Counterpart rates to massive black hole binary mergers in the LISA era

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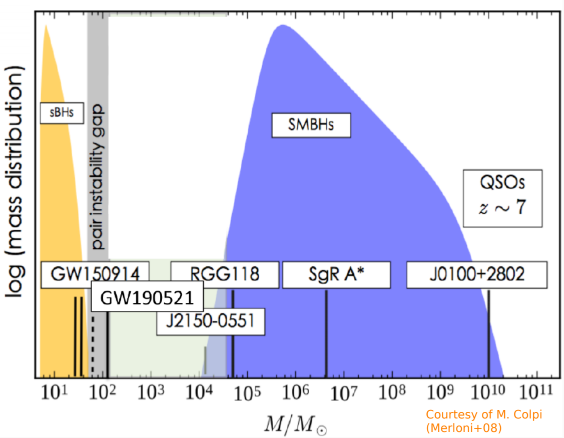
Laboratoire Astroparticule et Cosmologie (APC)

Growing Black Holes: Accretion and Mergers, 15-20 May 2022, Kathmandu, Nepal

Black hole mass spectrum



- Stellar BHs

$$\begin{cases} \mathrm{M}/\mathrm{M}_\odot \in [5, 100] \\ \text{Massive stars} \end{cases}$$

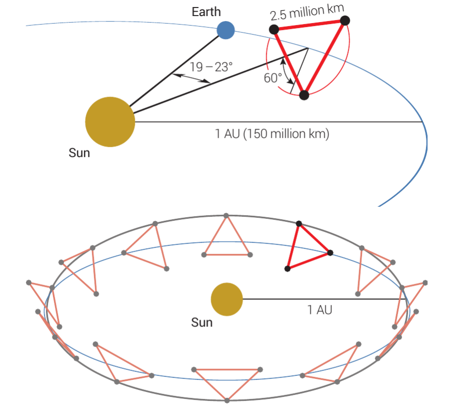
- Massive BHs (MBHs)

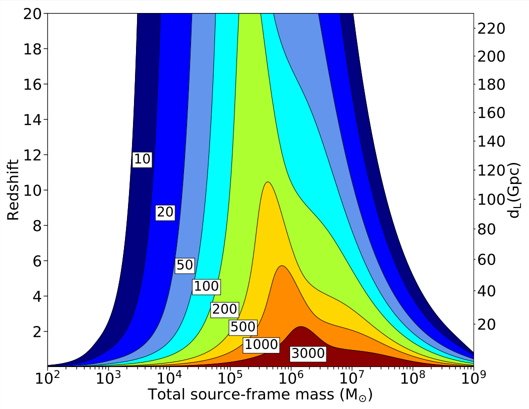
$$\begin{cases} \mathrm{M}/\mathrm{M}_\odot \in [10^5, 10^{10}] \\ \text{Accretion \& growth of DM halos} \end{cases}$$

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

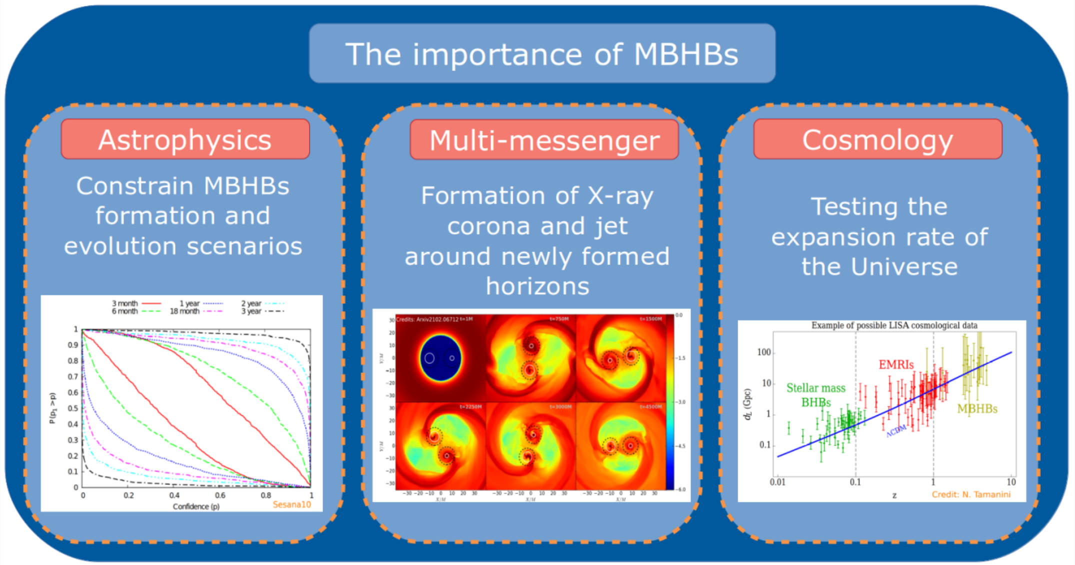
Observing the entire Universe with GWs

In ~ 2034 LISA (Laser Interferometer Space Antenna) will observe the GWs from the coalescence of MBHBs in the entire Universe



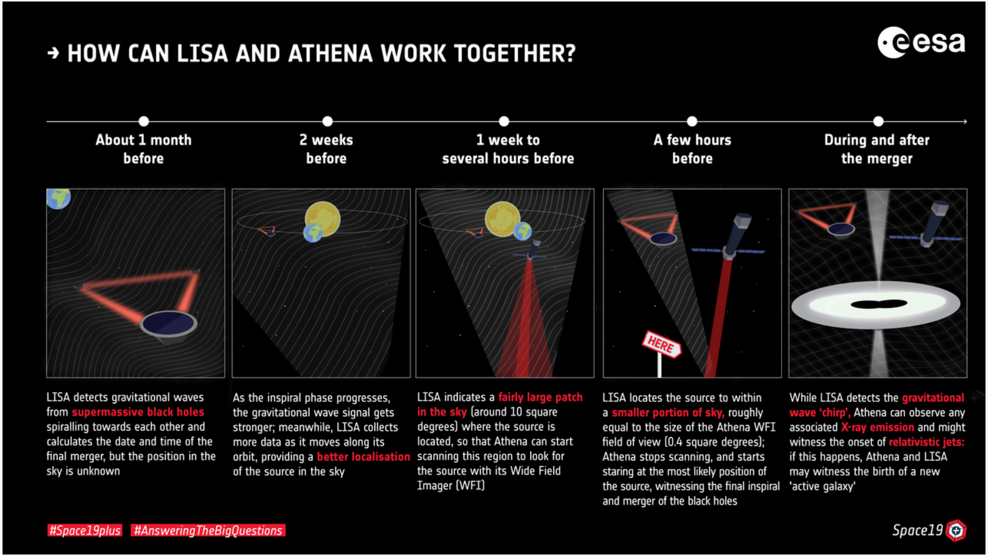


Why MBHBs?



The importance of MBHBs
Astrophysics
Constrain MBHBs formation and evolution scenarios
3 month
6 month
1 year
18 month
2 year
3 year
Confidence (p)
Sesana10
Multi-messenger
Formation of X-ray corona and jet around newly formed horizons
Cosmology
Testing the expansion rate of the Universe
Example of possible LISA cosmological data
Stellar mass BHBs
EMRIs
MBHBs
ΛCDM
z
Credit: N. Tamanini

Multi-messenger in practice



Motivation and aim of the project

Motivation

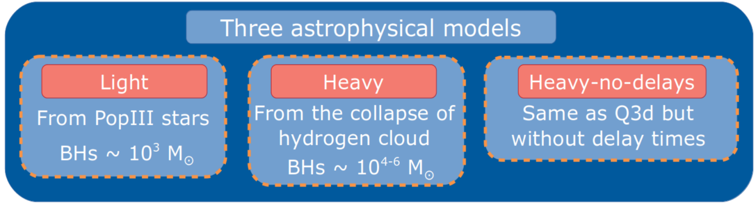
- How many counterparts do we expect over LISA time mission? (Improve Tamanini+16)
- How well we can constrain cosmological parameters? (not on this talk)

Aim of the project

Estimating the number of counterparts over LISA time mission and cosmology application

Starting point

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



Modeling the EM emission

Observing strategies

Optical

LSST

- 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
- Isotropic

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)

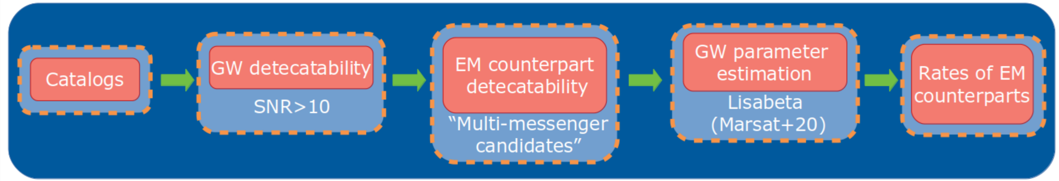
- Affect LSST and Athena
- Typical hydrogen column density distribution

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

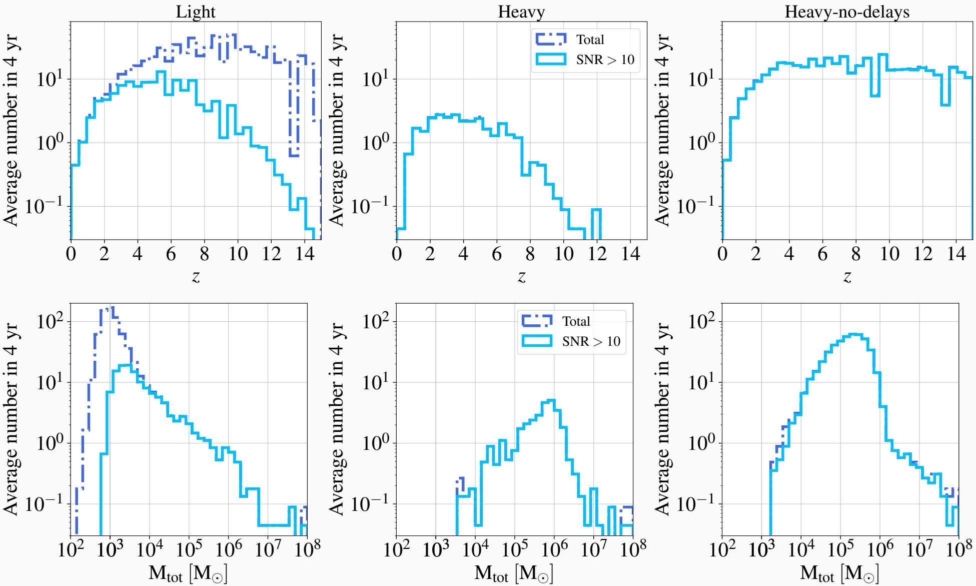
Maximizing

- no AGN obscuration
- Isotropic radio emission
- Eddington accretion for X-ray emission

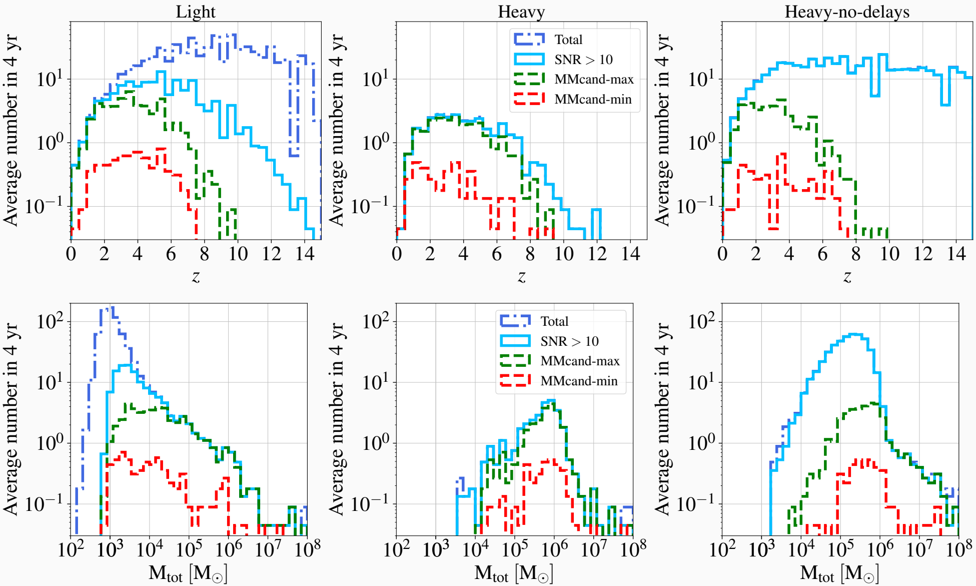
Minimizing

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

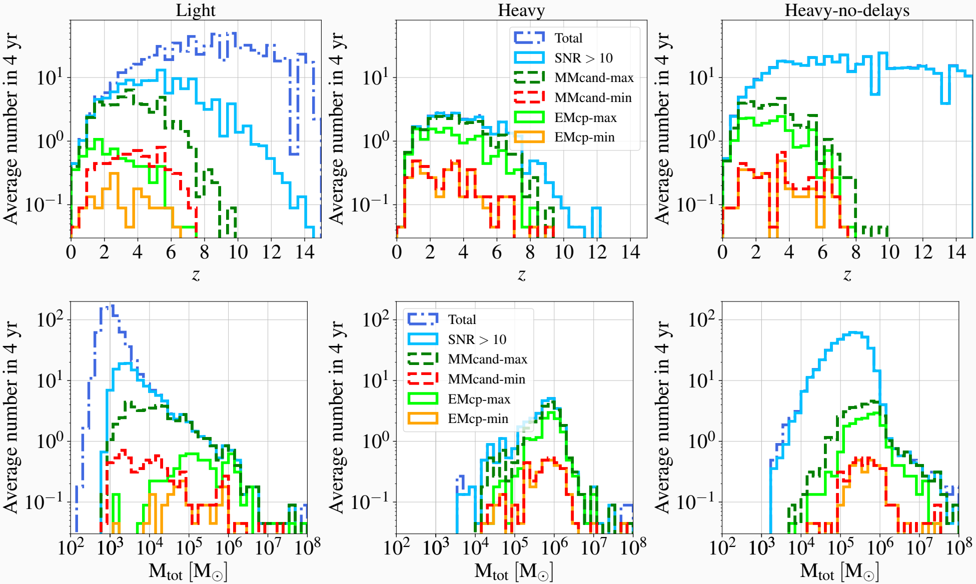
Redshift and total mass distributions



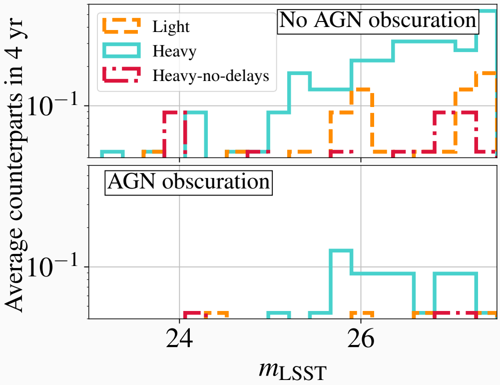
Redshift and total mass distributions

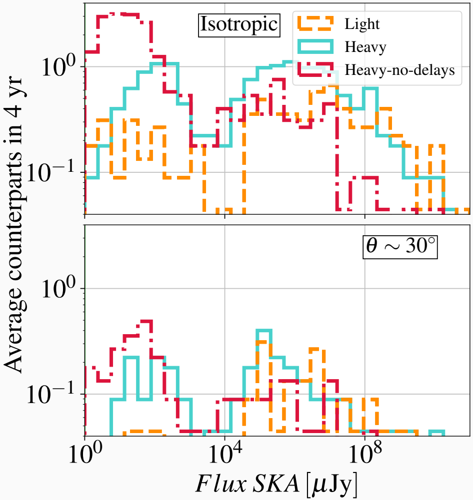


Redshift and total mass distributions

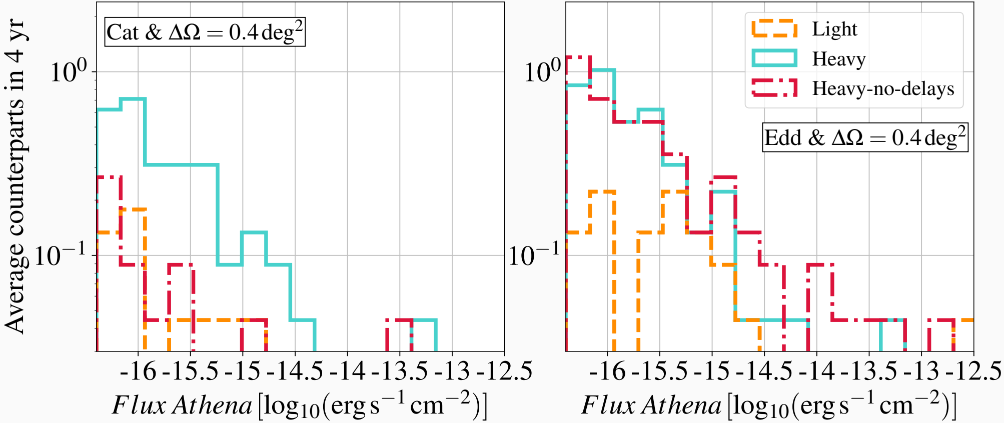


EMcps in optical and radio





EMcps in X-ray



Only few and faint sources in 4 yr

EMcp rates in 4 yr

(In 4 yr)	LSST	SKA+ELT			Athena+ELT				
					Catalog		Eddington		
		Isotropic	$\theta \sim 30°$	$\theta \sim 6°$	$F_{X,\,lim}$ = 4e-17	$F_{X,\,lim}$ = 2e-16	$F_{X,\,lim}$ = 4e-17	$F_{X,\,lim}$ = 2e-16	
	$\Delta\Omega = 10\,\text{deg}^2$				$\Delta\Omega = 0.4\,\text{deg}^2$	$\Delta\Omega = 2\,\text{deg}^2$	$\Delta\Omega = 0.4\,\text{deg}^2$	$\Delta\Omega = 2\,\text{deg}^2$	
No-obsc.	0.84	6.8	1.51	0.04	0.49	0.27	1.02	0.84	Light
	3.07	14.84	2.71	0.04	2.67	1.38	3.87	2.09	Heavy
	0.53	20.0	3.07	0.04	0.58	0.31	4.22	2.98	Heavy-no-delays
Obsc.	0.4	6.8	1.51	0.04	0.18	0.04	0.31	0.18	Light
	0.89	14.84	2.71	0.04	0.18	0.09	0.18	0.09	Heavy
	0.27	20.0	3.07	0.04	0.09	0.04	0.27	0.18	Heavy-no-delays

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

(In 4 yr)	Maximizing	Minimizing
Light	6.4	1.8
Heavy	14.8	3.6
Heavy-no-delays	20.3	3.3

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 the GW parameter estimation . . .

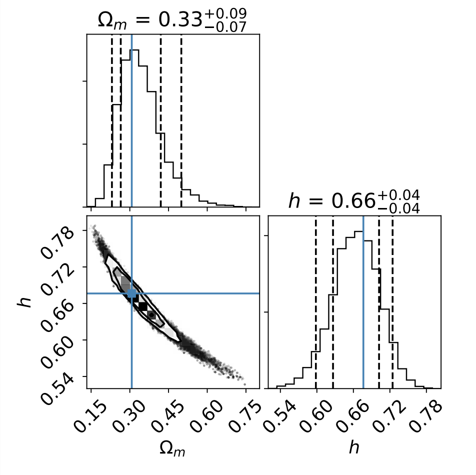
- Current limit on the number of counterparts
- Massive models predict more counterpart thanks the better sky-localization

MBHBs multi-messenger will be challenging!

Thanks

Backup slides

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

Backup slides

Radio emission

$$L_{\rm radio} = L_{\rm flare} + L_{\rm jet}$$

$$L_{\rm flare} = \frac{\epsilon_{\rm edd}\epsilon_{\rm radio}}{q^2} L_{\rm edd} \quad (q > 1) \quad \text{(Palenzuela+10)}$$

$$L_{\rm jet} = \begin{cases} 0.8 \times 10^{42.7}\,{\rm erg\,s^{-1}}\, m_9^{0.9} \left(\frac{\dot{m}}{0.1}\right)^{6/5} \left(1 + 1.1 a_1 + 0.29 a_1^2\right), & \text{if } 10^{-2} \leq \epsilon_{\rm edd} \leq 0.3 \\ 3 \times 10^{45.1}\,{\rm erg\,s^{-1}}\, m_9 \left(\frac{\dot{m}}{0.1}\right) g^2 \left(0.55 f^2 + 1.5 f a_1 + a_1^2\right) & \text{otherwise} \end{cases} \quad \text{(Meier00)}$$

In case of beamed emission, we have $L_{\rm radio,beamed} = L_{\rm radio}\delta^2(\theta, \iota)$

Backup slides

X-ray emission

$$\frac{L_{\rm bol}}{L_{\rm X}} = c_1 \left(\frac{L_{\rm bol}}{10^{10} L_\odot}\right)^{k_1} + c_2 \left(\frac{L_{\rm bol}}{10^{10} L_\odot}\right)^{k_2} \quad (Shen + 20)$$

Assuming 300ks as maximum observation time

- $F_{\rm X,\,lim} = 4 \times 10^{-17} {\rm erg\,s^{-1}\,cm^{-2}}$
- $\Delta\Omega = 0.4\,{\rm deg}^2$

- $F_{\rm X,\,lim} = 2 \times 10^{-16} {\rm erg\,s^{-1}\,cm^{-2}}$
- $\Delta\Omega = 2\,{\rm deg}^2$

We also assumed accretion from the catalogs or at Eddington

For simplicity we assume that the X-ray emission happens at some point after the merger.

Backup slides

Redshift measurements

LSST

Photometric measurements with

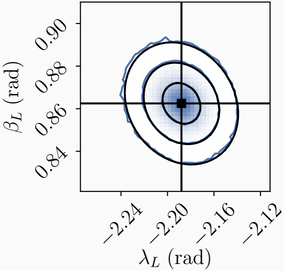
$\Delta z = 0.03(1+z)$ (*Laigle* + 19)

ELT

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

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

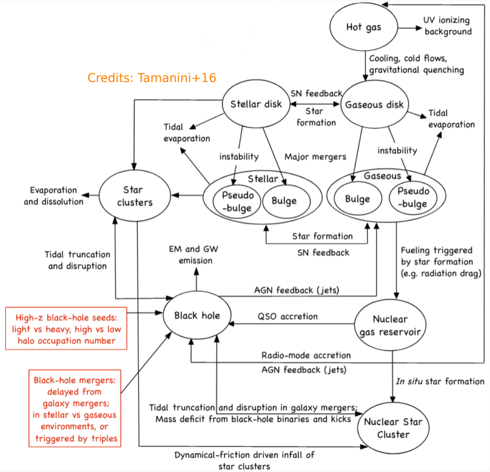
Backup slides

Number of detected events in 4 yr

	Total catalog	$\mathrm{SNR} > 10$
Light	690.9	129.3
Heavy	30.7	30.4
Heavy-no-delays	475.5	471.1

Backup slides

The physics of semi-analytical models



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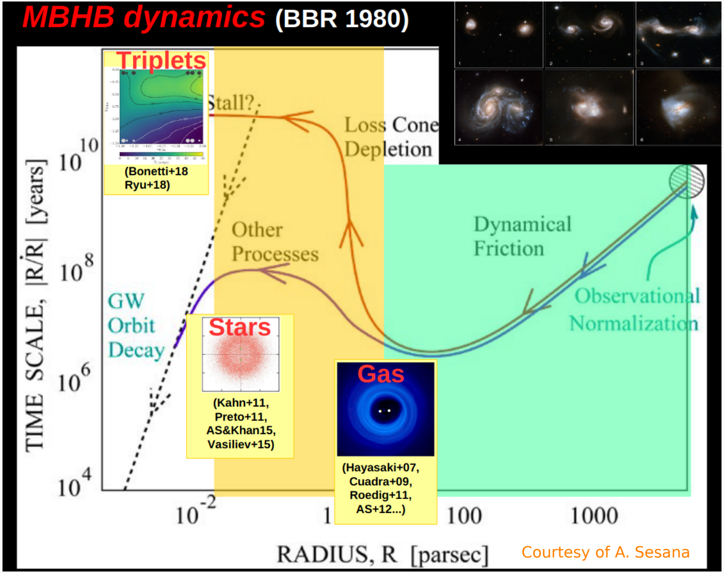

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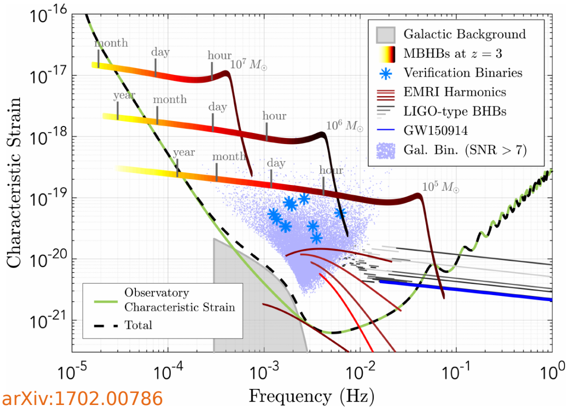
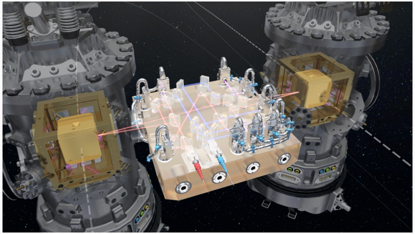
LISA = Laser Interferometer Space Antenna



arXiv:1702.00786

- Launch in 2034
- 4.5 yrs of taking data (90% efficiency)
- Sensitive in the mHz regime
- 2.5M km armlength



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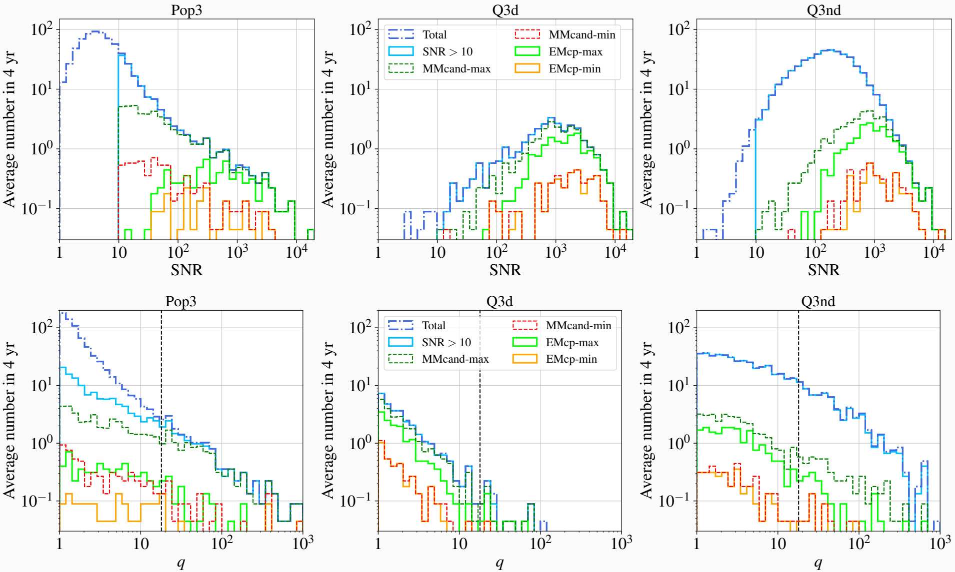

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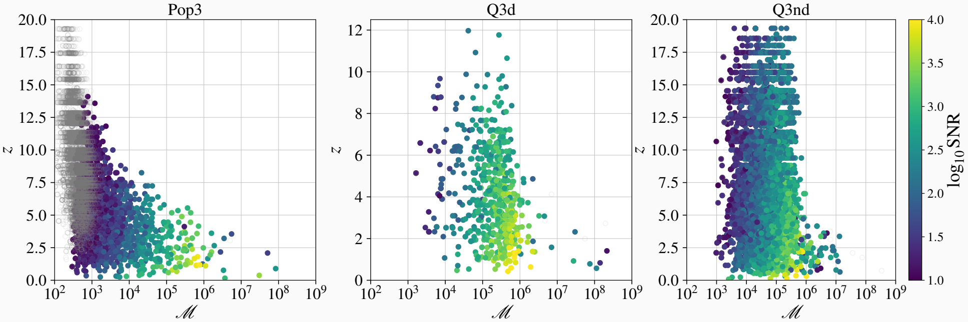
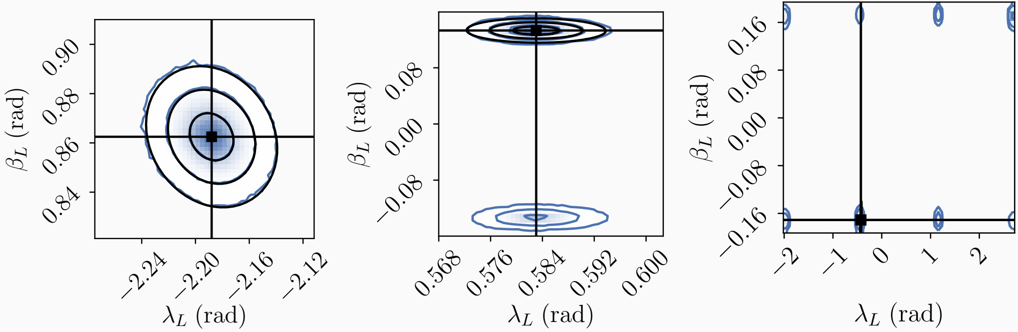
SNR distribution in the $z - \mathcal{M}$ plane



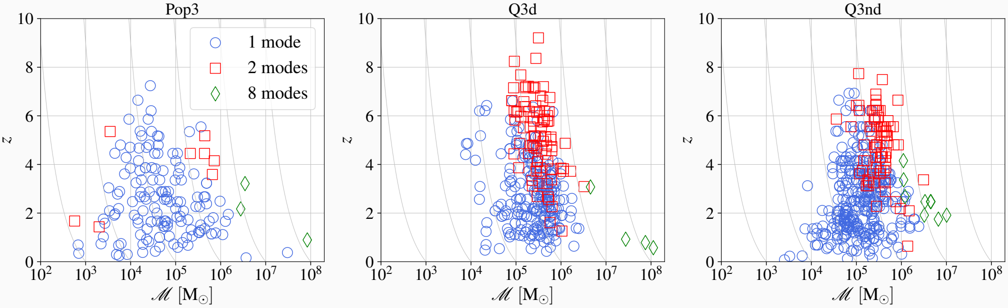
Backup slides

Systems with multimodal sky posterior distribution from LISA data analysis



- Arise from LISA degeneracy pattern function
- In special spots of the sky $\begin{cases} \beta = \beta_T & \text{(latitude)} \\ \lambda = \lambda_T + k\pi/2 \;\; k = 0, 1, 2, 3 & \text{(longitude)} \end{cases}$

Backup slides



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

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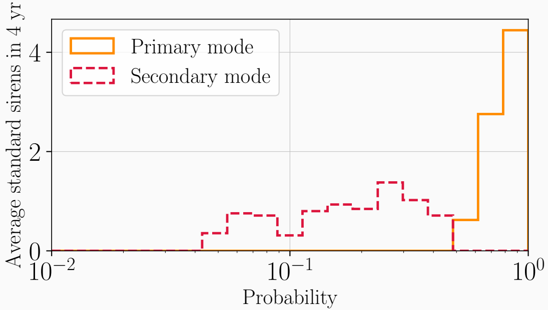
Focus only on the true binary spot

Modes probability



Contribution to the expected rate in 4 yr

	1mode	2modes	8modes
Pop3	6.3	0.36	0.13
Q3d	10.7	3.9	0.2
Q3nd	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 counterpart estimates

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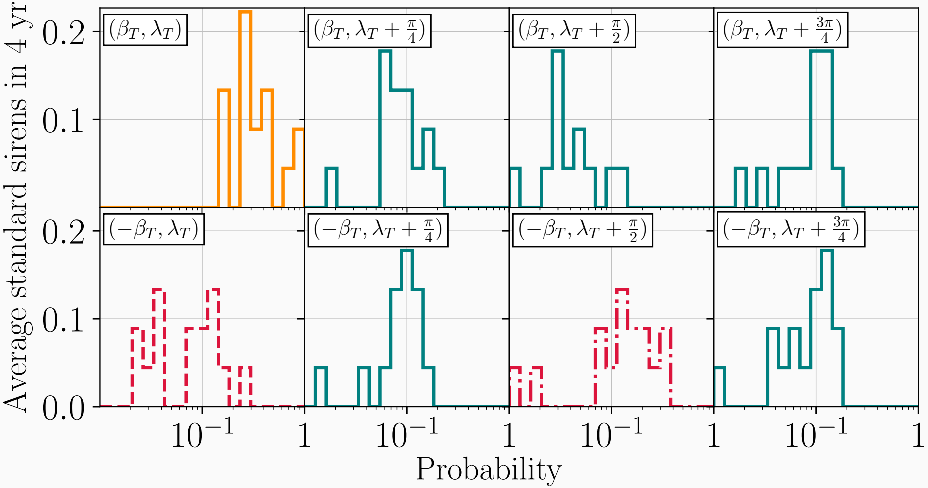
Probability for 8modes systems



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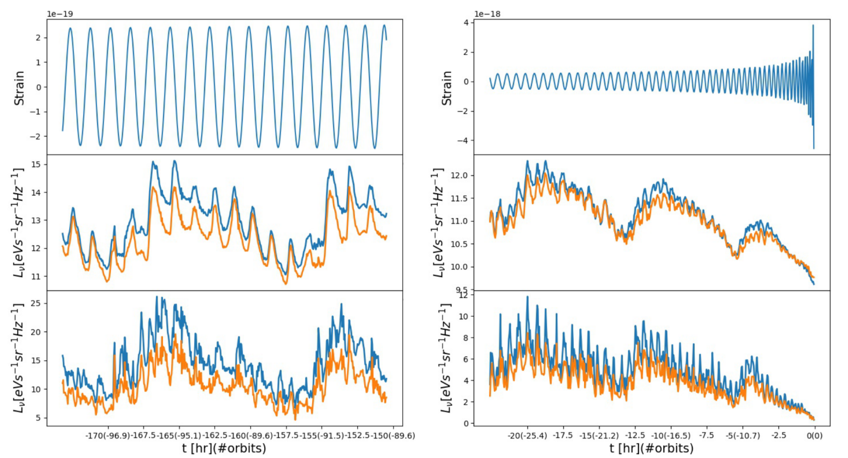
X-ray emission during inspiral (Dal Canton+19, Tang+18) or postmerger (Milosavljevic+04, Rossi+09)



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LISA-Athena synergies (McGee+19)