Image credit: ESO/M. Kornmesser/S.E. de Mink

Probing Massive Binary Stellar Evolution With Gravitational-wave Astronomy

Dr Simon Stevenson
ARC DECRA Fellow
Swinburne University of Technology, Melbourne, Australia

SWINBURNE UNIVERSITY OF TECHNOLOGY

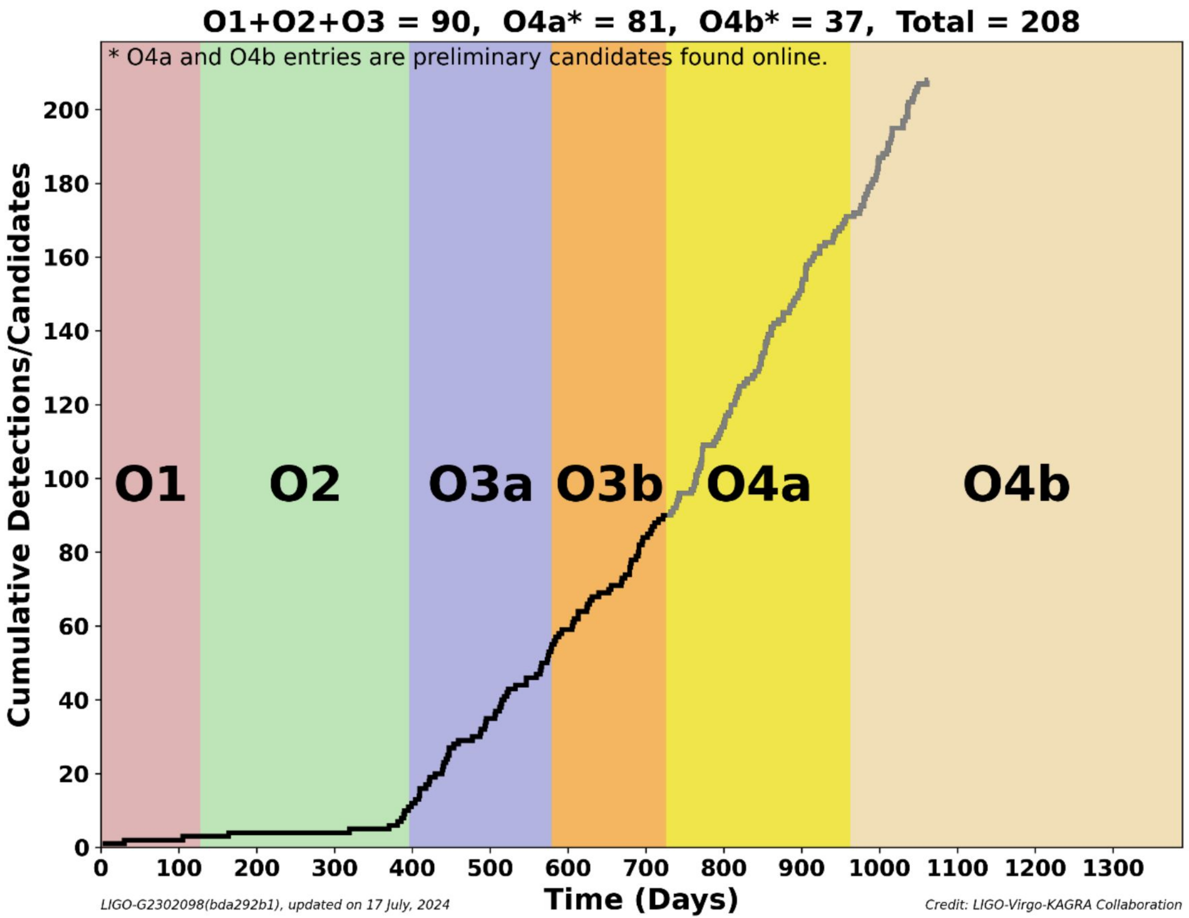
OzGrav

COMPAS

Gravitational Wave Detectors

- ➢ Ground-based laser interferometers
- ➢ L-shaped, km long arms
- ➢ Worldwide observing network
- ➢ Alternate between observing and upgrading

Current status of GW Astronomy



Current status of GW Astronomy

GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

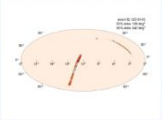
O4 Significant Detection Candidates: **147** (164 Total - 17 Retracted)

O4 Low Significance Detection Candidates: **2550** (Total)

Show All Public Events

Page 1 of 11. next last »

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S241009an	BBH (>99%)	Yes	Oct. 9, 2024 08:48:16 UTC	GCN Circular Query Notices | VOE		1 per 16402 years	

https://gracedb.ligo.org/superevents/public/O4/

The highlights: what have we already learned?

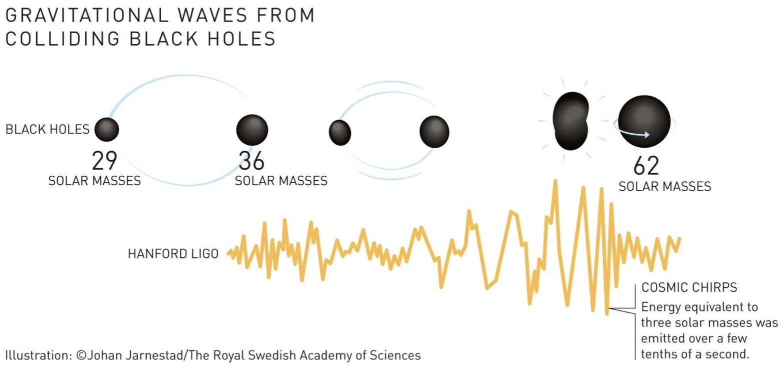
Discovery of gravitational waves (GW150914)
(Abbott et al. 2016 inc **SS**)

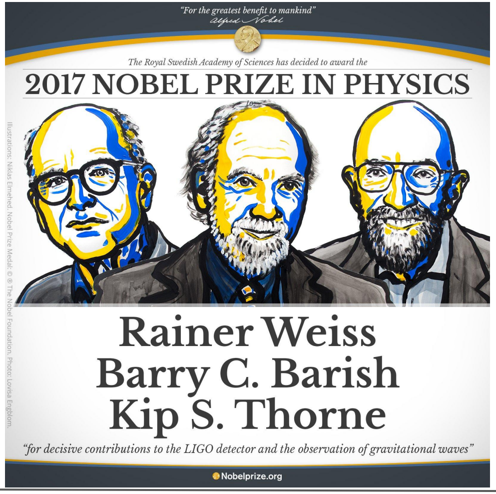
Observation of GWs and light from the BNS GW170817 - BNS lead to SGRBs (Abbott et al. 2017 inc **SS**)

NSBH exist and merge at an observable rate
(Abbott et al. 2021 inc **SS**)

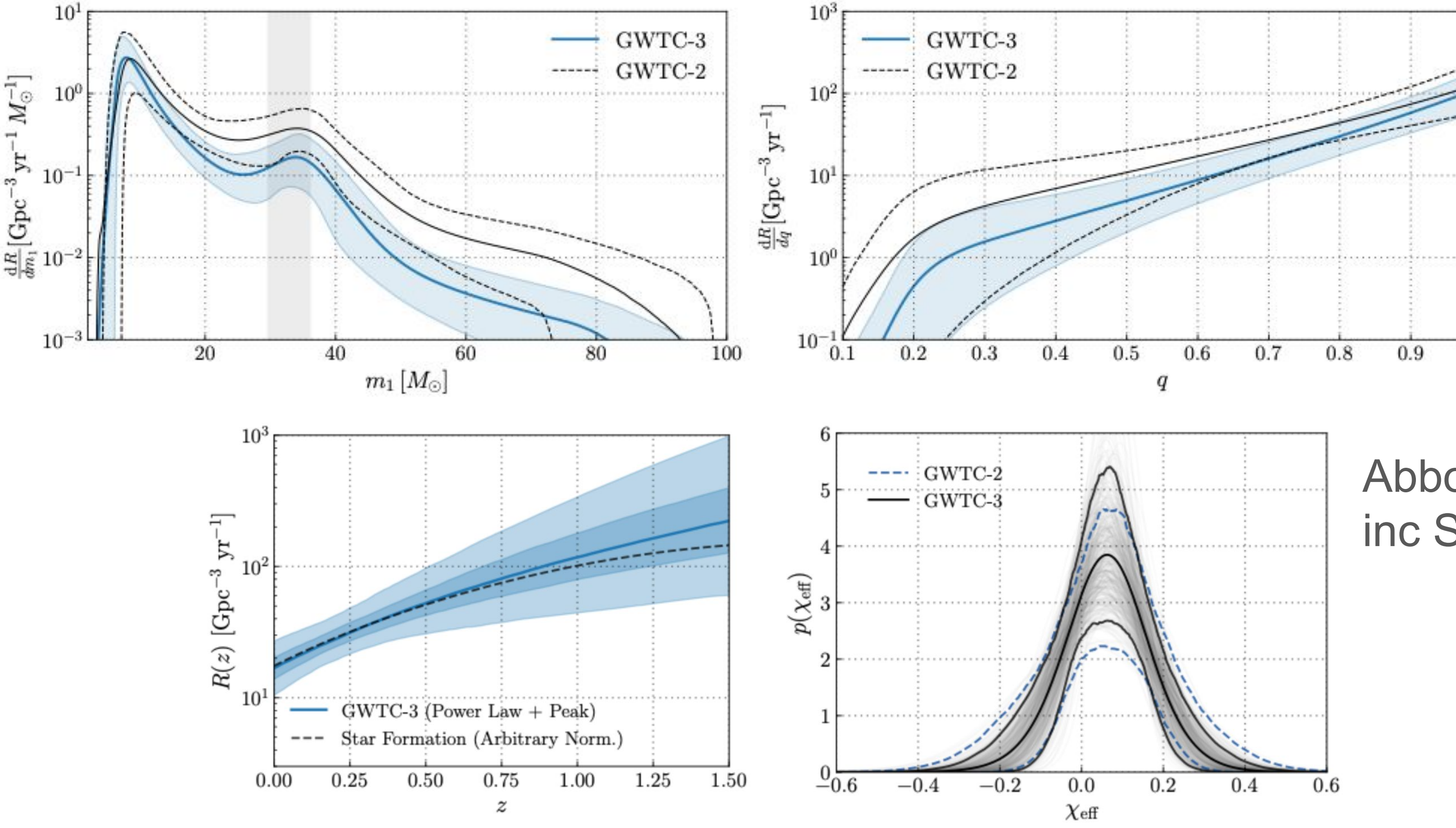
Intermediate-mass black holes (IMBHs) can be formed through black hole mergers
(GW190521; Abbott et al. 2021 inc **SS**)

BBHs exist and merge at an observable rate with a broad range of masses (10–150 solar masses)





The BBH population at a glance



Abbott et al. inc SS 2023

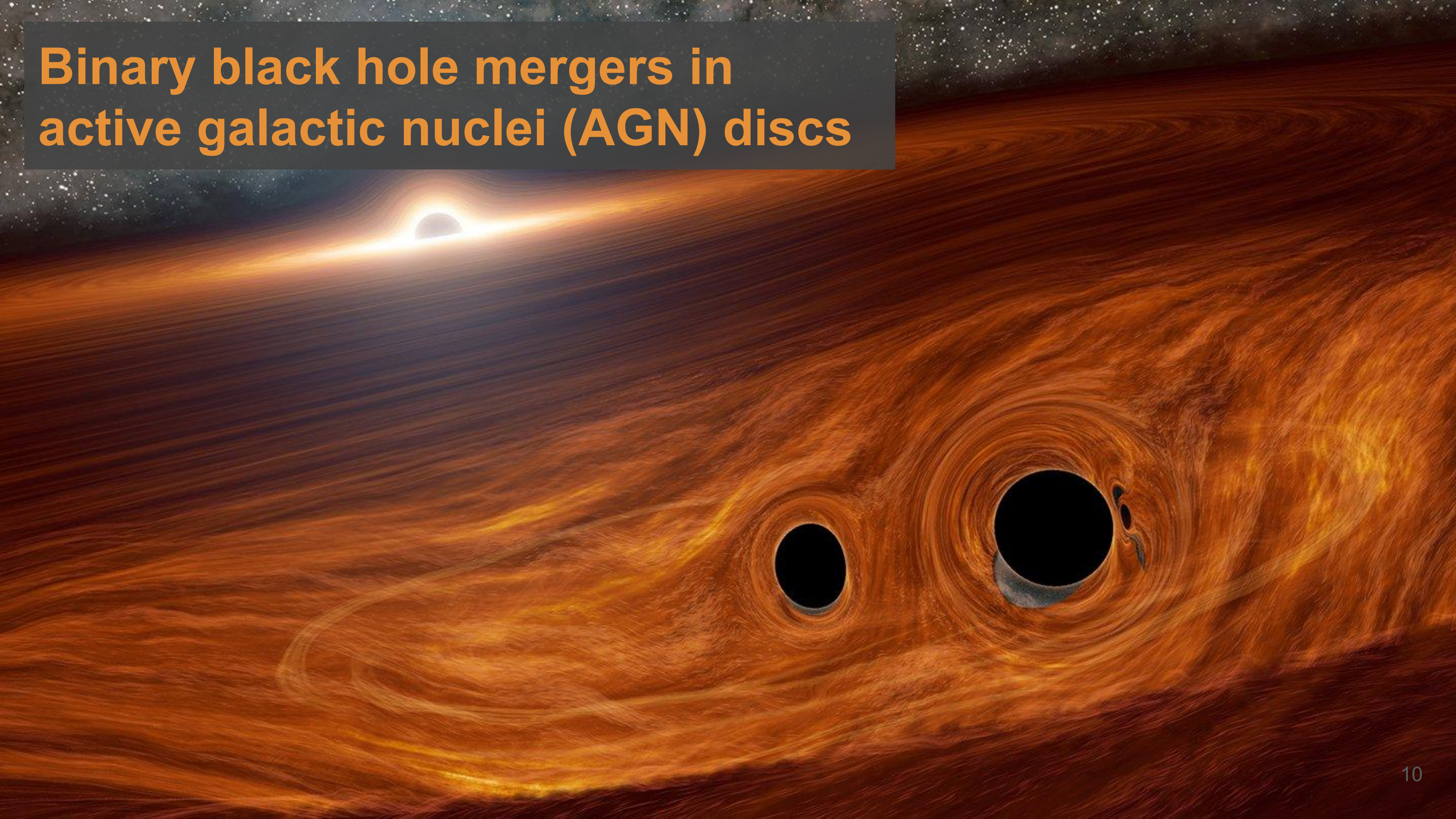
What are the open questions? What can we learn?

How do GW sources form?

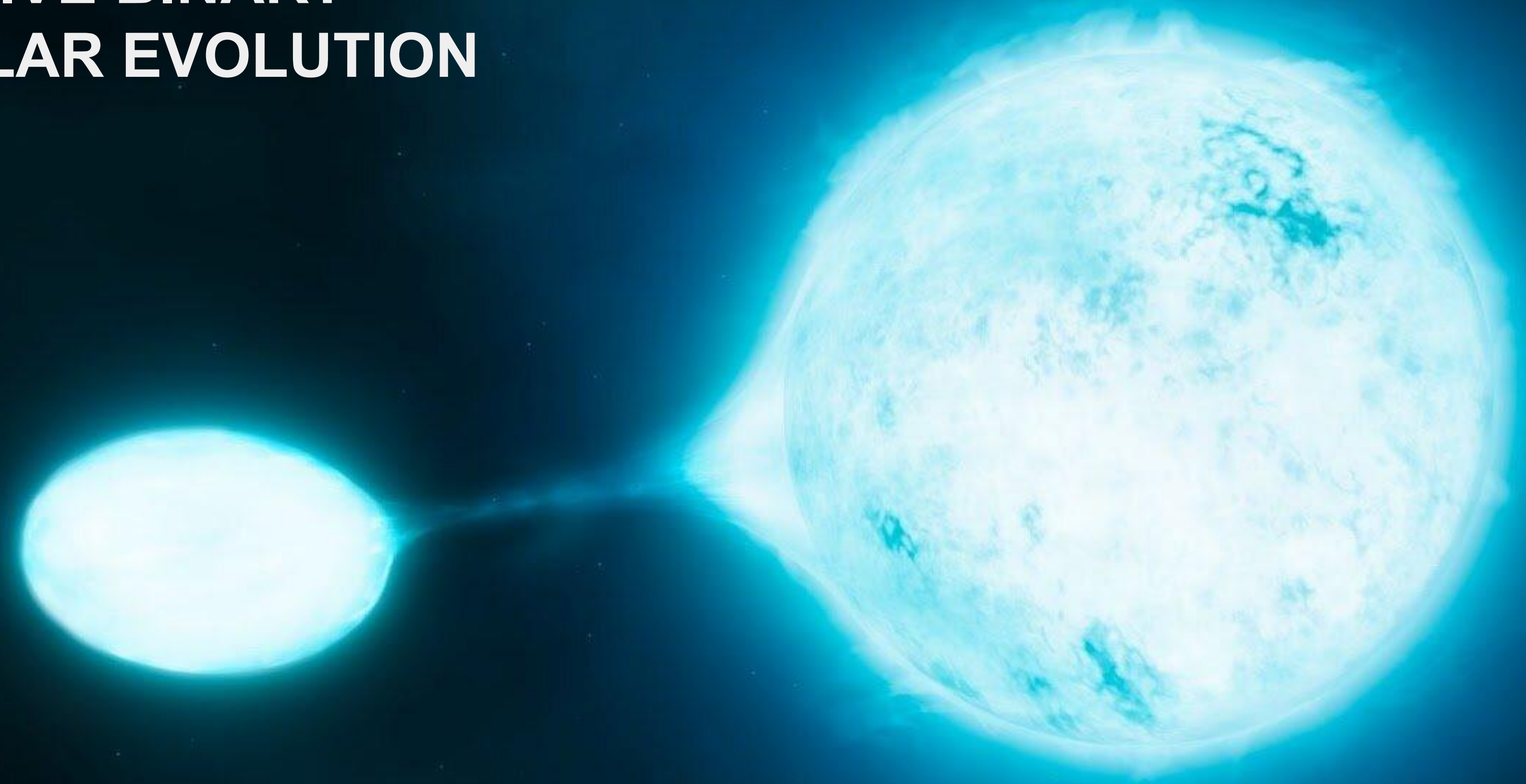
How do massive stars live and die?

DYNAMICAL FORMATION IN DENSE STAR CLUSTERS

Binary black hole mergers in active galactic nuclei (AGN) discs



MASSIVE BINARY STELLAR EVOLUTION



Binary evolution stages

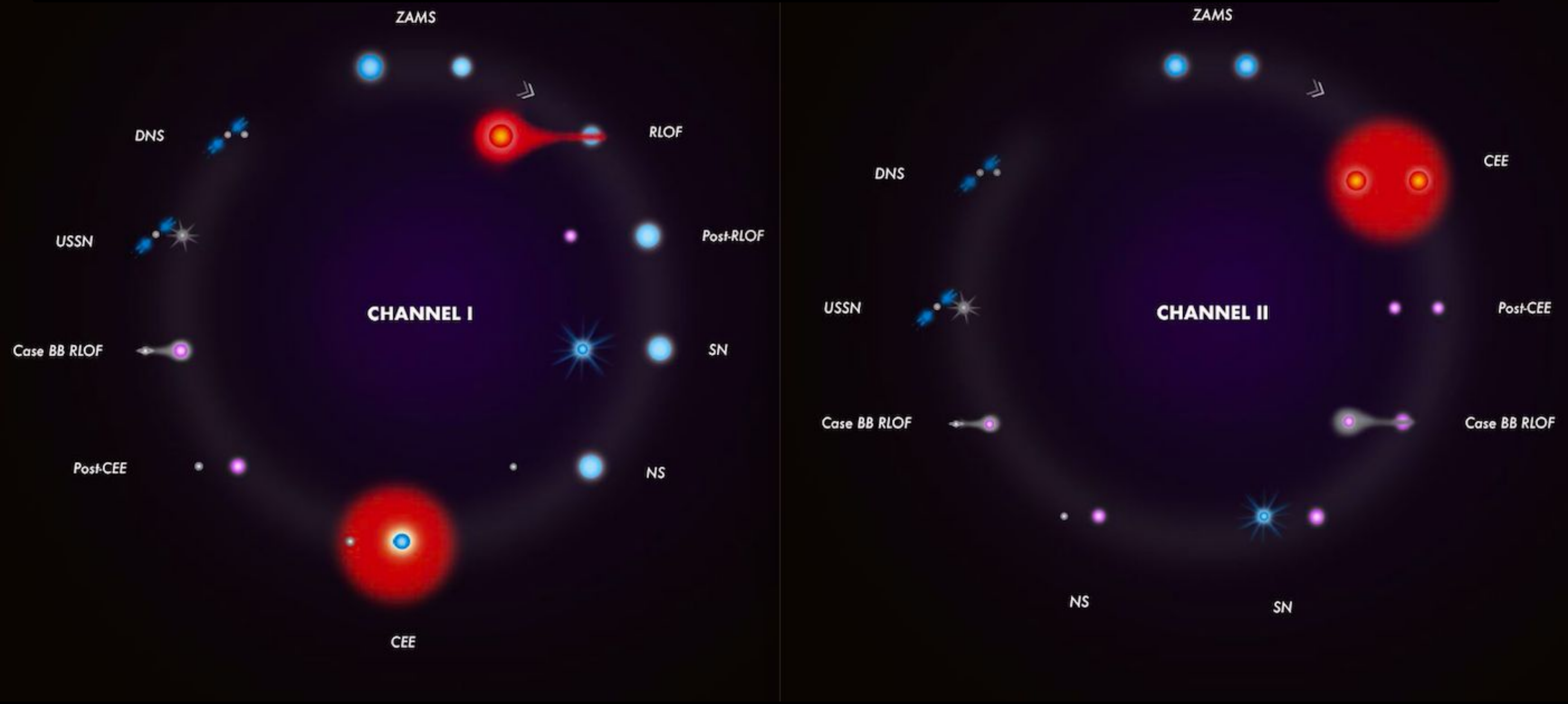


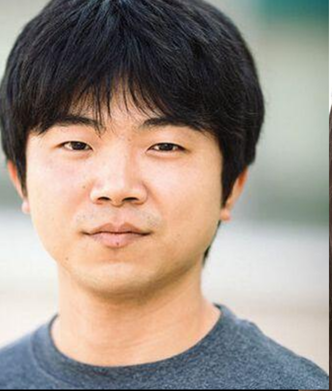
Image credit:A. Vigna-Gómez/T. Rebagliato

COMPAS

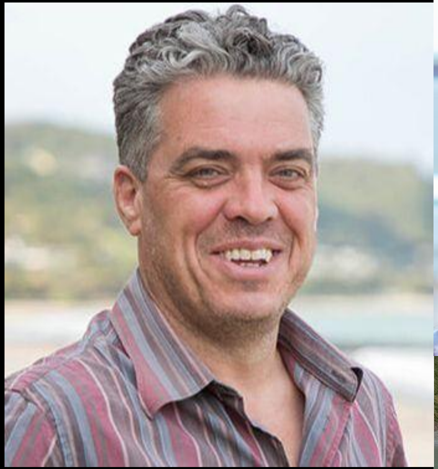
- Performs rapid population synthesis for single (SSE; Hurley et al. 2000) and binary (BSE; Hurley et al. 2002) stars
- Includes post-processing tools for incorporating cosmic star formation history of the Universe and gravitational-wave selection effects
- Designed (and most commonly used) for studying origins of gravitational-wave sources
- Also used to study X-ray binaries (Vinciguerra et al. 2020; Romero-Shaw et al. 2023), luminous red novae (Howitt et al. 2020) and pulsars (Song et al. submitted)

Stevenson et al. 2017, Nature Communications
Riley et al. inc **SS**, 2022, ApJS

Image credit: Carl Knox, OzGrav








And even more!






UNIVERSITY OF AMSTERDAM

POSTERA CRESCAM LAUDE

THE UNIVERSITY OF MELBOURNE

Max-Planck-Instit
für Gravitationsph
Albert-Einstein-I

PER ARDUA AD ALTA

UNIVERSITY OF BIRMINGHAM

DARK

VE RI TAS

HARVARD

ANCORA IMPARO

MONASH University

MAX PLANCK INSTITUTE FOR ASTROPHYSICS

SWINBURNE

SWINBURNE UNIVERSITY OF TECHNOLOGY

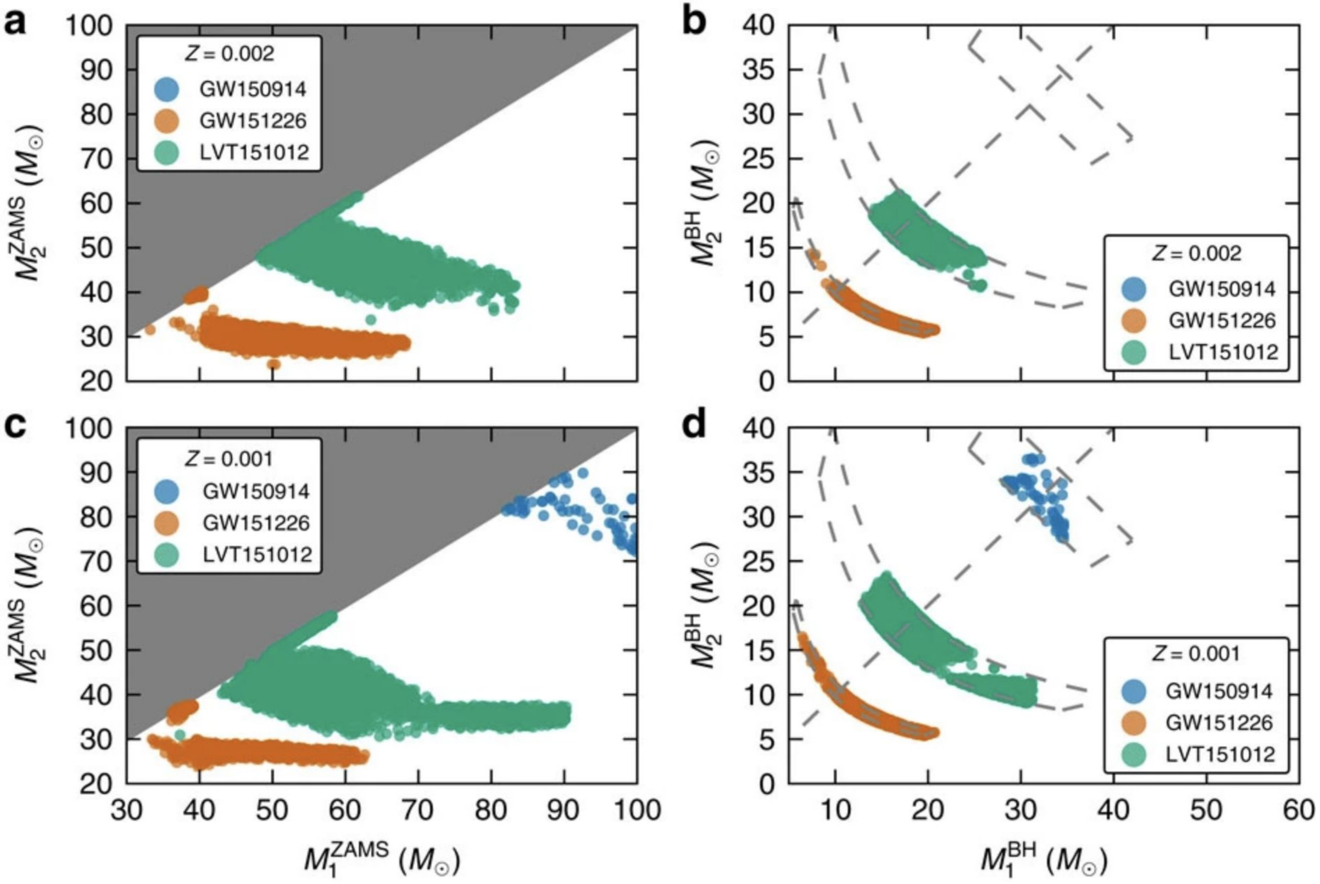
OzGrav

COMPAS

FOR COMPAS SCIENCE, VISIT COMPAS.SCIENCE

TO GET THE CODE GO TO HTTPS://GITHUB.COM/TEAMCOMPAS/COMPAS

Imprint of formation channels on observables - masses



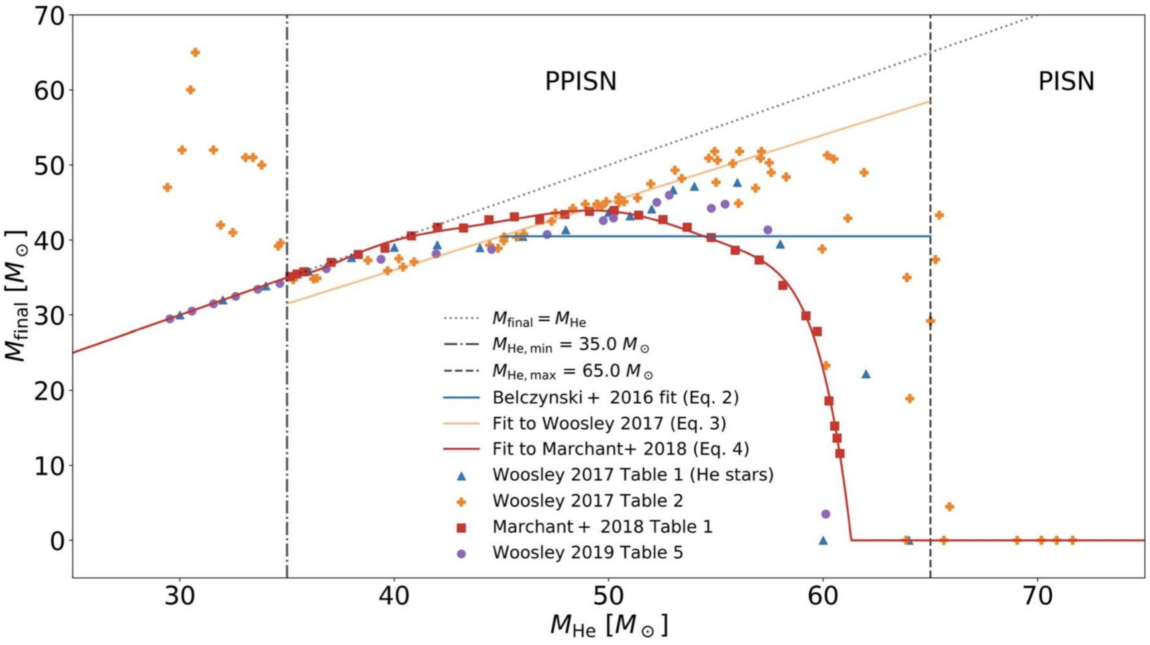
- First few GW observations consistent with isolated binary formation

Stevenson et al. 2017
Nature Communications

COMPAS

Impact of (pulsational) pair instability supernovae

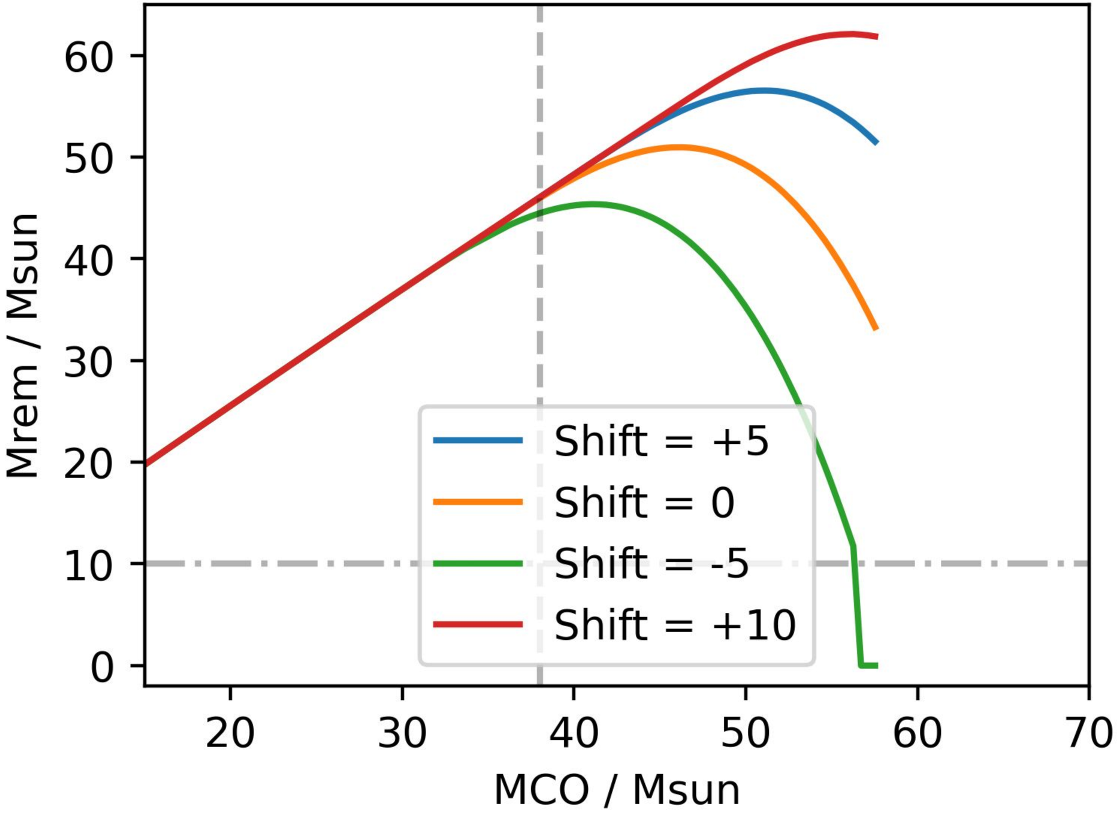
- ➢ Massive stars become unstable to electron-positron pair instability
- ➢ Leads to pair instability supernovae (PISN), leave no remnant
- ➢ At lower masses, pulsations lead to enhanced mass loss (and a potential pile-up of black hole masses)



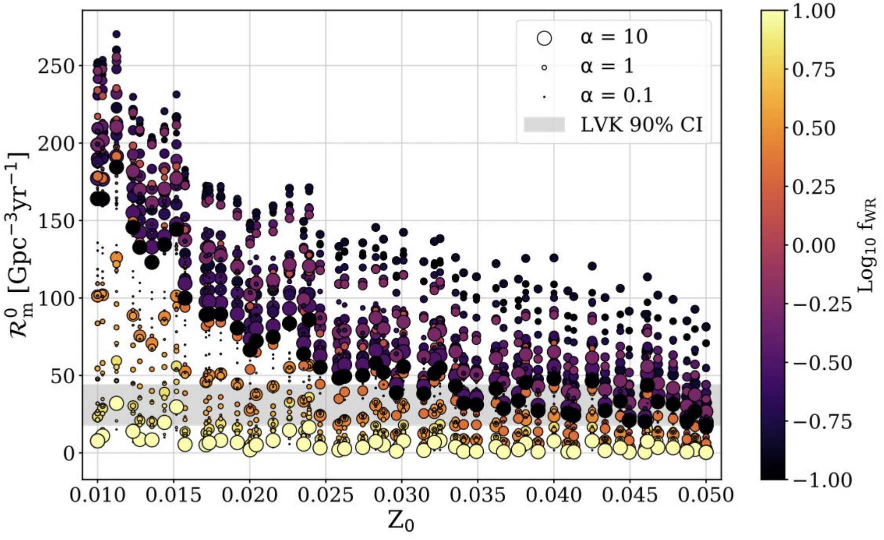
Stevenson et al. 2019, *ApJ*

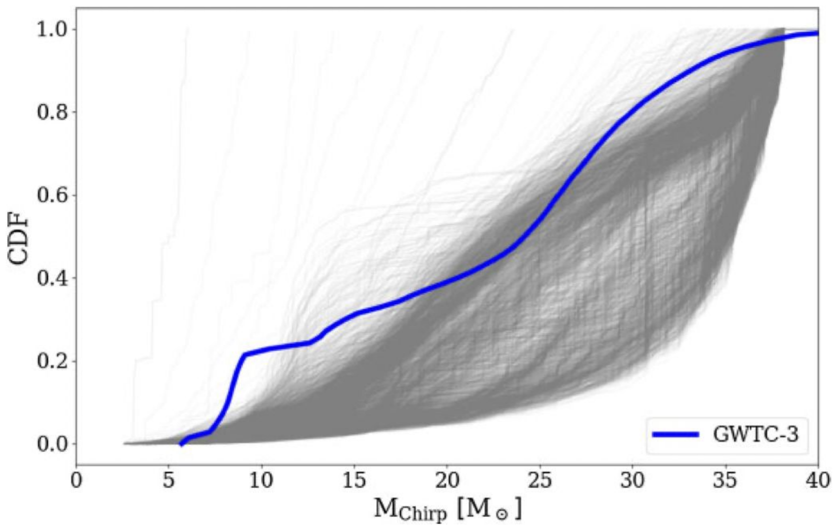
Impact of (pulsational) pair instability supernovae

- Recent models have shown a dependence on uncertain nuclear reaction rates (Farmer et al. 2019)
- Hendriks et al. 2024 introduce a flexible model for PPISN
- Allows us to probe the maximum black hole mass



Imprint of formation channels on observables - masses



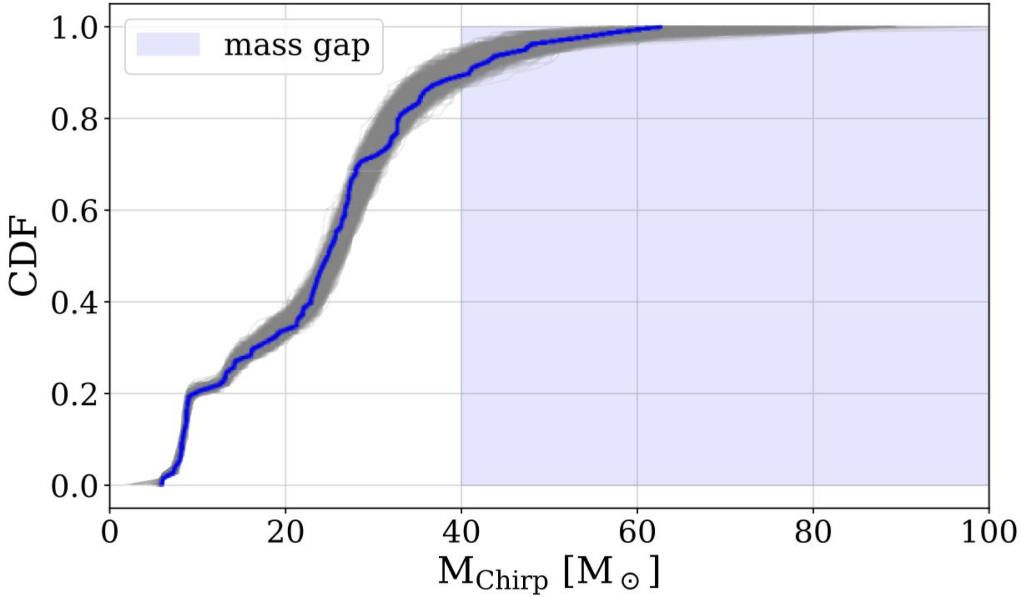


Stevenson & Clarke 2022

Large uncertainties in BBH mass distributions and merger rates from uncertainties in massive stellar evolution and star formation history (these models are all bad)

Imprint of formation channels on observables - masses

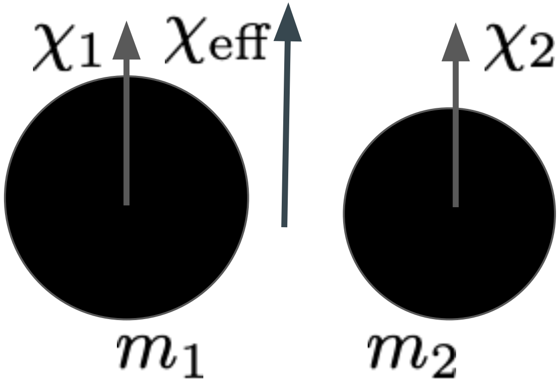
- ➢ More recently, around 10% of BBHs are too massive to form through isolated binary evolution in our model
- ➢ Potential contribution from another formation channel (clusters? AGN?)

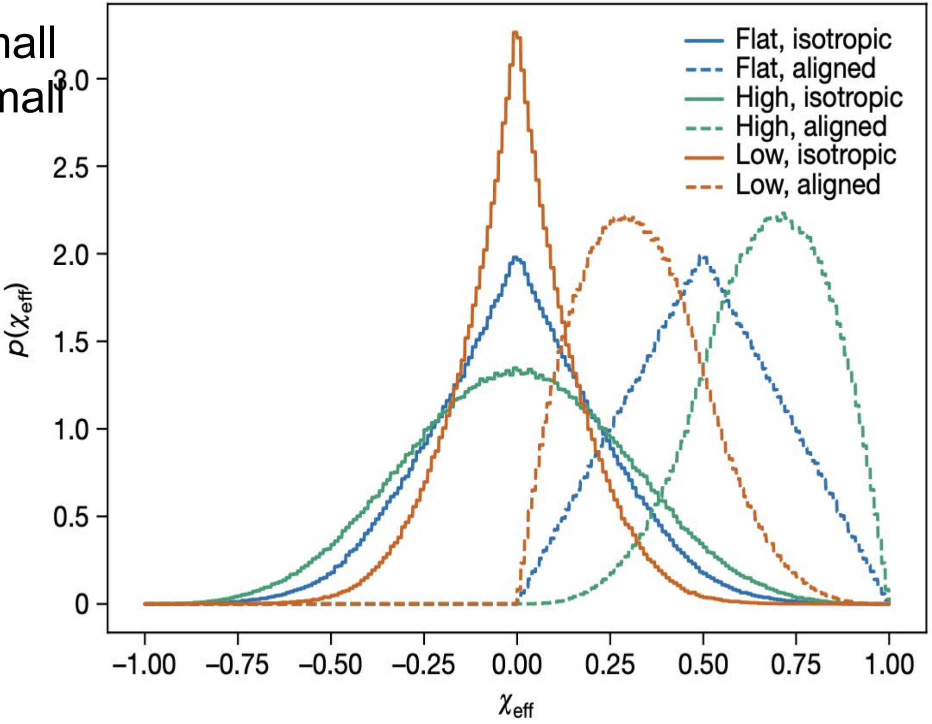


Stevenson & Clarke 2022

Imprint of formation channels on observables - spins

- ➢ Effective spins of merging BBHs are small
- ➢ Can originate from either intrinsically small spin magnitudes (binaries), or highly misaligned spins (dynamical)





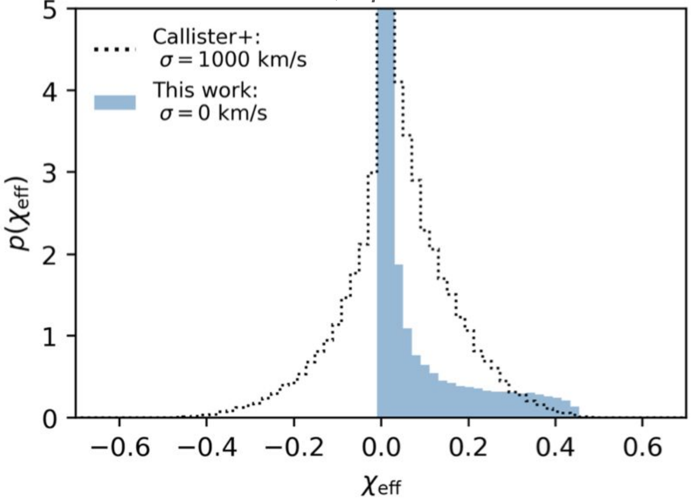
Stevenson et al. 2017 (spins)

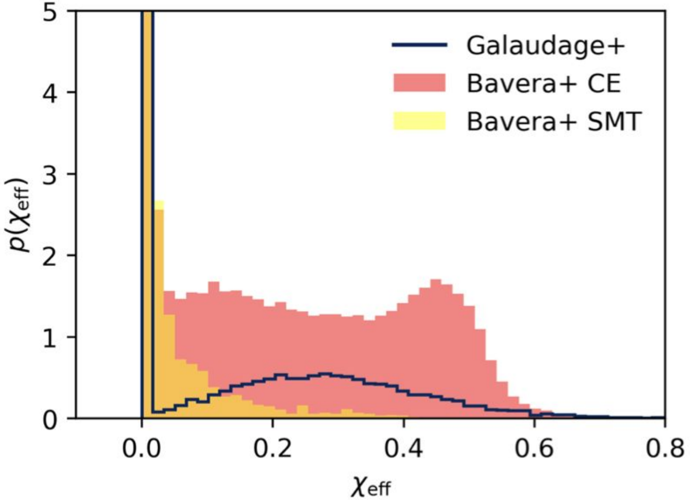
Farr, **Stevenson** et al. 2017, *Nature* (spins)

Imprint of formation channels on observables - spins

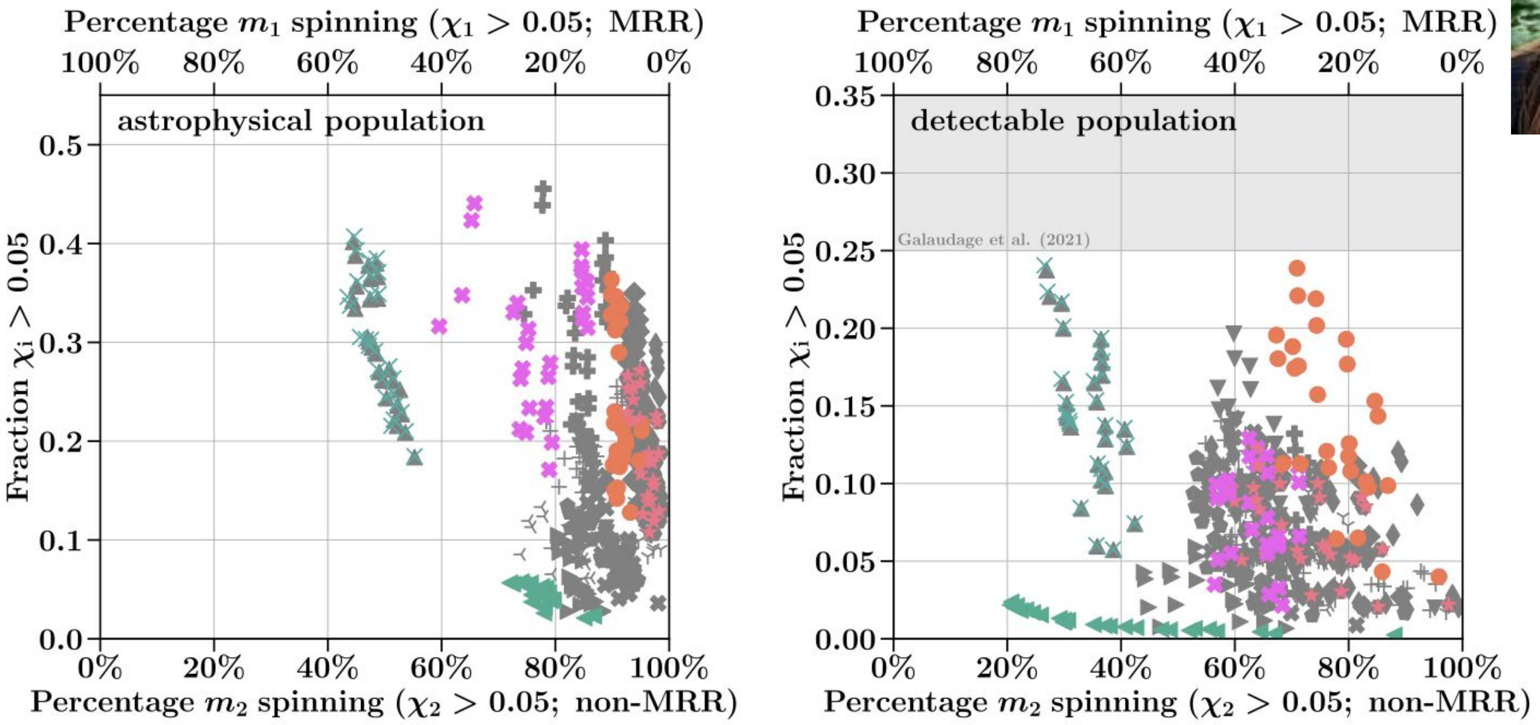
- In binaries, first born BH expected to have low spin due to efficient angular momentum transport
- Progenitor of second born BH can be tidally spun up, leading to highly spinning secondary
- Common envelope evolution produces tighter binaries, leads to larger spins

Stevenson 2022, *ApJL*





Imprint of formation channels on observables - spins

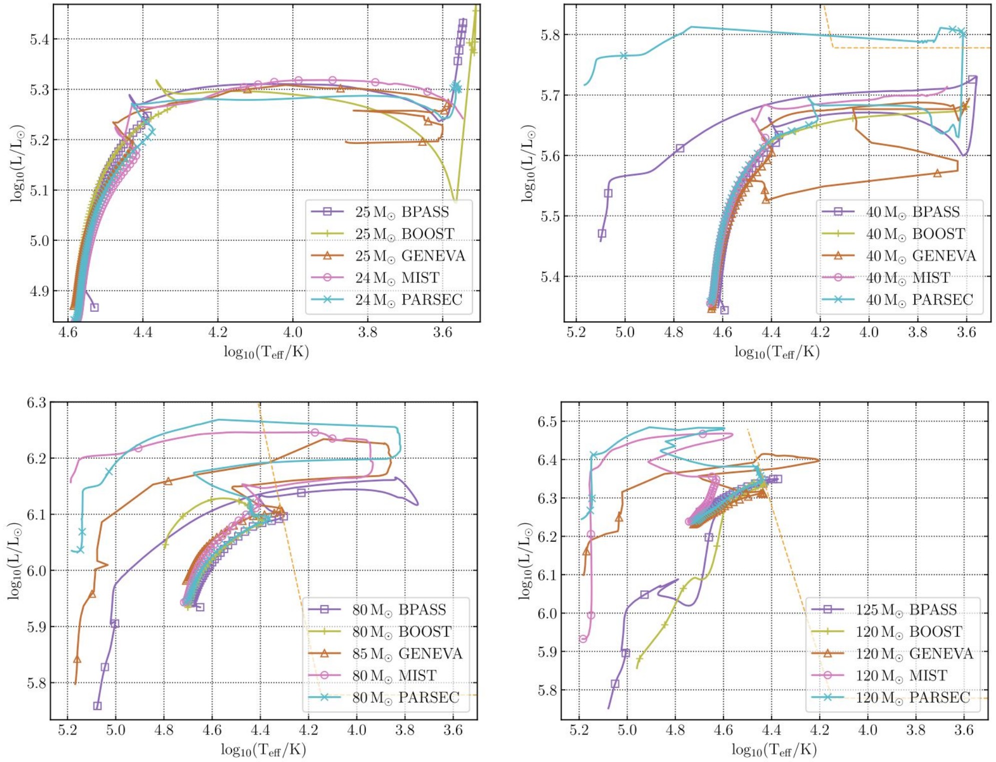


AProf Dr. Floor Broekgaarden, UC San Diego

Broekgaarden, **Stevenson** & Thrane 2022, ApJ (MRR and spins)

Different codes make very different massive star models

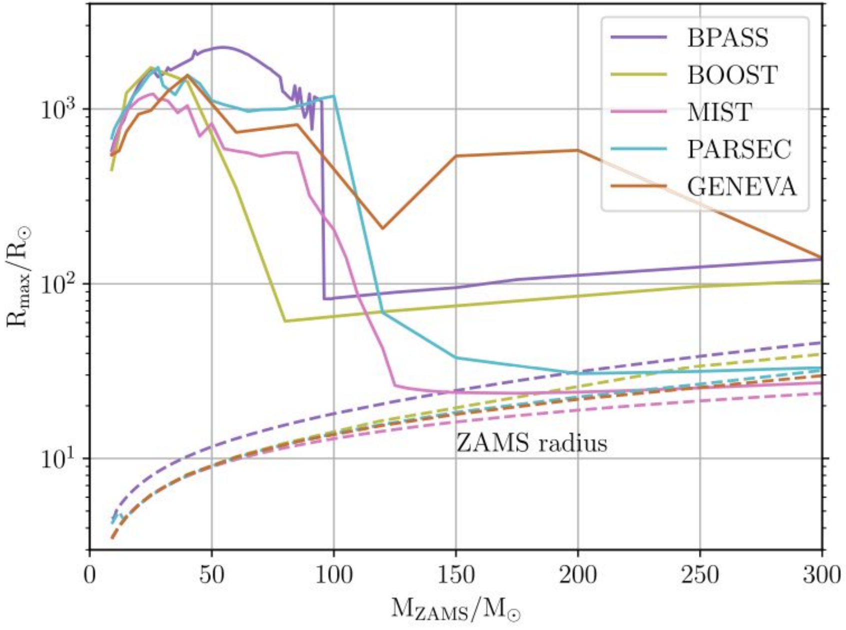
Dr. Poojan Agrawal, UNC

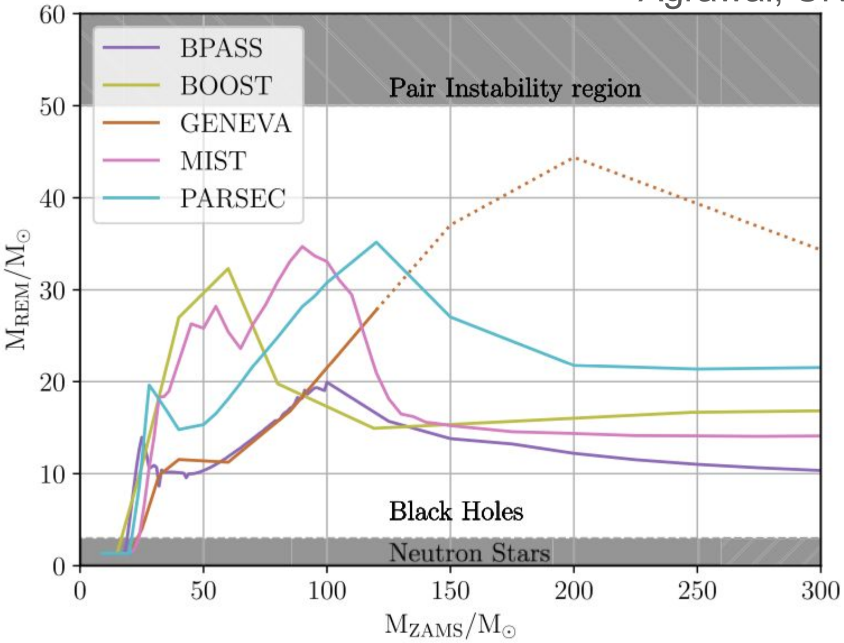


Agrawal et al. inc **SS** (2020, 2022ab, 2023)

Nair, **Stevenson** et al. in prep

Different predictions for maximum radius and core mass





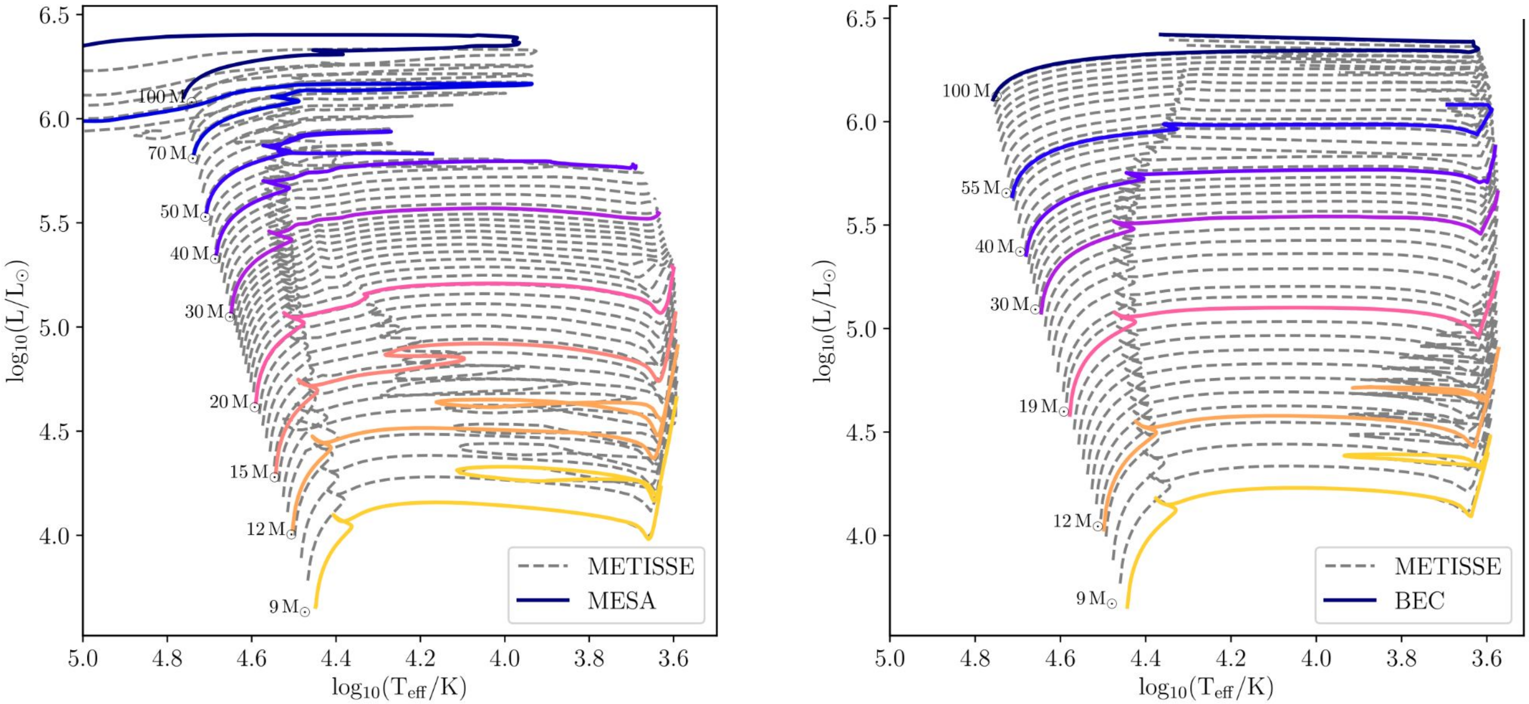
Dr. Poojan Agrawal, UNC

Agrawal et al. inc **SS** (2020, 2022ab, 2023)
Nair, **Stevenson** et al. in prep

Interpolating between detailed stellar models using METISSE

MESA

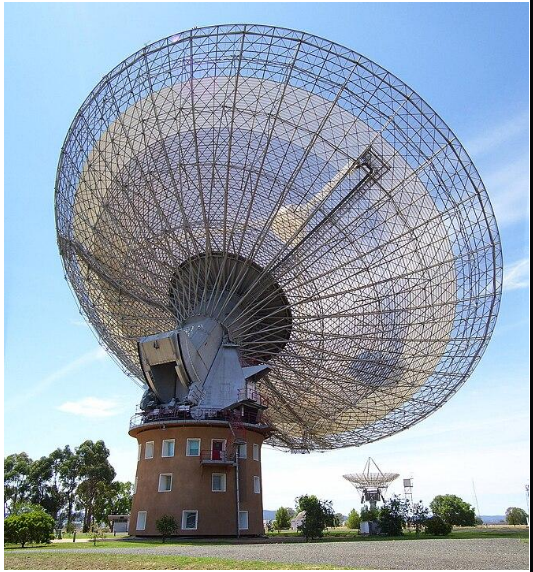
Dr. Poojan Agrawal, UNC

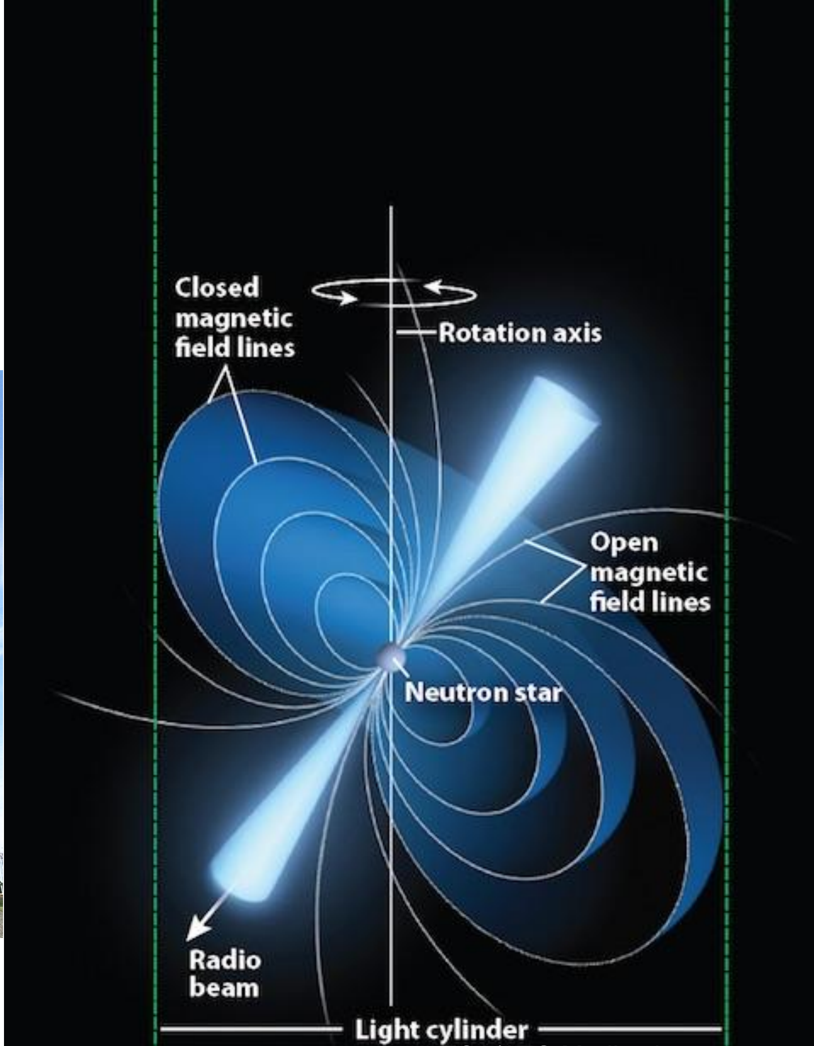


Agrawal et al. inc **SS** (2020, 2022ab, 2023)
Nair, **Stevenson** et al. in prep

Pulsars - background

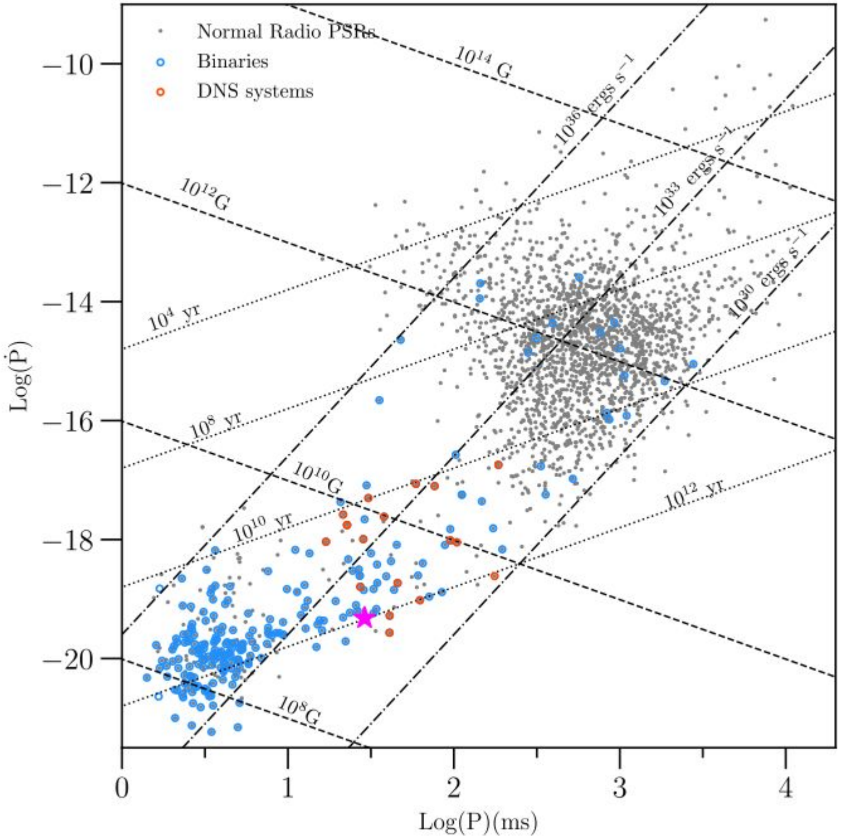
- Pulsars are rapidly rotating neutron stars
- Observed mainly in our galaxy in the radio (Parkes, MeeKAT) and gamma-rays (Fermi)





ESA/ATG Medialab

Pulsars - Observation



Sengar et al. inc **Stevenson** (2022, 2023)

Dr. Rahul Sengar, UWM

- Developed novel GPU pipeline
- Searching for highly accelerated binary pulsars like the long-sought pulsar-black hole binaries
- Reanalysed archival data from the High Time Resolution Universe (HTRU) radio survey with Parkes
- Found about 100 new pulsars
- Discovered and timed PSR J1325−6253 - a wide, low eccentricity double neutron star

Pulsars - theoretical predictions

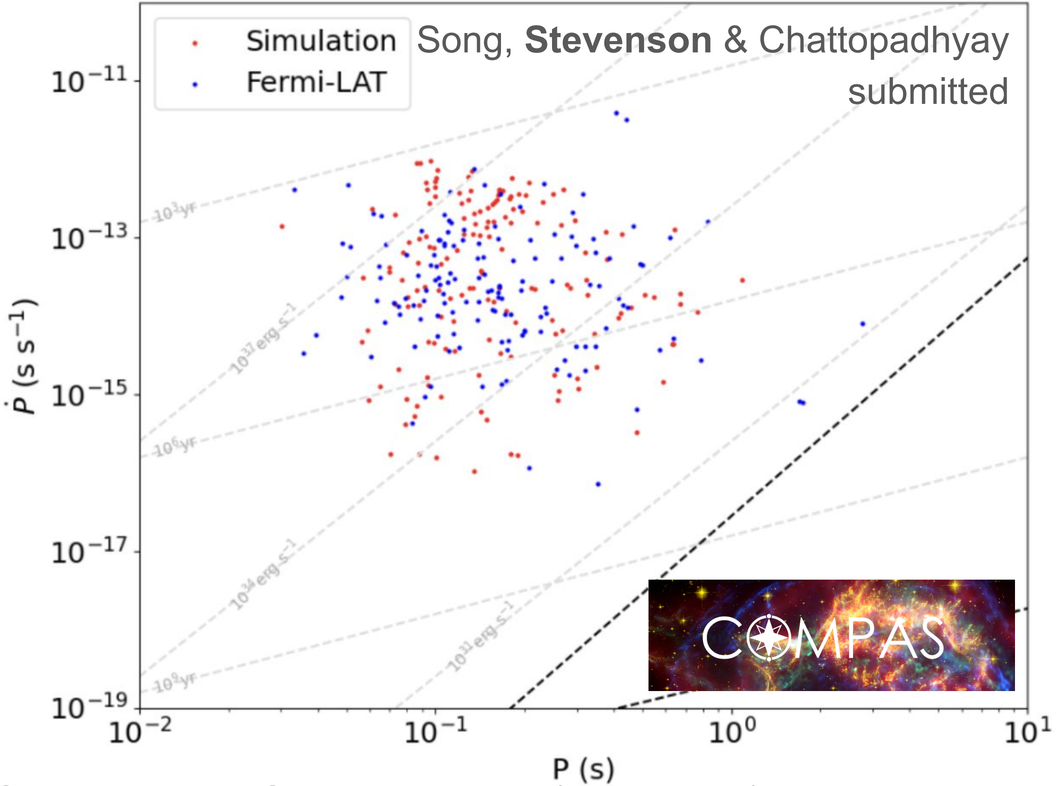
Dr. Yuzhe (Robert) Song, Swinburne

Dr. Debatri Chattopadhyay, Northwestern

Population synthesis of pulsar populations with COMPAS

Radio and gamma-ray populations, including selection effects

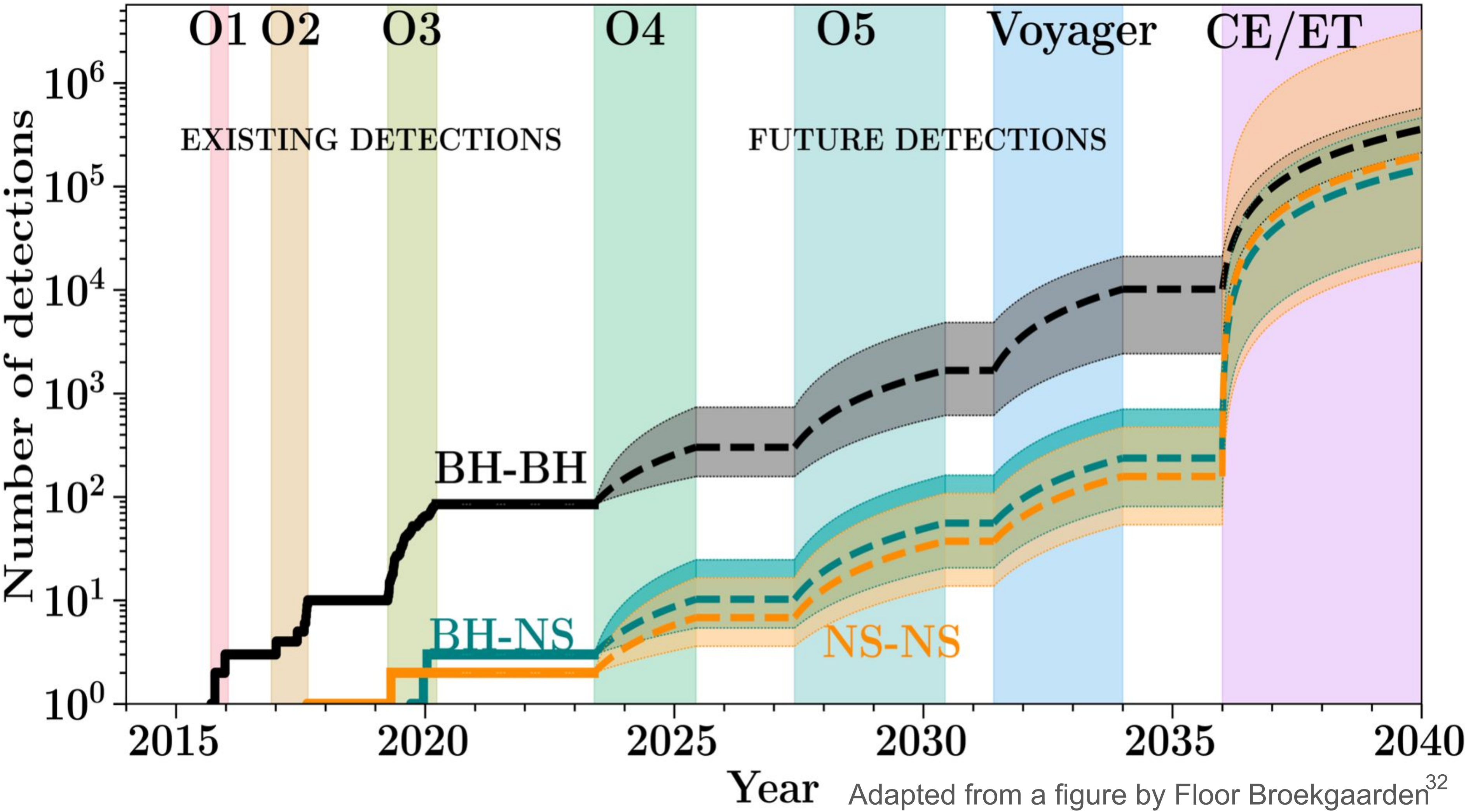
Allows for complementary constraints on neutron star population properties (like kicks)



Song, **Stevenson** & Chattopadhyay submitted

Chattopadhyay, **Stevenson** et al. (2020, 2021)
Willcox et al. inc **SS** 2021, ApJL
Stevenson et al. 2022
Song, **Stevenson** & Chattopadhyay, submitted to MNRAS

The Future



Adapted from a figure by Floor Broekgaarden

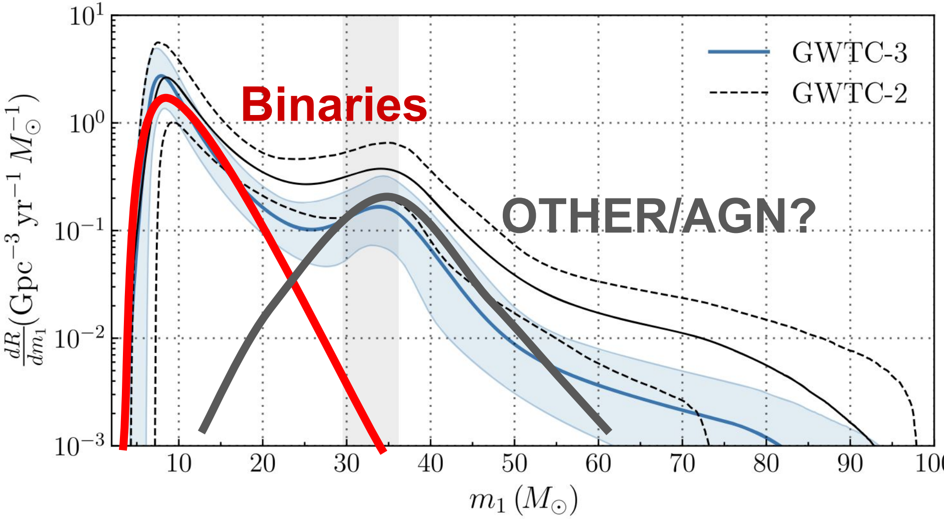
Next generation population models

Update/improve physics in population models

Improved CE model: Hirai & Mandel 2022; Mandel et al. inc SS in prep
Improved CHE: Stevenson & Houlden in prep
Improved Winds: Merritt, **Stevenson** et al. in prep

Analyse BBH population after O4 using mixture of formation channels (binaries, clusters, AGN, …)

Constrain physics in population models
Stevenson & Clarke 2022



Abbott et al. inc **SS** 2023
Stevenson et al. in prep

Laser Interferometer Space Antenna (LISA)

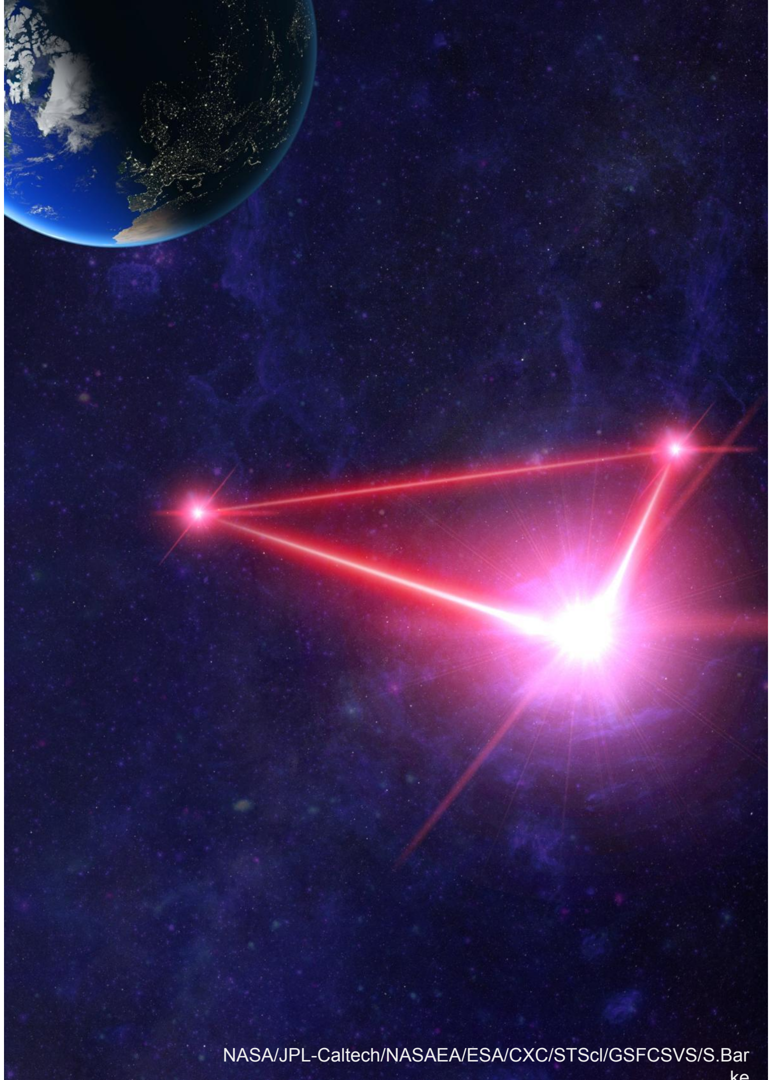
European Space Agency (ESA) space mission

Mission adoption earlier this year

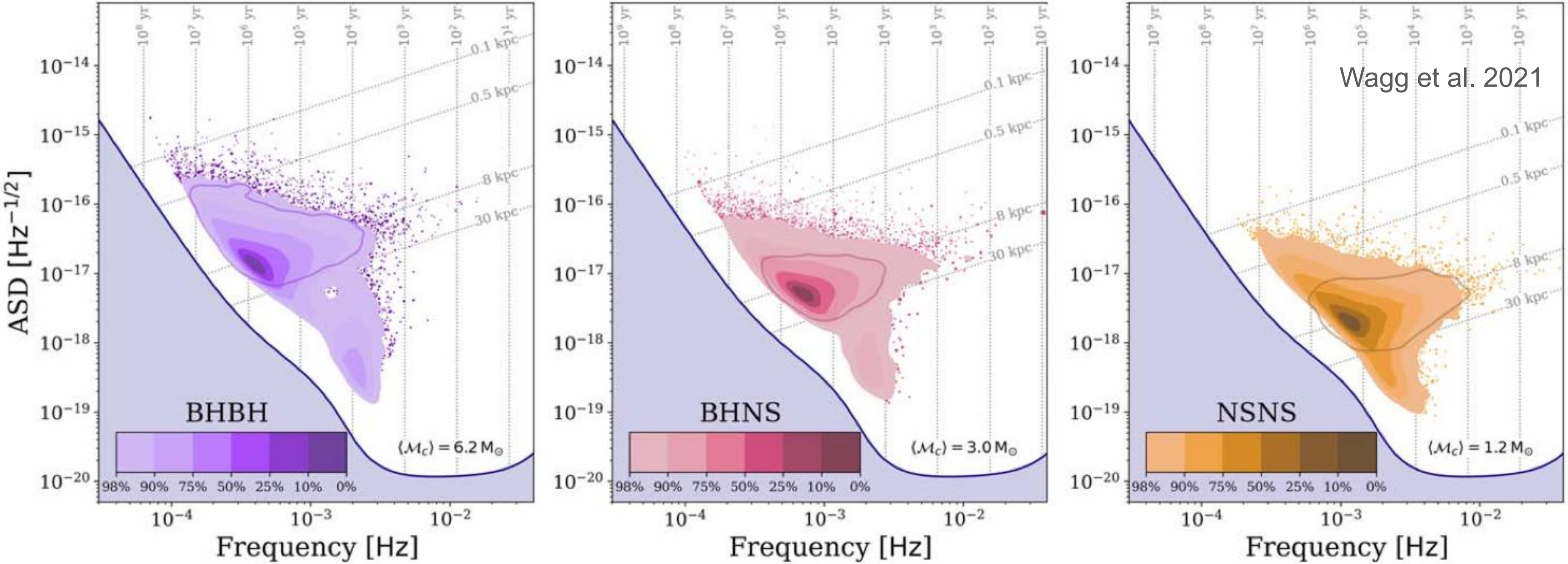
Launch in the mid 2030s

Sensitive to lower GW frequencies than LIGO/Virgo

Will detect GWs from inspiralling Galactic stellar-mass binaries including all mixtures of white dwarfs (WDs), neutron stars (NSs) and black holes (BHs).



Identifying the binary astrophysics accessible with LISA



Wagg et al. 2021

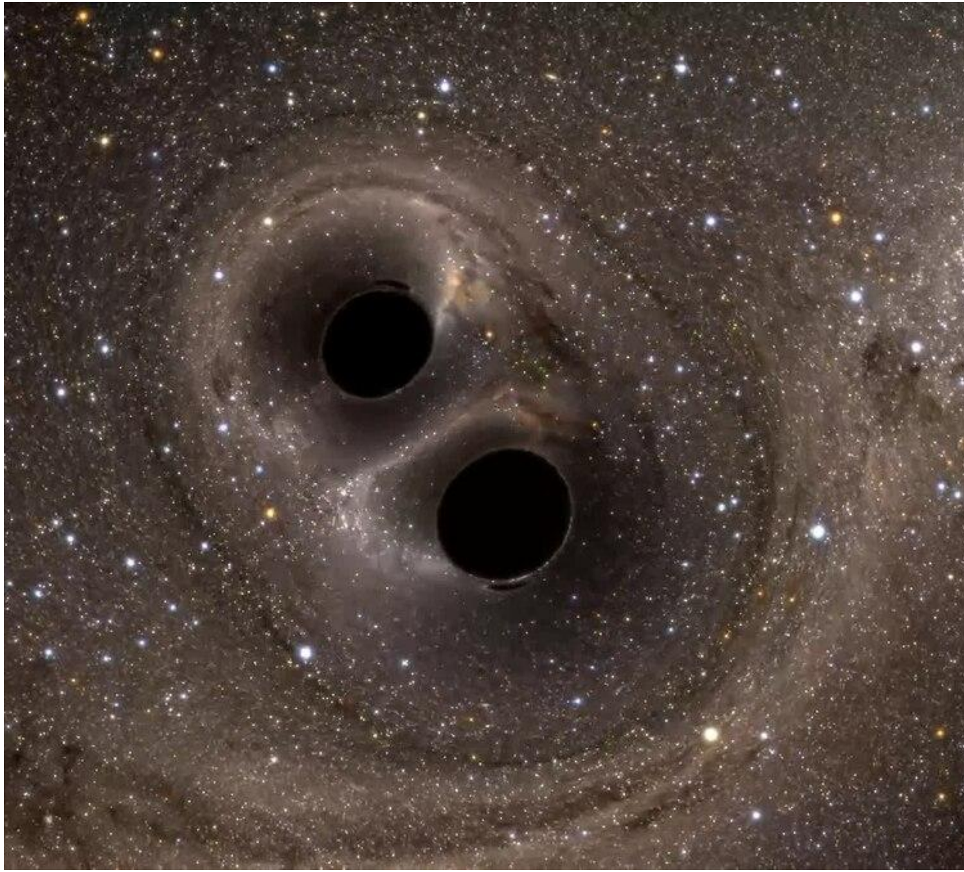
Mass transfer, common envelope evolution, neutron star kicks

Lau et al. inc **SS** 2020

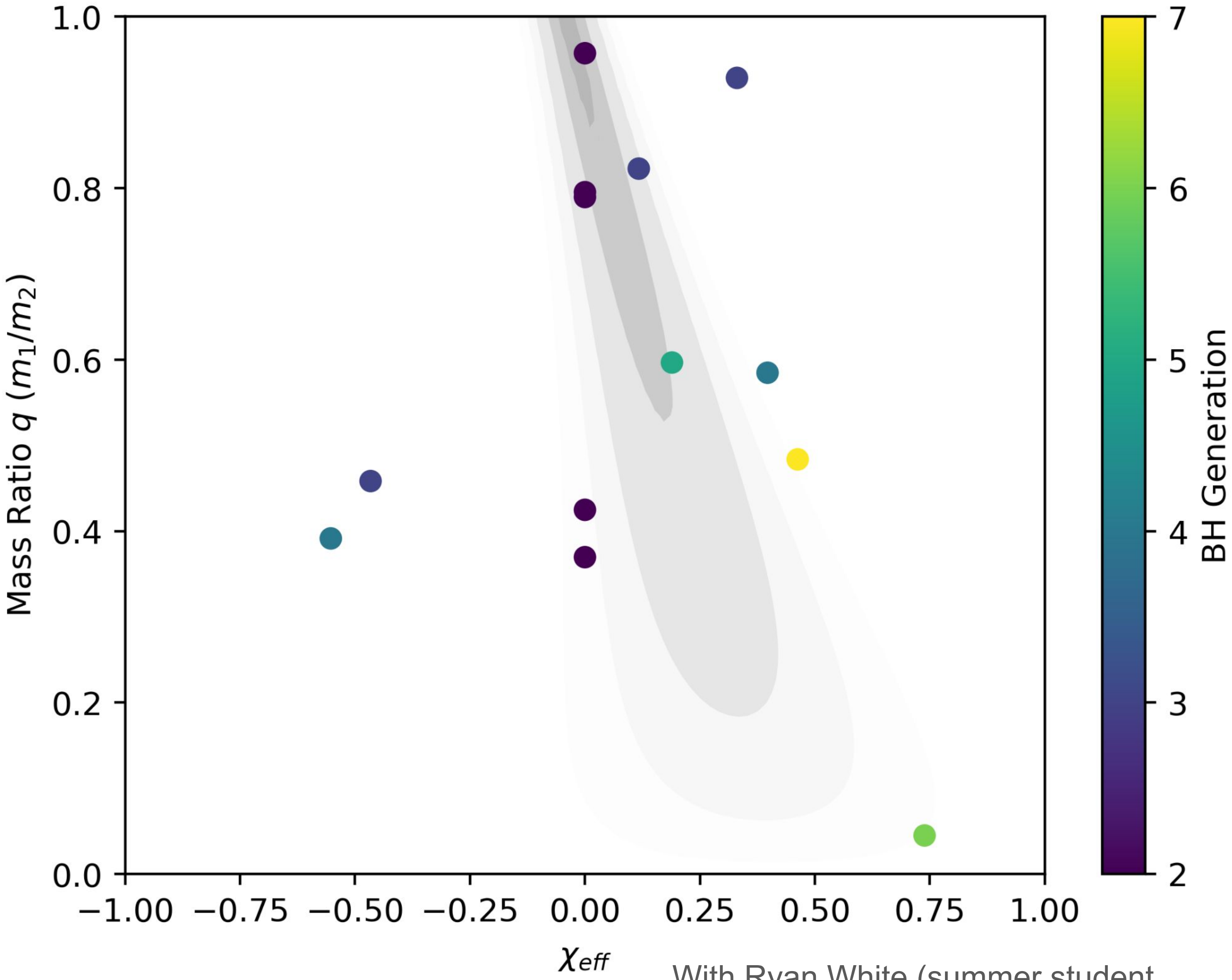
Chattopadhyay, **Stevenson** et al. 2021

Conclusions

- GW astronomy is on the rise
- Can use GW observations to understand the formation channels of compact binaries
- Provides us with a probe of massive binary/stellar evolution
- Exciting future for GW astronomy!



NBODY MODELS OF BBH FORMATION IN AGN DISCS



With Ryan White (summer student, UQ) and Evgeni Grishin (Monash)

Dynamical formation with the NBody code

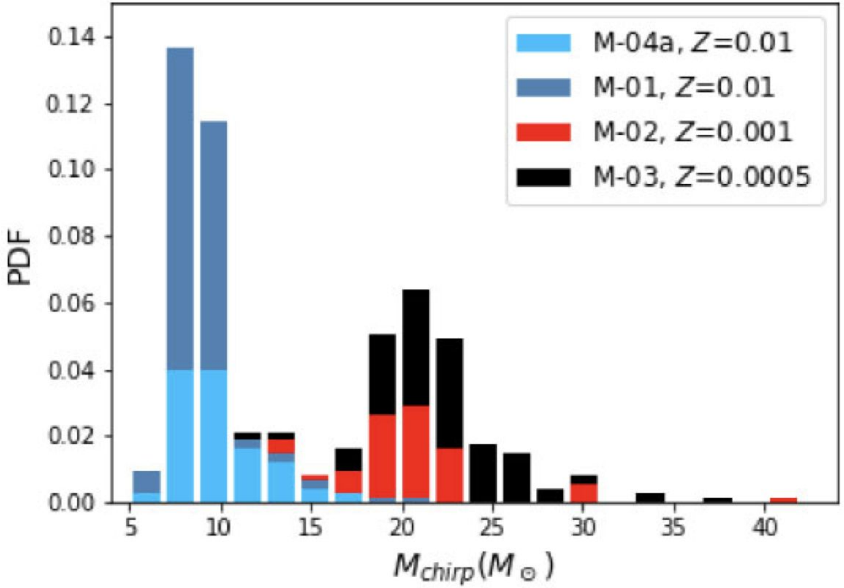
Dr. Debatri Chattopadhyay, Cardiff

Oliver Anagnostou, Melbourne

Full dynamical N-body simulations of intermediate-mass star clusters

Includes all relevant dynamical effects for merging BBH formation

Computationally expensive



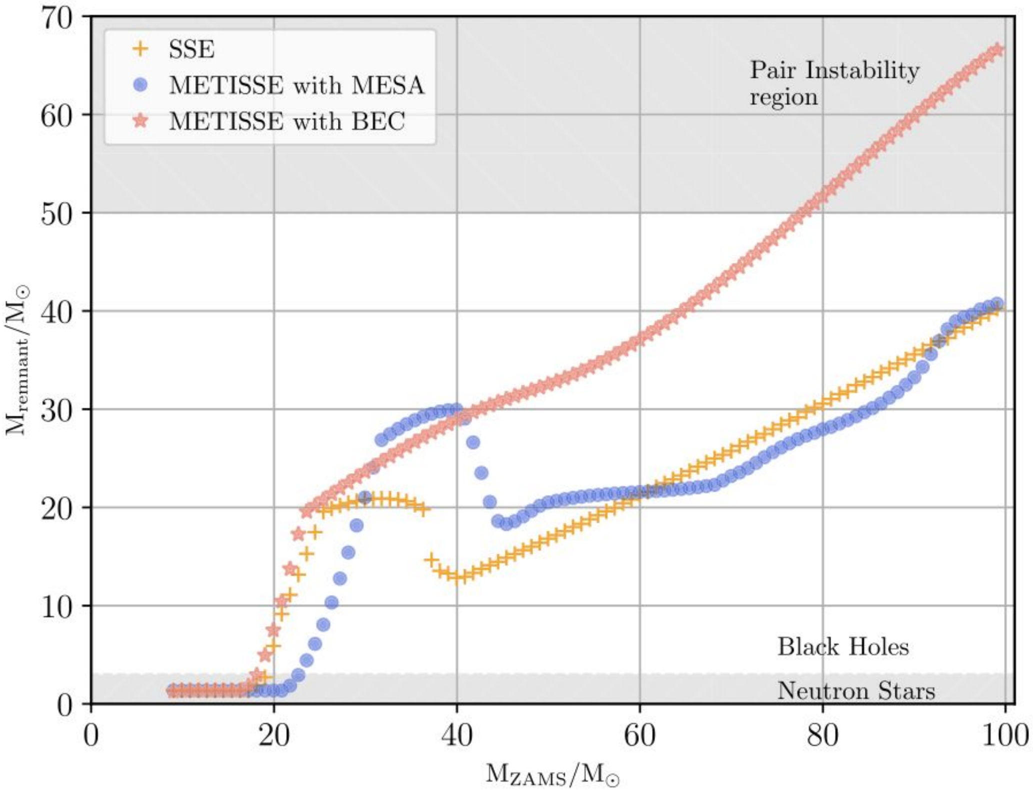
Chattopadhyay et al. 2022 inc **SS**

Anagnostou et al. inc **SS** in prep

Detailed stellar models using MESA and METISSE

MESA

Dr. Poojan Agrawal, UNC



Agrawal et al. inc **SS** (2020, 2022ab, 2023)

Nair, **Stevenson** et al. in prep