Title: No peaks without valleys: learning about massive stars from the masses of merging black holes

Speakers: Lieke van Son

Series: Strong Gravity

Date: November 24, 2022 - 1:00 PM

URL: https://pirsa.org/22110110

Abstract: Gravitational wave observations are revealing new features in the mass distribution of merging binary black holes (BBHs). The BBHs we observe today are relics of massive stars that lived in the early Universe, and we aim to use their properties to help reveal the lives and deaths of their stellar ancestors.

In this talk, I will discuss which of the observed features are robust, and if/how we can use them to constrain the uncertain progenitor physics. I will focus on the lowest mass BHs, just above the edge of NS formation because we find they I) contain crucial information about the most common formation pathway, II) are least affected by uncertainties in the cosmic star formation, and III) shine new light on the much-disputed mass-gap between neutron stars and black holes.

Zoom link: https://pitp.zoom.us/j/91476126992?pwd=QXdENmErYklaYTdLcDZNTVBXamlXdz09

LEARNING ABOUT STELLAR BINARIES FROM GRAVITATIONAL WAVE DETECTIONS

Lieke van Son

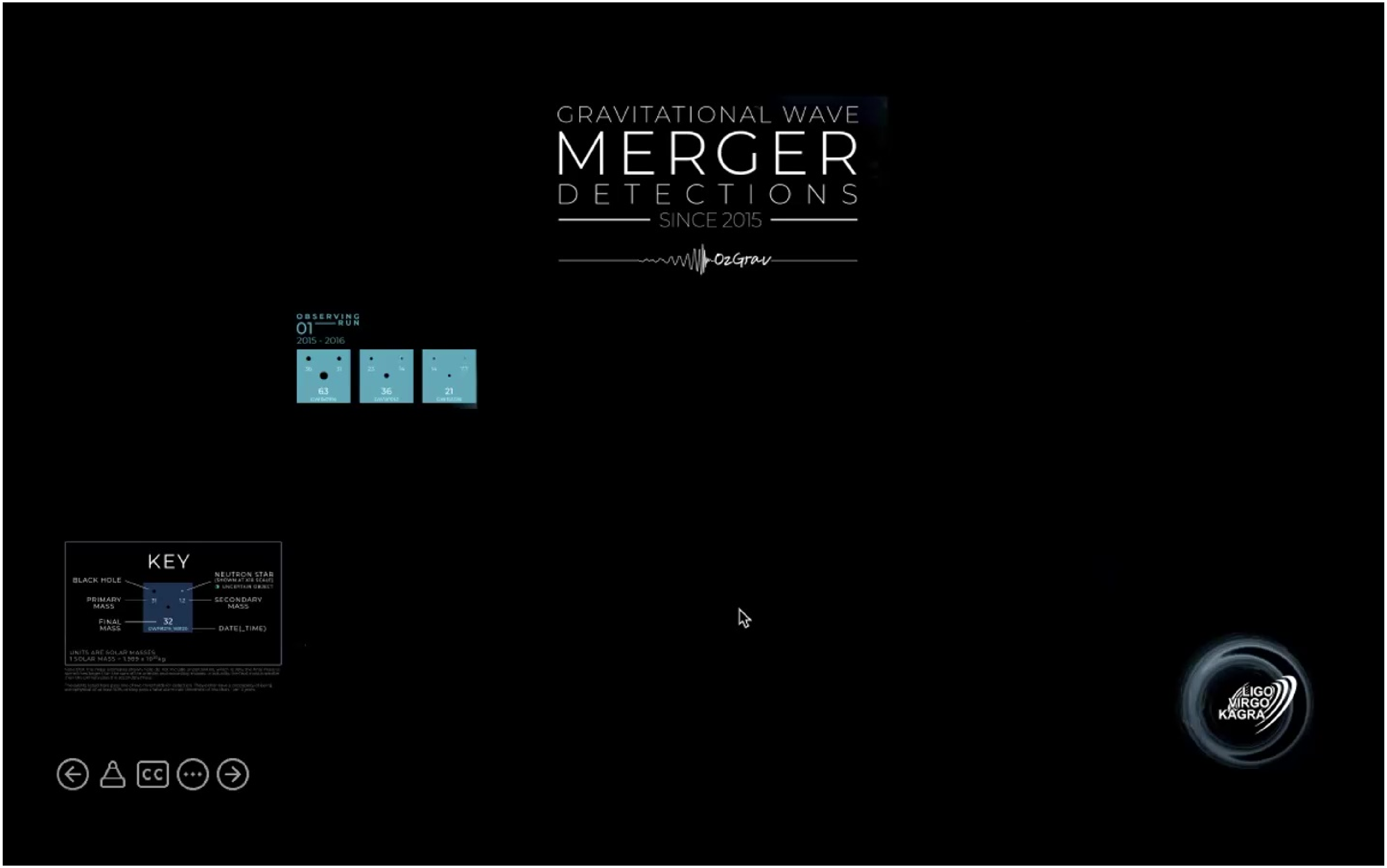
CfA, Harvard & Smithsonian

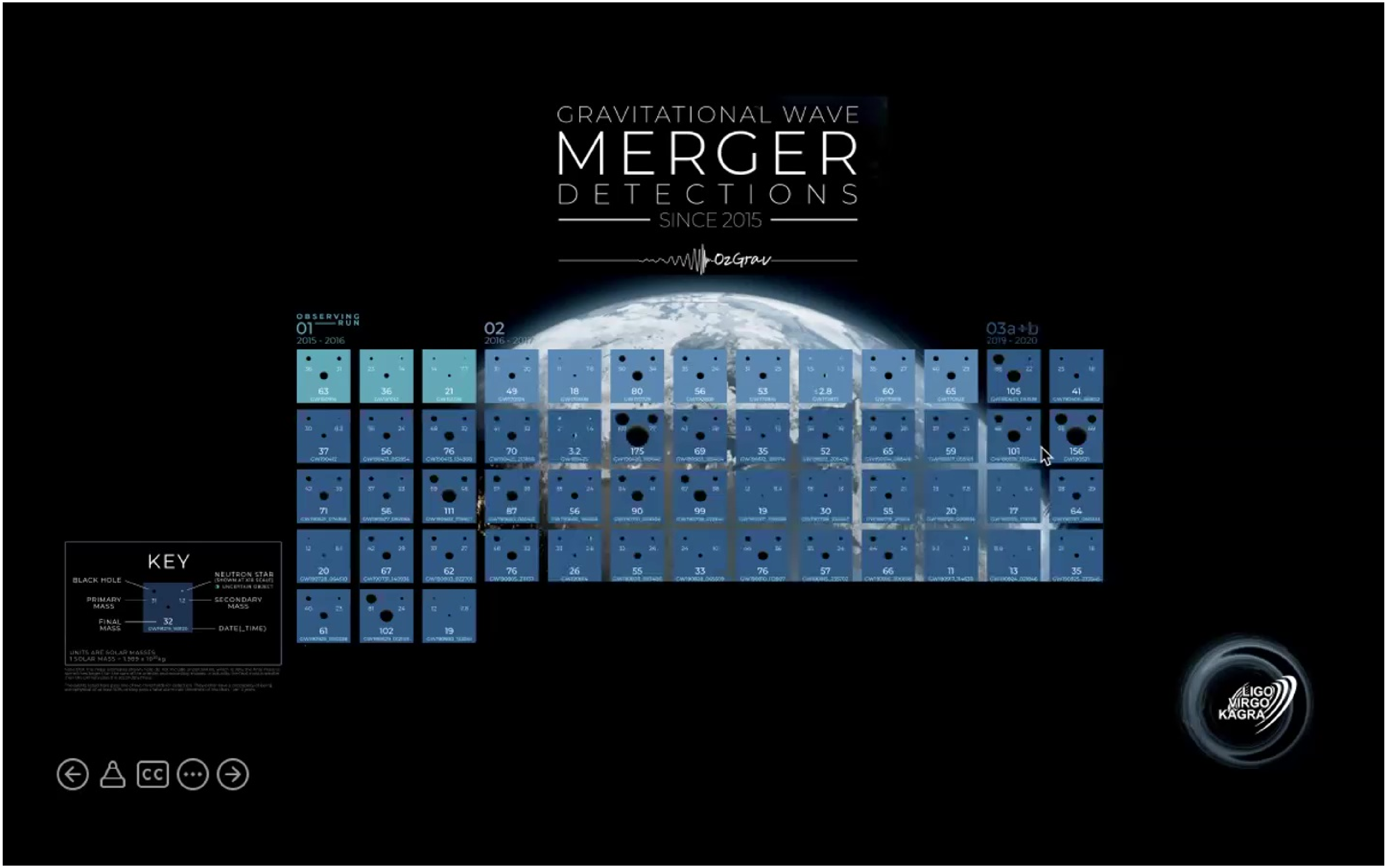
with many thanks to i.a. the BinCosmos group,
the Conroy group, the COMPAS collaboration,
and the GW and Compact object group at the CCA

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

UNIVERSITY OF AMSTERDAM

Credit SXS/ LIGO


GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
OBSERVING RUN
01
2015 - 2016
36
31
63
23
14
36
14
7.7
21
KEY
BLACK HOLE
NEUTRON STAR
(SHOWN AT X8 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
31
1.2
SECONDARY MASS
FINAL MASS
32
DATE(_TIME)
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^30 kg
LIGO
VIRGO
KAGRA



GRAVITATIONAL WAVE MERGER DETECTIONS

SINCE 2015

OzGrav

OBSERVING RUN

O1 2015 - 2016

O2 2016 - 2017

O3a+b 2019 - 2020

63	36	21	49	18	80	56	53	≤2.8	60	65	105	41
37	56	76	70	3.2	175	69	35	52	65	59	101	156
71	56	111	87	56	90	99	19	30	55	20	17	64
20	67	62	76	26	55	33	76	57	66	11	13	35
61	102	19										

KEY

BLACK HOLE

NEUTRON STAR (SHOWN AT X10 SCALE)

UNCERTAIN OBJECT

PRIMARY MASS

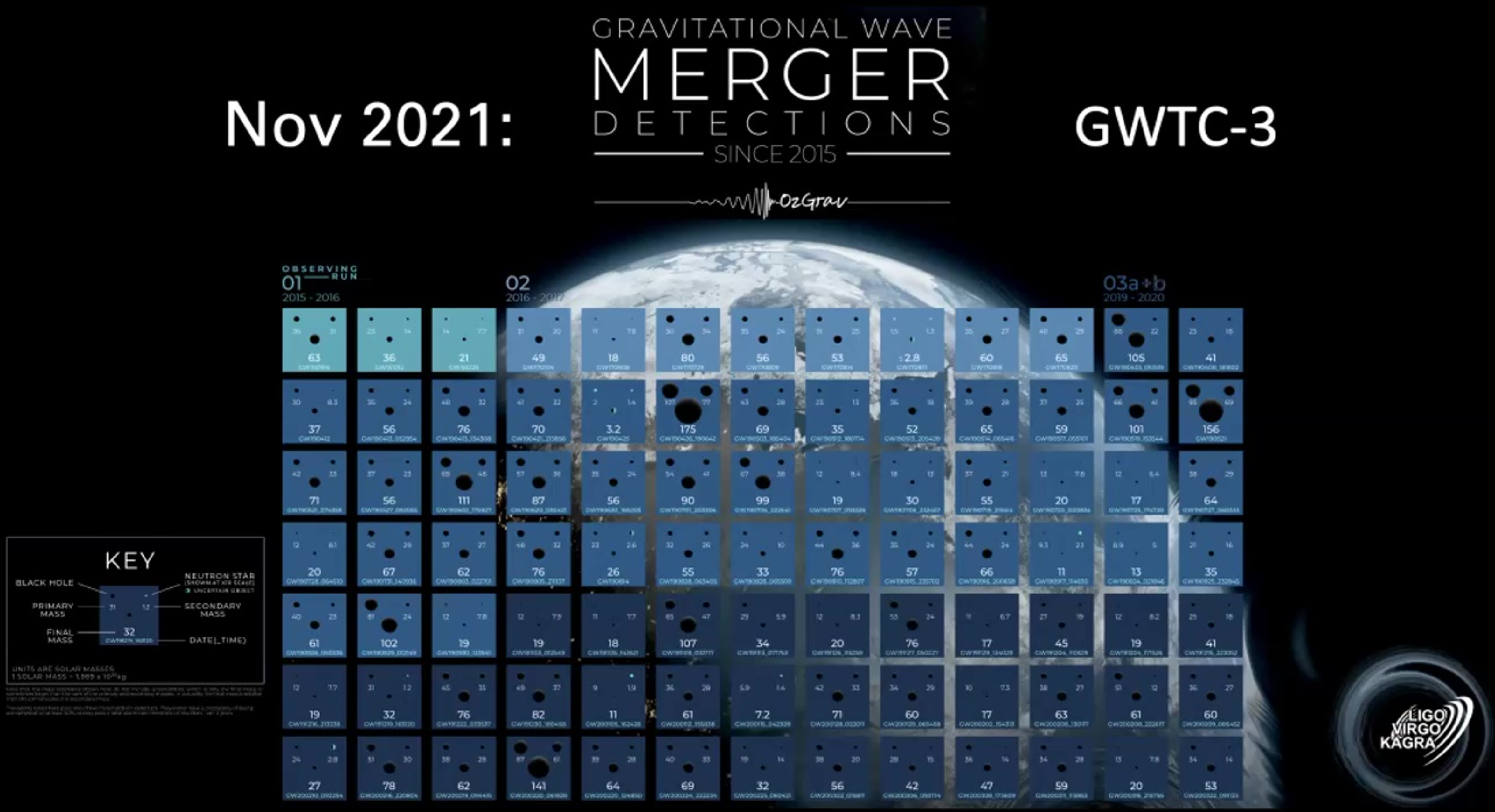
SECONDARY MASS

FINAL MASS

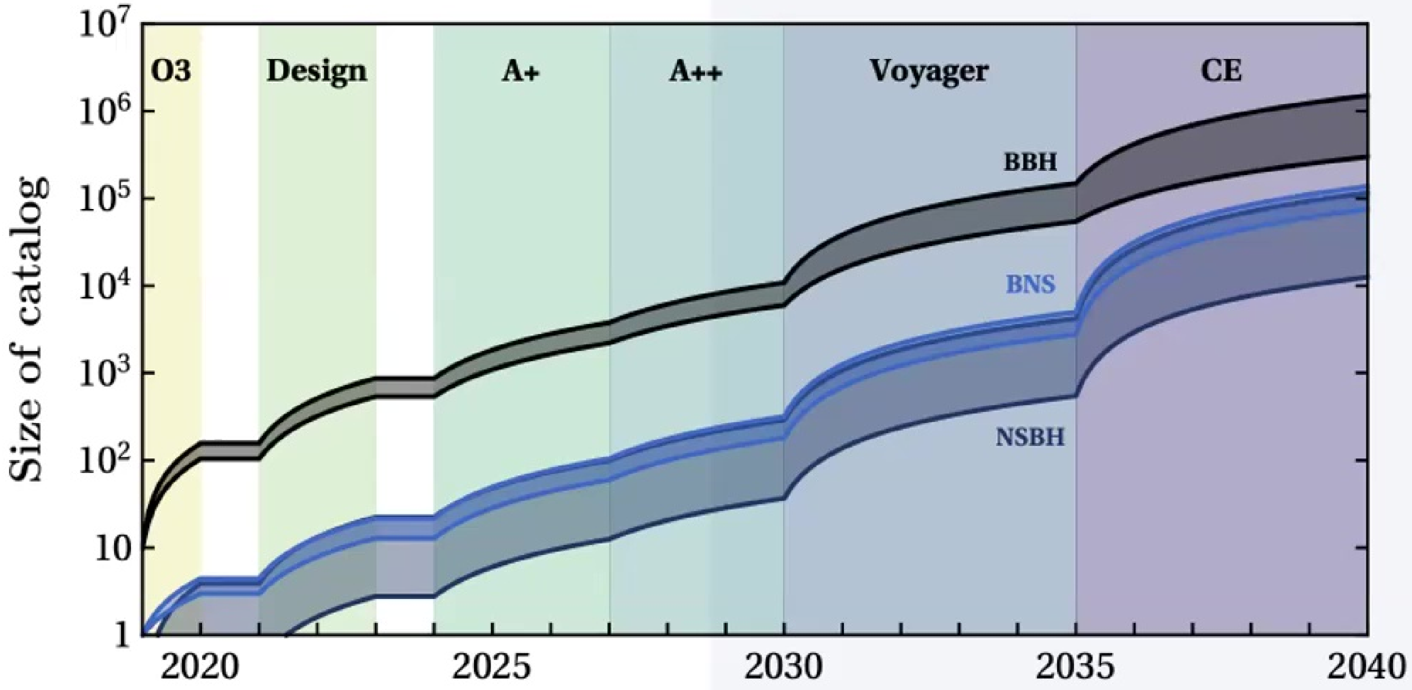
DATE(_TIME)

UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30} kg

Nov 2021: GWTC-3



A lot more data is imminent



Baibhav et al. 2019

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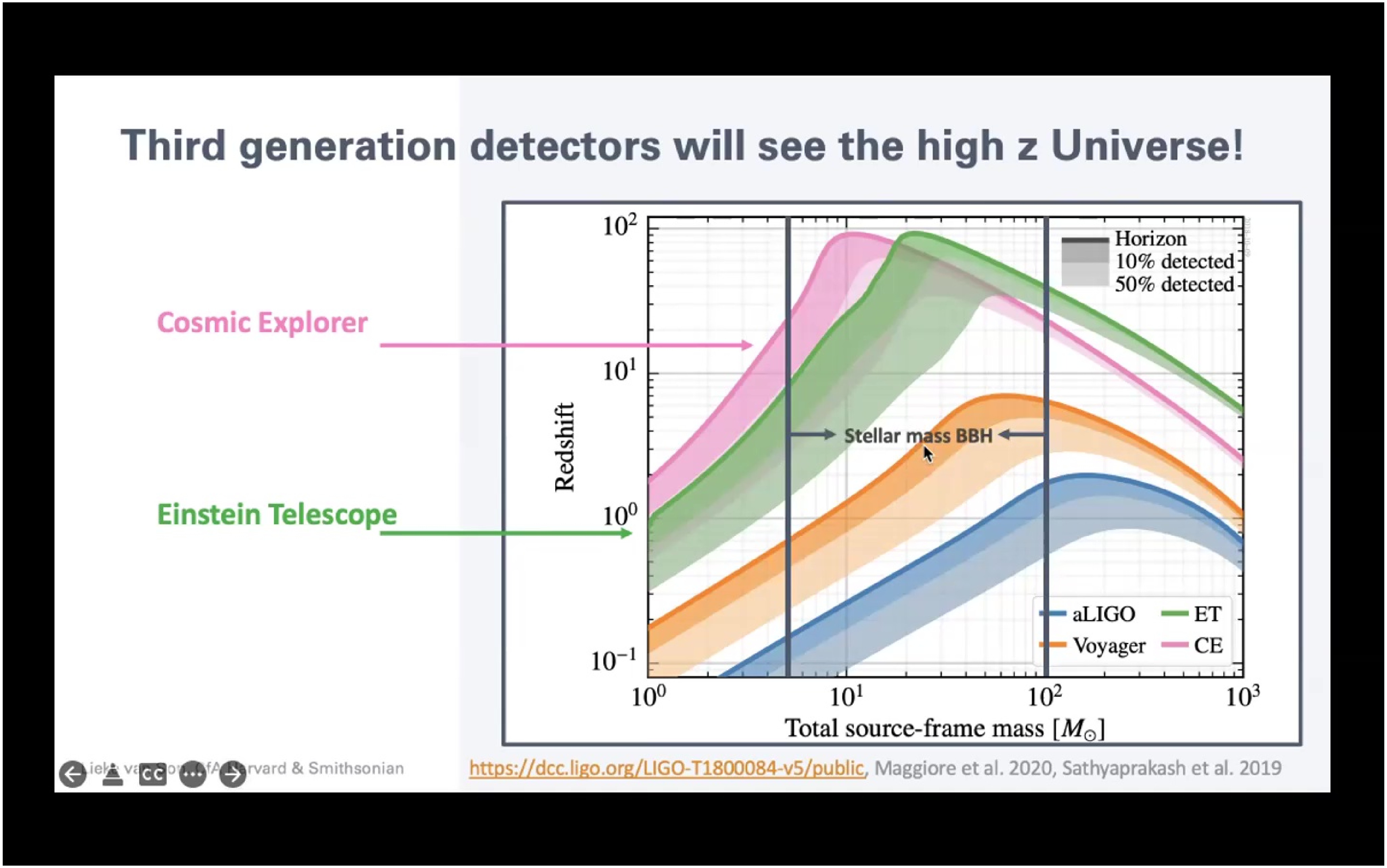

Third generation detectors will see the high z Universe!

Cosmic Explorer

Einstein Telescope

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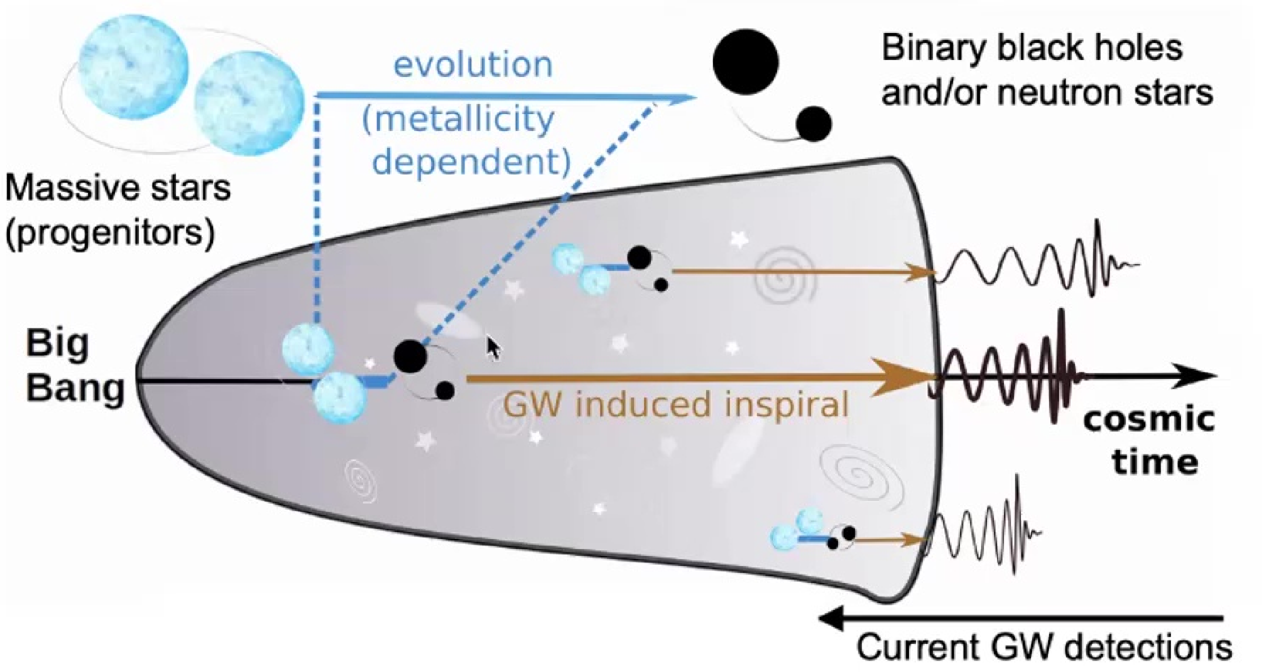
https://dcc.ligo.org/LIGO-T1800084-v5/public, Maggiore et al. 2020, Sathyaprakash et al. 2019

BBH mergers observed today probe early Universe



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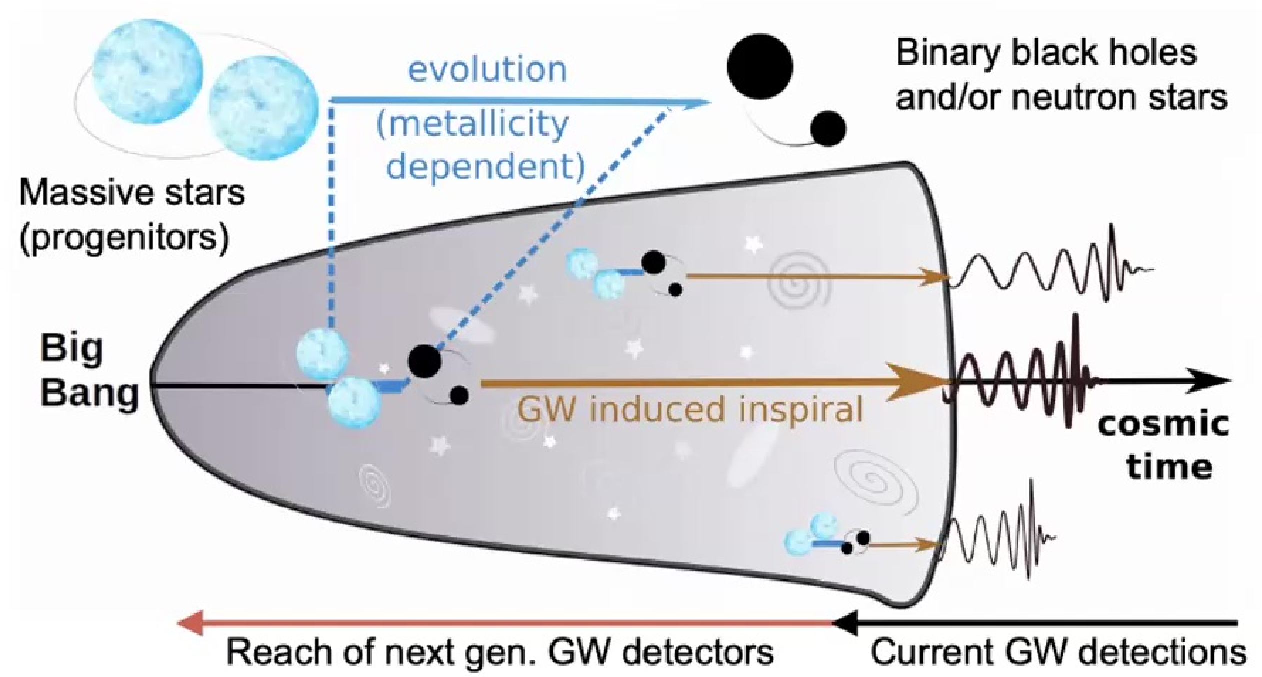
adapted from Chruślińska review 2022

BBH mergers observed today probe early Universe



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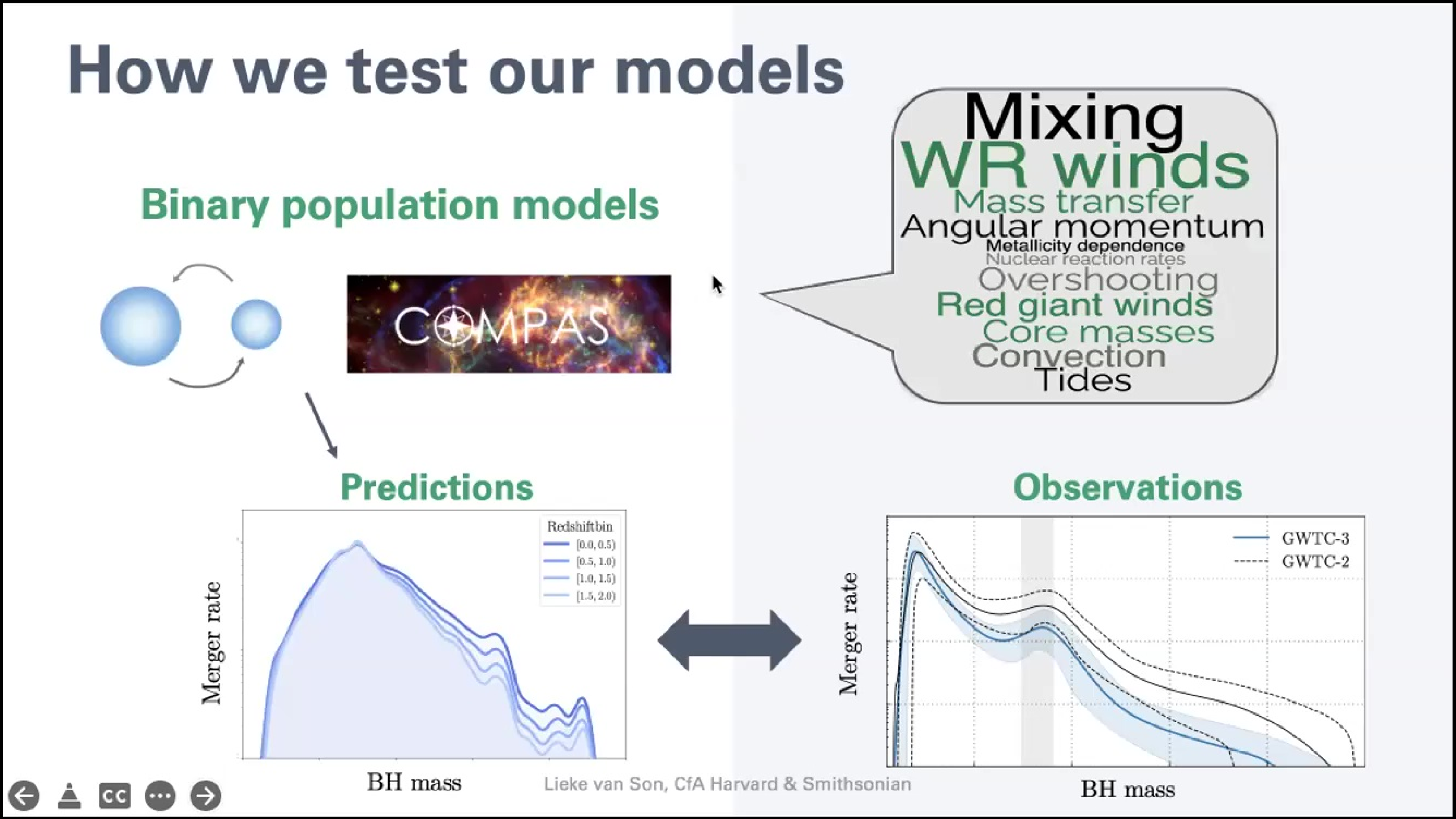
adapted from Chruślińska review 2022



How we test our models

Binary population models

COMPAS

Mixing
WR winds
Mass transfer
Angular momentum
Metallicity dependence
Nuclear reaction rates
Overshooting
Red giant winds
Core masses
Convection
Tides

Predictions

Observations

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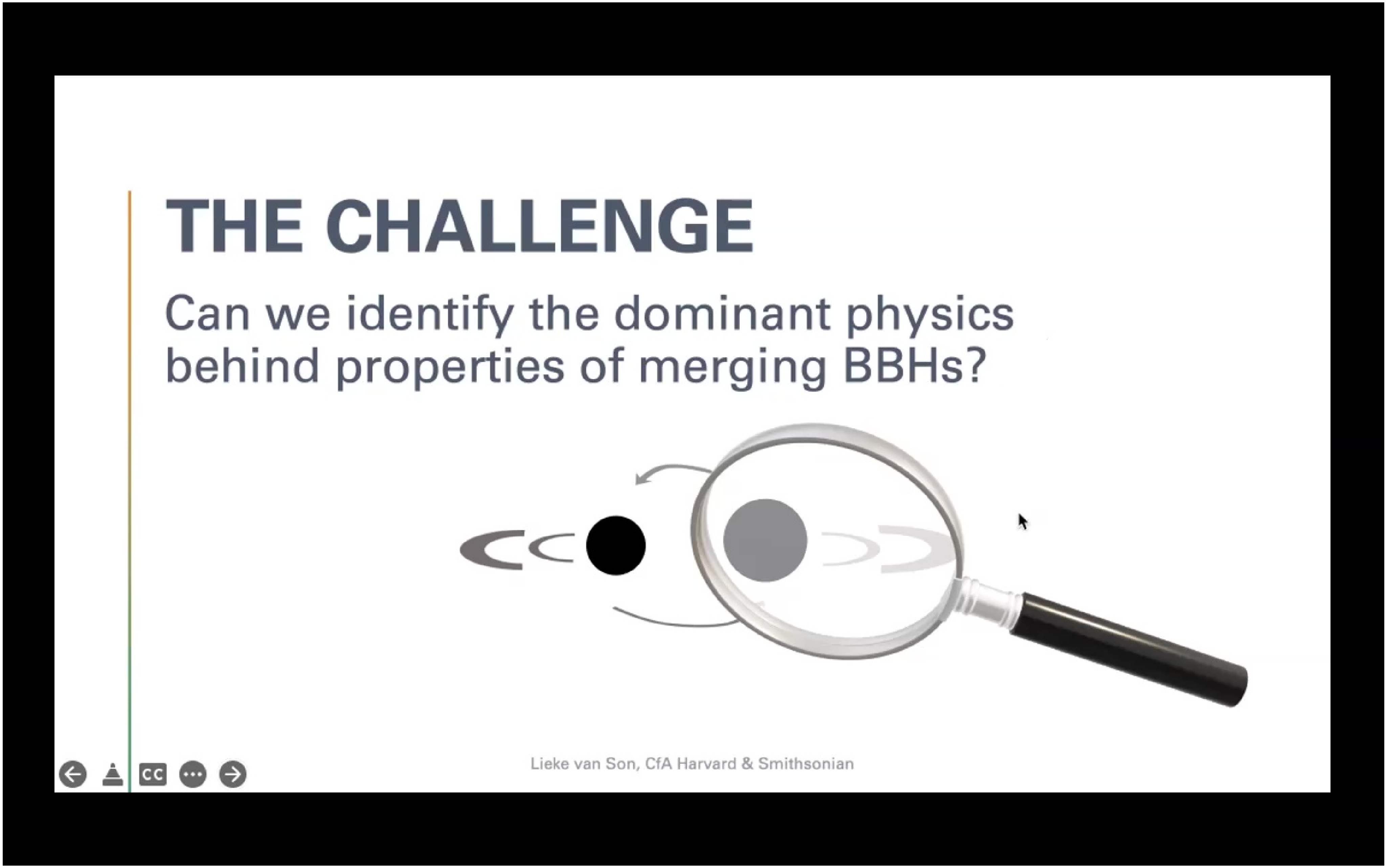

THE CHALLENGE

Can we identify the dominant physics behind properties of merging BBHs?

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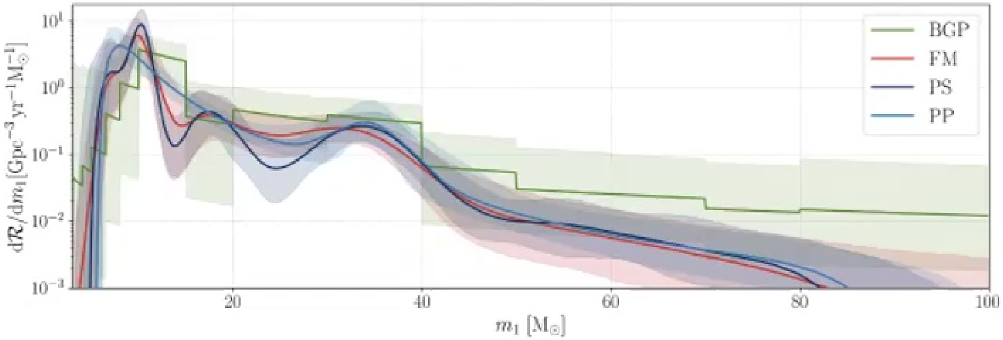
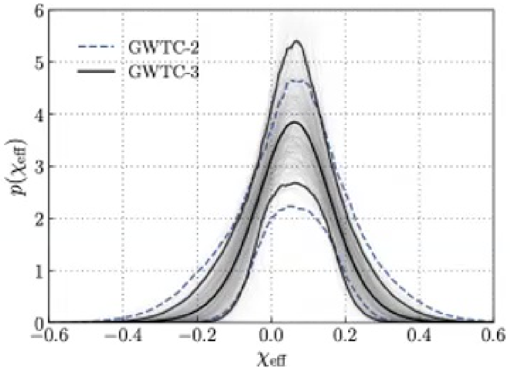
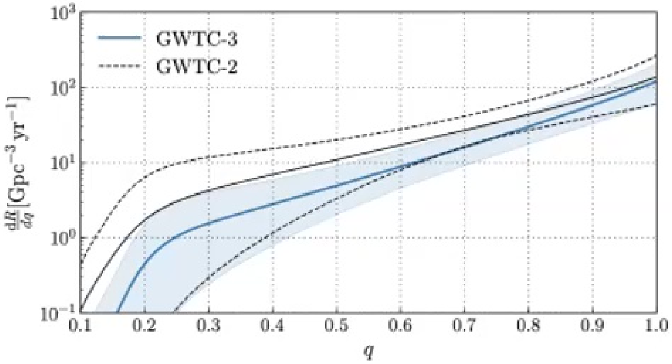
Observed properties of merging BBH

I. BH mass



II. BH spin

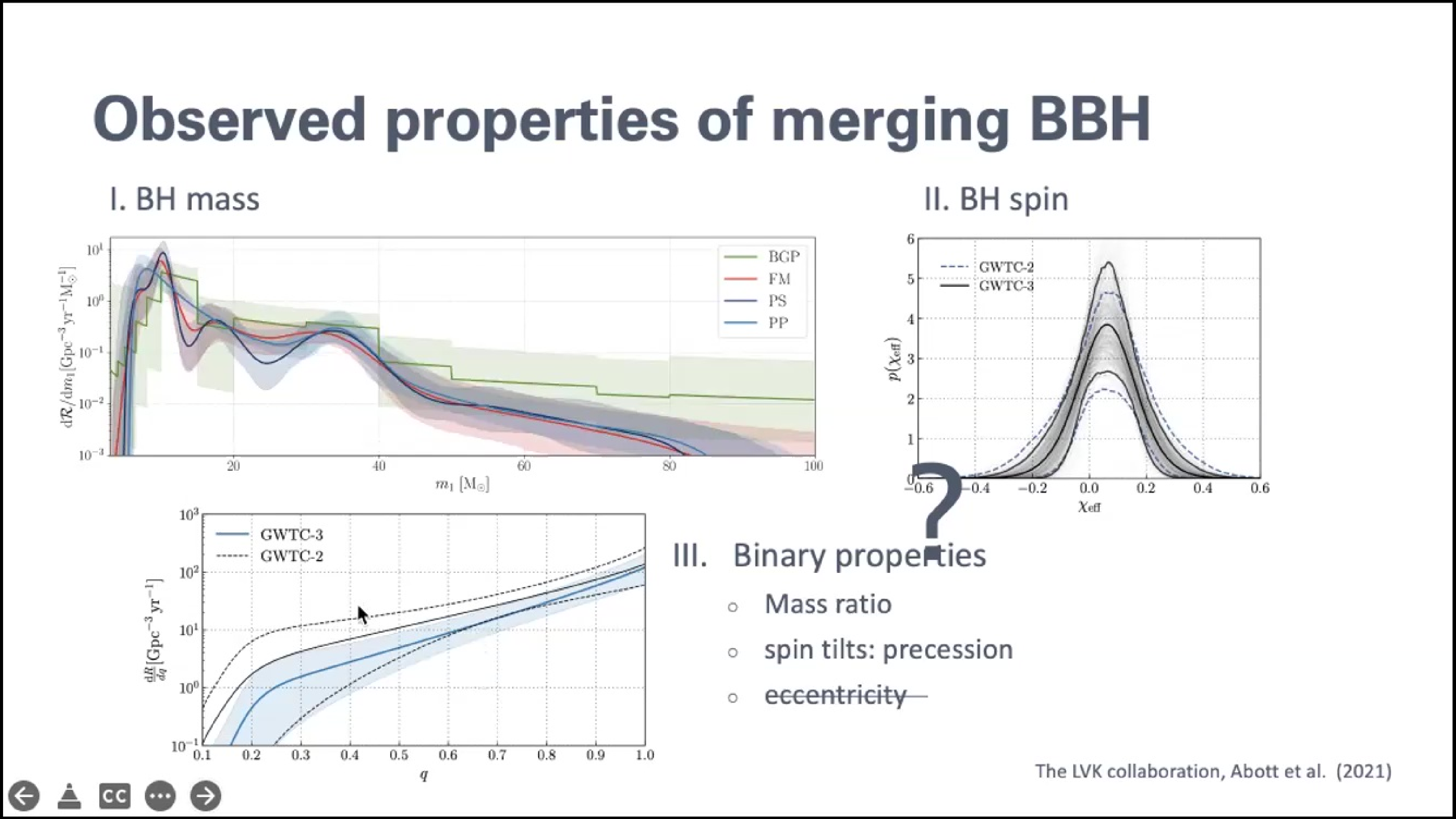




III. Binary properties

- Mass ratio
- spin tilts: precession
- ~~eccentricity~~

The LVK collaboration, Abott et al. (2021)



Observed properties of merging BBH

I. BH mass

II. BH spin

?

III. Binary properties

- Mass ratio
- spin tilts: precession
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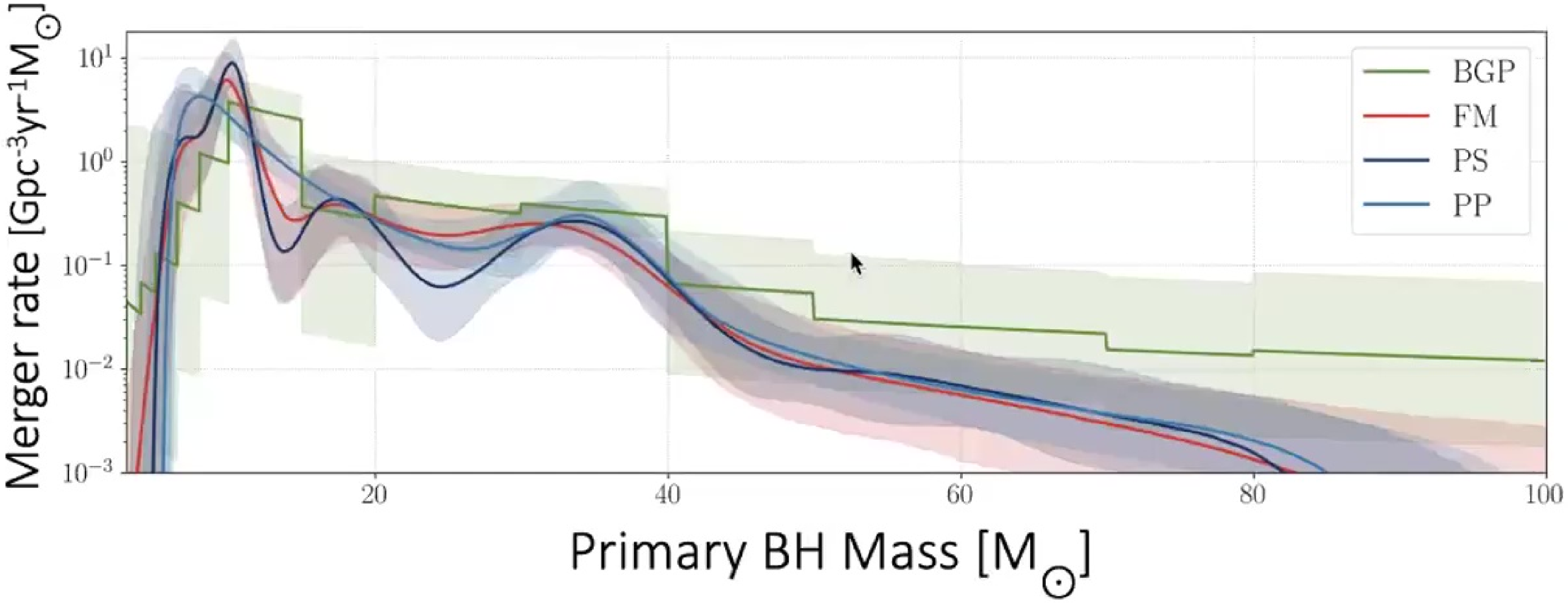
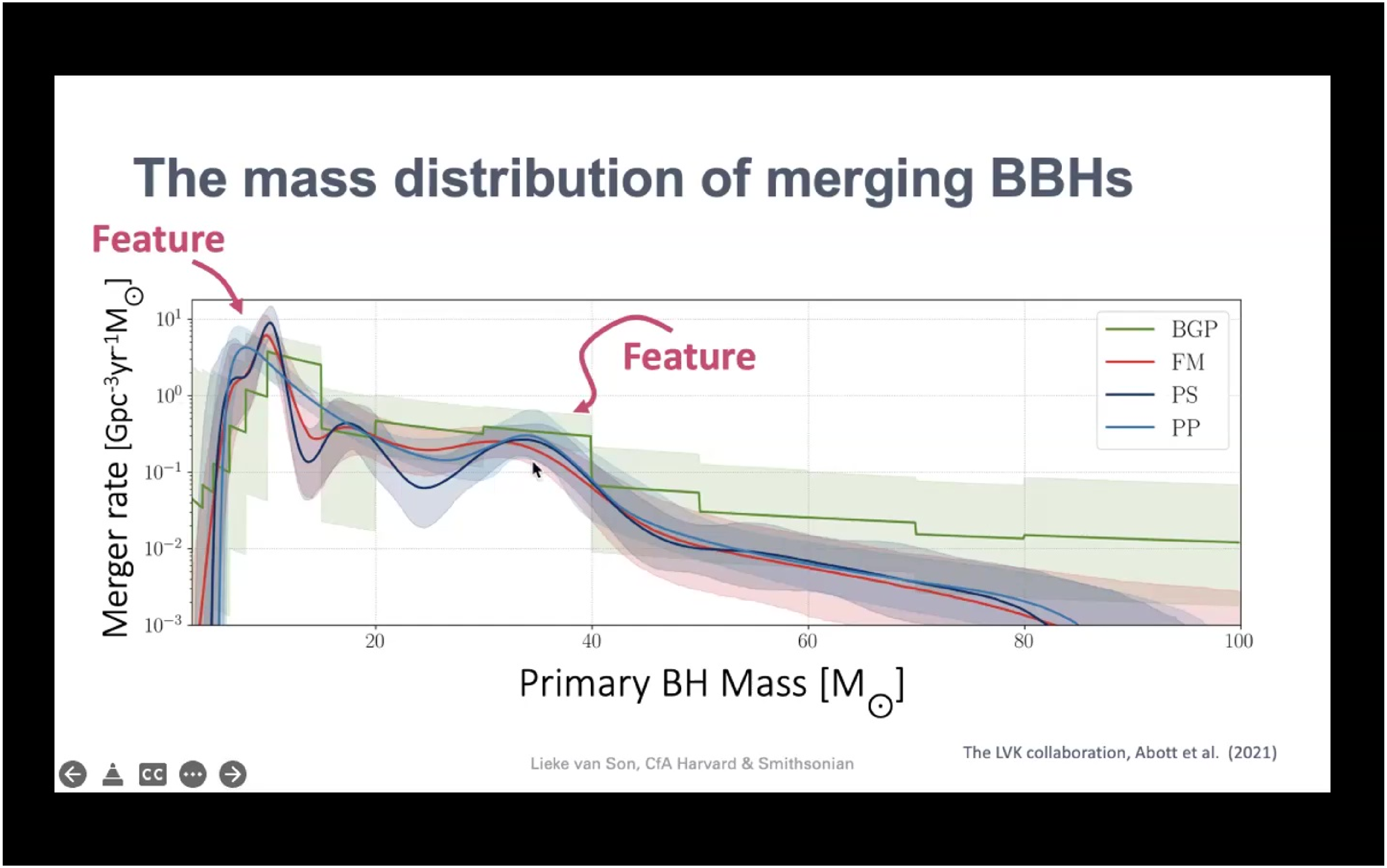
The mass distribution of merging BBHs



The LVK collaboration, Abott et al. (2021)

Lieke van Son, CfA Harvard & Smithsonian

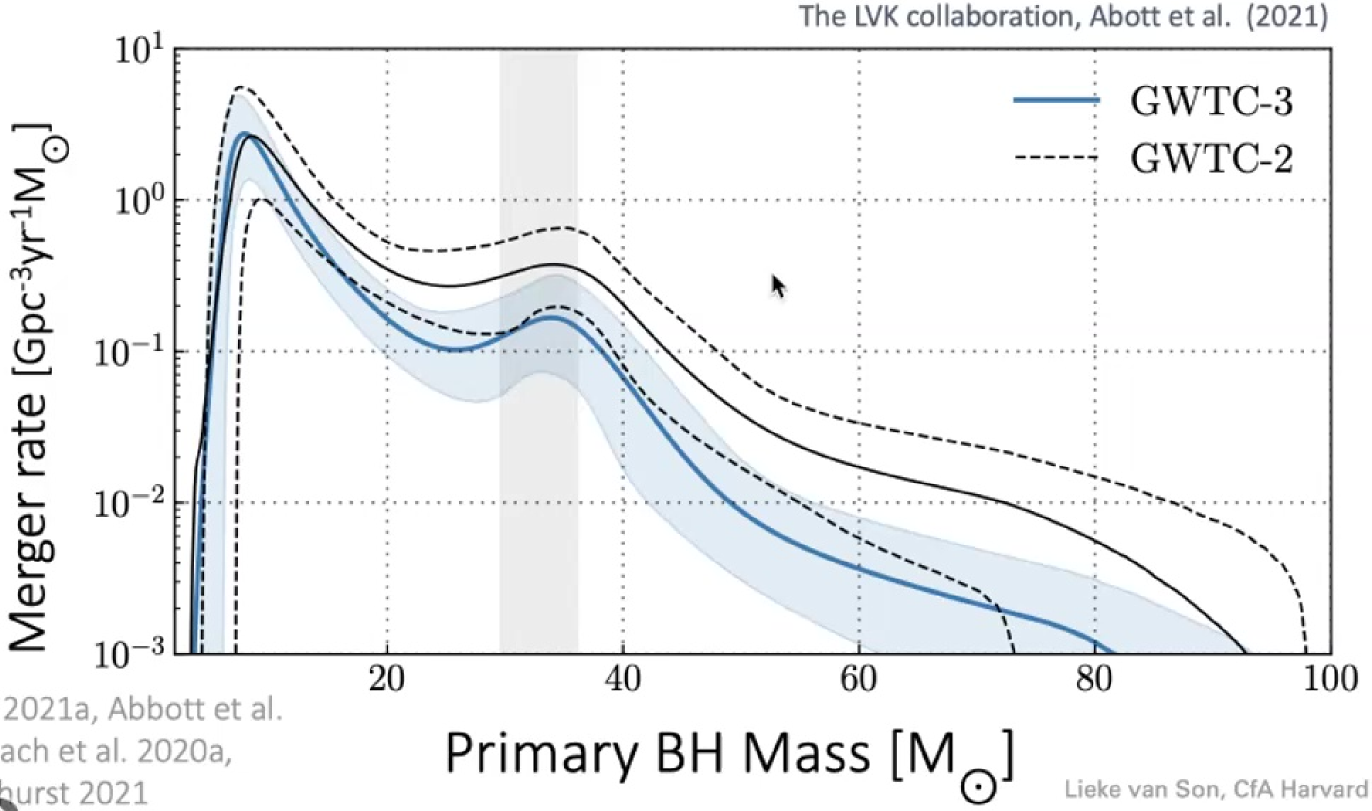


The mass distribution of merging BBHs

The LVK collaboration, Abott et al. (2021)

Lieke van Son, CfA Harvard & Smithsonian

There are features in the mass distribution!


The LVK collaboration, Abott et al. (2021)

Abbott et al. 2021a, Abbott et al. 2021b, Fishbach et al. 2020a, Tiwari & Fairhurst 2021

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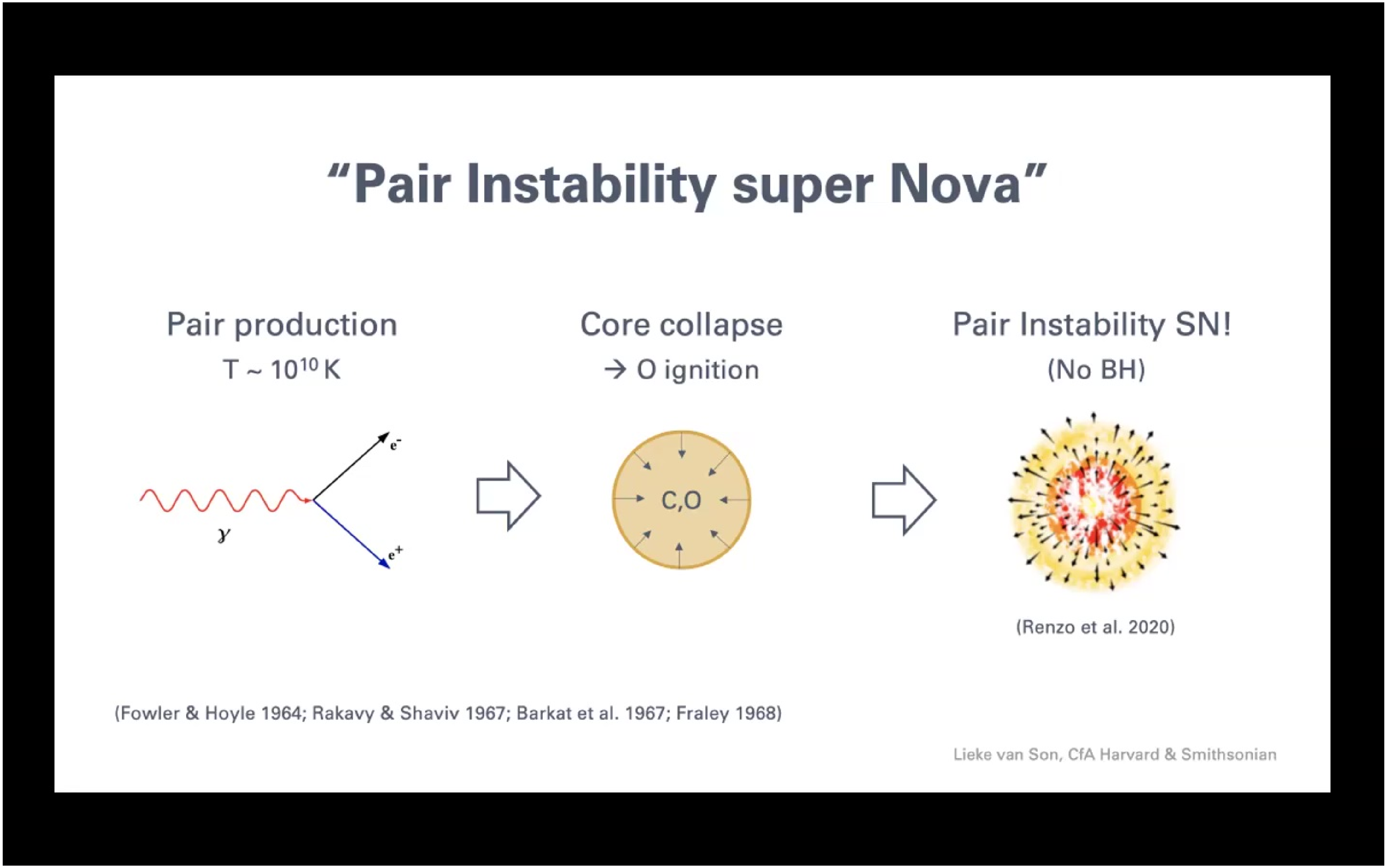

“Pair Instability super Nova”

Pair production

T ~ 10^{10} K

Core collapse

→ O ignition

Pair Instability SN!

(No BH)

(Renzo et al. 2020)

(Fowler & Hoyle 1964; Rakavy & Shaviv 1967; Barkat et al. 1967; Fraley 1968)

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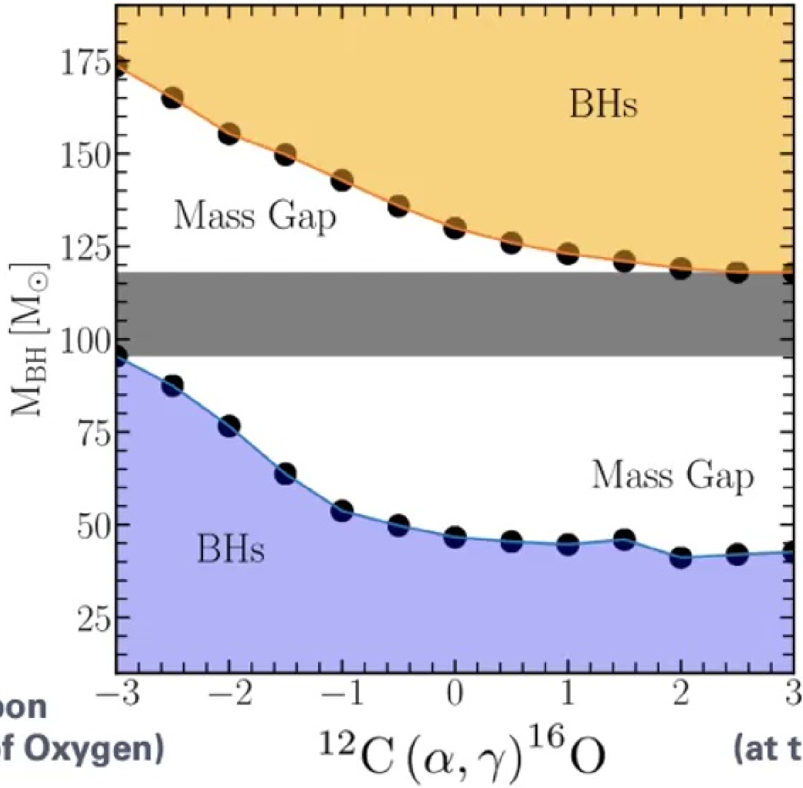
Only $^{12}C(\alpha,\gamma)^{16}O$ rate shifts the gap



More Carbon
(at the expense of Oxygen)

More Oxygen
(at the expense of Carbon)

Farmer et al 2020,
(cf. Farmer et al. 2019
Renzo et al. 2020)

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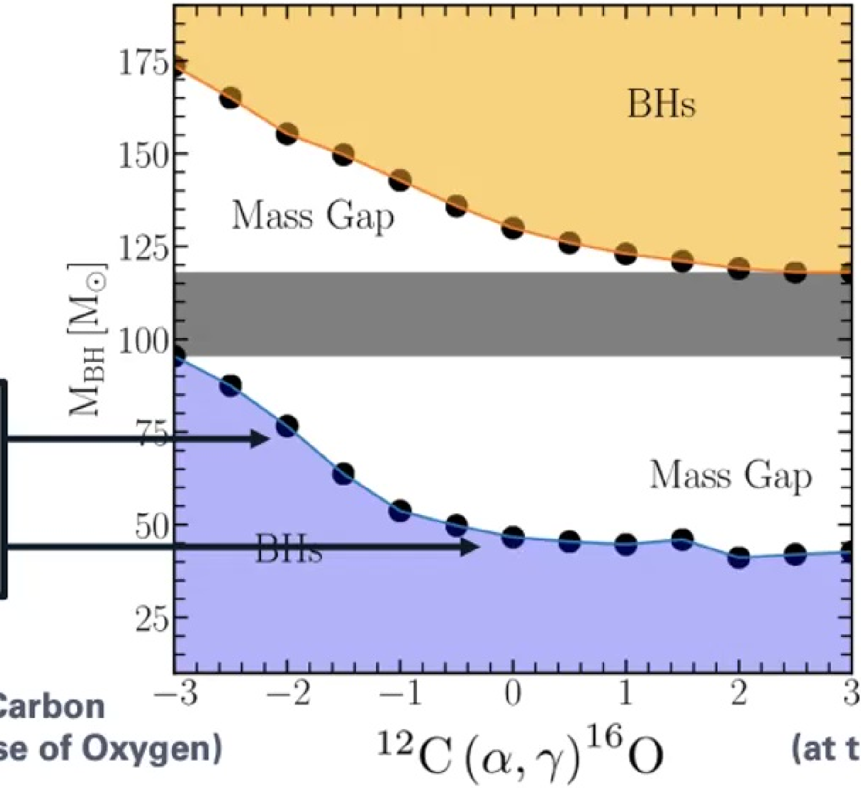
Only $^{12}C(\alpha,\gamma)^{16}O$ rate shifts the gap

We expect a pile-up just below this gap



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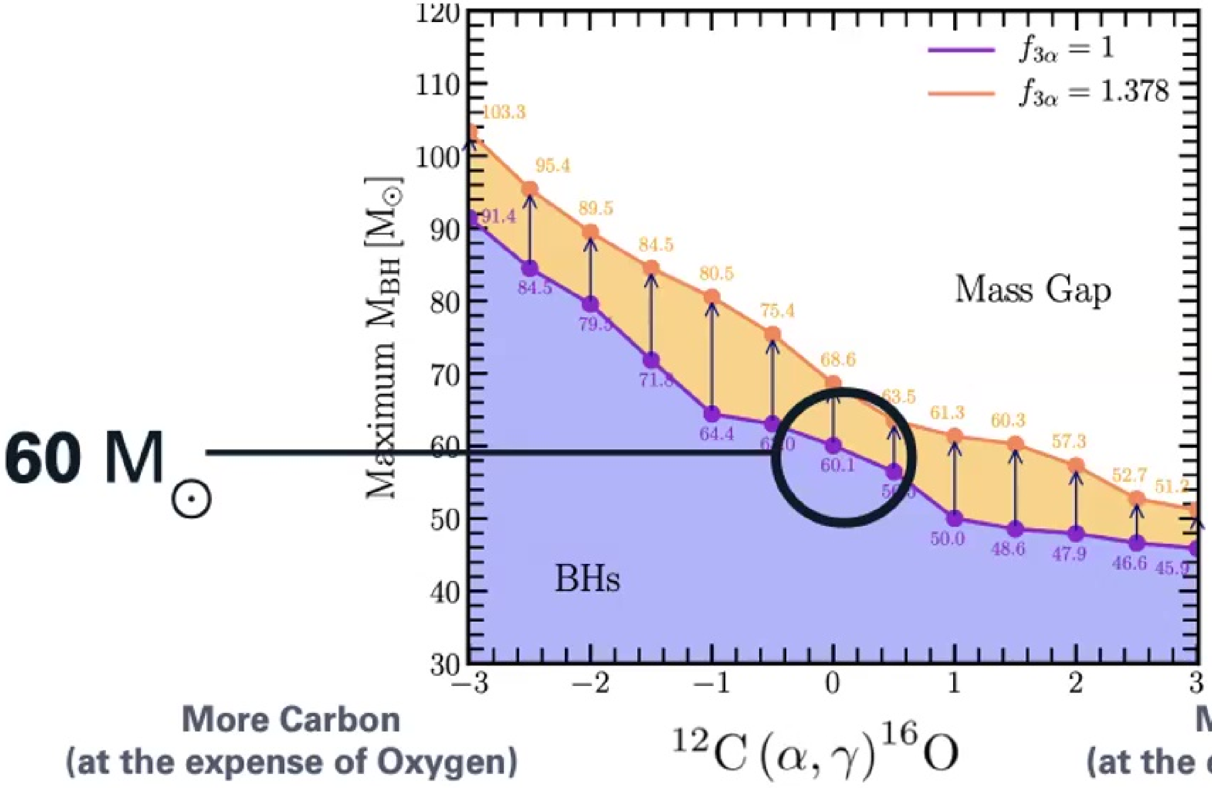
New rates shift the location of the gap up…



(Farag et al 2022,
cf. Mehta et al. 2022)

More Carbon
(at the expense of Oxygen)

More Oxygen
(at the expense of Carbon)

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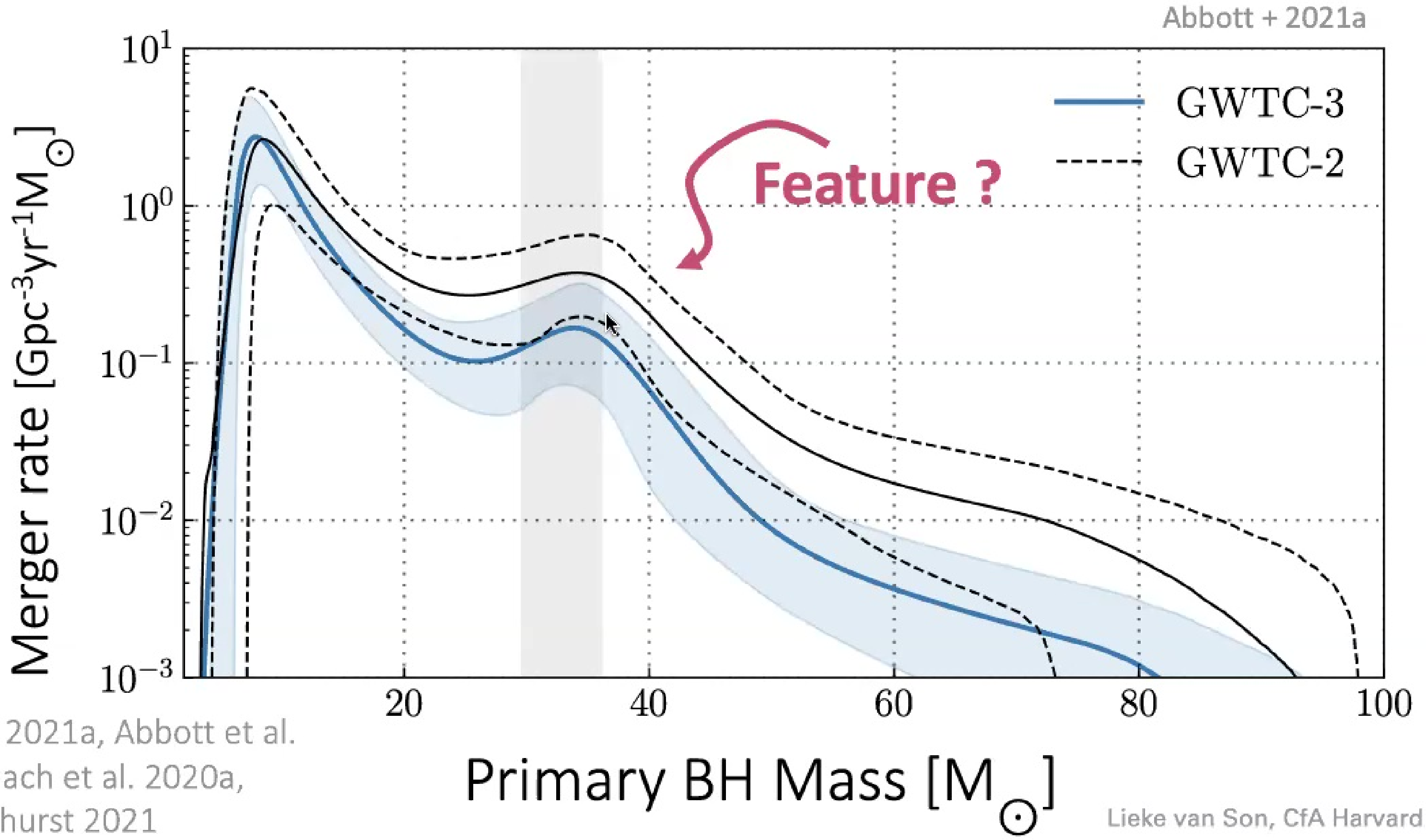
There are features in the mass distribution!



Abbott et al. 2021a, Abbott et al. 2021b, Fishbach et al. 2020a, Tiwari & Fairhurst 2021

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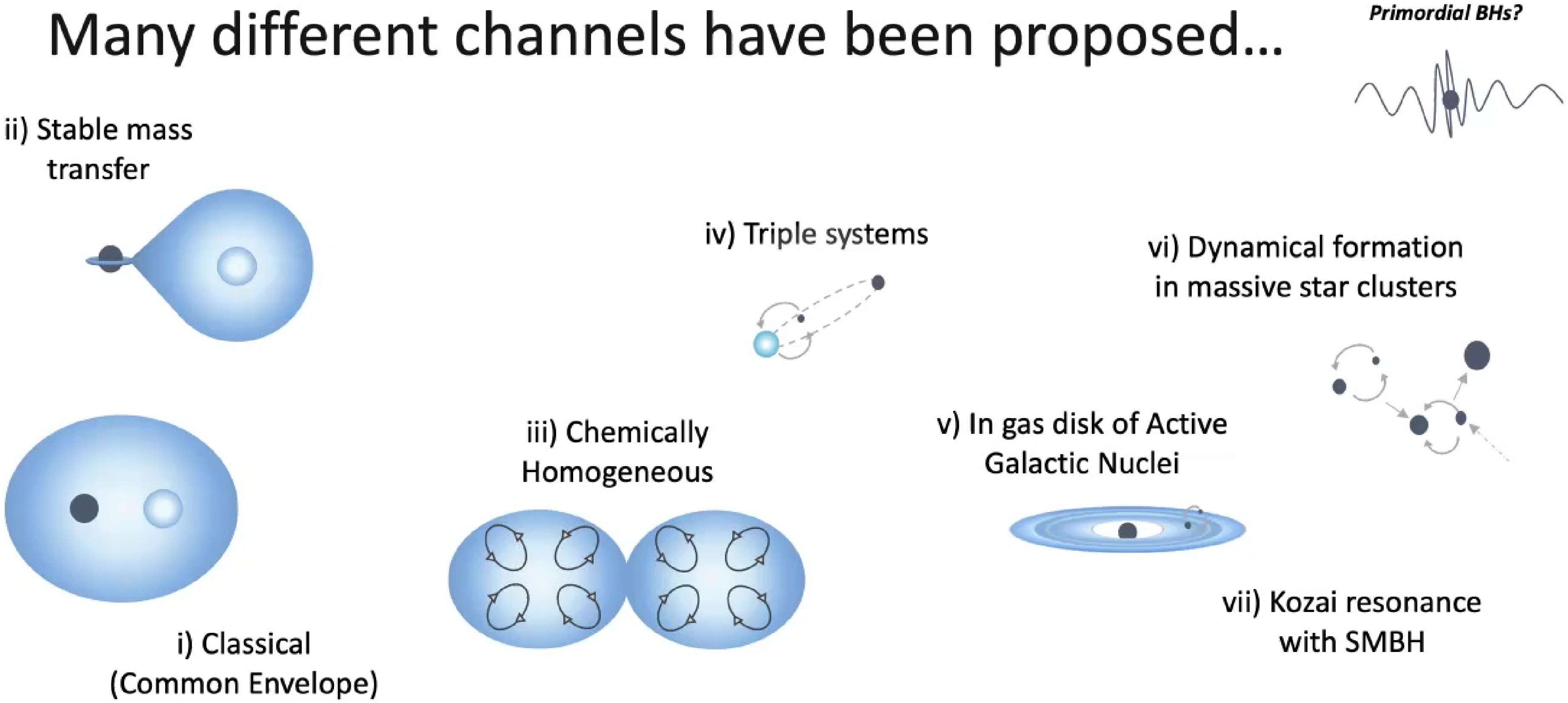
Why the low mass end is a great place to start

Many different channels have been proposed…



Primordial BHs?

ii) Stable mass transfer

iv) Triple systems

vi) Dynamical formation in massive star clusters

iii) Chemically Homogeneous

v) In gas disk of Active Galactic Nuclei

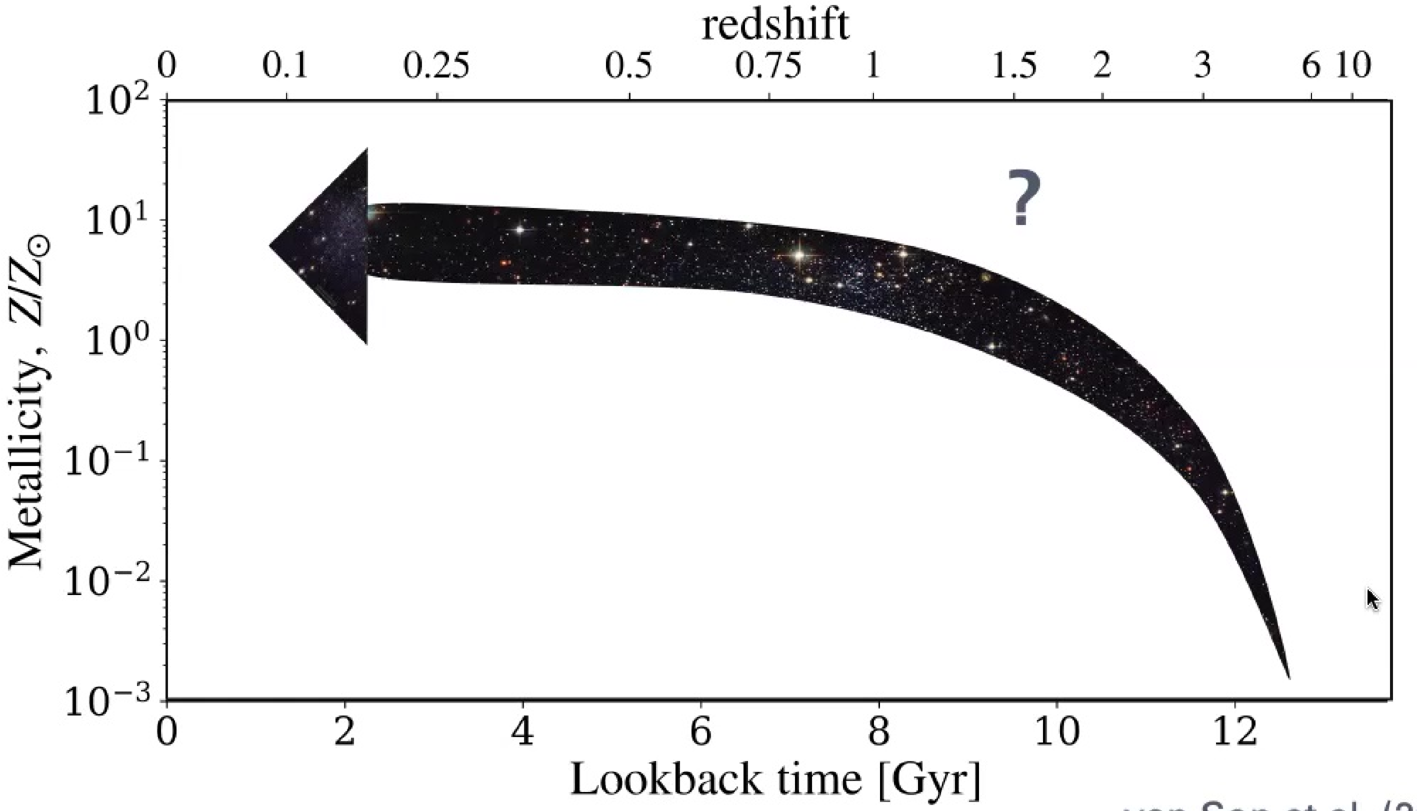
vii) Kozai resonance with SMBH

i) Classical (Common Envelope)

Adapted from de Mink In prep. for Annual Review A&A

See reviews by: Mapelli 2020 and Mandel & Farmer 2022, Mandel & Broekgaarden 2022

2) The low-mass end is Less affected by uncertainties in the “Metallicity-dependent cosmic star formation history $\mathcal{S}(Z, z)$”



van Son et al. (2022a)

Lieke van Son, CfA Harvard & Smithsonian

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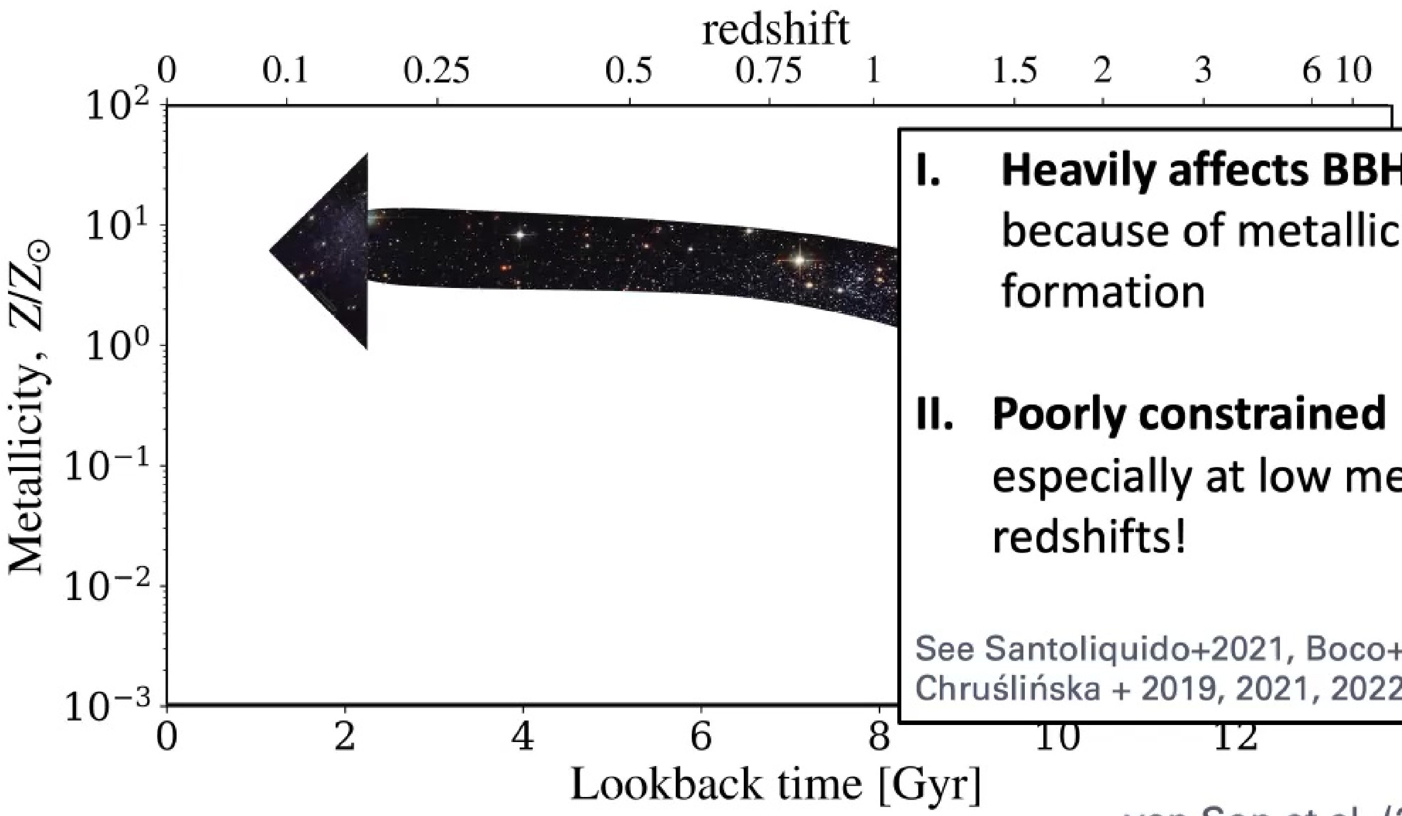

I. **Heavily affects BBH merger rate** because of metallicity dependence of BBH formation

II. **Poorly constrained** especially at low metallicity and high redshifts!

See Santoliquido+2021, Boco+2021 Broekgaarden+2021b, Chruślińska + 2019, 2021, 2022 and discussion on Monday

van Son et al. (2022a)

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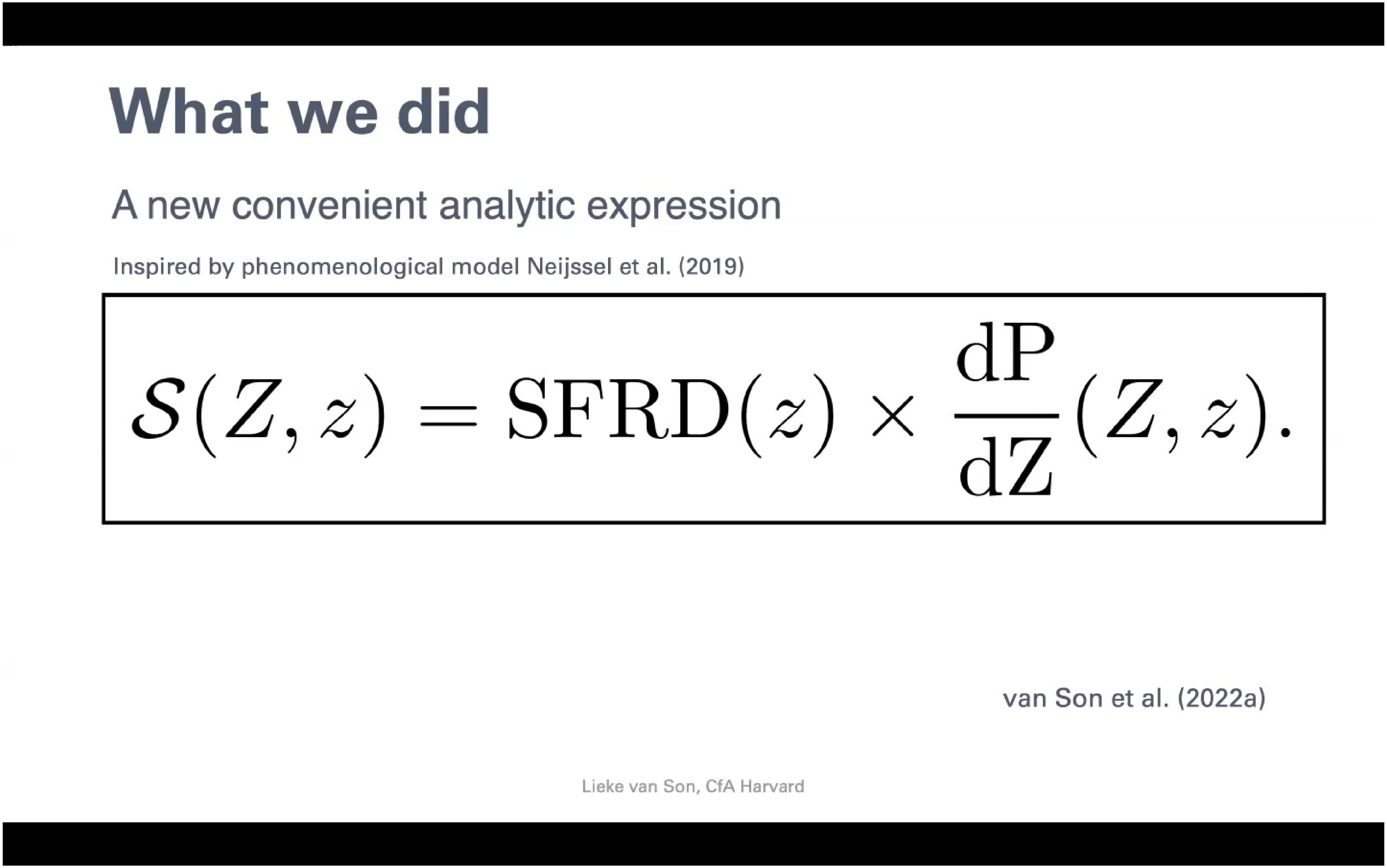


What we did

A new convenient analytic expression

Inspired by phenomenological model Neijssel et al. (2019)

$$\boxed{\mathcal{S}(Z,z) = \mathrm{SFRD}(z) \times \frac{\mathrm{dP}}{\mathrm{dZ}}(Z,z).}$$

van Son et al. (2022a)

Lieke van Son, CfA Harvard

What we did

A new convenient analytic expression

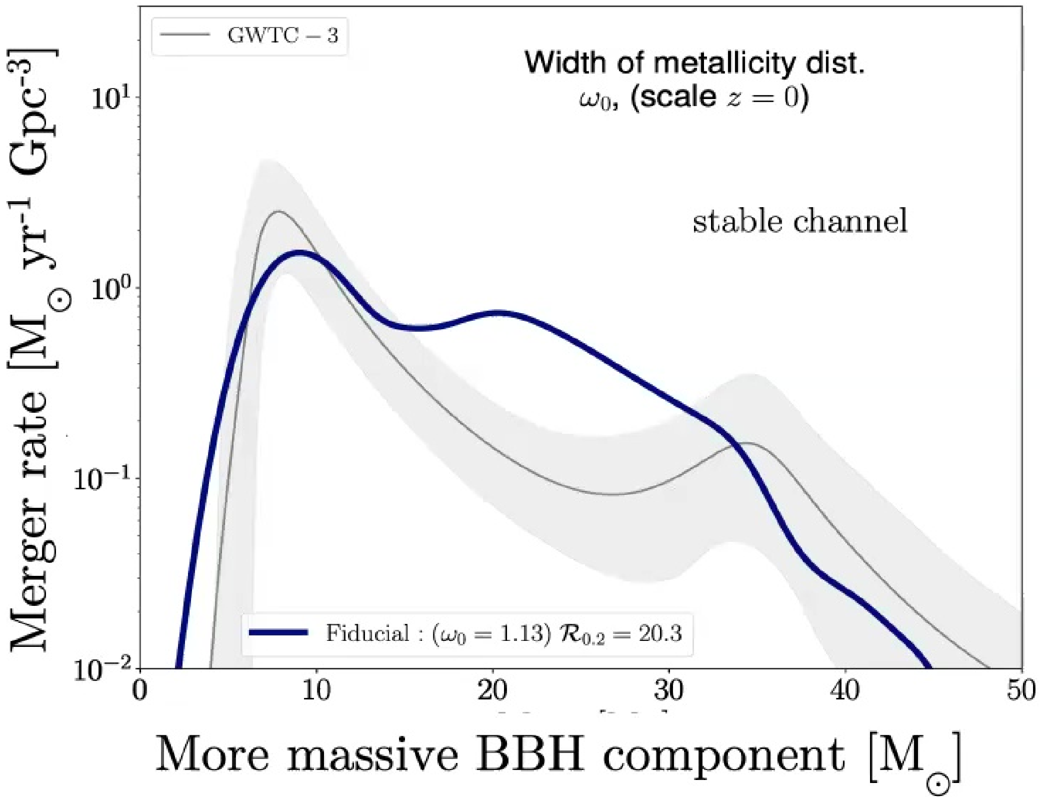
Inspired by phenomenological model Neijssel et al. (2019)

Cosmic metallicity density distribution

$$\mathcal{S}(Z,z) = \boxed{\mathrm{SFRD}(z)} \times \boxed{\frac{\mathrm{dP}}{\mathrm{dZ}}(Z,z).}$$

- **Can be easily updated when new information becomes available**
  e.g. JWST!
- **Allows for a systematic variation of the model parameters**
  We did exactly this.

systematic variation of $\mathcal{S}(Z, z)$



Fiducial model is fit* to TNG 100 simulation

https://www.tng-project.org/

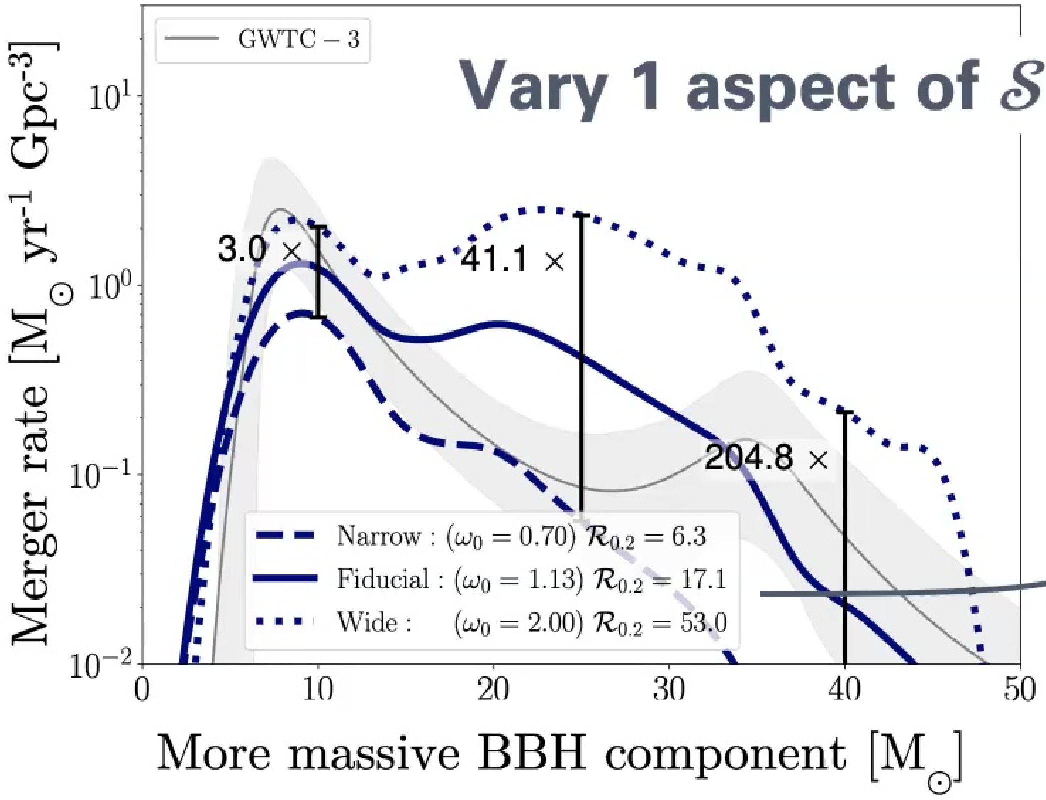
(Springel et al. 2018; Marinacci et al. 2018; Nelson et al. 2018; Pillepich et al. 2018a; Naiman et al. 2018; Nelson et al. 2019a; Pillepich et al. 2019

van Son et al. (2022a)

*We provide a Jupyter notebook this fit:
github.com/LiekeVanSon/SFRD_fit/blob/main/src/scripts/Fit_To_Cosmological_Simulation.ipynb

systematic variation of $\mathcal{S}(Z, z)$

van Son et al. (2022a)



Vary 1 aspect of $\mathcal{S}(Z, z)$:

width of the metallicity distribution at redshift 0

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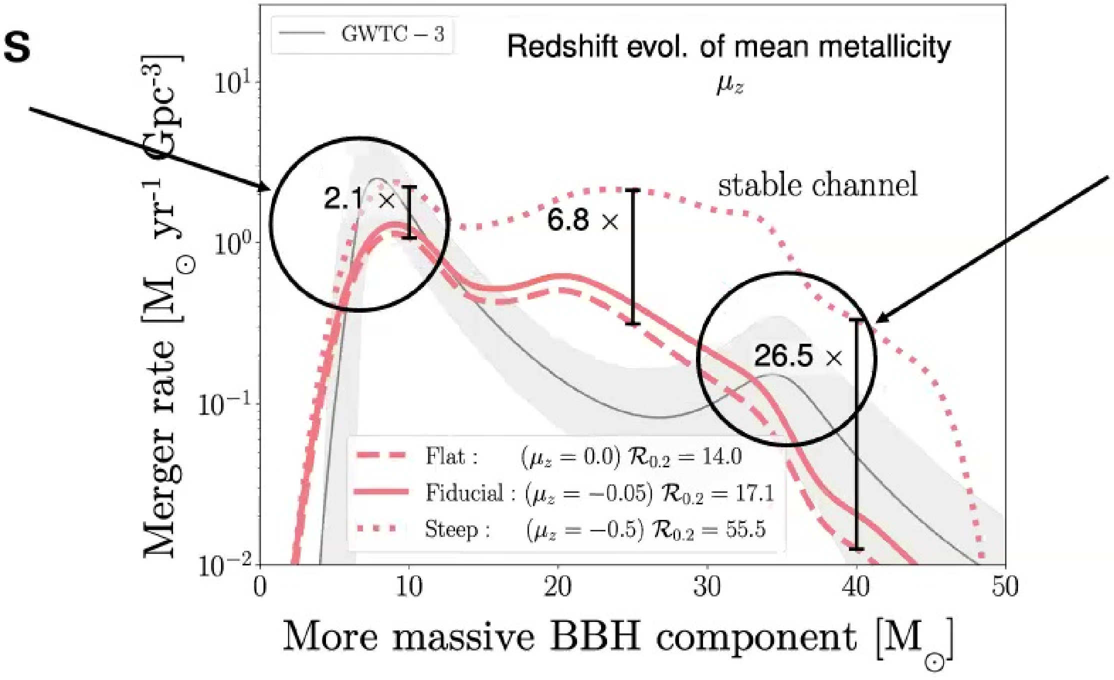
The low mass end is least affected

low mass
2 x



high mass
27 x

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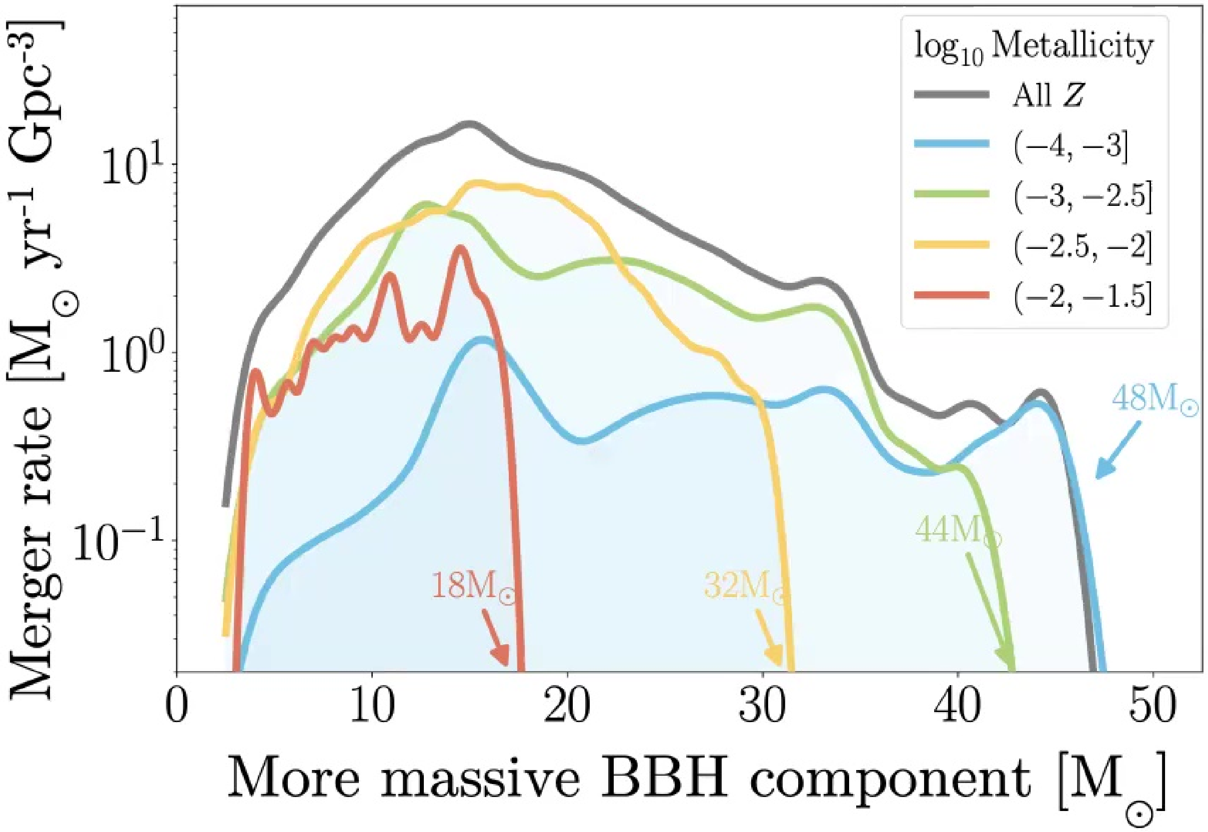
The lowest mass BHs come from higher metallicities ($Z > 10$-3)

van Son et al. (2022a)



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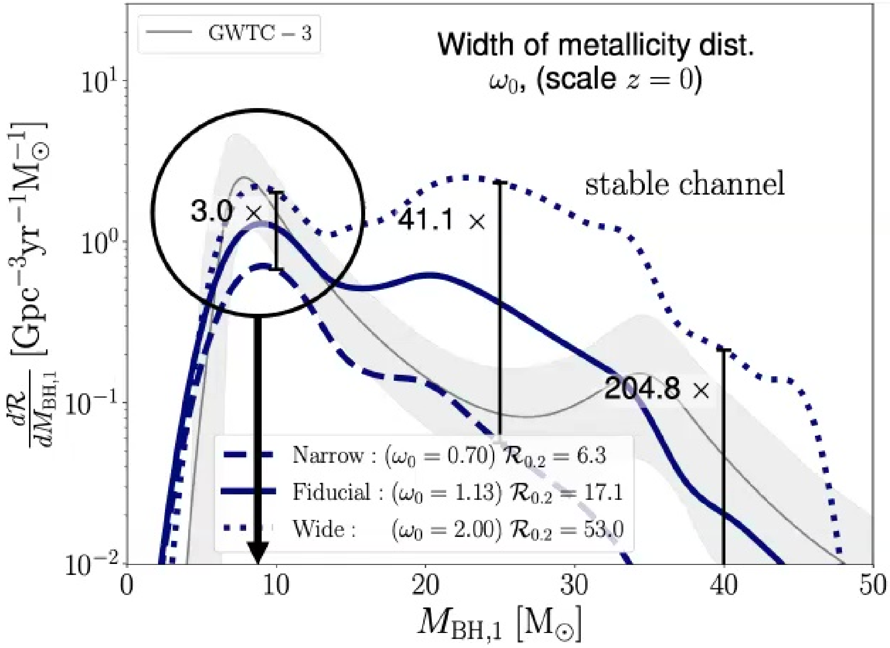
The location of features does not change!



van Son et al. (2022b)

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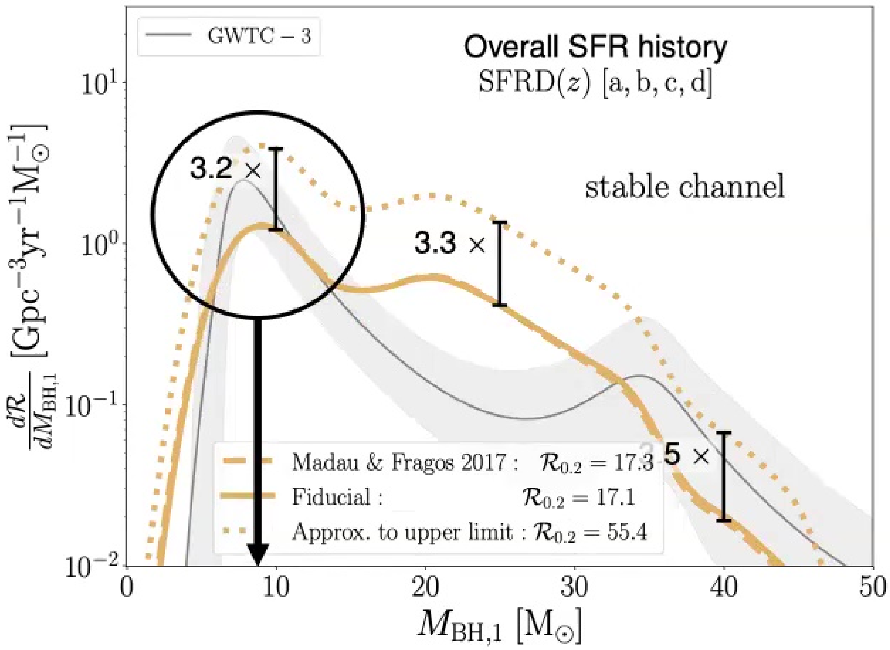
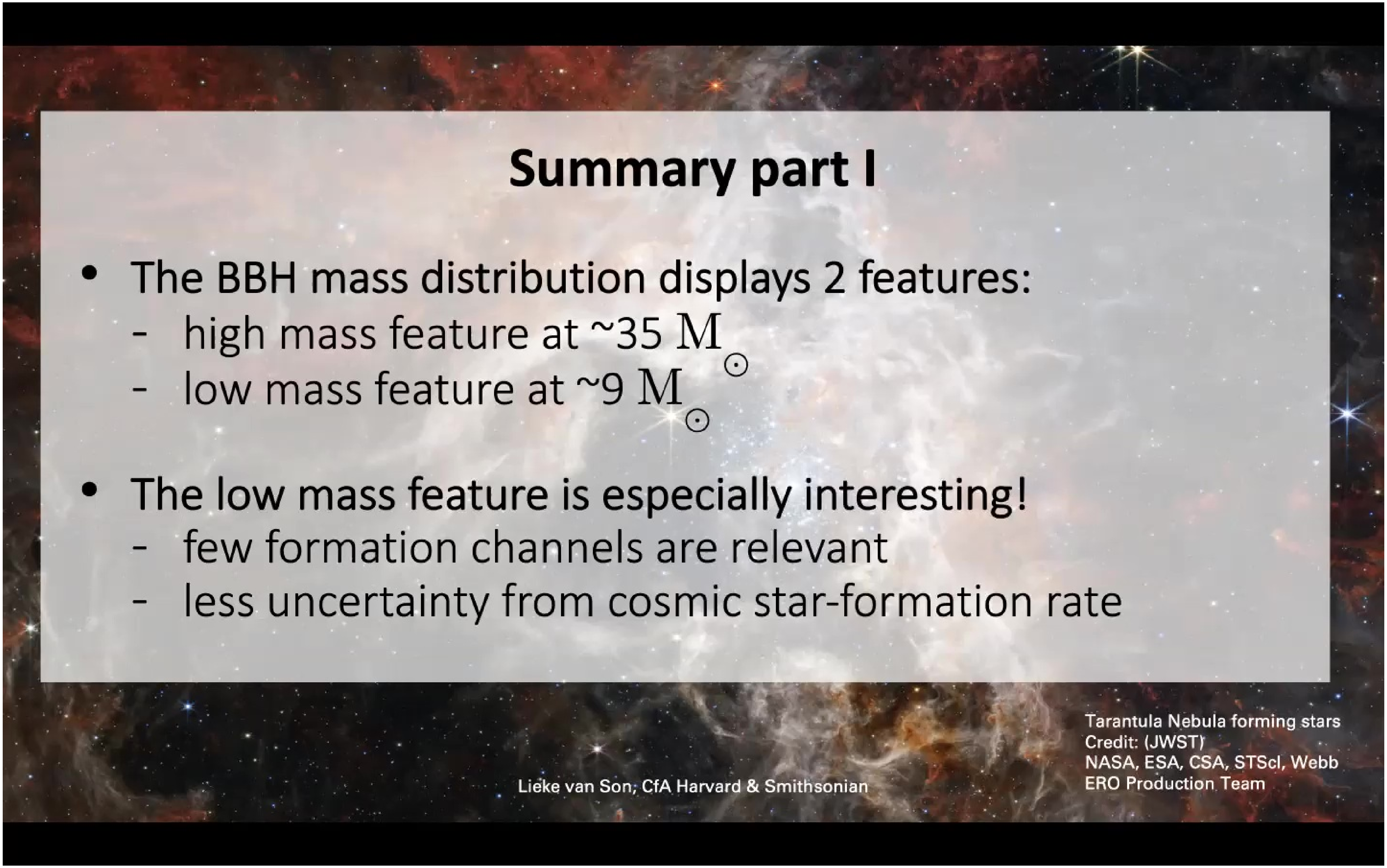


van Son et al. (2022b)



Summary part I

- The BBH mass distribution displays 2 features:
  - high mass feature at ~35 $M_\odot$
  - low mass feature at ~9 $M_\odot$

- The low mass feature is especially interesting!
  - few formation channels are relevant
  - less uncertainty from cosmic star-formation rate

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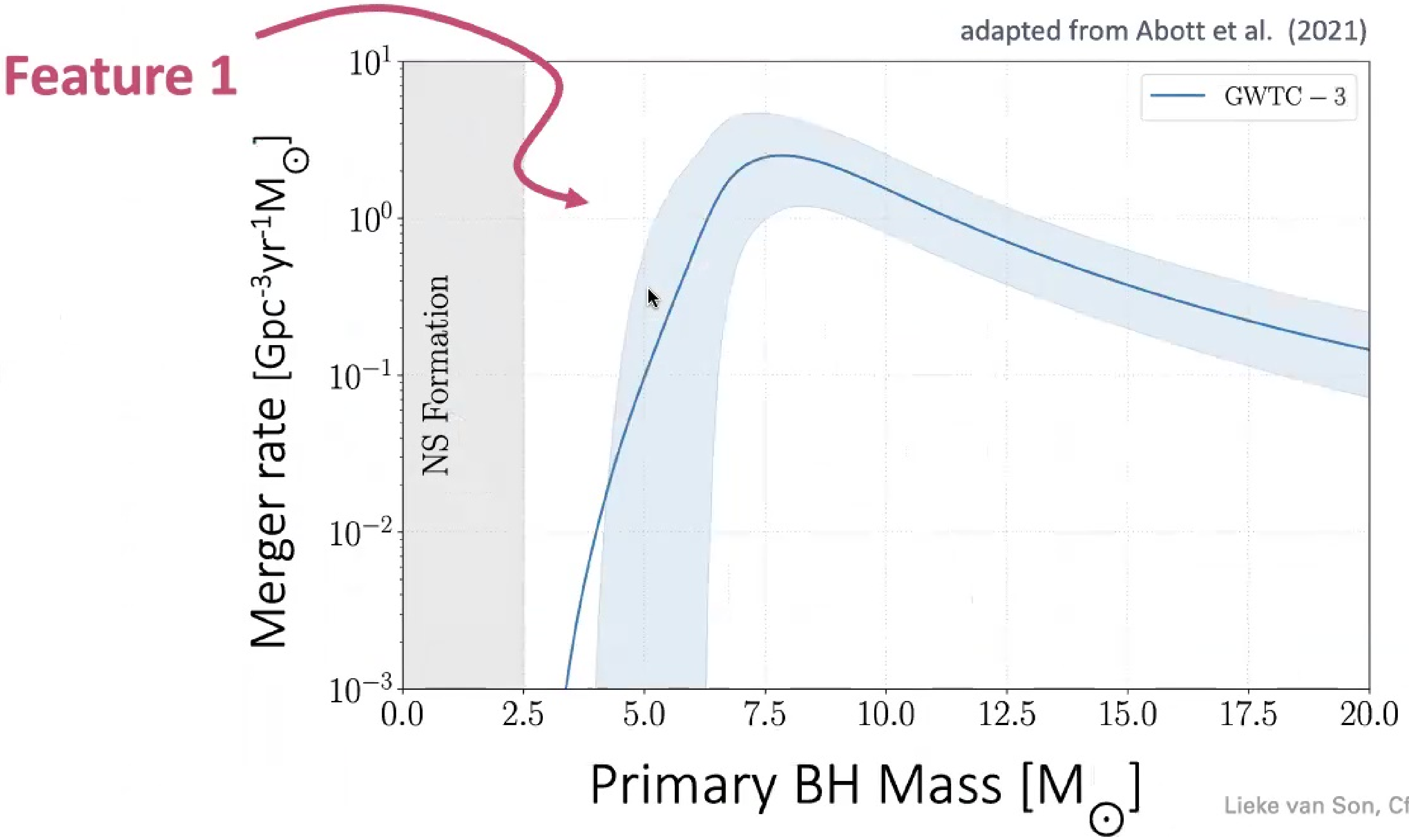
Tarantula Nebula forming stars
Credit: (JWST)
NASA, ESA, CSA, STScI, Webb
ERO Production Team

There are features in the mass distribution!



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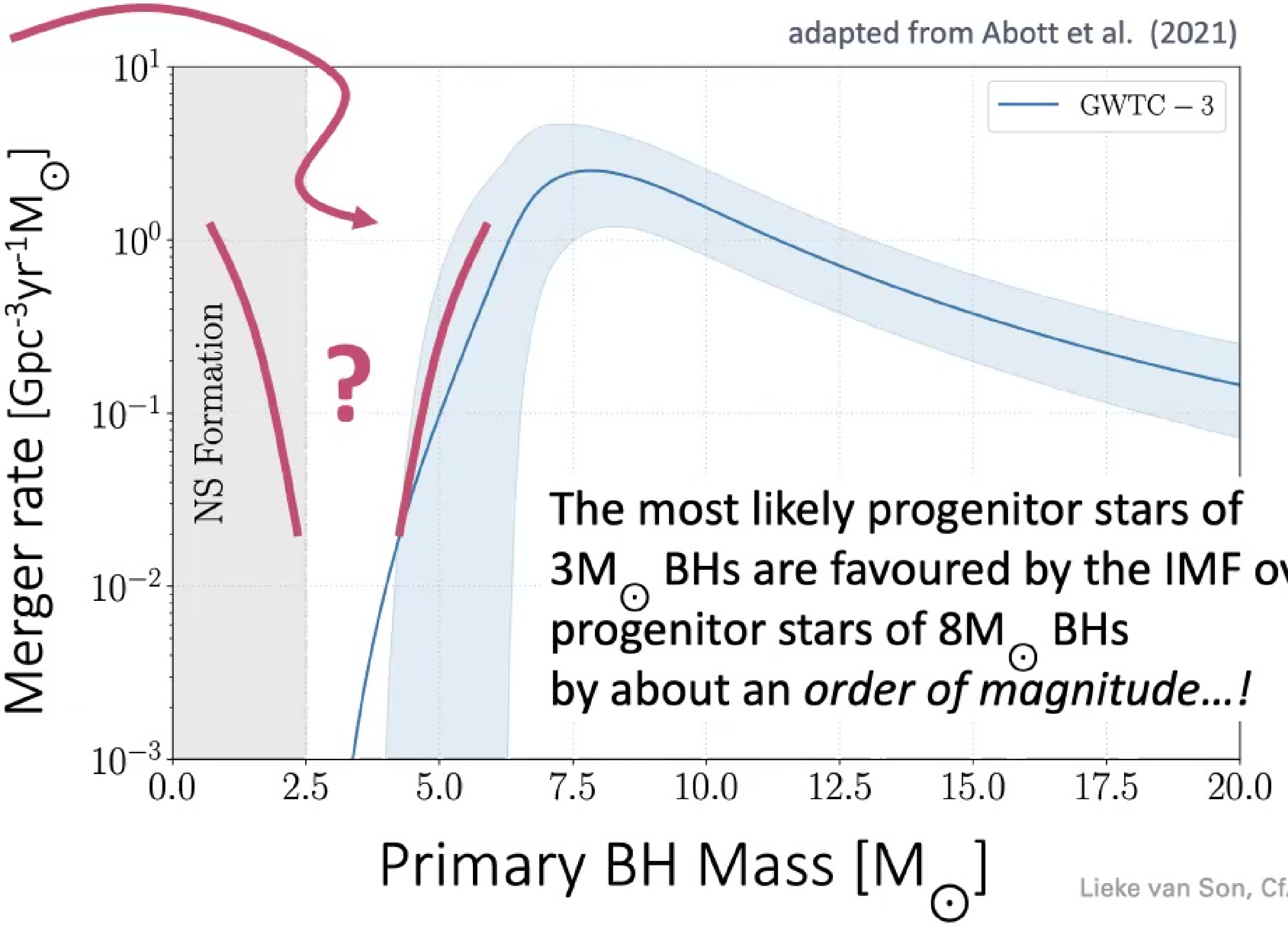
There are features in the mass distribution!

Feature 1

adapted from Abott et al. (2021)



The most likely progenitor stars of 3M$_\odot$ BHs are favoured by the IMF over progenitor stars of 8M$_\odot$ BHs by about an *order of magnitude…!* (e.g., Kroupa 2001)

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Where are the BH's with 3-6 $M_{\odot}$?

(There appears to be a lack of 3-6$M_{\odot}$ BHs: Fishbach + 2020, Abbott et al. 2021b, Farah + 2021, Ye & Fishbach 2021)

We don't see them	A: They don't exist	B: They don't merge
↓ Observational bias against detecting such systems?		

(e.g., Fishbach + 2017)

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A: They don’t exist?

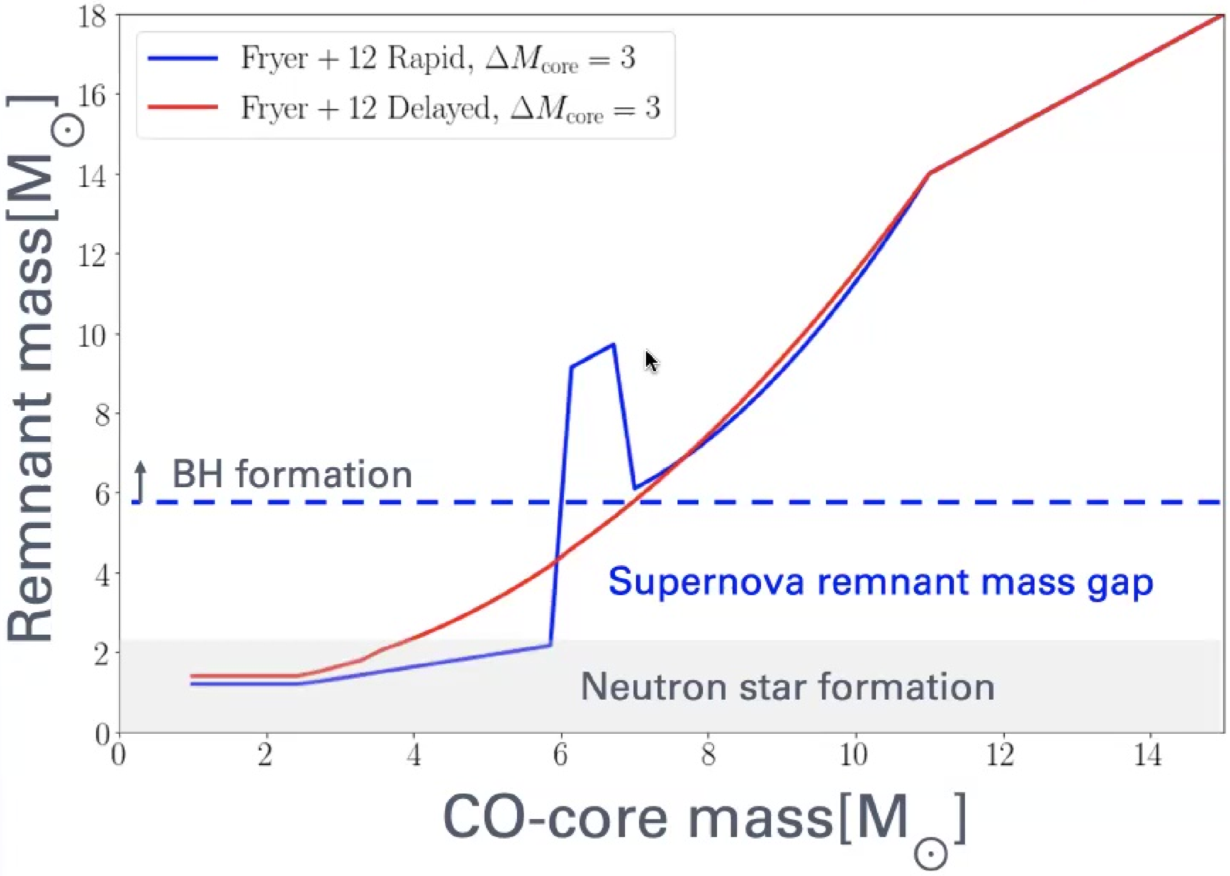
...or discontinuous

SN physics: Fryer & Kalogera 2001,
Fryer + 2012, Belczynski + 2012, Fryer + 2022,
Olejak + 2022

Discontinuous remnant mass distribution based on X-ray observations **(= NS-BH gap)**

Bailyn et al. 1998, Özel + 2010, Farr + 2011,
Kreidberg + 2012

Adapted from Fryer + 2012



see also Philipp Podsiadlowski’s talk on Tuesday

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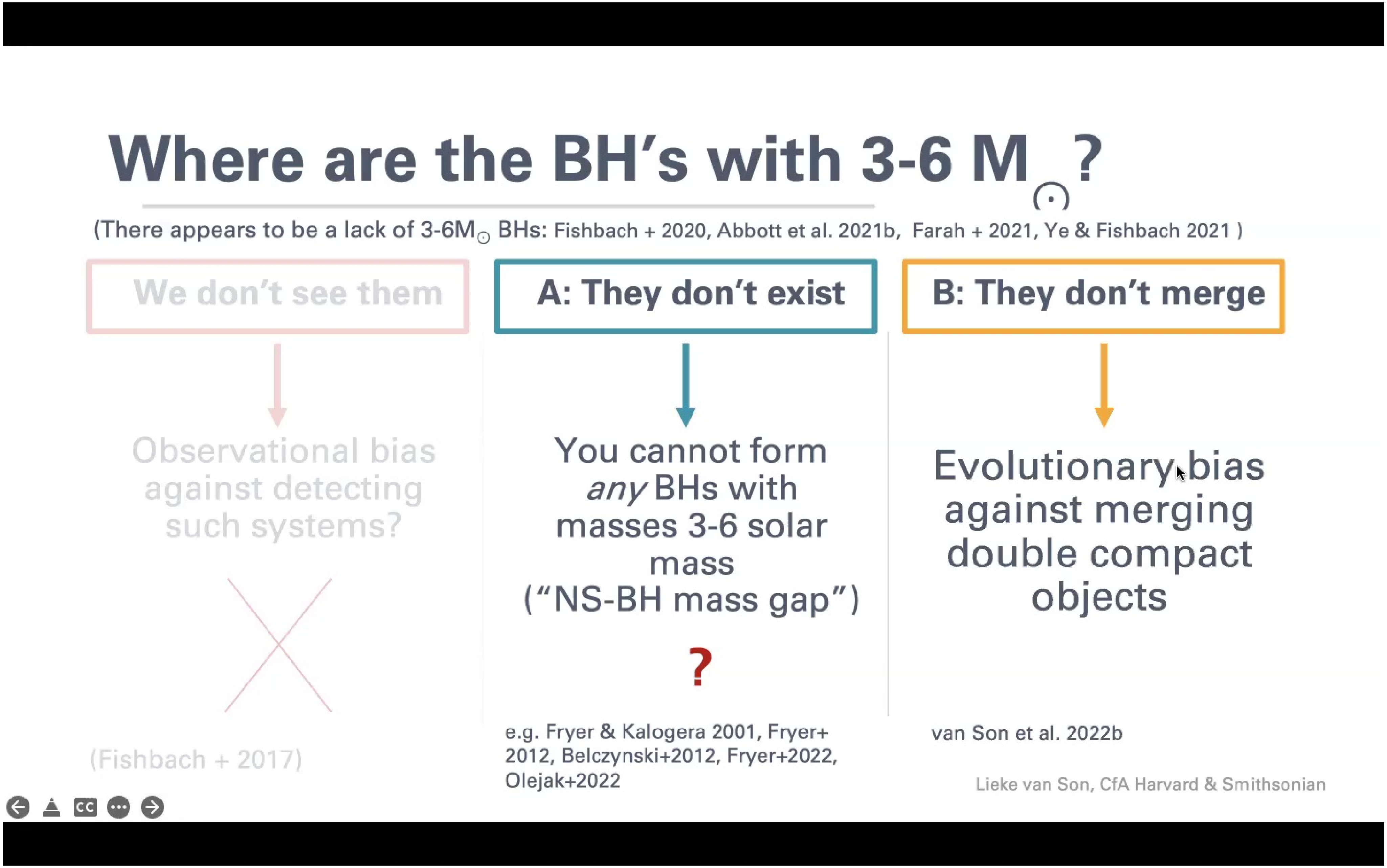

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We don't see them

Observational bias against detecting such systems?

(Fishbach + 2017)

A: They don't exist

You cannot form *any* BHs with masses 3-6 solar mass ("NS-BH mass gap")

?

e.g. Fryer & Kalogera 2001, Fryer+ 2012, Belczynski+2012, Fryer+2022, Olejak+2022

B: They don't merge

Evolutionary bias against merging double compact objects

van Son et al. 2022b

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Isolated binary formation can be roughly split in two

Common envelope channel:

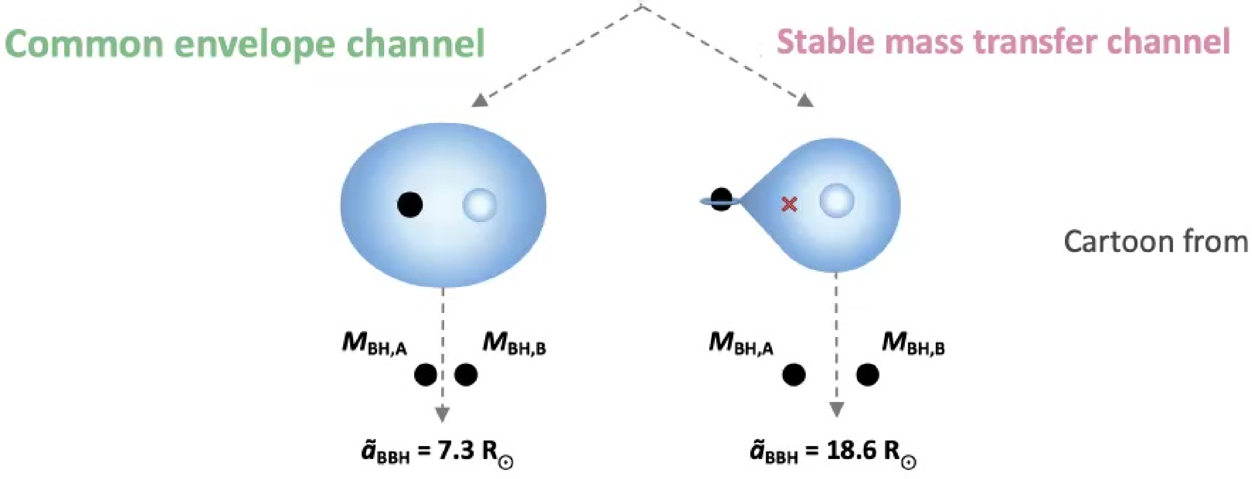
at least one common envelope

e.g. Belczynski et al. (2007); Postnov & Yungelson (2014); Belczynski et al. 2016a; Eldridge & Maund (2016); Lipunov et al. (2017); Vigna-Gomez et al. (2018)

Stable RLOF channel:

Experiences *only* stable mass transfer

van den Heuvel et al. (2017); Inayoshi et al. (2017); Neijssel et al. (2019); Bavera et al. (2021); Marchant et al. (2021); Gallegos-Garcia et al. (2021)



Cartoon from van Son et al. 2021

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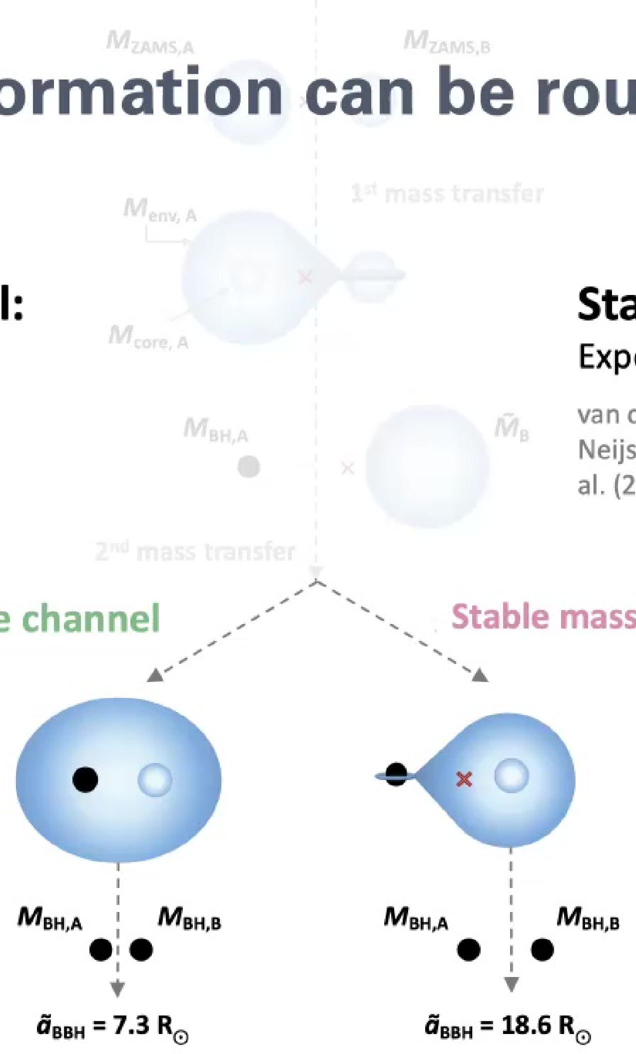

are CE less efficient than assumed?

Klencki+ 2020; 2021, Marchant + 2021, Gallegos-Garcia+ 2021, Olejak + 2021

Cartoon from van Son et al. 2021

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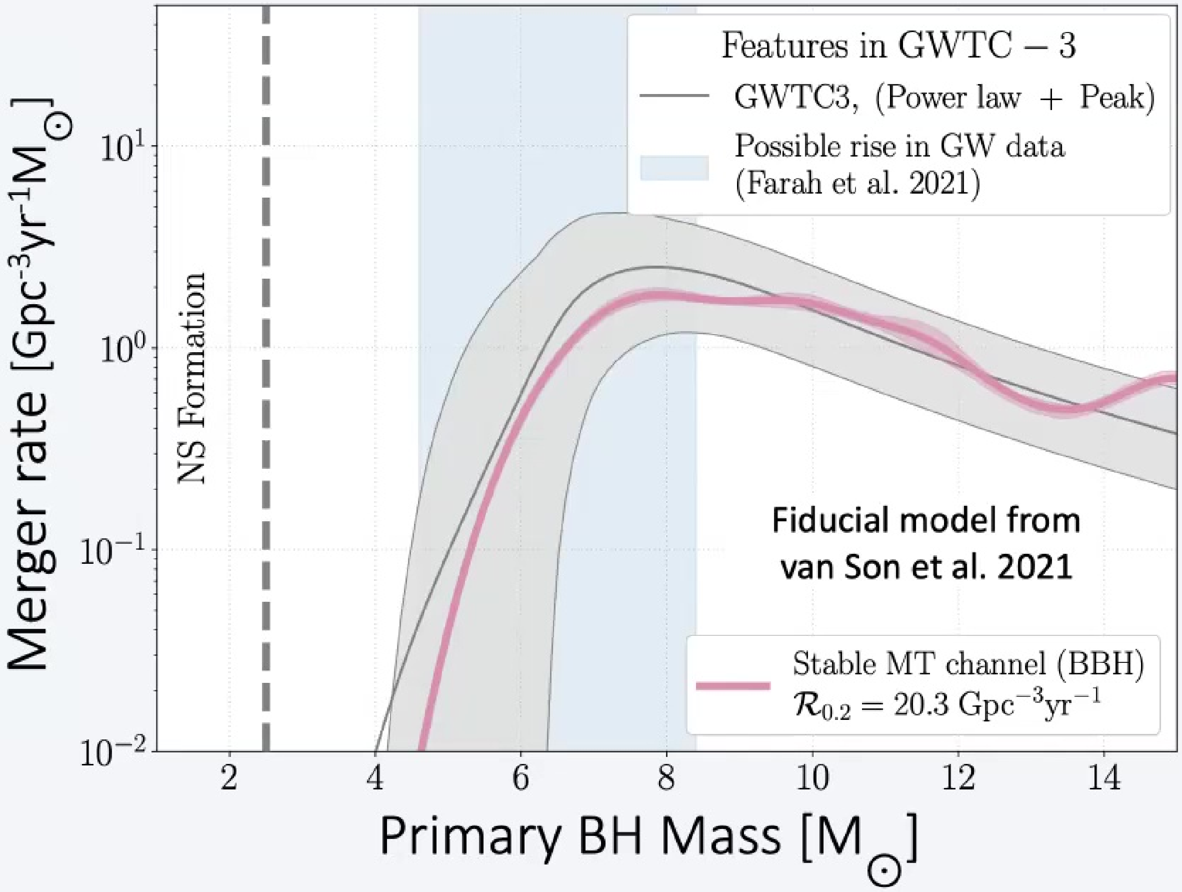
What does the stable channel predict?

The fiducial stable channel matches the *rate* and *shape* at low mass



van Son et al. (2022b)

Calculated using COMPAS

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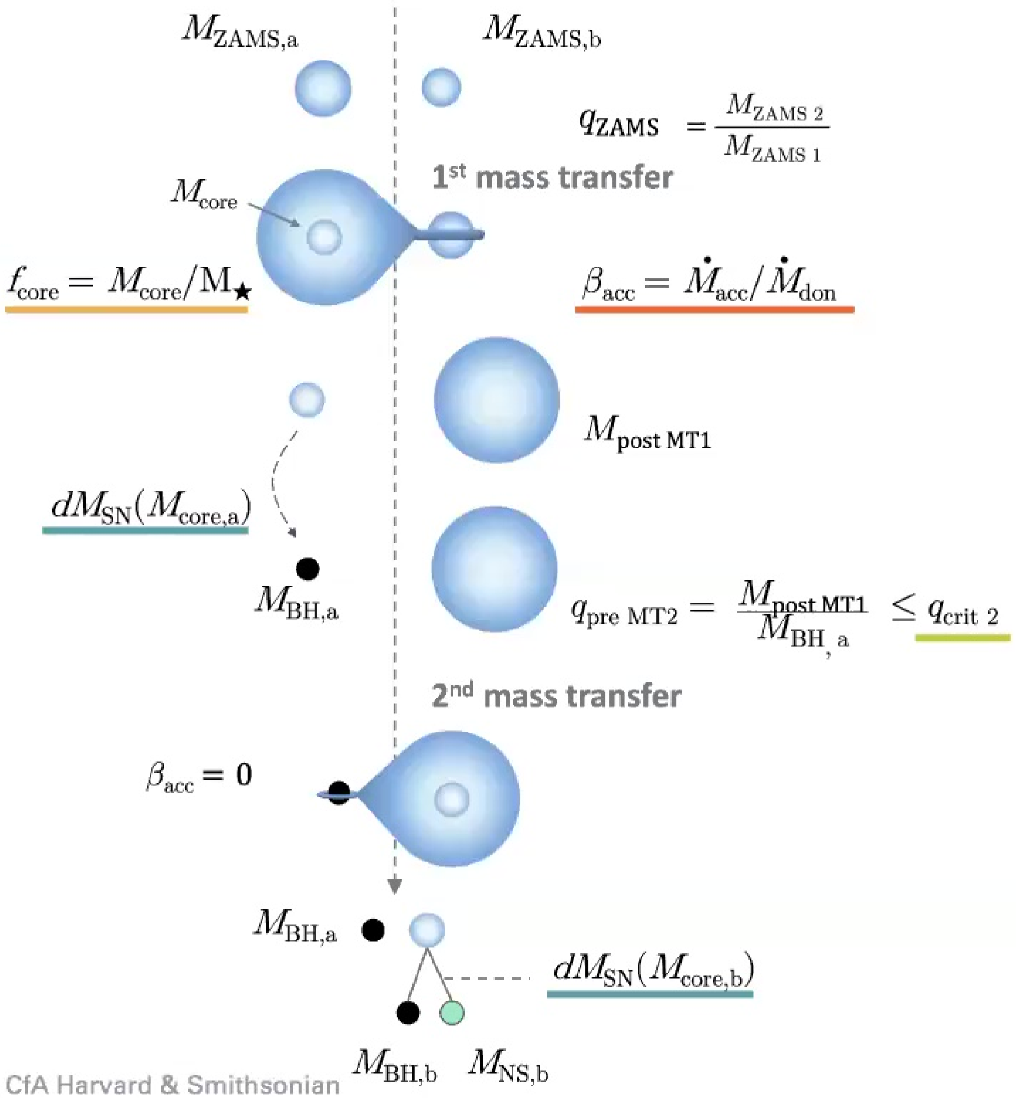
Why does the stable mass transfer channel drop below a certain mass?

Requiring mass transfer stability imposes a minimum on the mass!

van Son et al. (2022b)



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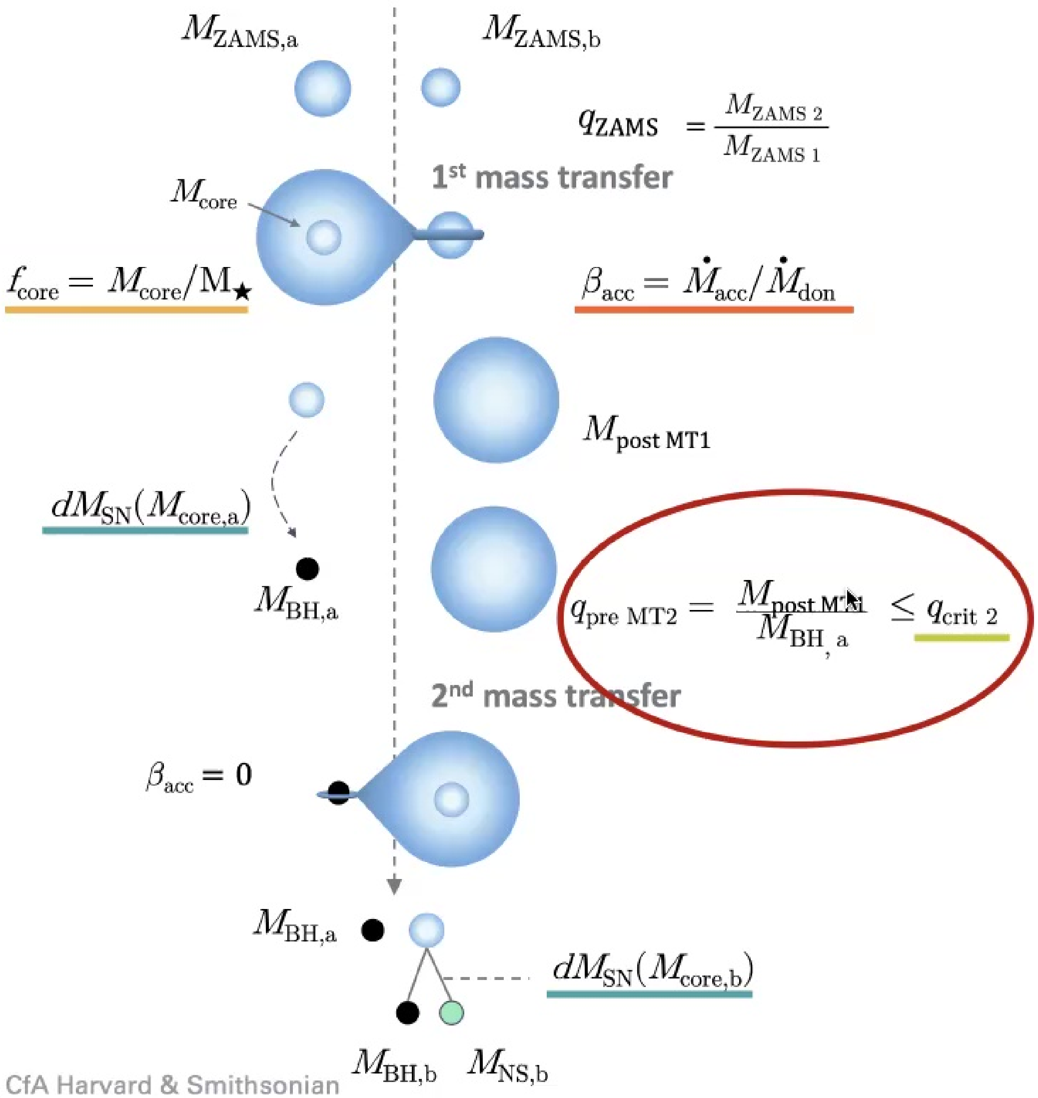

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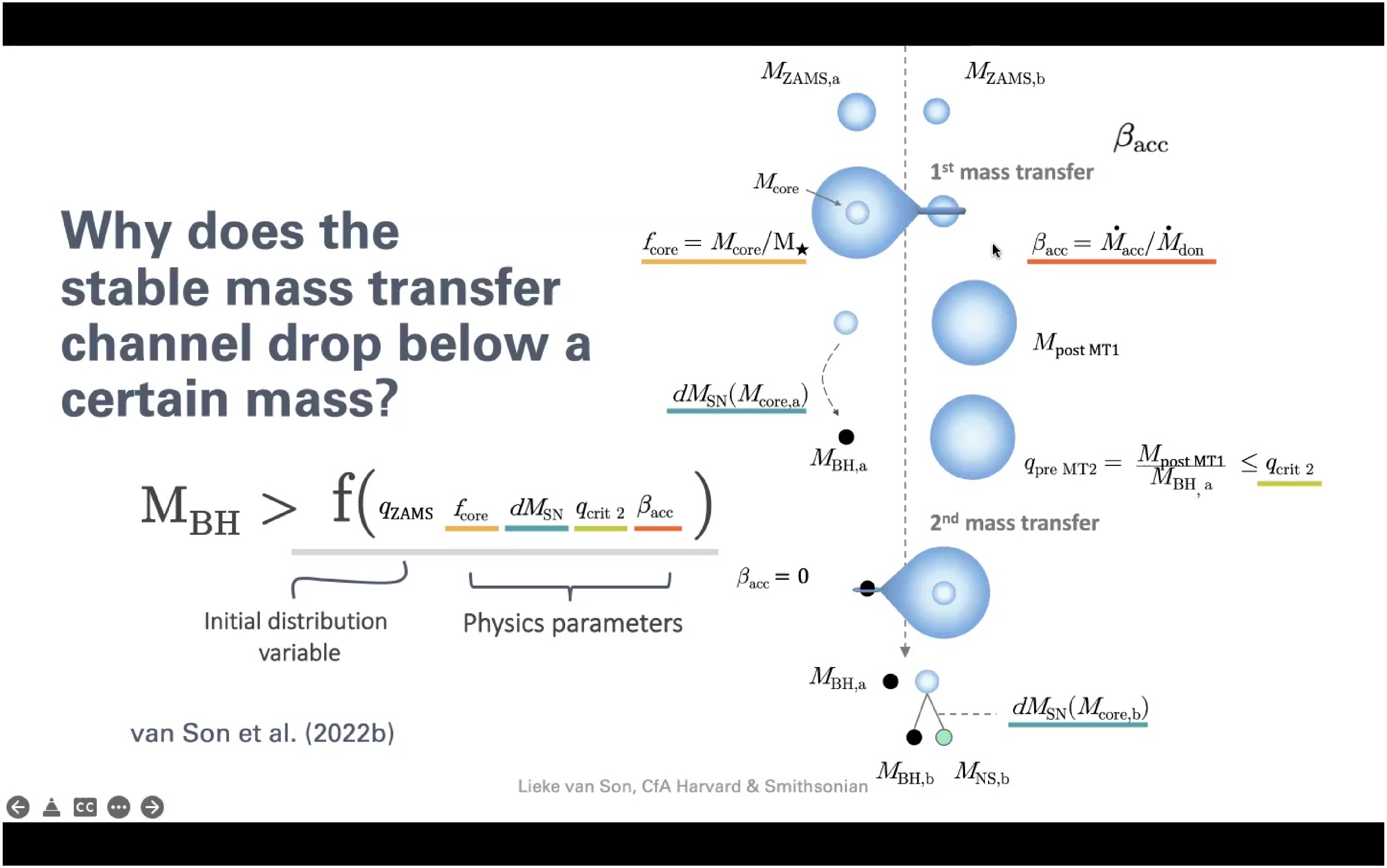

Why does the stable mass transfer channel drop below a certain mass?

$$M_{BH} > f(\underbrace{q_{ZAMS}}_{\text{Initial distribution variable}} \; \underbrace{f_{core} \;\; dM_{SN} \;\; q_{crit\ 2} \;\; \beta_{acc}}_{\text{Physics parameters}})$$

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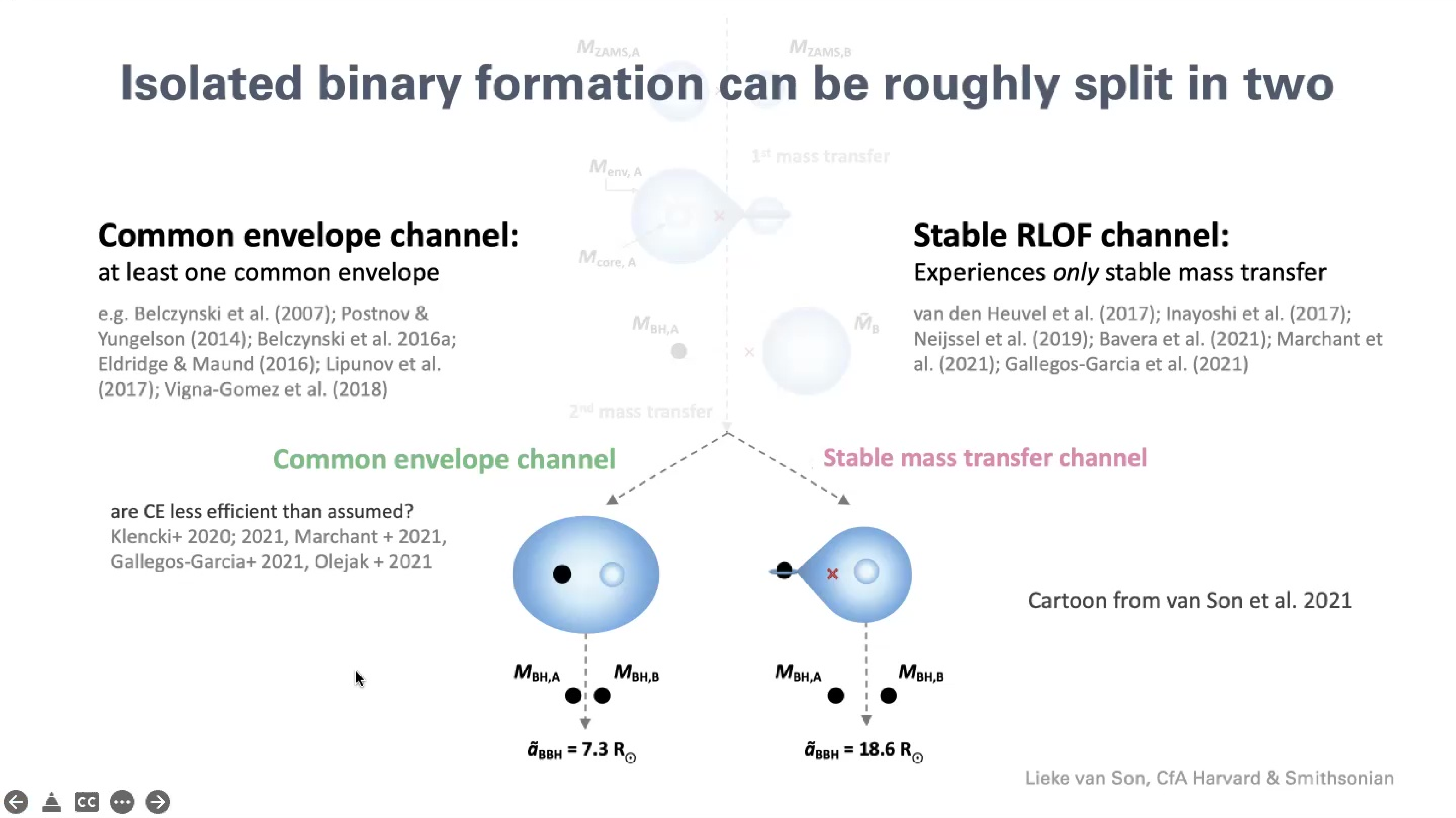

Isolated binary formation can be roughly split in two

Common envelope channel:
at least one common envelope

e.g. Belczynski et al. (2007); Postnov & Yungelson (2014); Belczynski et al. 2016a; Eldridge & Maund (2016); Lipunov et al. (2017); Vigna-Gomez et al. (2018)

Stable RLOF channel:
Experiences *only* stable mass transfer

van den Heuvel et al. (2017); Inayoshi et al. (2017); Neijssel et al. (2019); Bavera et al. (2021); Marchant et al. (2021); Gallegos-Garcia et al. (2021)

are CE less efficient than assumed?
Klencki+ 2020; 2021, Marchant + 2021, Gallegos-Garcia+ 2021, Olejak + 2021

Cartoon from van Son et al. 2021

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We can predict the minimum BH mass analytically ....!

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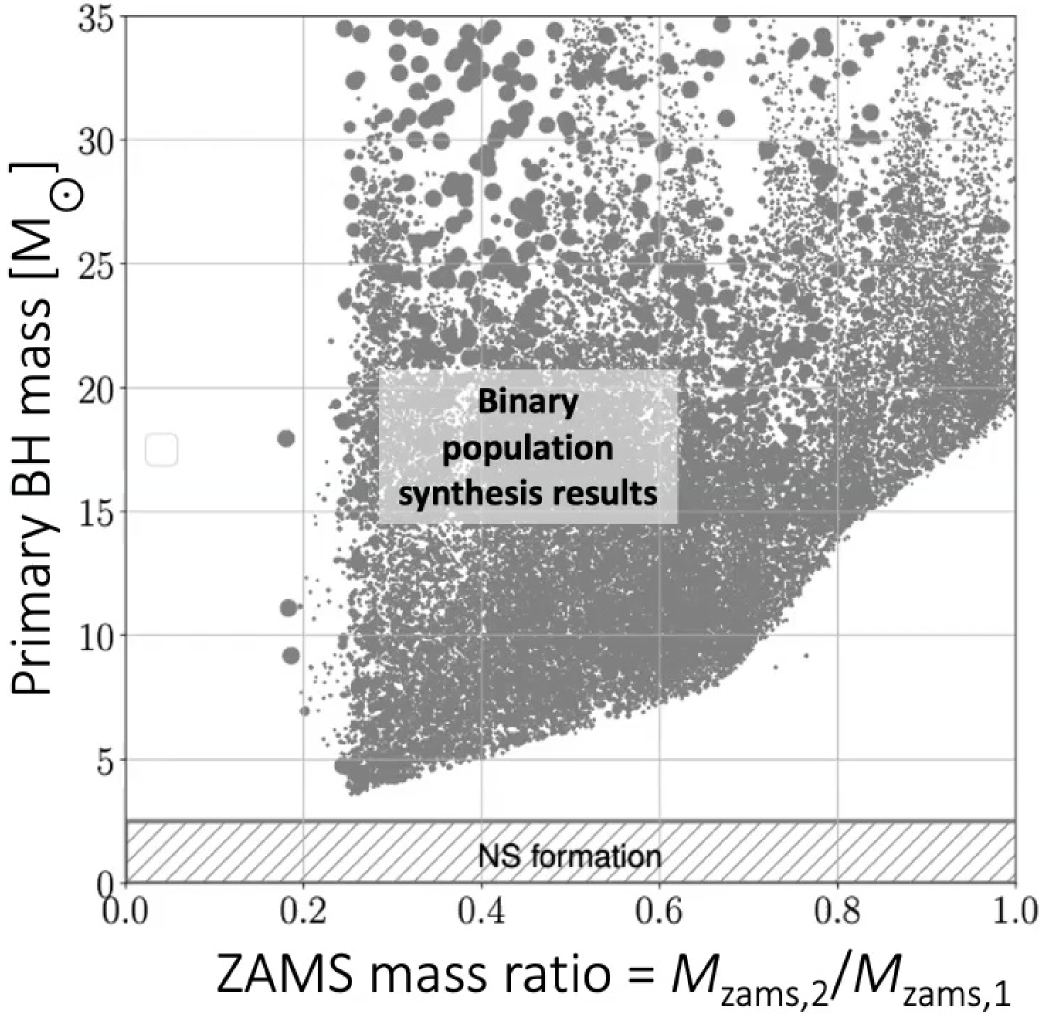

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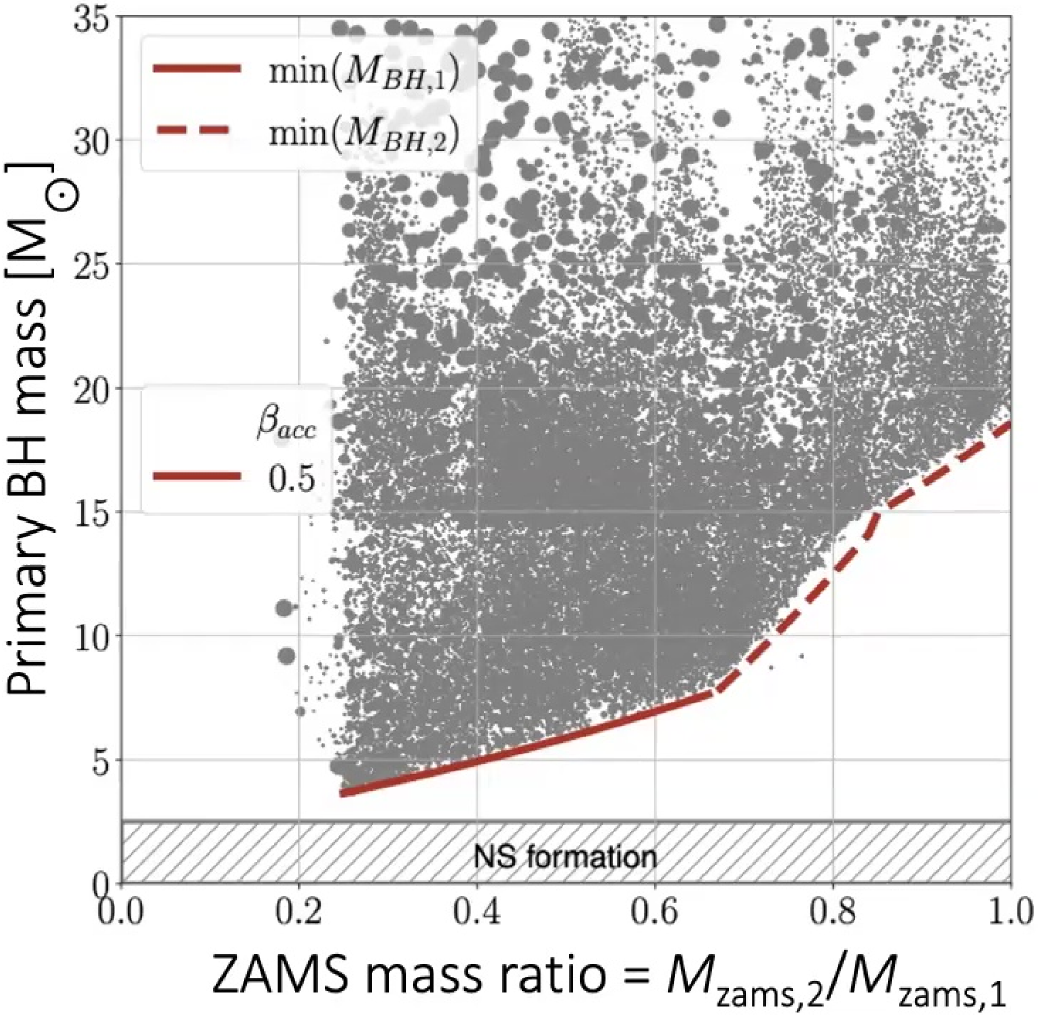

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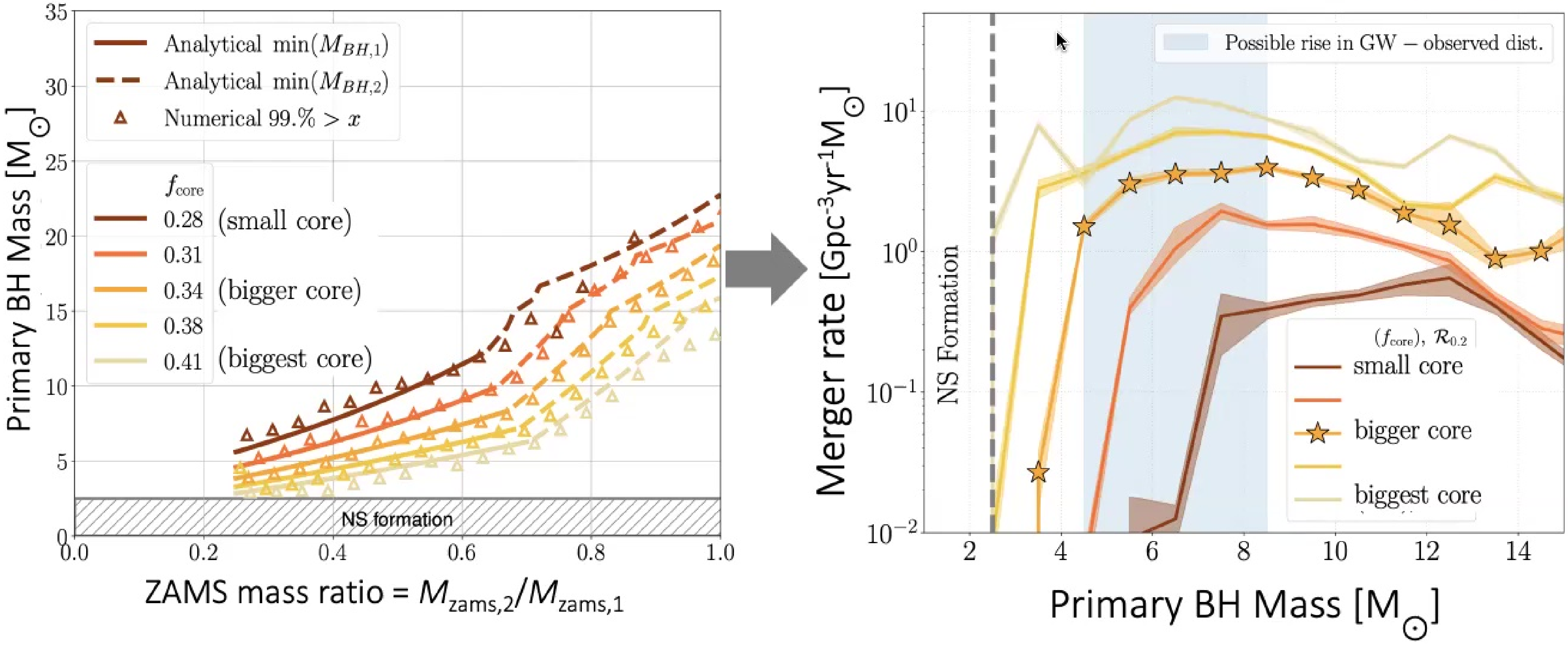
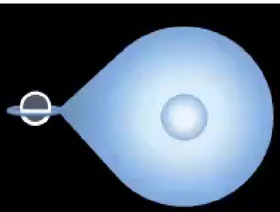
This creates a dearth of low mass BHs without the need for a gap in the remnant mass distribution..!

Variations in core mass fraction

van Son et al. (2022b)





The stable mass transfer channel leads to a **cut-off in the primary mass**

1. causes a lack of low mass BHs
   (could look like "NS-BH mass gap" in the GW inferred mass distribution)

2. determines the location of the peak!

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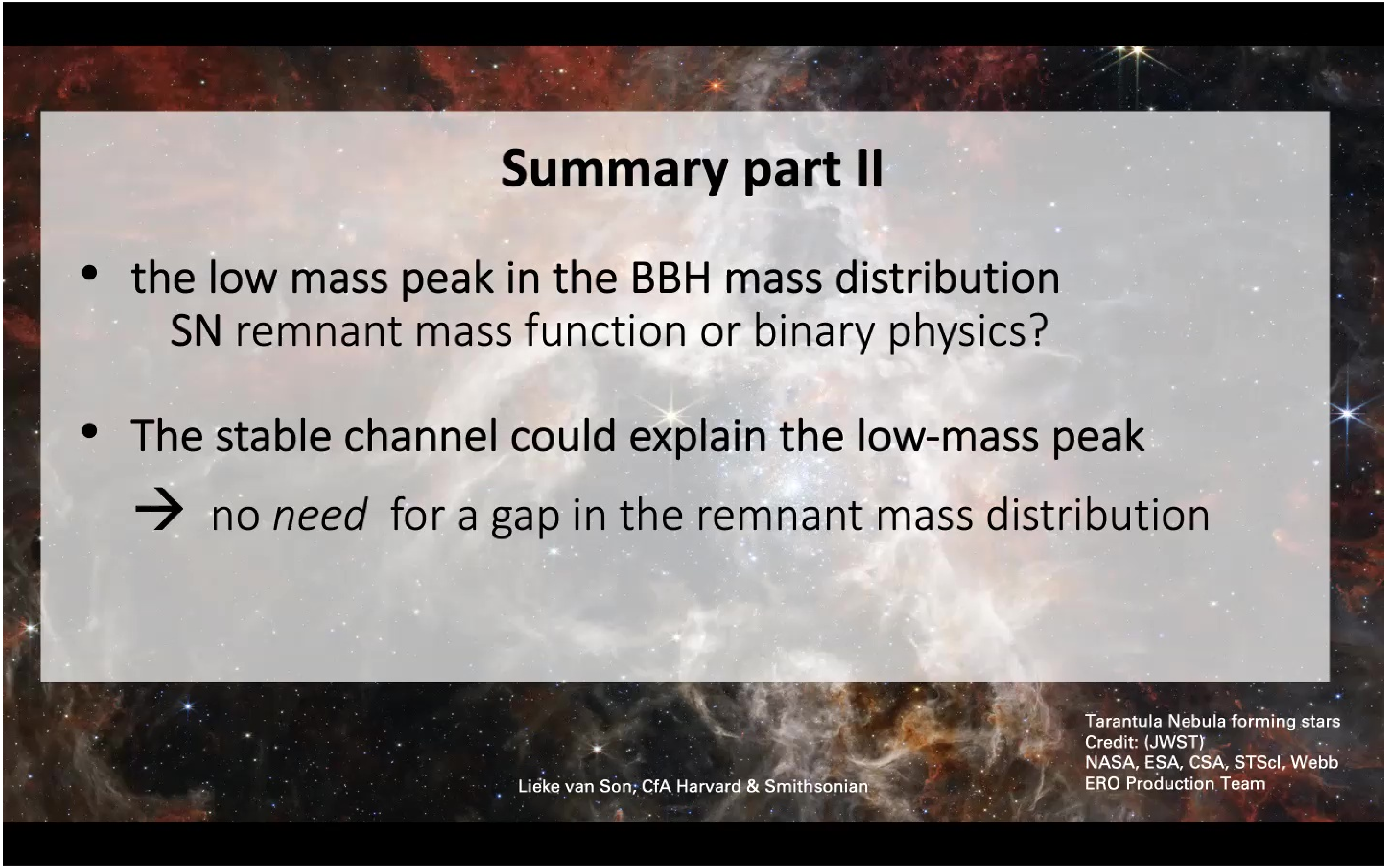

Summary part II

- the low mass peak in the BBH mass distribution
  SN remnant mass function or binary physics?
- The stable channel could explain the low-mass peak
  → no *need* for a gap in the remnant mass distribution

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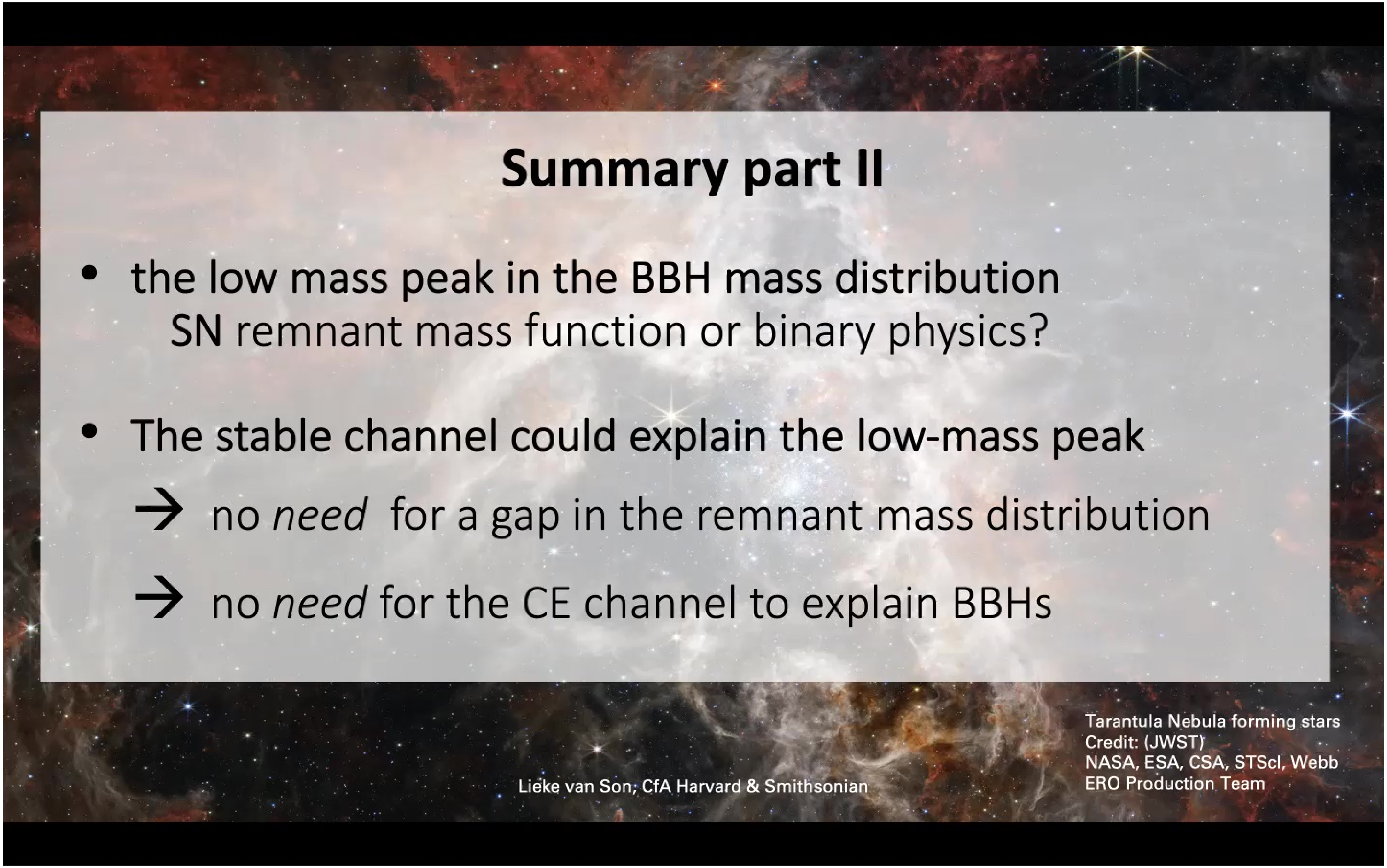
Tarantula Nebula forming stars
Credit: (JWST)
NASA, ESA, CSA, STScI, Webb
ERO Production Team



Summary part II

- the low mass peak in the BBH mass distribution
  SN remnant mass function or binary physics?
- The stable channel could explain the low-mass peak
  → no *need* for a gap in the remnant mass distribution
  → no *need* for the CE channel to explain BBHs

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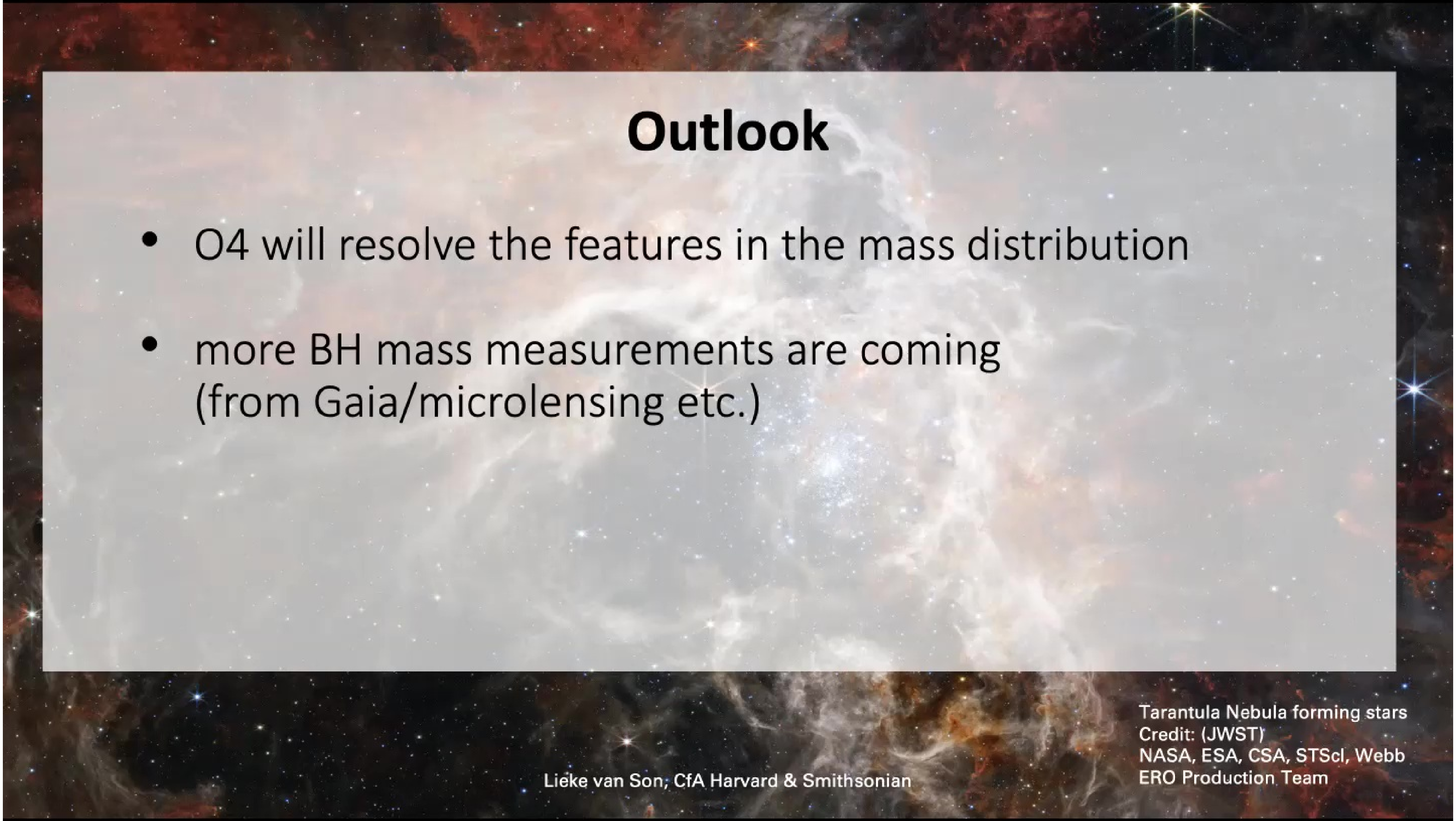

Outlook

- O4 will resolve the features in the mass distribution
- more BH mass measurements are coming
  (from Gaia/microlensing etc.)

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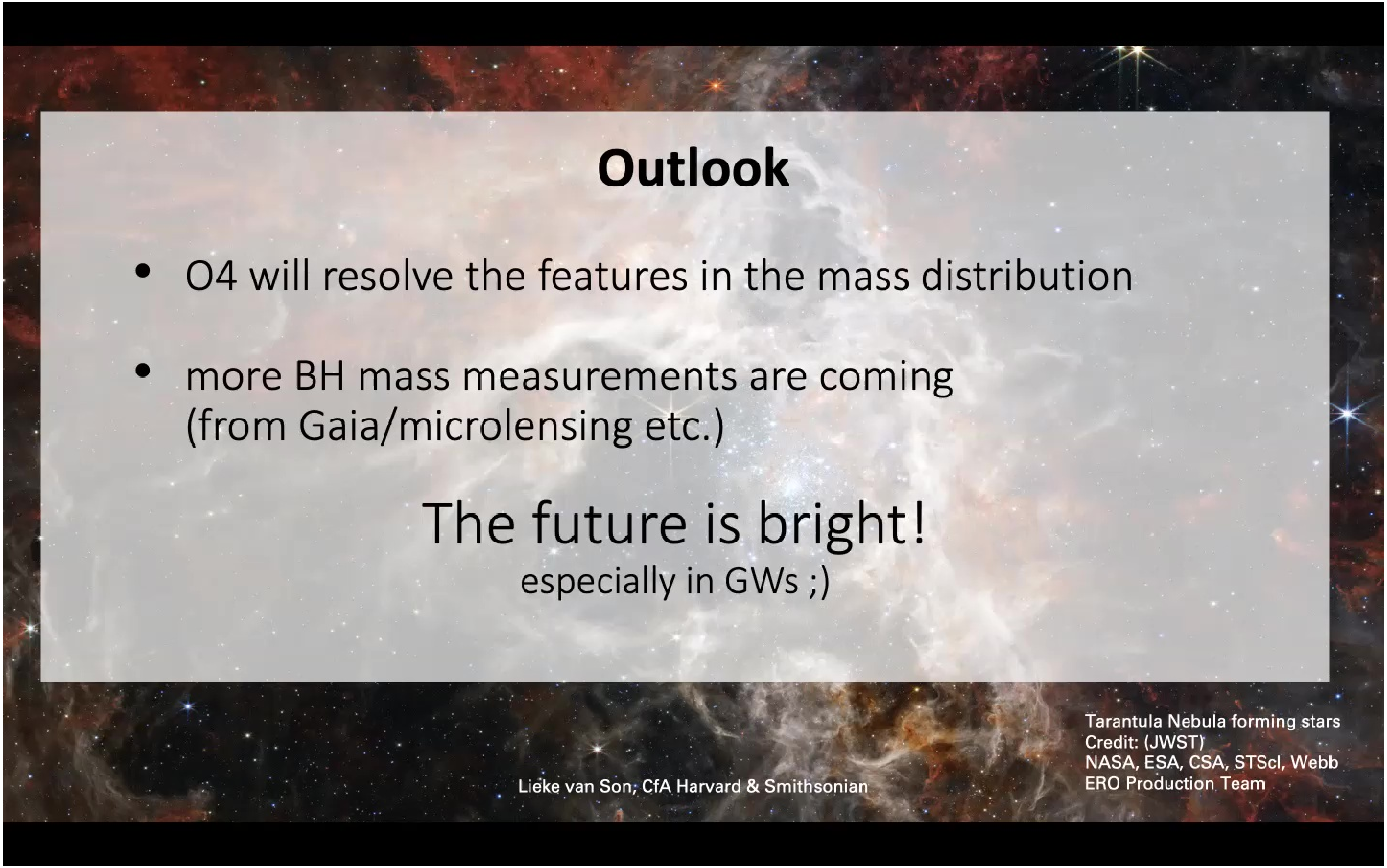

Outlook

- O4 will resolve the features in the mass distribution
- more BH mass measurements are coming
  (from Gaia/microlensing etc.)

The future is bright!
especially in GWs ;)

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