Unveiling early black hole growth with multi-frequency gravitational wave observations

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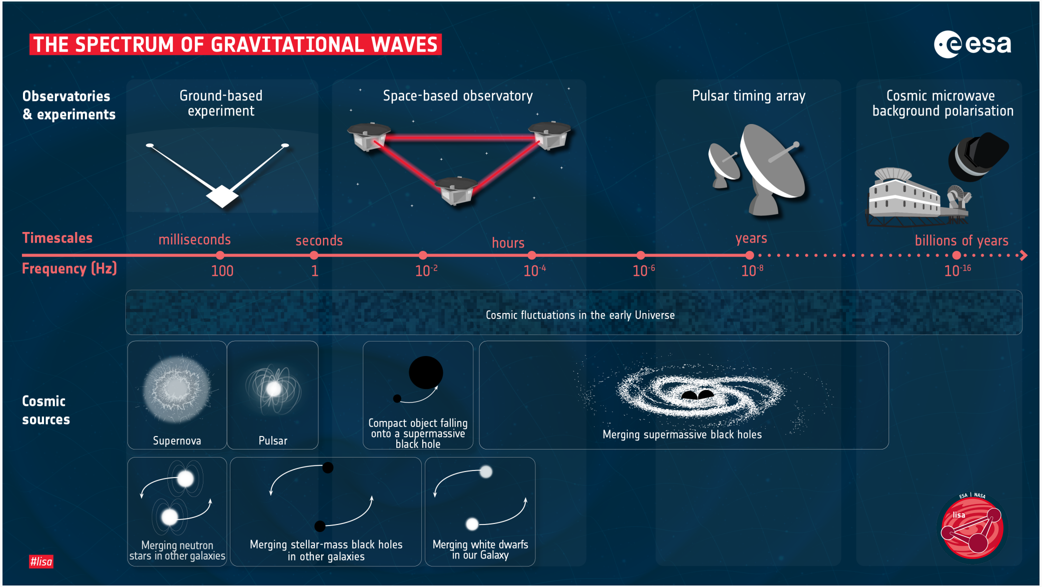
Outline

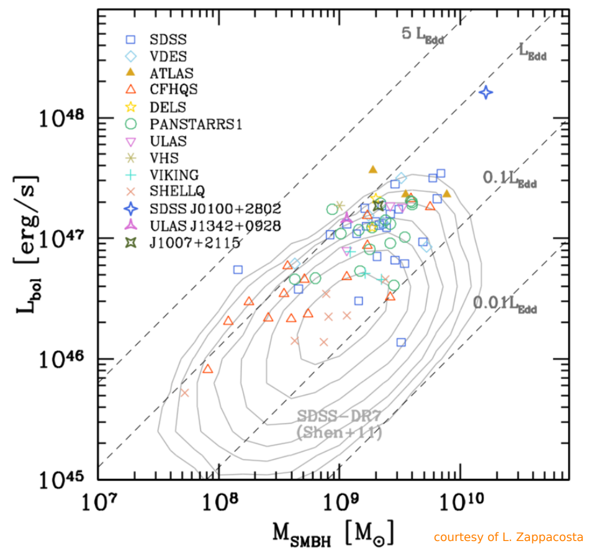
- Astrophysics of massive BH binaries (MBHBs)
- Electromagnetic (EM) and gravitational waves (GWs) emissions from MBHBs
- Combining realistic MBHBs population with EM counterparts
- Early seed BHs and future prospects

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

Observational evidences of high redshift objects



courtesy of L. Zappacosta

Supermassive quasars at high redhift

J0100, $M_{BH} \gtrsim 10^{10} \mathrm{M}_\odot$, $\mathrm{z} = 6.3$

(Wu+15)

J1342, $M_{BH} \simeq 10^{9} \mathrm{M}_\odot$, $\mathrm{z} = 7.54$

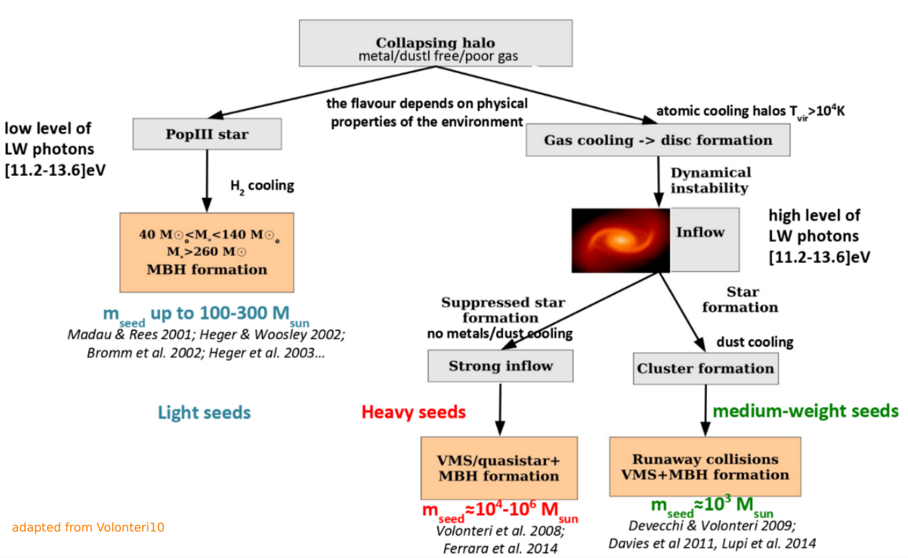
(Banados+20)

$\downarrow$

Population of seed BHs at earlier times

($z > 10$)

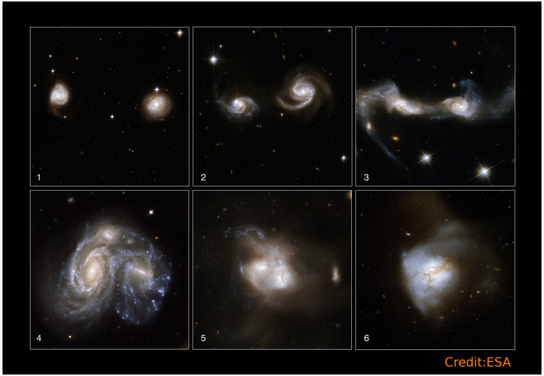
Seed BHs formation channels



Massive black hole binaries (MBHBs)

$\text{MBH} \sim 10^{5-7}\, M_\odot$

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?

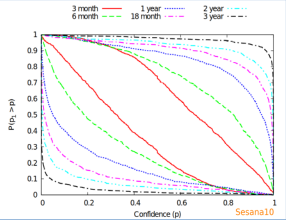
Large uncertainties in the event rate: from few to several hundreads per year

Why MBHBs?

The importance of MBHBs

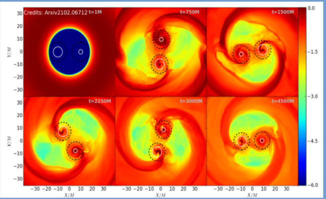
Astrophysics

Constrain MBHBs formation and evolution scenarios



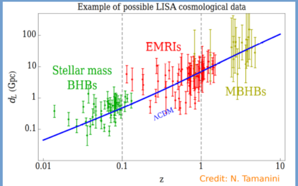
Multi-messenger

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



Cosmology

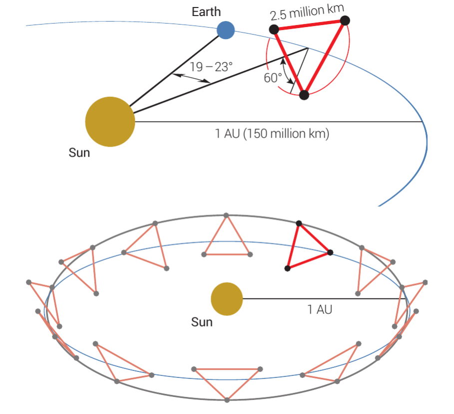
Testing the expansion rate of the Universe

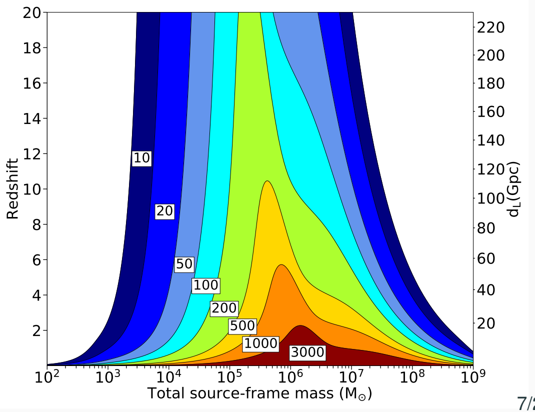


Observing the entire Universe with GWs

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

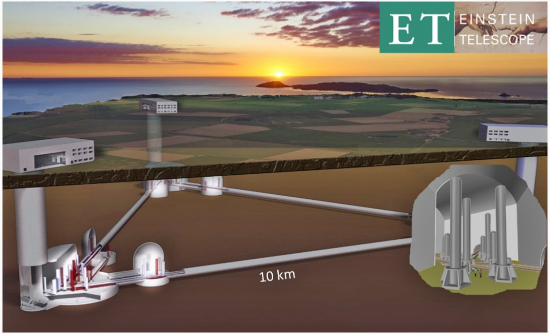
- 3rd Large class mission selected by European Space Agency (ESA)
- Successfully ended Phase A - Now in Phase B1 - Mission Adoption at end 2023

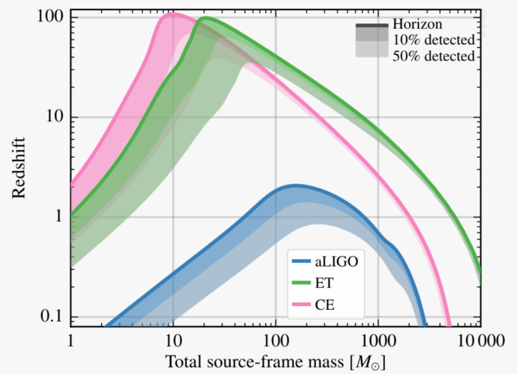




The next generation of ground-based detectors

In the same period, Einstein Telescope (ET) and cosmic explorer (CE) will observe the GWs from SBHBs up to the cosmic dawn



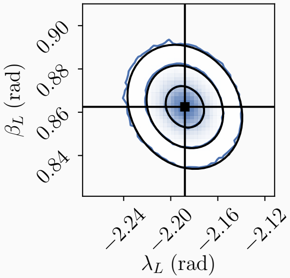


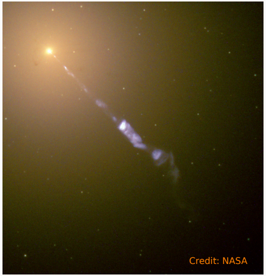
What EM counterparts do we expect from a MBHB merger?

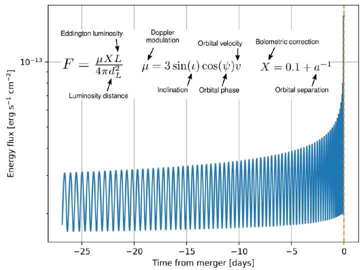
Let's make our wishlist

What we would like to have to detect EM emission?

- Good sky localization from LISA ($\Delta\Omega < 10\mathrm{deg}^2$)
- Bright EM emission (depending from the EM instrument)
- Smoking gun signatures in the EM spectrum to identify unambiguosly the host galaxy





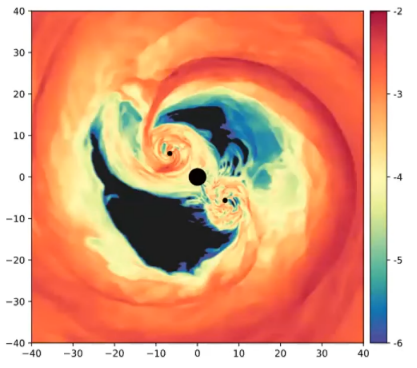


What EM emission do we expect?

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

During the inspiral . . .

Gas accretion in rapidly changing space-time

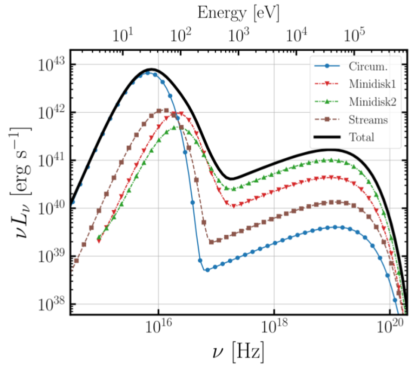


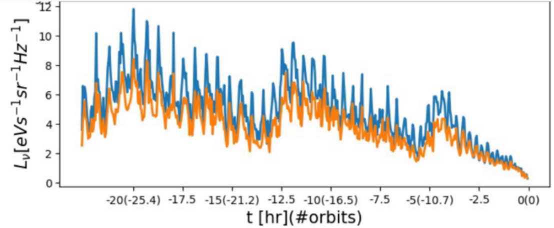
- The binary excavates a cavity
- Two bright minidisks around each BHs emitting in X-ray
- Gas streams flowing in the cavity
- Periodicities due to the orbital motion of the binary might be clear signatures (Dal Canton, AM +19)

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

What EM emission do we expect?

- UV contribution from the inner edge of the circumbinary disk
- X-ray emission from minidisk and streams due to inverse compton





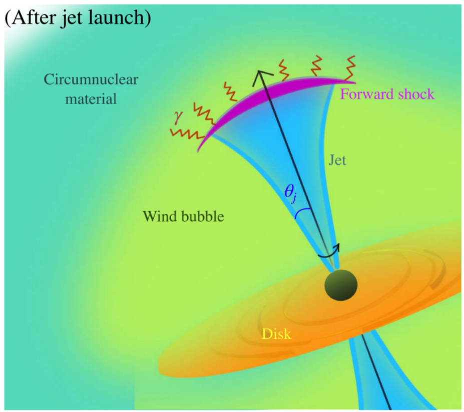
However, close at merger, minidisks might be depleated ⇒ Reduction in luminosity (Tang+18)

What EM emission do we expect?

Post-merger signatures

- ➤ Disk-rebrightening (Rossi+10)
  - ✓ In-plane kicks for BHs with spins aligned along the orbital momentum
  - ✓ Disk internal shocks due to the mass loss in GWs
  - ✗ Might be to weak to be observed

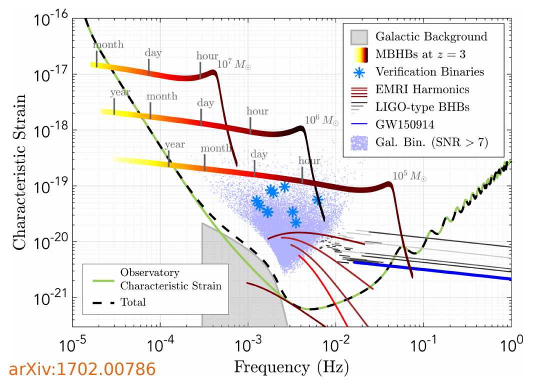
- ➤ Afterglow emission (Yuan+21)
  - ✓ Broad band emission from radio to X-ray
  - ✗ Delays from days to months



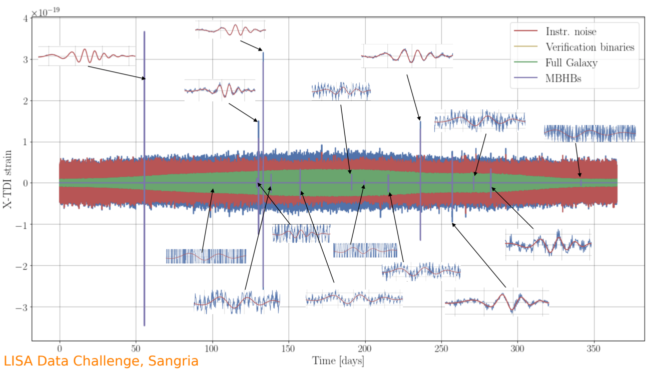
What information can we extract from the GW signal?

GW sources in LISA band

- Strong and long-lasting signals
- Strong overlap between signals from different sources $\rightarrow$ Global fit approach
- Unexplored parameter space $\rightarrow$ Large unceratainty on rate & sources' properties



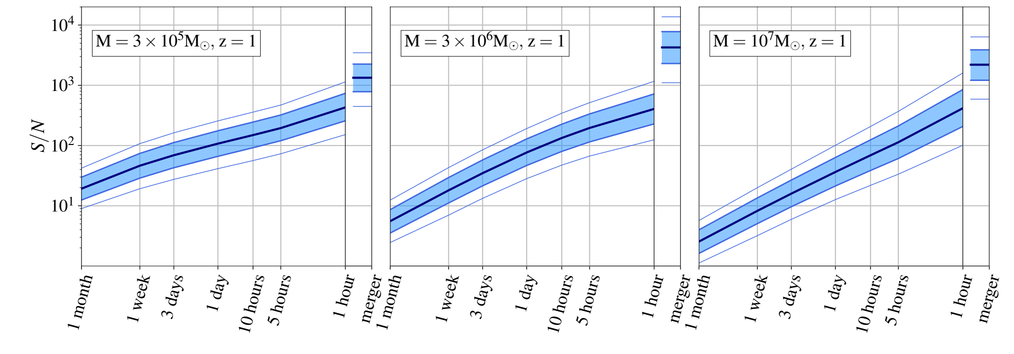
arXiv:1702.00786



LISA Data Challenge, Sangria

What information can provide LISA?

MBHBs can be detected days or weeks before merger

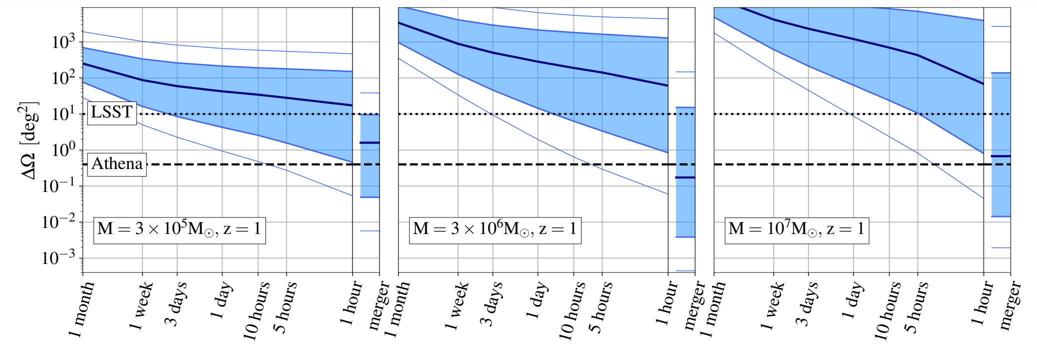


During the inspiral LISA can provide additional information: individual BH mass, spins and luminosity distance can be constrained to $\sim 5\%$ *before* merger

What about the sky localization?

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

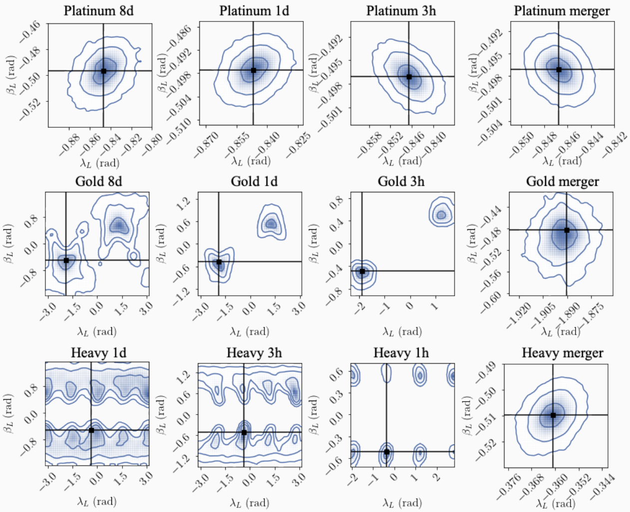
LISA sky localization for systems at $z = 1$



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

Large distributions $\rightarrow$ 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

Combine EM counterpart predictions with a population of merging MBHBs

A realistic population of MBHBs

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

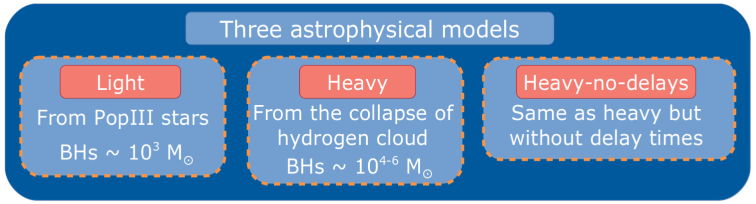
Estimate the number of counterparts over LISA time mission and cosmological parameters

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)

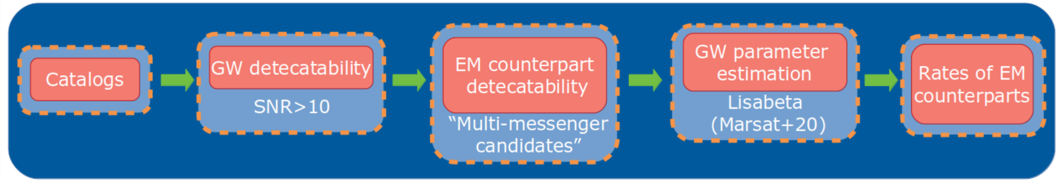
- Affect LSST/VRO and Athena
- Typical hydrogen column density distribution

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

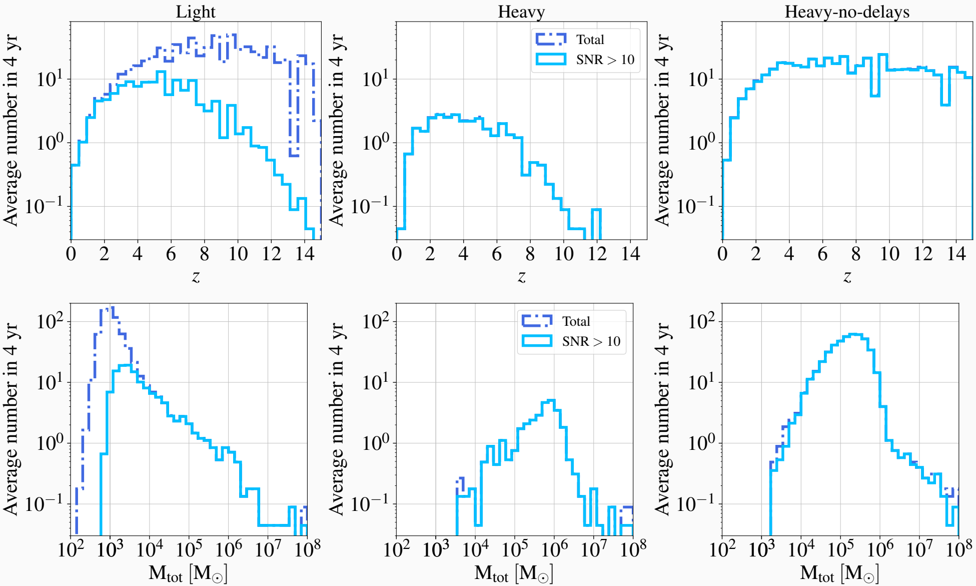
Maximising

- 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



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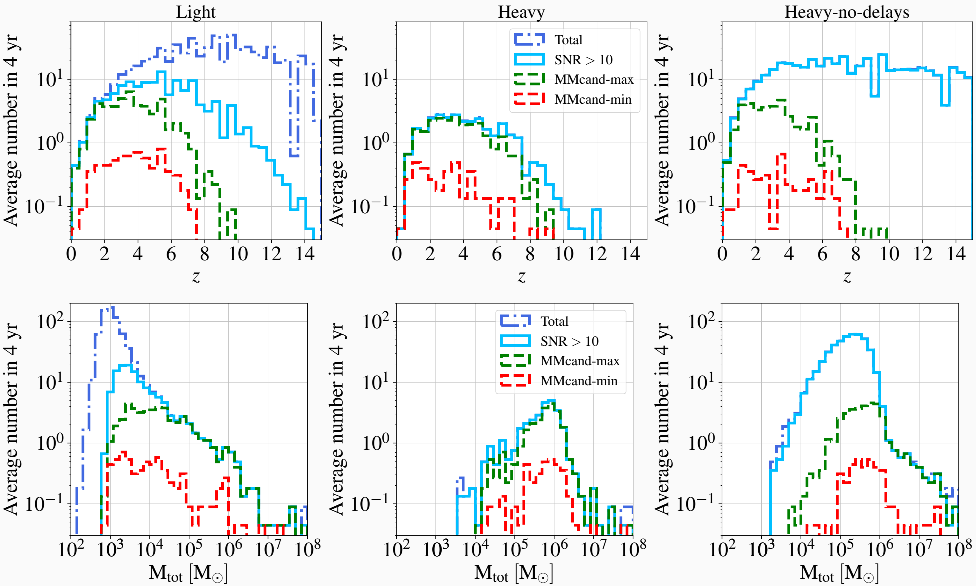
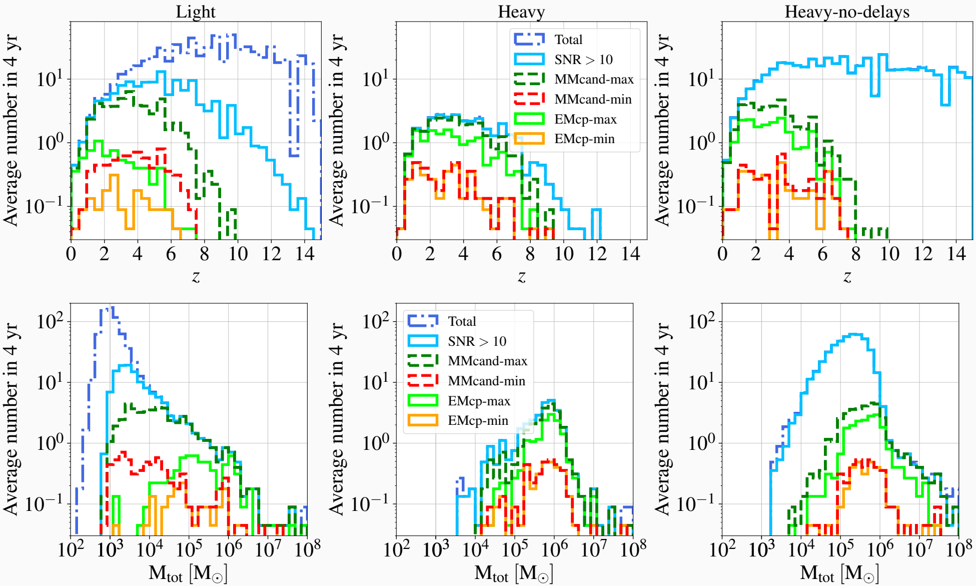
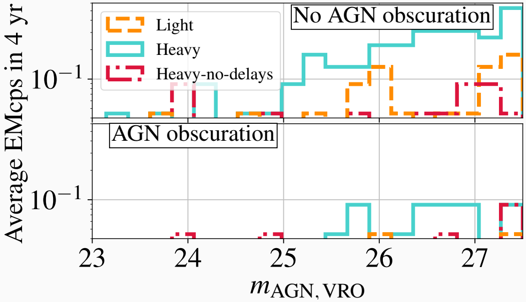
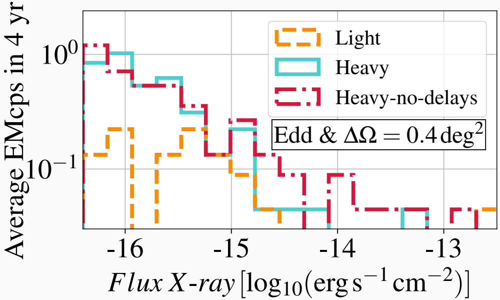


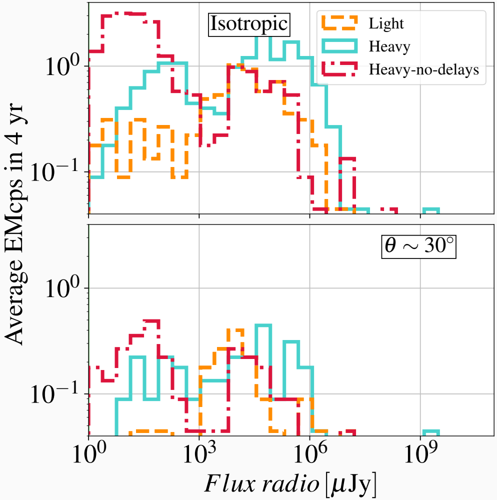
Redshift and total mass distributions



EMcps in optical, X-ray and radio







Only few and faint sources in 4 yr

EMcp rates in 4 yr

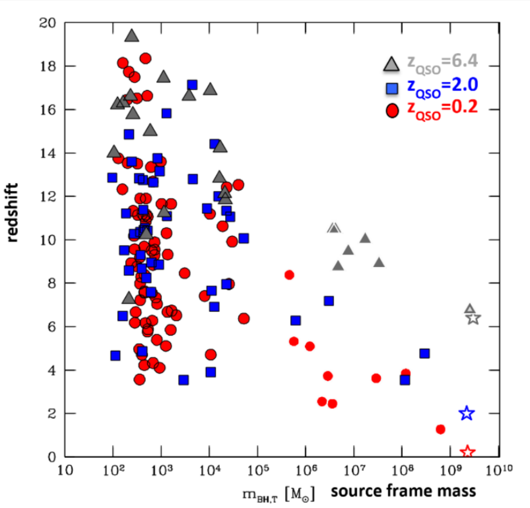
(In 4 yr)	LSST, VRO	SKA+ELT			Athena+ELT		
		Isotropic	$\theta \sim 30^\circ$	$\theta \sim 6^\circ$	Catalog $F_{\mathrm{X,\,lim}}$ = 4e-17	Eddington $F_{\mathrm{X,\,lim}}$ = 4e-17	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	
No-obsc.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

Seed BHs and future prospects

Seeds across cosmic epochs (Valiante+21)



Light/heavy seed form in pristine DM halos

↓

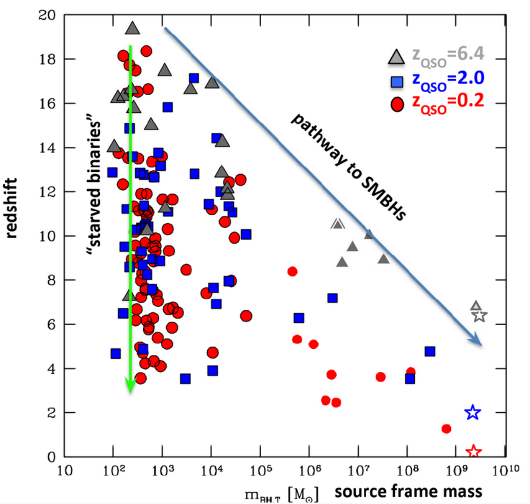
BHs pair during halo major mergers

$(\mu > 1:4)$

↓

Coalescence after triple interaction with another BHs

BH binaries at cosmic dawn



Light/heavy seed form in pristine DM halos

↓

BHs pair during halo major mergers ($\mu > 1:4$)

↓

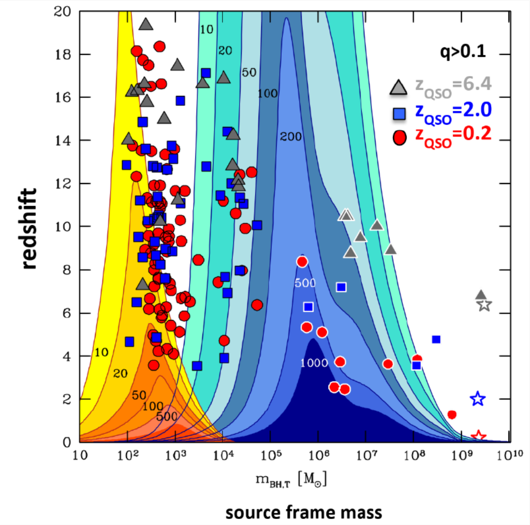
Coalescence after triple interaction with another BHs

Un-grown light seeds merge down to $z \simeq 3$

&

MBH binaries along the pathway to SMBH

GW observations



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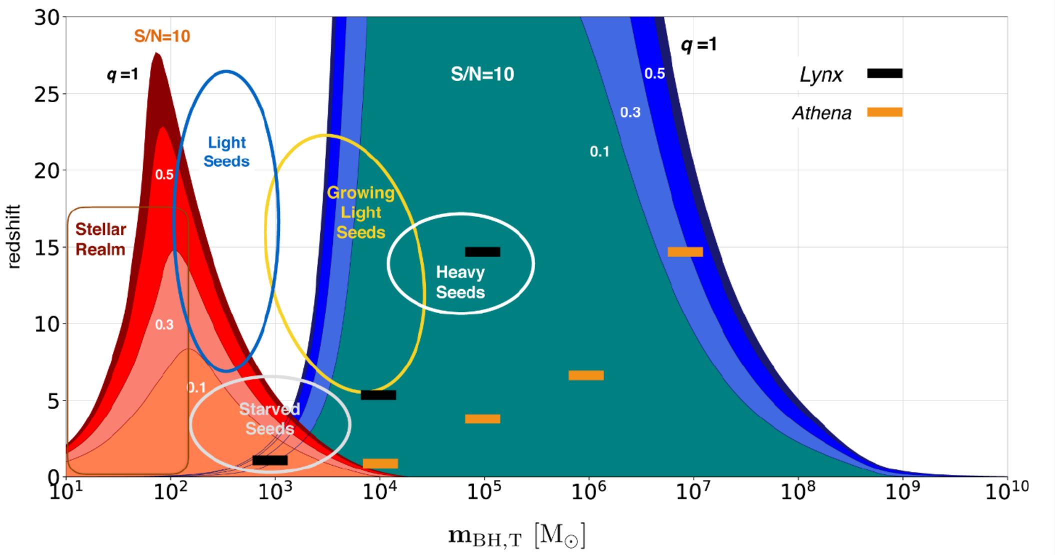
&

MBH binaries along the pathway to SMBH

Multi-frequency GW observations

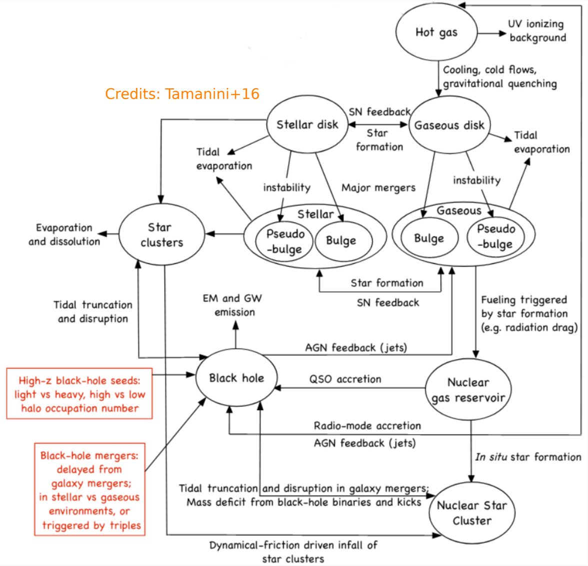


Thanks! Any questions?

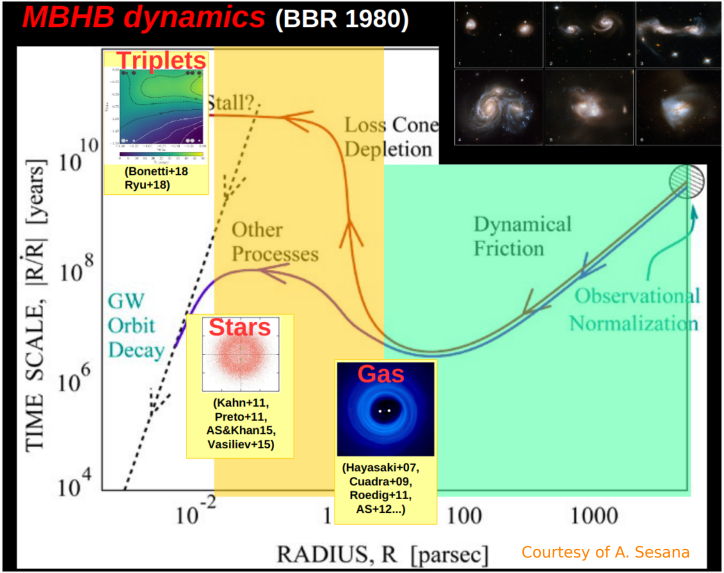
Backup slides

The physics of the semi-analytical model

Credits: Tamanini+16



Last parsec problem



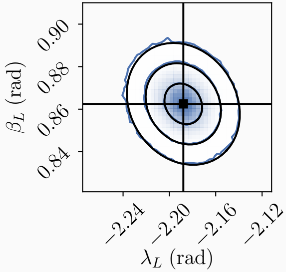
GW analysis

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

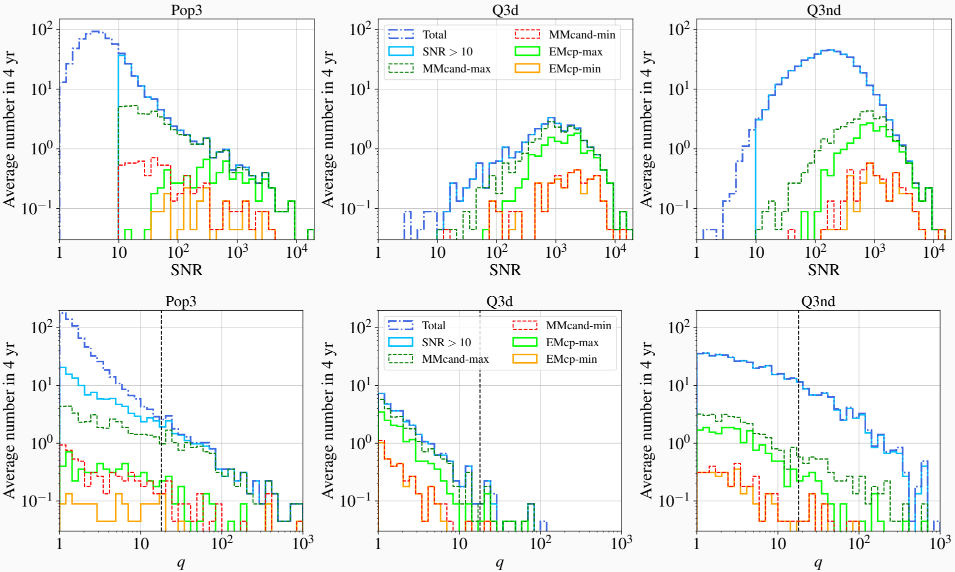
GW parameter estimation

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

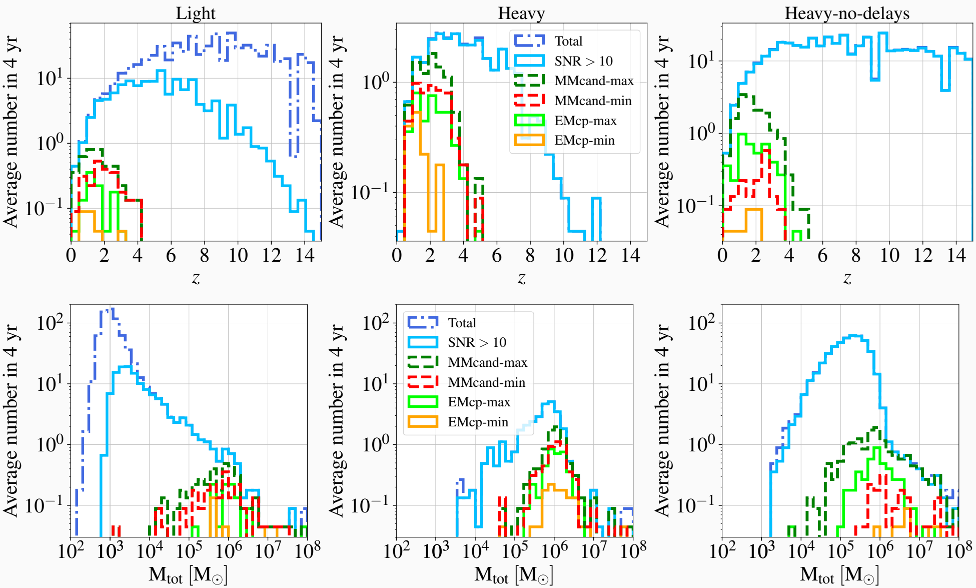


- MCMC formalism
- Include both low- and high-frequency LISA response
- Tested with independent codes

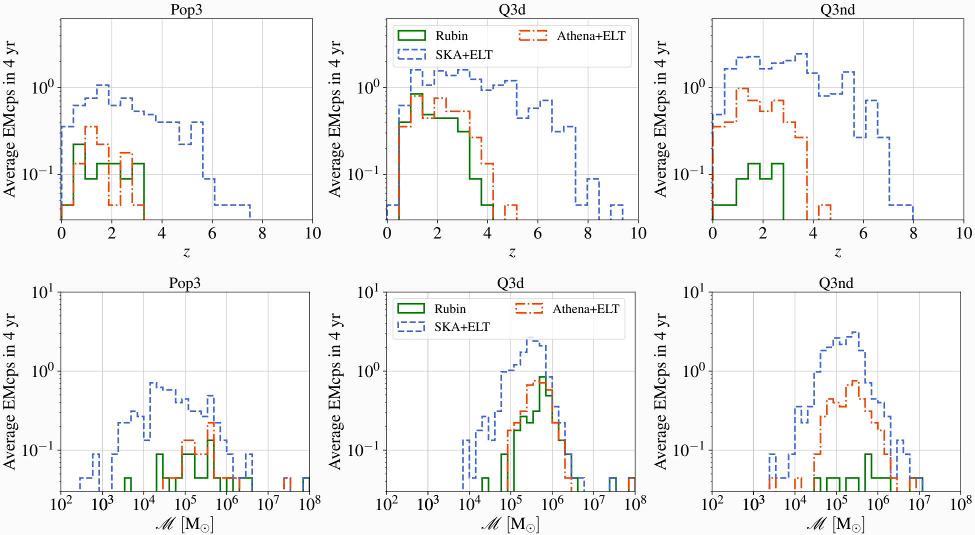
SNR and mass ratio distributions



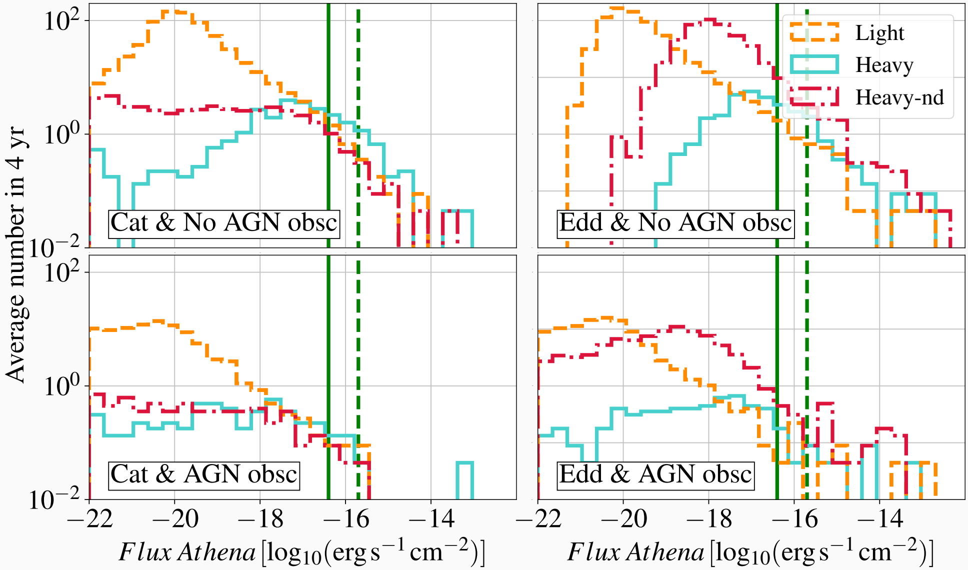
Redshift and total mass distributions for Athena



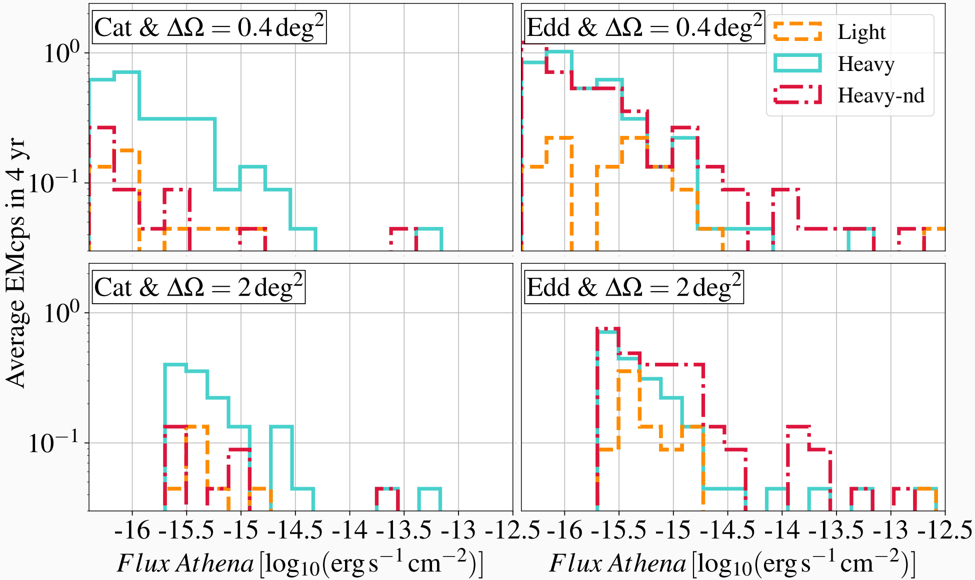
Redshift and total mass distributions for each strategy



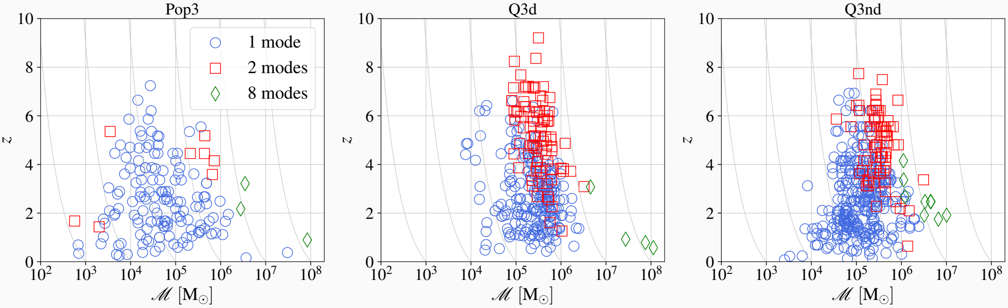
Distribution of X-ray fluxes



EMcps in X-ray (No obscuration) with Athena



Multimodal events

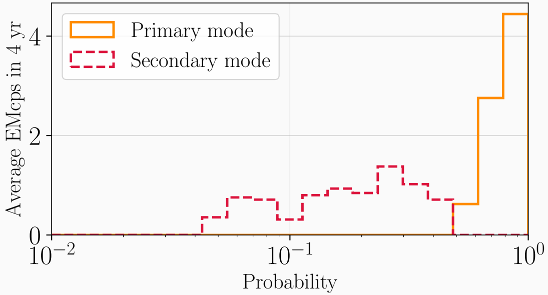


- 1mode systems are the vast majority
- 2mode systems appear at high mass and high redshift
- Still large spread across sub-populations

What about multimodal events?

Focus only on the true binary spot

Modes probability



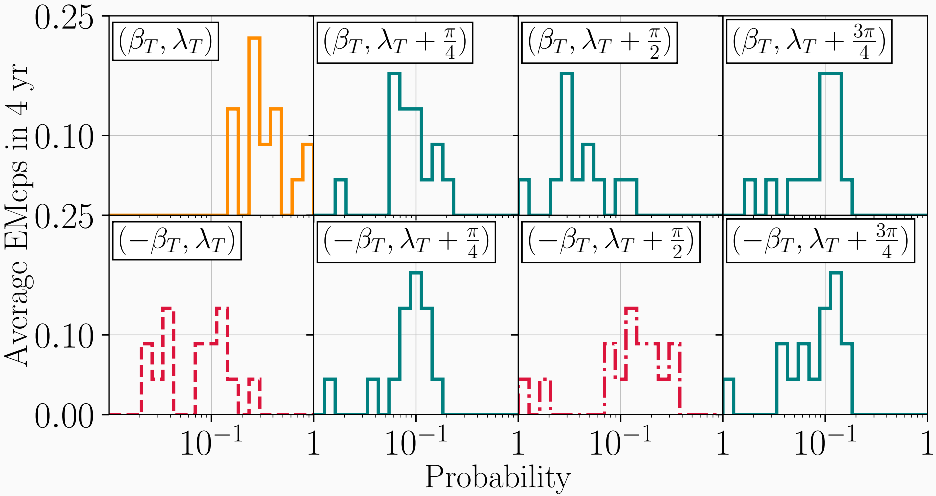
Contribution to the expected rate in 4 yr

	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

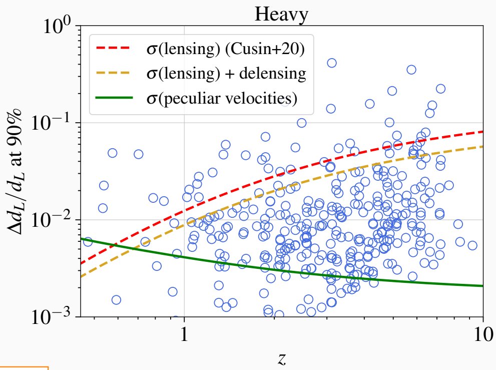
Probability for 8modes systems



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

	$m_{\rm ELT} < 27.2$	$27.2 < m_{\rm ELT} < 31.3$
$z < 1$		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