

TOWARDS POPULATION SYNTHESIS MODELS FOR LISA

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TWO SPECIFIC QUESTIONS

HOW RARE CAN SUPERMASSIVE BLACK HOLES BE AT HIGH REDSHIFT?

→ IN ONLY A FEW % OF GALAXIES AT $z=5$

CAN LISA CONSTRAIN THE BH MASS / VELOCITY DISPERSION
RELATION IN COSMOLOGICALLY DISTANT GALAXIES?

→ SEEMS POSSIBLE



THE POPULATION OF SUPERMASSIVE BHs

• DYNAMICAL STUDIES (MAGORRIAN ET AL. 1998):

- SMBHs ARE ALMOST UBIQUITOUS IN NEARBY LUMINOUS GALAXIES
- GALAXIES PROBED "EXTENSIVELY": $M \geq 10^{11} M_{sun}$

• QUASAR (OPTICAL) LUMINOSITY FUNCTION (E.G. RICHSTONE ET AL. 1998):

- COMOVING DENSITY OF LUMINOUS QUASARS AT $z=3$ IS 10^{-3} OF THAT OF CORRESPONDING BRIGHT HOST GALAXIES

• X-RAY STUDIES (MUSHOTZKY ET AL. 2000; BARGER ET AL. 2001):

- $\sim 1\%$ OF ALL BULGE-DOMINATED OPTICALLY-LUMINOUS GALAXIES SHOW HARD X-RAY ACTIVITY ($z < 3$)



BH MERGERS FROM GALAXY MERGERS

• CDM COSMOLOGY:

GALAXIES BUILD UP BY SUCCESSIVE MERGERS

→ ONE NAIVELY EXPECTS CENTRAL BHs TO MERGE AS WELL

• BUT: THE COALESCENCE OF A SMBH BINARY IS NOT AN OBVIOUS OUTCOME:

(BEGELMAN, BLANDFORD & REES 1980 + OTHERS)

- BHs SINK TOWARDS CENTER OF MERGED GALAXY VIA DYNAMICAL FRICTION
- BHs FORM A BOUND BINARY
- BH BINARY SHRINKS BY "EJECTING" SURROUNDING STARS ON LOW ANGULAR MOMENTUM ORBITS [BOTTLENECK]
- BINARY BECOMES COMPACT ENOUGH TO QUICKLY MERGE VIA GRAVITATIONAL WAVE EMISSION

BH MERGERS AS SEEN BY LISA

- ☉ DEPENDING ON SMBH MASSES & REDSHIFT, LISA CAN DETECT GW EMISSION OF:
 - INSPIRAL PHASE
 - MERGER/PLUNGE PHASE
 - RINGDOWN PHASE

- ☉ POSSIBILITY TO UNTANGLE MASS-REDSHIFT DEGENERACY (HUGHES 2001):
 - ALL MASS COMBINATIONS MEASURED ARE REDSHIFTED $(1+z)$
 - AMPLITUDE ALSO DEPENDS ON LUMINOSITY DISTANCE D
 - KNOWLEDGE OF $D(z)$ CAN BE USED TO REMOVE DEGENERACY
 - ONE CAN GET M_1, M_2 AND z

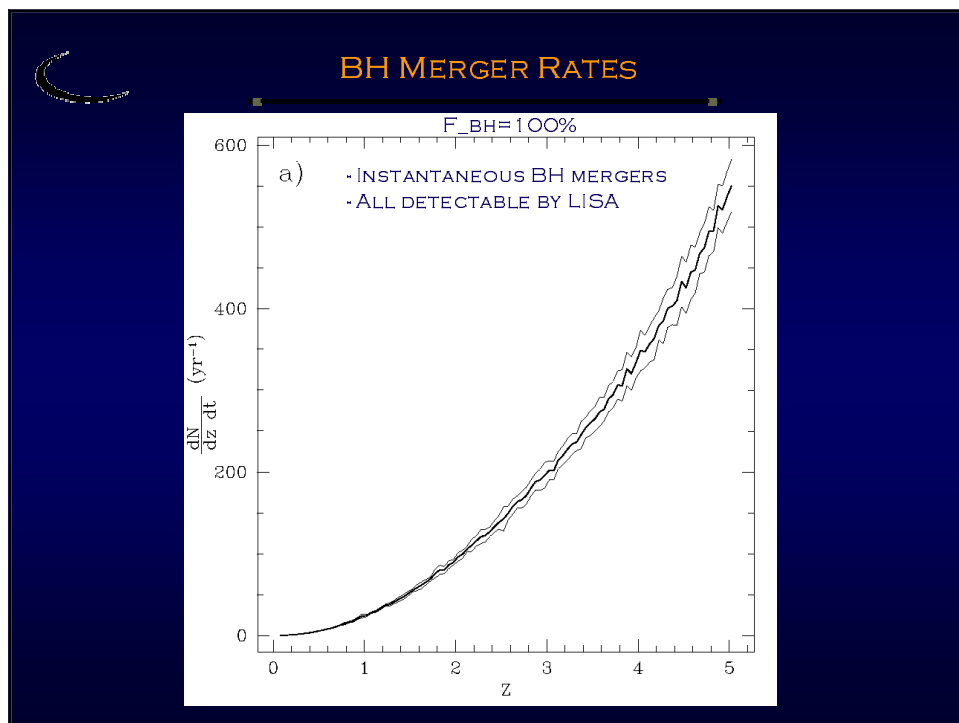
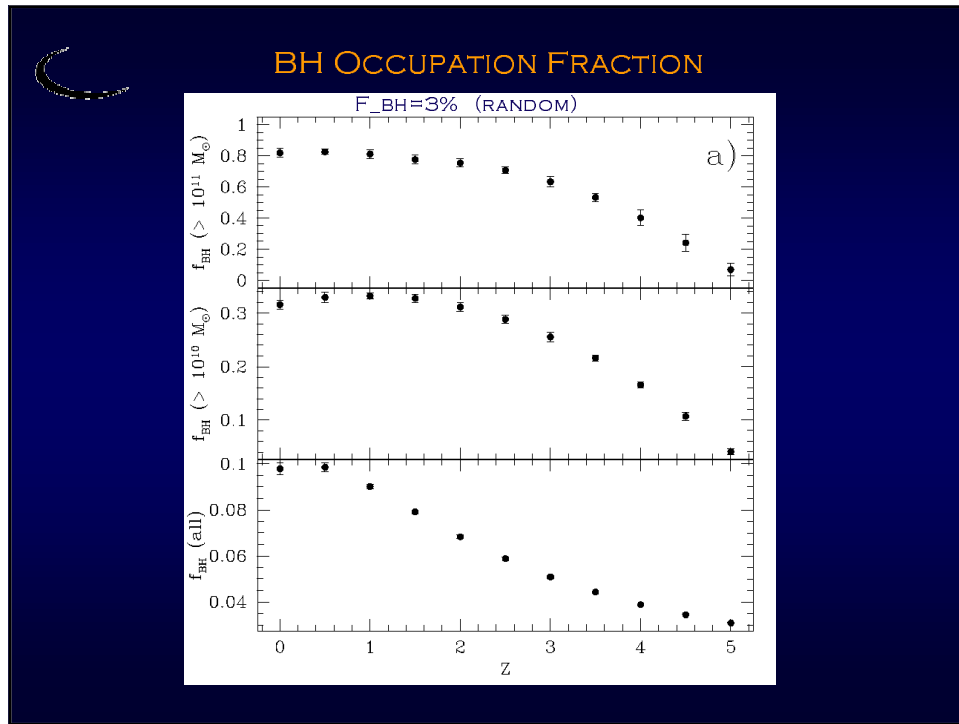
- ☉ SIMULATION FOR EQUAL MASS BINARIES:
 - GOOD PRECISION (30% OR BETTER) WITHIN ORDER OF MAGNITUDE OF $\approx \frac{10^5 M_{sun}}{1+z}$
 - EXQUISITE PRECISION ($\ll 1\%$) FOR REDSHIFTED CHIRP MASSES

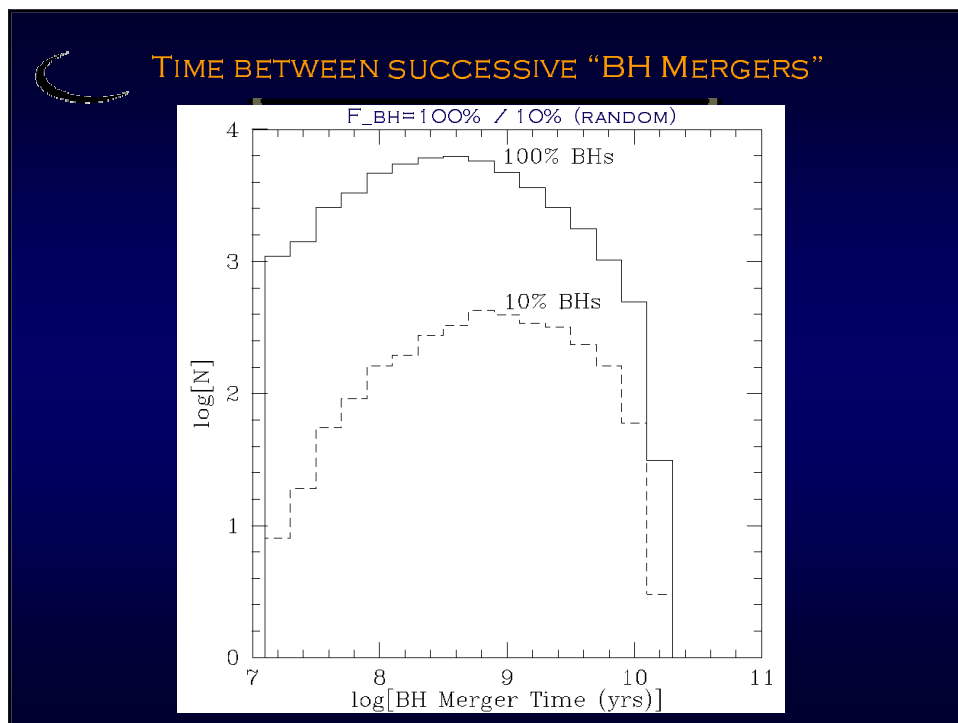
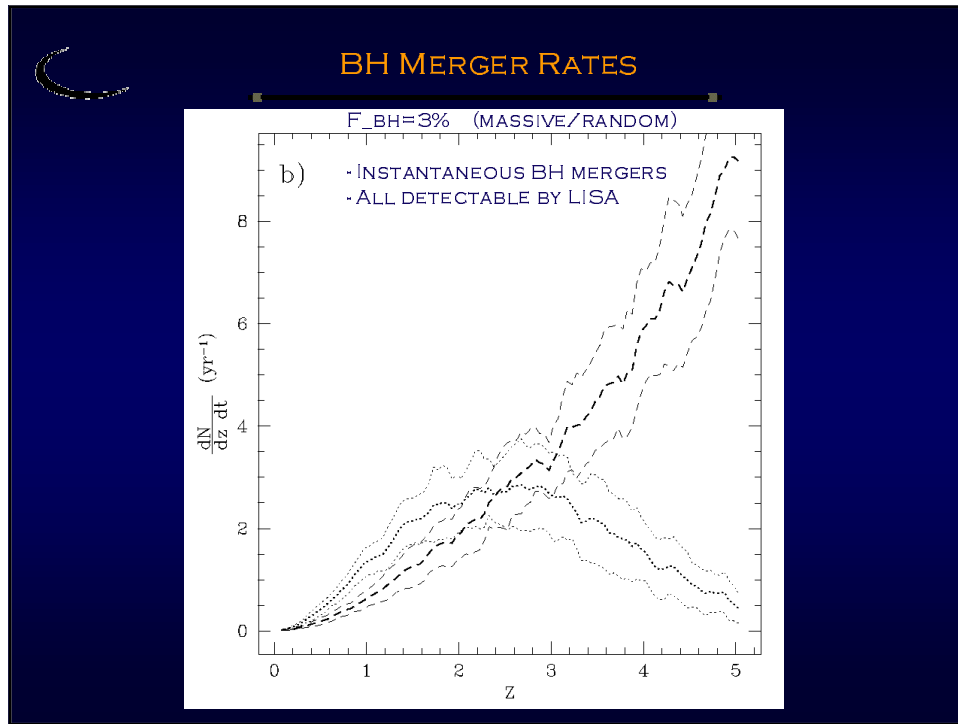
MERGER TREE

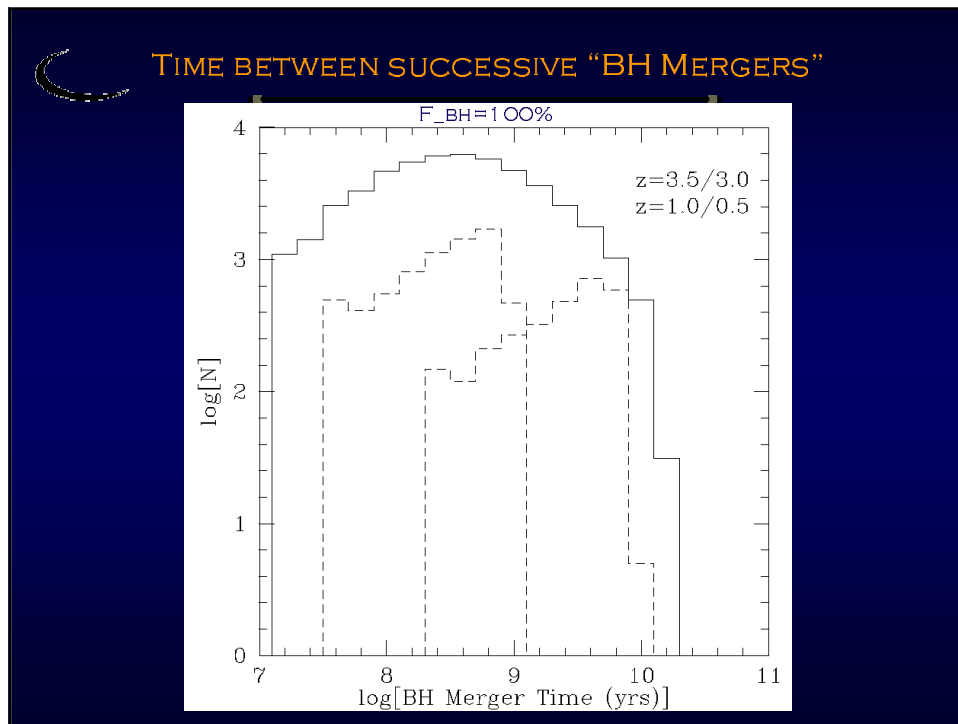
(MENO, HAIMAN & NARAYANAN 2001)

- ☉ DESCRIBES MERGER HISTORY OF DM HALOS IN LAMBDA-CDM COSMOLOGY:
 - ASSUME ONE-TO-ONE CORRESPONDENCE BETWEEN HALOS AND GALAXIES
 - ASSUME SMBHS CAN EXIST ONLY IN HALOS WITH $T_{vir} > 10^4$ K (BARYON COOLING)
 - $\sim 10^5$ HALOS AT $z=5$ MERGE INTO $\sim 10^4$ HALOS AT $z=0$ (COMOVING 10^4 Mpc^3)

- ☉ POPULATING GALAXIES WITH SMBHS (NO BH MASS REQUIRED SO FAR)
 - $F_{BH} = 1$ AT $z=5$ (ALL GALAXIES)
 - $F_{BH} < 1$ AT $z=5$: RANDOMLY OR MOST MASSIVE ONLY







PLAUSIBLE MASS MODEL FOR BHs

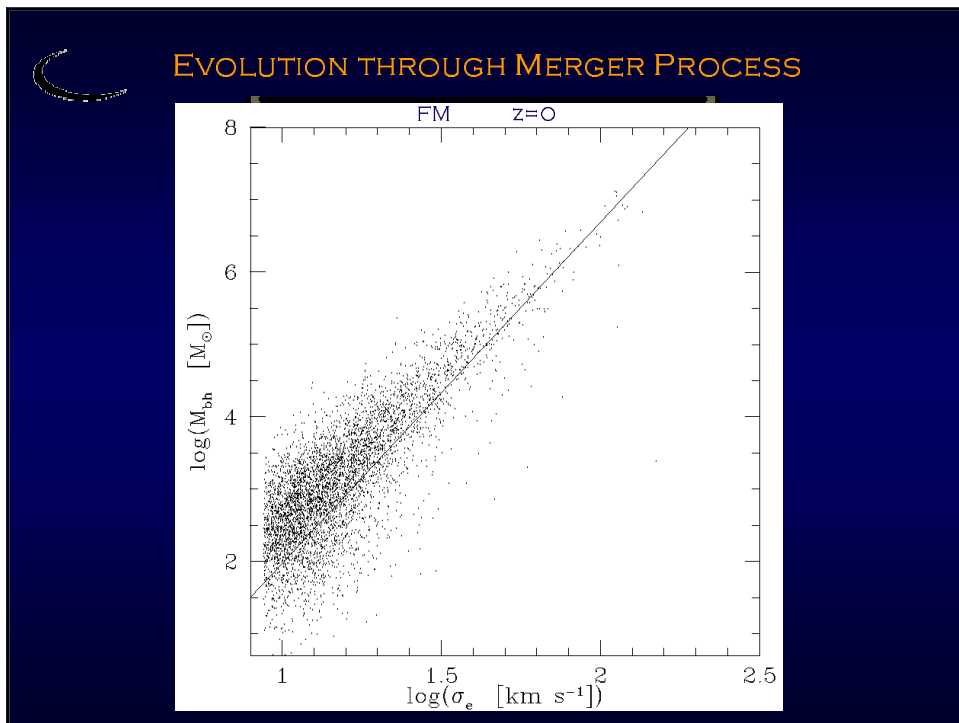
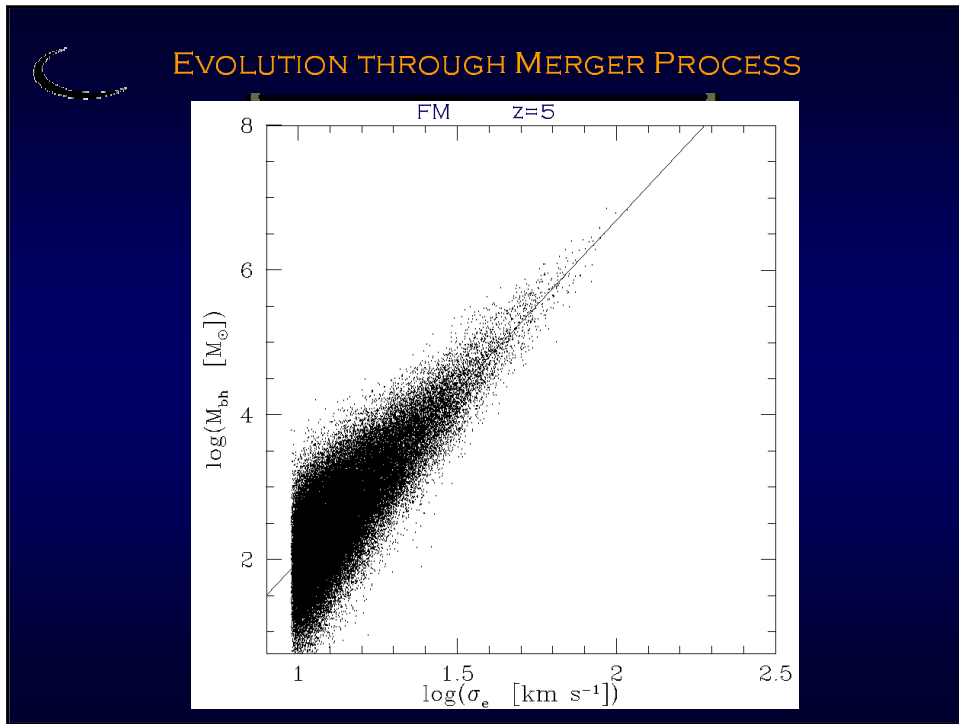
(100% BHs ONLY)

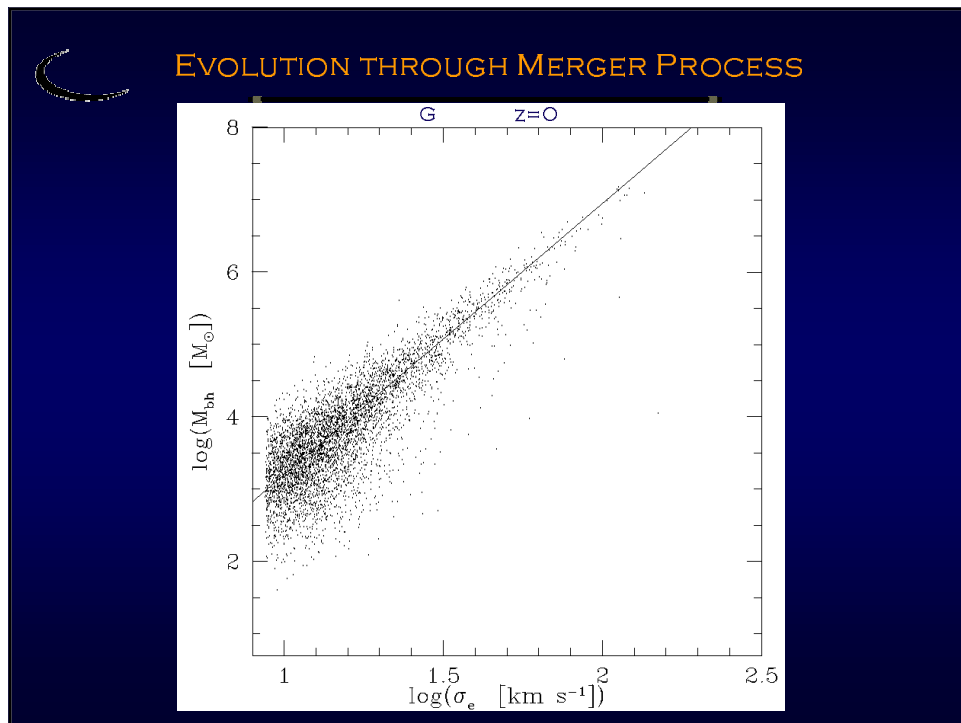
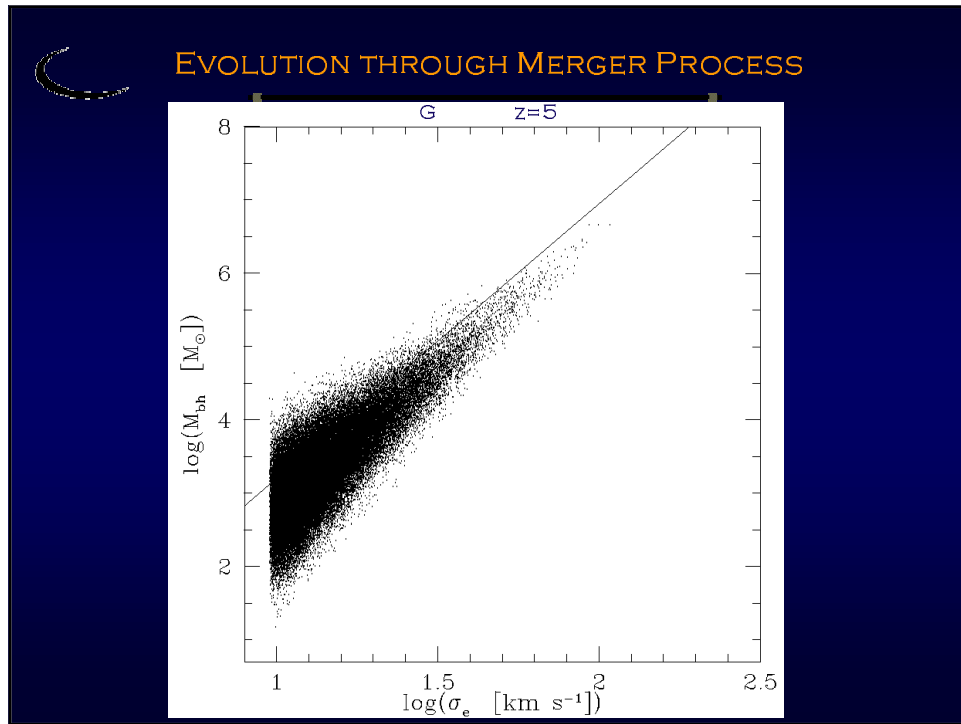
- USE KNOWN CONSTRAINTS AT Z=0 (+ EXTRAPOLATION AT SMALL MASSES)

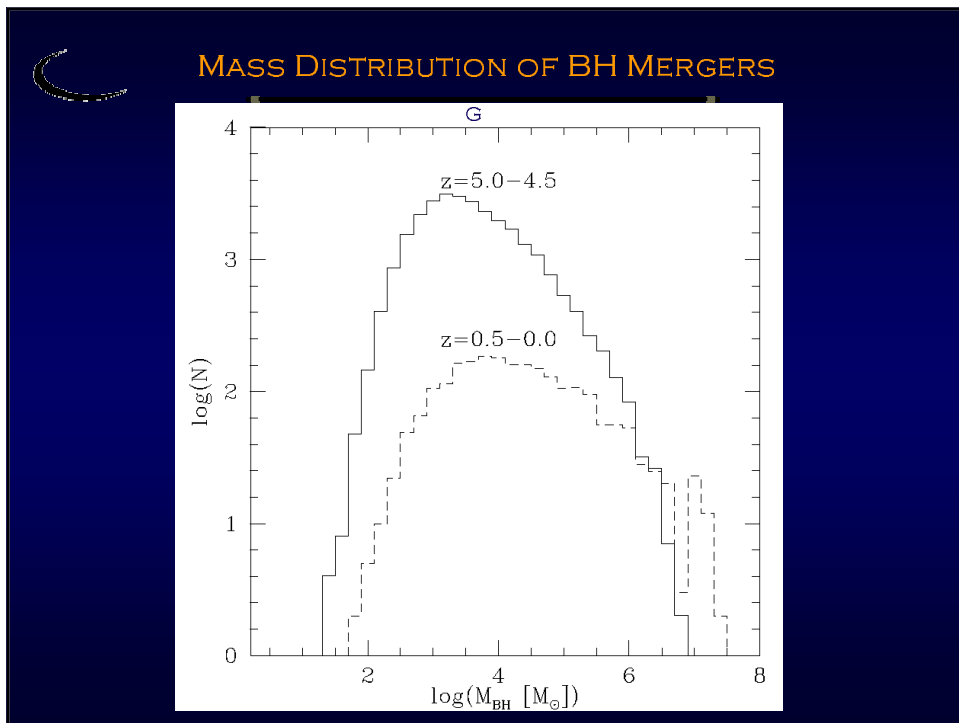
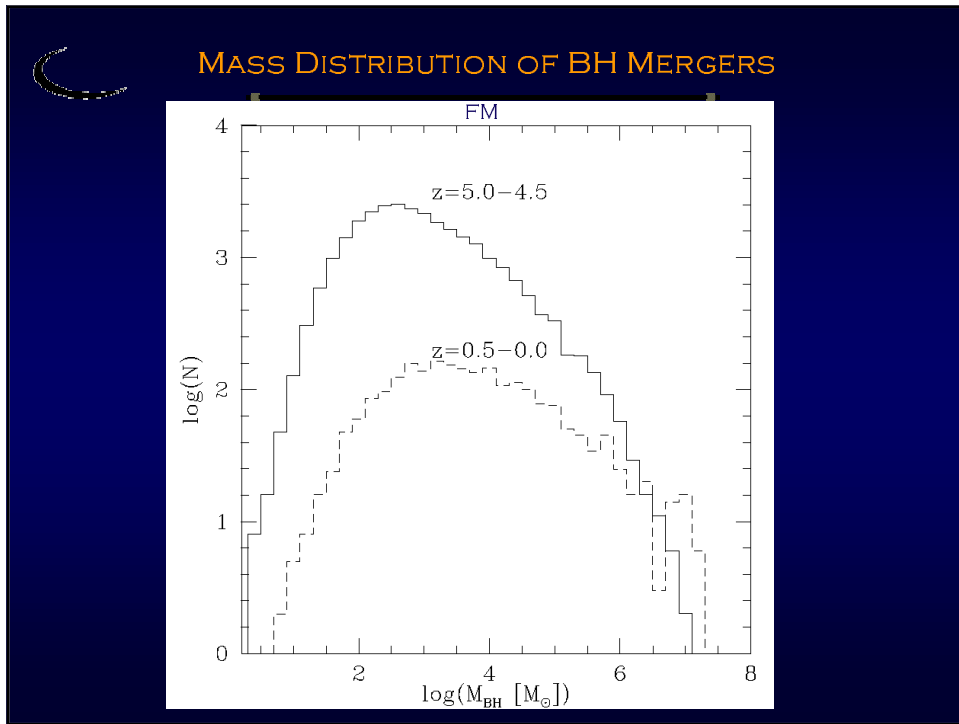
FM-MODEL $M_{BH} = 1.3 \pm 0.36 \cdot 10^8 M_{sun} \left(\frac{\sigma_e}{200 \text{ km s}^{-1}} \right)^{4.72 \pm 0.36}$ (MERRITT & FERRARESE 2001)

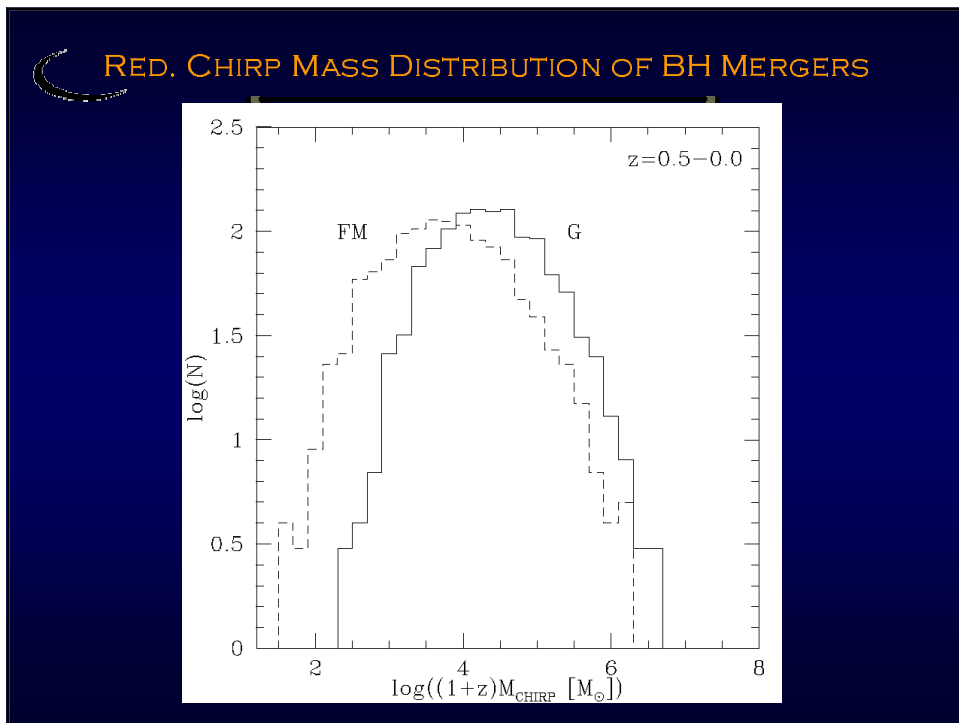
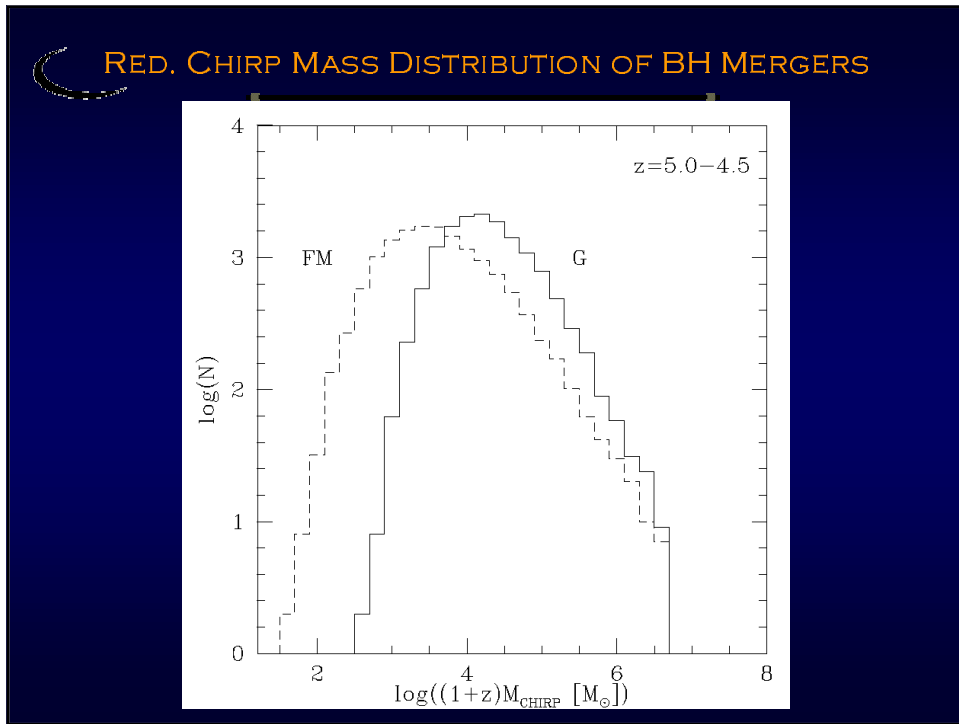
G-MODEL $M_{BH} = 1.2 \pm 0.2 \cdot 10^8 M_{sun} \left(\frac{\sigma_e}{200 \text{ km s}^{-1}} \right)^{3.75 \pm 0.3}$ (GEBHARDT ET AL. 2001)

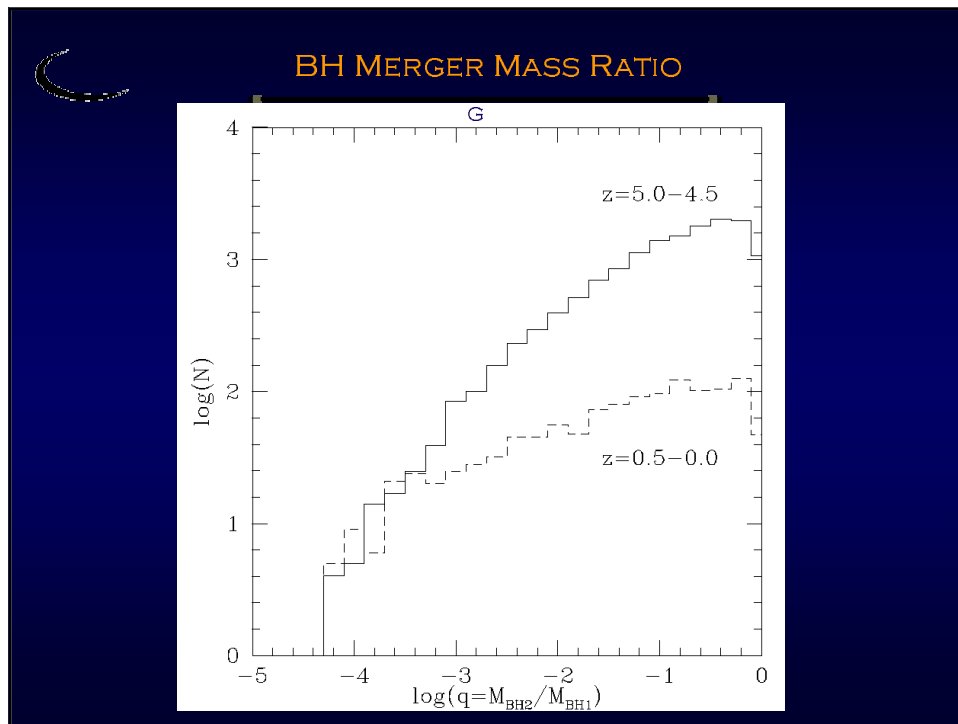
- ASSUMPTIONS ABOUT GALACTIC STRUCTURE:
 - ISOTHERMAL SPHERE FOR DARK MATTER ($R^{\wedge}2$)
 - TYPICAL BULGE/ELLIPTICAL DENSITY PROFILE AT R_E ($R^{\wedge}3$)
 - JEANS EQUATION FOR SPHERICAL, ISOTROPIC SYSTEM: $\sigma_e = \frac{\sigma_{DM}}{\sqrt{3/2}}$
- EXTRA ASSUMPTIONS:
 - NEGLIGIBLY SMALL MASS LOSS TO GW RADIATION DURING MERGERS
 - NEGLIGIBLY SMALL GROWTH BY ACCRETION
- SHORTCOMING: POPULATION OF BULGE-LESS GALAXIES? SPIRALS?












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- COSMOLOGY:
 - TREES FROM N-BODY SIMULATIONS ARE BETTER THAN FROM EXTENDED PRESS-SCHECHTER (OVERMERGING PROBLEM)
- GALAXY FORMATION:
 - $T_{\text{VIR}} = 10^4 \text{ K}$ DEPENDS ON METALLICITY, H_2 CHEMISTRY
 - BULGE-LESS AND SPIRAL GALAXIES ARE A POSSIBLE ISSUE
- GALACTIC STRUCTURE & DYNAMICS:
 - EFFICIENCY OF BINARY BH MERGERS? (AS A FUNCTION OF GALAXY TYPE, REDSHIFT)
- GENERAL RELATIVITY:
 - UNCERTAIN MASS LOSS TO GW RADIATION DURING BH MERGERS
- EXAMPLE:
 - LISA RATES ARE LOW \rightarrow RARE BHs, MASS SPECTRUM, INEFFICIENT MERGING?