Cosmology prospects for massive black hole binaries in LISA

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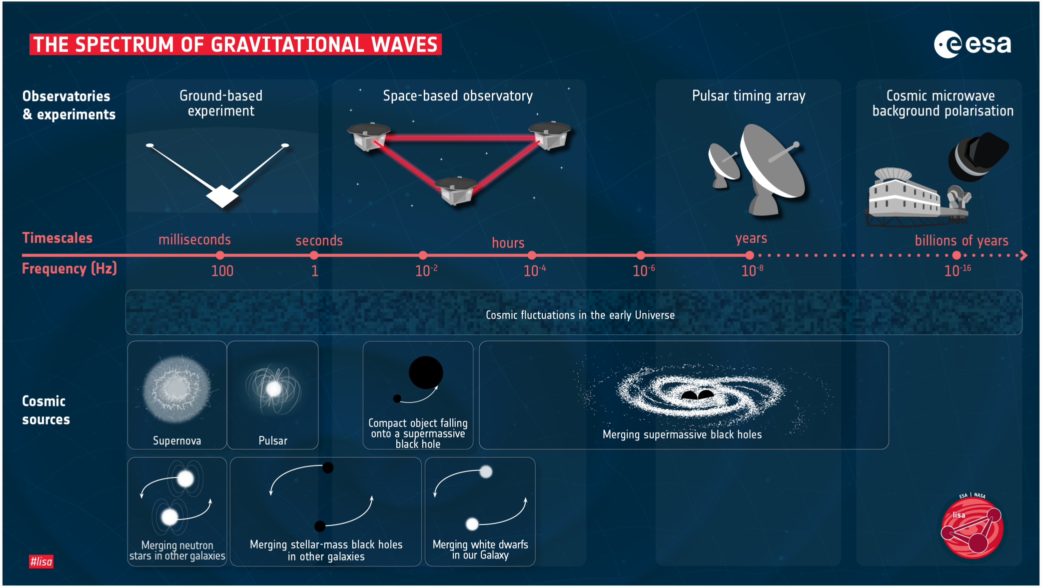
Laboratoire Astroparticule et Cosmologie (APC)

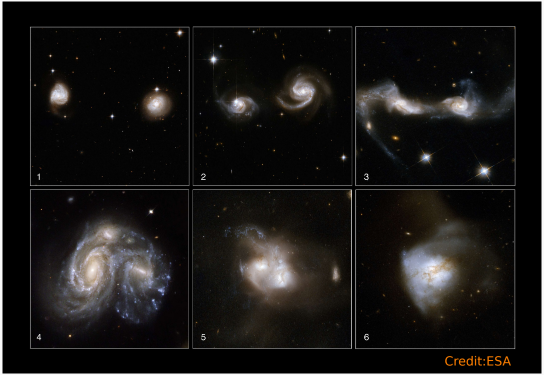
IJCLab, 20 June 2022, Saclay

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
ESA | NASA
lisa

Massive black hole binaries (MBHBs)

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

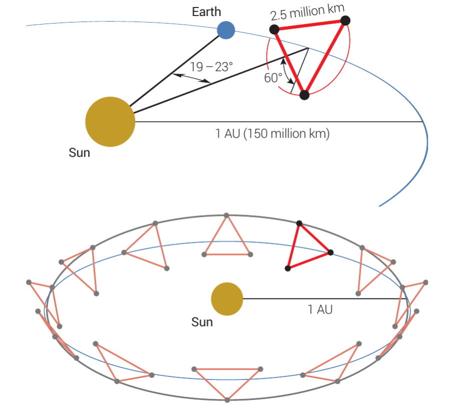
- Dynamical friction with gas and stars is efficient down to $\sim$pc scales
- 3-body interactions?
- Refill of loss cone?

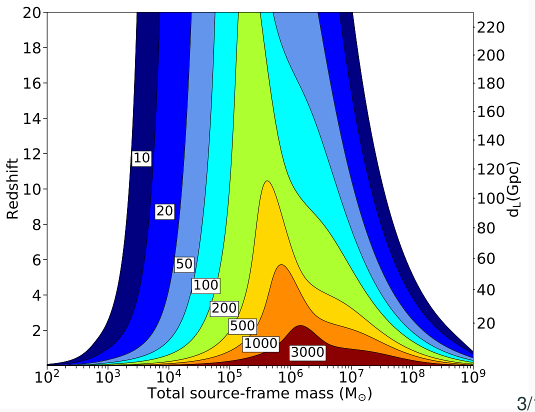
Large uncertainties in the event rate: from few to several hundreads per year

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

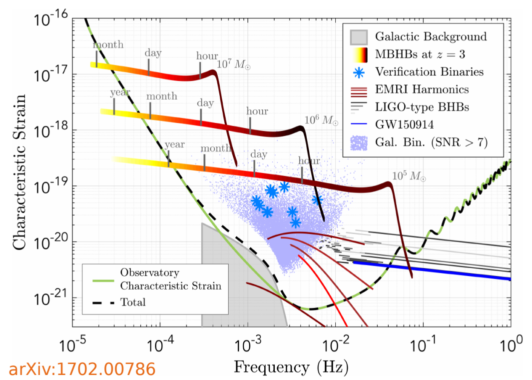
- 3rd Large class mission selected by European Space Agency
- Successfully ended Phase A - Now in Phase B1 - Mission Adoption in 2024



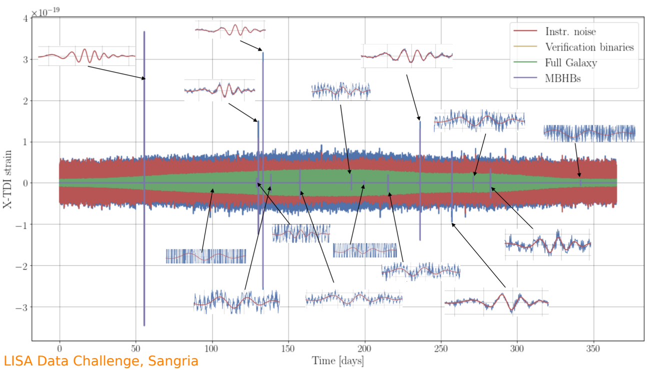


GW sources in LISA band

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



arXiv:1702.00786

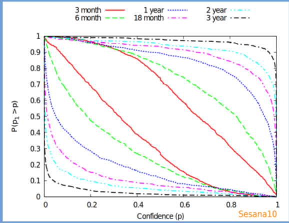


LISA Data Challenge, Sangria

The importance of MBHBs

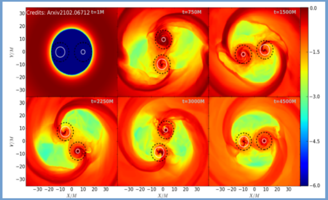
Astrophysics

Constrain MBHBs formation and evolution scenarios



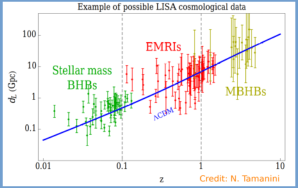
Multi-messenger

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



Cosmology

Testing the expansion rate of the Universe



Focus on cosmology with MBHBs

From the standard cosmological model

$$d_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$\frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_r(1+z)^4 + \Omega_k(1+z)^2}$$

Luminosity distance+redshift $\rightarrow$ Estimate cosmological parameters

GWs present several pros respect to standard techniques

- Direct information on d_L $\rightarrow$ No calibration errors
- Independent from CMB or SNIa $\rightarrow$ Independent estimates
- MBHBs can probe Universe at $z \sim 2-3$

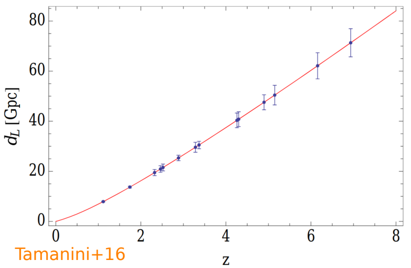
Bright and Dark sirens

Bright sirens

Redshift information from the EM counterpart

(Holz+05, Del Pozzo+12, Tamanini+16, LVC+ Nature 551)

- ✓ Direct redshift information
- ✗ Challenging detection of EM counterpart
- ✗ Few and faint sources



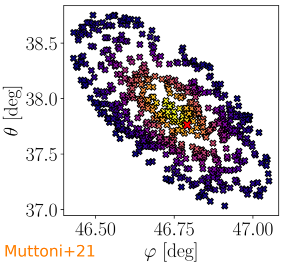
Tamanini+16

Dark sirens

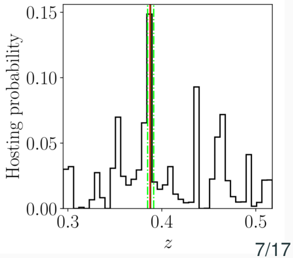
Redshift information from the galaxy distribution

(Schutz86, Petiteau+11, Muttoni+21)

- ✓ More systems
- ✗ Error volumes with $> 10^3$ galaxies
- ✗ Catalog completeness at $z \sim 2 - 3$



Muttoni+21



Motivation and aim of the project

Aim of the project

How many counterparts do we expect over LISA time mission? (Improve Tamanini+16)

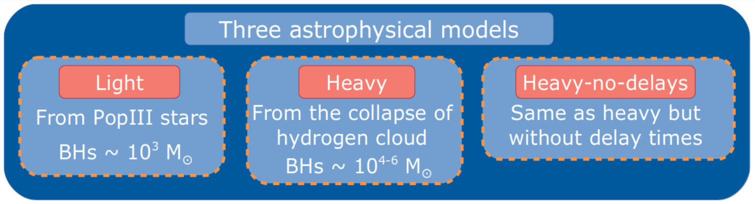
Estimate the number of counterparts over LISA time mission and cosmological parameters

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
- 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)

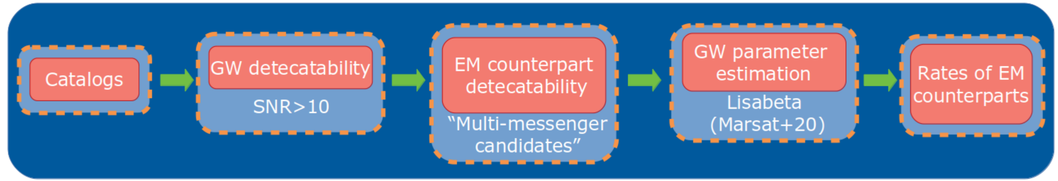
- Affect LSST/VRO and Athena
- Typical hydrogen column density distribution

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

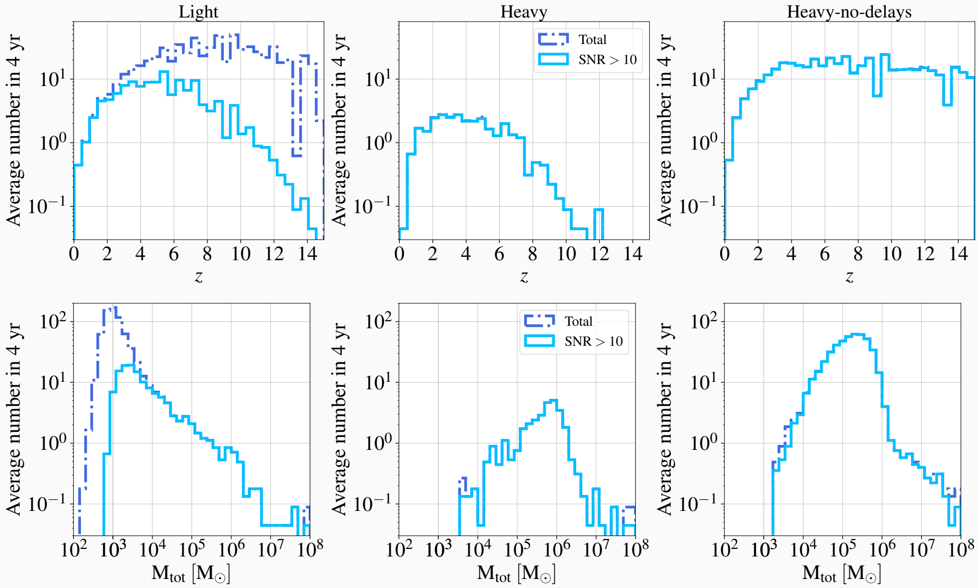
Maximising

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

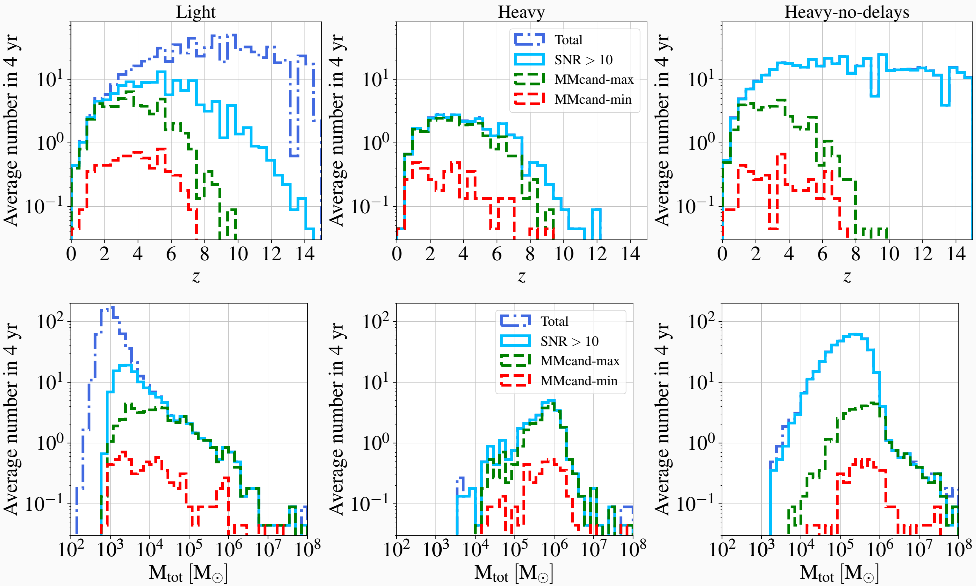
Minimising

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

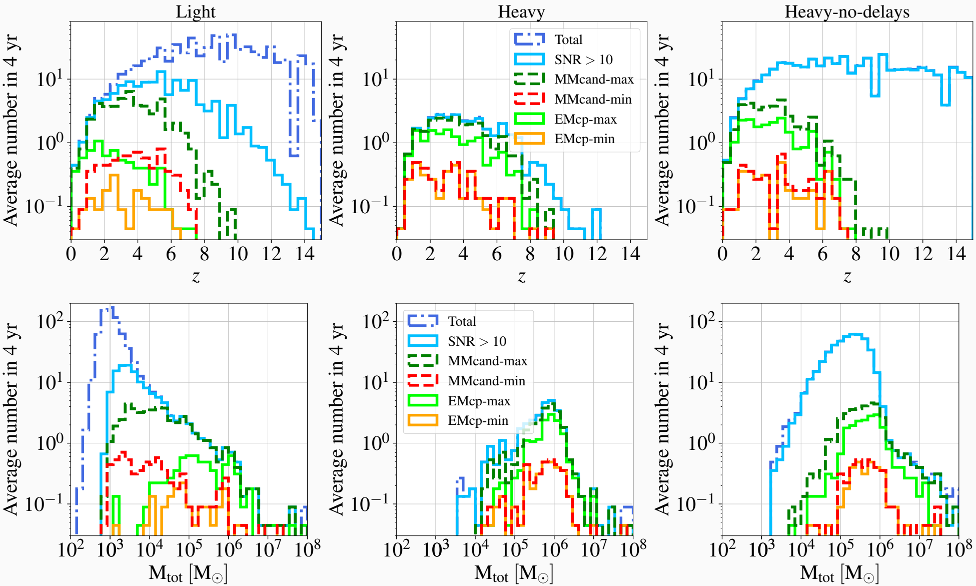
Redshift and total mass distributions



Redshift and total mass distributions



Redshift and total mass distributions



EMcp rates in 4 yr

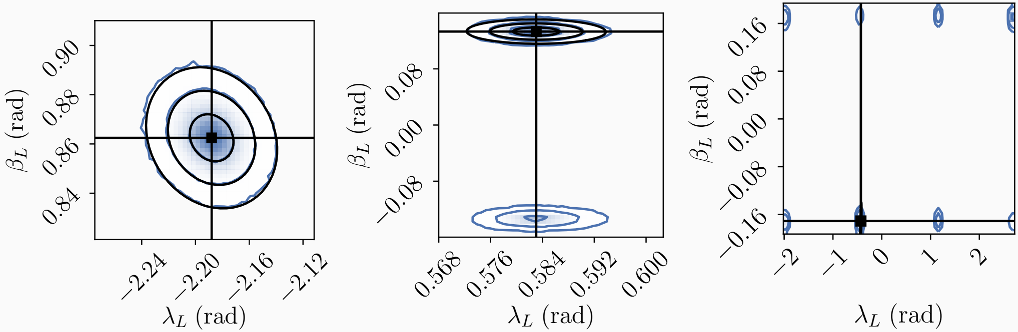
(In 4 yr)	LSST, VRO	SKA+ELT			Athena+ELT		
		Isotropic	$\theta \sim 30^\circ$	$\theta \sim 6^\circ$	Catalog $F_{\mathrm{X,\,lim}}$ = 4e-17	Eddington $F_{\mathrm{X,\,lim}}$ = 4e-17	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	
No-obsc.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

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

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

“Multimodal” LISA events

Systems with multimodal sky posterior distribution from LISA data analysis

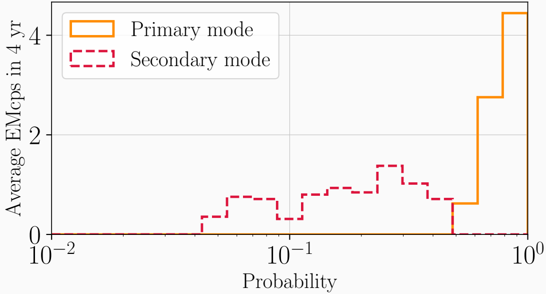


- Arise from LISA degeneracy pattern function
- Might pose issues for the search of the EM counterpart + problematic also for the dark sirens approach

How can we take them into account?

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

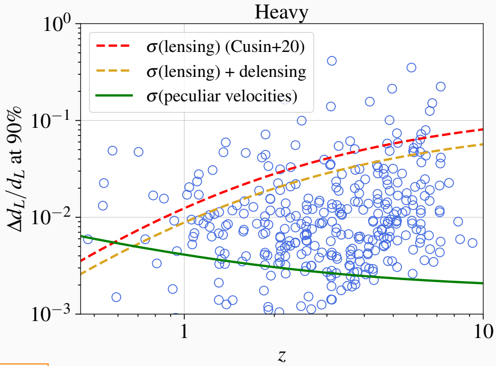
- 2modes have always one mode more probable than the other
- 8modes provides < 1 counterparts in the entire mission

Multimodal events does not affect (significantly) counterpart estimates

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

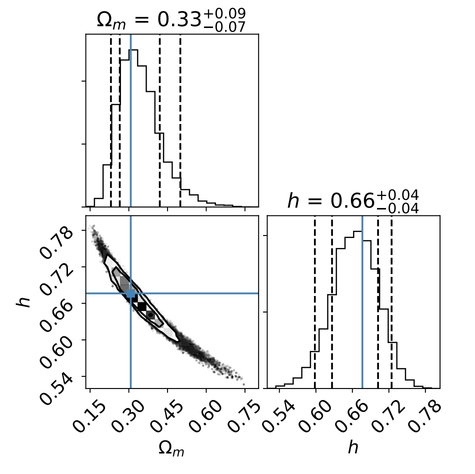
Photometric measurements with $\Delta z = 0.03(1+z)$ (*Laigle* + 19)

ELT

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

Cosmological applications

Combine the luminosity distance and redshift uncertainty to constrain cosmological parameters



H_0 can be constrained to few percent
Larger uncertainties on Ω_m

We plan to extend the analysis also for $H(z = 2)$

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 (see Danny's talk)

MBHBs multi-messenger & cosmology will be challenging!

Conclusions

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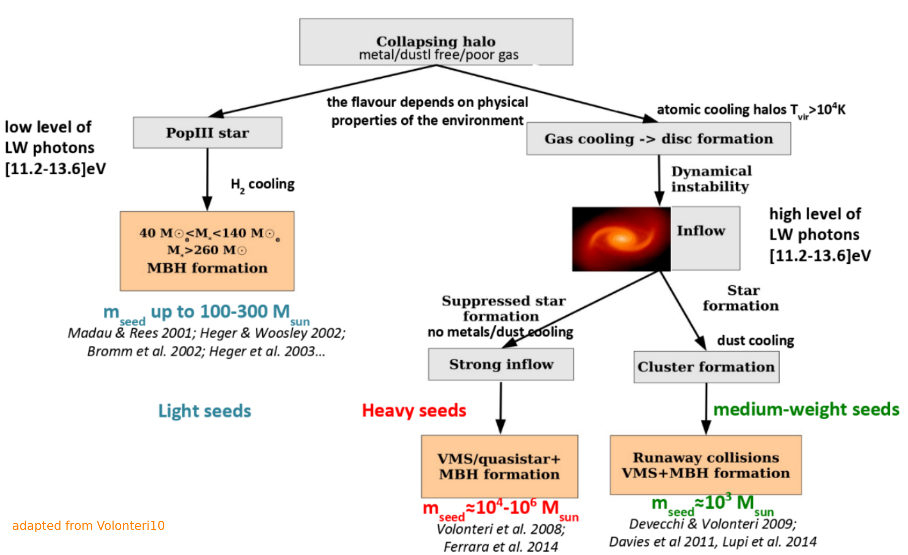
Thanks! Any questions?

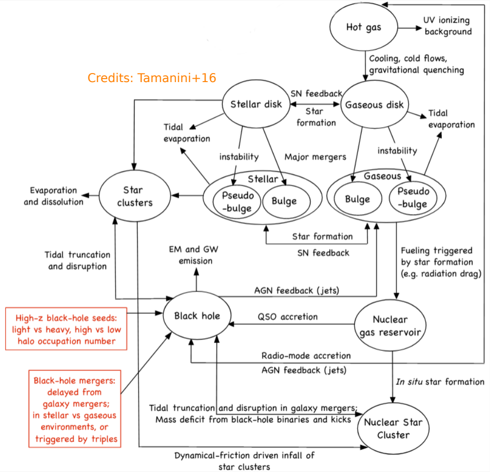
Backup slides

Seed BHs formation channels

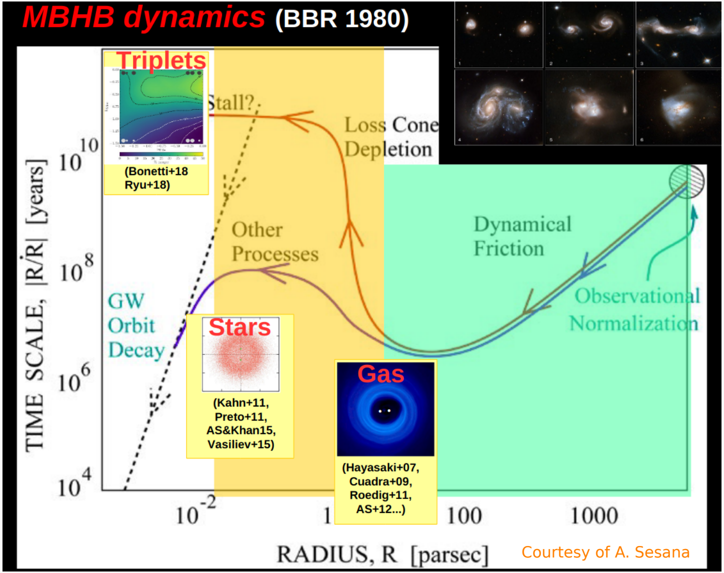


Backup slides

The physics of semi-analytical models



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.

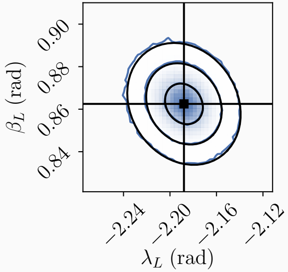
Backup slides

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

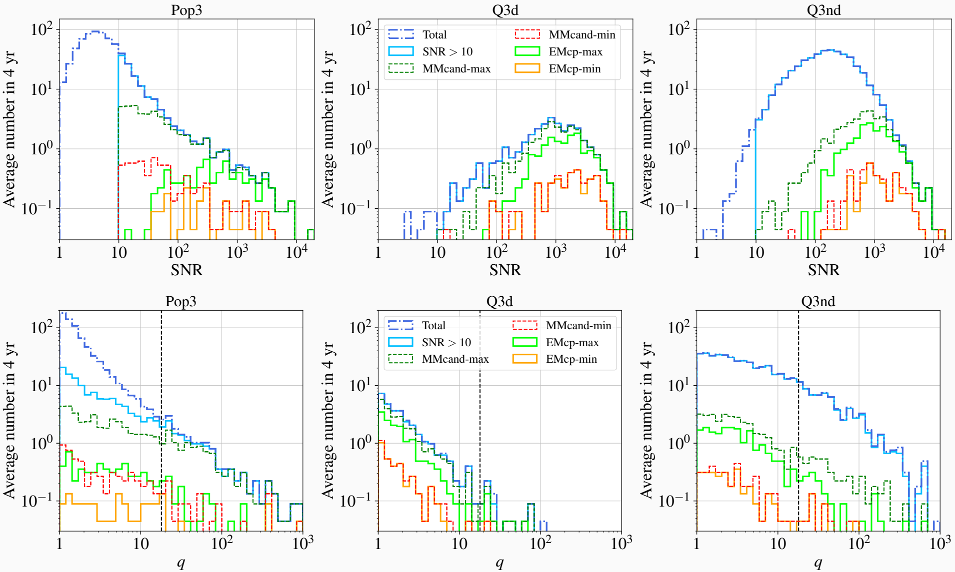
GW parameter estimation

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

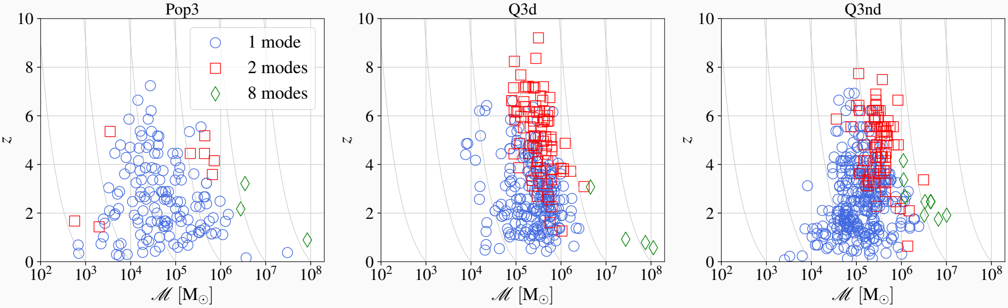


- MCMC formalism
- Include both low- and high-frequency LISA response
- Tested with independent codes

Backup slides



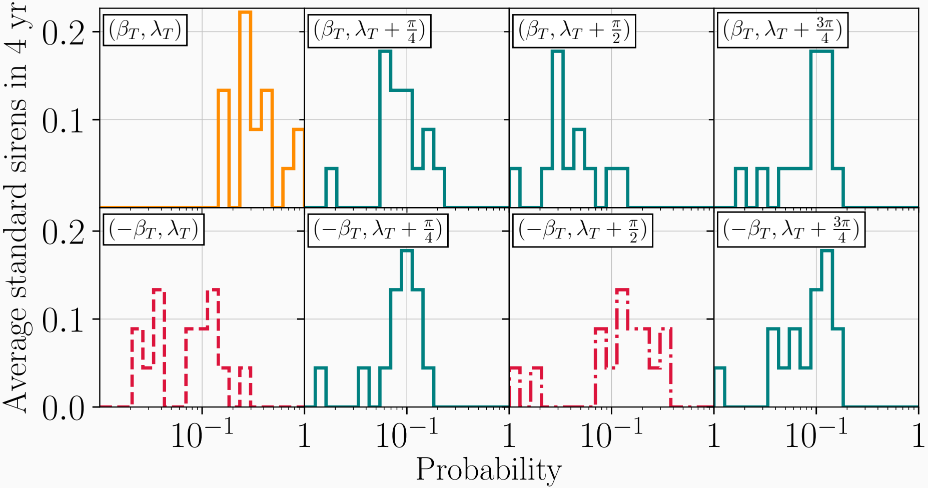
Backup slides



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

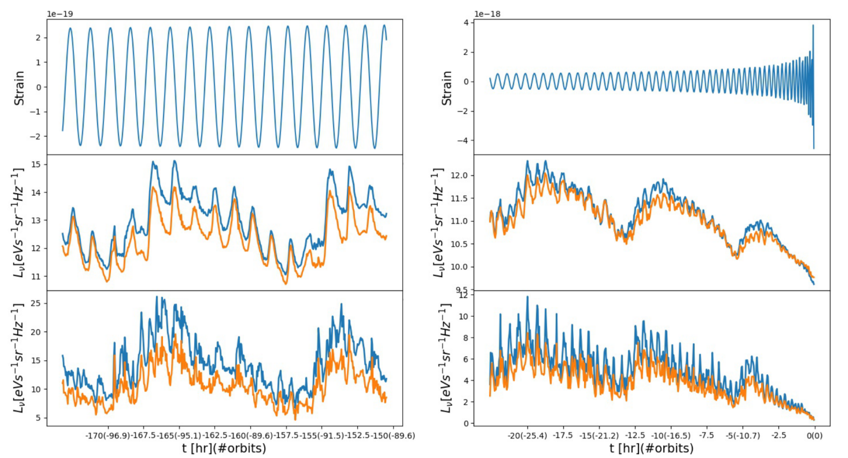
Backup slides

Probability for 8modes systems



Backup slides

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



Backup slides

LISA-Athena synergies (McGee+19)