Co-evolution of super massive BHs with galaxies

—stochastic GWB & galaxy clustering

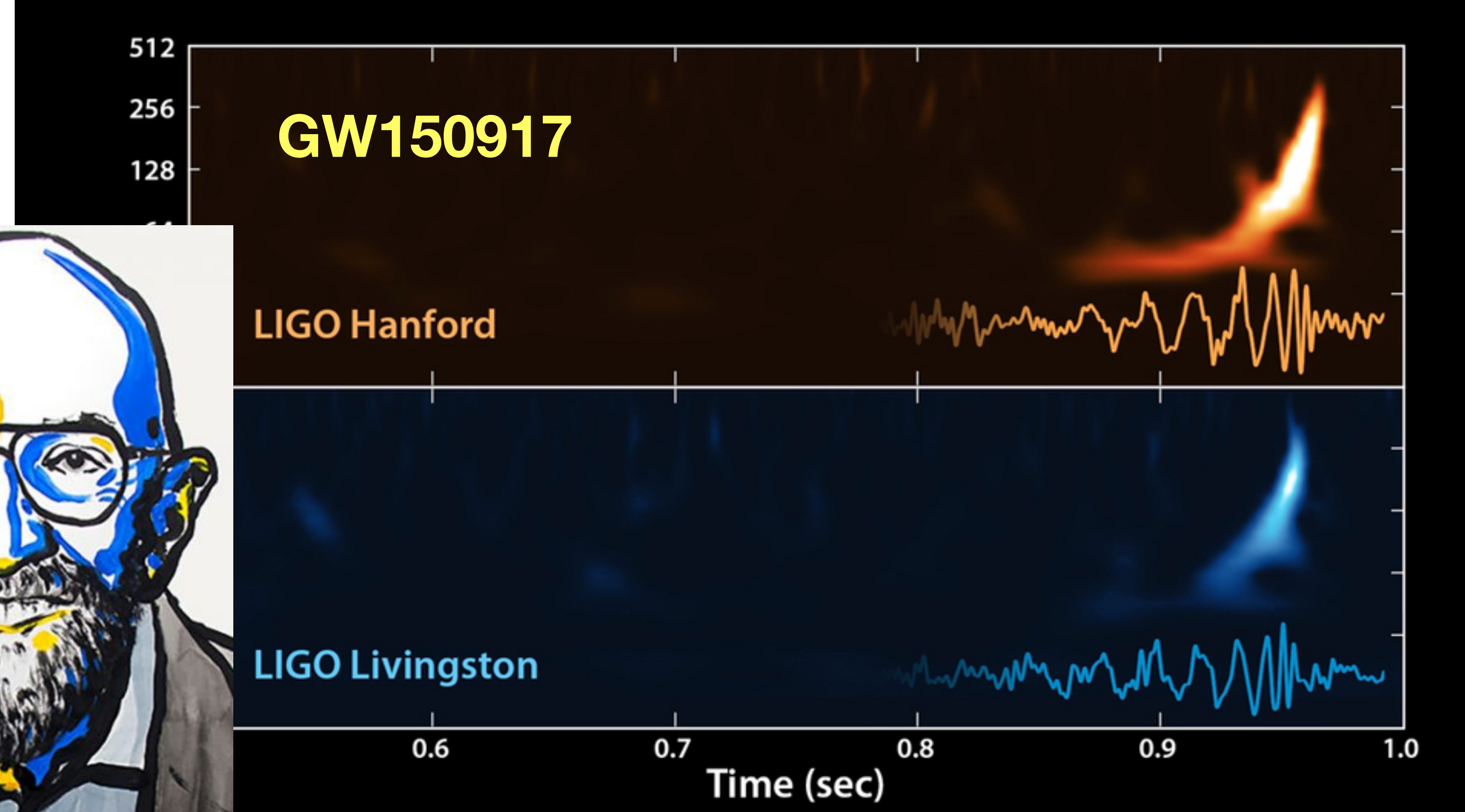
[arXiv:1802.03925]

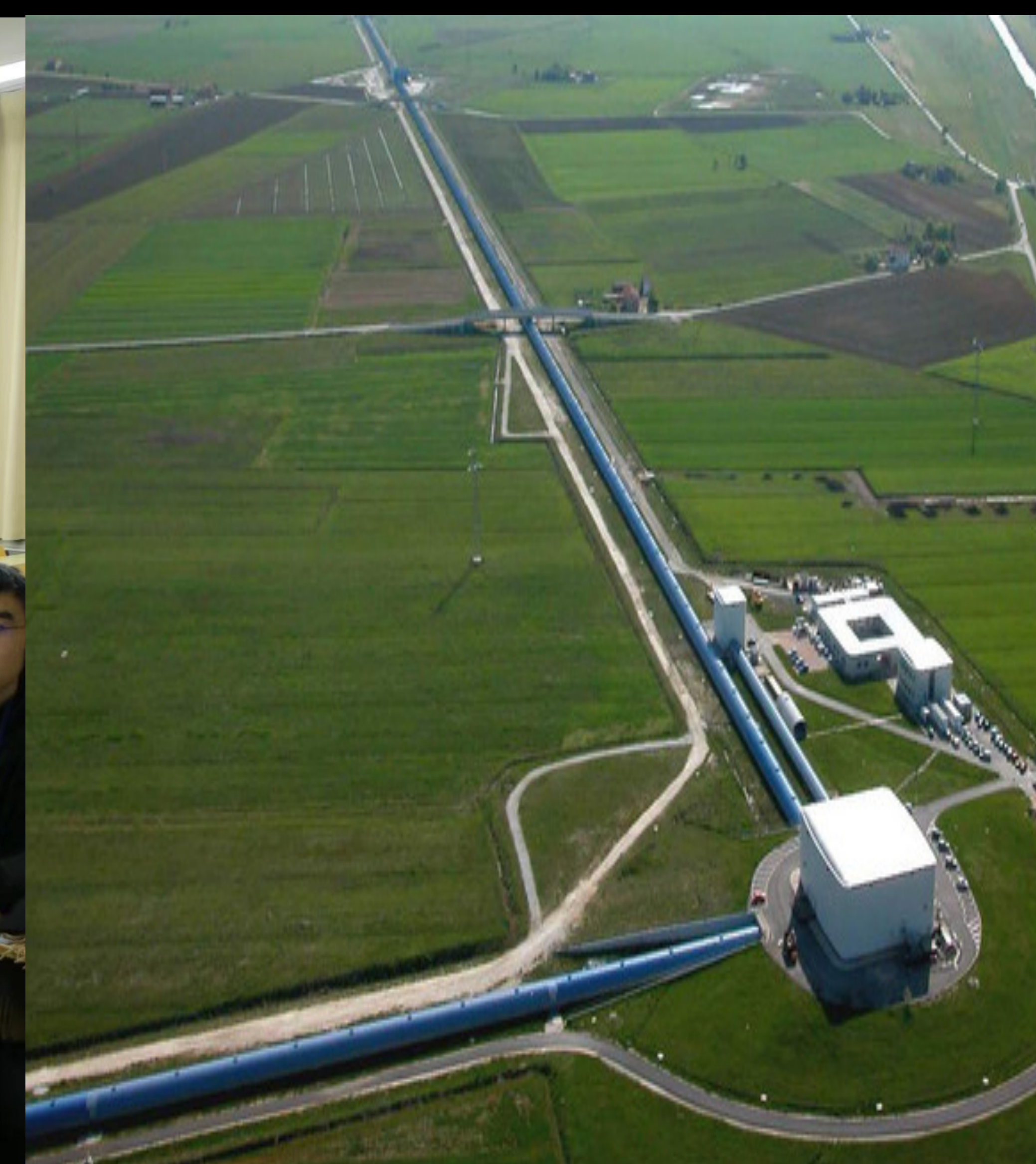
w. Qing Yang@BNU
Xiao-Dong Li@SYSU

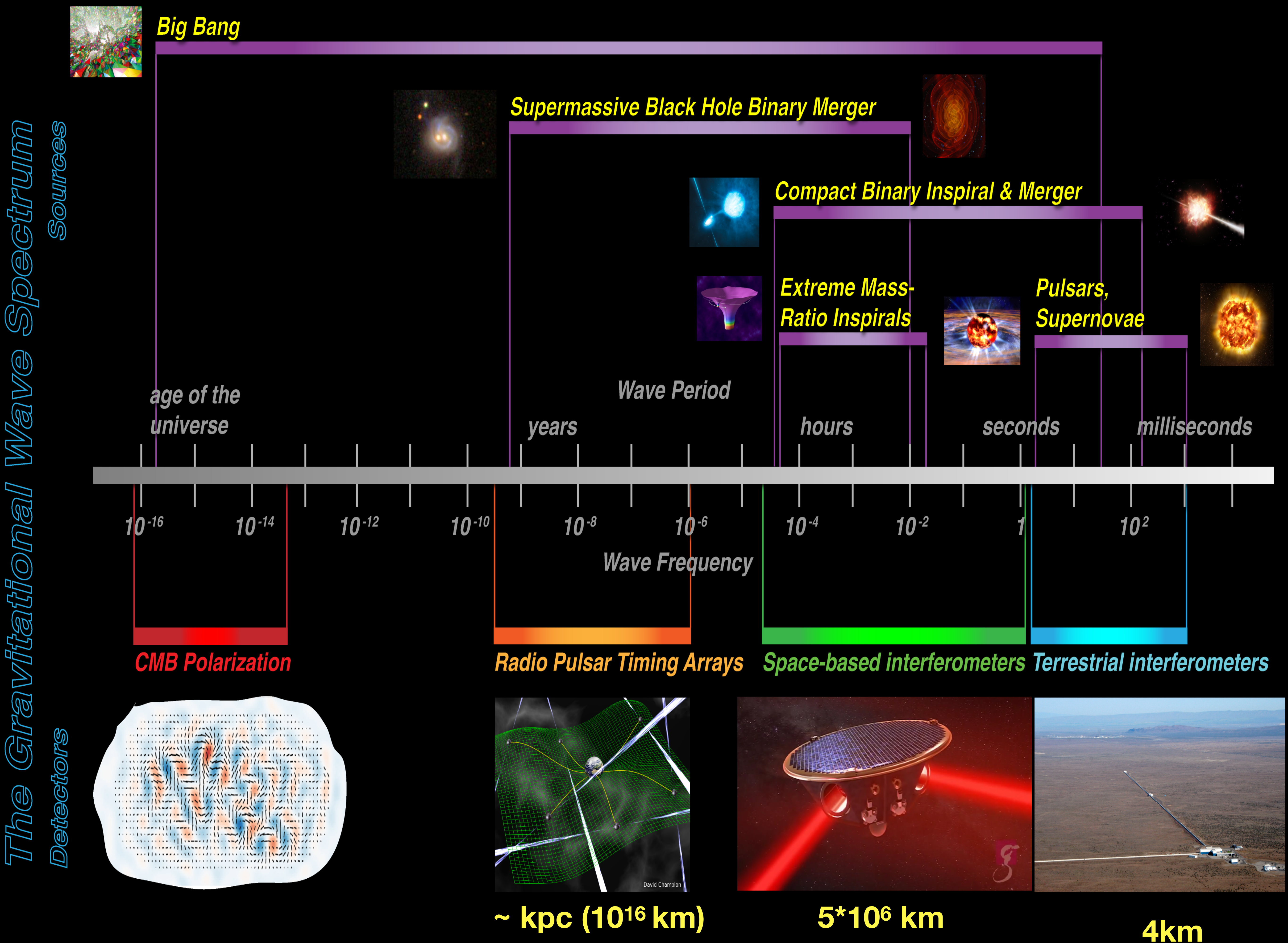
Bin HU @ BNU

2018/07 Leiden

Nobel Prize in Physics 2017






The Gravitational Wave Spectrum
Sources
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
age of the universe
Wave Period
years
hours
seconds
milliseconds
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
1
102
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers
Detectors
~ kpc (1016 km)
5*106 km
4km

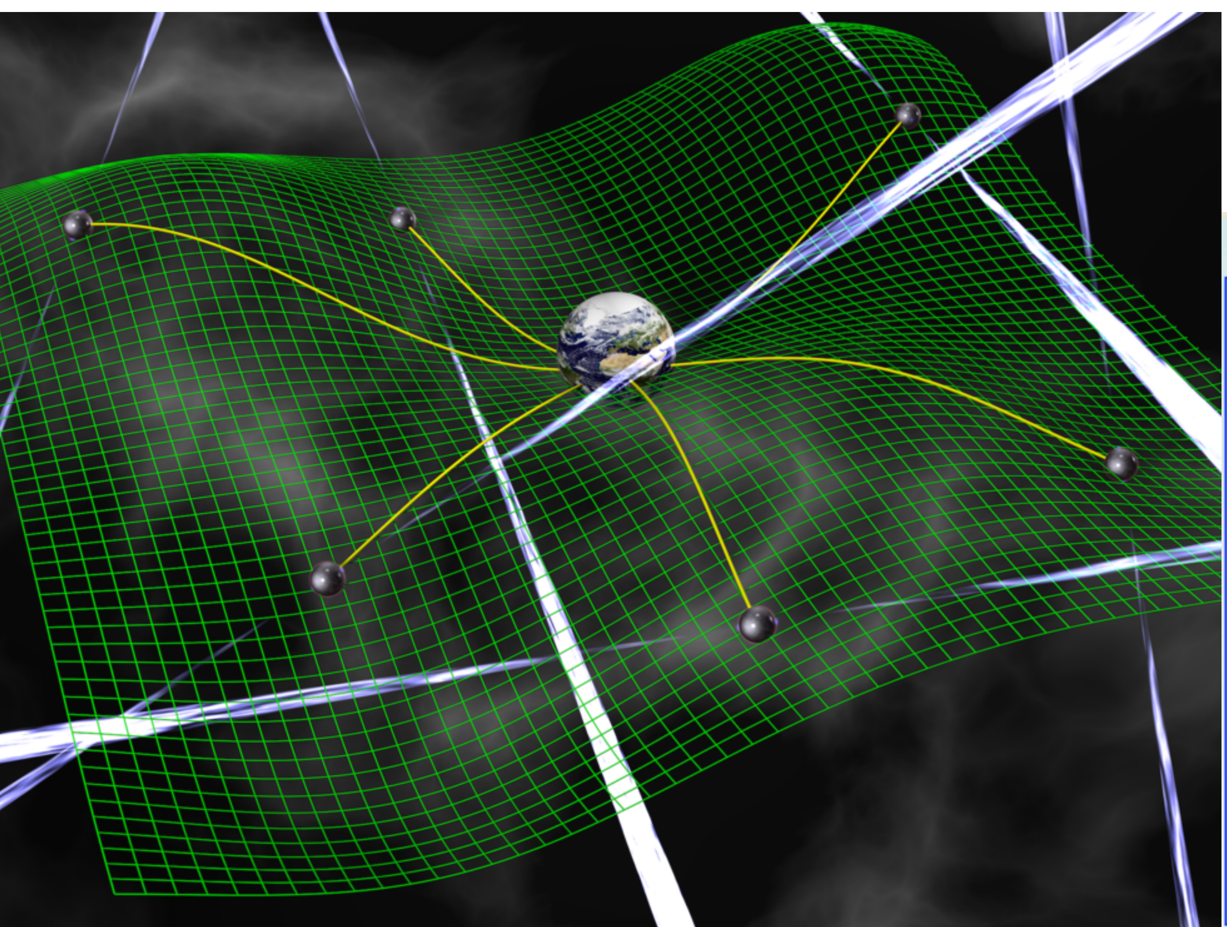
Gravitational Wave Background

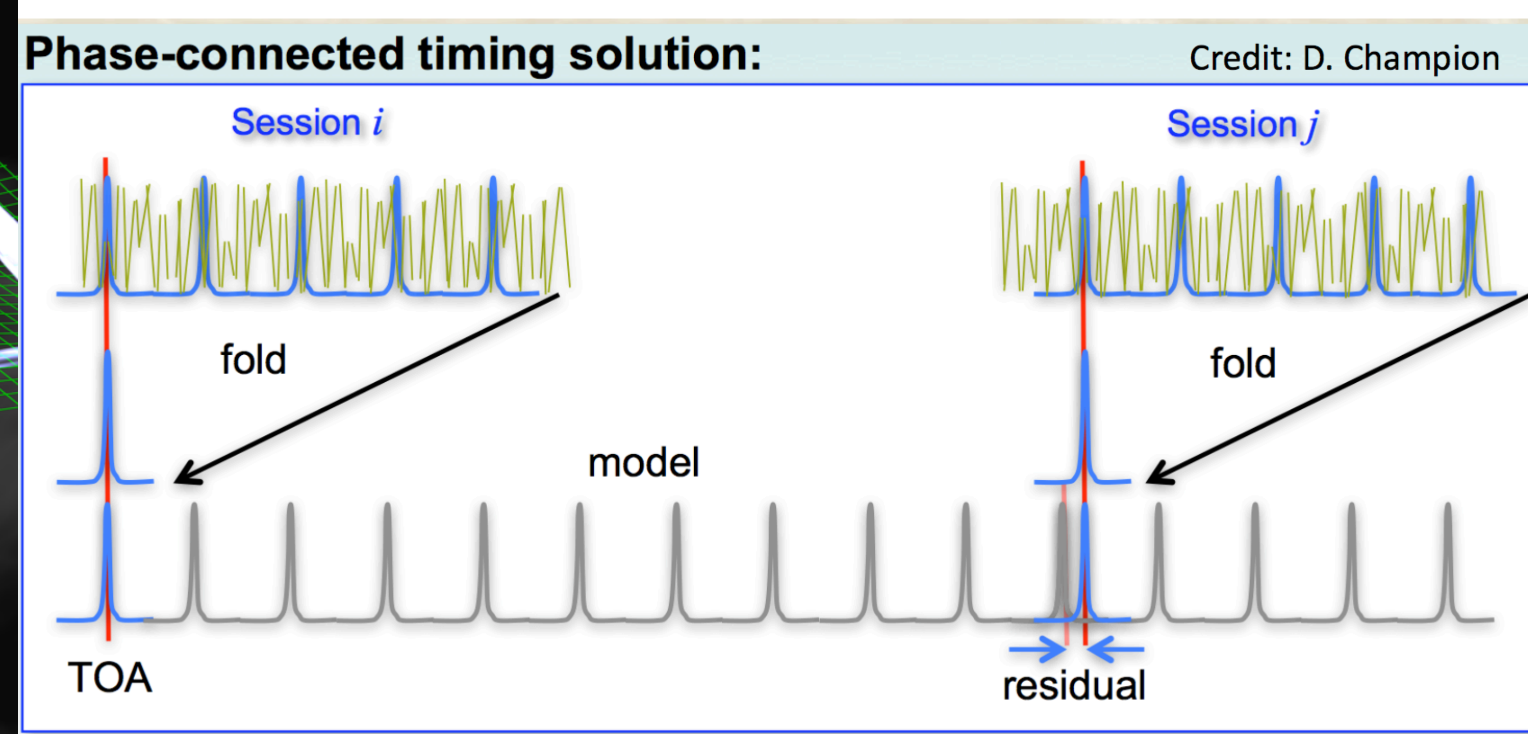
- **Frequency: 10^{-9} ~10^{-6} Hz** (typical orbit period ~ a few yrs)

- **Source: Supermassive Black Hole Binary merger**

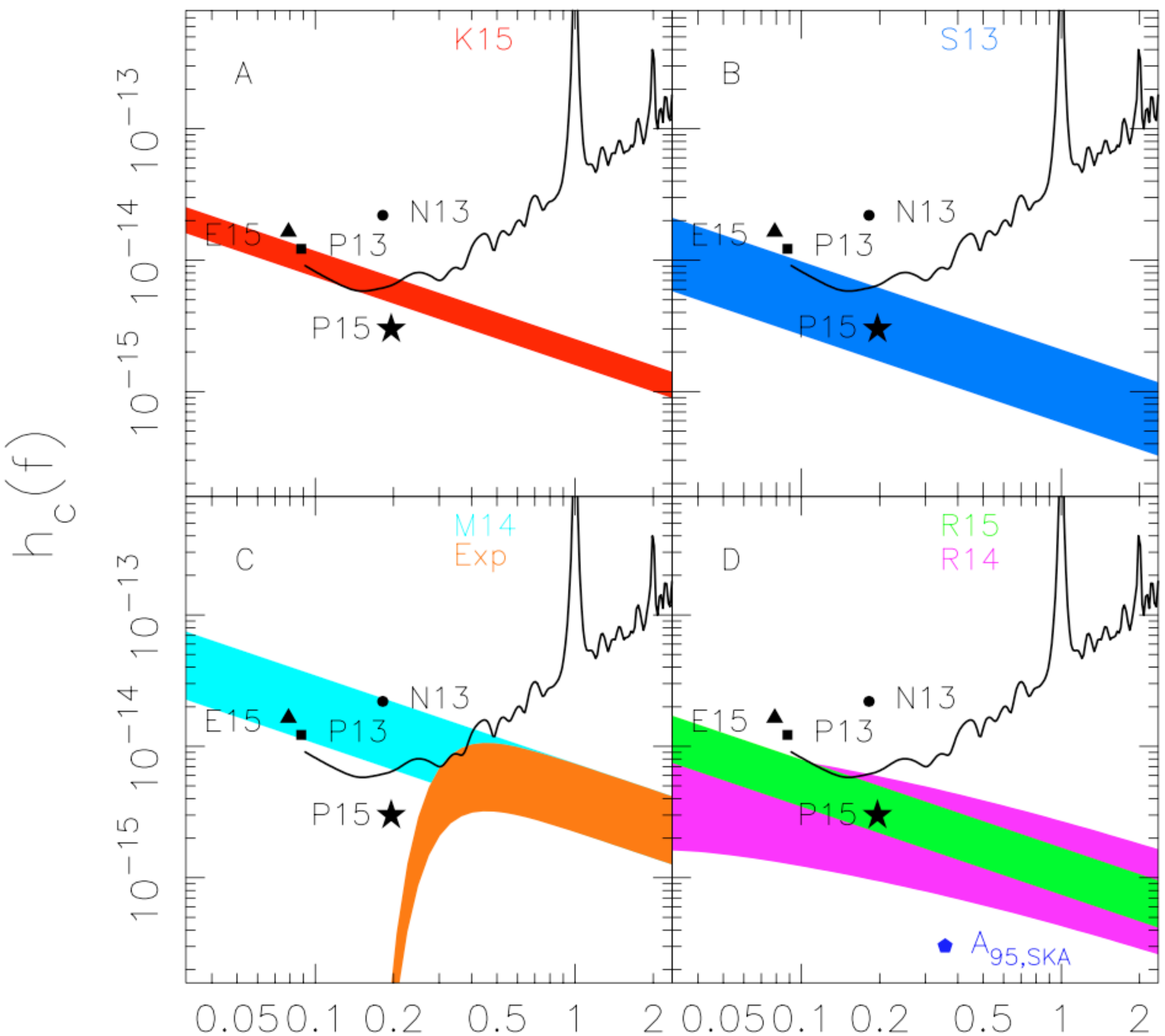
- **Detection method: Pulsar Time Array (Radio astronomy)**
PPTA (Australia), EPTA (Europe), NanoGrav (North American)

Not Yet Detected!





isotropic signal (monopole)

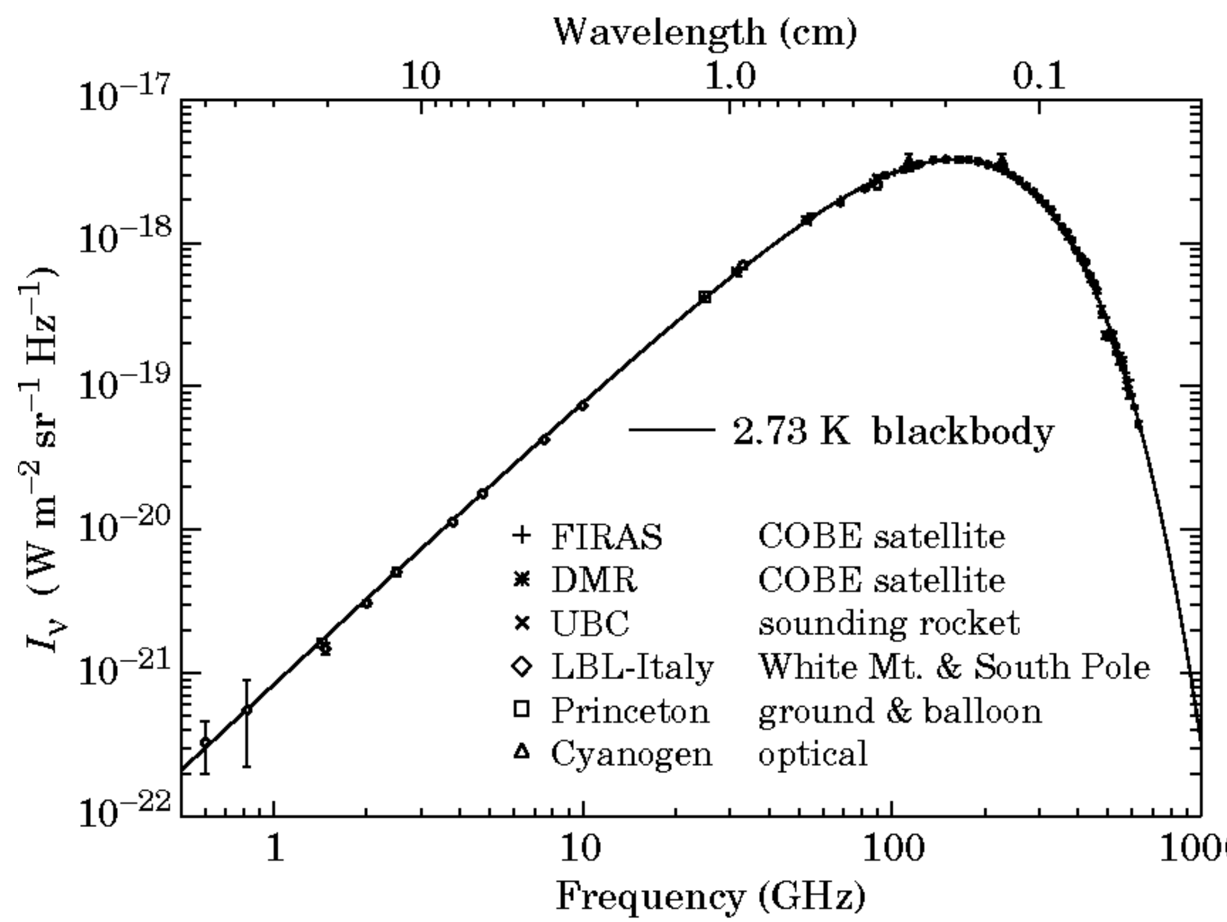


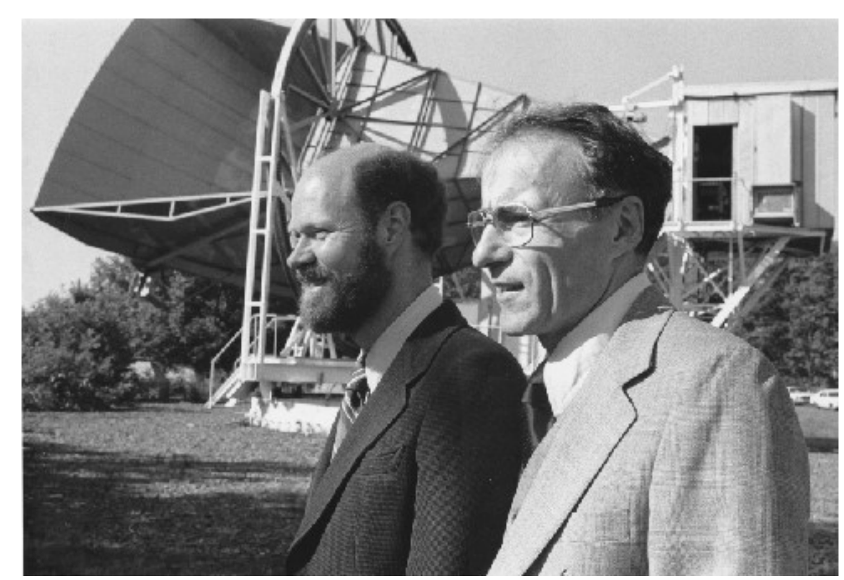
[from PPTA 2105]

$$h_c \sim A \times f^{-2/3}$$

upper bound: $A \sim 10^{-15}$

CMB monopole ~3K (1964)





$$\frac{\sigma_{\rm gw}(f)}{\mu_{\rm gw}(f)} \approx 3\times10^{-3}\left(\frac{f}{10^{-8}\,{\rm Hz}}\right)^{11/6}\left(\frac{5\,{\rm yr}}{T_{\rm obs}}\right)^{-1/2}\left(\frac{l}{2}\right)^{1/2}\alpha^{1/2}, \approx 0.2\left(\frac{f}{10^{-7}\,{\rm Hz}}\right)^{11/6}\left(\frac{5\,{\rm yr}}{T_{\rm obs}}\right)^{-1/2}\left(\frac{l}{2}\right)^{1/2}\alpha^{1/2}. \quad (29)$$

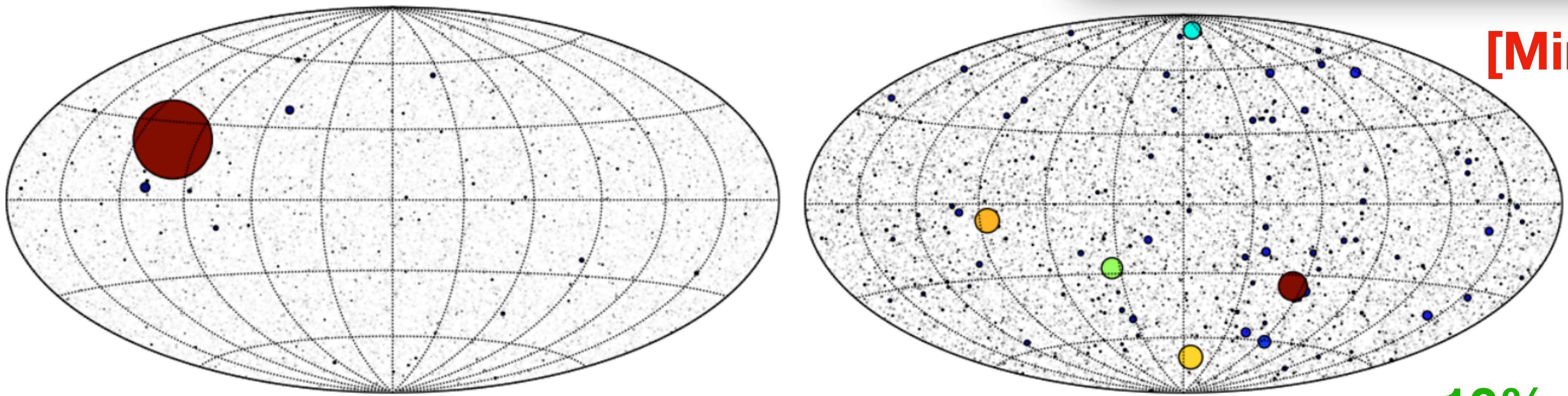
anisotropic signal

[Taylor & Gair 1306.5395]

[Mingarelli et. al. 1306.5394]

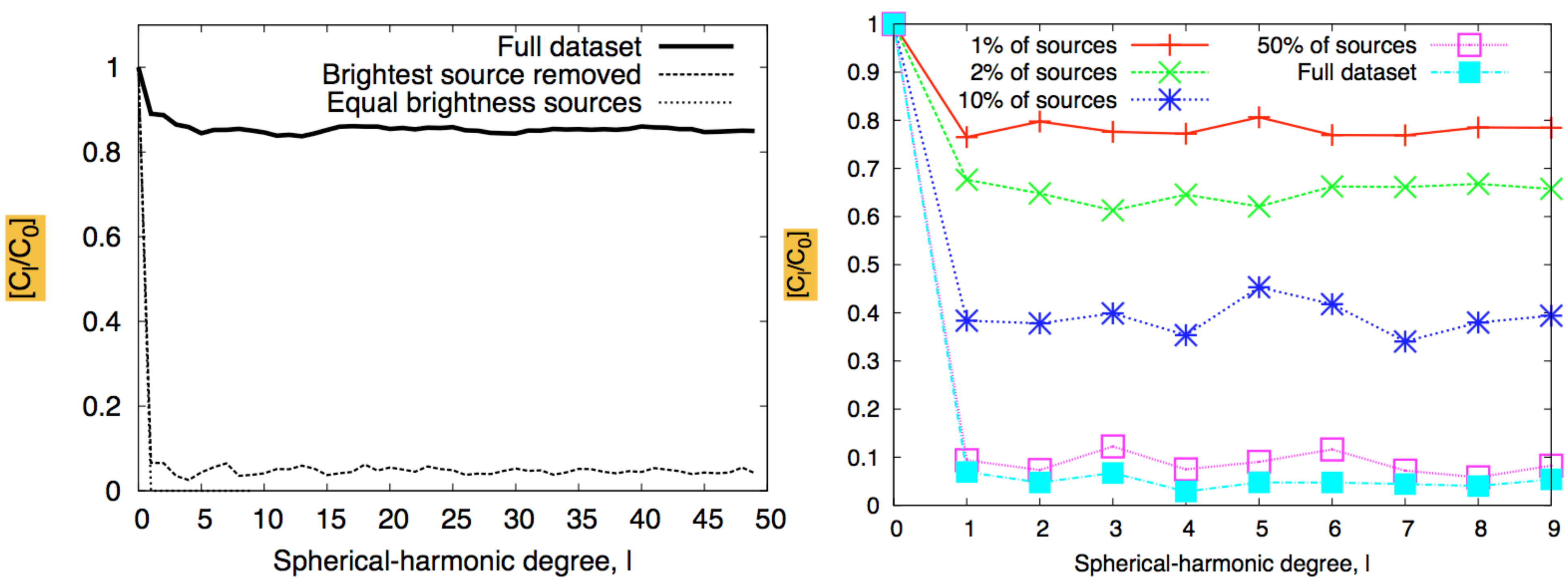
Assuming:
const merger rate
& const source mass

~10% @ high freq. & small scale



(a) (b)

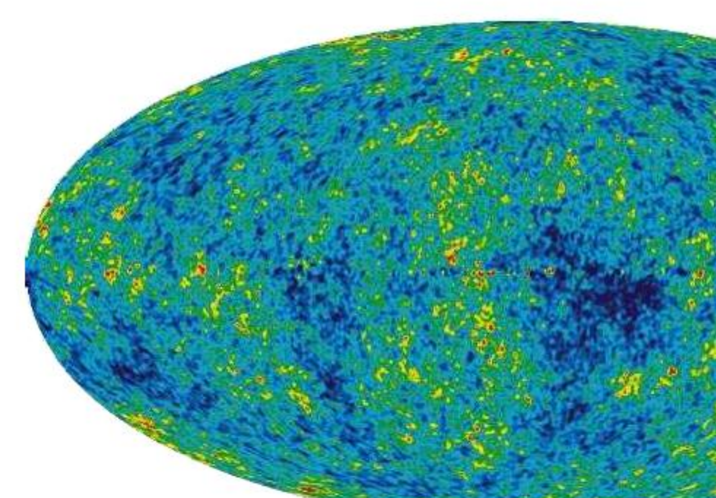
FIG. 1: Skymaps of GW source-populations generated by evolving a population of SMBHB systems. There are $\sim 2\times10^4$ systems in each catalogue, which are typically massive ($10^7 - 10^{10} M_\odot$) and close ($z < 2$). The relative size and colour of points within each skymap is indicative of the GW energy-flux from each system. The GW signal from the first dataset in (a) is clearly dominated by one very bright source. In the second dataset (b) we have several bright sources, however no outliers as in the first dataset.



(a) (b)

CMB anisotropy

$$C_\ell \sim 10^{-5}\times\ell^{-2}$$



Existence of SMBH

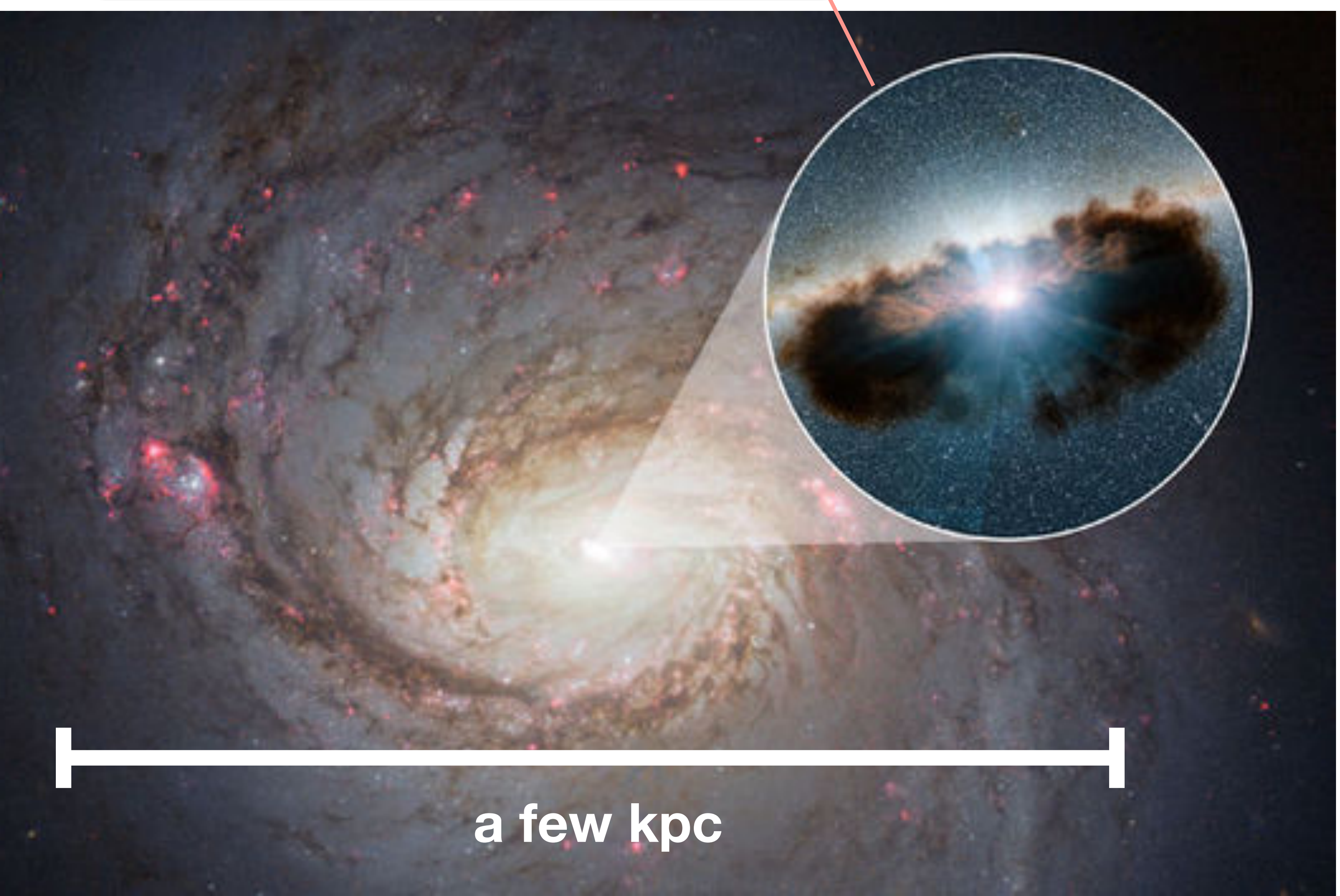
galaxy formation model theoretically pred:
Almost every galaxies, host centre SMBHs

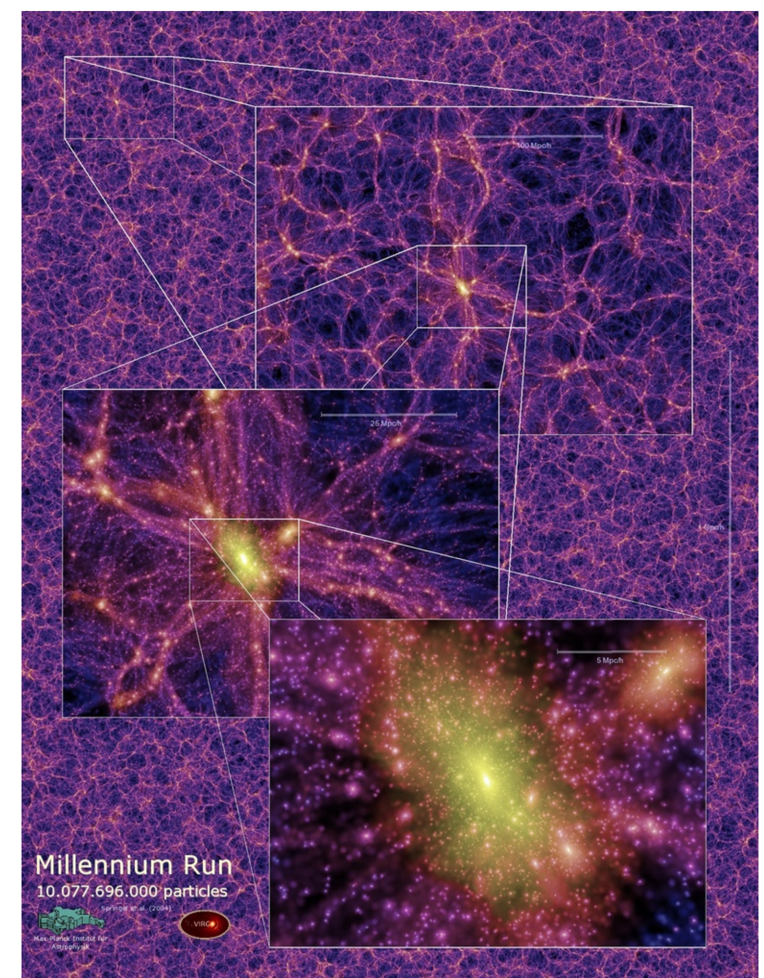
SMBH	Mass	Radius
Wilky Way **Sagittarius A***	**10^6 M_solar**	10^{-7}pc
Andromeda	**10^8 M_solar**	10^{-5}pc
NGC 4889	**10^{10} M_solar**	10^{-3}pc

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

(L~500^3 Mpc^3)

8668809 SMBHs,
51538704 galaxies
in total

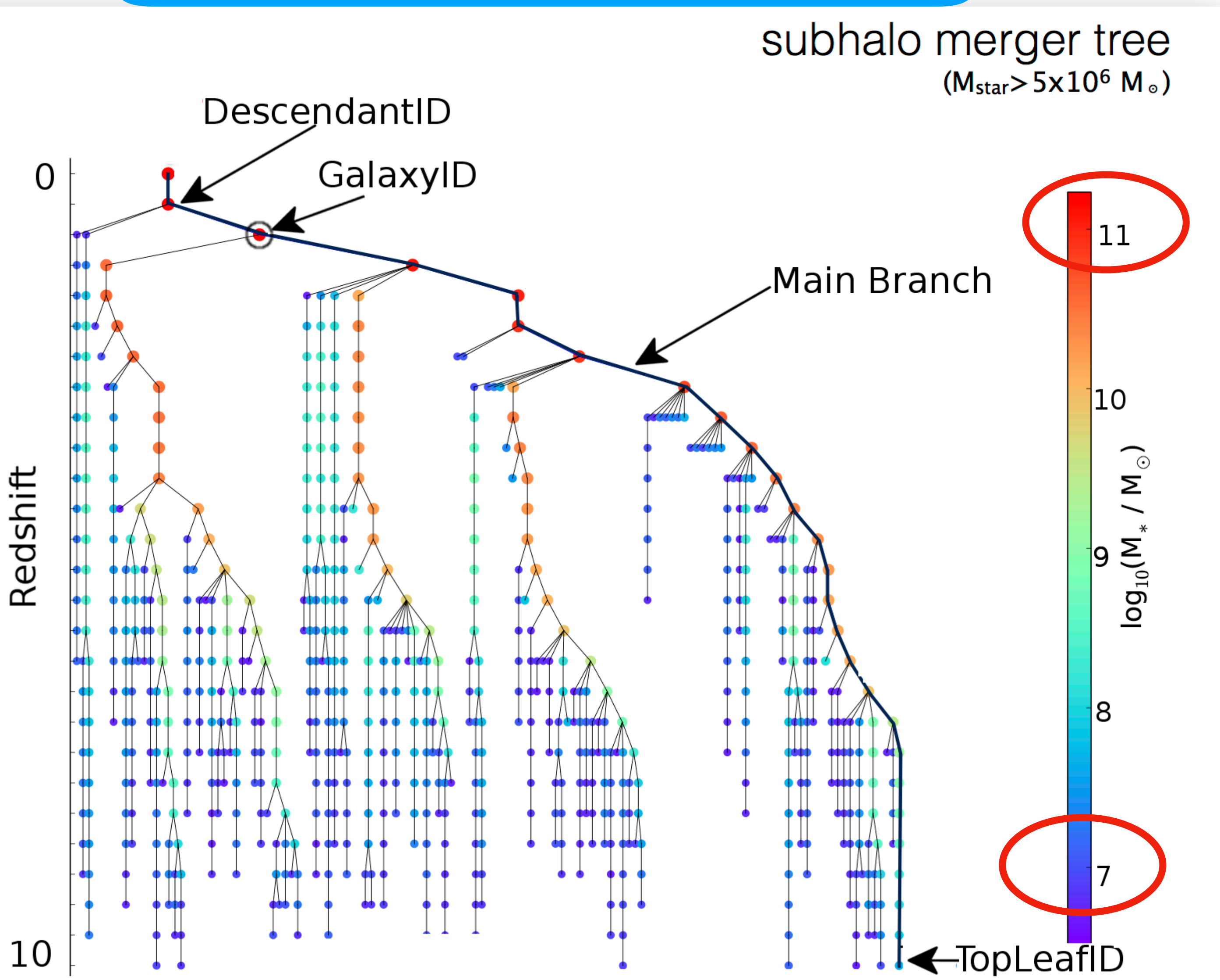


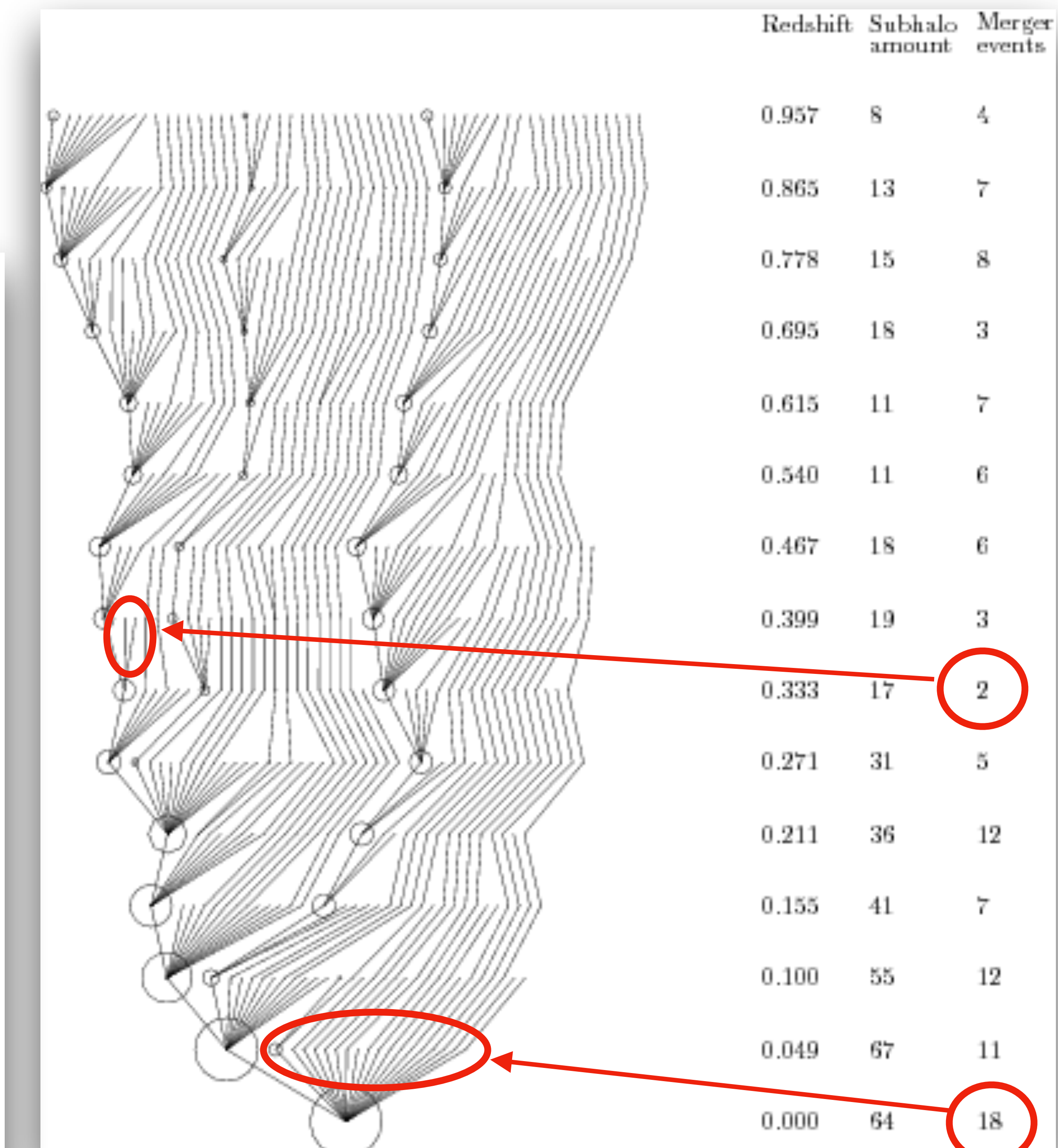


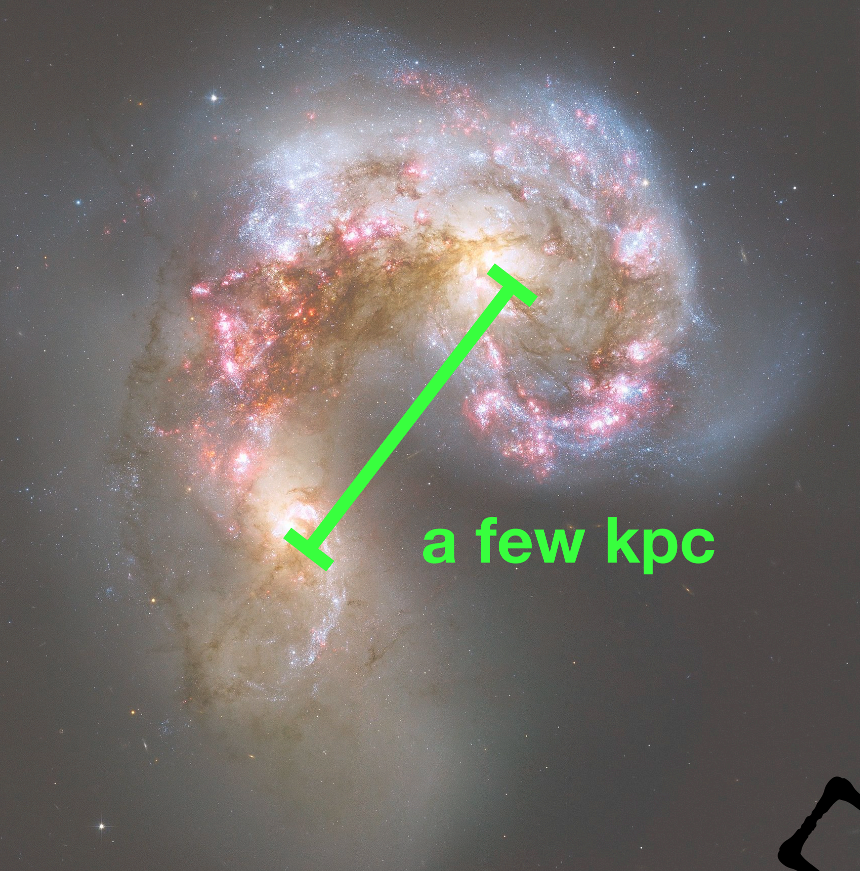
On average, 2 galaxies are separated ~ a few Mpc ~(10 or 100) times of galaxy size

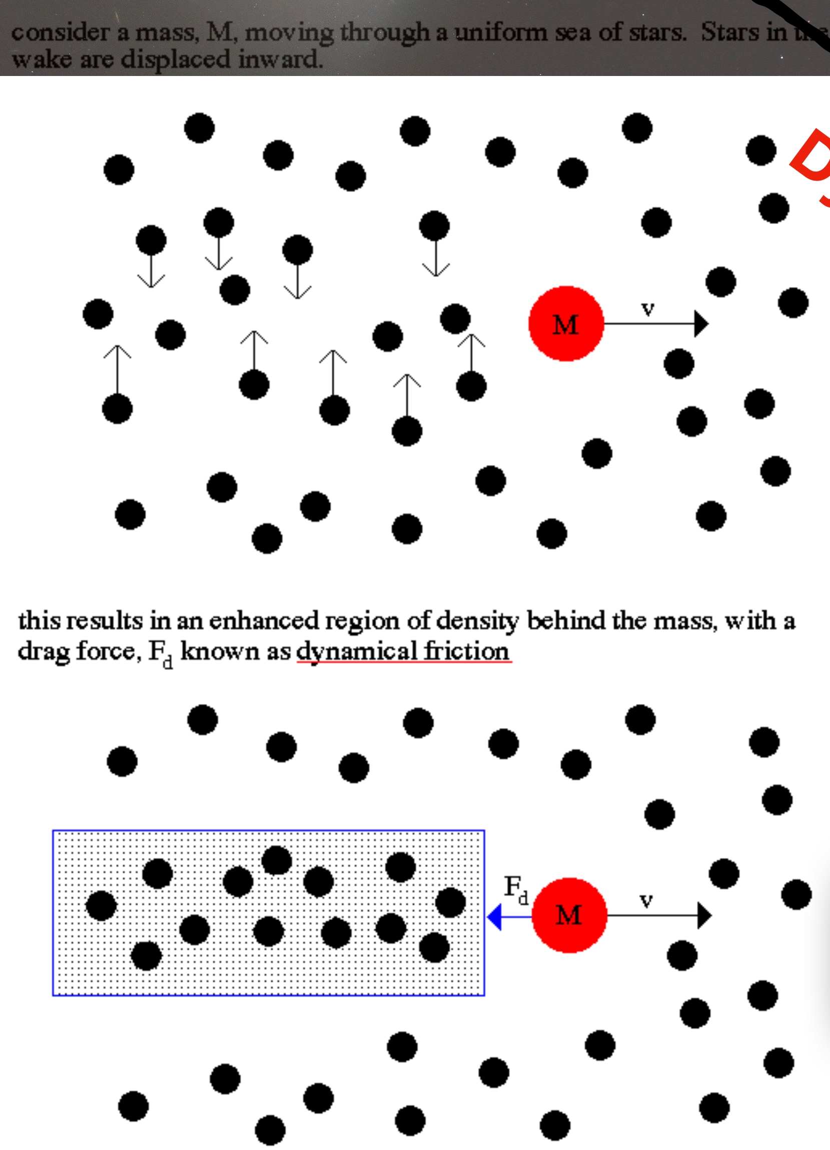
merger event is very possible!

merger is major channel for the galaxy gaining mass

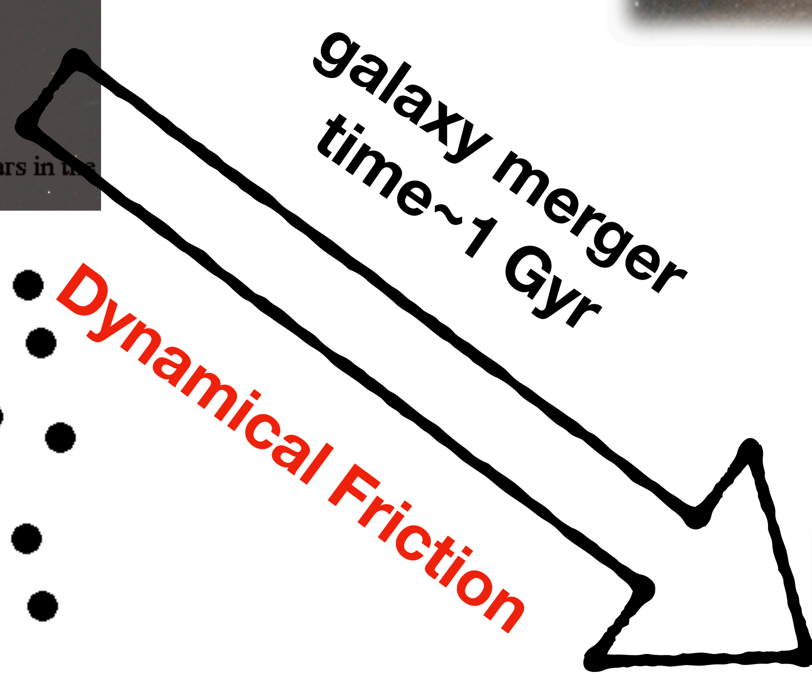




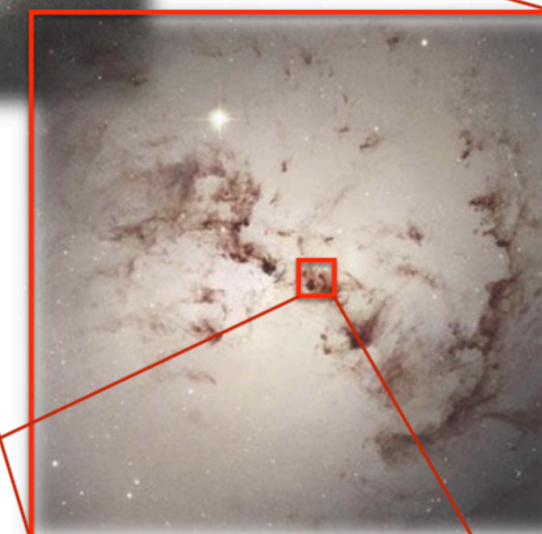


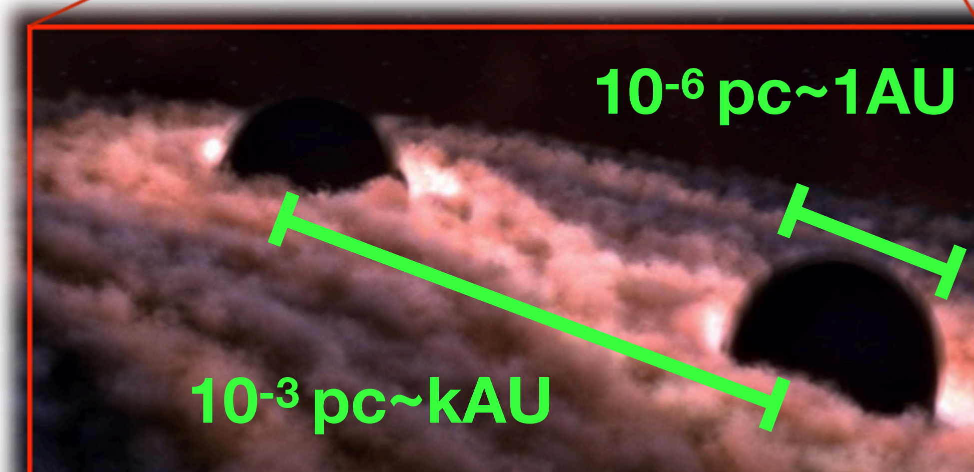


$$\frac{dv}{dt} = -\frac{2\pi G^2(M+m)\rho}{v^2}\ln\Lambda$$

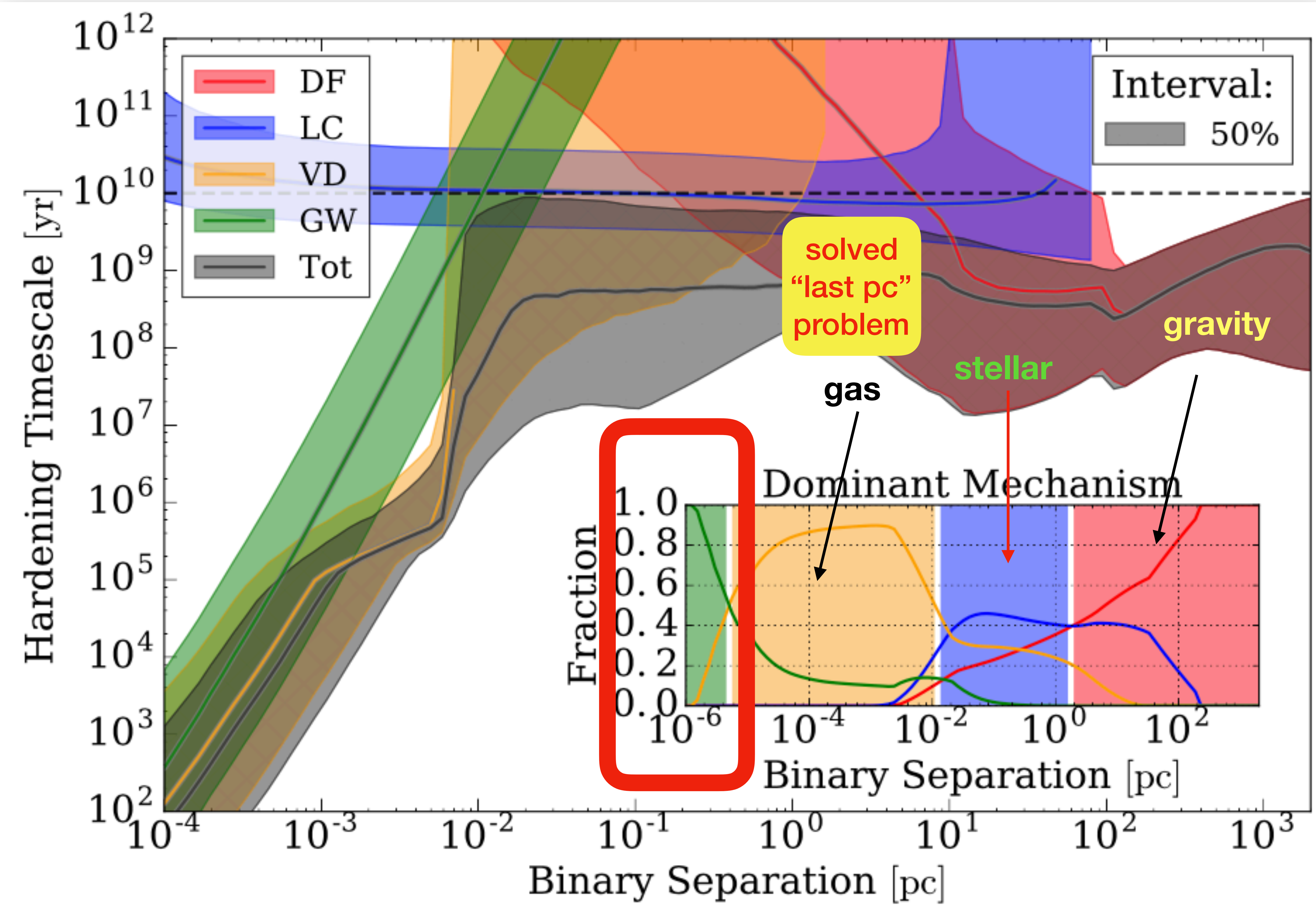


[Credit: Kelley]



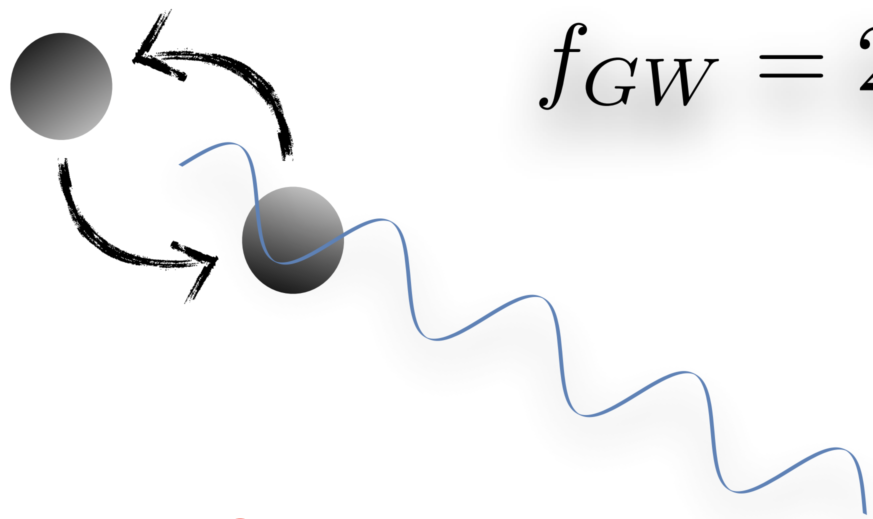


merger time with GW ~ a few Myr



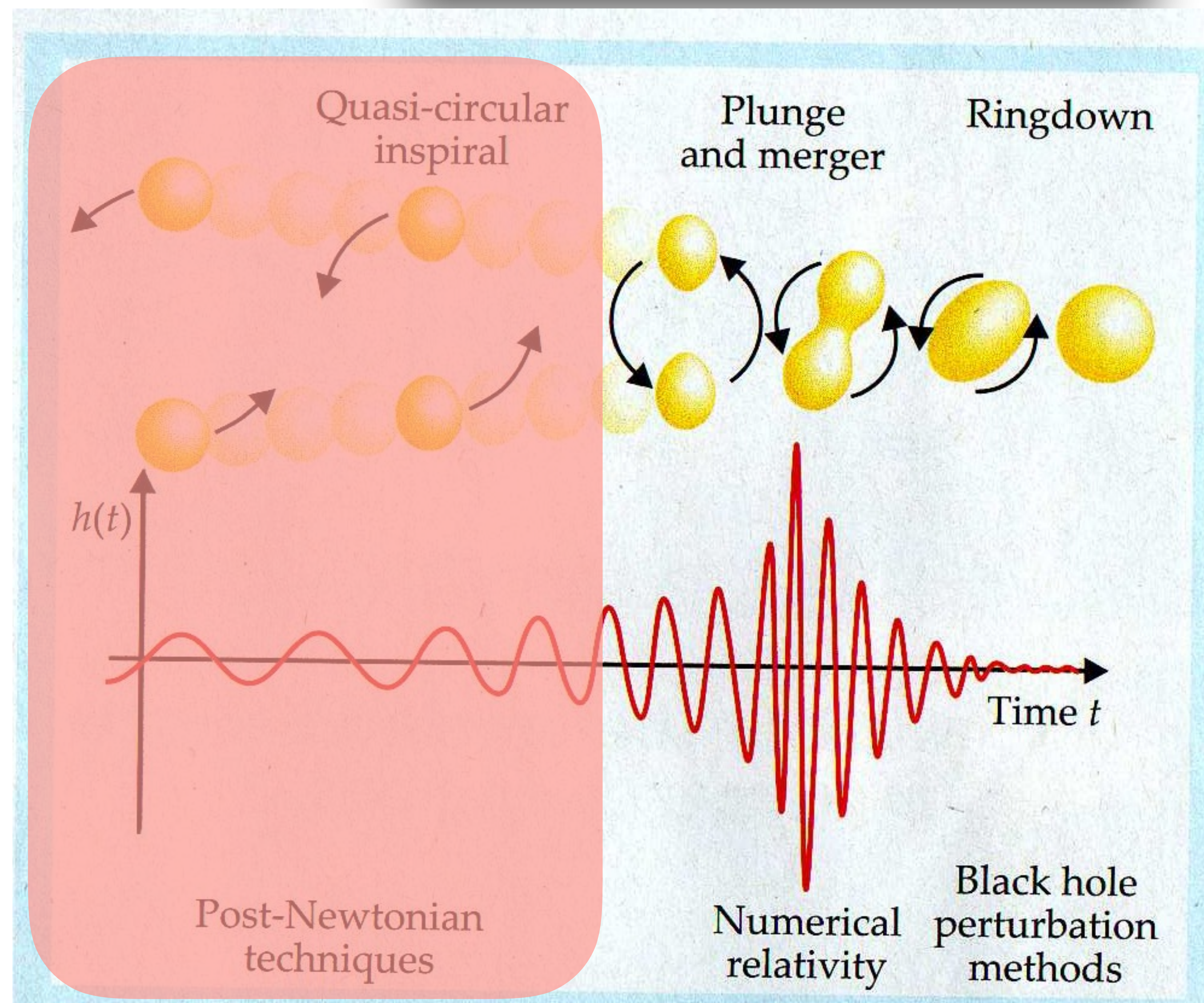
[Kelley, Blecha, Hernquist, 2017]

Single binary ~ circular orbit, Quadrupole formula is enough!



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

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



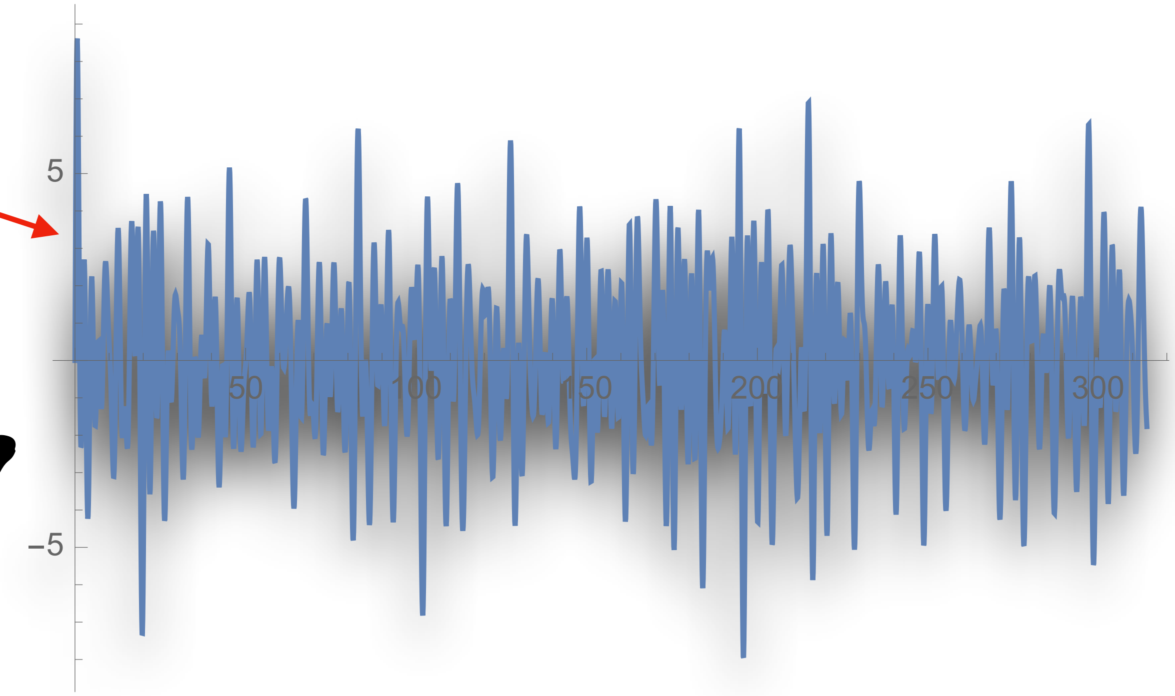
We can NOT observe the inspiral phase, except it is very very nearby!

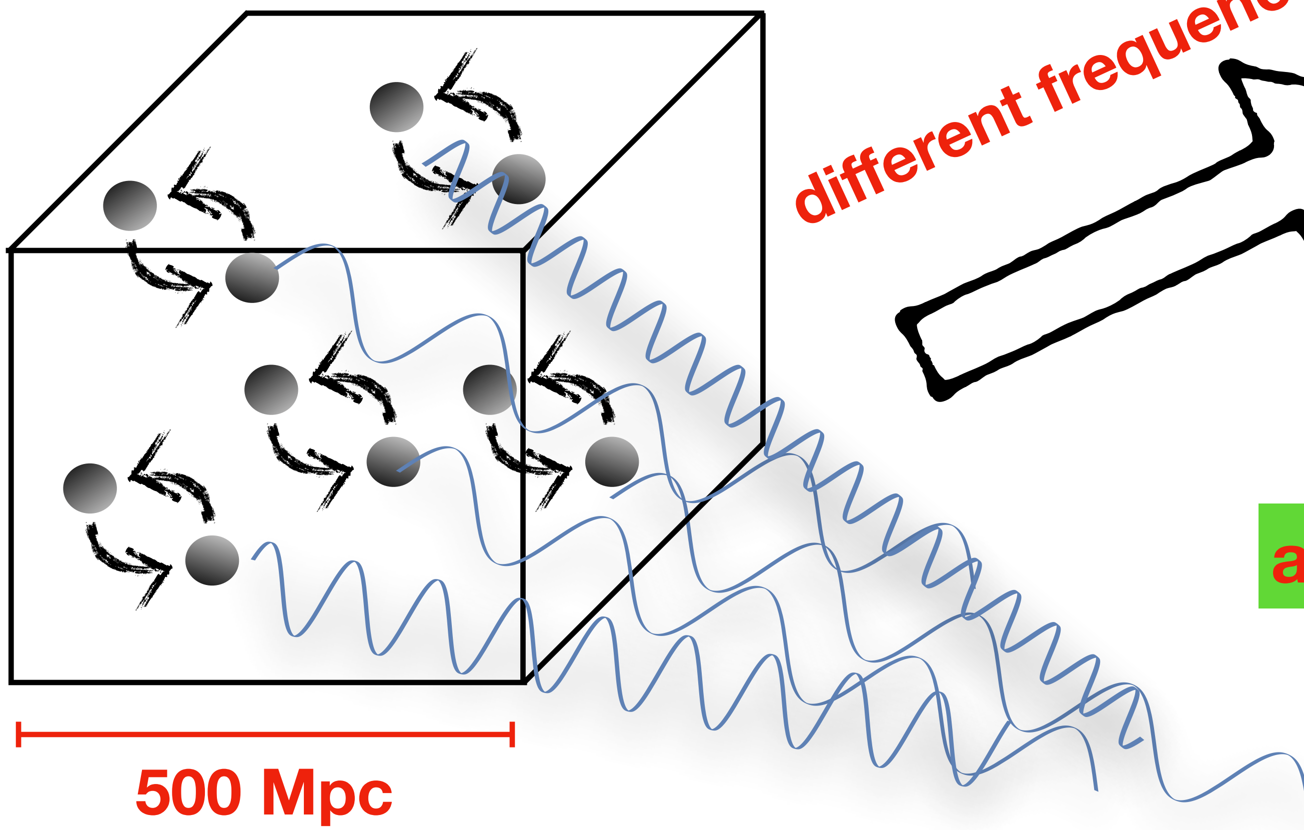
Sine wave form

[Credit: 蔡少芬 & wangyi]

Multi-binaries → **GWB**

GW signal we want! (noise-like)





different frequencies

Stochastic in time sequence!

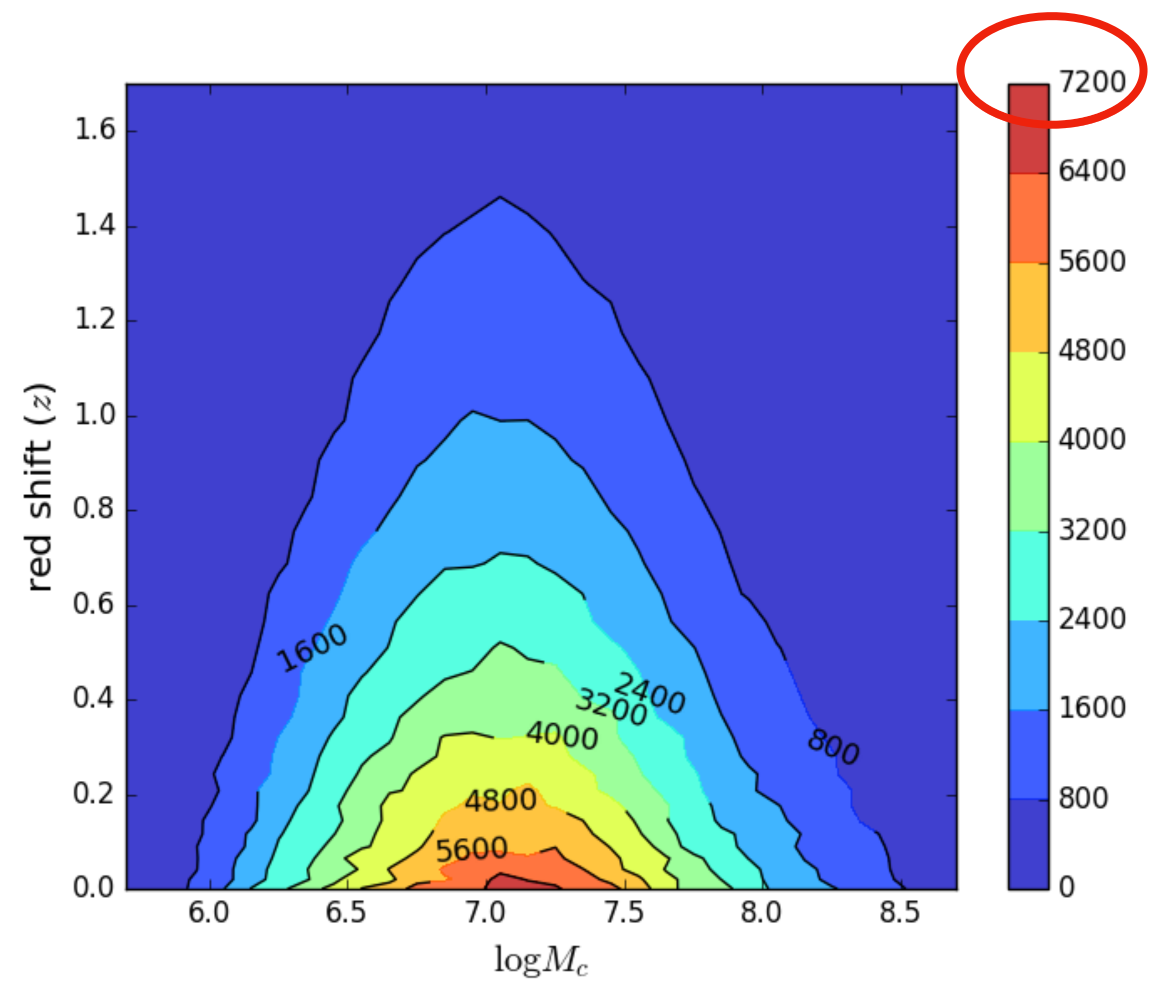
500 Mpc

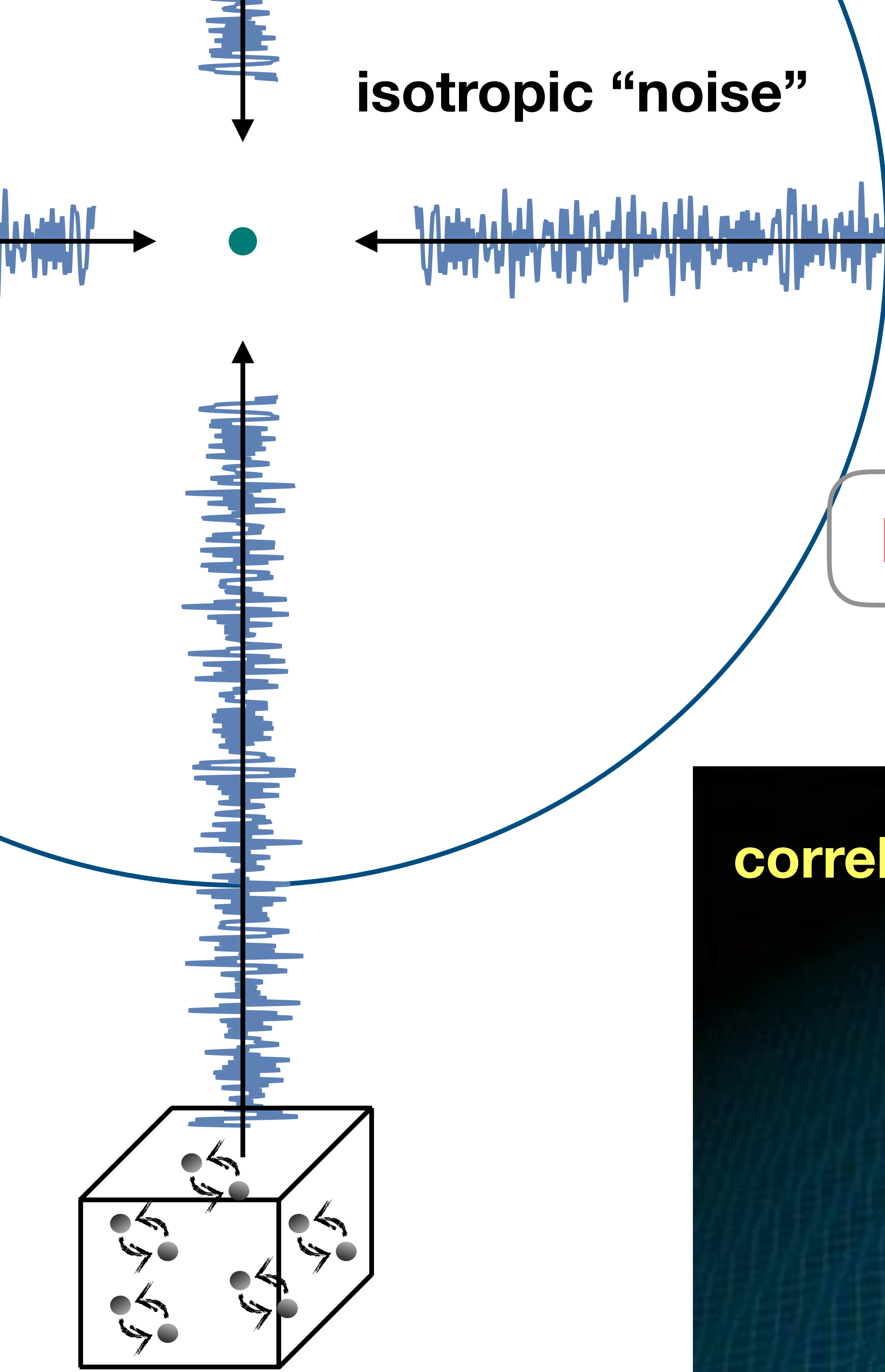
a few 10^3 BBH w. Chirp mass 10^7 M_{solar}

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

[Phinney 2001]

Merger rate!



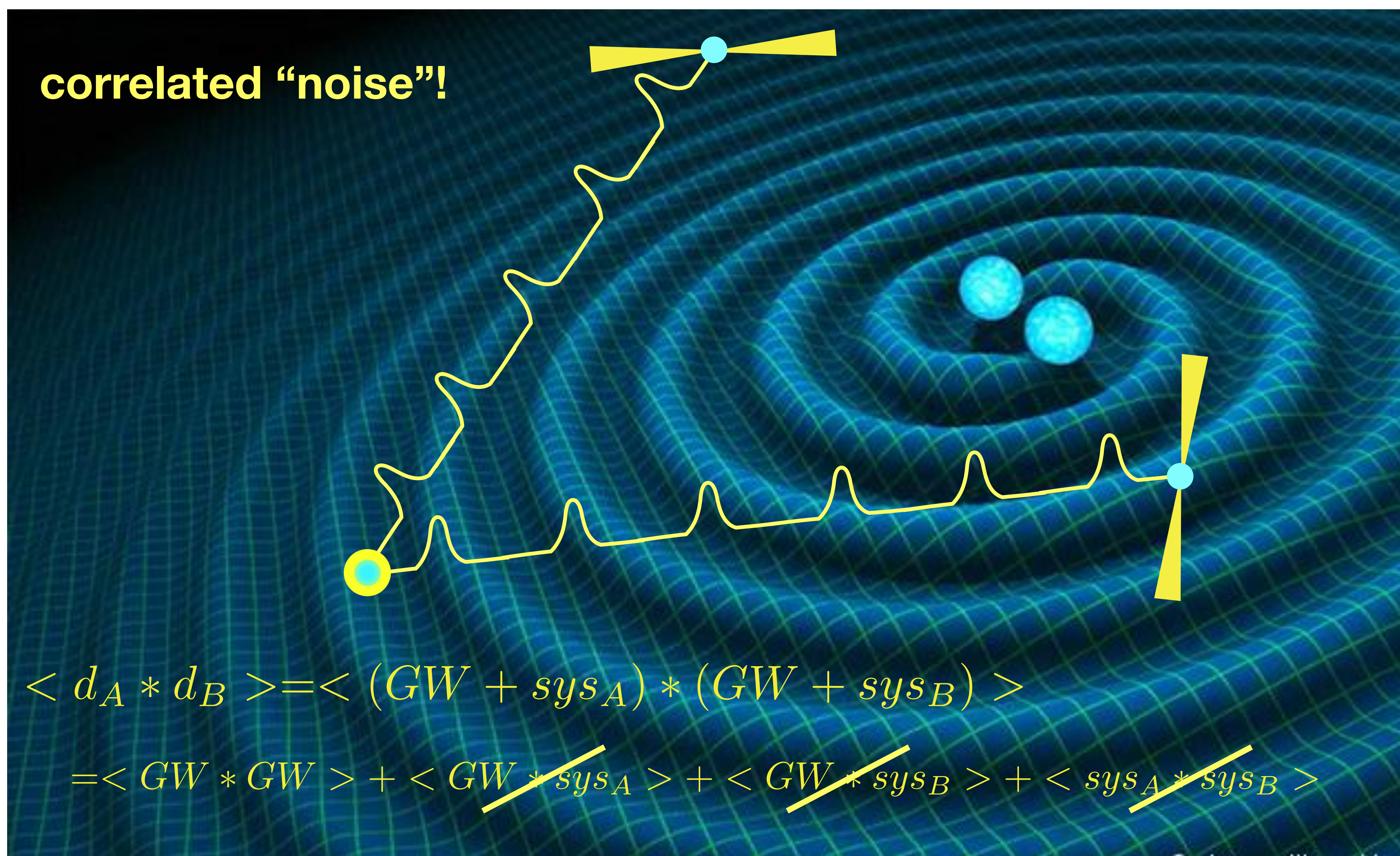


(Arm length > kAU) ⟶ **Pulsar**

How to measure?

ToA

multi-detectors ⟶ PTA



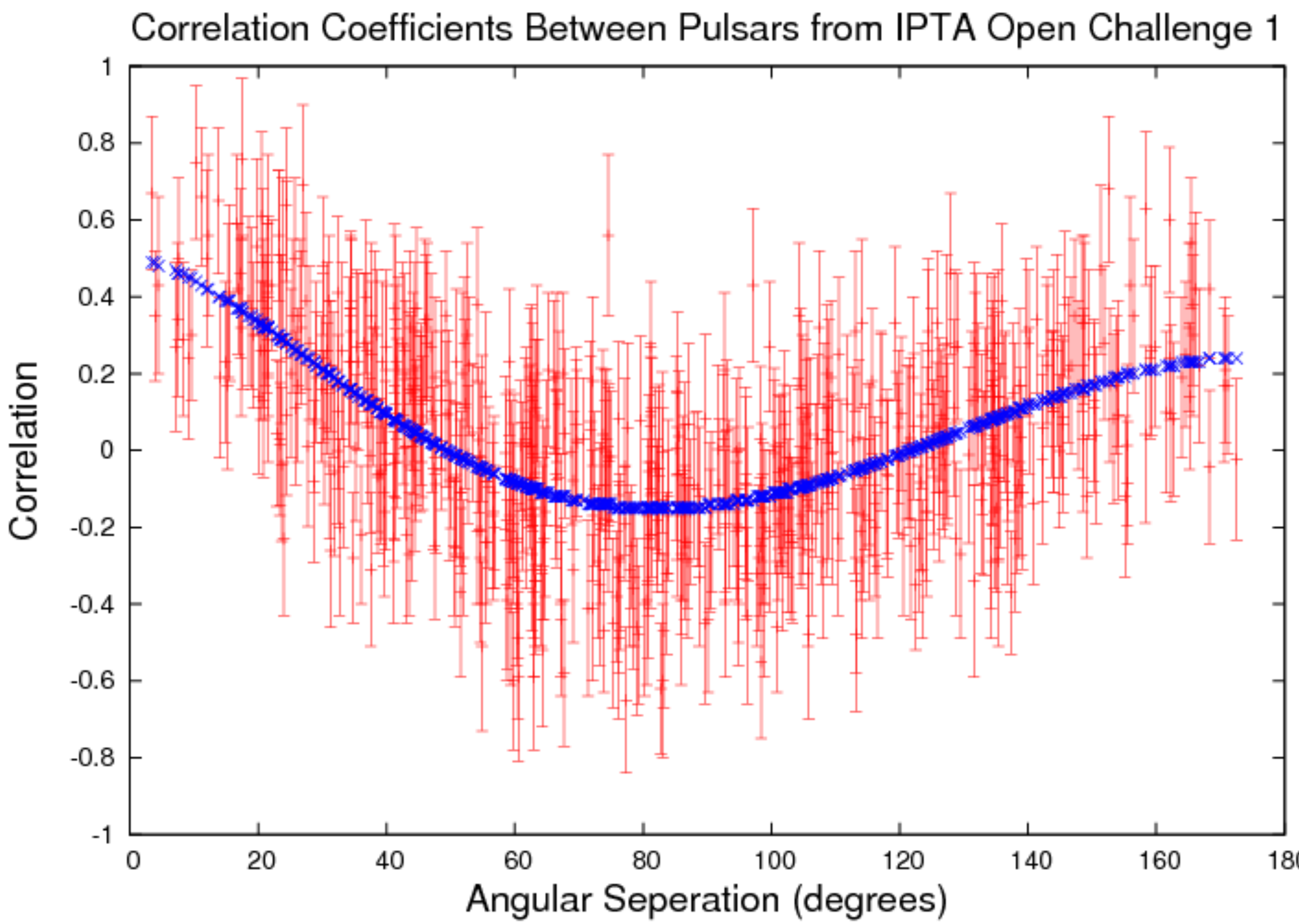
[Hellings & Downs 1983]

<GW*GW>=

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

average over GW from all direction

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



[Peters 1964]

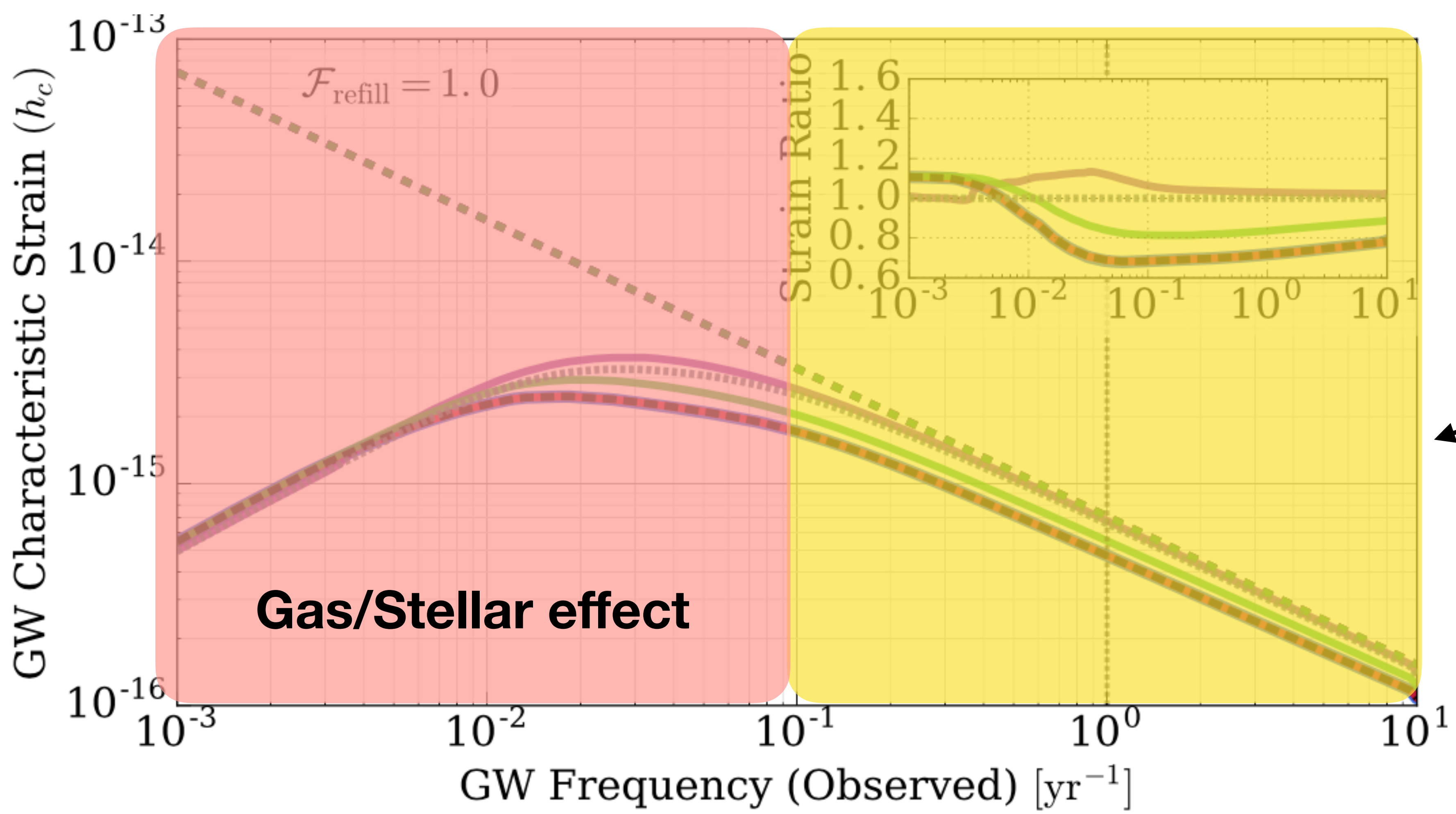
$$dt/d\ln f = \frac{5}{64\pi^{8/3}} \mathcal{M}^{-5/3} f_r^{-8/3}$$

time spend in per logarithmic frequency

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

Major eq.

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



energy loss only due to GW radiation during inspiral

[Credit: Kelley]

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

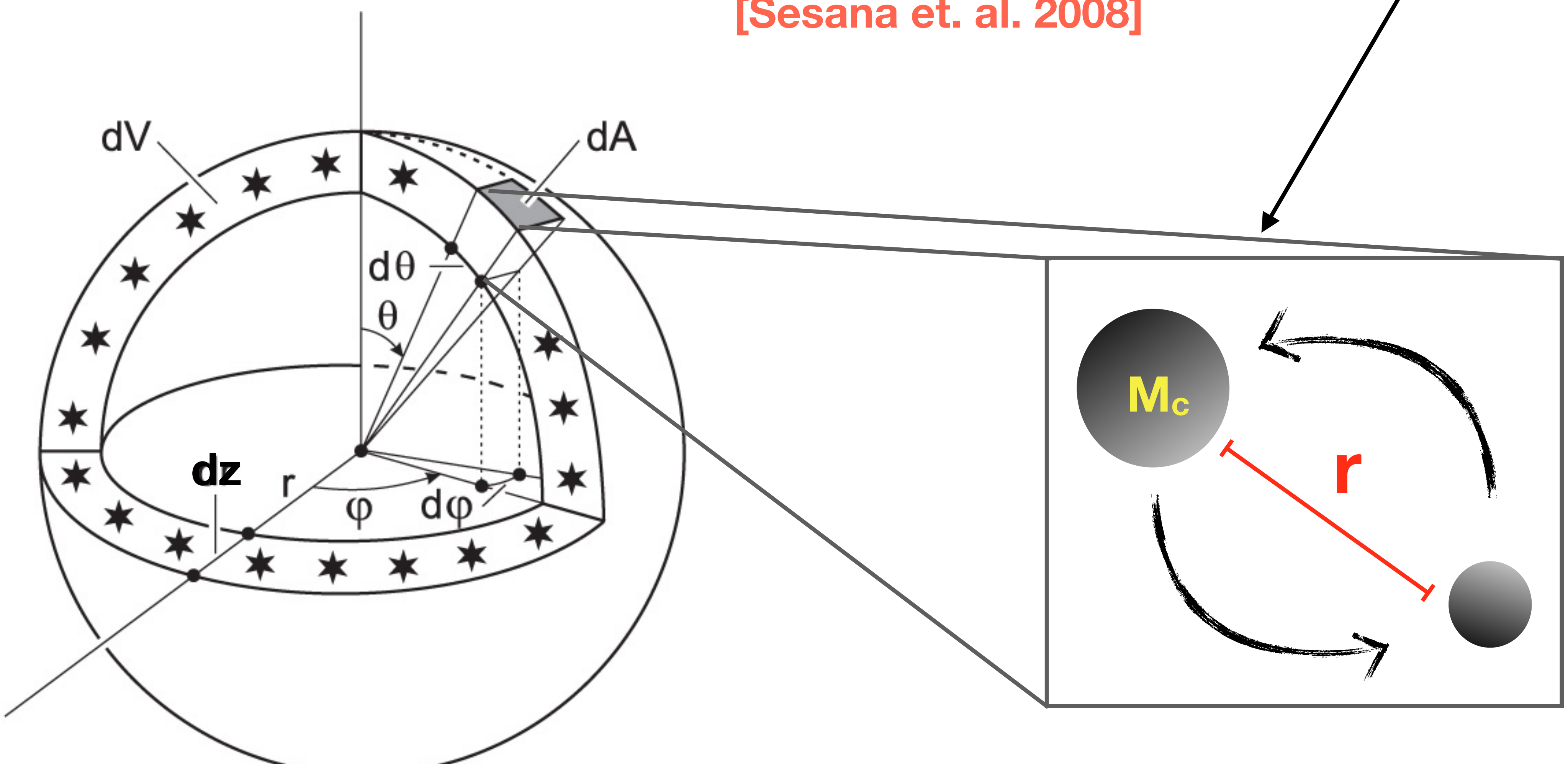
[Phinney 2001]

more accurate

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

BBH number per co-moving volume, in such configuration

[Sesana et. al. 2008]



Kejia Lee@KIAA-PKU

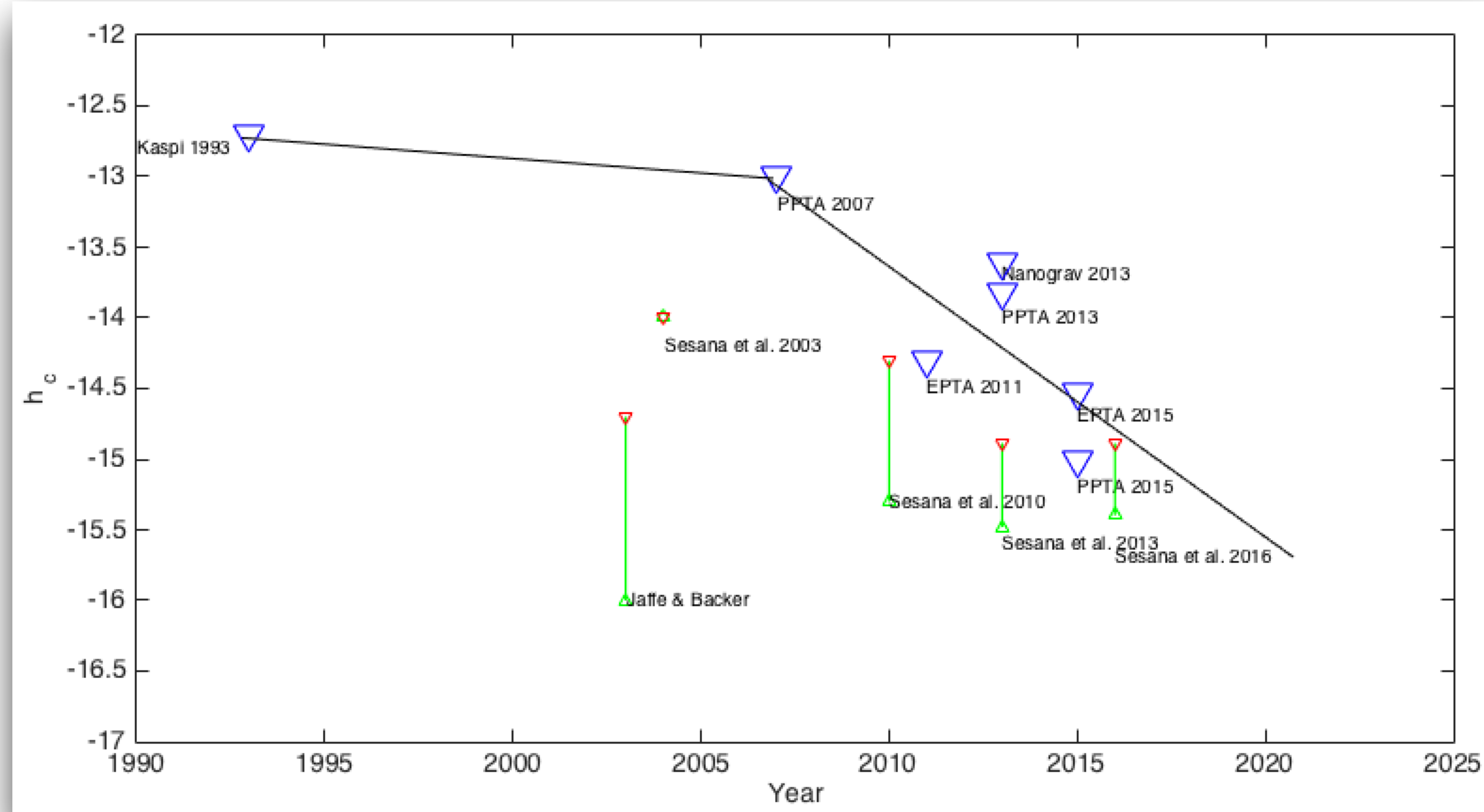
In 2005, if asked him "When will we detect GWB signal? "

A: FIVE years

Kejia Lee@KIAA-PKU

in 2010, if asked him "When will we detect GWB signal? "

A: **STILL** FIVE Years



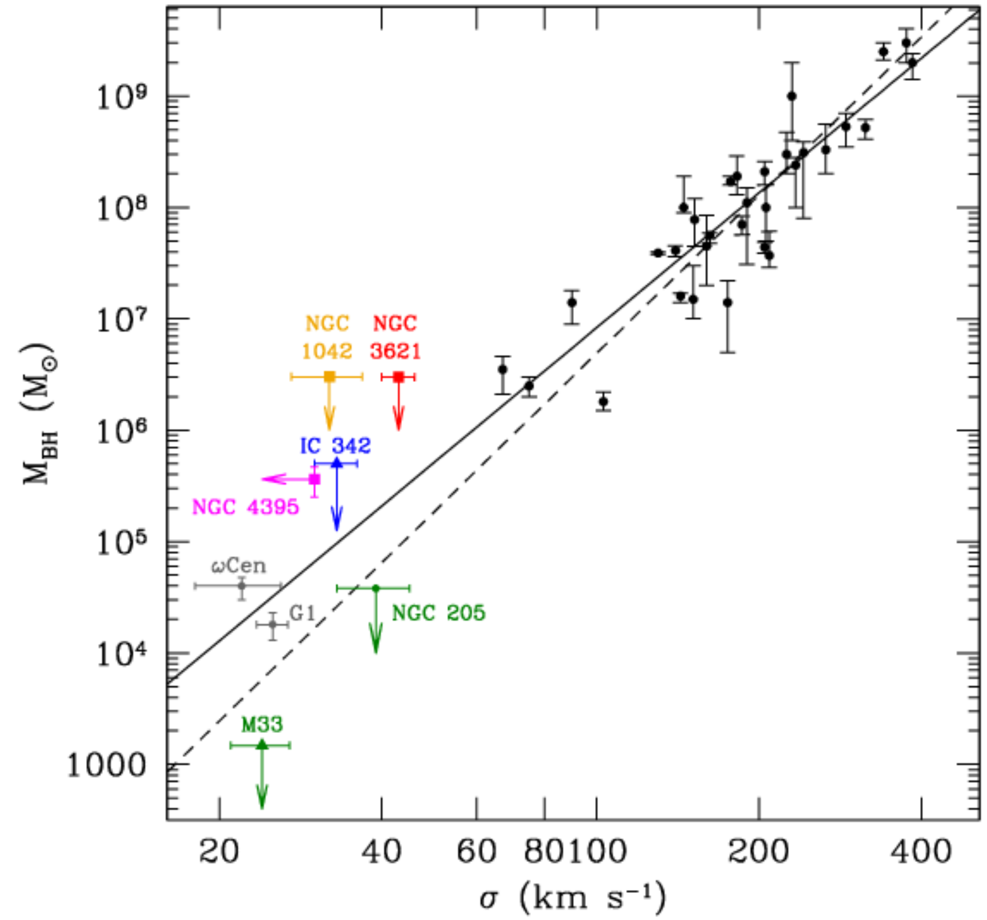
Predict the future is easy， but it is hard to predict the past!

Q： How to give a RELIABLE prediction on GWB?

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

phenomenology →

[Sesana 2012]



$M - \sigma$ **relation**

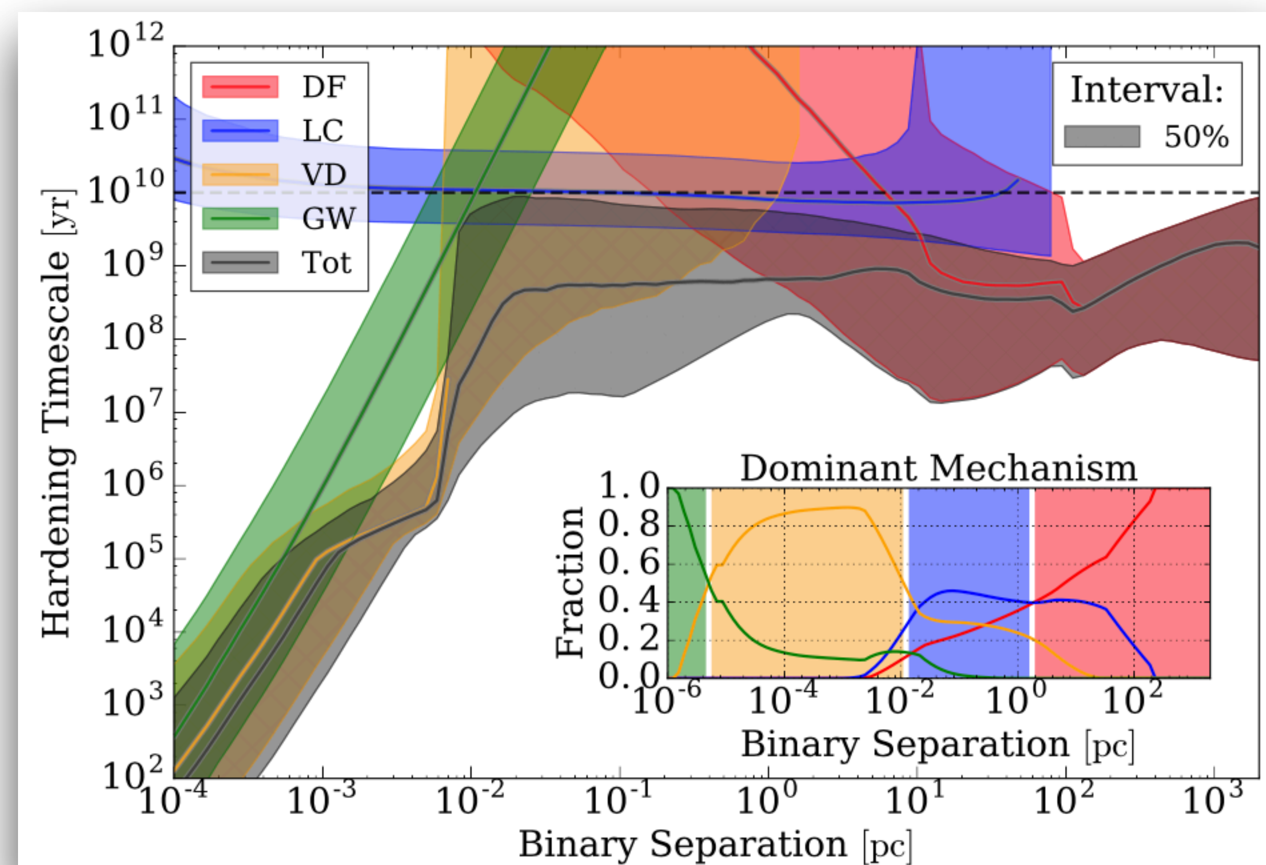
Preliminary Semi-Analytic Modelling ↓

SMBH merger modelling ↘

[Kelley et. al. 2017]

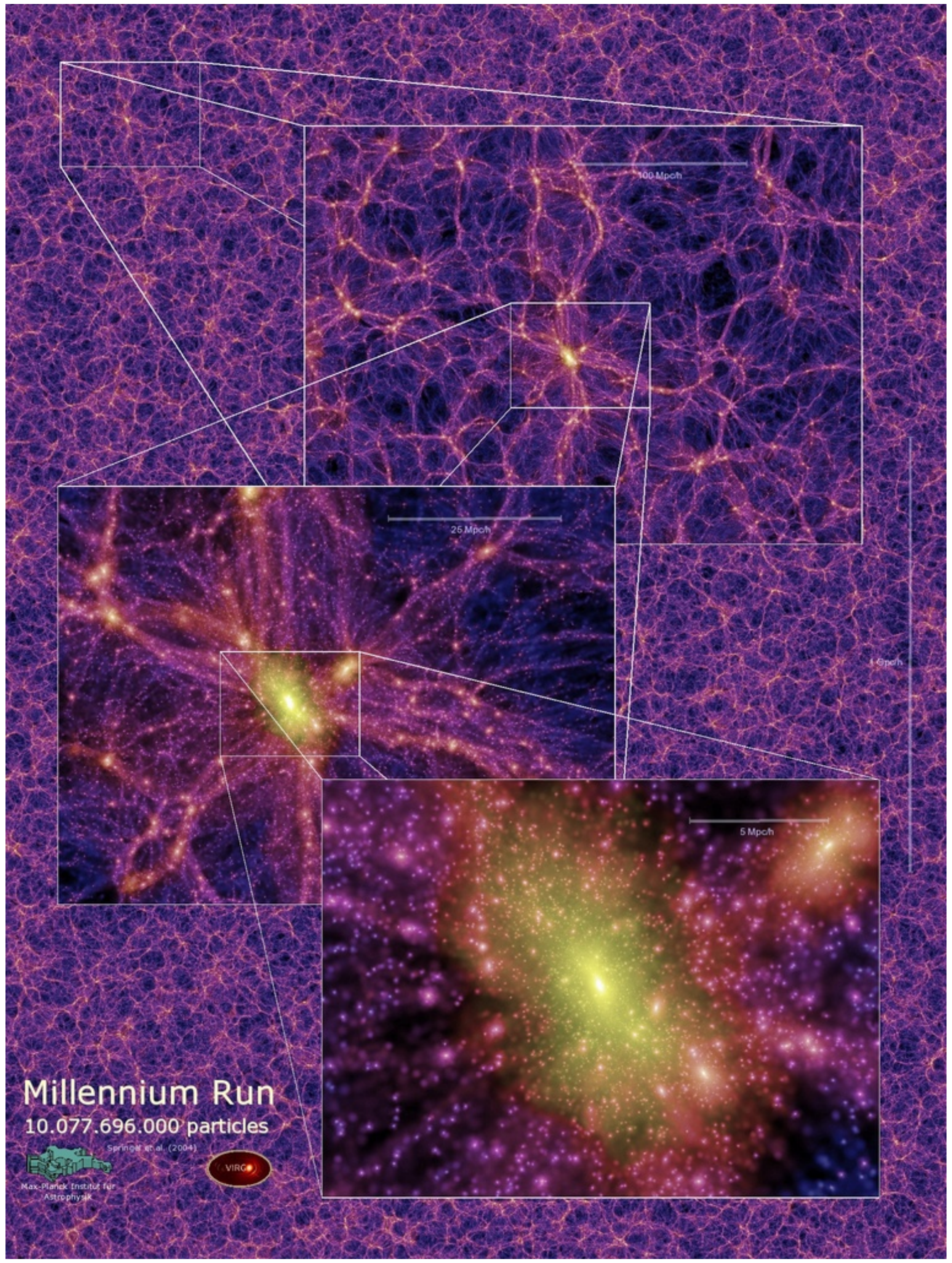
$$\frac{d^2 n_g}{dz dM}$$

[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

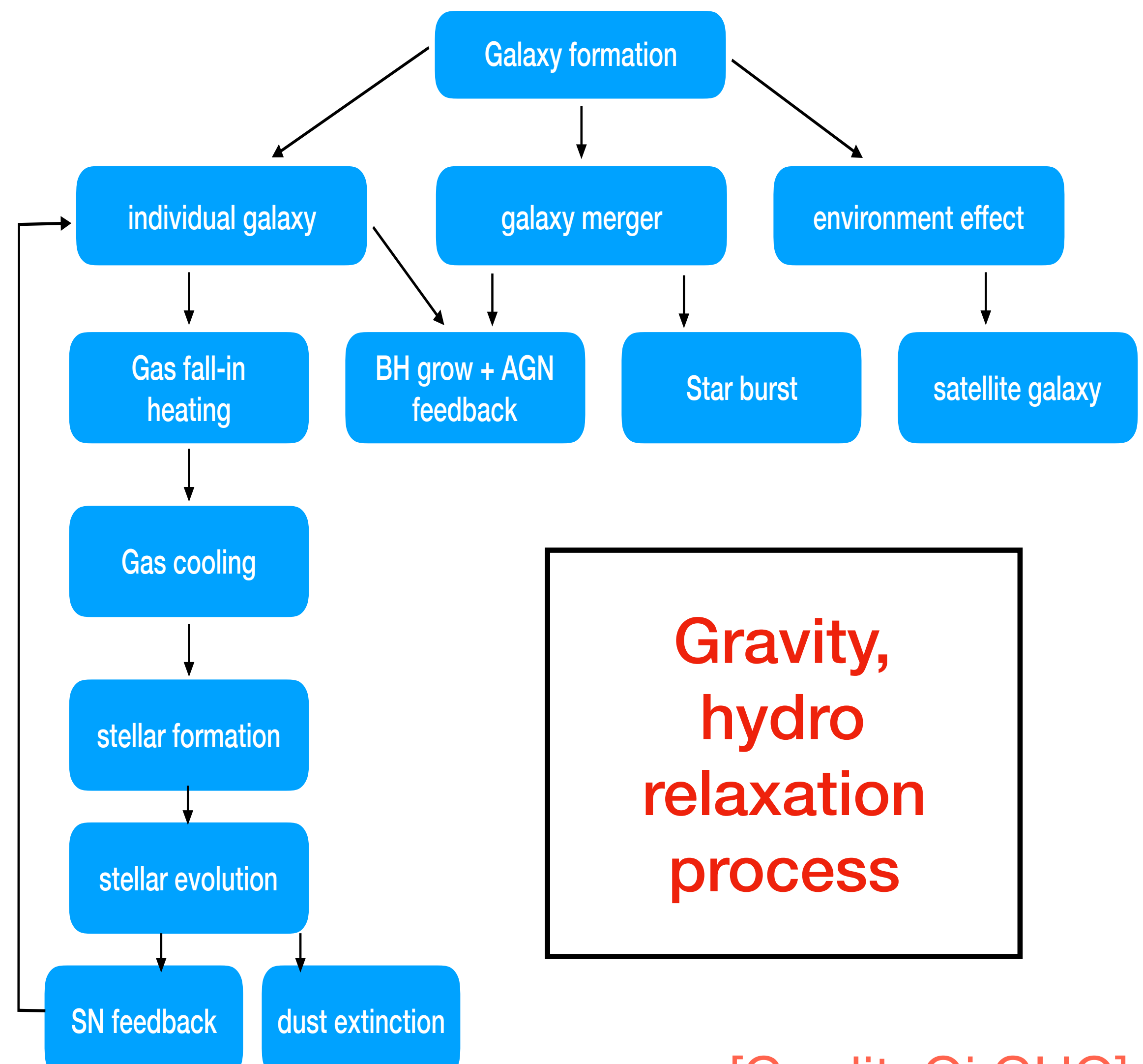


1. Run N-body simulation ⟶ DM halo merge tree

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

directly read BH mass function

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



V~500^3 Mpc^3

8668809 SMBHs, 51538704 galaxies in total

Gravity, hydro relaxation process

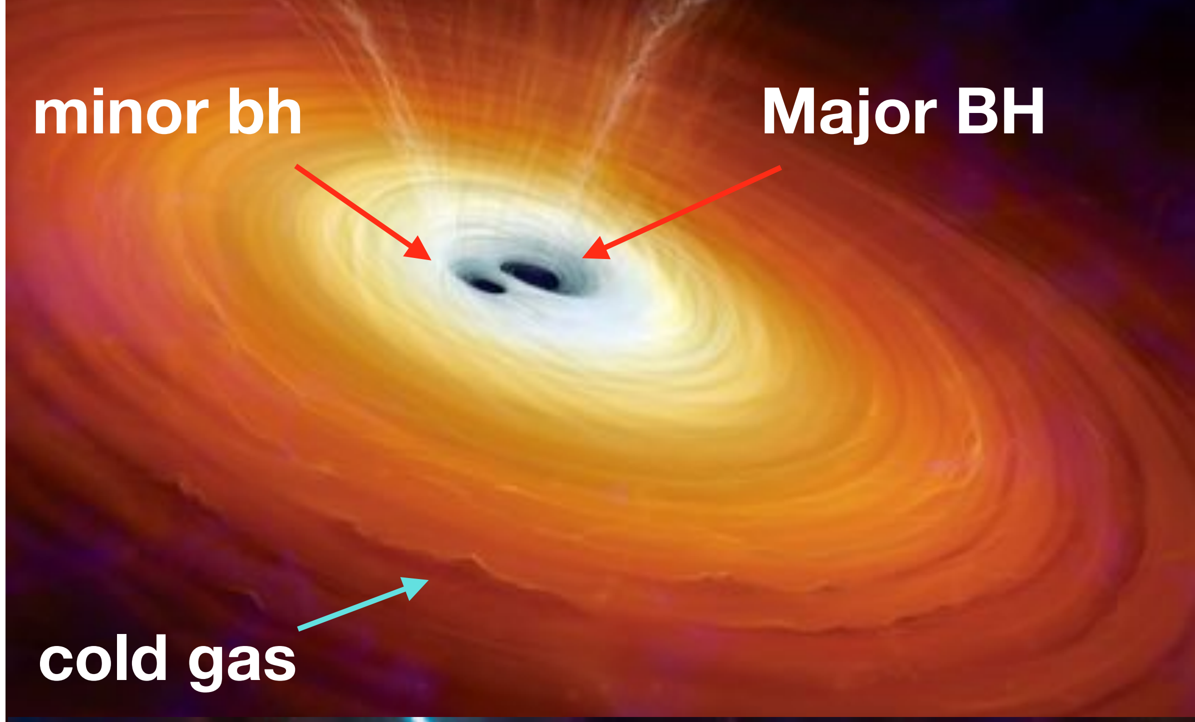
[Credit: Qi GUO]

code: L-galaxies

BH Self-regulated growth & feedback

Quasar mode: (gas-rich merger)

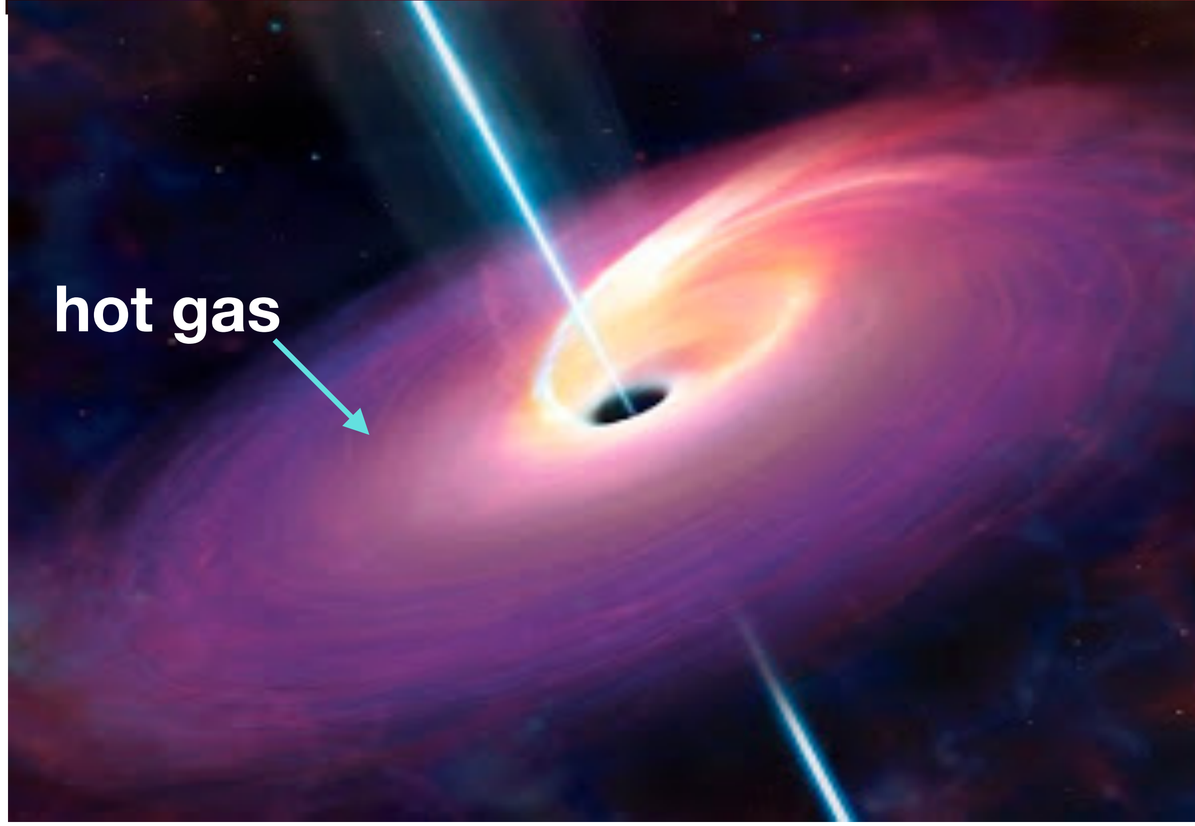
$$M_{\mathrm{bh},f} = M_{\mathrm{bh,maj}} + M_{\mathrm{bh,min}} + \Delta M_{\mathrm{bh},Q} \,,$$
$$\Delta M_{\mathrm{bh},Q} = \frac{f_{\mathrm{bh}} (M_{\mathrm{min}}/M_{\mathrm{maj}}) M_{\mathrm{cold}}}{1 + 280 \ \mathrm{km\ s^{-1}} / V_{vir}} \,,$$



Radio mode: (hot gas accretion)

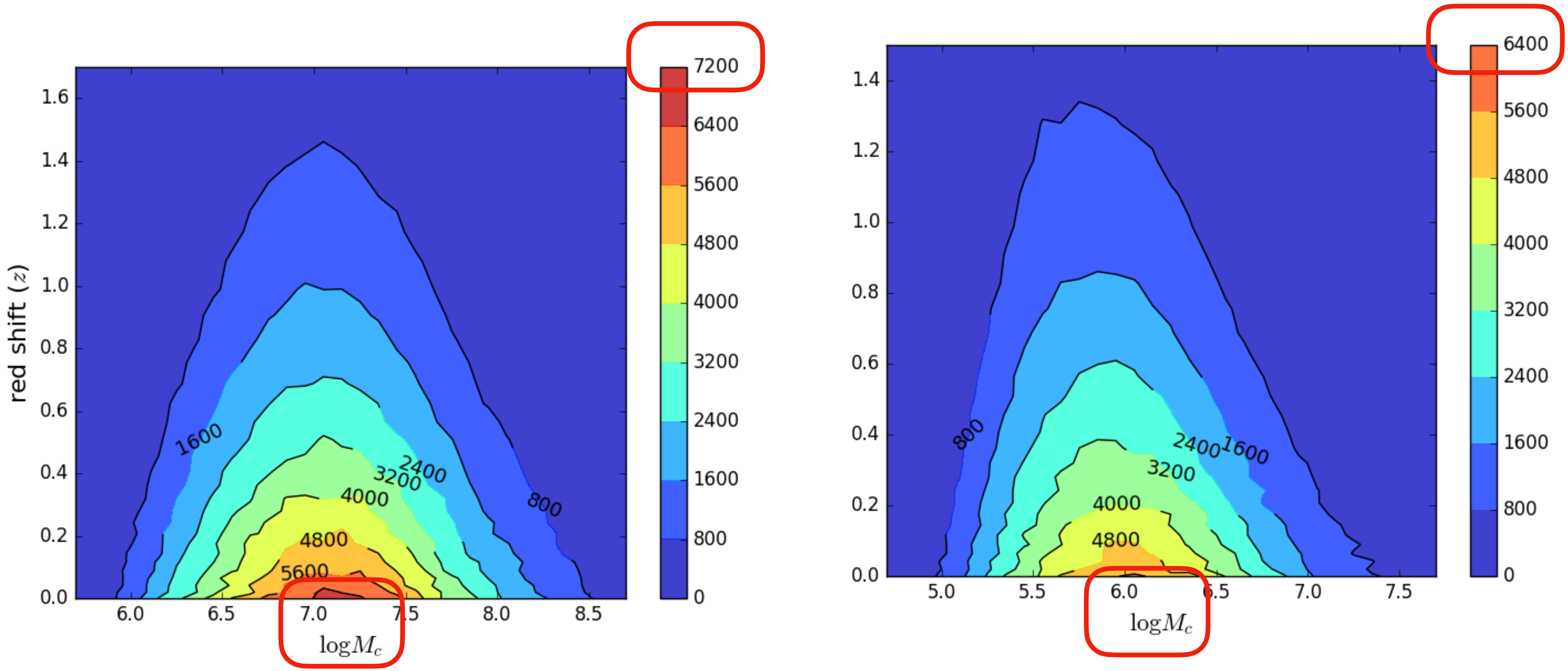
$$\dot{M}_{\mathrm{bh}} = \kappa \left(\frac{f_{\mathrm{hot}}}{0.1} \right) \left(\frac{V_{vir}}{200 \ \mathrm{km\ s^{-1}}} \right)^3 \left(\frac{M_{\mathrm{bh}}}{10^8 h^{-1} M_\odot} \right) M_\odot \ \mathrm{yr}^{-1}$$

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



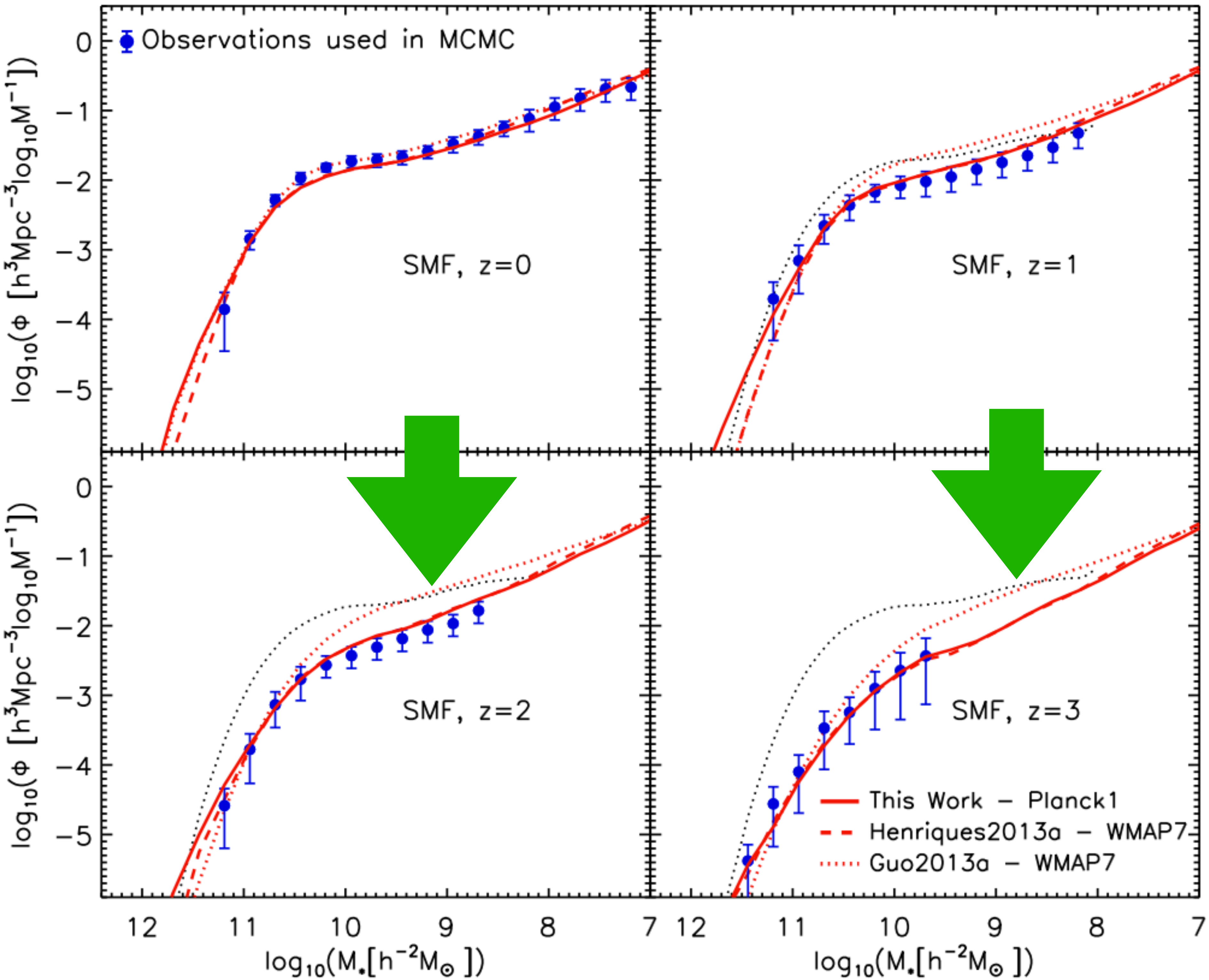
10% energy deposit into relativistic jet

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



Guo 2013
based WMAP7 cosmology

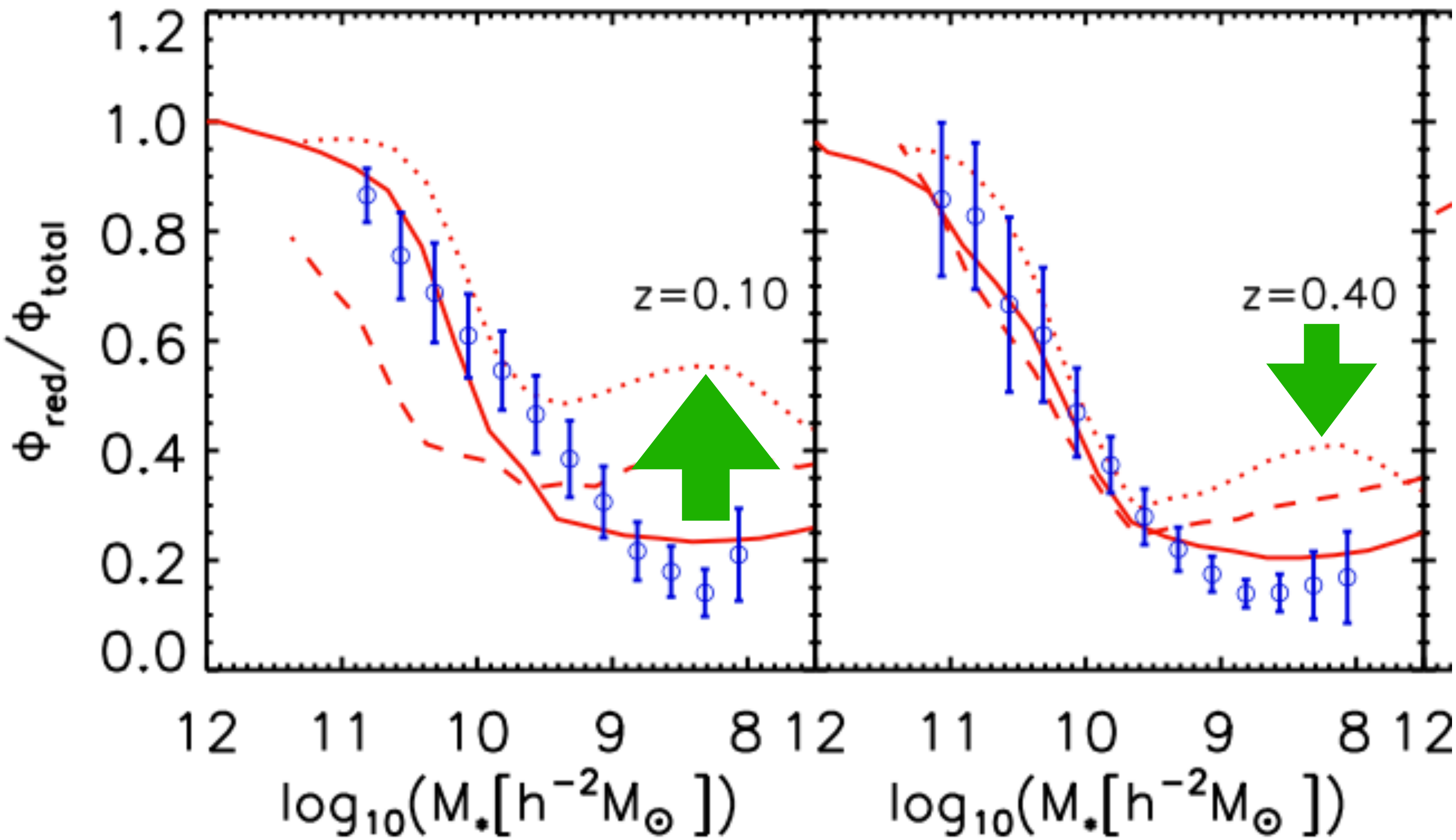
Henriques 2015
based Planck cosmology



[Henriques et. al. 2015]

overly early formation of low-mass galaxies in Guo2013

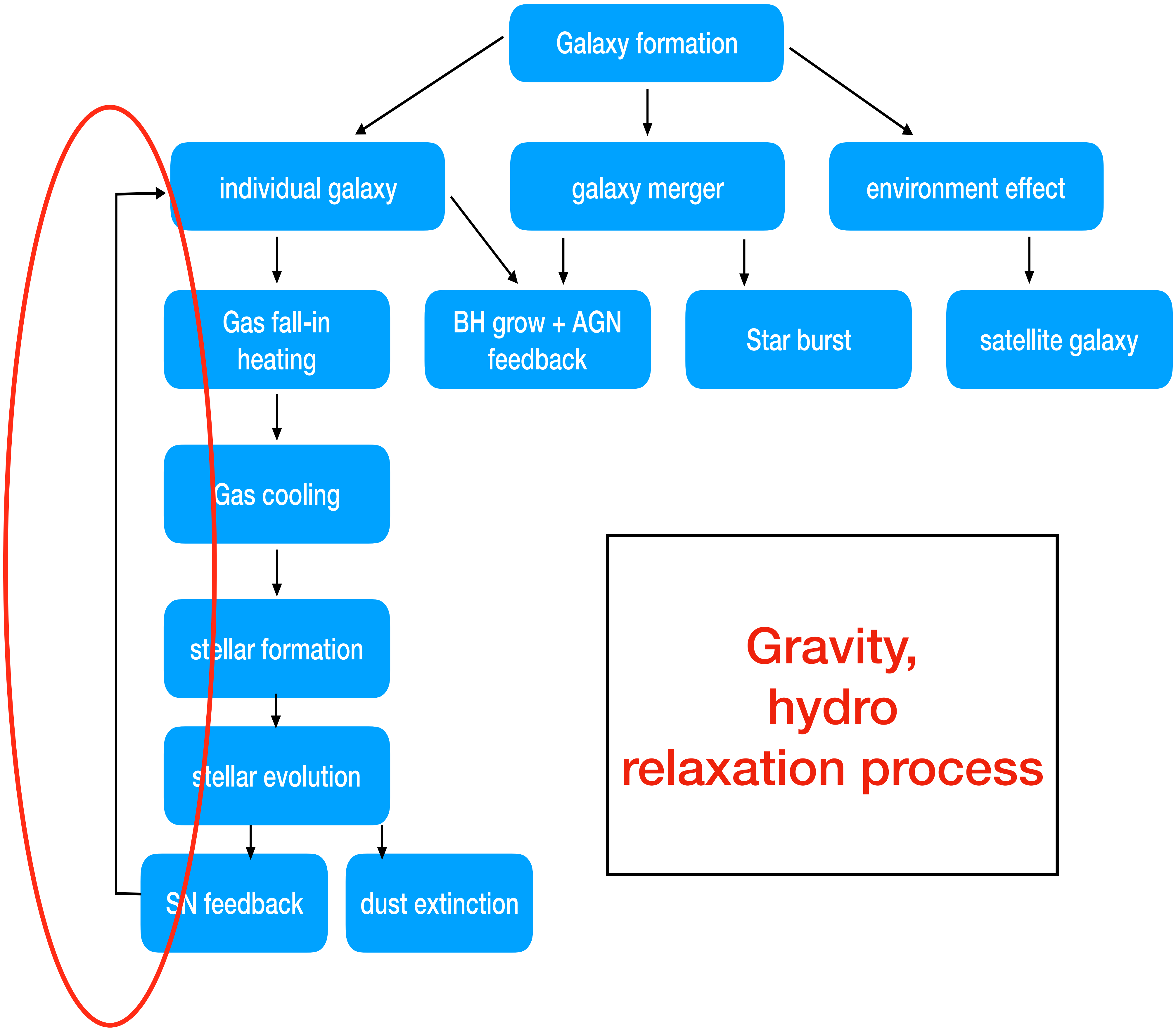
[Henriques et. al. 2015]



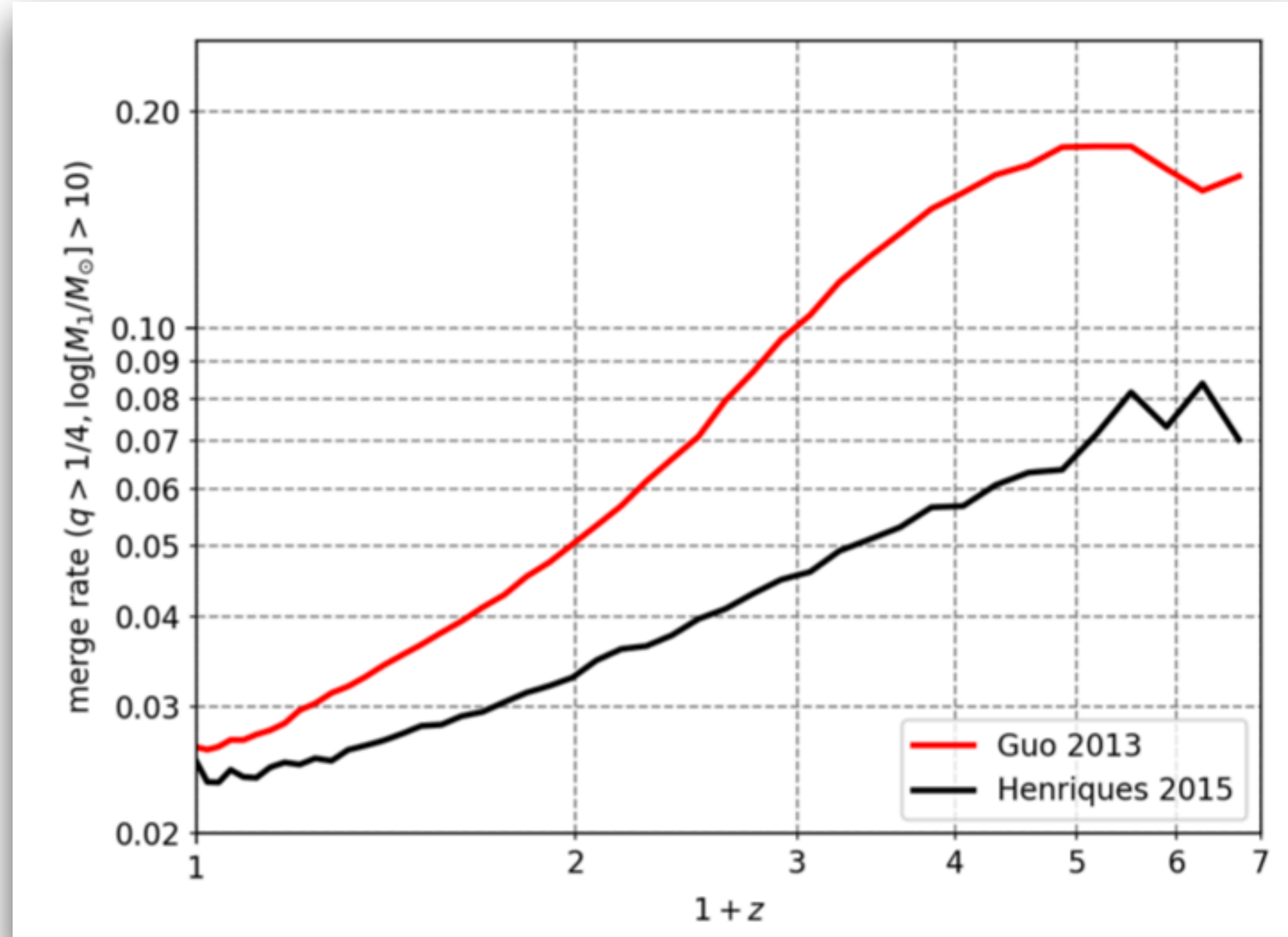
overly large fraction of them that are passive at late times in Guo 2013

solution:

slow down this process / make longer time scale

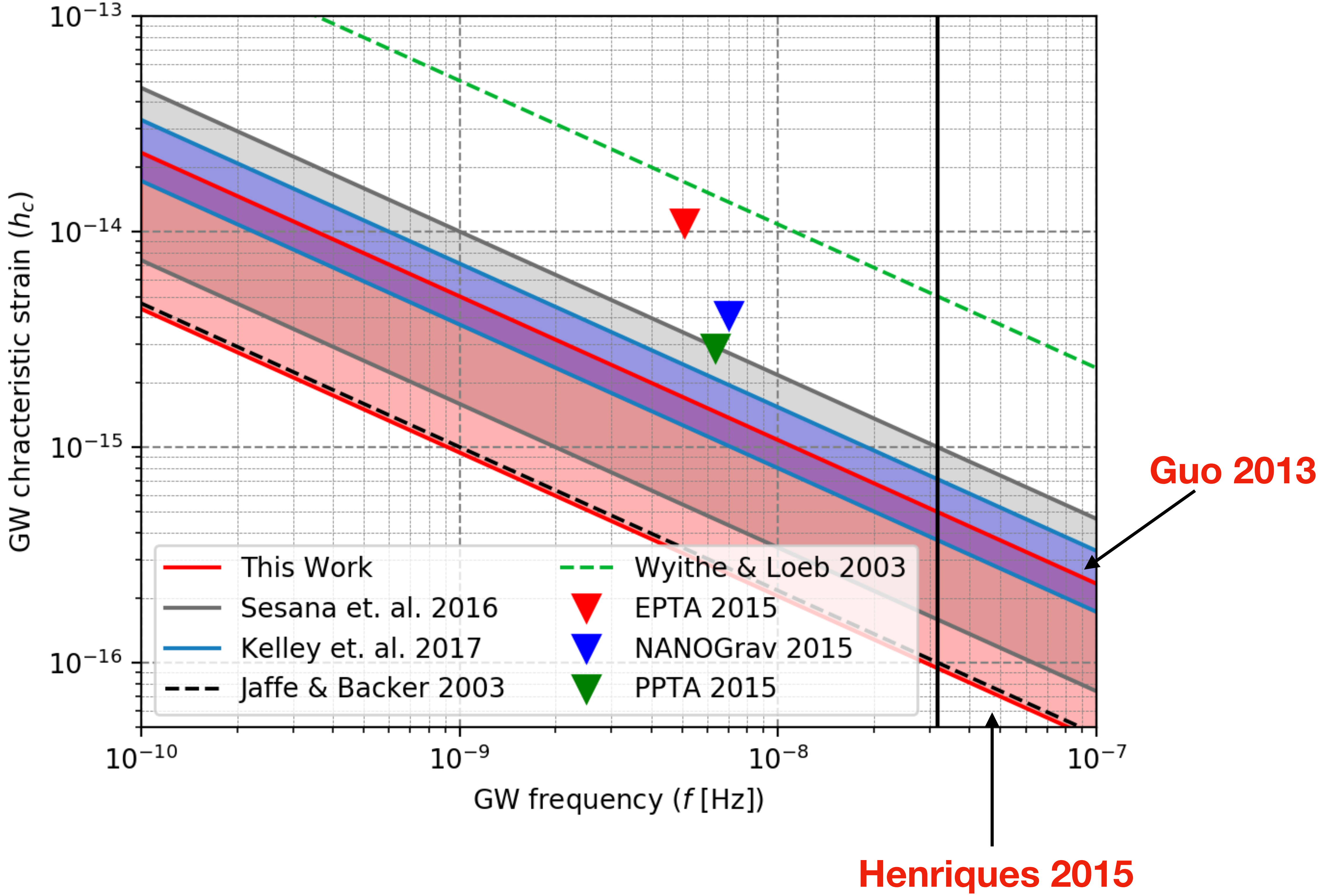


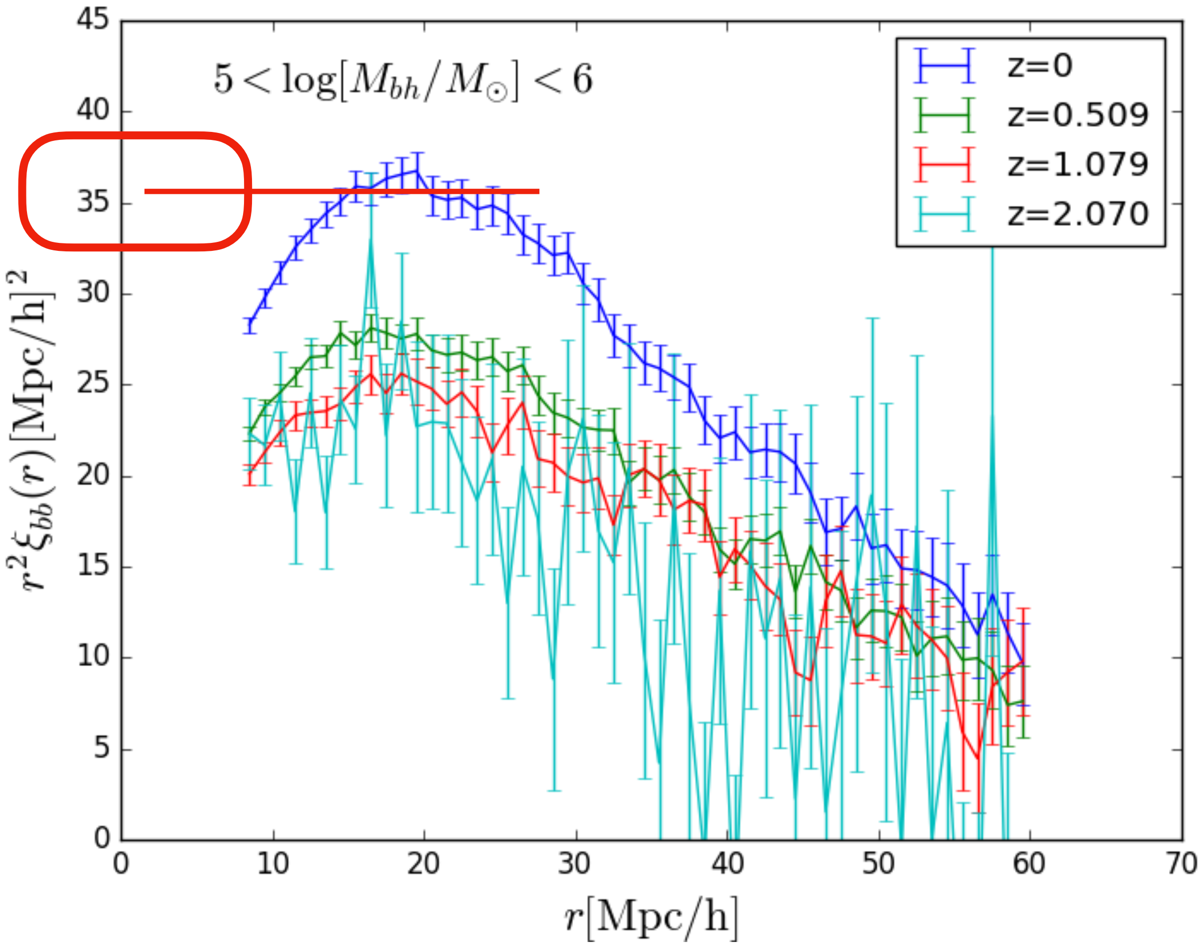
$$\frac{dn_g}{dz}$$

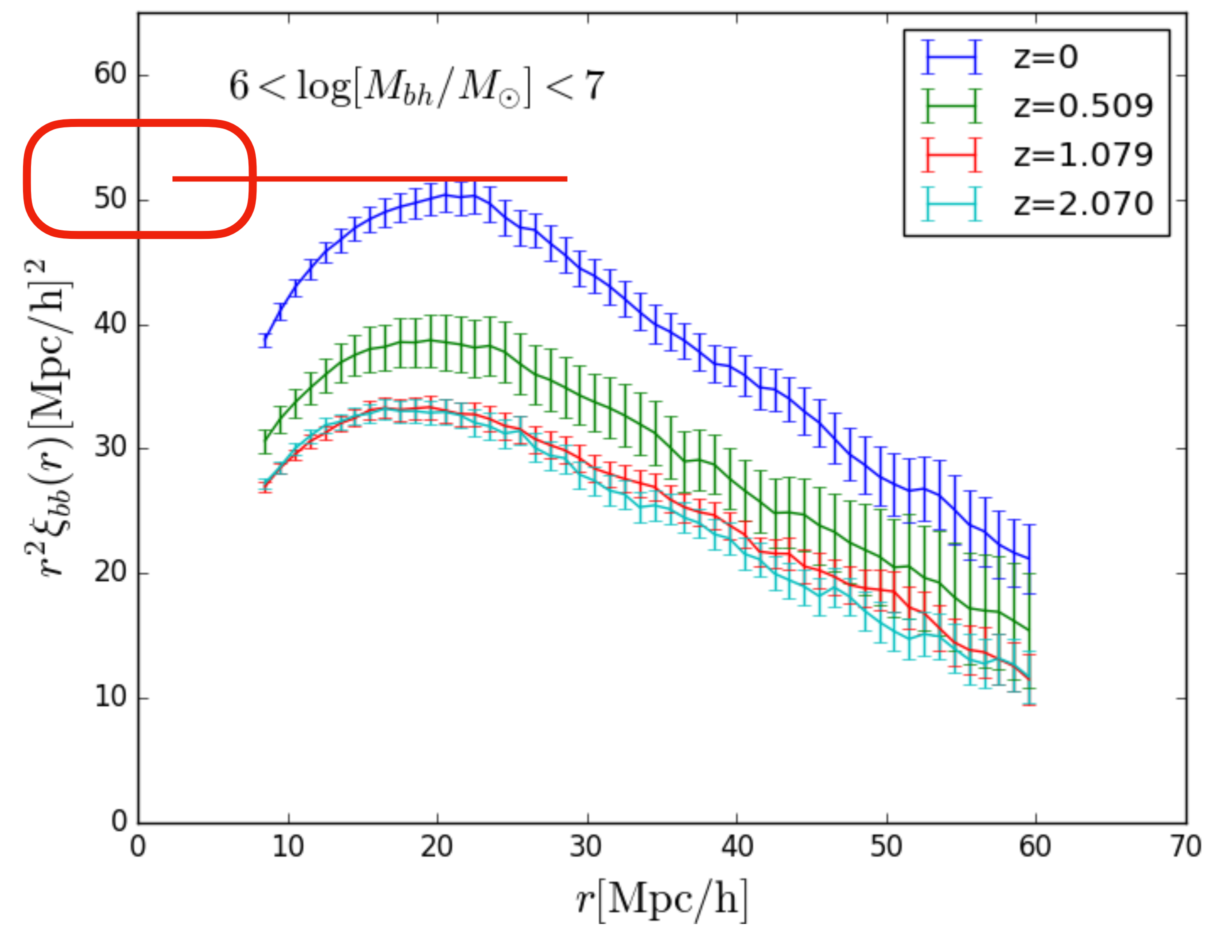


merge rate ($q > 1/4$, log[$M_1/M_\odot$] > 10)
0.20
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
1
2
3
4
5
6
7
$1 + z$
Guo 2013
Henriques 2015

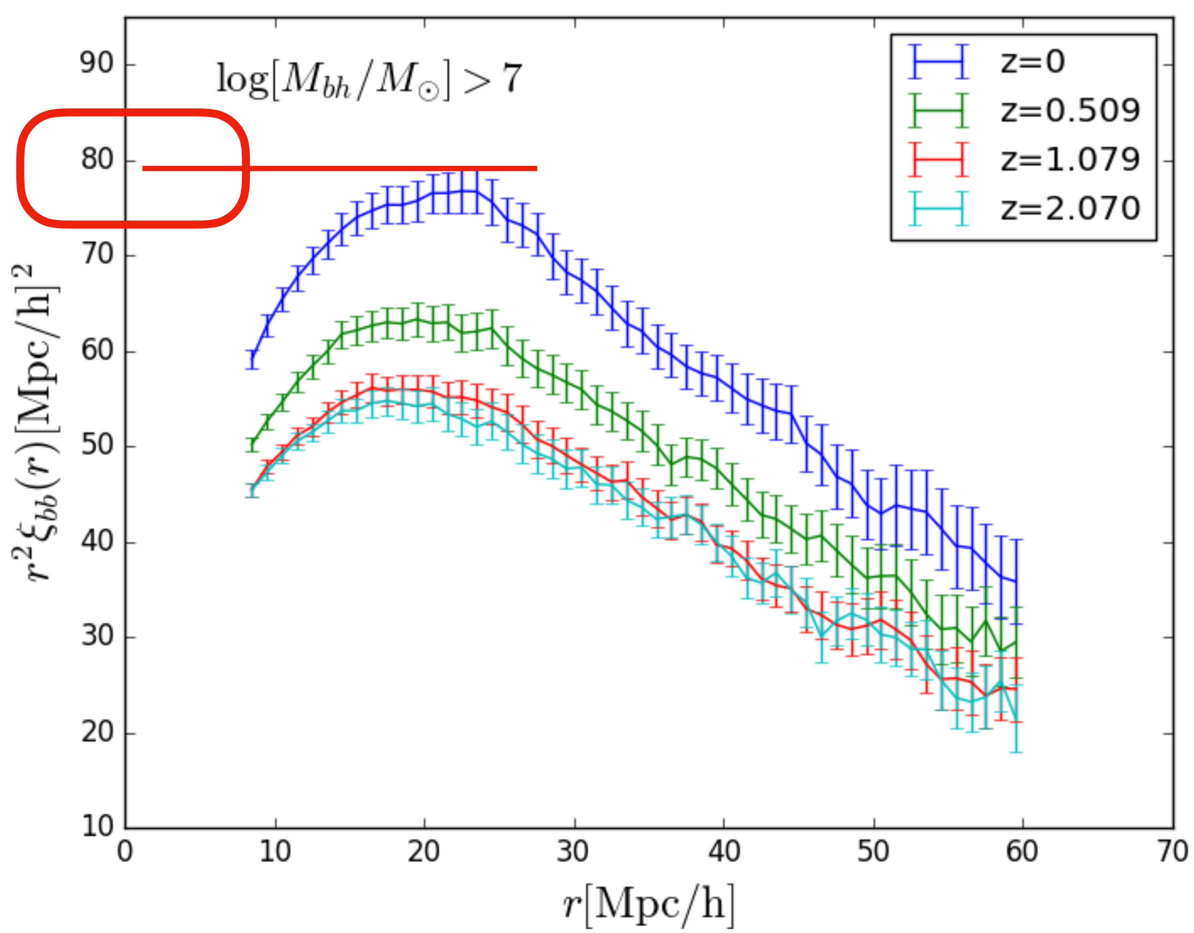
$$A_{yr^{-1}} = 5.00 \times 10^{-16} \text{ and } A_{yr^{-1}} = 9.42 \times 10^{-17}$$







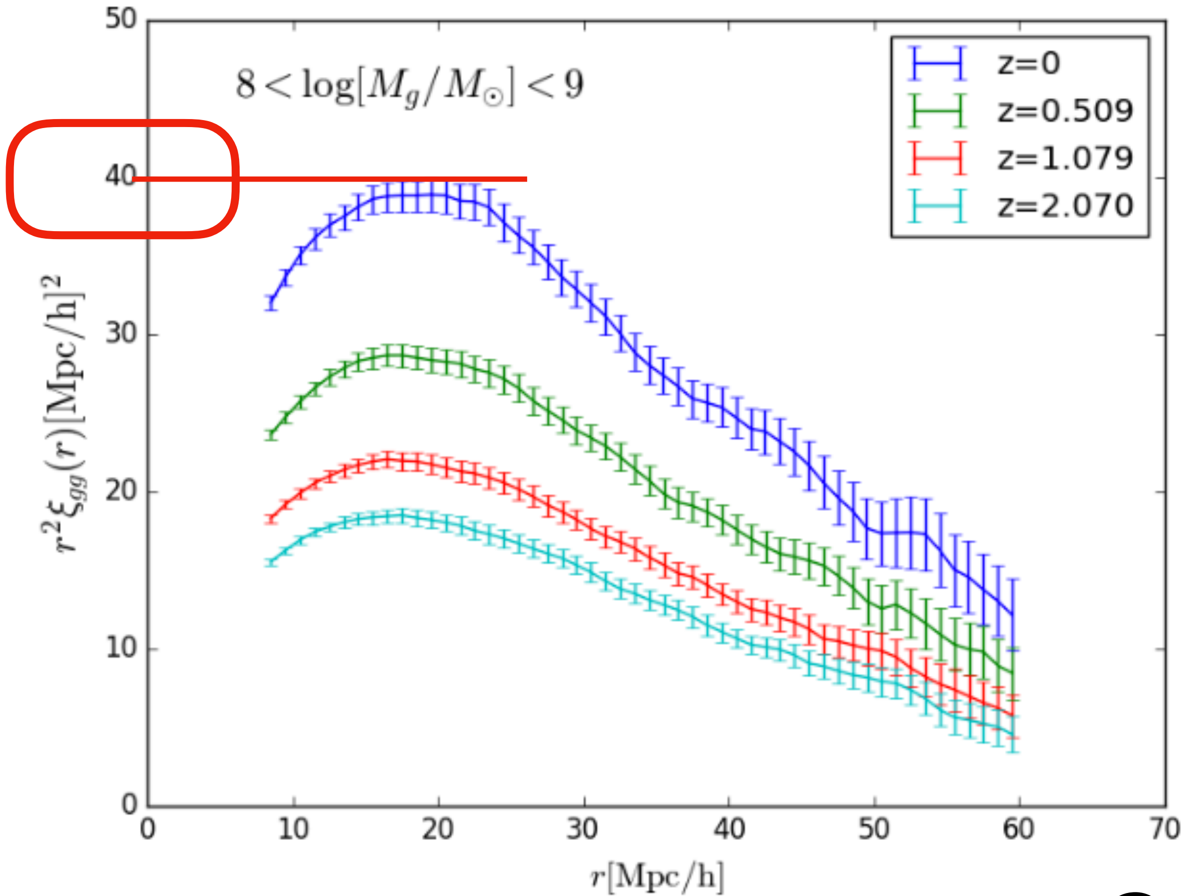
BHs

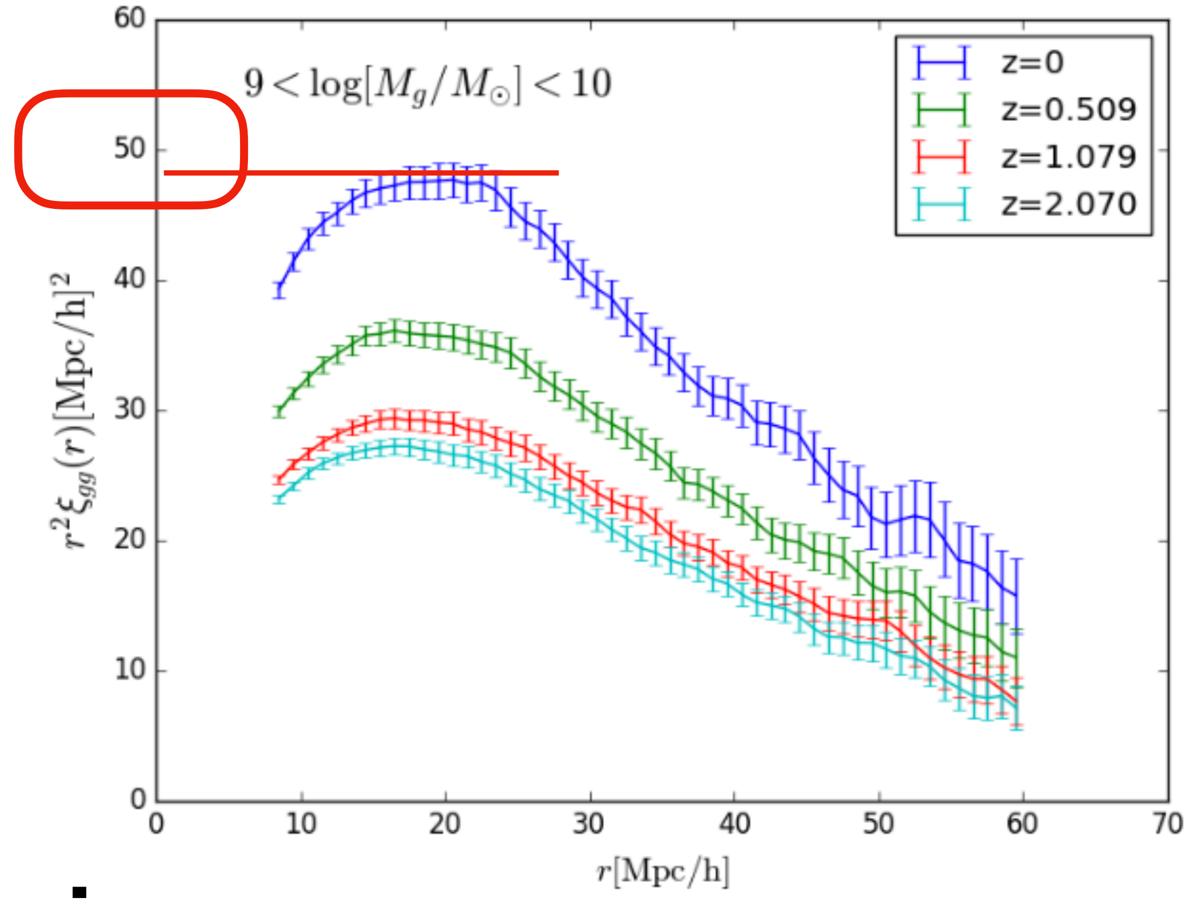


$$\xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}$$

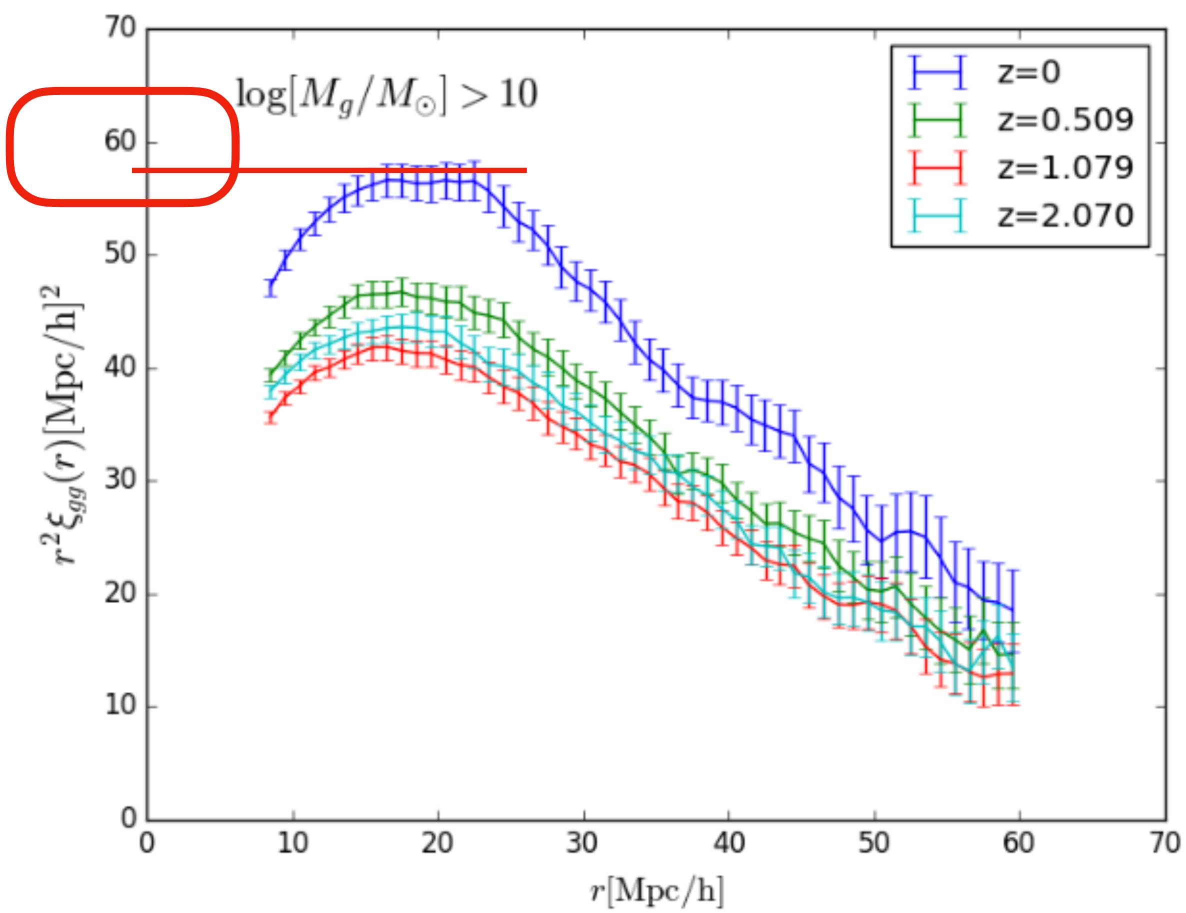
1. Clustering is enhanced in the lower redshift

2. Clustering is enhanced with mass increasing

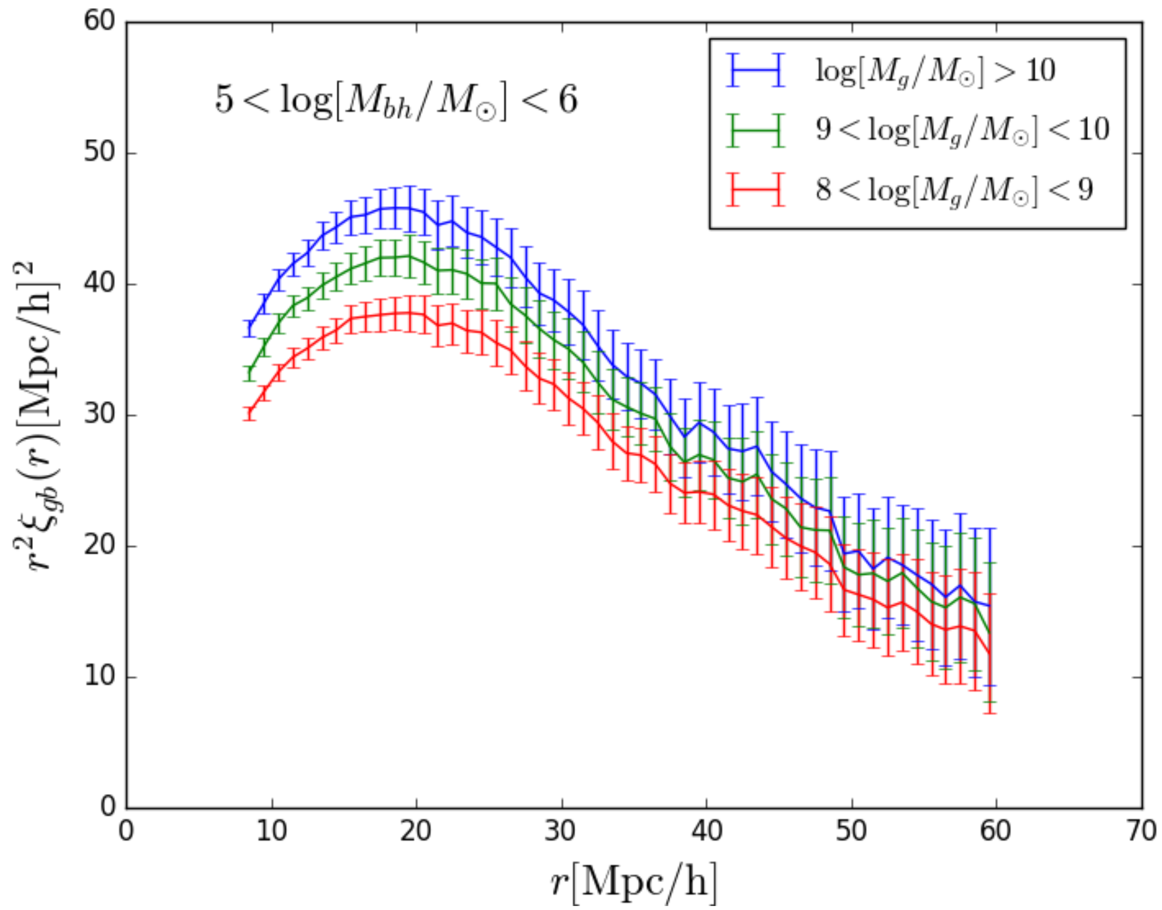


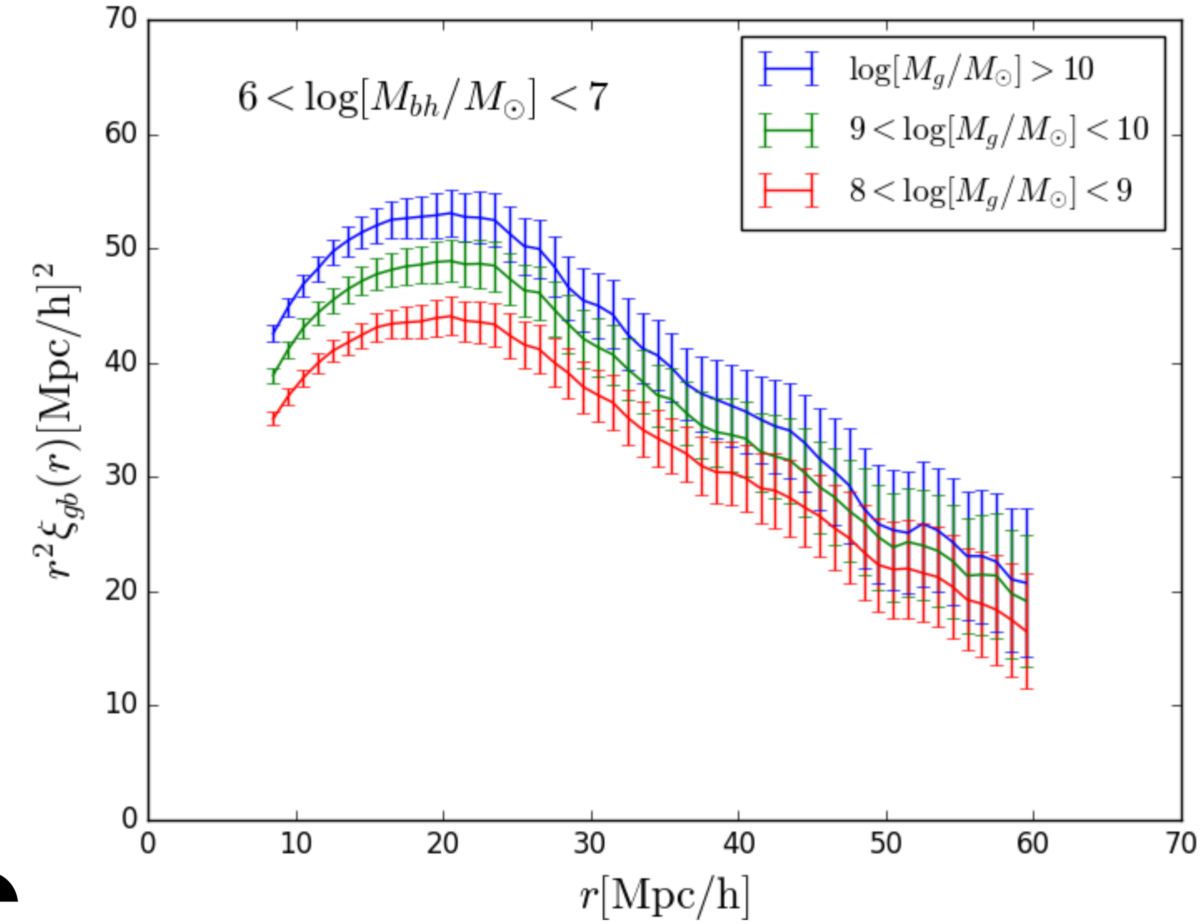


Galaxies

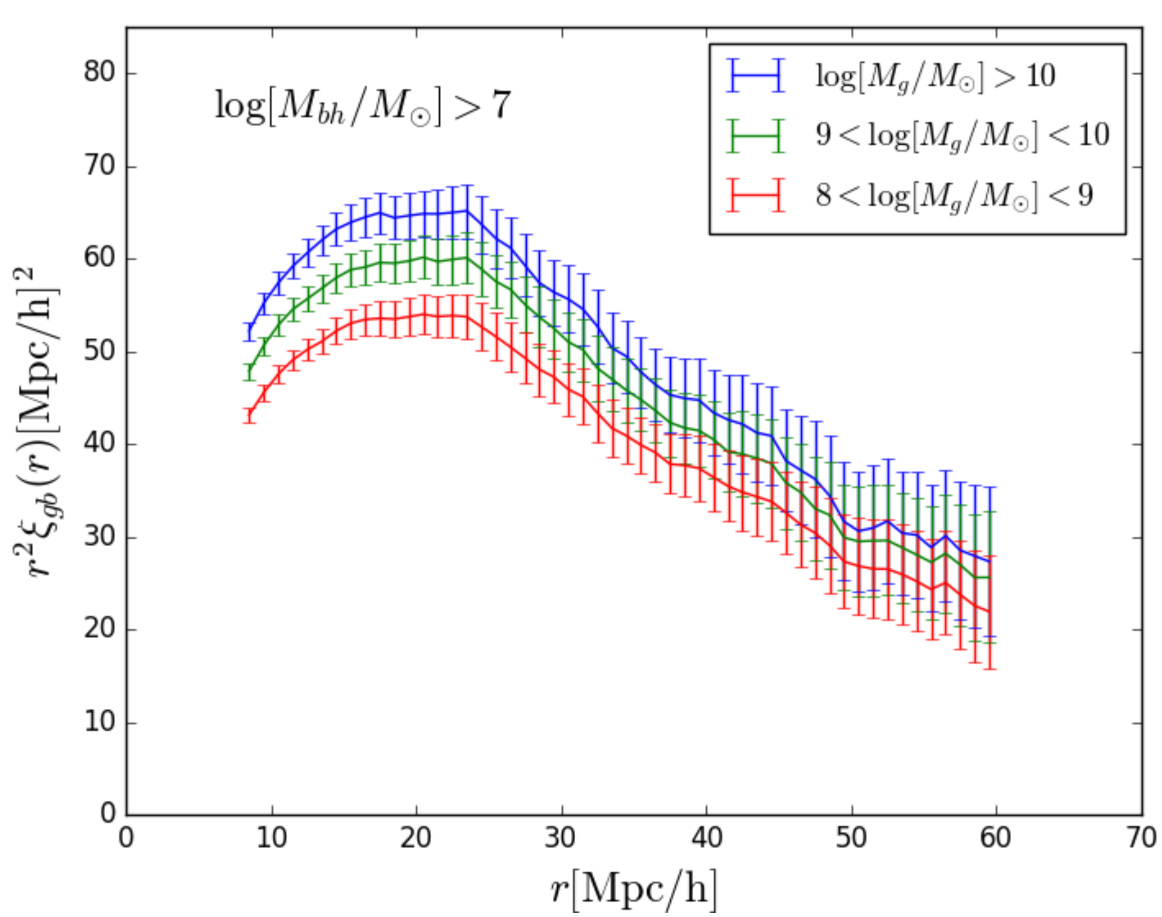


Same as BHs


$5 < \log[M_{bh}/M_{\odot}] < 6$
$\log[M_g/M_{\odot}] > 10$
$9 < \log[M_g/M_{\odot}] < 10$
$8 < \log[M_g/M_{\odot}] < 9$
$r^2\xi_{gb}(r)[\mathrm{Mpc/h}]^2$
$r[\mathrm{Mpc/h}]$


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

XC


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

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!