# Co-evolution of super massive BHs with galaxies

—stochastic GWB & galaxy clustering

[arXiv:1802.03925]
arguing w. MNRAS

w. Qing Yang@BNU
Xiao-Dong Li@SYSU

Bin HU @ BNU

2018/04 Nanjing

# 1. General Picture

galaxy formation model theoretically pred:
**Almost every galaxies, host centre SMBHs**

| SMBH | Mass | Radius |
|---|---|---|
| **Sagittarius A*** | **$10^6$ M_solar** | $10^{-7}$pc |
| **Andromeda** | **$10^8$ M_solar** | $10^{-5}$pc |
| **NGC 4889** | **$10^{10}$ M_solar** | $10^{-3}$pc |

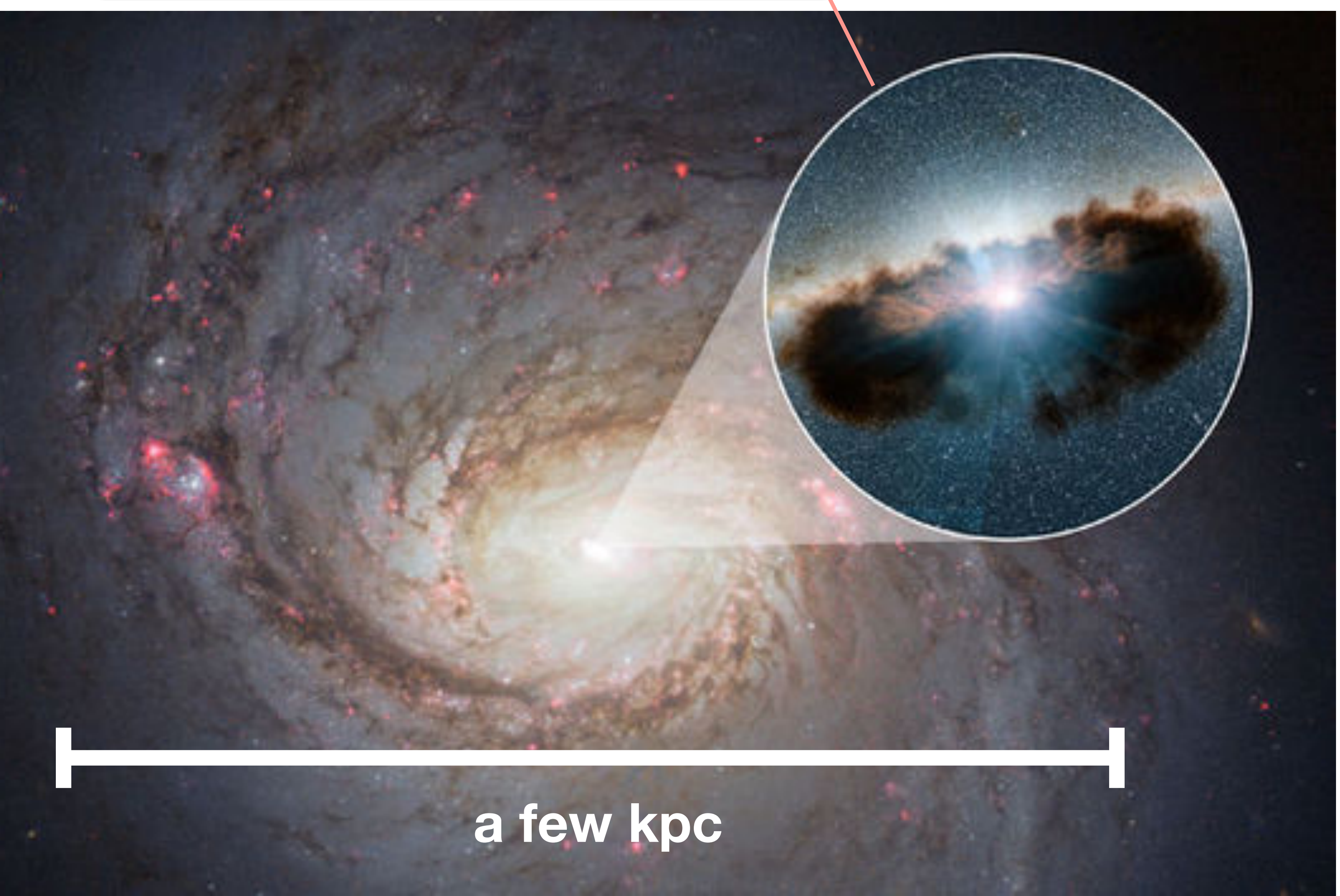
**e.g. Semi-Analytical Model of galaxy formation (SAM) based on Millennium simulation**

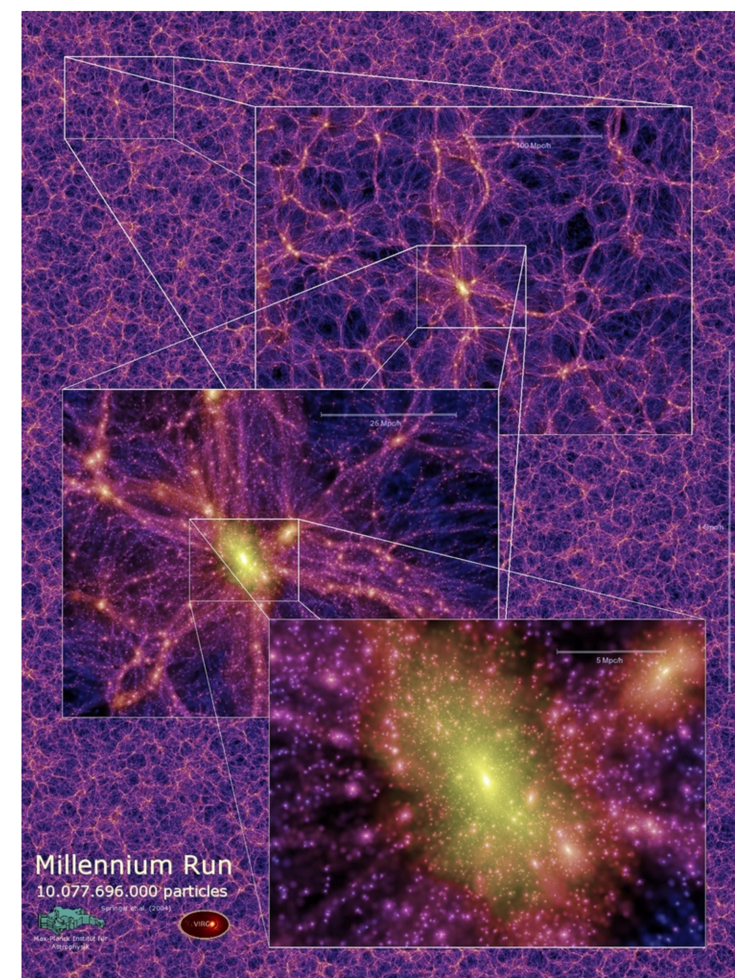
**(L~500 $Mpc^3$)**

**8668809 SMBHs,**

**51538704 galaxies**

**in total**

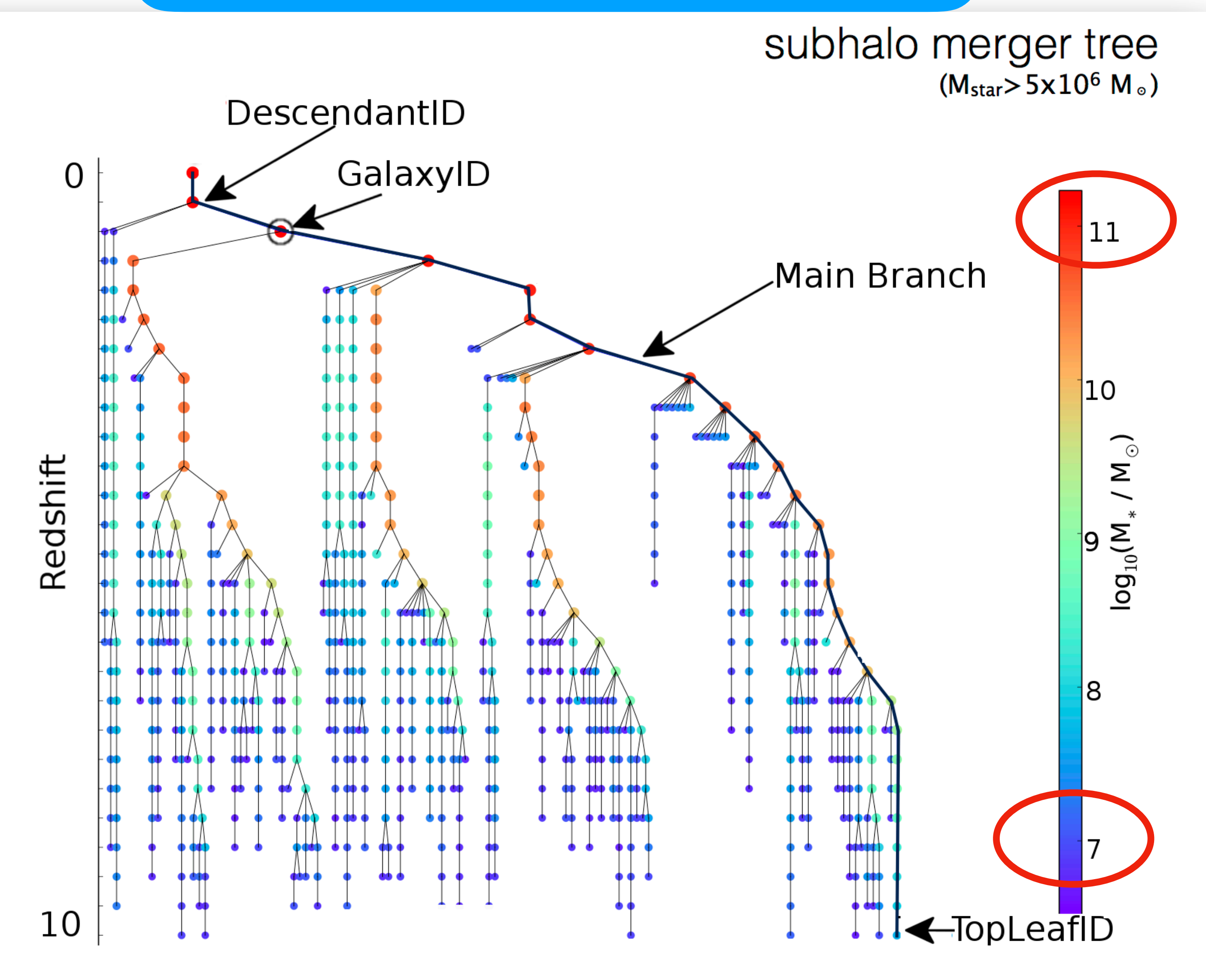


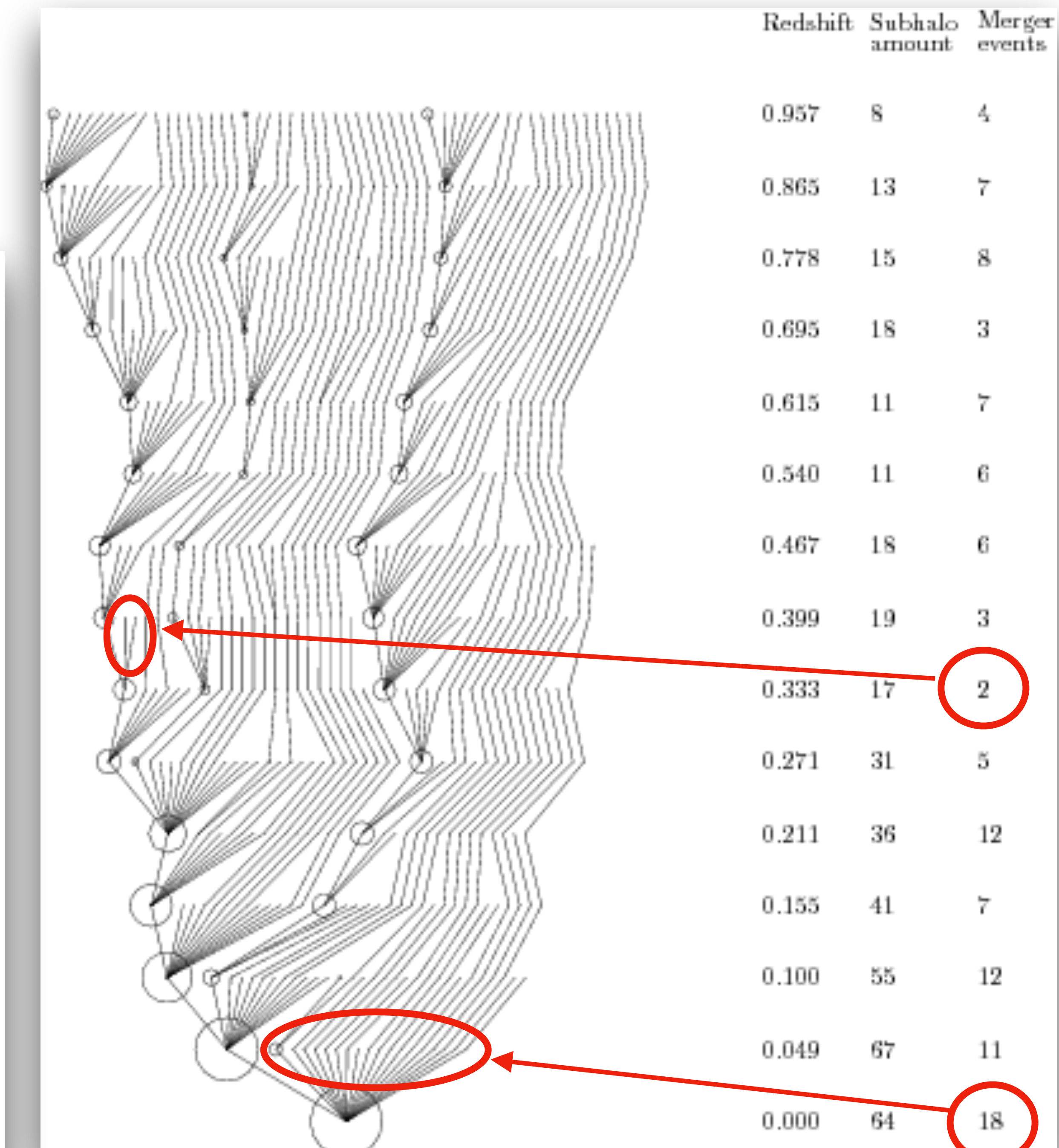



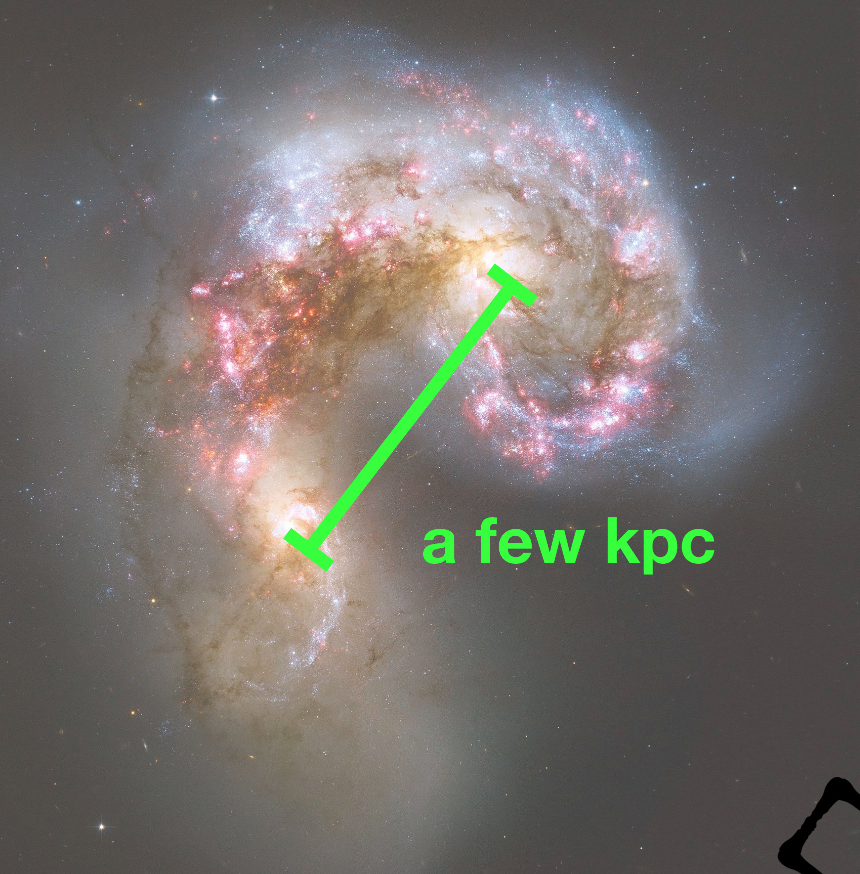
**On average, 2 galaxies are separated ~ a few Mpc ~(10 or 100) times of galaxy size**

**merger event is very possible!**

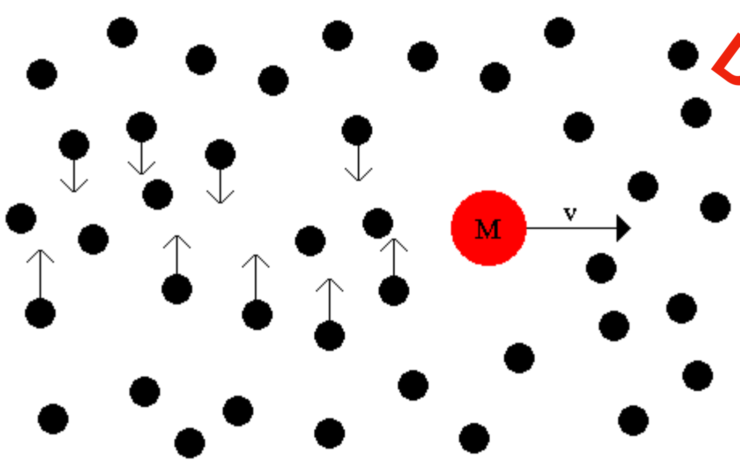
merger is major channel for the galaxy gaining mass



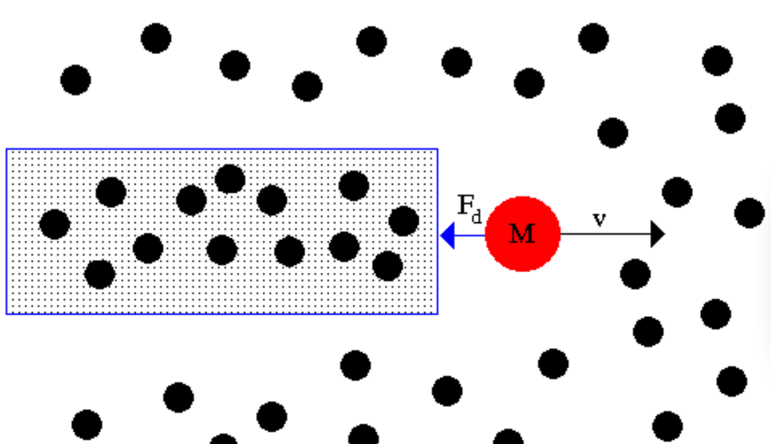





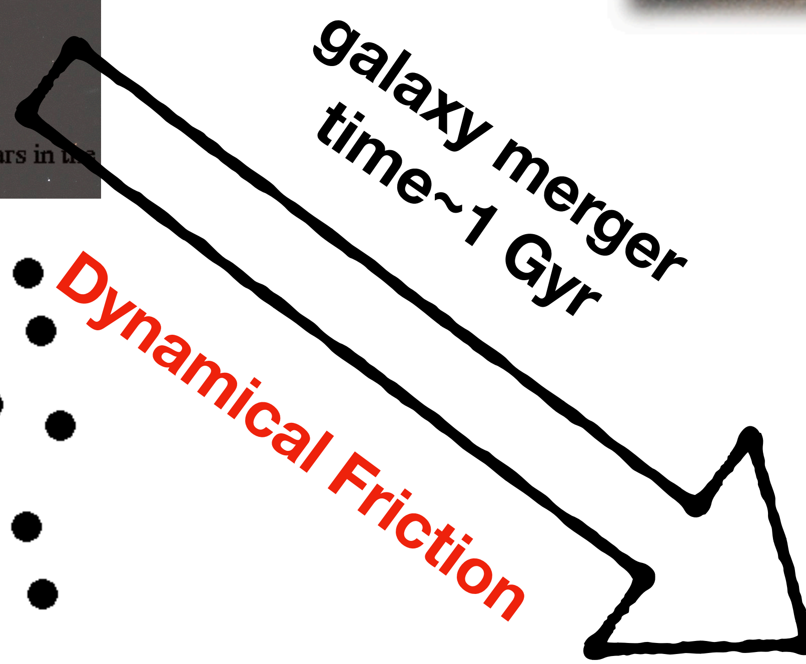

consider a mass, M, moving through a uniform sea of stars. Stars in the wake are displaced inward.



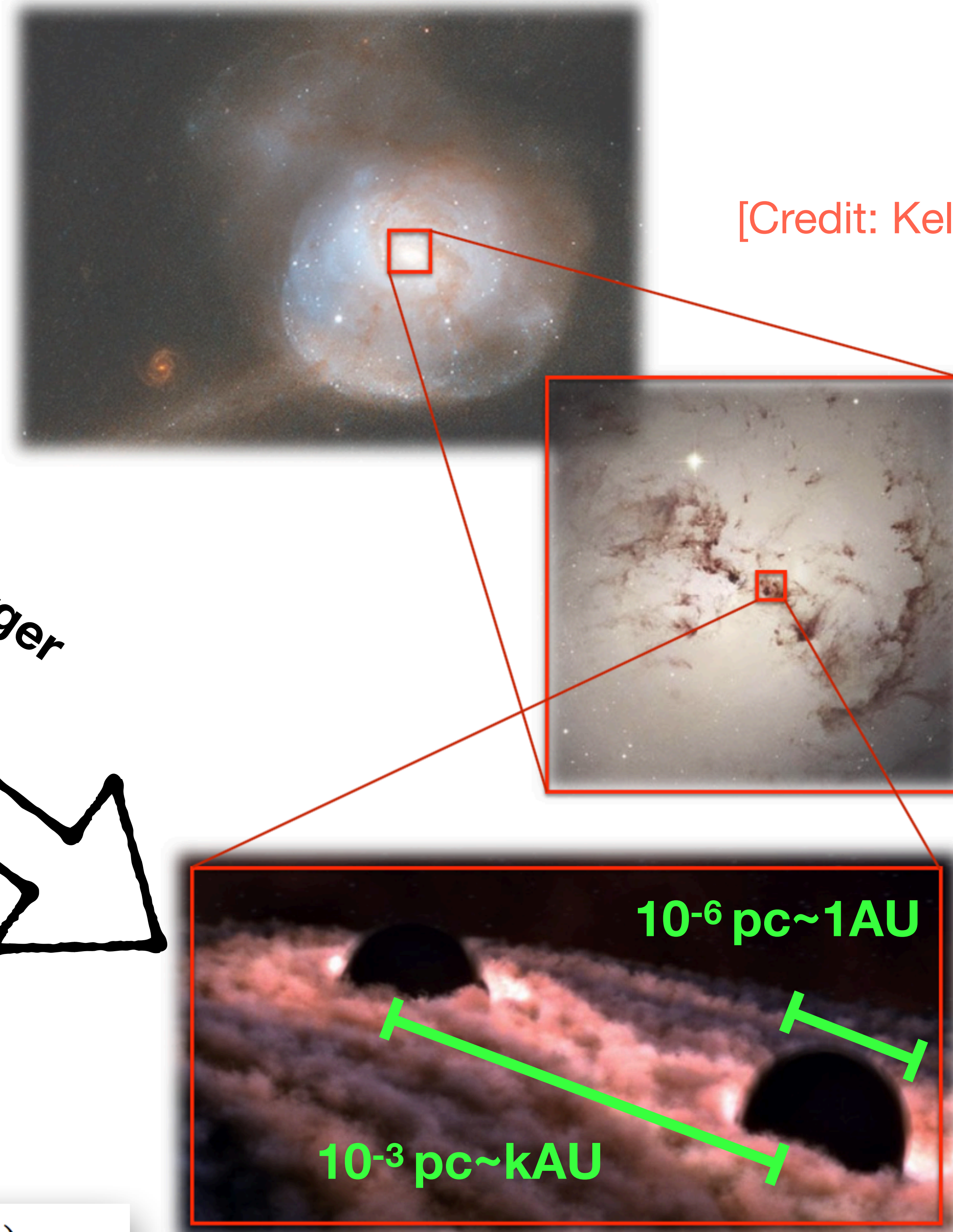

this results in an enhanced region of density behind the mass, with a drag force, $F_d$ known as dynamical friction




$$\frac{dv}{dt} = -\frac{2\pi G^2 (M+m)\rho}{v^2} \ln \Lambda$$



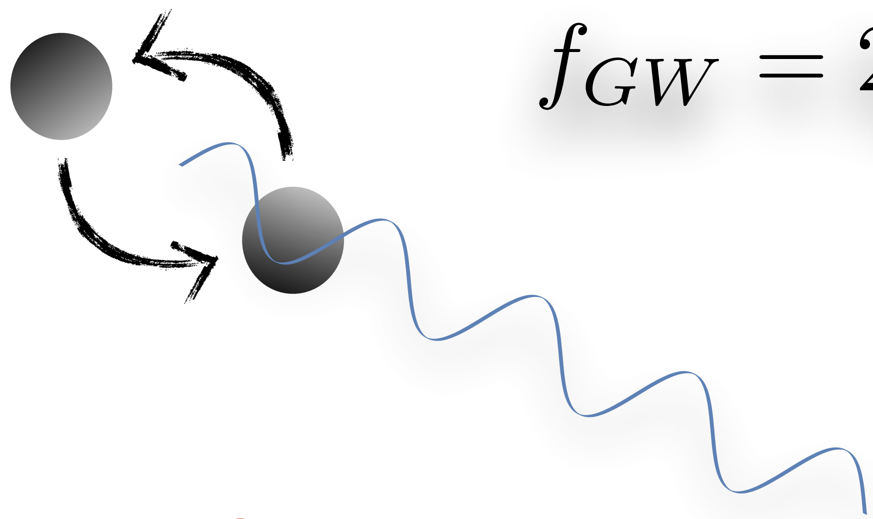

[Credit: Kelley]




$M_{bh} \sim 10^7\ M_{sun}$

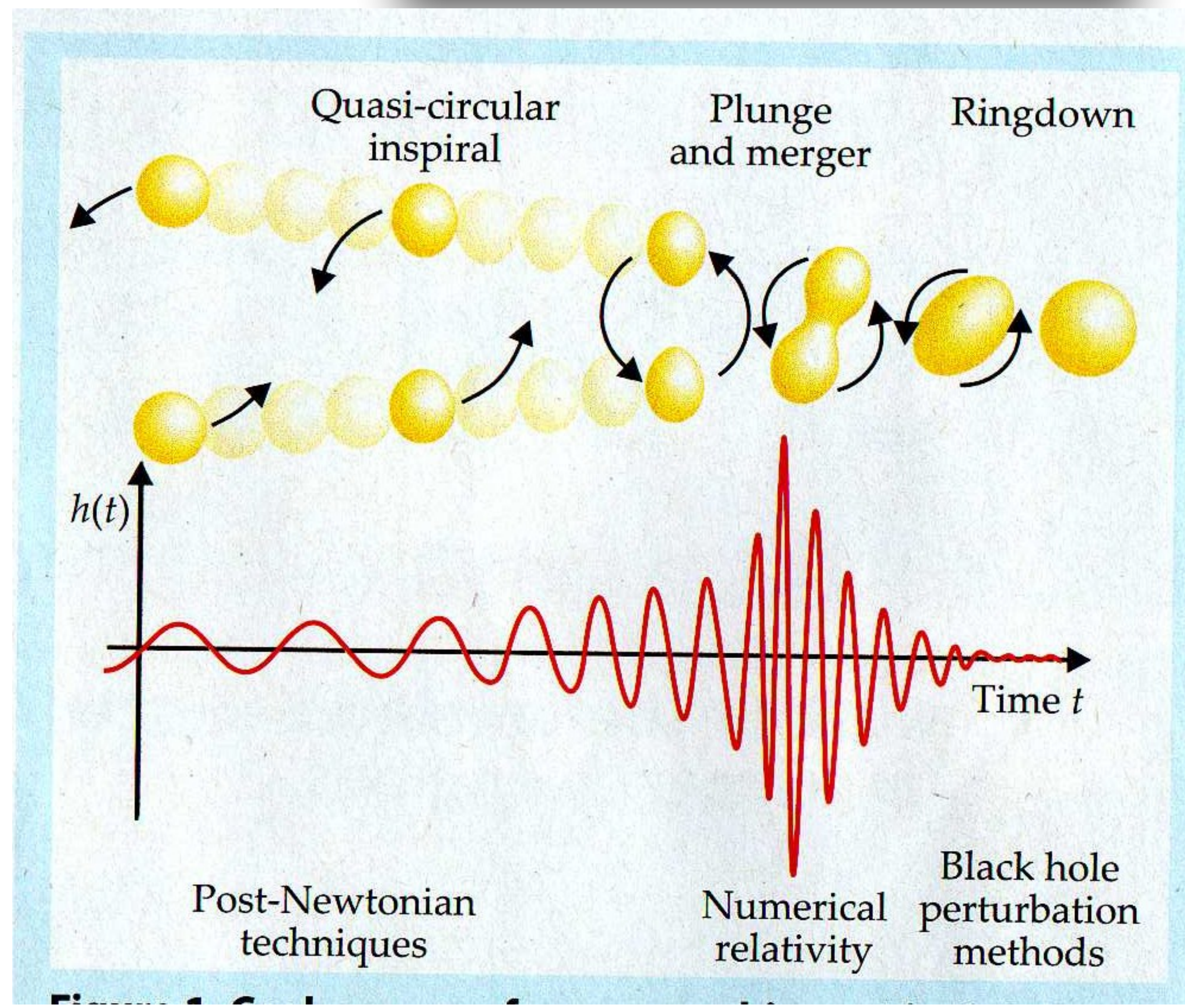
period ~ 10 yr, merger time ~ 1 Myr

**Single binary ~ circular orbit, Quadrupole formula is enough!**



$$f_{GW} = 2 f_K \sim [5yr]^{-1}$$

$$\bar{h}_{ij}(t,r) = \frac{2G}{c^4 r} \ddot{I}_{ij}(t - r/c),$$

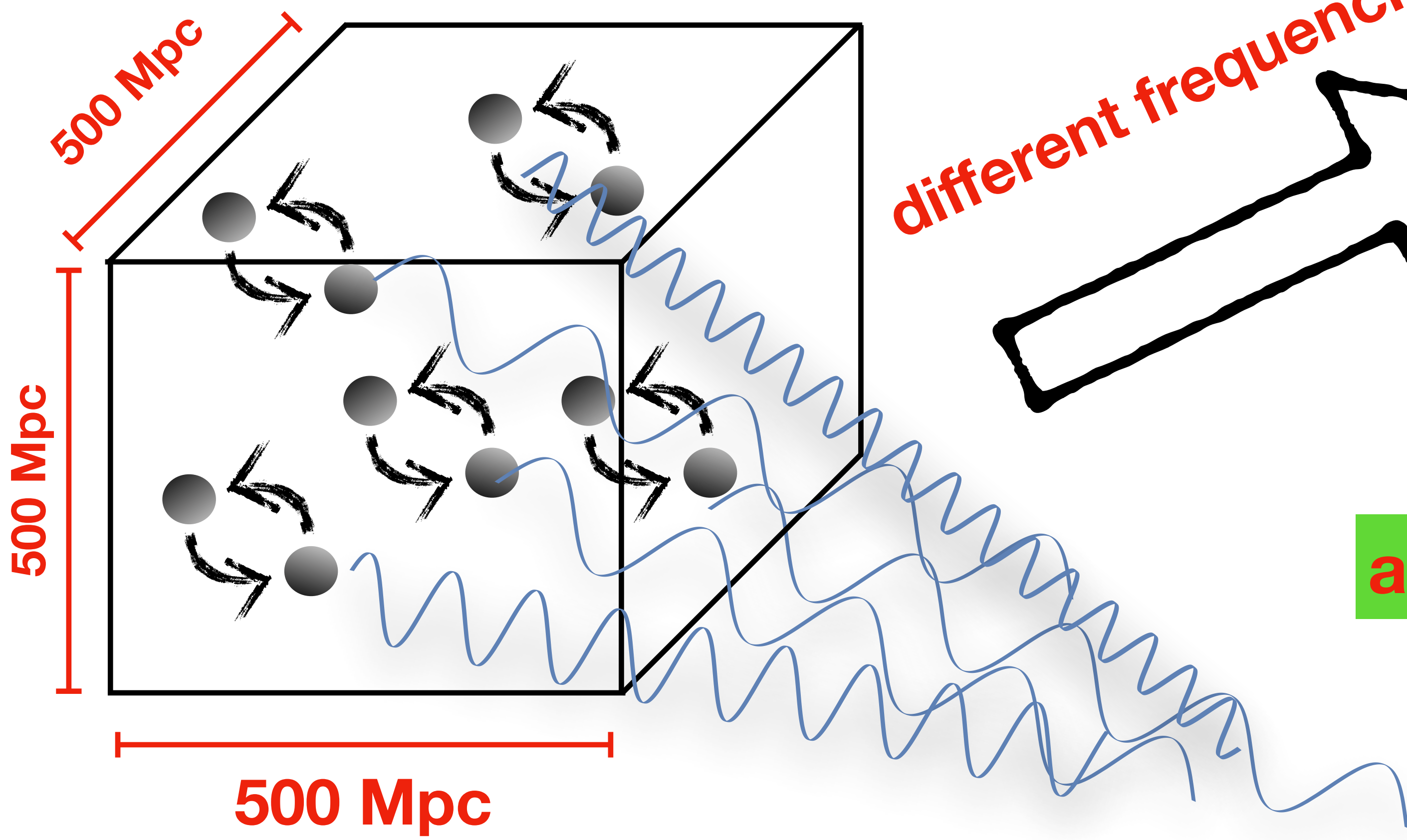



**We can NOT observe the inspiral phase, except it is very very nearby!**

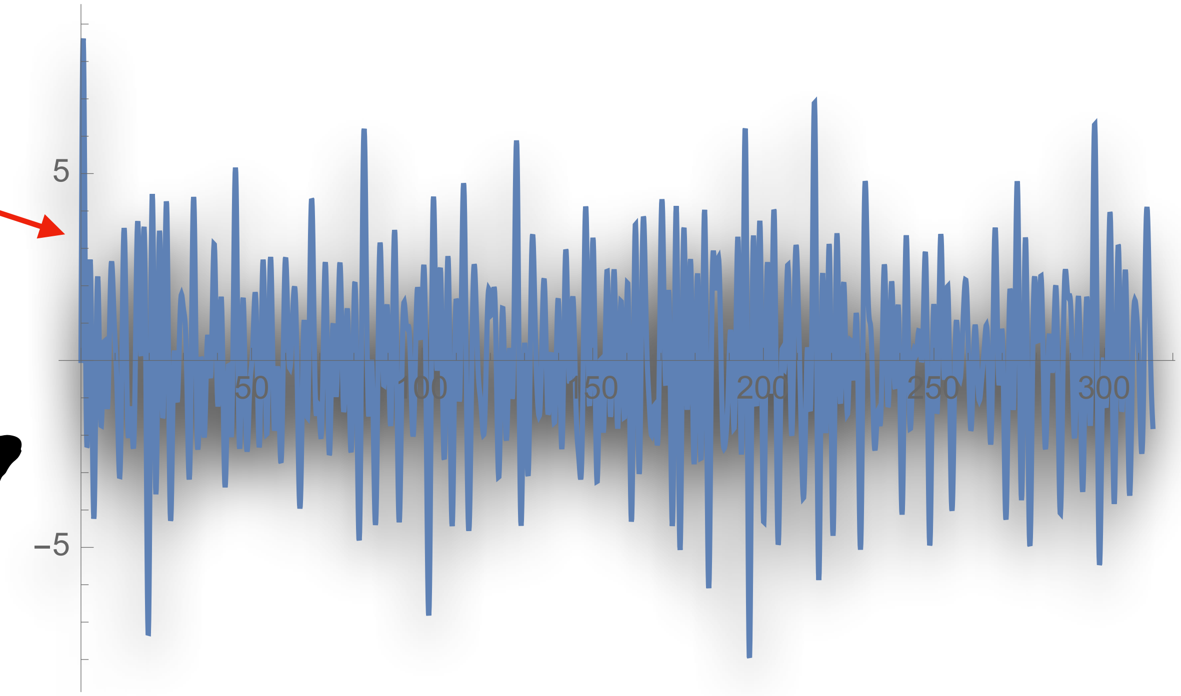

[Credit: 蔡少芬 & wangyi]

**Multi-binaries** → **GWB**

**GW signal we want! (noise-like)**

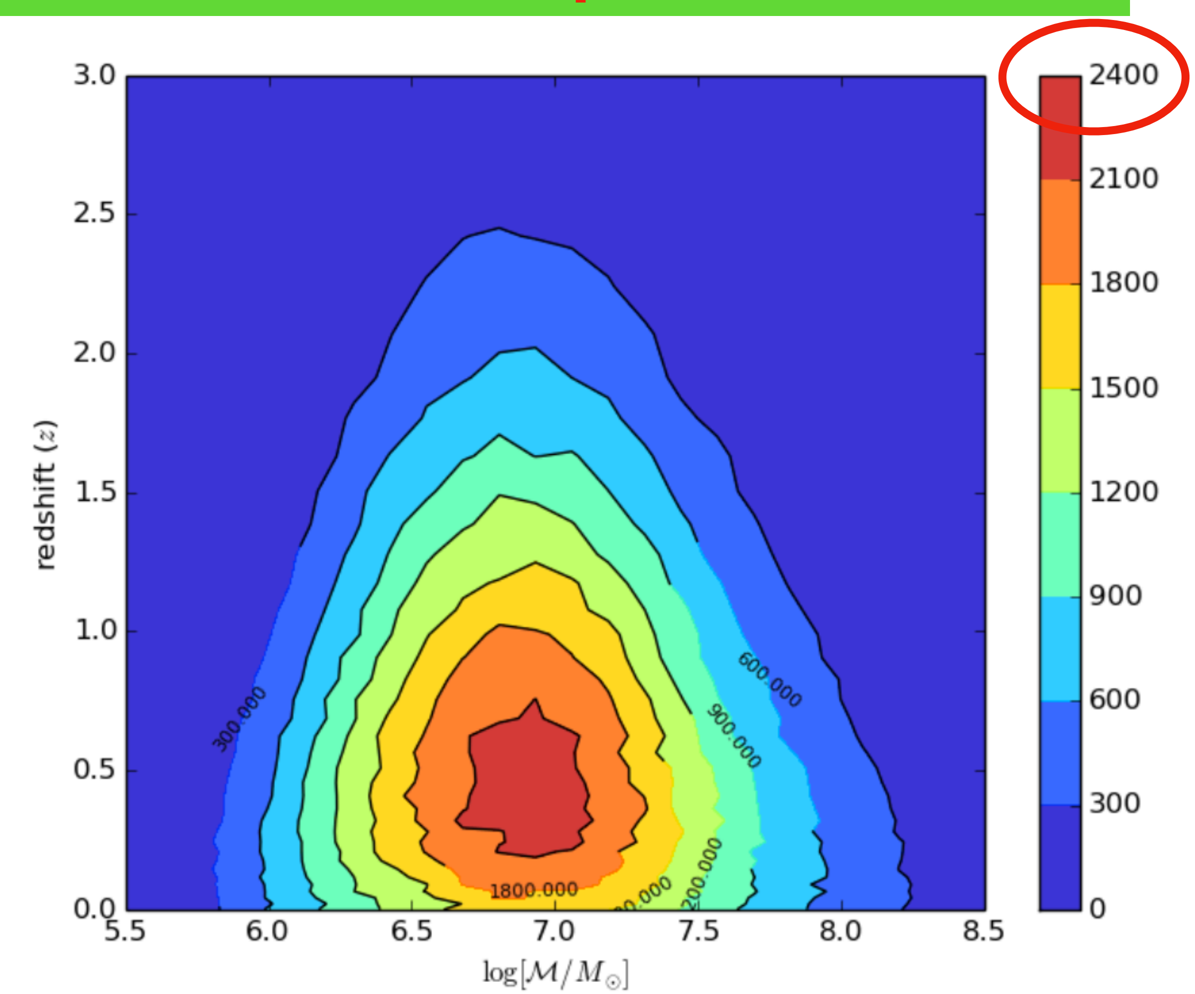



**different frequencies**




**Stochastic in time sequence!**

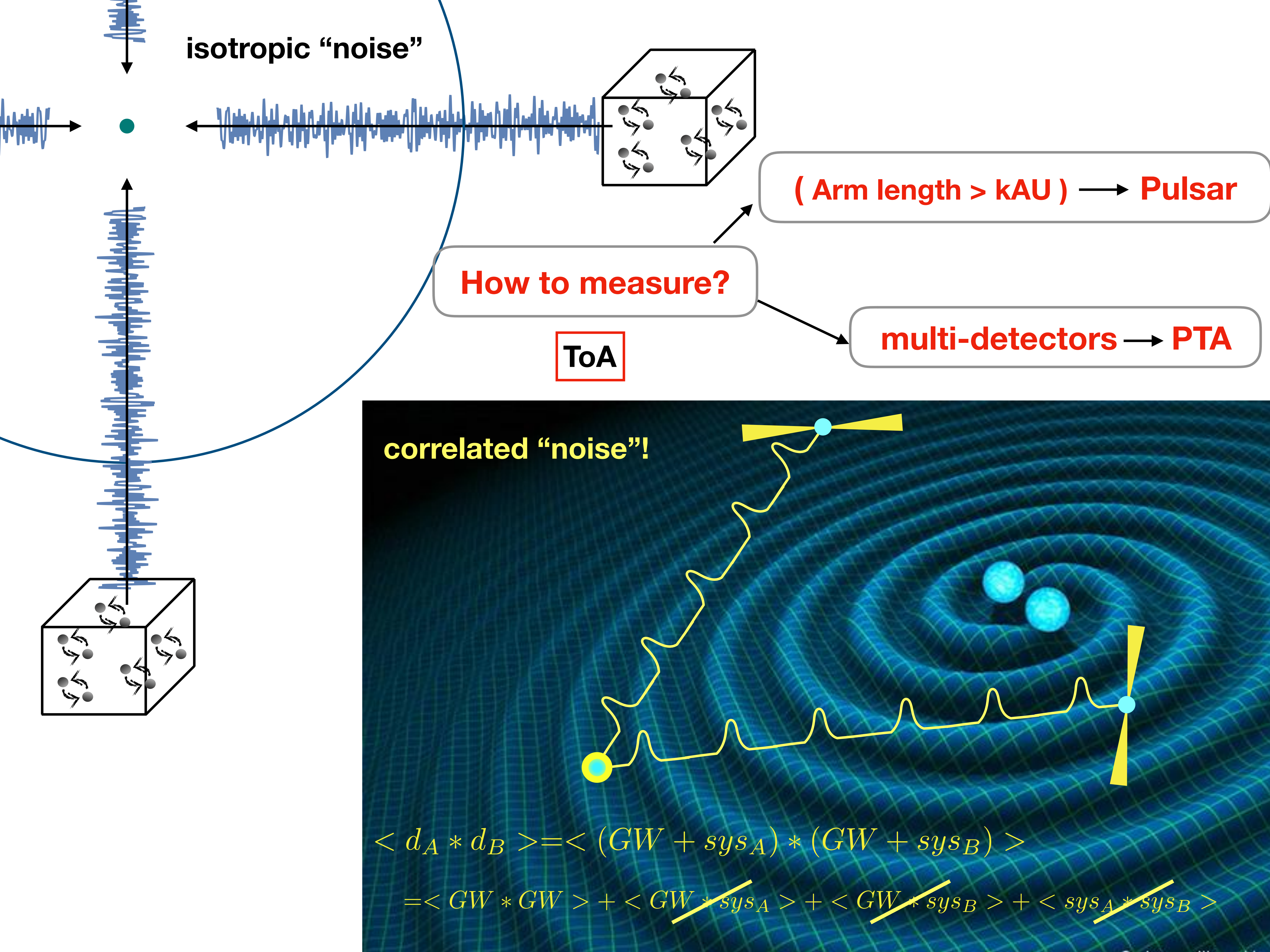
**a few $10^3$ BBH w. Chirp mass $10^7$ $M_{solar}$**




$$h_c^2(f) \propto \int \frac{1}{1+z} \boxed{\frac{dn}{dz}} \frac{d\varepsilon_{\rm GW}}{d\ln f_r}\bigg|_{f_r=f(1+z)} dz$$

[Phinney 2001]

**Merger rate!**

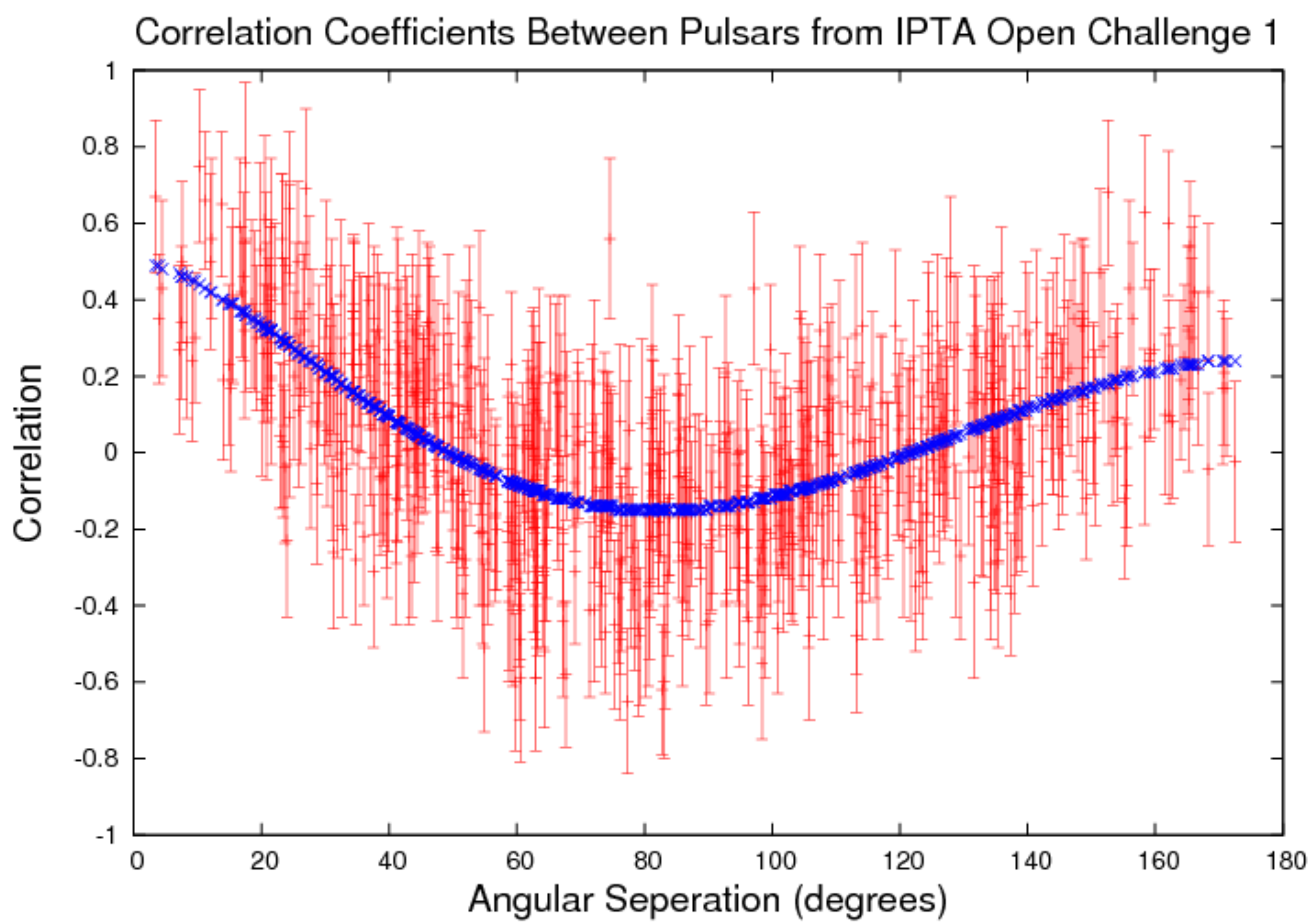

isotropic “noise”
How to measure?
( Arm length > kAU ) ⟶ Pulsar
multi-detectors ⟶ PTA
ToA
correlated “noise”!
$$< d_A * d_B > = < (GW + sys_A) * (GW + sys_B) >$$
$$= < GW * GW > + \cancel{< GW * sys_A >} + \cancel{< GW * sys_B >} + \cancel{< sys_A * sys_B >}$$

$$\langle GW{*}GW\rangle = \boxed{\alpha_{ij} \equiv \frac{1}{4\pi}\int \alpha_i \alpha_j \, d\Omega} = \frac{1-\cos\gamma_{ij}}{2}\ln\left(\frac{1-\cos\gamma_{ij}}{2}\right) - \frac{1}{6}\,\frac{1-\cos\gamma_{ij}}{2} + \frac{1}{3}, \qquad (5)$$

average over GW from all direction

where $\gamma_{ij}$ is the angle between the two pulsars.

[Hellings & Downs 1983]



$$h_c^2(f) \propto \int \frac{1}{1+z} \boxed{\frac{dn}{dz}} \frac{d\varepsilon_{\rm GW}}{d\ln f_r}\bigg|_{f_r=f(1+z)} dz$$

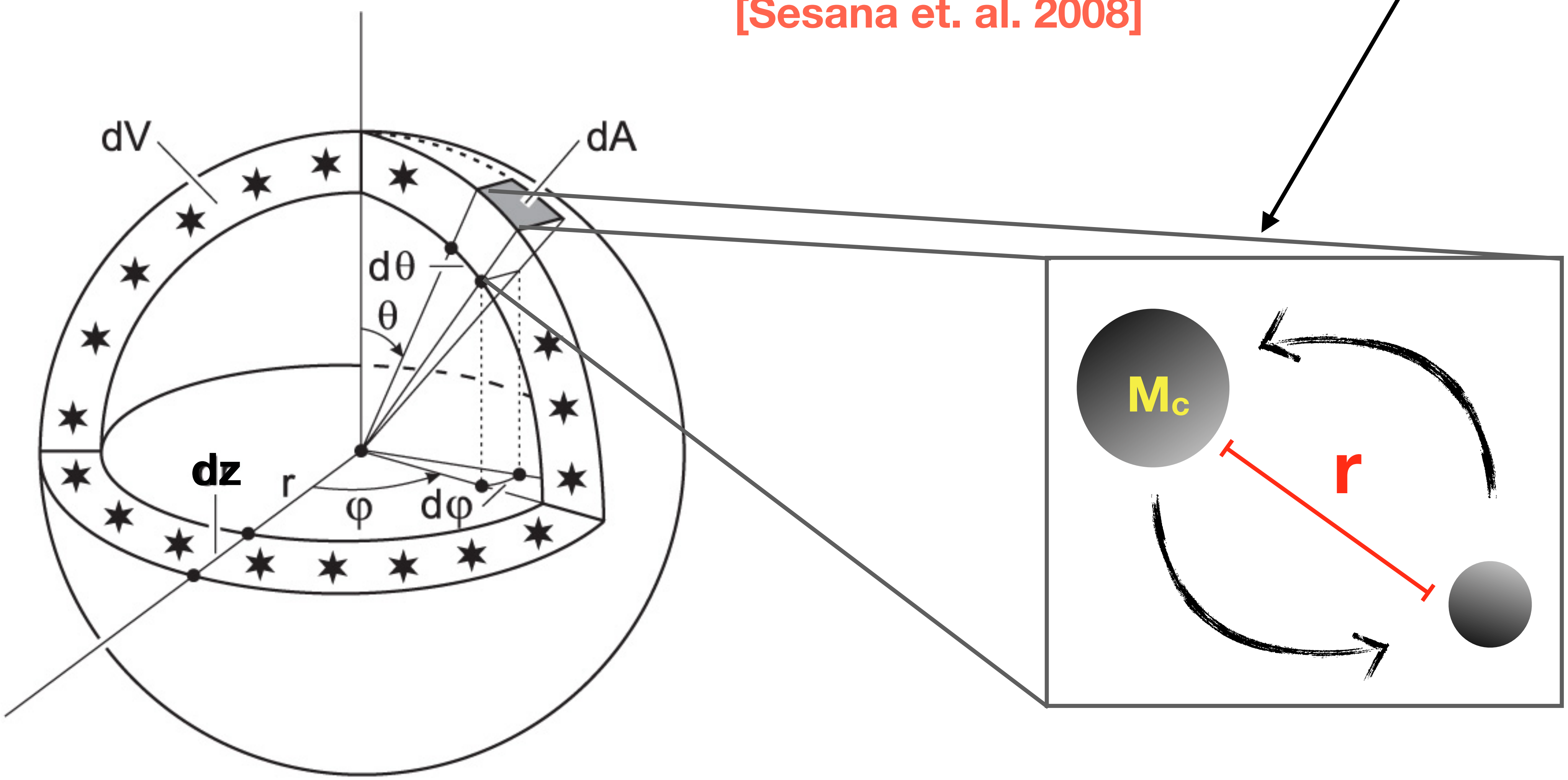
[Phinney 2001]

more accurate

$$h_c^2(f) = \int_0^\infty dz \int_0^\infty d\mathcal{M} \boxed{\frac{d^3N}{dz\,d\mathcal{M}\,d\ln f_r}} h^2(f_r),$$

BBH number per comoving volume, in such configuration

[Sesana et. al. 2008]



[Peters 1964]

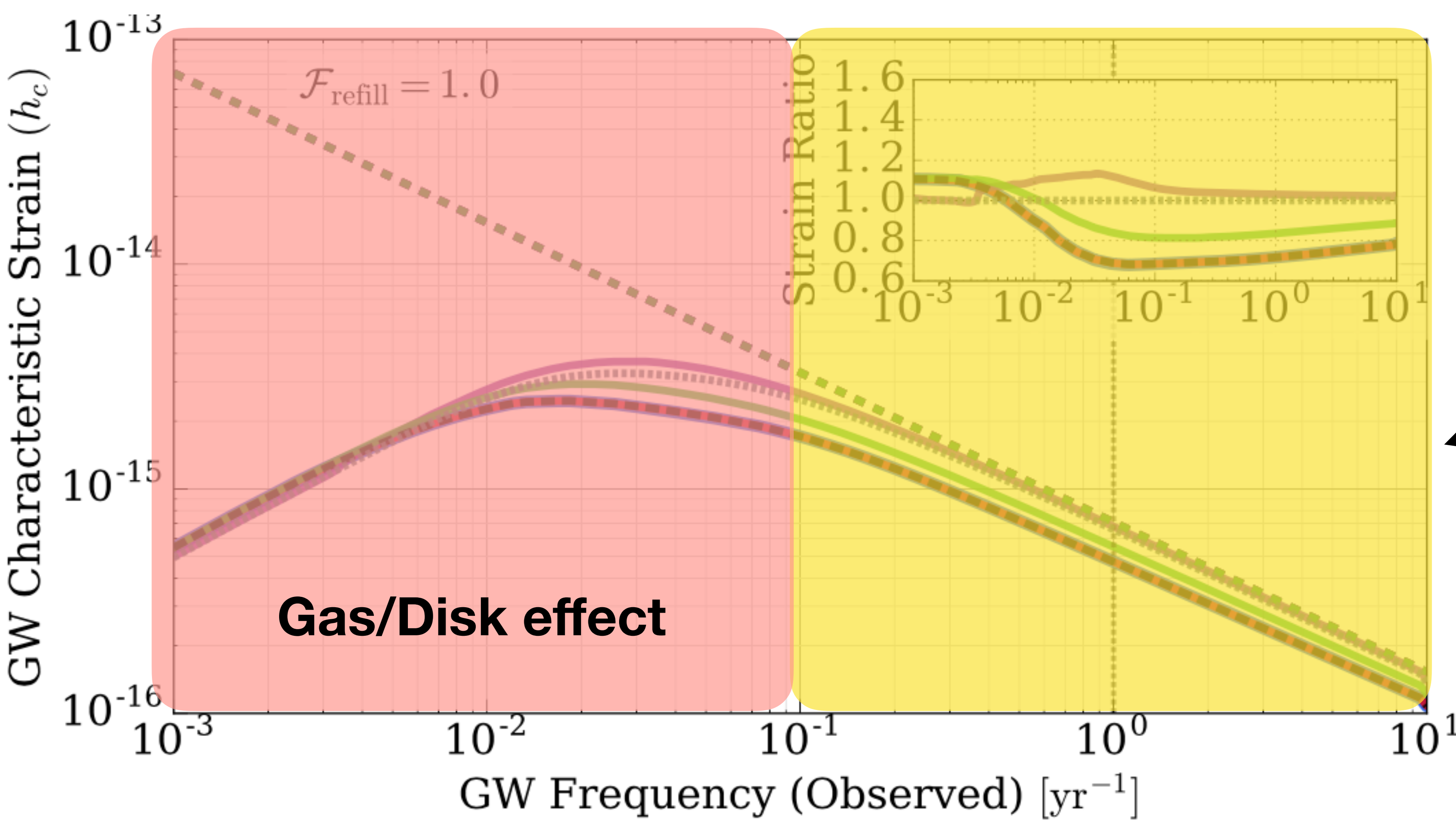
$$dt/d\ln f = \frac{5}{64\pi^{8/3}}\mathcal{M}^{-5/3} f_r^{-8/3}$$

**time spend in per logarithmic frequency**

$$h_c = A(f/f_0)^{-2/3}$$

**Major eq.**

$$h_c^2(f) = \frac{4f^{-4/3}}{3\pi^{1/3}} \int\int dz d\mathcal{M} \frac{d^2n}{dz d\mathcal{M}} \frac{1}{(1+z)^{1/3}} \mathcal{M}^{5/3}$$



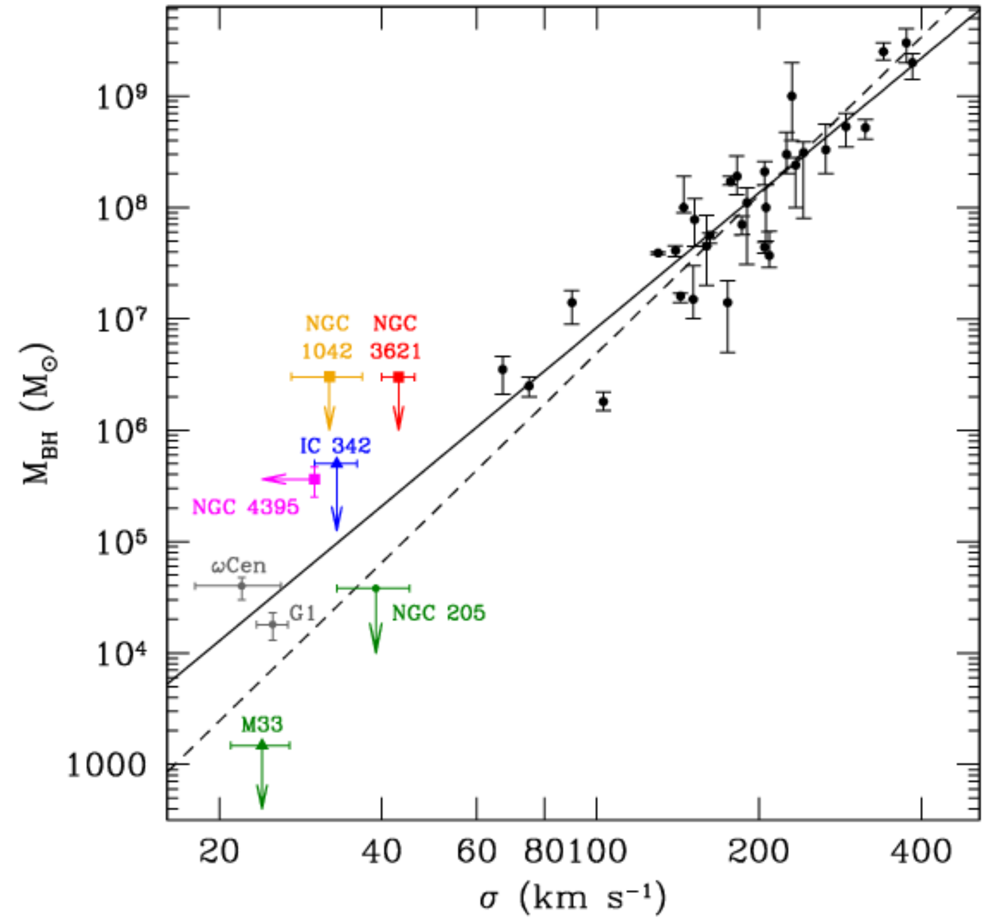

**Dry merger:**
**energy loss**
**only due to**
**GW radiation**
**during inspiral**

[Credit: Kelley]

$$\frac{d^2 n}{dz dM}$$

**phenomenology**

[Sesana 2012]



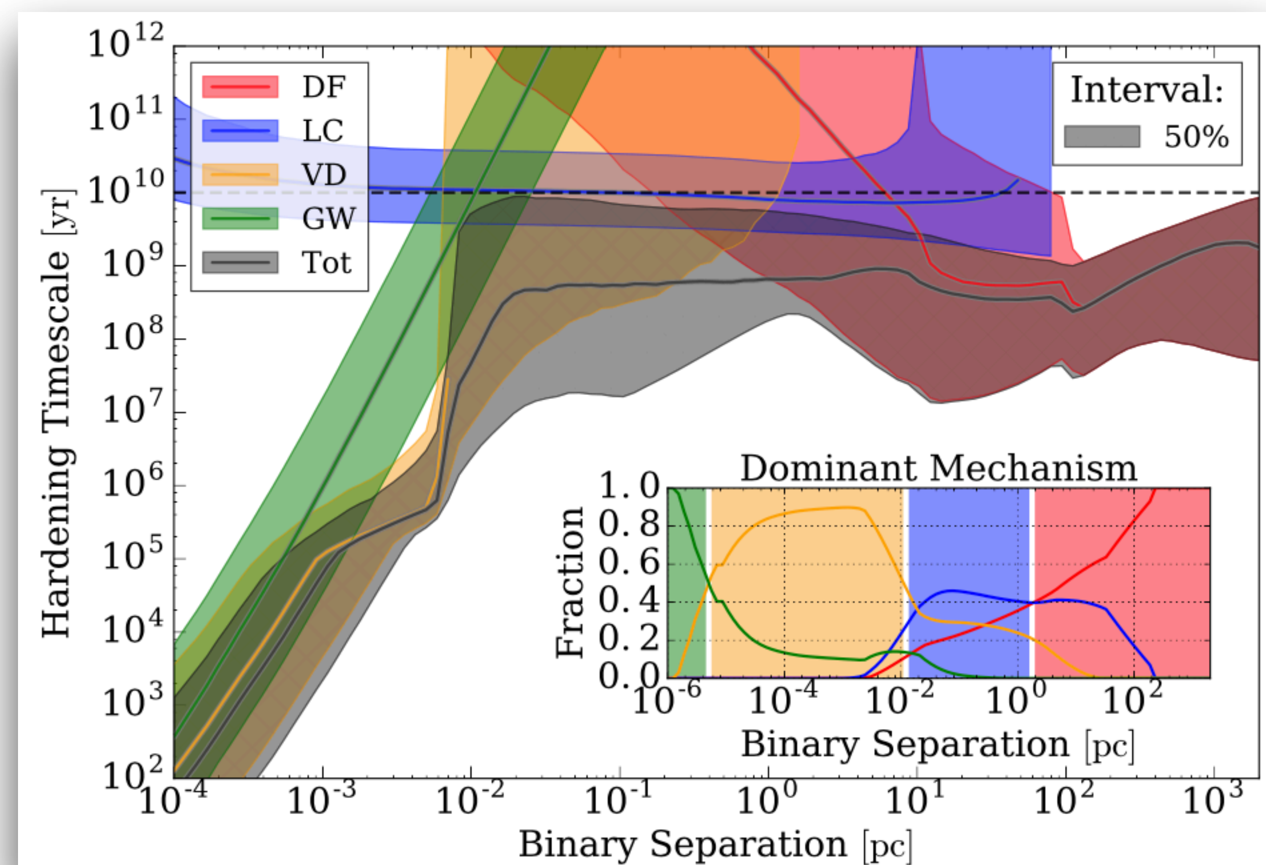

**hydro simulation**

[Kelley et. al. 2016]

**Preliminary Semi-Analytic Modelling**

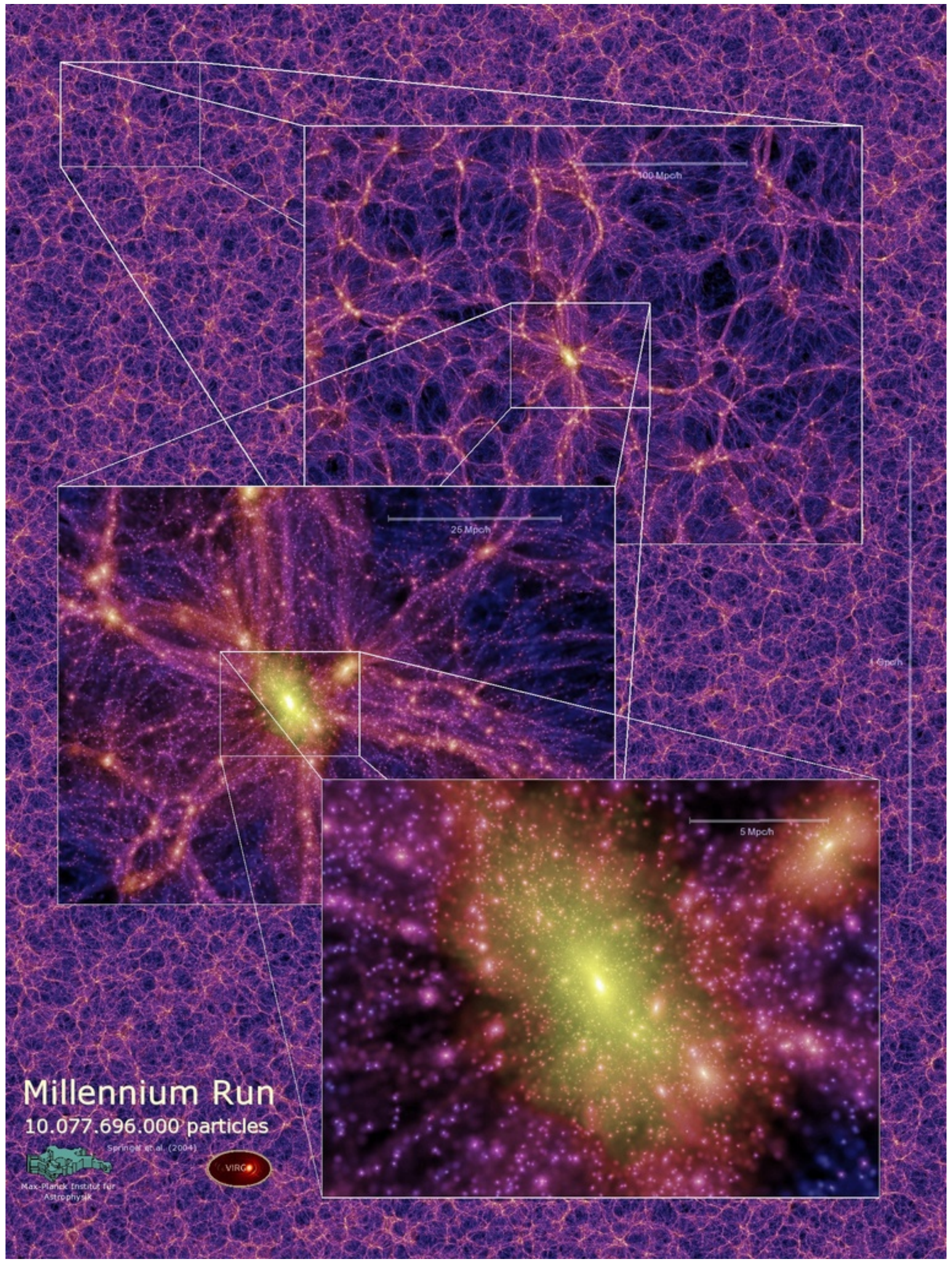
$$\frac{d^2 n_g}{dz dM}$$

[Sesana 2008]




**e.g. galaxy mass function is calculated via EPS formalism & with only hundreds of DM halos**

# Our method: Semi-Analytic Model (SAM) of galaxy formation




**V~500 Mpc$^3$**

8668809 SMBHs,

51538704 galaxies

in total

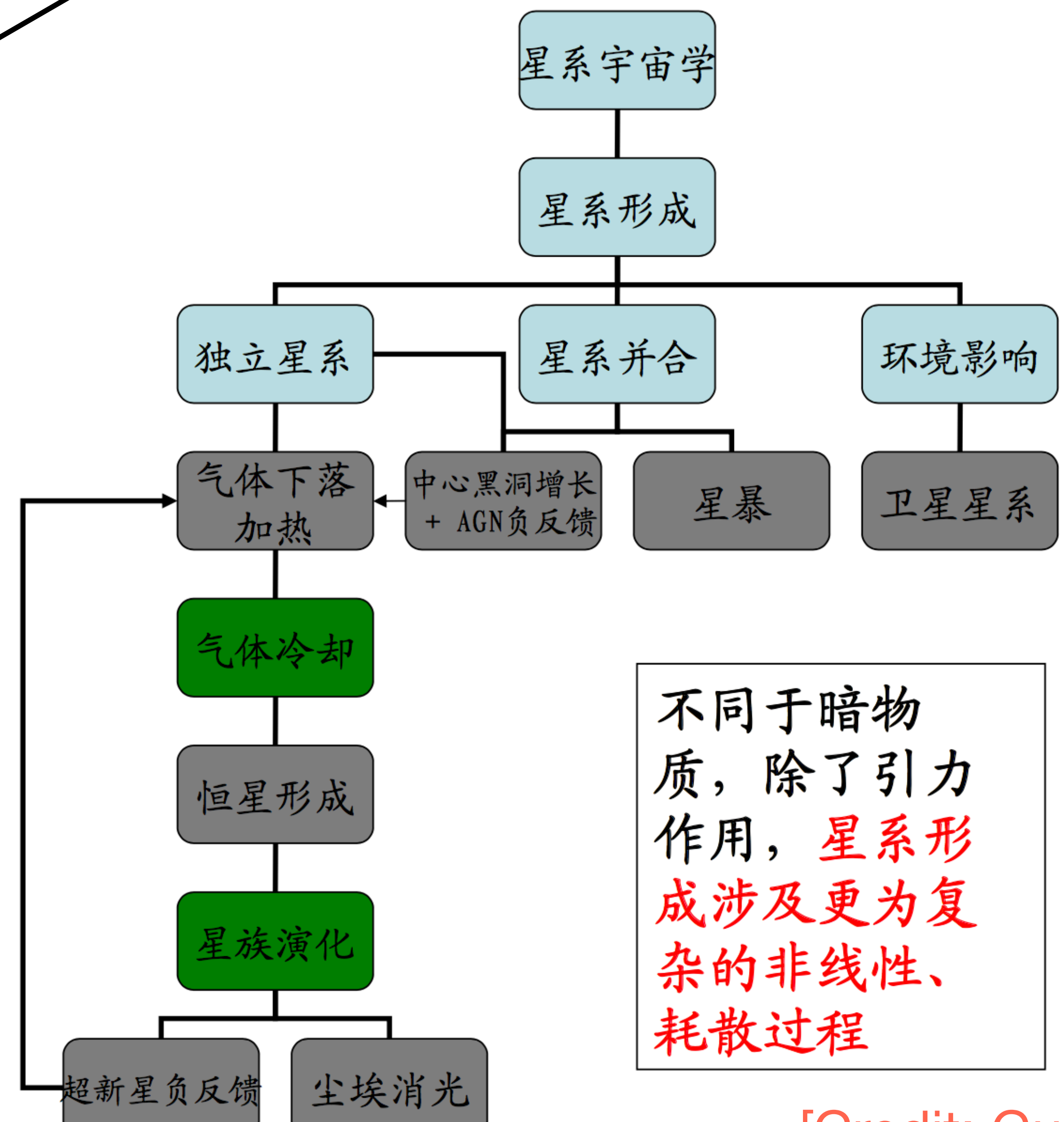
**code: L-galaxies**

**1. Run N-body simulation** $\longrightarrow$ **DM halo merge tree**

**2. Add SN, AGN, hot/cold gas, stellar, galaxies, BHs**

**directly read**
**BH mass function**

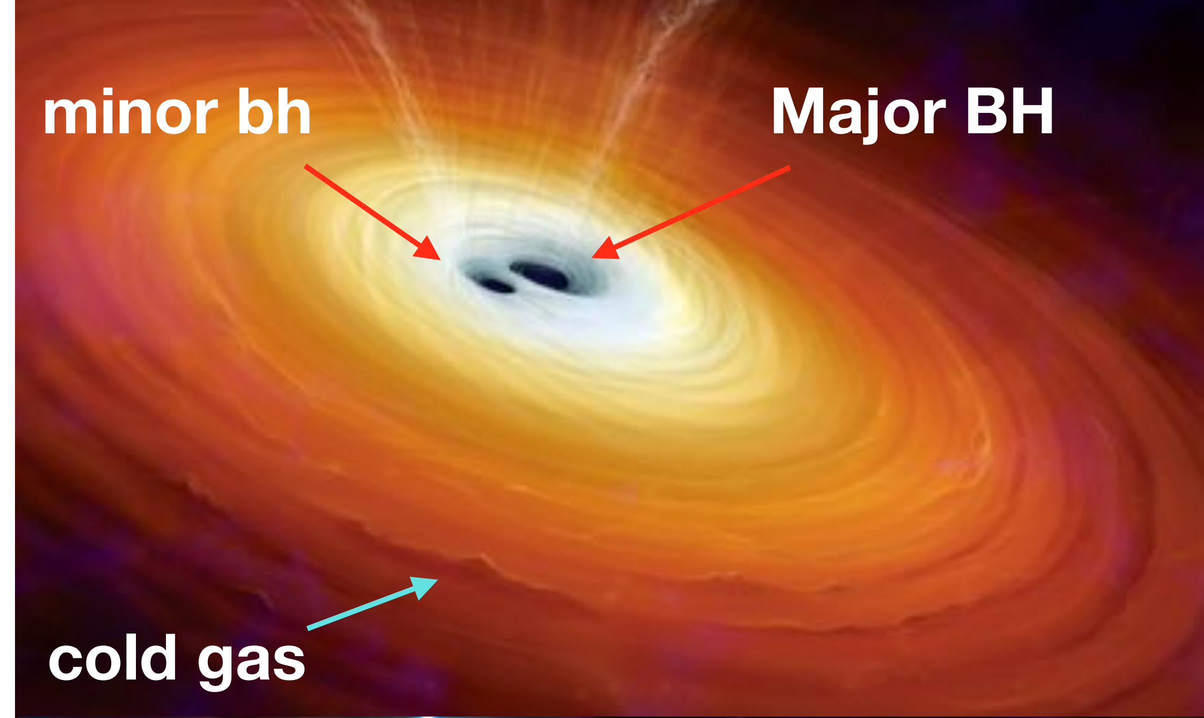
$$\frac{d^2n}{dzdM}$$




不同于暗物质，除了引力作用，星系形成涉及更为复杂的非线性、耗散过程

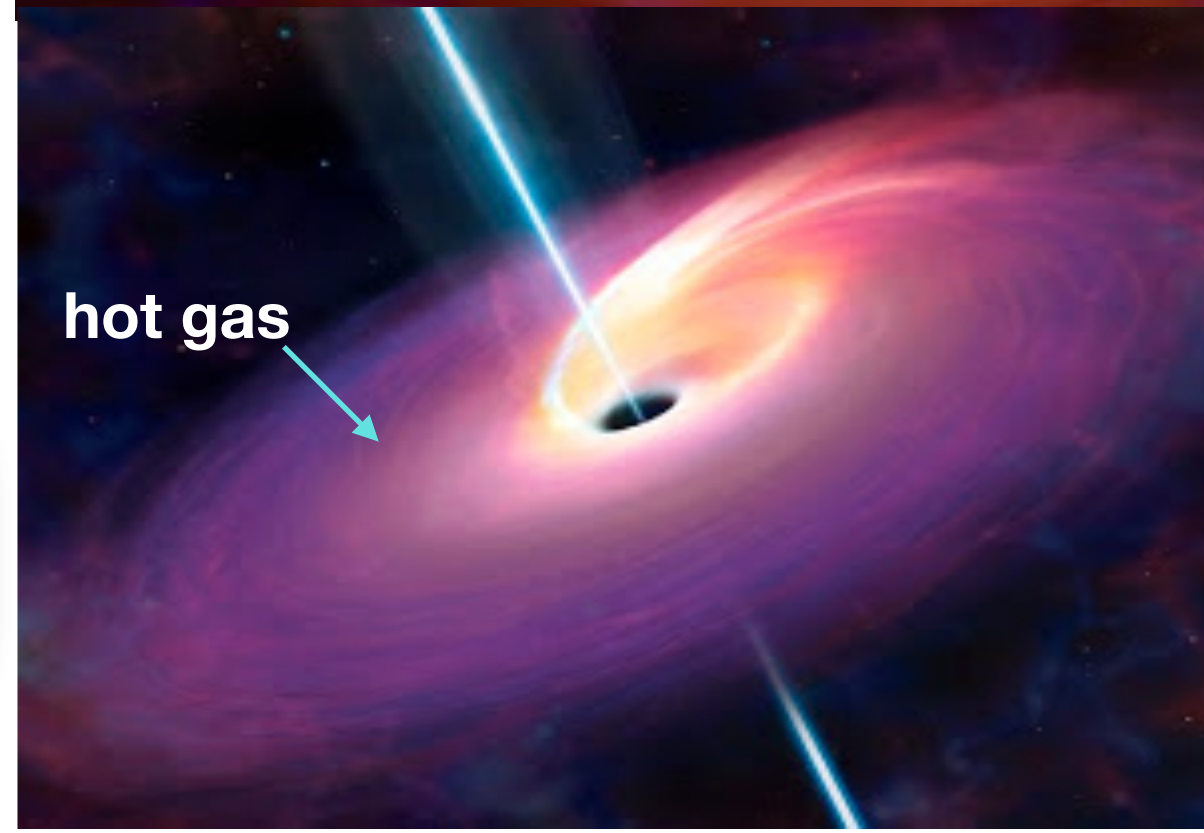
[Credit: Guoqi]

# BH Self-regulated growth & feedback




## Quasar mode: (gas-rich merger)

$$
\begin{aligned}
M_{\mathrm{bh},f} &= M_{\mathrm{bh,maj}} + M_{\mathrm{bh,min}} + \Delta M_{\mathrm{bh},Q} \,, \\
\Delta M_{\mathrm{bh},Q} &= \frac{f_{\mathrm{bh}}(M_{\mathrm{min}}/M_{\mathrm{maj}})M_{\mathrm{cold}}}{1 + 280\ \mathrm{km\ s^{-1}}/V_{vir}} \,,
\end{aligned}
$$



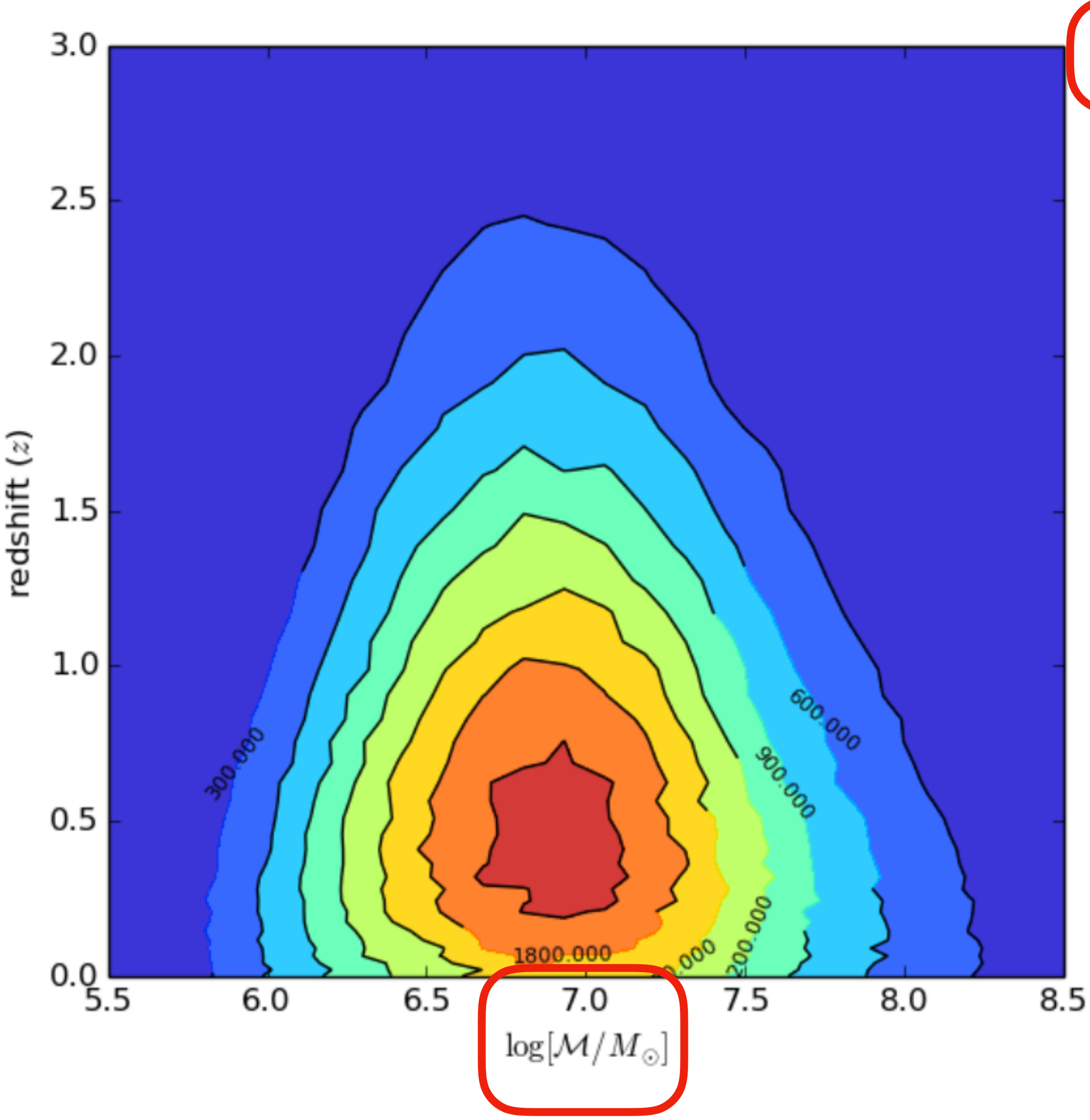

## Radio mode: (hot gas accretion)

$$
\dot{M}_{\mathrm{bh}} = \kappa \left(\frac{f_{\mathrm{hot}}}{0.1}\right) \left(\frac{V_{vir}}{200\ \mathrm{km\ s^{-1}}}\right)^3 \left(\frac{M_{\mathrm{bh}}}{10^8 h^{-1} M_\odot}\right) M_\odot\ \mathrm{yr^{-1}}
$$

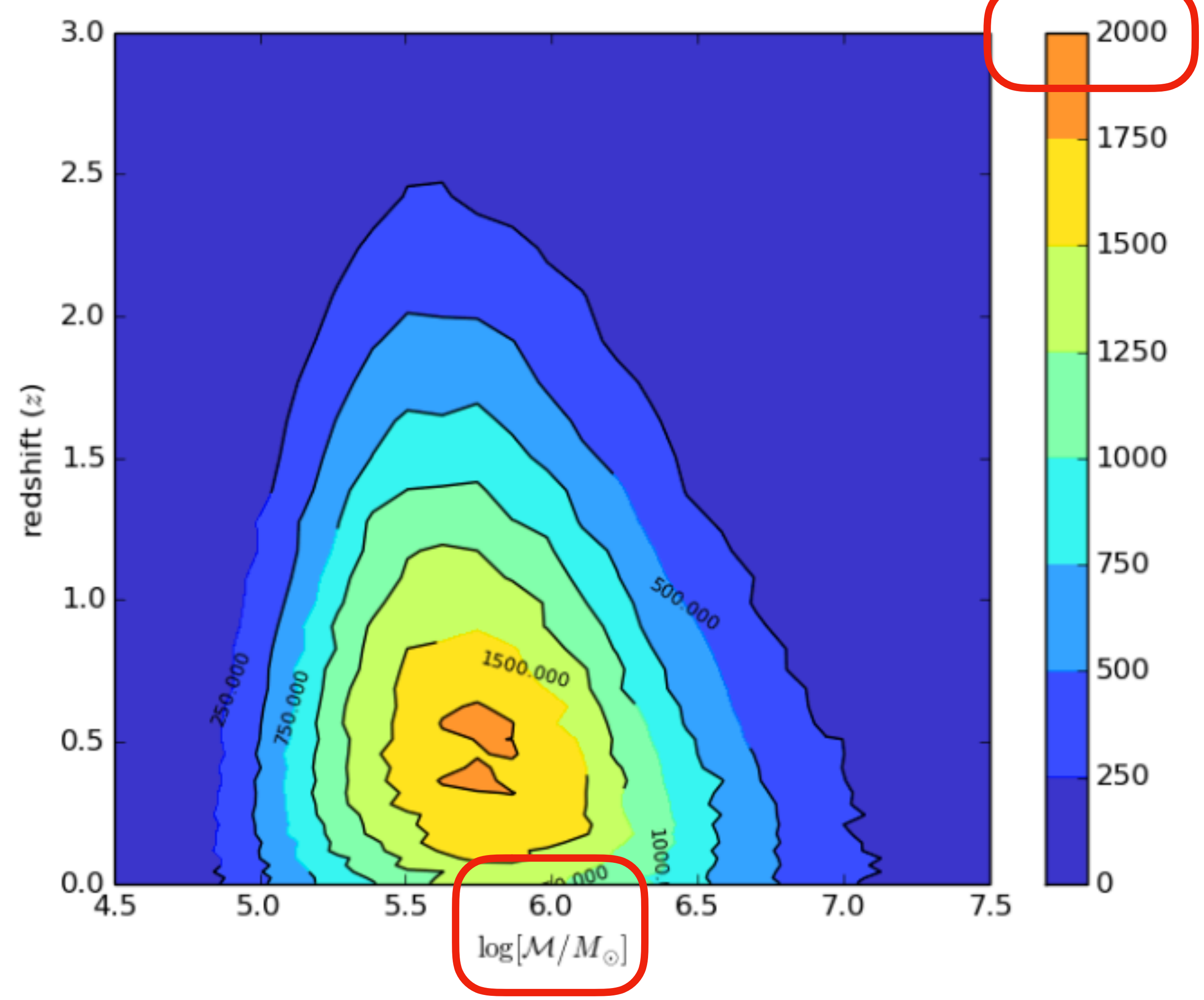
$$
\dot{E}_{\mathrm{radio}} = 0.1 \dot{M}_{\mathrm{bh}} c^2
$$

**10% energy deposit into relativistic jet**

$$\frac{d^2 n}{dz dM}$$

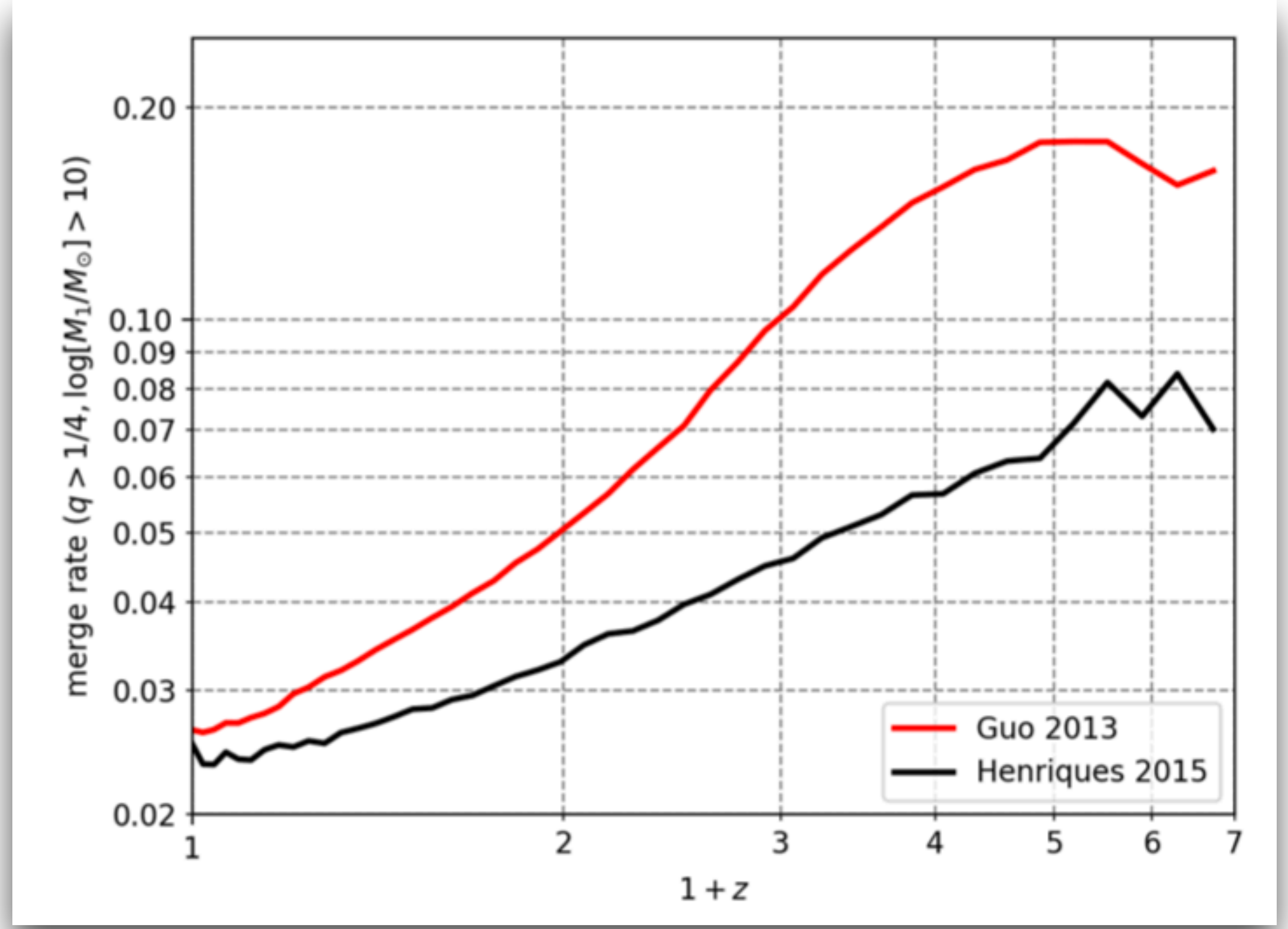



**Guo 2013**
**based WMAP7 cosmology**



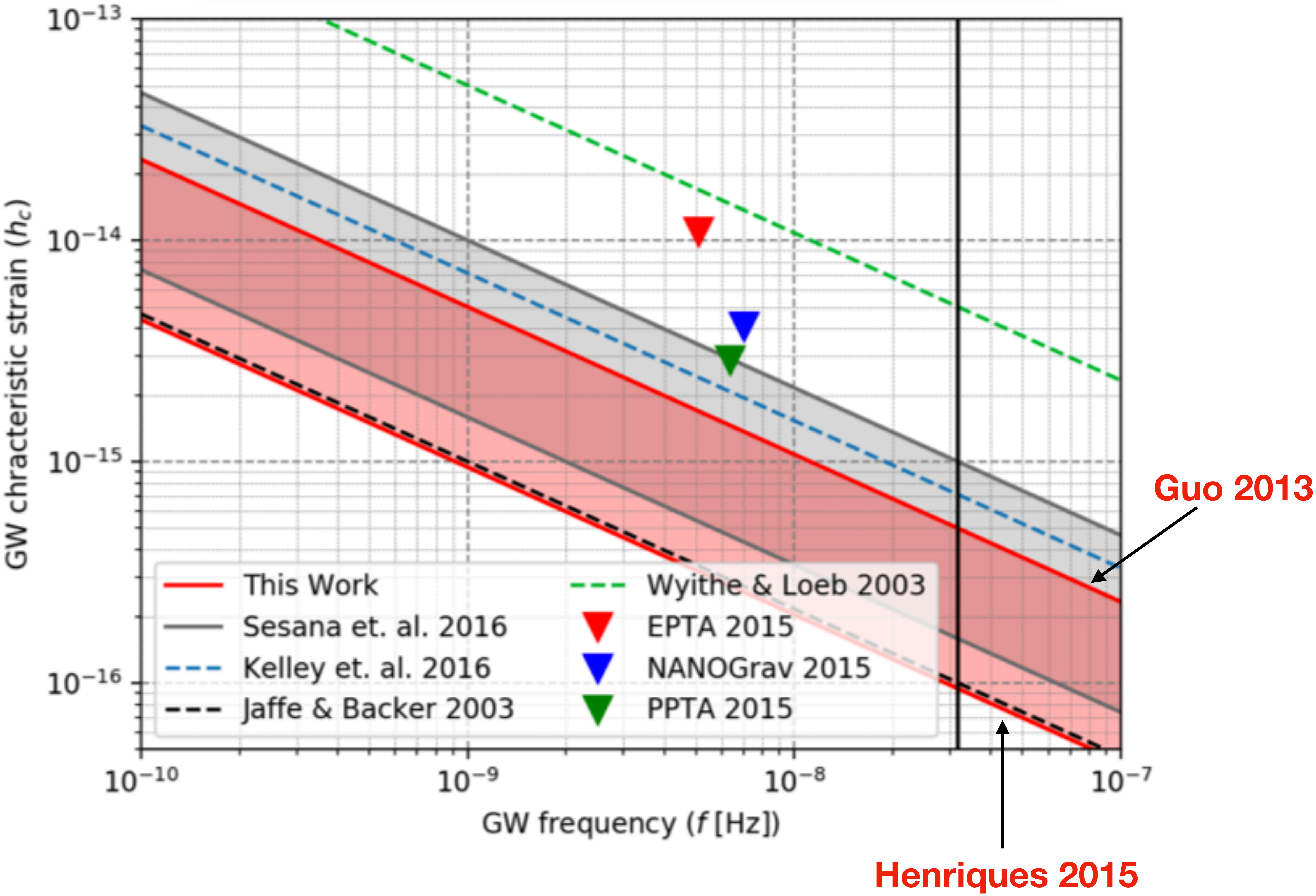

**Henriques 2015**
**based Planck cosmology**

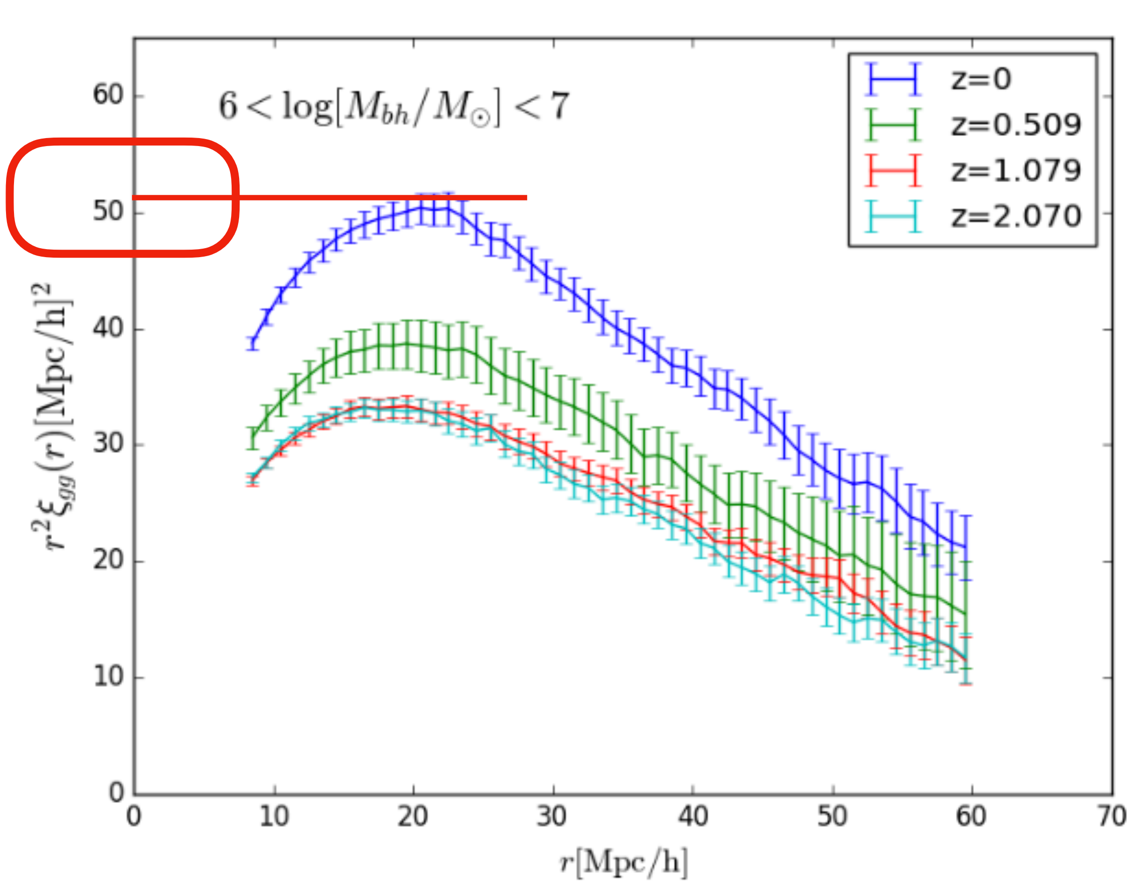
$$\frac{dn_g}{dz}$$

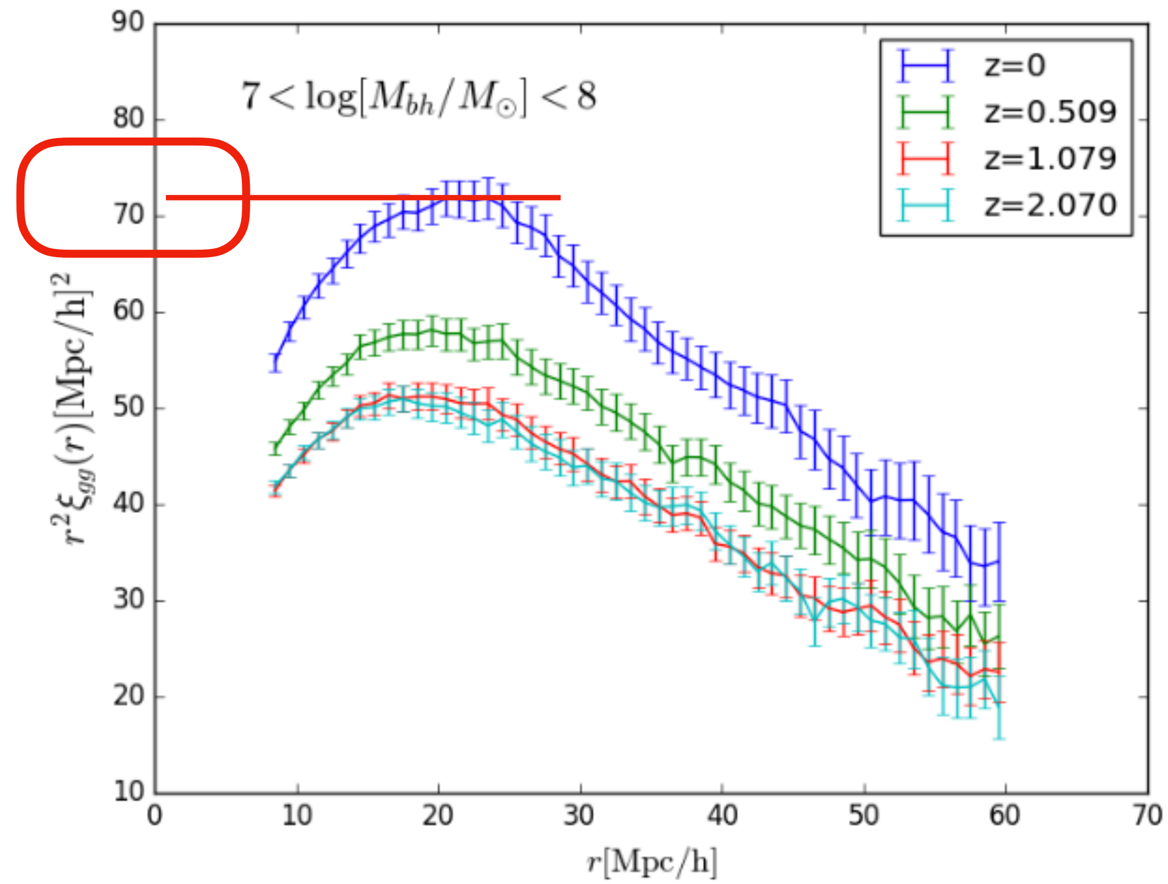


0.20
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
merge rate ($q > 1/4$, $\log[M_1/M_\odot] > 10$)
1
2
3
4
5
6
7
$1 + z$
Guo 2013
Henriques 2015

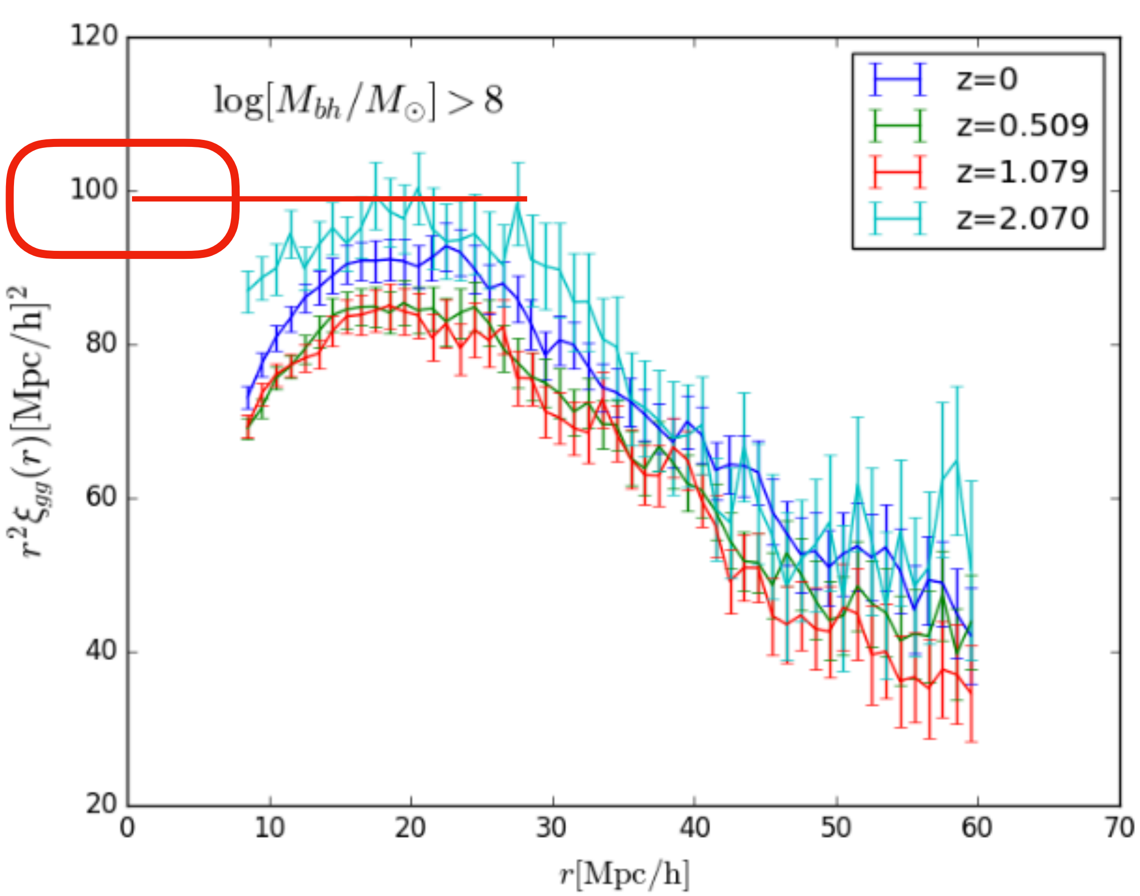
$A_{yr^{-1}} = 5.00 \times 10^{-16}$ and $A_{yr^{-1}} = 9.42 \times 10^{-17}$





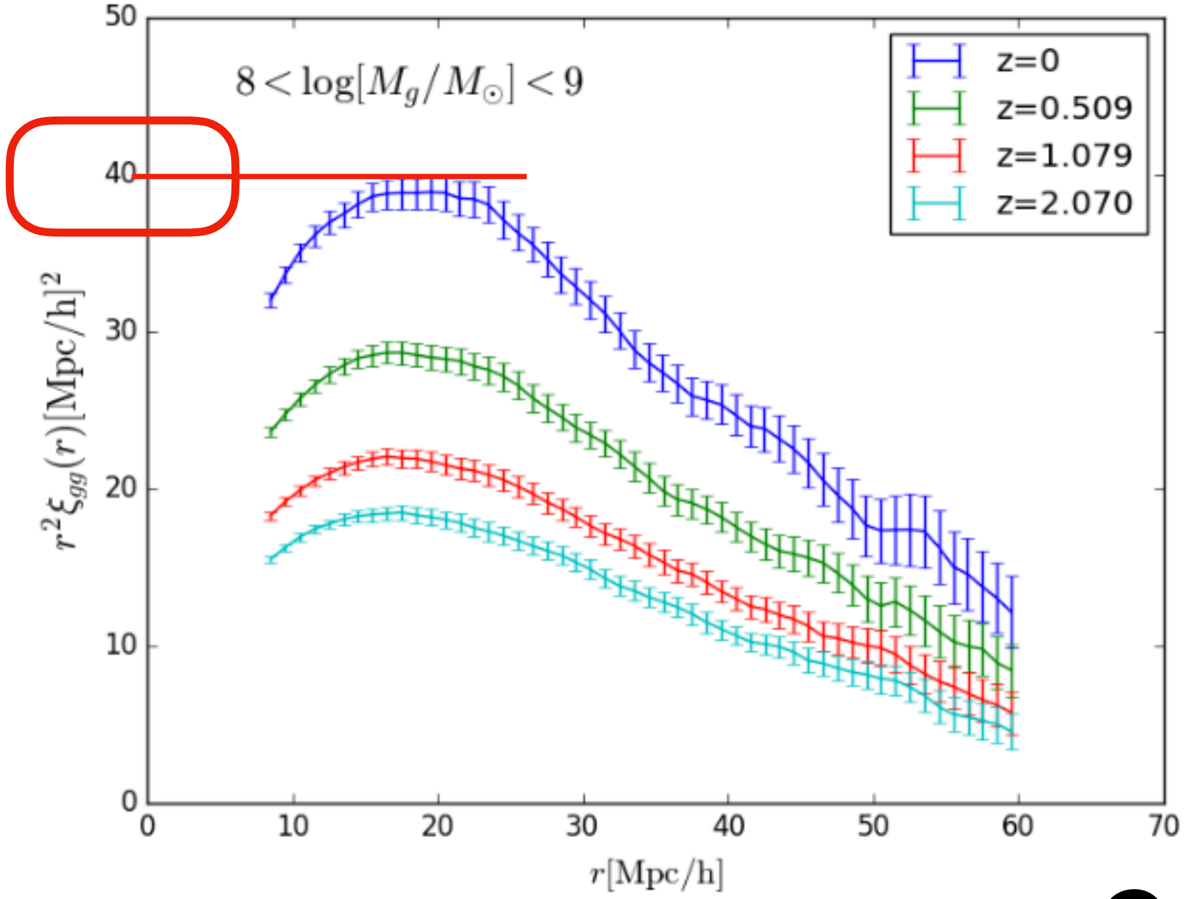



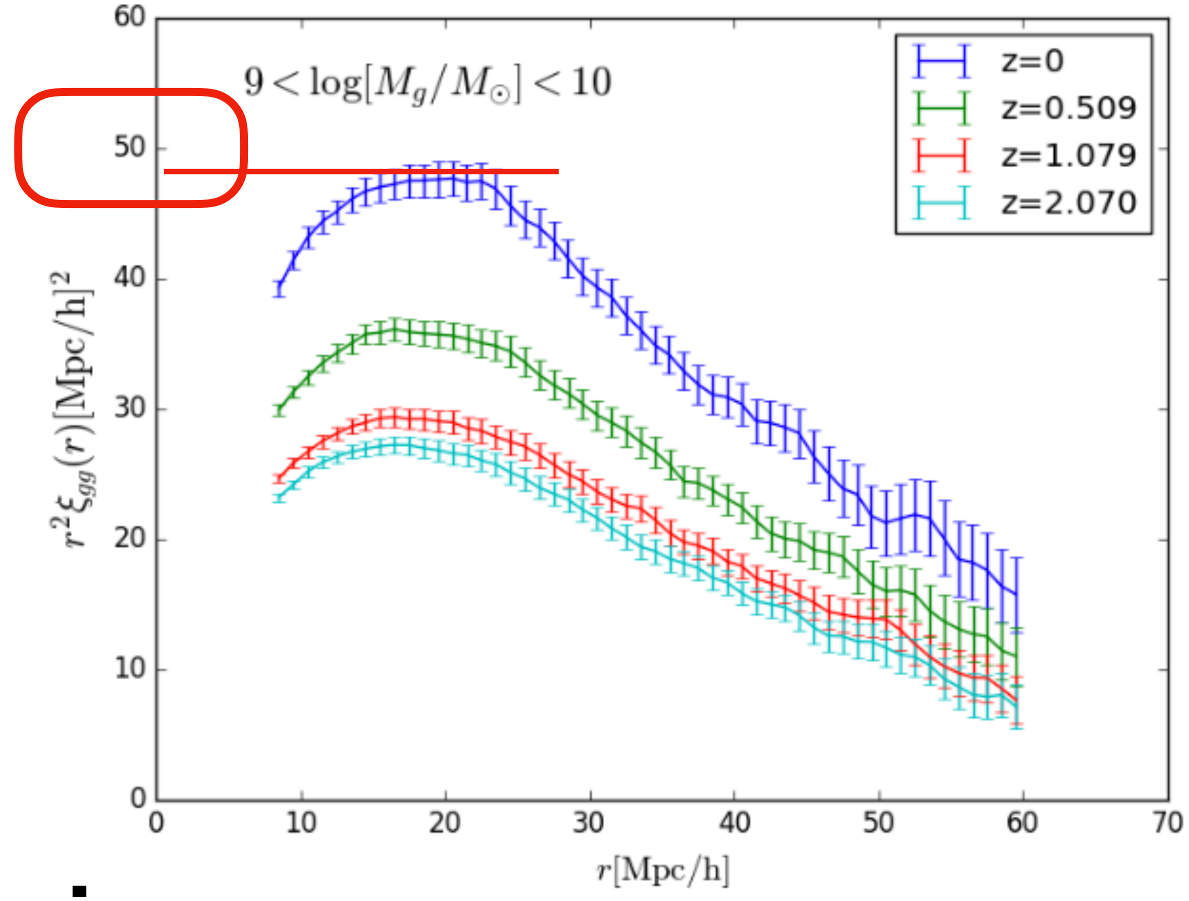

# BHs



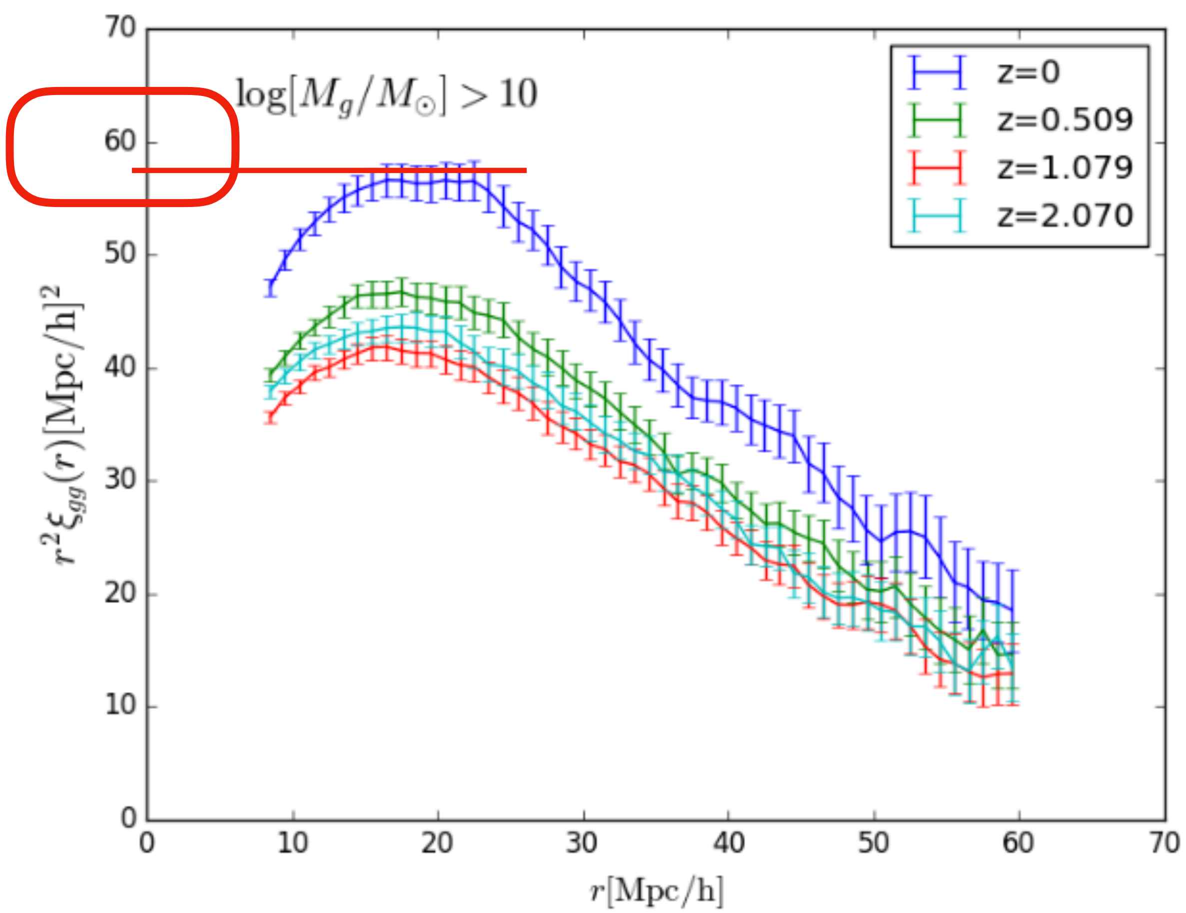

**1. Clustering is enhanced in the lower redshift**

**2. Clustering is enhanced with mass increasing**

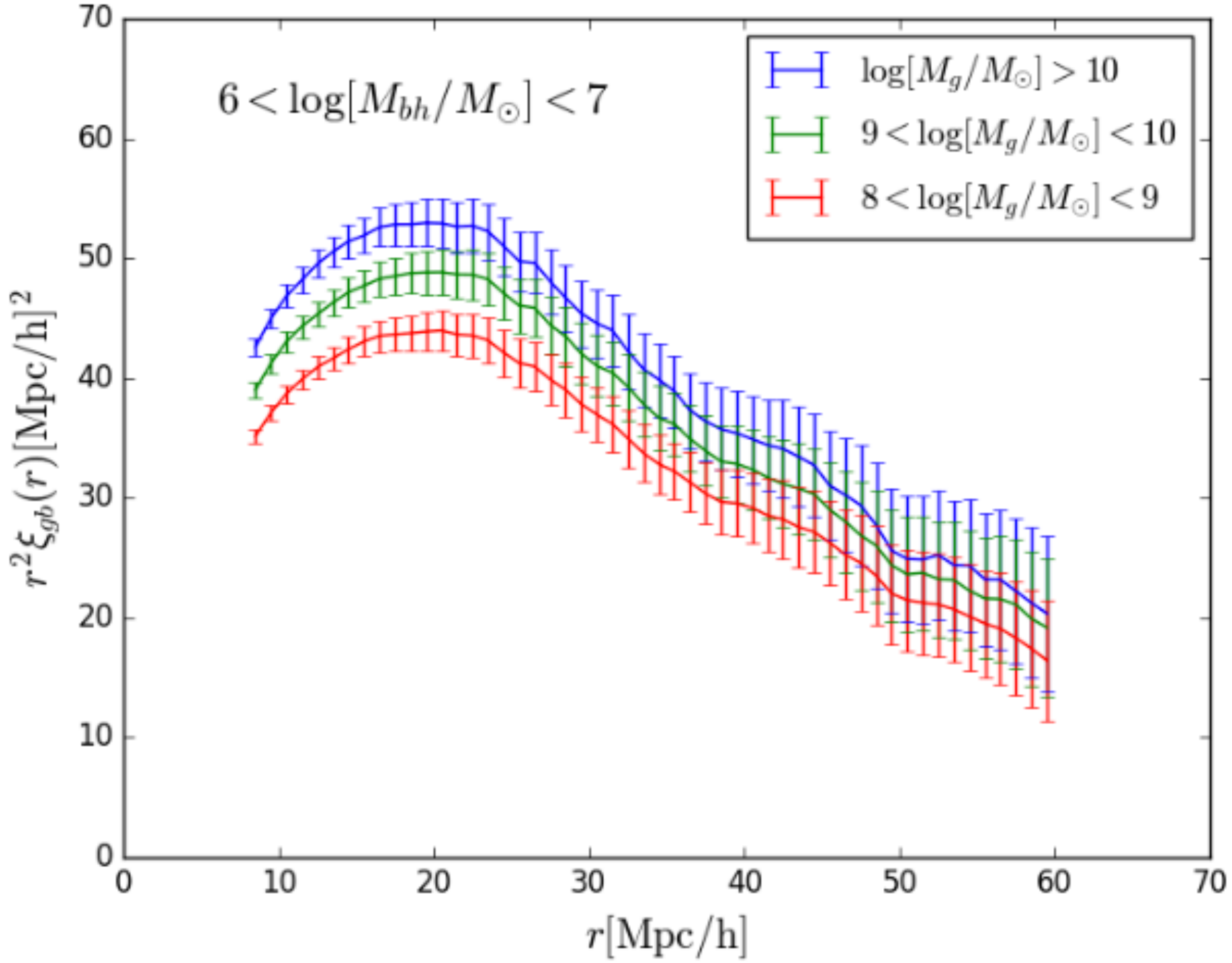


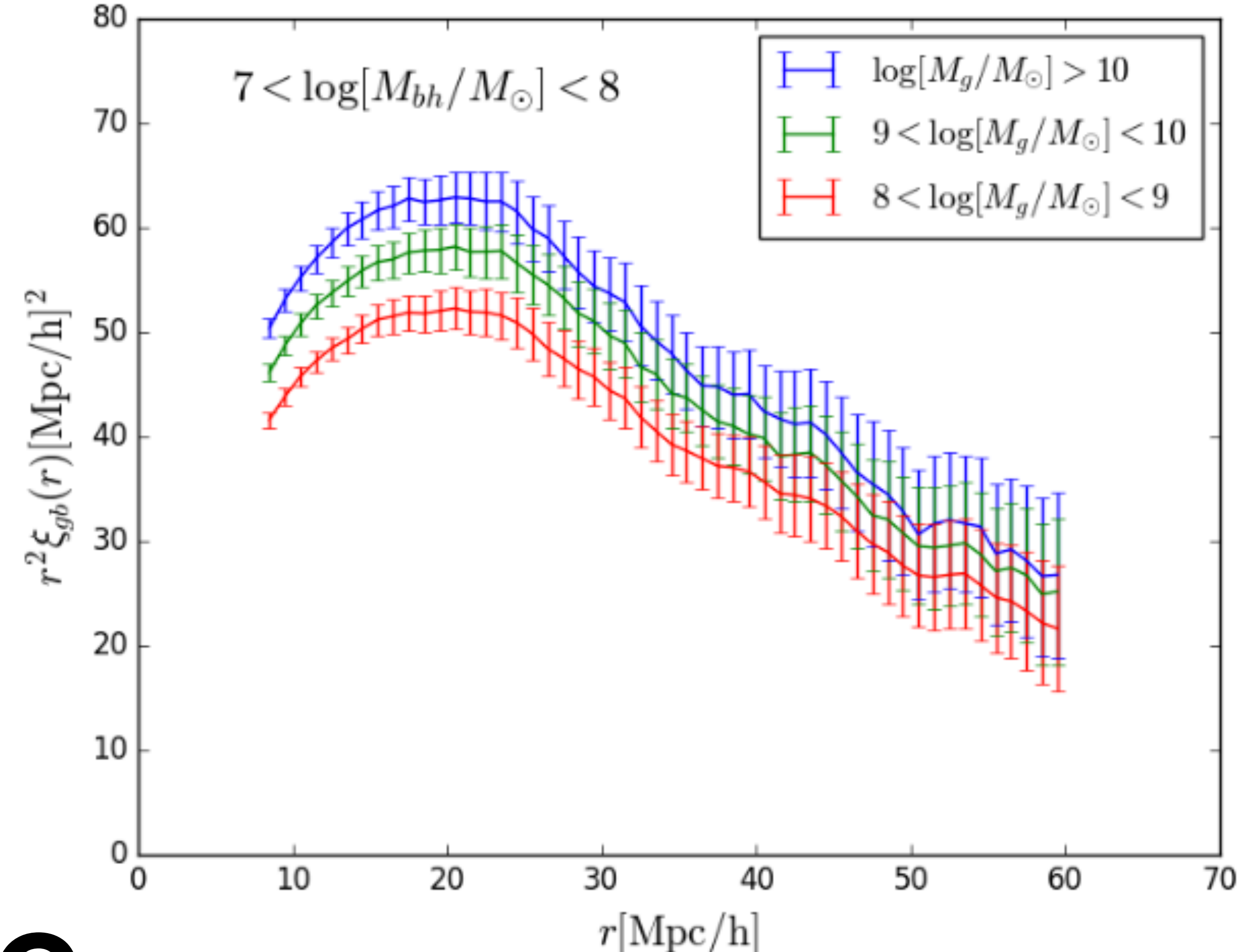




**Galaxies**

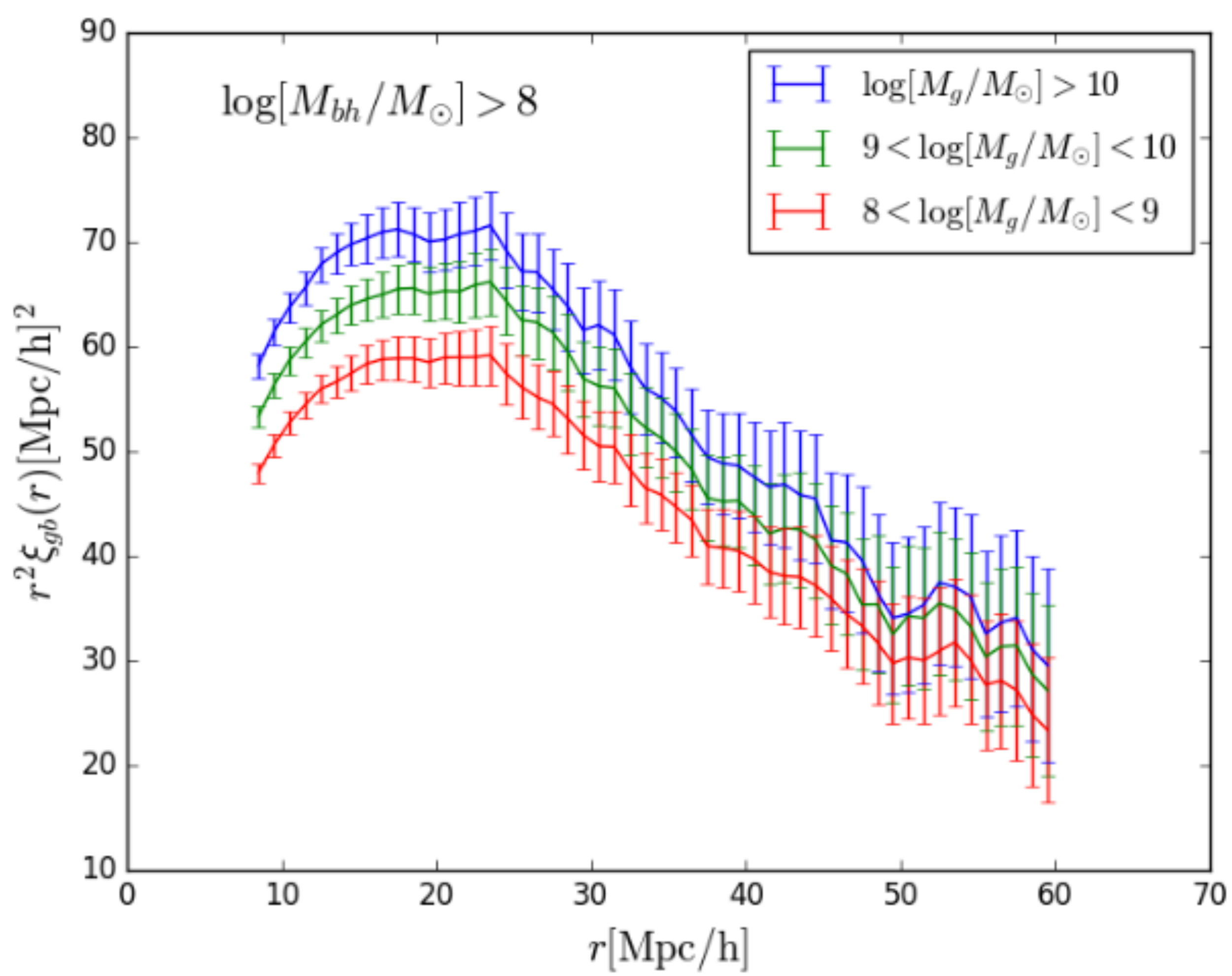



**Same as BHs**


$6 < \log[M_{bh}/M_\odot] < 7$
$\log[M_g/M_\odot] > 10$
$9 < \log[M_g/M_\odot] < 10$
$8 < \log[M_g/M_\odot] < 9$
$r^2\xi_{gb}(r)[\mathrm{Mpc/h}]^2$
$r[\mathrm{Mpc/h}]$


$7 < \log[M_{bh}/M_\odot] < 8$
$\log[M_g/M_\odot] > 10$
$9 < \log[M_g/M_\odot] < 10$
$8 < \log[M_g/M_\odot] < 9$
$r^2\xi_{gb}(r)[\mathrm{Mpc/h}]^2$
$r[\mathrm{Mpc/h}]$

**XC**


$\log[M_{bh}/M_\odot] > 8$
$\log[M_g/M_\odot] > 10$
$9 < \log[M_g/M_\odot] < 10$
$8 < \log[M_g/M_\odot] < 9$
$r^2\xi_{gb}(r)[\mathrm{Mpc/h}]^2$
$r[\mathrm{Mpc/h}]$

**$M_{bh}$ ↗ $M_g$ ↗ XC ↗**

# Summary

1. We compare the different GW prediction from different SAM model, namely Guo 2013 & Henriques 2015.

$$A_{yr^{-1}} = 5.00 \times 10^{-16} \text{ and } A_{yr^{-1}} = 9.42 \times 10^{-17}$$

2. Clusterings of SMBHs share great similarity as galaxies:

2.1 increase with mass

2.2 enhanced at low redshift

# Thanks!