EuCAPT Symposium – 16th May, 2024

Implications of GW detection for Stellar Astrophysics

Valeriya Korol

with help from Lieke van Son, Aleksandra Olejak and Selma de Mink

Max Planck Institute for Astrophysics (MPA)
korol@mpa-garching.mpg.de
www.valeriakorol.com

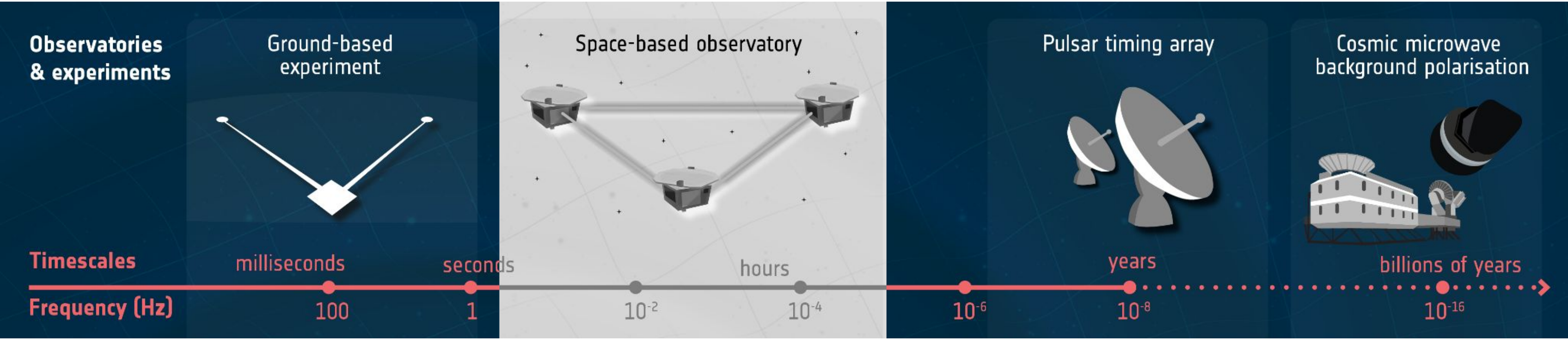
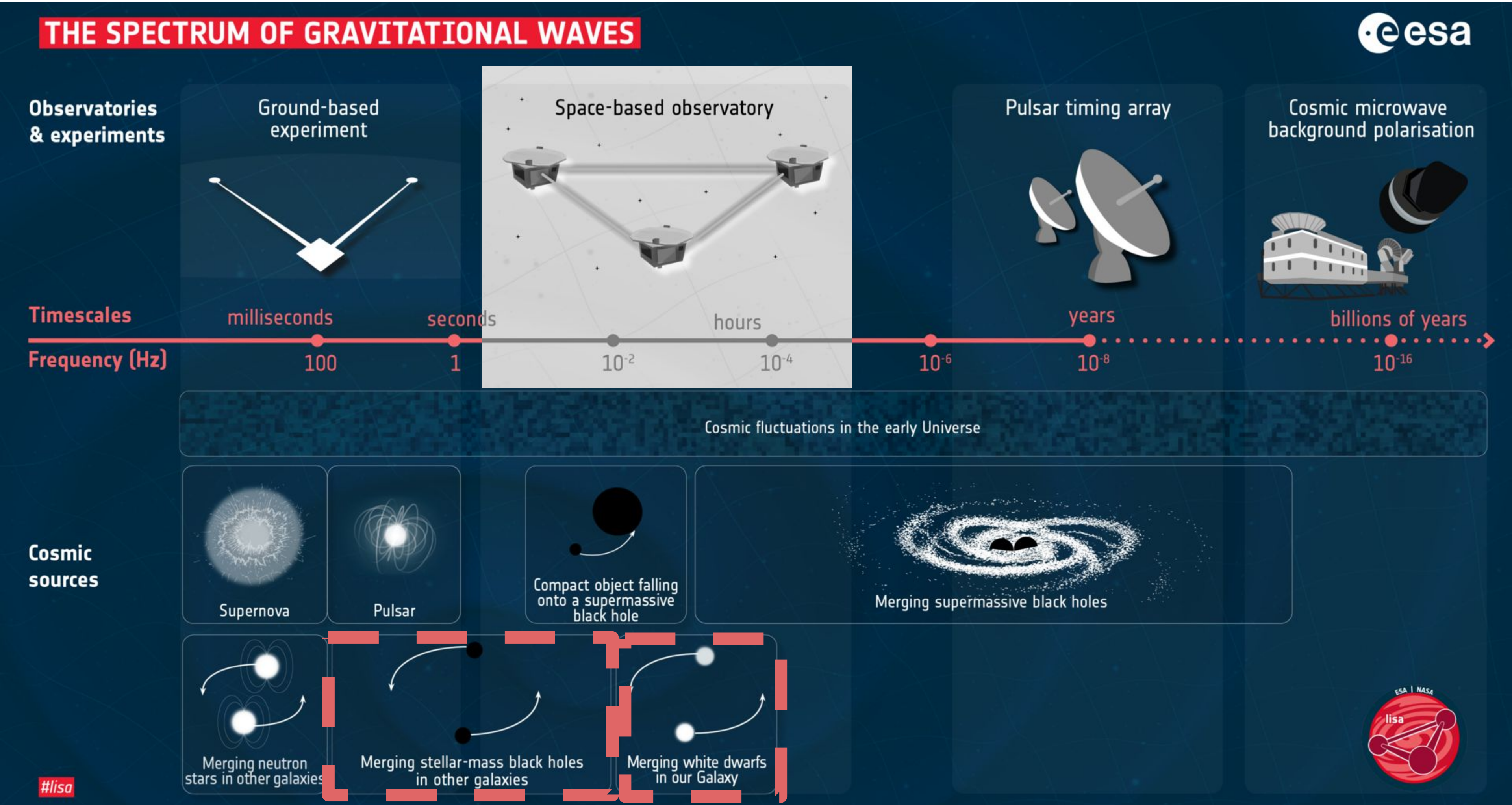


Image credit: ESA


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
ESA | NASA
lisa
#lisa

What are we learning from high-frequency GW detections?

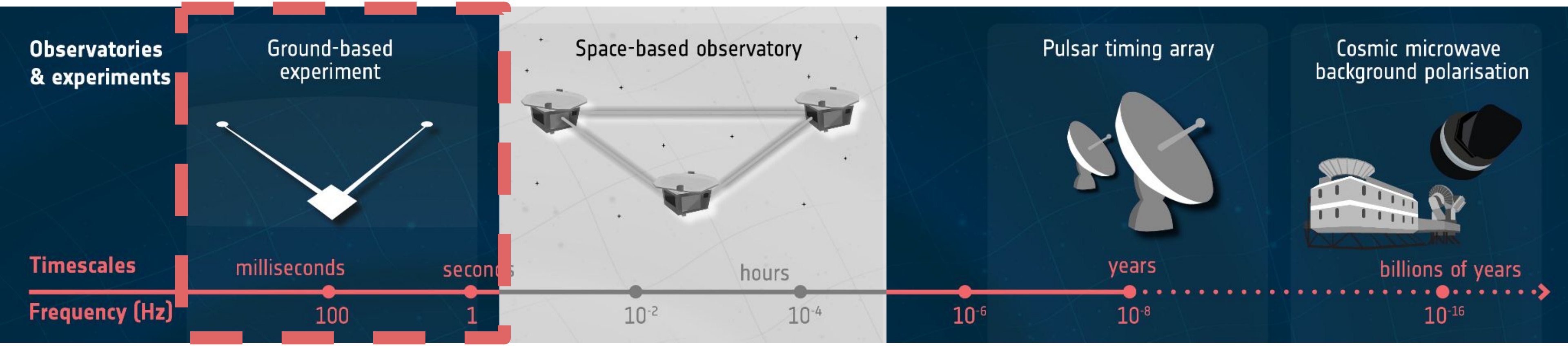
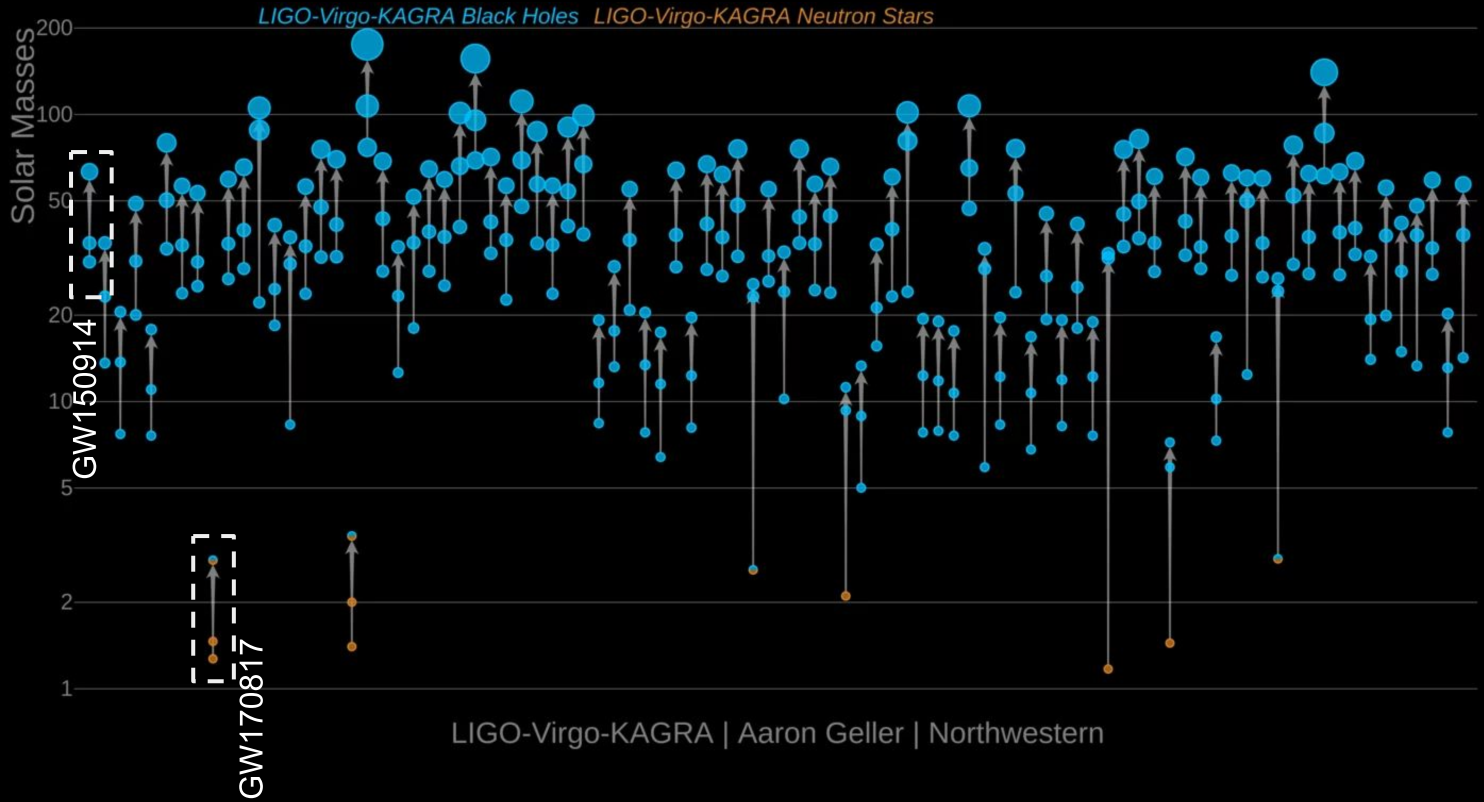


Image credit: ESA

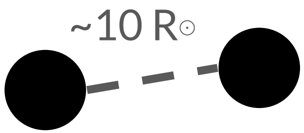
Over 100 detections by now and still counting!



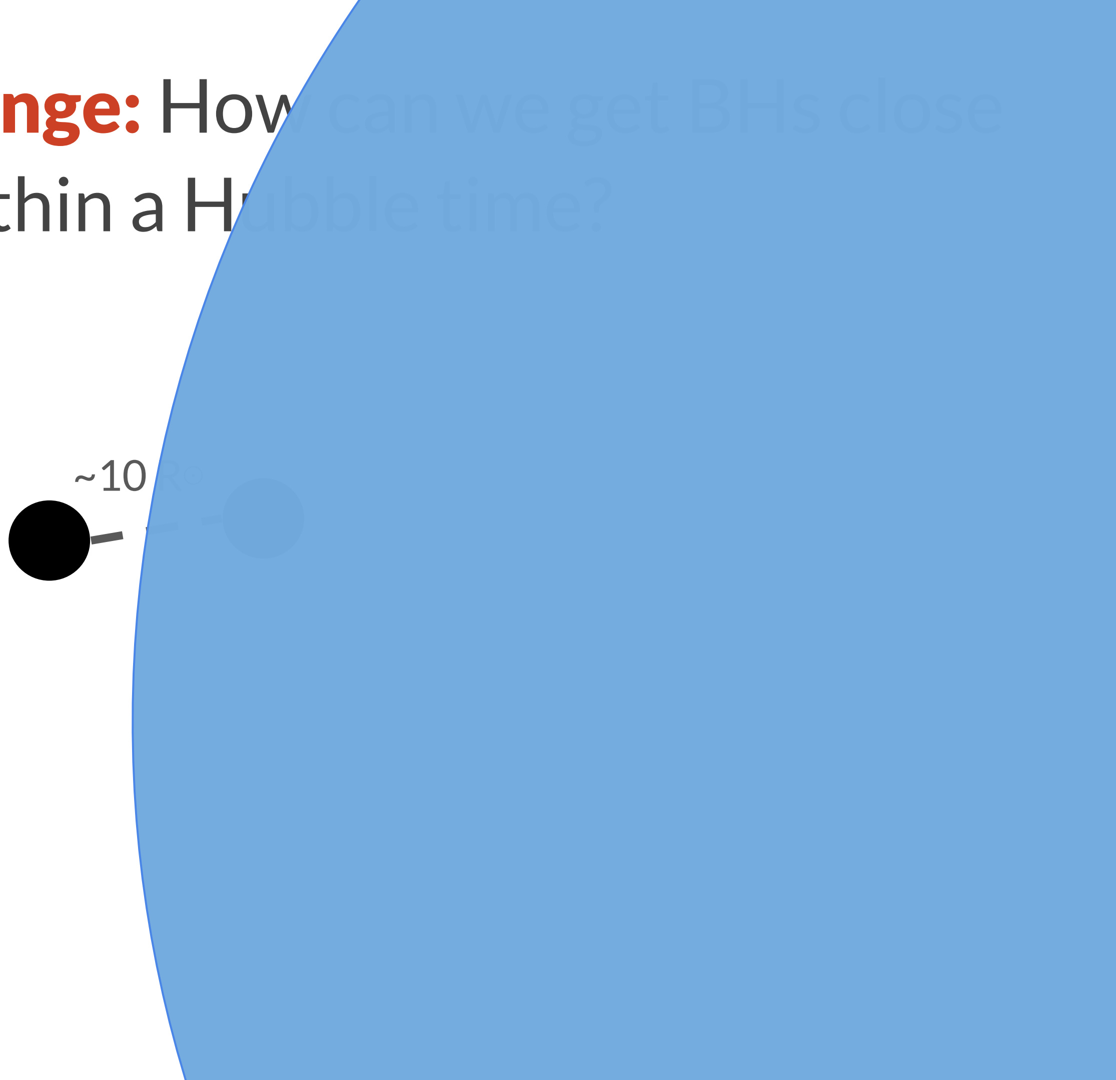
Over 100 detections by now and still counting!

How did they form?

The separation challenge: How can we get BHs close enough to coalesce within a Hubble time?

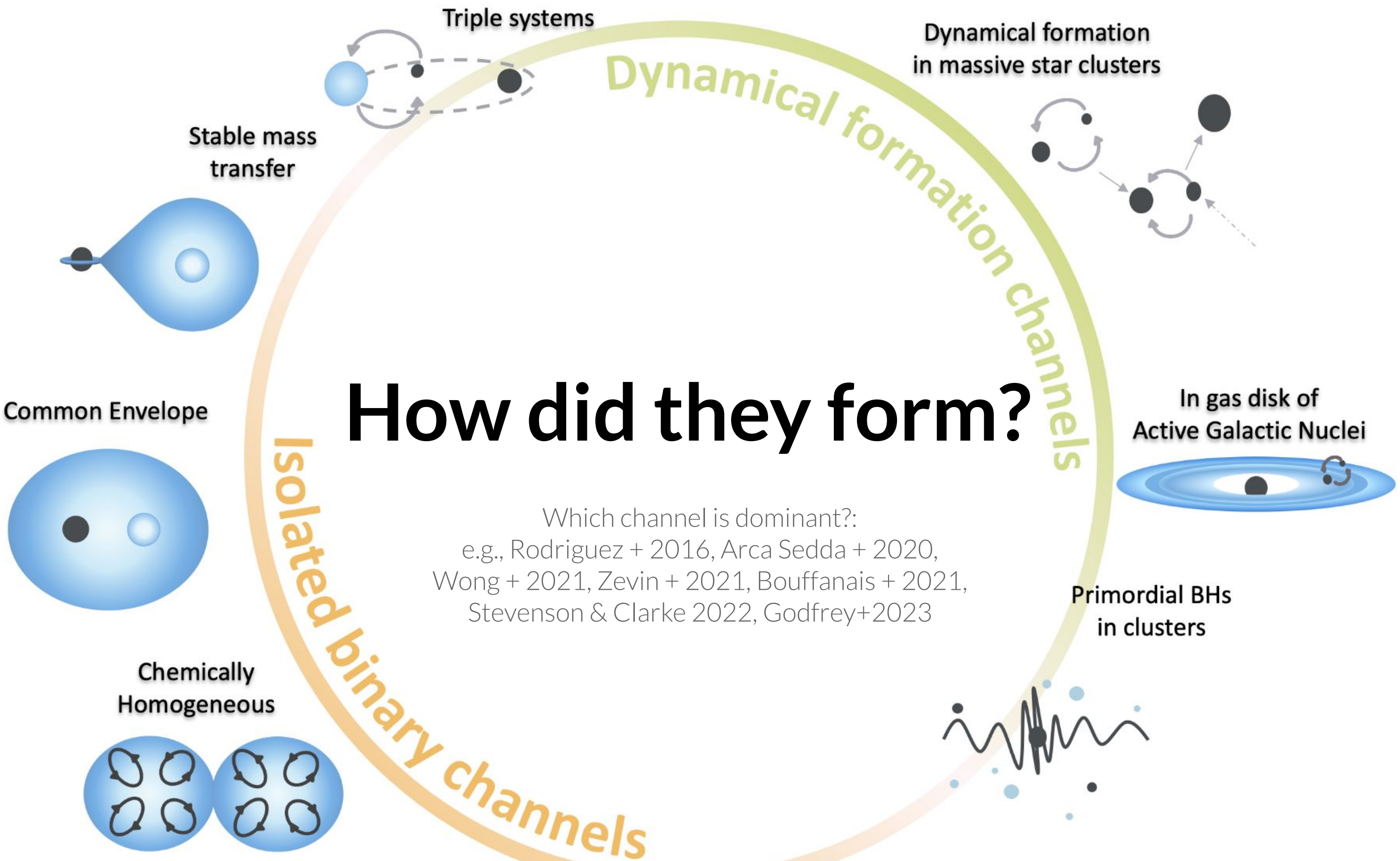


The separation challenge: How can we get BHs close enough to coalesce within a Hubble time?



How did they form?

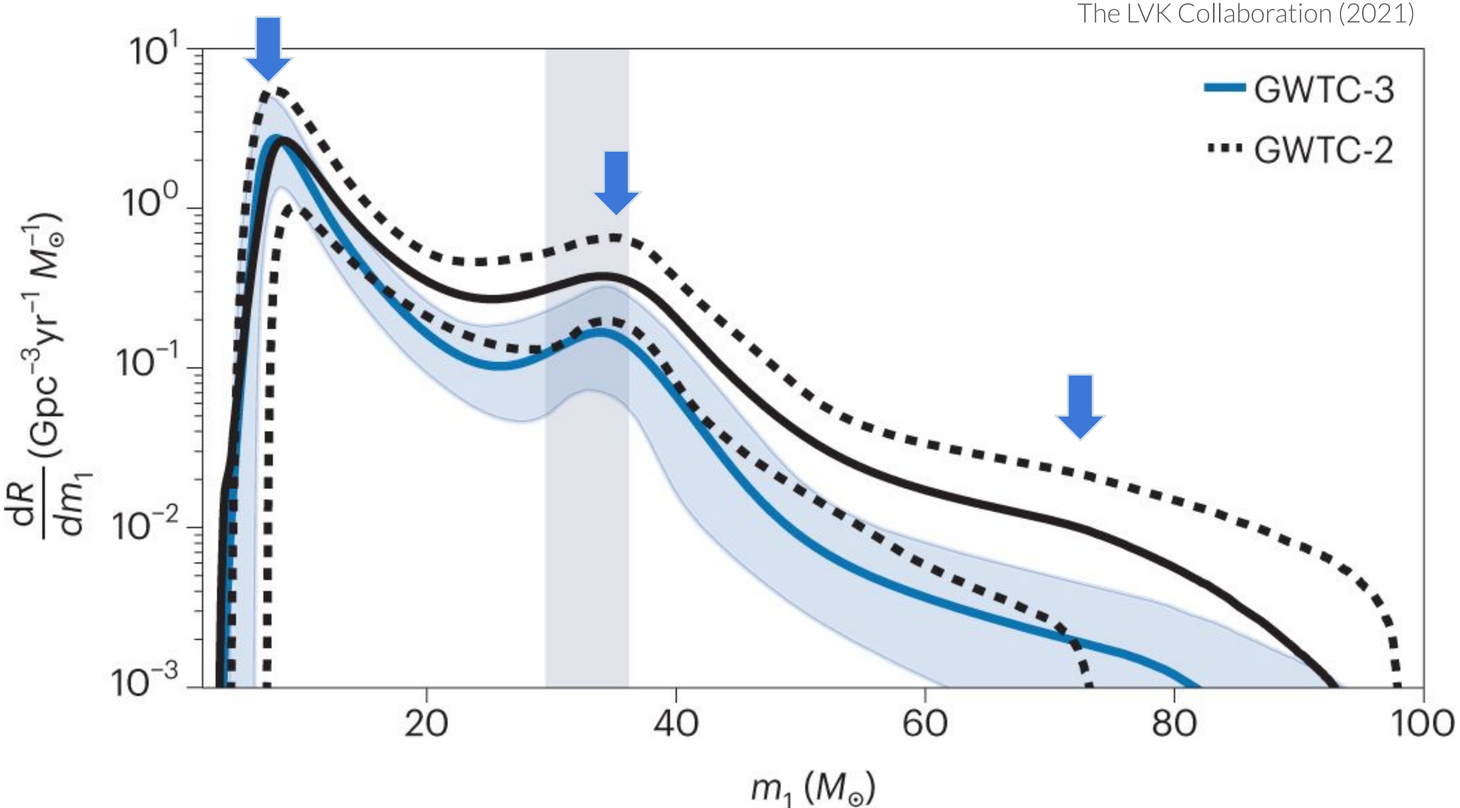
Which channel is dominant?:
e.g., Rodriguez + 2016, Arca Sedda + 2020,
Wong + 2021, Zevin + 2021, Bouffanais + 2021,
Stevenson & Clarke 2022, Godfrey+2023



Credit: Lieke van Son

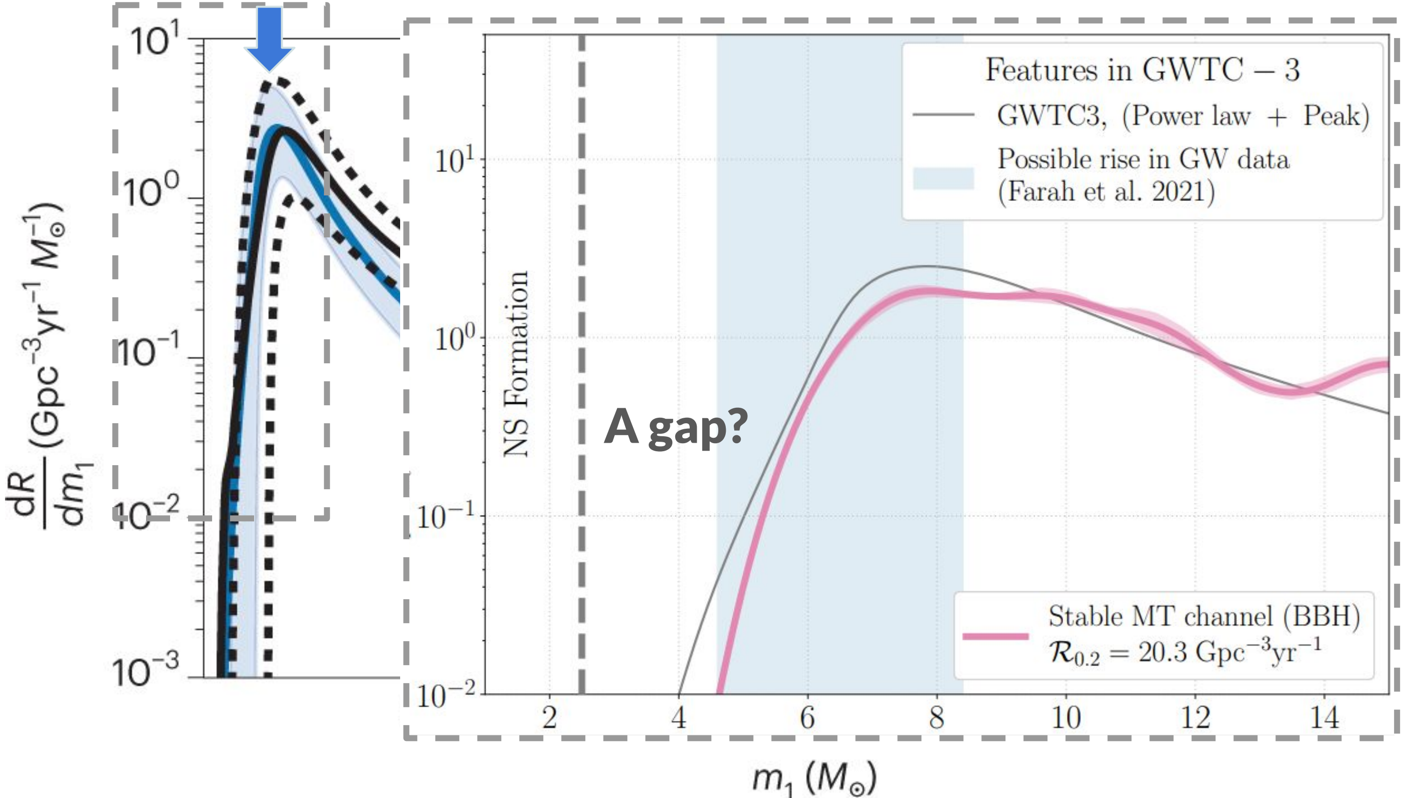
The observed BH mass distribution

The LVK Collaboration (2021)



There is a lack of 3-6 M⊙ BHs

… but the progenitor stars of lower-mass BHs are much more common than the progenitor stars of higher mass BHs ?!



van Son (2022)

There is a lack of 3-6 M$_\odot$ BHs

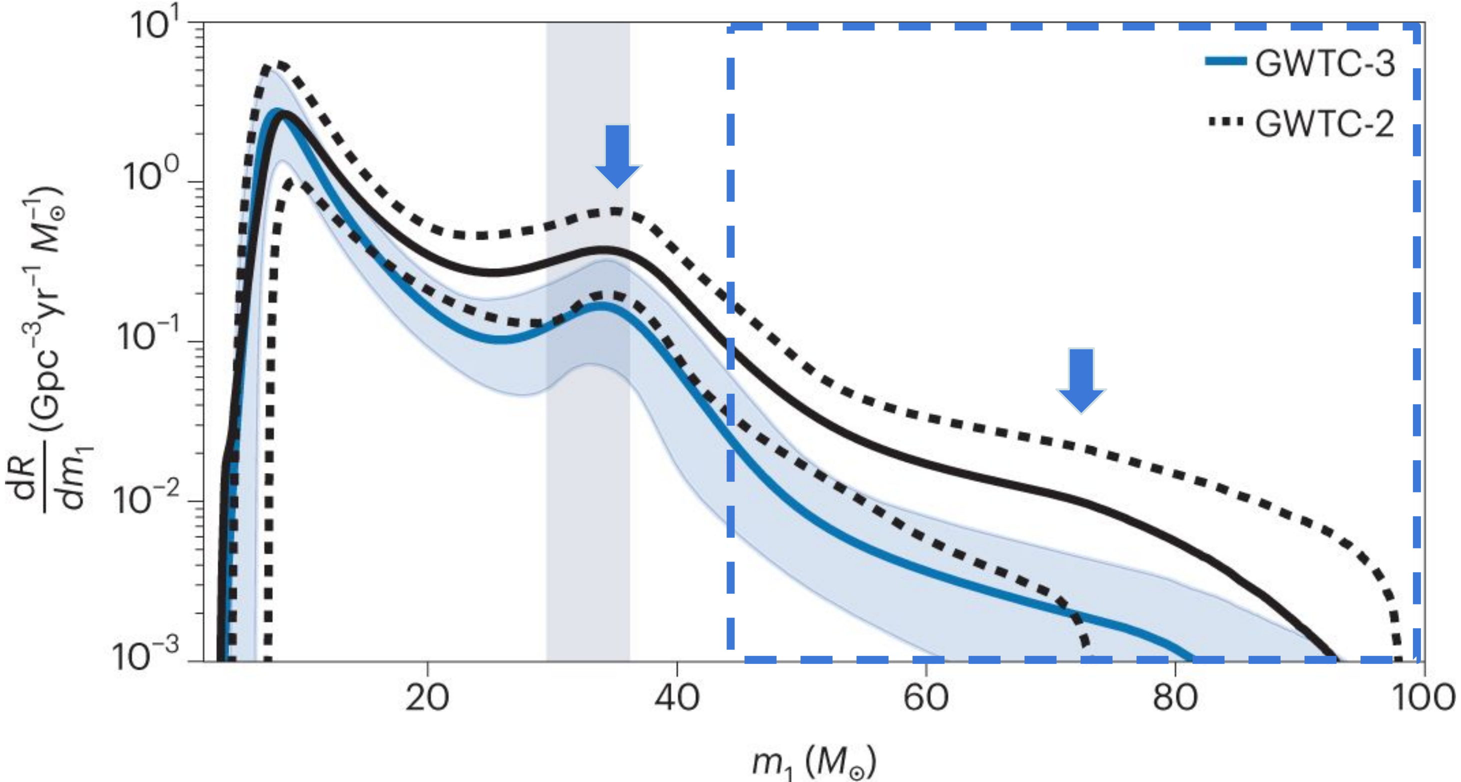
We don't see them	They don't exist	They don't merge
Observational bias against detecting such systems?	You cannot form *any* BHs with masses 3-6 solar mass ("NS-BH mass gap")	*Evolutionary selection effect* against merging double compact objects
The next crop of data will likely resolve this!	e.g. Fryer & Kalogera 2001, Fryer+ 2012, Belczynski+2012, Fryer+2022, Olejak+2022	Only in GW detection
e.g., Fishbach + 2017, Farah 2022;2023	**NS-BH mass gap is debated** Kreidberg et al., 2012; Wyrzykowski & Mandel, 2020; Jonker et al., 2021; Siegel + 2022 **(NGC 3201):** Giesers et al. 2019; **GW190814** (GW): LVK 2020. **GW190917** (GW): LVK 2020	van Son et al. (2022b)

Credit: Lieke van Son

The observed BH mass distribution

No BHs above 45 M⊙ were expected from stellar evolution.
Yet, here they are …

The LVK Collaboration (2021)



Pair instability supernova

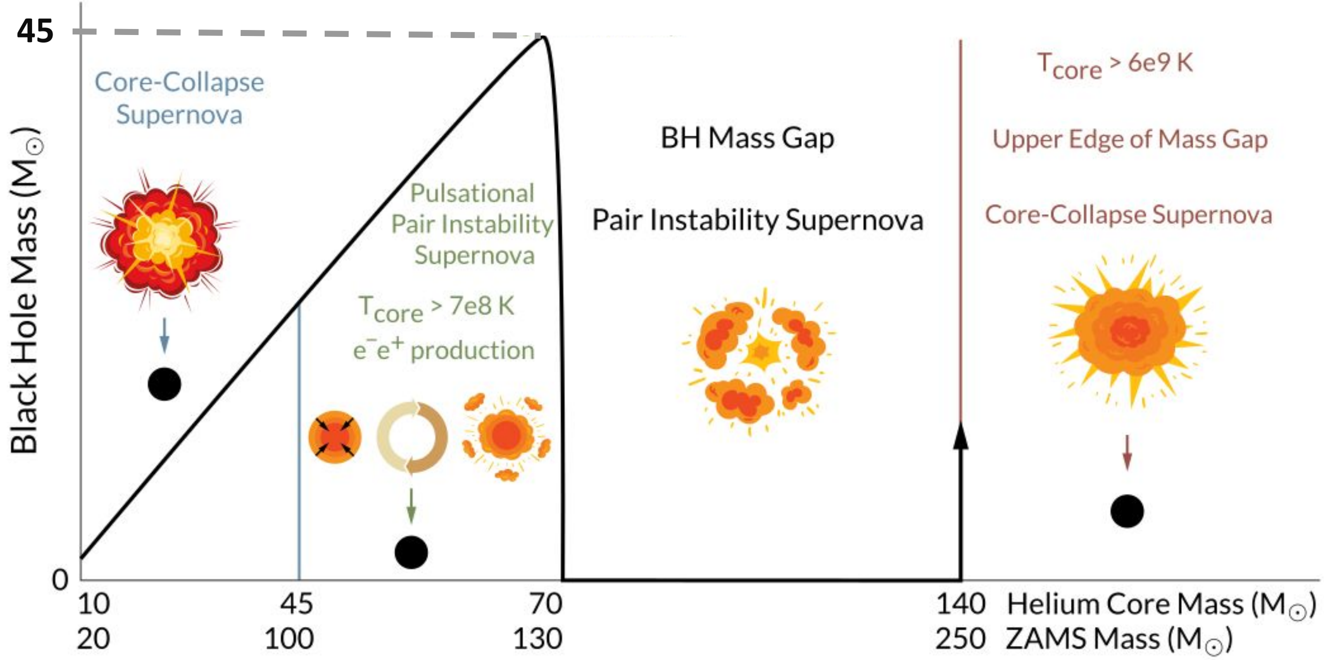


Figure adapted from Farag et al. 2022

Pair instability supernova

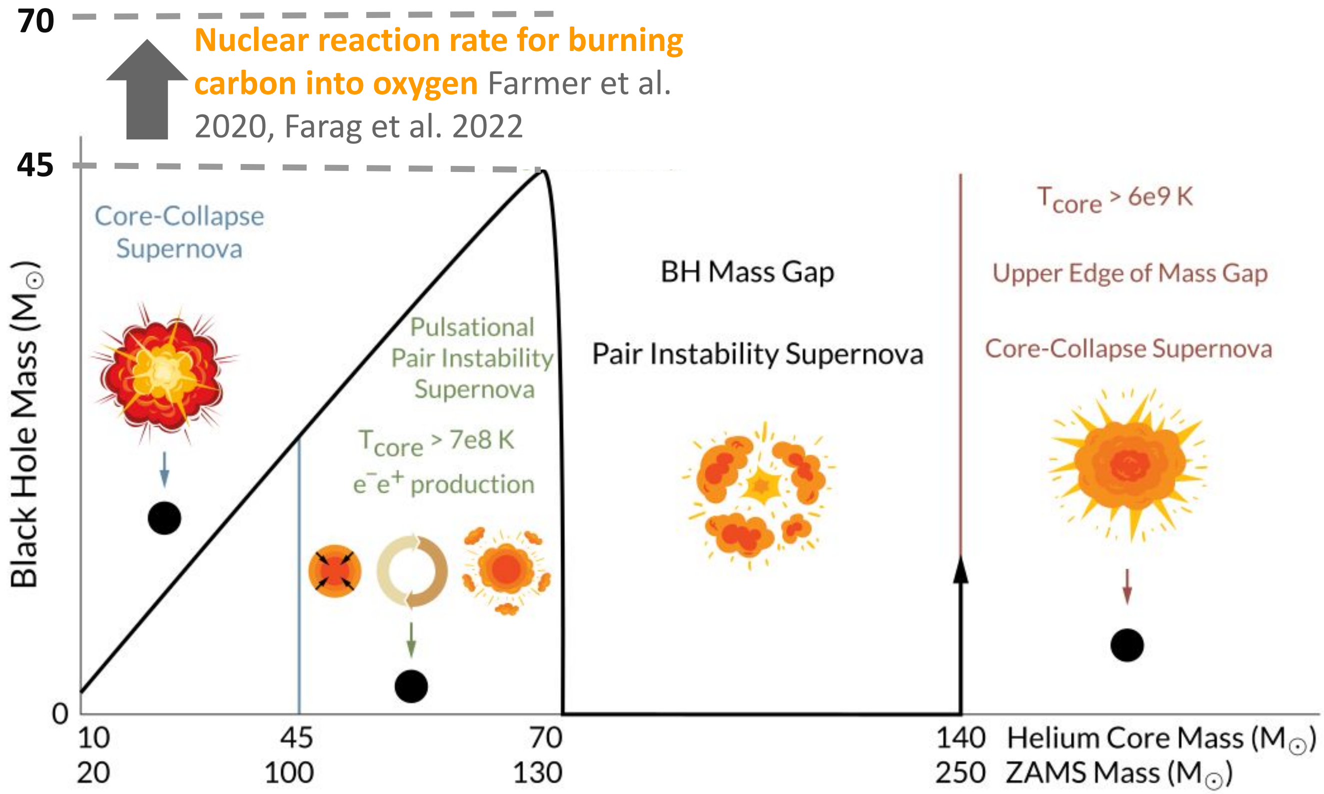
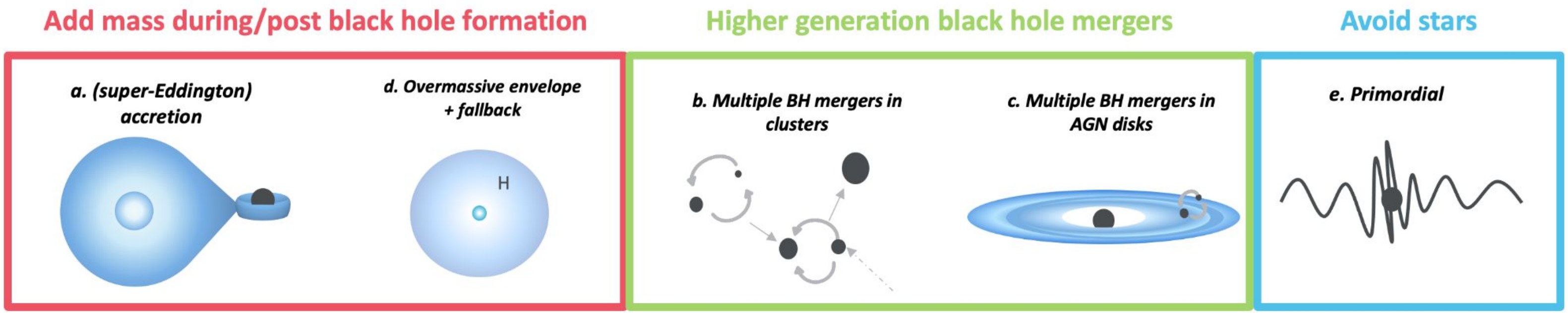


Figure adapted from Farag et al. 2022

How to get binary BH mergers in the mass gap?



Isolated Binaries: van Son et al. (2020)

Triples: Moreno Méndez et al. 2023

NC: Roupas & Kazanas (2019), Natarajan et al. (2020)

In the context of IMBHs: Vesperini et al. (2010), Davies et al. (2011) Leigh et al. (2012),

High z halo: Safarzadeh et al. (2020)

YSC: Di Carlo et al. (2019a,b) Vigna-Gómez et al. 2019; Kremer et al 2020 Mapelli et al. 2020,

PopIII stars: Kinugawa et al. (2020), Liu & Bromm (2020)

Stellar mergers: Renzo et al (2021) Ballone et al. (2023); Costa (2022)

Very low winds: Vink et al. 2021

YSC: Mapelli et al. 2020

GC: Rodriguez et al. (2019), Fragione et al. (2022); Rose (2022)

NC: Antonini et al. (2019) Fragione et al. (2020), Liu & Lai (2020) Martinez et al. (2020)

McKernan et al. (2014, 2018), Secunda et al. (2019, 2020),

migration traps: Bellovary et al. (2016), McKernan et al. 2020b, Sedda (2020), Yang et al. 2019,

Carr (1975), Bird et al. (2016), Sasakiet al. (2016), Raidal et al. (2017), Dvorkin et al. (2018)

(non) detection of stochastic background:
Wang et al. (2020), Lu et al (2019)

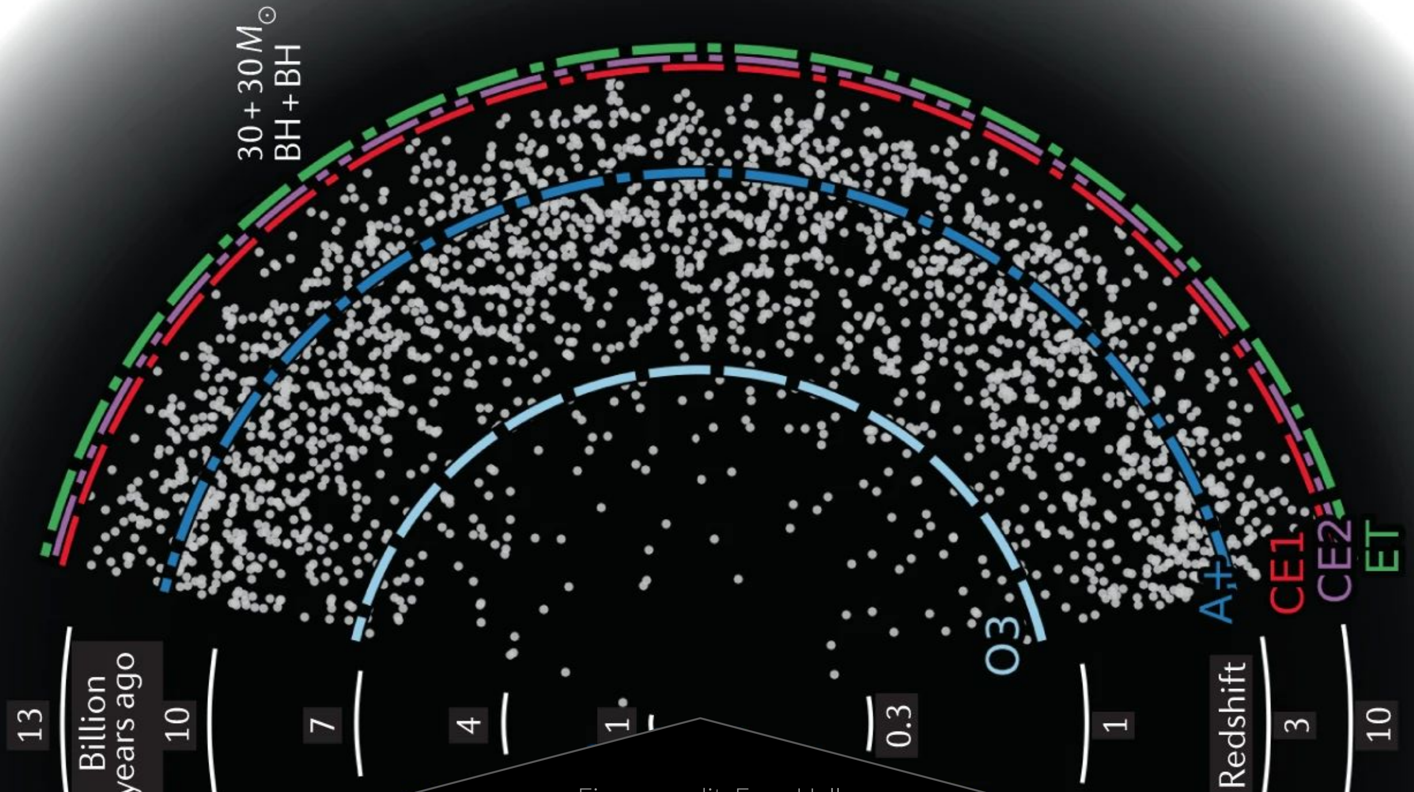
Credit: Lieke van Son

What are we learning from high-frequency GW detections?

- Binary BH (and NS) formation channels
  - Supernova mechanism and possibly nuclear reaction rates
- (Stellar) BH mass function
  - Evolution of this mass function with redshift (not covered in this talk)

and much more…

This is only the beginning ...



What will we learn in the **milli-Hz** GW detections?

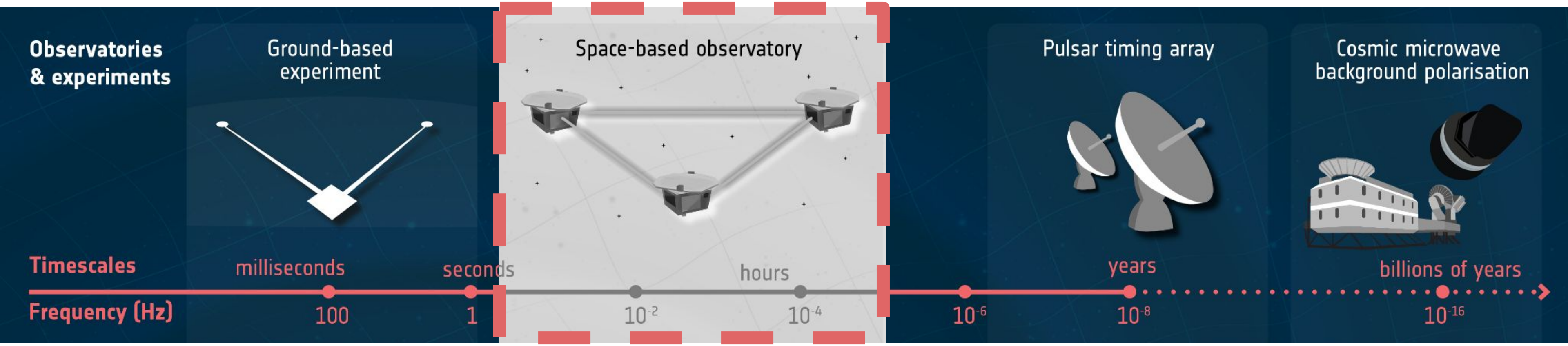
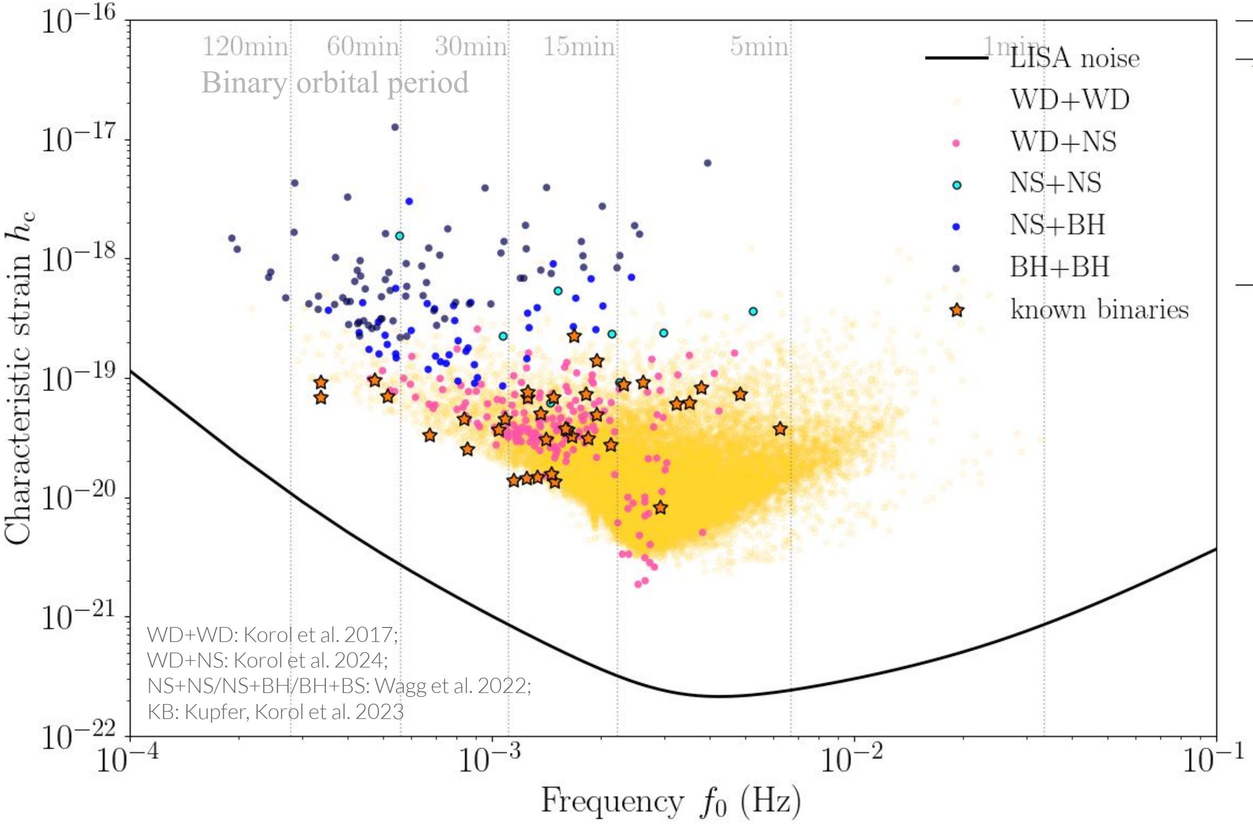


Image credit: ESA

LISA will detect a **variety of binaries** in the **Milky Way**



Source	N	N^{detected}
WD+WD	$\sim 10^8$	6,000–10,000
NS+WD	$\sim 10^7$	100–300
BH+WD	$\sim 10^6$	0–3
NS+NS	$\sim 10^5$	2–100
BH+NS	$\sim 10^4 - 10^5$	0–20
BH+BH	$\sim 10^6$	0–70

LISA Astrophysics white paper
Amaro-Seoane et al. /w Korol
Living Reviews in Relativity 26 (2) 2023

LISA's potential to solve type Ia SN progenitor dilemma

Single degenerate channel

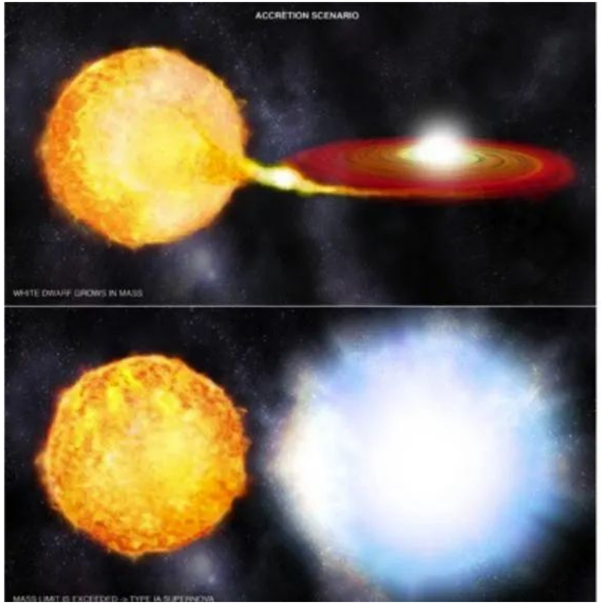
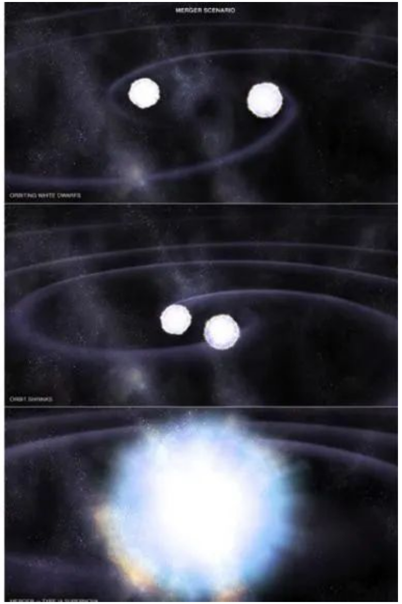


Image credits: NASA / CXC / M. Weiss

or

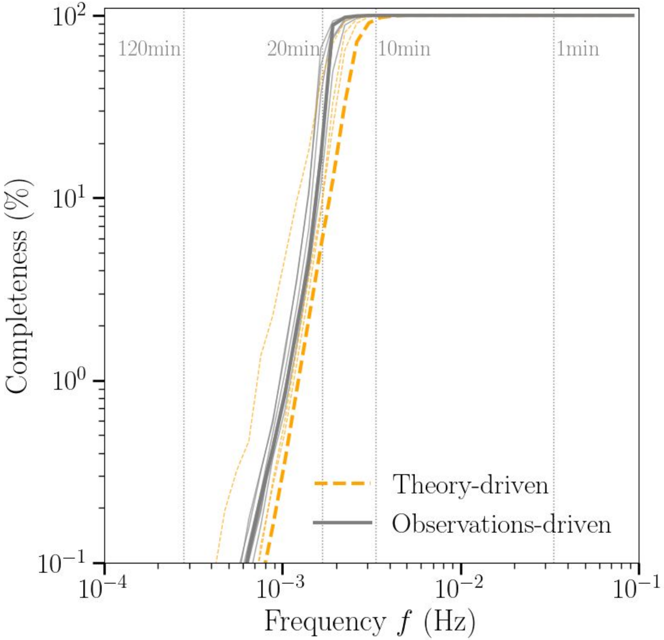
Double degenerate channel

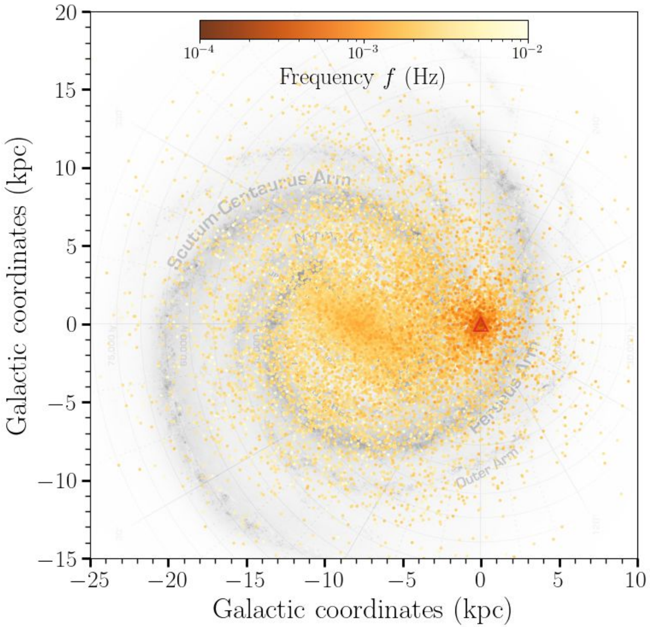


**This is an oversimplified picture, there are many many nuances to be considered…*

LISA's potential to solve type Ia SN progenitor dilemma

Complete sample up to orbital periods of ~15 min **across the entire Milky Way!**



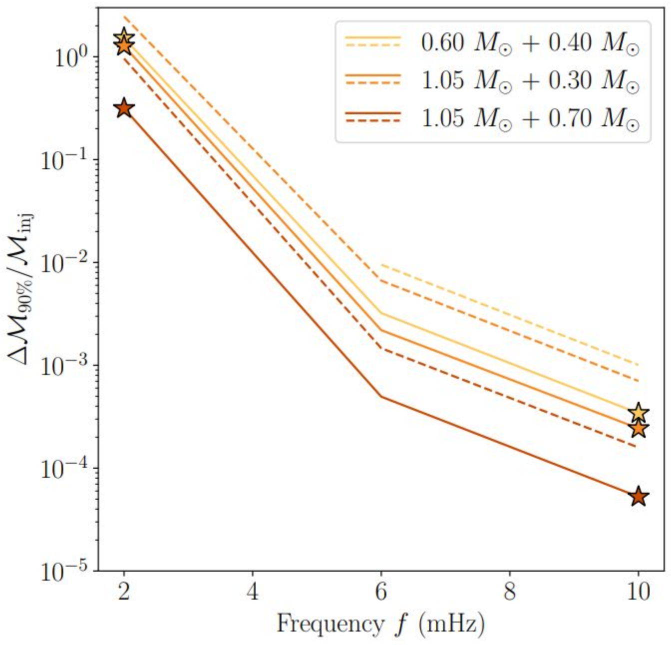


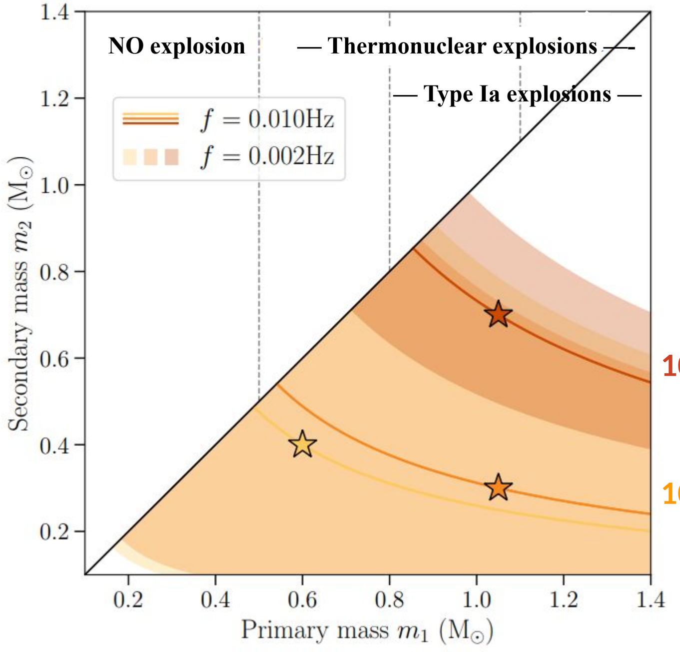
Korol et al. in prep.

LISA's potential to solve type Ia SN progenitor dilemma

At GW frequencies near to the merger (< 0.01 Hz) **chirp mass constraints at 0.01-0.001%**

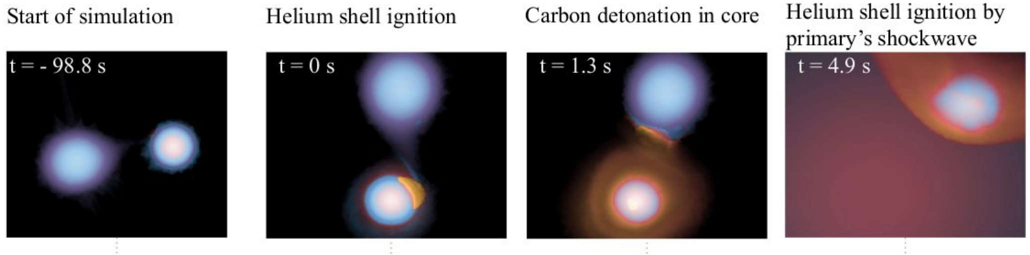
Chirp mass constraint translates into a **lower bound on the primary mass** making it possible to forecast the possibility and the type of thermonuclear transient.





Korol et al. in prep.

There is a 4-7% chance that we will see a type Ia SN with LISA
How its GW signal will look like?



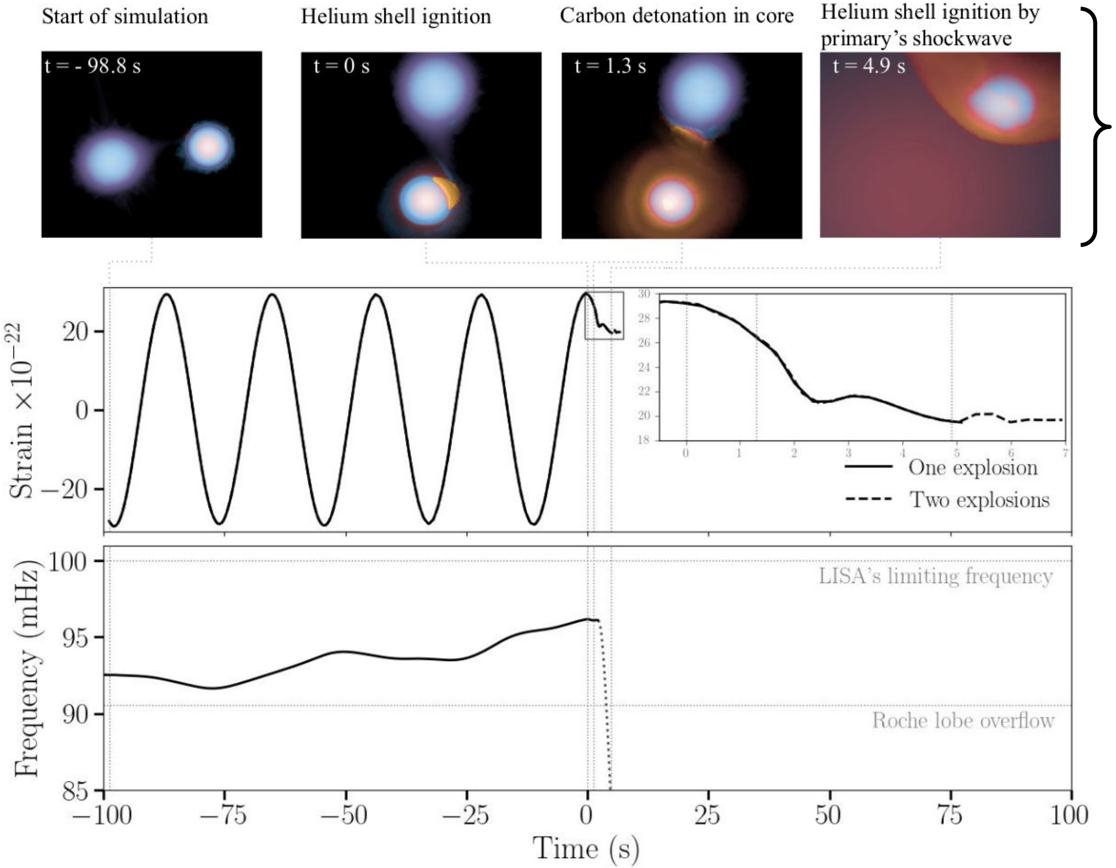
Double detonation mechanism

1. Dynamical accretion of helium on more massive WD (>0.8 M☉) ignites its helium shell

2. Helium detonation converges in the centre to ignite WD's CO core (type Ia supernova)

Korol et al. in prep.
based on Pakmor et al. 2022
and Morán-Fraile el al. 2023

There is a 4-7% chance that we will see a type Ia SN with LISA
How its GW signal will look like?

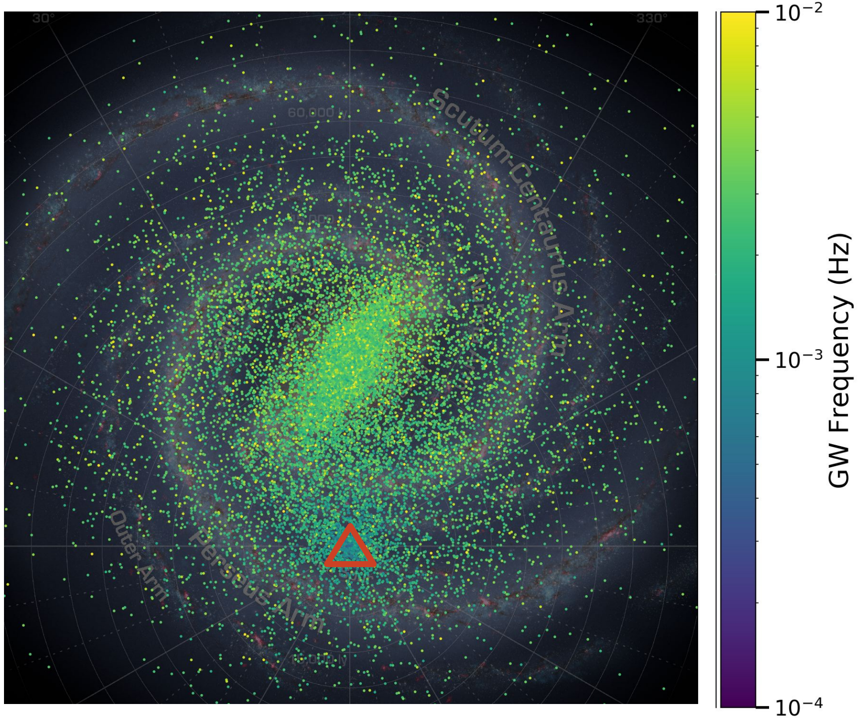


Double detonation mechanism

1. Dynamical accretion of helium on more massive WD (>0.8 M☉) ignites its helium shell
2. Helium detonation converges in the centre to ignite WD's CO core (type Ia supernova)

Korol et al. in prep.
based on Pakmor et al. 2022
and Morán-Fraile el al. 2023

Making a **map of the Milky Way** with LISA



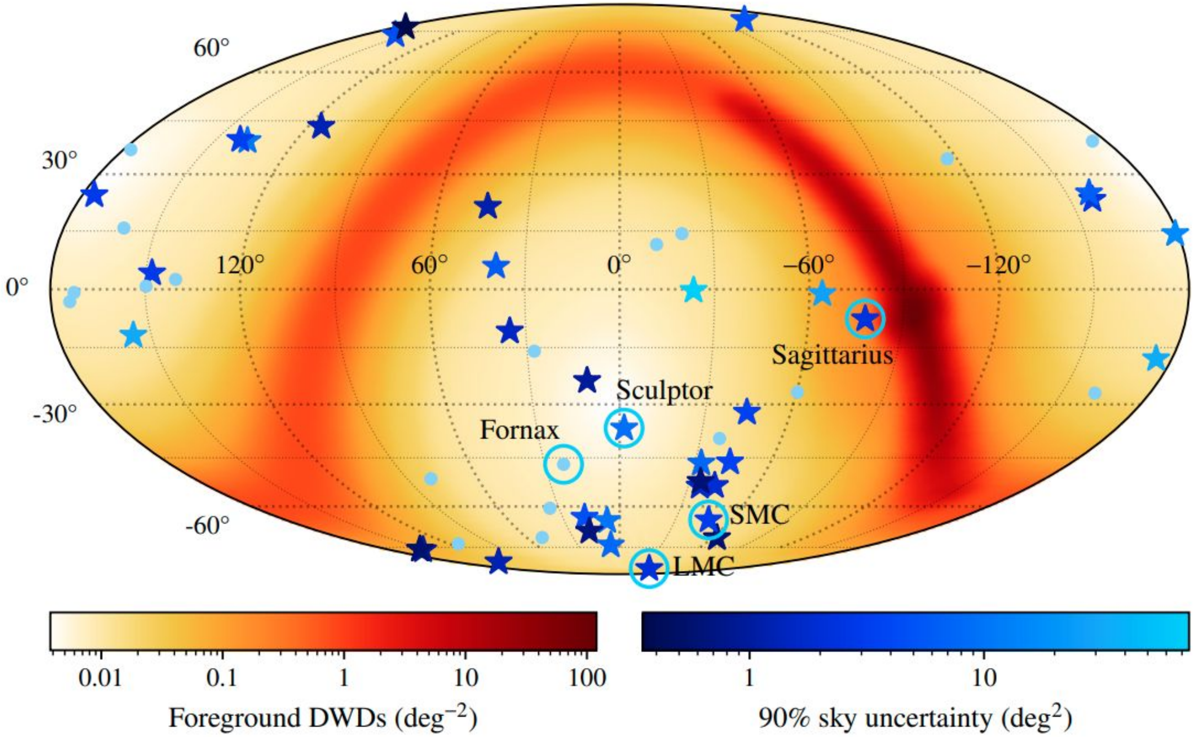
LISA Astrophysics white paper, Amaro-Seoane et al./w Korol 2023
LISA Definition Study Report (Red Book), Colpi et al./w Korol 2024

LISA's precision in locating WD+WD binaries will constrain structural parameters of the Milky Way, providing new, independent insights into its shape:

- Bulge Scale Radius: **2%** precision
- Disk Scale Radius: **3%** precision.
- Disk Scale Height: **16%** precision
- Bar Axis Ratio: **10%** precision
- Bar Length: **1%** precision
- Bar Orientation Angle: **<1°**

Korol et al. 2019; Wilhelm, Korol et al. 2021
(see also Adams et al. 2012)

(Re-)discovering Milky Way satellites with GWs



Roebber et al. (incl.Korol) 2020; Korol et al. (2020,2021); Keim, Korol et al. (2023)

What will we learning from **milli-Hertz frequency** GW detections?

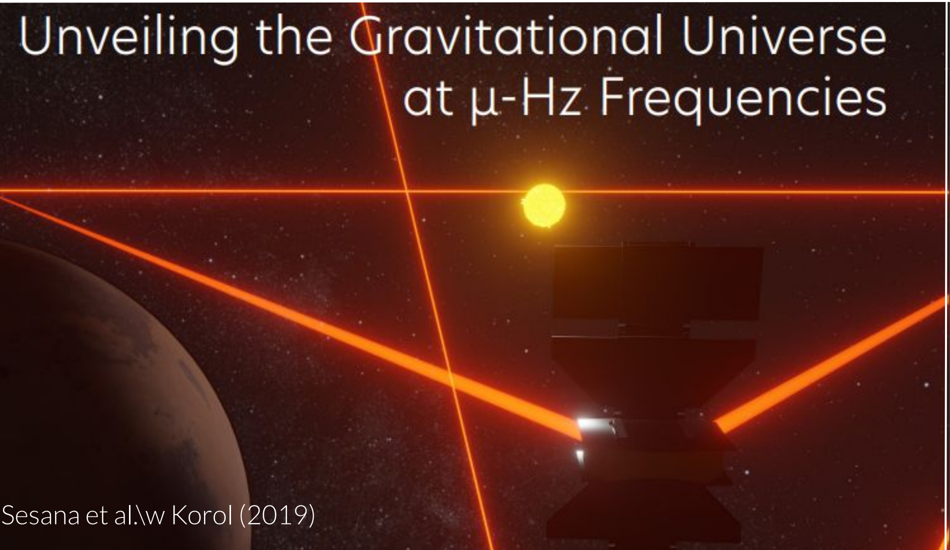
- Invisible stellar content of the Milky Way: BH, NS, and WD in binaries
- Type Ia supernova progenitors
- The shape of the Milky Way

and much more...

E.g., see LISA Astrophysics Living Review, Amaro-Seoane et al. 2023

What is the next BIG idea?

Harms et al. (2020)



Sesana et al.\w Korol (2019)

Arca Sedda et al. (2019)