UNMODELED SEARCHES FOR INTERMEDIATE MASS BLACK HOLES WITH FIRST AND SECOND GENERATION DETECTORS

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OUTLINE

PART 1 (results from the LIGO-Virgo collaboration)

- *Intermediate mass black holes (IMBHs)*
- *Observation of IMBHs*
- *Waveforms from coalescing binaries*
- *LIGO and Virgo detectors*
- *Coherent WaveBurst*
- *Coherent WaveBurst search for intermediate mass black holes on S5-VSR1 data*
- *Upper limits from coherent WaveBurst S5-VSR1 analysis*
- *Coherent WaveBurst search for intermediate mass black holes on S6-VSR2/3 data*

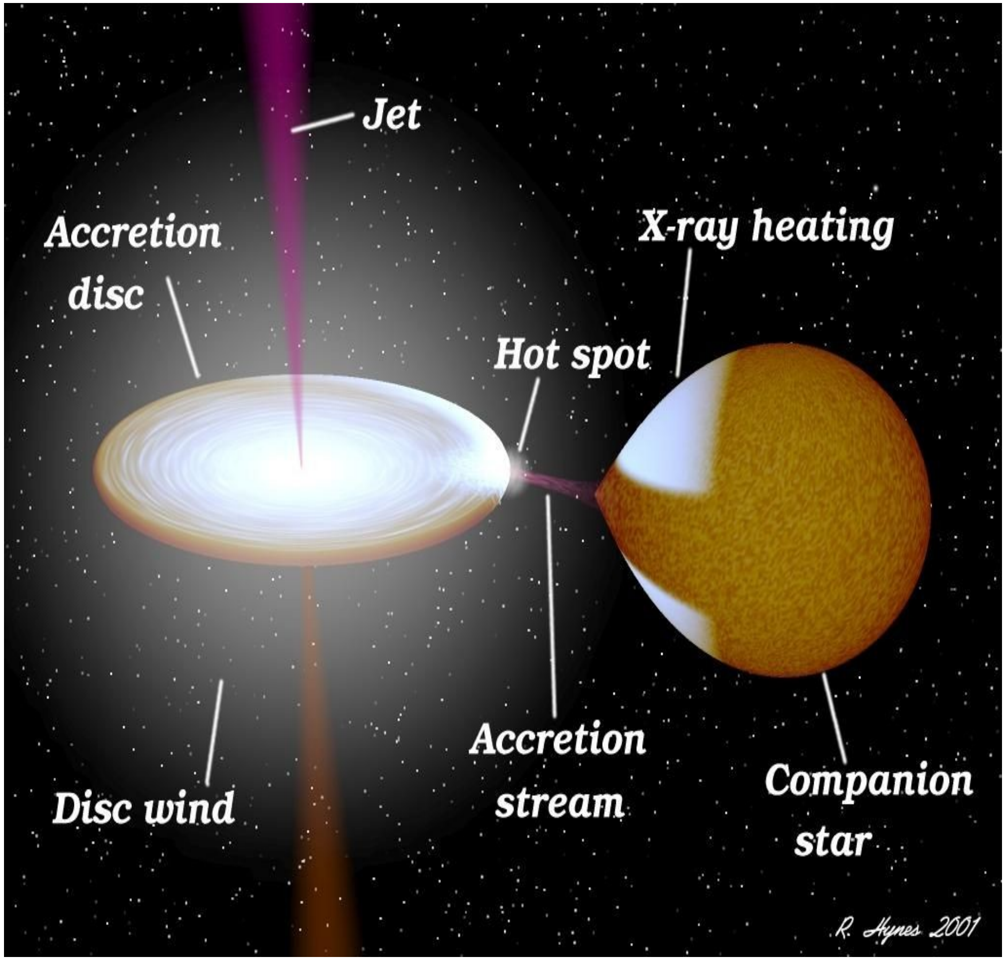
PART 2 (methodological study on simulated data)

- *Advanced detectors*
- *Impact of red shift*
- *Search range on simulated data*
- *IMBHs detection chances*

PART 1

INTERMEDIATE MASS BLACK HOLES (IMBHs)

- IMBHs cover the mass spectrum from tens to thousands solar masses[1]
- Possible engine of the ultraluminous X-ray sources (ULXs)
- Globular clusters (GCs) are the most likely hosts of IMBHs[2]



Artist's view of ULXs[3]

Formation mechanism under debate

- *collapse of population III stars*
- *progressive accretion from smaller objects (direct capture, binary coalescence)*

Their discovery could shed light on:

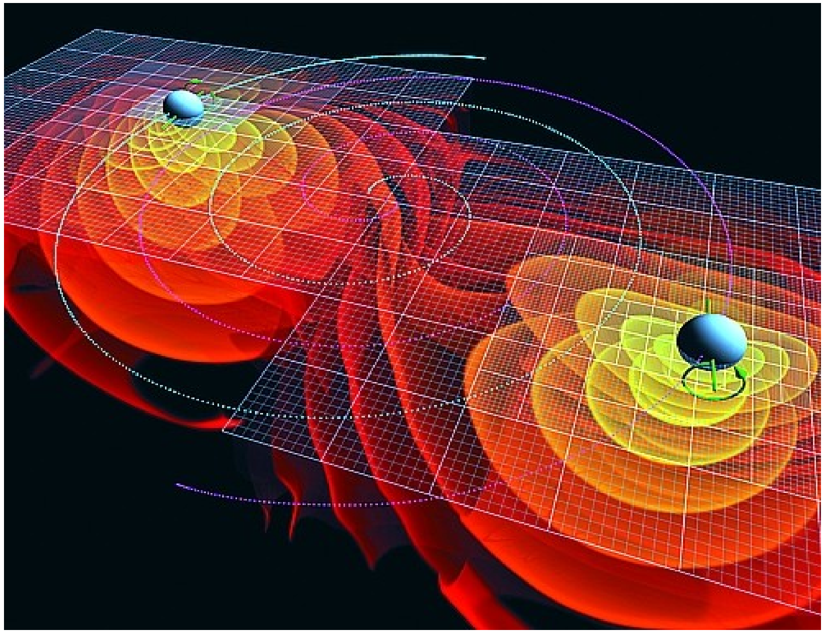
- *The plausible evolutionary process from stellar to super-massive black holes*
- *Dynamical aspects of the stellar clusters they might reside in*

OBSERVATION OF IMBHs

- In Globular Clusters, IMBHs interacting with:
  - *Black holes*
  - *Neutron stars*
  - *White dwarfs*
  - *Main sequence (MS) stars*

Decreasing interaction probability
(due to mass segregation)

- IMBHs expected to be observable via:
  - *Dynamical effects on nearby objects (measurements with large systematics)*
  - *Photons emission (negligible, significant only for MS star companion, ULXs)*
  - *Gravitational waves (GWs) when in binary with another black hole*[4]



Inspiralling black holes[6]

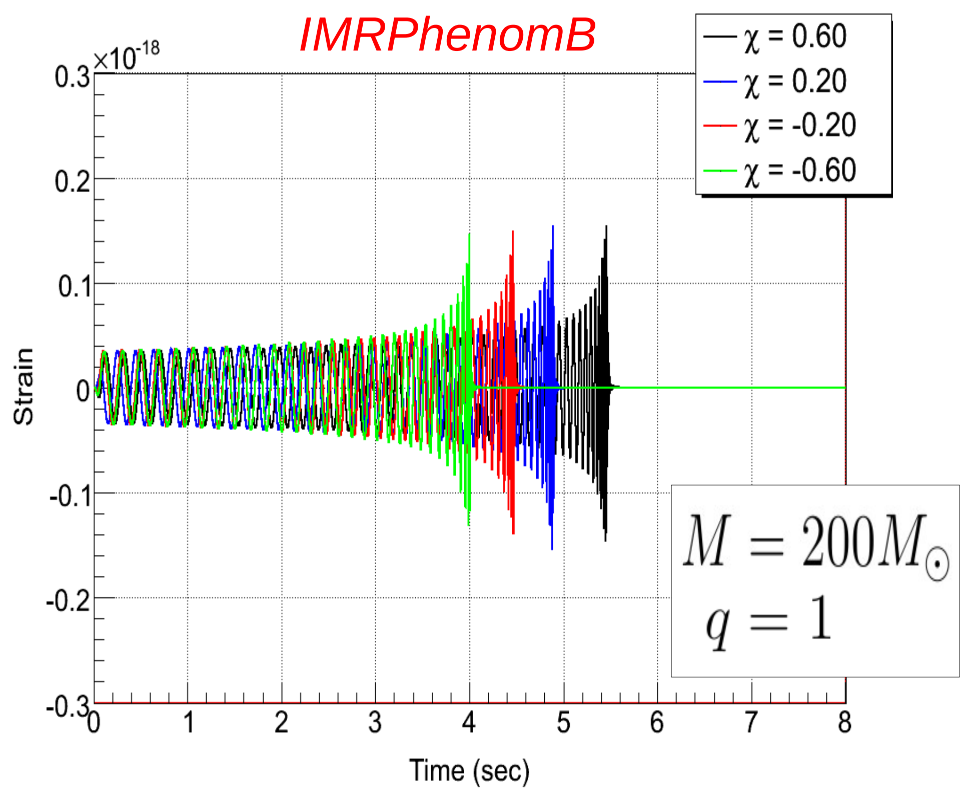
Upper limit on IMBH coalescence rate[5]:

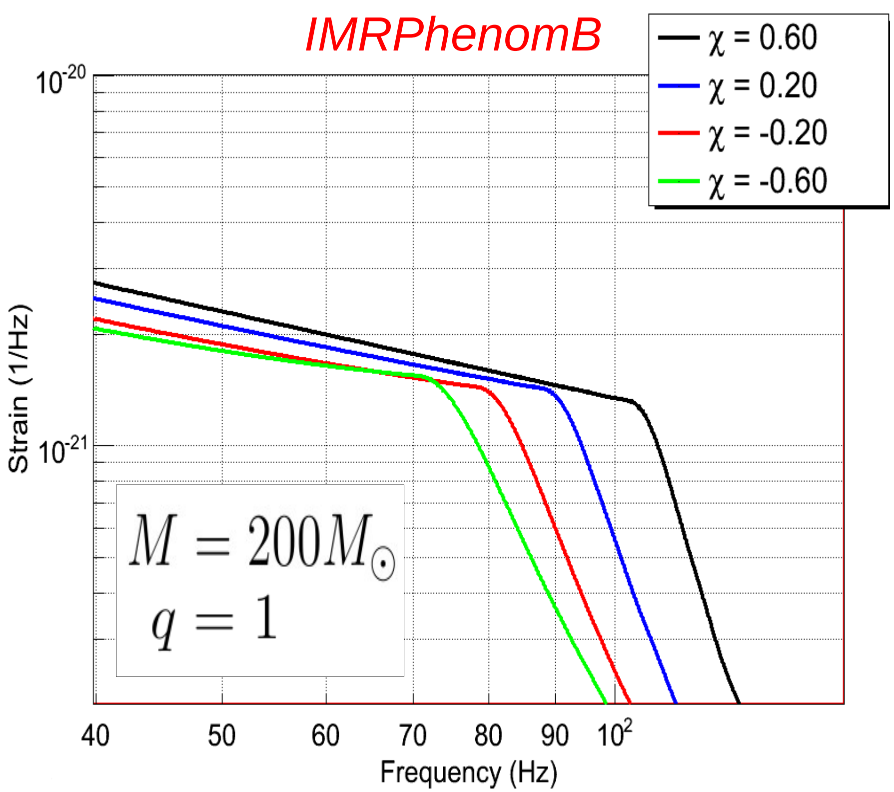
$2 * 10^{-5}\ Mpc^{-3}\ Myr^{-1}$

GW WAVEFORMS FROM COALESCING BINARIES

- EOBNRv2[7]
  - *Effective One Body Hamiltonian used to evolve the binary system up to merger*
  - *Superposition of ringdown frequency modes matched to the end of the merger*
  - *Non – spinning components*

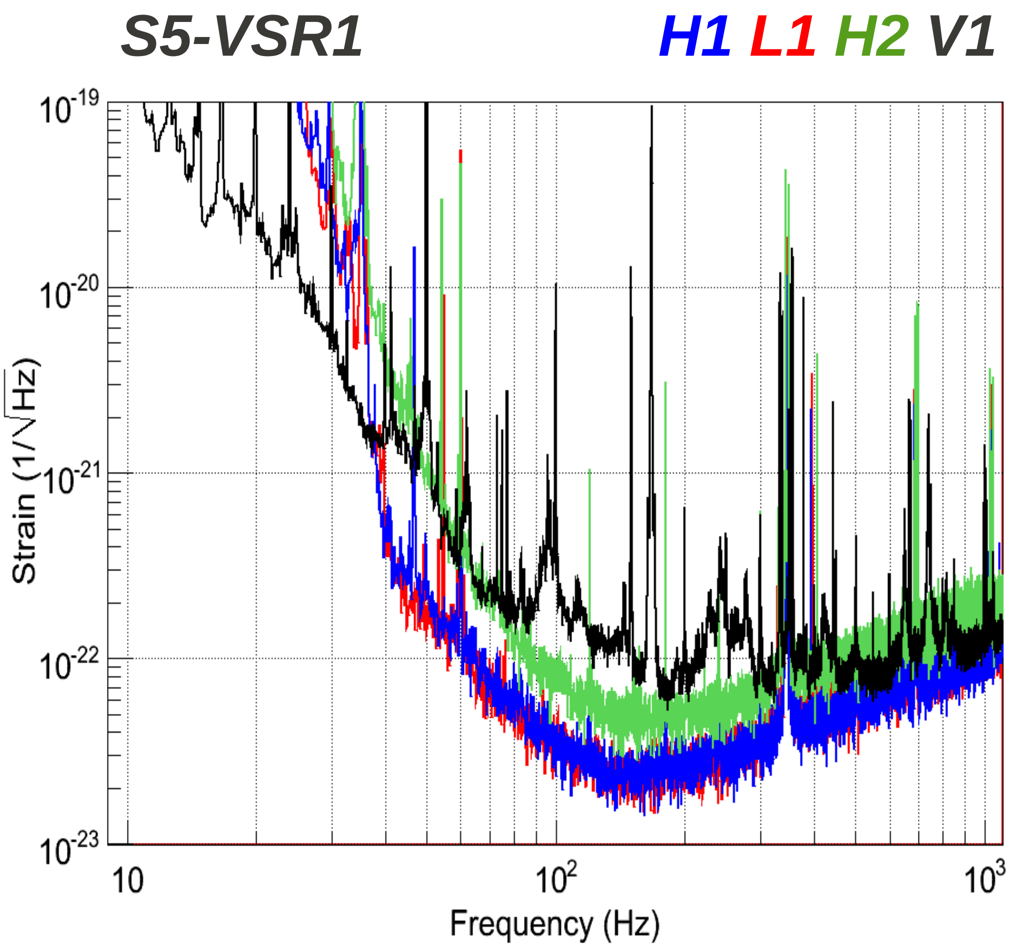
- IMRPhenomB[8]
  - *Hybrid waveforms: analytical PN inspiral waveform stitched to numerical merger waveform*
  - *Aligned and anti – aligned spin configurations*

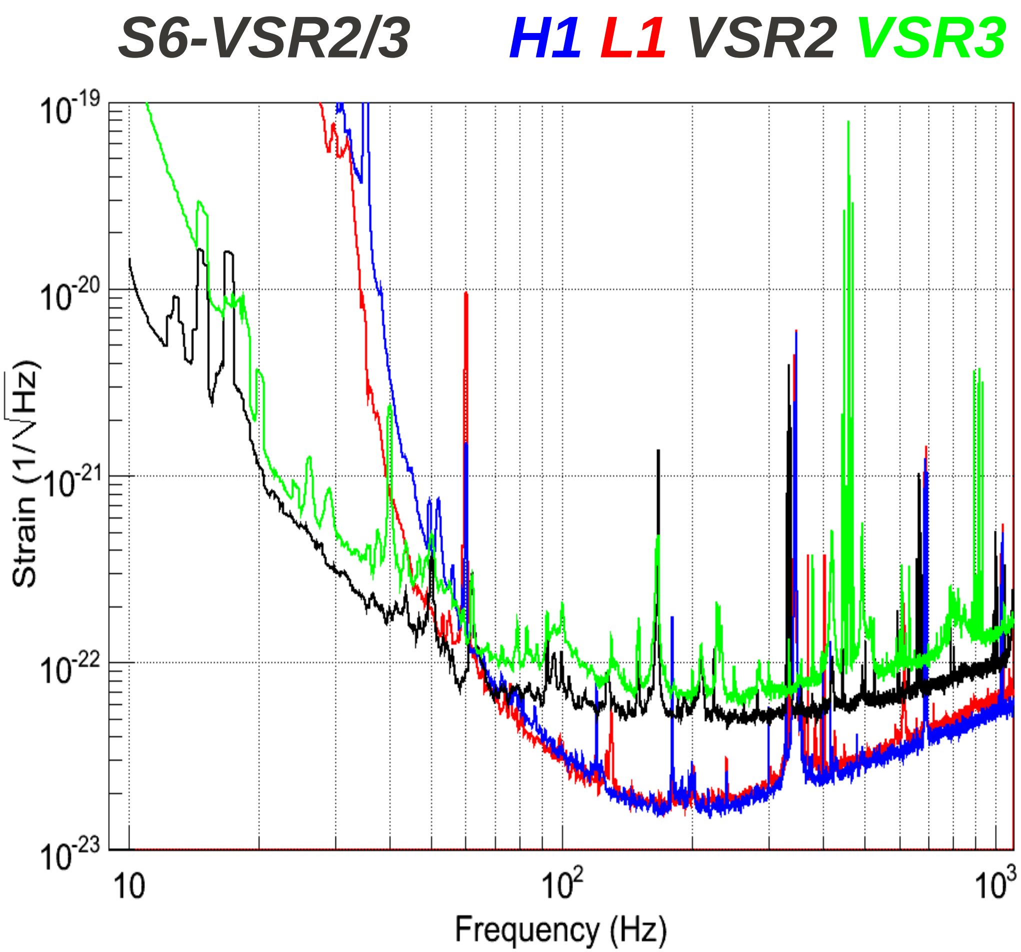




LIGO AND VIRGO DETECTORS

- Coalescing IMBHs expected to be visible in the frequency band of the LIGO-Virgo detectors
- LIGO-Virgo joint runs: S5-VSR1 (Nov. 2005 - Oct. 2007), S6-VSR2/3 (Jul. 2009 - Oct. 2010)
- Comparable sensitivities between S5-VSR1 and S6-VSR2/3

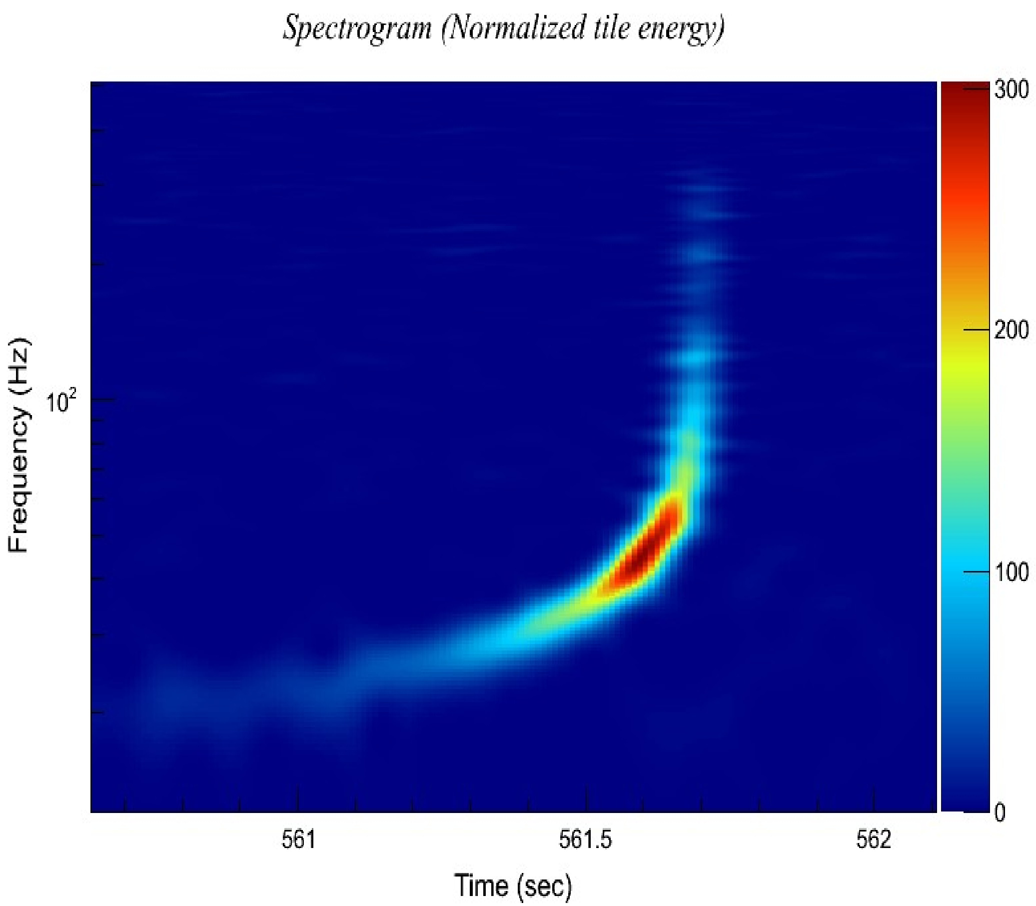




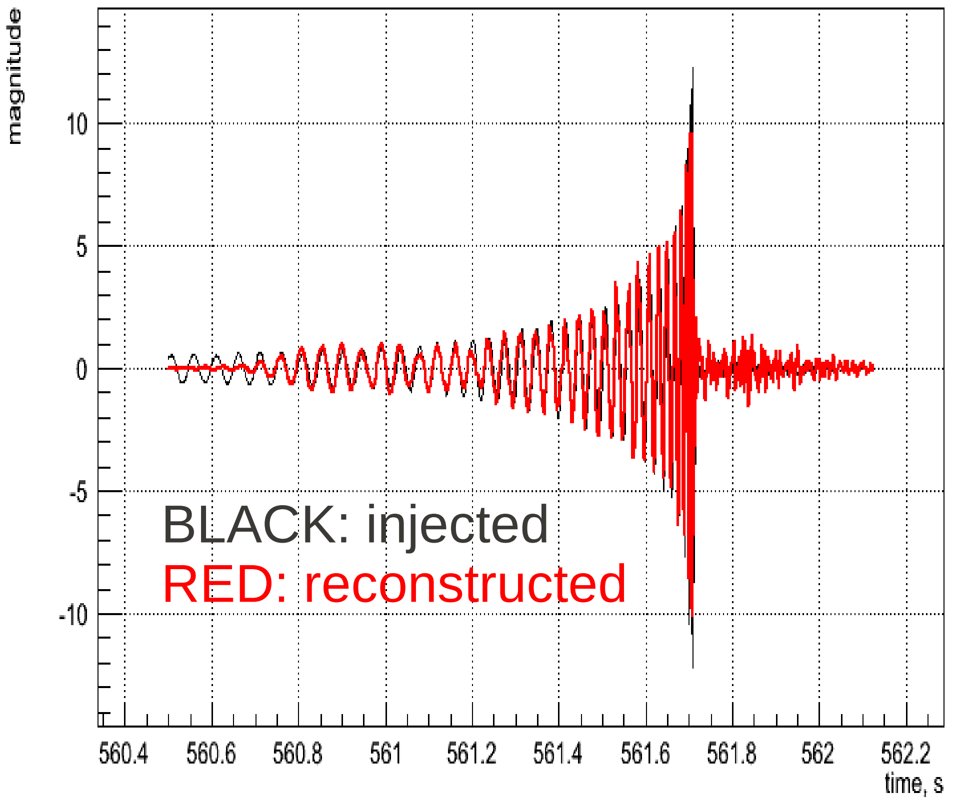
COHERENT WAVE BURST (cWB)

- cWB[9] is a data analysis algorithm developed by the LIGO and Virgo collaborations
- It performs unmodeled, coherent searches on data from networks of GW detectors
- Likelihood approach is considered (maximization over h+ hx, sky position.....)
- Developed to target bursts of gravitational radiation (duration < 1 s)

Can be used to search for signals from compact binaries coalescence for total masses larger than ~ 10 solar masses with no significant SNR loss

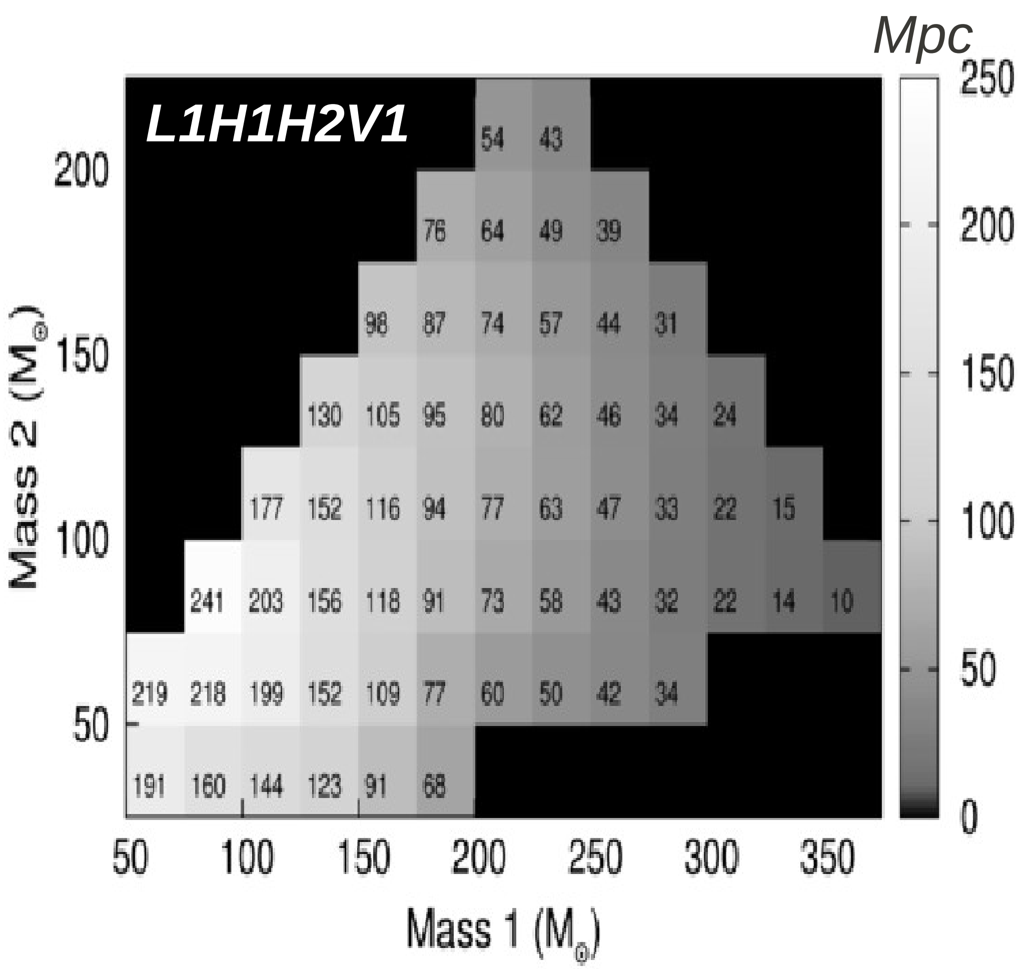


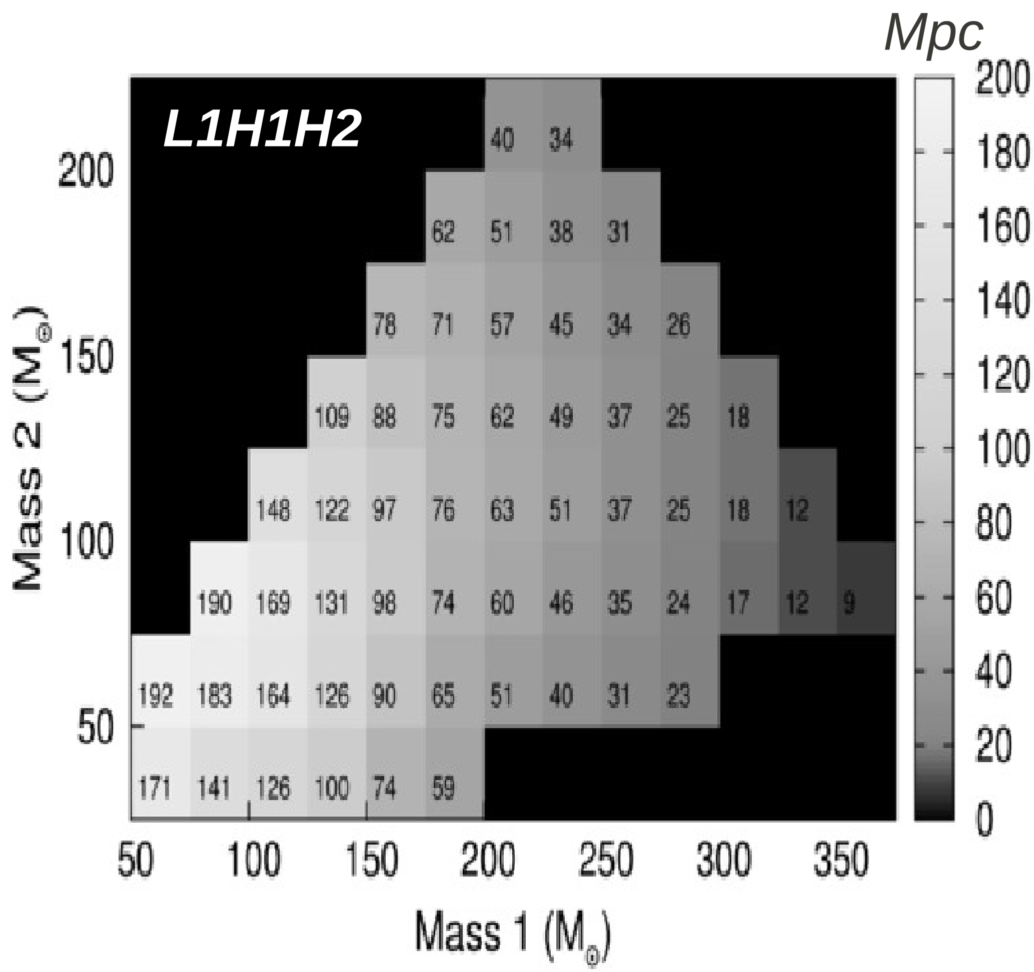
$$M = 55 M_{\odot} \quad q = 1.5$$



CWB SEARCH FOR IMBHS ON S5-VSR1 DATA

- Paper recently accepted by PRD[10]
- Two networks considered: H1H2L1V1 (58 days) and H1H2L1 (273 days)
- Simulations performed by injecting EOBNR waveforms (100 - 450 solar masses)
- Search range estimated for different total mass values



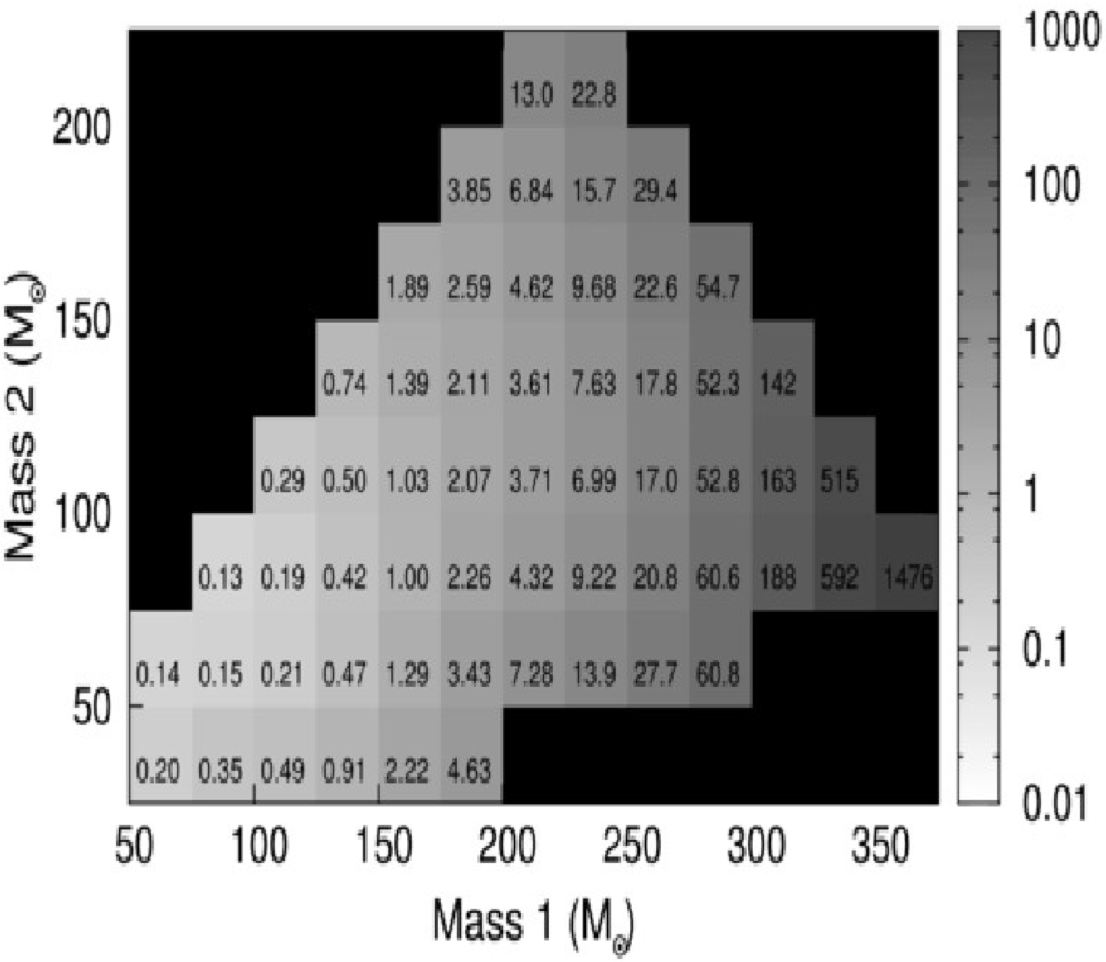


MAX RANGE: *241 Mpc*
AVERAGED RANGE: *87 Mpc*

MAX RANGE: *192 Mpc*
AVERAGED RANGE: *72 Mpc*

UPPER LIMITS FROM CWB S5-VSR1 ANALYSIS

- No gravitational wave candidates were found
- Events rate upper limits $R_{90\%}$ calculated combining H1H2L1V1 and H1H2L1 in terms of productivity ν (loudest event statistic[11])
- Upper limits (UL) few orders of magnitude larger than expected rates



$$\nu = \sum_k T_{obs}[k] V_{vis}[k]$$

$$R_{90\%} = \frac{2.3}{\nu}$$

BEST UPPER LIMIT: 0.13 Mpc^{-3} Myr^{-1}

AVERAGED UL: 0.9 Mpc^{-3} Myr^{-1}

CWB SEARCH FOR IMBHS ON S6-VSR2/3 DATA

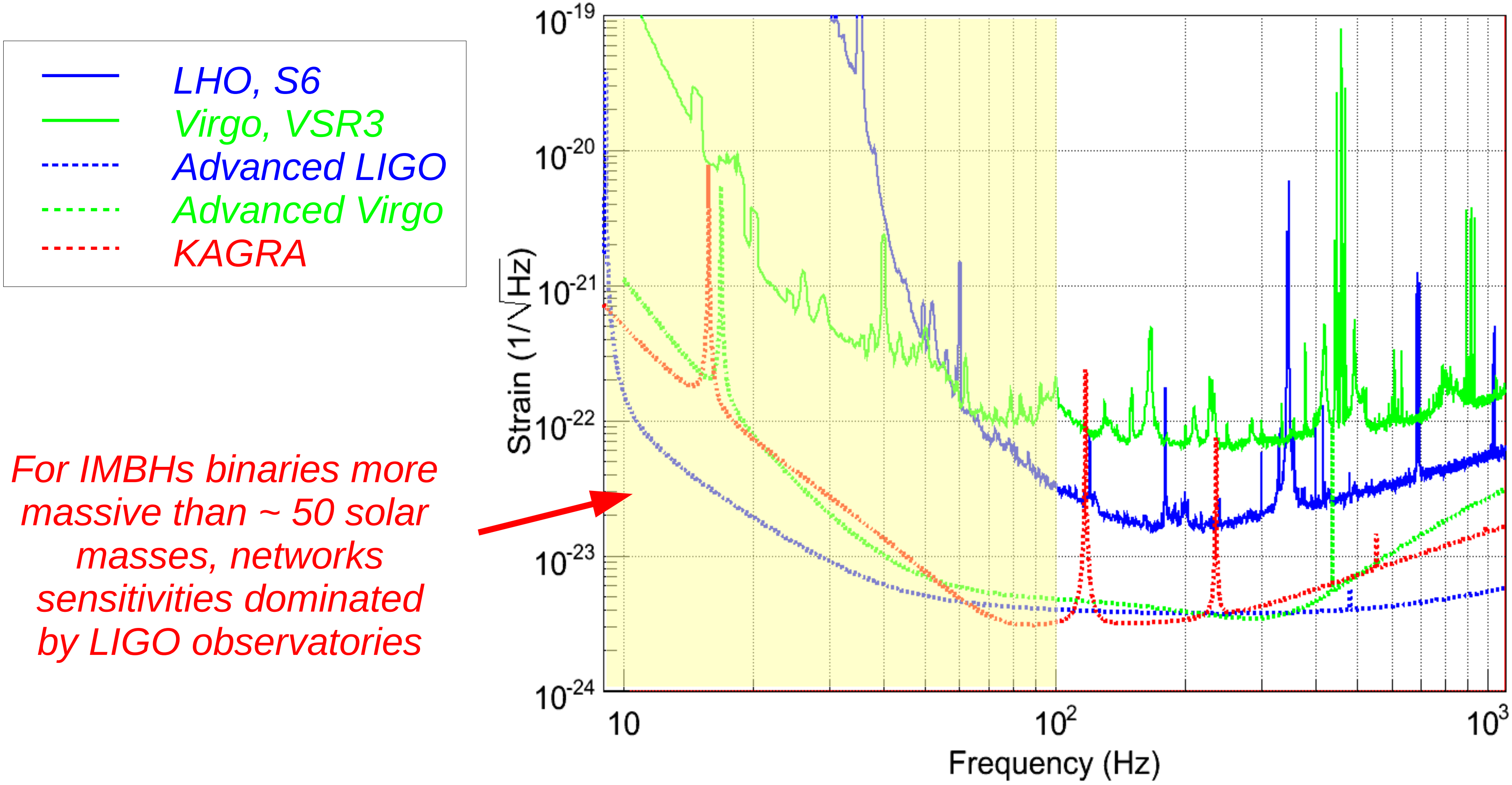
- CWB search for IMBH binaries in S6-VSR2/3 close to completion
- Some differences with respect to the S5-VSR1 search:
  - *No four detectors network (no H2)*
  - *S6-VSR2/3 total live time ~ ½ of S5-VSR1 one*
  - *EOBNRv2, EOBNRv2 with higher modes[12] and IMRPhenomB injected*
  - *Investigated total mass spectrum extended down to 50 solar masses*
- If no GW event will be found, S5-VSR1 and S6-VSR2/3 combined upper limits will be calculated

	S5-VSR1	S6-VSR2/3
Four detectors network	yes	no
Analyzed networks	H1H2L1V1 and H1H2L1	H1L1V1 and H1L1
Live time (days)	$58 + 273 = 331$	$42 + 117 = 159$
Most of live time from	H1H2L1	H1L1
Mass range ($M_\odot$)	100 - 450	50 - 450

PART 2

ADVANCED DETECTORS

- Advanced LIGO-Virgo[13,14] detectors and KAGRA[15] will start operating in ~ 2015
- Target sensitivities (TS) expected to be reachable few years after first run
- At TS, ten times better sensitivity, 1000 times larger visible volume
- Larger IMBH parameter space will be accessible (heavier systems)

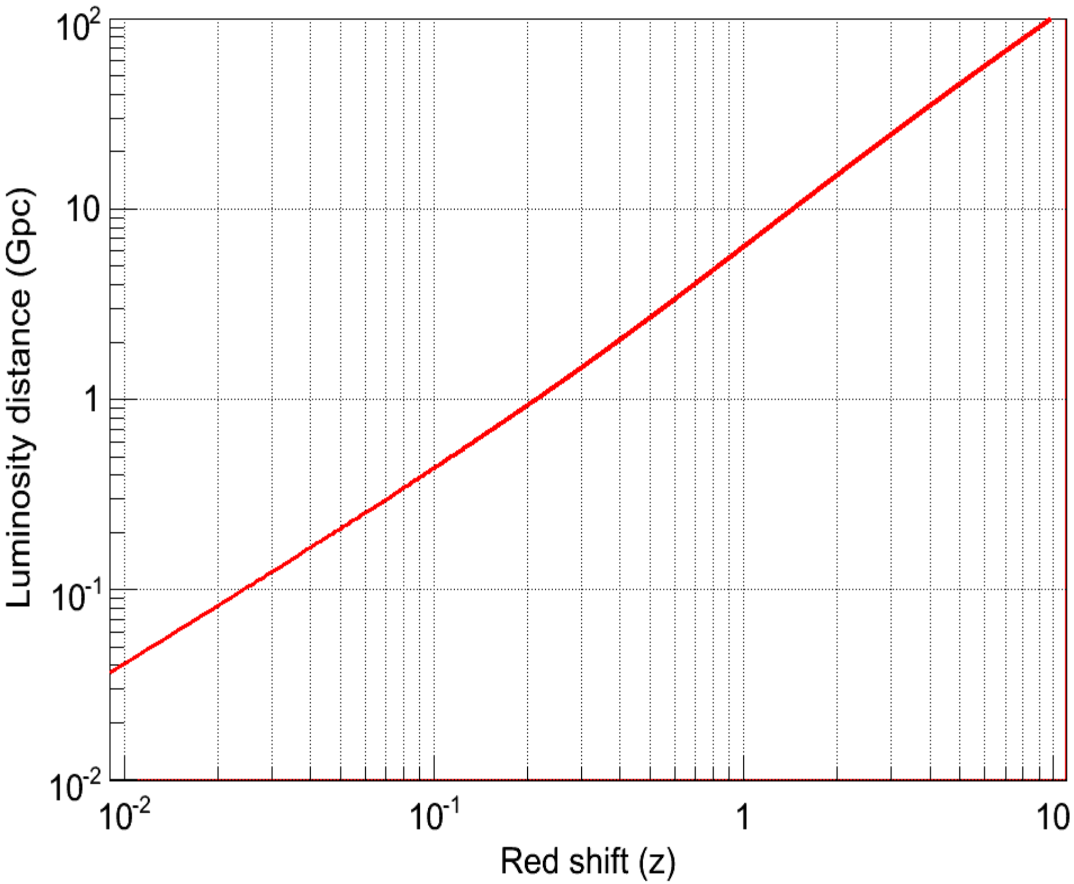


For IMBHs binaries more massive than ~ 50 solar masses, networks sensitivities dominated by LIGO observatories

IMPACT OF RED SHIFT

- With advanced detectors, IMBH visible by cWB up to *O*(few Gpc)
- Red shift effects not negligible anymore
- Astrophysical objects observed as heavier and farther than they are

$$m_{chirp,z} = (1+z)\, m_{chirp} \qquad m_z = (1+z)\, m \qquad D_L = (1+z)\,\frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

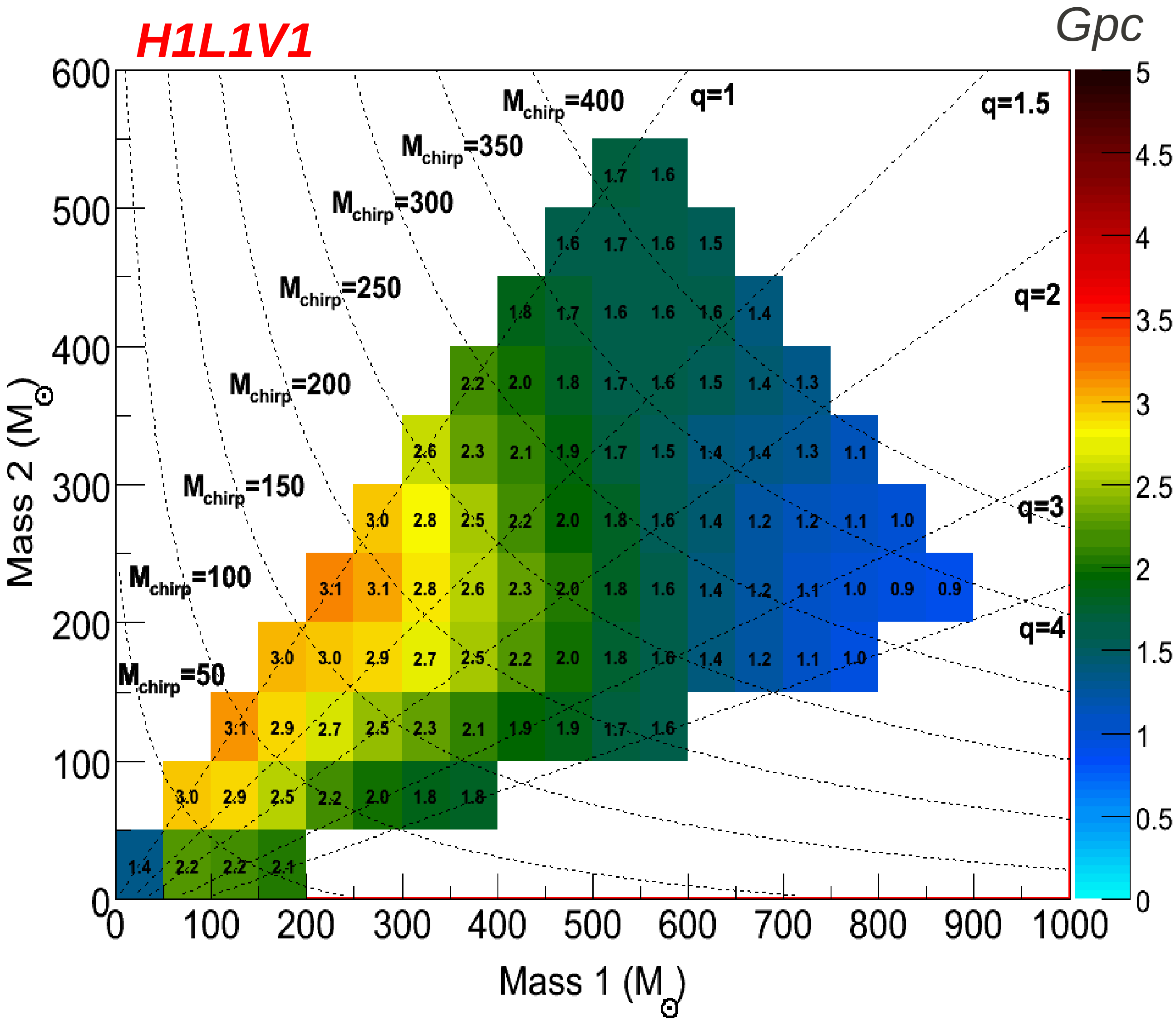


ΛCDM cosmological model[16] assumed

$$\begin{cases} H_0 = 70\ \frac{km}{s\ Mpc} \\ \Omega_m = 0.27 \\ \Omega_\Lambda = 1 - \Omega_m \end{cases}$$

SEARCH RANGE ON SIMULATED DATA

- EOBNRv2 injected in advanced H1L1V1, H1L1 and H1J1L1V1 simulated data
- Total mass spectrum extended up to 1100 solar masses
- Comparable performances from the different networks (sensitivity dominated by LIGO)



$$M_{chirp} = \frac{(M_1 M_2)^{3/5}}{(M_1+M_2)^{1/5}}$$

MAX RANGE: 3.1 Gpc

AVERAGED RANGE: 1.9 Gpc

Search more sensitive to equal mass components and total mass ~ 500 solar masses

IMBHs DETECTION CHANCES

- Productivity *v* with advanced detectors can be estimated

MAX RANGE: *3.1 Gpc* → $v_{H1L1V1} \sim 1.2 * 10^5 \, (T/yr) \, Mpc^3 \, Myr$

AVERAGED RANGE: *1.9 Gpc* → $v_{H1L1V1} \sim 2.9 * 10^4 \, (T/yr) \, Mpc^3 \, Myr$

WITH SUCH IMPROVEMENT IN PRODUCTIVITY,
GOOD CHANCE TO DETECT IMBHS WITH ADVANCED DETECTORS

- In the no detection scenario, for T = 1 yr, upper limits are:
  - *MAX RANGE:* $UL_{H1L1V1} \sim 10^{-5} \, Mpc^{-3} \, Myr^{-1}$
  - *AVERAGED RANGE:* $UL_{H1L1V1} \sim 3.5 * 10^{-5} \, Mpc^{-3} \, Myr^{-1}$

- ULs now compatible with expected rates

CONCLUSIONS

- Intermediate mass black holes are very exciting astrophysical objects
  - *Evolutionary process of black holes and dynamics of globular clusters could be better understood with the discovery of IMBHs*
  - *GWs from coalescing IMBHs expected to be visible within the interferometers bandwiths*
- Unmodeled approaches (e.g, cWB) can be used to search for IMBHs binaries
  - *First cWB IMBH search performed on S5-VSR1 data, no GW found*
  - *Rate upper limits calculated*
  - *cWB IMBH search on S6-VSR2/3 data close to completion*
- Advanced GW detectors will start operating in the next years
  - *Improved sensitivity, larger visible volume*
  - *More massive IMBH binaries accessible*
  - *On simulated data, cWB performances almost independent of considered network if H1 and L1 included*
  - *CWB IMBHs searches more sensitive to equal mass components with total mass ~ 500 solar masses*
  - *At ~ 1 Gpc, systems with total mass ~ 1000 solar masses still visible*

GOOD CHANCE TO DETECT IMBHs WITH ADVANCED DETECTORS

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