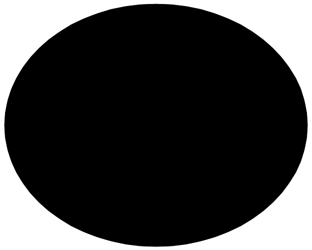
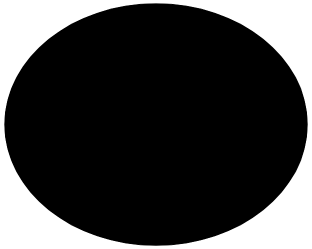
Beauty, the beast, and gravitational waves

Sterl Phinney
Caltech

Beauty,



Beauty,

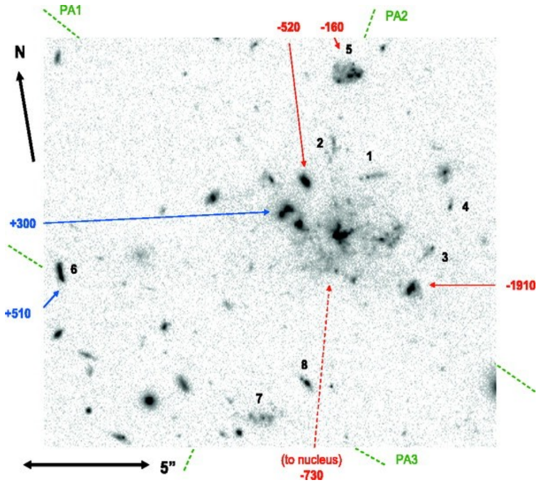


The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time.

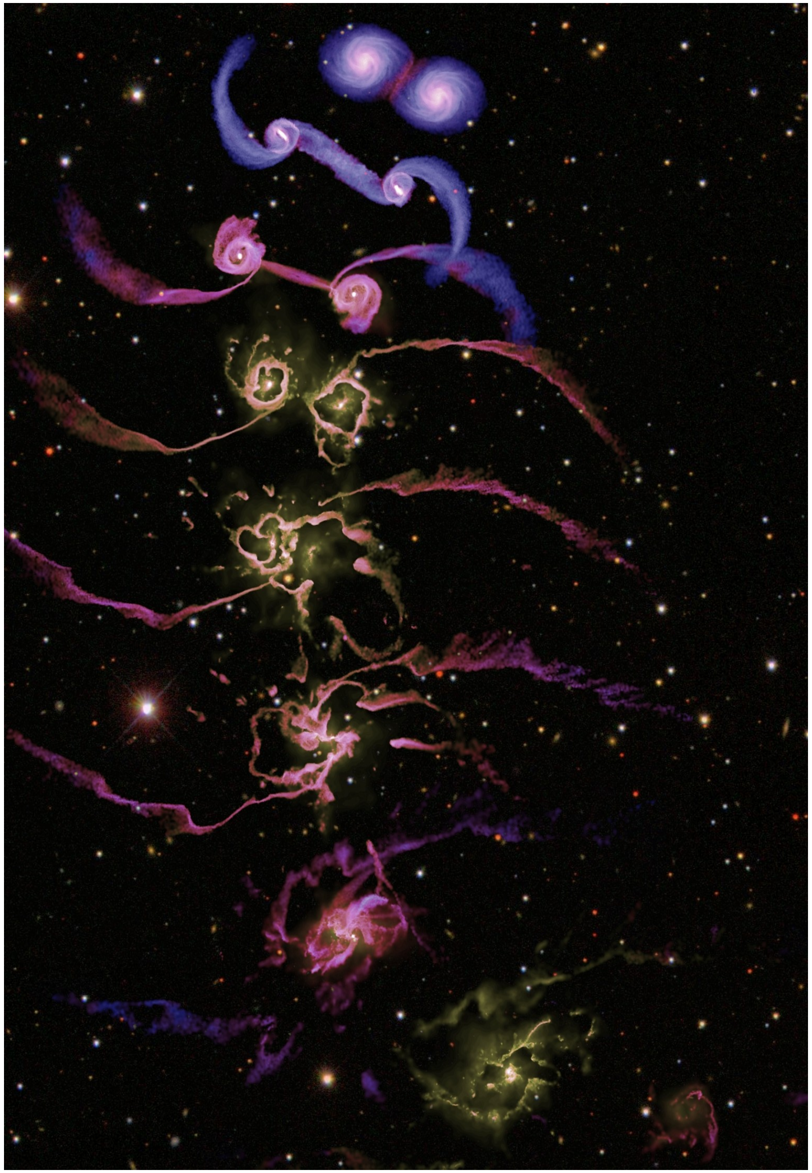
And since the general theory of relativity provides a single unique two-parameter family of solutions for their descriptions, they are the simplest objects as well.
---S. Chandrasekhar

In all cultures studied, the single most important criterion of human beauty and attractiveness to the opposite sex is symmetry of the facial features. -Jones et al, *Nature* 2003

the beast,

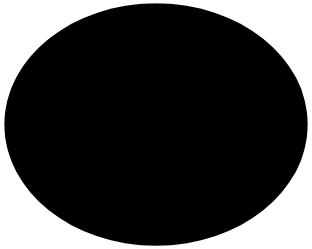


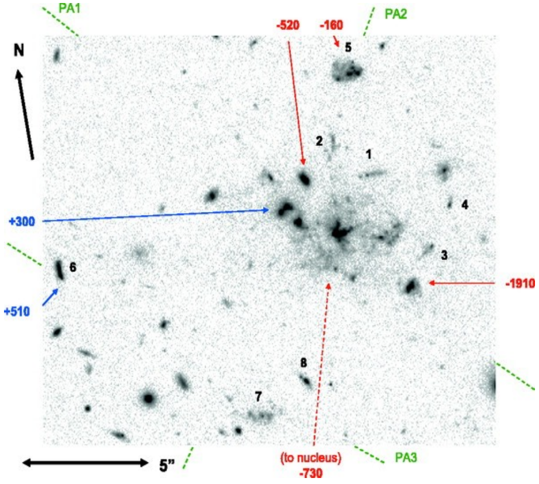
“This is mudwrestling”
-M.J. Rees

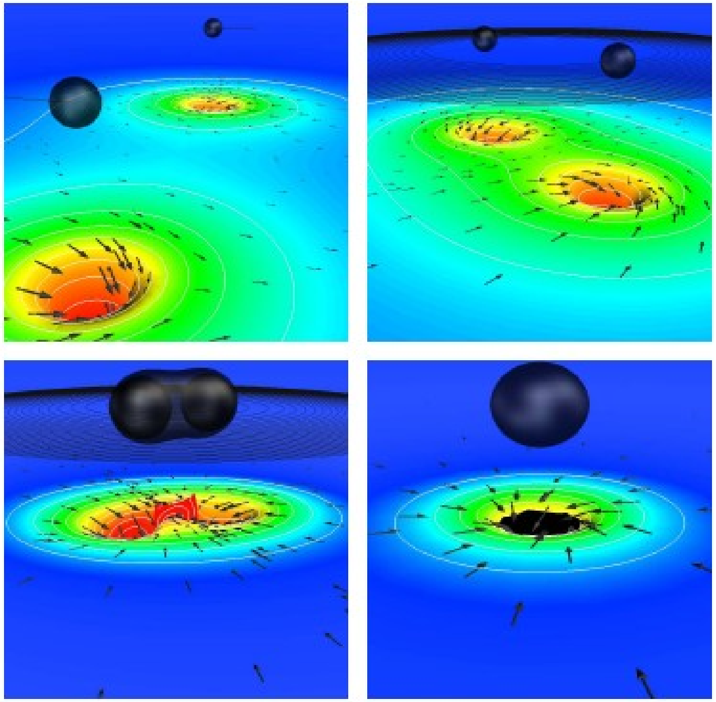


di Matteo 2006

Beauty, the beast, and gravitational waves





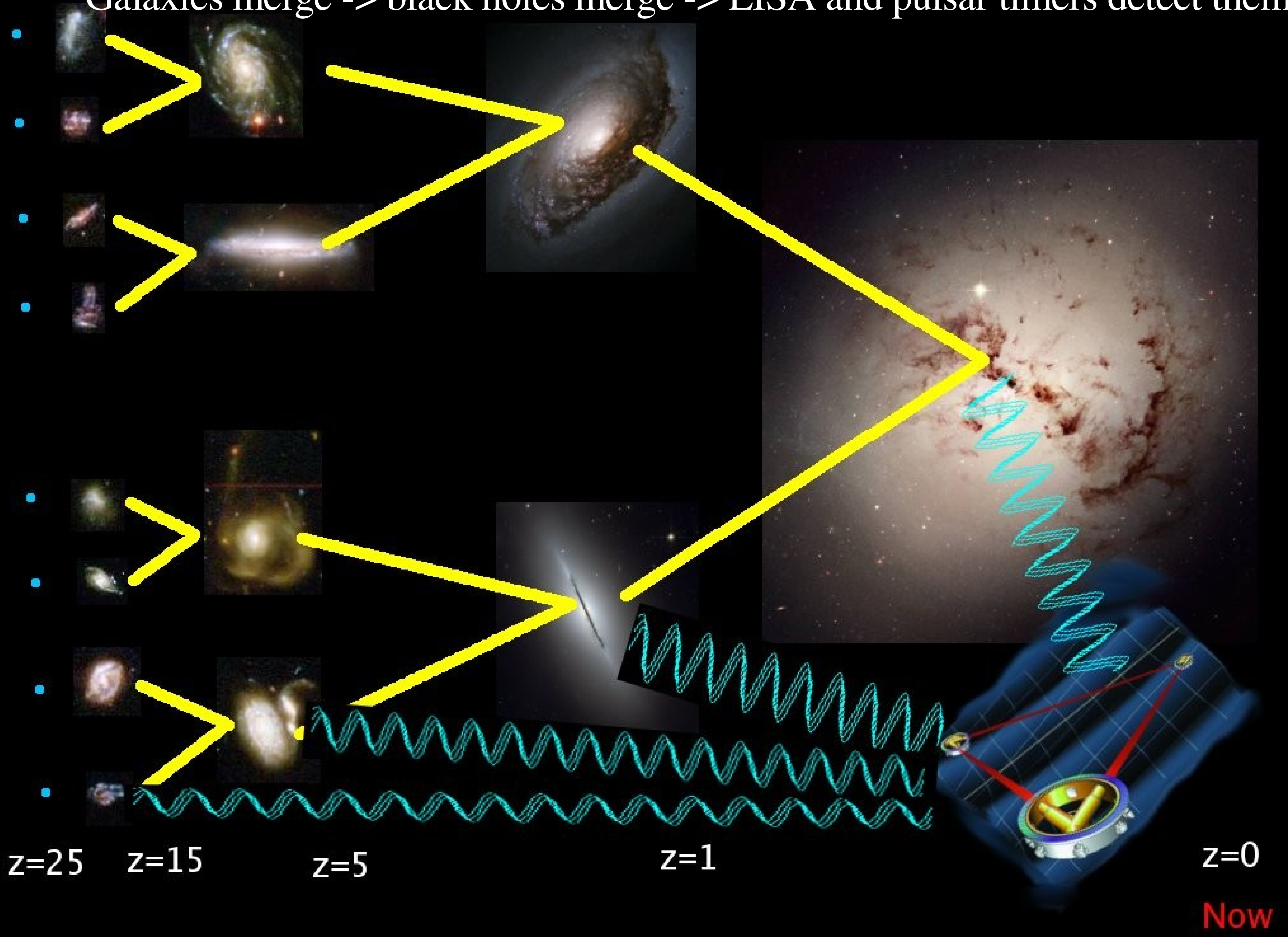


M.Scheel et al, Caltech

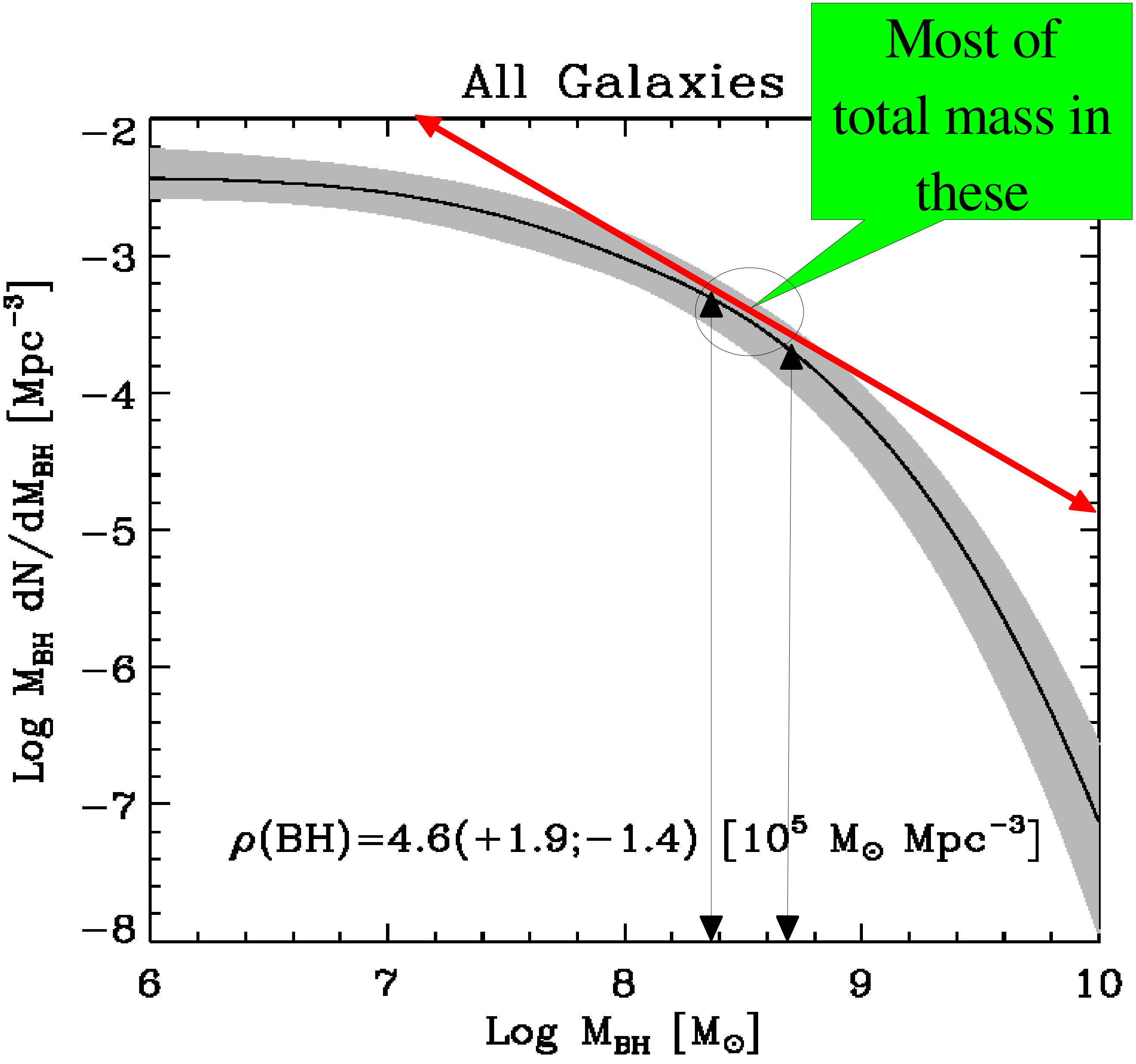
Sterl Phinney

Caltech

Galaxies merge -> black holes merge -> LISA and pulsar timers detect them



Local black hole mass function



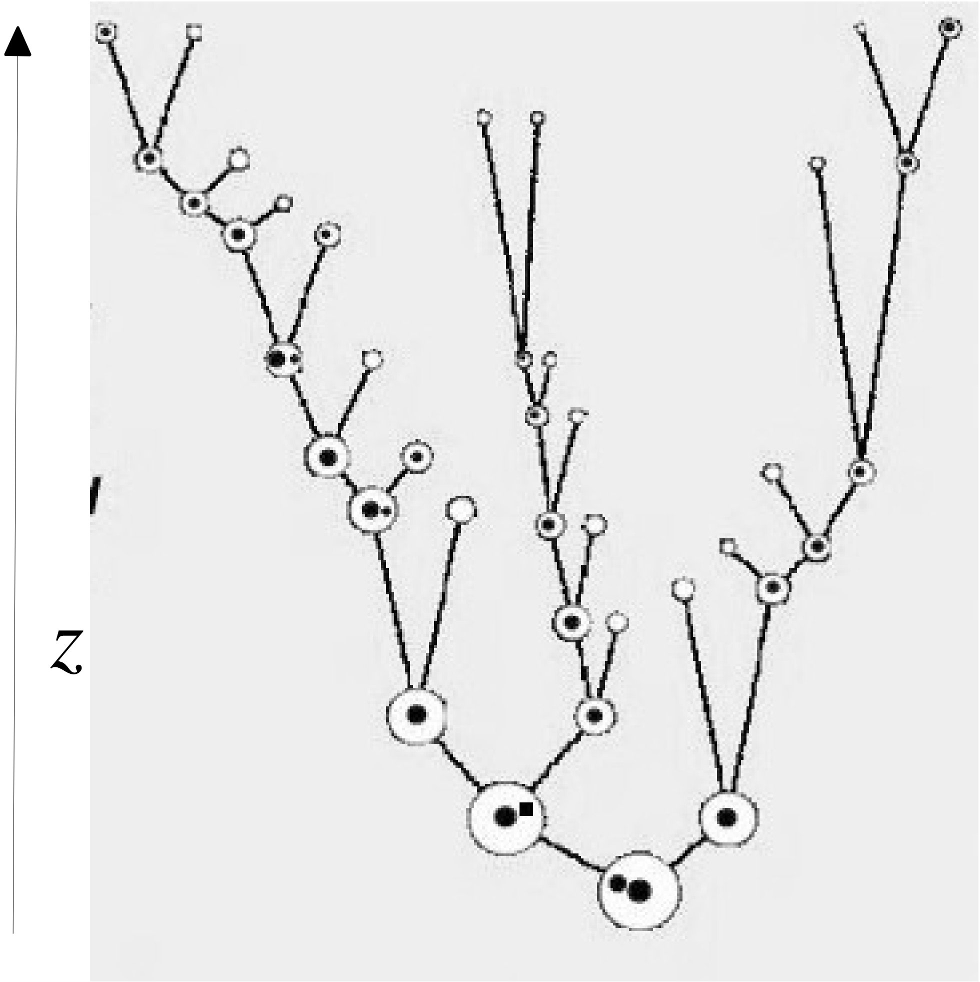
Most of total mass in these

Every galaxy in which BH could have been seen had one.

M-sigma relation or M-M*

N(M*) or N(sigma)

dark matter N-body simulators' merger rates



cf Haehnelt & Kaufmann 2000,
Volonteri et al 2004, 2007... -knobs added

Start with seed black holes in fraction *f* of high z halos.

In every major halo merger, asssume a fraction (adjusted to fit M-sigma) of baryons accrete onto BH.

Predictions: black holes grow inexorably -high mass formed recently. $\sim 10^2 f$ mergers per present-day galaxy.

dark matter N-body simulators' merger rates

Predictions: black holes grow inexorably

-most BH mass accumulated recently.

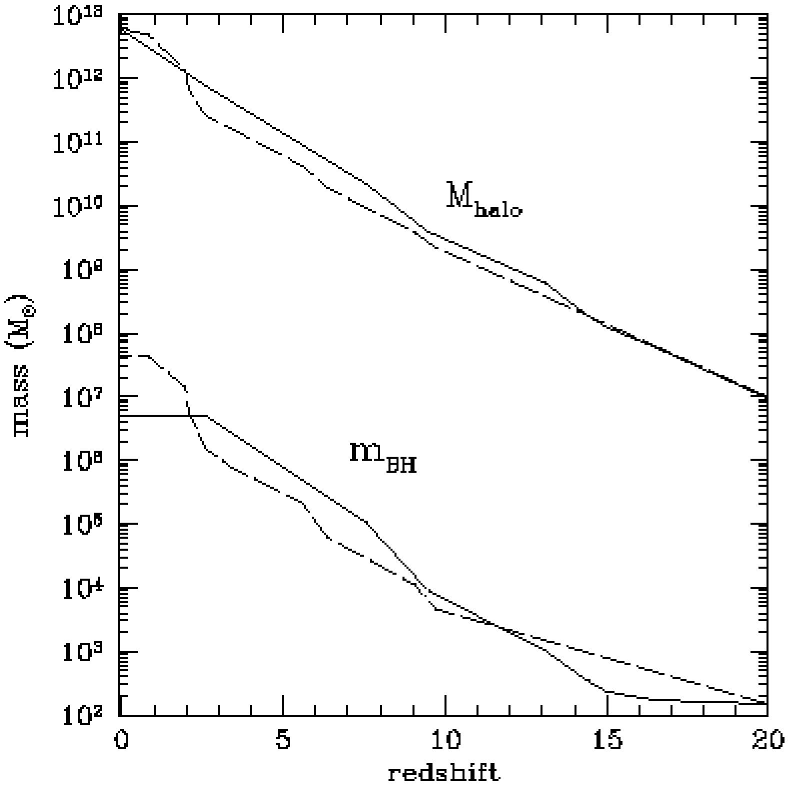
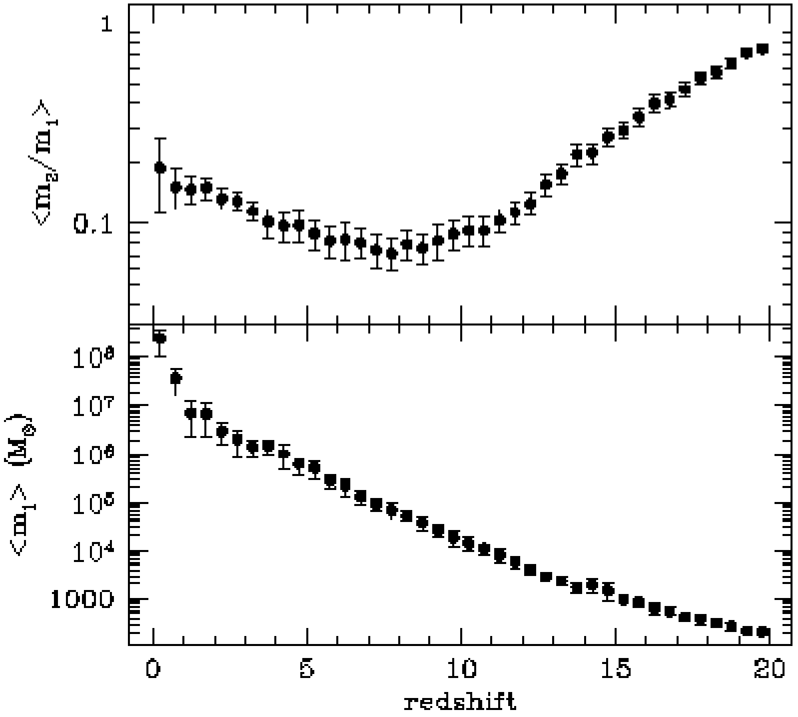


FIG. 11.— Two different realizations for the mass-assembly history of a galaxy halo with today velocity dispersion $\sigma_{DM} = 160 \text{ km s}^{-1}$ and its central SMBH. *Dashed line:* the halo experiences its last major merger at low redshift, and its hole follows the observed $m_{BH} - \sigma_c$ relation. *Solid line:* the halo has its final major merger at $z = 2.6$, when only a small fraction of its dark mass was already in place. The mass of its SMBH is only about 10% of that expected from the $m_{BH} - \sigma_c$ relation.

dark matter N-body simulators' merger rates



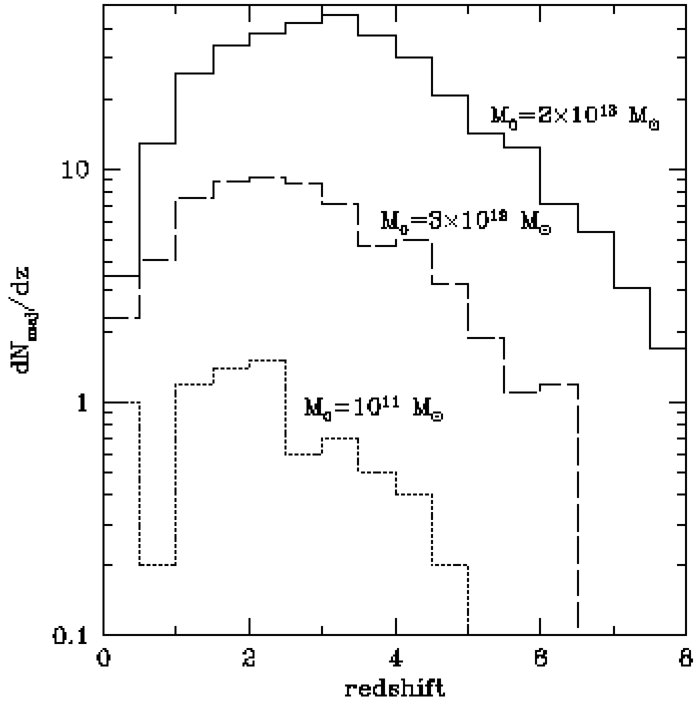


FIG. 3.— Mean number of major mergers experienced per unit redshift by halos with masses $> 10^{10}\ \mathrm{M}_\odot$. *Solid line:* progenitors of a $M_0 = 2 \times 10^{13}\ \mathrm{M}_\odot$ halo at $z = 0$. *Dashed line:* same for $M_0 = 3 \times 10^{12}\ \mathrm{M}_\odot$. *Dotted line:* same for $M_0 = 10^{11}\ \mathrm{M}_\odot$.

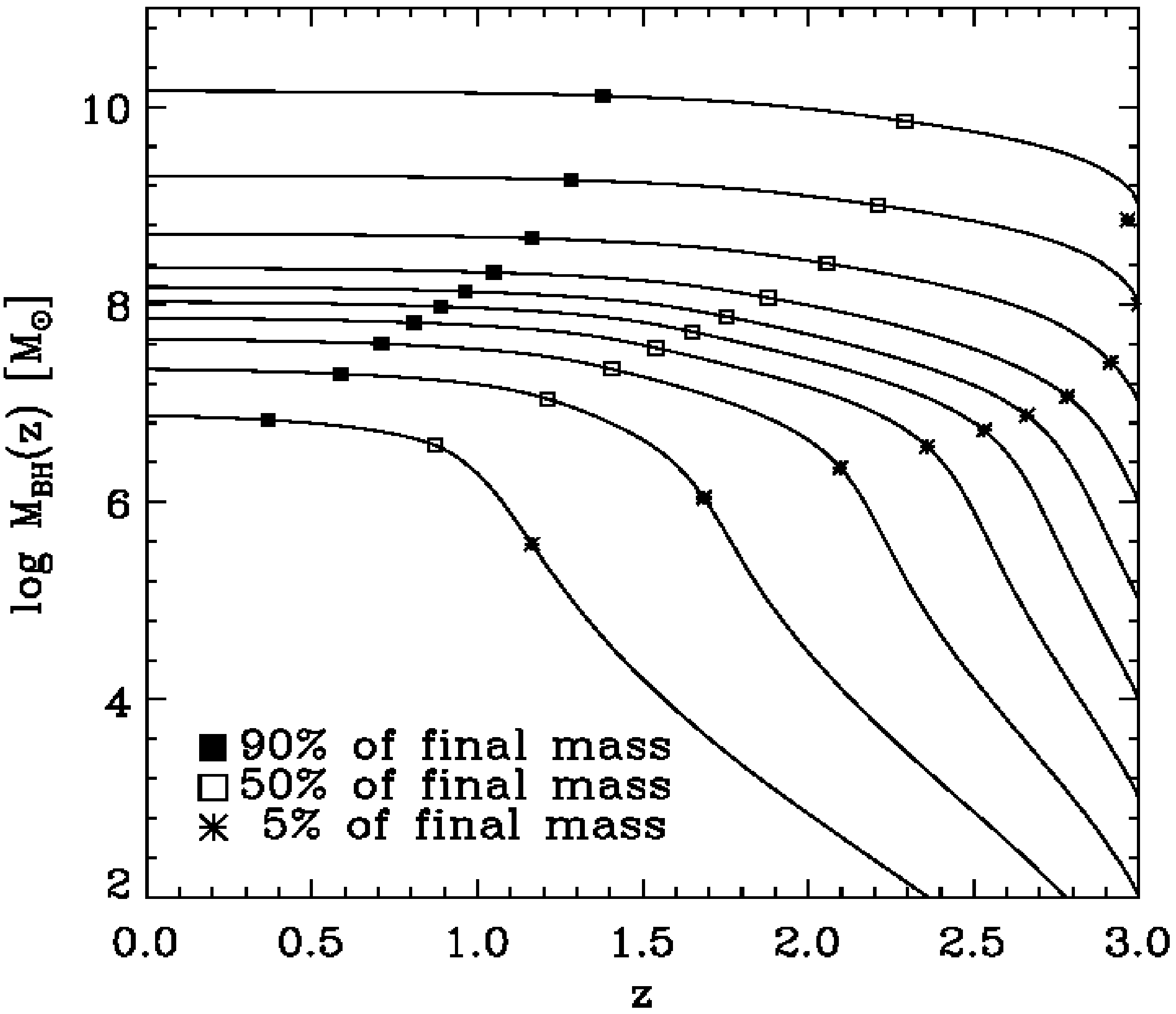
Predictions: black holes grow inexorably

-most BH mass accumulated recently.

-mass ratios low recently.

~10^2 *f* mergers per present-day galaxy.

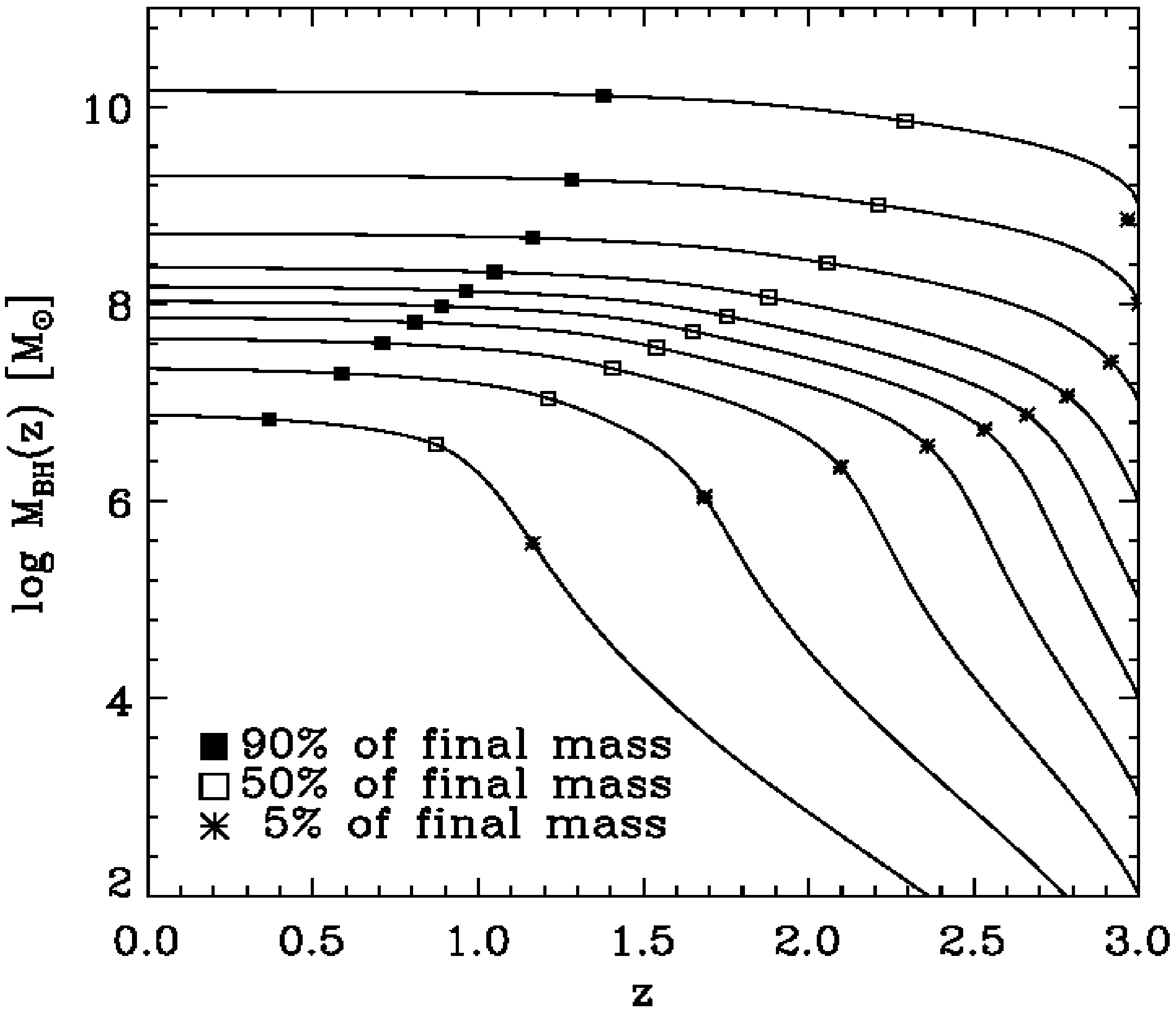
The AGN-observers evolution of BH mass function ("downsizing")



Simplest version: observed N(L,z)

Assume
L(M) -e.g.
L/L_{Edd}=const
ε=const
Constrain to
N(M,z=0).

The AGN-observers evolution of BH mass function ("downsizing")



Big black holes grew up early (z>3).

Small black holes formed recently (z<1.5)

Opposite to simple cold dark matter halo prescriptions!

Simple consequences of energy conservation of gravitational waves in a homogenous universe

(Phinney astro-ph/0108028)

$$\rho_c c^2 \Omega_{gw}(f) = \frac{\pi}{4}\frac{c^2}{G} f^2 h_c^2(f) = \int_0^\infty N(z)\frac{1}{1+z}\left(f_r \frac{dE_{gw}}{df_r}\right)\Bigg|_{f_r=f(1+z)} dz\ .$$

$$\frac{dE_{gw}}{df_r} = \frac{\pi}{3}\frac{1}{G}\frac{(G\mathcal{M})^{5/3}}{(\pi f_r)^{1/3}} \quad \text{for } f_{\rm min} < f_r < f_{\rm max}\ ,$$

where $\mathcal{M}$ is the chirp mass, $\mathcal{M}^{5/3} = M_1 M_2 (M_1 + M_2)^{-1/3}$.

$$h_c^2(f) = \frac{4}{3\pi^{1/3}}\frac{1}{c^2}\frac{(G\mathcal{M})^{5/3}}{f^{4/3}} N_0 \langle (1+z)^{-1/3} \rangle\ ,$$

$$N(f_r) = \frac{5\pi}{96}\frac{c^5}{(G\mathcal{M})^{5/3}}\frac{\dot{N}}{(\pi f_r)^{11/3}}\ .$$

Number of merger results per comoving volume today.

$$h_c(f) = 3.0 \times 10^{-24} \left(\frac{\mathcal{M}}{M_\odot}\right)^{5/6} \left(\frac{f}{10^{-3}\mathrm{Hz}}\right)^{-2/3} \left(\frac{N_0}{\mathrm{Mpc}^{-3}}\right)^{1/2} \left(\frac{\langle (1+z)^{-1/3} \rangle}{0.74}\right)^{1/2}\ ,$$

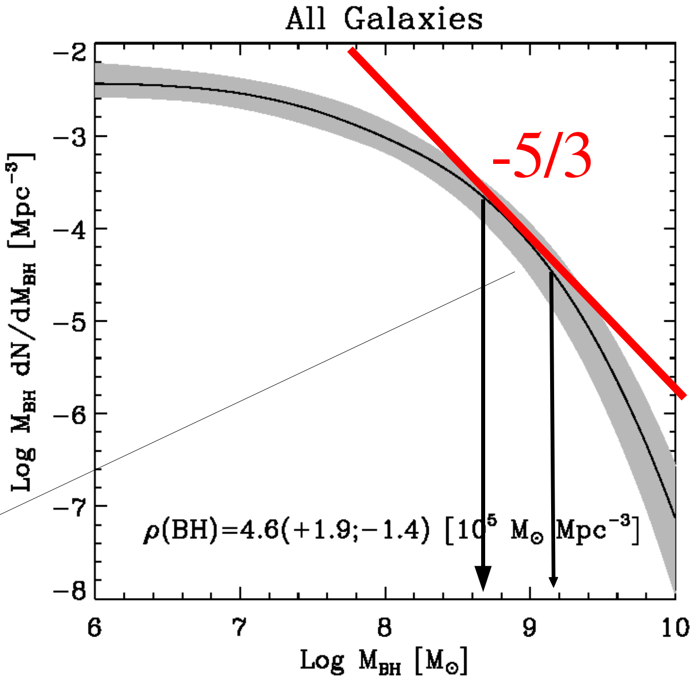
Simple consequences of energy conservation of gravitational waves in a homogenous universe

Redshift at which the mergers happen hardly matters.

$$h_c(f) = 3.0\times10^{-24}\left(\frac{\mathcal{M}}{M_\odot}\right)^{5/6}\left(\frac{f}{10^{-3}\mathrm{Hz}}\right)^{-2/3}\left(\frac{N_0}{\mathrm{Mpc}^{-3}}\right)^{1/2}\left(\frac{\langle(1+z)^{-1/3}\rangle}{0.74}\right)^{1/2},$$

$$M^{5/6} N_0^{1/2} \simeq M_1^{1/3}(N_0 M_2)^{1/2} = M_1^{1/3}(\Delta\rho_1)^{1/2}$$

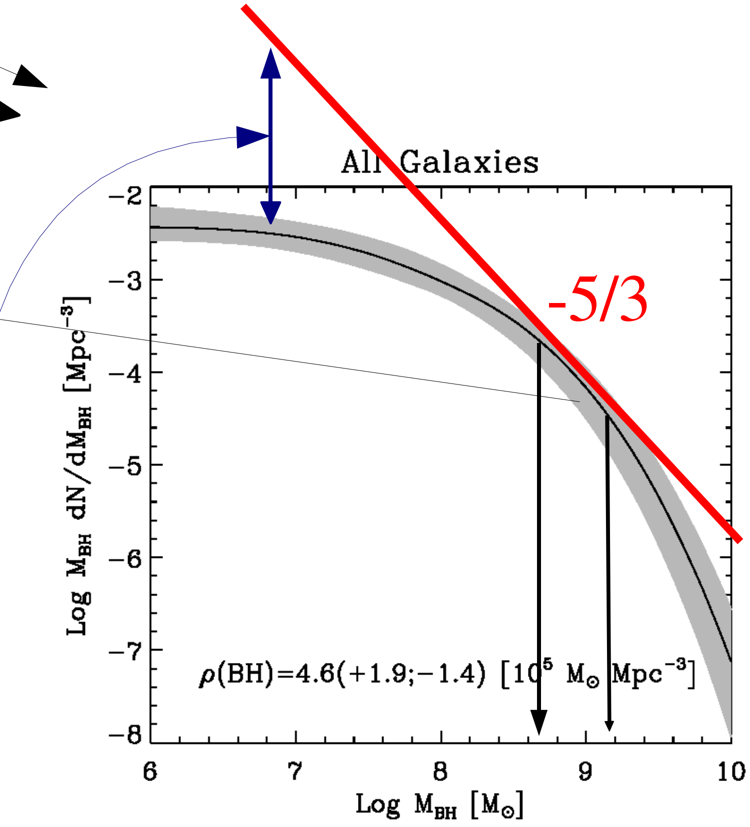
Only total mass merged matters -doesn' t matter if is via lots of small q mergers or one equal mass merger.



If black holes of all masses have the same fraction of growth from mergers, 10^9 Msun black holes dominate background.

Simple consequences of energy conservation of gravitational waves in a homogenous universe

$$h_c(f) = 3.0 \times 10^{-24} \left(\frac{\mathcal{M}}{M_\odot}\right)^{5/6} \left(\frac{f}{10^{-3}\mathrm{Hz}}\right)^{-2/3} \left(\frac{N_0}{\mathrm{Mpc}^{-3}}\right)^{1/2} \left(\frac{\langle(1+z)^{-1/3}\rangle}{0.74}\right)^{1/2} ,$$



If black holes of all masses have the same fraction of growth from mergers, 10^9 Msun black holes dominate background. Read off, for 50% growth: $h_c = 0.7 \times 10^{-15} f_{yr}^{-2/3}$

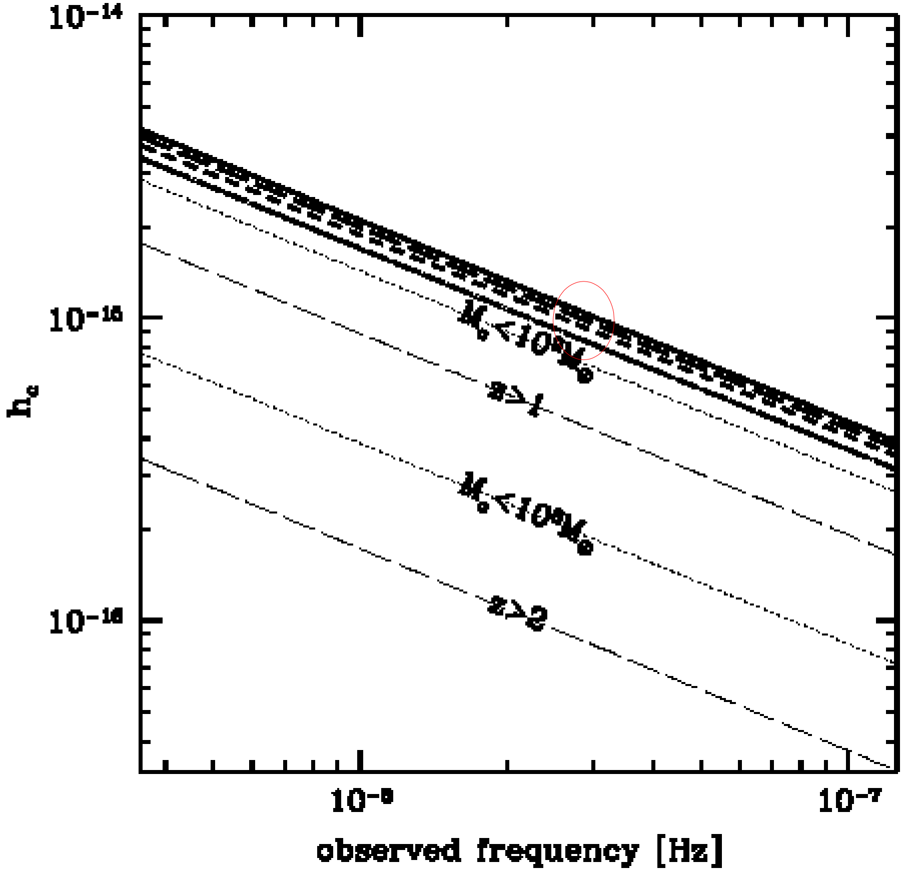
LISA sources with significant event rate (<10^7 Msun) contribute <10% of the pulsar timing background h_c.

Comparison with merger-tree simulations

Sesana arXiv:0804.4476

Has more mergers, flatter BH mass function, h_c about twice simple estimate:

$$h_c = 0.7\times10^{-15} f_{yr}^{-2/3}$$



Subtleties

$$\frac{dE_{gw}}{df_r} = \frac{\pi}{3}\frac{1}{G}\frac{(G\mathcal{M})^{5/3}}{(\pi f_r)^{1/3}} \quad \text{for } f_{\min} < f_r < f_{\max} \ ,$$

where $\mathcal{M}$ is the chirp mass, $\mathcal{M}^{5/3} = M_1 M_2 (M_1 + M_2)^{-1/3}$.

$$\rho_c c^2 \Omega_{gw}(f) = \frac{\pi}{4}\frac{c^2}{G} f^2 h_c^2(f) = \int_0^\infty N(z)\frac{1}{1+z}\left(f_r \frac{dE_{gw}}{df_r}\right)\Bigg|_{f_r=f(1+z)} dz \ .$$

$$N(f_r) = \frac{5\pi}{96}\frac{c^5}{(G\mathcal{M})^{5/3}}\frac{\dot{N}}{(\pi f_r)^{11/3}} \ .$$

Assumes at f that GW inspiral (not e.g. dynamical friction) dominates evolution with freq.

High mass, high frequency -short gw life -very few sources!

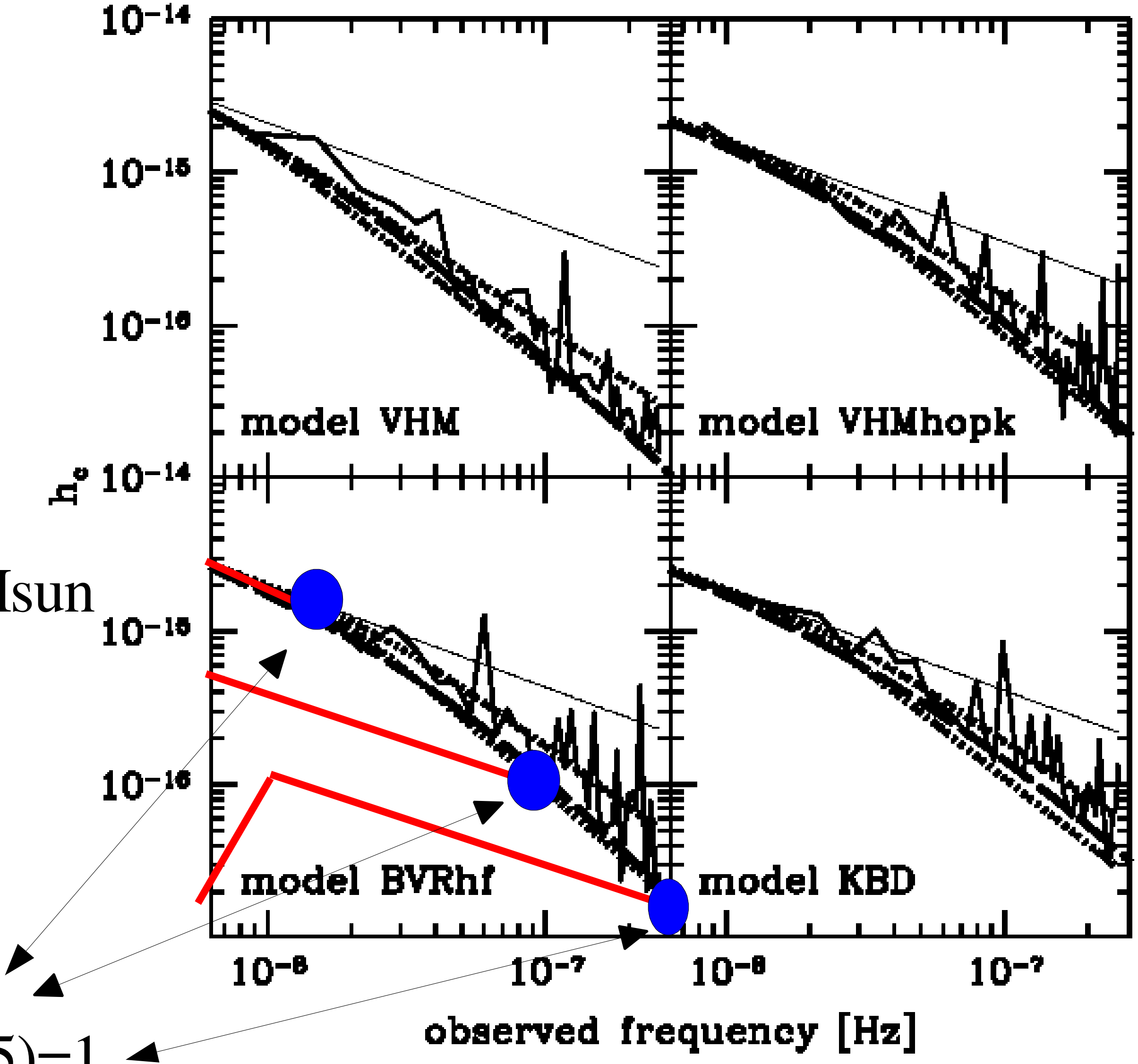
For $m/M = 0.3$,

$f > 10^{-9}\,Hz : 10^{10}\,Msun$ has $N(z < 1.5) < 1$

$f > 10^{-8}\,Hz : 10^{9.2}\,Msun$ has $N(z < 1.5) < 1$

$f > 10^{-7}\,Hz : 10^{8.5}\,Msun$ has $N(z < 1.5) < 1$

Subtleties



10^{10} Msun

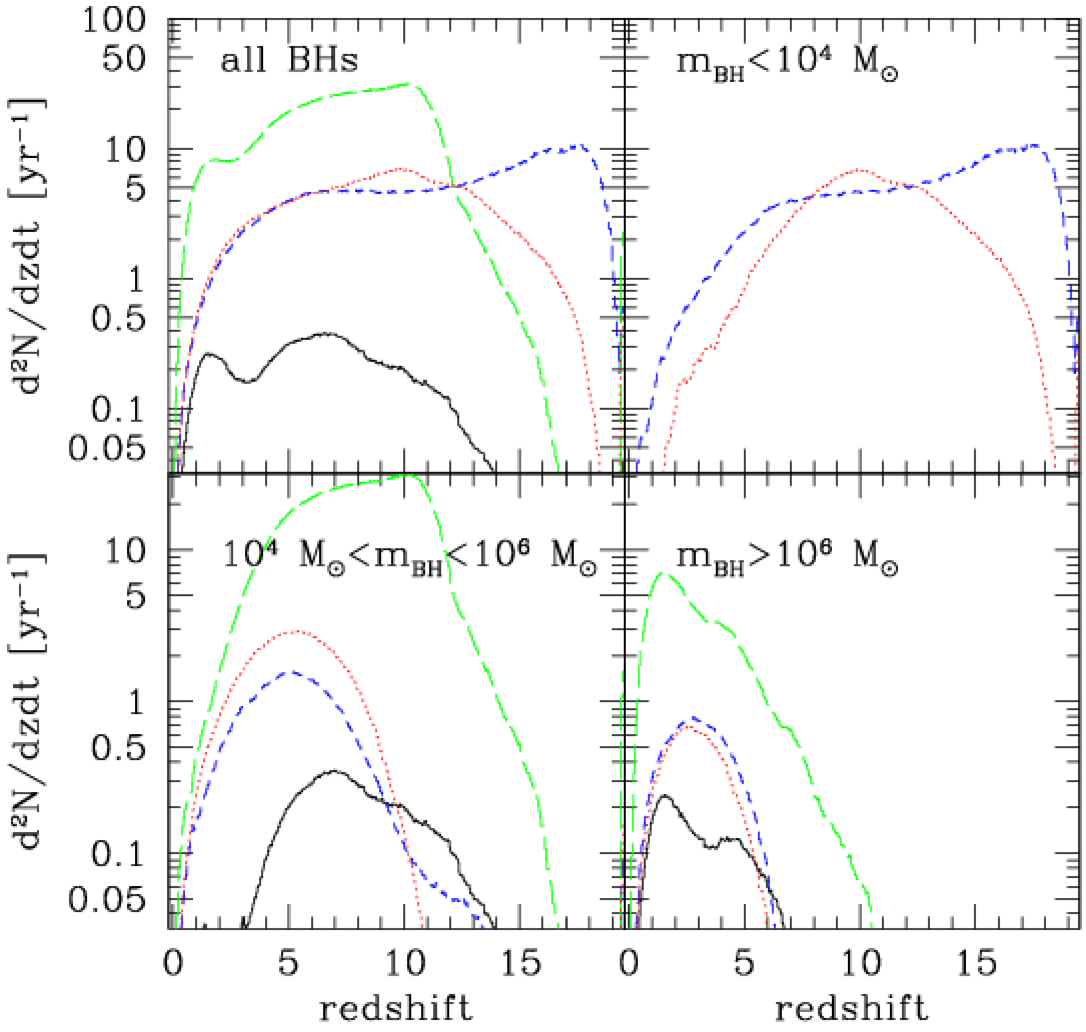
10^{9}

10^{8}

N(z<1.5)=1

Sesana et al 2008

Does this constrain LISA rates?

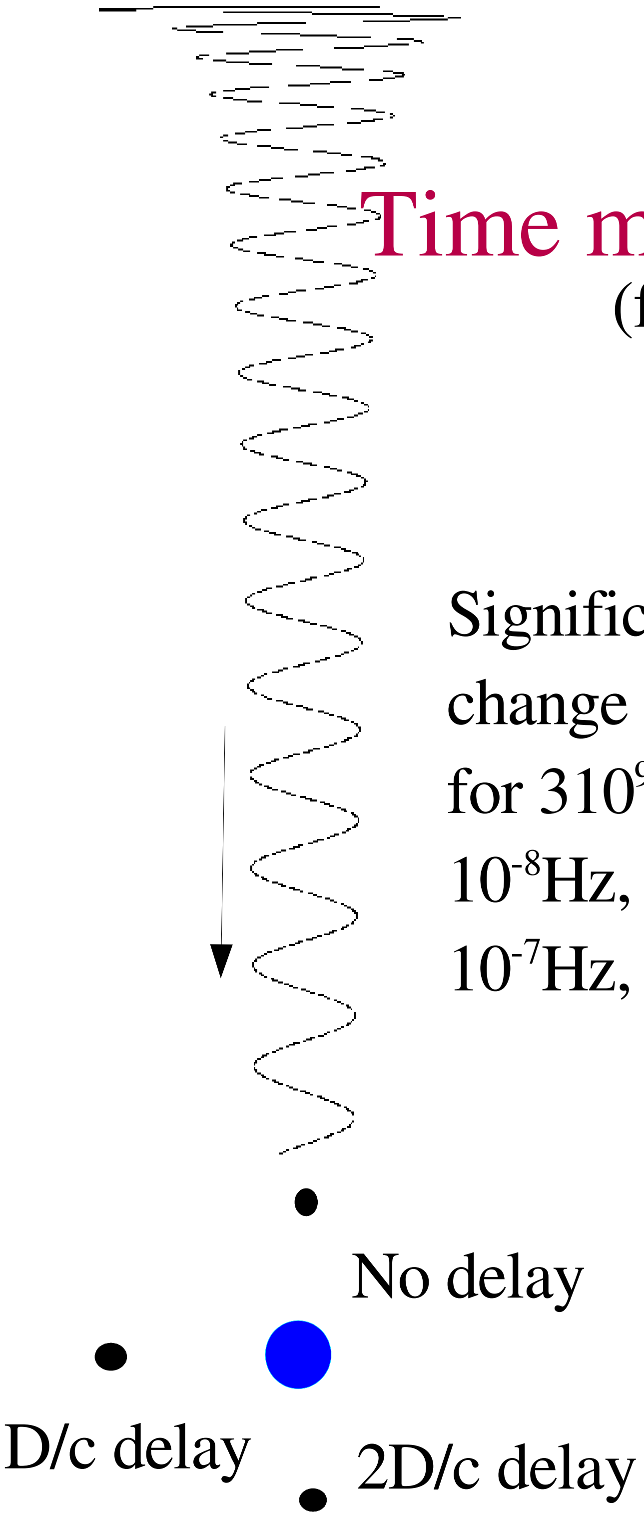


No: only measurements above 10^{-7}Hz would constrain.

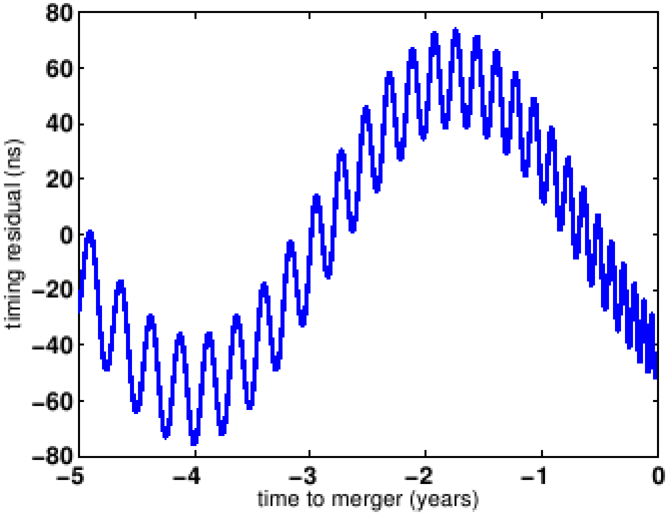
Volonteri 2007

Time machine for merger observers

(fun but currently impractical)



Significant frequency change over 10,000y for 310^{9} Msun at 10^{-8}Hz, 10^{8} Msun at 10^{-7}Hz, etc.



Pitkin et al 2008,
Jenet et al 2006

Pulsar at 3kpc distance, 90deg to BH.
z=0.25 merger of 5 10^{9} Msun pair
High freqs: last 5 years acting on earth
Low freq: one period, 10^{4} years before merger, acting on pulsar!

The BIG questions

- Are they really black holes?
  - (Kerr metric, vacuum, GR?, M, S)

LISA

- What were the seeds? How many seeds?
  - (Stellar mass, Pop III 100-300 Msun, “superstars” >10^4 Msun?)
  - A seed in every z=15 dwarf? Or only one per present-day >L*?

LISA, JWST?

- What were the relative contributions of gas accretion, stellar capture and black hole mergers to their growth at each redshift?

LISA, all electromagnetic wavelengths.