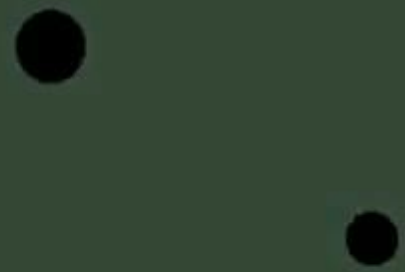
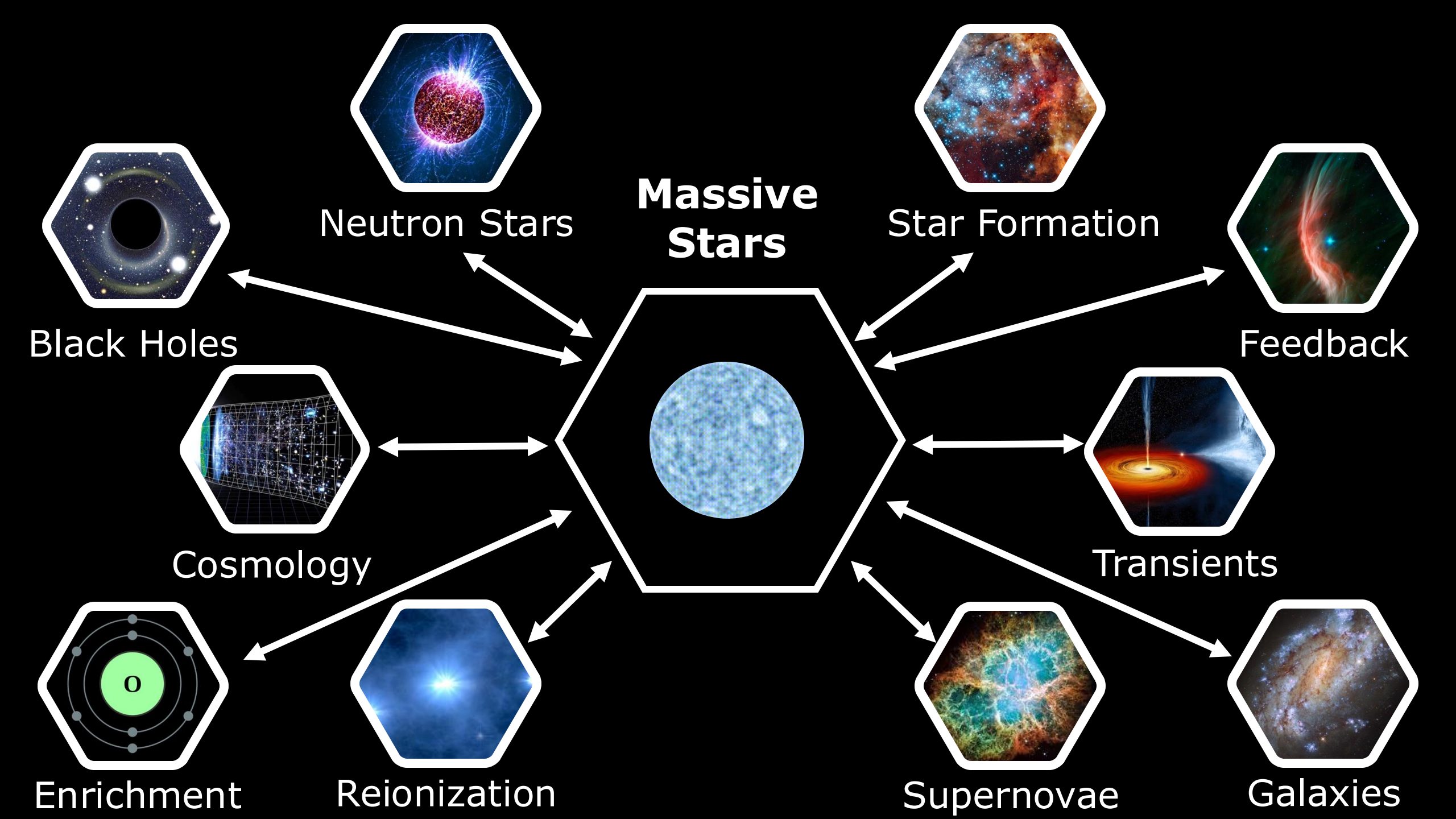
Chasing Cosmic DinoSTARS*: Using Next-Generation GW Detectors To Unravel the Fossil Origins of Compact Object Mergers

Floor Broekgaarden

Assistant Professor, Astronomy & Astrophysics, UC San Diego



* The concept “DinoSTARS” is from Lucas Ellerbroek’s son


Massive Stars
Neutron Stars
Star Formation
Black Holes
Feedback
Cosmology
Transients
O
Enrichment
Reionization
Supernovae
Galaxies

It is challenging to observe a statistically significant population of Massive Stars…

- Massive stars live fast and die young

  Kippenhanh & Weigert (1990):

$$\tau_* \propto M^{-2.8}$$

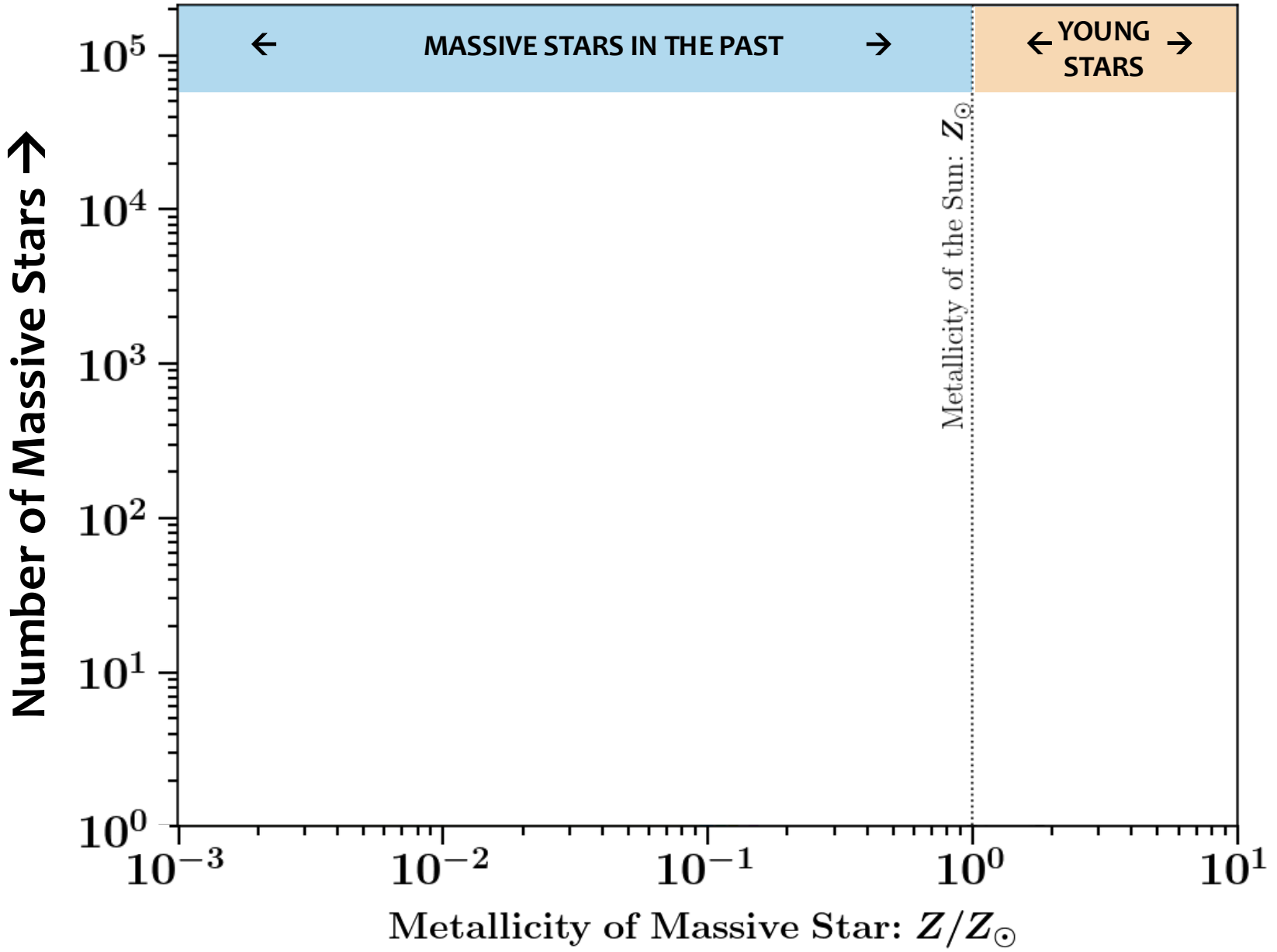
- Massive stars are rare

  Salpeter IMF (1955):

$$p(M) \propto M^{-2.3}$$

Cartoon: Getty Images/iStockphoto

Massive stars we can study in detail*



(billion years) ← Time in the Past

* e.g. measure masses

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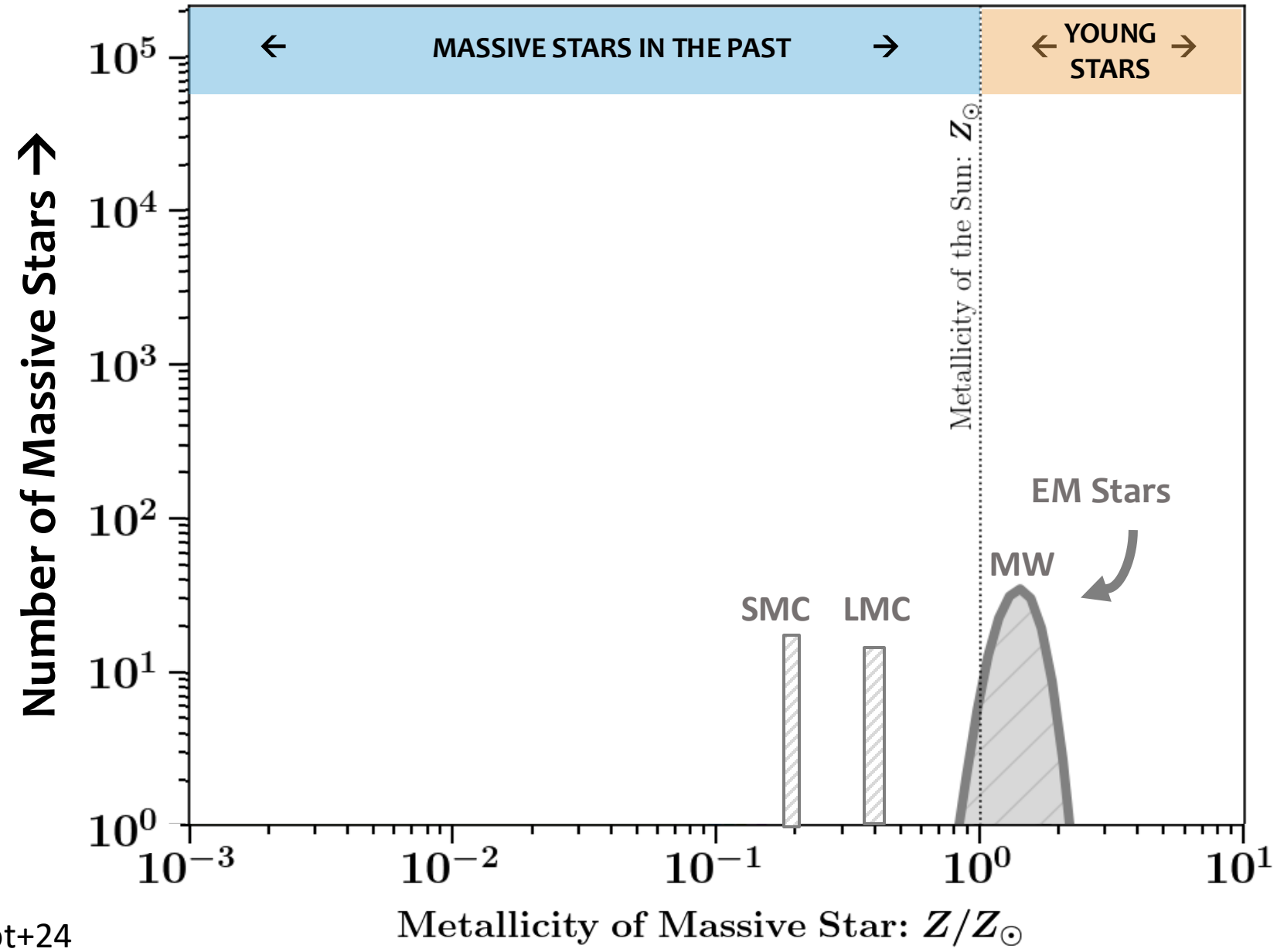

SMC: BloEm Survey (Shenar+25)
Gaia Collaboration, El-Badry+24, Balbinot+24

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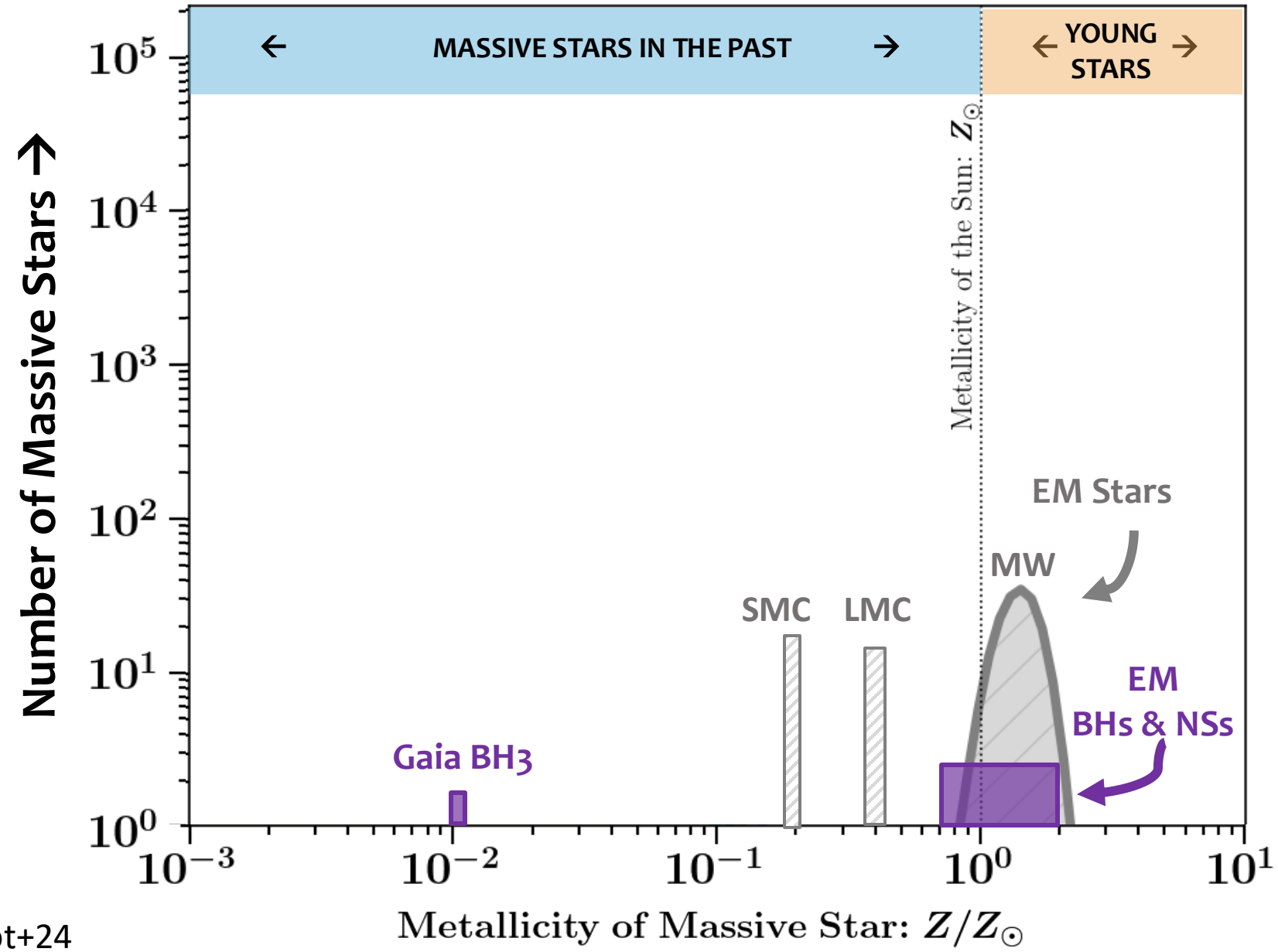

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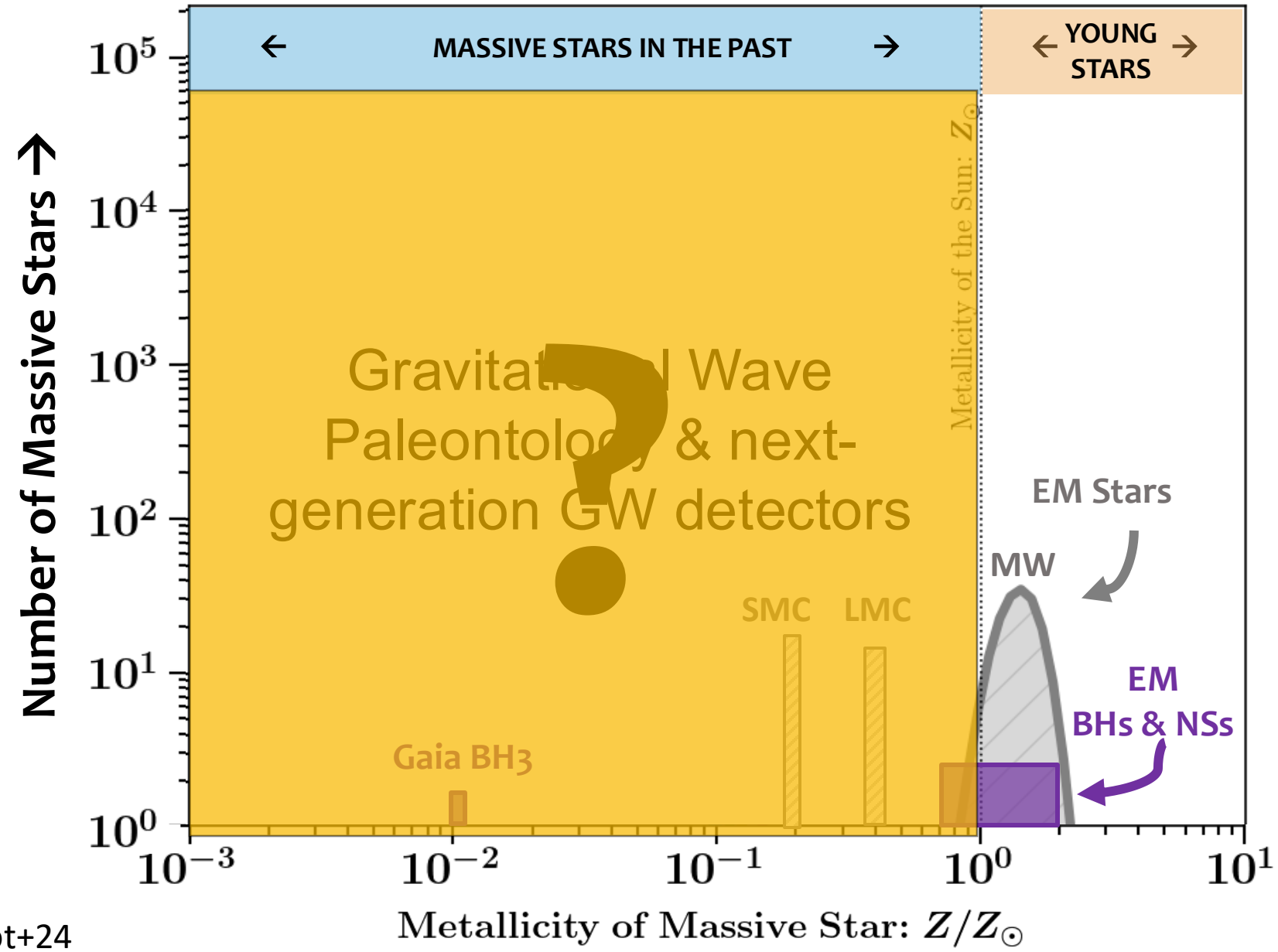

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Gravitational Wave Paleontology & next-generation GW detectors

Are poised to change our understanding of massive stars across cosmic time!

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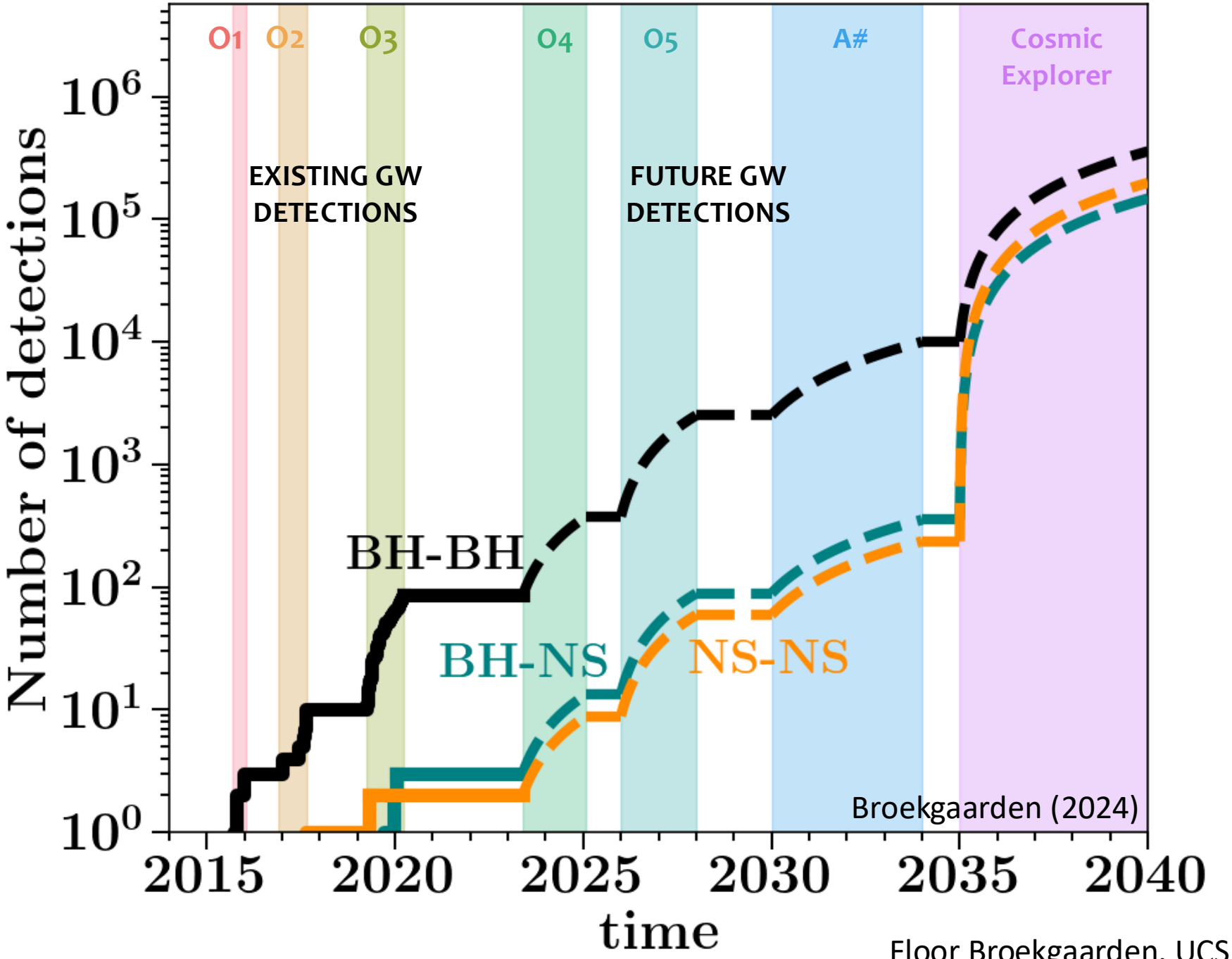
1) The Number of detected Gravitational-Wave Sources is rapidly increasing

Cosmic Explorer (& Einstein Telescope) numbers based on: Gupta+24, Gupta+23, Ronchini+22, Iacovelli+22, Borhanian & Sathyaprakash+22, Baibhav+19



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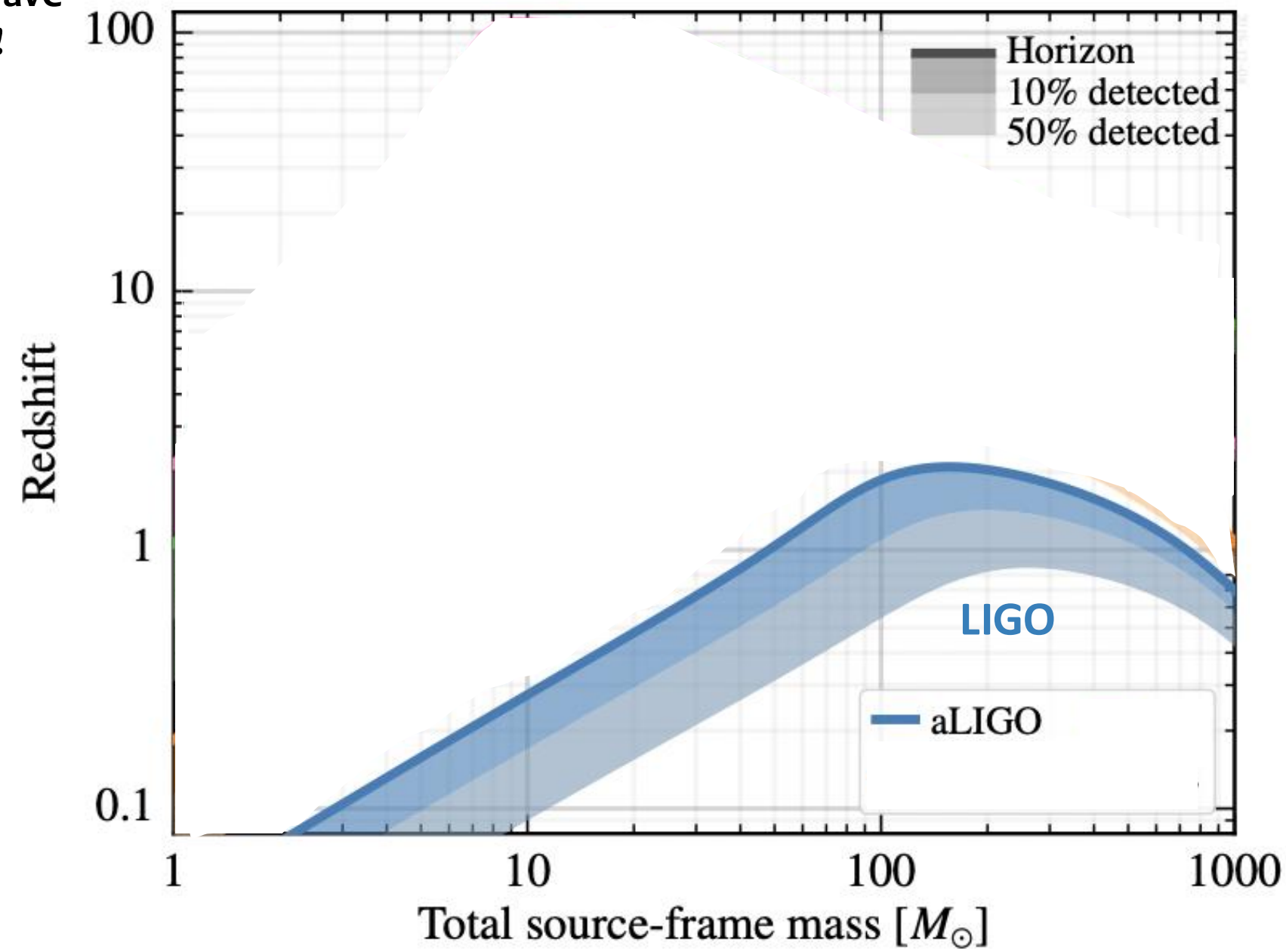
2) We will detect Gravitational-Wave Sources across vast Cosmic Time!

e.g. Hall & Evans +19, Evans +21, but see also Gupta+24, Gupta+23, Ronchini+22, Iacovelli+22, Borhanian & Sathyaprakash+22, Baibhav+19

From Hall & Evans (2019)



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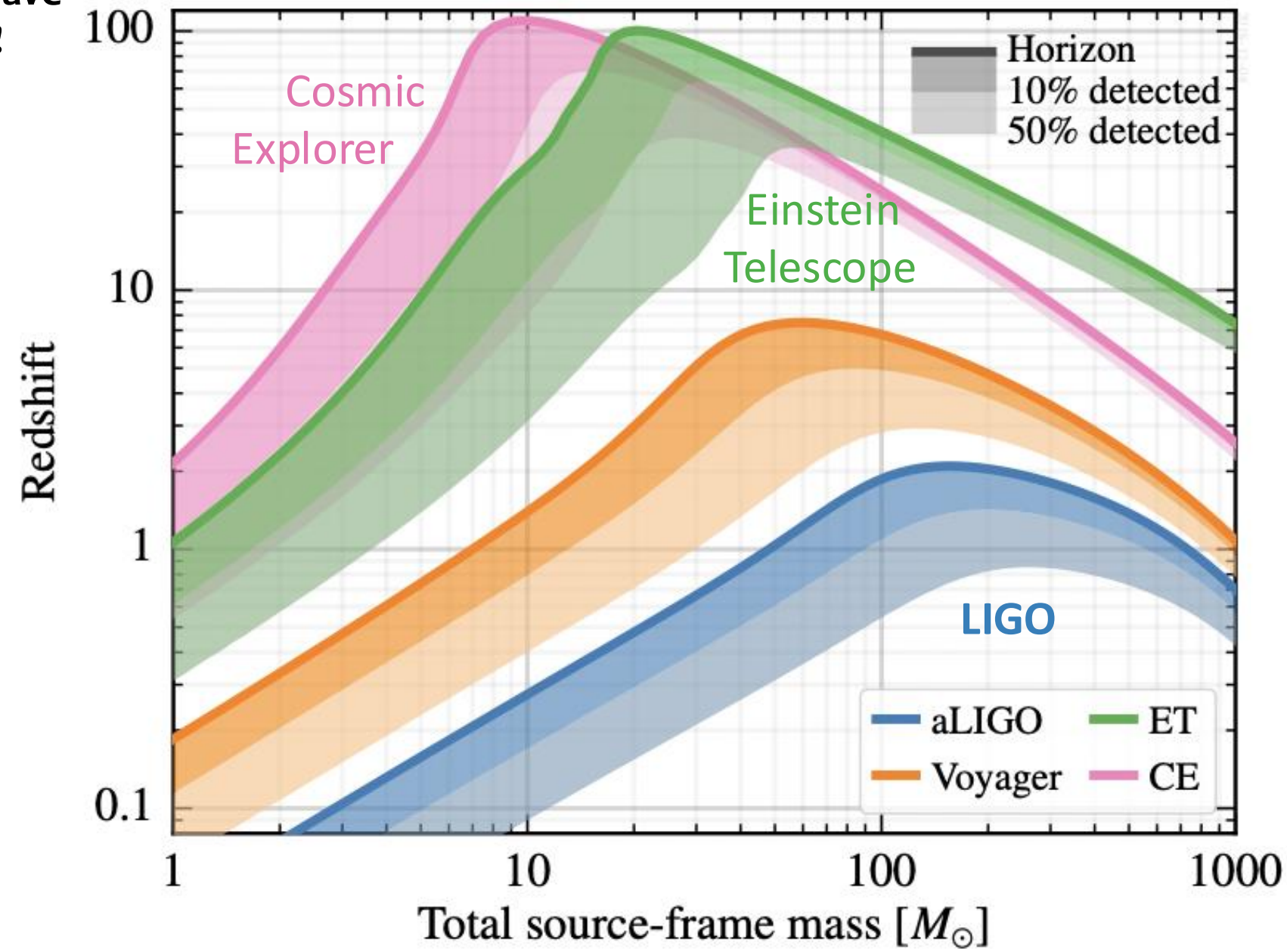
We might see *every* merging stellar mass BH-BH in the Universe!

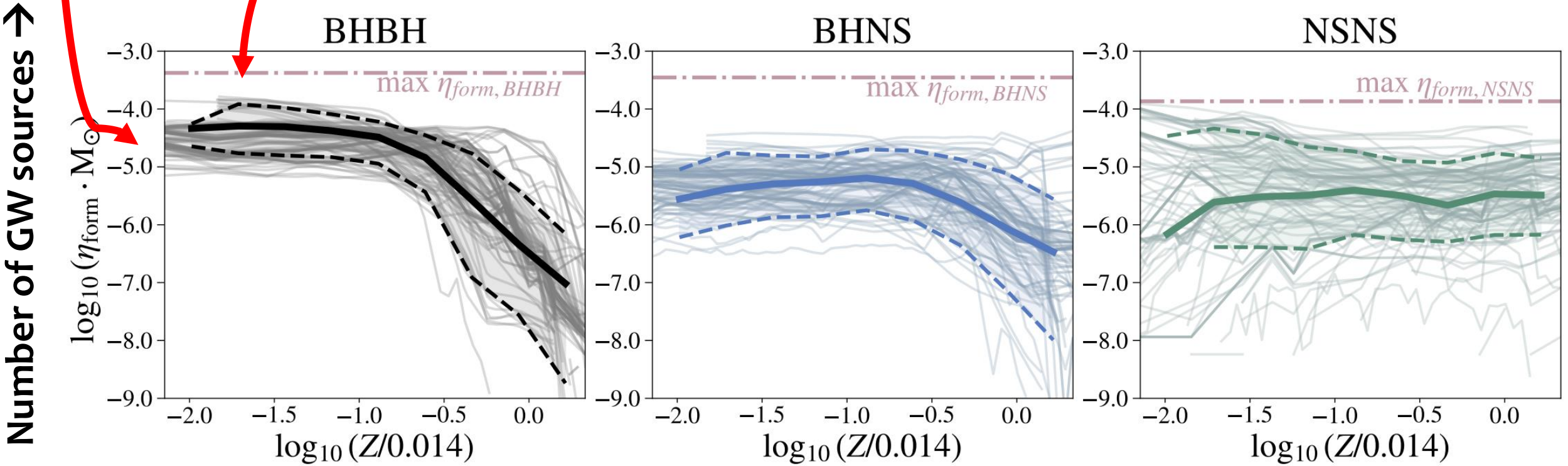
From Hall & Evans (2019)



3) Formation of stellar-mass GW sources - especially BBHs - is often significantly boosted at lower metallicity (higher redshift)

Figure from Van Son +25 (based on earlier work from Iorio+24)

See Giacobbo & Mapelli 2018; Klencki+2018; Neijssel+2019; Spera+19, Santoliquido+2021; Broekgaarden+2022,2023; Iorio et al. 2023, Chruslinska+23, Smith+25, van Son+25,



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4) Many formation channels produce (a subset of systems with) long delay times of several Gyr

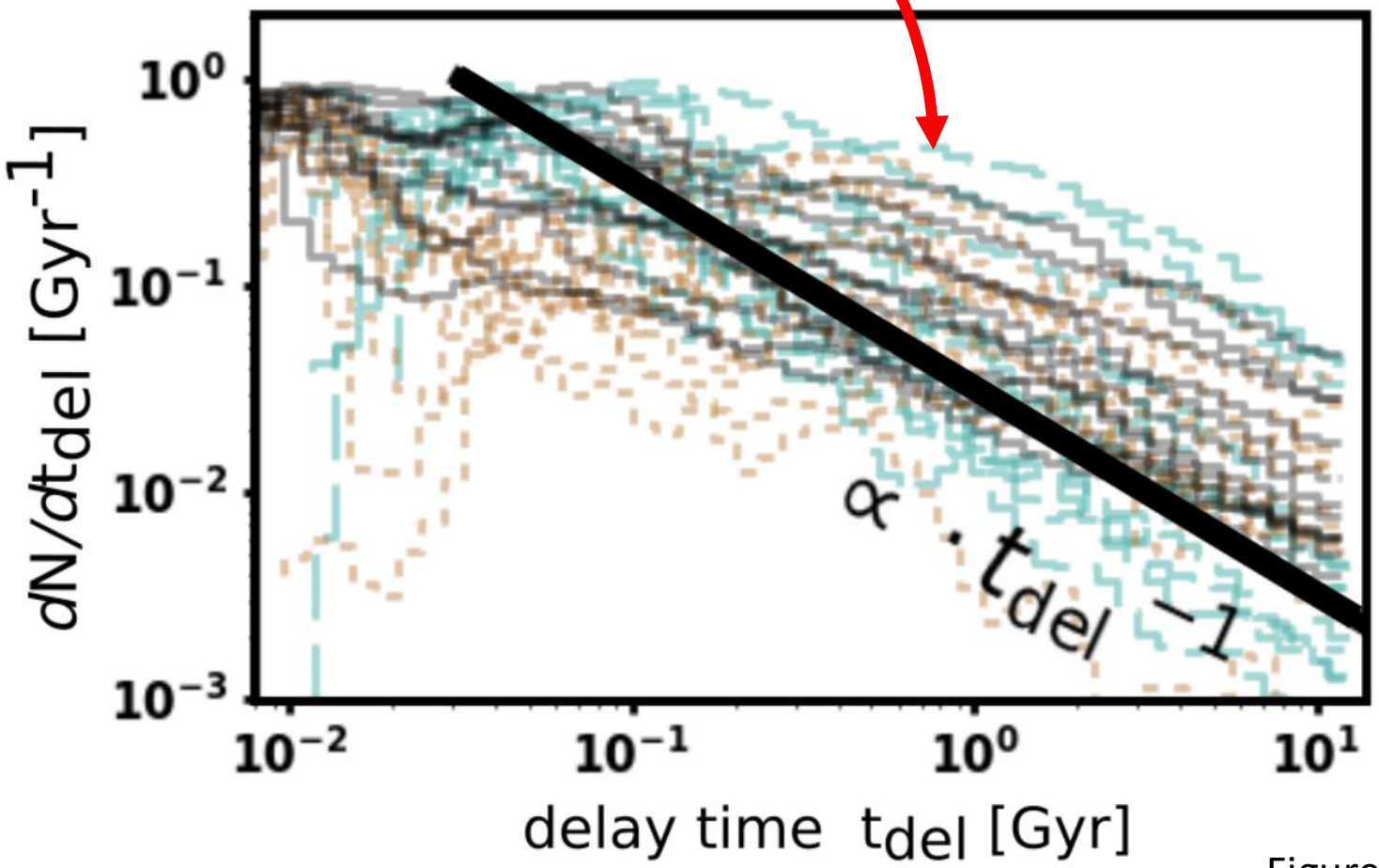
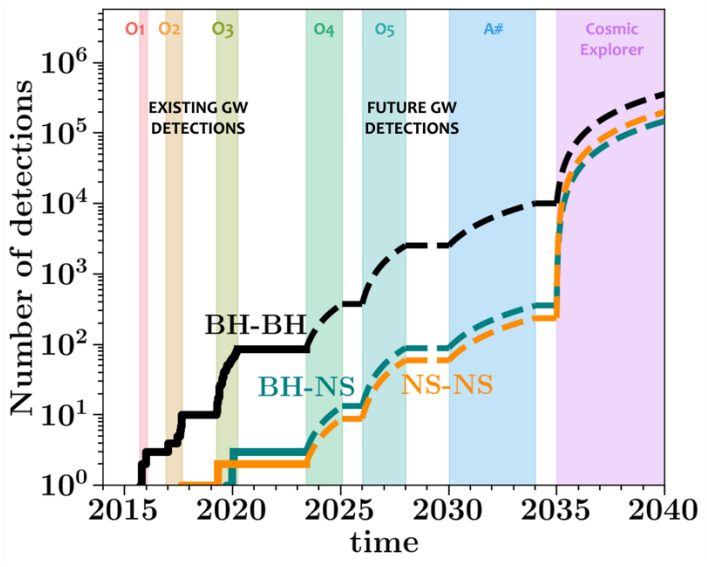
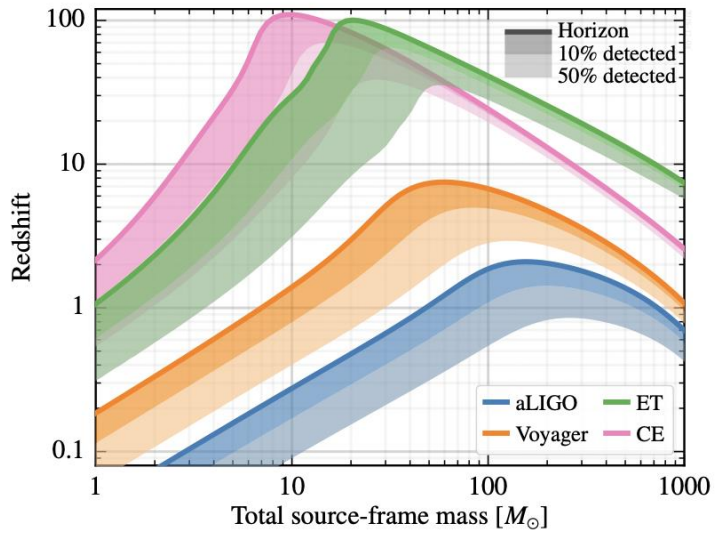


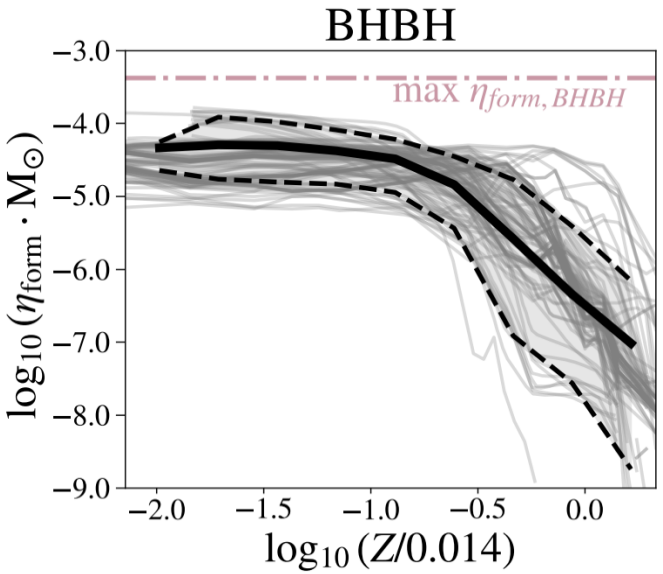
Figure from "The Science of the Einstein Telescope"+25

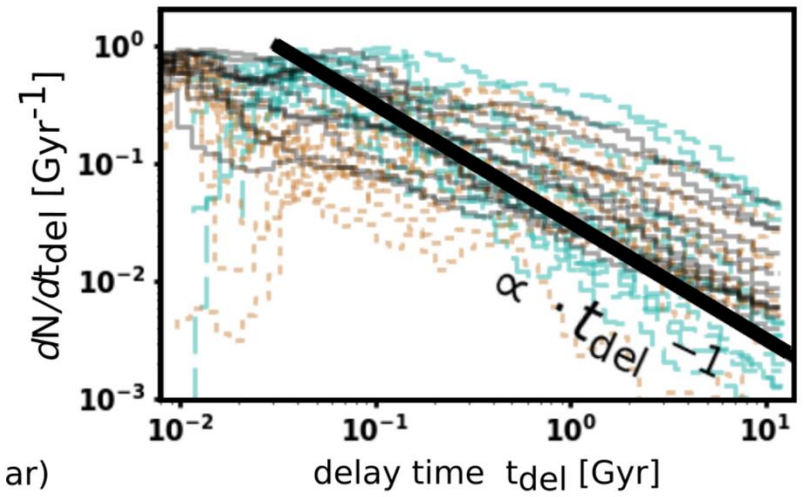
Combined, this means that GW detections - even "local" ones - already probe massive stars* across vast cosmic times & metallicities!

See e.g. Chruslinska+22, Fishbach+23,+24



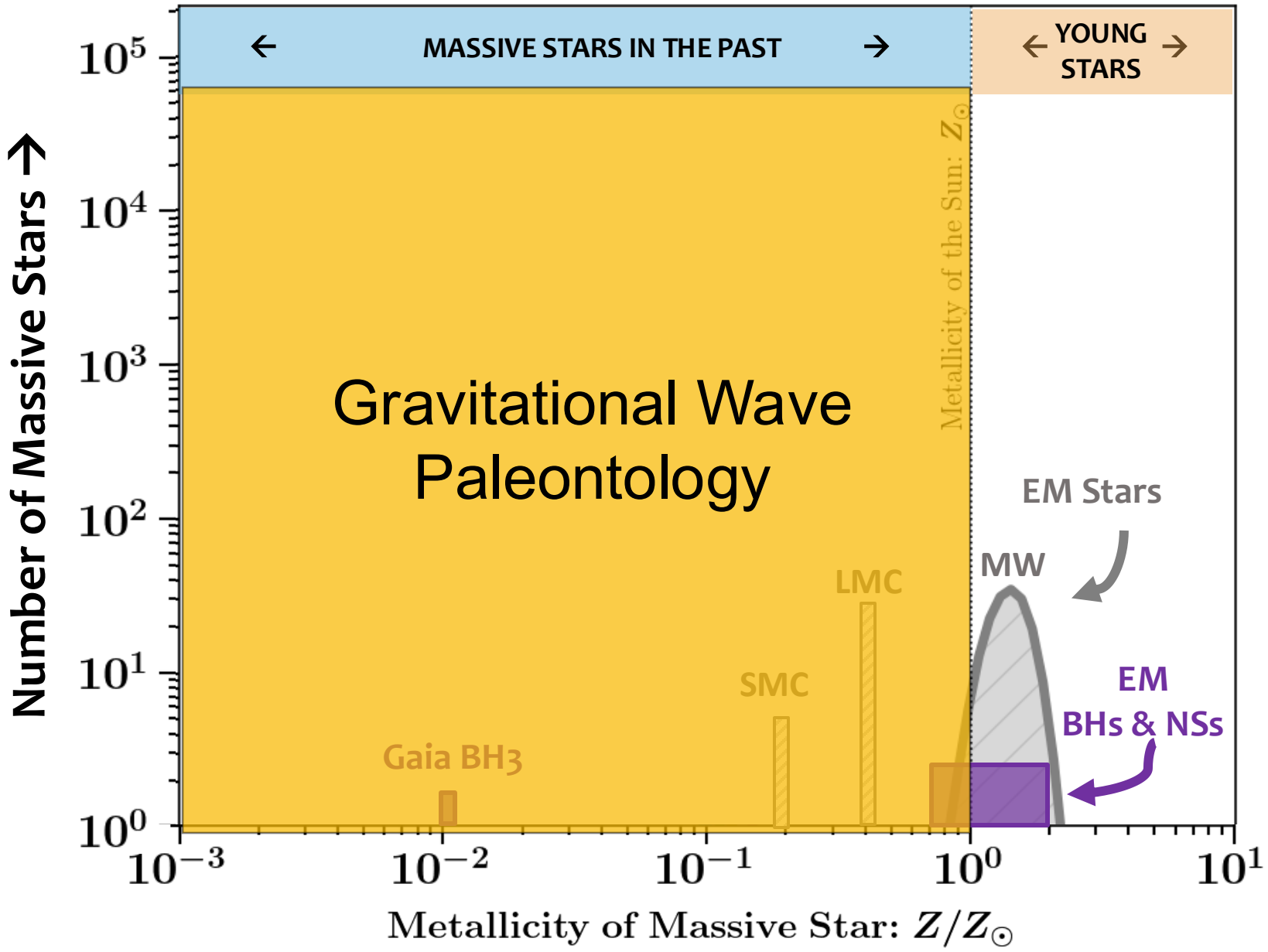






*or more generally: progenitors of GW sources

Massive stars we can study in detail*



(billion years) ← Time in the Past

* e.g. measure masses

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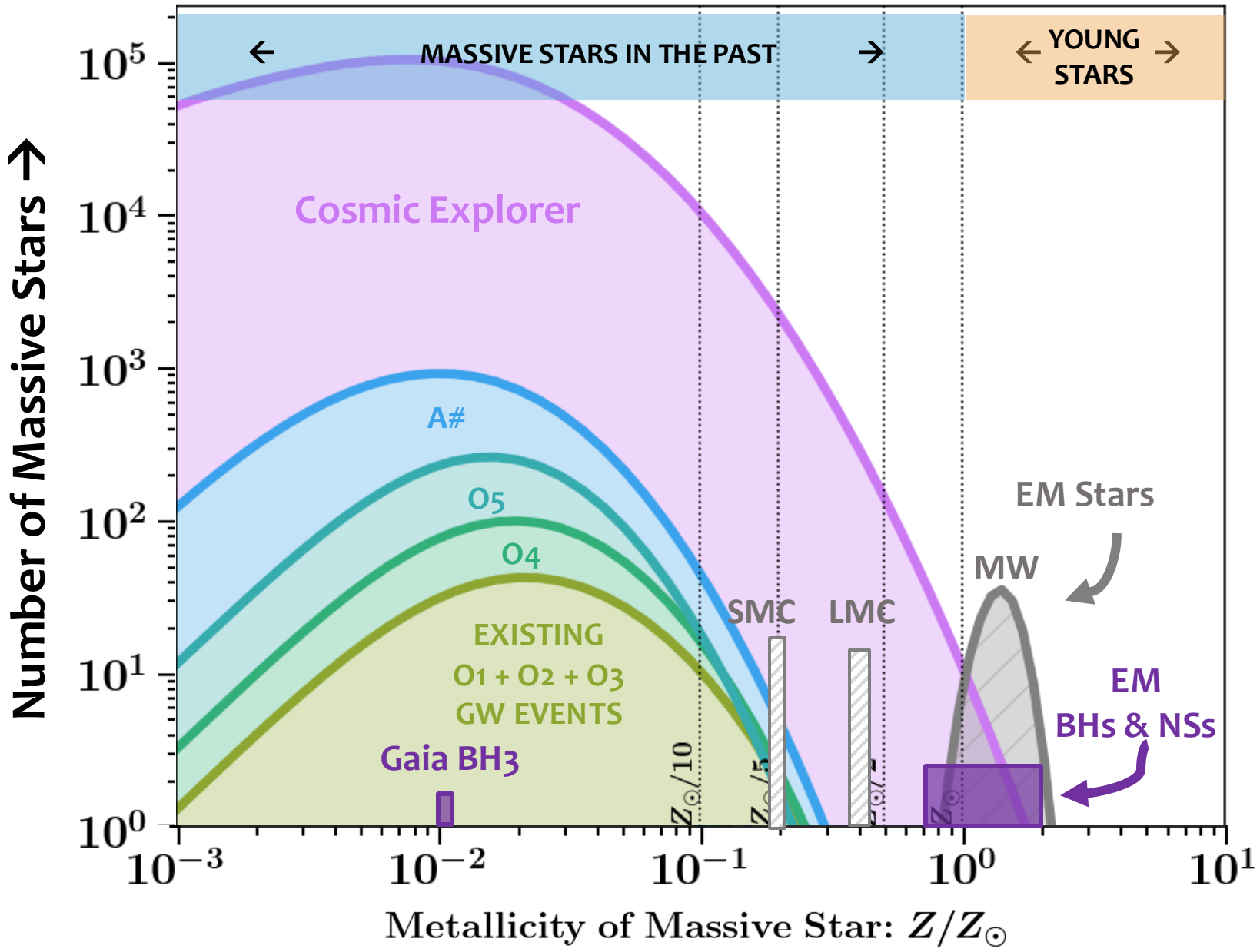
Massive stars we can study in detail*

Cosmic Explorer:
"a unique instrument to study massive stars across cosmic time for $100/star" ***if*** **we can connect GW sources to formation pathway histories**



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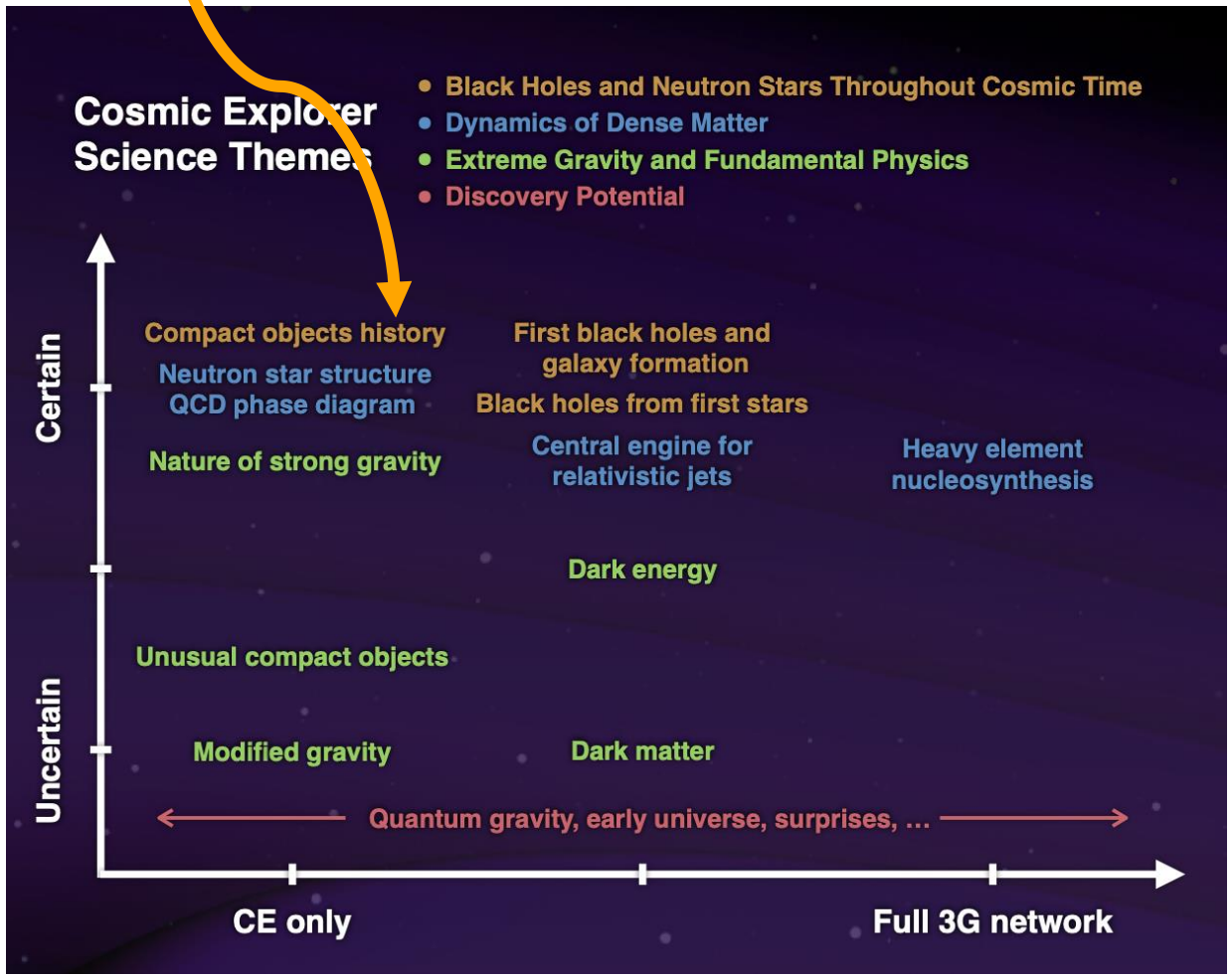
Should we add **"Exploring Massive Stars" / "Gravitational Wave Paleontology" more explicit to CE Science Case?**

- low metallicity star formation - lives of massive stars - deaths of massive stars



Figures from Evans+21 (Cosmic Explorer Book)

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This endeavor & ambition comes with a big *if:*

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Cosmic Explorer:
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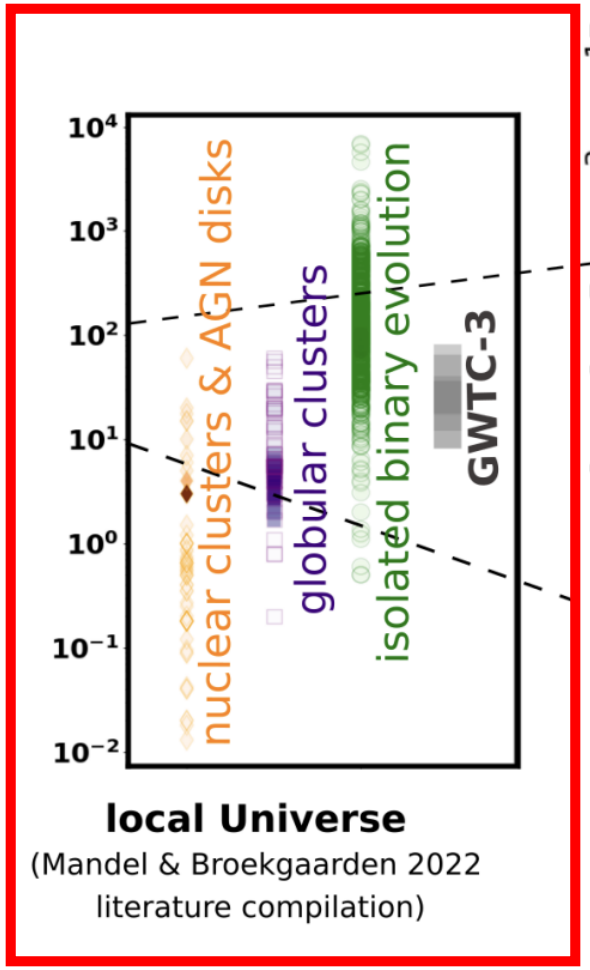
We learned in 2022: Formation Channels are uncertain!
(Rates alone cannot constrain channels)



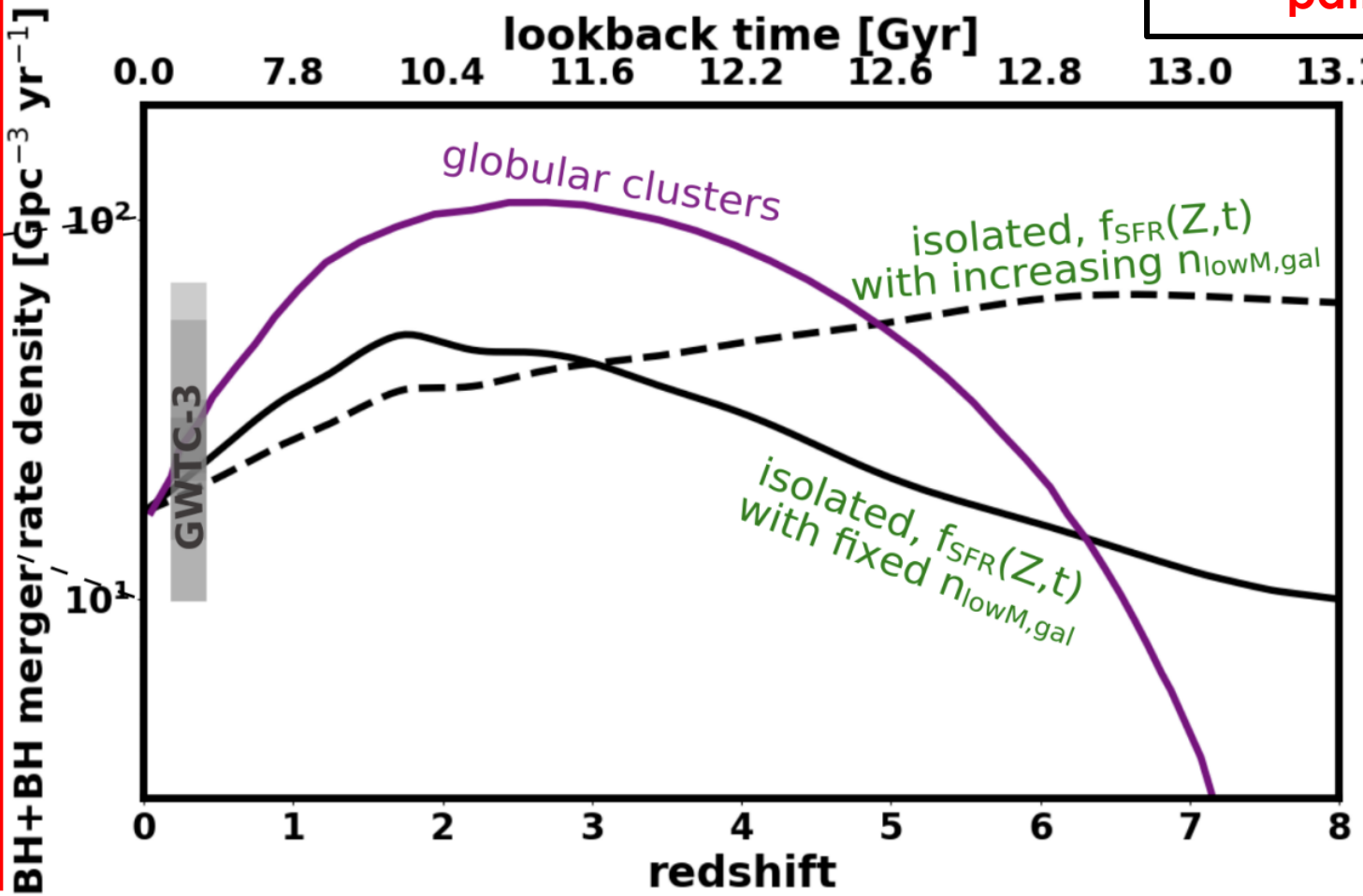


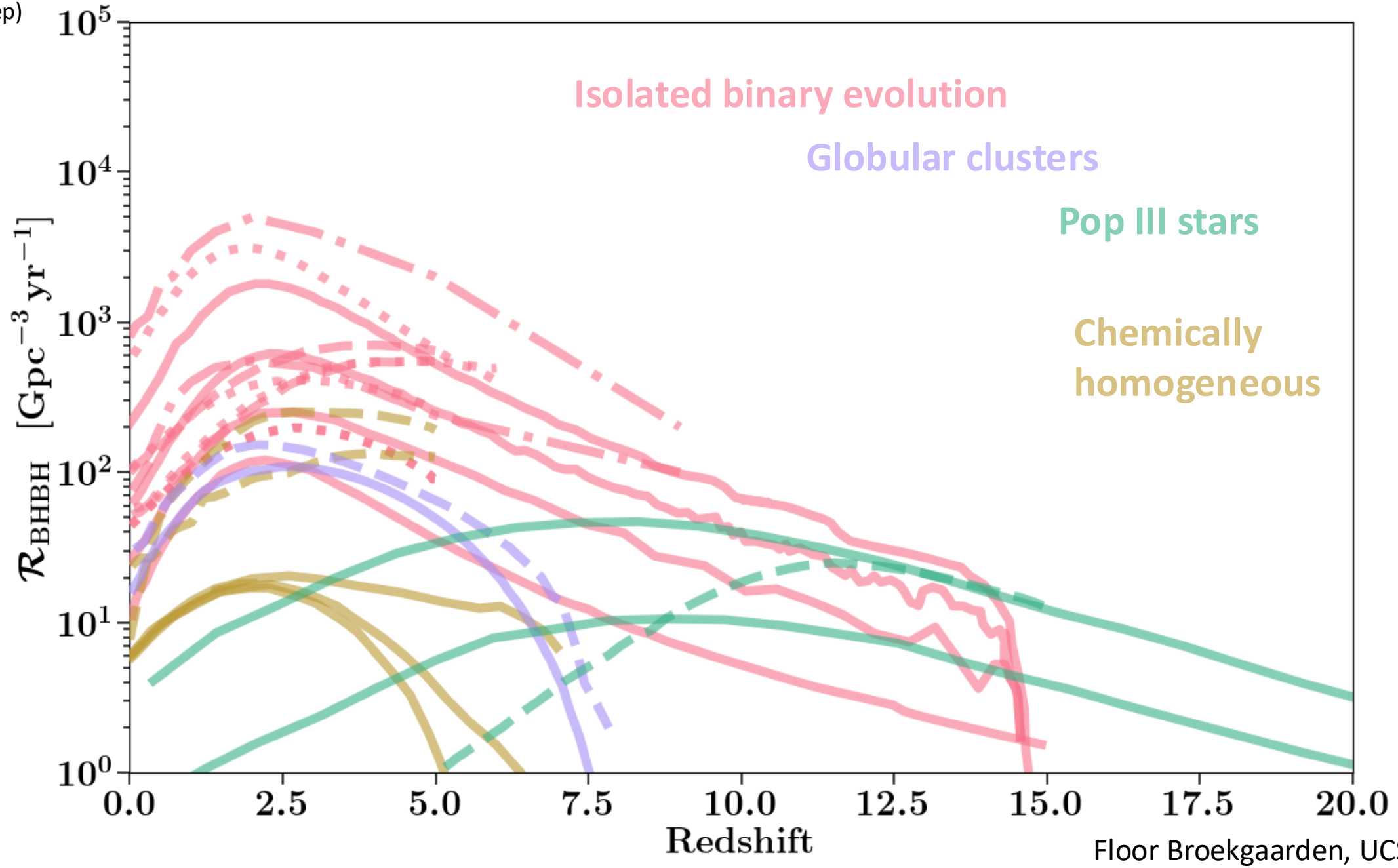
Figure from "The Science of the Einstein Telescope"+25

Gravitational Wave Paleontology today

But there's a lot of hope & progress! *Because it will be a game-changer!*

Redshift dependent rates

Broekgaarden (in prep)



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What causes features in the BBH distributions?

Star formation history artifact (Levina+in prep.)

Stable mass transfer channel? (van Son+24)

Globular Clusters?

Model uncertainty?

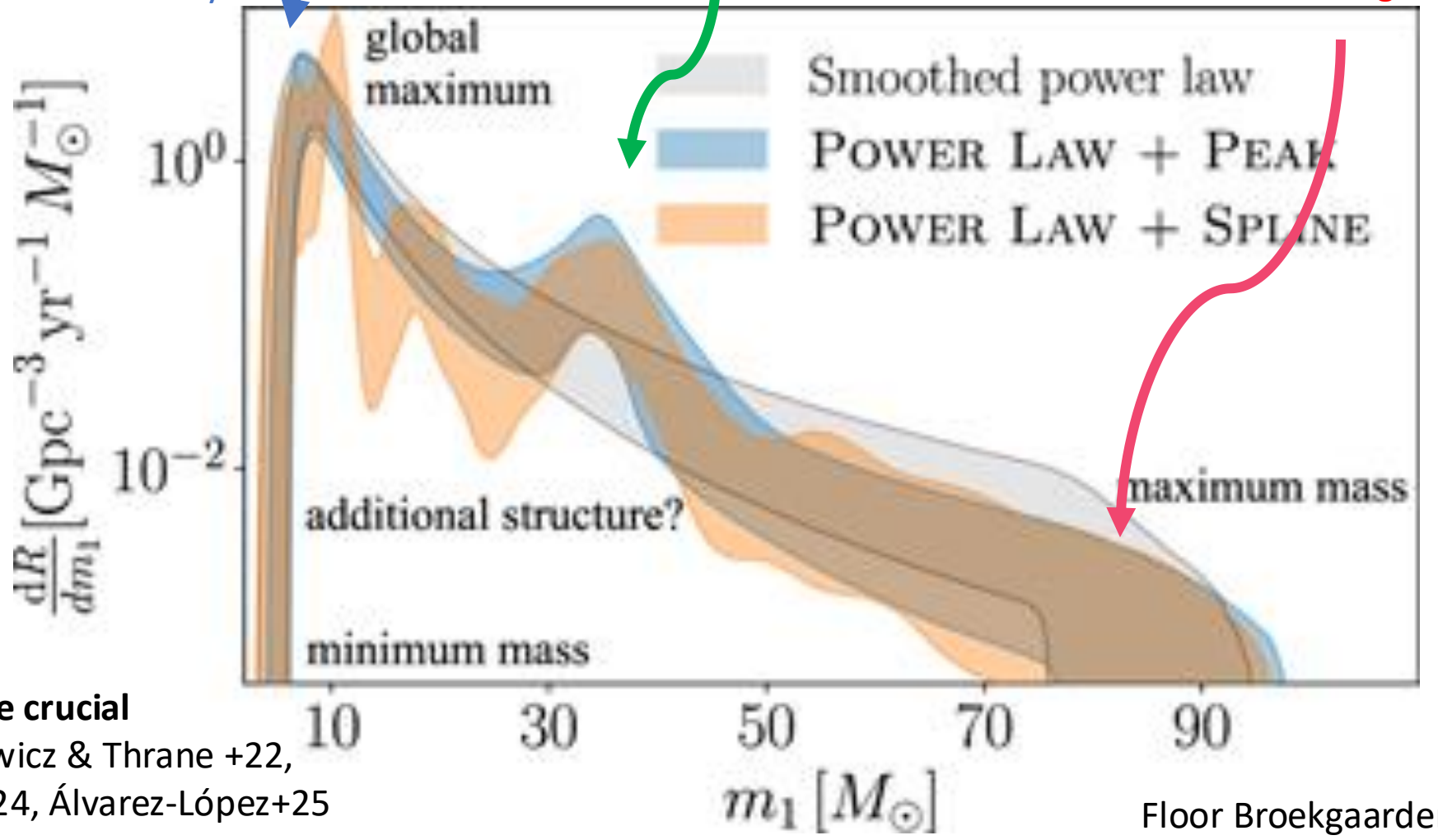
Chemically Homogeneous Channel? (de Sa in prep.)

Stable Mass Transfer? (Briel+24)

Pair instability Supernova?

Globular Clusters? AGN?
Hierarchical mergers?

See Einstein Telescope & Cosmic Explorer Blue Book & References therein



Parameter correlations will be crucial

e.g. Callister+21+24, Adamcewicz & Thrane +22, Heinzel, Biscoveanu, Vitale +24, Álvarez-López+25

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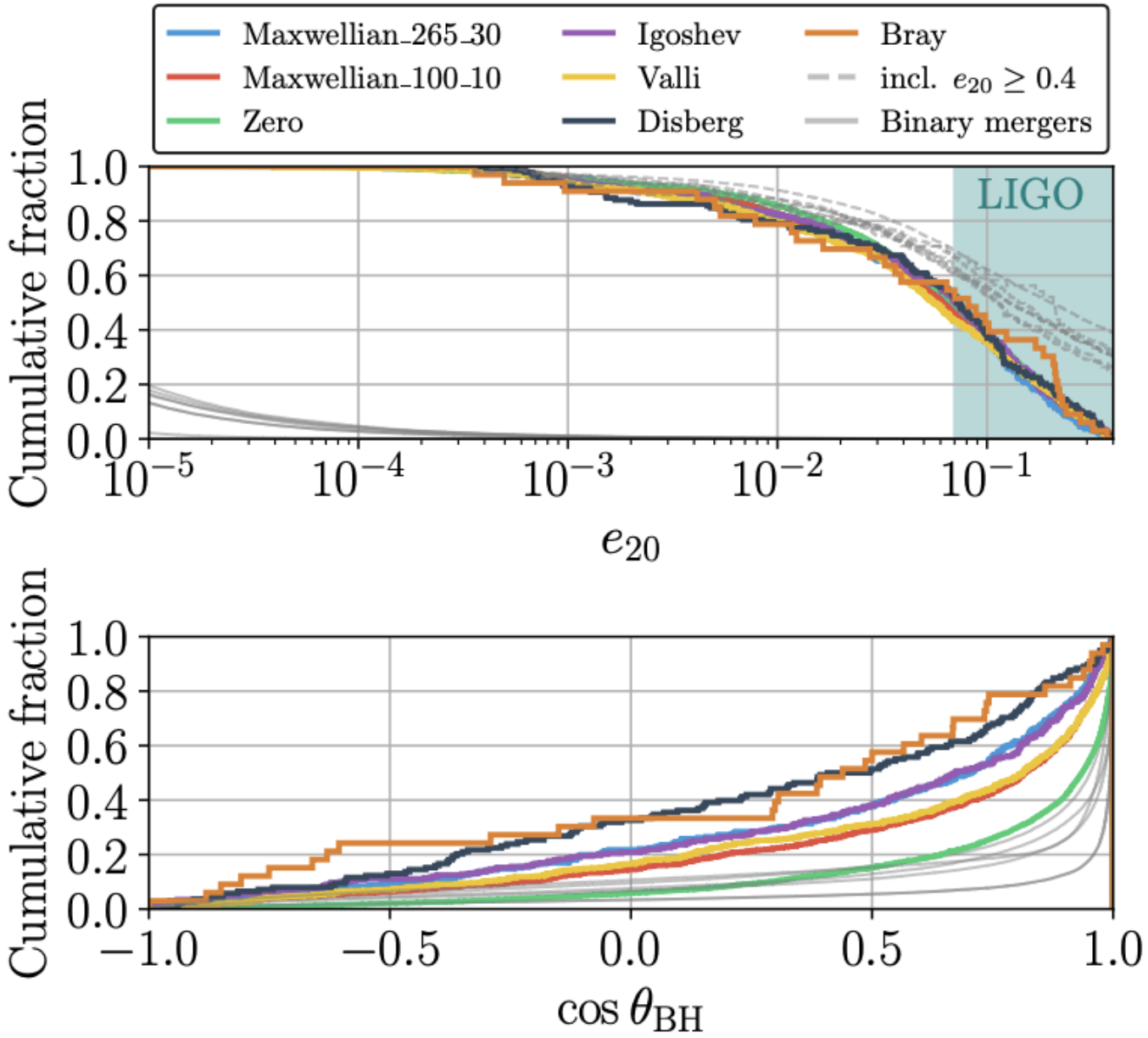
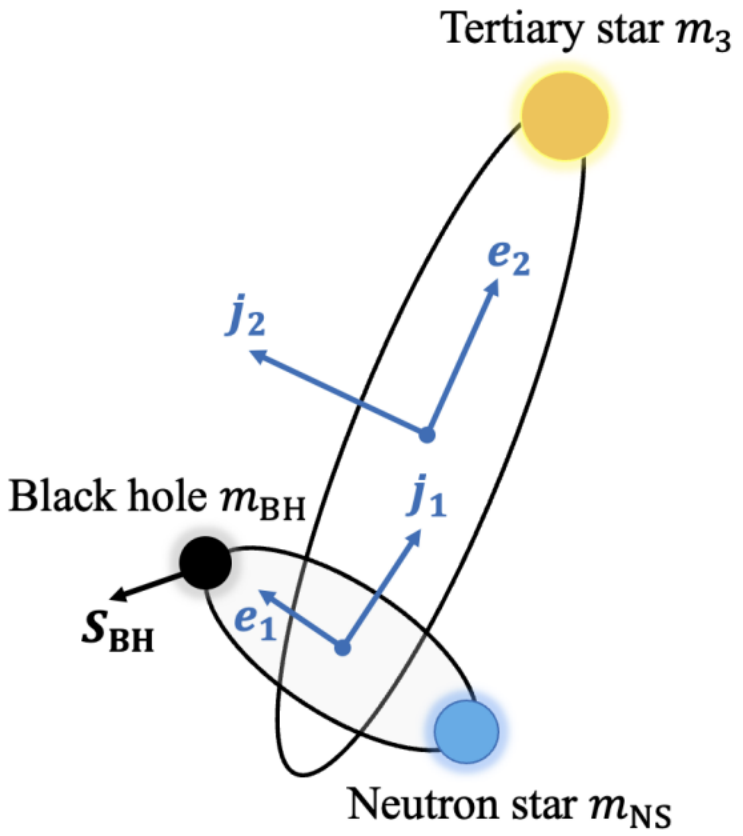
Triples might explain large BH spin-orbit misalignment observed in NSBH (and produce eccentric events)

Stegman & Klencki 2025





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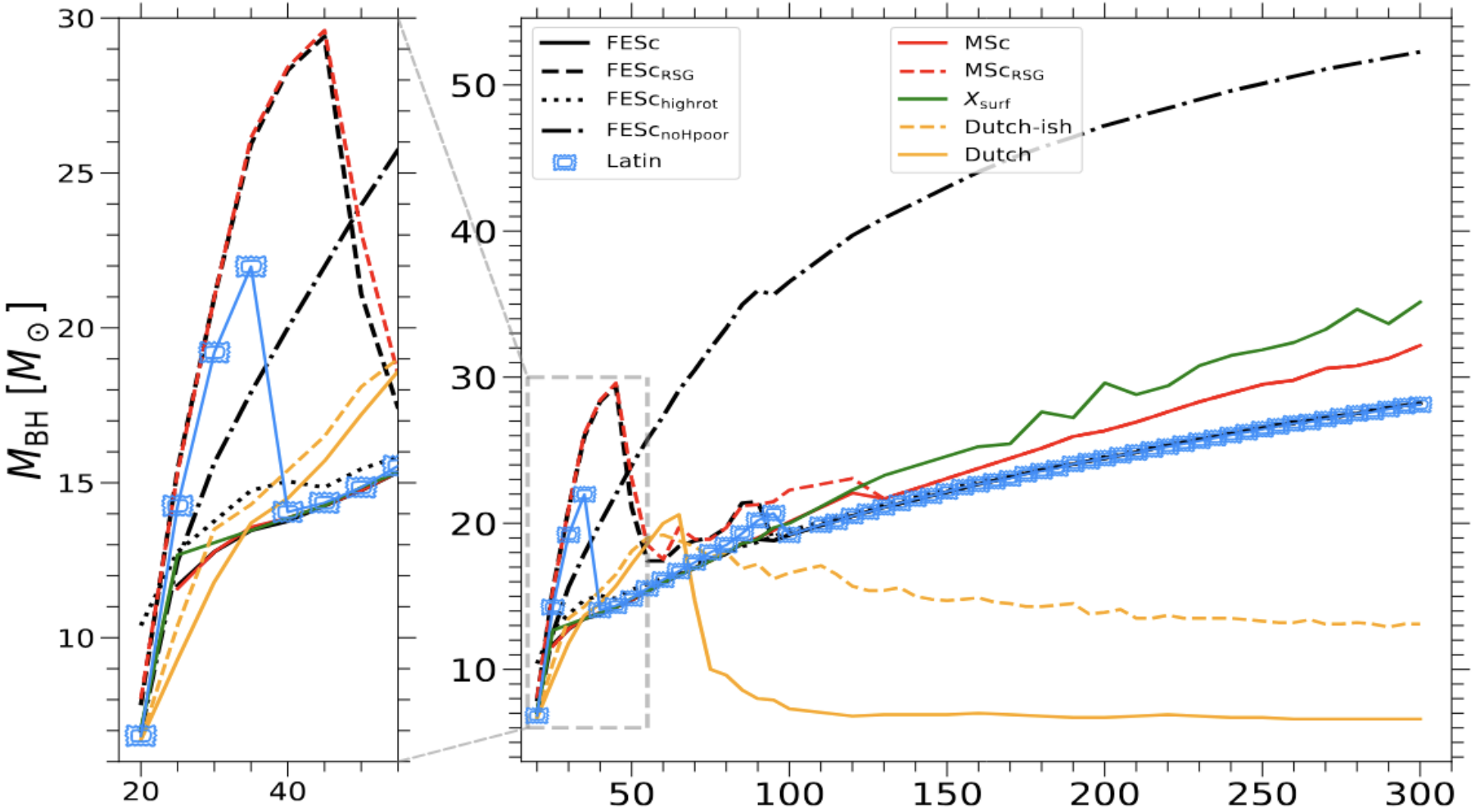
We are improving our models & Physics !

New Supernovae & SN kick insights (e.g. Valli+25, Disberg+25), **new/updated models: KRIOS** (Tep+25), **POSYDON** (Fraggos+24**), SEVN** (Ioro+24)

Amedeo Romagnolo

How stellar winds impact BH masses: Romagnolo+25,



These are simulations at solar metallicity

Initial mass stars →

Gravitational Wave Paleontology

Today

Future

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Massive stars we can study in detail*

Cosmic Explorer:
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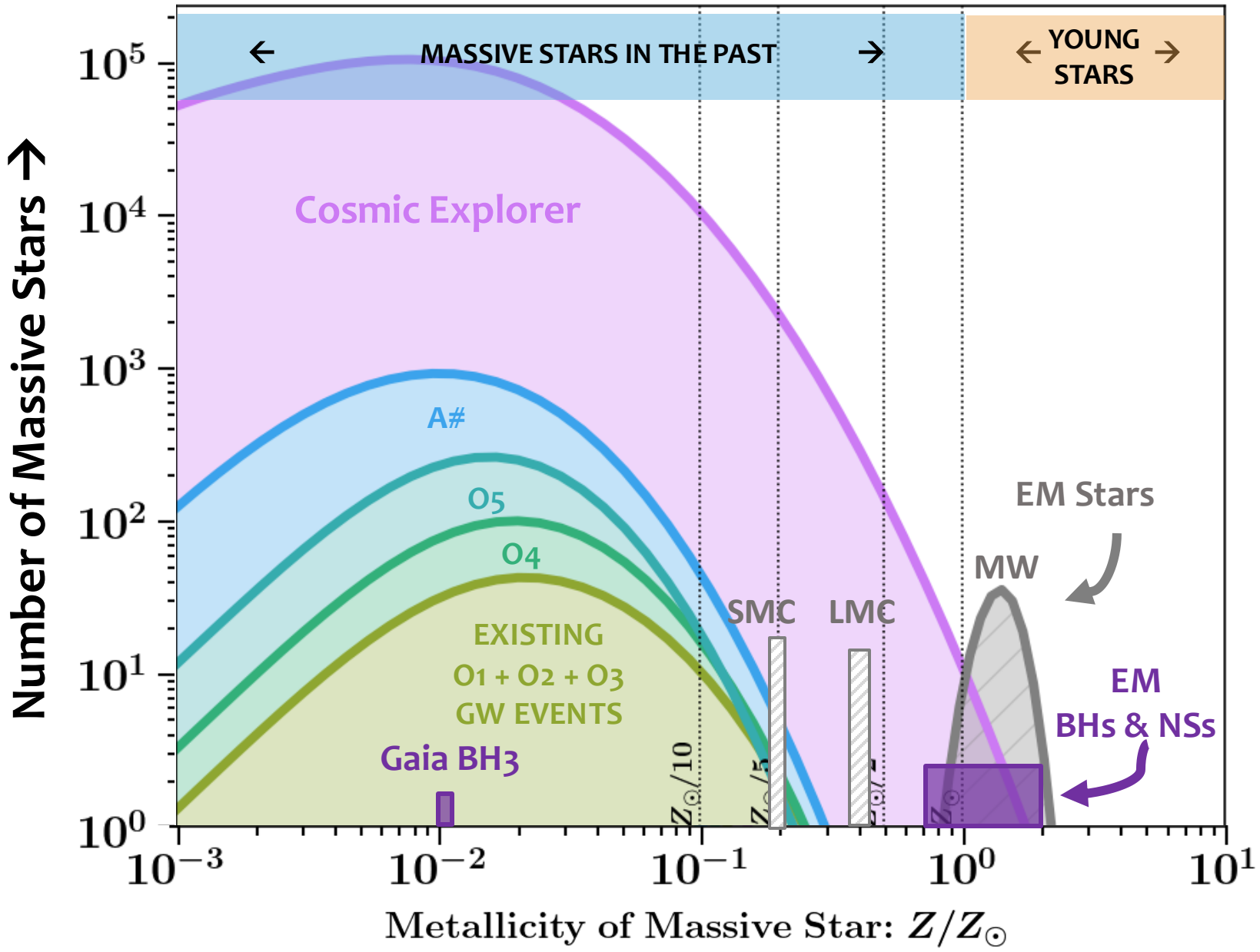

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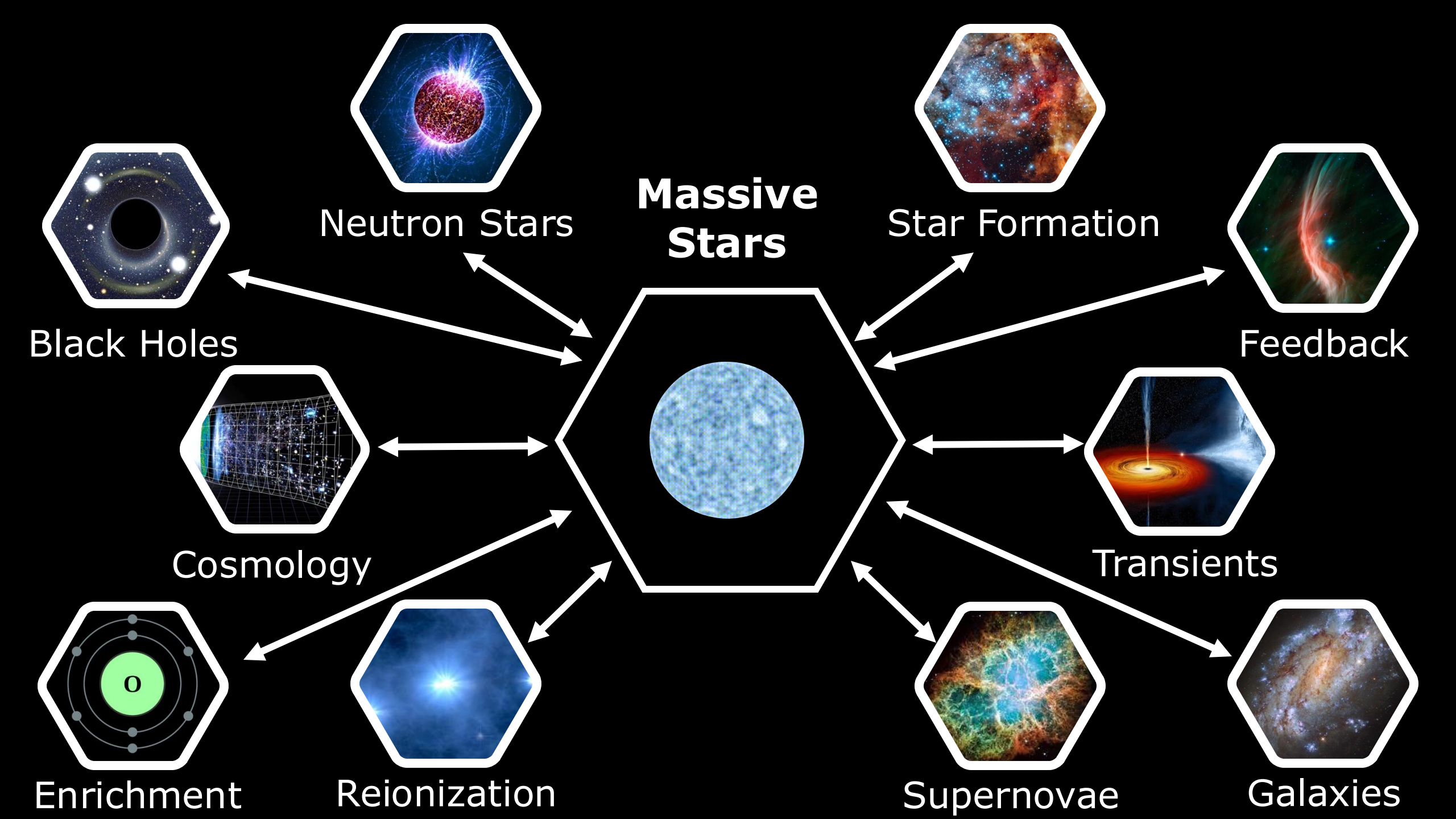
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UC San Diego Black Hole Paleontology Lab

visualizations/data science/software


Esther Park


Caua Rodrigues


Aobo Li


Ann-Kathrin Schuetz


Eugene Shang


Meera Desawale


Alex Migala


Prajakta Saraf


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Sasha Lavina


Marko Ristic

Kyle Rocha


Khushi Karthikeyan


Laya Binu


Amedeo Romagnolo


Ana Lam


Steffani Grondin


Jayanth Bharadwaj


Tyler Smith


Kyle Kremer


Adam Boesky


Feranmi Falodun


Andrea Zonca


Tom Wagg


Lucas de Sa

YOU?


Shasha Arani

stellar evolution

AI/ML Enrichment

Gravitational waves

Astro-statistics transients

Cosmic star formation history

Other things to check out:

New Astro Resources websites

https://www.broekgaarden.nl/floor/wordpress With resources for:

- **Applying for PhD/MSc/Postdoc/Fellowships/Faculty etc.**
- **Recorded workshops on applications, thriving in your PhD/PD etc.**

Applying to PhD

Websites that provide overviews/resources.

- Melinda Soares-Furtado, has created a **Discord for undergraduate students** who are applying the coming year(s) to PhD programs and who would benefit from connecting with a digital network of grad school applicants (including current PhD students, postdocs and professor who can answer questions.). You can email her if you want to get an invite to this Discord: mmsoares[@]wisc.edu.

Additionally:

- A document on **"applying fo**
  students and gives tips and t
  advices from former student
  See: https://docs.google.con
  usp=sharing – the departm
USA focused:

- **Really helpful Workshop/Vid**
  Project: https://thewocproje
- **USA PhD application timelin**
  on: https://sites.astro.caltec
- **NSF GRFP**: website with exa

Applying to Postdocs

General overviews demystifying the application process:

- **"Guide to postdocs Applications part 1"** https://astrobites.org/2022/08/02/guide-to-postdoc-apps-part1/ ,
  "Guide to postdoc Applications part 2" https://astrobites.org/2022/08/03/guide-to-postdoc-apps-part2/
  These are great guides that walk you through the main things to think about when applying for postdocs, and provide li
  resources for each stage of the postdoc application.
  Astrobites: *The series written by Mia de los Reyes and Luna Zagorac and edited by Pratik Gandhi, Lina Kimmig, Ishan Mi*
  Jenny Calahan.

- Workshop presentation on **"How to apply for PostDocs (in the USA)"** by David Charbonneau: https://www.youtube.co
  v=hTc8_5B6zzU&ab_channel=HarvardAstronomyVideo, & slides: Charbonneau_how_to_apply_to_a_postdoc

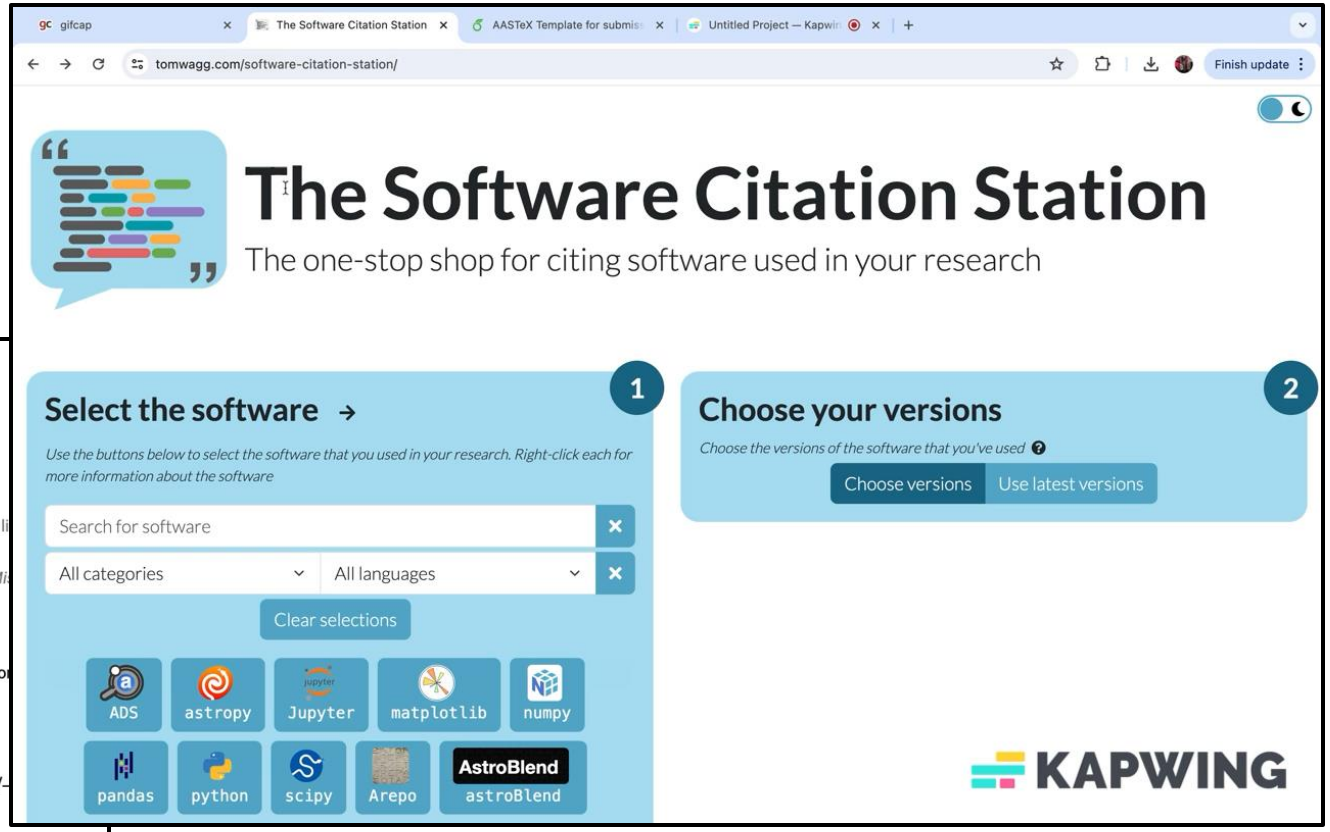
More Postdoc application ppt slides and guides:

- Great PDF of presentation slides on "how to apply for PhD/PostDocs by Sera Markoff", with many advices: how2apply_
  https://www.dropbox.com/s/bxqtqislktyaif9/how2apply_bhi_slides.pdf?dl=0
- Great PDF slides of "how to apply for postdocs" by Richard Alexander (U. of Leicester)
  https://www.astro.le.ac.uk/~rda5/rda_jobs_talk_2019.pdf and more resources on Richard's website:
  https://www.astro.le.ac.uk/~rda5/jobs_2019.html
- Great slides on "How to apply for postdoc positions in Astronomy" by Mary Loli Martinez Aldama (CFT/Poland) and Dhanya Nair (JIVE/NL) http://astro.udec.cl/titans/postdoc.pdf

- Guide by Bryan Gaensler & Sarah Maddison on "how to apply for postdocs"
  https://www.dunlap.utoronto.ca/~bgaensler/papers/gaensler_maddison_jobs_2012.pdf
- the many many helpful career resources by Astrobetter https://astrobetter.com/wiki/Possible+Career+Paths... Which includes many blogs and resources for careers outside of academia!! (which is so important!)

The software citation station

Tom Wagg & FSB (2024): to make citing software incredibly easy



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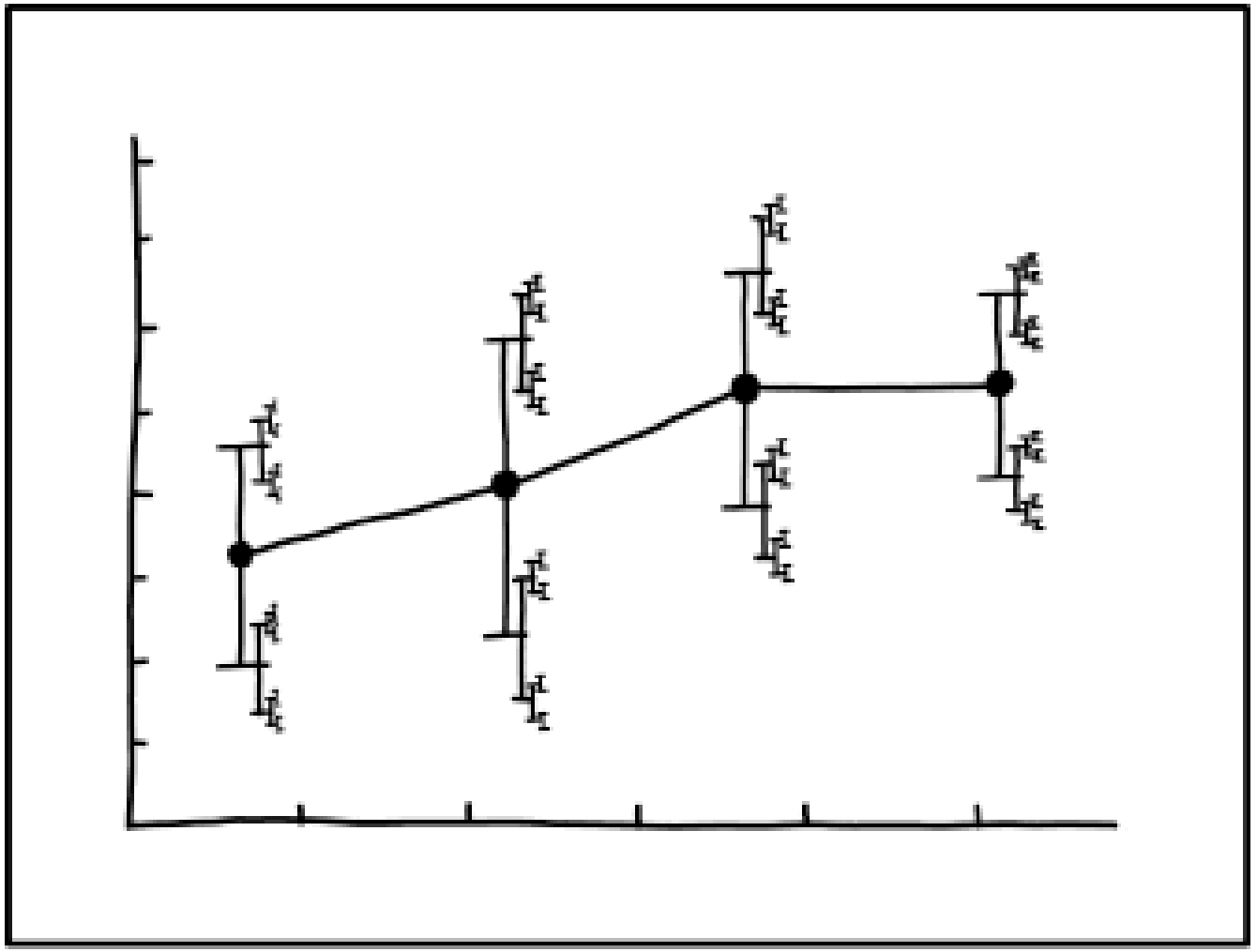
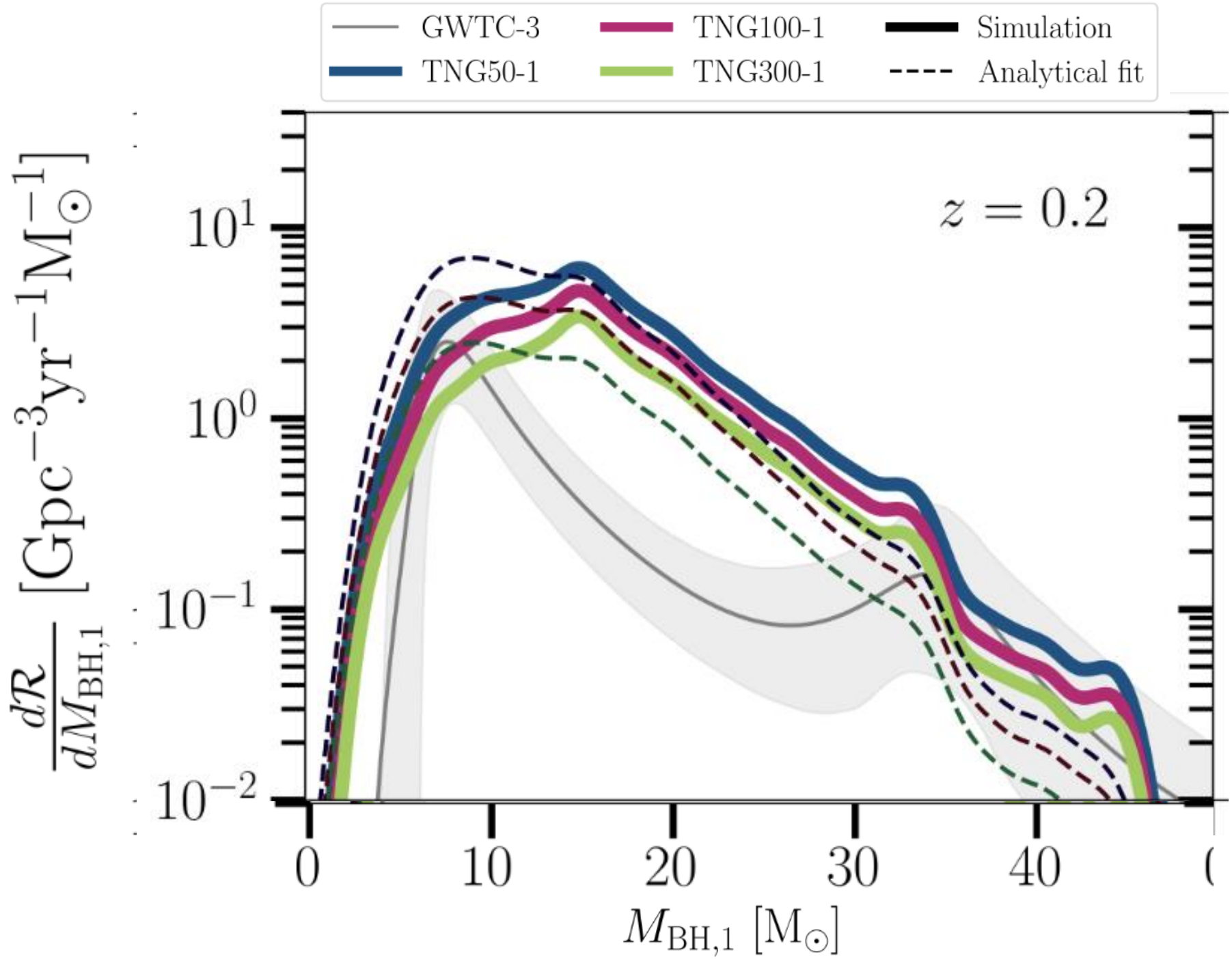
With so many uncertainties, can we learn anything from Gravitational Waves?



Cartoon: xkcd

Sasha Levina (2025a,b; in prep)

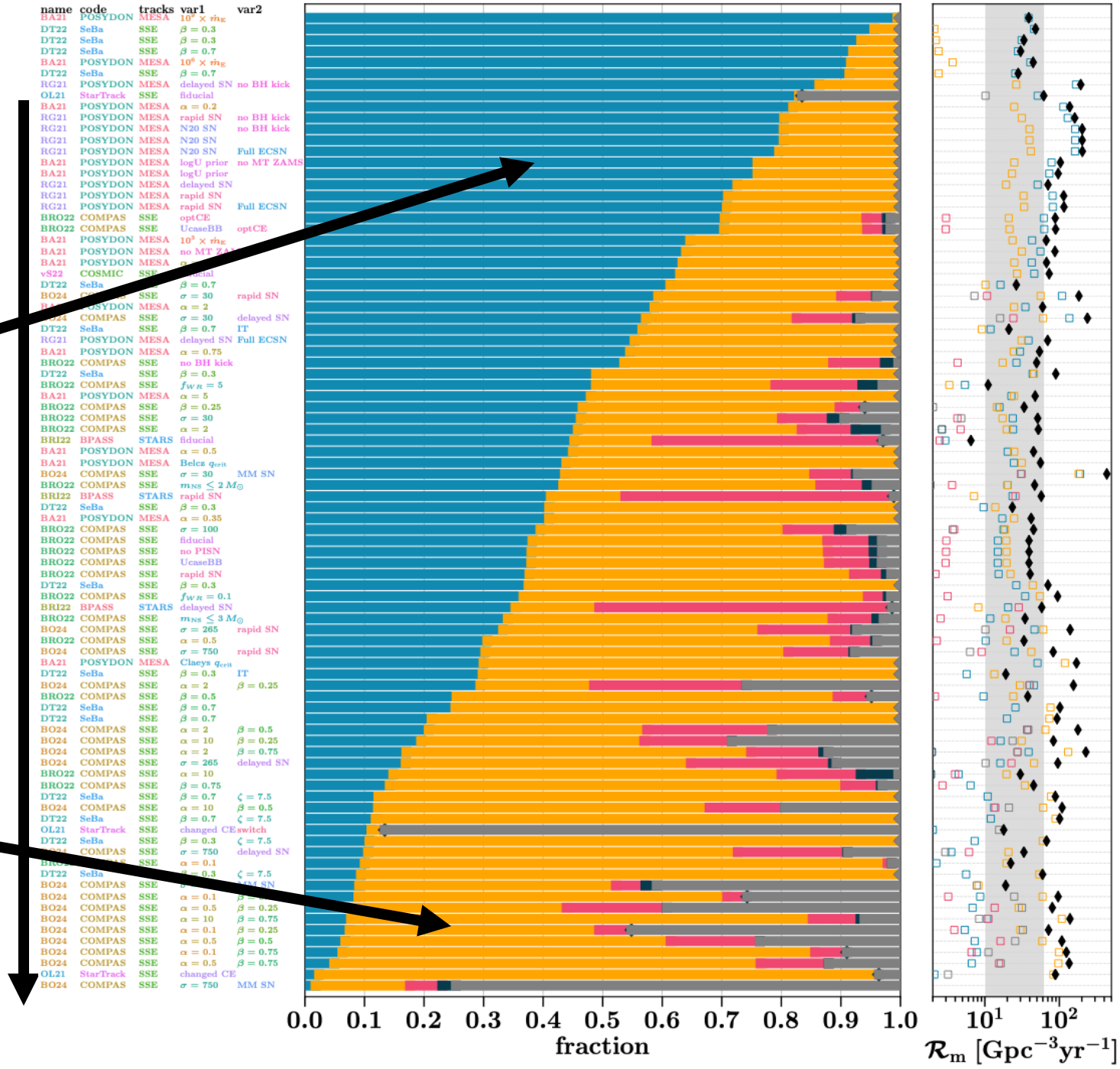


Do the majority of BHBH mergers experience a Common Envelope phase??

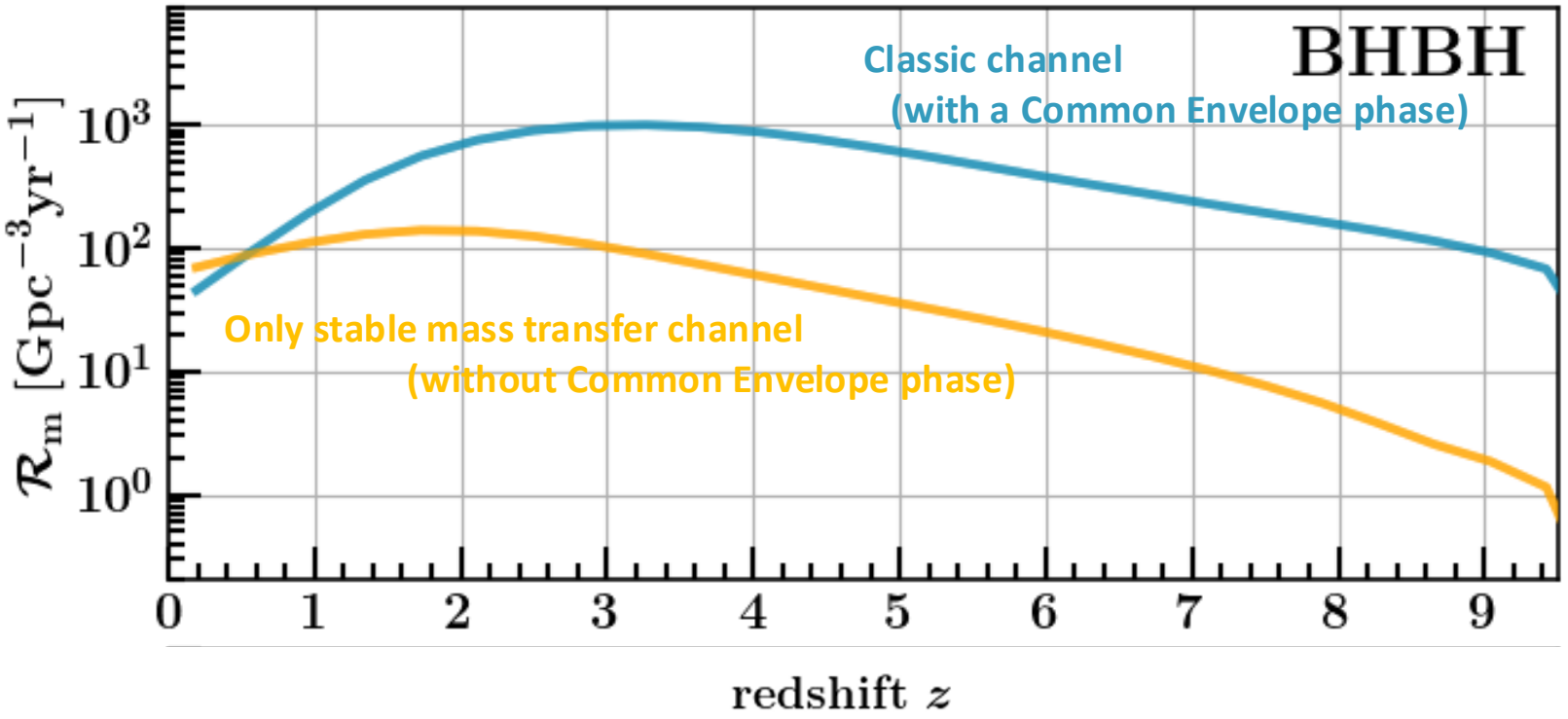
Yes!

No!

different codes and uncertainties

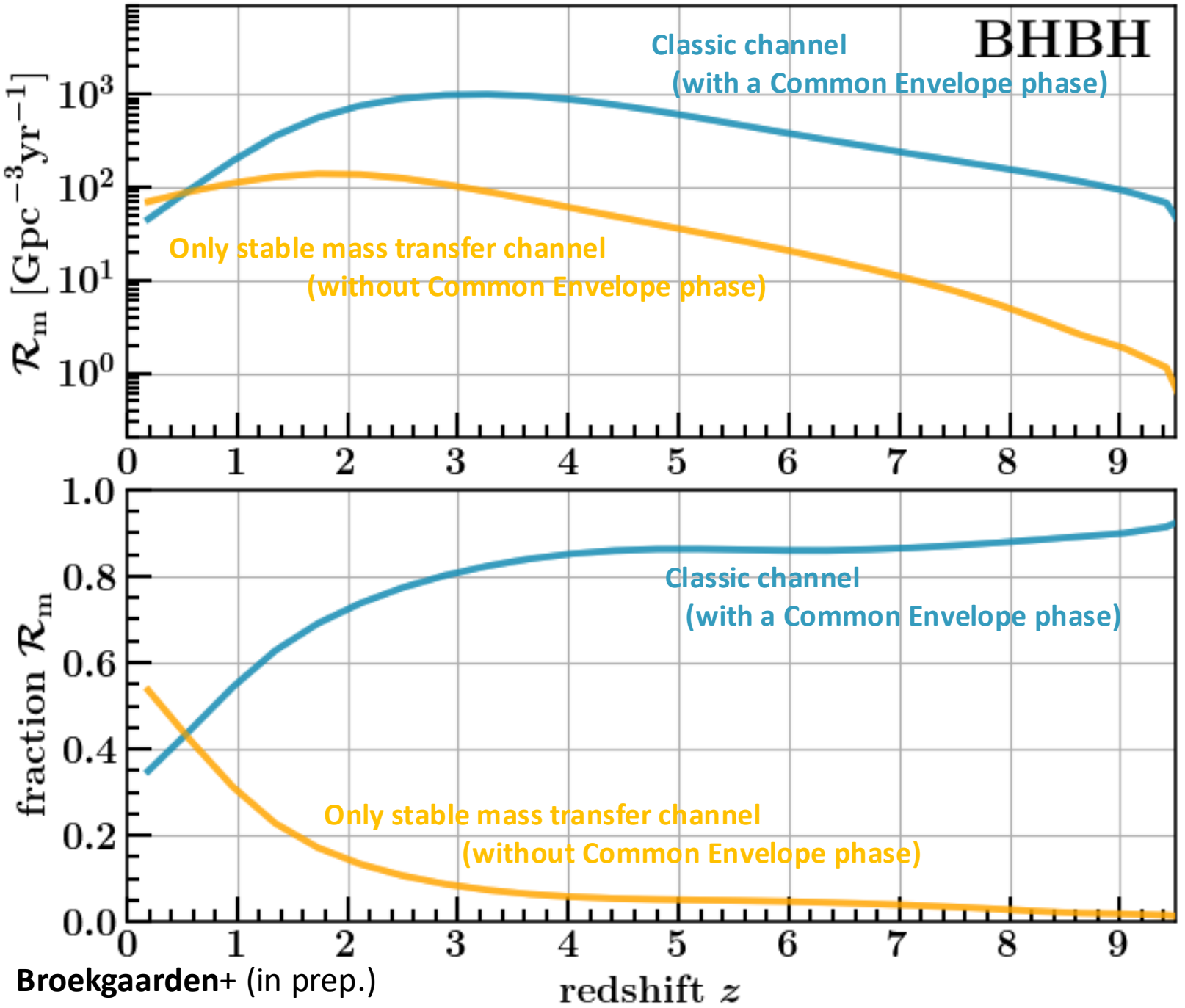


Broekgaarden+ (in prep.)



Merger Rate
without or **with** a
Common Envelope phase

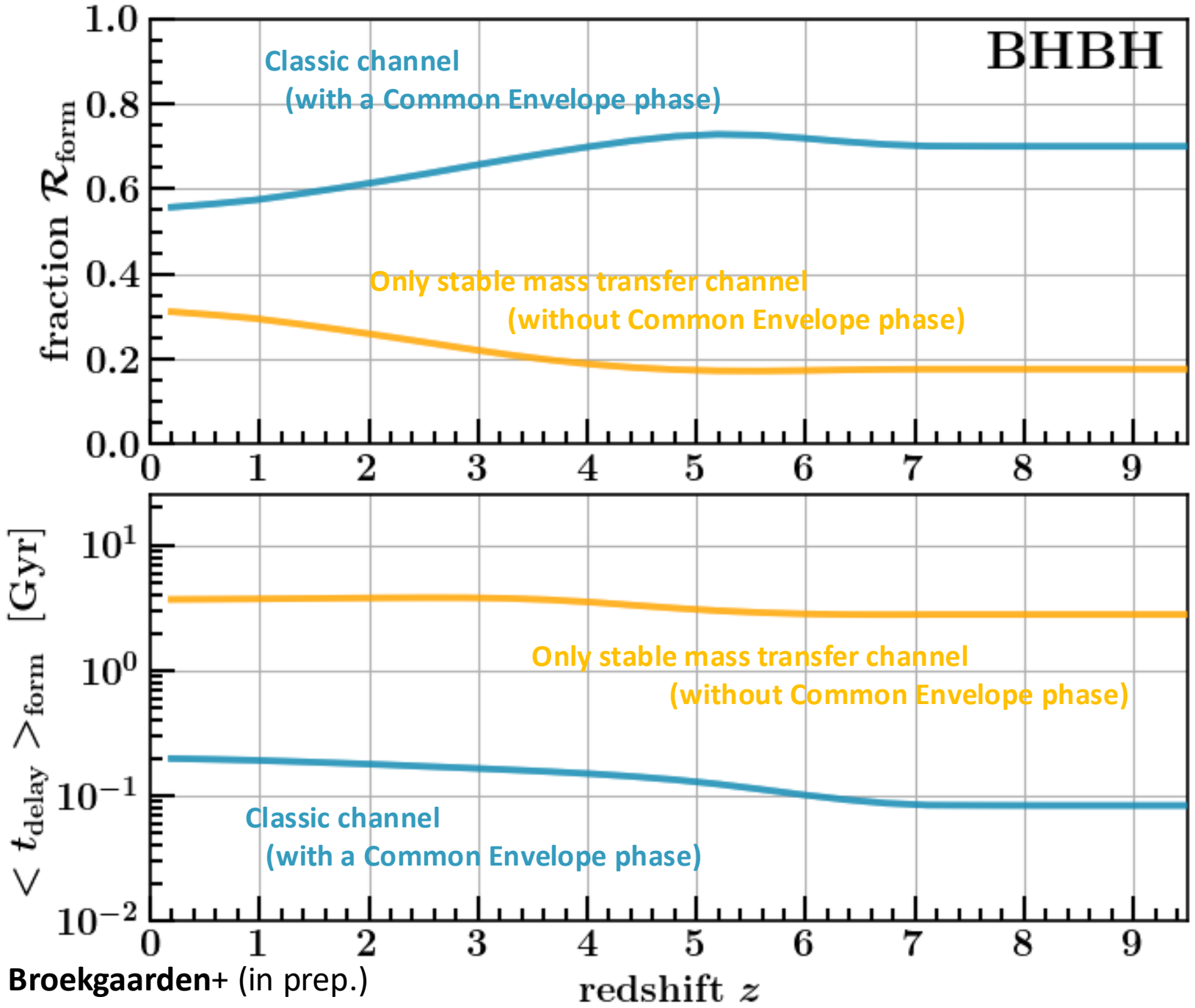
Broekgaarden+ (in prep.)



Broekgaarden+ (in prep.)

Merger Rate
without or **with** a
Common Envelope phase

Merger Fraction
without or **with** a
Common Envelope phase



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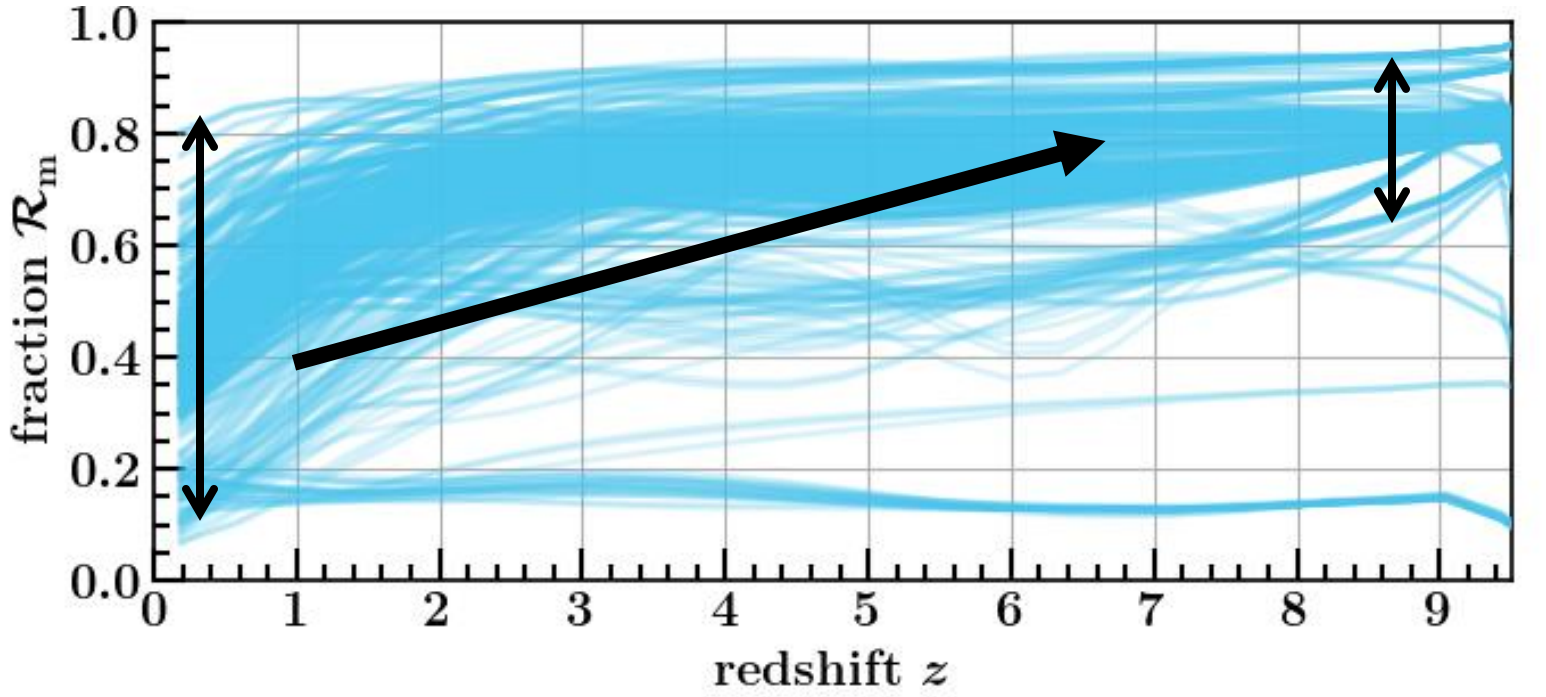
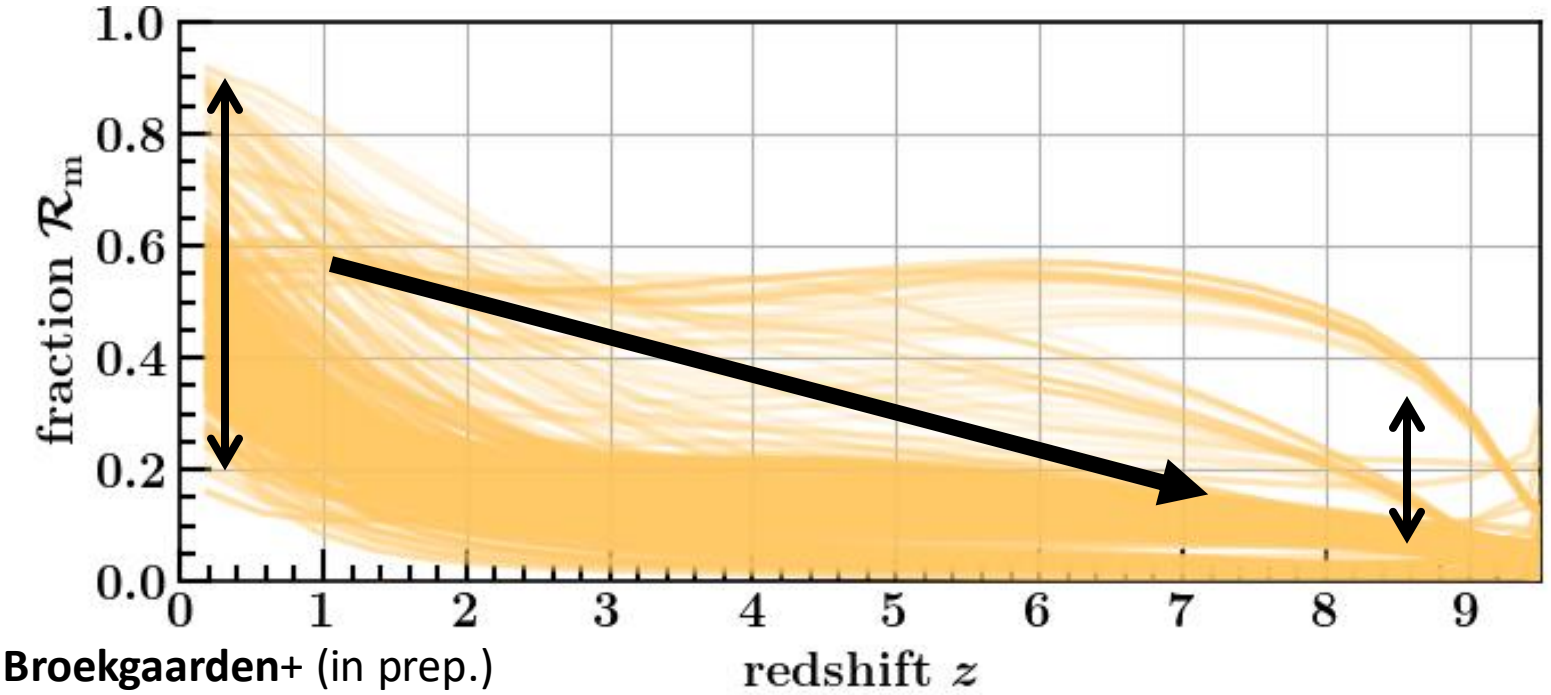
Formation Rate

without or **with** a Common Envelope phase

Formation Inspiral time

without or **with** a Common Envelope phase





Broekgaarden+ (in prep.)

Merger Rate

without or **with** a

Common Envelope phase

5 Constraints from intermediate stages

Ana Lam