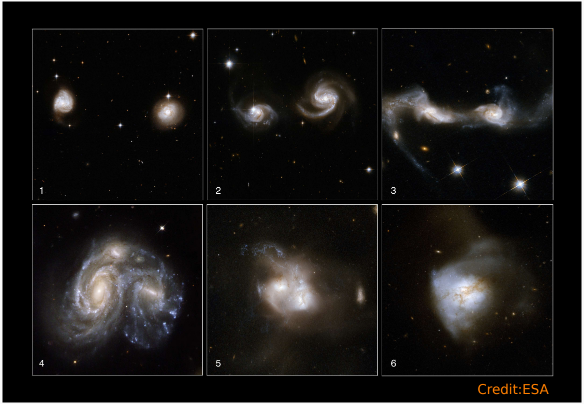
Multimessenger prospects for massive black hole binaries in LISA

Alberto Mangiagli

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

Laboratoire Astroparticule et Cosmologie (APC)

Massive black hole binaries (MBHBs)



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

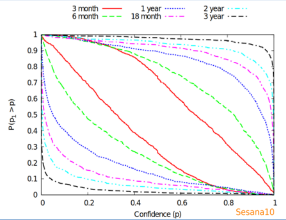
We currently believe that MBHs are hosted at the center of galaxies

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

The importance of MBHBs

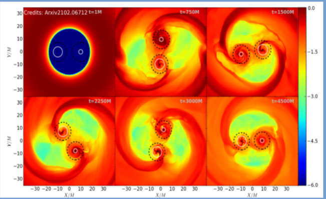
Astrophysics

Constrain MBHBs formation and evolution scenarios



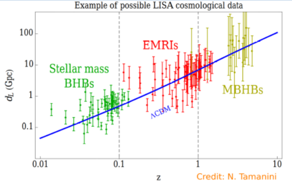
Multi-messenger

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



Cosmology

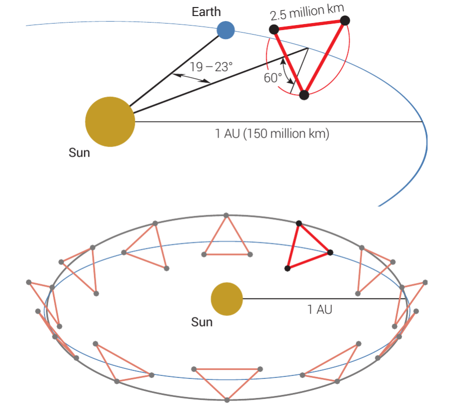
Testing the expansion rate of the Universe

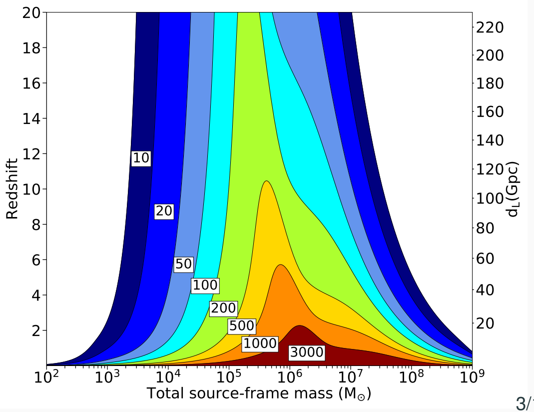


Observing the entire Universe with GWs

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





A realistic population of MBHBs

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

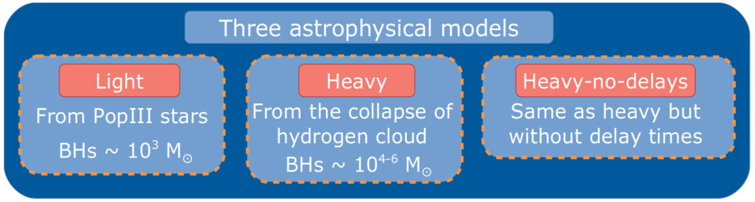
Estimate the number of EM counterparts over LISA time mission and cosmological parameters

Key improvements respect to previous works

- Improve the modeling of the EM counterpart (Tamanini+16)
- Bayesian parameter estimation for GW signal (Marsat+20) → 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)

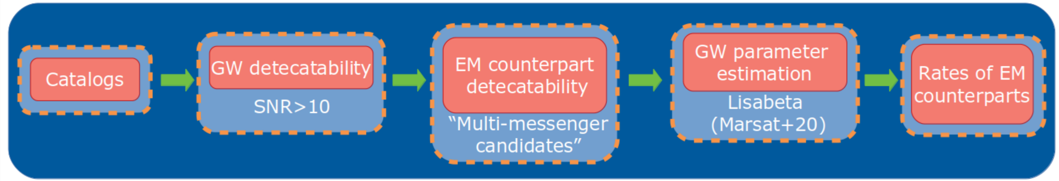
- Affect LSST/VRO and Athena
- Typical hydrogen column density distribution

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

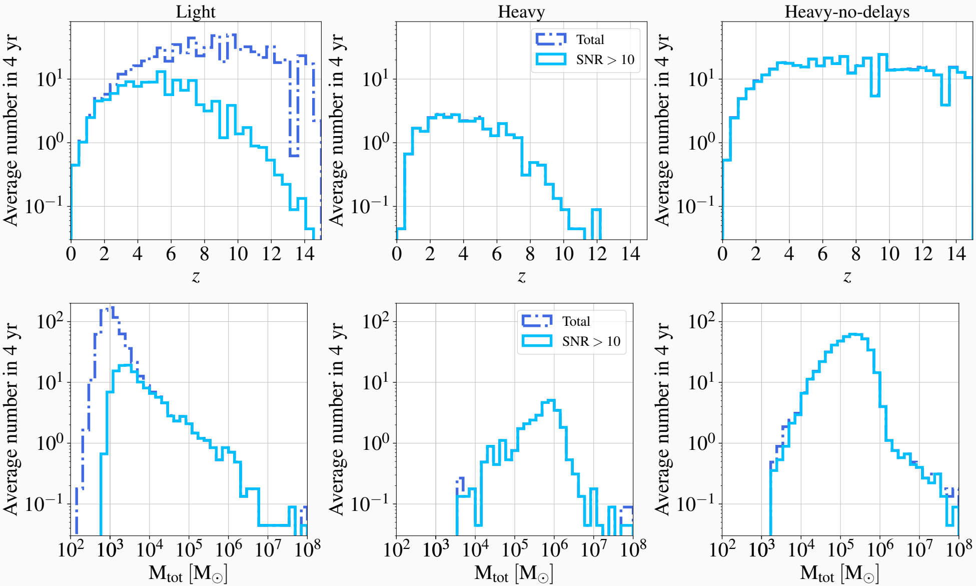
Maximising

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

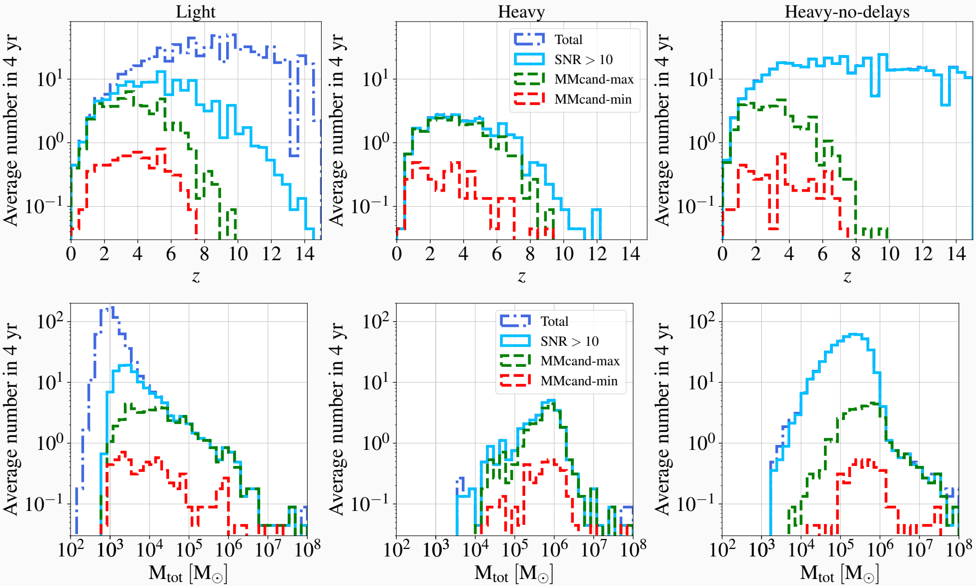
Minimising

- 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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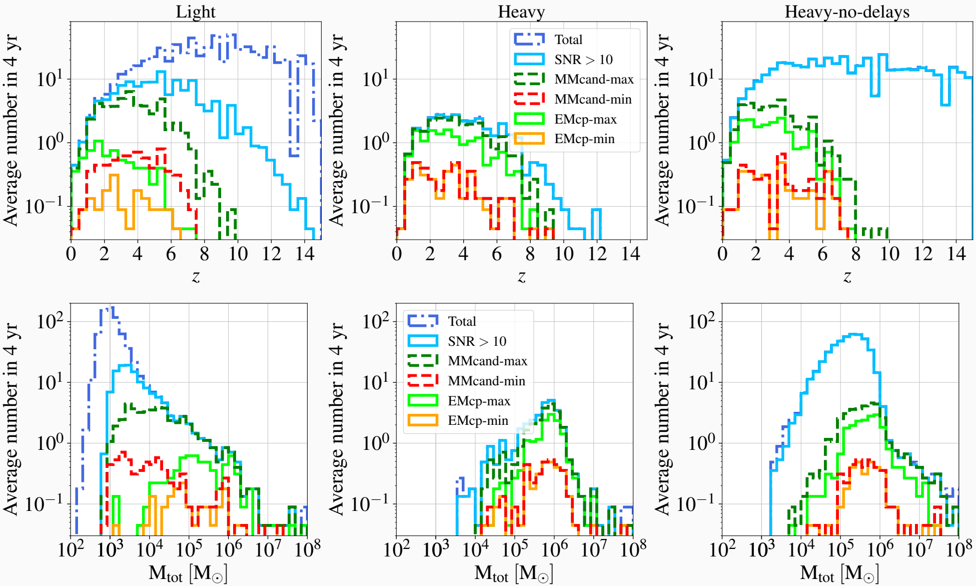
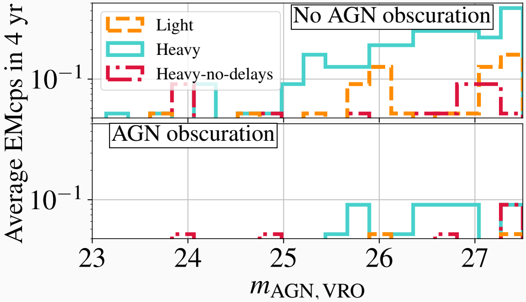
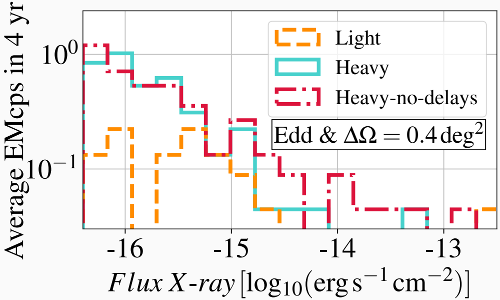
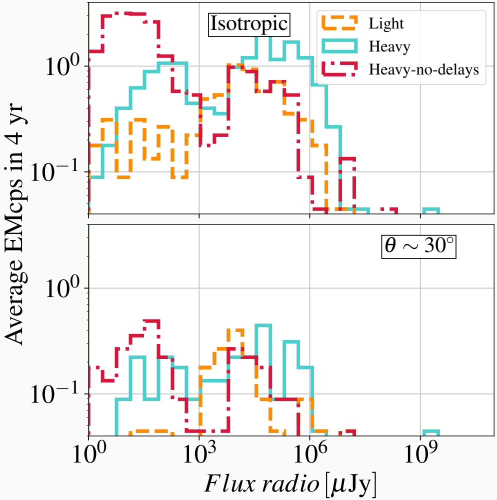


EMcps in optical, X-ray and radio







Only few and faint sources in 4 yr

EMcp rates in 4 yr

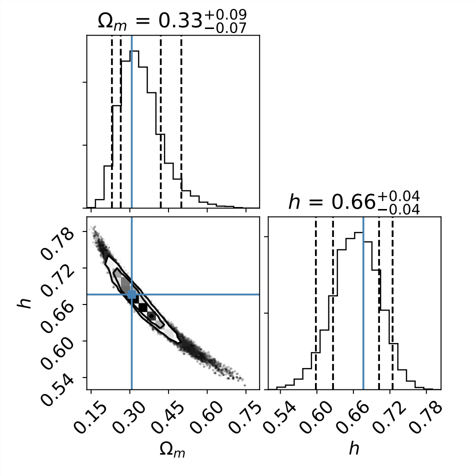
(In 4 yr)	LSST, VRO	SKA+ELT			Athena+ELT		
		Isotropic	$\theta \sim 30°$	$\theta \sim 6°$	Catalog $F_{\mathrm{X,\,lim}}$ = 4e-17	Eddington $F_{\mathrm{X,\,lim}}$ = 4e-17	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	
No-obsc.	0.84	6.8	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

Cosmology applications

Combine the luminosity distance and redshift uncertainty to constrain cosmological parameters (still preliminary)



No instruments will provide estimates at high redshift (+ no calibration errors)

H_0 can be constrained to few percent
Larger uncertainties on Ω_m

Conclusions

Estimating the number of counterpart for MBHB mergers in LISA

- Most sources are faint
- Obscuration and collimated radio emission decrease the counterpart rates by $\sim 75\%$
- Few events $\Rightarrow$ we need accuratly planned follow-up strategy

For cosmology

- At the end, we expect $\Delta H_0 \sim 10\%$ with only MBHBs
- Worst results than previous studies but better modeling of the EM counterpart and more realistic GW parameter estimation
- We can combine MBHBs with stellar BHBs and EMRIs

MBHBs multi-messenger will be challenging!

Conclusions

Estimating the number of counterpart for MBHB mergers in LISA

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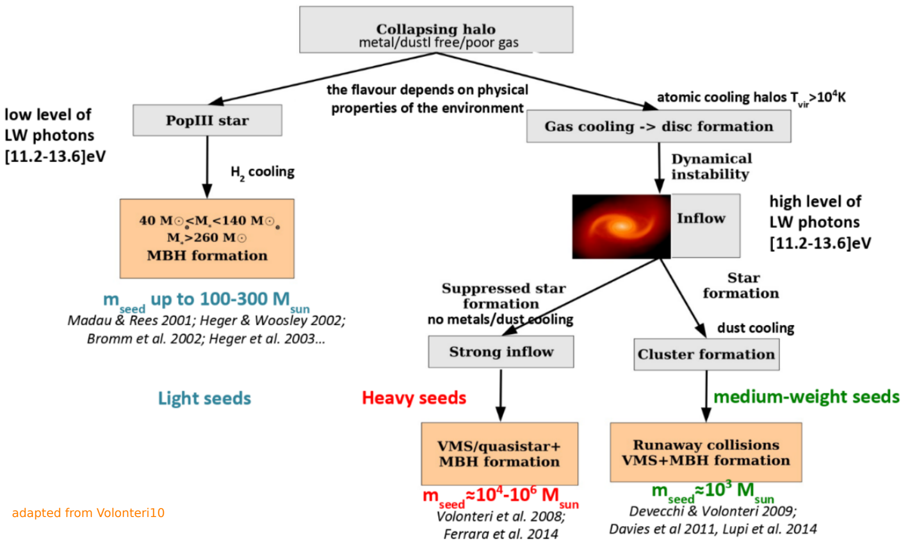
MBHBs multi-messenger will be challenging!

Thanks! Any questions?

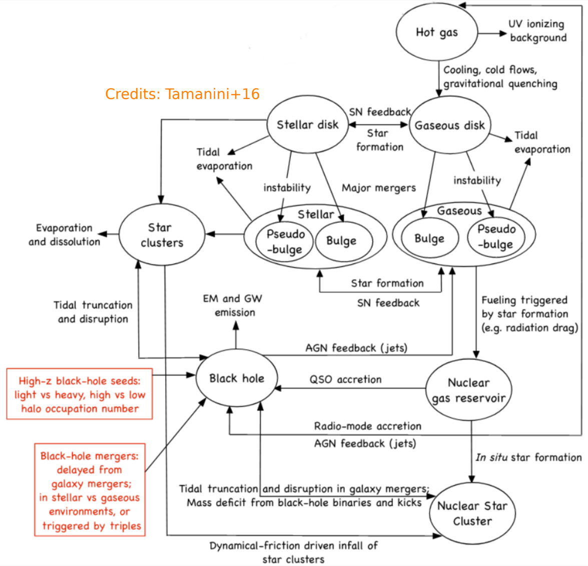
Backup slides

Seed BHs formation channels

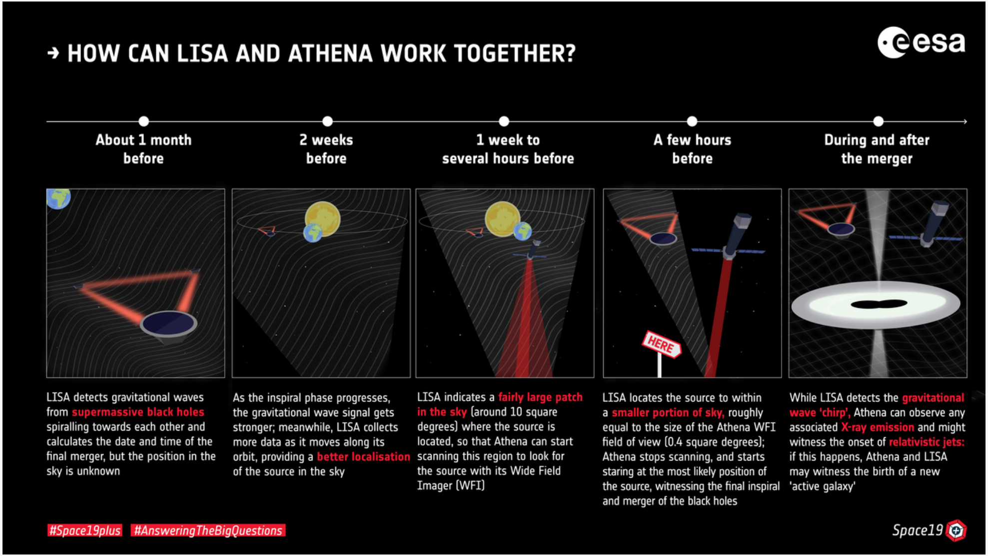


adapted from Volonteri10

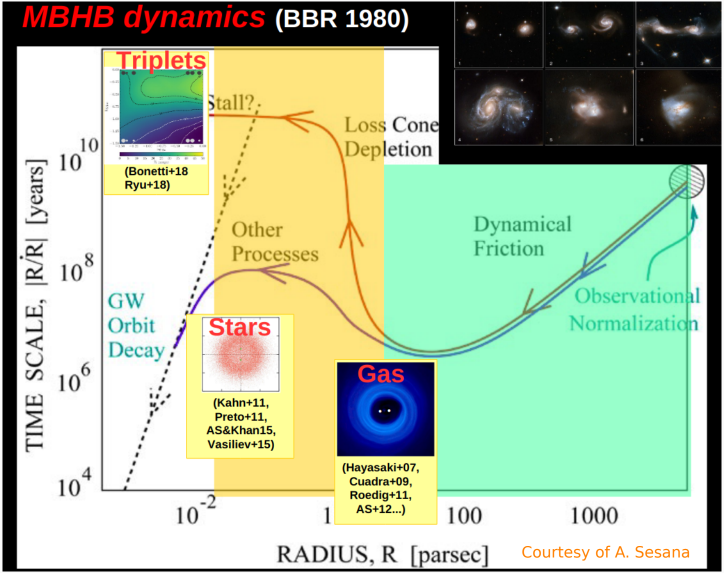
The physics of the semi-analytical model



Multi-messenger in practice

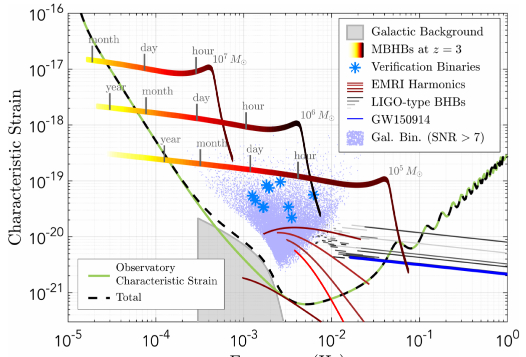


Last parsec problem

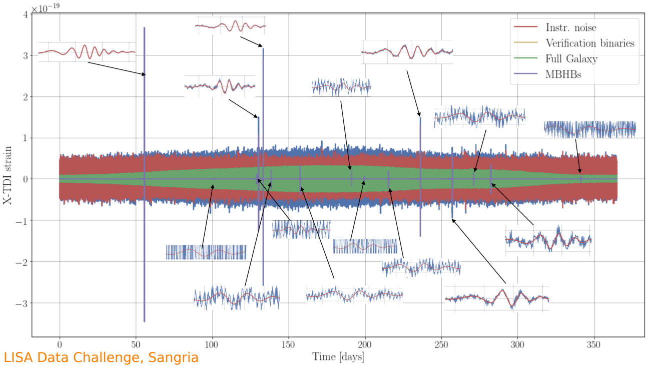


GW sources in LISA band

- 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

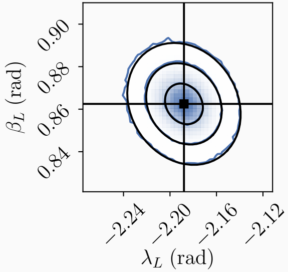
GW analysis

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

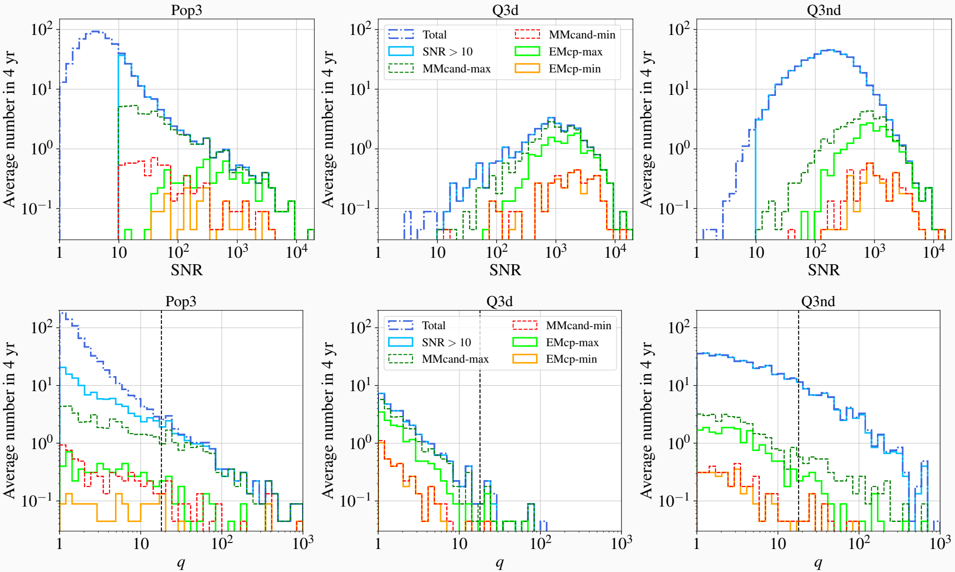
GW parameter estimation

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

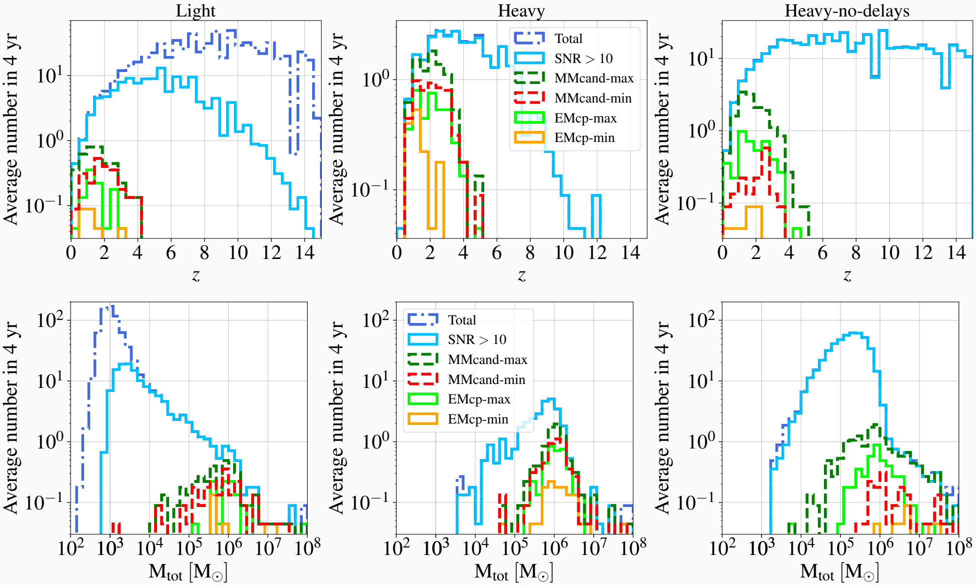


- MCMC formalism
- Include both low- and high-frequency LISA response
- Tested with independent codes

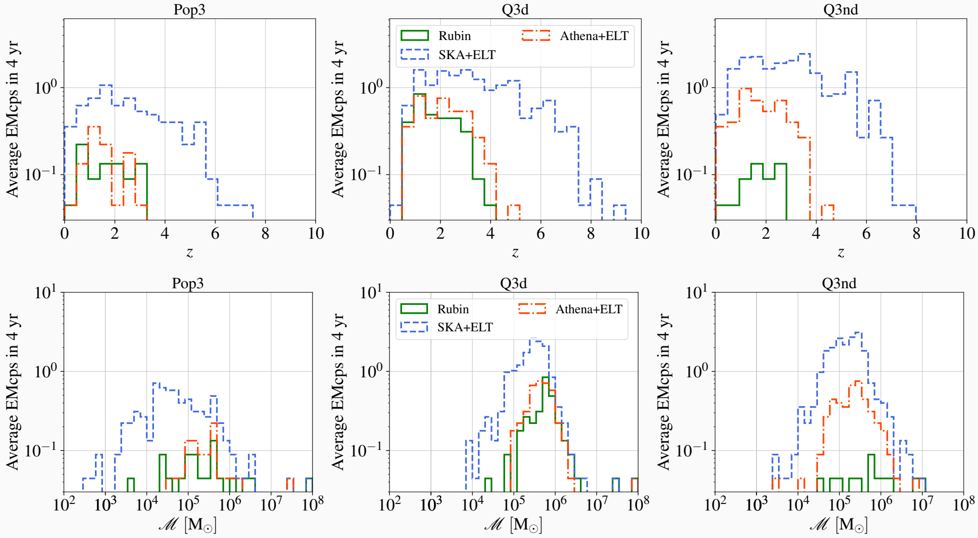
SNR and mass ratio distributions



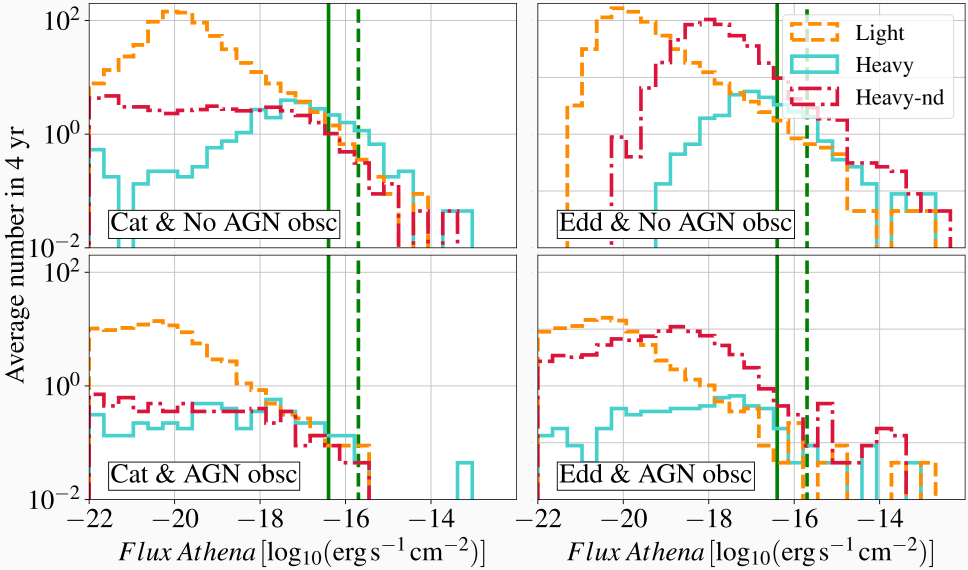
Redshift and total mass distributions for Athena



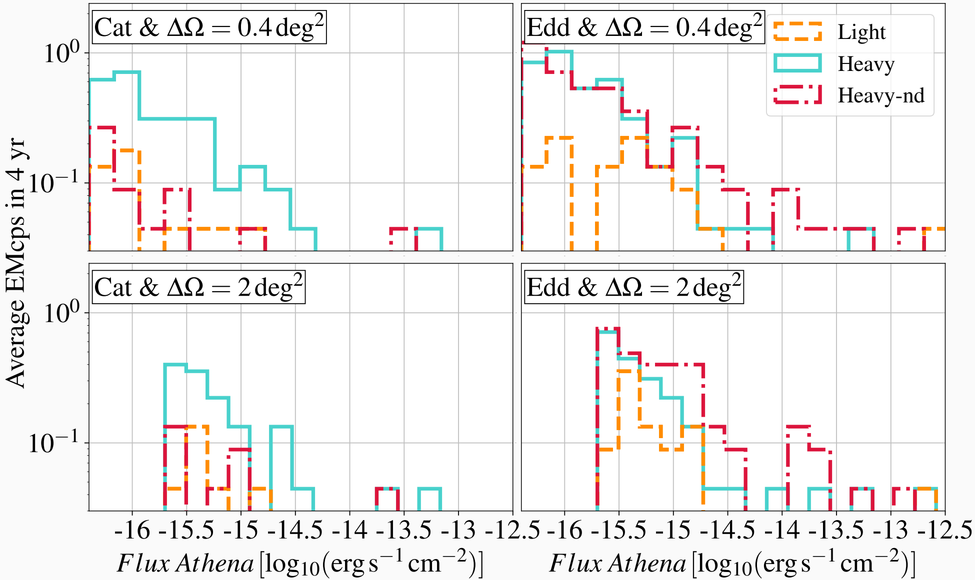
Redshift and total mass distributions for each strategy



Distribution of X-ray fluxes

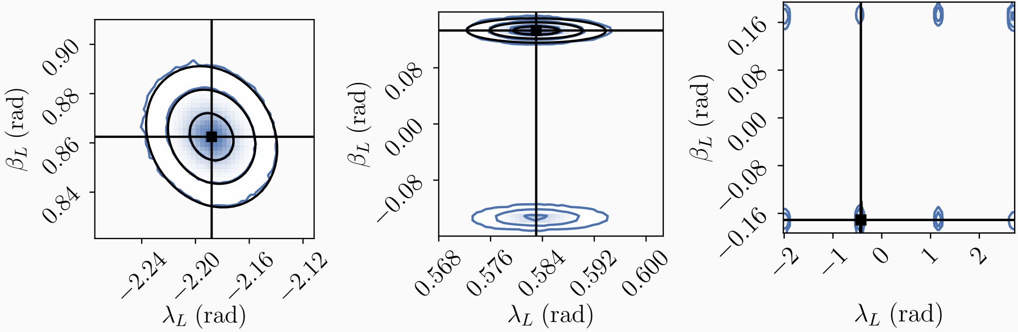


EMcps in X-ray (No obscuration) with Athena



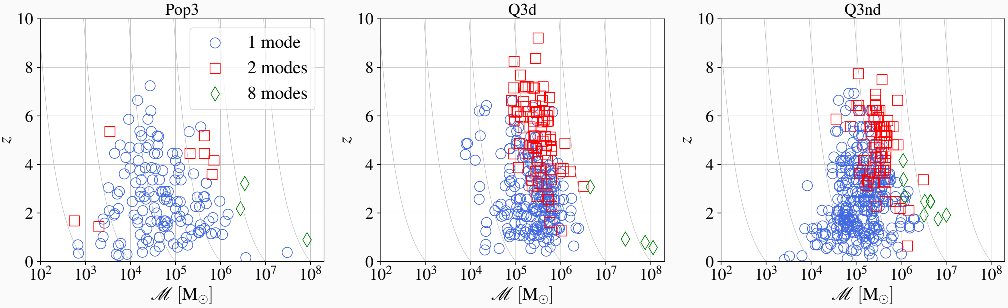
“Multimodal” LISA events

Systems with multimodal sky posterior distribution from LISA data analysis



- Arise from LISA degeneracy pattern function
- Might pose issues for the search of the EM counterpart + problematic also for the dark sirens approach

Multimodal events

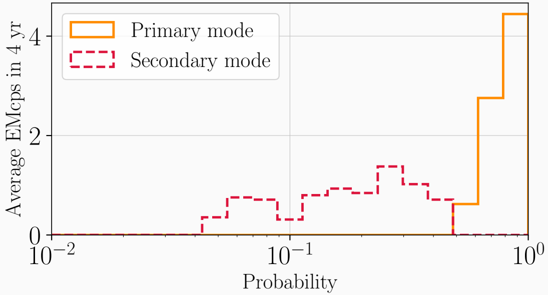


- 1mode systems are the vast majority
- 2mode systems appear at high mass and high redshift
- Still large spread across sub-populations

What about multimodal events?

Focus only on the true binary spot

Modes probability



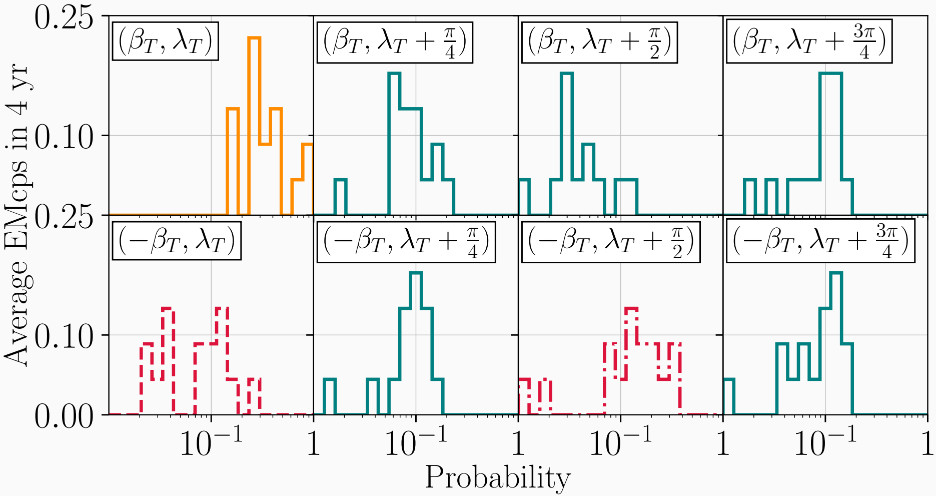
Contribution to the expected rate in 4 yr

	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

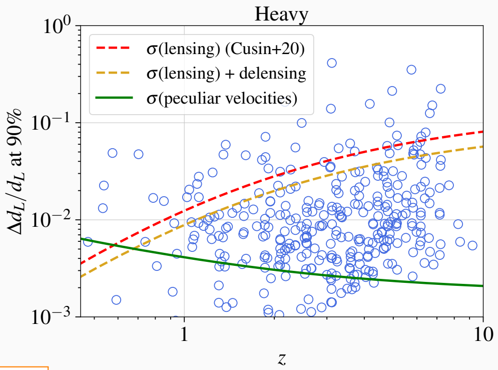
Probability for 8modes systems



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

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

Galaxies in LISA error boxes