Multimessenger synergies between LISA and Athena

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Based on : Piro+22, AM+22, Piro+21, AM+20

Elephant in the room

In 2022, ESA communicated that the predicted Athena cost would significantly exceed ESA allocated resources.

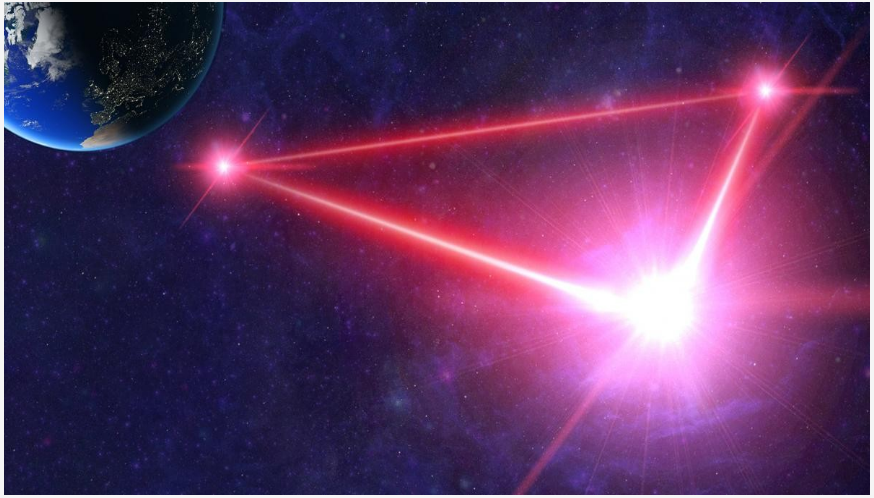
Therefore, Athena is currently undergoing a design-to-cost exercise, redesigning the mission in order to be within the cost cap while preserving as much as possible the original configuration.

Here, I assume the nominal scientific performance of Athena.

The *newAthena* science performance will be known at the end of its Phase A, expected to be completed by 2024.

Overview of the two missions

Gravitational-waves (GW) spectrum with LISA



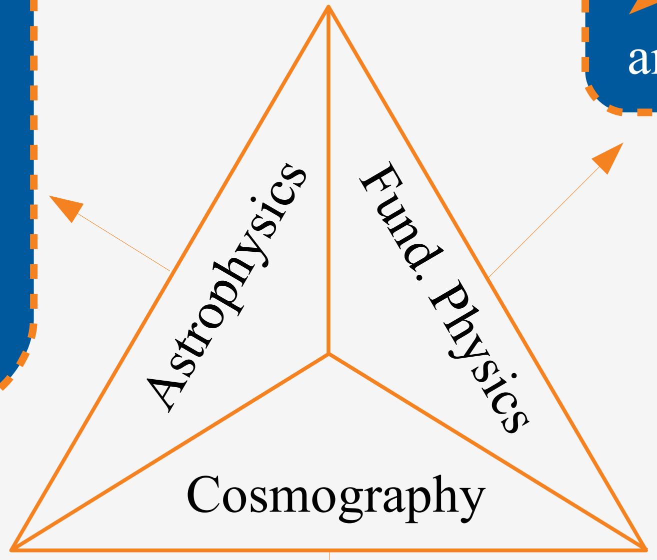
- 3rd Large class mission from ESA
- GWs in [0.1, 100] mHz
- Launch date : ~2035
  First data in ~2037
- Now in Phase B1 - Adoption end 2023/2024

Electro-magnetic (EM) spectrum with Athena

- 2nd Large class mission from ESA
- Wide Field Imager :
  - FoV ~ 0.4 deg^2
  - $F_X \sim 2\times10^{-17}$ erg cm^{-2} s^{-1}
- Launch date: Late 2030

Synergies between the two missions

- Fluid flows in fast changing space-time
- Formation of X-ray corona and jet launching around new horizons
- Accretion disc structure

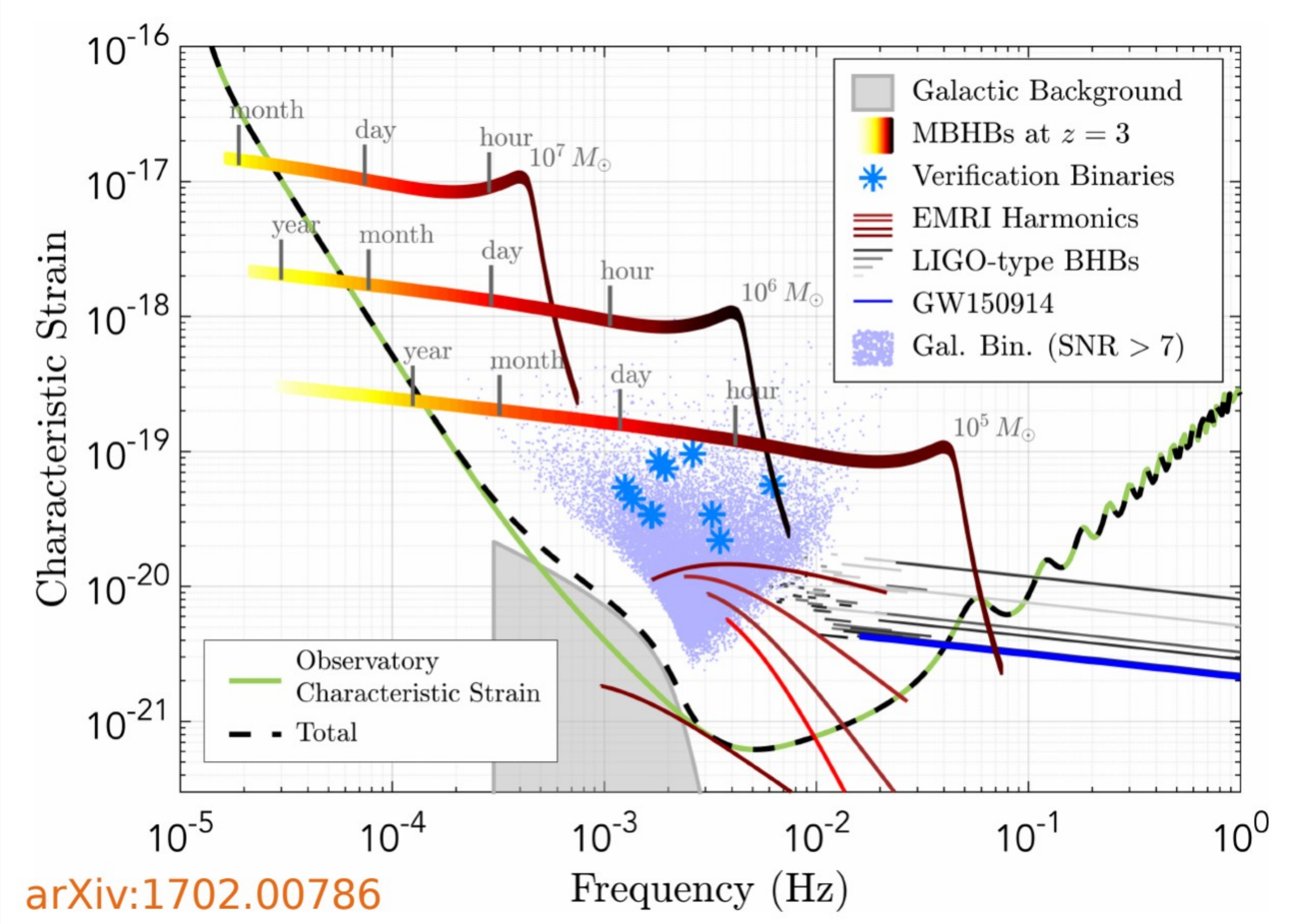


- Testing General Relativity
- Measuring the speed of GWs and dispersion properties

- Testing the expansion rate of the Universe

« The additional science […] the two missions could achieve may provide breakthroughs in scientific areas beyond what each individual missions is designed for. »
(Piro+22, credit : M. Colpi)

What sources do we have with LISA ?



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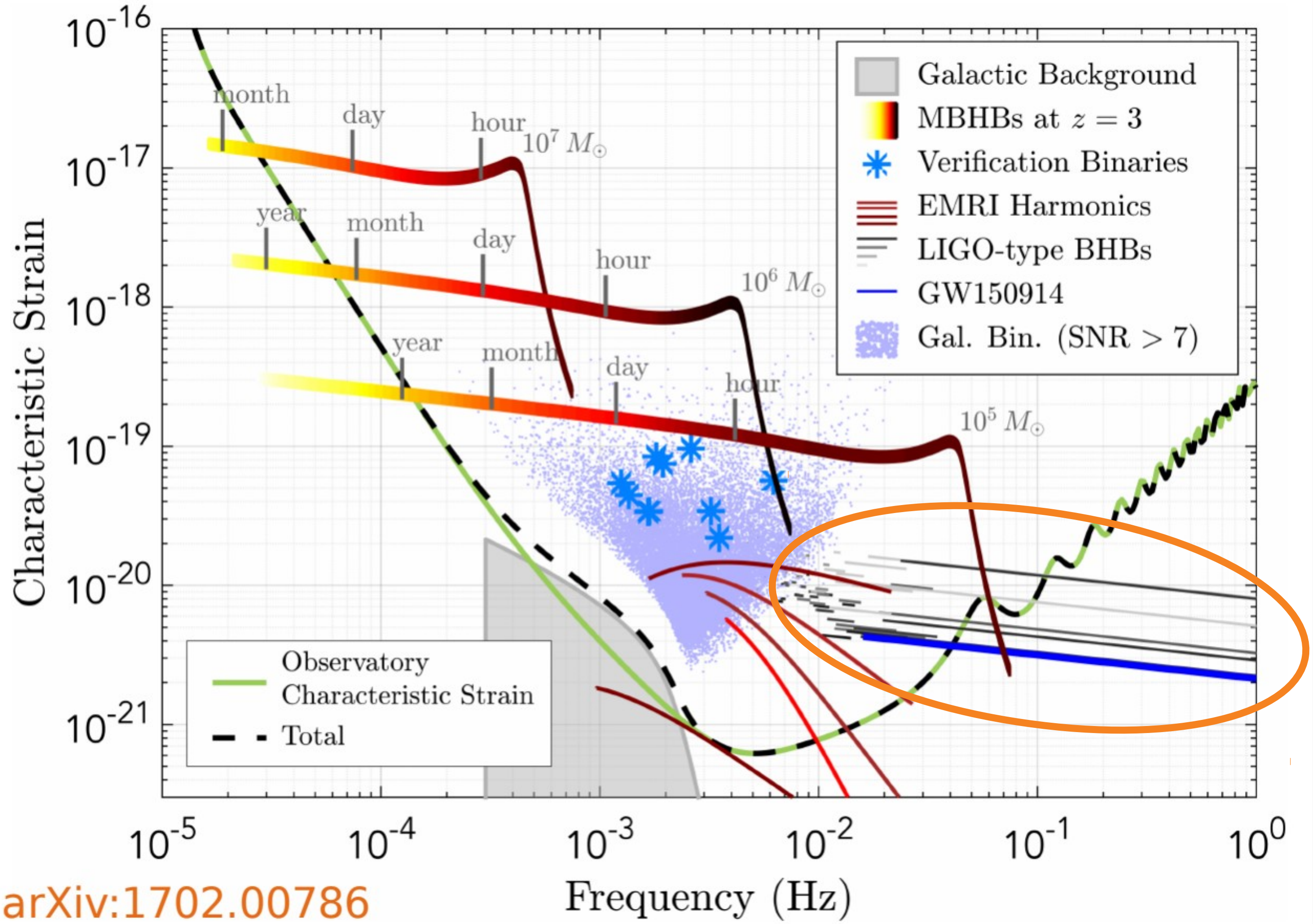

arXiv:1702.00786

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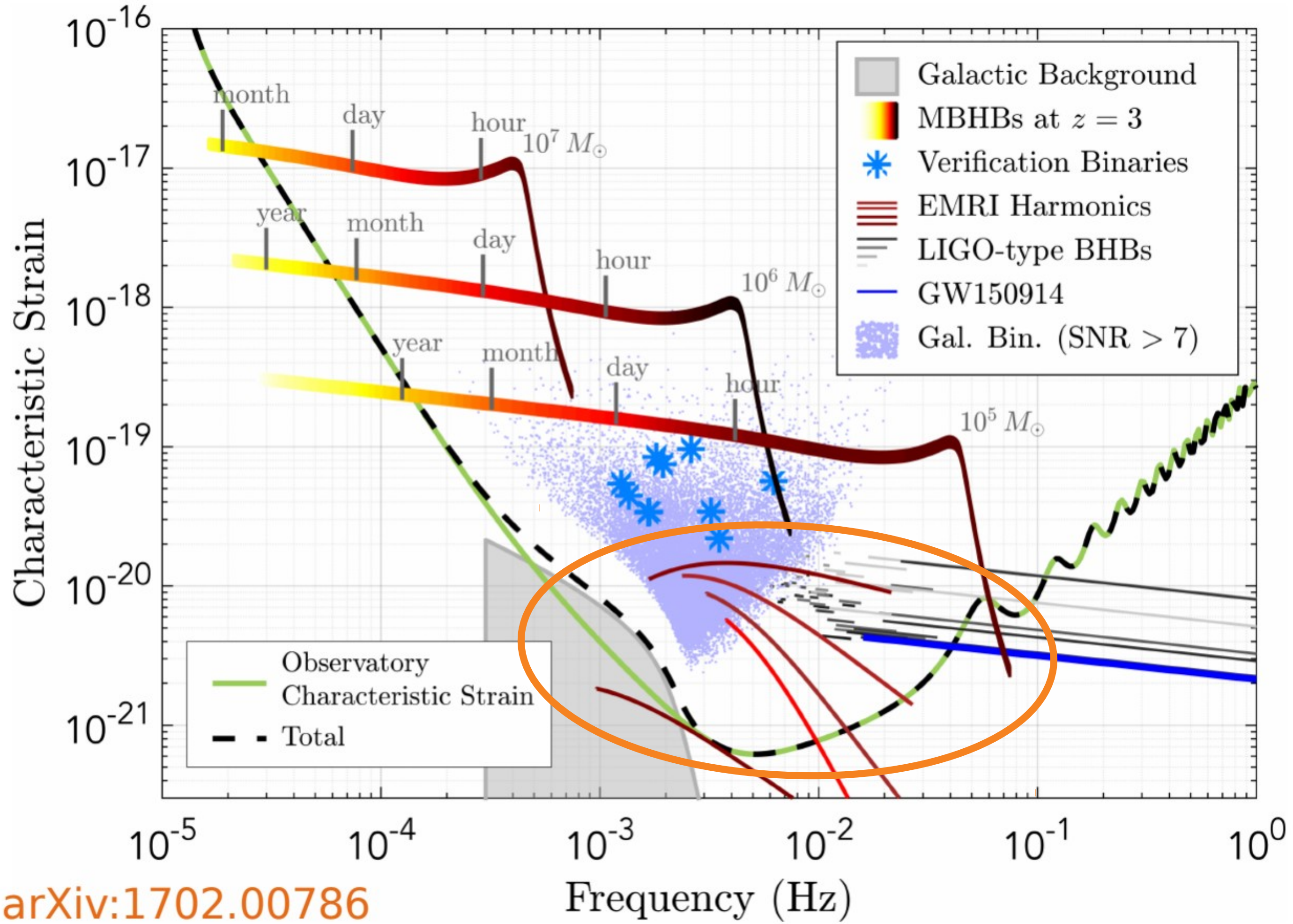

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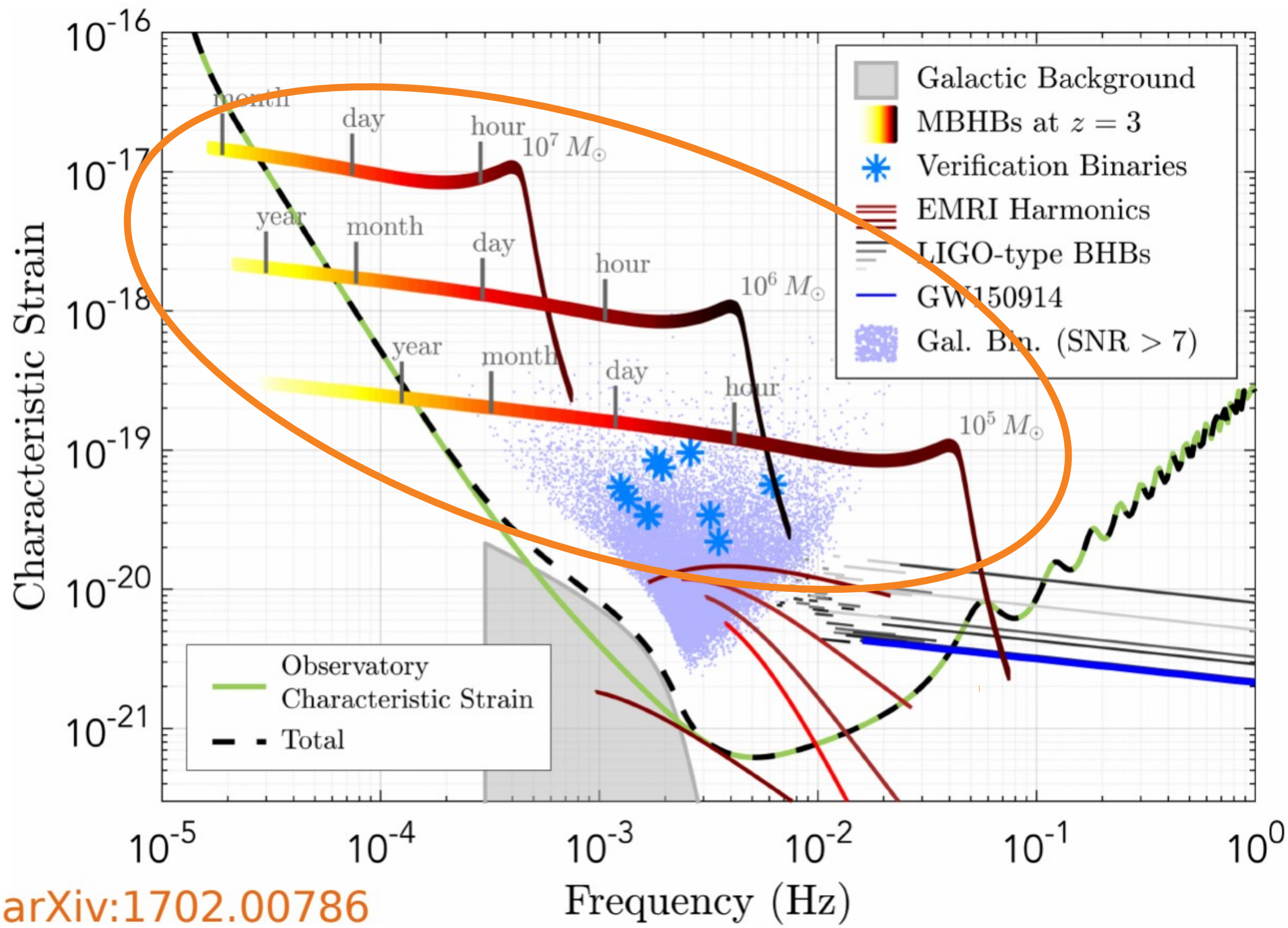

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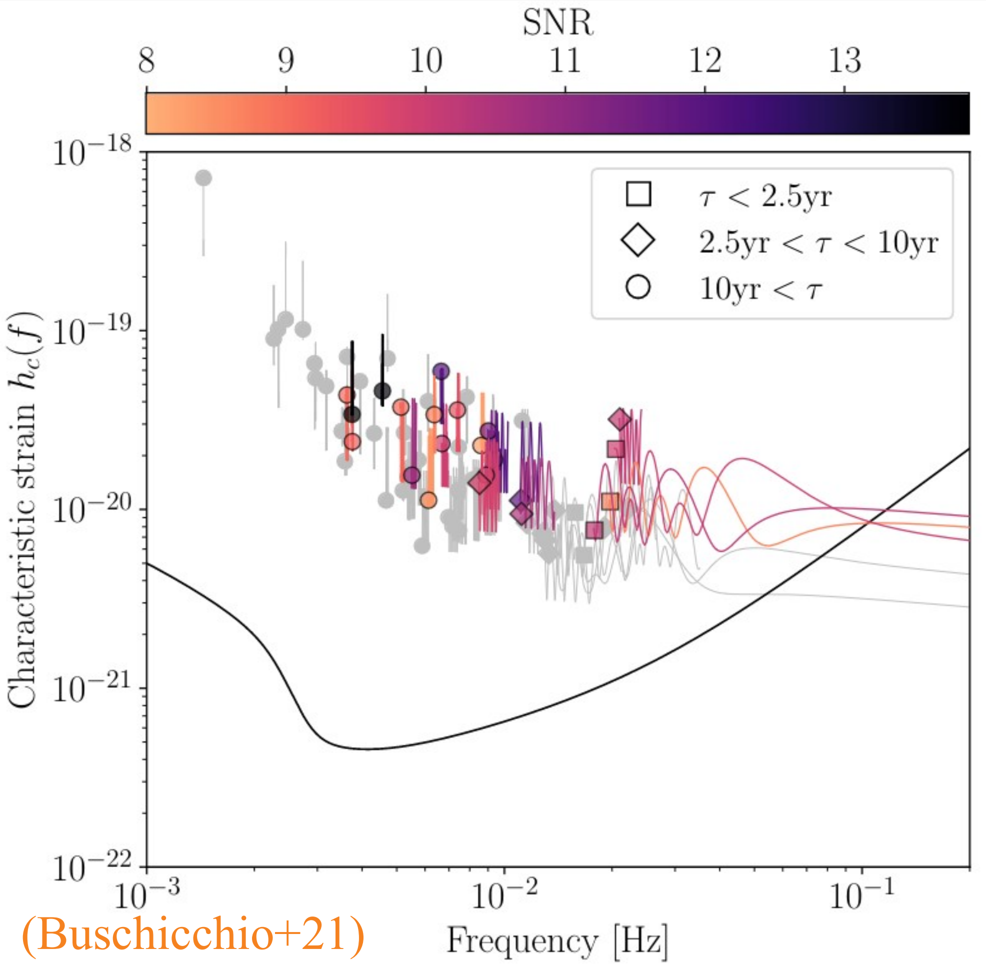
Stellar black hole binaries (SBHBs)

Stellar BHBs at high frequency : LISA point of view



(Buschicchio+21)

➤ We expect ~10 in 4 yrs and 1-2 multi-band systems during LISA

➤ Long-lived sources

↓

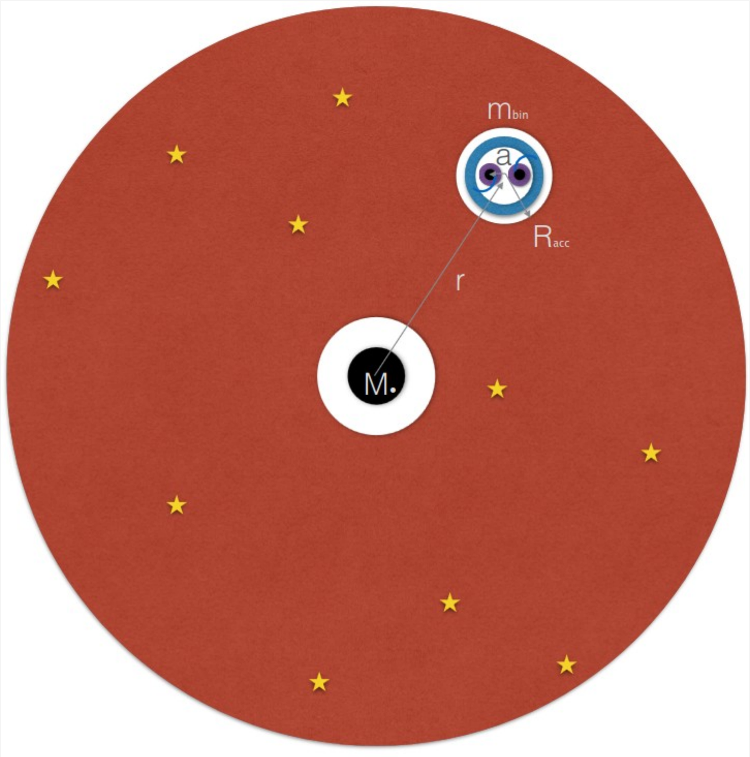
✔ Accurate sky localization (~10 deg^2)

✘ Poor d_L estimates

✔ Time to search for EM counterpart in the inspiral and Δt_{merger} ~ mins

EM counterpart to Stellar BHBs mergers

Isolated and dynamical formation channels do not predit an EM counterpart, but...



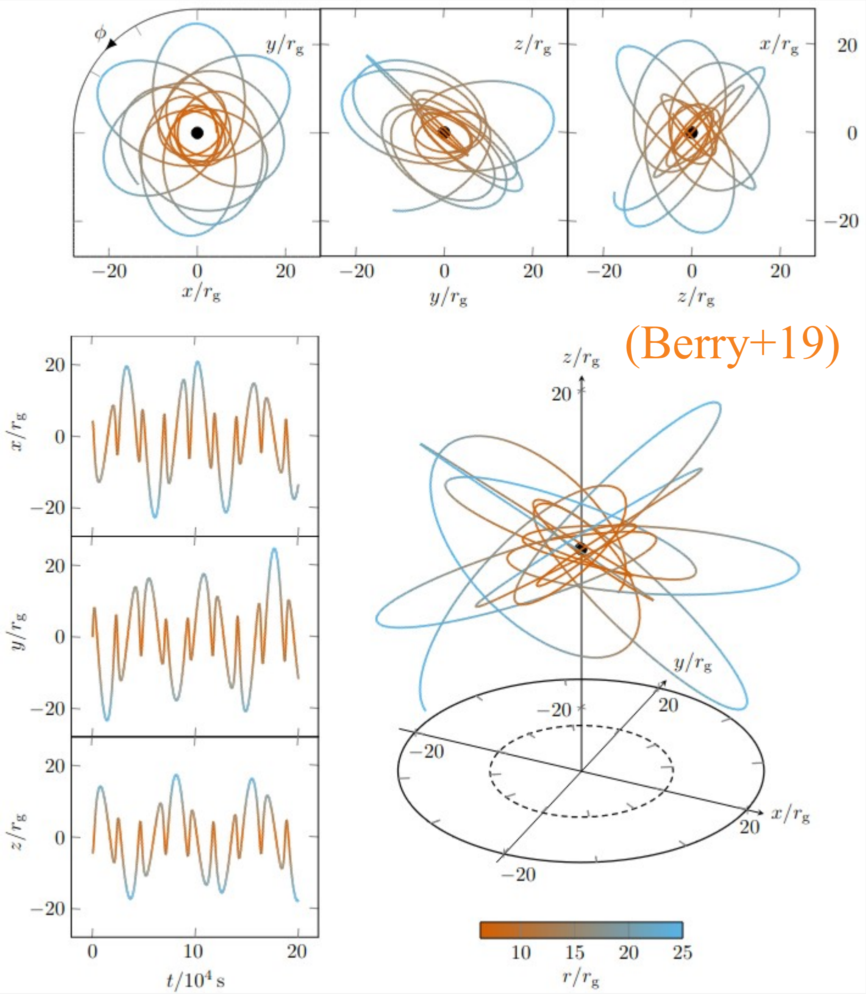
(Stone+16, Bartos+16, Caputo+20)

- ✗ X-ray :
  - ➤ Accretion still requires $L > 10^4 L_{edd}$
  - ➤ Remnant kicks are uncertain
- ✗ EM emissions might be AGN-dominated
- ✓ $L \sim 2\text{-}5 \times L_{edd}$ leaves a detectable imprint in the GW signal (Sberna+22)

Detection of EM emission will probe alternative formation channels

Extreme/Intermediate mass ratio inspirals (EMRIs/IMRIs)

Extreme mass ratio inspirals in LISA



Massive BH + lighter companion

- ➤ Uncertain merger rate : ~1-10^3/yr events
- ➤ Long-lived sources as SBHBs

↓

✔ Accurate sky localization (~10 deg^2)

✗ Poor d_L estimates

- ➤ Complex data analysis procedure :
  - ✗ Overlapping signals
  - ✗ Higher harmonics

EM counterpart from EMRIs

Direct EM counterpart

If the secondary BH is >100 $M_\odot$:

- Broad Fe Kα line at 6.4 Kev (McKernan+13,+14)

Tidal Disruption Events (TDEs) from :

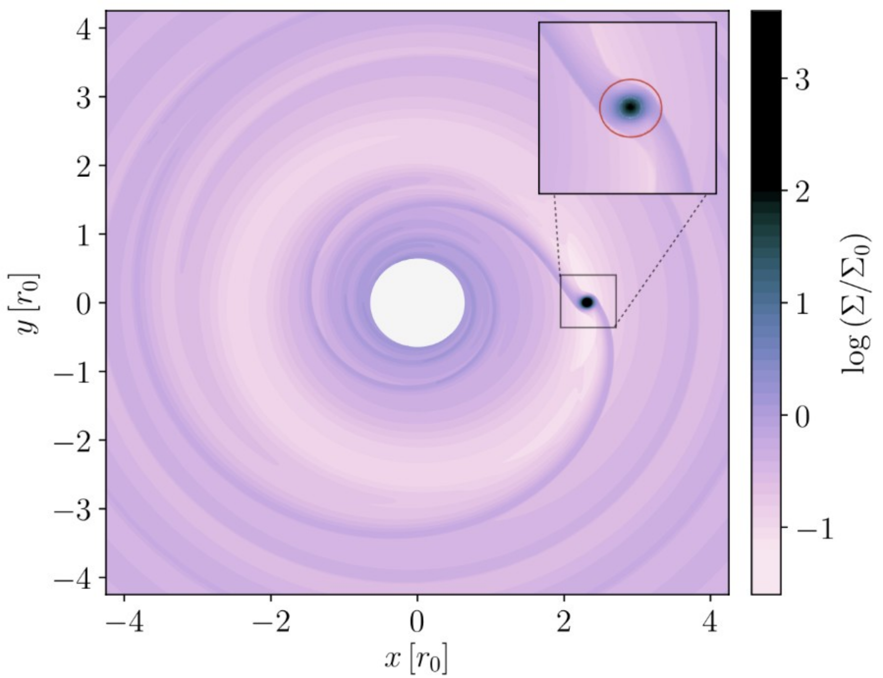
- White Dwarfs
- Massive stars (Sesana+08,Eracleous+19,Wang+21)

- Broad rate : 0.01-10^2 /yr

✓ Bright X-ray emission ~ $10^{44\text{-}45}$ erg/s

Gas effect on GW signal

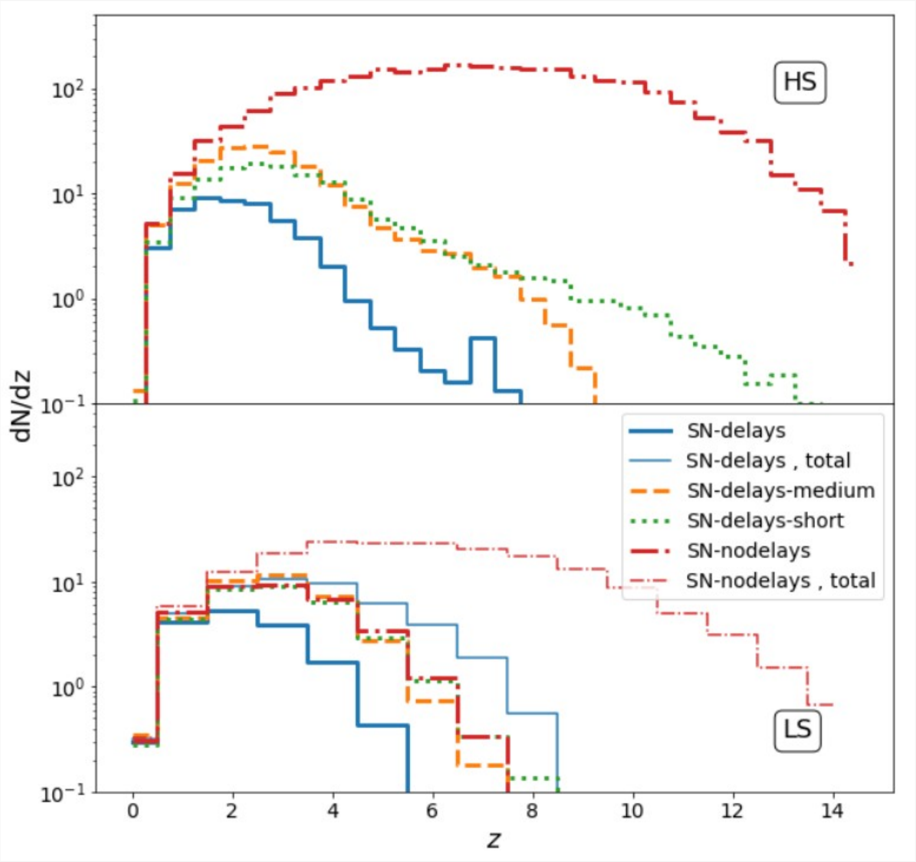
- If the error volume hosts few AGNs, we can spot the galaxy



Massive black hole binaries (MBHBs)

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) :

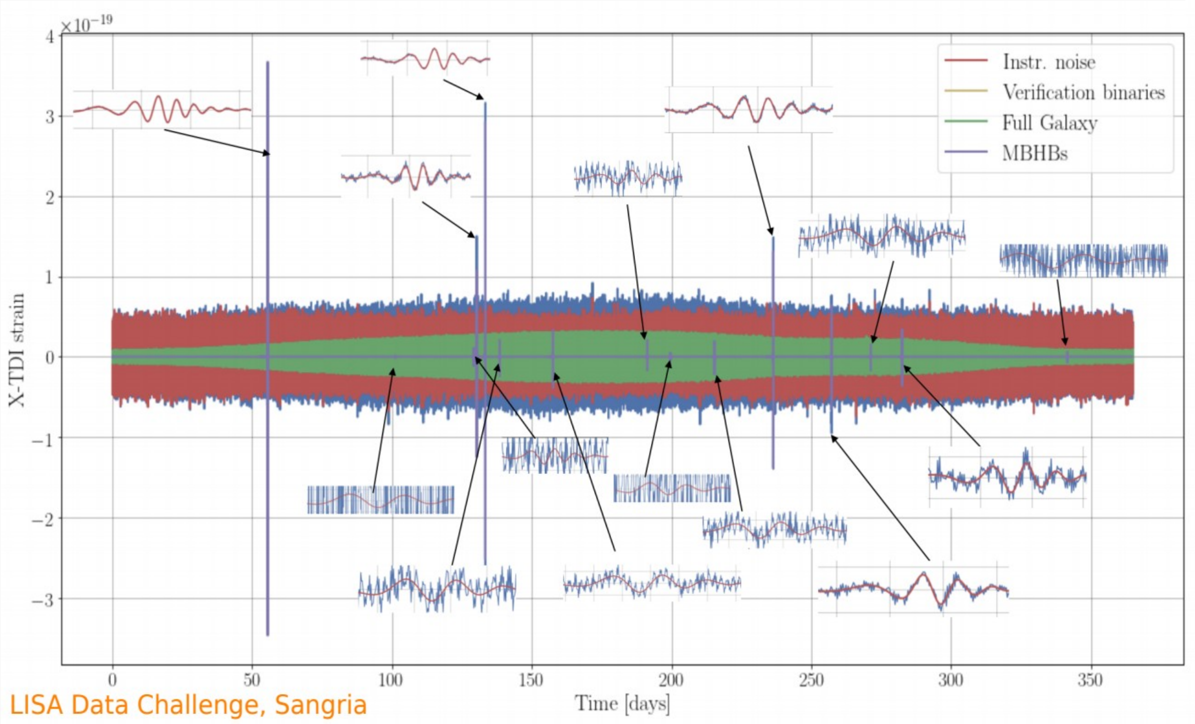
- Initial seed mass
- Time delays between galaxy and MBHB merger
- Feedback processes

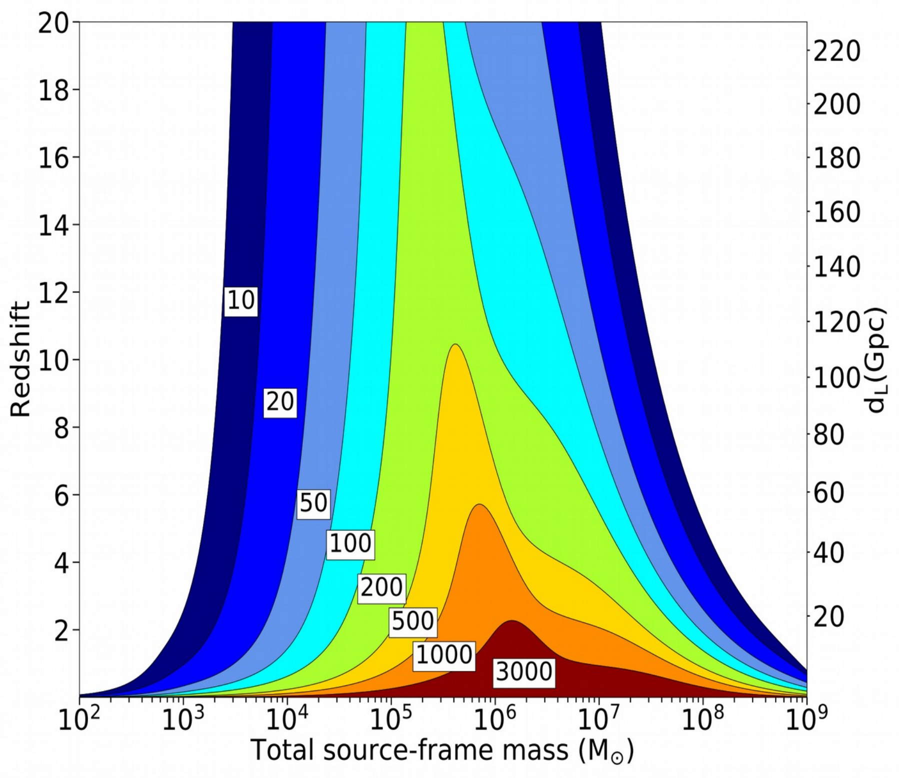
Cosmological simulations predicts ~ 1/yr with $M_{BH} \sim 10^5\ M_\odot$

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 ∼ 20

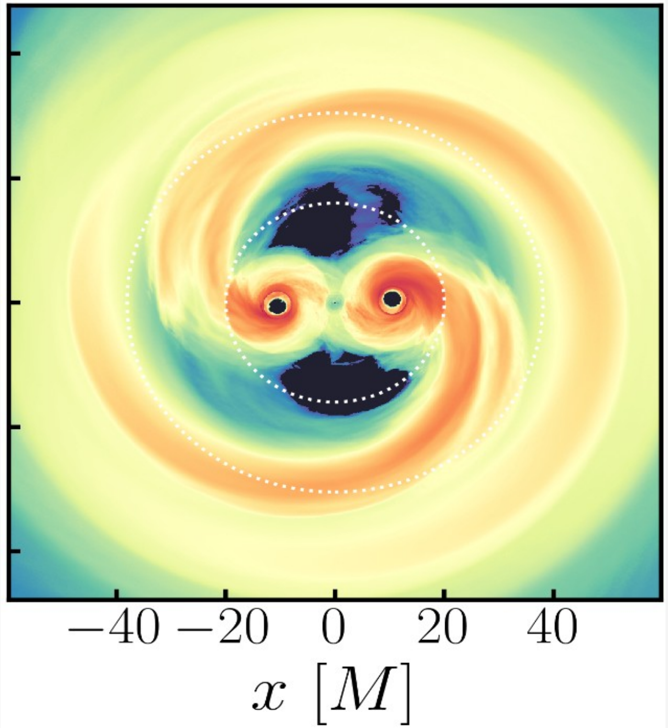




What EM emission do we expect?

- ➤ 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

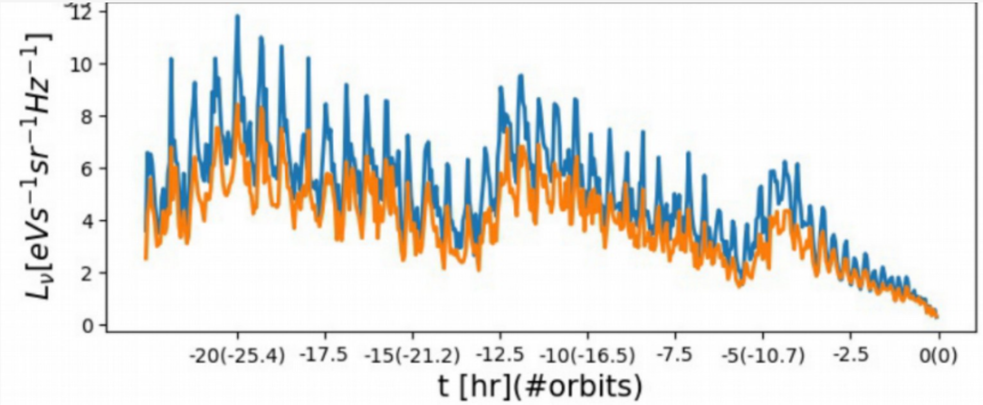
During the inspiral . . .



- ➤ 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, Haiman+17, Tang+18, Nobel+21, Combi+22, Cattorini+22, Gutiérrez+22 …)

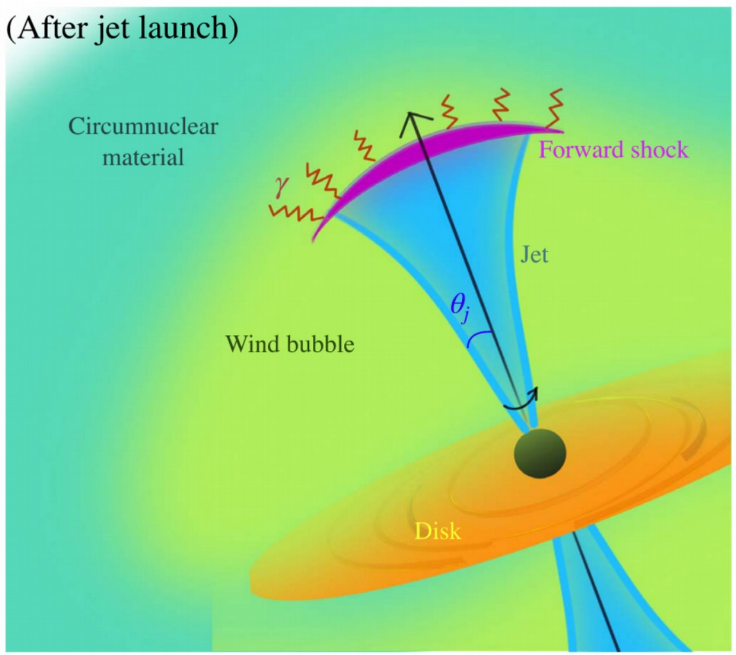
What EM emission do we expect?



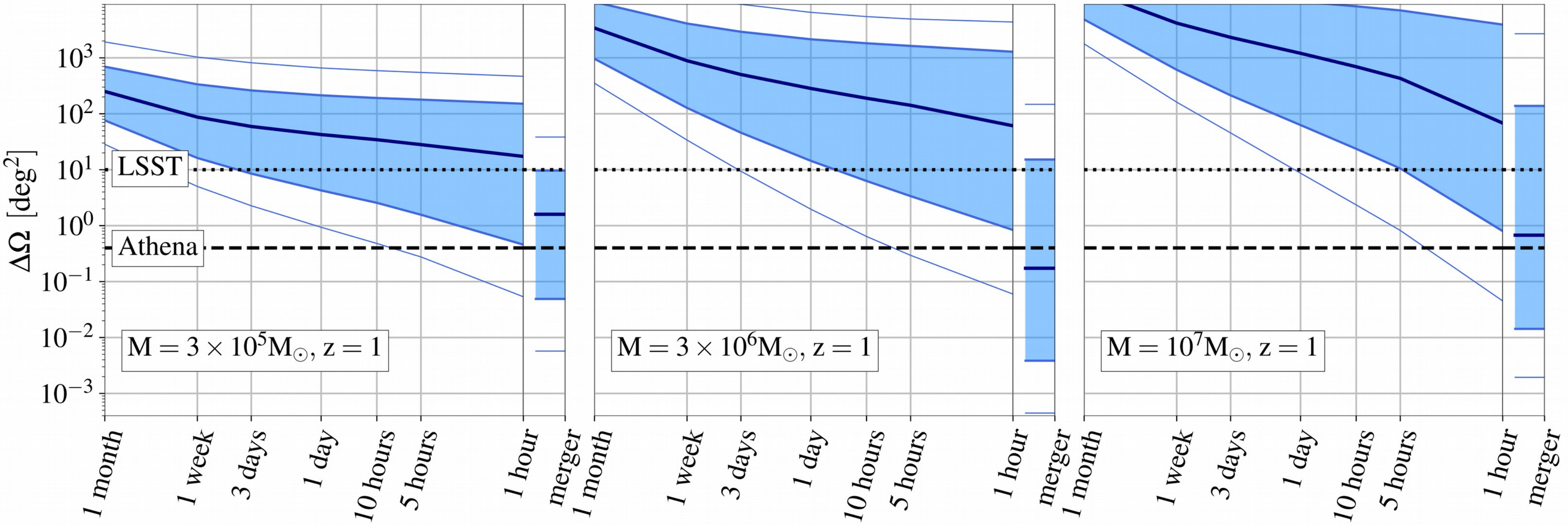
However, close at merger, minidisks might be depleated ⇒ Reduction in luminosity (Tang+18)

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



LISA sky localization for systems at z = 1



$\Delta\Omega$ ~ telescope FOV only close to merger → < 10 hrs **LSST** ; → merger **Athena**

Large distributions → strong dependence from true binary position

Estimating the number of multimessenger MBHBs

In AM+2207.10678 we estimate the rate of MBHBs with a detecatable EM counterpart

Estimate the number of X-ray counterparts over LISA time mission

Key improvements respect to previous works (Tamanini+16)

- Improve the modeling of the EM counterpart
- Bayesian analysis for GW signal (Marsat+20) → expensive but realistic

Starting point

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

Three astrophysical models

Light	Heavy	Heavy-no-delays
From PopIII stars BHs ~ 10^3 $M_\odot$	From the collapse of hydrogen cloud BHs ~ $10^{4\text{-}6}$ $M_\odot$	Same as Q3d but without delay times

Modeling the EM emission

X-ray emission (Shen+20)

$$\frac{L_{\rm bol}}{L_X} = c_1 \left(\frac{L_{\rm bol}}{10^{10} L_\odot}\right)^{k_1} + c_2 \left(\frac{L_{\rm bol}}{10^{10} L_\odot}\right)^{k_2}$$

- FoV ~ 0.4 deg^2
- Deep as $F_{X,\,\mathrm{lim}} \sim 2\times10^{-17}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Assuming 300ks as maximum observation time

AGN obscuration (Ueda+14, Gnedin+07)

- No obscuration
- Typical hydrogen column density distribution

Accretion scenarios

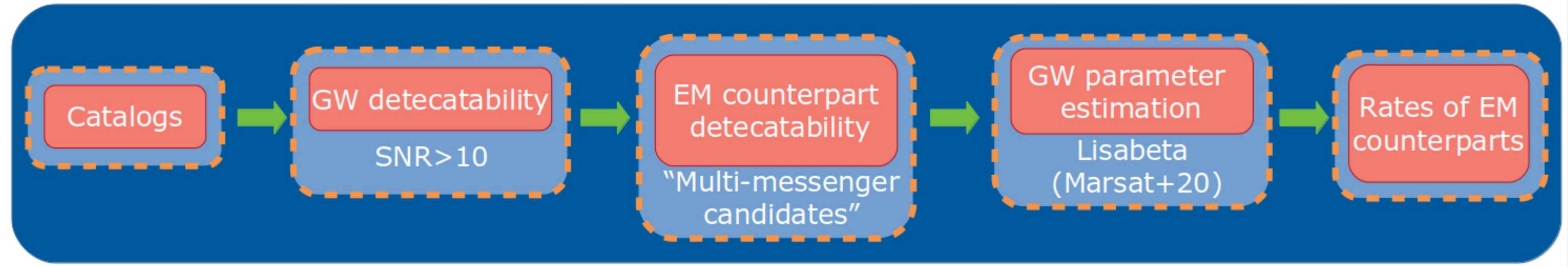
- The accreting gas comes from the catalog
- Assuming Eddington accretion

Some caveats

- Detection is claimed when $F_X > F_{X,\,\mathrm{lim}}$
- No tiling of LISA area (more complicated detection strategy)
- Analysis valid only for post-merger emission

Two main scenarios

General procedure



We focus on two scenarios (No obscuration for the moment!)

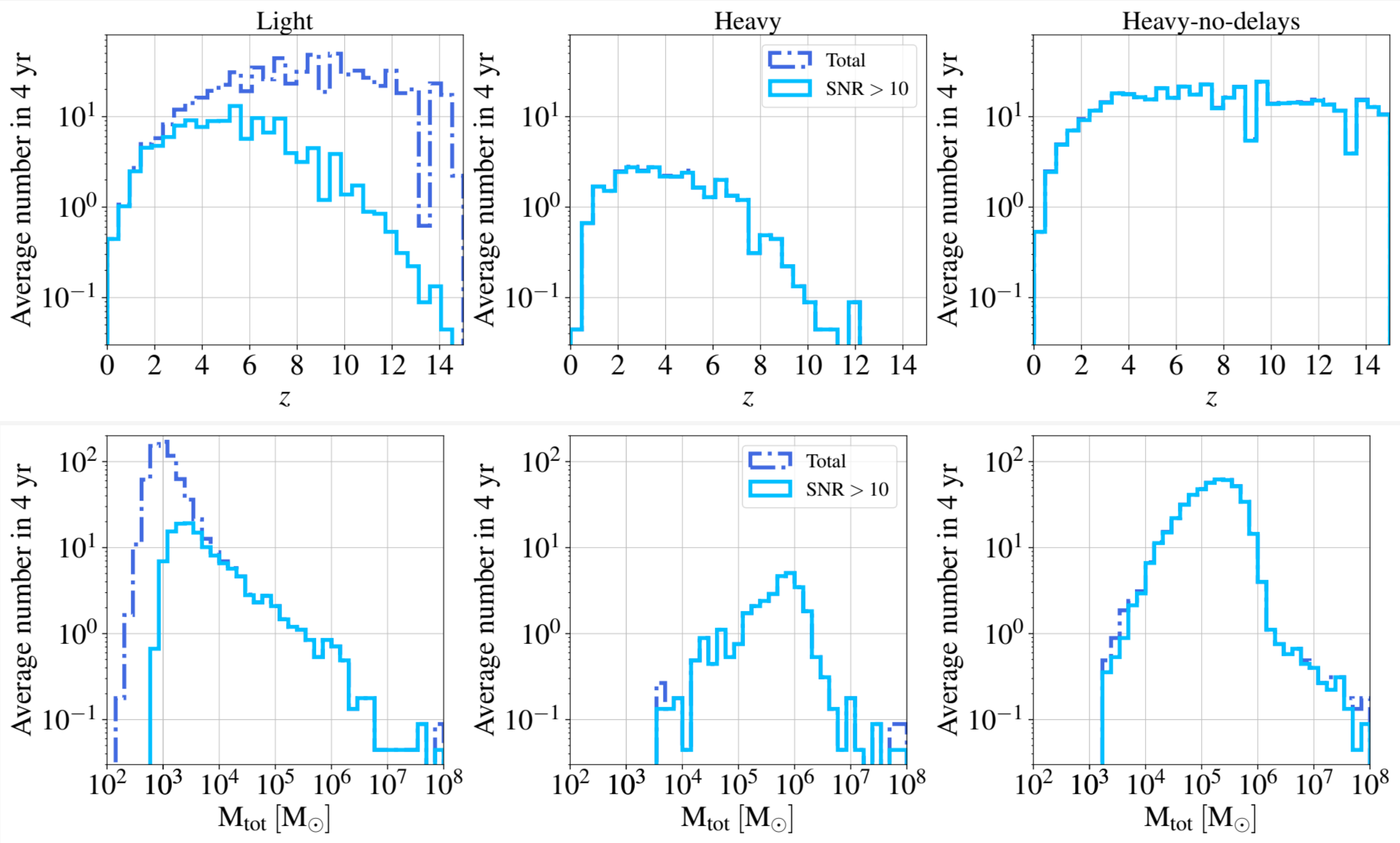
<u>Maximising</u>

- Eddington accretion for X-ray emission
- $\Delta\Omega \sim 0.4\ \mathrm{deg}^2$, $F_{X,\ lim} \sim 2\times10^{-17}$ erg $cm^{-2}s^{-1}$

<u>Minimising</u>

- Catalog accretion for X-ray emission
- $\Delta\Omega \sim 2\ \mathrm{deg}^2$, $F_{X,\ lim} \sim 2\times10^{-16}$ erg $cm^{-2}s^{-1}$

Redshift and total mass distributions



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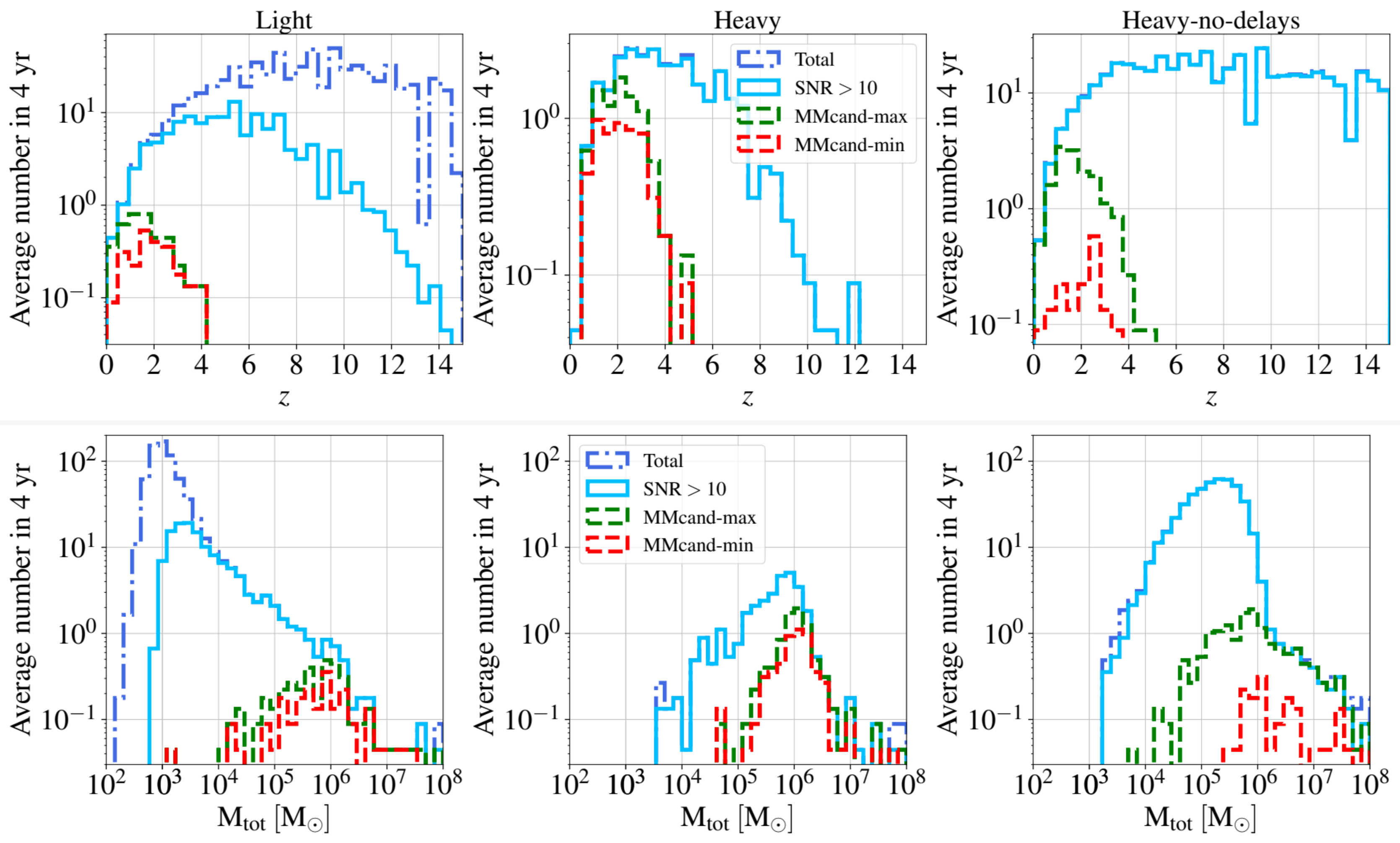

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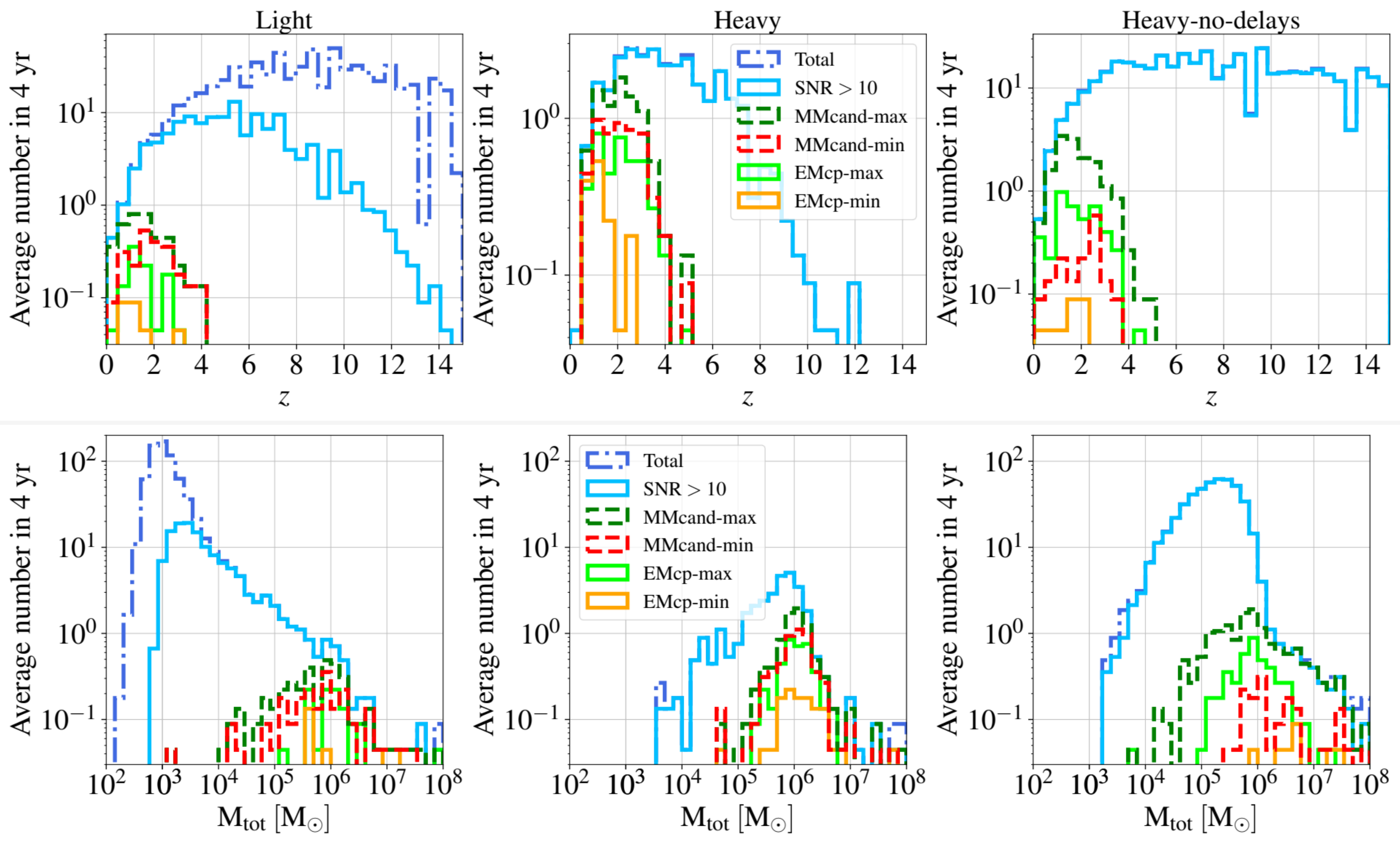
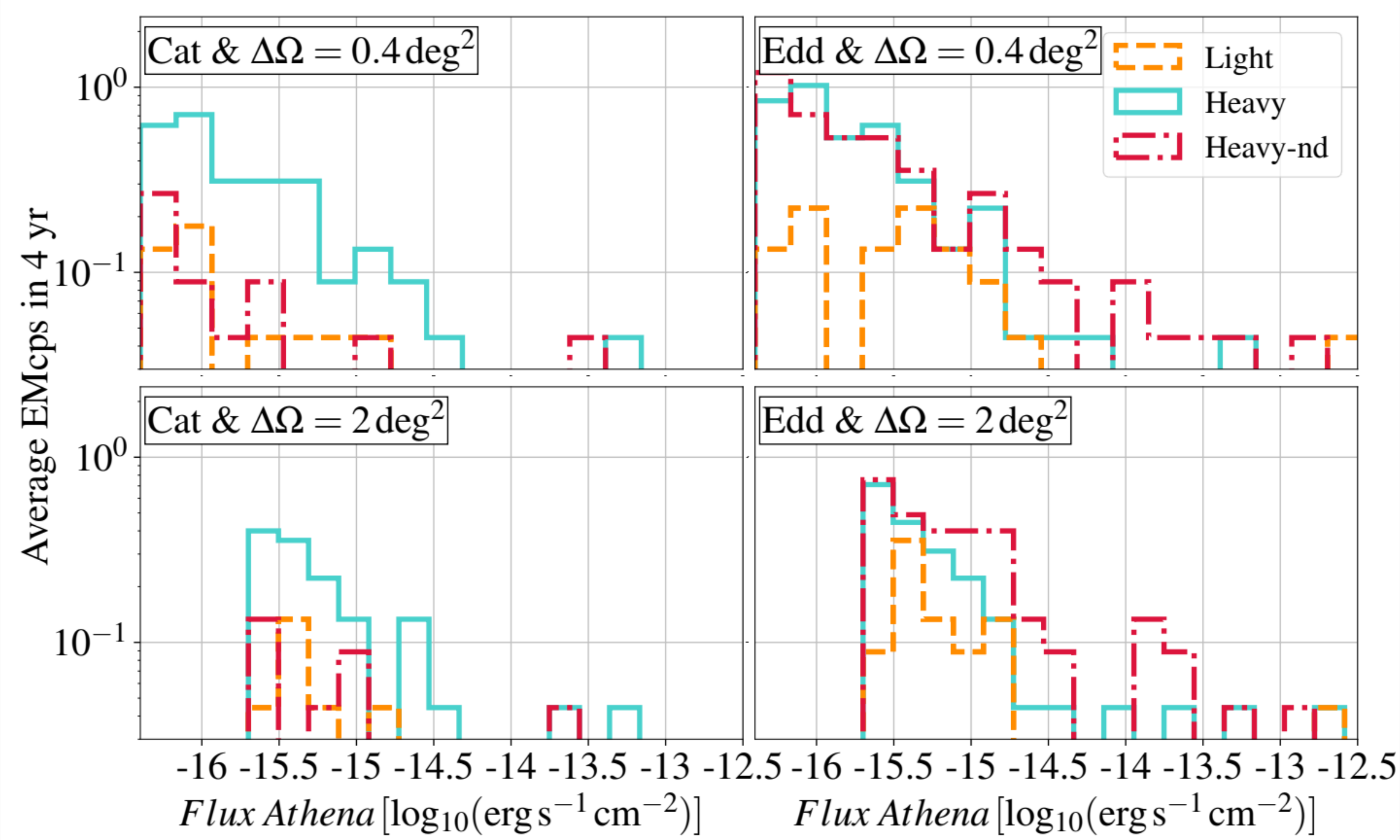


Distribution of X-ray fluxes of multimessenger MBHBs



Number of EMcps in 4 yr

(in 4 yr)	Athena				
	Catalog		Eddington		
	$F_{X,\mathrm{lim}}$ = 4e-17 $\Delta\Omega = 0.4\,\mathrm{deg}^2$	$F_{X,\mathrm{lim}}$ = 2e-16 $\Delta\Omega = 2\,\mathrm{deg}^2$	$F_{X,\mathrm{lim}}$ = 4e-17 $\Delta\Omega = 0.4\,\mathrm{deg}^2$	$F_{X,\mathrm{lim}}$ = 2e-16 $\Delta\Omega = 2\,\mathrm{deg}^2$	
No-obsc.	0.49	0.27	1.02	0.84	Light
	2.67	1.38	3.87	2.09	Heavy
	0.58	0.31	4.22	2.98	Heavy-nd
Obsc.	0.18	0.04	0.31	0.18	Light
	0.18	0.09	0.18	0.09	Heavy
	0.09	0.04	0.27	0.18	Heavy-nd

- A factor $\sim$ 2 between accretion from catalogs and Eddington
- Dramatic decrease with obscuaration
- LISA parameter estimation selects preferentially heavy systems

Conclusion

Multimessenger will be challenging !

Stellar BHBs

✔ Granted sources from LVK

✖ EM counterpart might be too faint

EMRIs

✖ Uncertainties in the merger rate

✔ EM counterpart is comparable to AGN luminosity

✖ Only few studies on the topic

Massive BHBs

✖ Uncertainties in the merger rate

✔ Broad type of EM emission

✖ Most sources are intrinsically faint and at high redshift

✖ We need better understanding of obscuration

Prospects for the future

➤ Transients associated to MBHB mergers

➤ Study to identify the host galaxies if we have $>10^3$ galaxies in LISA error box

➤ Simulate observational campaigns