# Sea of Black Holes:

## Characterizing the LISA Signature for Stellar-Origin Black Hole Binaries

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**Krystal Ruiz-Rocha *et al* 2025 *ApJ* 981 27**

# Big Question:

How many Stellar-Origin Black Hole Binaries(sBHB) will LISA and LIGO/Virgo/KAGRA see over a 4 – 10-year LISA mission?

# Building a binary overview

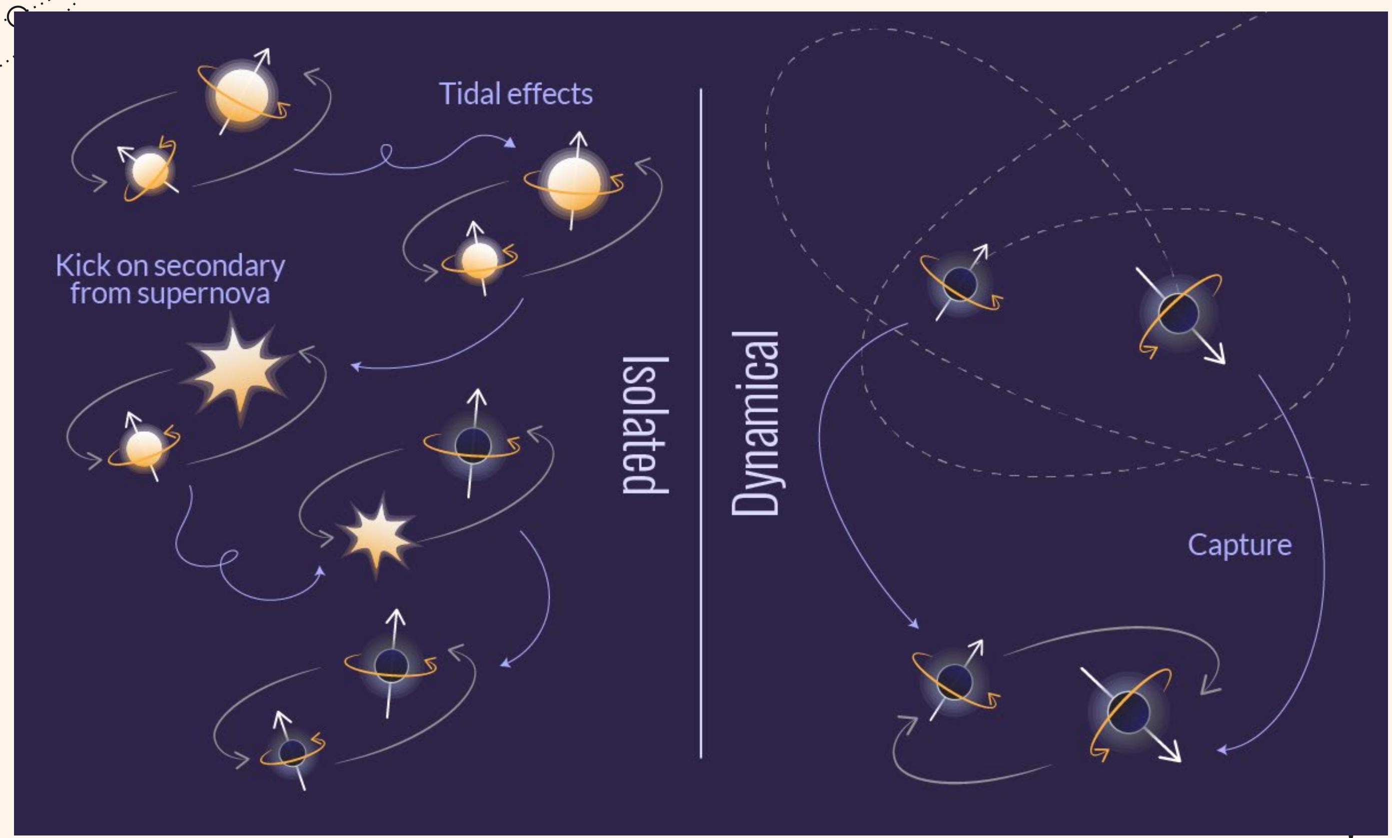
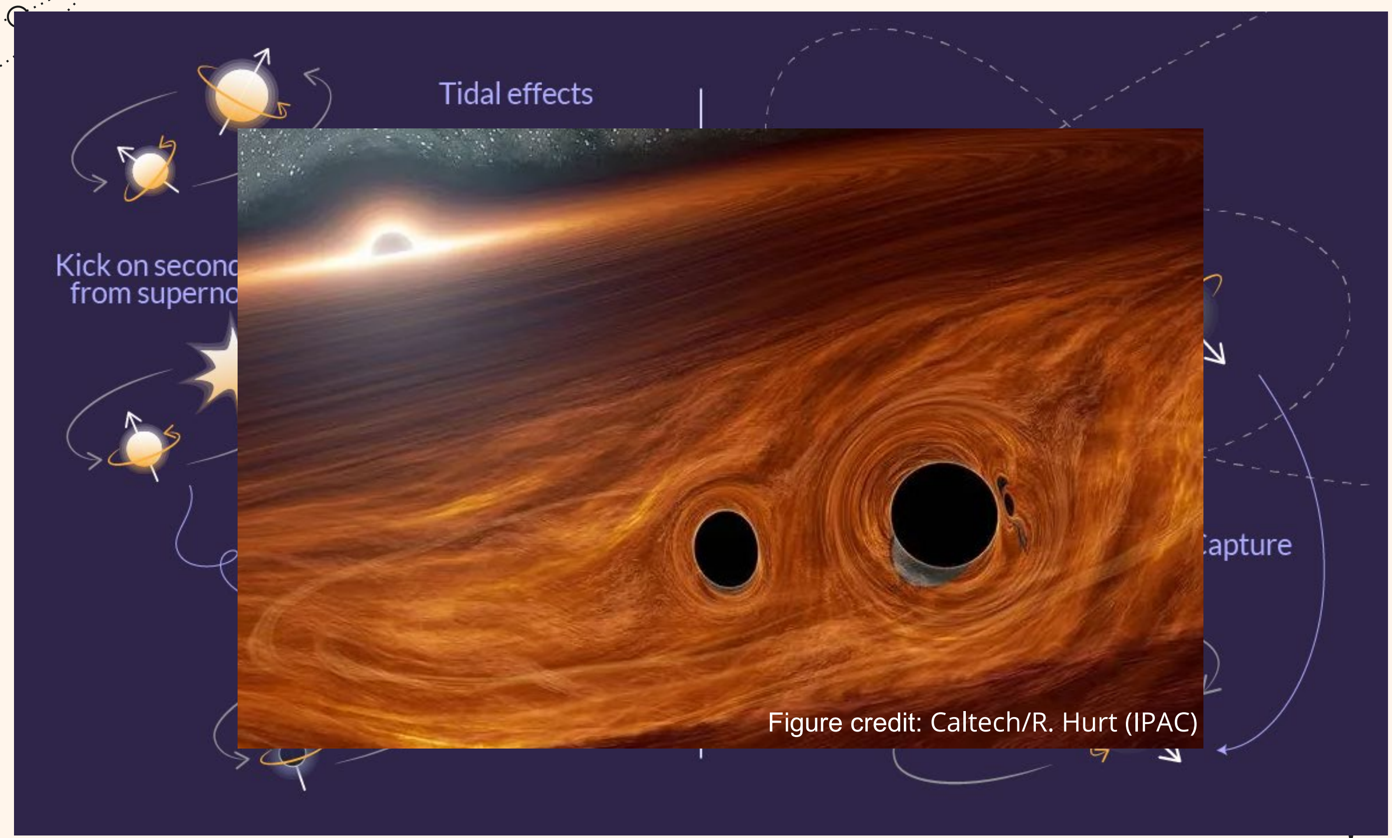



Figure credit: Shanika Galaudage

# Building a binary overview

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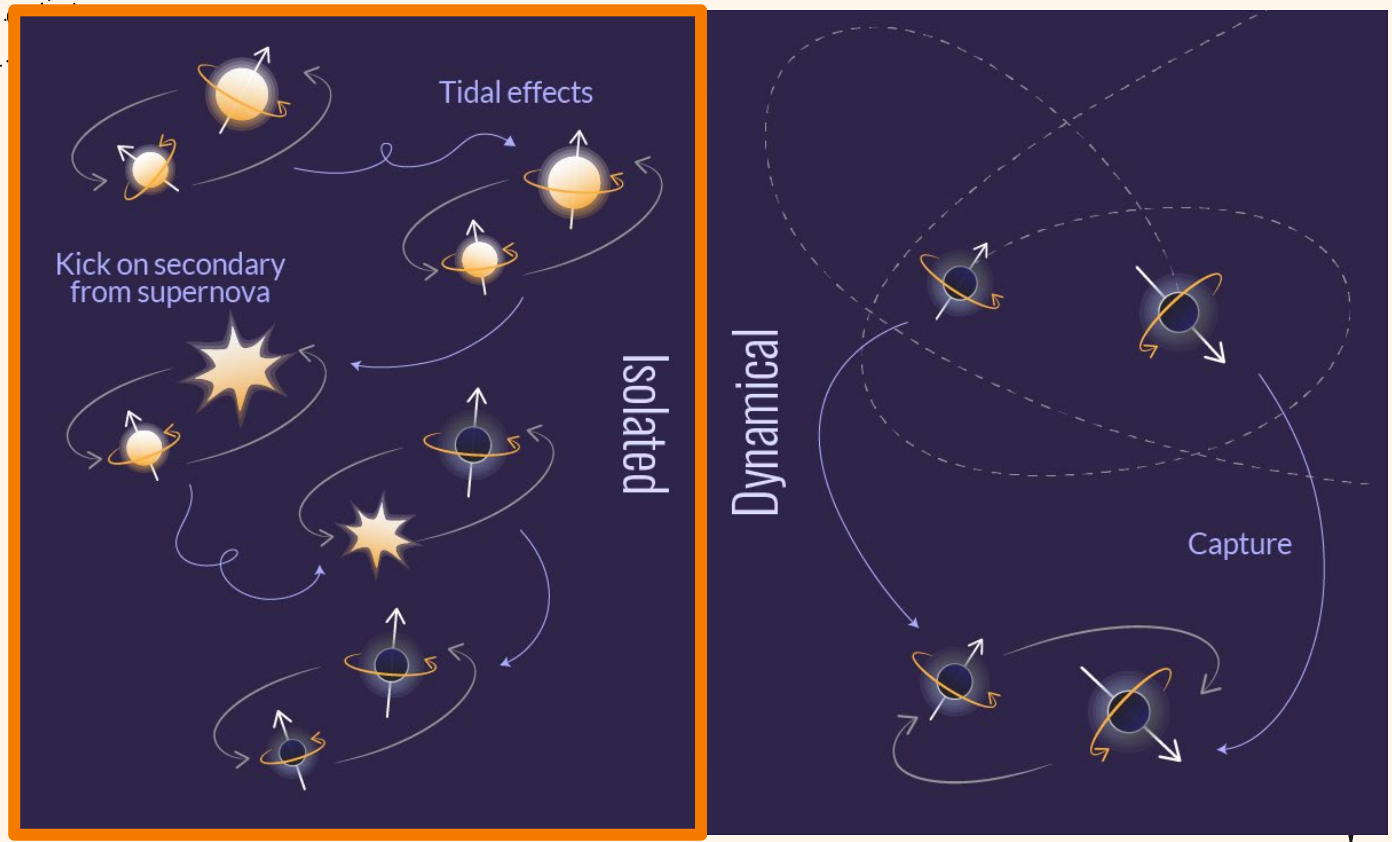



Figure credit: Shanika Galaudage

# Importance of Multiband Astronomy

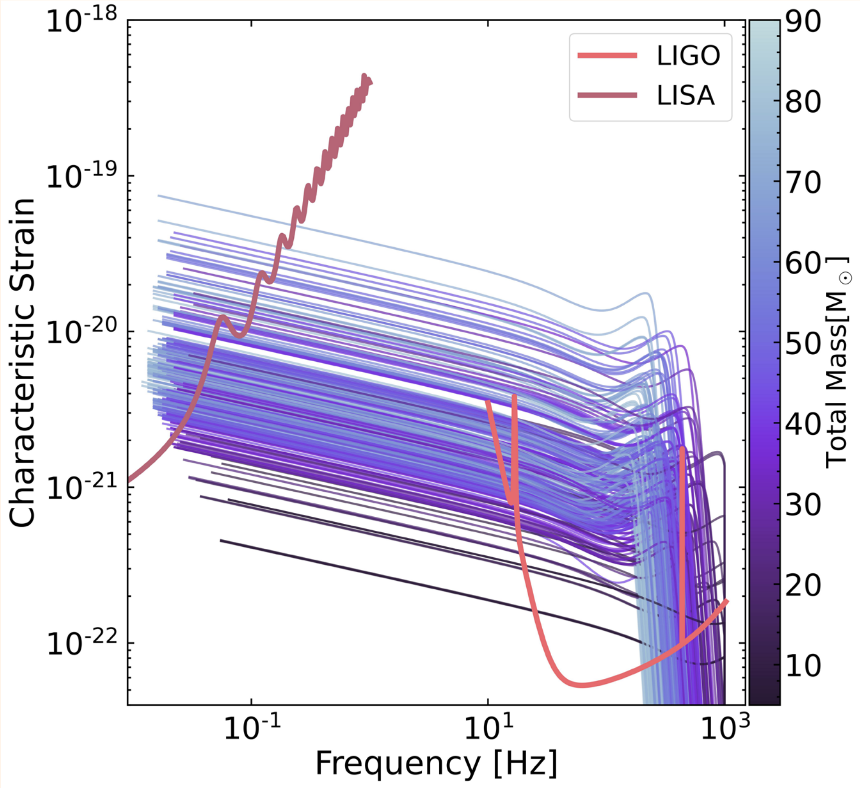
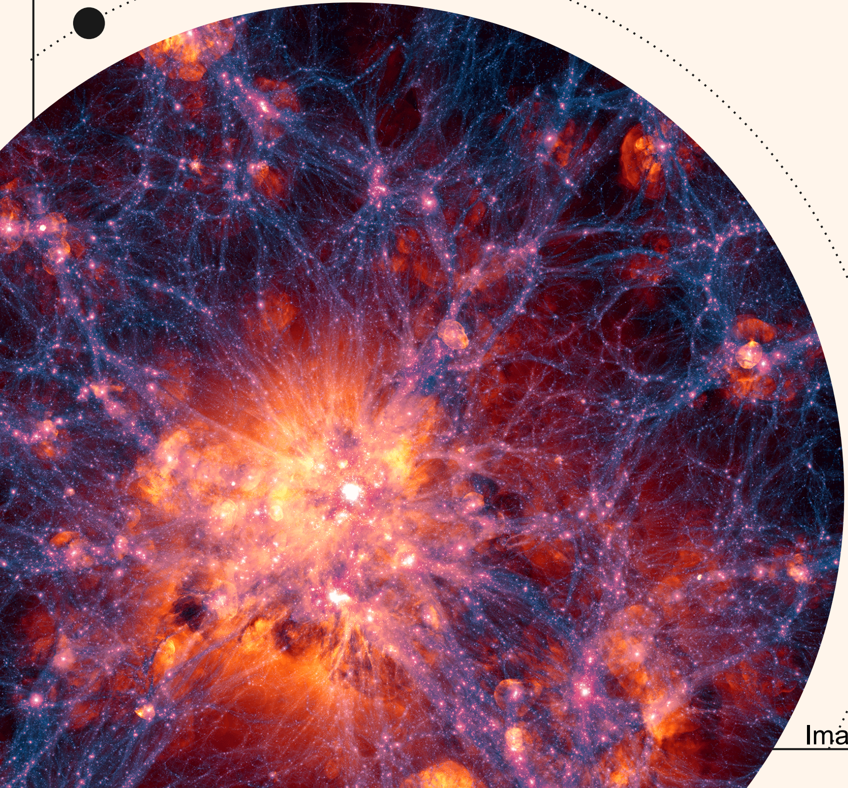



Figure credit: Ruiz-Rocha et al. 2025

- More accurate measurements of:
  - mass, spins, eccentricity, and distance
- Differentiate between different formation channels
- Electromagnetic counterparts

# Novel approach using Ilustris-1

Illustris-1 models galaxy formation and evolution in a cosmological context



## Properties:

- Box with co-moving volume of (106.5 Mpc)$^3$
- Softening length: 710 pc @ z= 0

## Prescriptions:

- Gas cooling
- Star formation models
- Supernovae
- SMBH formation and accretion
- AGN feedback

Image credit: Illustris Collaboration

# Adding sBHB to Illustris-1

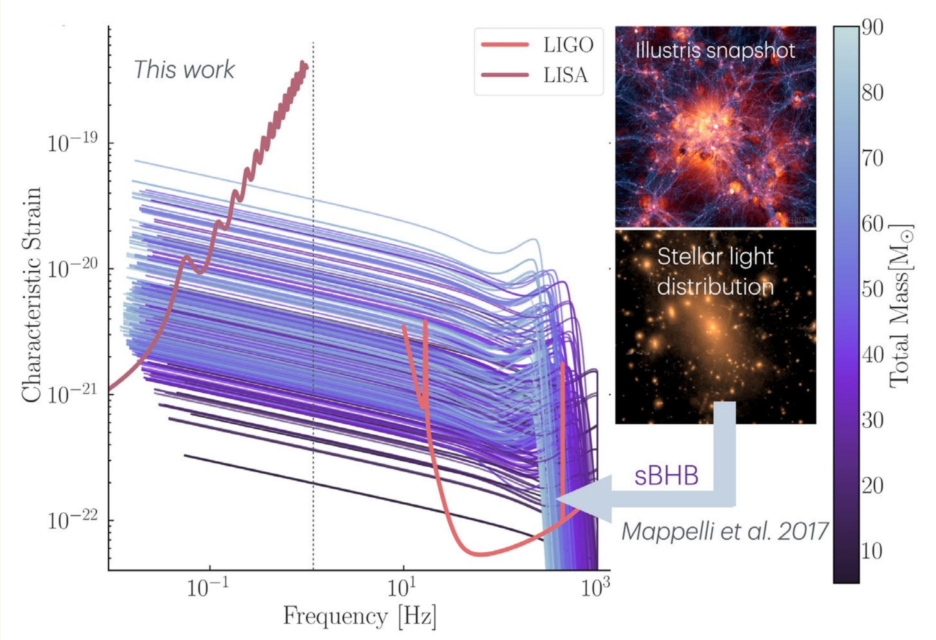
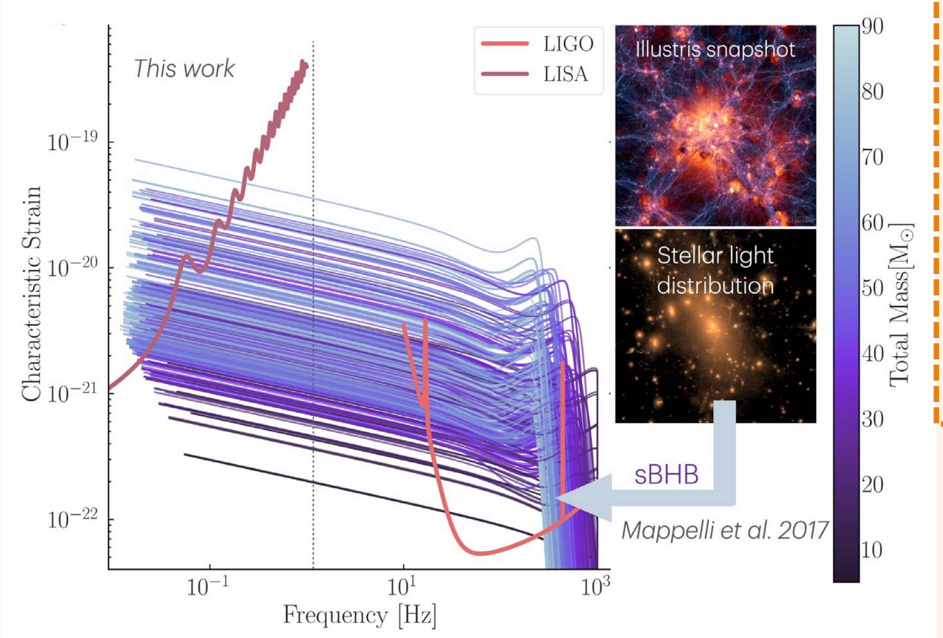



Figure adapted from Ruiz-Rocha et al. 2025 by Karan Jani

## ✦ Adding sBHB to Illustris

- Monte Carlo code to add sBHB to Illustris-1
  - Based on modified version of BSE(MOBSE)
  - BHB associated to Illustris particle
  - Merge within a Hubble time
- For each binary:
  - Masses
  - Merger times
  - Formation times

# Adding sBHB to Illustris-1

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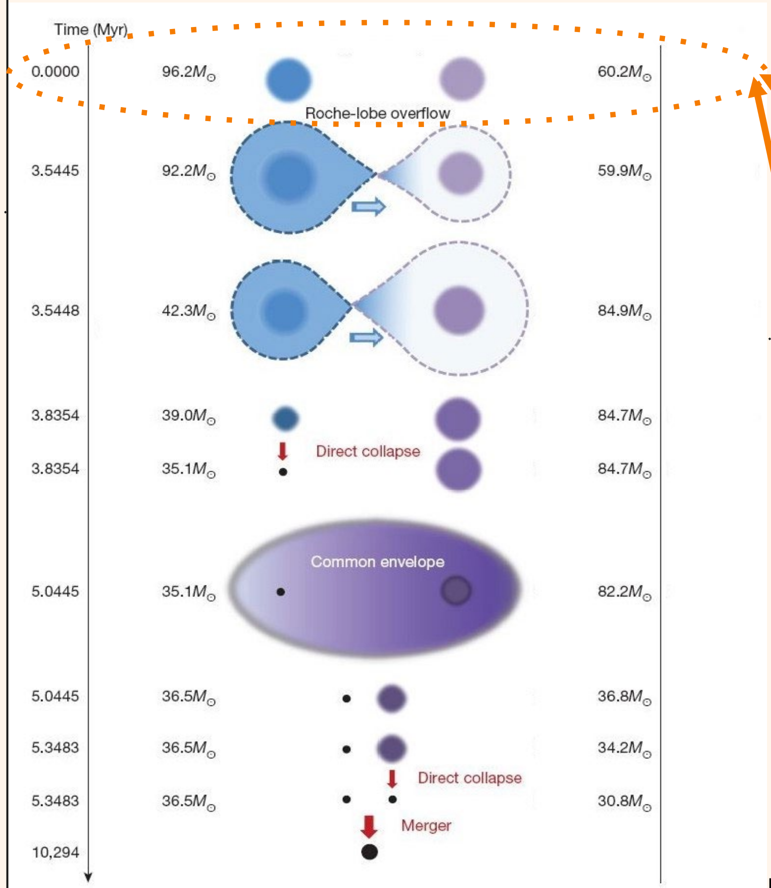
# Building a Binary Population - The Models




- 6 different pathways with different physics choices
  - 12 stellar populations each with different metallicity choices
- 72 total models

- Metallicity and mass of original stellar particle determines which stellar population to use

Figure credit: Belczynski (2016)

# Building a Binary Population - The Models

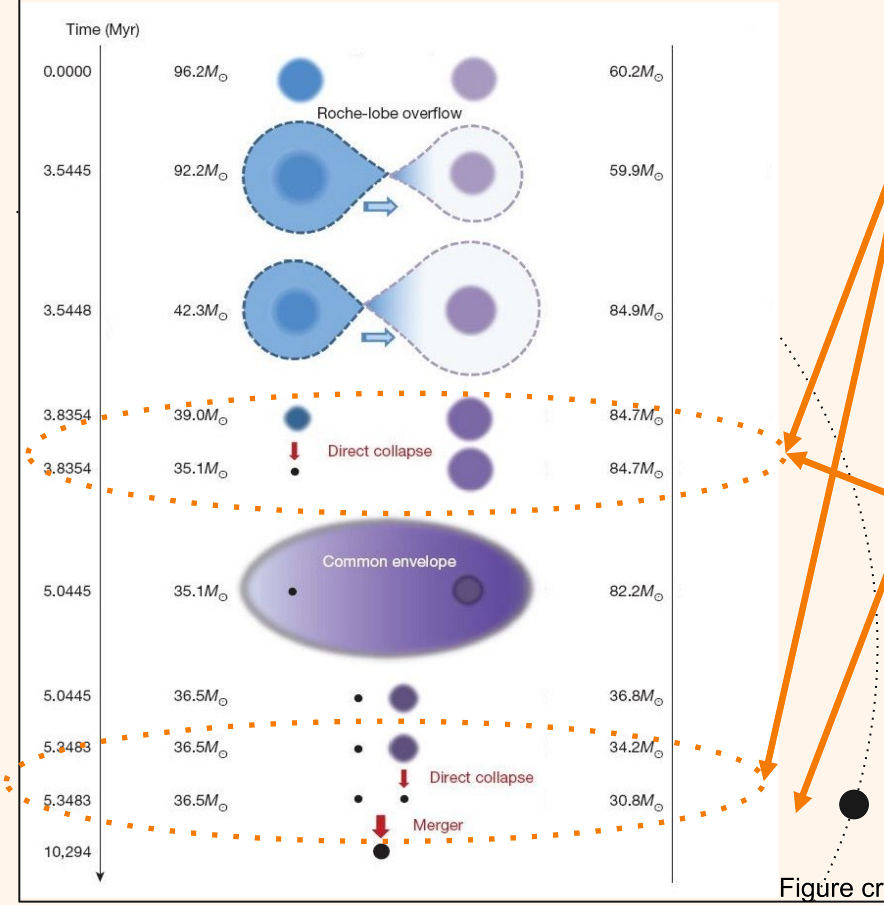



Figure credit: Belczynski (2016)

- Delayed Supernovae
- Natal Kicks
  - Model DK
    - $v_{BH} = v_{NS}$

      $v_{NS}$ neutron star velocity distribution
  - Model D(Fiducial Model)
    - $v_{BH} = v_{NS}(1 - f_{fb})$

      $f_{fb}$ fallback onto stellar envelope

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# sBHB Database

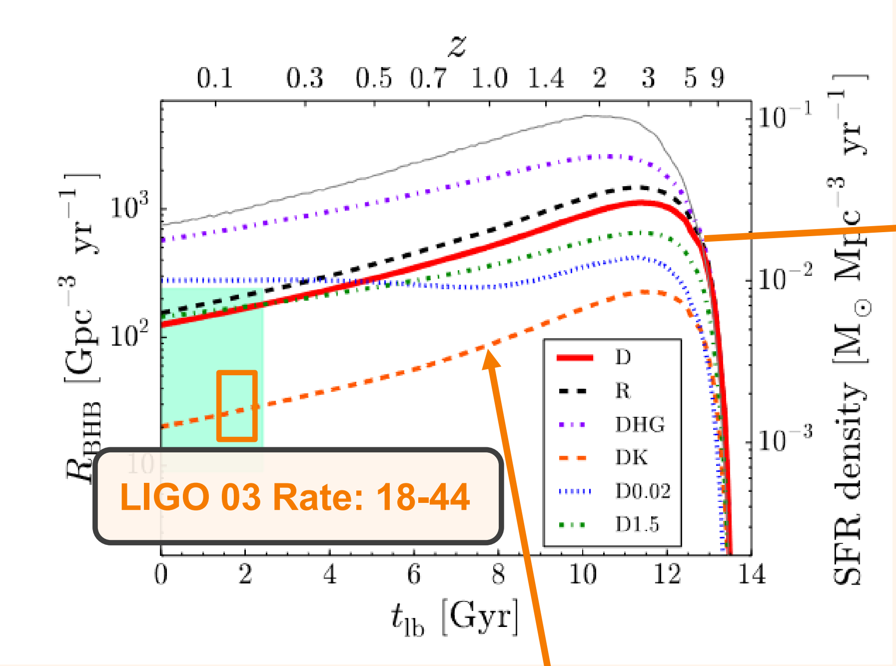
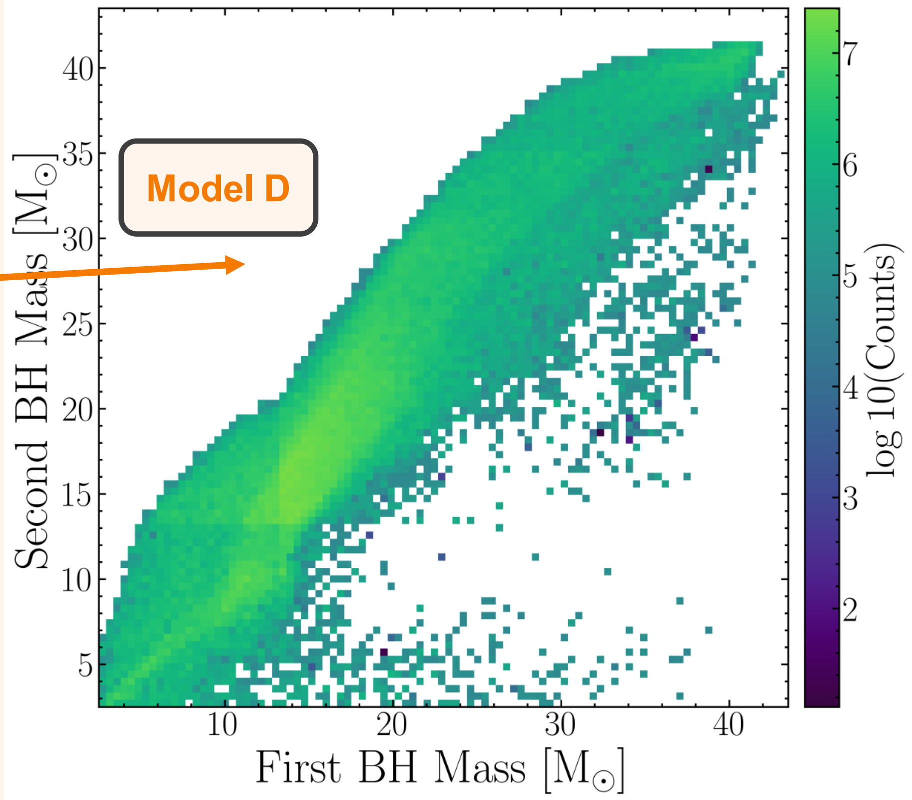



Figure credit: Mapelli et al. 2017

LIGO 03 Rate: 18-44

Model DK fits LIGO O3 Observations

Model D



# Zooming In

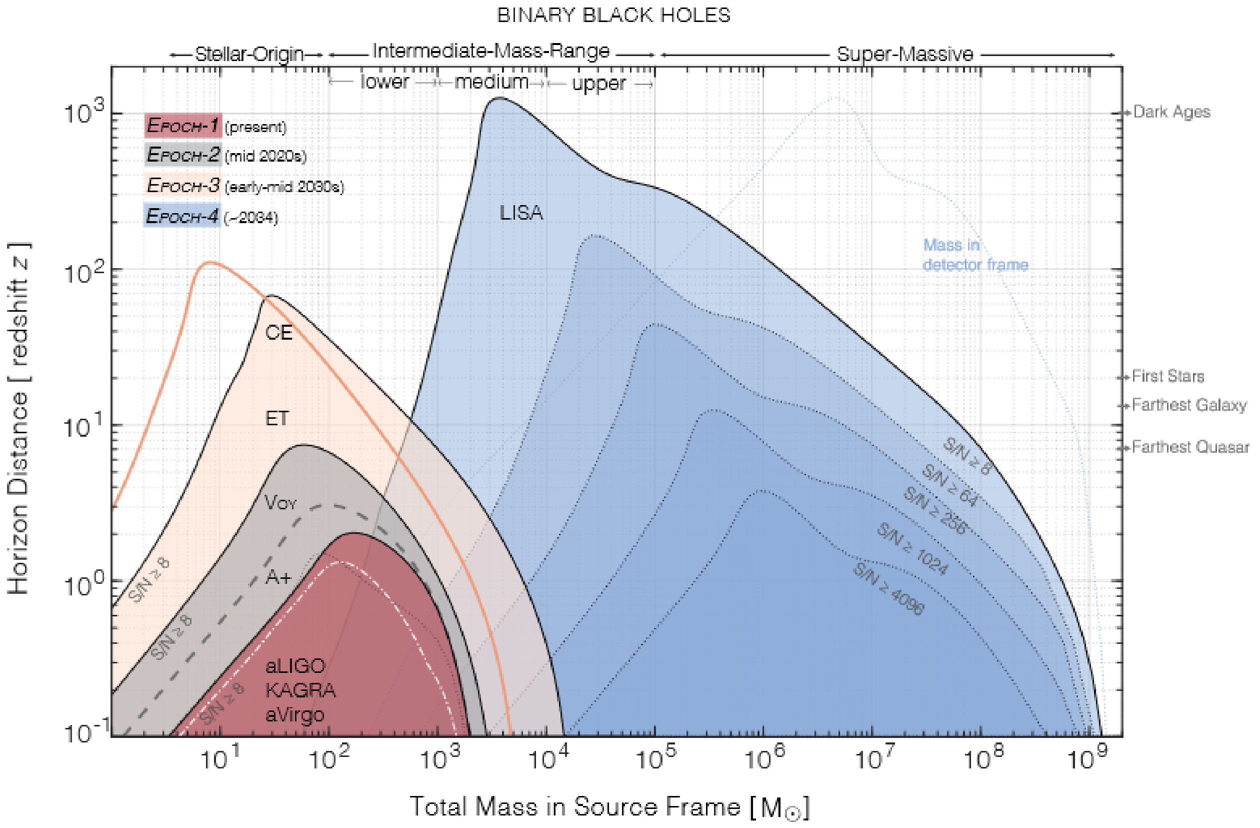



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Figure credit: Jani et al. 2020

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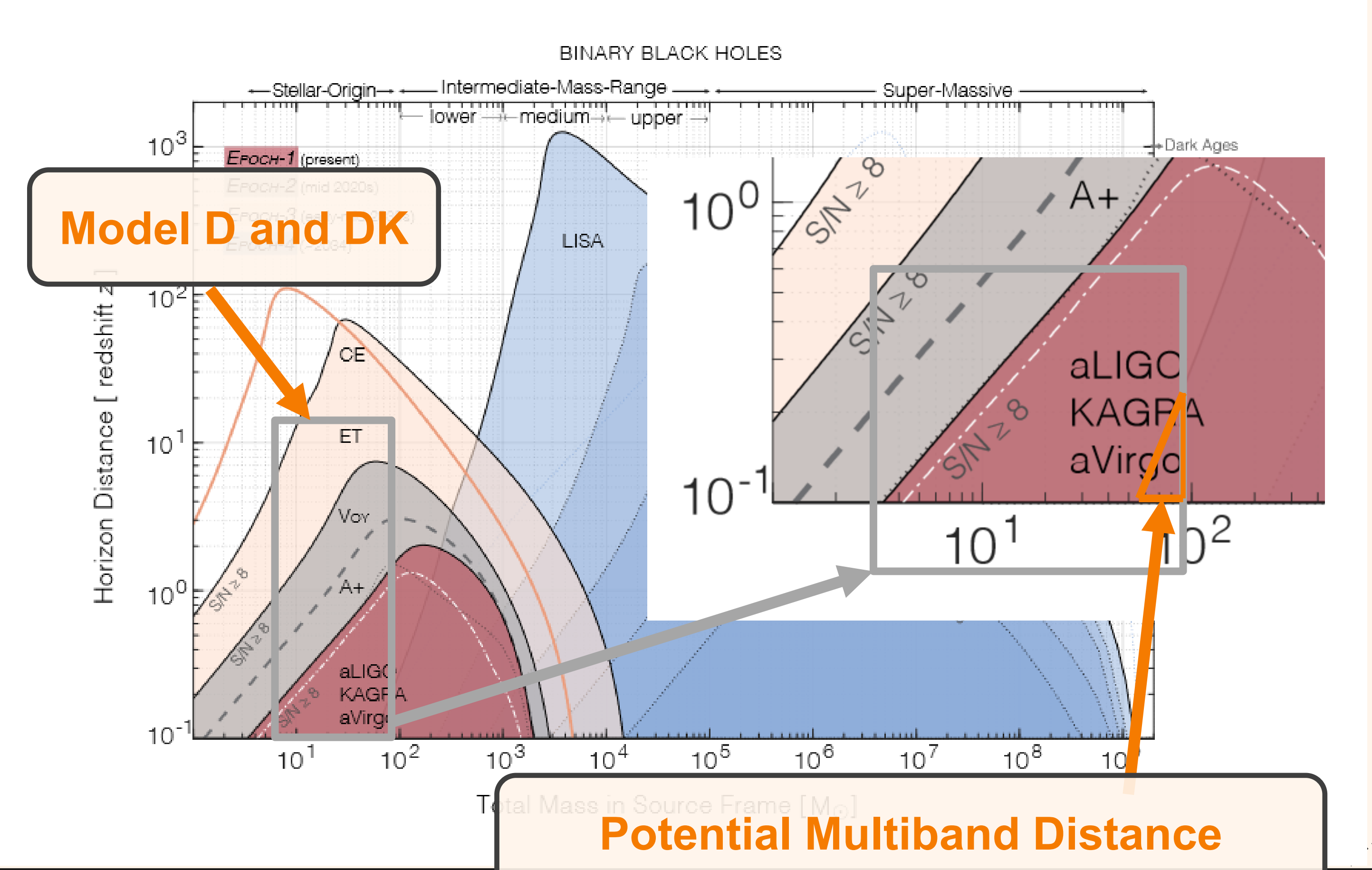


Model D and DK

Potential Multiband Distance

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Figure credit: Jani et al. 2020

# High Natal Kicks Consistent with LIGO O3 Rates

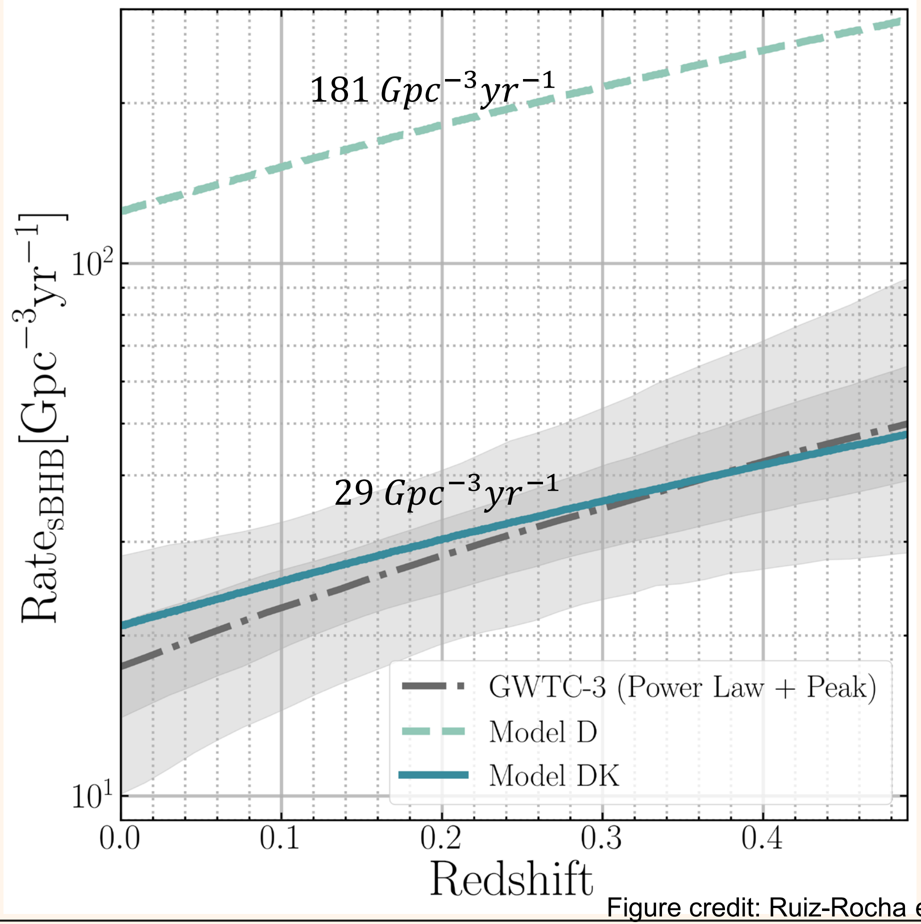



Figure credit: Ruiz-Rocha et al. 2025

# Calculating Signal-to-Noise Ratio

- $f_{beg}$: 4, 6, 8, 10 years before merger for a 4, 6, 8, 10 year LISA run
- Use LISA Sensitivity code from Robson et al. 2019
- Assumes:
  - PhenomA waveform model
  - No spin
  - No eccentricity

# Our Database

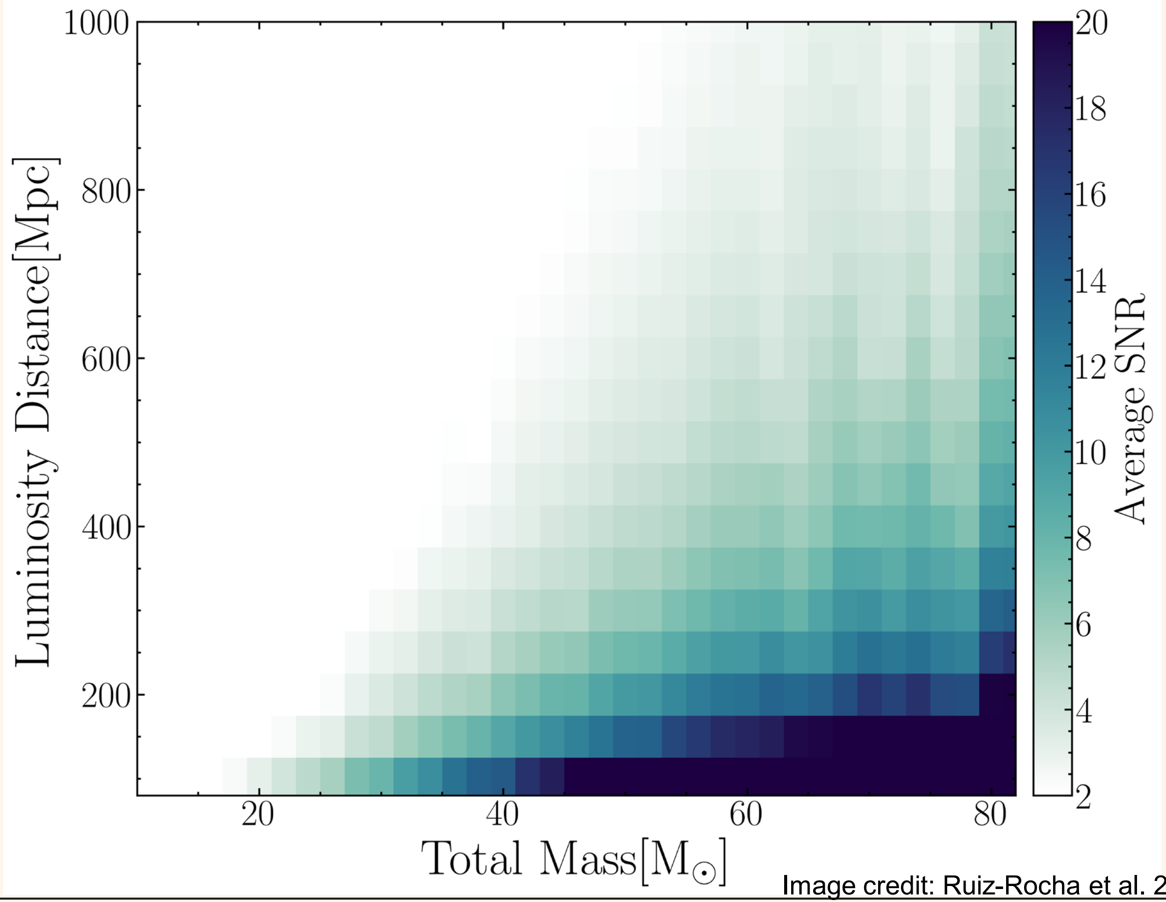



Image credit: Ruiz-Rocha et al. 2025

# Calculating Rates

Conversion of the time element to observer frame

Comoving Volume at z

$$\frac{\mathrm{d}N}{dzdt} = \frac{d^2n(z,\rho)}{dzdV_c}\frac{dz}{dt}\frac{dV_c}{dz}\frac{1}{1+z}$$

Number of Mergers at a z and SNR Threshold

Total number of mergers

$$\frac{d^2n(z,\rho)}{dzdV_c} = \frac{N(z,\rho)}{\Delta z V_{sim}}$$

Redshift Bin

Simulation Volume

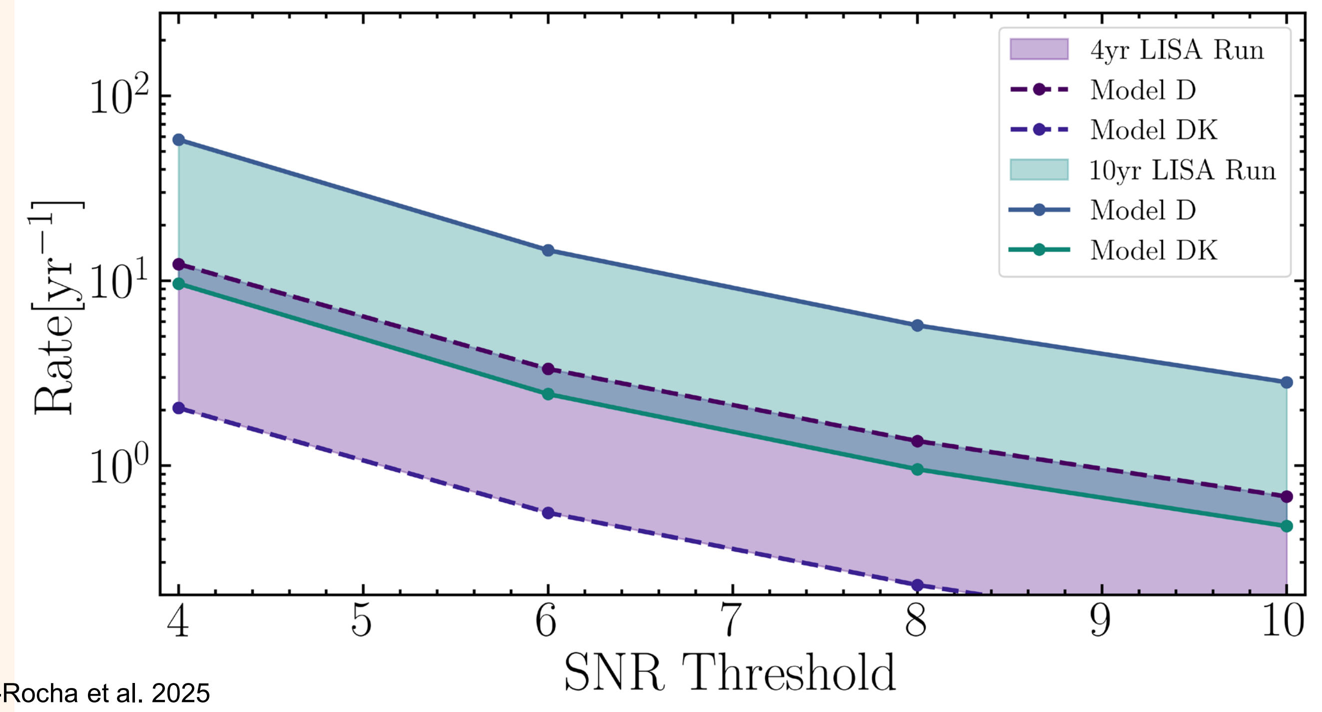
**With this equation we can make predictions of Multiband rates!**

Chen et al. 2022

Krystal Ruiz-Rocha

# What are the Expected Rates?

$$\frac{\mathrm{d}N}{dzdt} = \frac{d^2 n(z,\rho)}{dzdV_c}\frac{dz}{dt}\frac{dV_c}{dz}\frac{1}{1+z}$$

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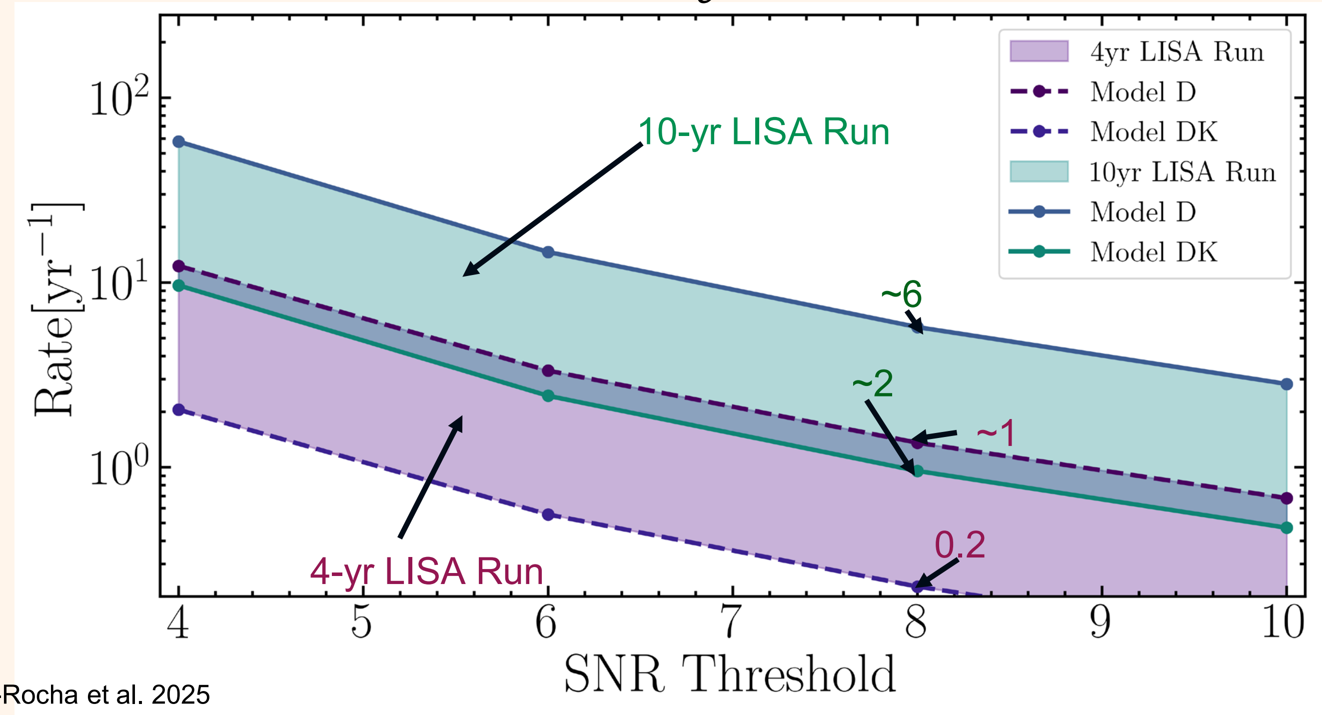


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# How many Multi-Band events will LISA see?

$$N = \frac{dN}{dzdt} T_{obs}$$

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| LISA mission lifetime | Marginal sBHB detections ($\rho \geq 4$) | Confirmed sBHB detections ($\rho \geq 8$) |
|---|---|---|
| 4 years | 8.2 – 49.2 | 0.9 – 5.4 |
| 6 years | 24.2 – 145 | 2.6 – 15.3 |
| 8 years | 52.5 – 315.2 | 5.4 – 32.5 |
| 10 years | 96.5 – 578.9 | 9.6 – 57.4 |

Model DK

Model D

Table credit: Ruiz-Rocha et al. 2025

# Summary

- ✦ Model DK has larger natal kicks leading to lower predictions
- ✦ Our values are broadly consistent with:
  - **LISA Study Report** $t_{coalescence} < 4.5$ yr: $<$ **1.4 events**
  - **Zhao 2023** $T_{obs} = 4$ yr: **3-15 events**
  - **Kyutoku & Seto 2016** $T_{obs} = 10$ yr: **8-100 events**
  - **Gerosa 2019** $T_{obs} = 10$ yr: **4-22 events**

| LISA mission lifetime | Confirmed sBHB detections |
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Adapted from: Ruiz-Rocha et al. 2025

# Future Work

- No IMBHs in database
  - Follow up with an IMBH version of work

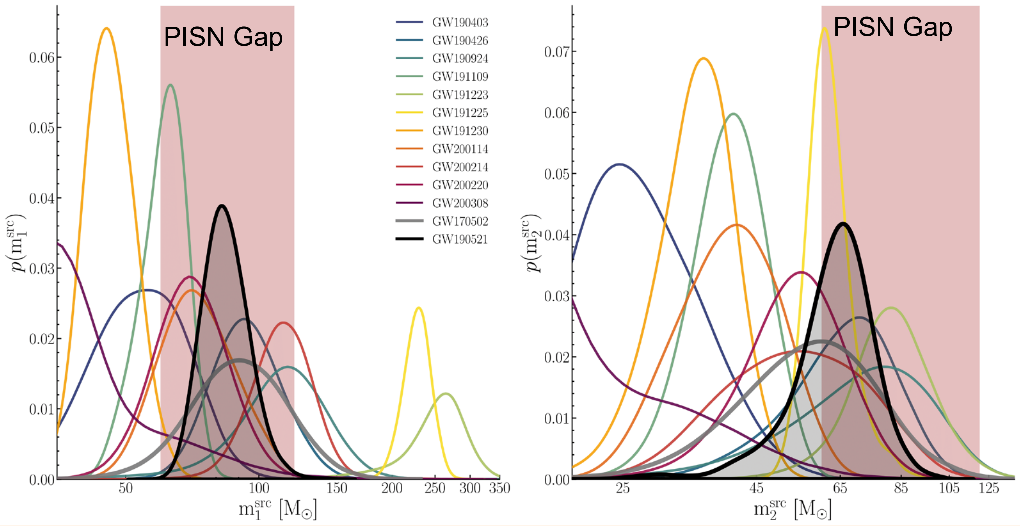


Figure credit: Ruiz-Rocha and Yelikar et al. 2025(Accepted APJ Letters)

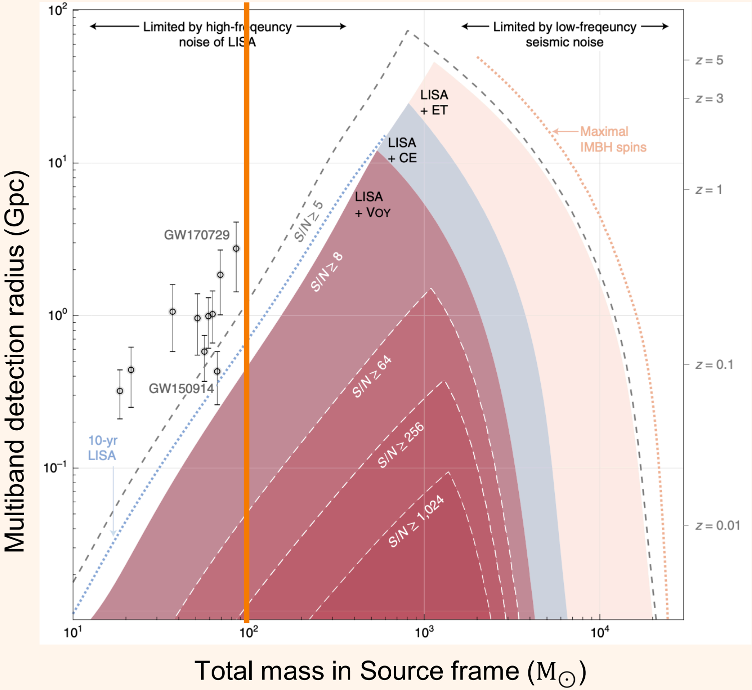


Figure credit: Jani et al. 2020

# Thank you.
# Any Questions?

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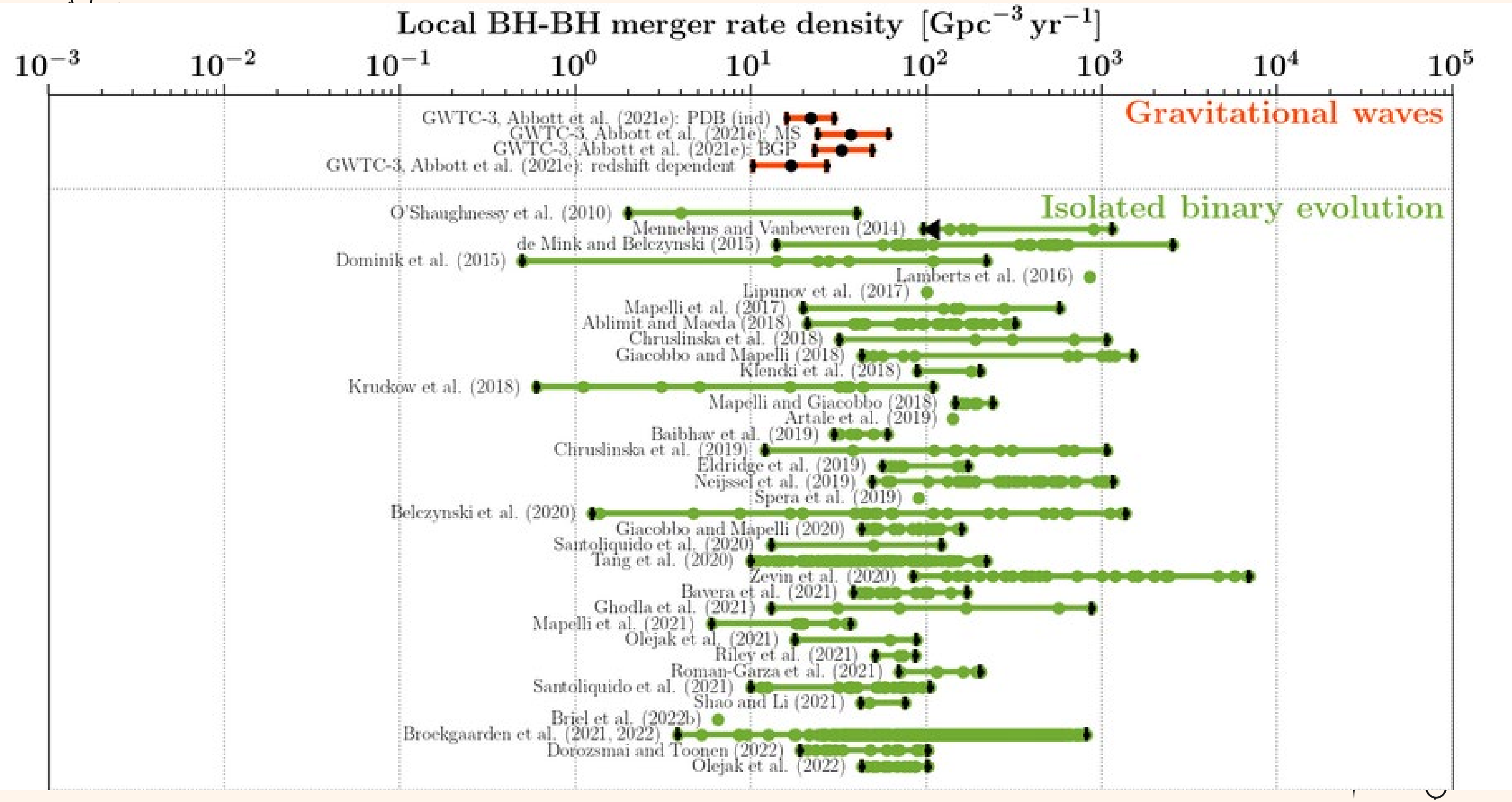
# BACKUP SLIDES

# Rates per model




Mandel & Broekgaarden (2021)

# Mapelli's Models

**Table 1.** Properties of the population-synthesis simulations.

| Name | SN | $\alpha$ | $\lambda$ | HG | Kick |
|---|---|---|---|---|---|
| D | Delayed | 1.0 | 0.1 | new | F12 |
| R | Rapid | 1.0 | 0.1 | new | F12 |
| DHG | Delayed | 1.0 | 0.1 | BSE | F12 |
| DK | Delayed | 1.0 | 0.1 | new | H05 |
| D0.02 | Delayed | 0.2 | 0.1 | new | F12 |
| D1.5 | Delayed | 3.0 | 0.5 | new | F12 |

Column 1: model name; column 2: SN model (delayed and rapid from Fryer et al. 2012); column 3: value of $\alpha$; column 4: value of $\lambda$; column 5: treatment for HG stars ('BSE' means same treatment as in BSE, 'new' means that we force all CE binaries with a HG donor to merge); column 6: model for the SN kick. H05 means that we use the distribution from Hobbs et al. (2005). F12 means that we rescale the natal kicks by the fallback, as described in Fryer et al. (2012). See also equation 1 and the text for details.

Table Credit: Mapelli et al. 2017

# Rates

**Table 2.** Comoving BHB merger-rate density at redshift $z = 0$ and $z = 0.2$ (corresponding to $t_{\rm lb} = 0$ and 2.43 Gyr, respectively).

| Name | $R_{\rm BHB}(z=0)$ [Gpc$^{-3}$ yr$^{-1}$] | $R_{\rm BHB}(z=0.2)$ [Gpc$^{-3}$ yr$^{-1}$] |
|---|---|---|
| D | 125 | 181 |
| R | 155 | 228 |
| DHG | 572 | 772 |
| DK | 20 | 29 |
| D1.5 | 145 | 181 |
| D0.02 | 278 | 279 |

Column 1: model name; column 2: present-time BHB merger rate density; column 3: BHB merger rate density at $z = 0.2$.

Table Credit: Mapelli et al. 2017