OSB Division 3: Population Studies

Giulia Cusin, Michela Mapelli, Antonio Riotto

Institut d'Astrophysique de Paris (IAP)

2nd ET annual meeting 14-16 November

What do we mean for population studies?

Astrophysical sources **Michela Mapelli**

- Compact binary mergers: binary neutron stars, binary black holes, neutron star-black hole binaries;
- Core-collapse supernovae;
- Neutron star flares and glitches

→ Other divisions dedicated to this

Primordial black holes **Antonio Riotto**

Stochastic backgrounds of astrophysical origin **Giulia Cusin**

Summary of our activities

- One **telecon every second Tuesday of each month** at 16h: one talk plus discussion. The idea is to present various key points of population study science, to be developed in Blue Book

- Next telecon on December the 12th

- **Blue Book organisation**: we have now writing team. Chapter structure, and for each section, coordinators in charge of the writing

- In this presentation: **overview of "table of content"**, with key questions to be addressed

Contents

Preliminary

Reconstruction merger rate evolution with redshift

Adv LIGO - Virgo - KAGRA:

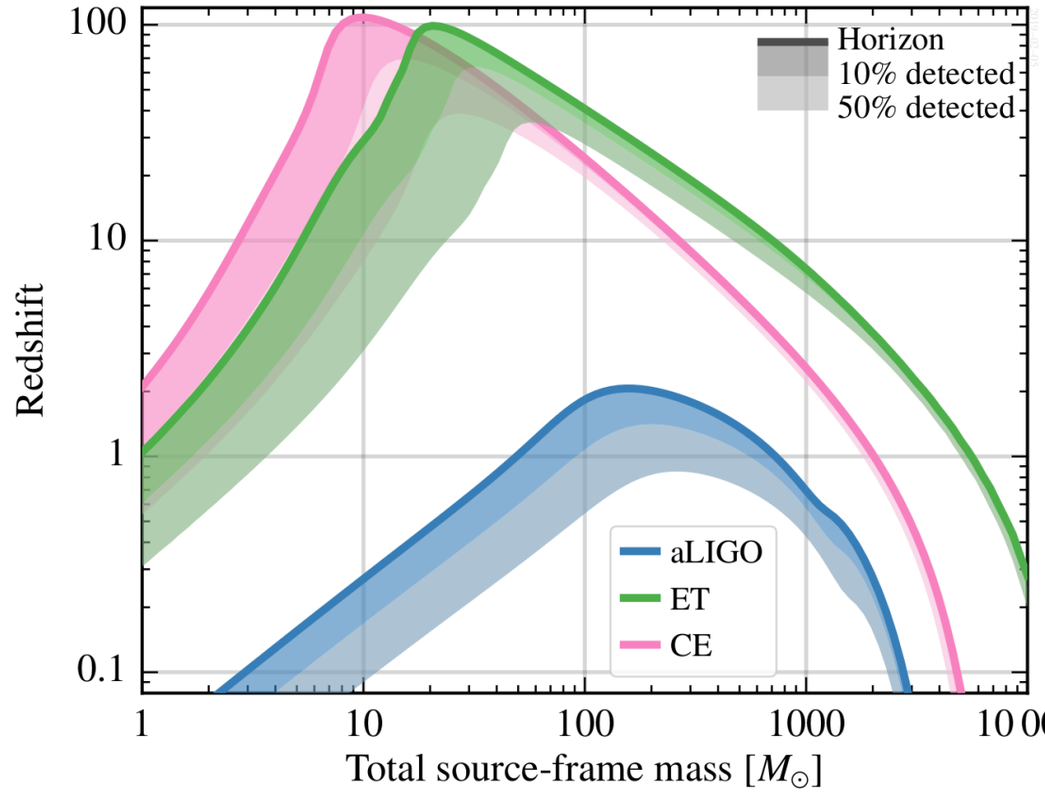
BBHs only up to z~1

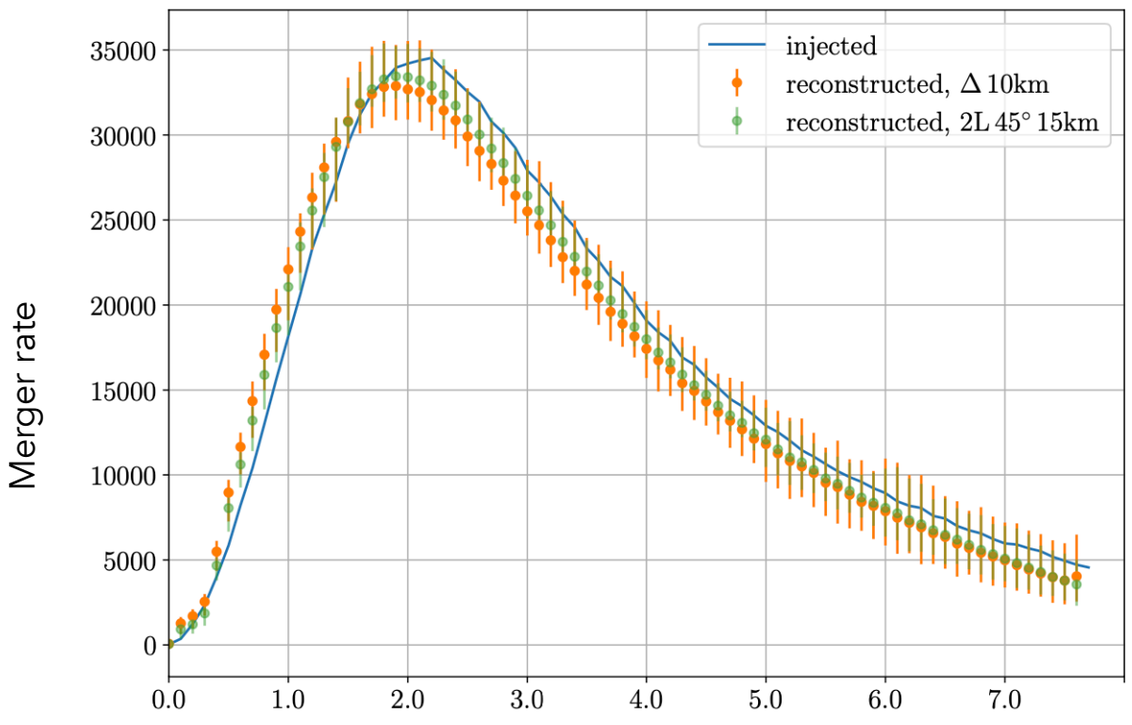
BNSs in the very local Universe

Einstein Telescope:

BBHs up to cosmic Dark Ages (z > 30)

BNSs up to z~2





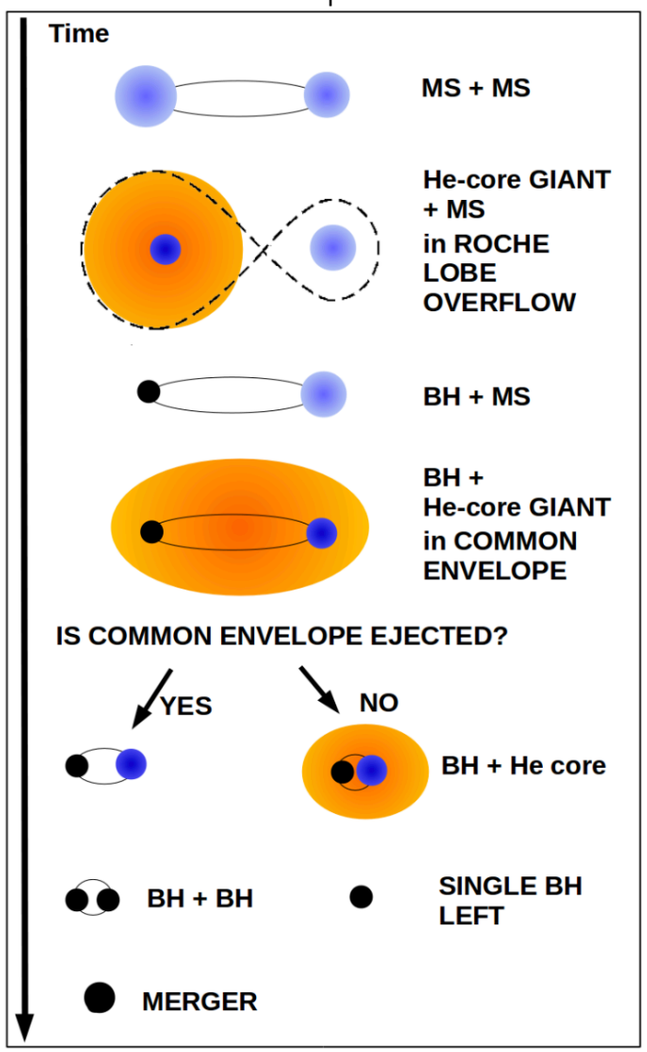
Connected fundamental questions:

- primordial / astrophysical BBHs?
- which progenitors?

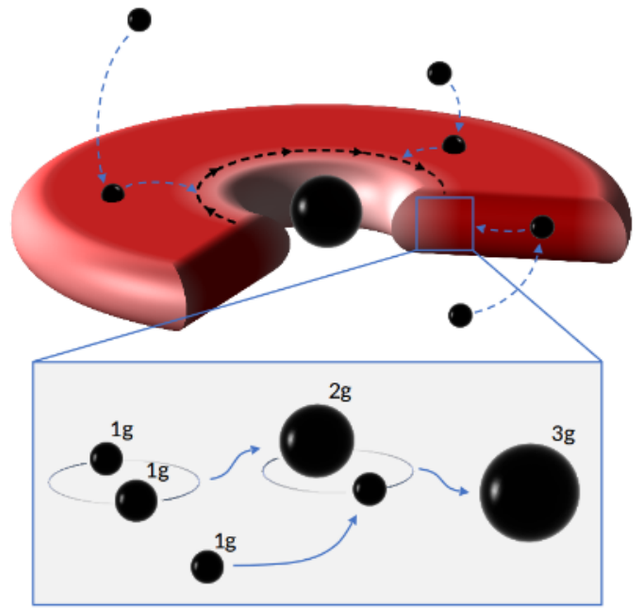
What are the formation channels of binary compact objects?

ISOLATED FORMATION:
Massive binary star evolving through stable mass transfer or **common envelope**

Credit: Michela Mapelli



DYNAMICAL FORMATION:
in triple systems,
globular clusters,
nuclear star clusters, AGN disks…



Credit: Imre Bartos

Different distribution of masses, spins etc

What is the spin distribution of BHs?

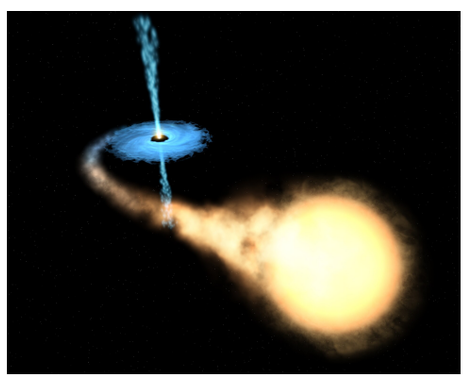
Einstein Telescope will probe spins and their redshift evolution

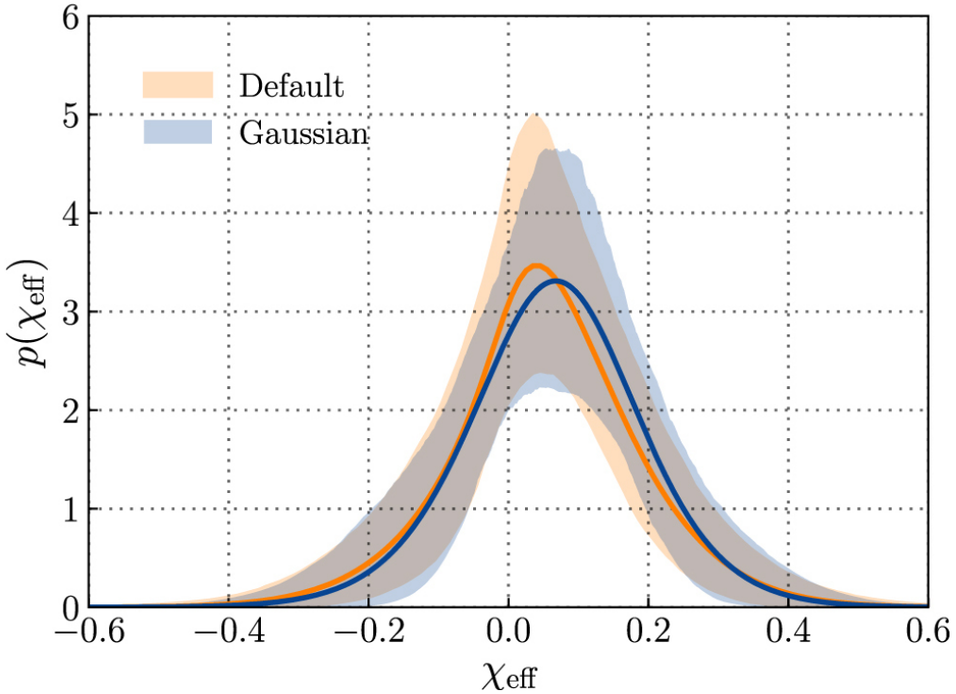
→ key to understand BBH formation channels *(e.g. dynamical formation in dense stellar clusters typically produces an isotropic distribution of spin directions …)*

(e.g. Reynolds 2021 arXiv:2011.08948)

Current open issue on spins:

- LVK favor low spins for most BHs
- high-mass X-ray binaries favor high spins



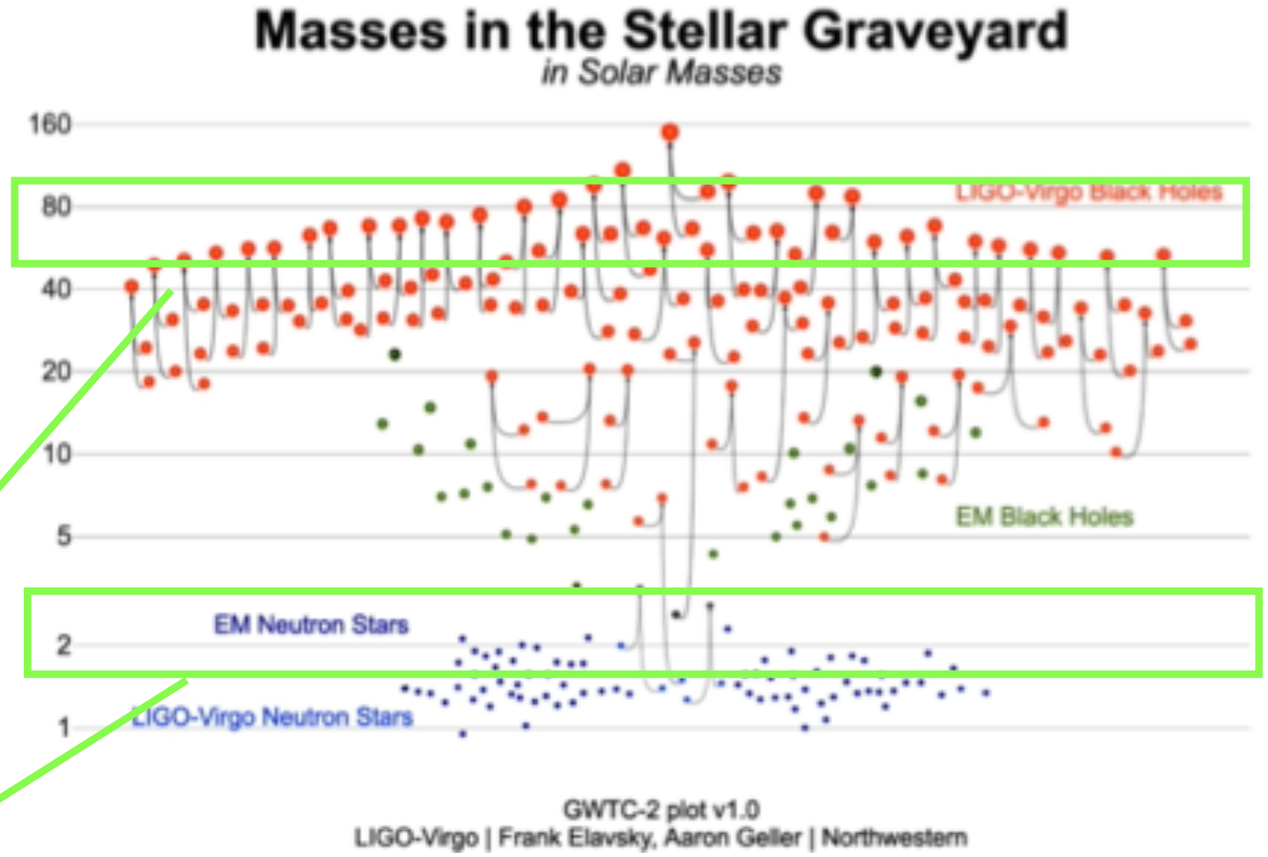


Abbot et al. 2021

$$\chi_{\rm eff} \equiv \frac{m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2}{m_1 + m_2} \cdot \hat{L}$$

What is the mass function of BHs? Are there mass gaps?

LVC draw the first "sketch"of BH mass function



Einstein Telescope will probe their redshift evolution (if any)

→ key to understand BBH formation channels: isolated vs dynamical vs primordial

Are there mass gaps?

(upper, predicted by theory of pair instabilities and lower from observation of X-ray binaries)

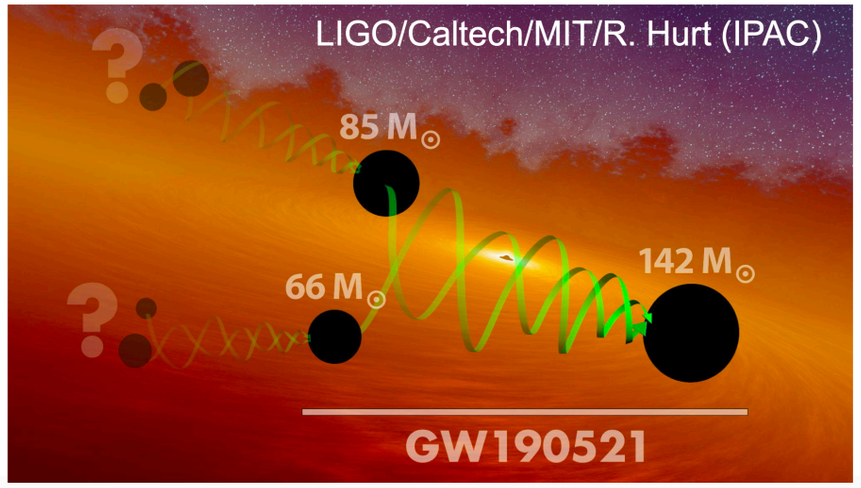
Dynamical processes in dense stellar systems can trigger the formation of BHs in the mass gap and intermediate-mass BHs via hierarchical BH mergers and via multiple stellar collisions

Where are the intermediate-mass BHs? And pop III stars?

Where are the intermediate-mass BHs (IMBHs)?

Mass 10^2 - 10^5 $M_\odot$ → bridge gap between stellar-sized and supermassive BHs

- When do they form?
- What is their merger rate across cosmic time?
- What are their formation channels?
- Are they seed of supermassive BHs?



Is it possible to infer the properties of population III stars from their compact remnants?

- When did they form?
- What is their mass function?
- What is their binary fraction?

Primordial black holes

- Astrophysical BHs forms from the gravitational collapse of a star. We know they exist. Their mass must be above the Chandrasekhar limit,

$$M > \mathcal{O}(1)\, M_\odot$$

- PBHs are formed in the early universe. Their mass can be small and they can still be around as long as they do not evaporate within the age of the universe

$$M > 10^{-18}\, M_\odot$$

Key questions on PBH in the GW era

1. How many PBHs do we expect to observe with ET?
2. What are the smoking-gun evidences for PBHs and how to distinguish them from astrophysical sources?
3. Which is the fraction of dark matter made of PBHs?

Key questions on PBH in the GW era

1. How many PBHs do we expect to observe with ET?
2. What are the smoking-gun evidences for PBHs and how to distinguish them from astrophysical sources?
3. Which is the fraction of dark matter made of PBHs?

Depends on modelling: need to know merger rate, evolution and survival of PBH binaries between formation and merger, effect of clustering *(increases merger rate for binaries forming at late times)*…

Key questions on PBH in the GW era

1. How many PBHs do we expect to observe with ET?
2. What are the smoking-gun evidences for PBHs and how to distinguish them from astrophysical sources?
3. Which is the fraction of dark matter made of PBHs?

Sub-solar BHs masses
Merger rate function extends to high redshifts
Spin of PBHs (tendency of large spins for large masses)
Stochastic GW background from PBHs at high redshifts

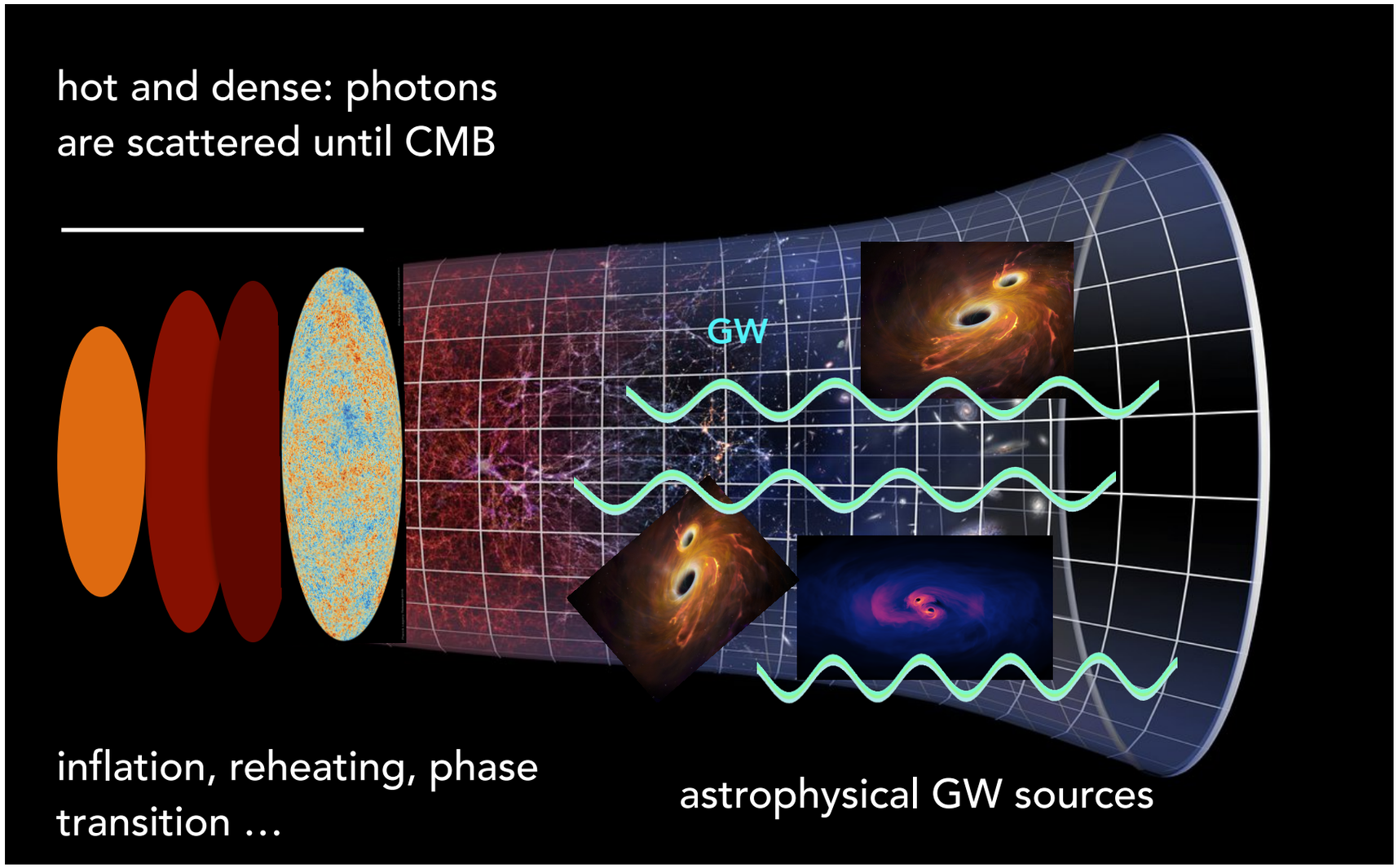
Key questions on PBH in the GW era

1. How many PBHs do we expect to observe with ET?
2. What are the smoking-gun evidences for PBHs and how to distinguish them from astrophysical sources?
3. Which is the fraction of dark matter made of PBHs?

Observing (or not) PBH will set further constraints in the plot mass-DM fraction

Astrophysical background

The “voices” of all astrophysical sources in the Universe

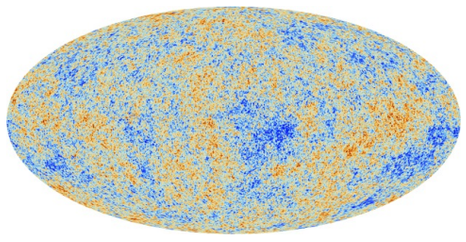
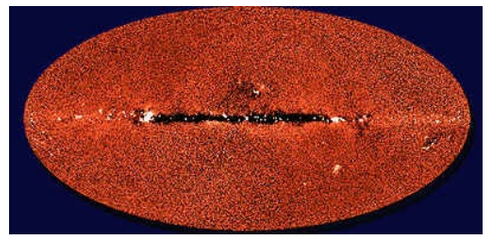


Big Bang → observer

time

Stochastic backgrounds of radiation

Stochastic background: incoherent superposition of signals from all sources

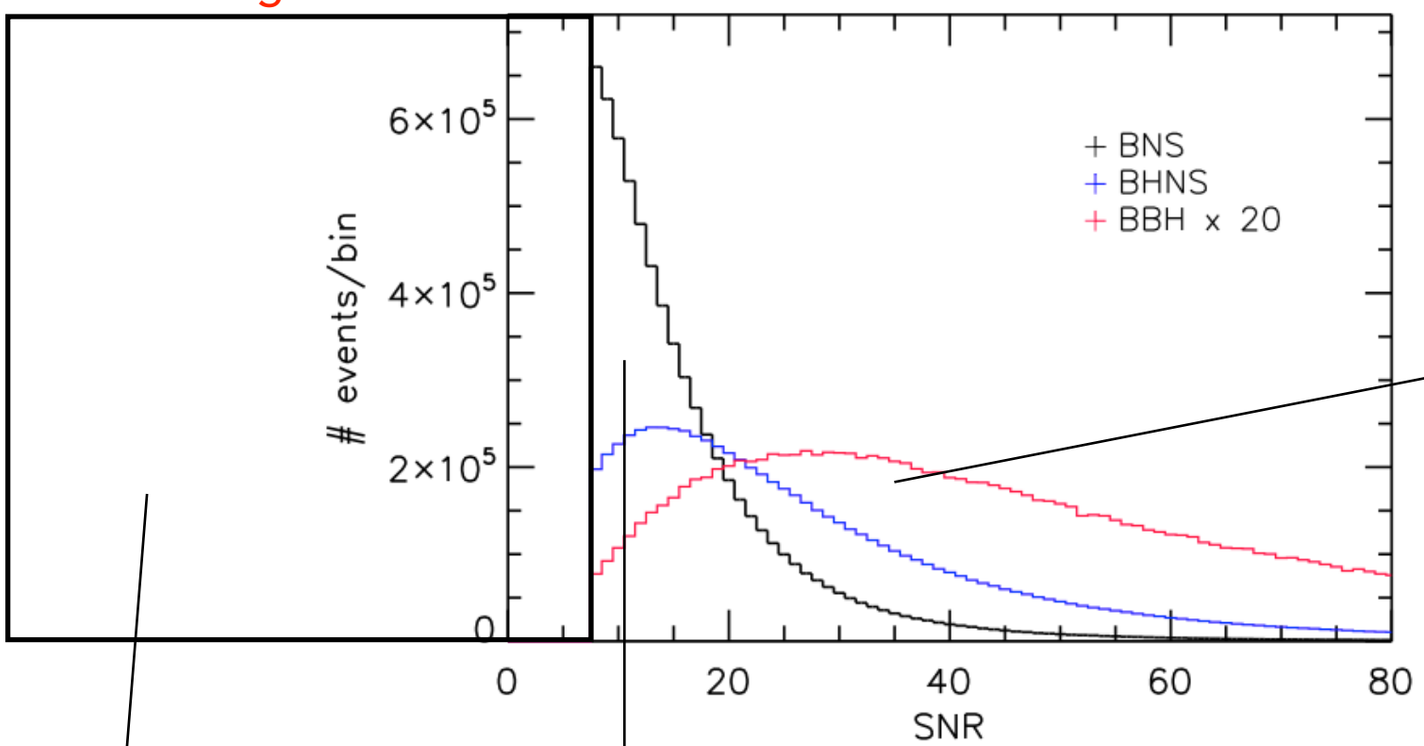
	cosmological origin	astrophysical origin
EM radiation	CMB	cosmic infrared background (CIB)
	 Plank CMB map	 Plank IR map
GW radiation	cosmological background	**astrophysical background**

foreground for cosmological GW background

Complementarity catalogue-background approach

background

resolvable events



I want to infer properties BNS population here

most of BNS are below threshold

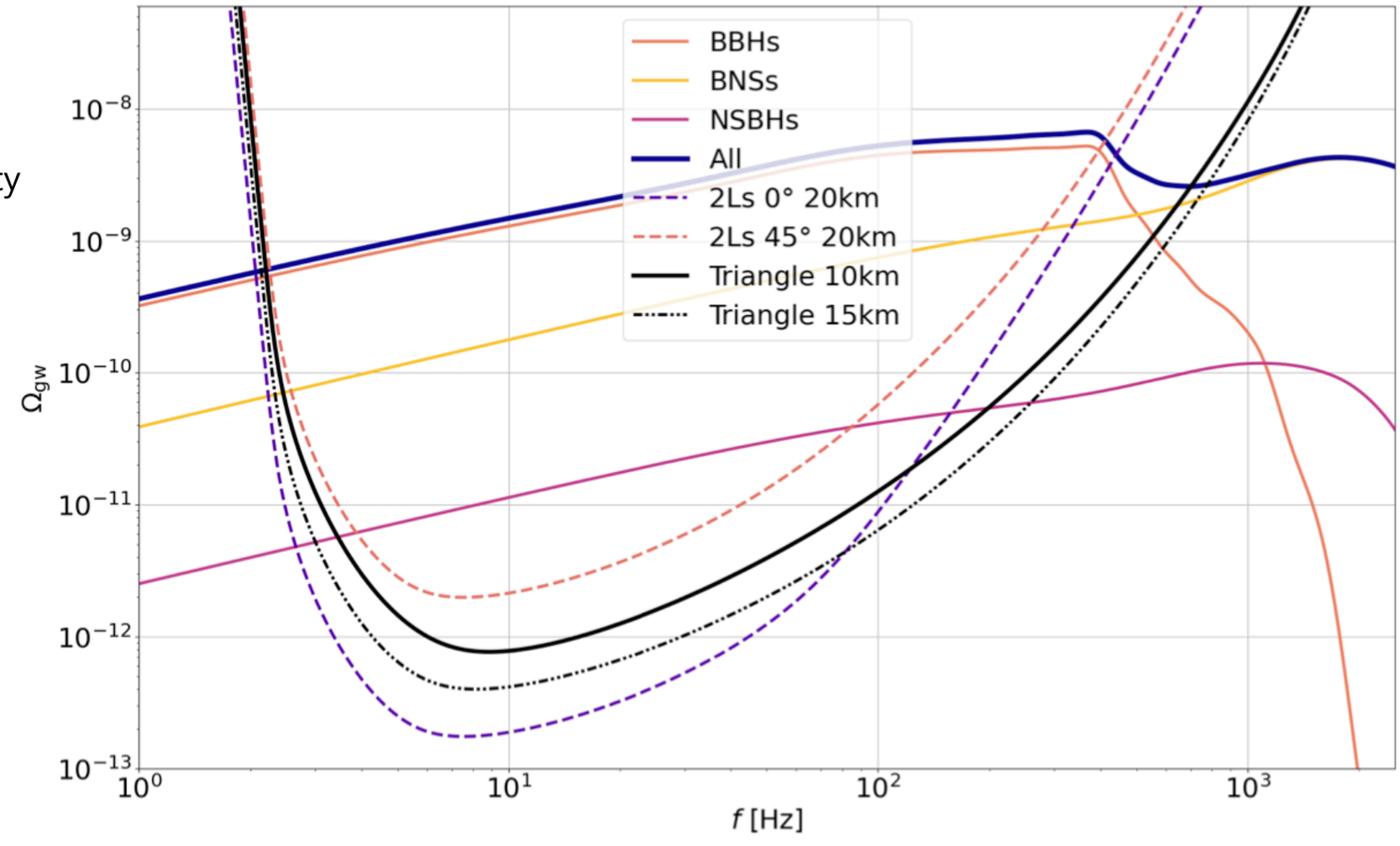
most BBH are detectable individually by Einstein Telescope

From study of residual background: astrophysical information on a population of BNS sub-threshold

credit Cuoco, Calore, Regimbau, Serpico

Background energy density: features at merger

Background energy density

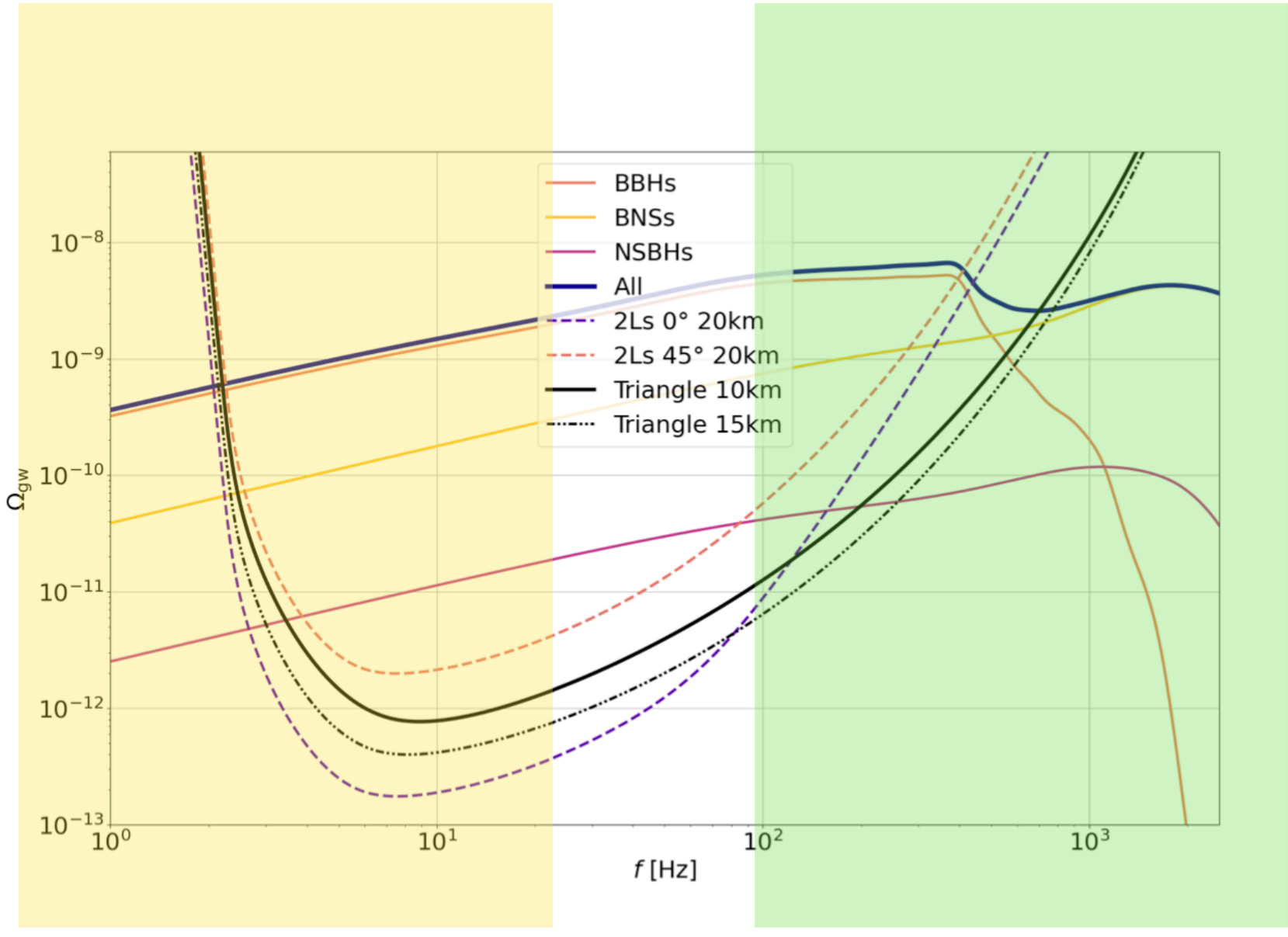


Frequency

CoBA Study 2023

Features in the spectrum at merger

Background energy density



Frequency

Quadrupole formula

$$\propto f^{2/3}$$

Deviations from quadrupole formula when sources merge: info on specific population

CoBA Study 2023

Expected signatures

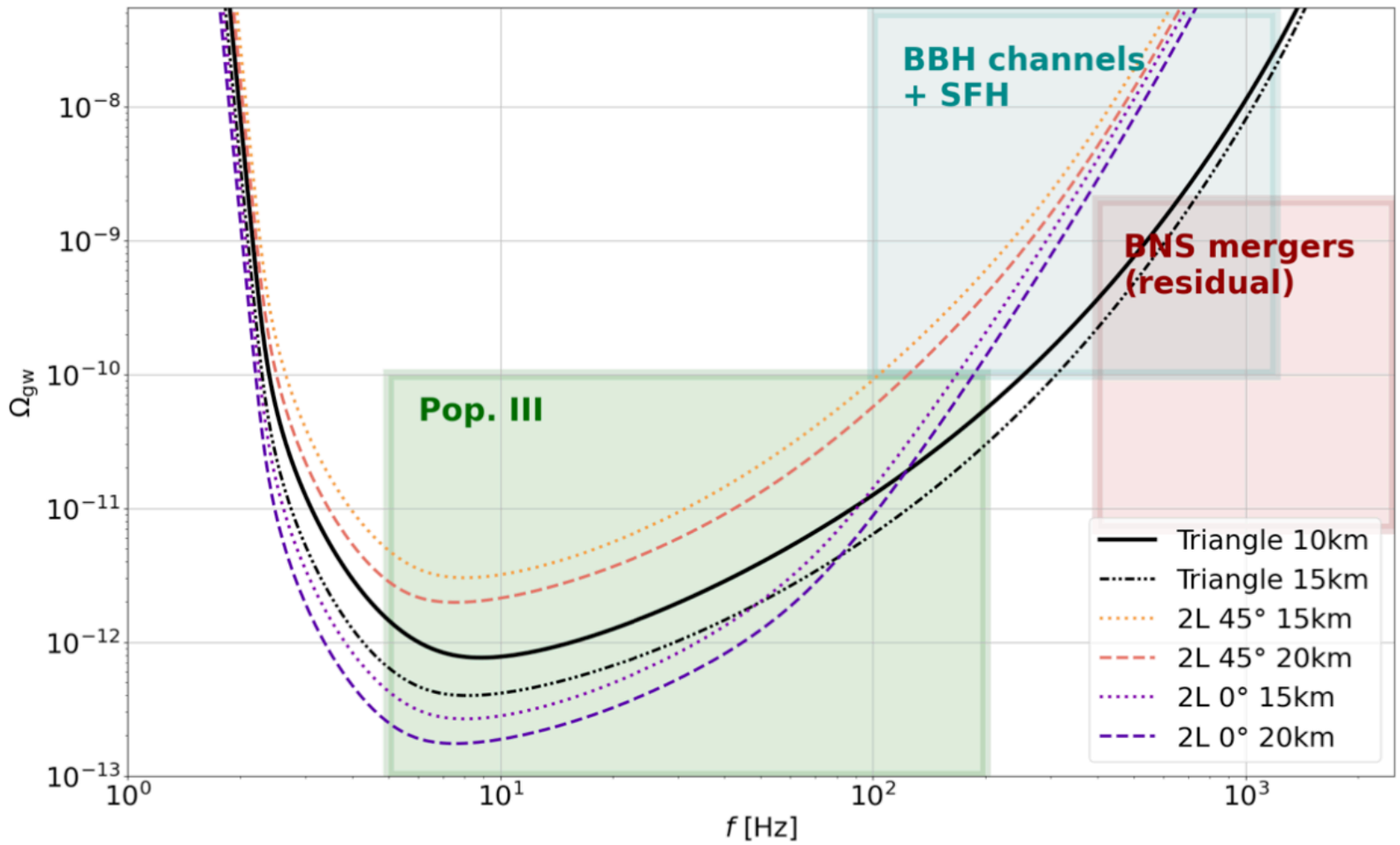
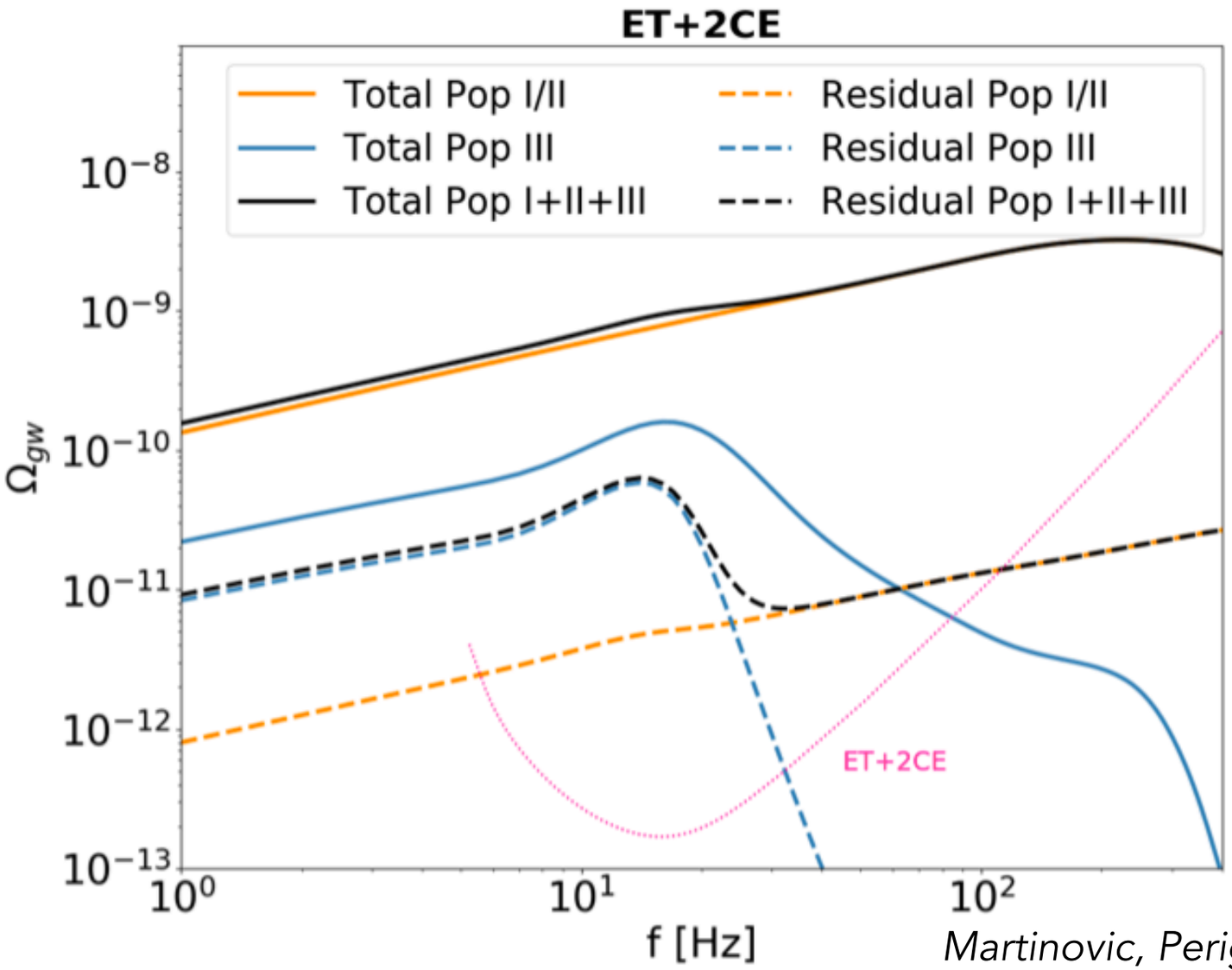


Figure 32: Location of the predicted signatures for the three main challenges for the CBC background.

Example: information from residual background

Unresolved superposition of compact binaries coalescence in Hz band from pop I-II-III
Pop III stars: the oldest stars in the universe. At high redshift and low metallicity



Pop III dominate the residual background.
From **position of the peak**: info on the (average) total redshifted mass

Martinovic, Perigois et al.

Background mapping: tools and challenges

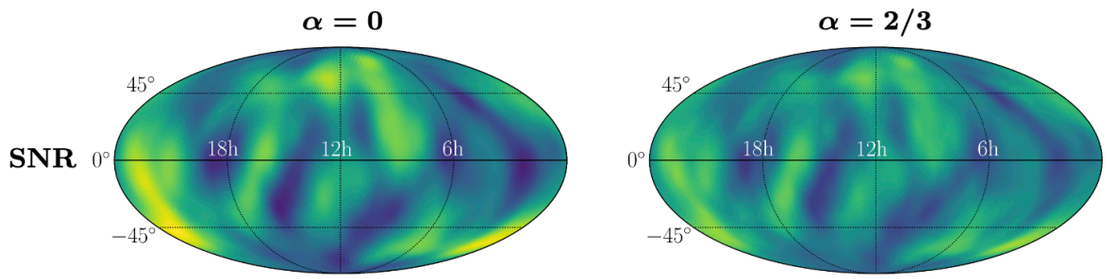
Background Mapping

Theoretical and data analysis tools

to create a map of background

(resolved and unresolved)

LVC 2022



Reconstruction of spectral shape

Can we adapt methods developed for LISA?

Cross-correlation with galaxy distribution

Promising way to distinguish primordial vs astrophysical background components

Good way to get a first detection of anisotropic component?

Problem of subtraction of resolvable events

Contents

Timeline

December 2023
Structure of the chapter and organisation completed

April 2024
Bulk of the text written

Summer 2024
Final version ready

Thank you