LISA-Athena synergies for detecting GW and HE counterparts of supermassive binary BH mergers

Alberto Mangiagli

Collaborators: Marta Volonteri, Chiara Caprini, Sylvain Marsat, Susanna Vergani, Nicola Tamanini, Henri Inchauspe, Lorenzo Speri

Laboratoire Astroparticule et Cosmologie (APC)

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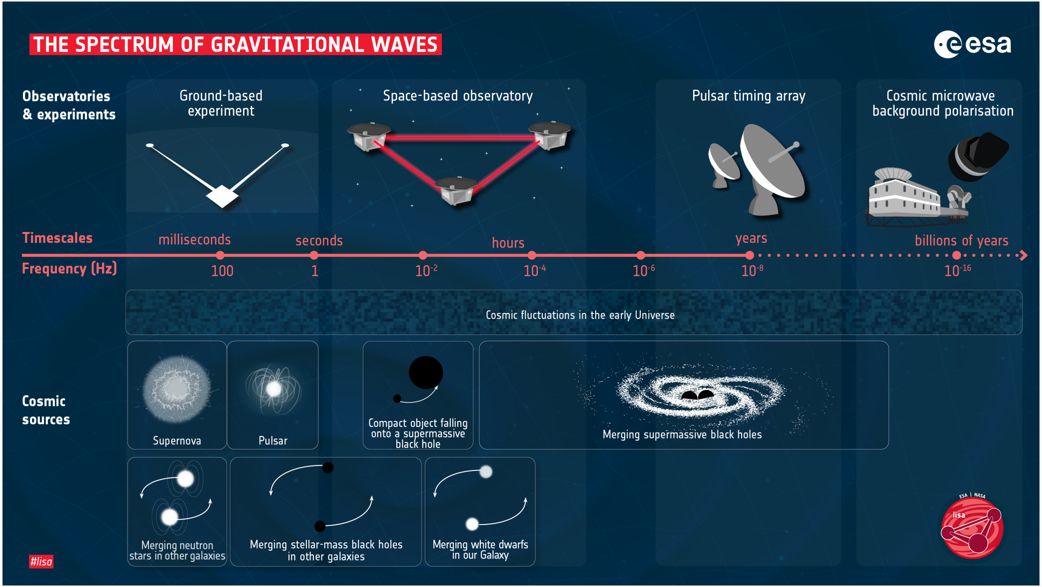
Outline

- Multimessenger astronomy with massive BH binary (MBHBs)
- Electromagnetic (EM) and gravitational waves (GWs) emissions from MBHBs
- EMcps from a realistic MBHBs population

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
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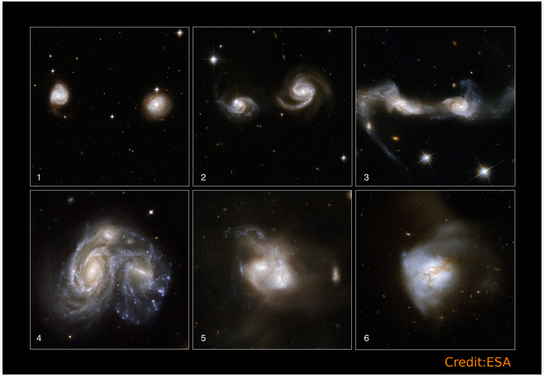
Massive black hole binaries (MBHBs)

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

We currently believe that MBHs are hosted at the center of galaxies



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?

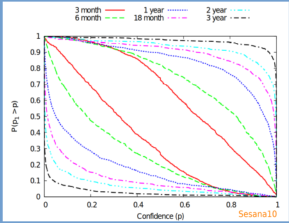
Large uncertainties in the event rate: from few to several hundreads per year

Why MBHBs?

The importance of MBHBs

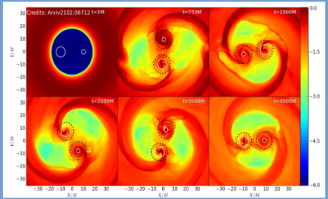
Astrophysics

Constrain MBHBs formation and evolution scenarios



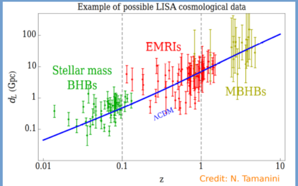
Multi-messenger

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



Cosmology

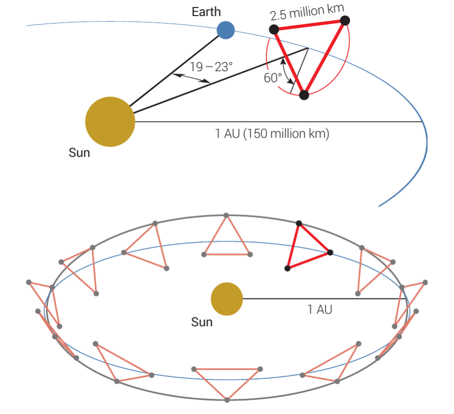
Testing the expansion rate of the Universe

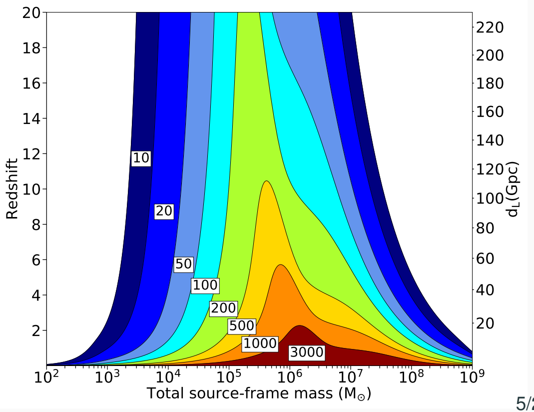


Observing the entire Universe with GWs

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





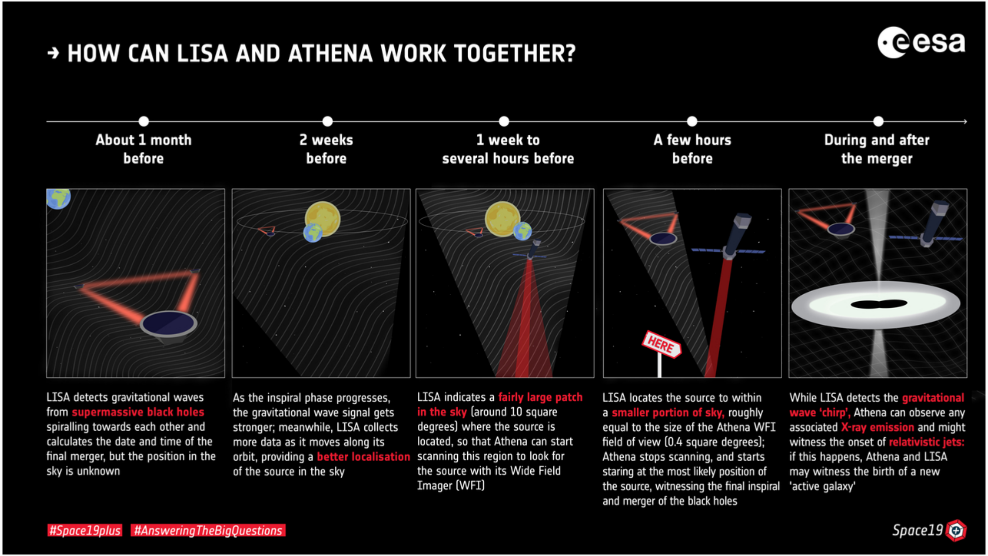
Exploring the high energetic Universe in X-ray

In the same period, Athena (Advanced Telescope for High Energy Astrophysics) will observe the X-ray emission from accretion-powered objects

- 2rd Large class mission selected by ESA
- AGN, transients, gas in intergalactic medium and more
- Strong synergies with LISA

> The *additional* science [. . .] the two missions could achieve may provide breakthroughs in scientific areas beyond what each individual missions is designed for
> (Athena-LISA Synergy Working Group)
> (ArXiv:2120.15677)

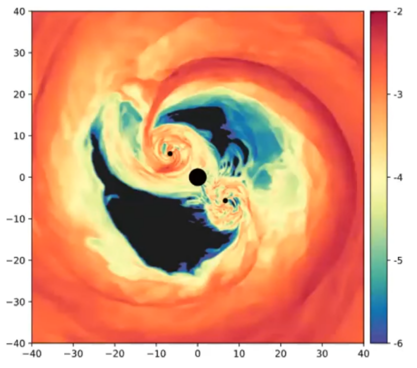
Multi-messenger in practice



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

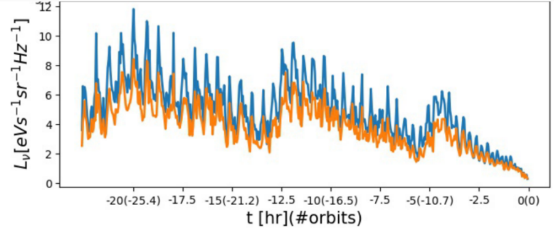
During the inspiral . . .



- 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, . . .)

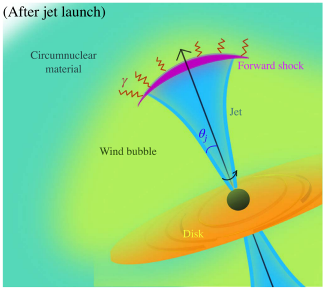
What EM emission do we expect?



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

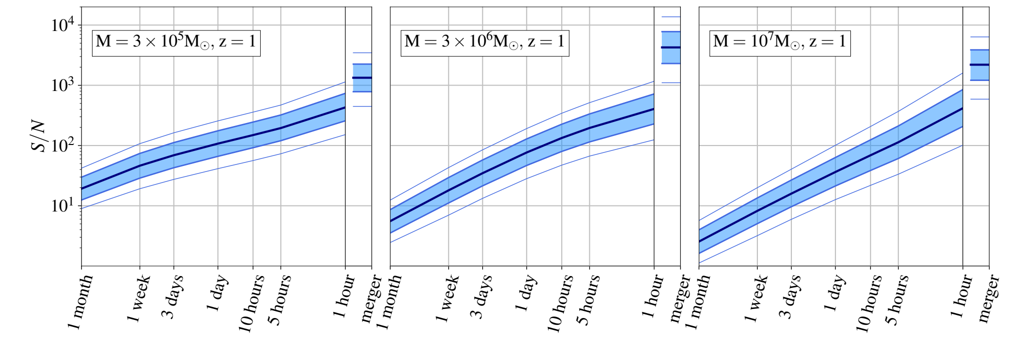
Post-merger signatures

- ➤ 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



What information LISA can provide?

MBHBs can be detected days or weeks before merger

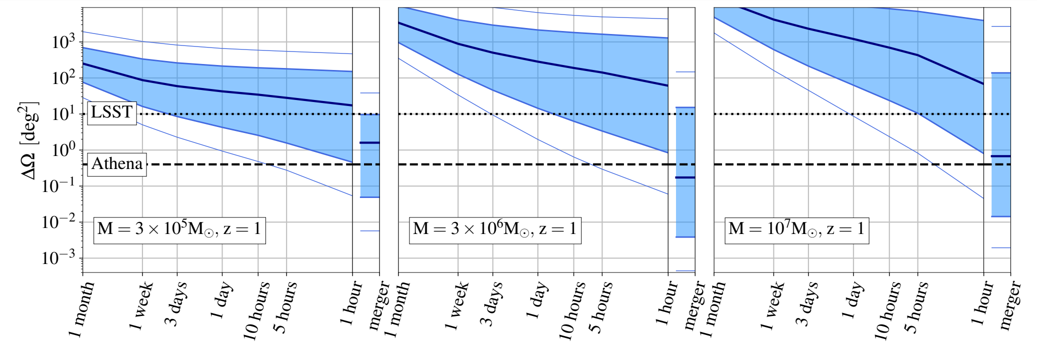


During the inspiral LISA can provide additional information: individual BH mass, spins and luminosity distance can be constrained to $\sim 5\%$ *before* merger

What about the sky localization?

(AM+20, Piro+22 in prep.)

LISA sky localization for systems at $z = 1$

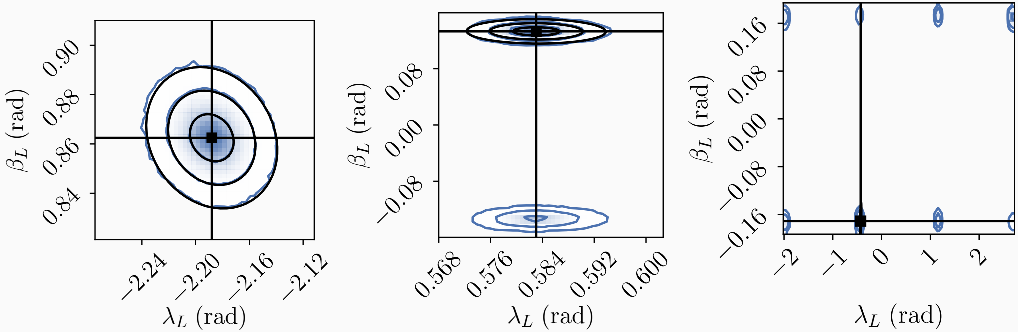


$\Delta\Omega \simeq$ telescope FOV only close to merger $\begin{cases} < 10\,\text{hrs} & \text{LSST} \\ \text{merger} & \text{Athena} \end{cases}$

Large distributions → 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

A realistic population of MBHBs

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

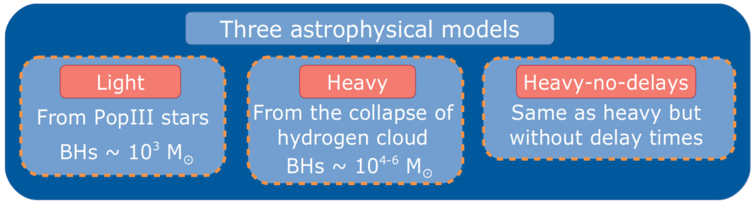
Estimate the number of counterparts over LISA time mission and cosmological parameters

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)

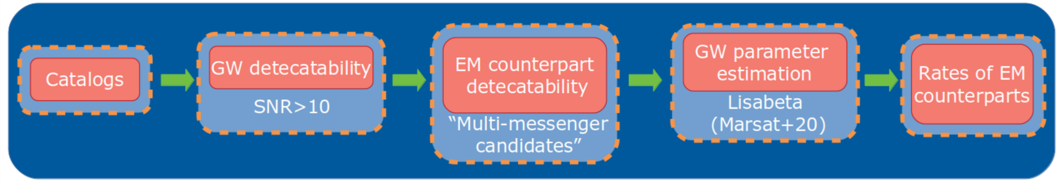
- Affect LSST/VRO and Athena
- Typical hydrogen column density distribution

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

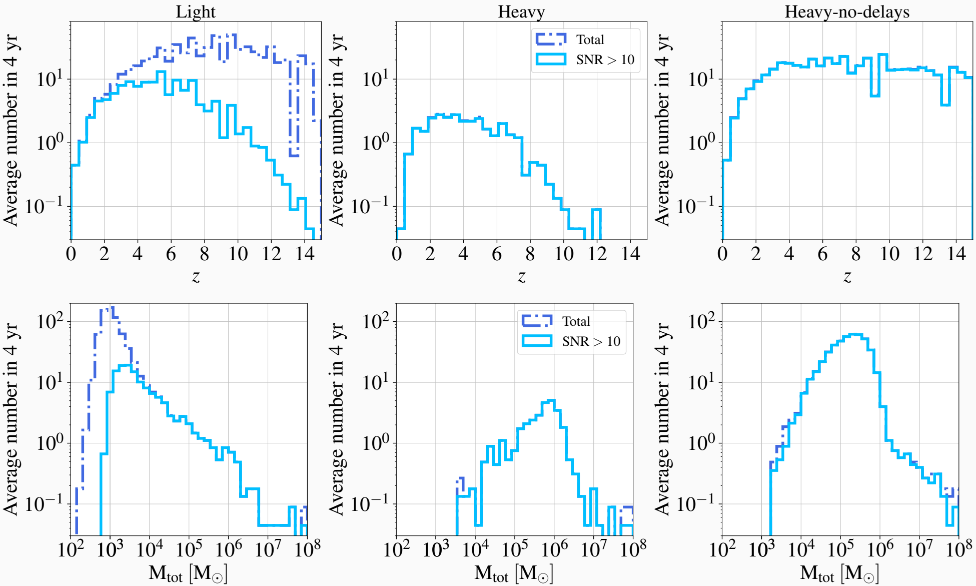
Maximising

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

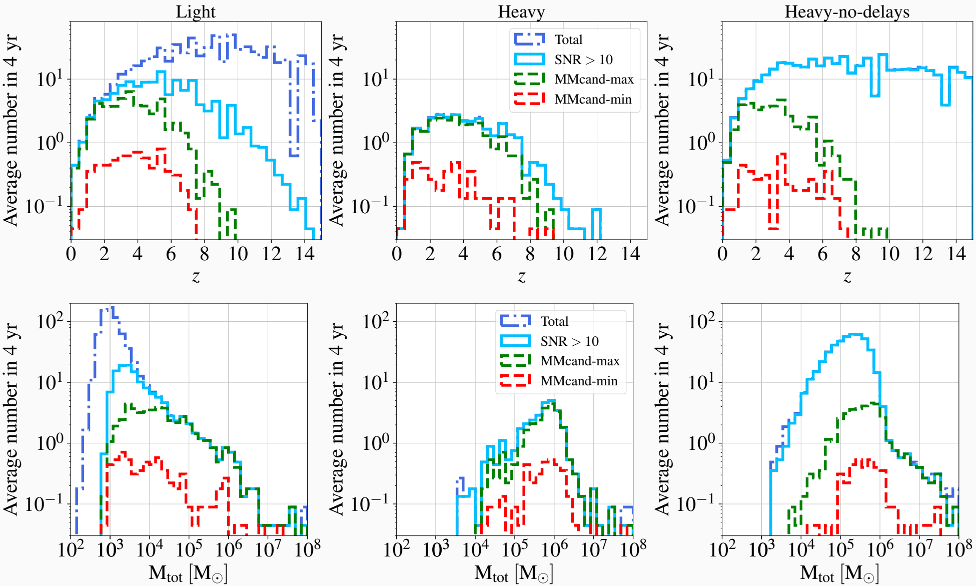
Minimising

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

Redshift and total mass distributions



Redshift and total mass distributions



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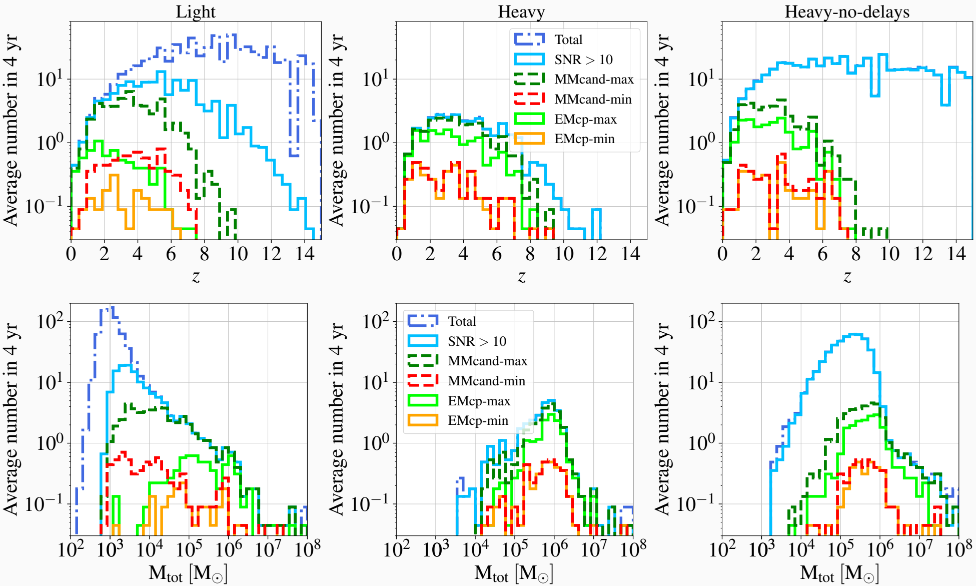
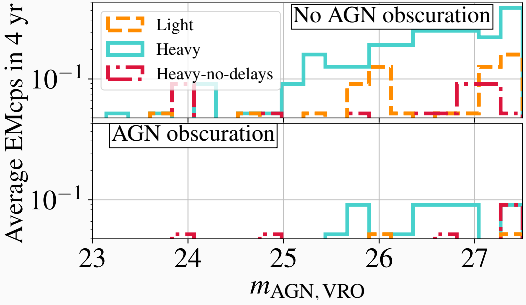
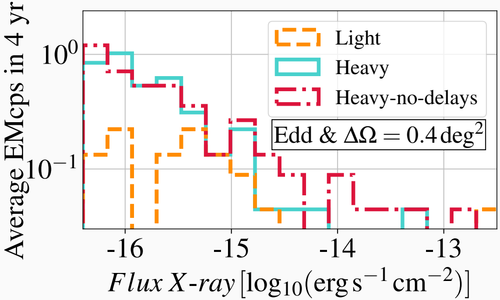
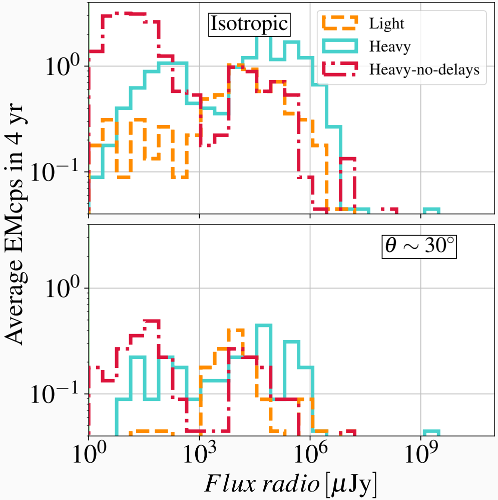


EMcps in optical, X-ray and radio







Only few and faint sources in 4 yr

EMcp rates in 4 yr

(In 4 yr)	LSST, VRO	SKA+ELT			Athena+ELT		
		Isotropic	$\theta \sim 30^\circ$	$\theta \sim 6^\circ$	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	6.8	1.51	0.04	0.49	1.02	Light
	3.07	14.9	2.71	0.04	2.67	3.87	Heavy
	0.53	20.6	3.2	0.04	0.58	4.4	Heavy-no-delays
Obsc.	0.27	6.8	1.51	0.04	0.04	0.37	Light
	0.84	14.9	2.71	0.04	0.22	0.18	Heavy
	0.22	20.6	3.2	0.04	0.09	0.4	Heavy-no-delays

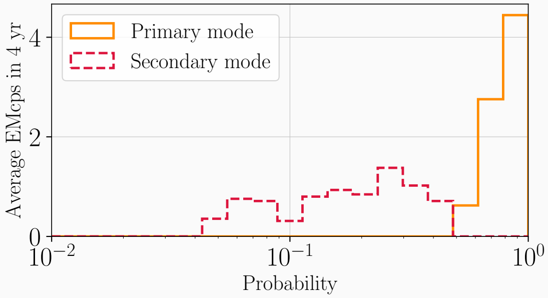
- Dramatic decrease with obscuaration and radio jet
- Parameter estimation selects preferentially *heavy*

(In 4 yr)	Maximising	Minimising
Light	6.8	1.7
Heavy	14.9	3.4
Heavy-no-delays	20.9	3.4

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	6.3	0.36	0.13
Heavy	10.7	3.9	0.2
Heavy-nd	16.4	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

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

MBHBs multi-messenger will be challenging!

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- Systems can be detected weeks before merger but the sky localization is poor
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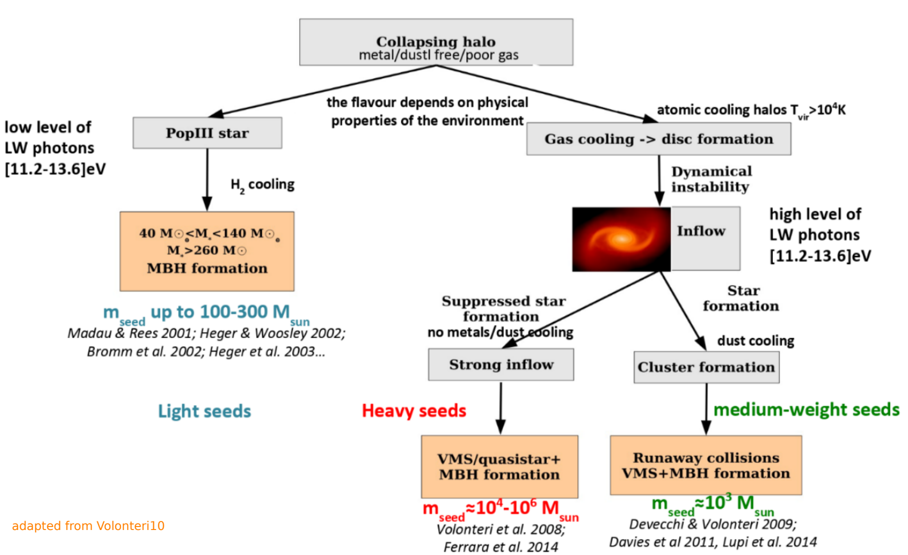
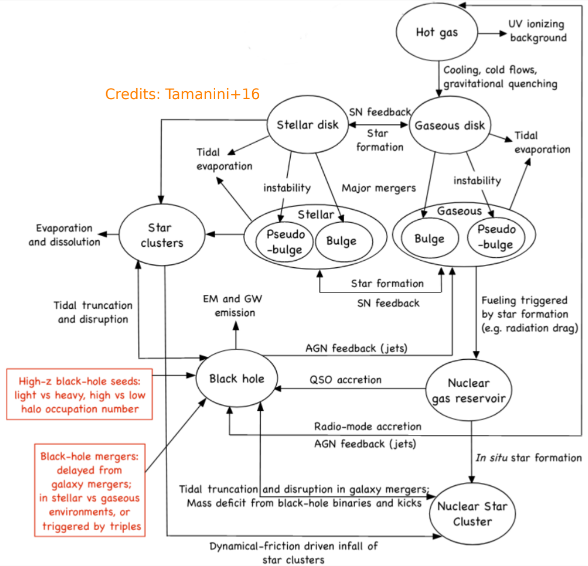
Thanks! Any questions?

Backup slides

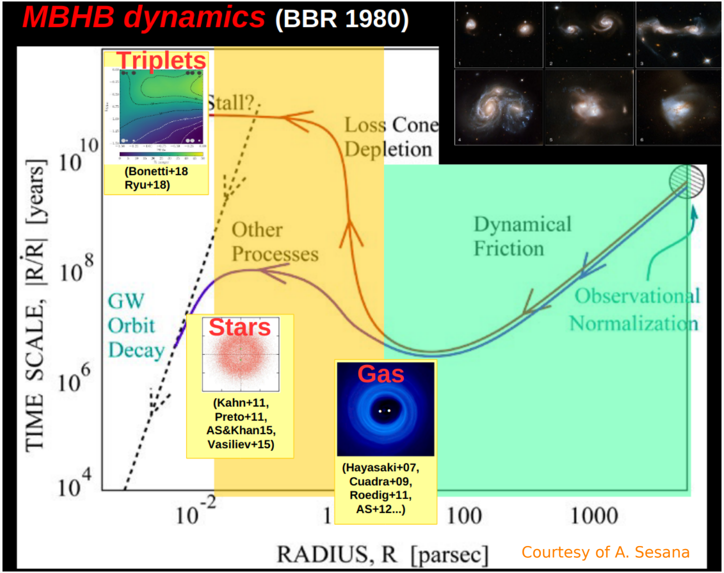
Seed BHs formation channels



The physics of the semi-analytical model

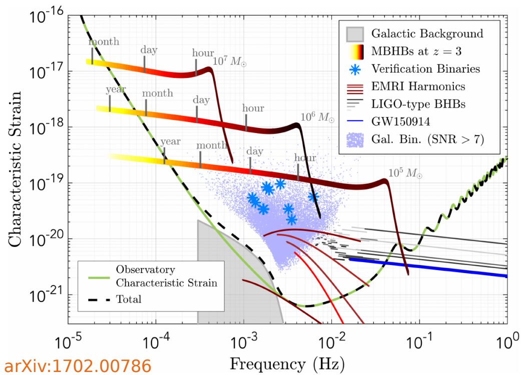


Last parsec problem

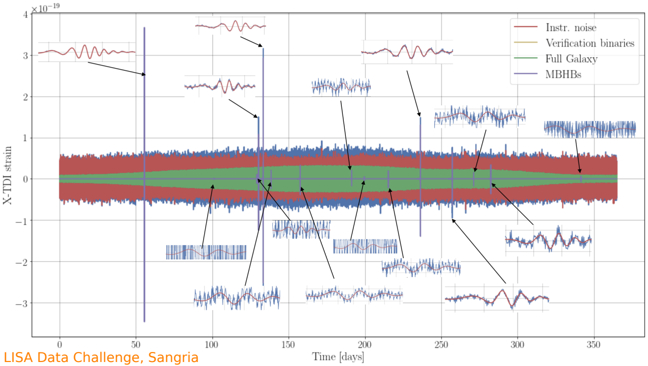


GW sources in LISA band

- Strong and long-lasting signals
- Strong overlap between signals from different sources → Global fit approach
- Unexplored parameter space → Large unceratainty on rate & sources’ properties



arXiv:1702.00786



LISA Data Challenge, Sangria

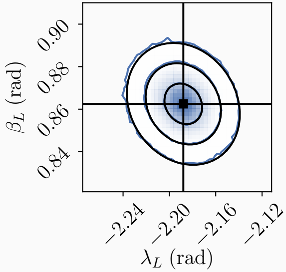
GW analysis

Number of detected events in 4 yr

	Total catalog	SNR > 10
Light	690.9	129.3
Heavy	30.7	30.4
Heavy-no-delays	475.5	471.1

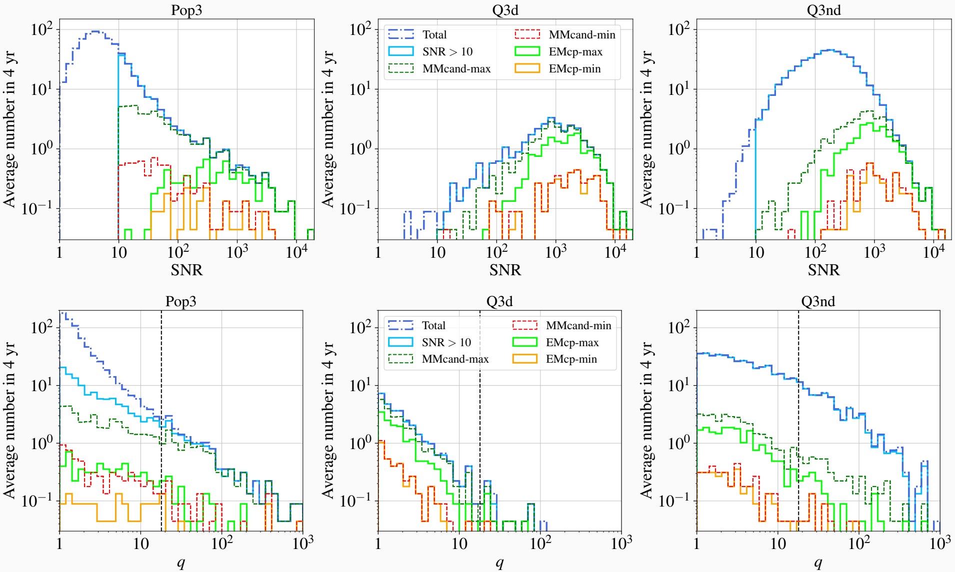
GW parameter estimation

For multimessenger candidates, we use *lisabeta* (Marsat+2021) for parameter estimation

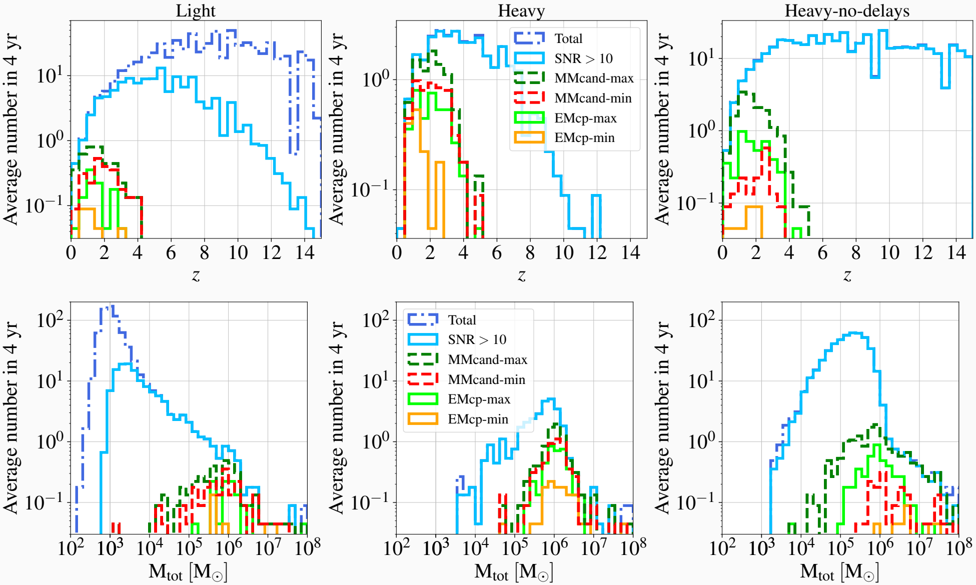


- MCMC formalism
- Include both low- and high-frequency LISA response
- Tested with independent codes

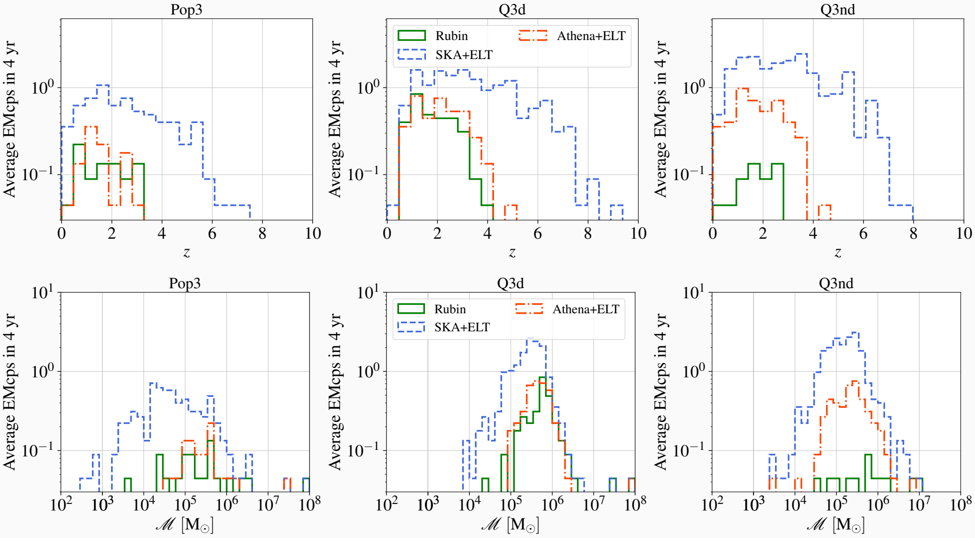
SNR and mass ratio distributions



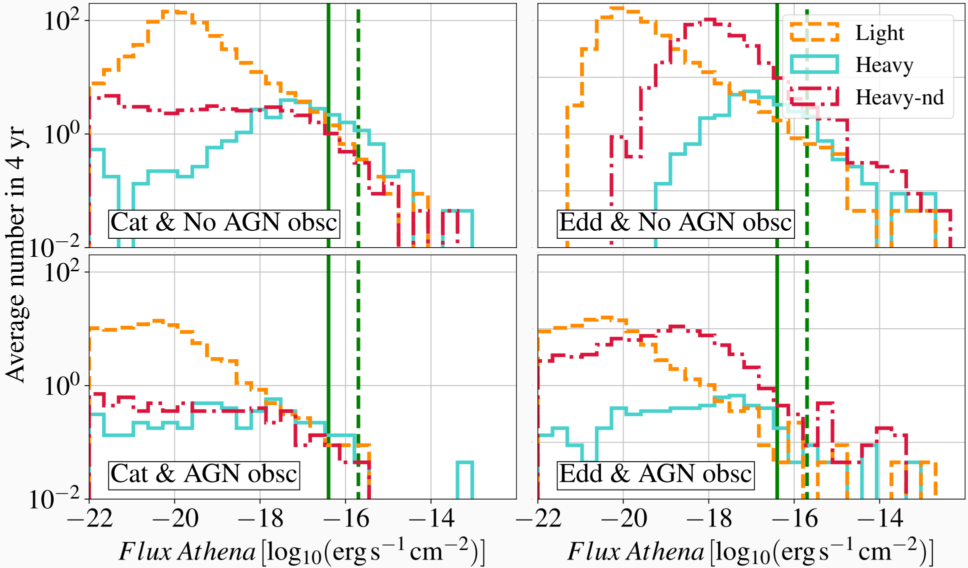
Redshift and total mass distributions for Athena



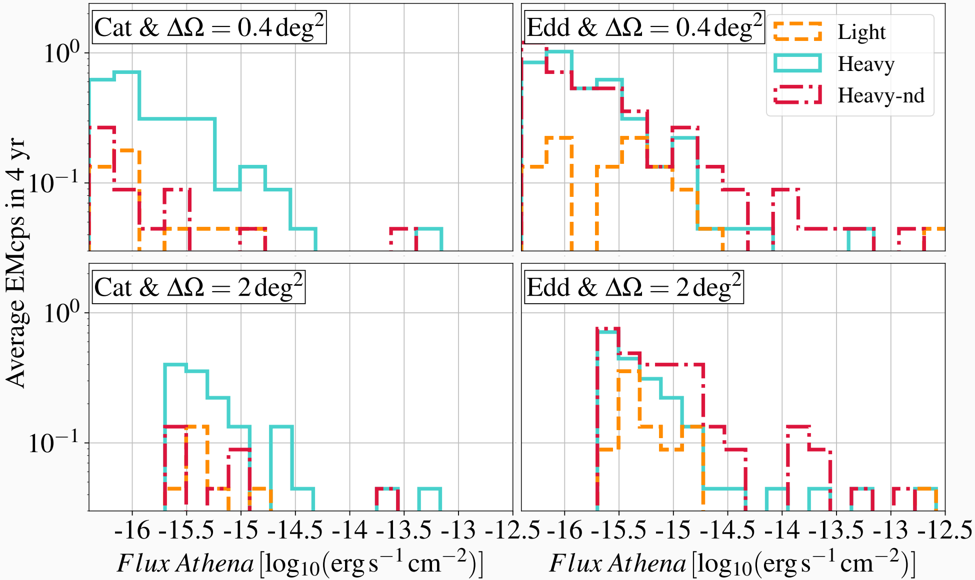
Redshift and total mass distributions for each strategy



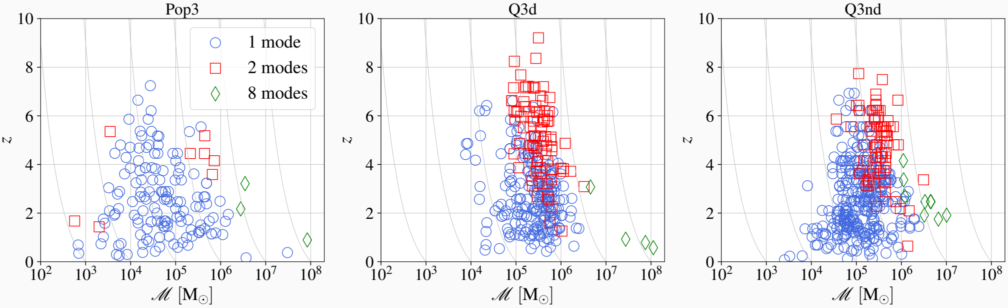
Distribution of X-ray fluxes



EMcps in X-ray (No obscuration) with Athena

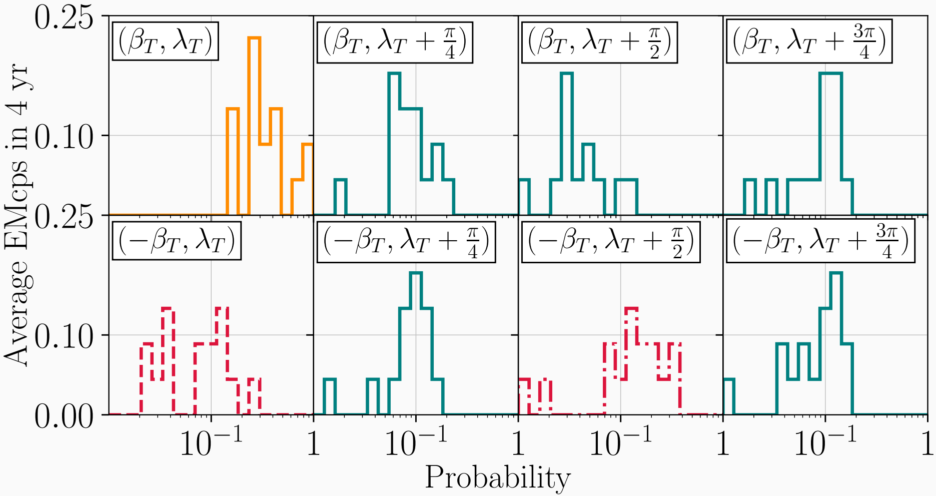


Multimodal events



- 1mode systems are the vast majority
- 2mode systems appear at high mass and high redshift
- Still large spread across sub-populations

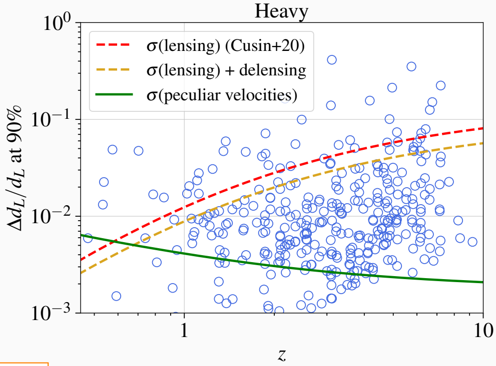
Probability for 8modes systems



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
$1 < z < 5$	$\Delta z = 10^{-3}$	$\Delta z = 0.5$
$z > 5$		$\Delta z = 0.2$

Galaxies in LISA error boxes