Multimessenger prospects for massive black hole binaries in LISA

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Laboratoire Astroparticule et Cosmologie (APC)

IAP seminar, Paris

Outline

- Introduction on gravitational waves (GWs) and massive black hole (MBHs)
- GWs from the coalescence of MBH binaries (MBHBs)
- Electromagnetic (EM) and GW emissions from MBHBs
- Cosmology prospects

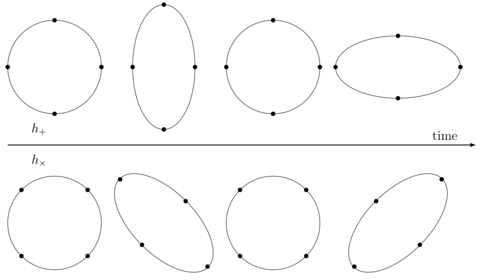
From General Relativity

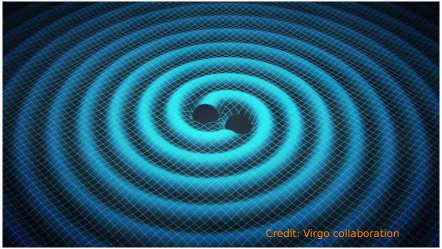
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu\nu} \ll 1$$

Every accelerating mass distribution with non-zero quadrupole momentum emits GWs!

$$\downarrow$$

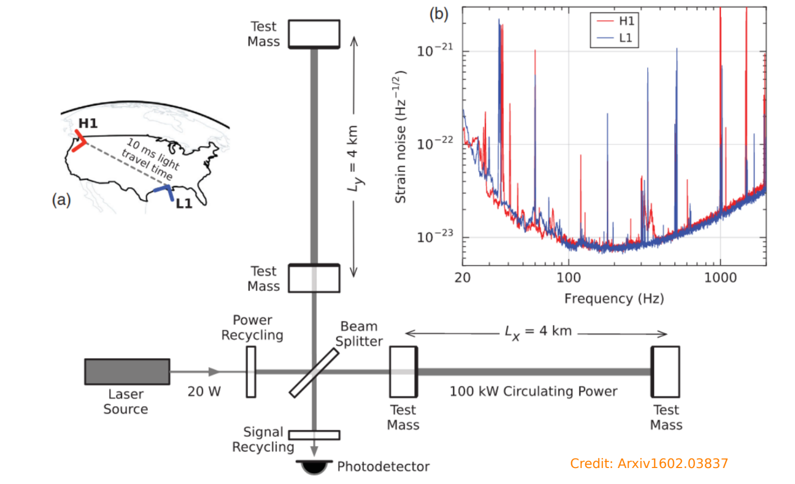
Compact objects binaries are perfect candidates!



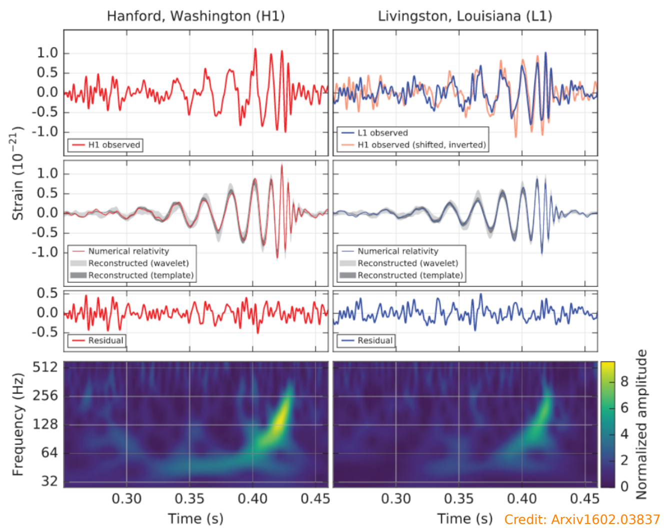


How can we detect them?

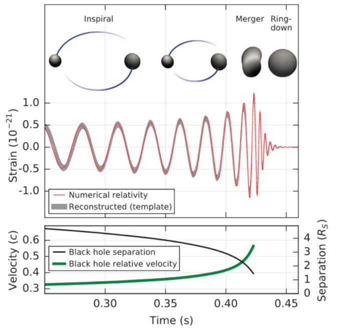
Typical strain $h \simeq \frac{\Delta L}{L} \simeq 10^{-21} \rightarrow$ Weak signal!



The first detection: GW150914!

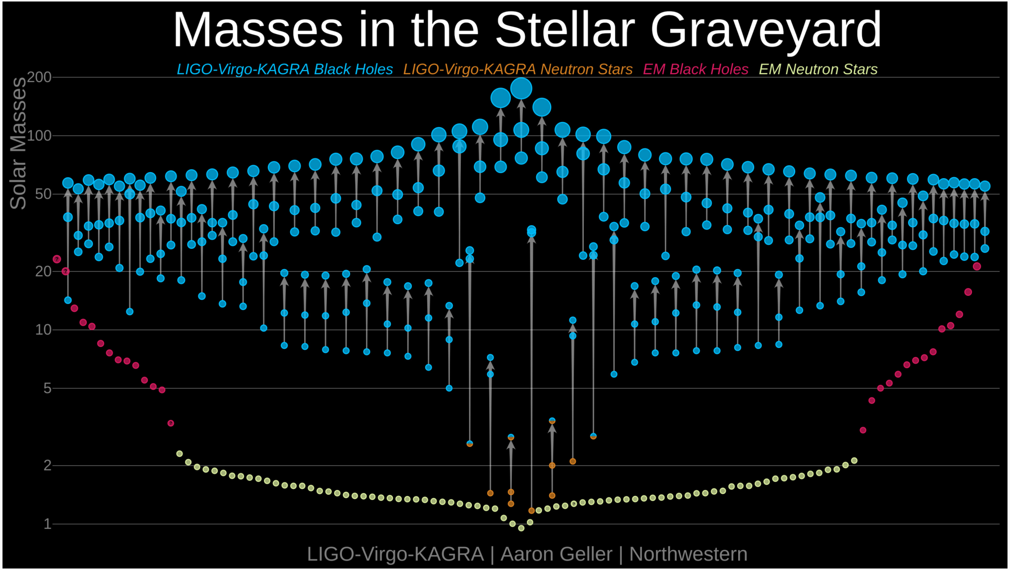


Credit: Arxiv1602.03837



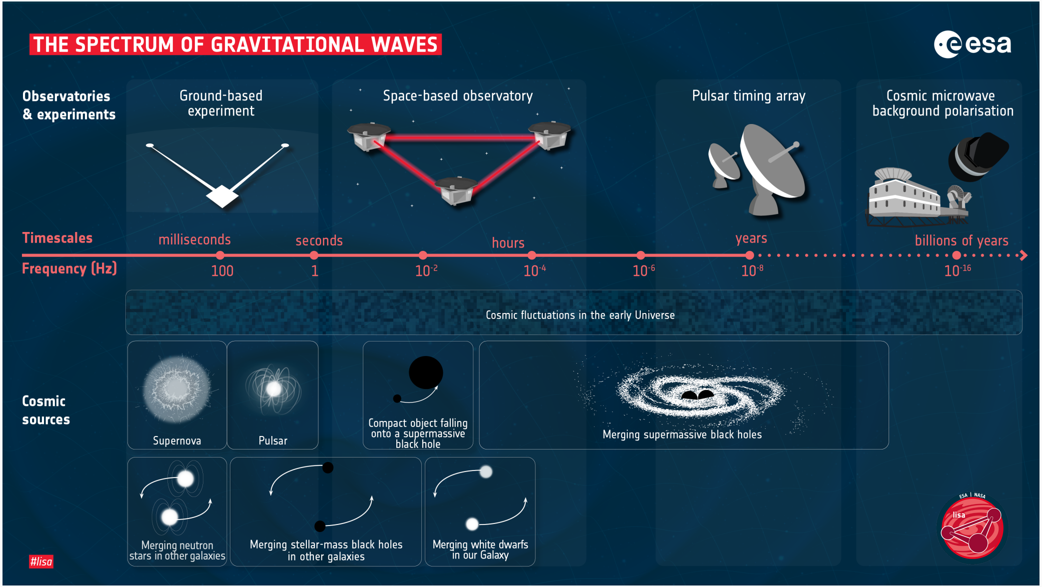
- BH-BH merger
- $d_L = 410$ Mpc ($z \sim 0.09$)
- $m_1 = 36 M_\odot$, $m_2 = 29 M_\odot$
- Peak luminosity $\sim 10^{56}$ erg/s

Up so far . . .



Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Overview



THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
ESA | NASA
lisa

What are massive black holes (MBHs)?

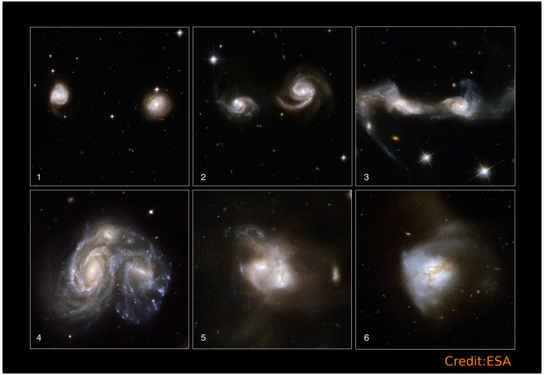
We currently believe that MBHs are hosted at the center of galaxies with masses up to $\sim 10^9 - 10^{10} \mathrm{M}_\odot$

For today talk, let's focus on the interval

$$\mathrm{M}_{\mathrm{BH}} \sim 10^{5-7} \, \mathrm{M}_\odot$$

Do MBH form binaries?

When two galaxies merge, the MBHs in their center form a binary and, eventually, merge emitting gravitational waves (GWs)



The path to coalescence is still unclear and long: from $\sim$ 10 kpc to 10^{-3} pc

- Dynamical friction with gas and stars is efficient down to $\sim$pc scales
- 3-body interactions?
- Refill of loss cone?

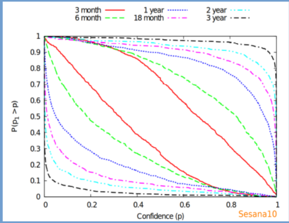
(For reviews : Volonteri+10, Mayer+13, De Rosa+19, arXiv:2203.06016)

Why should we focus on MBHBs?

The importance of MBHBs

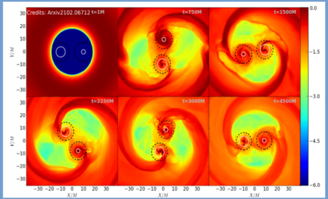
Astrophysics

Constrain MBHBs formation and evolution scenarios



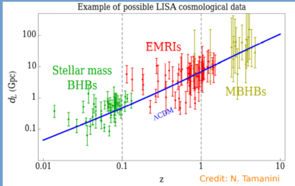
Multi-messenger

Formation of X-ray corona and jet around newly formed horizons



Cosmology

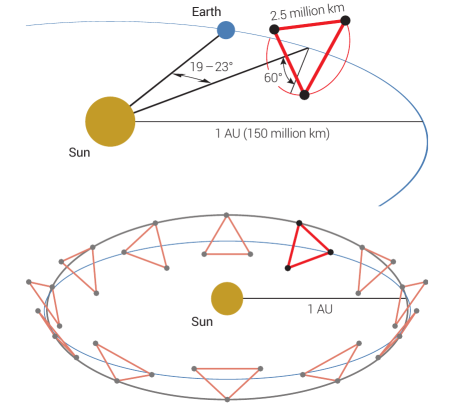
Testing the expansion rate of the Universe

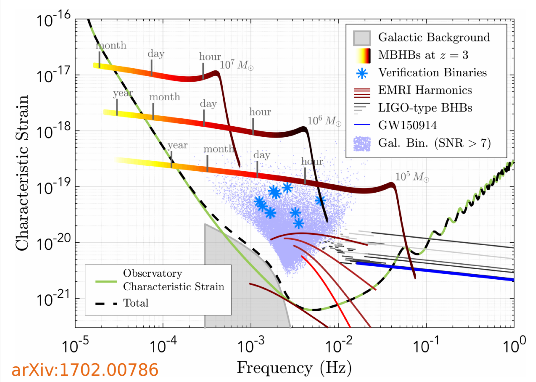


Observing the entire Universe with GWs

In mid-2030s LISA (Laser Interferometer Space Antenna) will observe the GWs from the coalescence of MBHBs in the entire Universe (ArXiv:1702.00786)

- 3rd Large class mission selected by European Space Agency (ESA)
- Successfully ended Phase A - Now in Phase B1 - Mission Adoption at end 2023





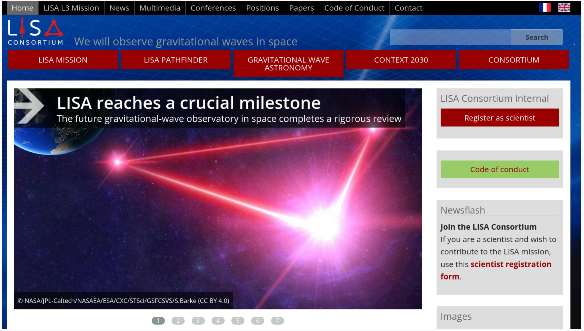
arXiv:1702.00786

The LISA Consortium

A large community to support LISA mission:

- +1300 full and associate members
- 5 Working Groups: Data Challenges, Astrophysics, Cosmology, Fundamental Physics, Waveform
- 2 Consortium meetings/yr, LISA Symposium every 2 yrs and WG meetings every year

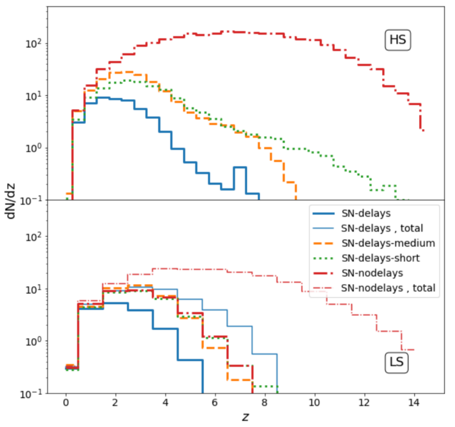
https://www.elisascience.org/



GWs from the coalescence of MBH binaries

MBHB merger rates

Let's proceed with order: How many MBHB mergers do we expect?



Large uncertainties in astrophysical processes (Klein+16, Katz+19, Barausse+20):

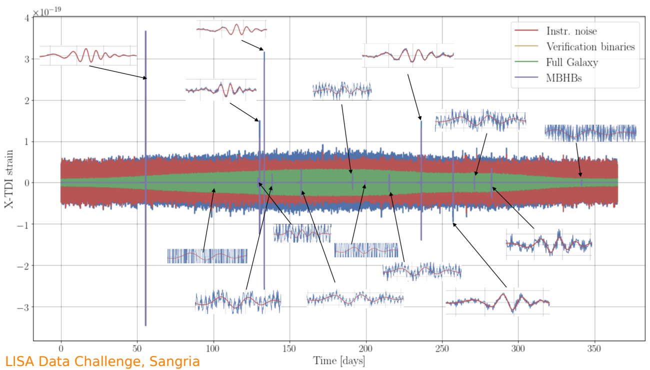
- Initial seed mass
- Time delays between galaxy and MBHBs merger
- Feedback processes

Cosmological simulations predicts $\sim$ 1/yr with $M_{BH} \gtrsim 10^5\,M_\odot$

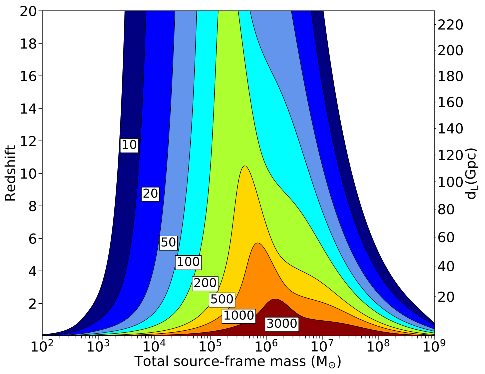
From few to several hundreads per year

How MBHBs do look like in LISA?

- Strong and long-lasting signals
- Strong overlap between signals from different sources → Global fit approach
- Detectable up to $z \sim 20$

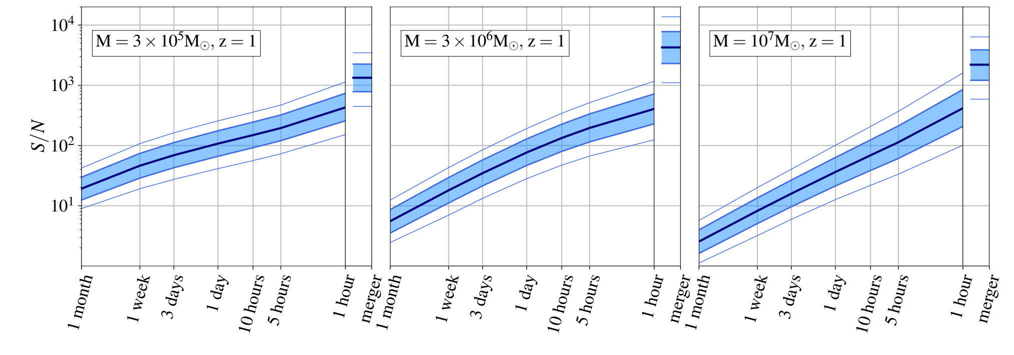


LISA Data Challenge, Sangria



What information LISA can provide?

MBHBs can be detected days or weeks before merger

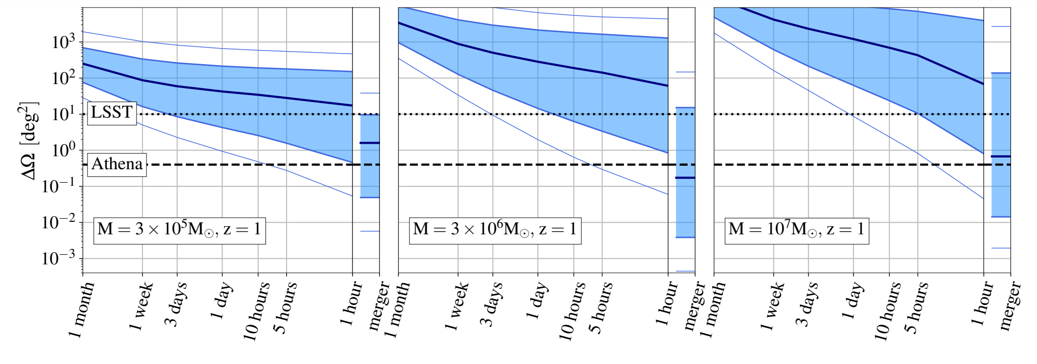


During the inspiral LISA can provide additional information: individual BH mass, spins and luminosity distance can be constrained to $\sim 5\%$ *before* merger

What about the sky localization?

(AM+20, Piro+22)

LISA sky localization for systems at $z = 1$

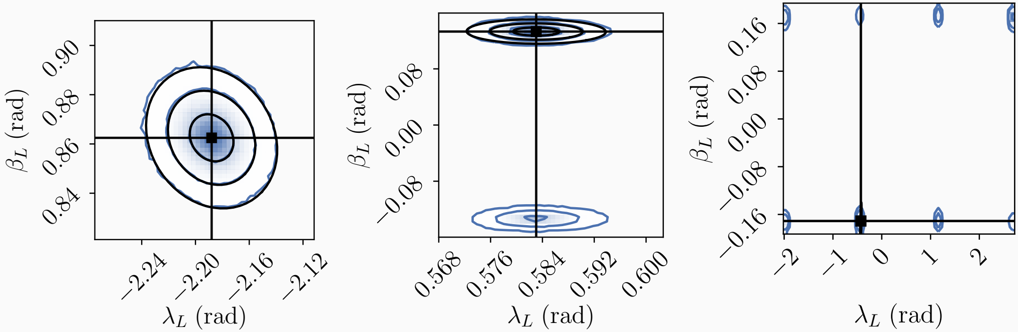


$\Delta\Omega \simeq$ telescope FOV only close to merger $\begin{cases} < 10\,\text{hrs} & \text{LSST} \\ \text{merger} & \text{Athena} \end{cases}$

Large distributions $\rightarrow$ strong dependence from true binary position

“Multimodal” LISA events

Systems with multimodal sky posterior distribution from LISA data analysis



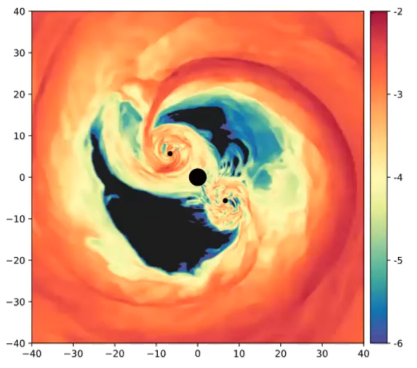
- Arise from LISA degeneracy pattern function
- Relevant especially for the inspiral search
- Might pose issues for the search of the EM counterpart

EM and GW emissions from MBHBs

What EM emission do we expect?

- No transient AGN-like emission has been associated unambiguously to a MBHBs
- Uncertainties on BH of $10^{5-7}\ M_\odot$ concerning bolometric correction, obscuration, spectra and variability

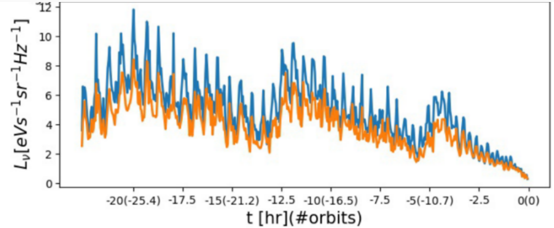
During the inspiral . . .



- The binary excavates a cavity
- Two bright minidisks around each BHs emitting in X-ray
- Gas streams flowing in the cavity
- Periodicities due to the orbital motion of the binary might be clear signatures (Dal Canton, AM +19)

(Bowen+18, Gold+14, Haiman+17, Tang+18, Nobel+21, Combi+22, . . .)

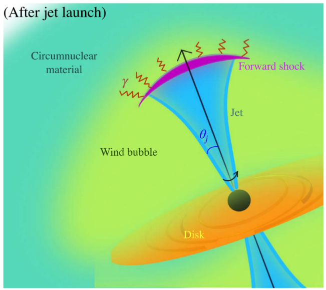
What EM emission do we expect?



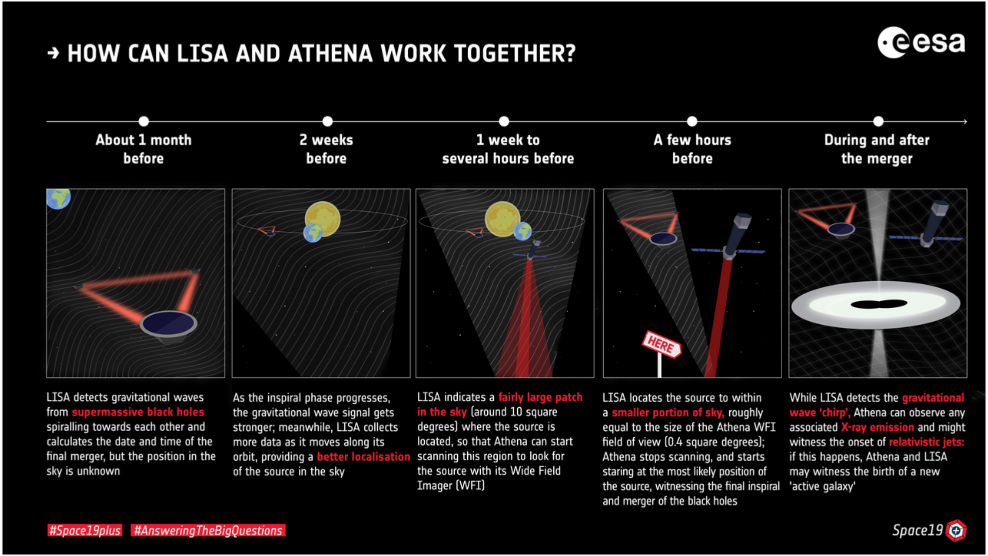
However, close at merger, minidisks might be depleated ⇒ Reduction in luminosity (Tang+18)

Post-merger signatures

- ➤ Disk-rebrightening (Rossi+10)
  - ✓ In-plane kicks for BHs with spins aligned along the orbital momentum
  - ✗ Might be to weak to be observed
- ➤ Afterglow emission (Yuan+21)
  - ✓ Broad band emission from radio to X-ray
  - ✗ Delays from days to months



Multi-messenger in practice



A realistic population of MBHBs

How many counterparts do we expect over LISA time mission? (AM+2207.10678)

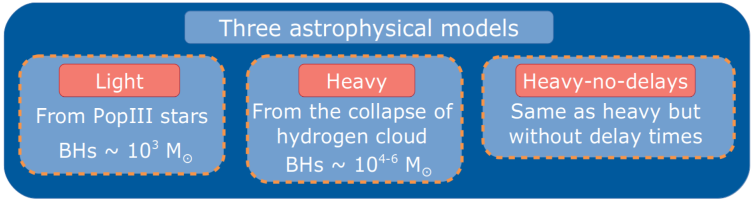
Estimate the number of counterparts over LISA time mission and cosmological parameters

Key improvements respect to previous works

- Improve the modeling of the EM counterpart
- Bayesian parameter estimation for GW signal (Marsat+20) $\rightarrow$ expensive but realistic

Starting point

Semi-analytical models: tools to construct MBHBs catalogs (Barausse+12)



Modeling the EM emission

Observing strategies

Optical

LSST, VRO

- Identification+redshift
- Deep as m$\sim$ 27.5
- FOV $\sim 10\,\mathrm{deg}^2$

Radio

SKA

- Only identification
- Deep as $F \sim 1\ \mu\mathrm{Jy}$
- FOV $\sim 10\,\mathrm{deg}^2$
- Redshift with ELT
- Flare+Jet emission

X-ray

Athena

- Only identification
- Deep as $F_X \sim 3 \times 10^{-17}\ \mathrm{erg/s/cm^2}$
- FOV $\sim 0.4\,\mathrm{deg}^2$
- Redshift with ELT
- Accretion from catalog or Eddington

Additional variations

AGN obscuration (Ueda+14, Gnedin+07)

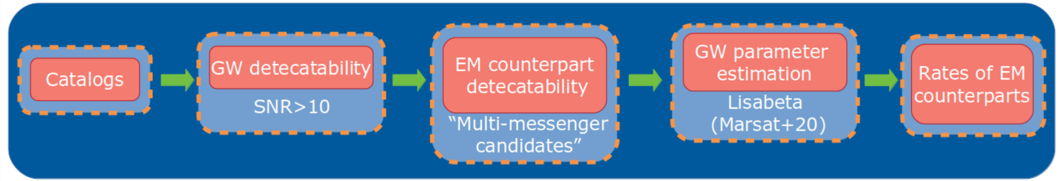
- Affect LSST/VRO and Athena
- Typical hydrogen column density distribution

Radio Jet (Cohen+06)

- Affect SKA
- Assume a jet opening angle of $\sim 30^\circ$ (Yuan+21)

Two main scenarios

Procedure



We focus on two scenarios

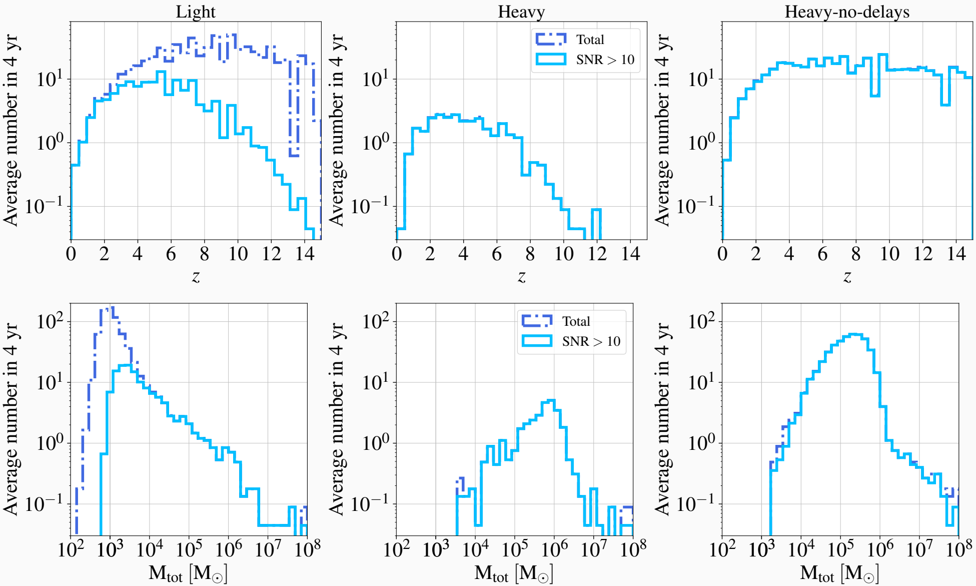
Maximising

- AGN obscuration neglected
- Isotropic flare emission
- Eddington accretion for X-ray emission

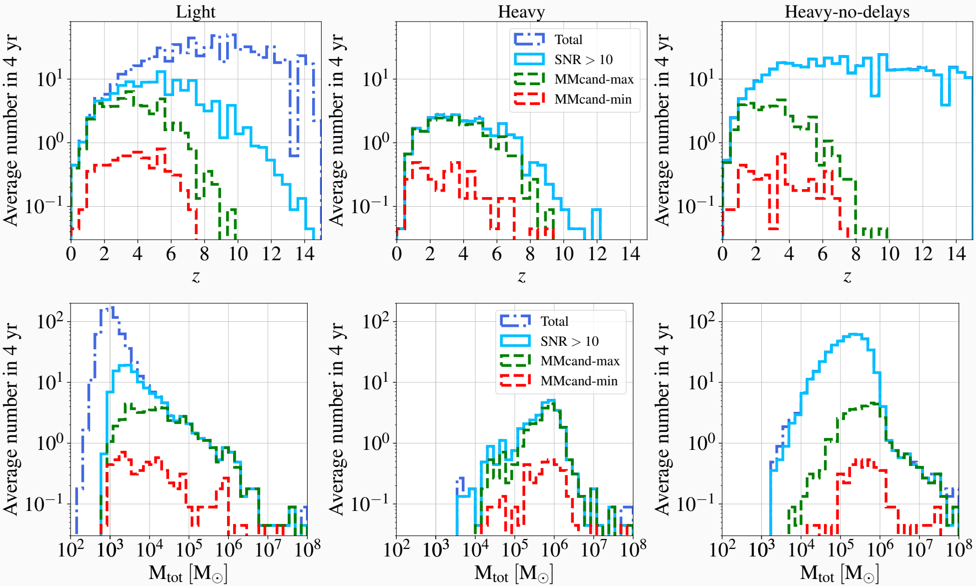
Minimising

- AGN obscuration included
- Collimated flare emission with $\theta \sim 30^{\circ}$
- Catalog accretion for X-ray emission

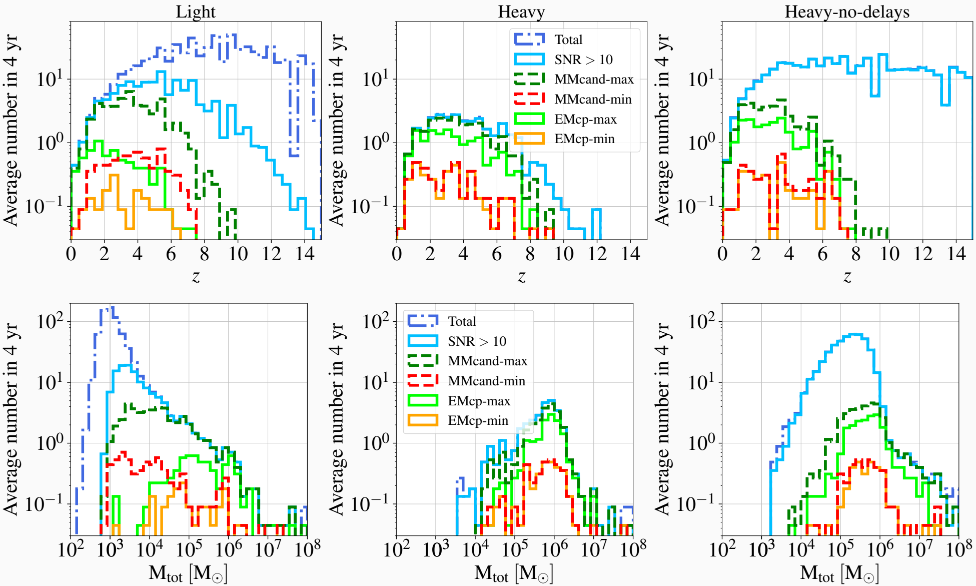
Redshift and total mass distributions



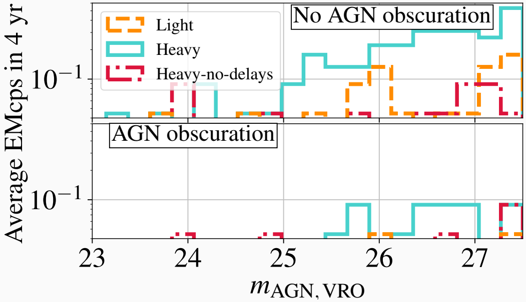
Redshift and total mass distributions

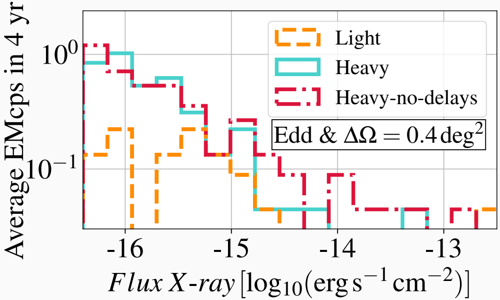


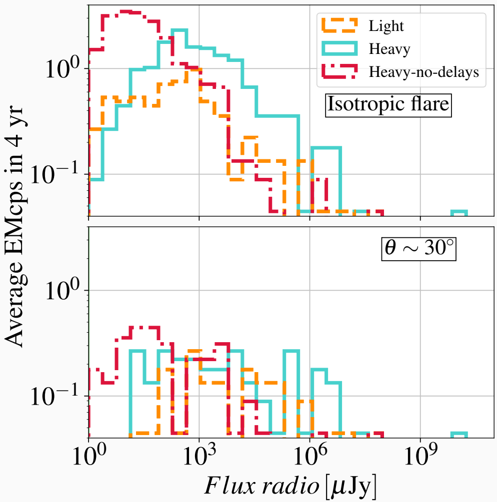
Redshift and total mass distributions



EMcps in optical, X-ray and radio







Only few and faint sources in 4 yr

EMcp rates in 4 yr

(In 4 yr)	LSST, VRO	SKA+ELT			Athena+ELT		
		Isotropic	$\theta \sim 30°$	$\theta \sim 6°$	Catalog $F_{\mathrm{X,\,lim}}$ = 4e-17	Eddington $F_{\mathrm{X,\,lim}}$ = 4e-17	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	
No-obsc.	0.84	6.4	1.51	0.04	0.49	1.02	Light
	3.07	14.8	2.71	0.04	2.67	3.87	Heavy
	0.53	20.3	3.2	0.04	0.58	4.4	Heavy-no-delays
Obsc.	0.13	6.4	1.51	0.04	0.04	0.13	Light
	0.75	14.8	2.71	0.04	0.22	0.18	Heavy
	0.35	20.3	3.2	0.04	0.18	0.27	Heavy-no-delays

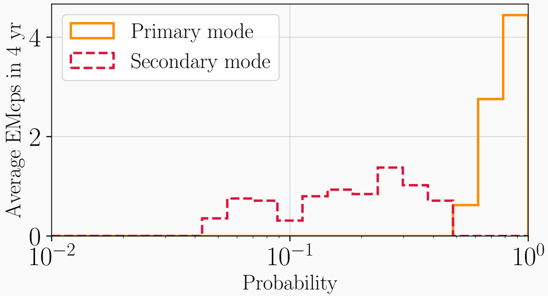
- Dramatic decrease with obscuaration and radio jet
- Parameter estimation selects preferentially *heavy*

(In 4 yr)	Maximising	Minimising
Light	6.4	1.6
Heavy	14.8	3.3
Heavy-no-delays	20.7	3.5

What about multimodal events?

Focus only on the true binary spot

Modes probability



Contribution to the expected rate in 4 yr

	1mode	2modes	8modes
Light	6.0	0.31	0.13
Heavy	10.7	3.9	0.18
Heavy-nd	16.8	3.5	0.4

- 2modes have always one mode more probable than the other
- 8modes provides < 1 counterparts in the entire mission

Multimodal events does not affect (significantly) counterpart estimates

Cosmology prospects

MBHBs as cosmological probes

The Λ-Cold Dark Matter (ΛCDM) is the most common cosmological parametrization:

- ✓ Simple model with good fit to the bulk of data
- ✗ Current tensions :
  - ➤ Early Universe: Cosmic Microwave Background (CMB) observations at $z > 1000$
  - ➤ Late Universe: SNIa, lensed images, standard sirens at $z \lesssim 2.5$

Compact object binaires are standard sirens

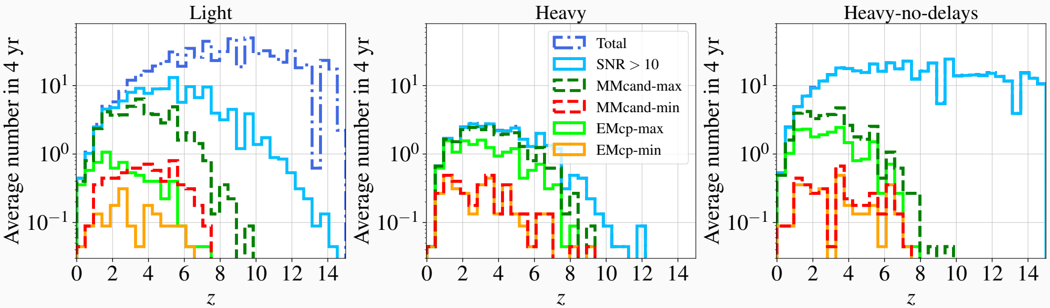
GWs present several pros respect to standard techniques

- ➤ Direct information on $d_L \rightarrow$ No calibration errors
- ➤ Independent from CMB or SNIa $\rightarrow$ Independent estimates

Can MBHBs solve the Hubble tension?

MBHBs as cosmological probes

Probably no, but ...



MBHBs can test the expansion of the Universe at $z > 2$

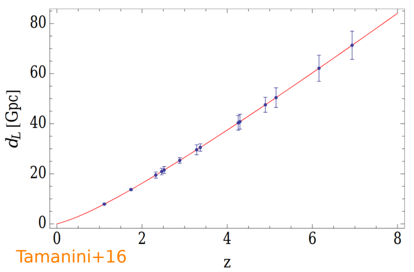
Bright and Dark sirens

Bright sirens

Redshift information from the EM counterpart

(Holz+05, Del Pozzo+12, Tamanini+16, LVC+ Nature 551)

- ✓ Direct redshift information
- ✗ Challenging detection of EM counterpart
- ✗ Few and faint sources



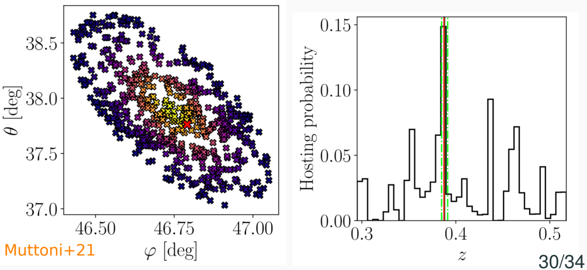
Tamanini+16

Dark sirens

Redshift information from the galaxy distribution

(Schutz86, Petiteau+11, Muttoni+21)

- ✓ More systems
- ✗ Error volumes with $> 10^3$ galaxies
- ✗ Catalog completeness at $z \sim 2 - 3$

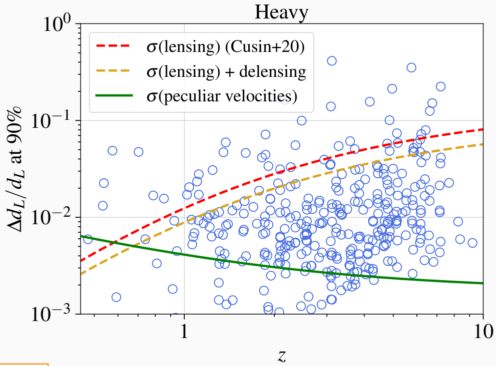


Muttoni+21

Luminosity distance and redshift estimates

Luminosity distance

- Accurate estimate of luminosity distance $\rightarrow \frac{\Delta d_L}{d_L} < 10\%$
- Lensing relevant for $z \gtrsim 2-3$
- Peculiar velocities are negligible



Redshift measurements

LSST/VRO

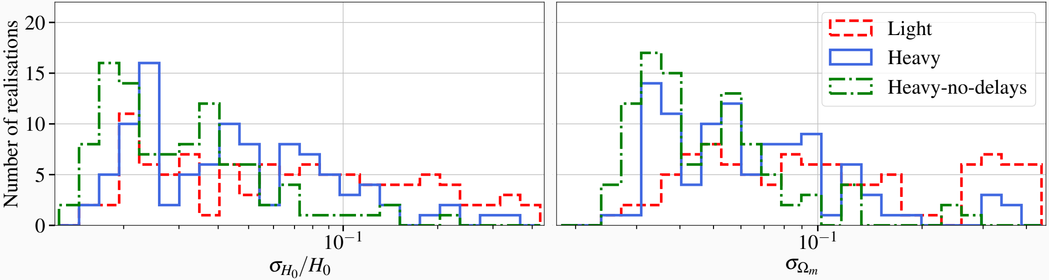
Photometric measurements with $\Delta z = 0.03(1+z)$ (*Laigle* + 19)

ELT

	$m_{\rm ELT} < 27.2$	$27.2 < m_{\rm ELT} < 31.3$
$z < 1$		No z measure
$1 < z < 5$	$\Delta z = 10^{-3}$	$\Delta z = 0.5$
$z > 5$		$\Delta z = 0.2$

Preliminary results

Combine the luminosity distance and redshift uncertainty to constrain cosmological parameters



H_0 can be constrained to few percent
Larger uncertainties on Ω_m

Conclusions

MBHBs multi-messenger will be challenging!

Concerning the GW signal

- Systems can be detected weeks before merger but the sky localization is poor
- The sky localization improves significantly at merger
- There might be many galaxies in LISA error box (See Lops+22)

Estimating the number of counterpart for MBHB mergers in LISA

- Large uncertainties on the type of EM emissions we expect
- Most sources are intrinsically faint and at high redshift
- Obscuration decreases the number of EMcps $\Rightarrow$ We need better modeling and predictions
- Few events $\Rightarrow$ We need accurately planned follow-up strategies

Conclusions

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Thanks! Any questions?