

FIRST MBH OBSERVED

1963 SCHMIDT, "3C 273: A STAR-LIKE OBJECT ...", $L \sim 10^{46} \frac{\text{erg}}{\text{s}}$

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WHY NOT A STAR:

1) FOR A STAR $L \propto M^{7/2} \Rightarrow M_{\text{star}} \sim 10^4 \cdot 10^5 M_{\odot}$
MUCH LARGER THAN ANY STAR OBSERVED

2) $L = \eta \dot{M} c^2$ AND IF $\eta \sim 1\% \Rightarrow \dot{M} \sim 10 \frac{M_{\odot}}{\text{yr}}$
 $\Rightarrow$ INCREDIBLY SHORT LIVING STAR

3) SPECTRAL ENERGY DENSITY (SED) NOT A BLACK-BODY
IT WAS MORE FLAT FROM γ TO RADIO

MAYBE A GALAXY? NO, DUE TO ITS VARIABILITY

$\delta t_{\text{var}} \approx \text{days} \Rightarrow R \lesssim c \delta t_{\text{var}} \approx 0.01 \text{ LIGHT-YEAR}$
 $\sim \text{SOLAR-SYSTEM SCALE}$

(FROM SPECTRUM THEY EXCLUDED A GALACTIC ORIGIN)

AGN / QSO MODEL PROPOSED IN 1969 BY LYNDEN-BELL.

HOW DO WE OBSERVE MBHs?

RESOLVED STELLAR MOTION

SGRA* $\rightarrow$ RESOLVE MOTION OF STARS AROUND IT

ENSEMBLE MOTION

OBSERVATION OF ~~STAR~~ VELOCITY DISPERSION OF STARS DUE TO THE INFLUENCE RADIOS

$$b(r) = \sqrt{\frac{2GM(r)}{r}} \xrightarrow{r \rightarrow \infty} \begin{cases} 0 & \text{IF } M(r) = M_{\text{GALAXY}} \\ \sim \sqrt{\frac{1}{r}} & \text{IF } M(r) = M_{\text{GALAXY}} + M_{\text{BH}} \end{cases}$$

TEMPORALLY RESOLVED

REVERBERATION MAPPING. INTRODUCE THE BROAD LINE REGION (BLR)

(TIME LAG ~~BEFORE~~ BETWEEN ~~CALIBRATION~~ ^{CALIBRATION} AND LINE ~~THE~~ EMISSIONS ^{DISK})

$$R_{\text{BLR}} = c \delta t$$

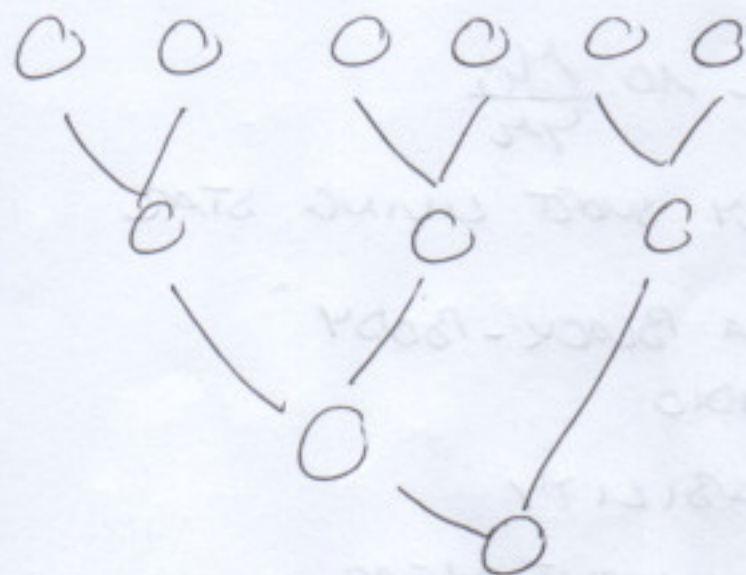
$$\Rightarrow M = f \frac{R_{\text{BLR}} v}{G}$$

SIMULATING BU_s

A PROBLEM OF SCALES

SEMI-ANALYTICAL MODEL

- DARK MATTER MERGER TREES



- ANALYTICAL PRESCRIPTIONS FOR PHYSICS

(AMOUNT OF BARYON, STAR FORMATION, FEEDBACK, TIME DELAYS)

PROs:

- FAST
- COVER THE PARAMETER SPACE

CONs:

- NO SPATIAL INFORMATION
- ~~ONLY~~ ANALYTICAL EFFECTS

EXAMPLES:

- BACH (BLACK HOLE ACROSS COSMIC HISTORY)
- L-GALAXIES
- CAT (COSMIC ARCHEOLOGY TOOL)

SKY LOCALIZATION OF MBUBs (2003.00357)

TIME-DEPENDENCE: ORBITAL MOTION OF LISA

FREQUENCY-DEPENDENCE: BREAK OF LOW-FREQUENCY APPROXIMATION

$$\lambda_{GW} \gg L$$

- DETECTOR IS POINT-LIKE
- THE GW STRAIN IS ALMOST CONSTANT

$$\text{IF } f_{GW} = 0.05 \text{ Hz}$$

$$\Rightarrow \lambda_{GW} = \frac{c}{f_{GW}} \approx 6 \cdot 10^9 \text{ m}$$

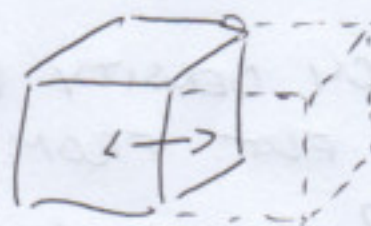
$$(L_{LISA} = 2.5 \cdot 10^9 \text{ m})$$

HYDRODYNAMICAL SIMULATIONS

EVOLUTION OF A BOX OF UNIVERSE

CONSERVATION OF: $\sim 10^2 \text{ Mpc}$

- MASS
- MOMENTUM
- ENERGY



PROs:

- SPATIAL INFORMATION
- COMPLEX

CONs:

- HIGH COMPUTATIONAL COST

($\sim 10^7 \text{ CPU HRS}$)

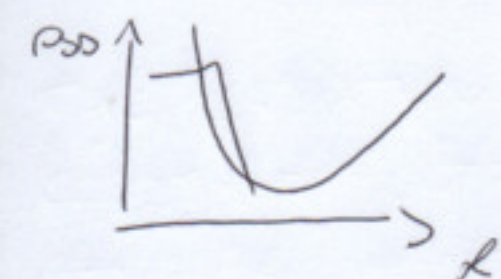
- RESOLUTION $\sim \text{kpc}$
(IN MASS $\sim 10^6 M_{\odot}$)

- POST-PROCESS FOR SUB-GAL PHYS!
(LOSE STATISTIC)

EXAMPLES:

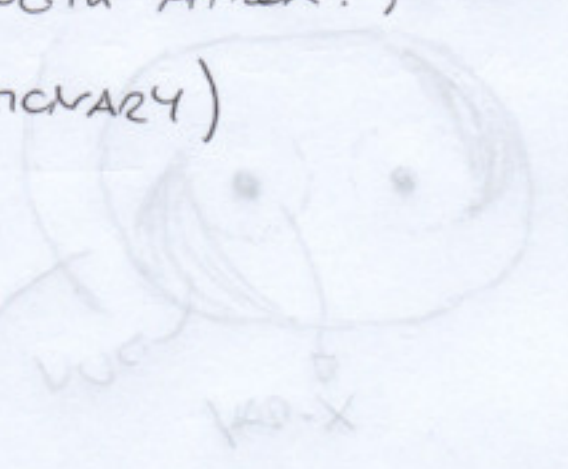
- ILLUSTRIS
- MURIZEL-AGN
- REMULUS

LET'S CONSIDER A MBUB $\approx 10^8 M_{\odot}$



$\lambda_{\text{GW}} \gg \lambda_{\text{LISA}}$ (LONG-WAVELENGTH APPROX.)

$T_{\text{OBS}} \approx 10^5 \text{ s}$ (LISA IS STATIONARY)



FULL EXPRESSING IS SEC. VB OF 2003.00357

EXAMPLE: REFLECTED SKY POSITION

$$\begin{cases} \lambda'_L = \lambda_L \\ \beta'_L = -\beta_L \\ \psi'_L = \pi - \psi_L \\ i' = \pi - i \\ \ell' = \ell \end{cases}$$

RELEVANT FOR HIGH-MASS BUBS $\Rightarrow$ MOST LUMINOUS
($L_{\text{EDD}} \propto M_{\text{BH}}$)



MULTIMESSENGER

"ADDITIONAL (COMBINED) SCIENCE MAY PROVIDE BREAKTHROUGHS IN SCIENTIFIC AREAS BEYOND WHAT EACH INDIVIDUAL MISSIONS IS DESIGNED FOR"

- 1) TEST ASTROPHYSICS AT EXTREME SCALES
- 2) COSMOLOGY
- 3) FUNDAMENTAL PHYSICS (PROPAGATION TESTS)

CONTINUATION

HOW MM WORKS:

- 1) PRE-LISA EM SEARCHES (MINIMUM DETECTABLE PERIODICITY IS DETERMINED BY THE SURVEY)
- 2) ARCHIVAL SEARCH AFTER THE EVENT
- 3) T.O.O.: TARGET OF OPPORTUNITY

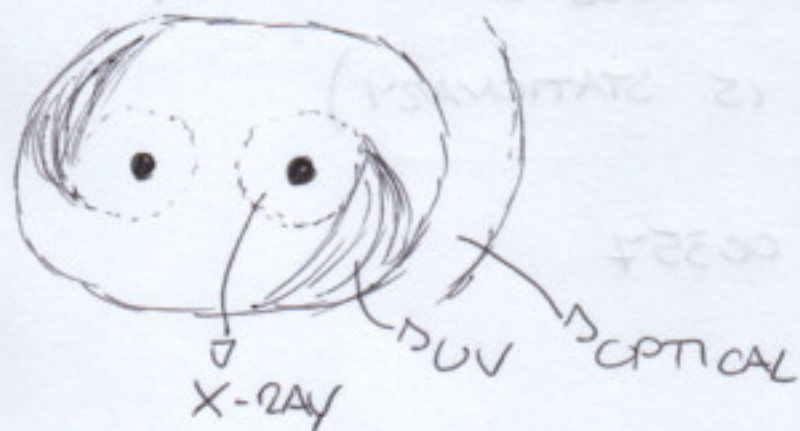
EM COUNTERPARTS

- 1) NO TRANSIENT AGN-LIKE EMISSION
DUAL AGN: $\sim 1 \text{ pc} - 10 \text{ kpc}$
BINARY AGN: $\lesssim 1 \text{ pc}$

- 2) UNCERTAINTIES ON SPECTRA, OBSCURATION, BOLOMETRIC CORRECTIONS, ...

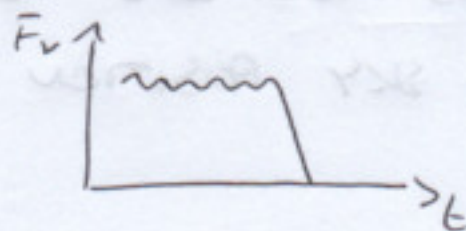
PRE-MERGER

NEED TO RELY ON GRMHD SIMULATIONS



2 FEATURES:

- 1) MODULATION OF EM
- 2) DROP CLOSE TO MERGER



CONS:

- 1) SKY POSITION IS MULTIMODAL
- 2) LONG EXPOSURE

AFTER-MERGER



"RE-BRIGHTENING"

- 1) MBH KICKED IN THE DISK
- 2) START ACCRETING AGAIN

CONS:

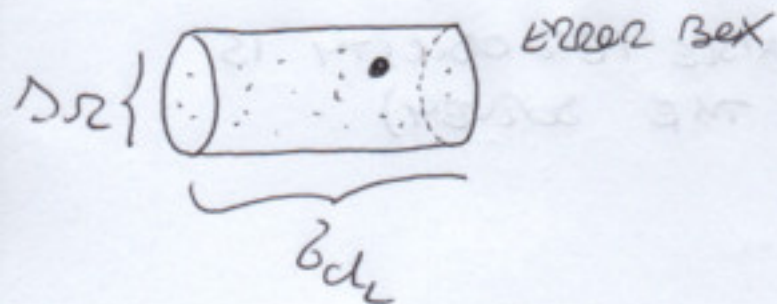
- NOT CLEAR WHEN THE EM COUNTERPART WILL APPEAR

REMARKS:

- 1) ENVIRONMENTAL EFFECTS AS PRE-MERGER SIGNATURE (ZHAO 17305)
(EVIDENCE OF GAS BUT DOES NOT GUARANTEE A DETECTION)
- 2) 1-20 EVENTS IN 4YR WITH EM COUNTERPARTS

CONTAMINATION

DETECTION $\neq$ IDENTIFICATION



- 1) POTENTIAL GALAXIES
- 2) " TRANSIENTS

REMARKS:

- 1) MM IS CHALLENGING
- 2) MM IS TIME-SENSITIVE