

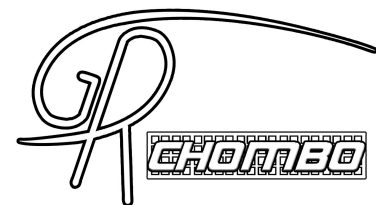
# Compact objects in the High Redshift Universe

Chair: Katy Clough

Panelists: Josu Aurrekoetxea, Suvodip Mukherjee,  
Luca Reali, Isobel Romero-Shaw

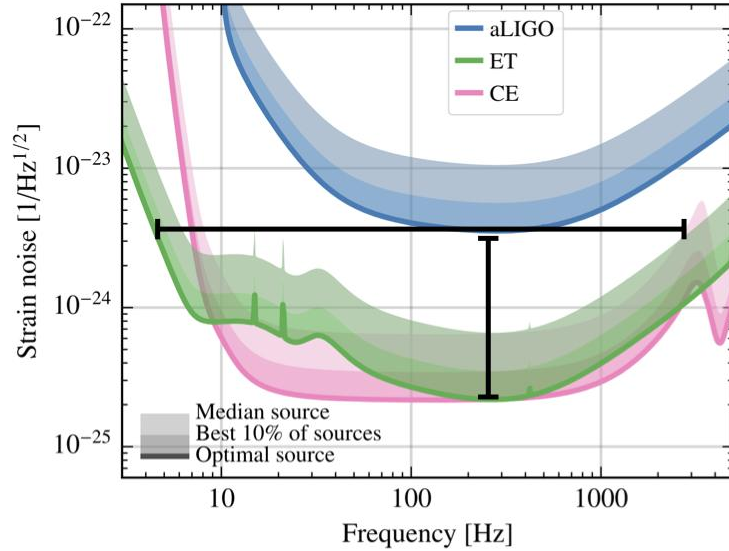
# Josu Aurrekoetxea

- **Beecroft Fellow at Oxford** → **CTP Fellow at MIT**
- Expertise in **Numerical Relativity** and **Fundamental Physics**
  - **Strong gravity** phenomena in the **early universe**
  - **GW** modelling of **exotica** (DM, strings, boson stars)
- ***How can we search for new physics with GWs?***
  - The effect of wave DM on equal-mass BH mergers (2023)
  - Revisiting the cosmic string origin of GW190521 (2023)

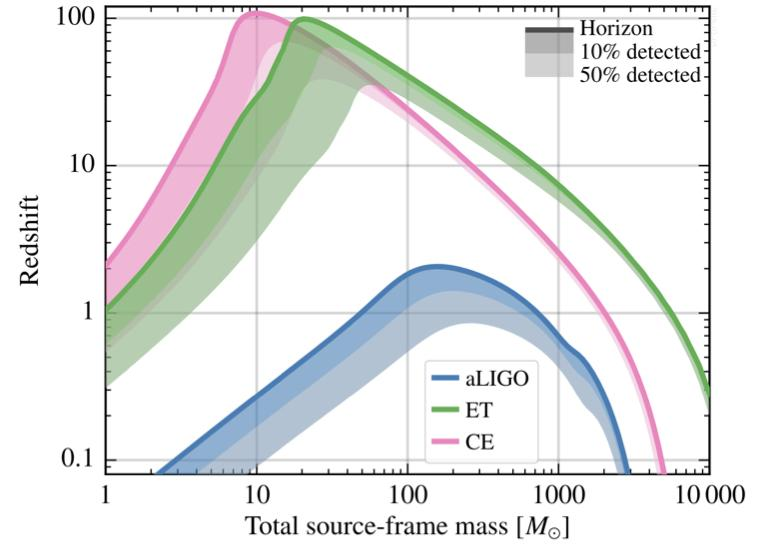


# 2G vs 3G

Sathyaprakash et al. (2019)  
GWIC Science Book (2021)



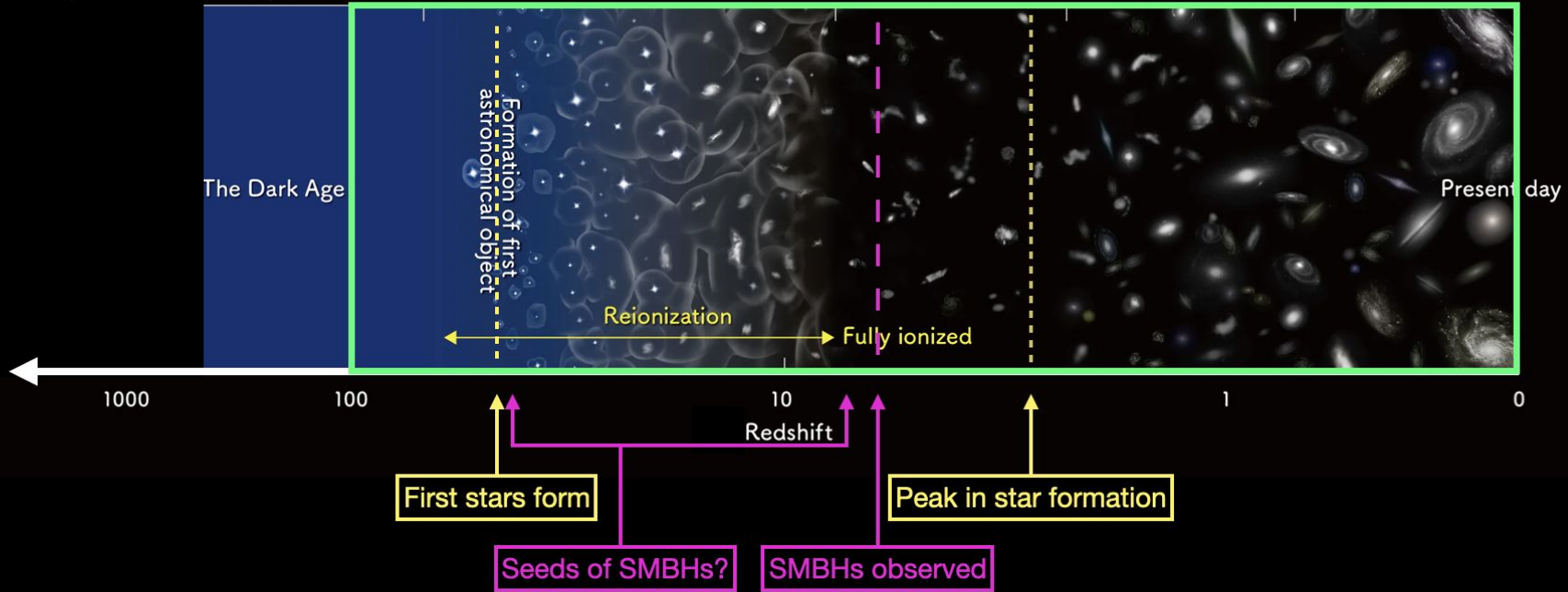
- **20x better sensitivity**
- **Higher bandwidth**



- **100x larger redshift**
- **More massive and for longer**

Image credit: Redshift Wrangler

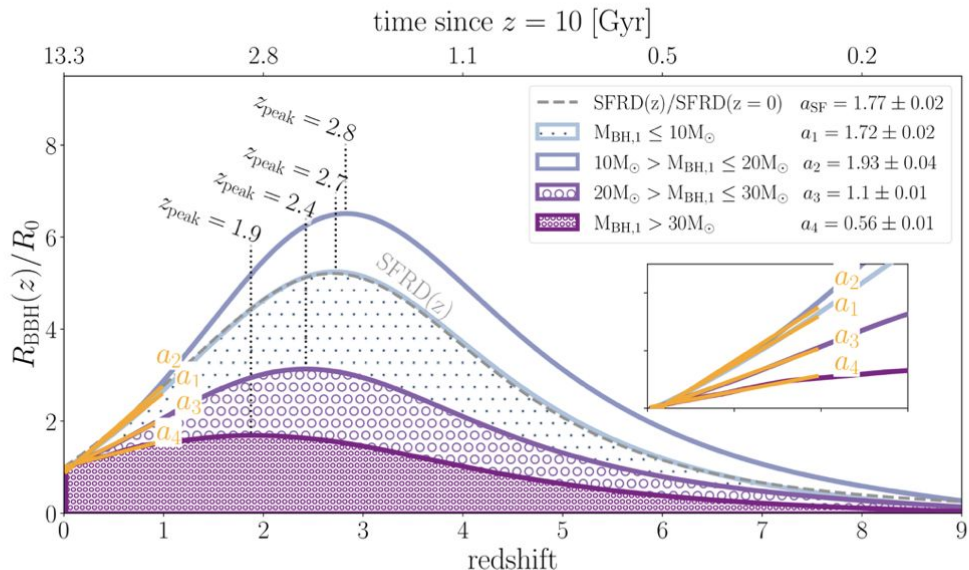
### 3G stellar BBHs



**Detect BBHs across all redshifts**

**Detect BBHs with higher SNR**

# Merger rate vs redshift



Van Son et al. (2022)

• How does the rate depend on

- the star formation rate?
- the metallicity?
- the galaxy formation?
- the environment? (GCs, AGNs...)

# ***Better parameter estimation***

**Higher sensitivity**

**Higher bandwidth**

**Louder and longer events**

**Pin down mass and spins**  
**Track better precession and eccentricity**

(How much do we need to improve our waveforms?)

+ many +

**Population properties**

**Do they evolve with redshift?**

# Formation processes/environments

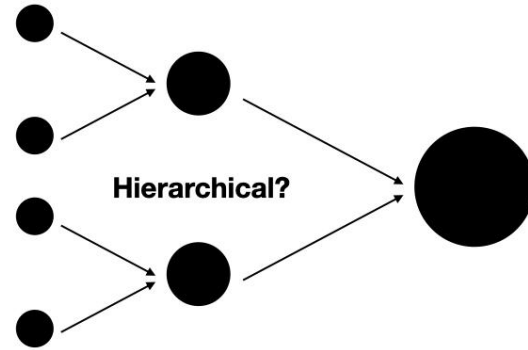
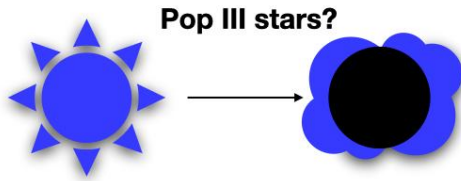
## - Isolated binary evolution



## - Dynamical formation in dense clusters



# Origin of supermassive BHs

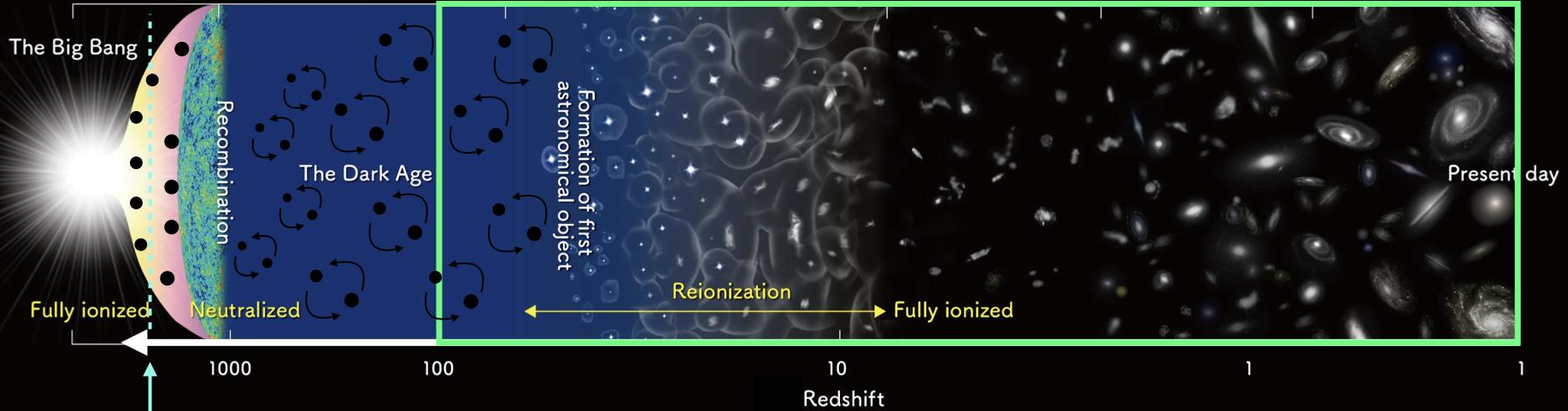


- **3G will allow connecting stellar mass black holes with SMBHs.**
- **What is the role of accretion and hierarchical mergers in their growth?**
- **Combined with LISA, we should be able to see the same event at different phases.**



Image credit: Redshift Wrangler

### 3G stellar BBHs



PBHs form

PBHs merge

observed merger rate

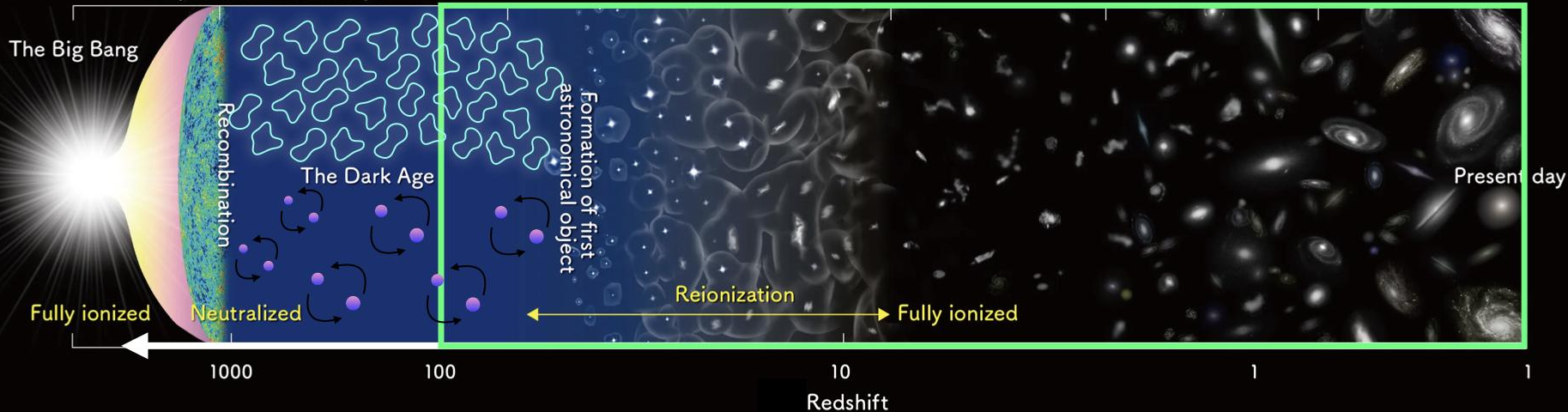
Stellar

PBH

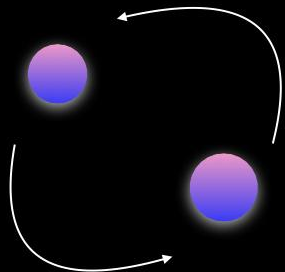
# 3G will provide definite evidence for PBHs

Image credit: Redshift Wrangler

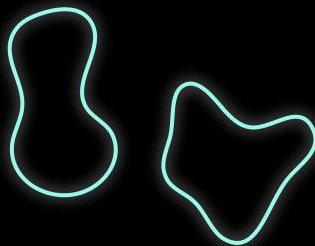
### 3G stellar BBHs



Boson stars



Cosmic strings

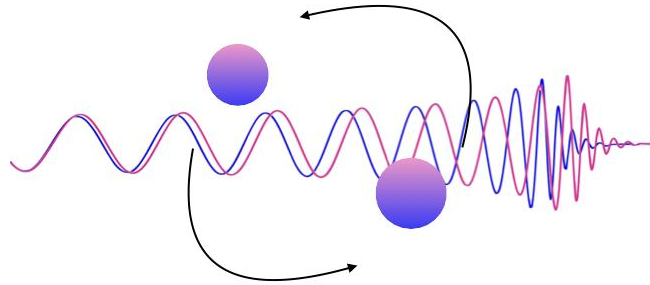


**Exotic objects  
also emit GWs**

**Higher sensitivity increases chances to observe rare events**

# Black hole mimickers

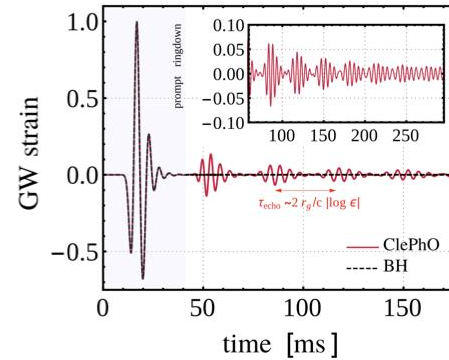
Pre-merger



**Dephasing of the GW:**

Tidal effects, extra radiation channels...

Post-merger



Cardoso & Pani (2017)

**QNMs:**

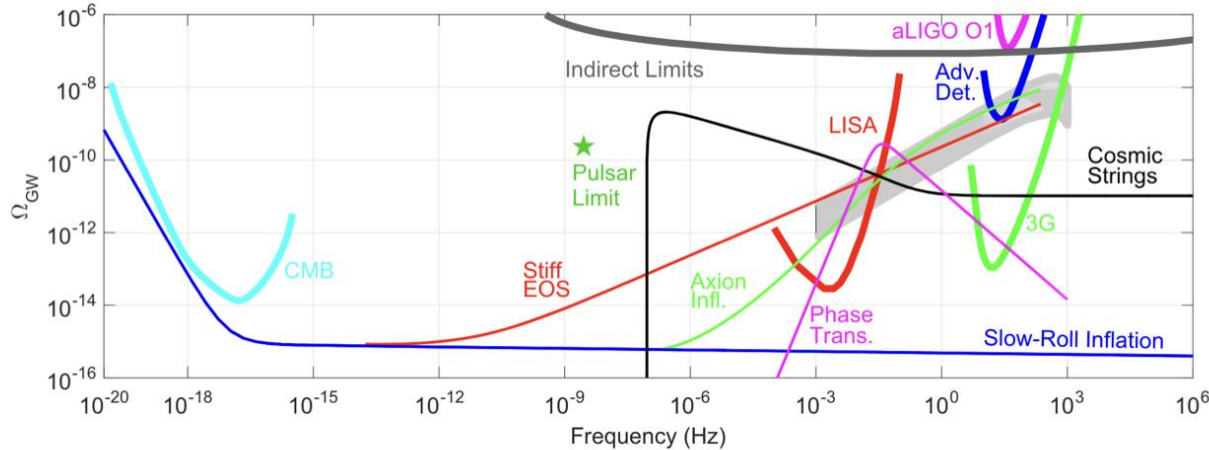
Different from Kerr

**Echoes:**

No horizon, so emit bursts

**Not enough NR waveforms? Huge parameter space to explore?  
Degeneracies? Smoking-gun signatures?**

# Stochastic GW Background



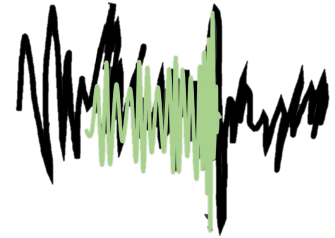
Sathyaprakash et al. (2019)

- **Monopole of SGWB will be detected. What can we learn from it?**
- **How to distinguish between different SGBWs?**
- **Detect spatial anisotropy? Instrumental noise dominated for  $\ell > \mathcal{O}(1 - 10)$  ?**
- **How well do we understand the predictions? How much we rely on models?**

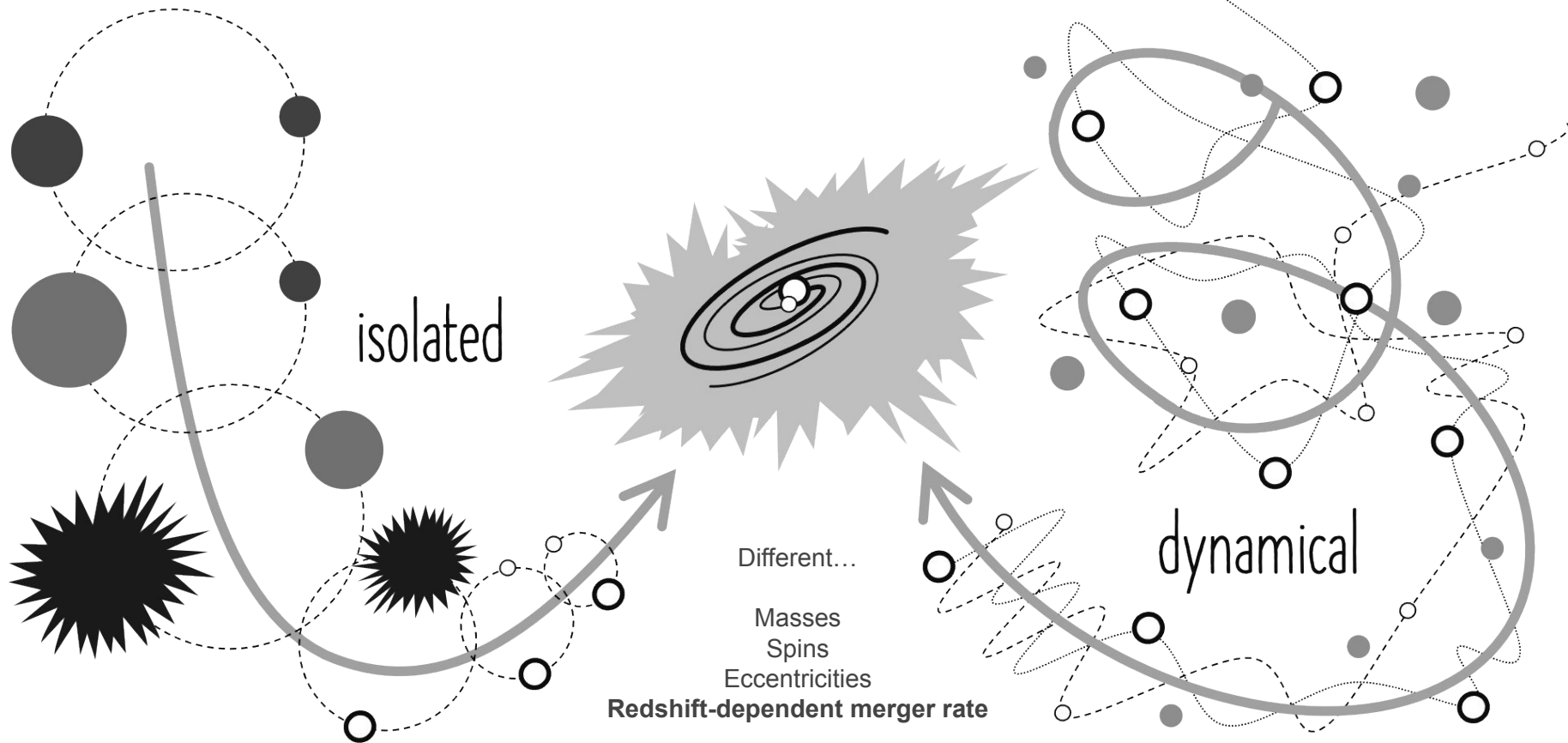
Alonso+ (2020)

# Isobel Romero-Shaw

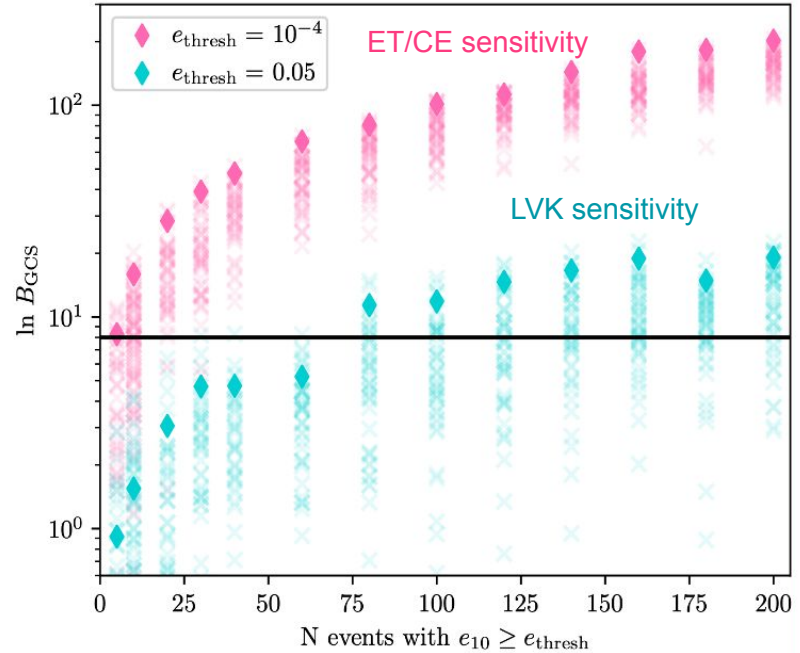
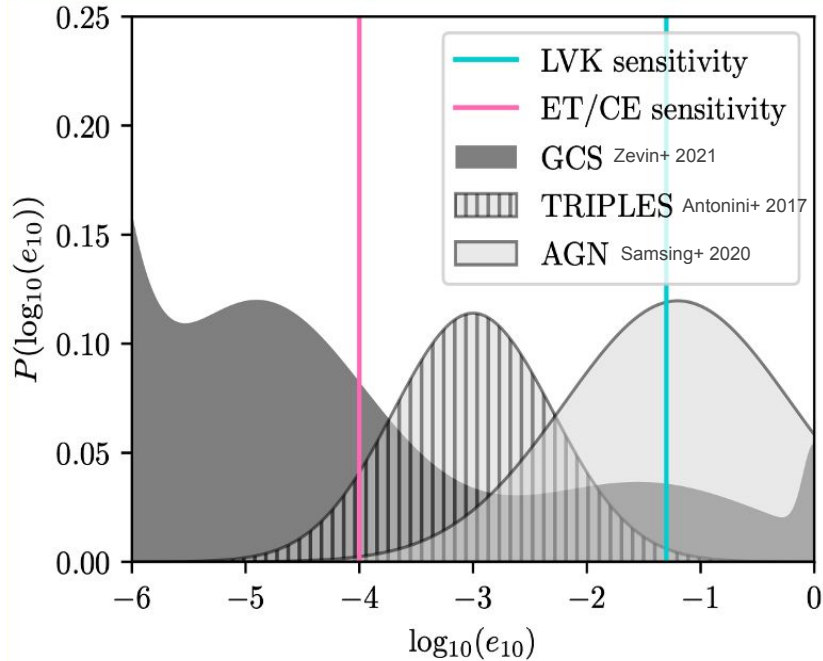
- PhD at **Monash** 2022
- Now **Herchel Smith fellow** at **Cambridge**
- Expertise in **eccentric CBCs**
- Interested in **using GWs to probe CBC formation environments**
- How can **BBH mergers** in **dynamical environments** offer clues to the **formation and evolution** of those environments?
  - **ET will provide unrivalled constraints on GC formation epochs** - **IRS, Kremer, Lasky, Thrane & Samsing 2021**



# How do merging binaries form?



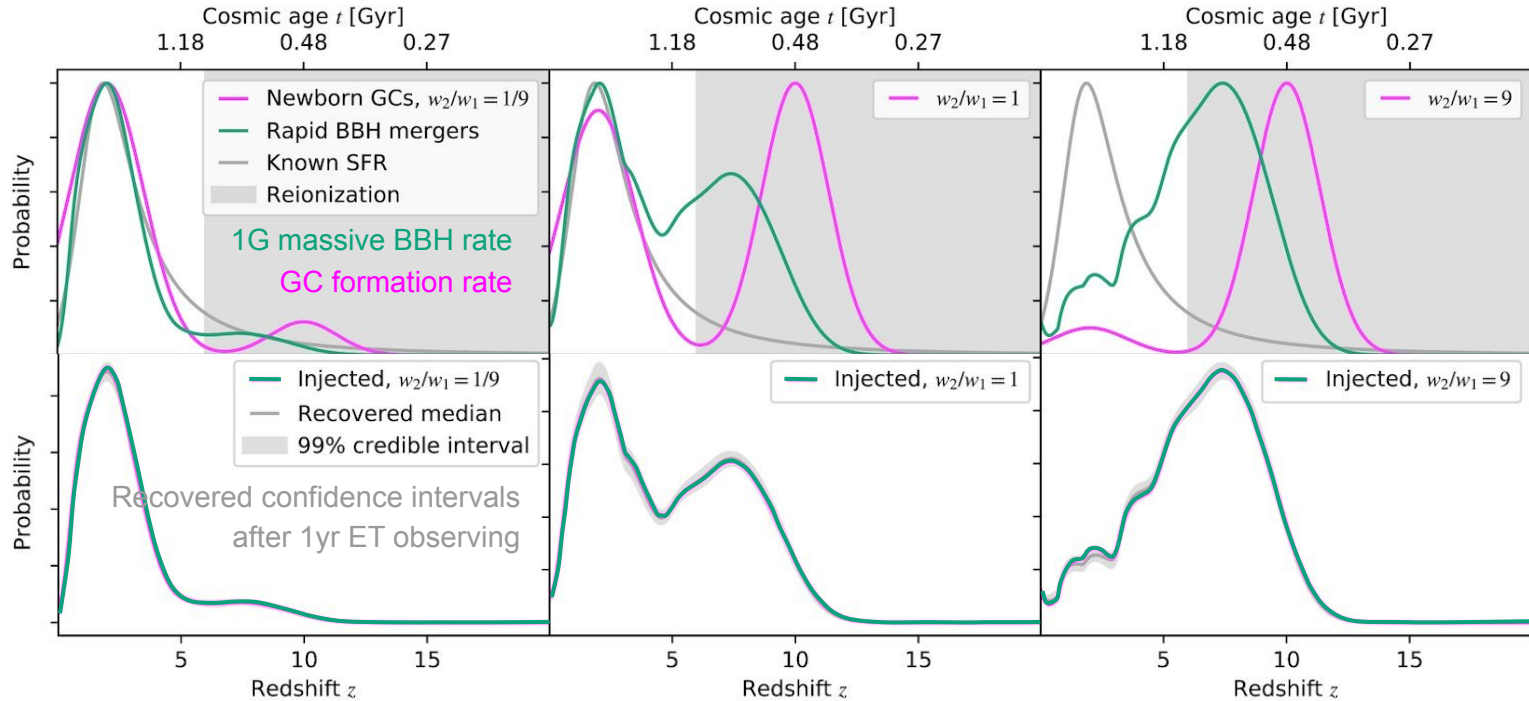
# Identifying BBH environments



Dynamically-formed mergers can be eccentric, but predictions differ for different dynamical environments

Romero-Shaw, Lasky, Thrane 2022

# BBH mergers trace globular cluster formation



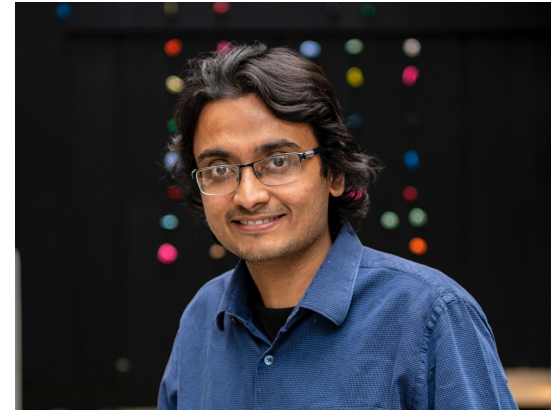


# Suvodip Mukherjee

Reader (Assistant Professor) and Group Leader of <Data|Theory> Universe Lab at Tata Institute of Fundamental Research

**Interests:** Astrophysics, Cosmology, Gravitational Waves.

**Expertise:** Astrophysical modelling of GW sources, Inference of astrophysics/cosmology using GW observations, GW data analysis.



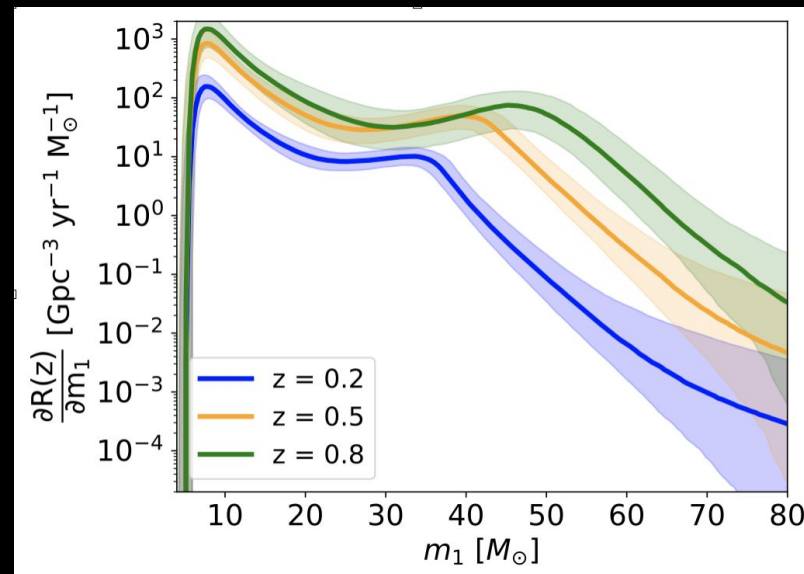
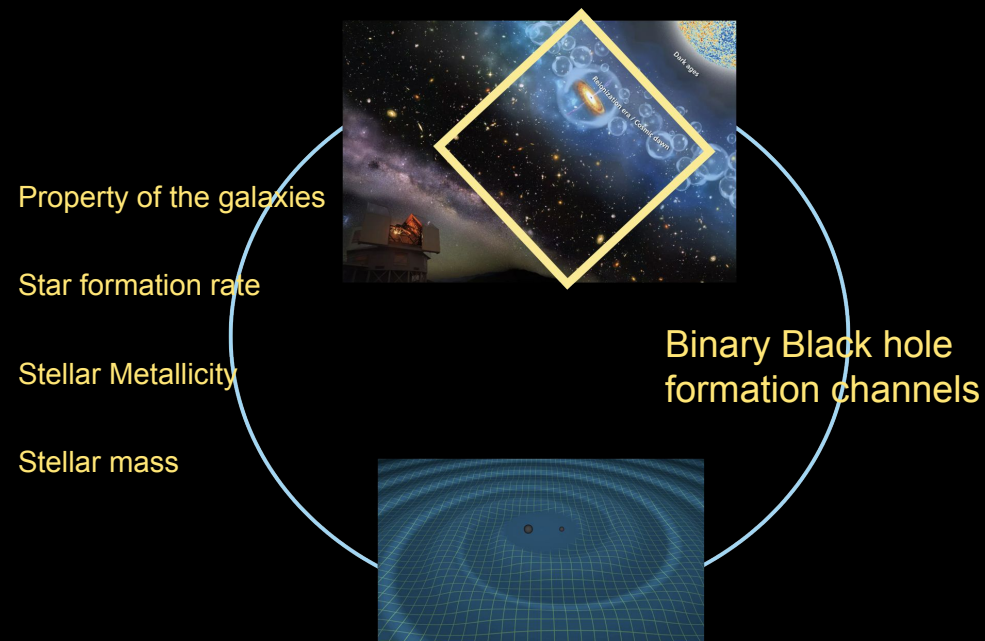
## Today's topics

How compact objects form and grow?

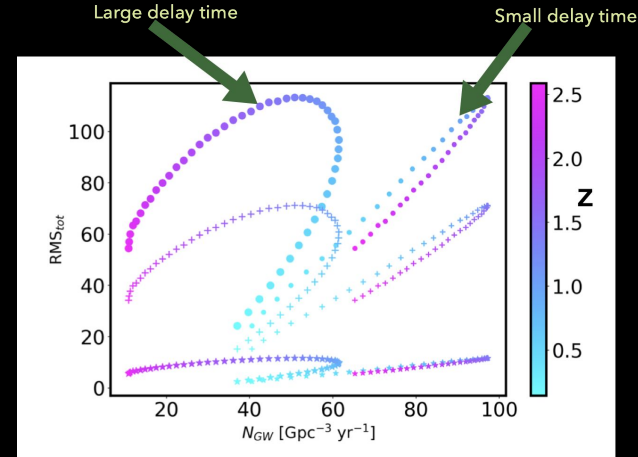
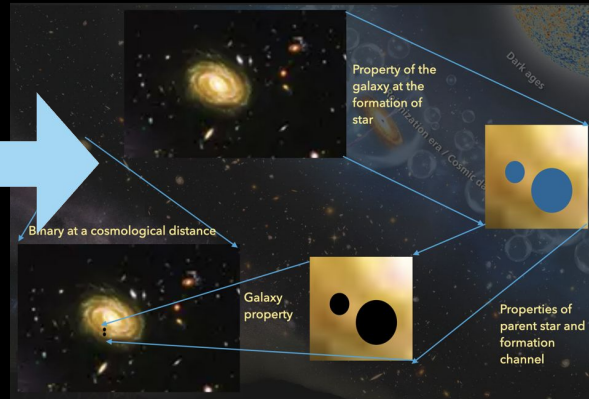
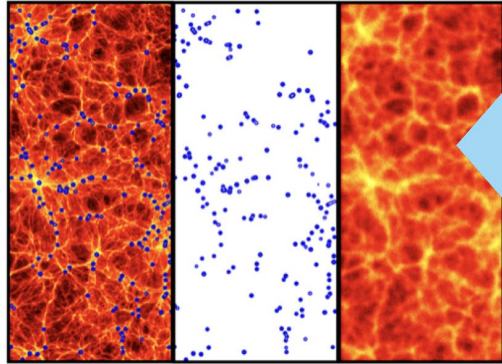
How massive and how early black holes form?

How compact object evolution synergies with evolution of the Universe?

# Binary Compact Objects: Tracer to the last FEW Billion Years of the Universe

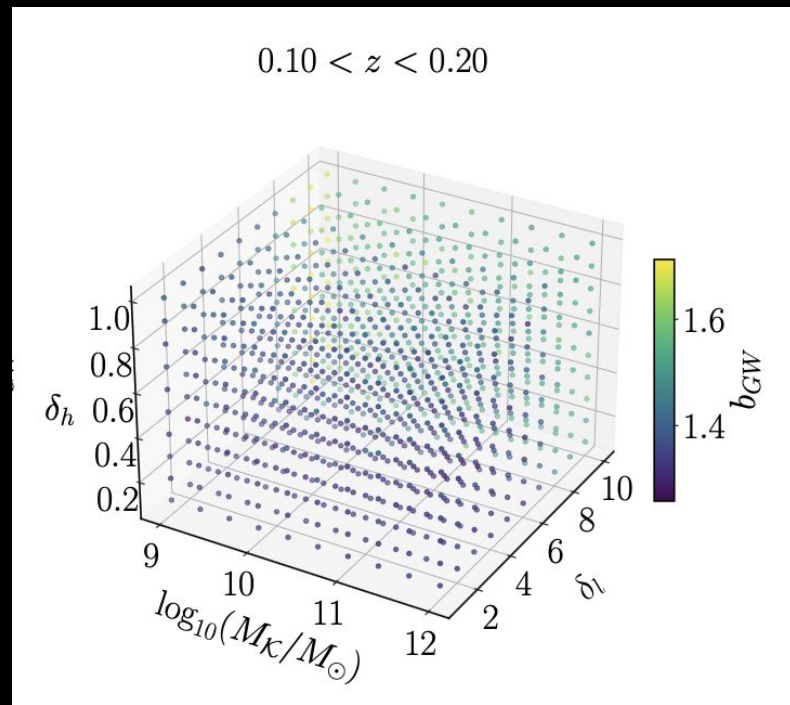
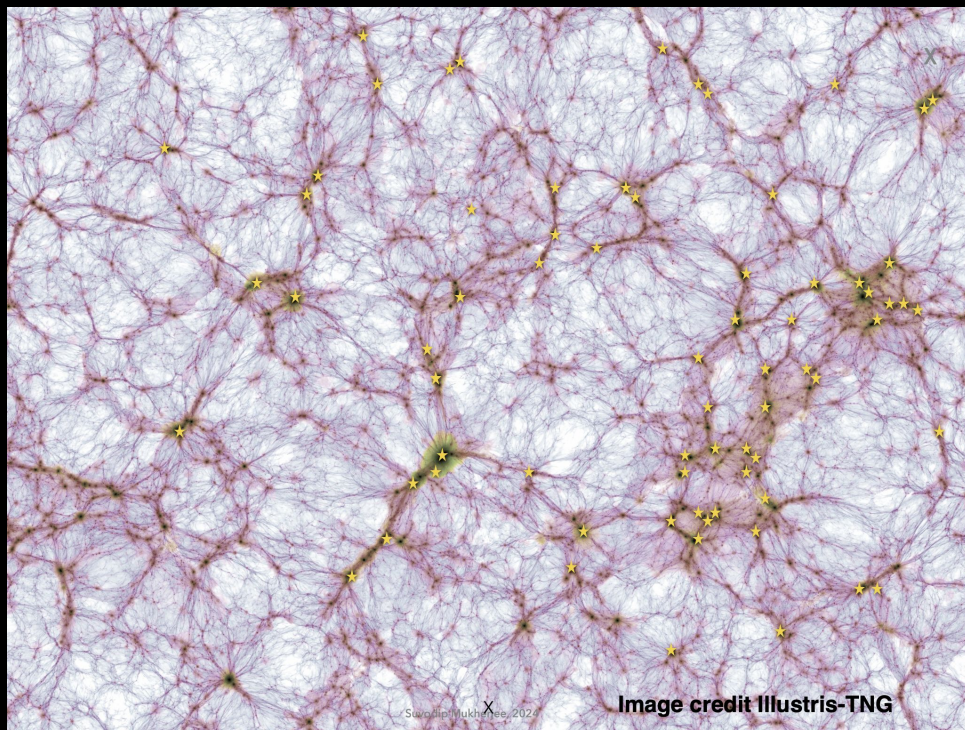


# GW Astrochemistry Connection



Mukherjee, Digzah (2023)

# GW Bias parameter: How compact objects tracing the galaxies?



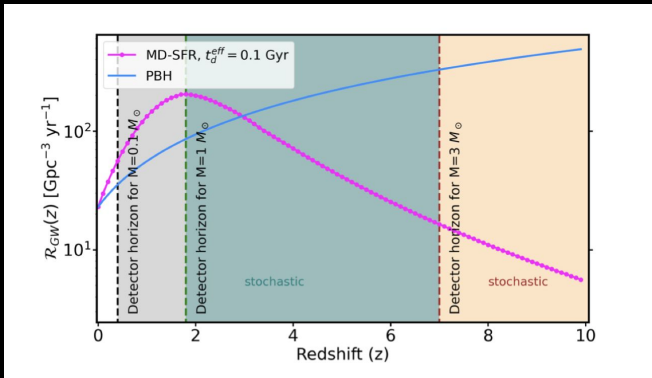
Dehghani et al. (soon to be on arXiv)

# Stochastic GW Background: High Redshift Population Properties

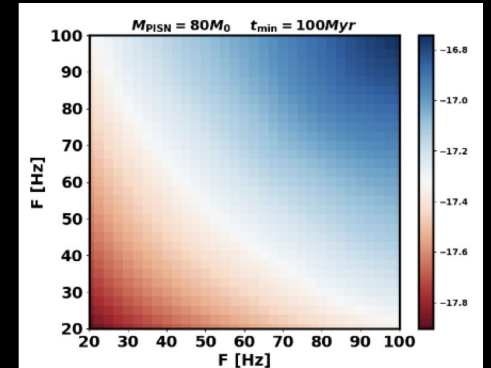
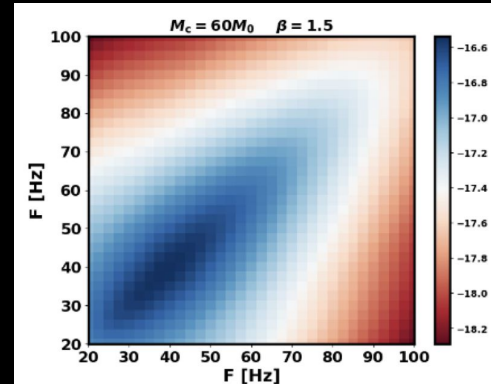
## When are we sure it is 'Not' Astrophysical?



Mukherjee, Meinema, Silk (2022)



Raj Sah and Mukherjee (2023)



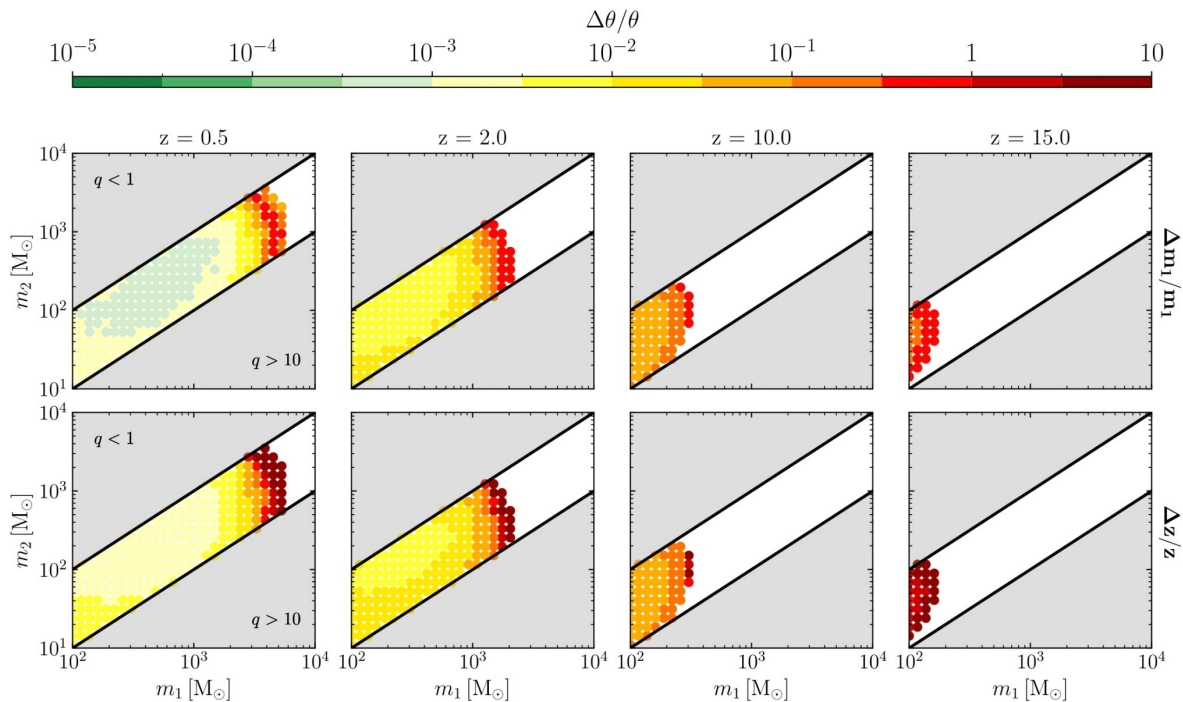
# Luca Reali

- PhD student at **Johns Hopkins University**
- Research interests:
  - **SGWBs** (foreground subtraction, confusion noise,...)
  - Probing **IMBHs** with **GWs**
  - **Waveform systematics**
  
- When high-redshift compact binaries are a **nuisance**:
  - **Reali** et al., 2022, **Reali** et al. 2023
  - Zhou, **Reali** et al. 2021, Zhong, Zhou, **Reali**, et al., 2024
  - Zhong, **Reali**, et al. in prep.
- How much/what information can we extract from **SGWB** vs **individual detections**?



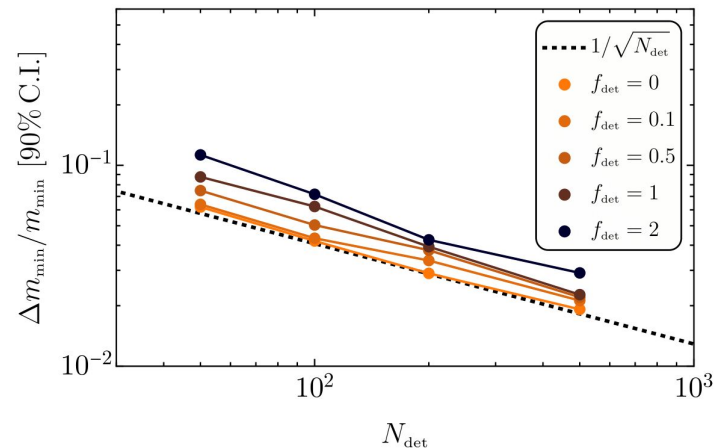
JOHNS HOPKINS  
UNIVERSITY

# IMBHs and POP III remnants



Reali et al. 2024, Fairhurst et al. 2023

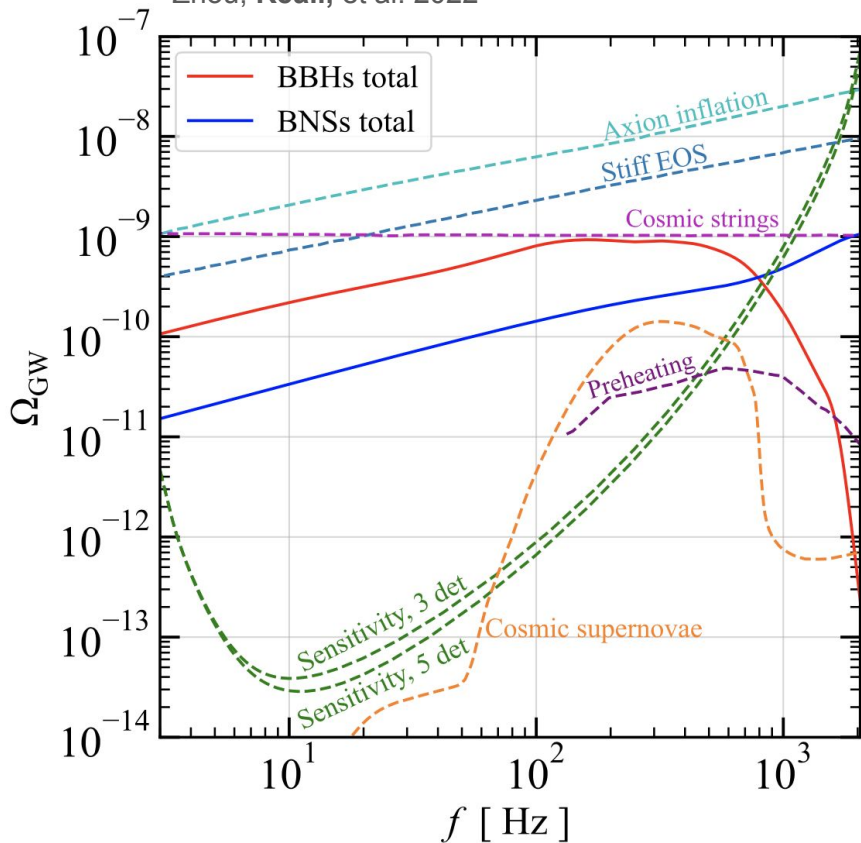
Franciolini, Kritos, **Reali**, et al. 2024



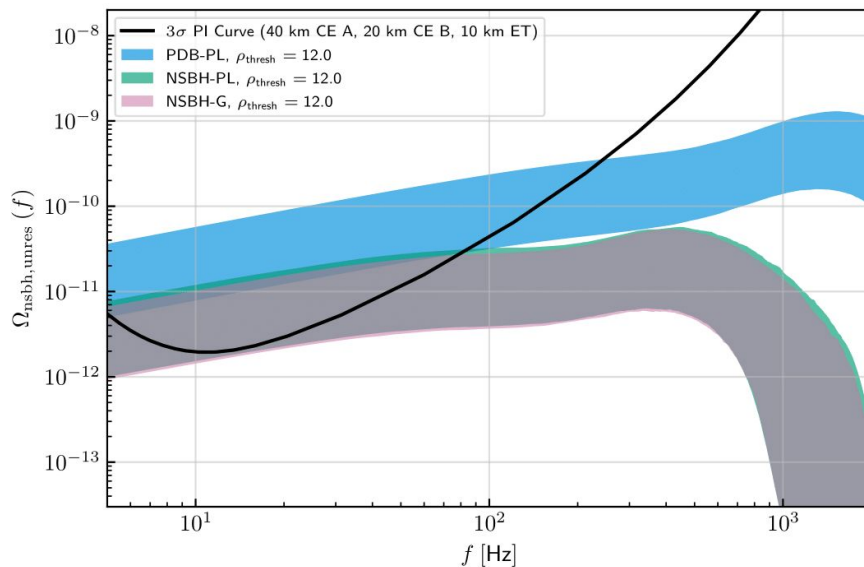
- GWs can confidently probe IMBHs at high redshifts (**low frequency sensitivity?**)
- **What astrophysical info** can be extracted? (POP III, clusters, dwarf galaxies...)

# SGWBs from compact binaries: a blessing and a curse

Zhou, Reali, et al. 2022



Bellie et al. 2024



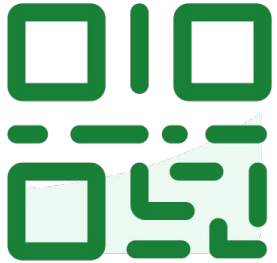
- CB Foreground is going to be “loud”
- Important information on high-redshift populations
- Dominates over cosmological backgrounds



# SGWBs from compact binaries: a blessing and a curse

- How do we **deal with the CB foreground** when hunting for subdominant backgrounds? (Subtraction, notching, global fit...)  
Zhong, Zhou, **Reali**, et al. 2024, Biscoveanu et al. 2020, ..., Smith et al. 2020
- How do we **disentangle different populations?** (BNSs, NSBHs, POP III...)
- Can we **combine resolved events with SGWBs?** What's the best way to do this? Are we prone to biases?  
Callister et al. 2020, C. Zhou, et al. 2024, ...

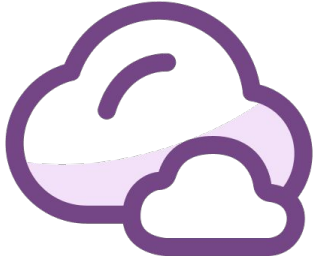
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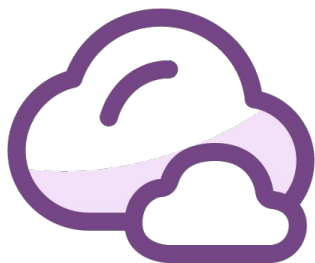
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**What would you most like to see from the high redshift universe?**

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What do you think we are most likely to see?

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**Are there any other aspects of high redshift observations that you would like to see discussed?**

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