# Gravitational Radiation from Coalescing SMBH Binaries in a Hierarchical Galaxy Formation Model


**<u>Motohiro ENOKI</u>**

**(National Astronomical Observatory of Japan)**

**Kaiki Taro INOUE**

**(Kinki University)**

**Masahiro NAGASHIMA**

**(Kyoto University)**

**Naoshi SUGIYAMA**

**(National Astronomical Observatory of Japan)**

# § 1. Introduction

## *Spheroids (bulge or elliptical galaxy) in the local universe

Many nearby galaxies have central Supermassive Black Holes (SMBHs) ($M_{BH}=10^{6} - 10^{9}\,M_{SUN}$) and their physical properties correlate with those of spheroids of their host galaxies.

--- $M_{BH} / M_{bulge} = 0.001 - 0.006$

--- $M_{BH} \propto \sigma_{bulge}^{\ n}$ , $n = 3.7 - 5.3$

SMBH formation physically link spheroid formation !

# *Galaxy formation and SMBH

Galaxy formation in the CDM universe

=> ***Hierarchical clustering scenario***

-- Dark haloes cluster gravitationally and merge together.

-- In each dark halo, a galaxy is formed.

-- Several galaxies in a common dark halo sometimes merge and a more massive galaxy is formed.

When galaxies merge, SMBHs sink toward the center of the new merged galaxy and form a binary.

If the binary loses enough energy and angular momentum, it will evolve to the gravitational wave (GW) emitting regime, and eventually coalesce.

# *Can we detect GW from SMBH binary coalescence?

- An ensemble of GWs from in-spiraling SMBH binaries.

=> Gravitational wave background radiation

$f \sim 1\text{n} -- 1\mu$ Hz

Spectrum ?

- Coalescence of SMBH

=> Gravitational wave burst

$h \sim 10^{-18} -- 10^{-15}$

*LISA* can detect this gravitational burst events.

Events rate ?

In order to estimate the feasibility of detecting such GWs, we need to know the SMBH coalescing rate.

In this study,

**Semi-analytic model of galaxy formation**
**(SA-model)**
**+ SMBH formation**

↓

SMBH coalescence rate

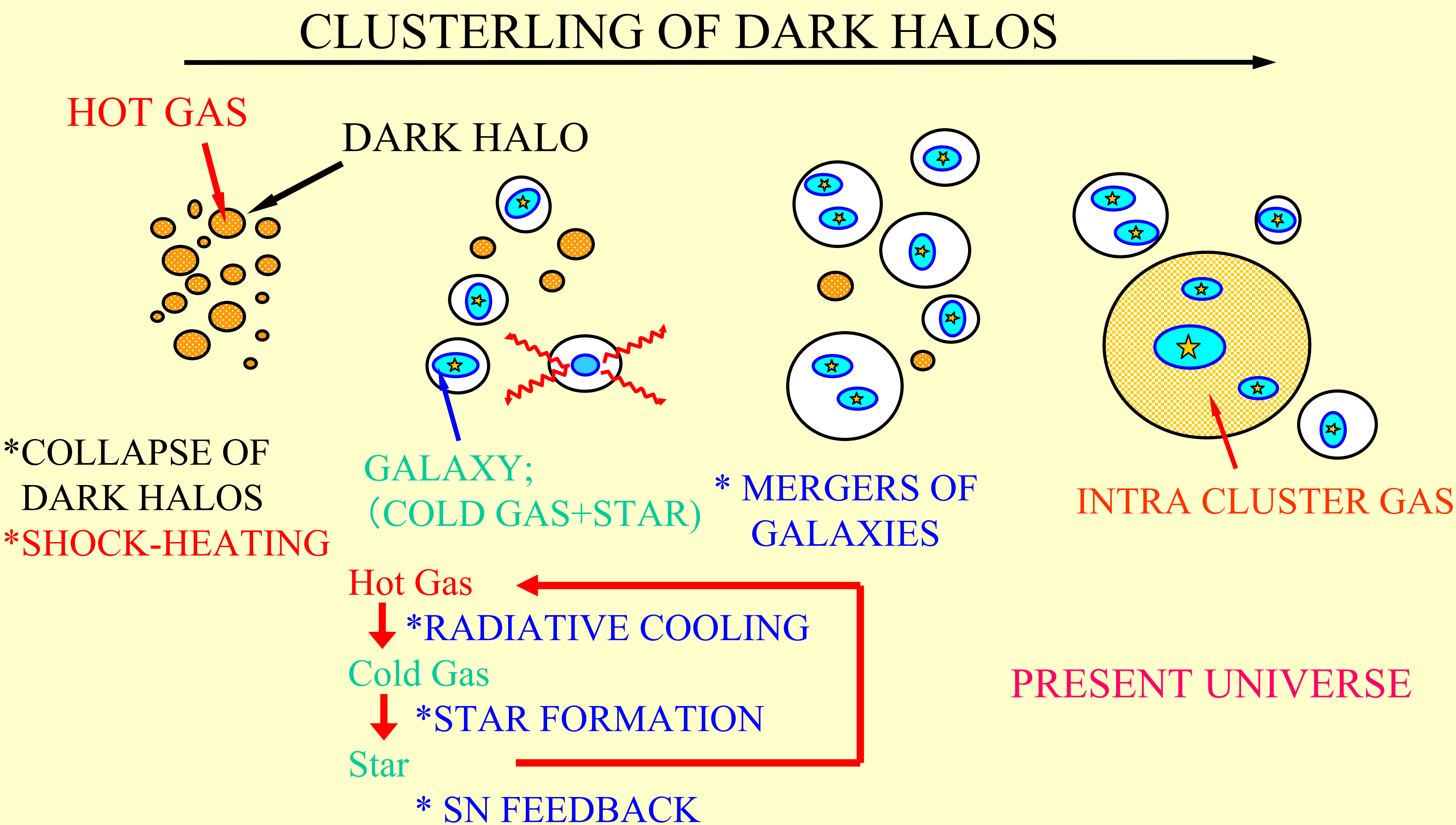
↓

*GW background radiation spectrum from SMBH binaries

* Events rate of GW burst from SMBH  coalescence

# § 2. Galaxy Formation Model

- Galaxy Formation in Hierarchical Clustering Scenario



# *The physics of galaxy formation

--Clustering of dark halos (Merging history of dark halos)

- -Gas cooling
- -Star formation
- -Supernova feedback
- -Galaxy merging => Bulge formation
- -Chemical evolution
- -Stellar population synthesis
- -Dust formation etc

Various physical processes are intricately involved in galaxy formation!

=>*Semi-analytic model of galaxy formation (**SA-model**)

# *Semi-analytic model of galaxy formation (**SA model**)

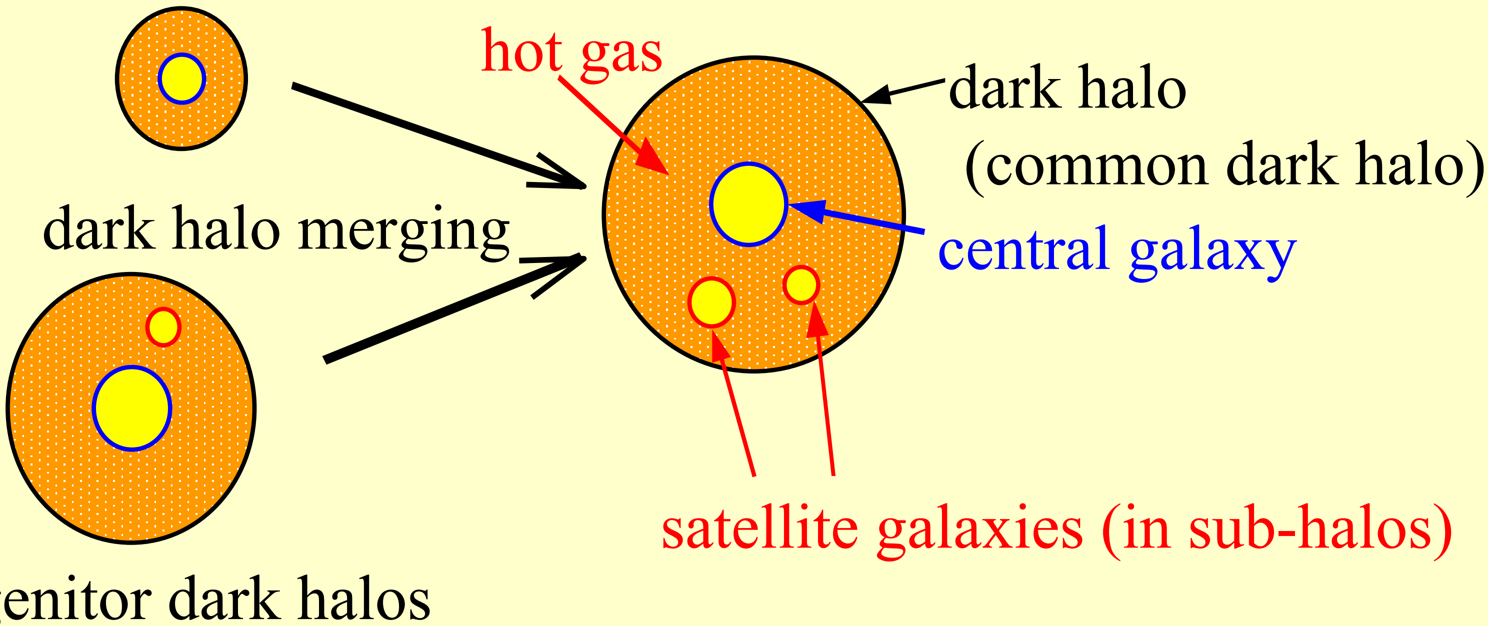
-- The merging history of dark halos are realized using Monte Carlo algorithm.

-- Evolution of baryonic components within dark halo is calculated using simple analytical models for physical processes (gas cooling, star formation, SN feedback, galaxy merging and etc.)

(Our SA-model: Nagashima et al. 2001, Enoki et al. 2003)

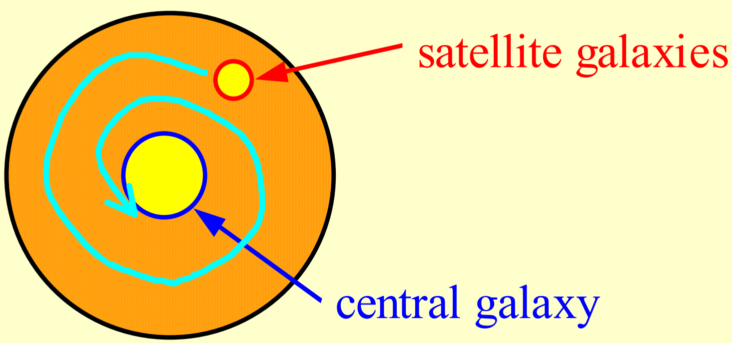
$$\Lambda\mathrm{CDM};\ \Omega_0 = 0.3,\ \lambda_0 = 0.7,\ h = 0.7,\ \sigma_8 = 0.9$$

# *Galaxy Merging (**NOT** dark halo merging)




- satellite-central merger

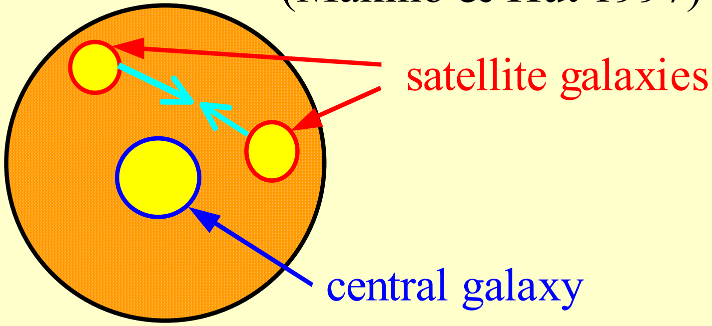
  dynamical friction




- satellite-satellite merger

  random collision

  (Makino & Hut 1997)



# *Galaxy merger time scale

- Satellite-Central merger

$t_{\rm fric}$ (dynamical friction time-scale)

$$\tau_{\rm fric} = \frac{260}{\ln \Lambda_c}\left(\frac{R_{\rm H}}{\rm Mpc}\right)^2 \left(\frac{V_{\rm circ}}{10^3 {\rm km\ s^{-1}}}\right)\left(\frac{M_{\rm sat}}{10^{12} M_\odot}\right)^{-1} {\rm Gyr},$$

- Satellite-Satellite merger

$t_{\rm coll}$ (random collision)

$$\tau_{\rm coll} = \frac{500}{N^2}\left(\frac{R_{\rm H}}{\rm Mpc}\right)^3 \left(\frac{r_{\rm gal}}{0.12\ {\rm Mpc}}\right)^{-2}\left(\frac{\sigma_{\rm gal}}{100\ {\rm km\ s^{-1}}}\right)^{-4}\left(\frac{\sigma_{\rm halo}}{300\ {\rm km\ s^{-1}}}\right)^3 {\rm Gyr},$$

(Makino & Hut 1997)

- Major merger: $m_{small}/\ m_{large} > f_{bulge}$

=> Star burst + Bulge formation

- Minor merger: $m_{small}/\ m_{large} < f_{bulge}$

=> A smaller galaxy is absorbed into the disk of a larger galaxy.

# § 3. SMBH growth model (Enoki et al. 2003)

*$M_{BH} \propto M_{bulge}$

*Gas-dynamical simulation of galaxy major merger

=> gaseous inflow, starburst, bulge formation,

SMBH formation <=> Bulge formation via galaxy merger

## Assumptions

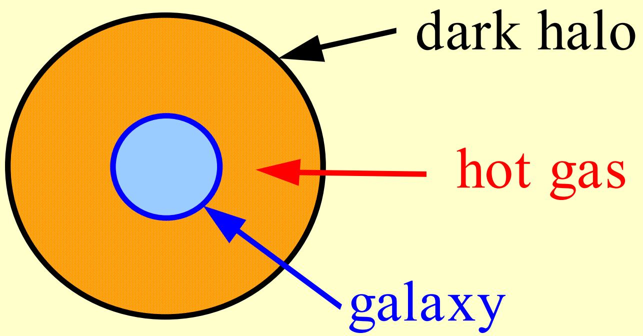
1) A certain fraction of the cold gas that is proportional to the total mass of stars newly formed at starburst (major merger) accretes onto the newly formed SMBH.

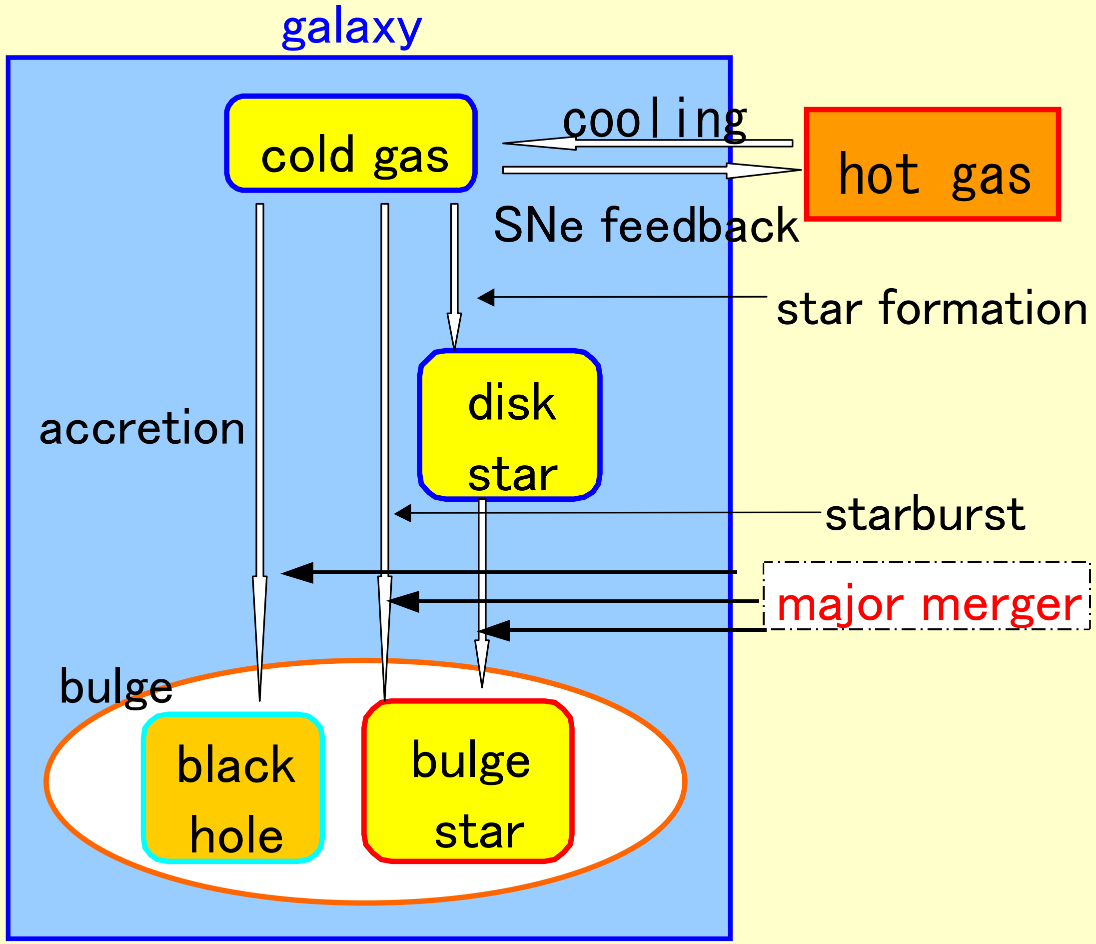
$$M_{acc} = f_{BH} M_{*,burst}$$

(cold gas => BH)

2) When host galaxies merge, the pre-existing SMBHs in the progenitors immediately evolve to the GW emission regime and coalesce.

# *Gas recycling in star formation




*galaxy = disk + bulge

disk = disk star + cold gas

bulge = bulge star + black hole

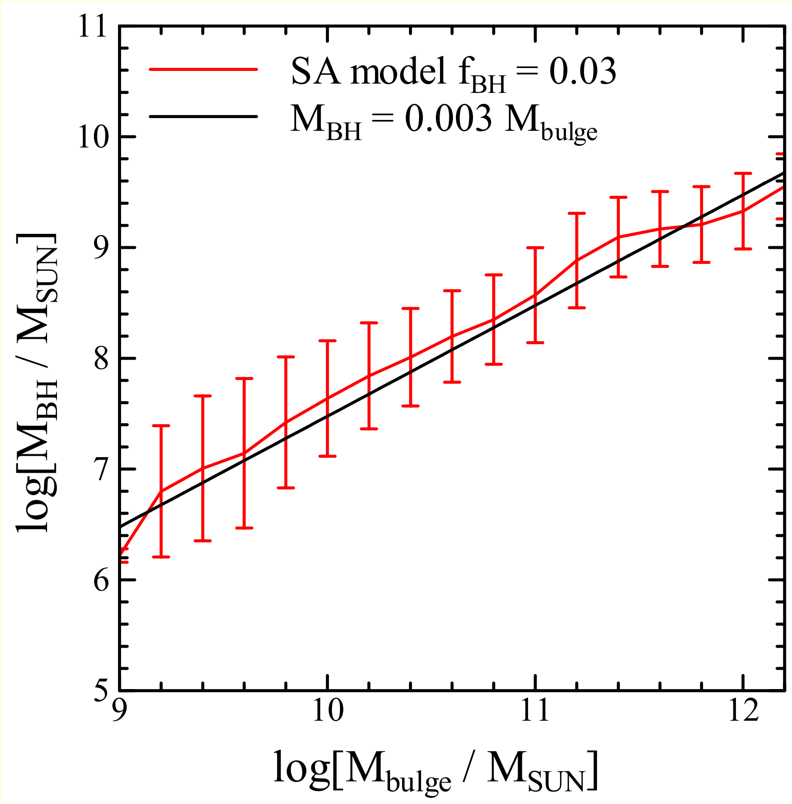
* hot gas ; diffuse gas, virial temperature

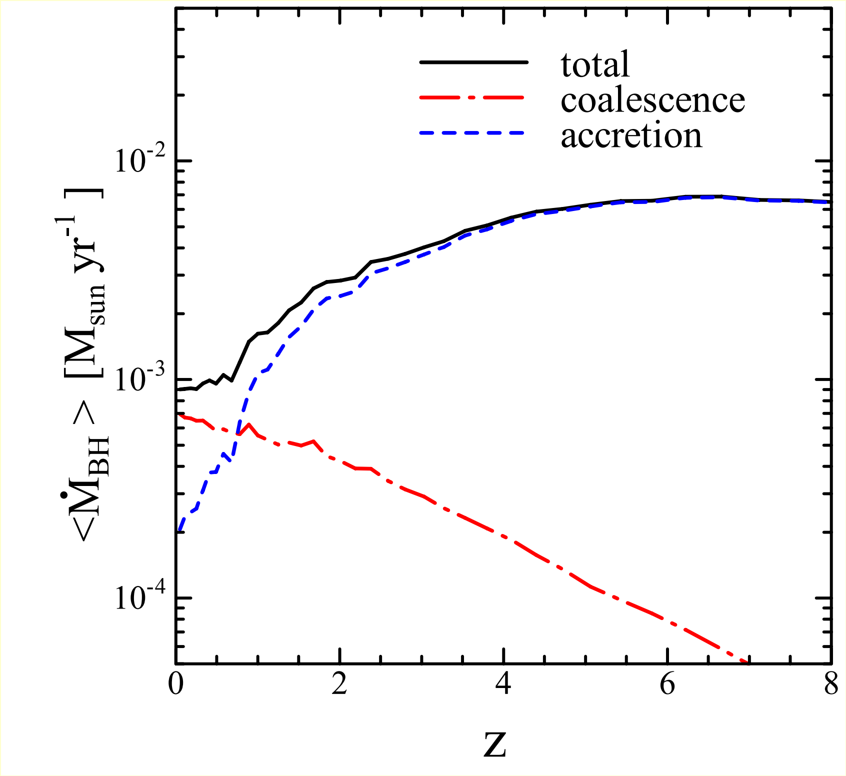
# * SMBH growth

$$M_{acc} = f_{BH}\ M_{*,burst}$$

$f_{BH}$: fixed by matching the observed relation $M_{buluge}$-$M_{BH}$

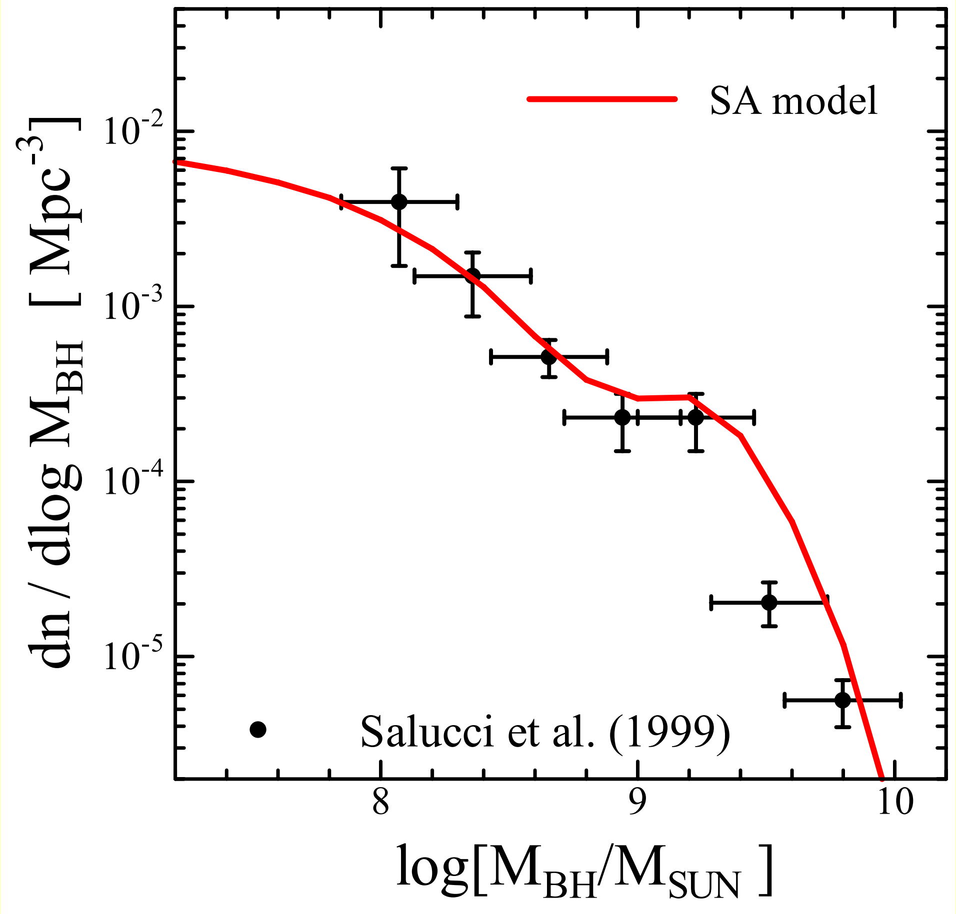
SMBH growth;
*coalescence
*accretion




We chose : $f_{BH}$ = 0.03

# * SMBH mass function



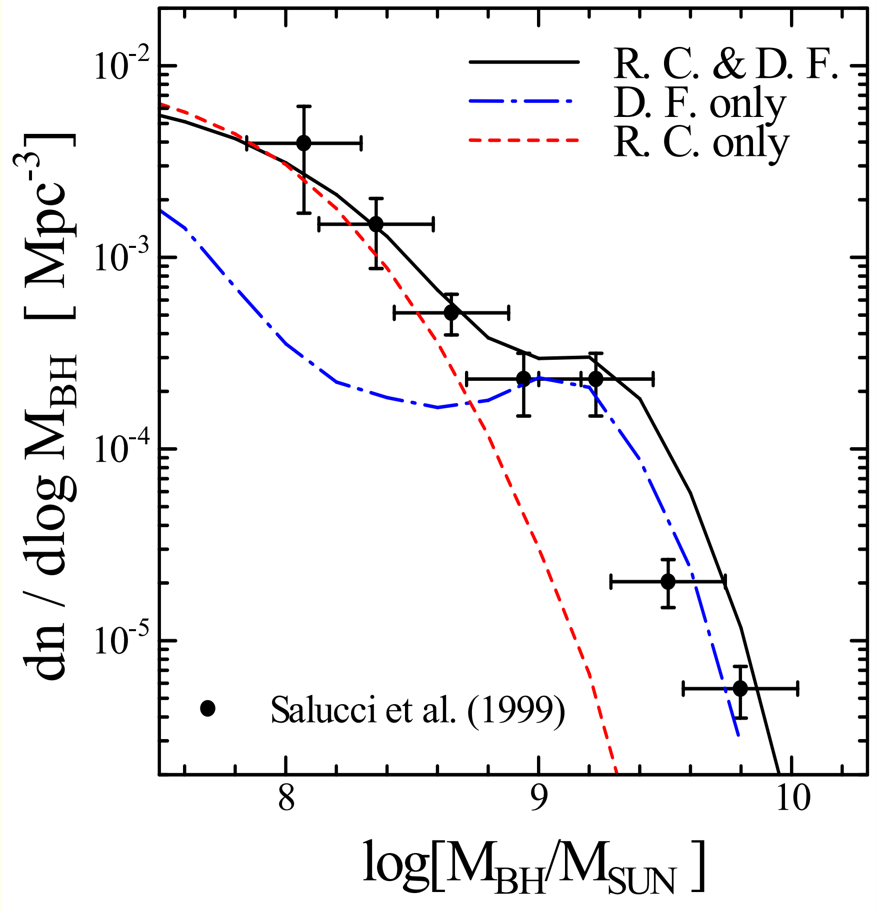

Our model result is consistent with the observed black hole mass function (Salucci et al. 1999).

# * SMBH mass function 2

galaxy merging processes;

*dynamical friction [D.F.] (satellite-central merger)

*random collision [R.C.] (satellite-satellite merger)




SMBHs in central galaxies

=>The main contribution of mass increments is cold gas accretion.

=> SN feedback remove this cold gas more efficiently in smaller galaxies

=>The growth of the SMBHs in small central galaxies suffers from SNe feedback.

# § 4. GW background radiation from SMBH binaries

To calculate the spectrum of GW background radiation, we adopt a formulation derived by Jaffe & Backer (2003).

$$h_c^2(f) = \int dz\, dM_1\, dM_2\, h_s^2\, \nu(M_1, M_2, z)\, \tau_{\rm GW,obs}\, \theta(f_{\max} - f).$$
$$= \int dz\, dM_1\, dM_2\, \frac{4\pi c^3}{3} \left(\frac{GM_{\rm chirp}}{c^3}\right)^{5/3} (\pi f)^{-4/3} (1+z)^{-1/3} n_c(M_1, M_2, z)\, \theta(f_{\max} - f)$$

$M_{chirp} = [M_1 M_2 (M_1 + M_2)^{-1/3}]^{3/5}$ ; the chirp mass

$f$ ; the observed frequency of GW

$f_{\rm max}$ ; the max frequency ($3 \times$ Schwarzschild radius)

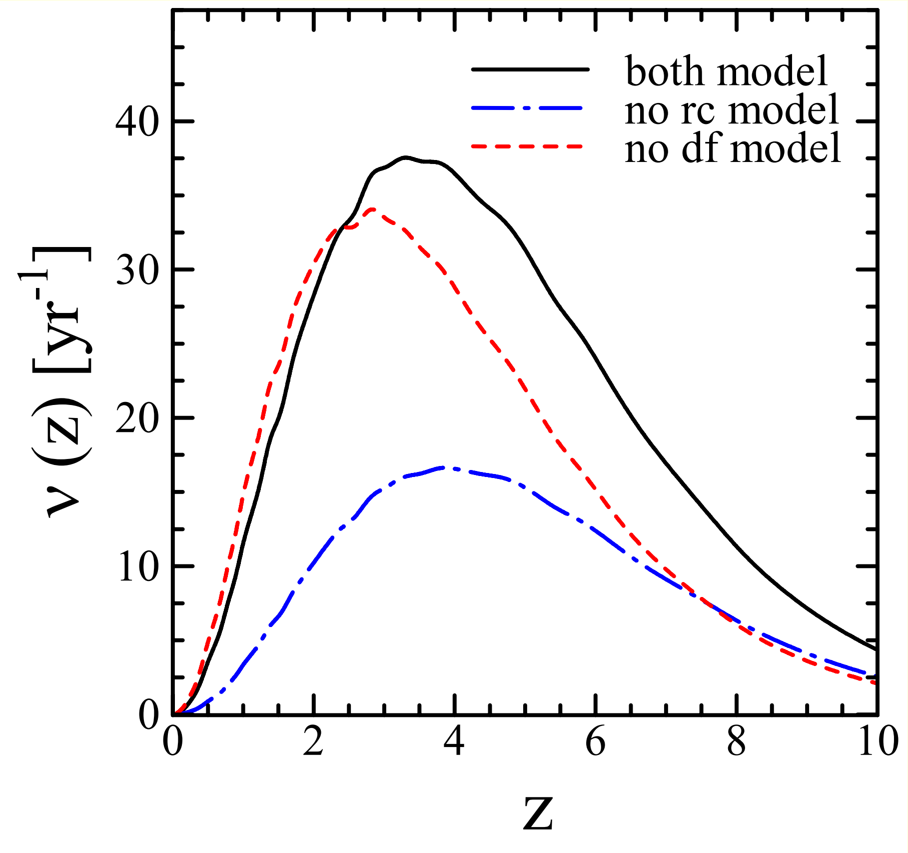
$\tau_{\rm GW,obs}(M_1, M_2, z, f)$ ; the GW timesclae of a binary in circular orbit

*SA model => the SMBH coalescence rate; $n_c(M_1, M_2, z)$

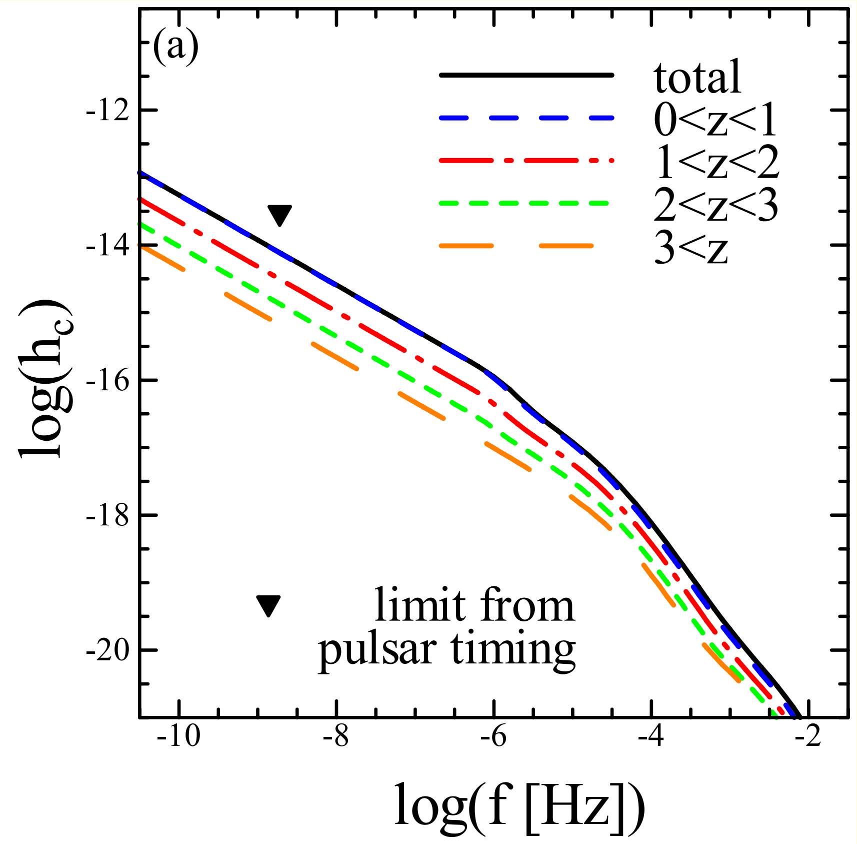
=> the background radiation spectrum; $h_c(f)$

# SMBH coalescence rate

SMBH coalescence rate in observer's unit a year



# *Spectrum of GW background




The predicted amplitude is just blow the limit from the pulsar timing measurements (Lommen2002).

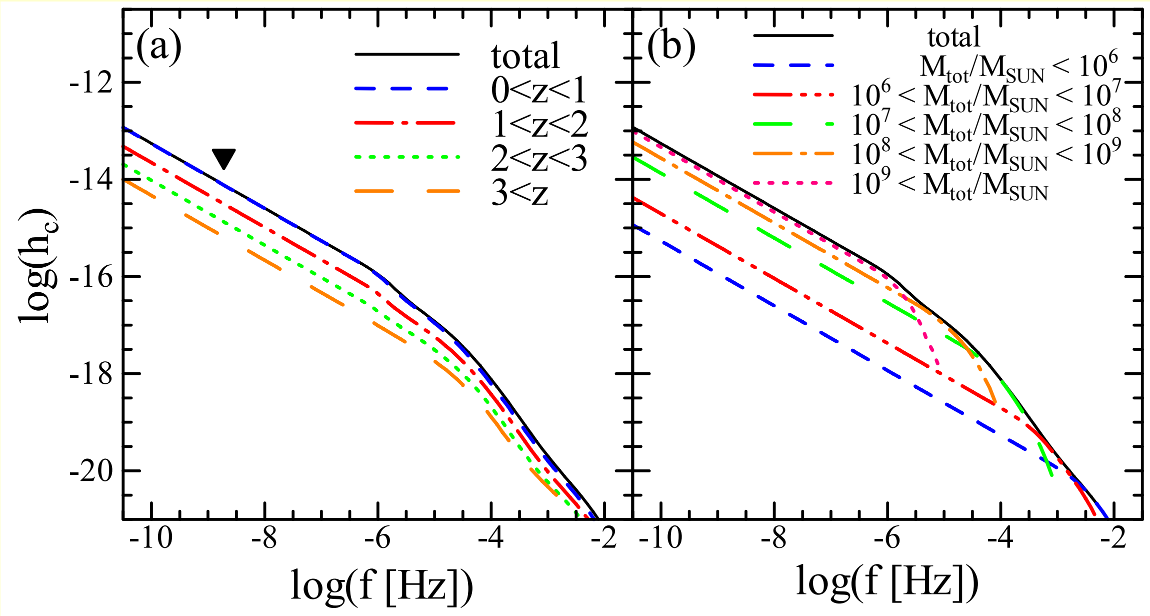
For $f < 10\ \mu$ Hz,

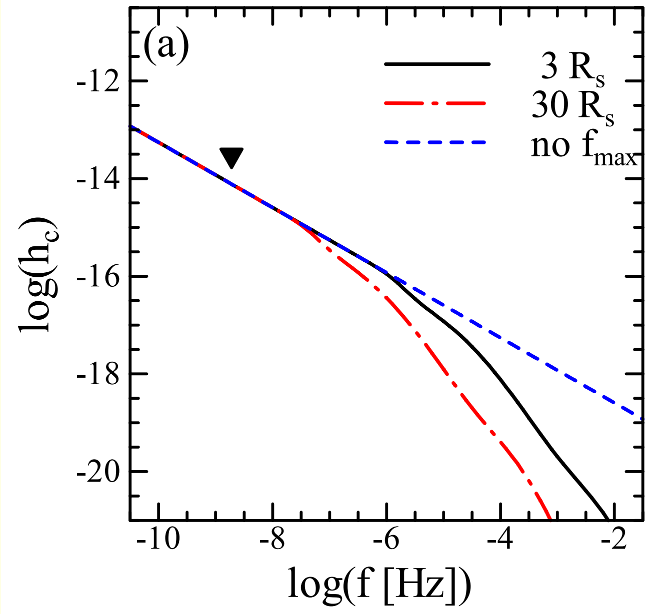
$$h_c = 10^{-16} \times (f / 1\ \mu\text{Hz})^{-2/3}$$

At $f \sim 10\ \mu$ Hz,
the spectrum changes its slope owing to lack of power associated with the upper limit frequency, $f_{max}$.

The main contribution to the background radiation is GW from the coalescing SMBH binaries at low redshift, $0 < z < 1$.

# *Spectrum of GW background 2




For $f < 10^{-4}$ Hz,
the total spectrum comes from coalescing SMBH binaries with total mass $M_{tot}>10^8 M_{SUM}$.

# § 5. GW burst from SMBH coalescence

The SMBH coalescence releases energy, $\varepsilon M_{BH} c^2$, and produces GW burst. (Thorne & Braginsky 1976)

--The observed characteristic frequency

$$f_c = \frac{c^3}{3^{3/2} G M_{tot} (1+z)}$$

--The GW energy flux

$$F_{GW} = \frac{\epsilon M_{tot} c^2 f_c}{4\pi D(z)^2 (1+z)}$$

--The GW amplitude

$$h^2 = \frac{2 G F_{GW}}{\pi c^3 f_c^2},$$

--The expected event rates of GW burst

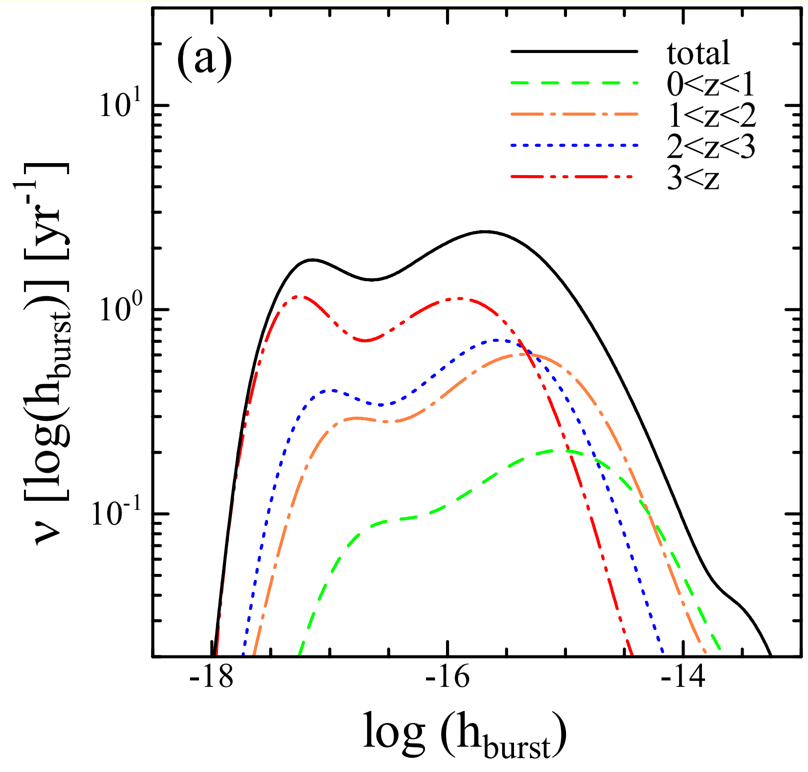
$$\nu_{burst}(h_{burst}, f_c) = \int n_{burst}(h_{burst}, f_c, z) \frac{dV}{dt_0} dz$$

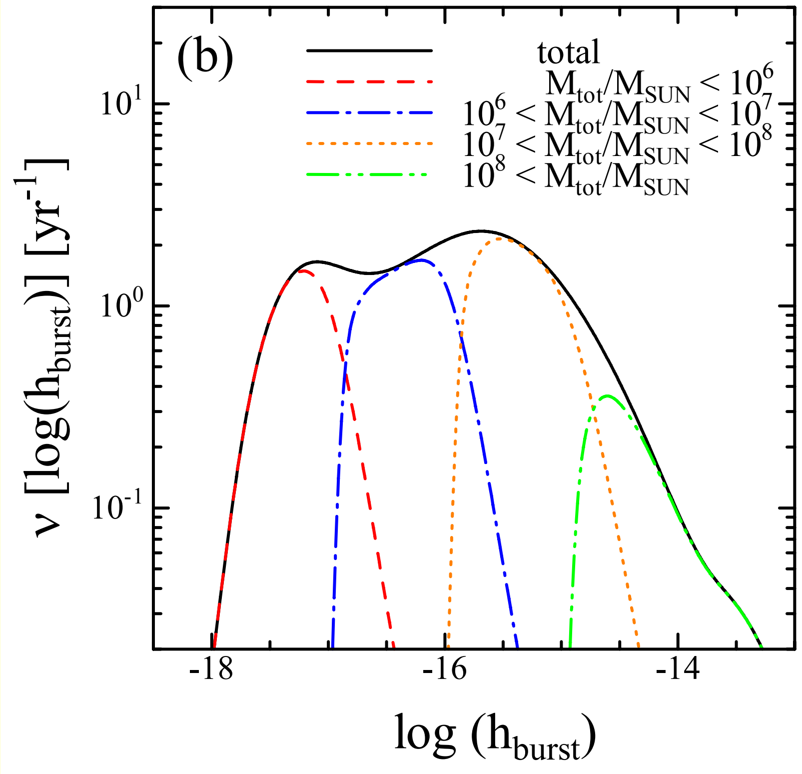
*SA model => the SMBH coalescence rate; $n_c(M_1, M_2, z)$

=> GW burst rate; $\nu_{burst}(h, f)$

# *Integrated GW burst rate

Integral event rate of GW burst; ν(log[h])



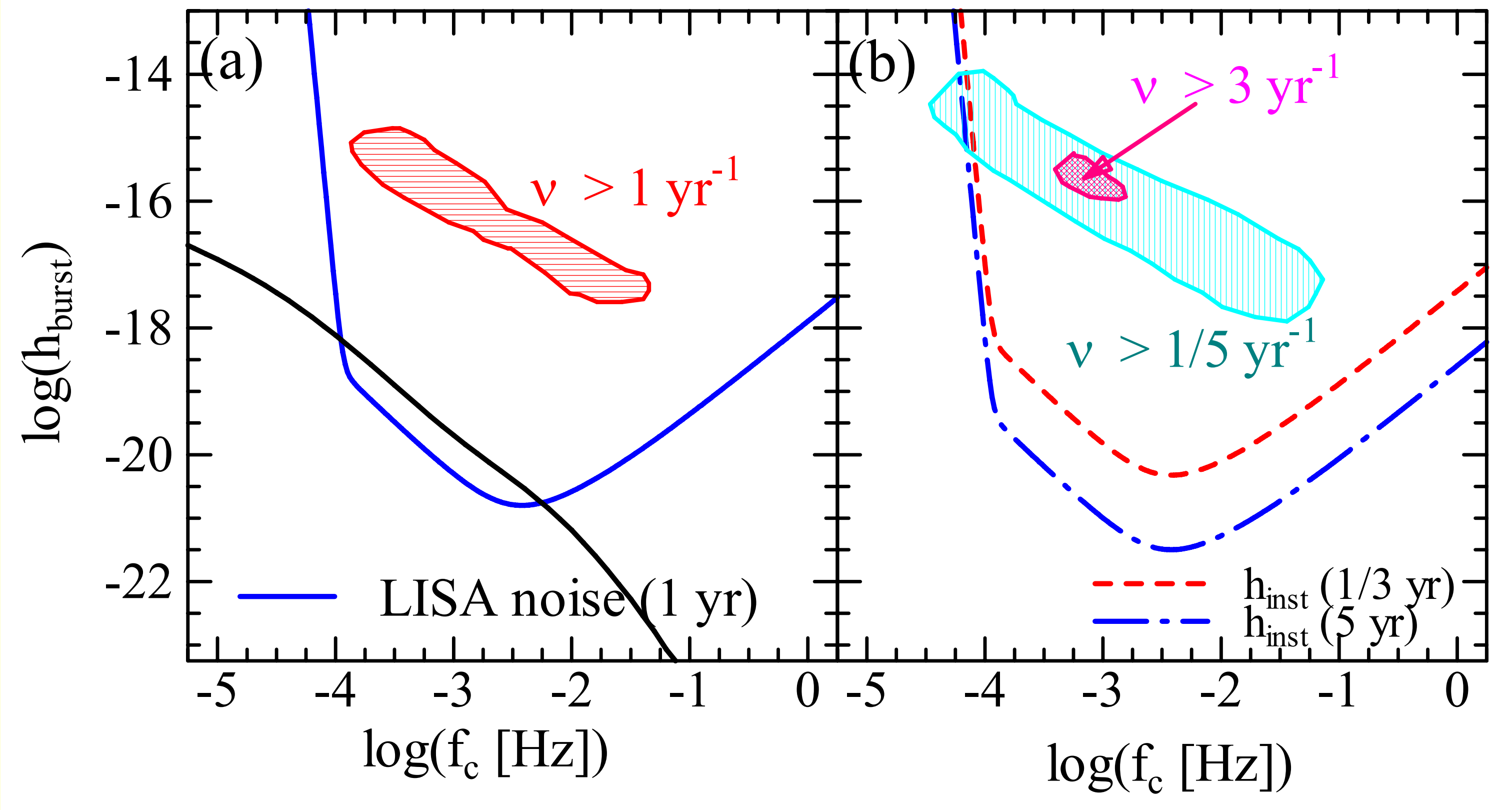




$h^{-17}$ ; $M_{BH} < 10^{6} M_{sun}$ from $z > 3$

$h^{-15}$ ; $M_{BH} \sim 10^{7} - 10^{8} M_{sun}$ from $z < 3$

# *GW burst rate

Expected signals of GW burst; ν（log[h], log[f]）




We adopt $\varepsilon = 0.1$

NB, $h \propto \varepsilon^{1/2}$

# § 6. Summary and Conclusion

We have estimated the coalescence rate of SMBH binaries in the centers of galaxies using a new semi-analytic model of galaxy and quasar formation (SA model).
Then, we calculated

- Gravitational wave background radiation spectrum
- Gravitational wave burst rate

*GW background

- The main contribution comes from inspiraling SMBH binaries at $0 < z < 1$.

*GW bursts

- *LISA* might detect them at a rate 0.1 ~ 1 /yr .
- The main contribution to the event rate comes from SMBH binary coalescence at high redshift $z > 2$

# *References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