement: 5.3

Median D_l improvemen: 3.2

Mean $\Delta\Omega$ improvement 29

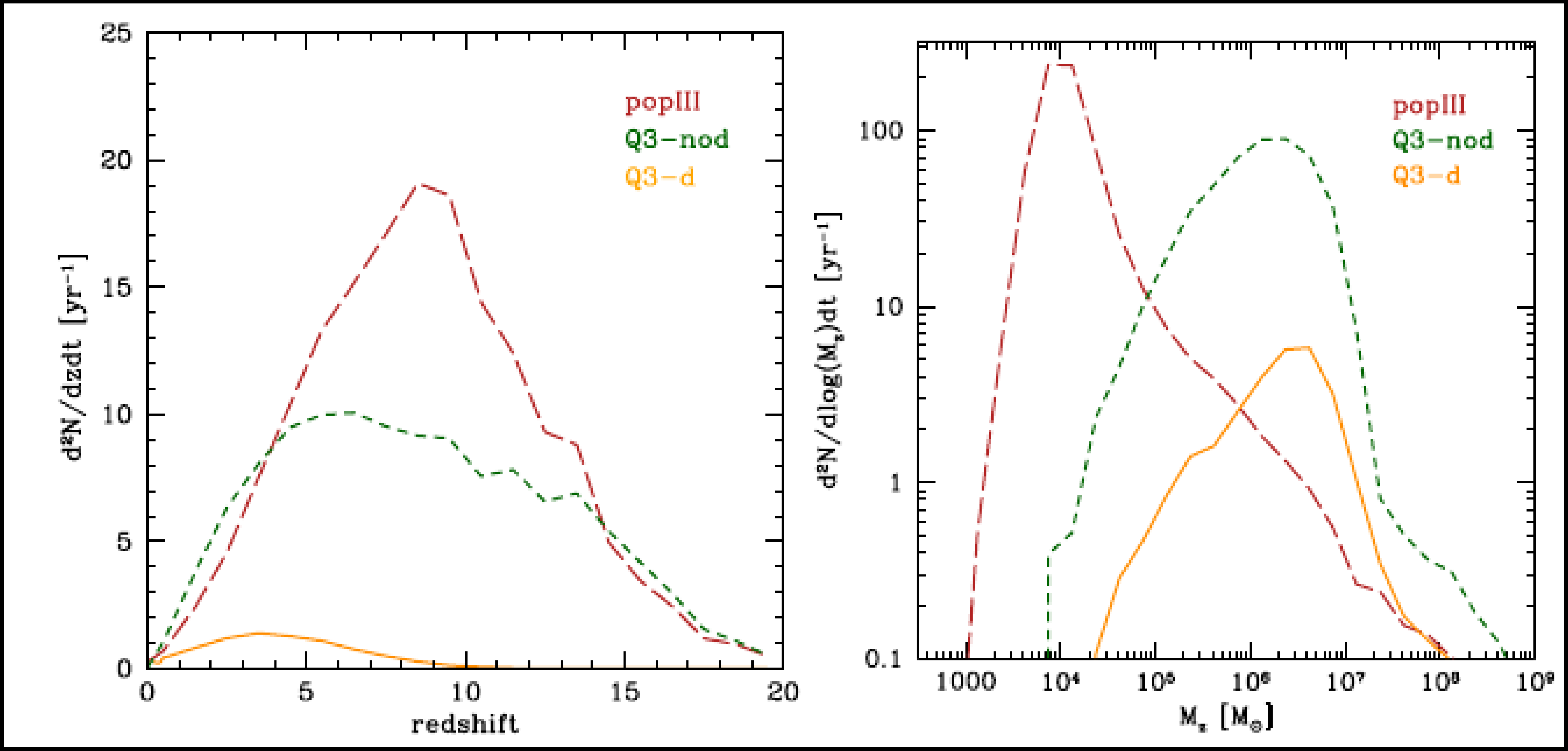
Median $\Delta\Omega$ improvement 8.4

MBHB population models

Semianalytic models for galaxy and MBH formation and evolution (Barausse).

The explored scenarios cover a wide range of merger histories:

- -Heavy seeds no time delays
- -Heavy seeds time delays
- -PopIII seeds time delays



Summary of LISA parameter estimation

Assuming 4 years of operation and 6 links:

~100+ detections

~100+ systems with sky localization to 10 deg2

~100+ systems with individual masses determined to 1%

~50 systems with primary spin determined to 0.01

~50 systems with secondary spin determined to 0.1

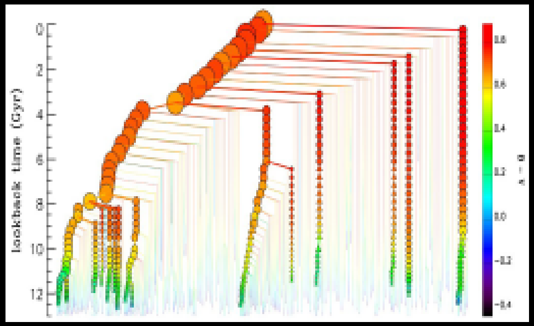
~50 systems with spin direction determined within 10deg

~30 events with final spin determined to 0.1

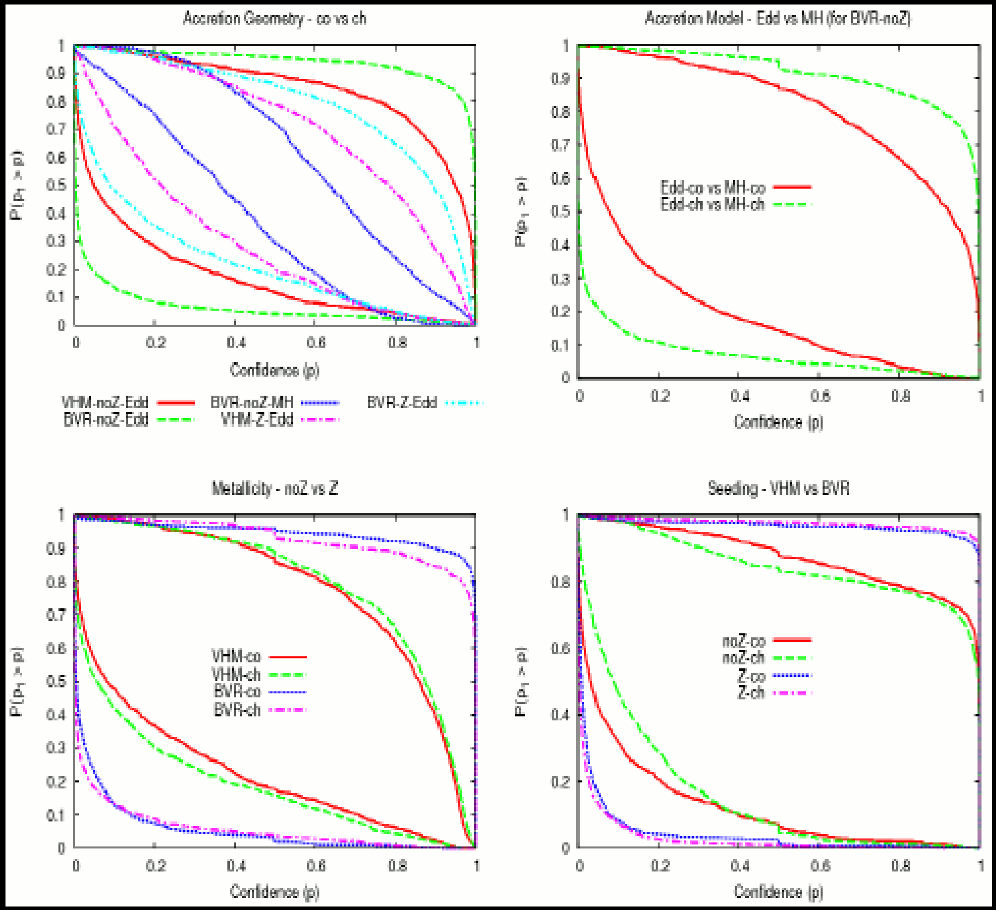
MBH astrophysics with GW observations

Astrophysical unknowns in MBH formation scenarios

1- MBH seeding mechanism (heavy vs light seeds)
2- Metallicity feedback (metal free vs all metallicities)
3- Accretion efficiency (Eddington?)
4- Accretion geometry (coherent vs. chaotic)



CRUCIAL QUESTION:
Given a set of LISA observation of coalescing MBH binaries, what astrophysical information about the underlying population can we recover?

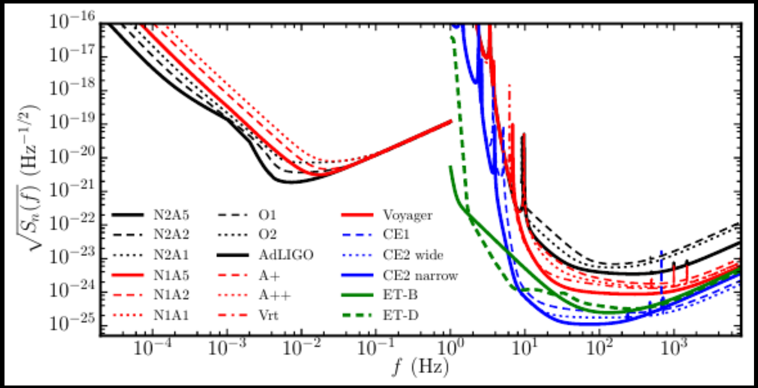


Create catalogues of observed binaries including errors from eLISA observations and compare observations with theoretical models

AS et al. 2011, see also Plowman et al 2011

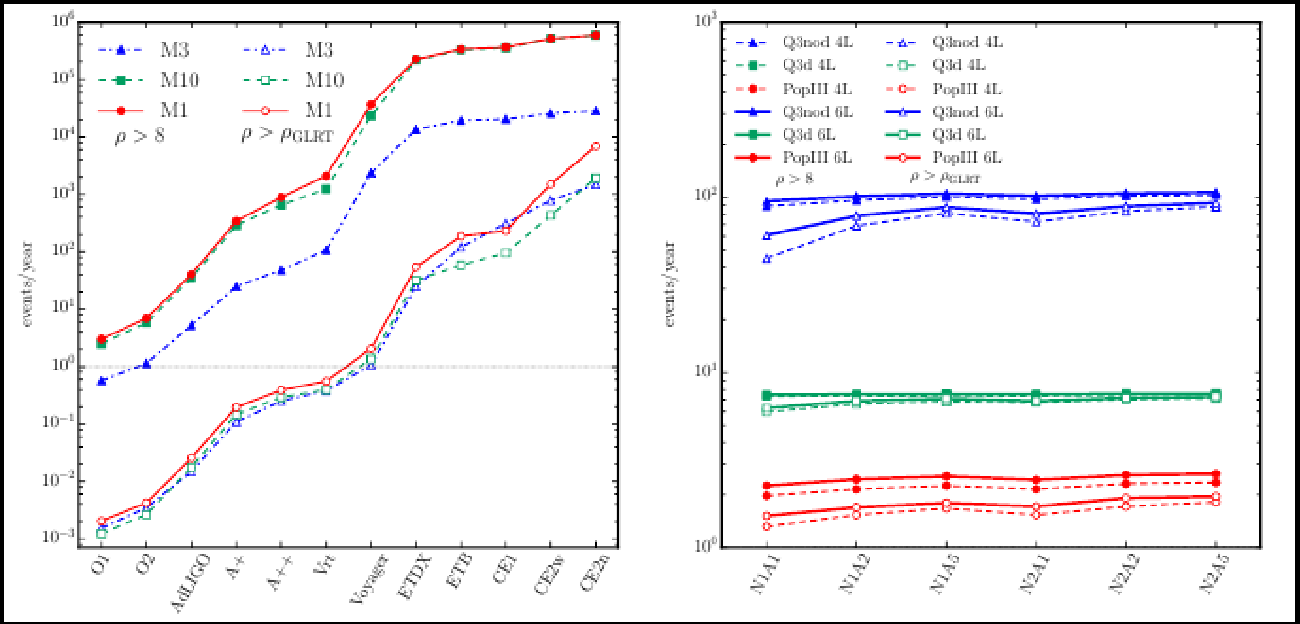
Resolving ringdown modes: BH spectroscopy

(Berti et al. 2016)



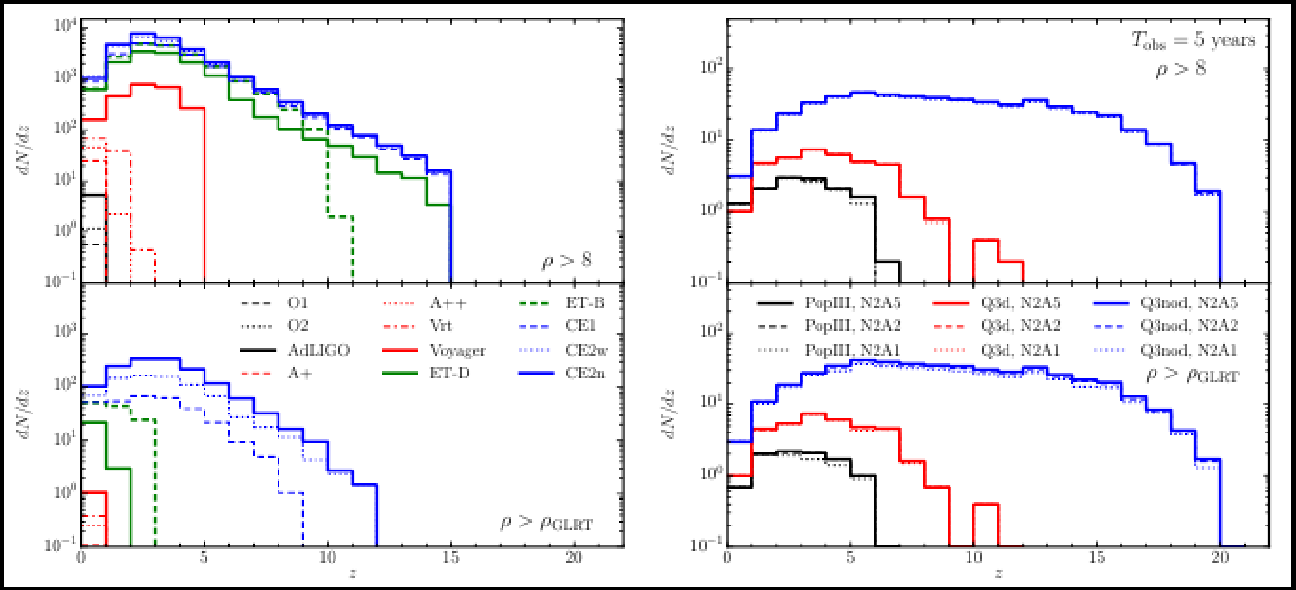
$$\rho^{2,3}_{\rm GLRT} = 17.687 + \frac{15.4597}{q-1} - \frac{1.65242}{q}\,,$$

$$\rho^{2,4}_{\rm GLRT} = 37.9181 + \frac{83.5778}{q} + \frac{44.1125}{q^2} + \frac{50.1316}{q^3}$$



LIGO will not enable BH spectroscopy on individual BHB mergers

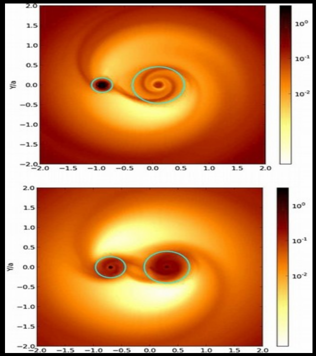
Voyager/ET type detectors are needed



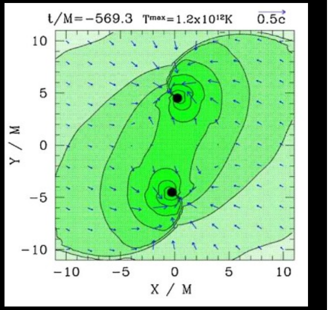
eLISA will enable precise BH spectroscopy on few to 100 events/yr also at very high redshifts

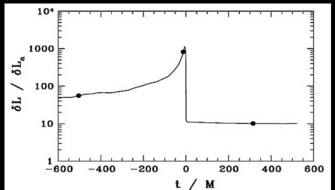
Associated electromagnetic signatures?

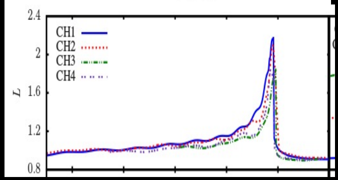
In the standard circumbinary disk scenario, the binary carves a cavity: no EM signal **(Phinney & Milosavljevic 2005)**.
However, all simulations (hydro, MHD) showed significant mass inflow **(Cuadra et al. 2009, Shi et al 2011, Farris et al 2014...)**

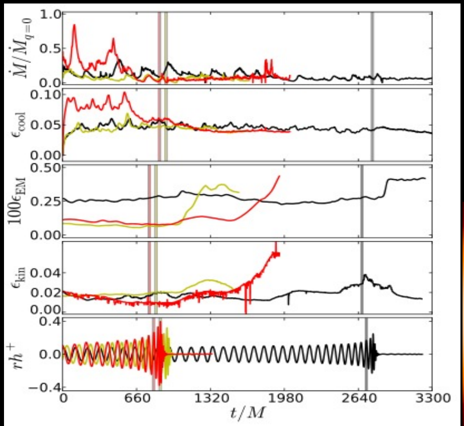


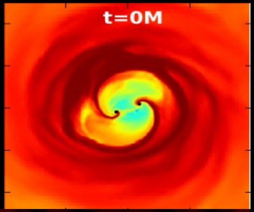
Simulations in hot gaseous clouds. Significant flare associated to merger **(Bode et al. 2010, 2012, Farris et al 2012)**

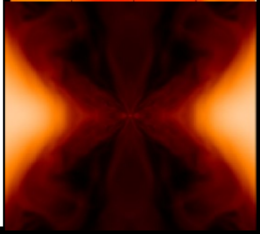






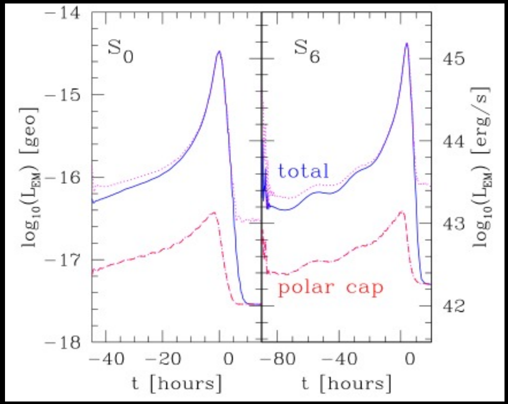


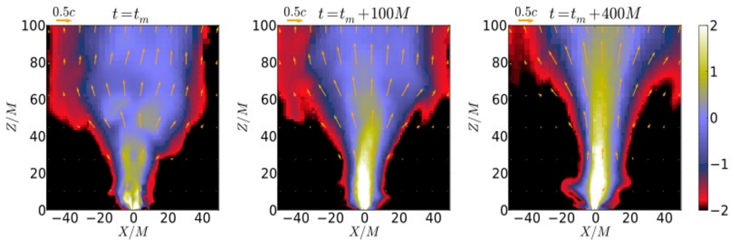




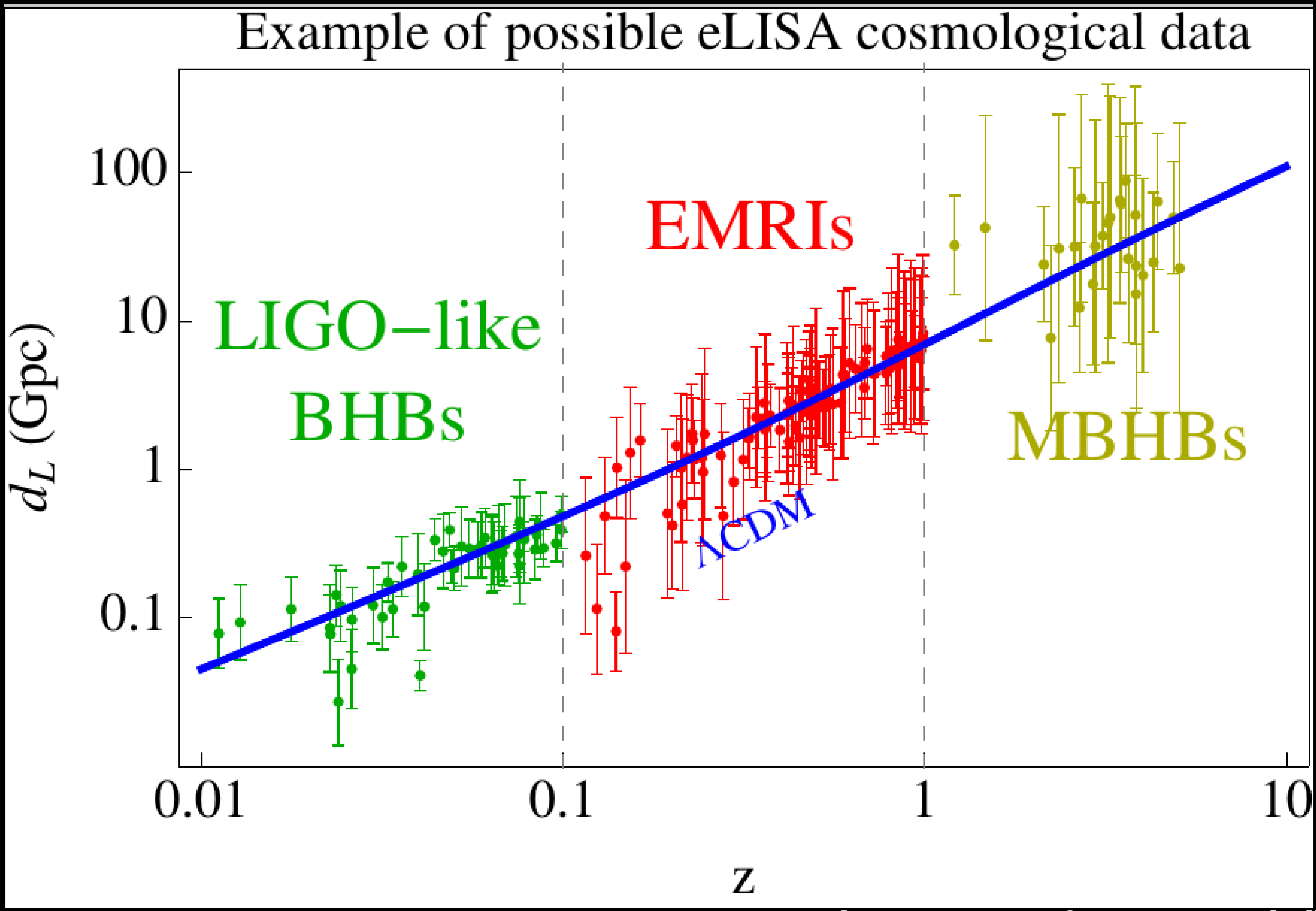
Simulations in disk-like geometry. Variability, but much weaker and unclear signatures **(Bode et al. 2012, Gold et al. 2014)**

Full GR force free electrodynamics **(Palenzuela et al. 2010, 2012)**





Cosmology with gravitational waves



(Courtesy of N. Tamanini)

Different GW sources will allow an independent assessment of the geometry of the Universe at all redshifts.