Observing Massive Black Hole Binary Coalescence with LISA

Joan Centrella

John Baker

NASA/GSFC

5th International LISA Symposium

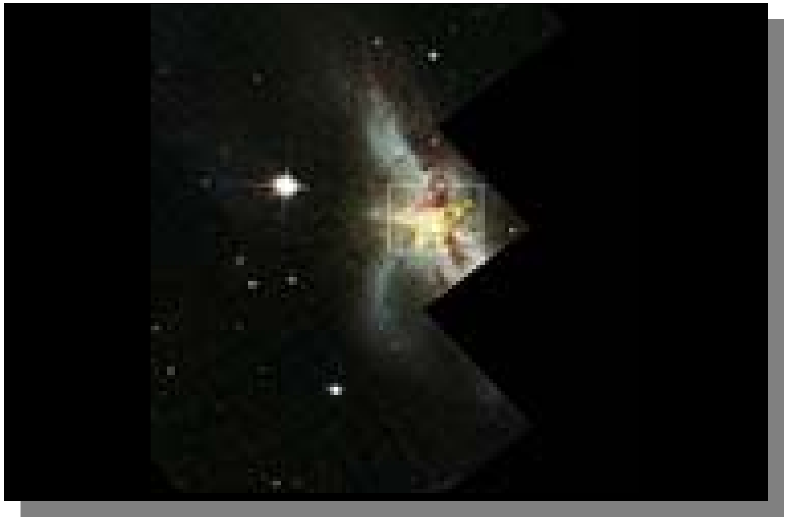
ESTEC July 12 - 15, 2004

Massive Black Hole Mergers

- MBHs lurk at the centers of all galaxies with bulges
- Chandra X-ray observatory found the first known system of 2 MBHs starting to merge in the galaxy NGC 6240
- Most galaxies are believed to have undergone at least one merger
- ΛCDM models of cosmic structure formation feature hierarchical build-up of galaxies from smaller structures

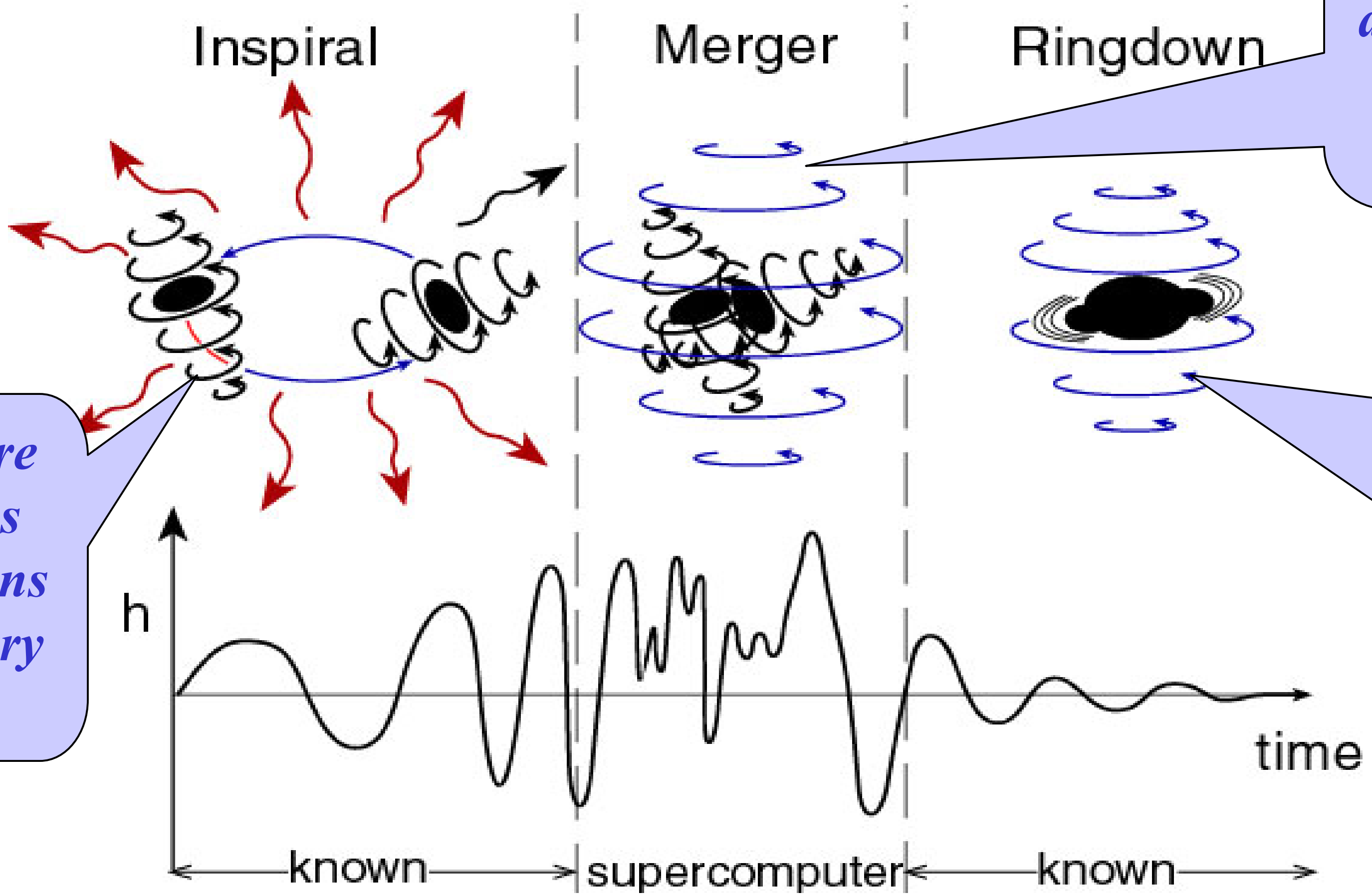
→ ***binary black hole mergers***

- Merger rates depend on size of “seed” black holes, accretion, stellar effects,...
- Rates: expect ~ 10s (more or less) per year (Sesana et al., Islam et al.)
- Detectable by LISA to high z



Final coalescence of MBH binary

- Binary separation << 1 pc (to coalesce within a Hubble time)
- Gravitational radiation reaction dominates energy losses
- Waveforms & dynamics scale with BH masses and spins



strong-field spacetime dynamics, spin flips and couplings…

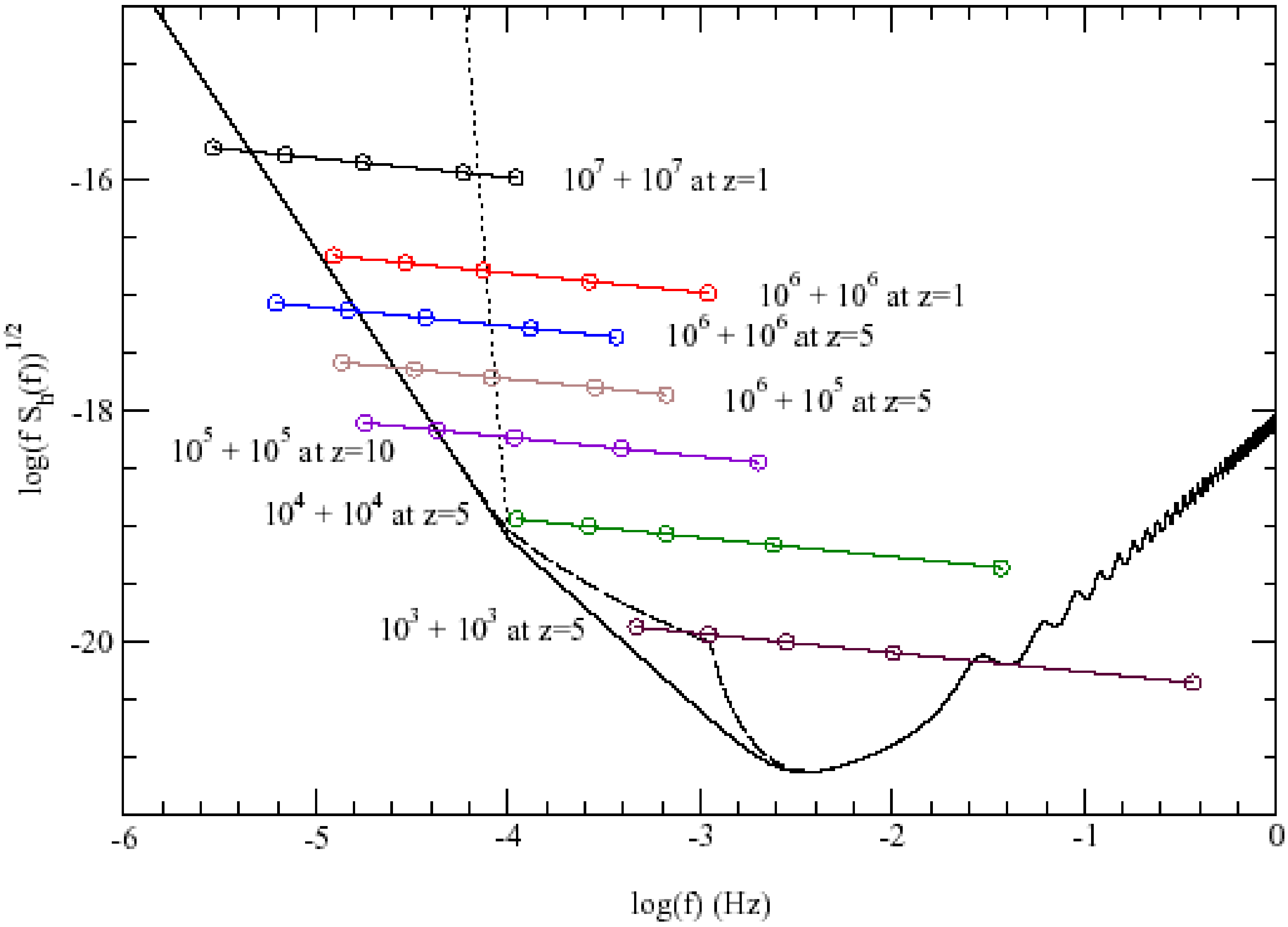
measure masses and spins of binary BHs

detect normal modes of ringdown to identify final Kerr BH

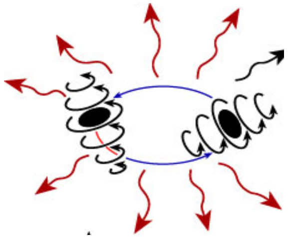
(graphic courtesy of Kip Thorne)

MBH inspirals and LISA

- symbols at 10 years, 1 year, 1 month, & 1 day before the onset of merger.
- the merger itself and subsequent ringdown occur at higher frequencies



Observing MBH binary inspirals

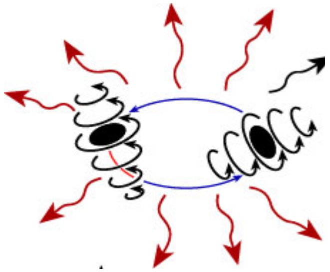


- **Parameter estimation:** how well can we learn the masses, spins, binary orientation, sky position, luminosity distance…to do astronomy
  - LISA measures redshifted masses (1+z)M
  - Need good measurement of sky position & orientation to obtain $\mathbf{D_L}$
- Cutler (1998): 1st detailed analysis of parameter extraction with LISA
- Hughes (2002): detailed estimates of LISA's precision for MBH binary parameters
  - Use knowledge of cosmological parameters (WMAP) to get z from D_L
  - Assume steep "wall" in sensitivity curve for $f < 10^{-4}$ Hz
  - → ***need to observe MBH inspiral for ~ 1 radian (~ 2 months) of its orbit for a good measurement of D_L and z to study merger history of MBHs***
- Vecchio (2003): effects of spin-induced precession of orbital plane; more in progress
- Holz & Hughes (2003): move cutoff from 10^{-4} Hz to $10^{-4.5}$ Hz

2-month rule-of-thumb: need to observe MBH inspiral for ~ 2 mos in band

  - Good measurement of source parameters, GW astronomy
  - Enable LISA to be used as a cosmological probe of galaxy merger history

Characterizing MBH binary inspirals



- **Which MBH binary systems are observable for *T* = 2 months, for various candidate low-frequency sensitivities?**

- Orientation-averaged SNR

  (FH 1998, matched filtering)

$$\langle \rho^2 \rangle = \int_0^\infty \frac{df}{f} \frac{h_{\mathrm{char}}^2(f)}{h_{\mathrm{n}}^2(f)}$$

where $h_{\mathrm{n}}(f) = \sqrt{\langle f S_h(f) \rangle}$ and $h_{\mathrm{char}} = \frac{\sqrt{2}(1+z)}{\pi D_{\mathrm{L}}(z)} \frac{dE}{df}[(1+z)f]$

f = frequency observed by the detector

and $f_{\mathrm{e}} = (1+z)f$ emitted (source) GW frequency

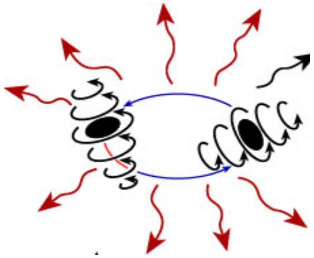
- Binary total mass $m = m_1 + m_2$ and chirp mass $M_{\mathrm{c}} = \mu^{3/5} m^{2/5}$

- Use Newtonian quadrupole approximation (agrees with PN expressions to within 25% or better for $M_c < 10^{8.5}\,\mathrm{M}_{\mathrm{sun}}$)

$$\frac{dE}{df} = \frac{1}{3} \pi^{2/3} M_{\mathrm{c}}^{5/3} f_{\mathrm{e}}^{-1/3}$$

Characterizing MBH binary inspirals

- At time *T* before final coalescence, LISA observes the MBH binary at frequency



$$f \cong 0.46\left(\frac{M_{\mathrm{c}}(1+z)}{\mathrm{M}_{\mathrm{sun}}}\right)^{-5/8}\left(\frac{T}{2\mathrm{mos.}}\right)^{-3/8}$$

with characteristic strain amplitude

$$h_{\mathrm{char}} \cong 4.9\times 10^{-17}\left(\frac{D_{\mathrm{L}}(z)}{1\mathrm{Gpc}}\right)^{-1}\left(\frac{T}{2\mathrm{mos.}}\right)^{-1/2}\left(\frac{f}{10^{-4}\,\mathrm{Hz}}\right)^{-3/2}$$

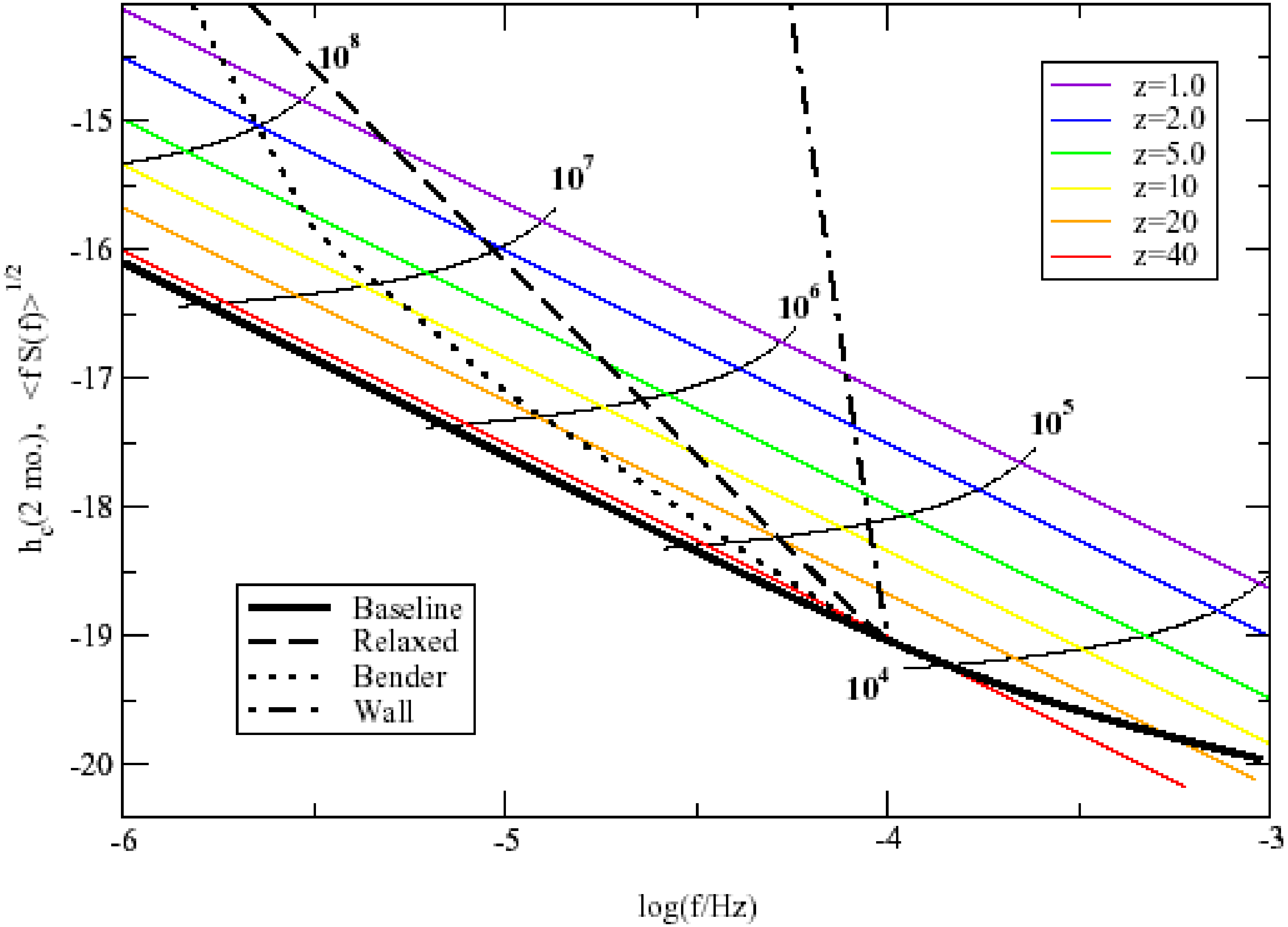
- Plot h_{char} vs. frequency
  - Colored lines: systems at *T* = 2 mos before final coalescence for specified redshifts z
    - **$h_{\mathrm{char}} \sim f^{-3/2}$ → parallel to baseline sensitivity curve $\langle f\,S_h(f)\rangle^{1/2} \sim f^{-3/2}$**
  - Black lines: systems with fixed chirp masses M_c at *T* = 2 months

Low frequency sensitivity of LISA

- LISA’s sensitivity below 0.1 mHz affects observations of MBH binaries
- Assume baseline sensitivity above 0.1 mHz (http://www.srl.caltech.edu/~shane/sensitivity/MakeCurve.html)
- Examine candidate low frequency sensitivity curves below 0.1 mHz:
  - Baseline: extends baseline with white accel noise, so $(S_h(f))^{1/2} \sim f^{-2}$
  - Bender: $(S_h(f))^{1/2} \sim f^{-2.5}$ from 10^{-4} Hz to 10^{-5} Hz, f^{-3} out to $10^{-5.5}$ Hz, then f^{-6} below $10^{-5.5}$ Hz
  - Relaxed: $(S_h(f))^{1/2} \sim f^{-3.5}$
  - Wall: $(S_h(f))^{1/2} \sim f^{-20}$
- Also consider relaxed sensitivity at 0.1 mHz
  - 0.1-mHz x5: relaxed by factor of 5 from baseline
  - Minimum mission: degrading the Bender curve by factor of 10
- Note: sensitivity curves to be shown *include* WD background noise

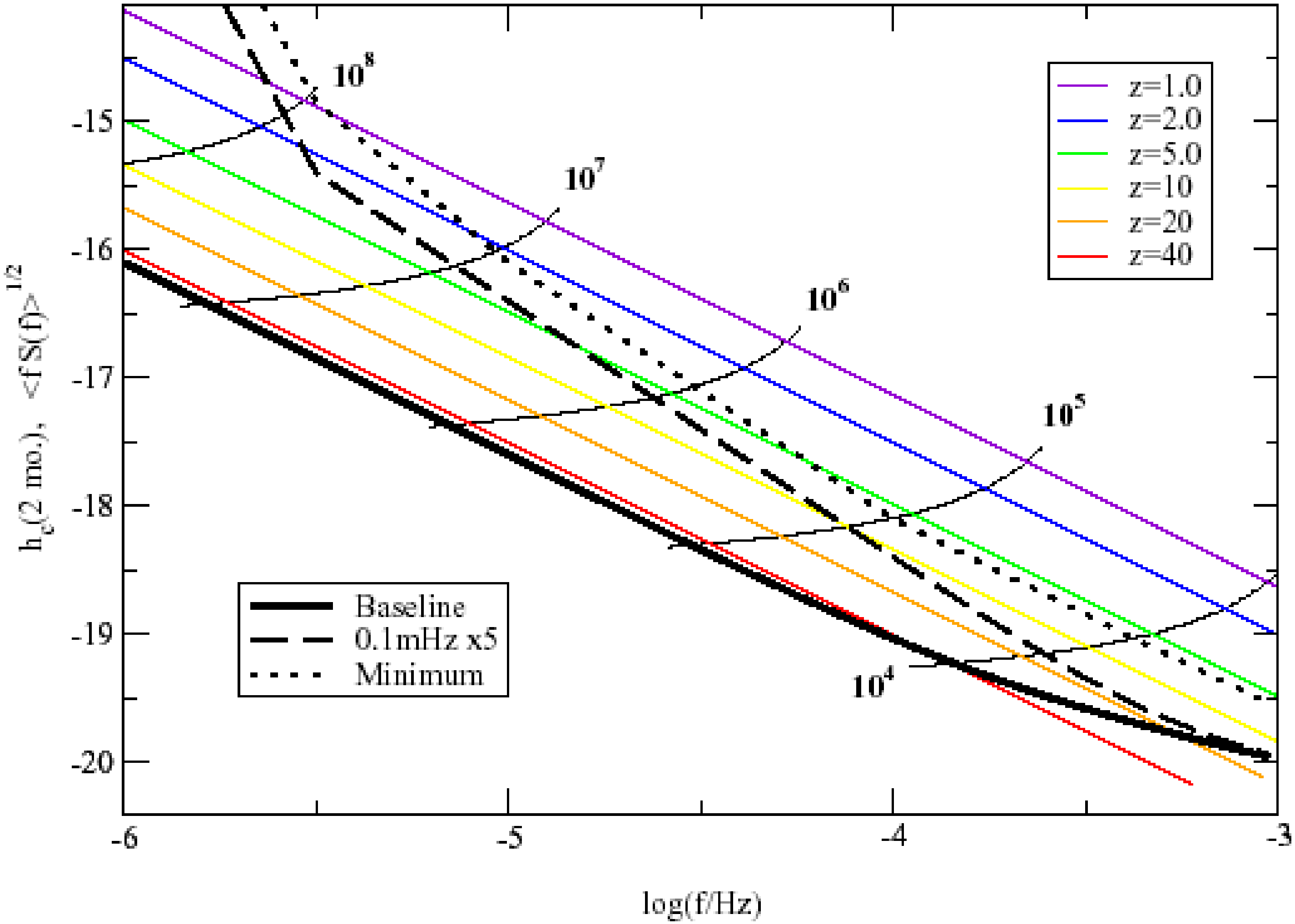
Science Reach – MBH inspirals

- An MBH binary with chirp mass M_c at redshift z can be observed for 2 months in band if it is above a given sensitivity curve



Science Reach – MBH inspirals

- An MBH binary with chirp mass M_c at redshift z can be observed for 2 months in band if it is above a given sensitivity curve



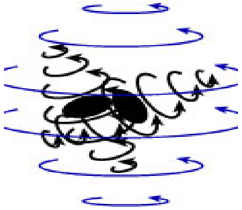
Caveats and comments….

- These results apply to an “average” source
  - 2-month rule based on Monte Carlo simulations with random orientations
  - Any real system will have a specific orientation that will increase or decrease its detectability somewhat relative to these plots
- More extensive parameter estimation studies would be useful
  - Spin effects (Vecchio, in progress)
  - Effects of expected noise (not just averaged sensitivity curves)
  - Effects of actual LISA performance, TDI, etc.

→ ***Is the 2-month rule-of-thumb modified?***

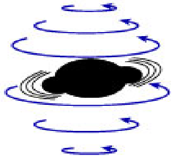
- How realistic are these low-frequency sensitivity curves?
  - Experimental, observational effects
  - Cost of implementation

MBH mergers….



- BHs leave their quasi-circular orbits to begin final plunge & merger near “innermost stable circular orbit” or ISCO at separation ~ 6*M*

$$f_{\text{isco}} \approx 4\times10^{-3}\left(\frac{10^{6}\,\mathrm{M}_{\text{sun}}}{(1+\mathrm{z})M}\right)\mathrm{Hz}$$



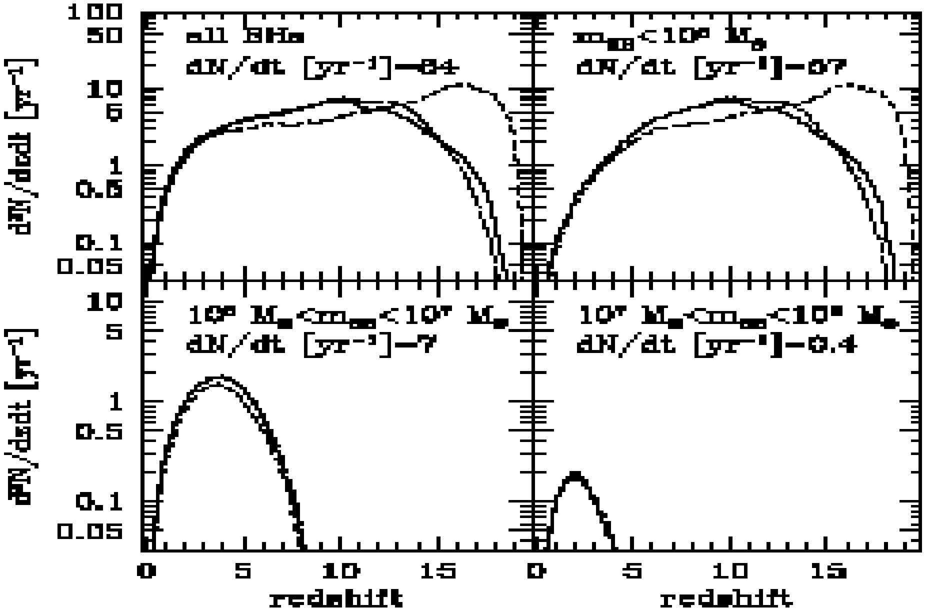
- Common EH forms → distorted BH emits GW in quasinormal ringing
  - Expect *l* = *m* = 2 mode will be dominant: longest lived, bar-like

$$f_{\text{qnr}} \cong 3.2\times10^{-2}\left[1-0.63(1-a)^{3/10}\right]\left(\frac{10^{6}\,\mathrm{M}_{\text{sun}}}{(1+z)M}\right)\mathrm{Hz},\qquad 0\le a\le 1$$

- Merger and ringdown are burst signals, at higher frequencies than inspiral
  - Zero-signal solution w/ TDI (Tinto & Larson 2004) may help w/ source location
- How well can we estimate MBH binary parameters using merger & ringdown?
  - Knowledge of merger – waveforms, phenomenology (GSFC, UTB….)
  - Occur at higher frequencies → less sensitive to low frequency performance

Observing MBH binary inspirals….

- Overall, expect younger (higher z) MBHs to have smaller masses than older (lower z) systems, which have had more time to grow
- Current observations revealing more quasars (and thus MBHs) at higher redshifts
- Bromm & Loeb (2003): scenario for formation of SMBHs inside the first galaxies
  - ~ 5 x 10^6 M_{sun} MBH formation at z > 10
  - MBHs may form in binary system → source of GWs for LISA
  - What are the rates?
- Merger rates depend on assumptions about the size of “seed” black holes, accretion, stellar effects, …
- Sesana, et al.(2004): merger tree →
- Alicea-Muñoz, Baker, Centrella, and Matzner (in progress)
  - Test effects of assumptions about mergers, accretion…
  - Various low frequency sensitivities



Summary

- Low frequency sensitivity of LISA is important for parameter estimation of MBH binaries at high redshifts
- Parameter estimation
  - How robust is 2 month rule-of-thumb?
  - Effects of spin, higher harmonics
  - Data analysis issues: realistic noise, account for TDI….
- Astrophysical issues
  - Rates, MBH scenarios in early universe
- Balance with instrumental issues, cost
- Science payoff from good low frequency sensitivity is substantial
  - MBH demographics
  - Merger history and relation to hierarchical structure formation….
  - Outstanding probe of early universe