Co-evolution of super massive BHs with galaxies

—stochastic GWB & galaxy clustering

[arXiv:1802.03925]
arguing w. MNRAS

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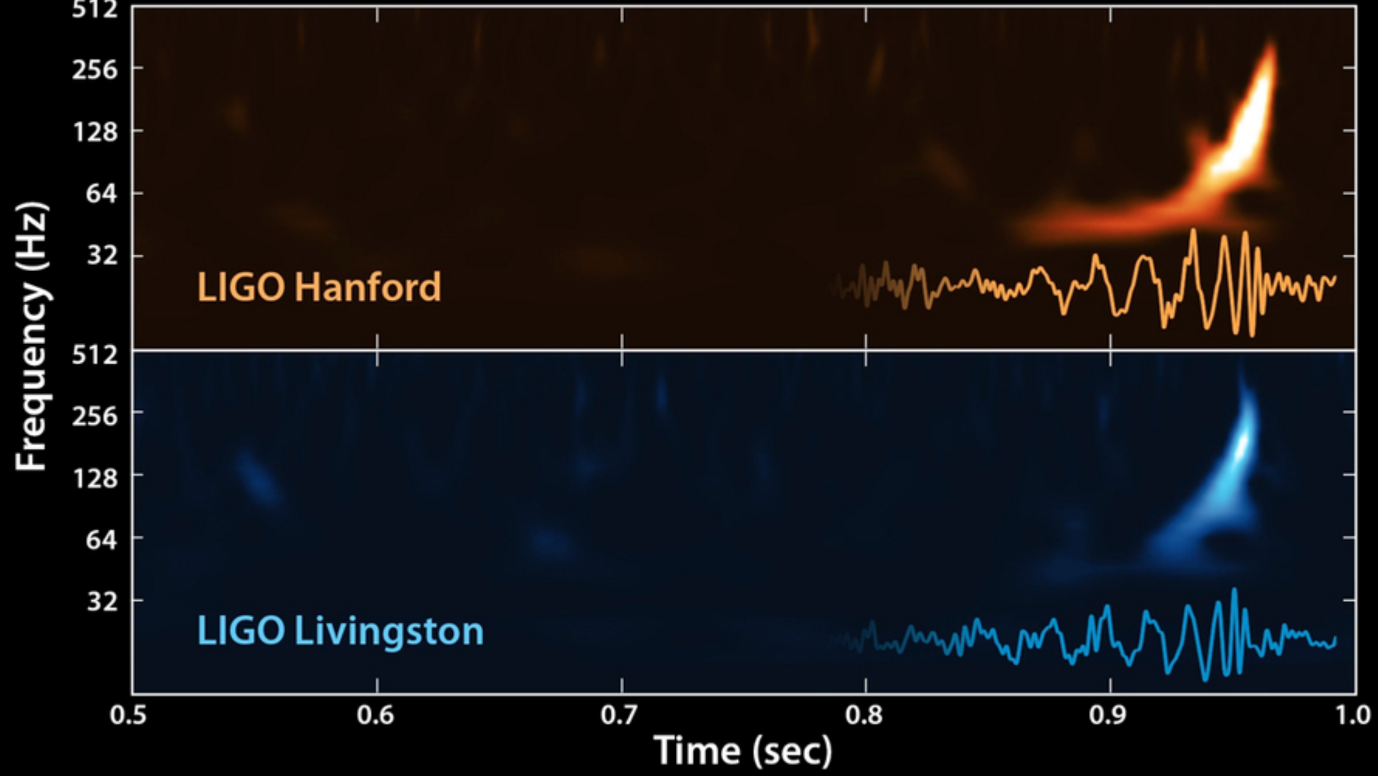
2018/05 Yangzhou

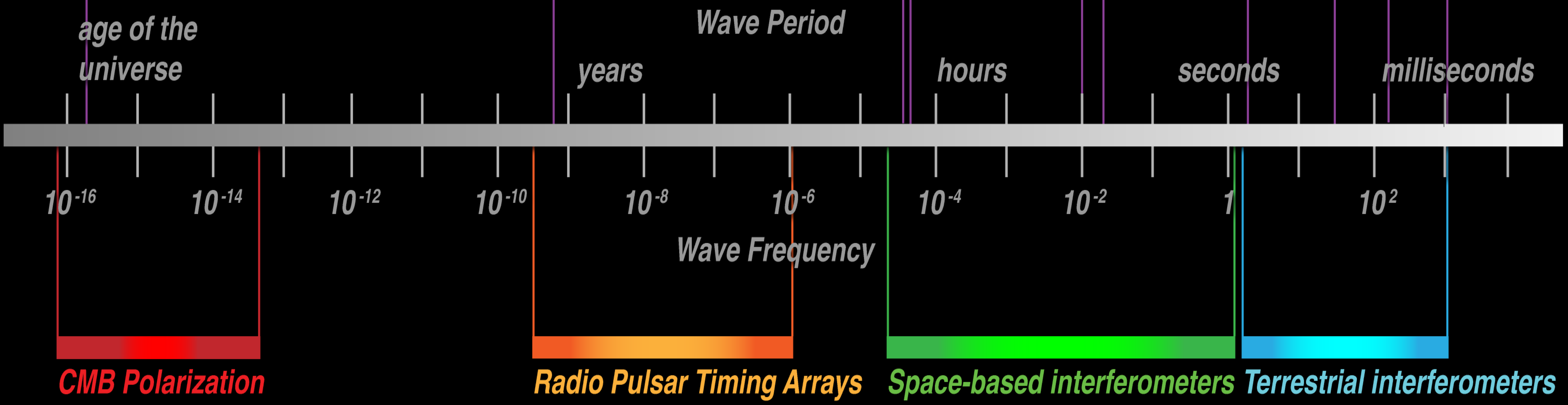
The Gravitational Wav

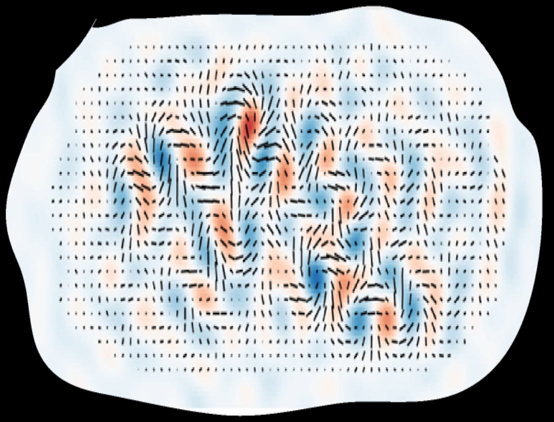
Detectors

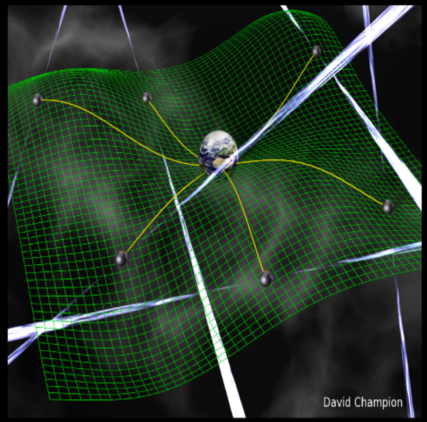
Big Bang

Supermassi

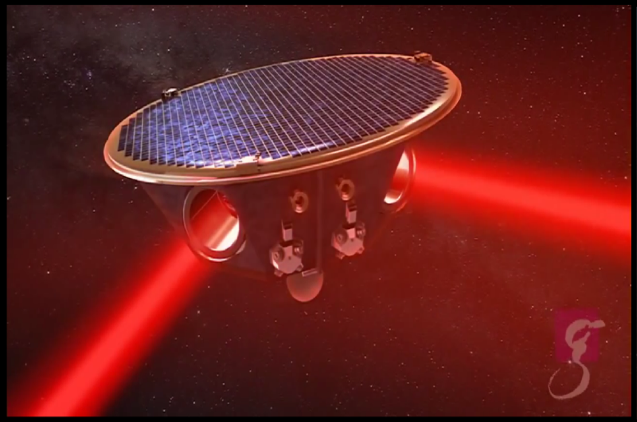




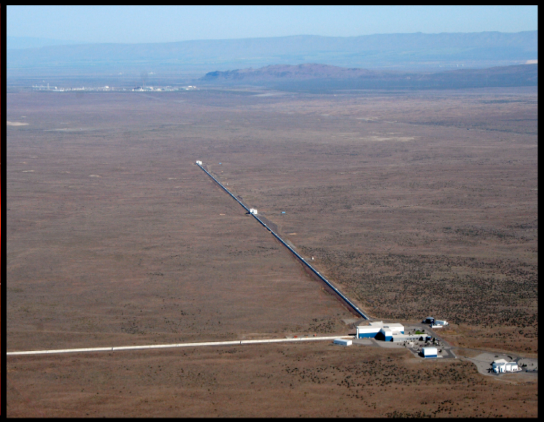




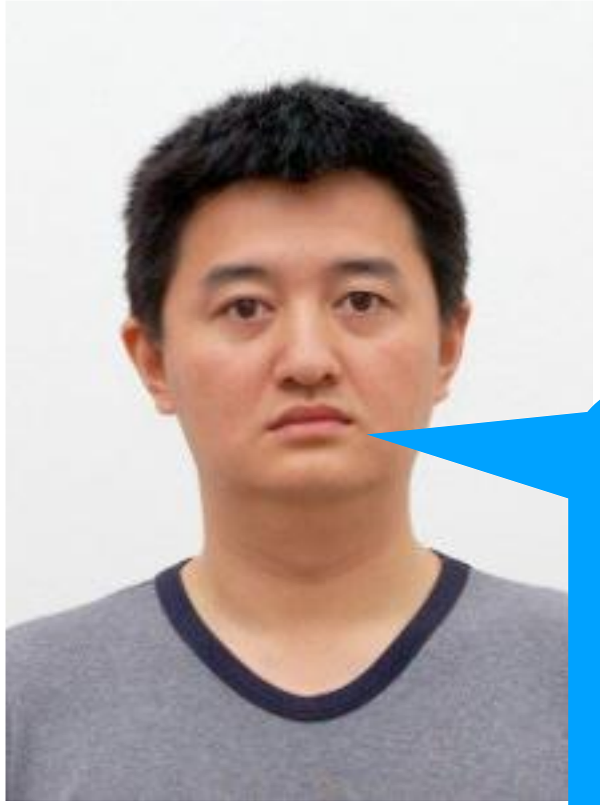
~ kpc (10^{16} km)



5*10^6 km



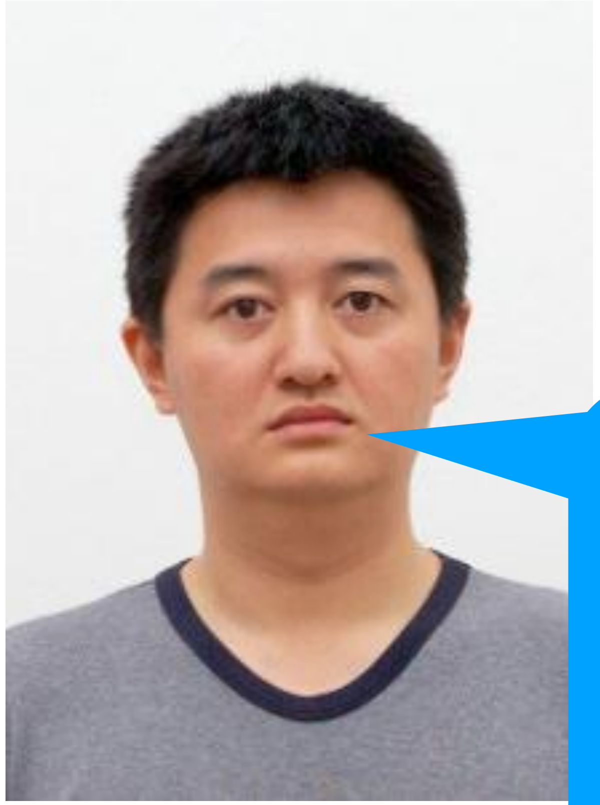
4km



李柯伽@北大

如果2005年，你问“我们什么时候能探测到随机引力波背景信号？”

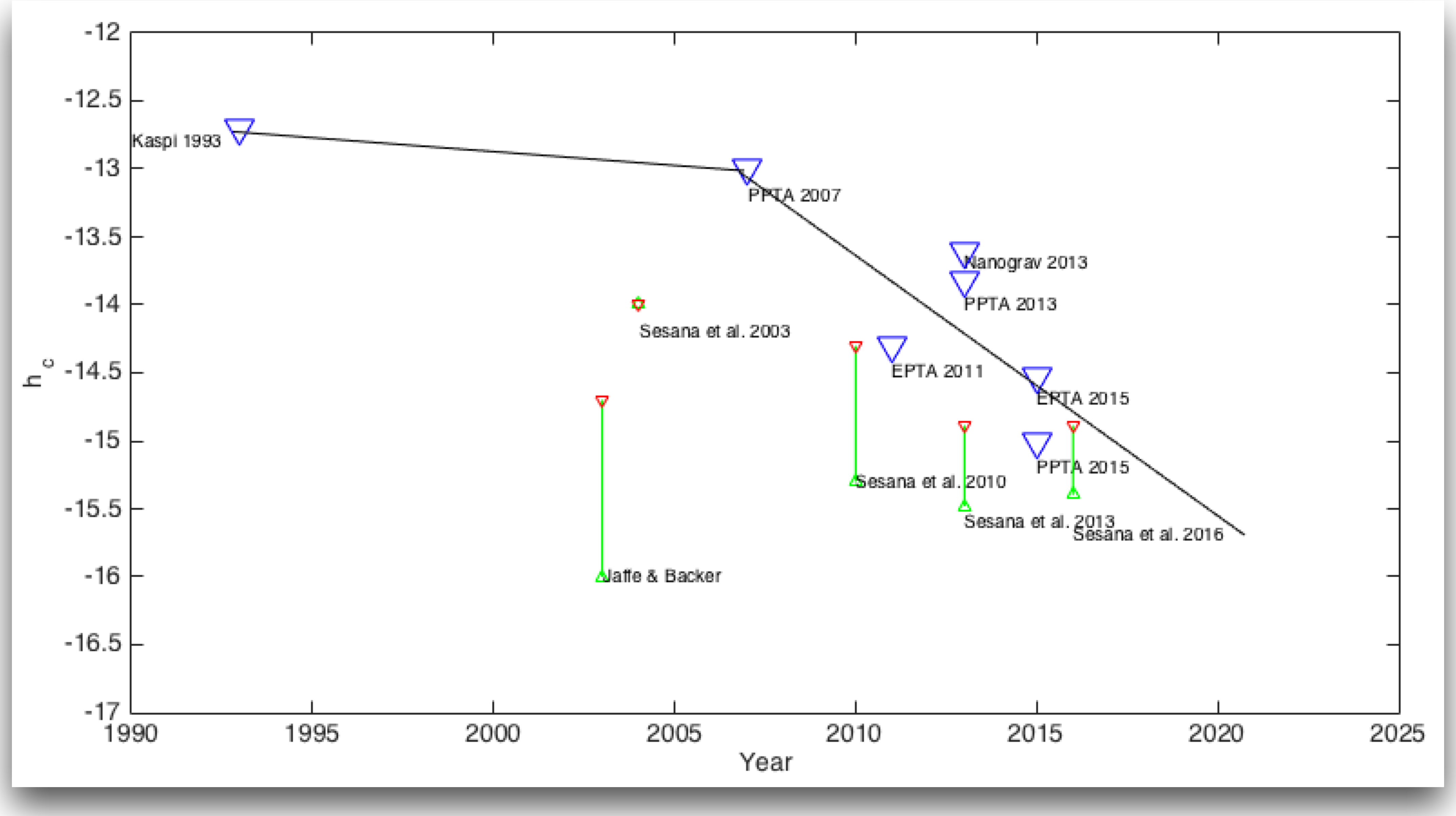
答案：五年



李柯伽@北大

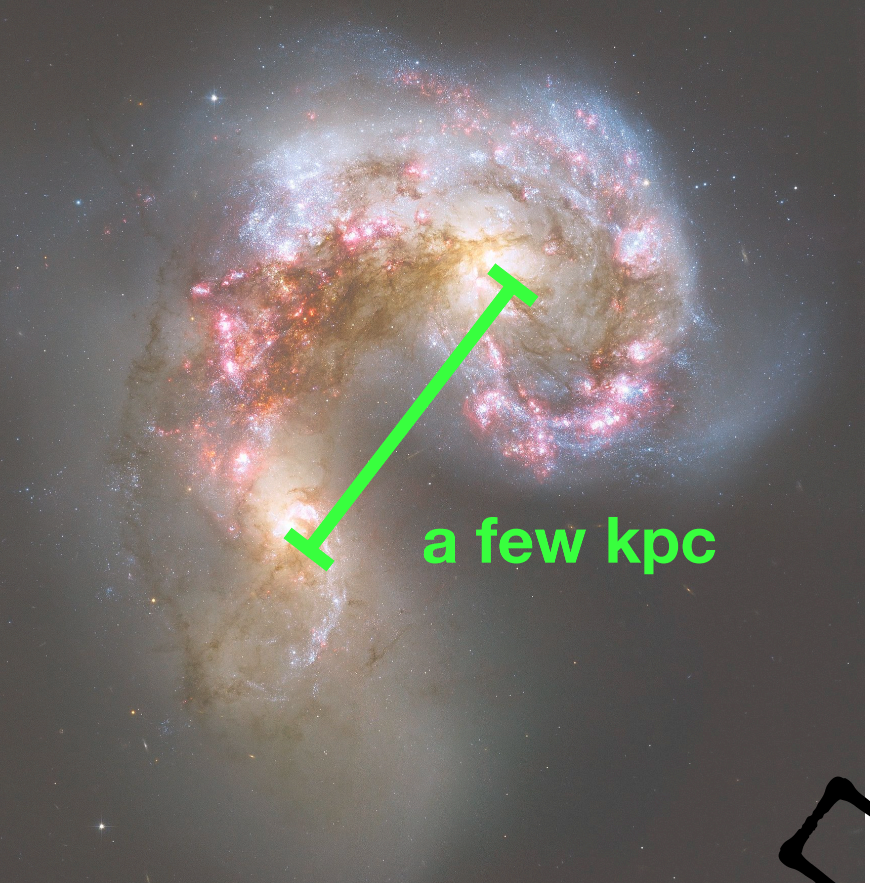
如果2010年，你问“我们什么时候能探测到随机引力波背景信号？”

答案：**依然**是五年

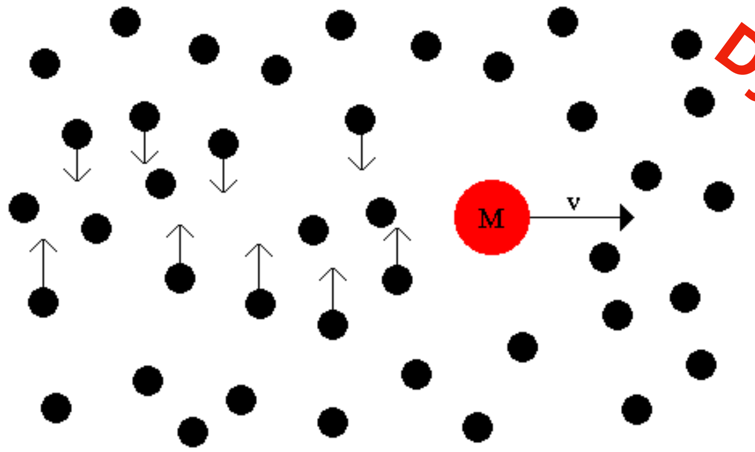


预测未来总是容易的， 但是预测过去总是很困难！

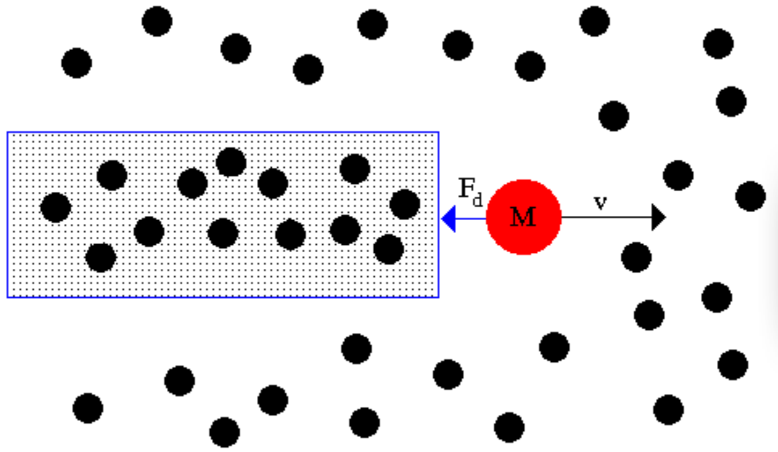
Q： 如何靠谱地计算随机引力波背景信号的大小?



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



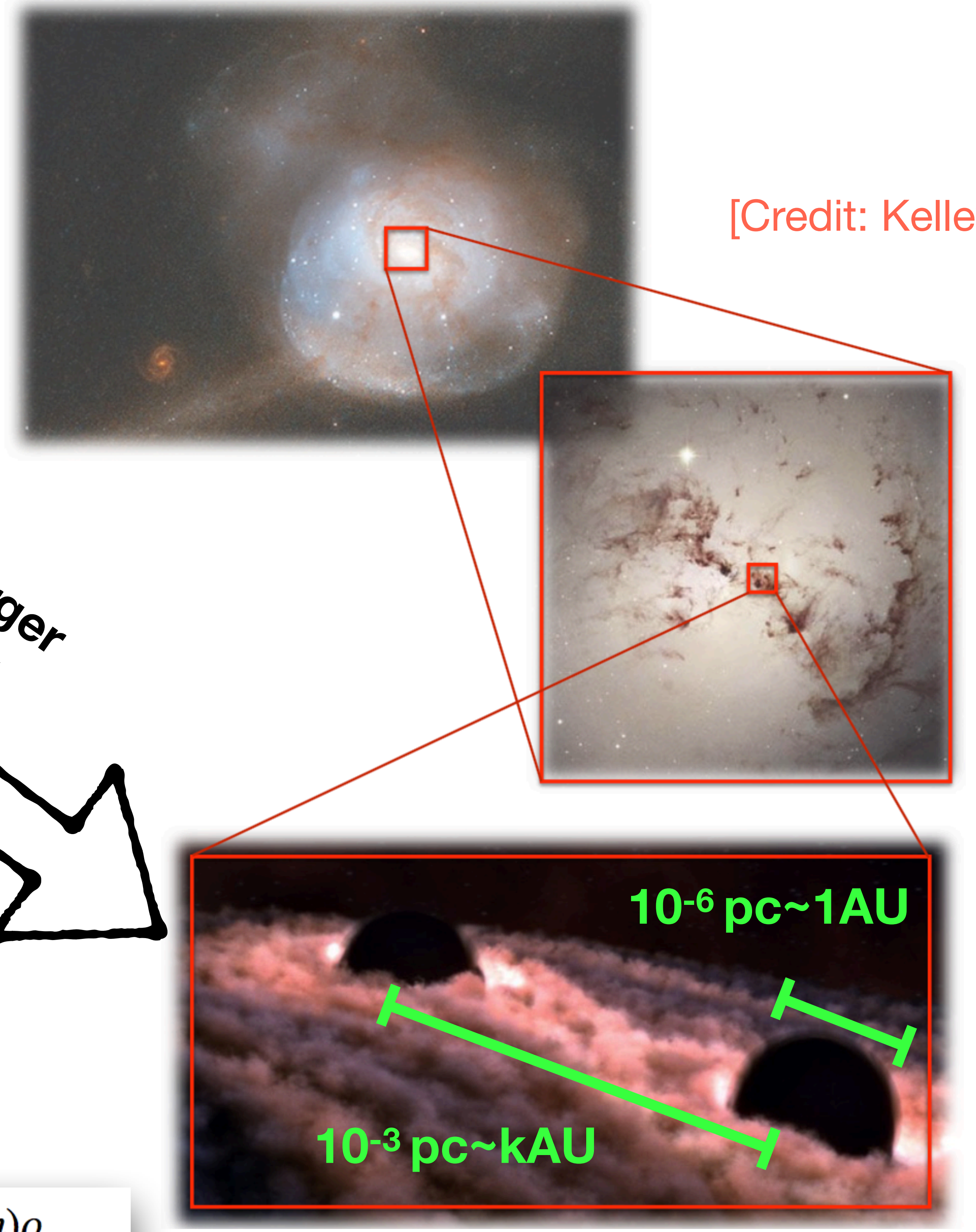
this results in an enhanced region of density behind the mass, with a drag force, F_d known as dynamical friction



galaxy merger time~1 Gyr

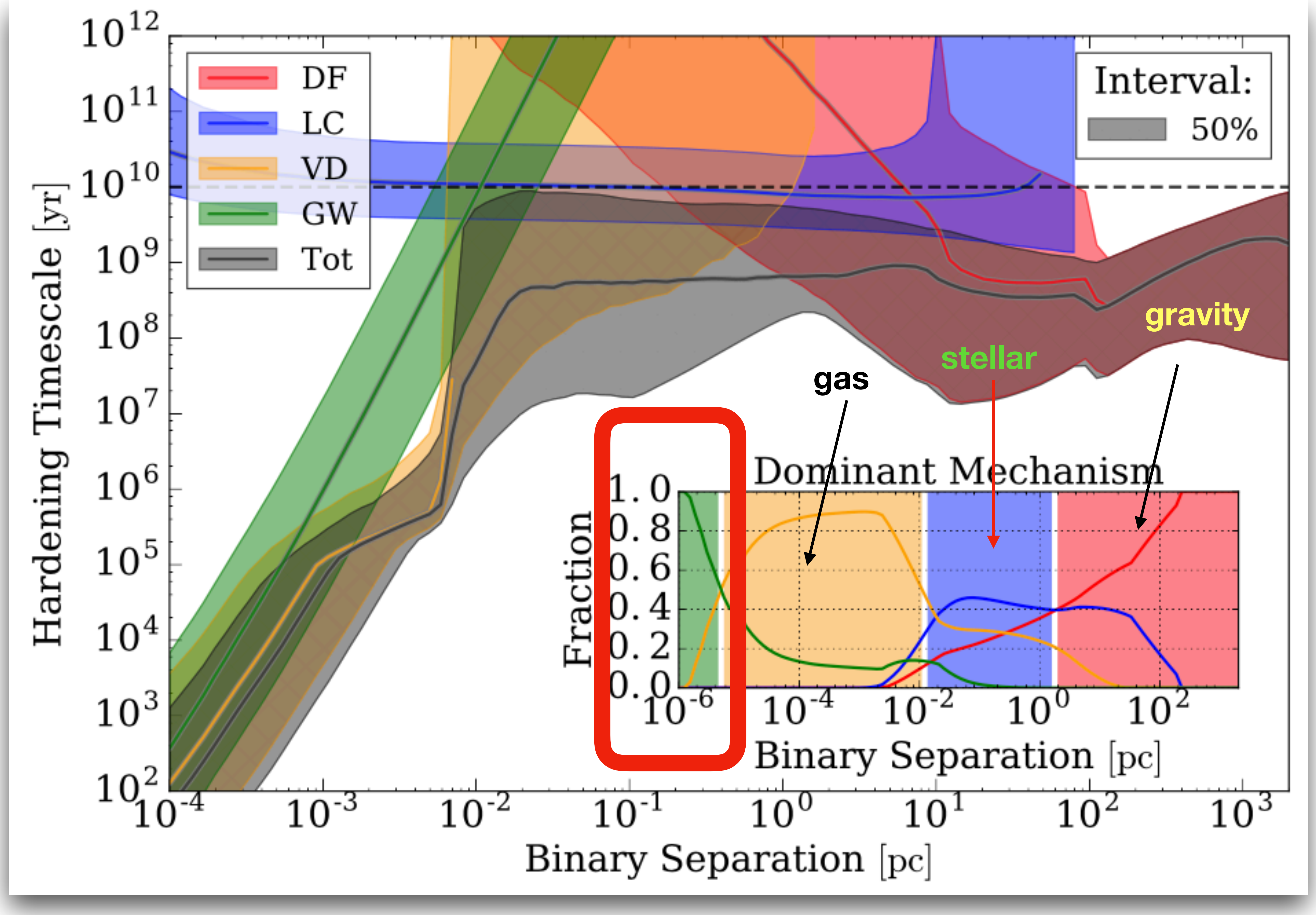
Dynamical Friction

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



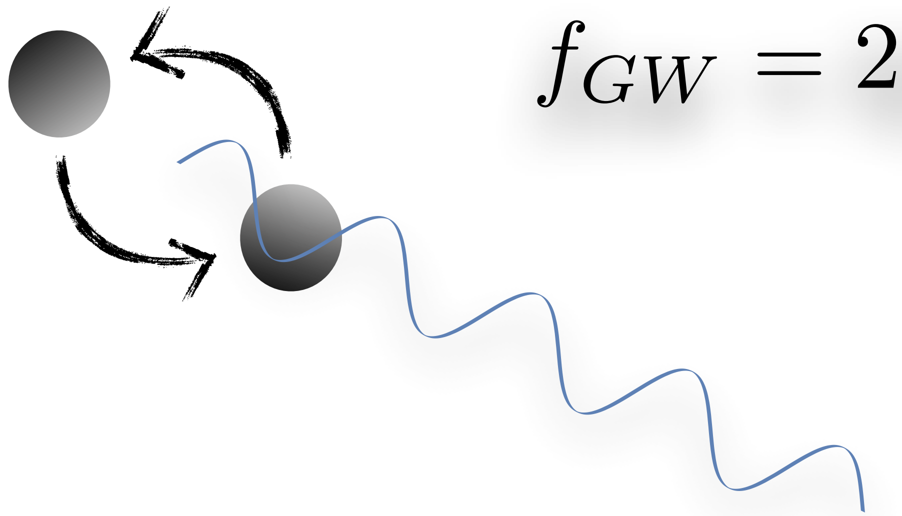
[Credit: Kelley]

merger time with GW ~ a few Myr



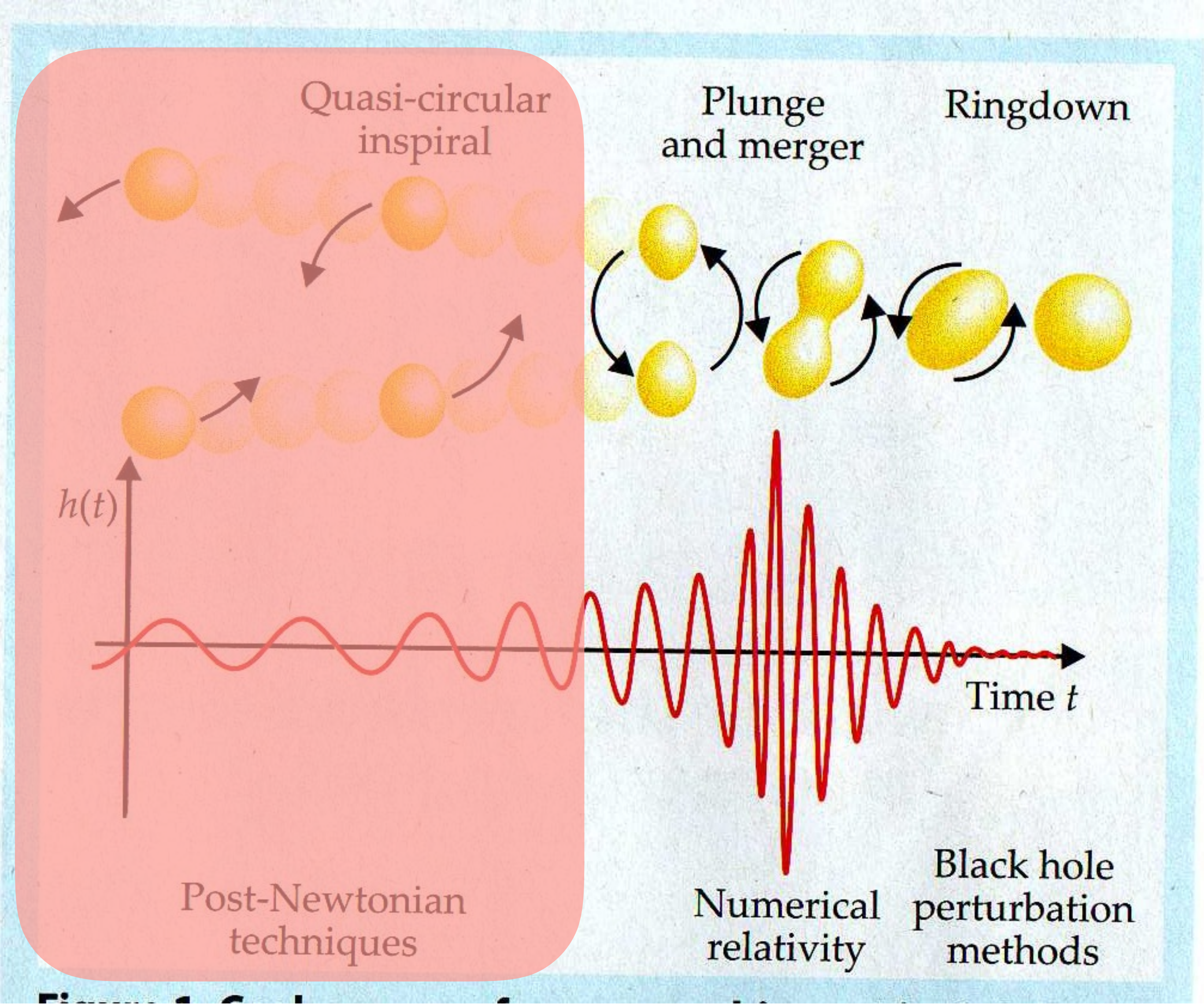
[Kelley, Blecha, Hernquist, 2017]

Single binary ~ circular orbit, Quadrupole formula is enough!



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

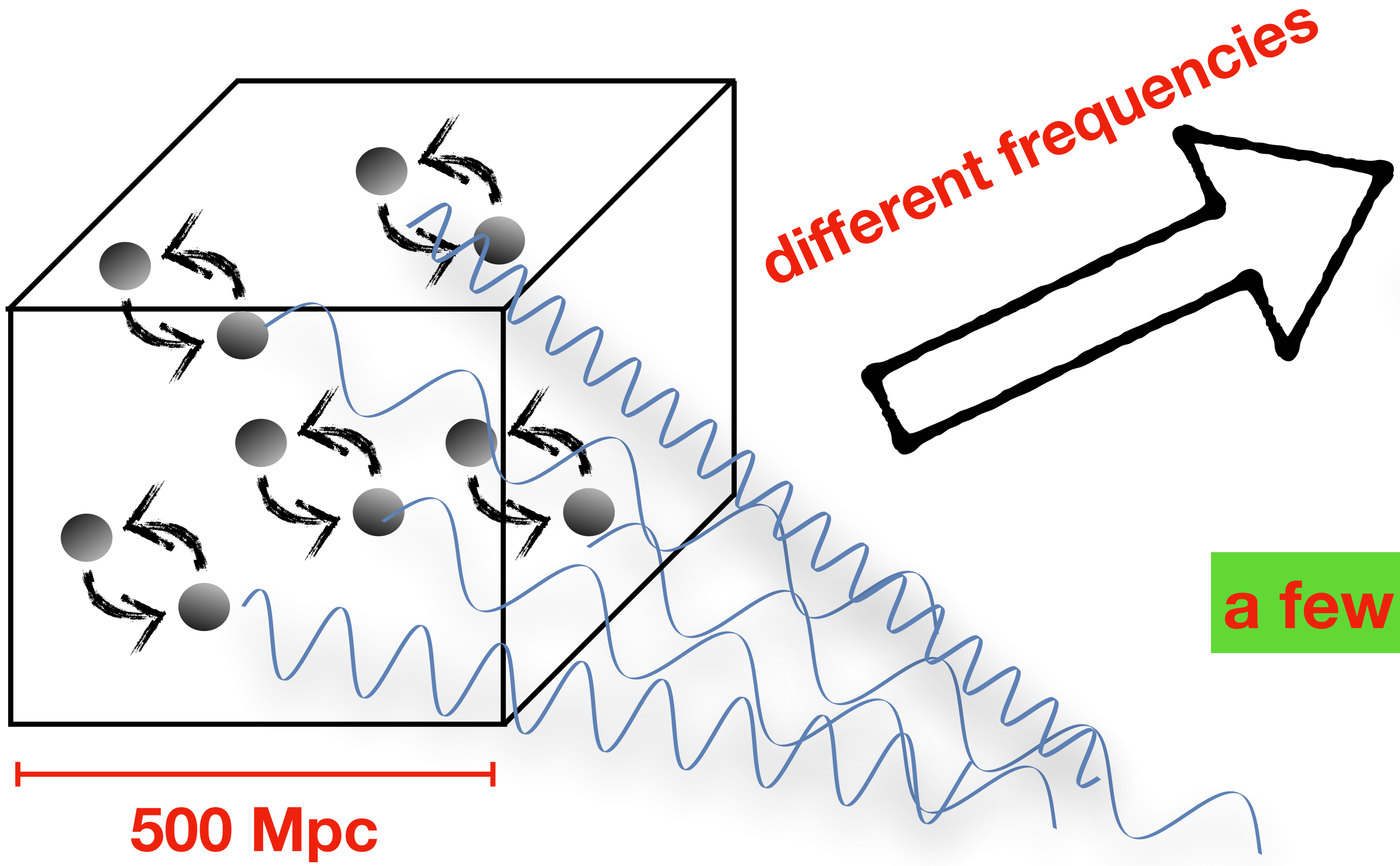
$$\bar{h}_{ij}(t,r) = \frac{2G}{c^4 r} \ddot{I}_{ij}(t - r/c),$$



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

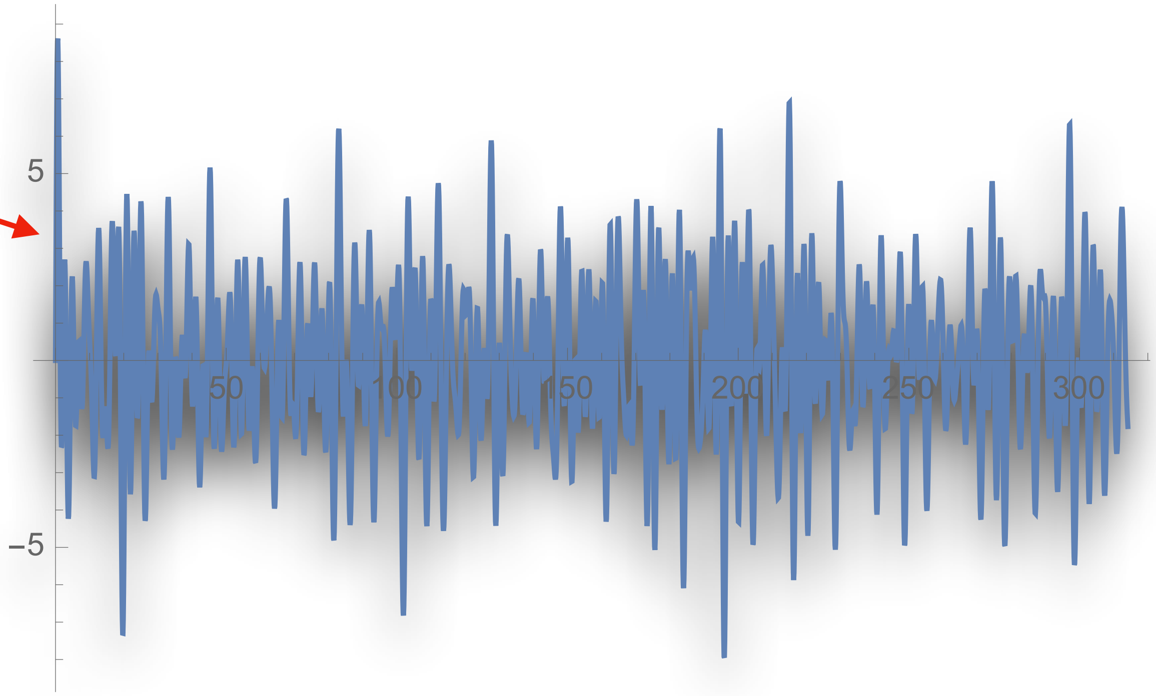
[Credit: 蔡少芬 & wangyi]

Multi-binaries → GWB



500 Mpc

GW signal we want! (noise-like)



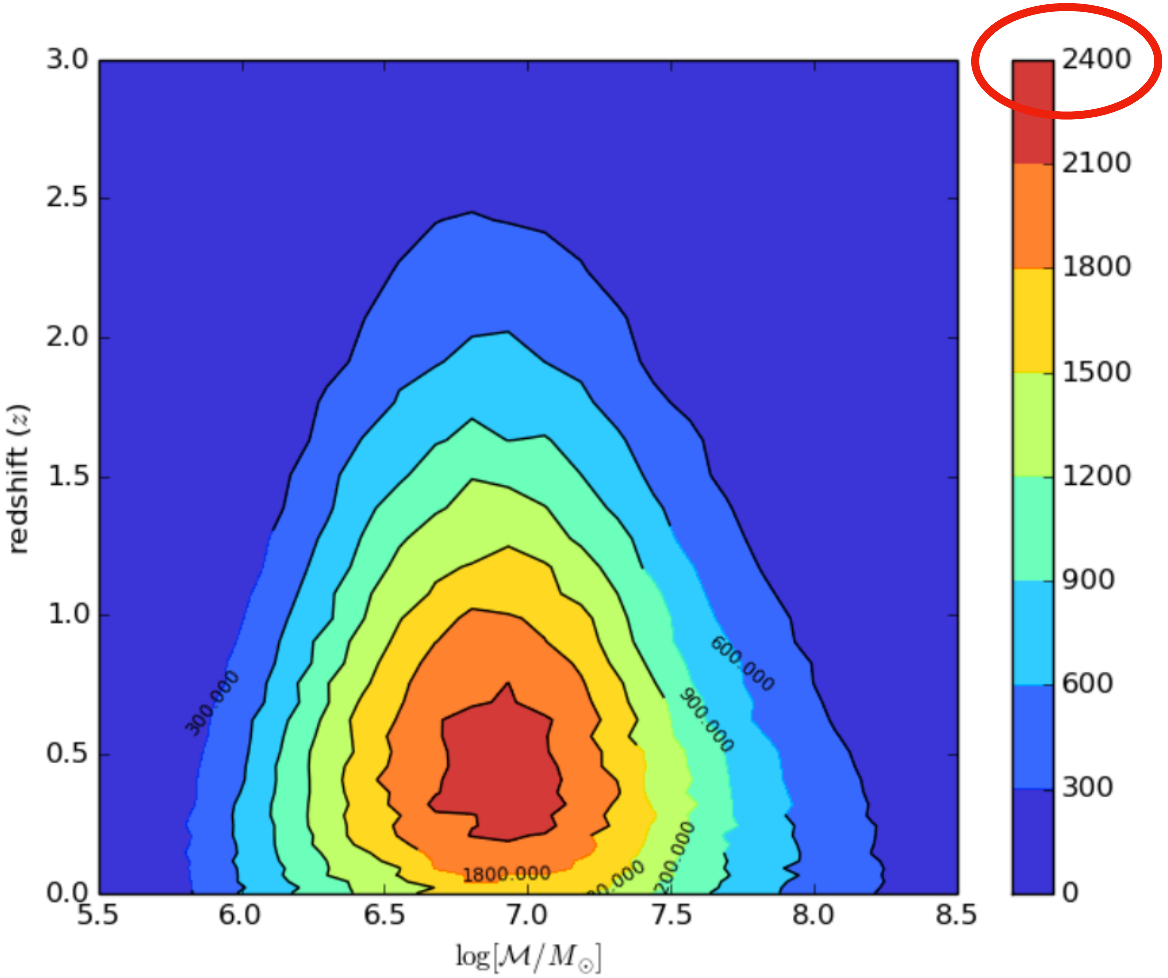
Stochastic in time sequence!

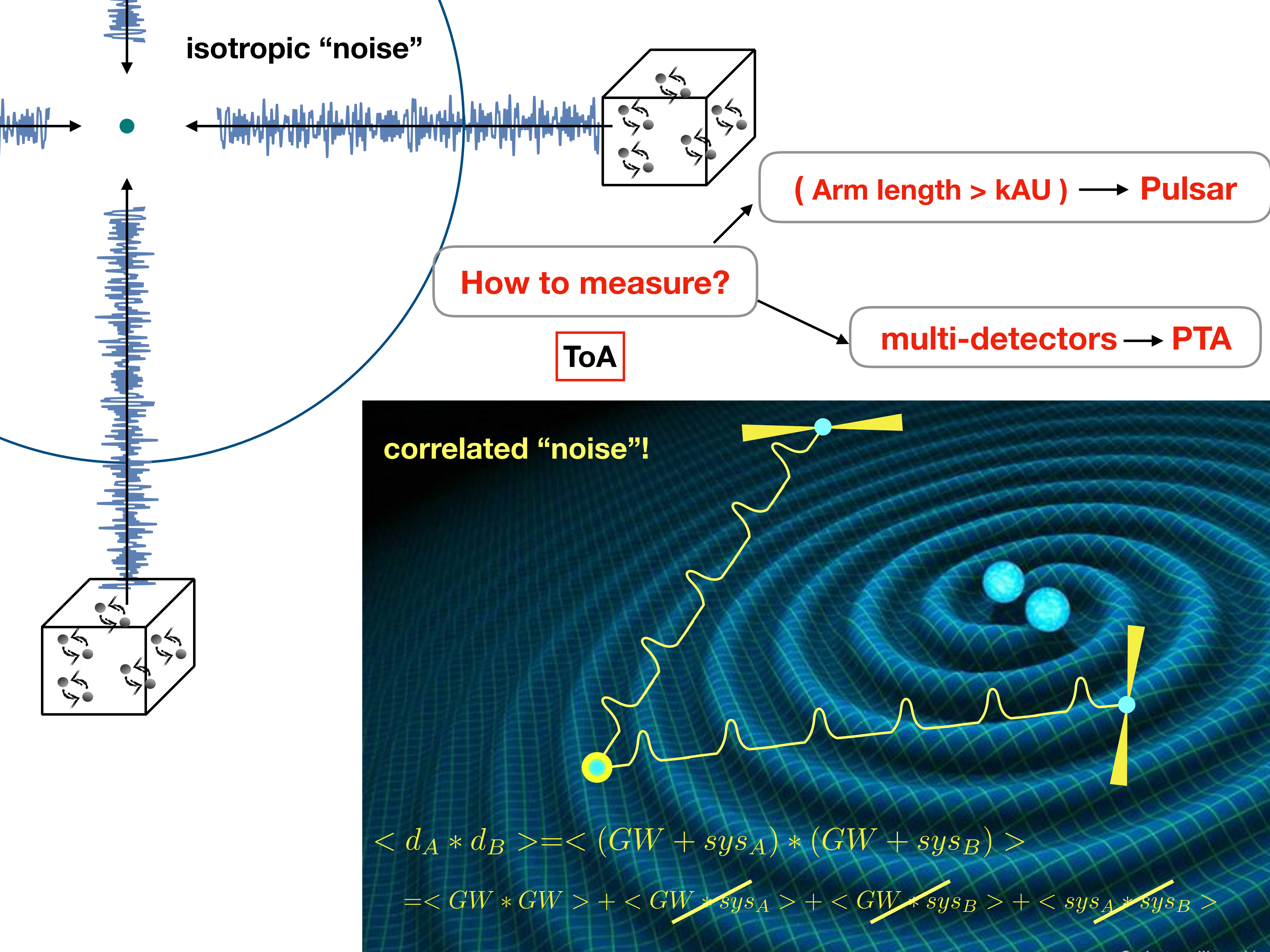
$$h_c^2(f) \propto \int \frac{1}{1+z}\boxed{\frac{dn}{dz}}\frac{d\varepsilon_{\mathrm{GW}}}{d\ln f_r}\bigg|_{f_r=f(1+z)} dz$$

[Phinney 2001]

Merger rate!

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





How to measure?

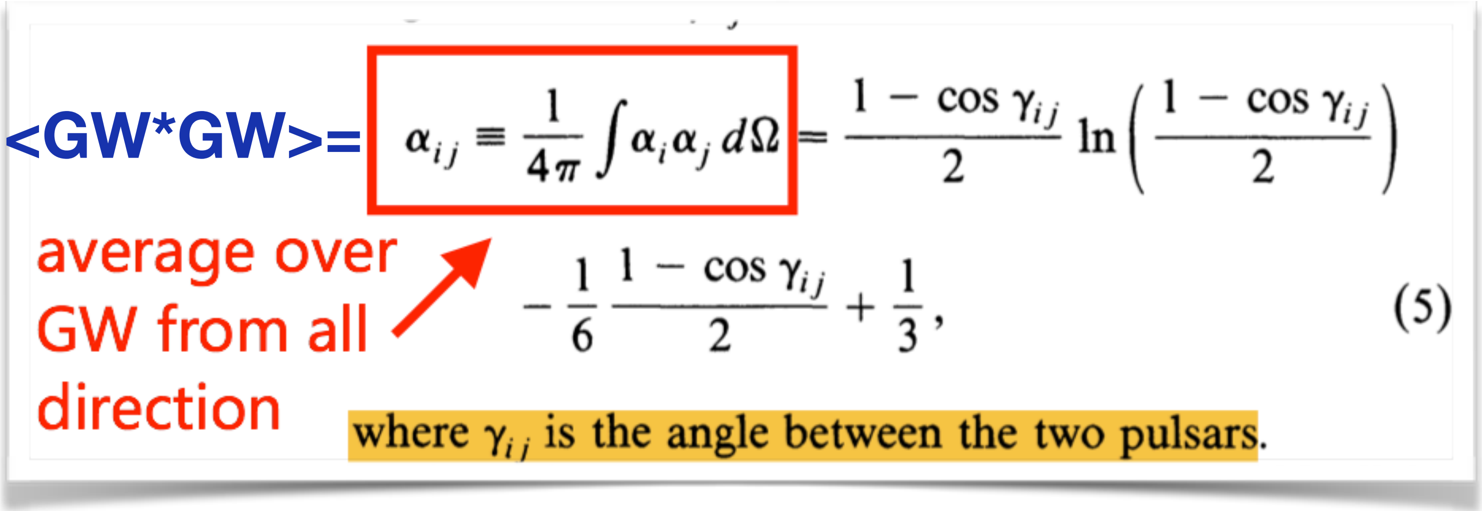
(Arm length > kAU) → Pulsar

multi-detectors → PTA

ToA

$$< d_A * d_B >=< (GW + sys_A) * (GW + sys_B) >$$

$$=< GW * GW > + < \cancel{GW * sys_A} > + < \cancel{GW * sys_B} > + < \cancel{sys_A * sys_B} >$$

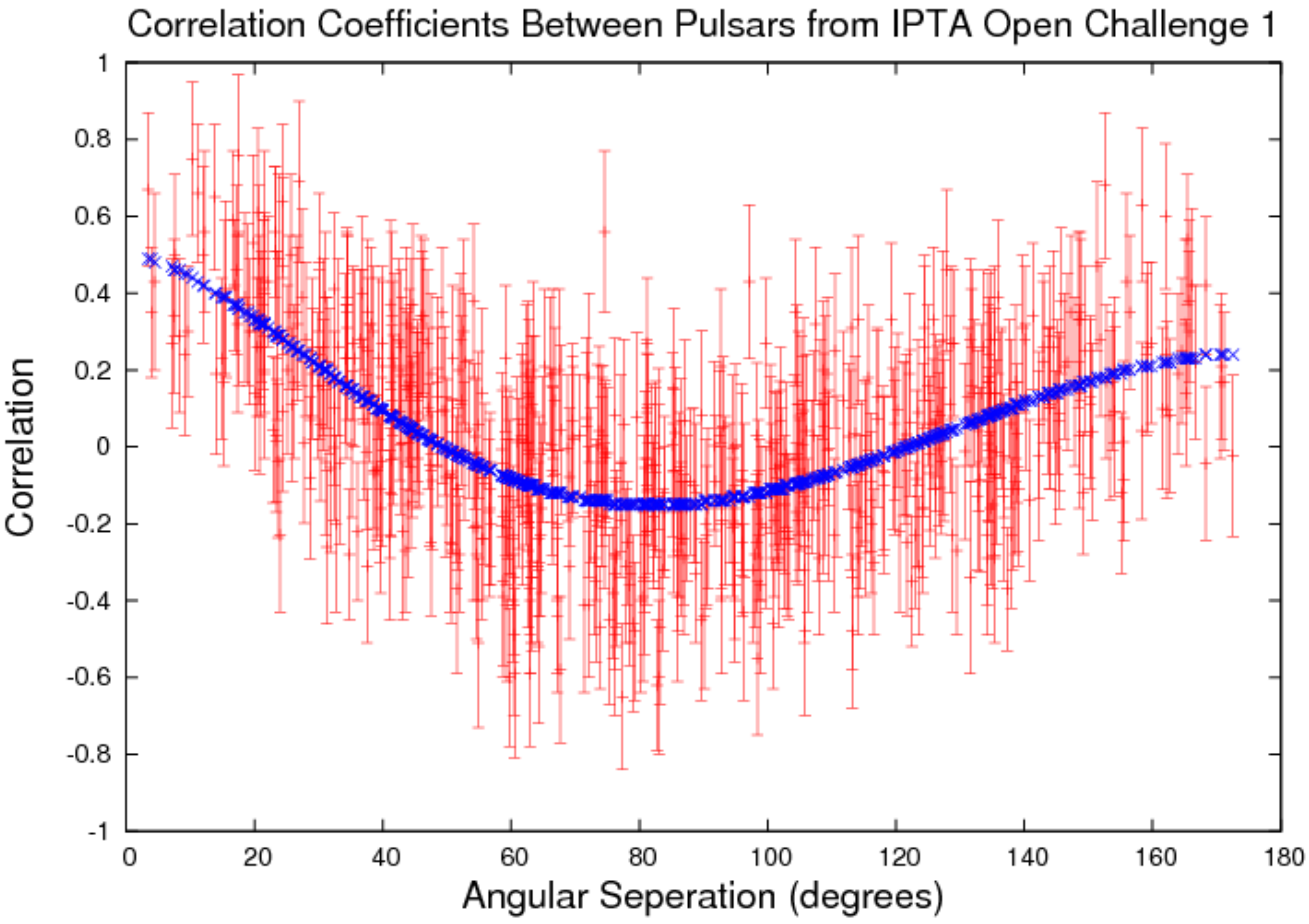


$$\langle GW{*}GW\rangle = \boxed{\alpha_{ij} \equiv \frac{1}{4\pi}\int \alpha_i \alpha_j \, d\Omega} = \frac{1-\cos\gamma_{ij}}{2}\ln\left(\frac{1-\cos\gamma_{ij}}{2}\right) - \frac{1}{6}\,\frac{1-\cos\gamma_{ij}}{2} + \frac{1}{3}, \qquad (5)$$

average over GW from all direction

where γ_{ij} is the angle between the two pulsars.

[Hellings & Downs 1983]



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

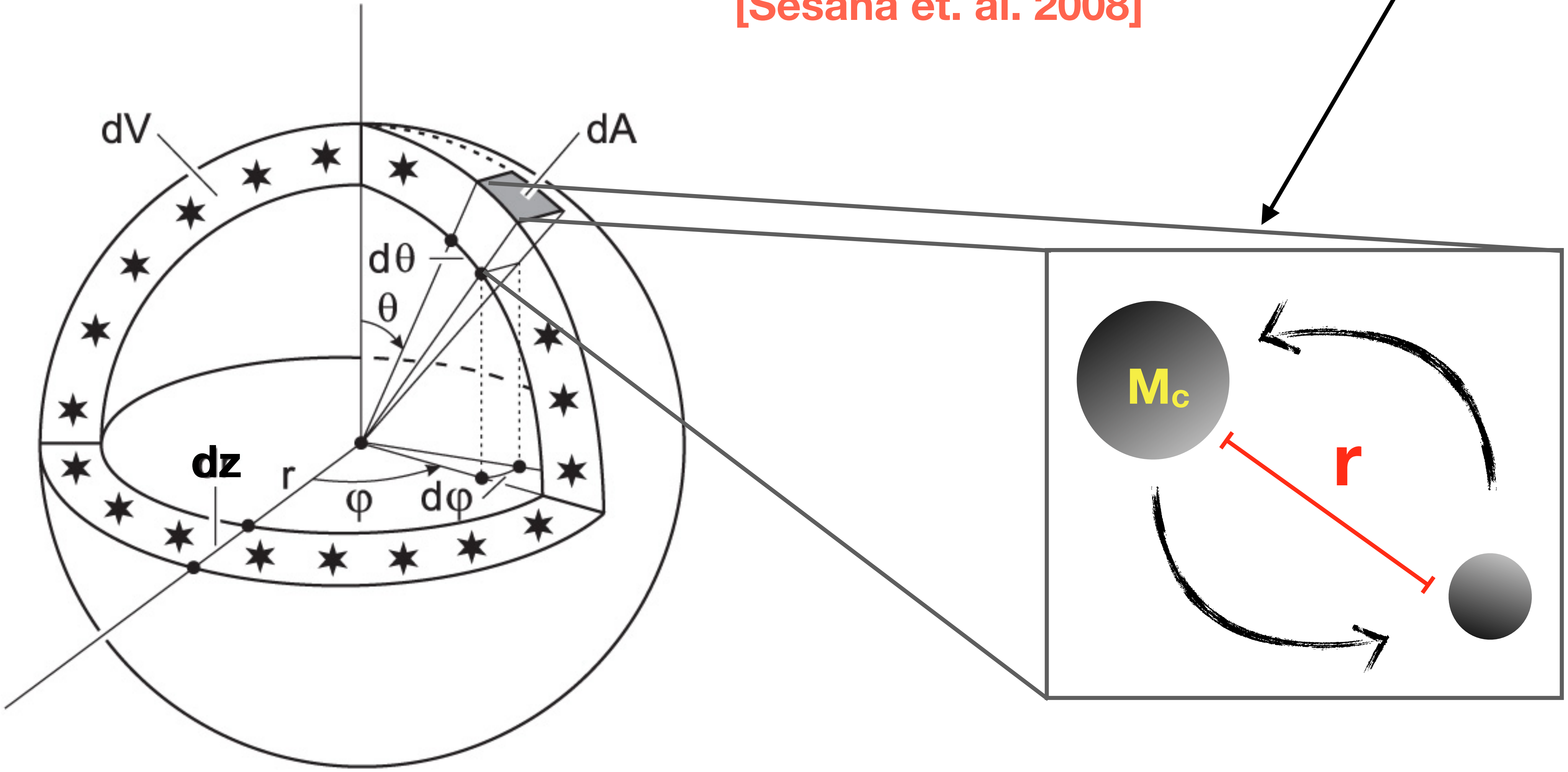
[Phinney 2001]

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]

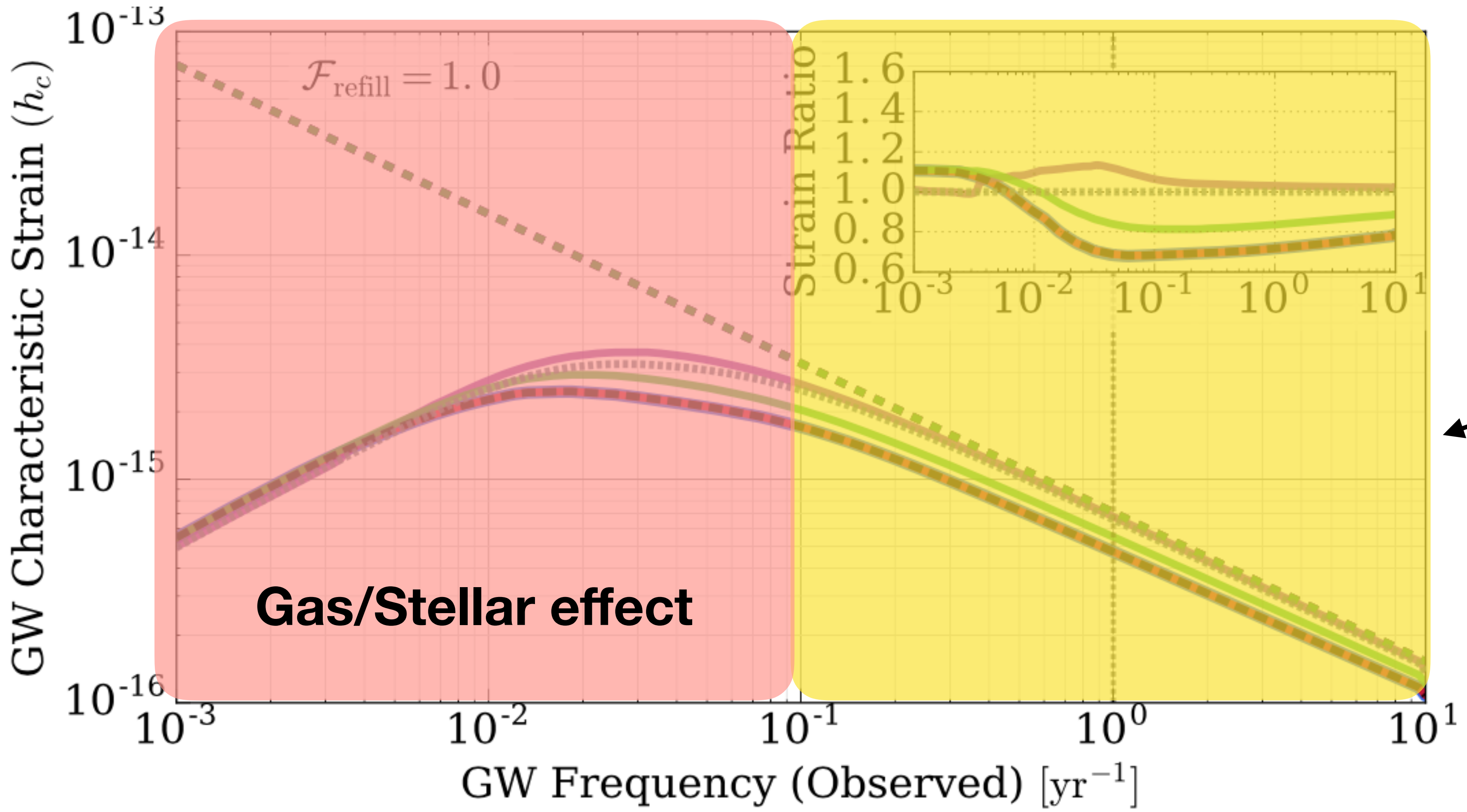
$$dt/d\ln f = \frac{5}{64\pi^{8/3}} \mathcal{M}^{-5/3} f_r^{-8/3}$$

time spend in per logarithmic frequency

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

Major eq.

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



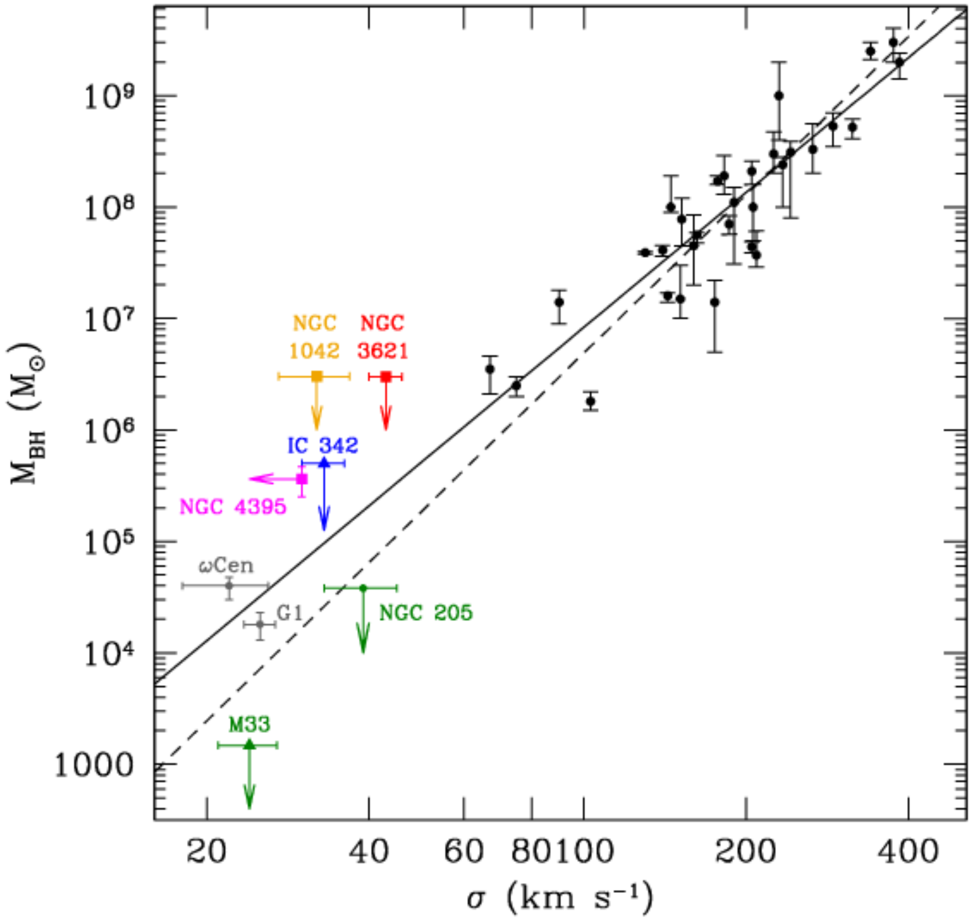
energy loss only due to GW radiation during inspiral

[Credit: Kelley]

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

phenomenology

[Sesana 2012]



$$M - \sigma$$

relation

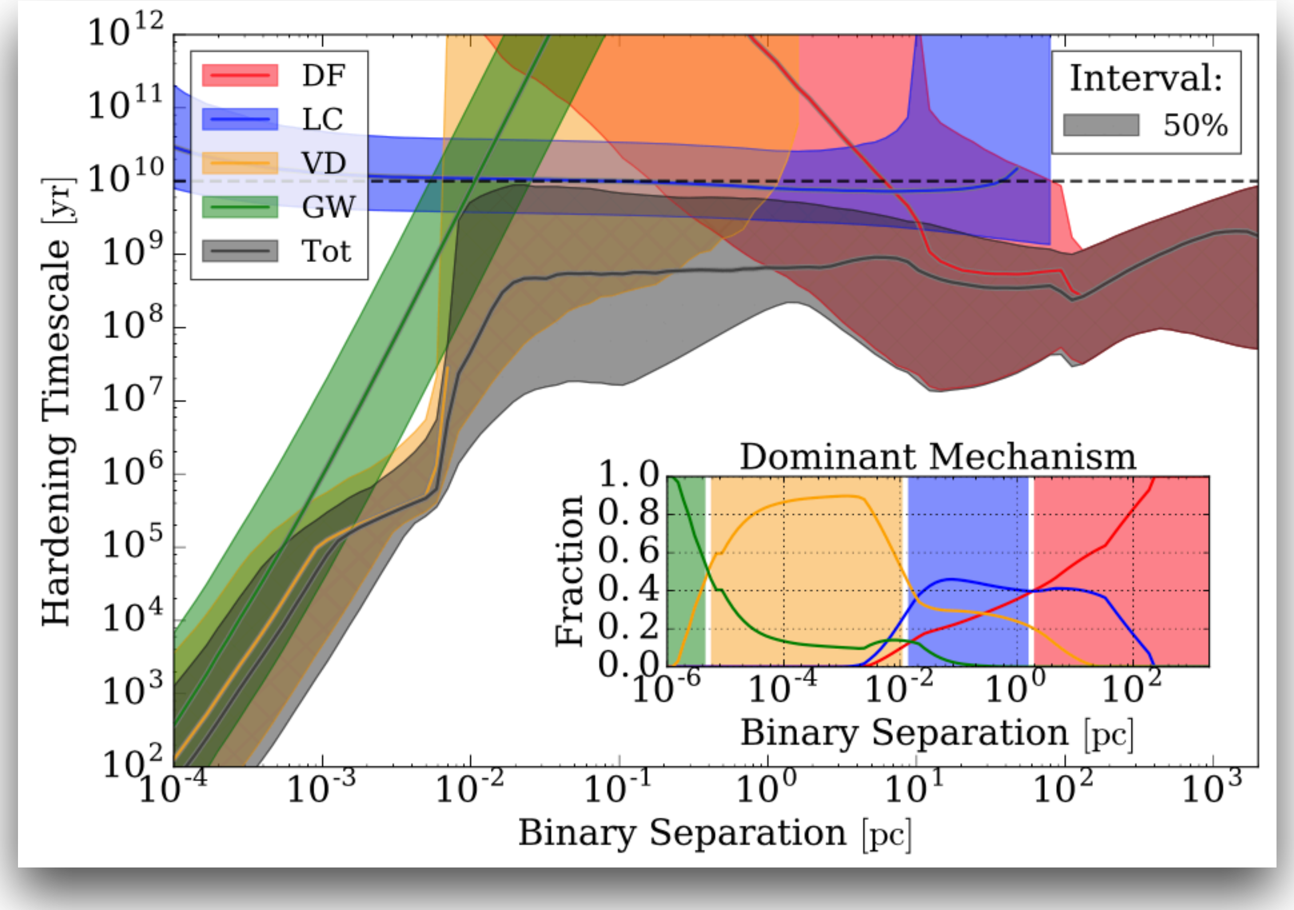
Preliminary Semi-Analytic Modelling

SMBH merger modelling

[Kelley et. al. 2017]

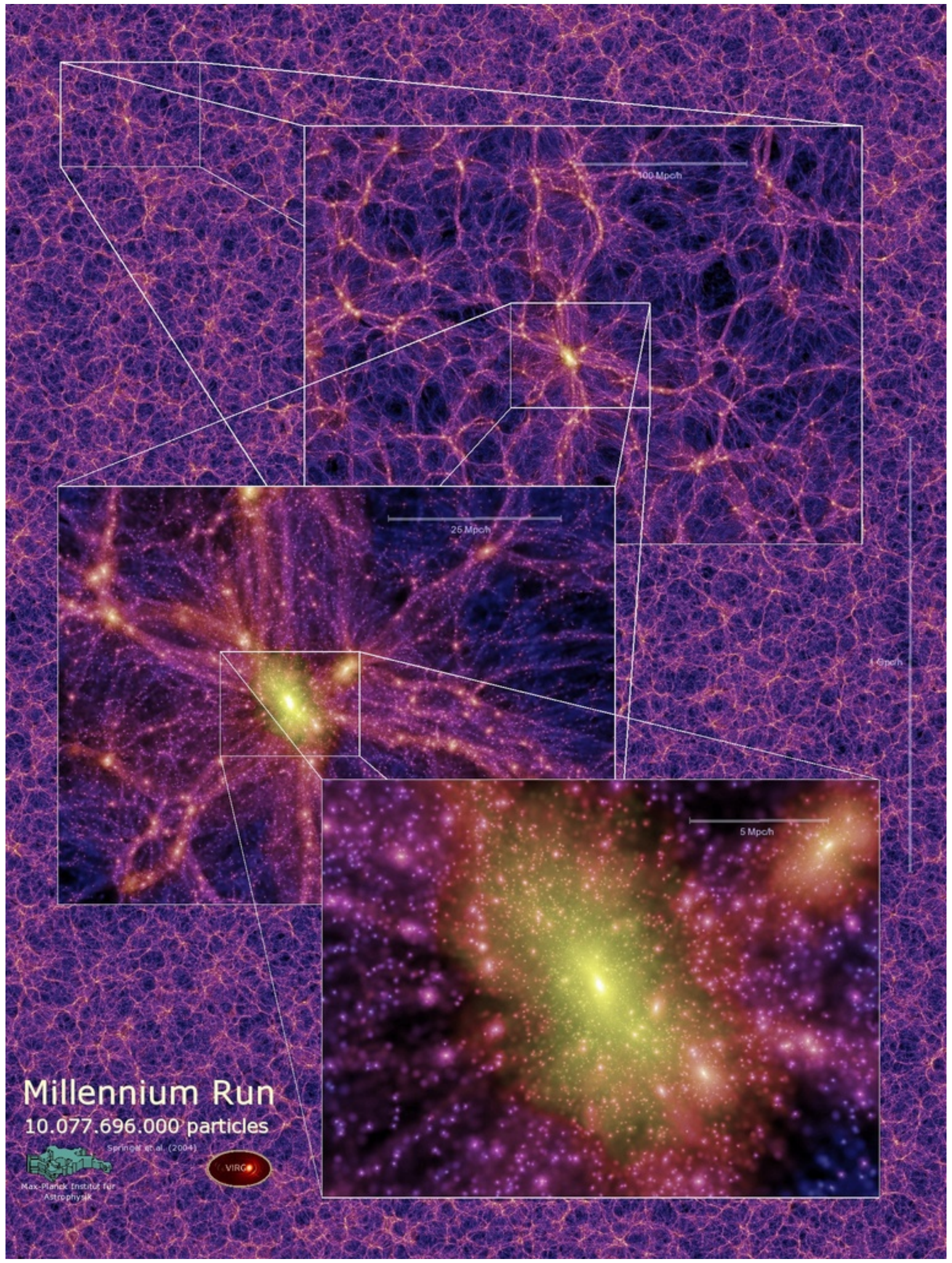
$$\frac{d^2n_g}{dzdM}$$

[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~500^3 Mpc^3

8668809 SMBHs,

51538704 galaxies

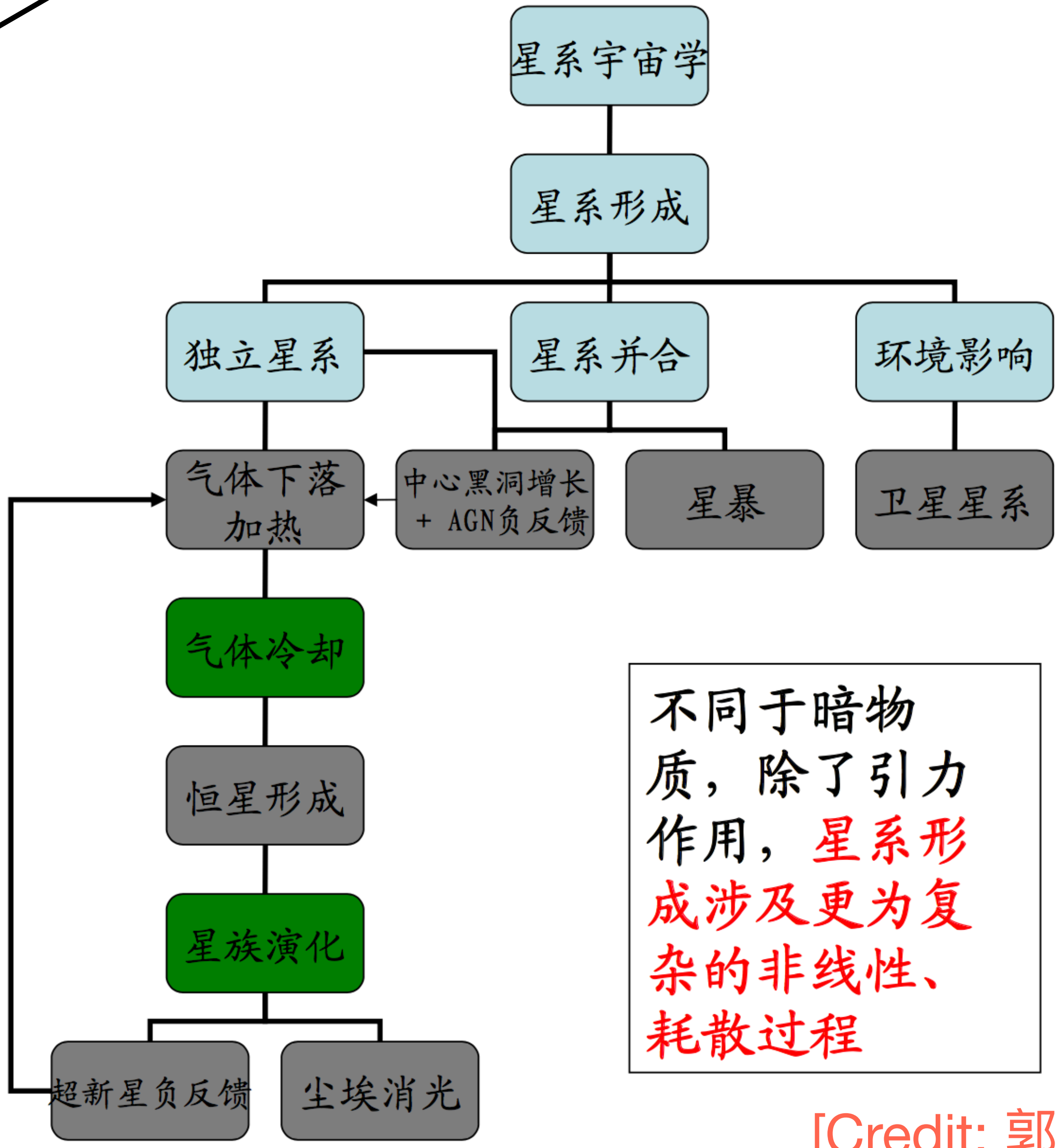
in total

1. Run N-body simulation ⟶ DM halo merge tree

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

directly read
BH mass function

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


星系宇宙学
星系形成
独立星系
星系并合
环境影响
气体下落加热
中心黑洞增长 + AGN负反馈
星暴
卫星星系
气体冷却
恒星形成
星族演化
超新星负反馈
尘埃消光

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: 郭琦]

code: L-galaxies

BH Self-regulated growth & feedback

Quasar mode: (gas-rich merger)

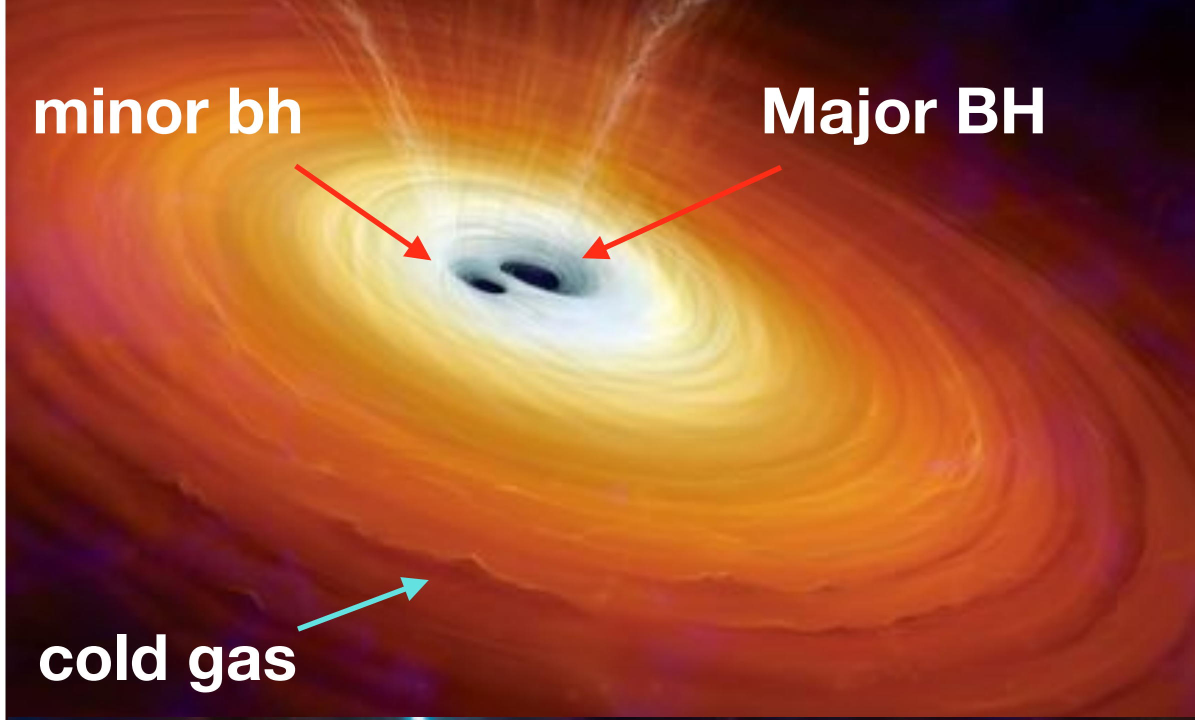
$$
\begin{aligned}
M_{\mathrm{bh},f} &= M_{\mathrm{bh,maj}} + M_{\mathrm{bh,min}} + \Delta M_{\mathrm{bh},Q}\,, \\
\Delta M_{\mathrm{bh},Q} &= \frac{f_{\mathrm{bh}}(M_{\mathrm{min}}/M_{\mathrm{maj}})M_{\mathrm{cold}}}{1 + 280\ \mathrm{km\ s^{-1}}/V_{vir}}\,,
\end{aligned}
$$

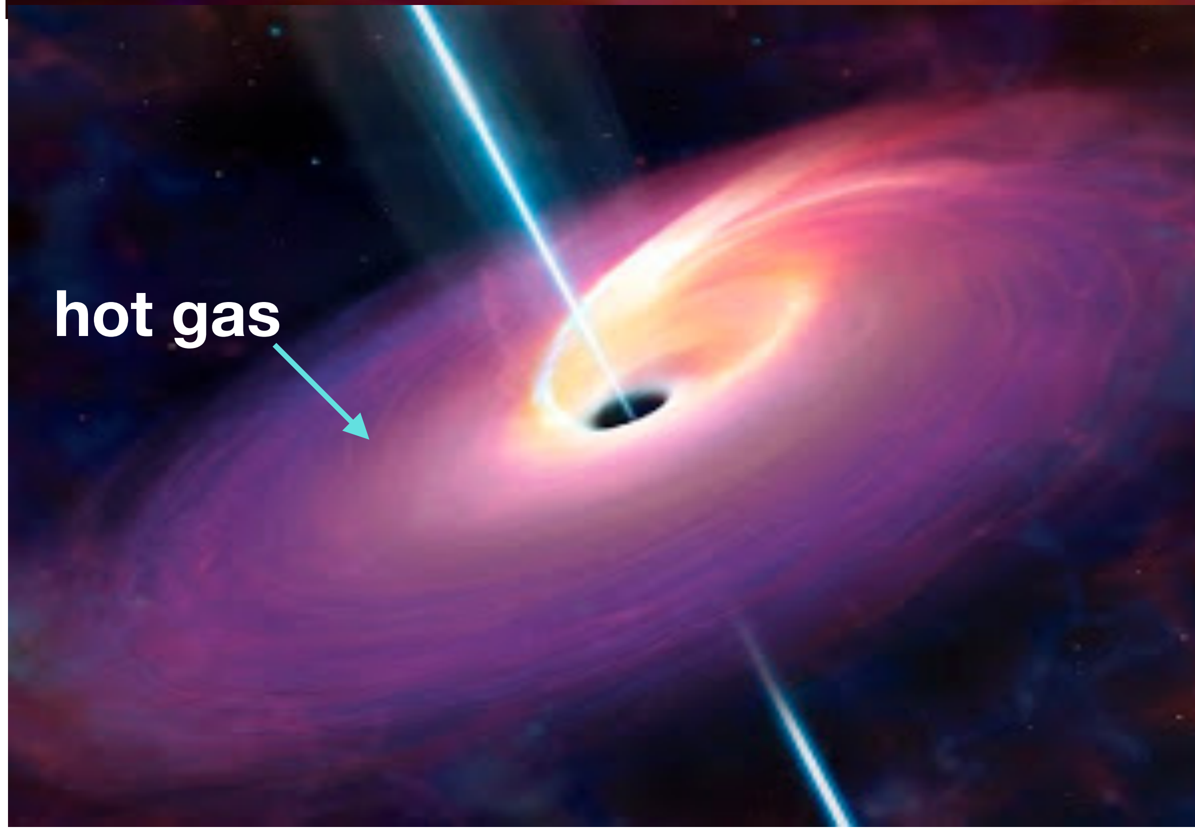
Radio mode: (hot gas accretion)

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

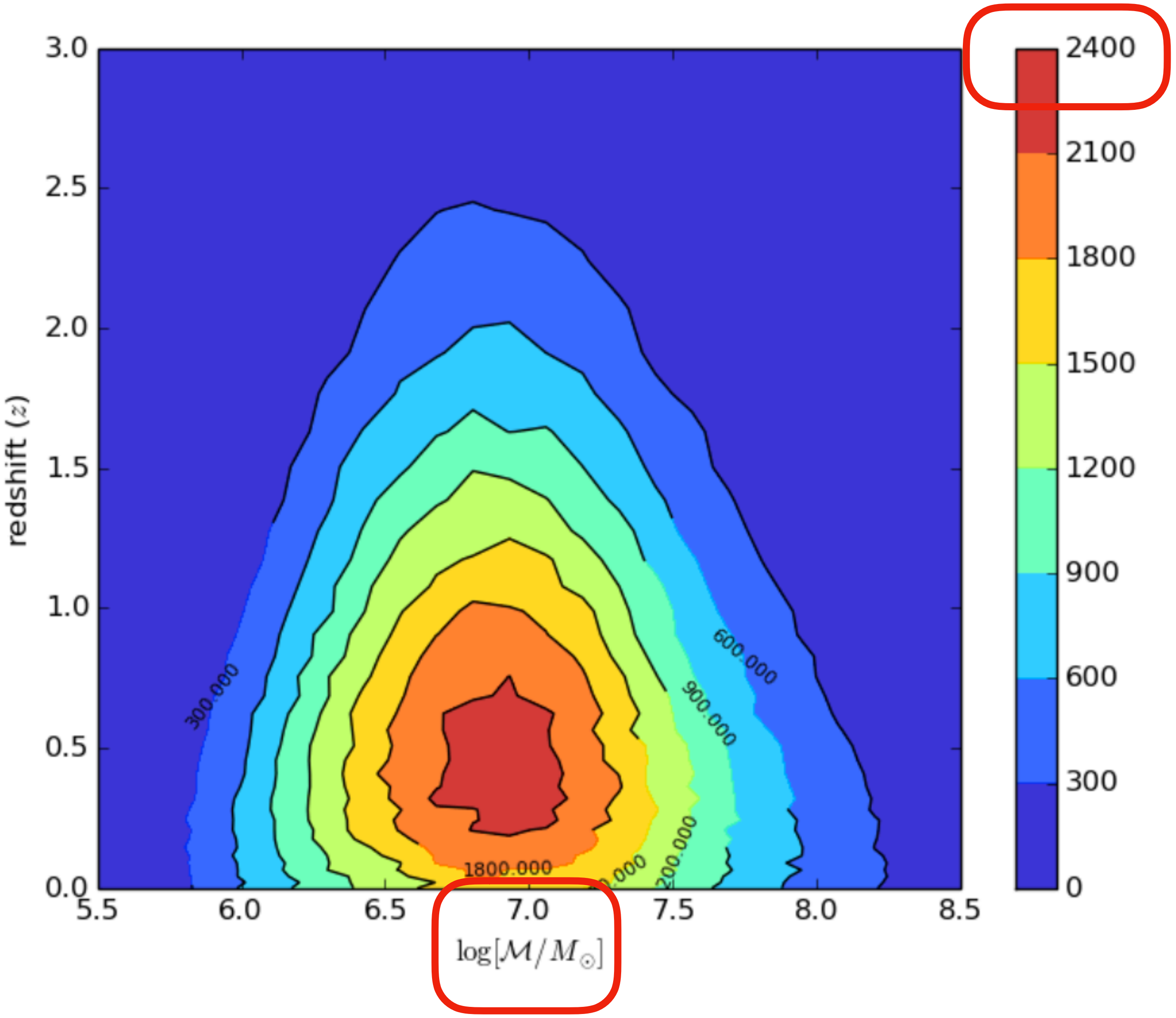
$$
\dot{E}_{\mathrm{radio}} = \boxed{0.1}\dot{M}_{\mathrm{bh}} c^2
$$

10% energy deposit into relativistic jet

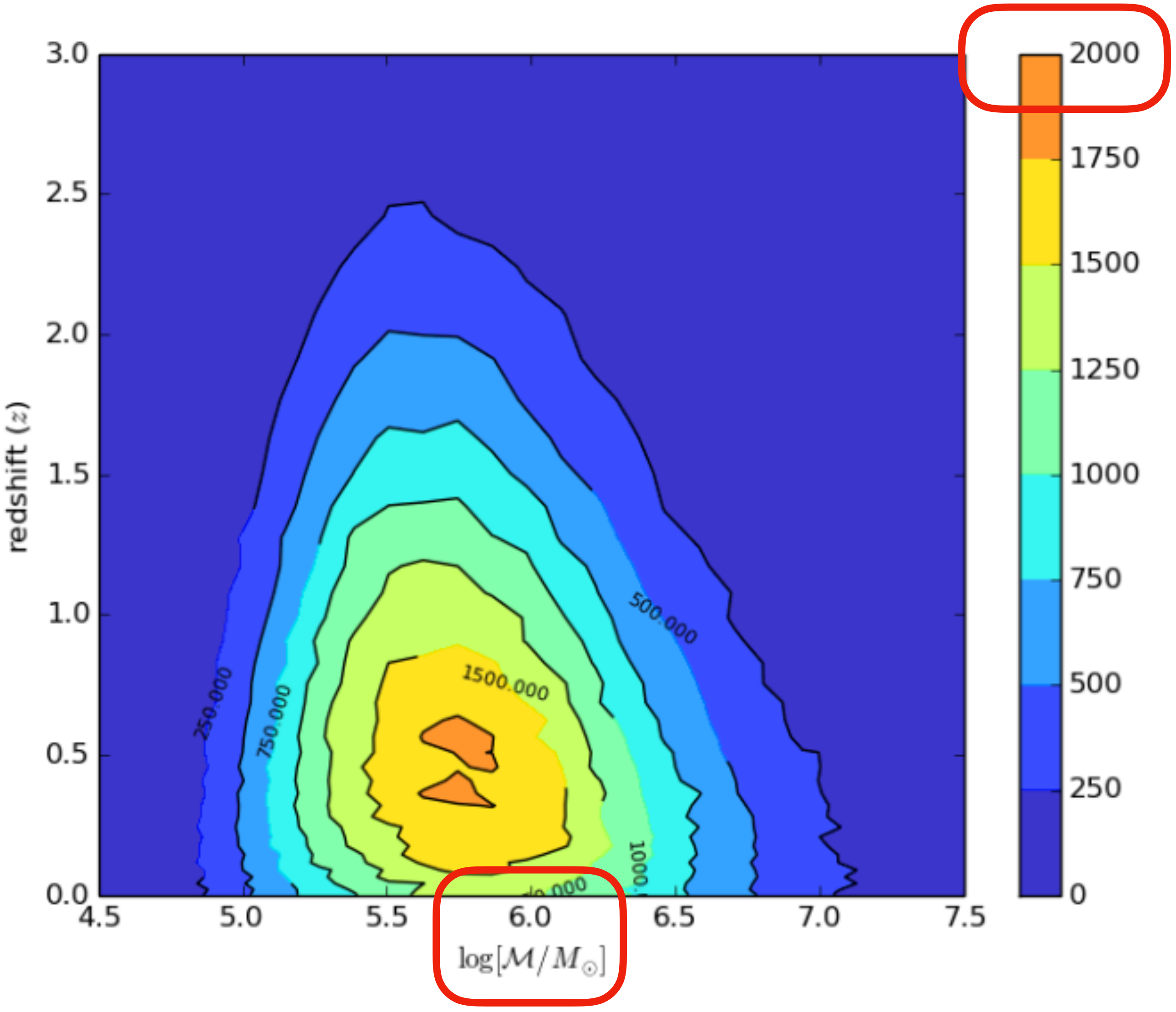




$$\frac{d^2 n}{dz\,dM}$$

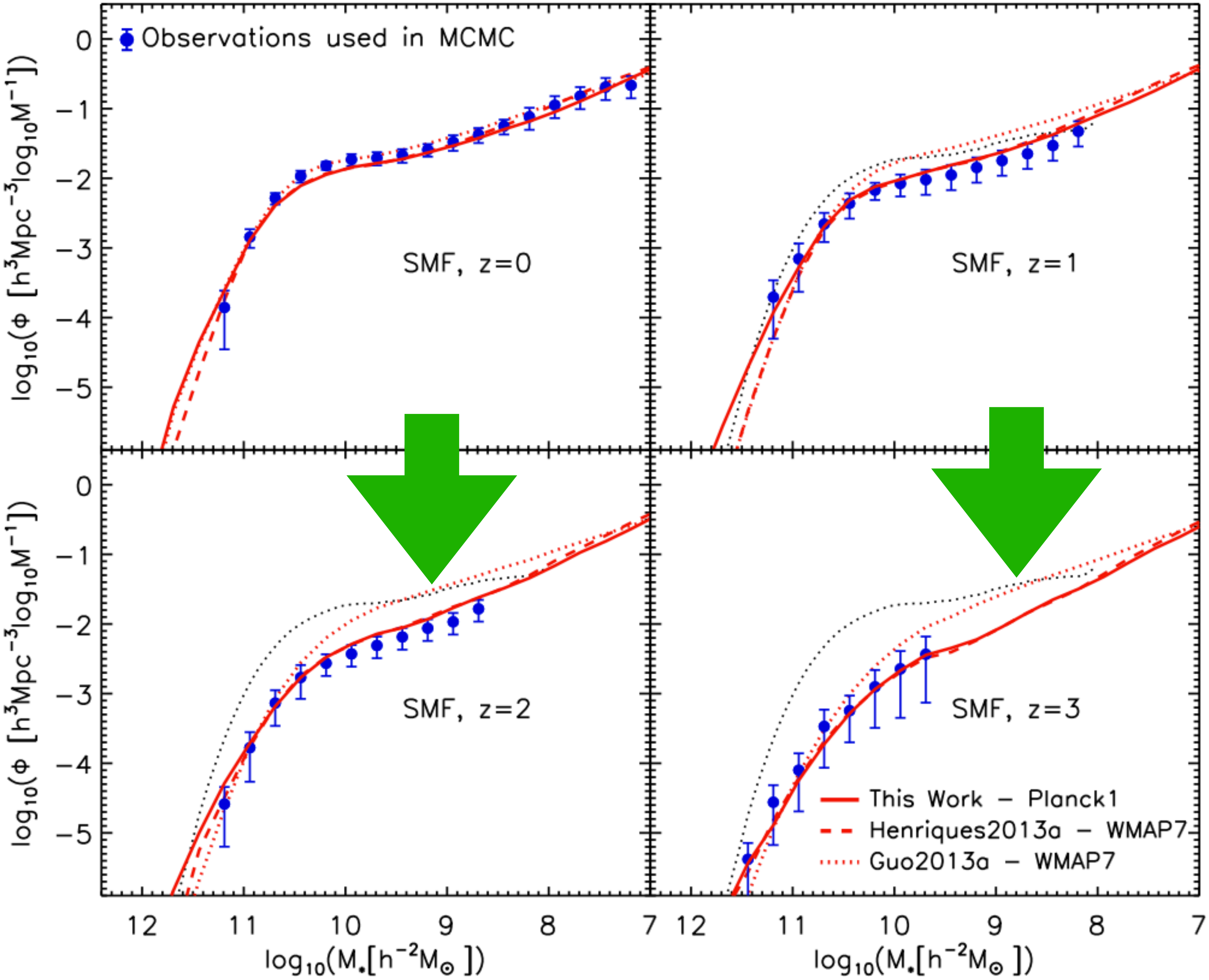


Guo 2013
based WMAP7 cosmology



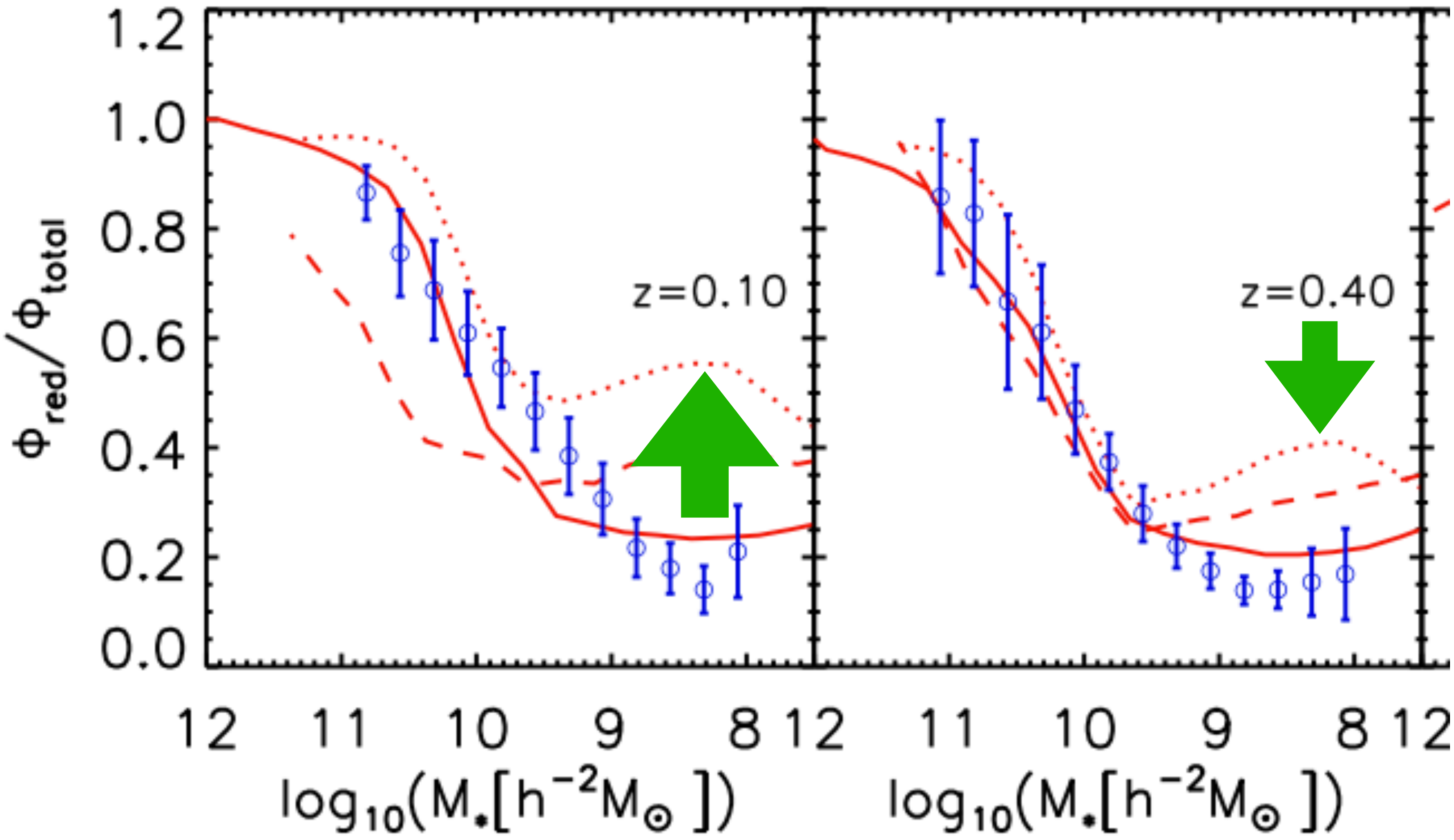
Henriques 2015
based Planck cosmology

[Henriques et. al. 2015]



overly early formation of low-mass galaxies in Guo2013

[Henriques et. al. 2015]



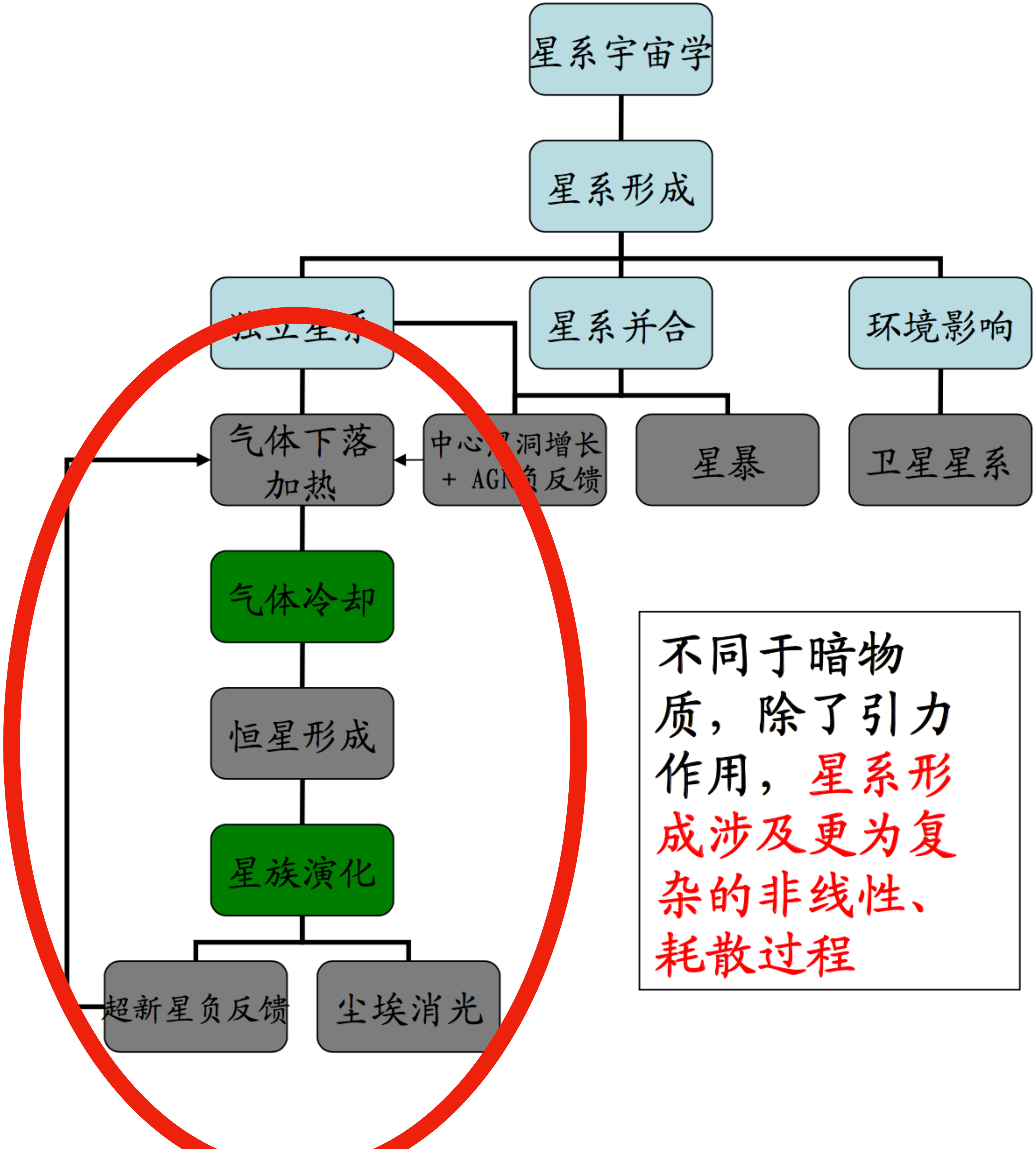
overly large fraction of them that are passive at late times in Guo 2013

解决方案：

拉长

该过程

的时标



星系宇宙学

星系形成

独立星系

星系并合

环境影响

气体下落
加热

中心黑洞增长
+ AGN负反馈

星暴

卫星星系

气体冷却

恒星形成

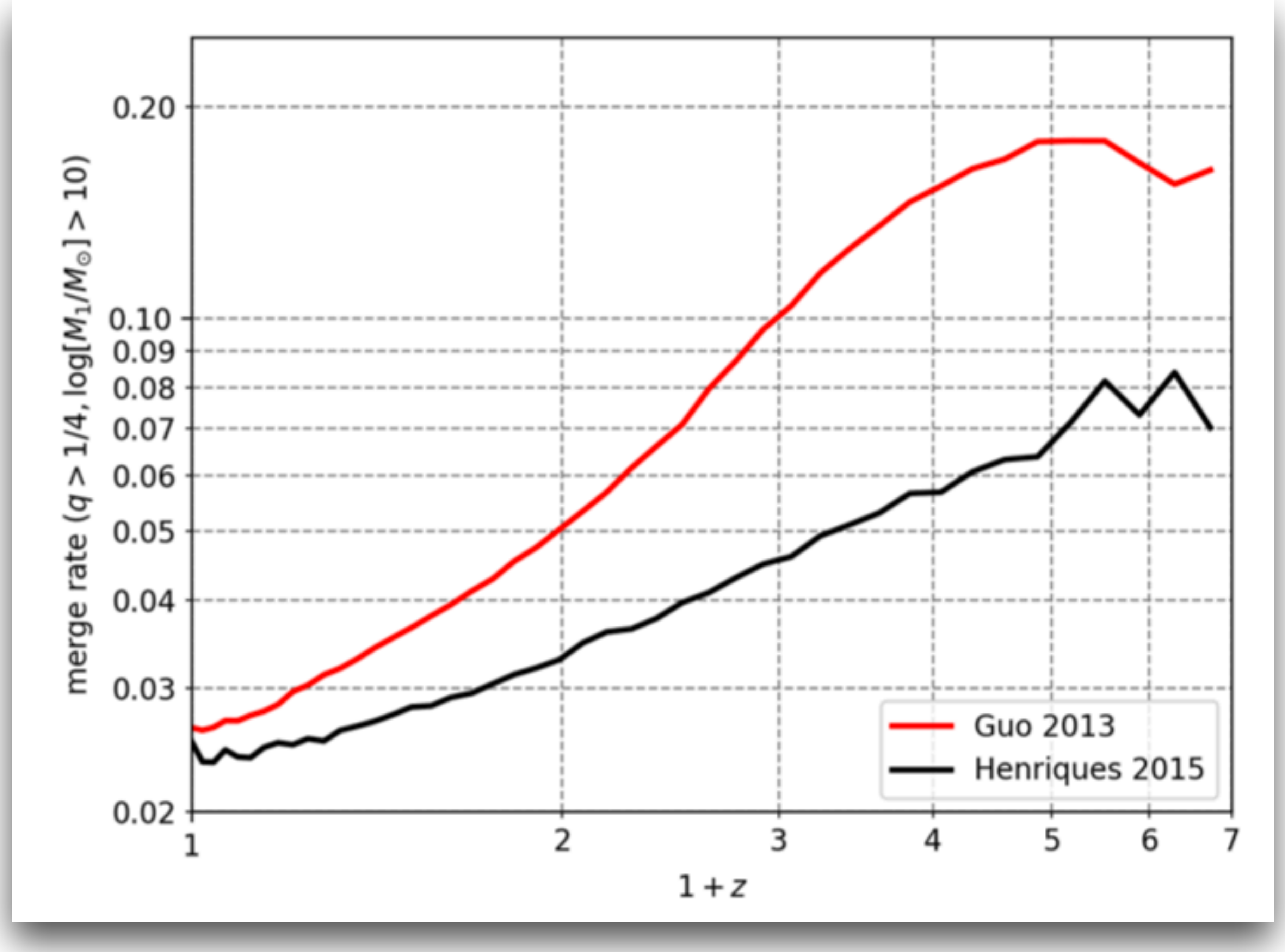
星族演化

超新星负反馈

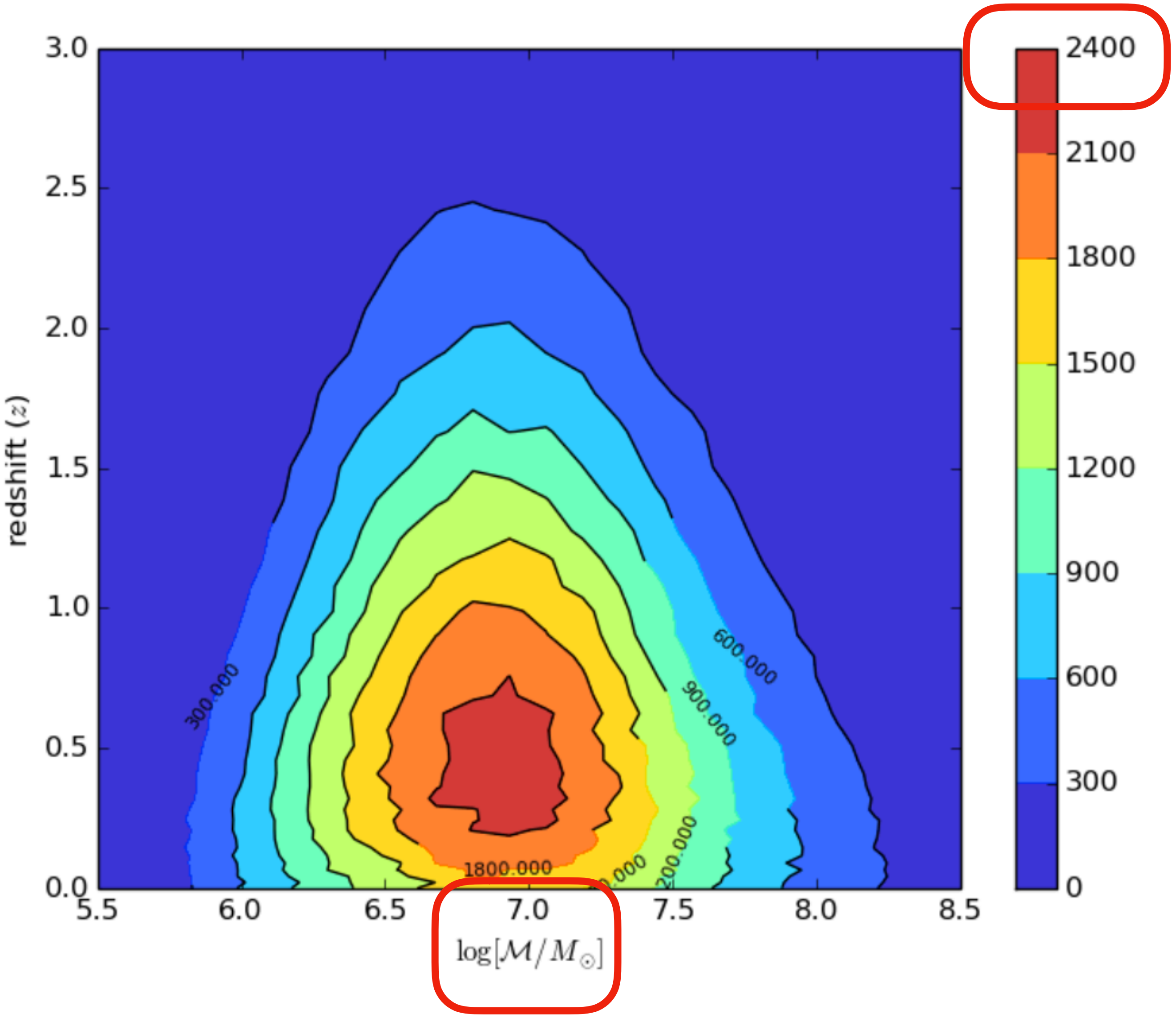
尘埃消光

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

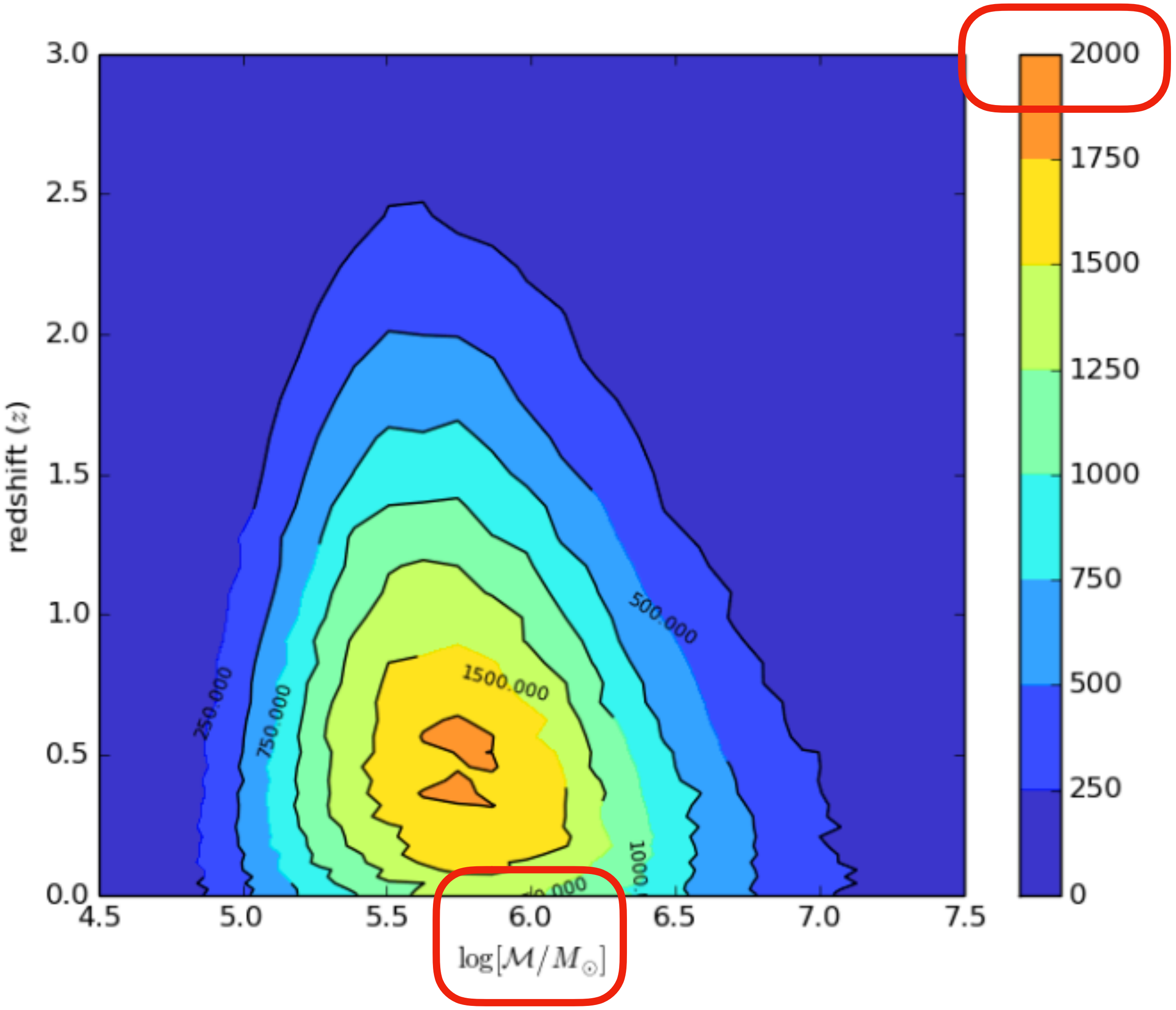
$$\frac{dn_g}{dz}$$


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

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

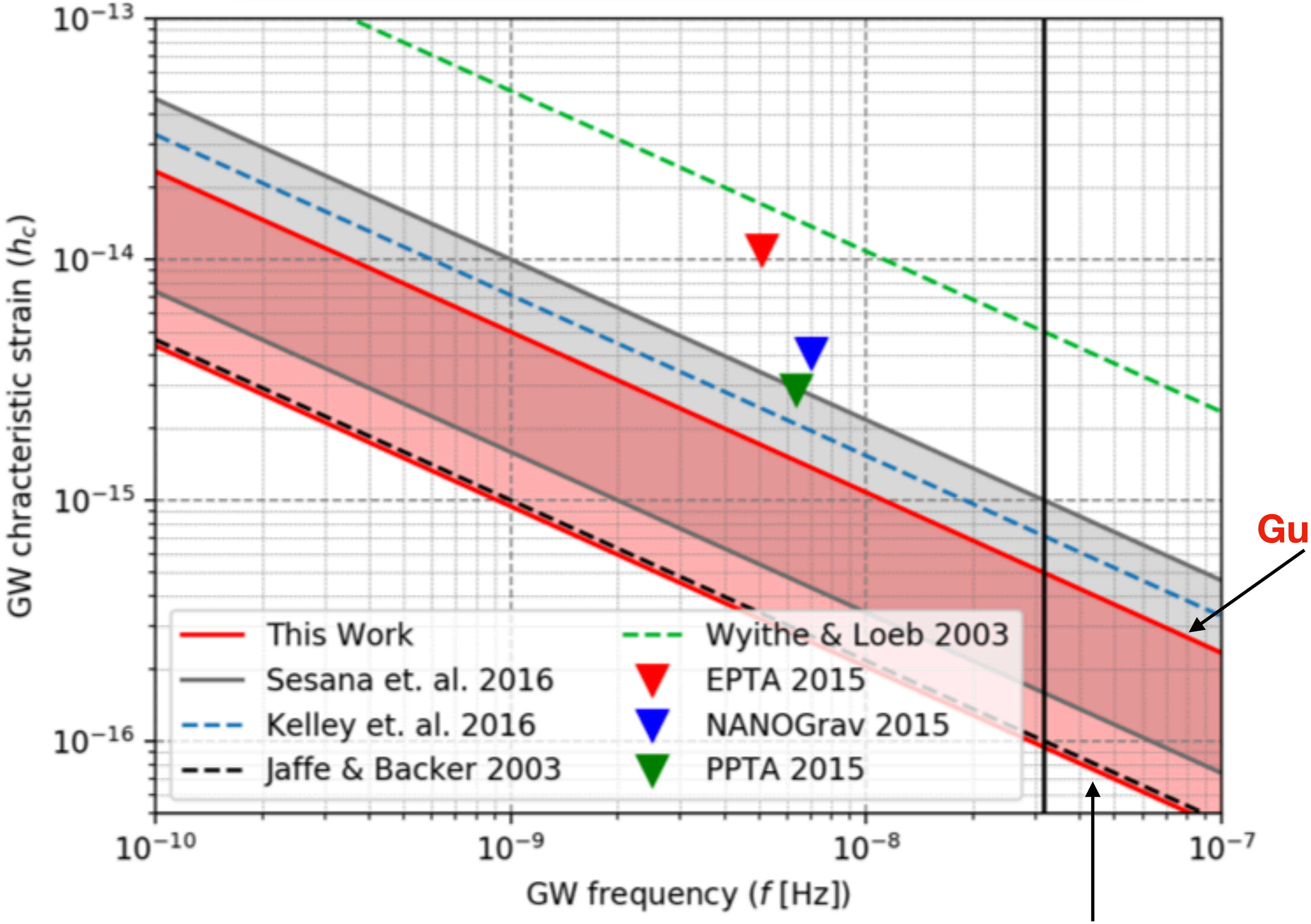


Guo 2013
based WMAP7 cosmology



Henriques 2015
based Planck cosmology

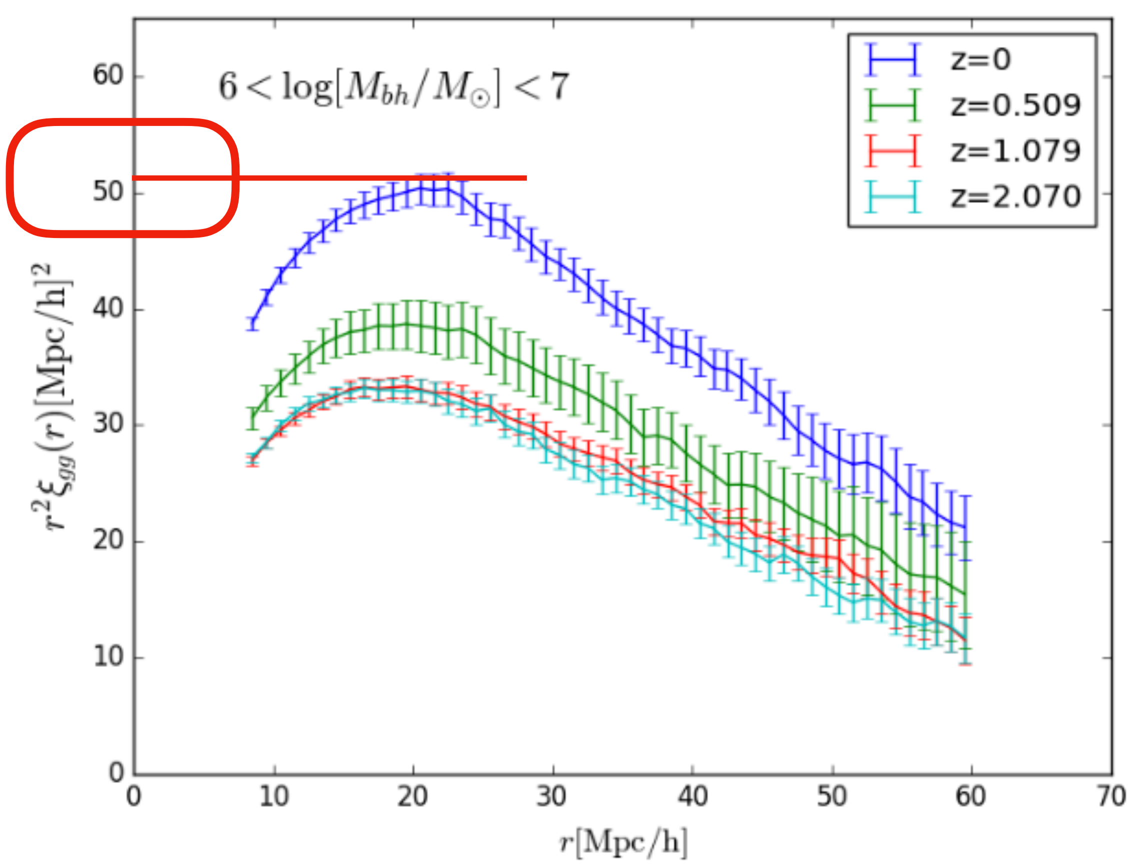
$A_{yr^{-1}} = 5.00 \times 10^{-16}$ and $A_{yr^{-1}} = 9.42 \times 10^{-17}$

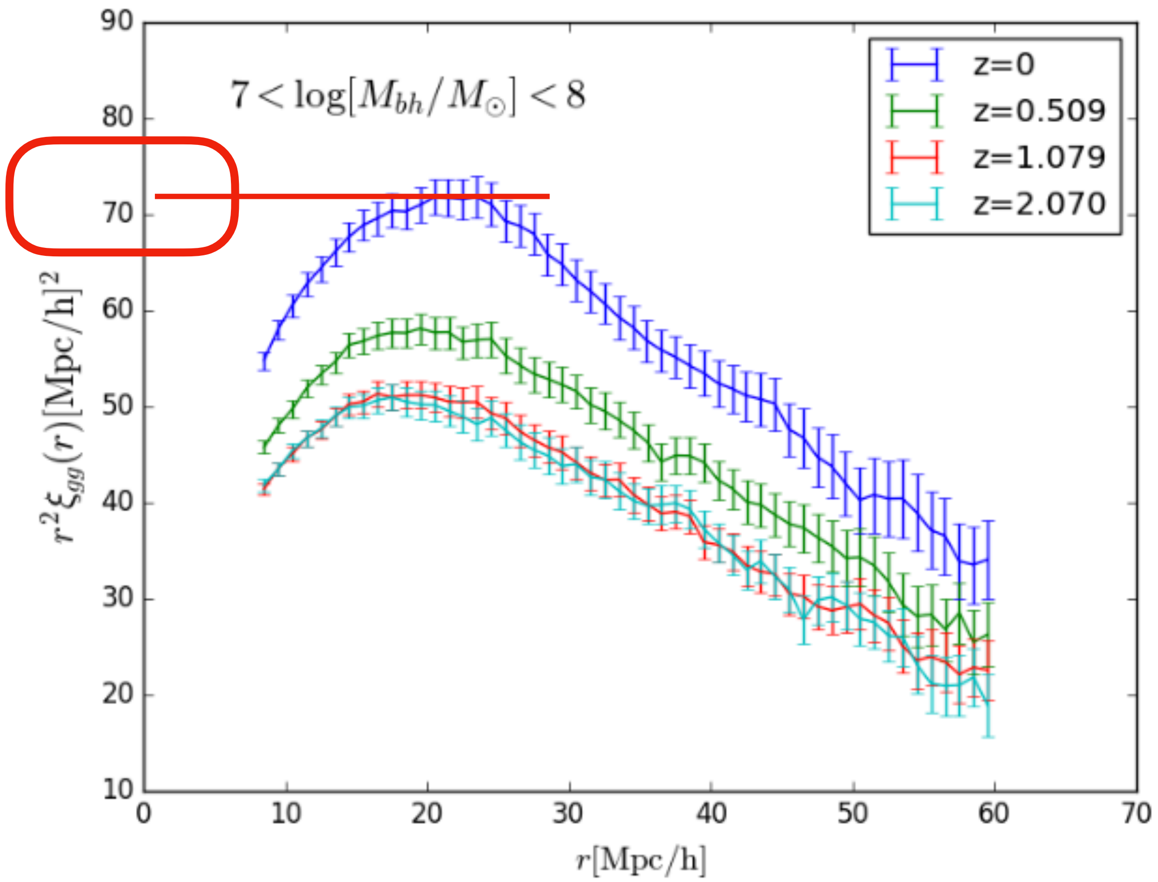


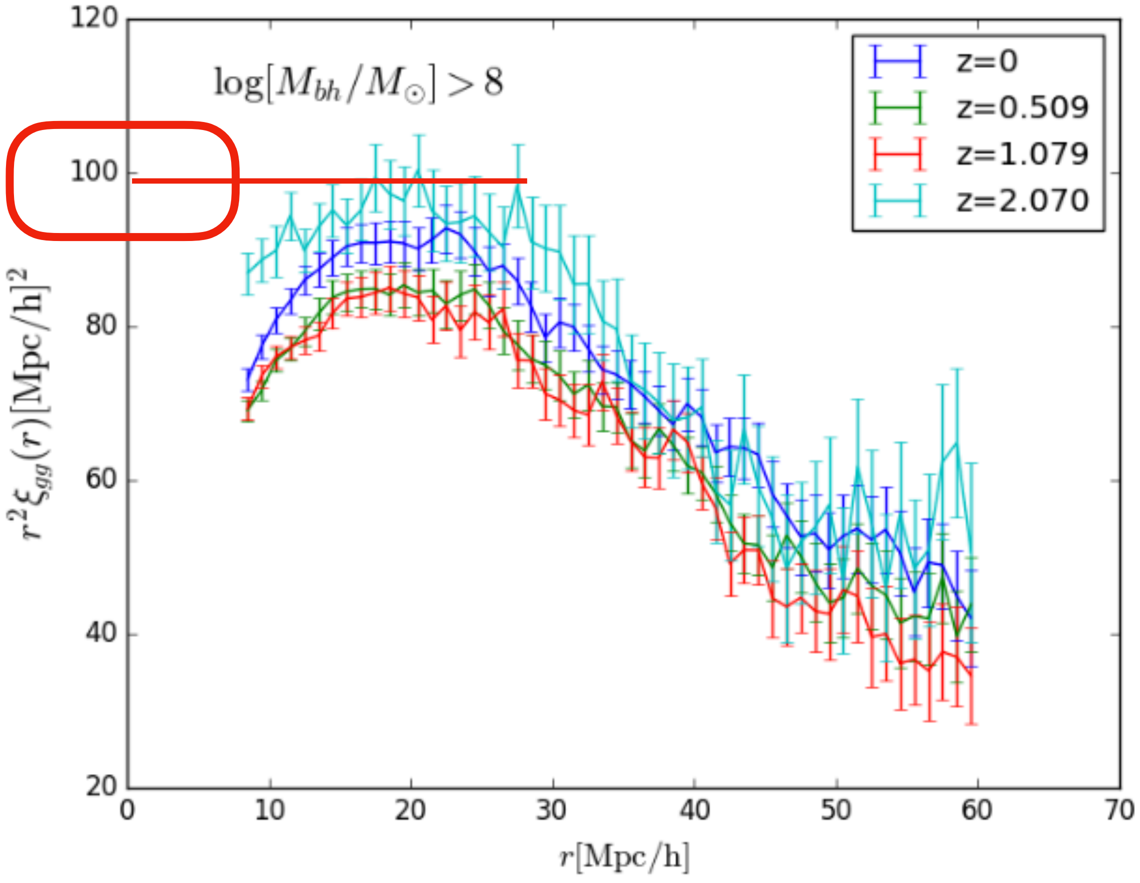
Guo 2013

Henriques 2015

BHs



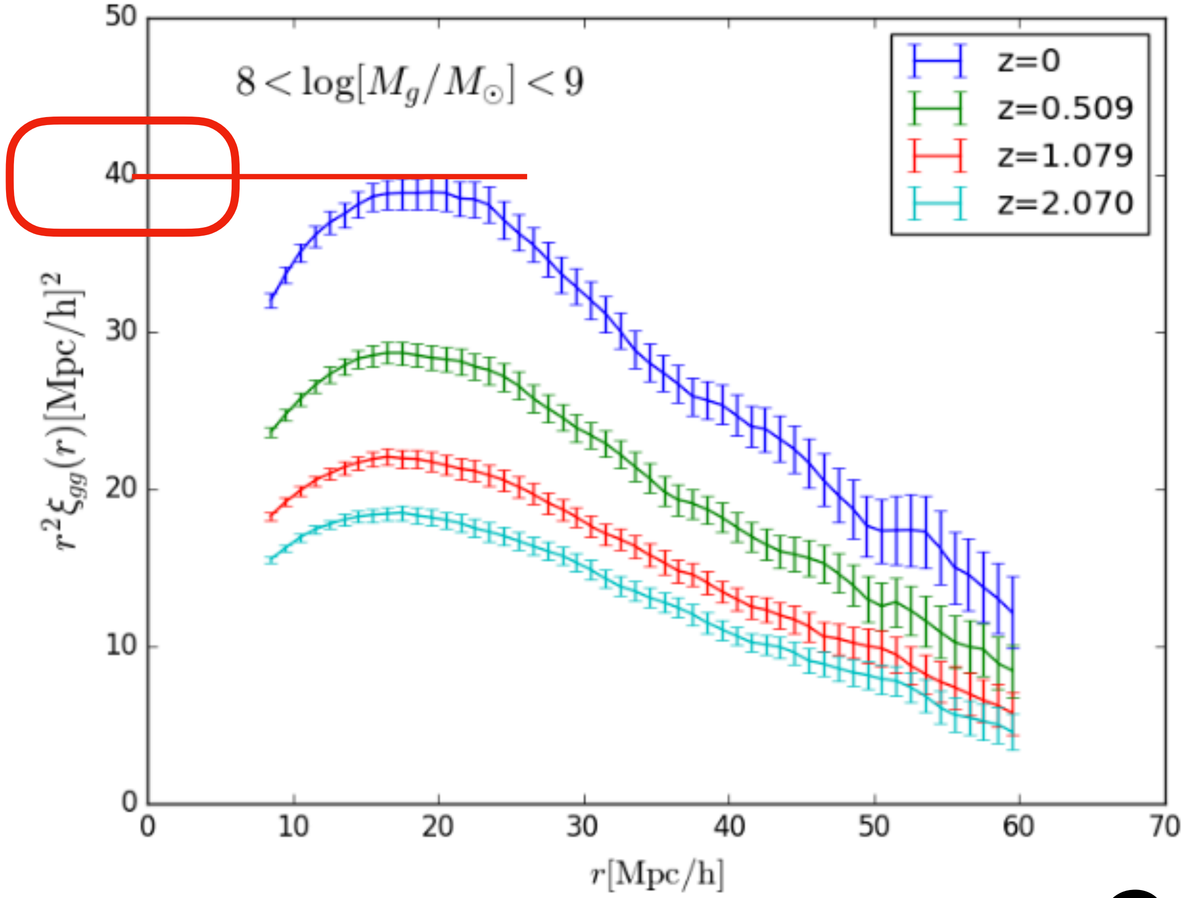


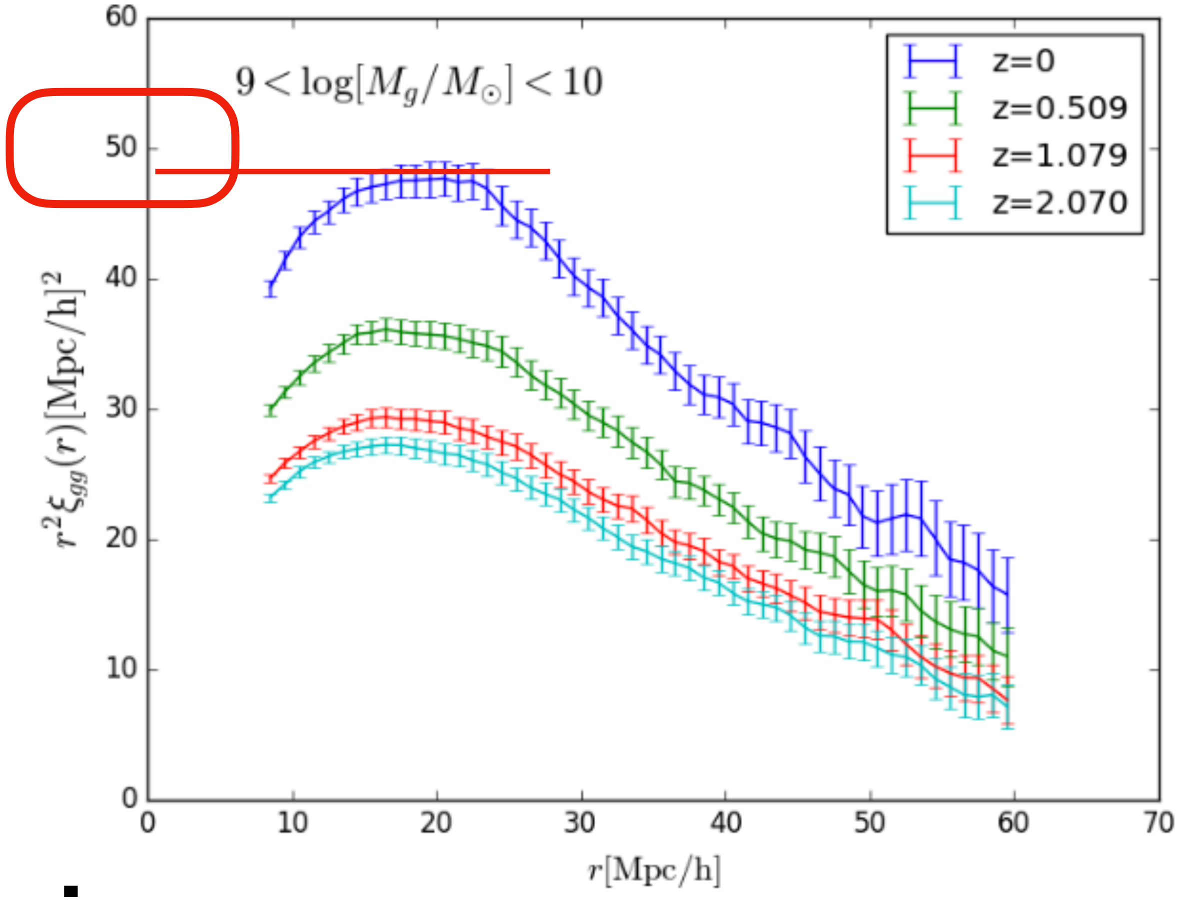


$$\xi(r) = \frac{DD(r) - RR(r)}{RR(r)}$$

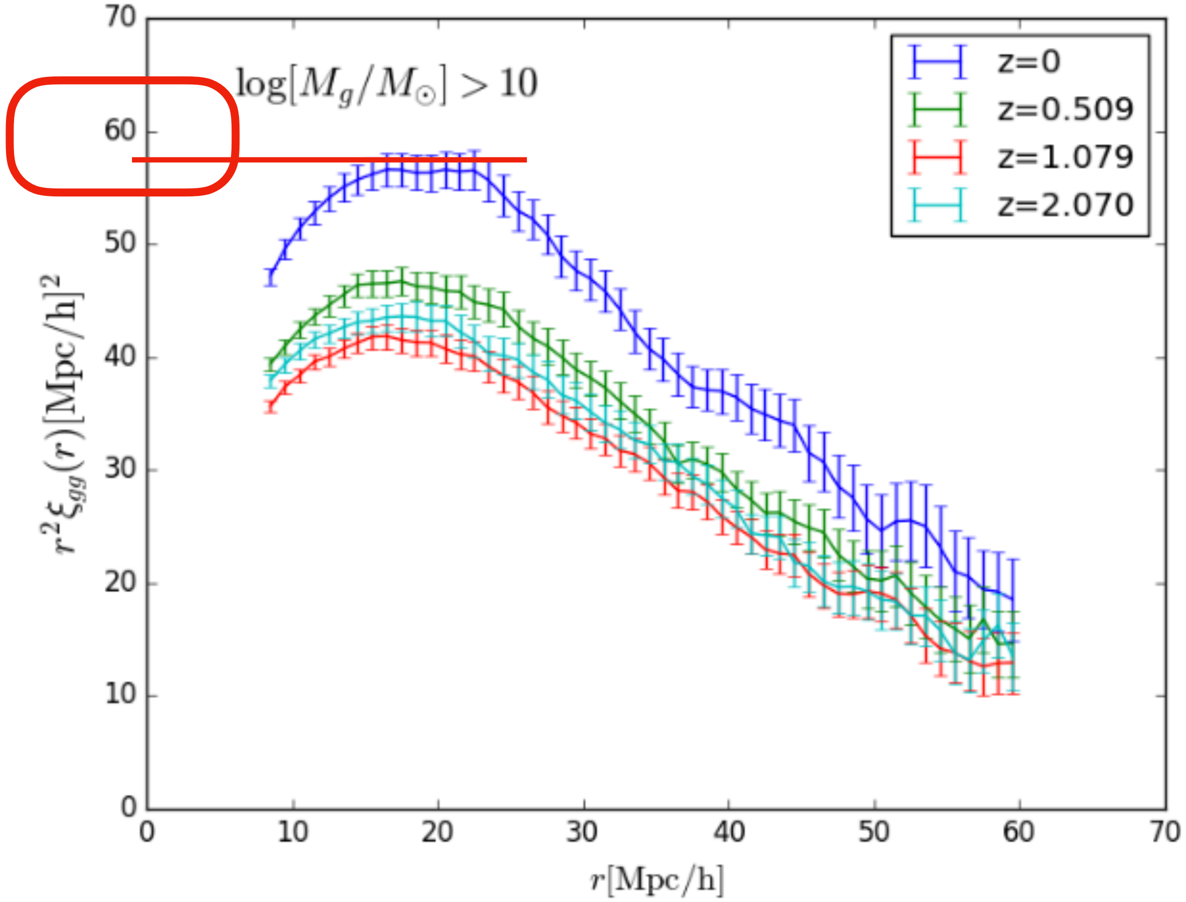
1. Clustering is enhanced in the lower redshift

2. Clustering is enhanced with mass increasing

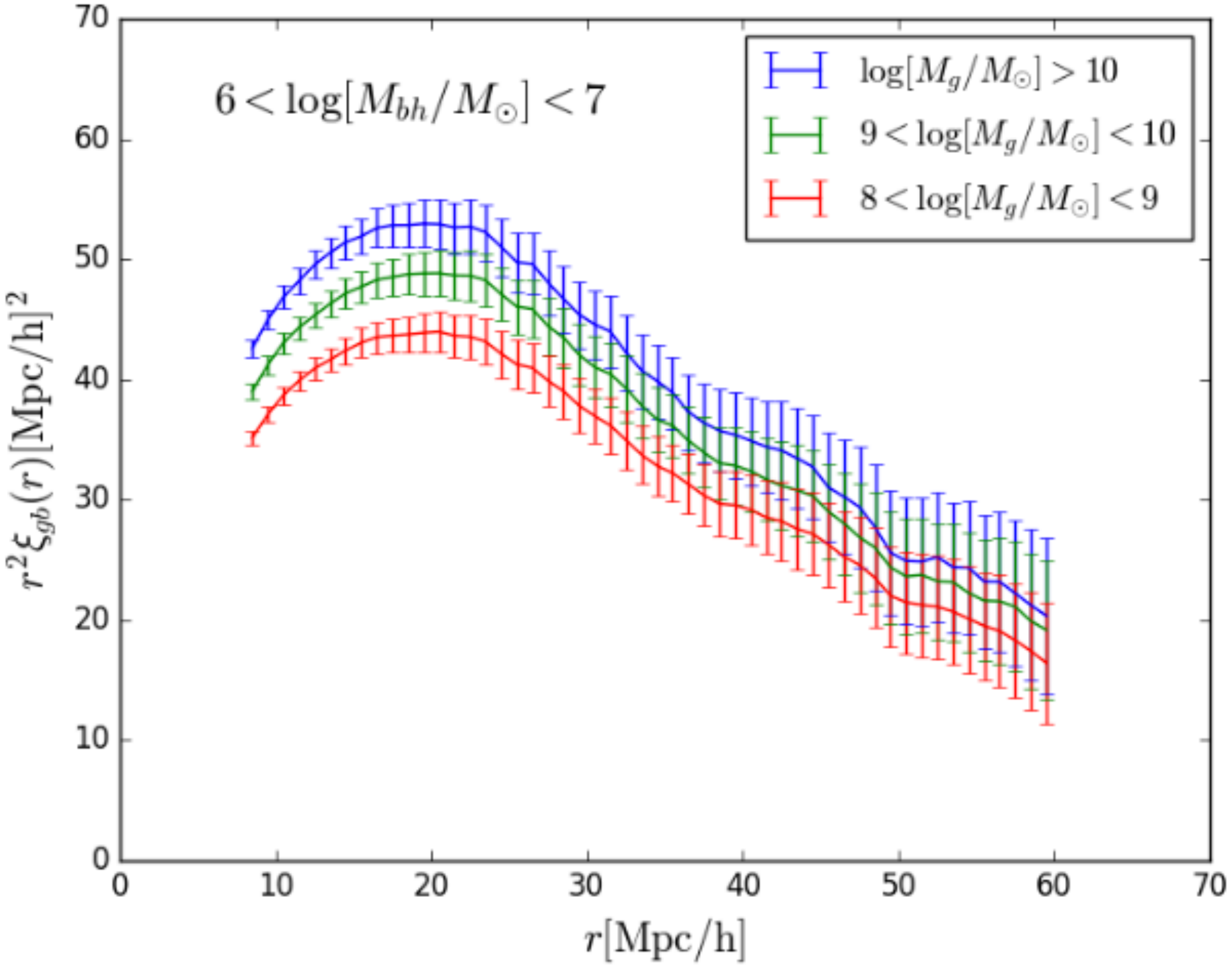


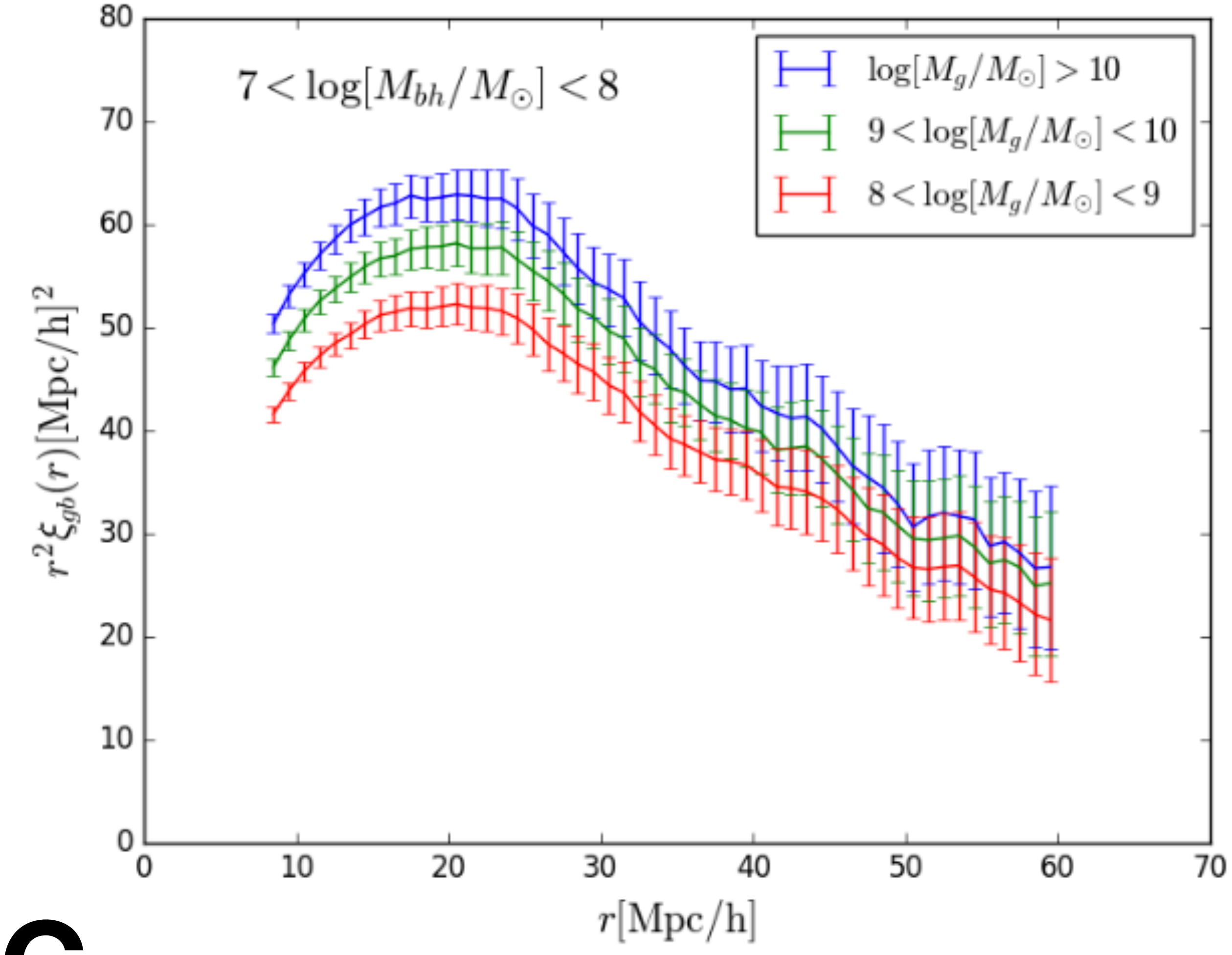


Galaxies

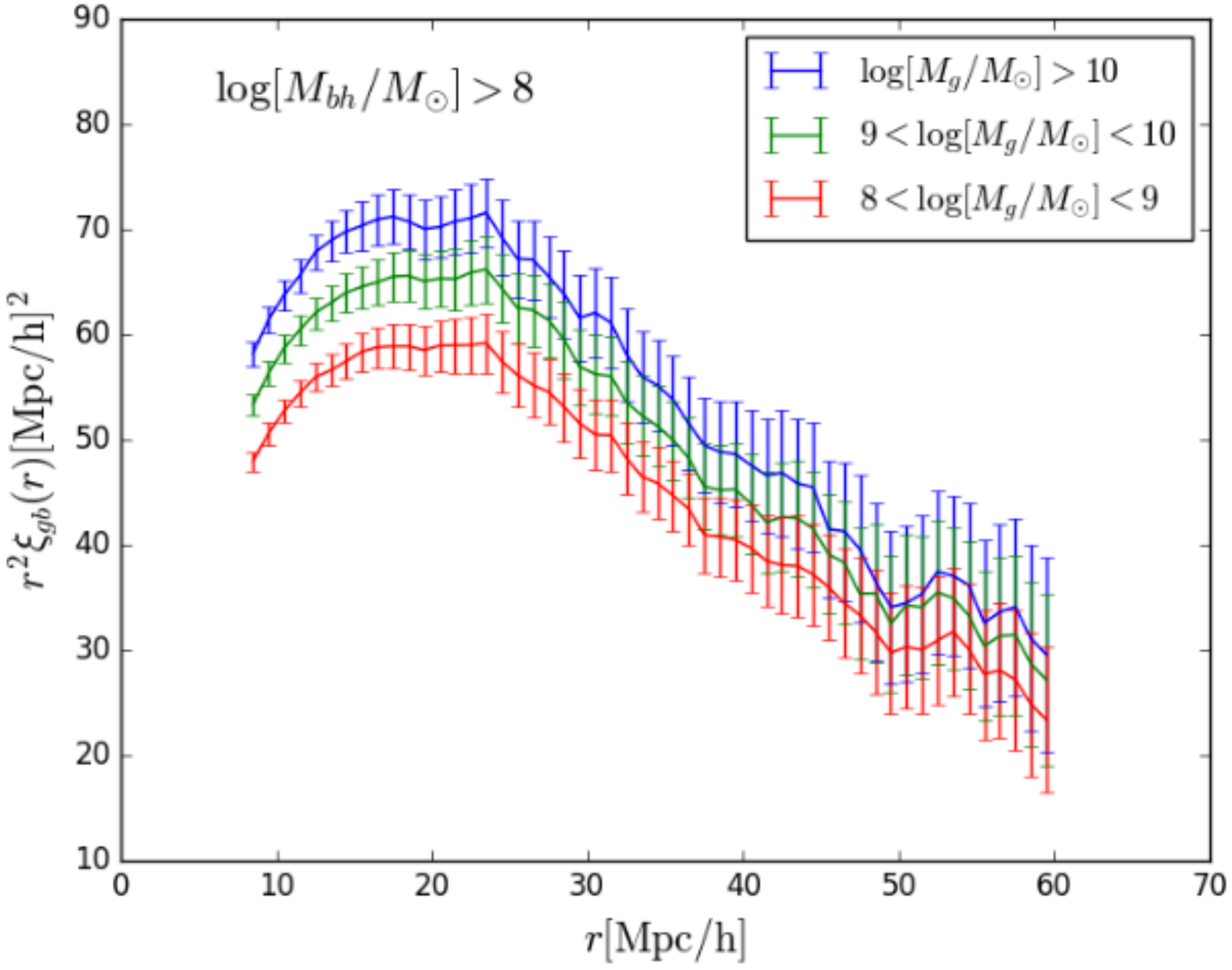


Same as BHs


$6<\log[M_{bh}/M_\odot]<7$
$\log[M_g/M_\odot]>10$
$9<\log[M_g/M_\odot]<10$
$8<\log[M_g/M_\odot]<9$
$r^2\xi_{gb}(r)[\mathrm{Mpc/h}]^2$
$r[\mathrm{Mpc/h}]$
0
10
20
30
40
50
60
70


$7<\log[M_{bh}/M_\odot]<8$
$\log[M_g/M_\odot]>10$
$9<\log[M_g/M_\odot]<10$
$8<\log[M_g/M_\odot]<9$
$r^2\xi_{gb}(r)[\mathrm{Mpc/h}]^2$
$r[\mathrm{Mpc/h}]$
0
10
20
30
40
50
60
70
80

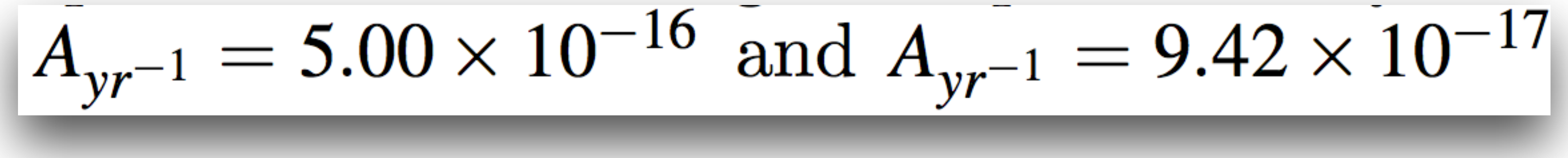
XC


$\log[M_{bh}/M_\odot]>8$
$\log[M_g/M_\odot]>10$
$9<\log[M_g/M_\odot]<10$
$8<\log[M_g/M_\odot]<9$
$r^2\xi_{gb}(r)[\mathrm{Mpc/h}]^2$
$r[\mathrm{Mpc/h}]$
0
10
20
30
40
50
60
70
80
90

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!