# Cosmology with massive black hole binary mergers in the LISA era

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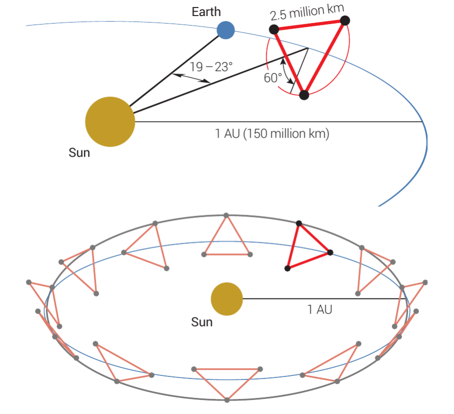
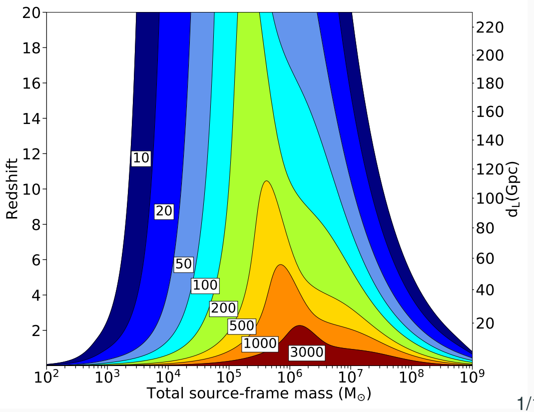
ICHEP2022, 6-13 July 2022, Bologna, Italy

# 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 end 2023/2024



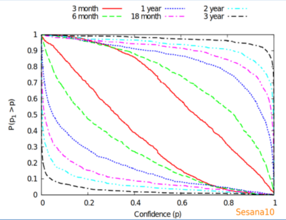



# Why MBHBs?

## The importance of MBHBs

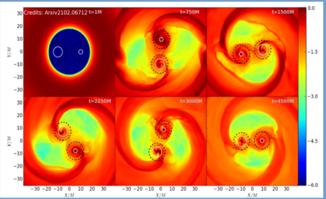
### Astrophysics

Constrain MBHBs formation and evolution scenarios



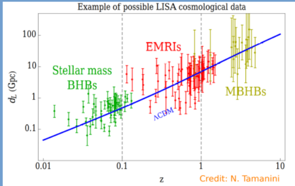

### Multi-messenger

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




### Cosmology

Testing the expansion rate of the Universe



# 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 $z \sim 2-3$

Here we assume $z$ determination from the EM counterpart to the GW signal

# Motivation and aim of the project

## Aim of the project

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

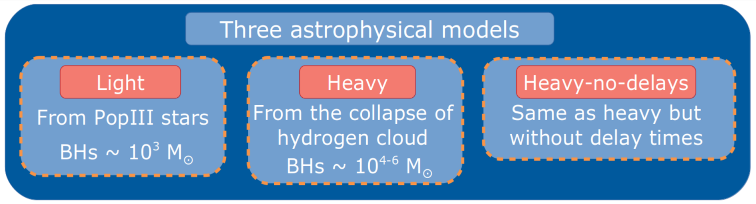
Estimate the number of counterparts over LISA time mission and cosmological parameters

## 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)**

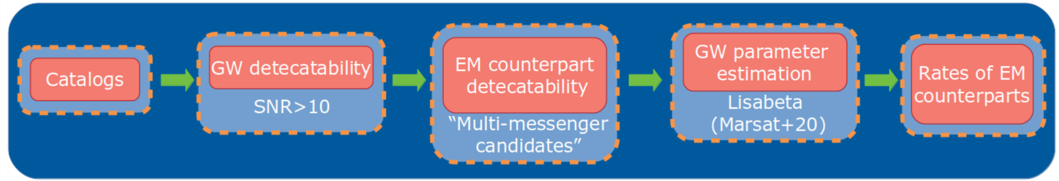
- Affect LSST/VRO and Athena
- Typical hydrogen column density distribution

**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

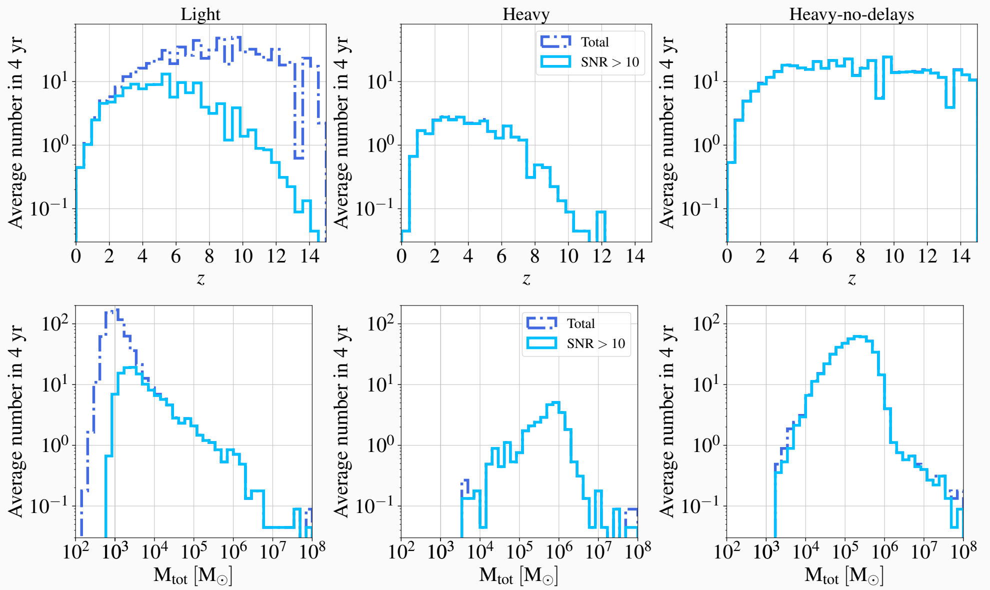
**Maximising**

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

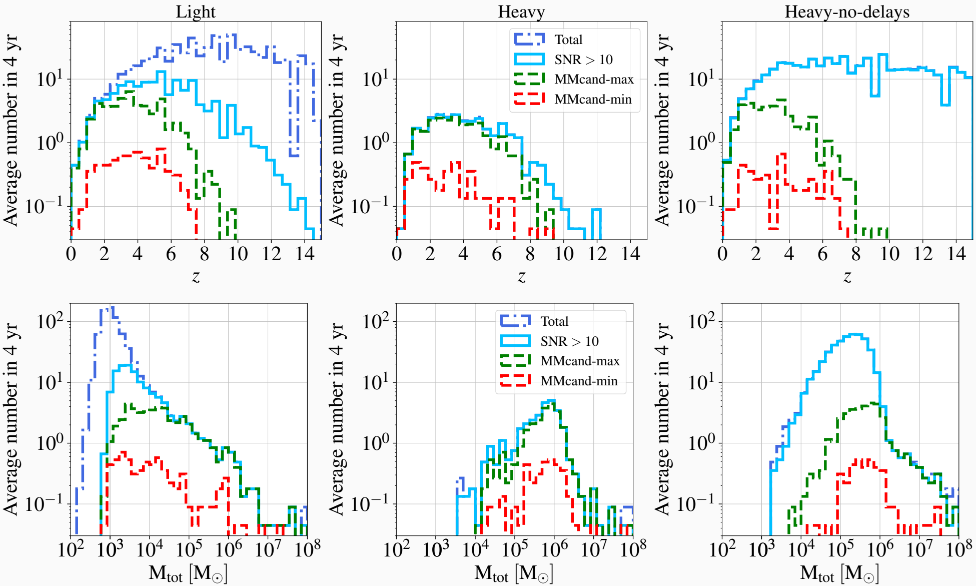
**Minimising**

- 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



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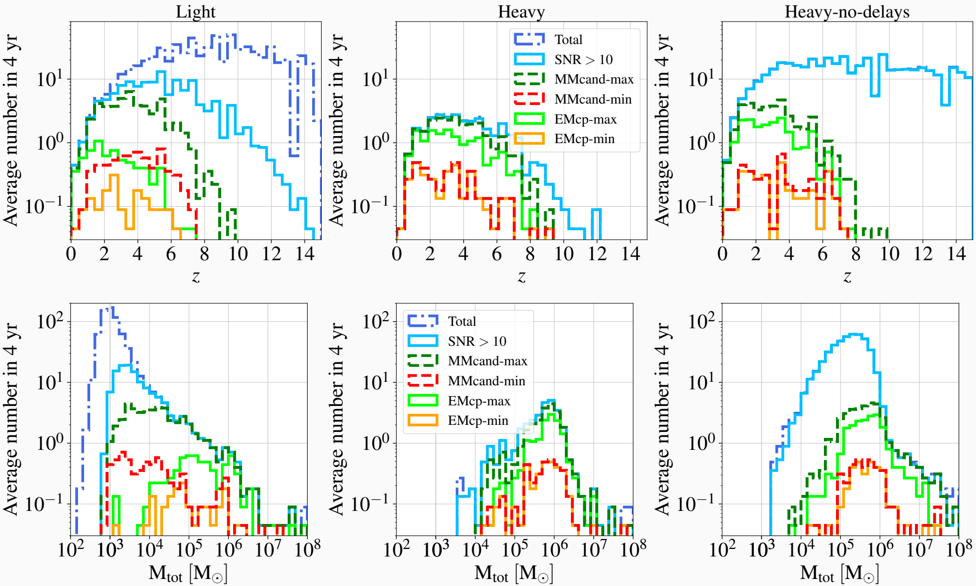


# EMcp rates in 4 yr

| (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 |

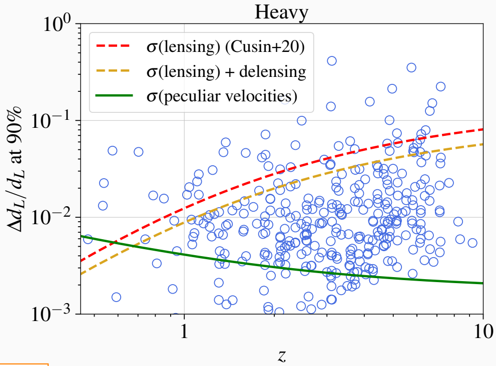
- Dramatic decrease with obscuaration and radio jet
- Parameter estimation selects the *heavy* model

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

# 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

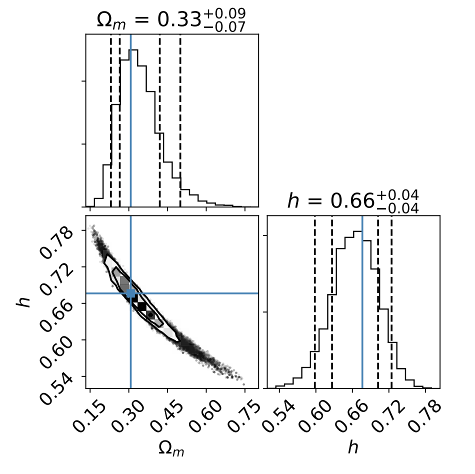
Photometric measurements with $\Delta z = 0.03(1+z)$ (*Laigle* + 19)

ELT

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

# Cosmological applications

Combine the luminosity distance and redshift uncertainty to constrain cosmological parameters




$H_0$ can be constrained to few percent
Larger uncertainties on $\Omega_m$

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

MBHBs multi-messenger & cosmology will be challenging!

# Conclusions

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Thanks! Any questions?

# Backup slides

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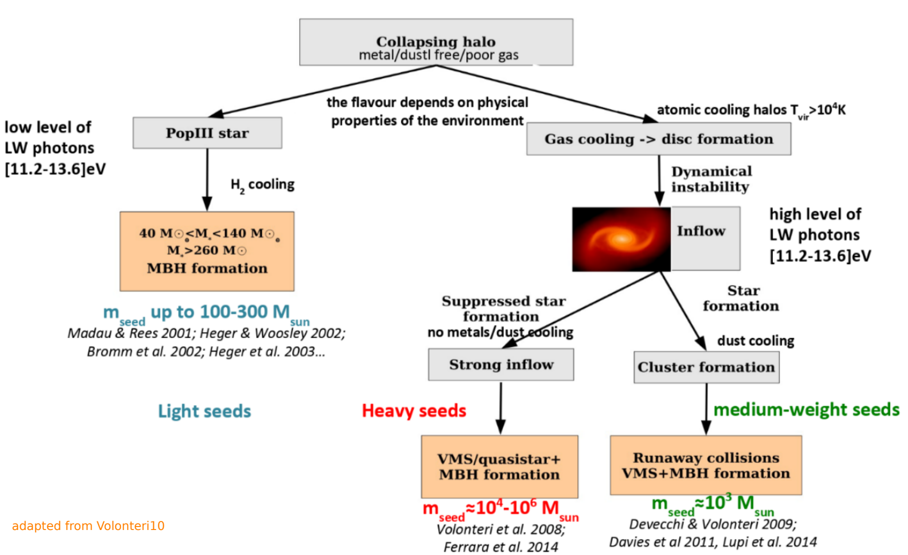
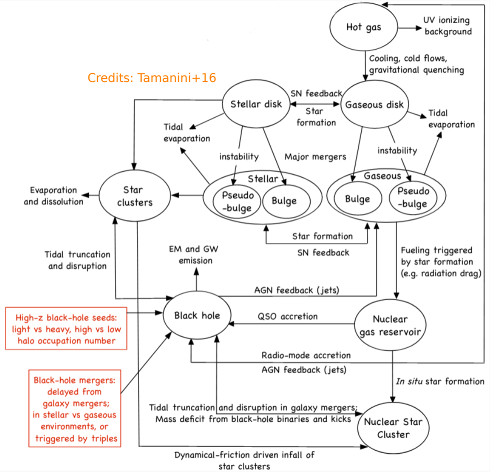
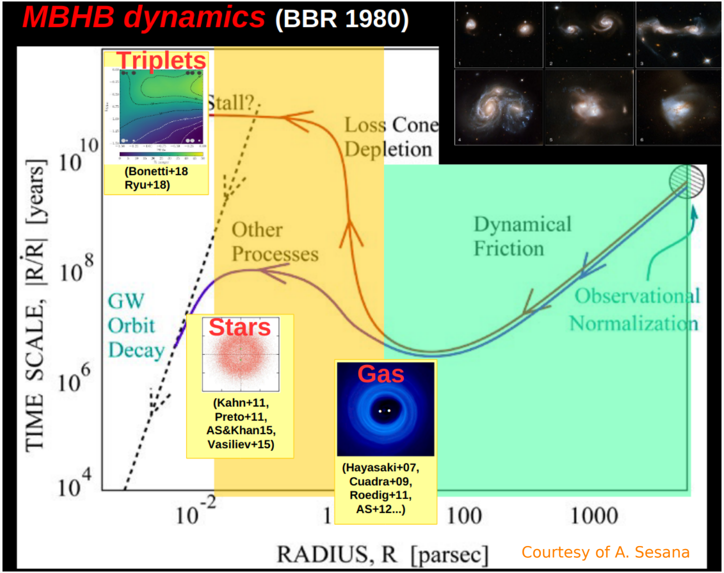


# Backup slides

## The physics of semi-analytical models

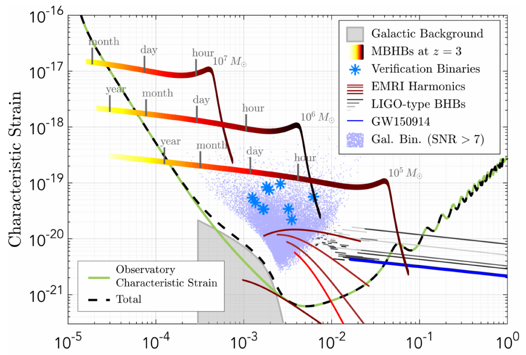


# Backup slides

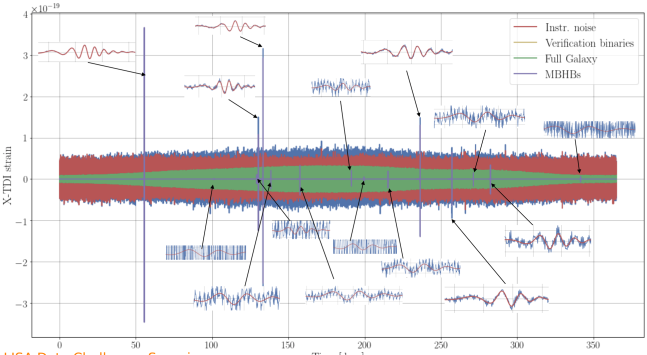


# Backup slides

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



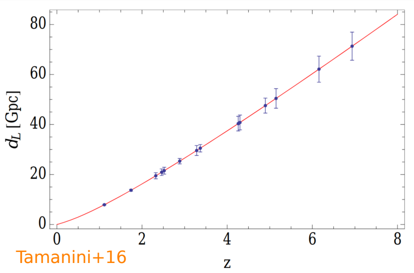

arXiv:1702.00786



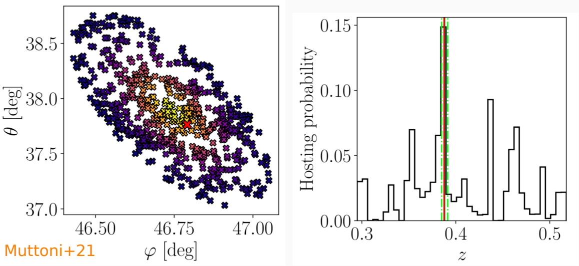

LISA Data Challenge, Sangria

# Backup slides

| Bright sirens | Dark sirens |
|---|---|
| Redshift information from the EM counterpart | Redshift information from the galaxy distribution |
| (Holz+05, Del Pozzo+12, Tamanini+16, LVC+ Nature 551) | (Schutz86, Petiteau+11, Muttoni+21) |
| ✓ Direct redshift information | ✓ More systems |
| ✗ Challenging detection of EM counterpart | ✗ Error volumes with $> 10^3$ galaxies |
| ✗ Few and faint sources | ✗ Catalog completeness at $z \sim 2 - 3$ |



Tamanini+16



Muttoni+21

# Backup slides

**Radio emission**

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

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

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

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.

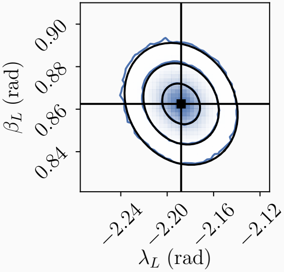
# Backup slides

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 |

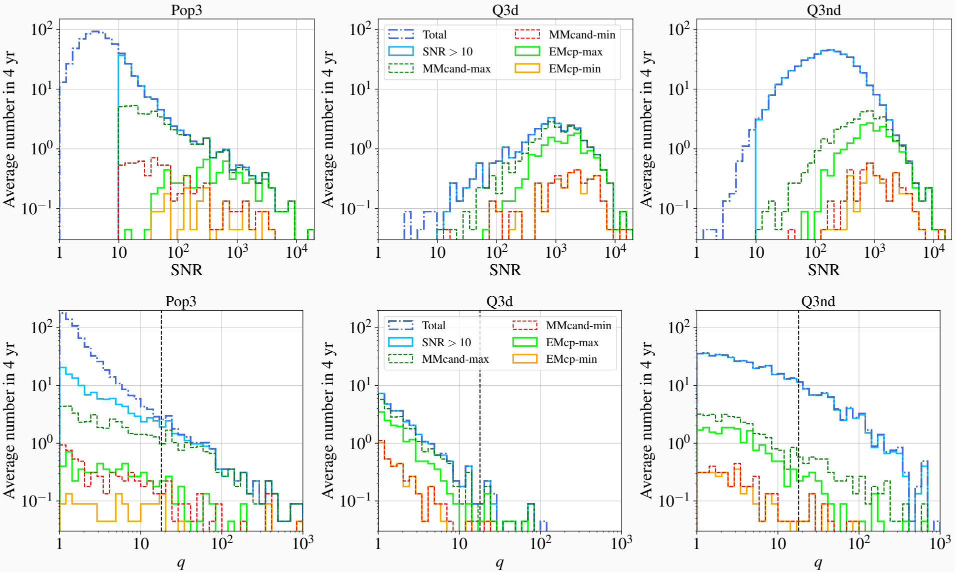
**GW parameter estimation**

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



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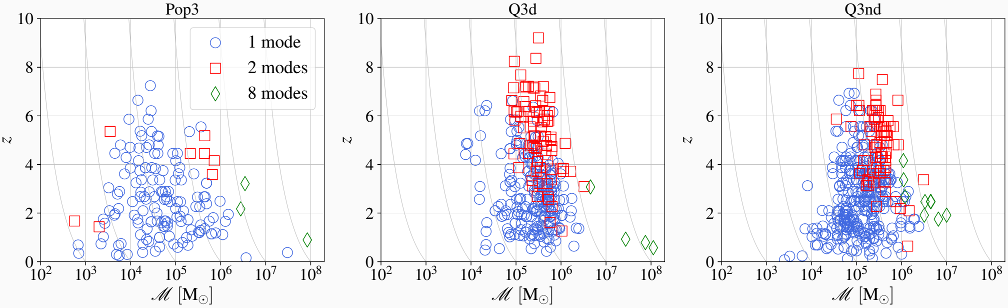
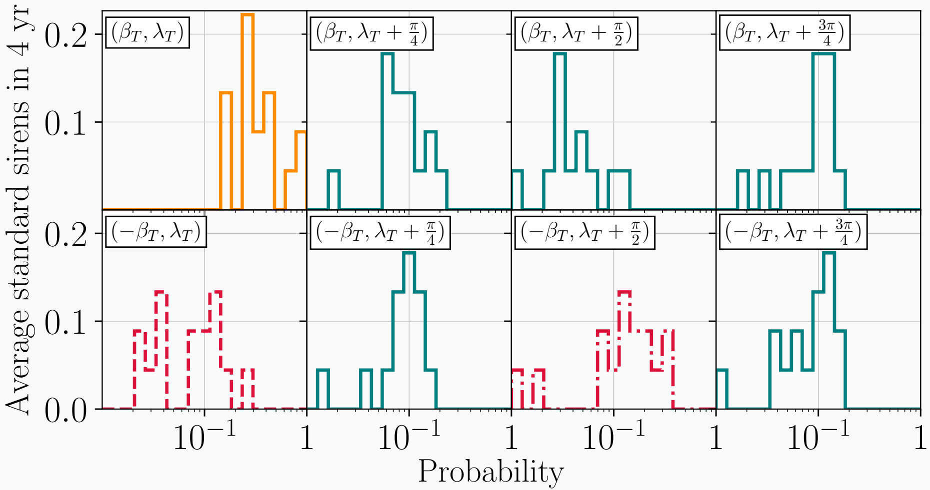



- 1mode systems are the vast majority
- 2mode systems appear at high mass and high redshift
- Still large spread across sub-populations

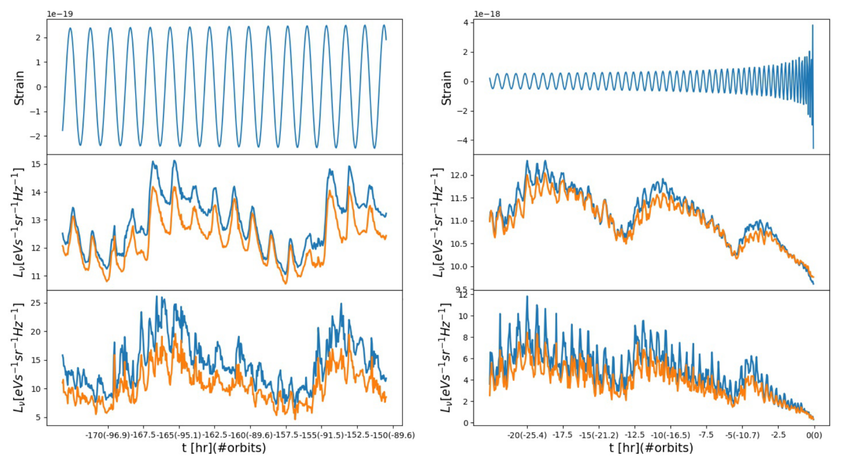
# Backup slides

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)