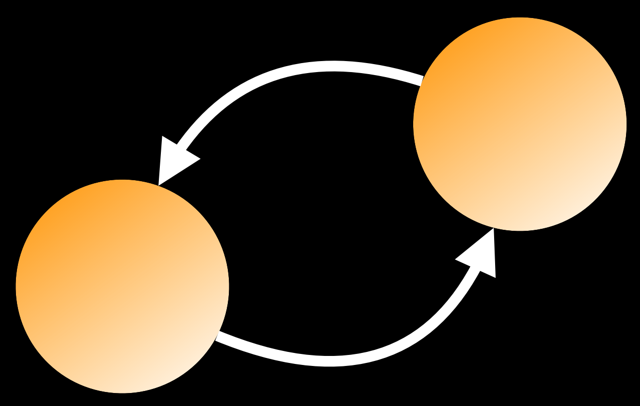
What we learned about the amount of r-process elements produced from binary mergers from LIGO-Virgo's observations

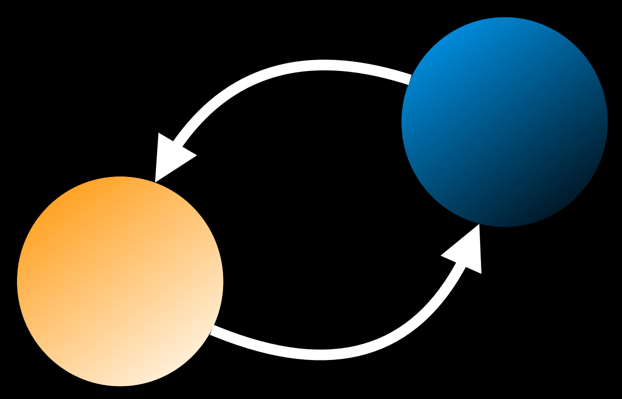
Hsin-Yu Chen

(NASA Einstein Fellow, MIT)

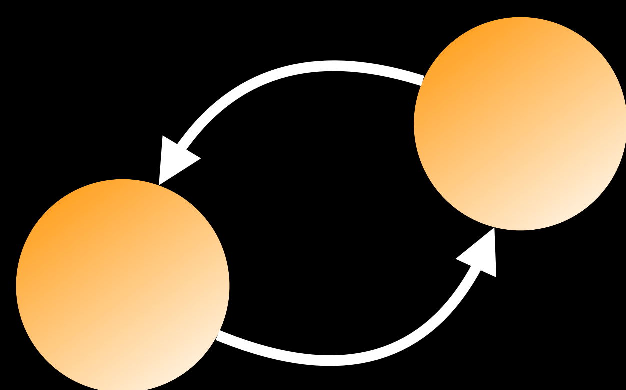
INT 20R-1b Workshop, May 2022



Neutron star-neutron star



Neutron star-black hole



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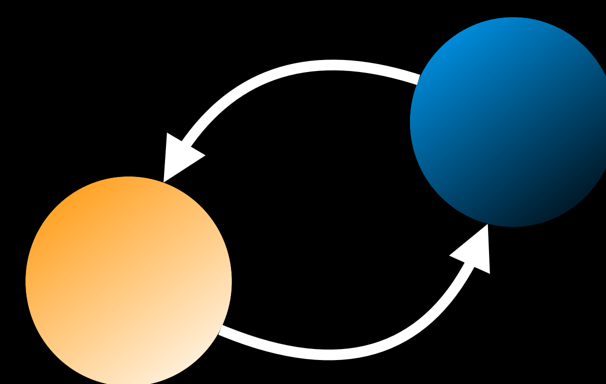

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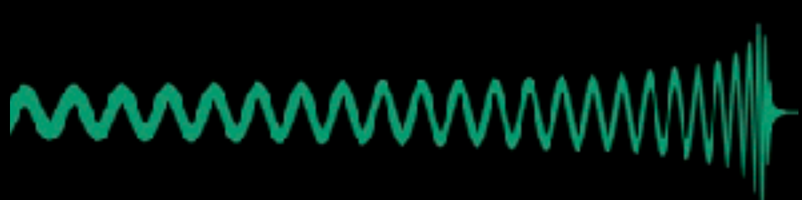

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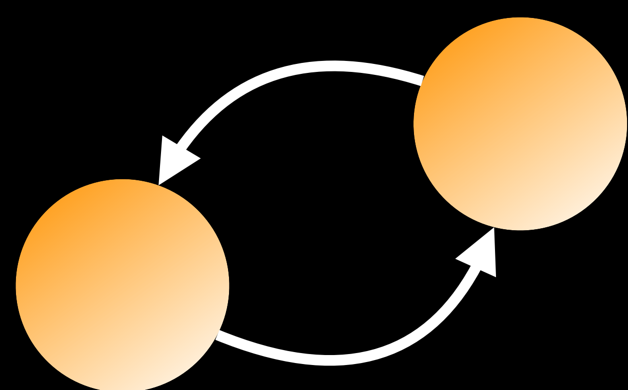

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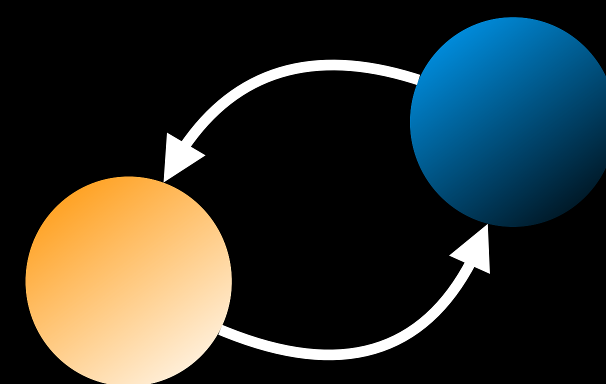

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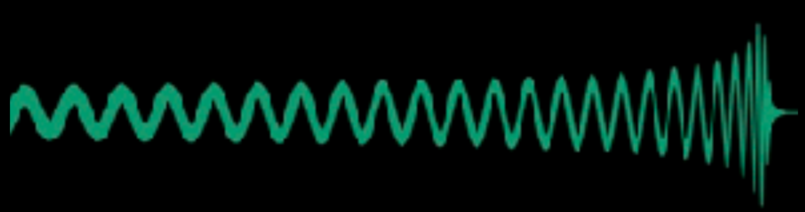

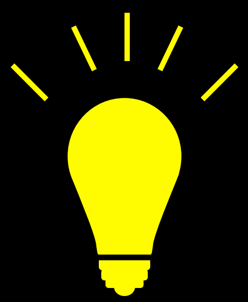

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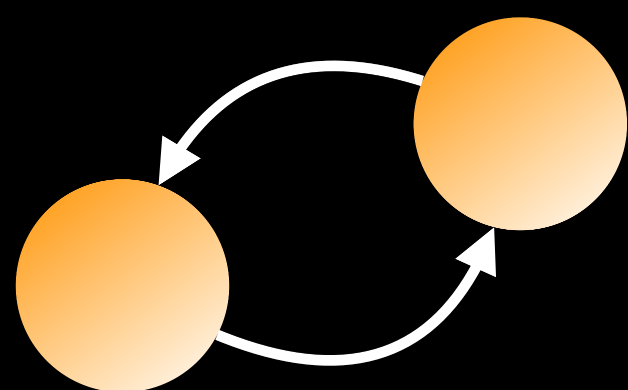
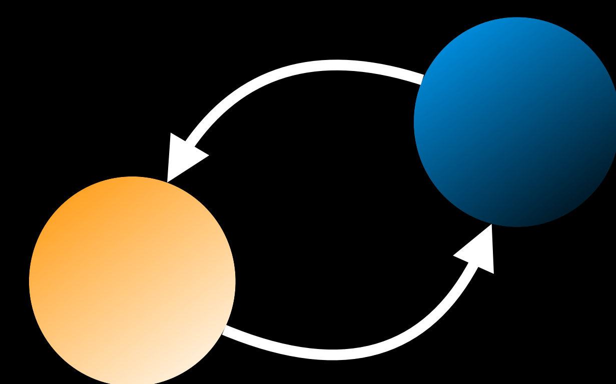
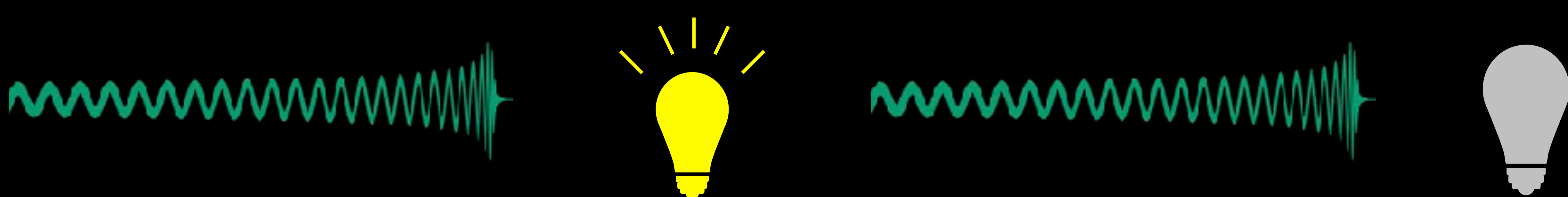
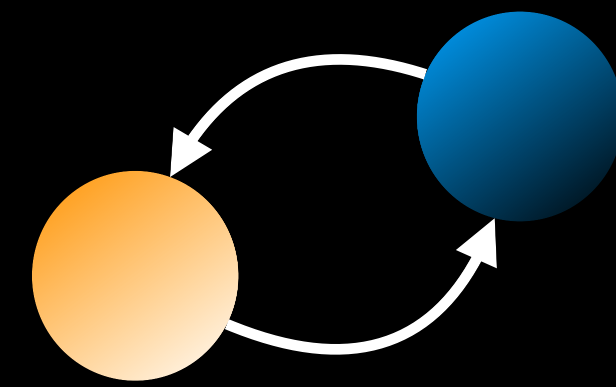




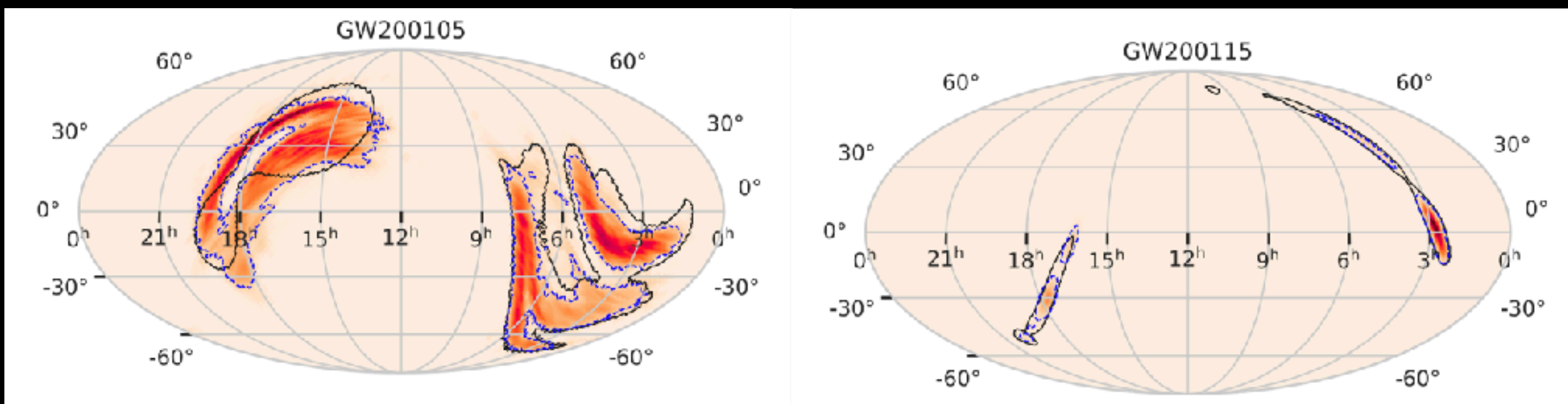
Neutron star-neutron star *Neutron star-black hole*



It would have been difficult to find the electromagnetic counterparts if presented.



LVK, ApJL (2021)



Both ~300 Mpc

Even without the observations of tides or electromagnetic counterparts,

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-LIGO-Virgo observations of the mergers can still teach us about the merger production of r-process elements from the population properties.

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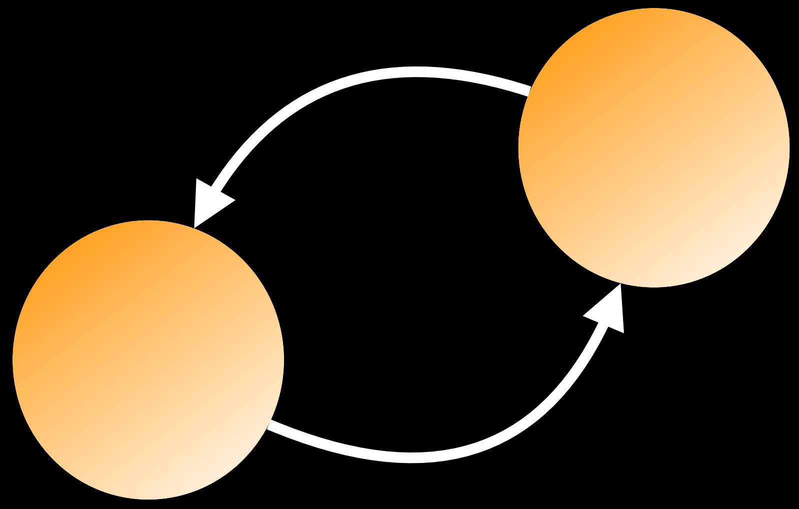
-LIGO-Virgo observations of the mergers can still teach us about the merger production of r-process elements from the population properties.

-Total amount of r-process ejecta

What kind of binary neutron star mergers produce more heavy elements?

-Longer lifetime of the merger remnant.



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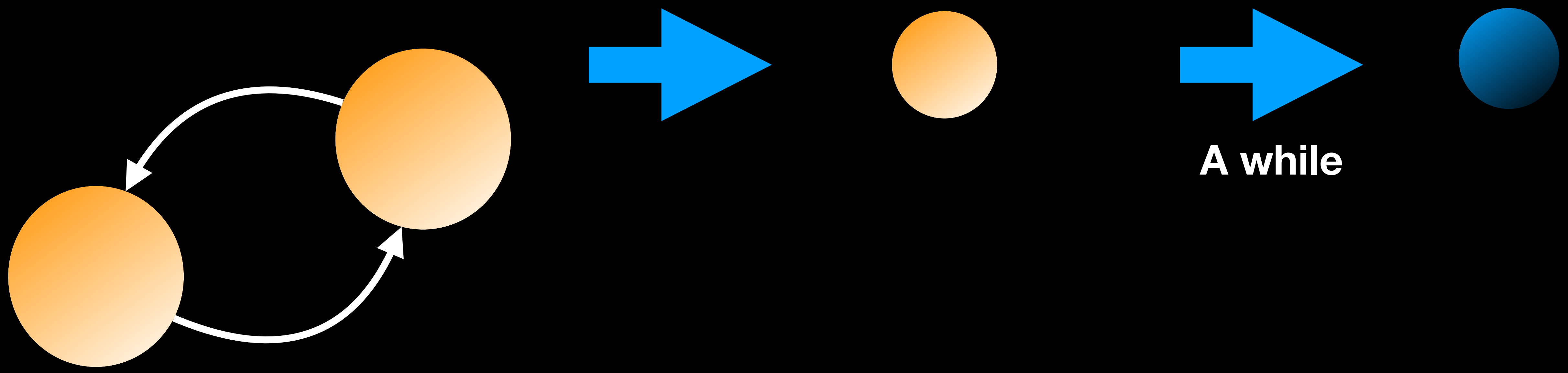

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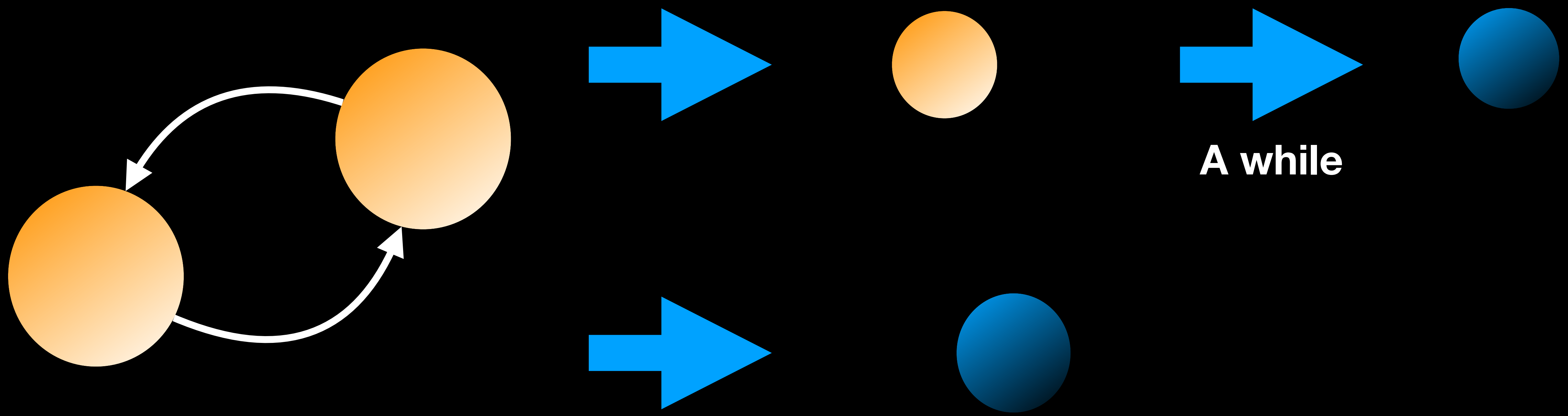

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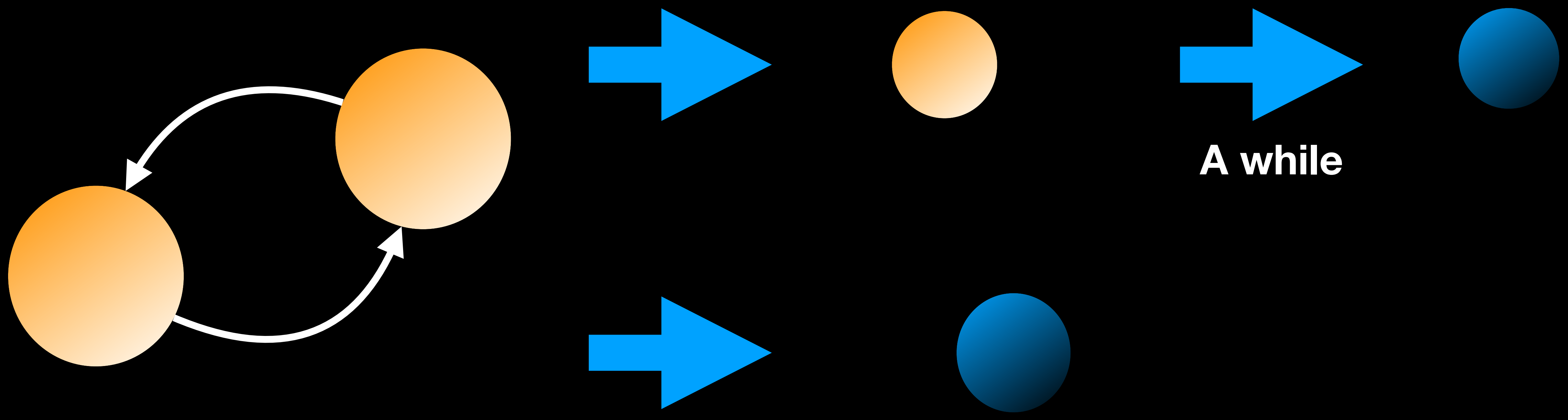

Less massive neutron stars in the binary.

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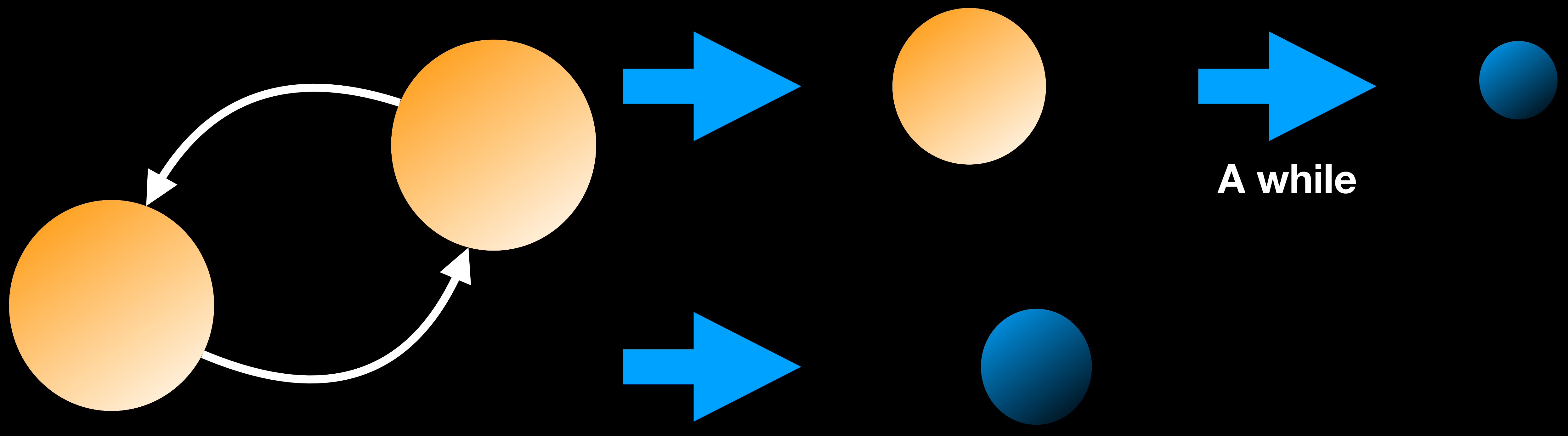

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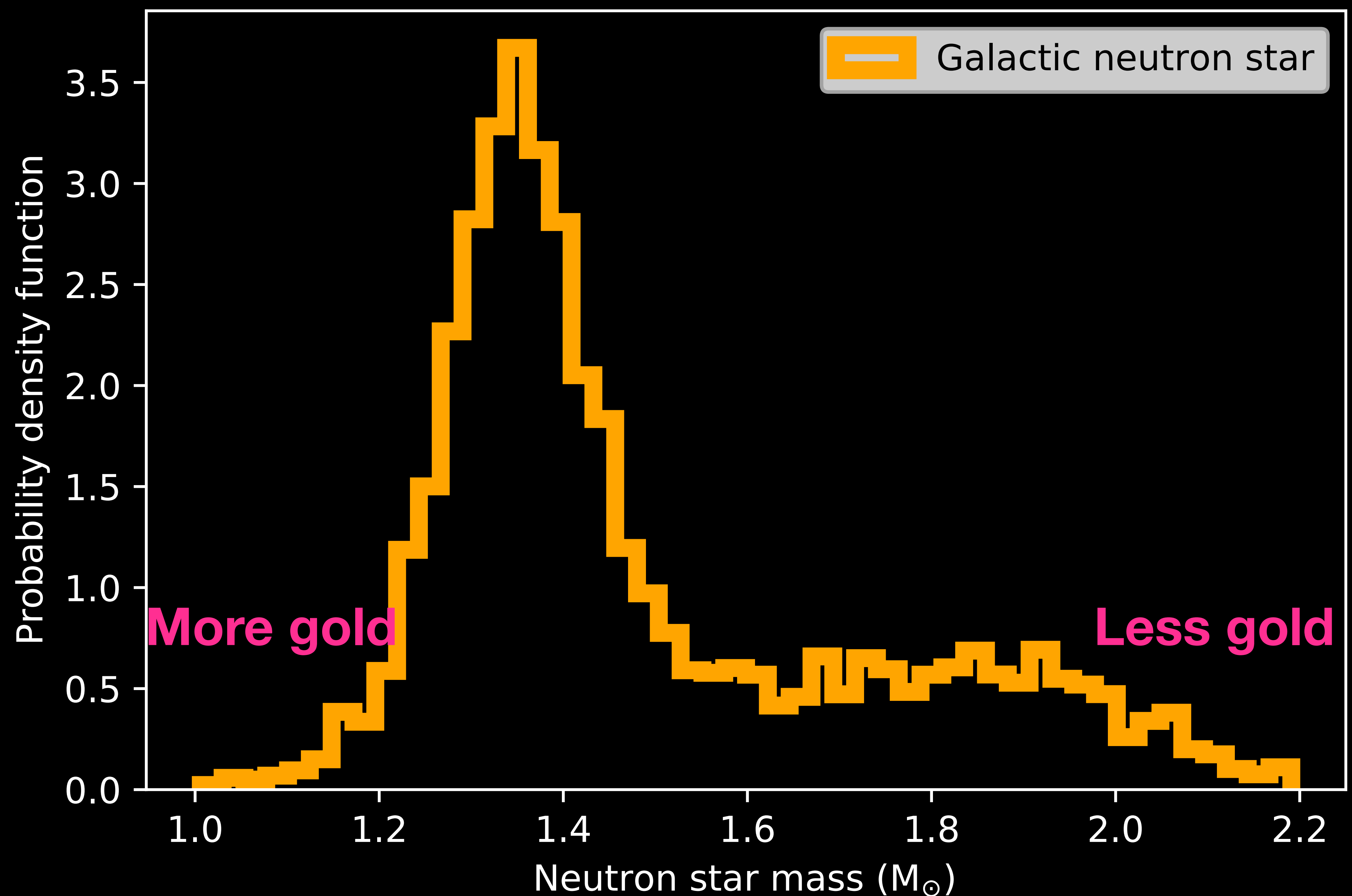
Neutron star mass distribution

Abbott et al., ApJL (2021)



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See also Landry&Read, ApJL (2021)

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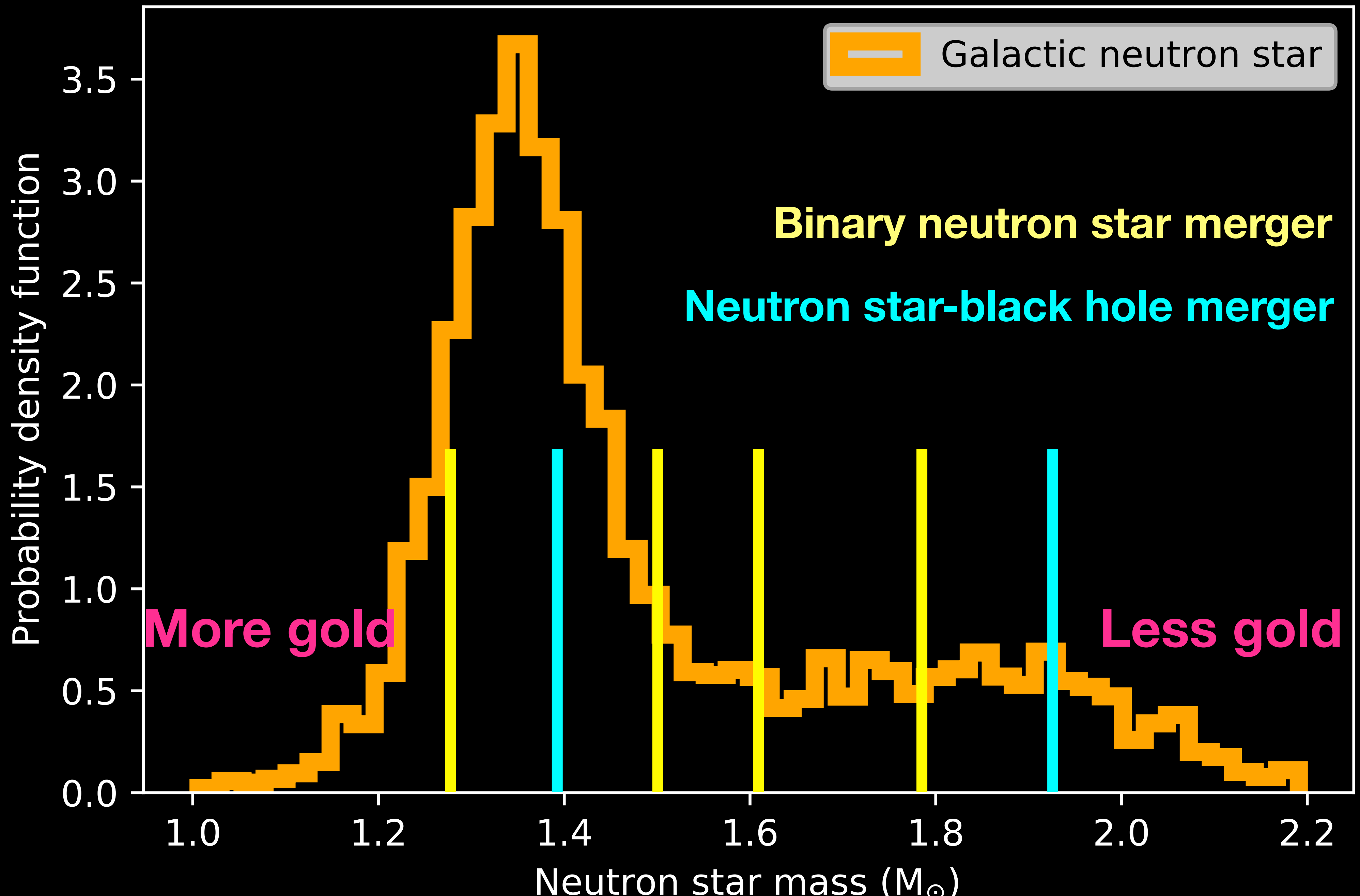

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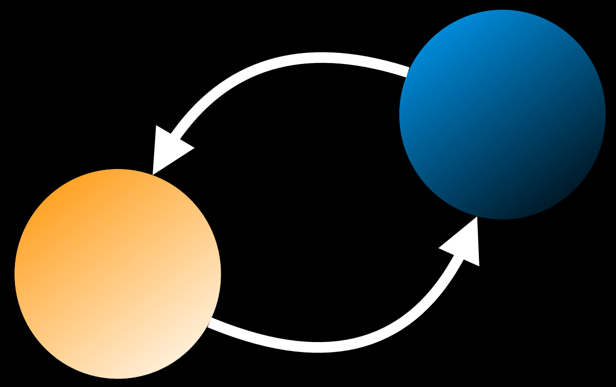
-Neutron star tidal radius > Black hole innermost stable circular orbit

R_T R_{ISCO}



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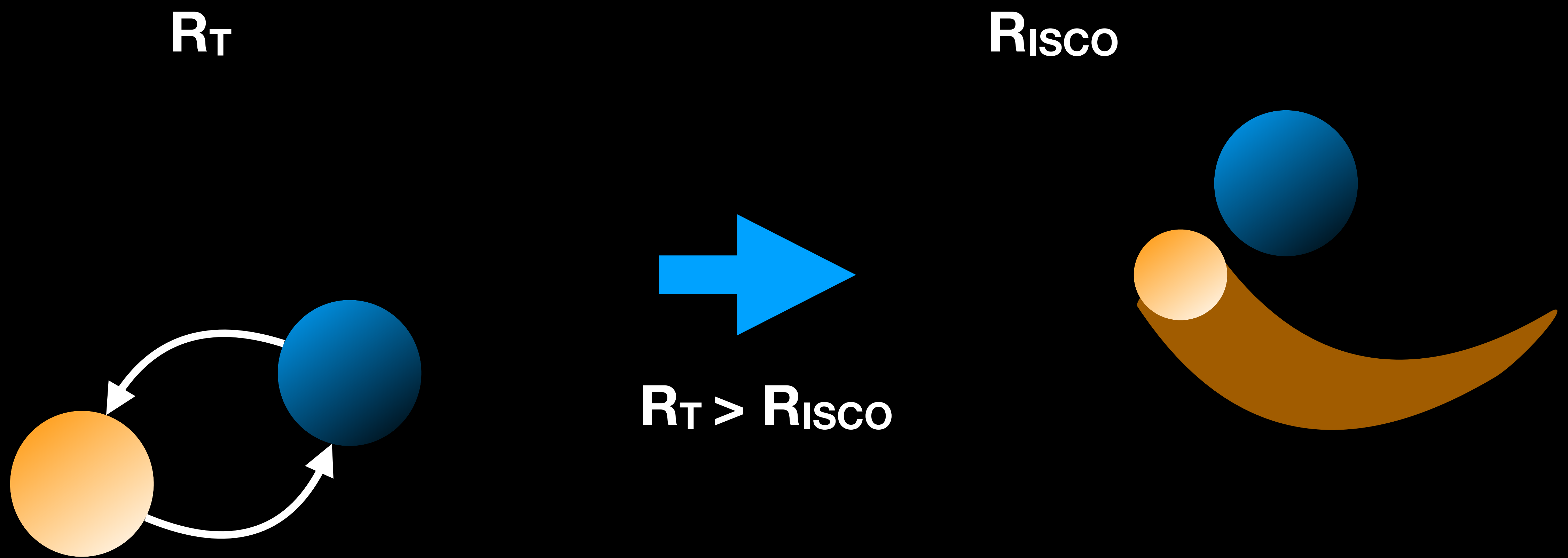

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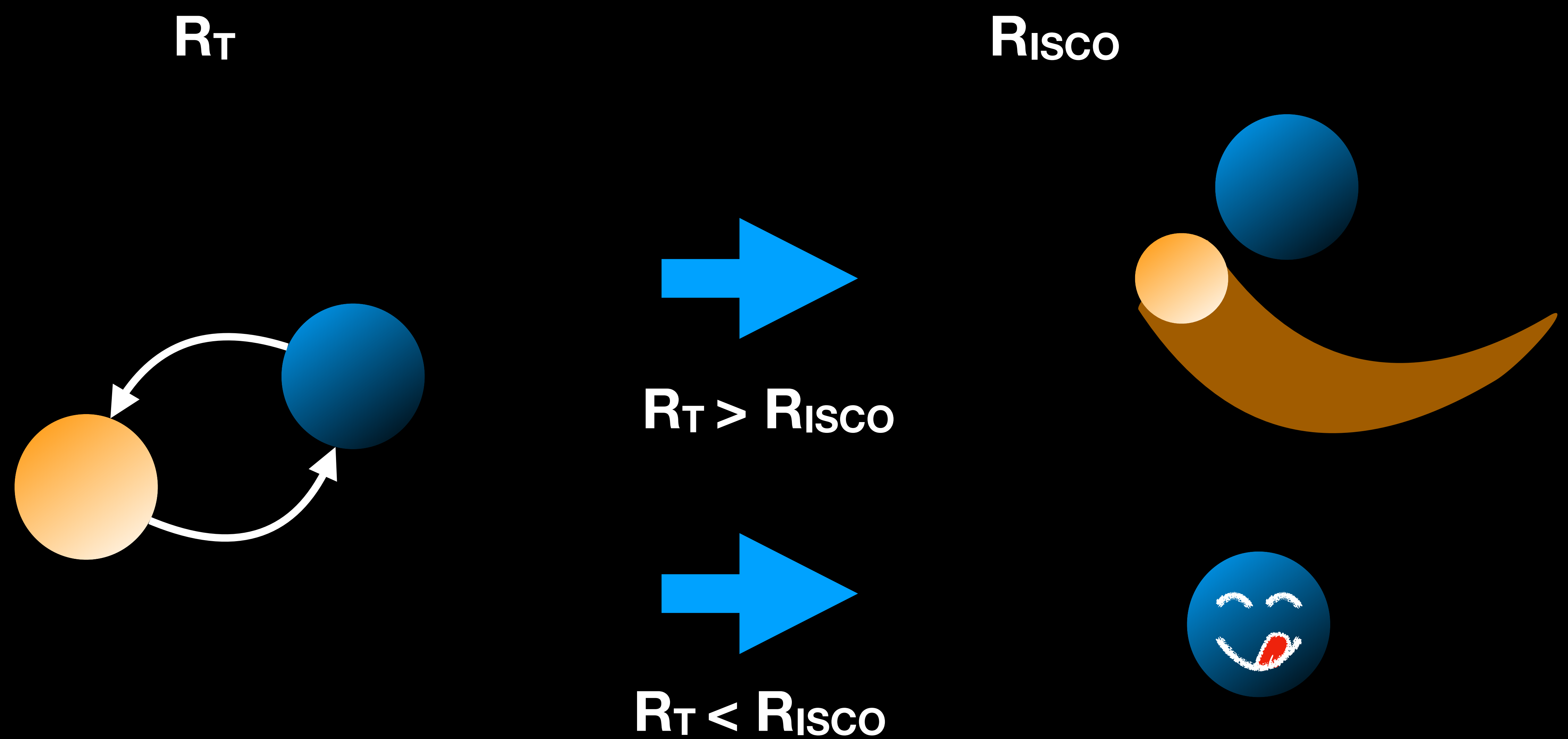

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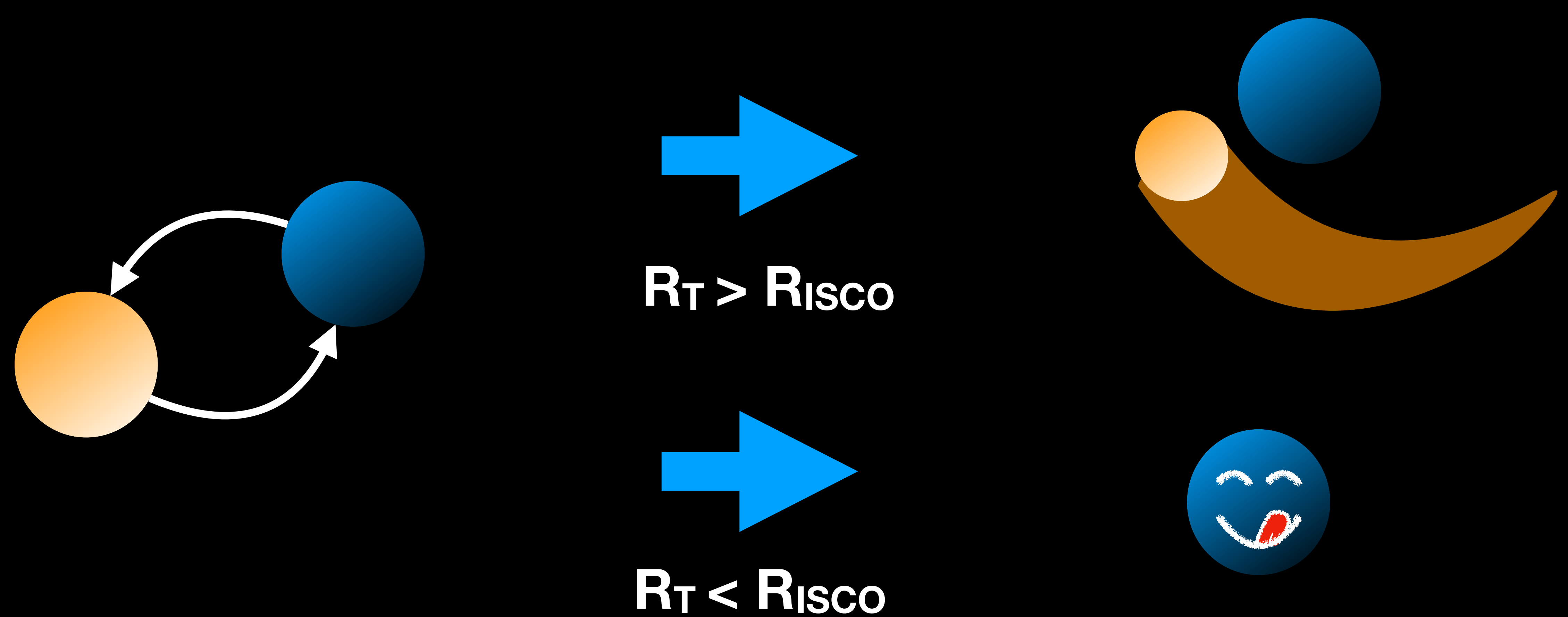

Smaller initial mass of the black hole

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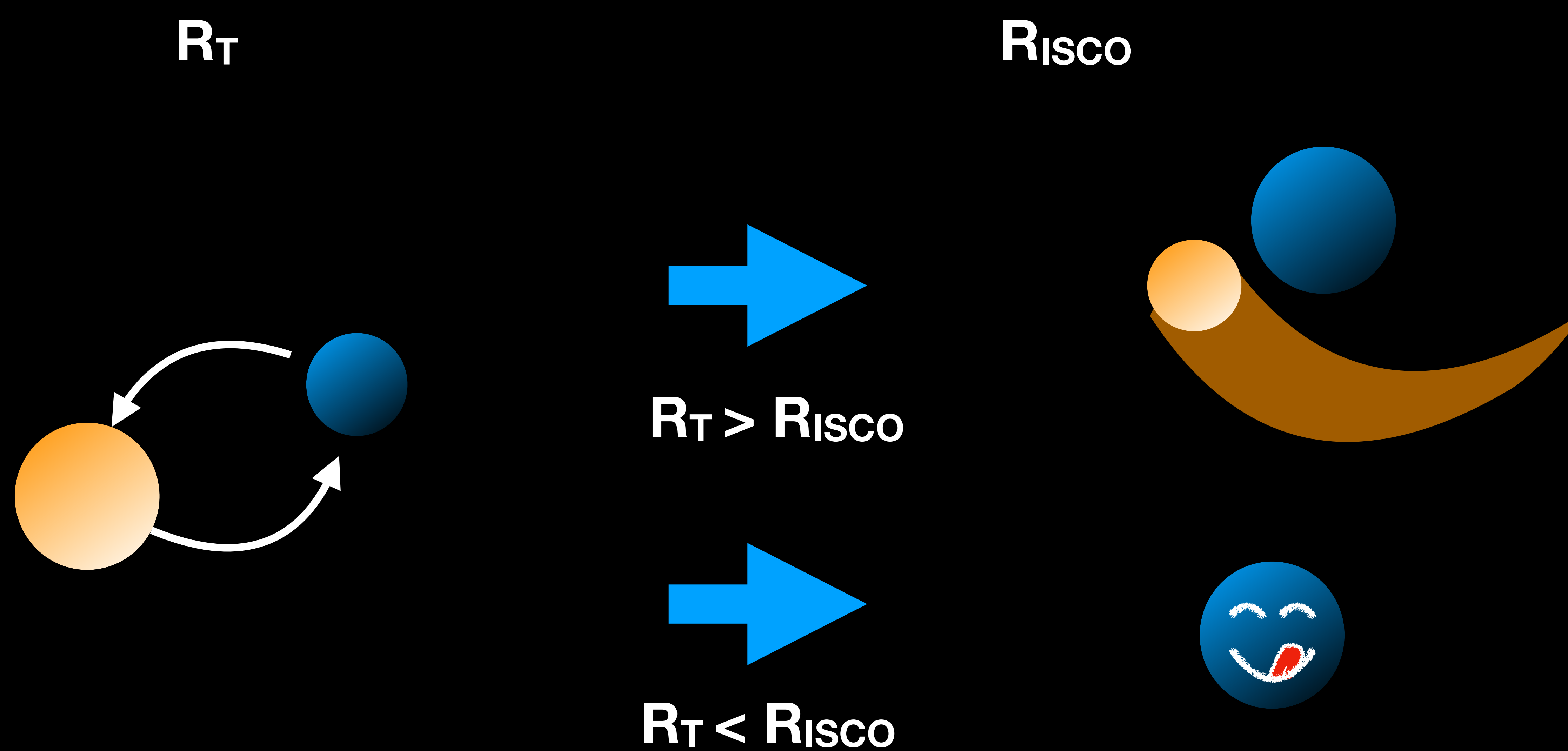
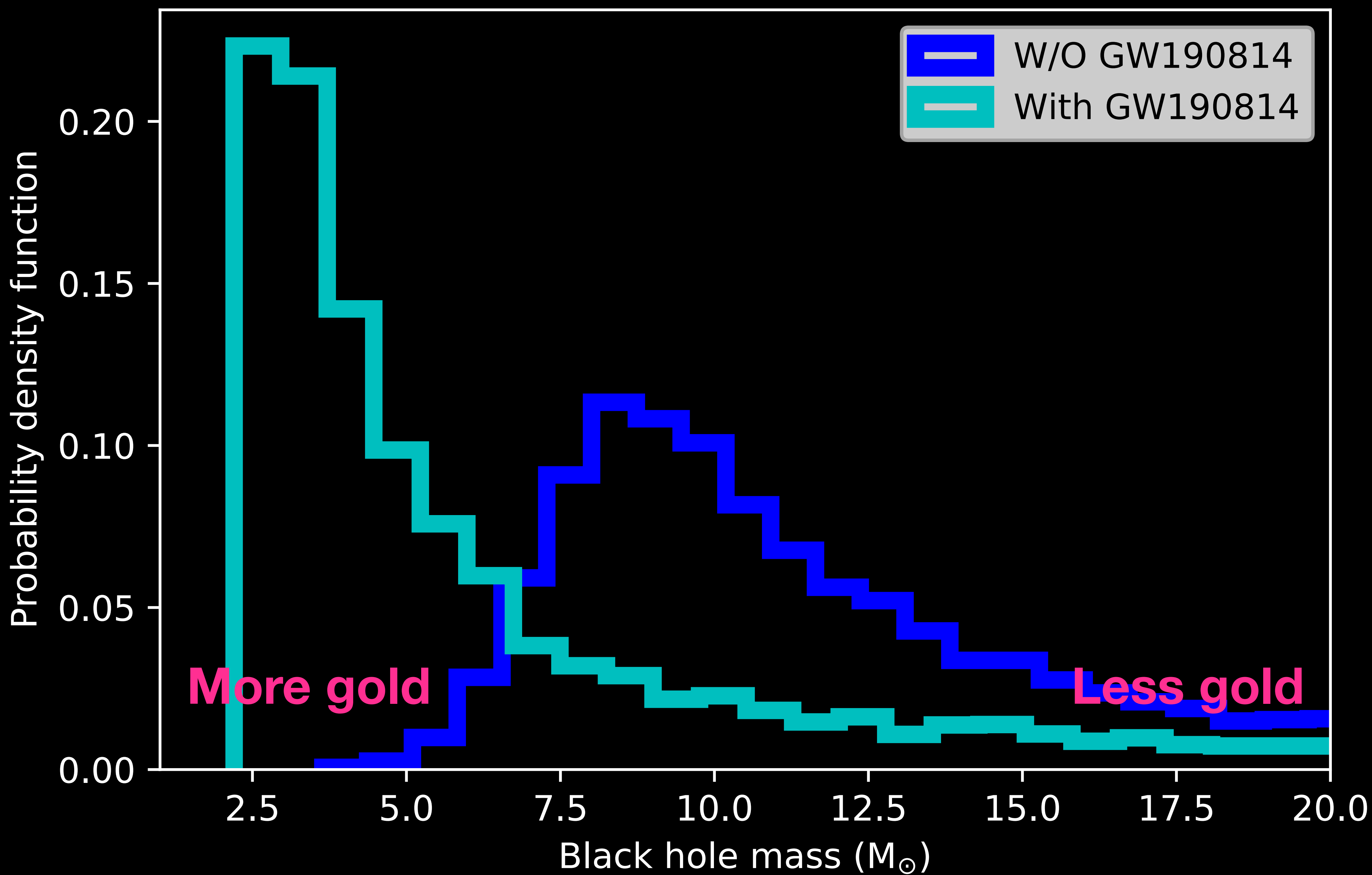


Smaller initial mass of the black hole

Hsin-Yu Chen / MIT

Black hole mass distribution

-Inferred from LIGO-Virgo binary black hole merger observations.



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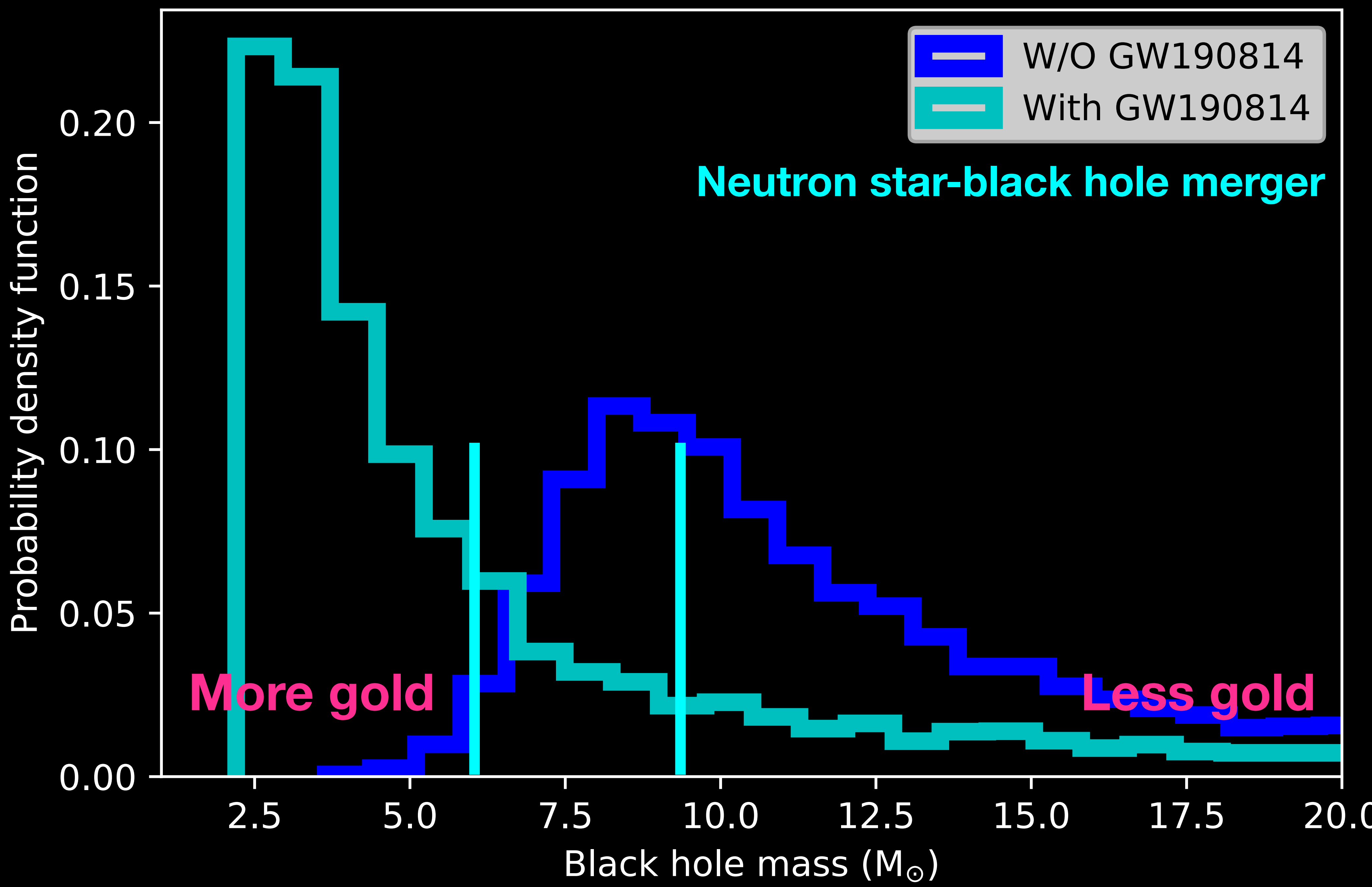

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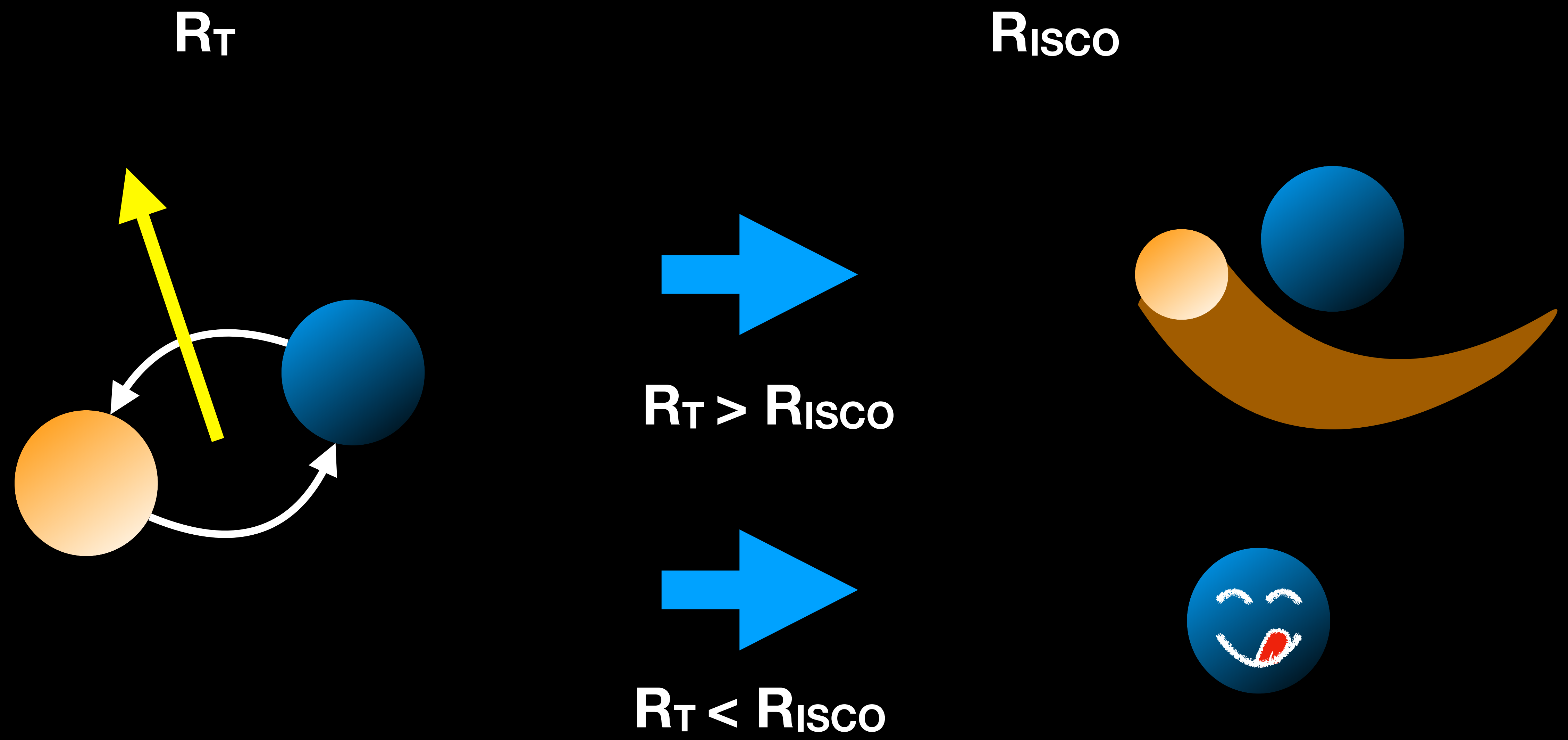

Black hole spin aligned with the binary

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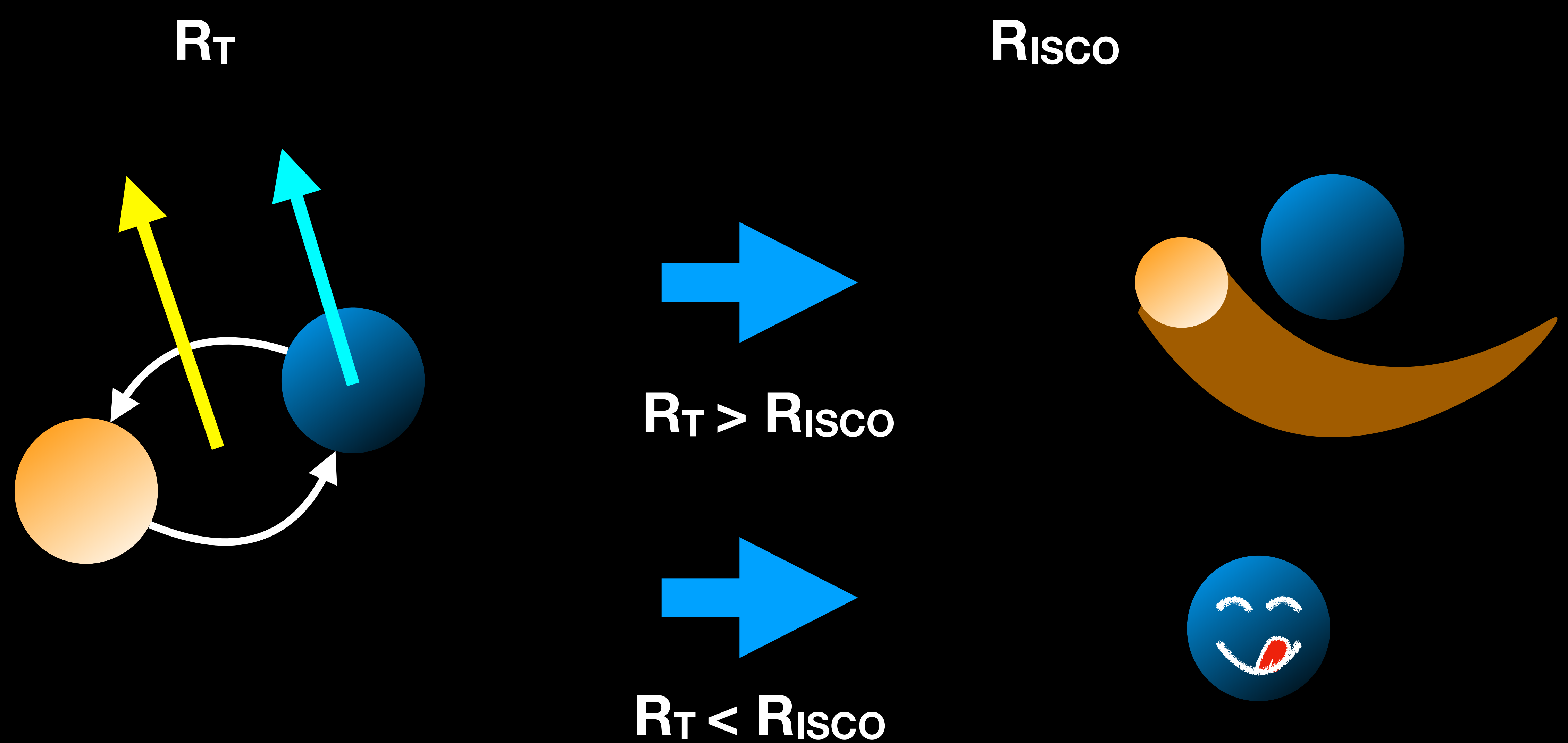
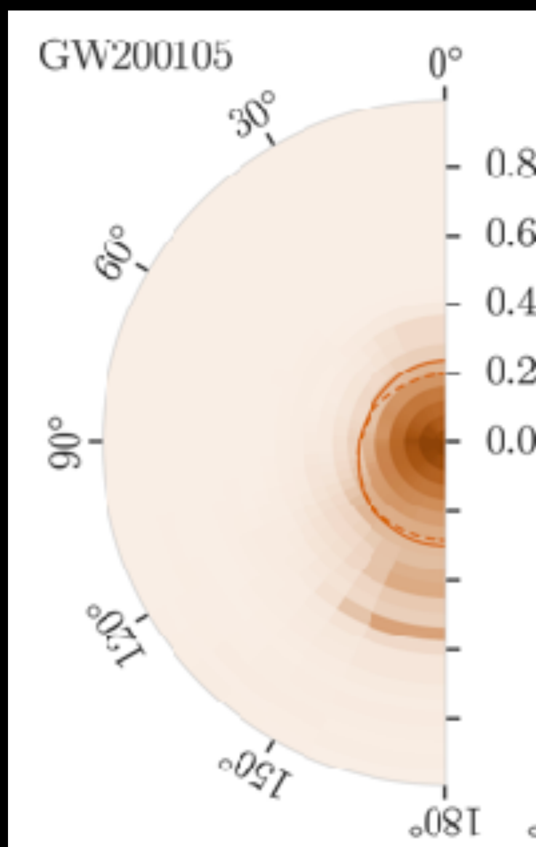
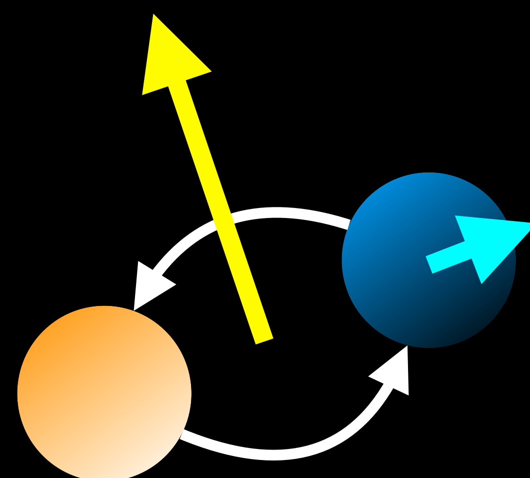
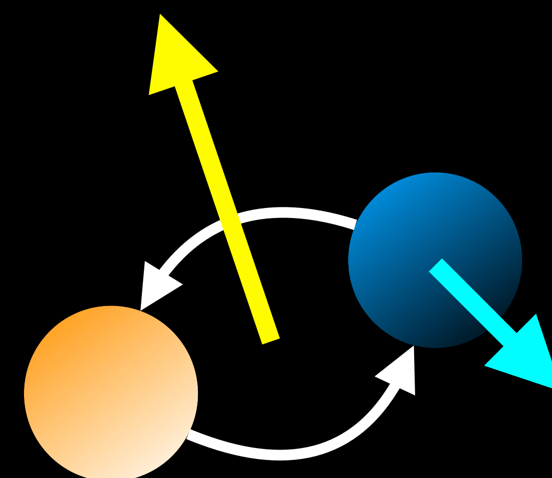


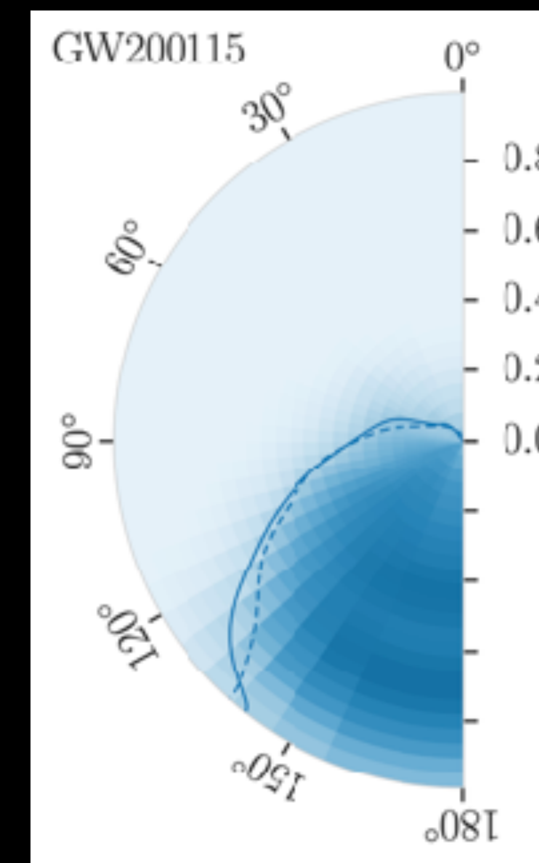
Black hole spin aligned with the binary

Inferred black hole spins









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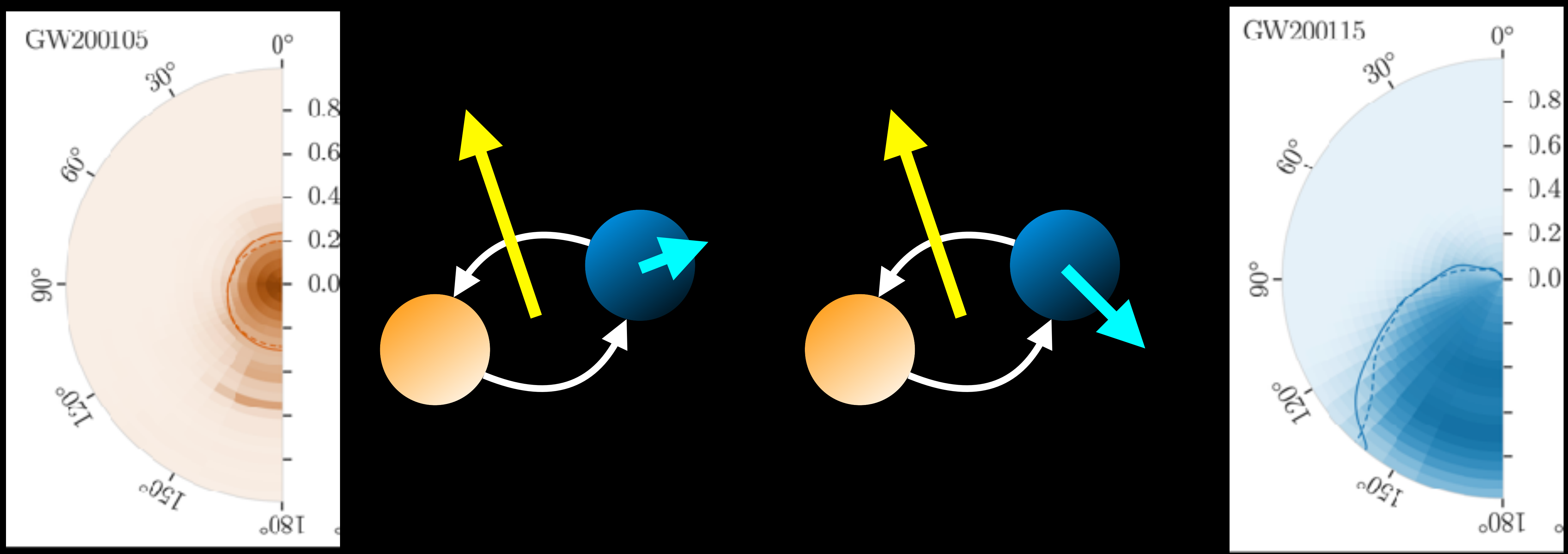
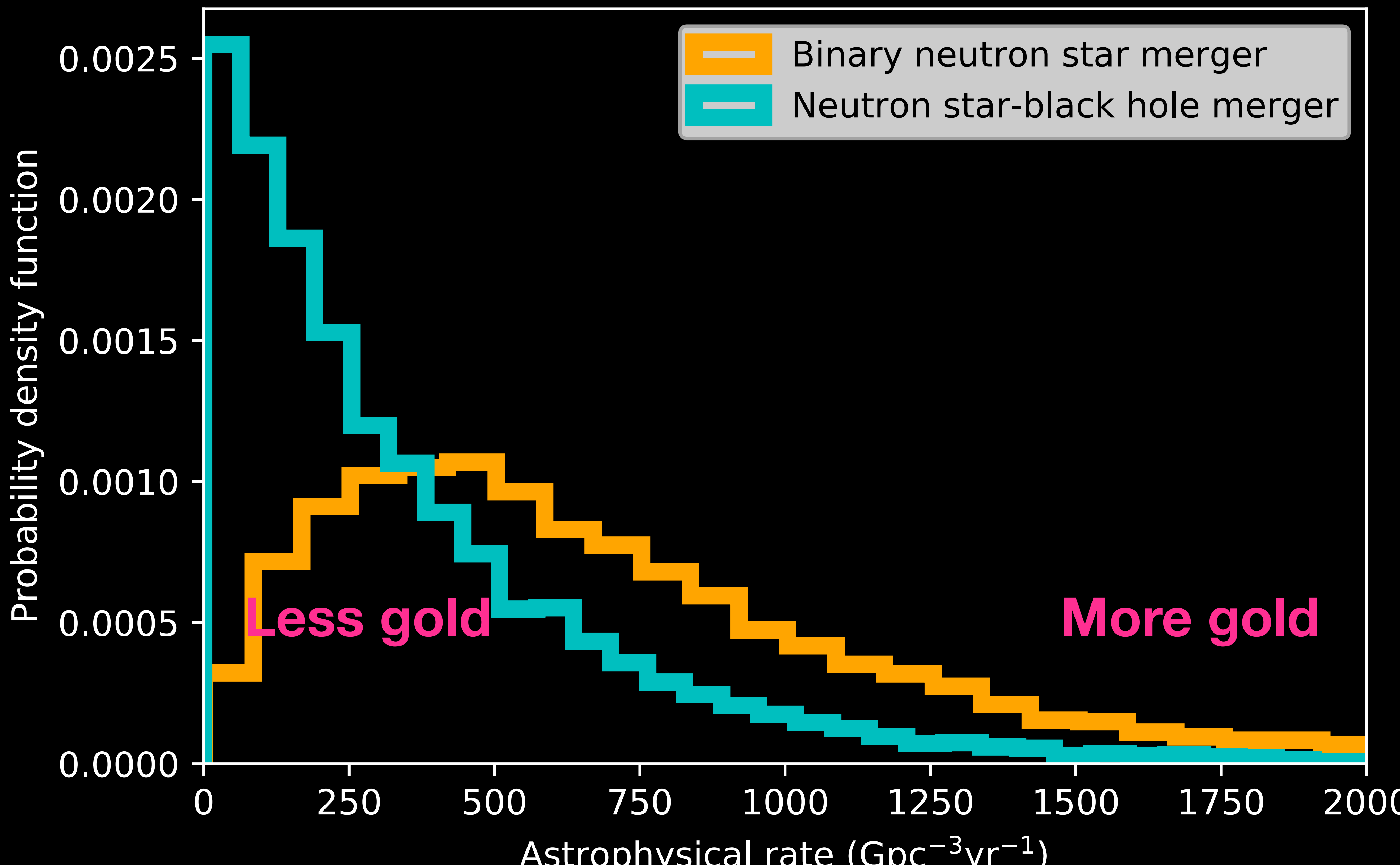


Abbott et al., ApJL (2021)

The black hole spins didn't show too much support to the aligned component.

How often did they merge? The astrophysical rates.

-Inferred from LIGO-Virgo neutron star merger observations.



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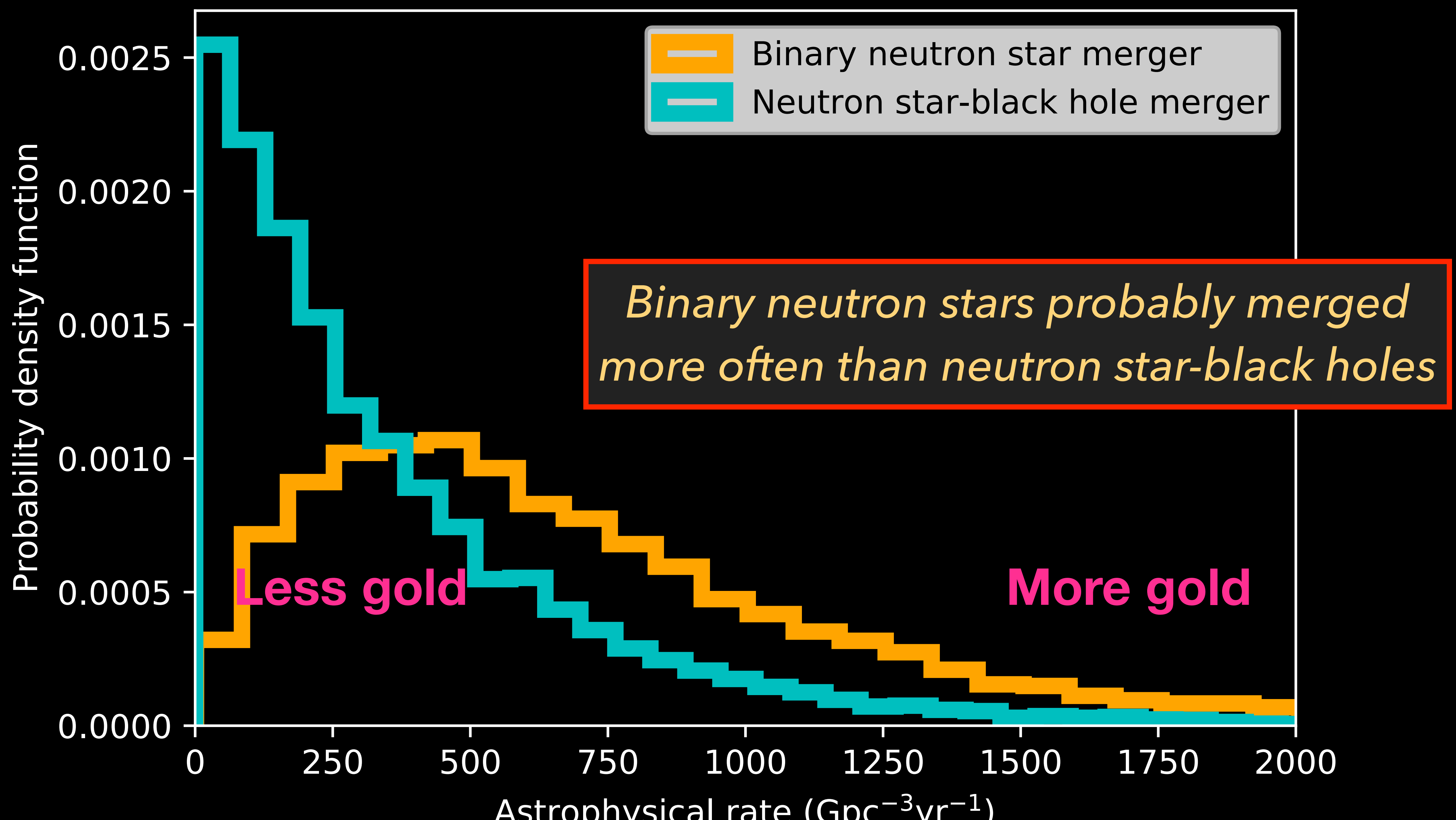

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Different sources of uncertainties

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LIGO-Virgo

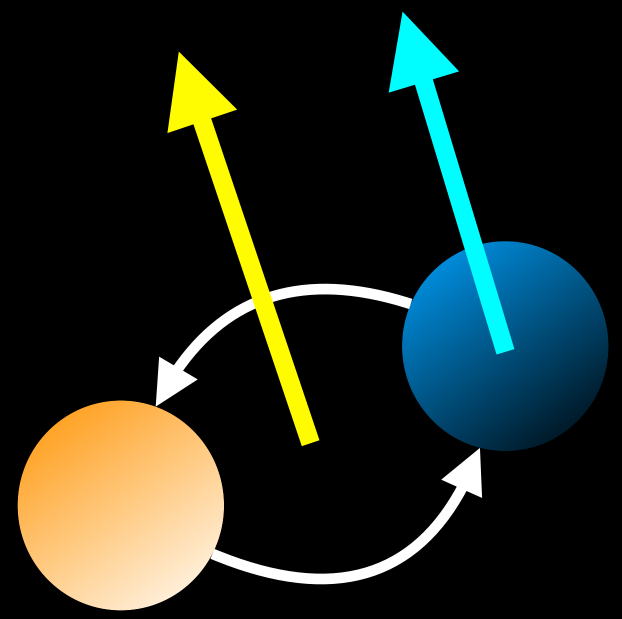
-Astrophysical rate of binary neutron star and neutron star-black hole mergers. ✓

Optimal fraction of neutron star-black hole ejecta

$$\frac{M_{\mathrm{ejecta,NSBH}}}{M_{\mathrm{ejecta,NSBH}} + M_{\mathrm{ejecta,BNS}}}$$

Pick the scenarios (EoS, uncertainty of fitting formula, astrophysical rate) that maximize the fraction of neutron star-black hole ejecta.

The effect of black hole spin distribution



Chen, Vitale & Foucart, 2107.02714, ApJL (2021)

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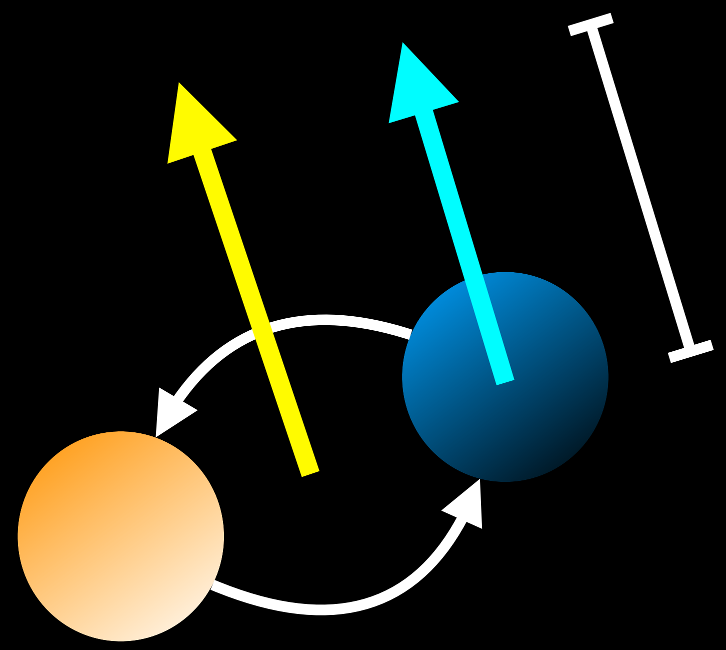

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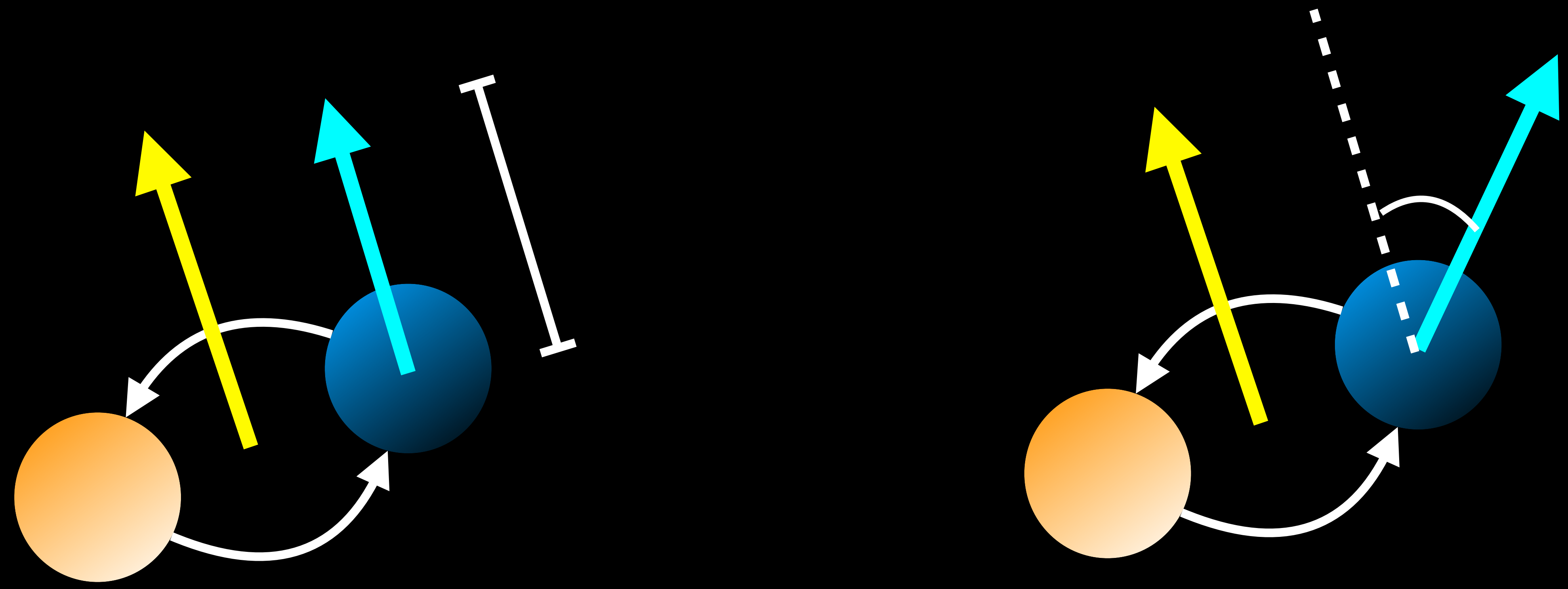

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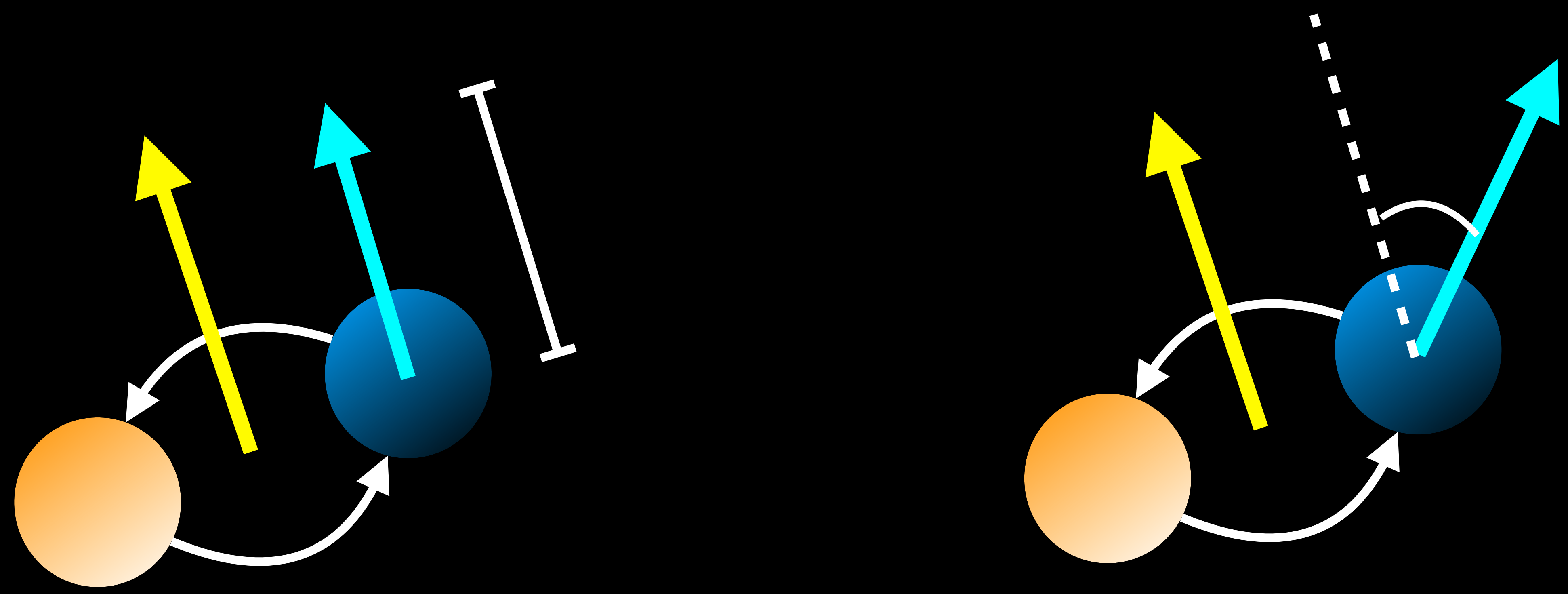

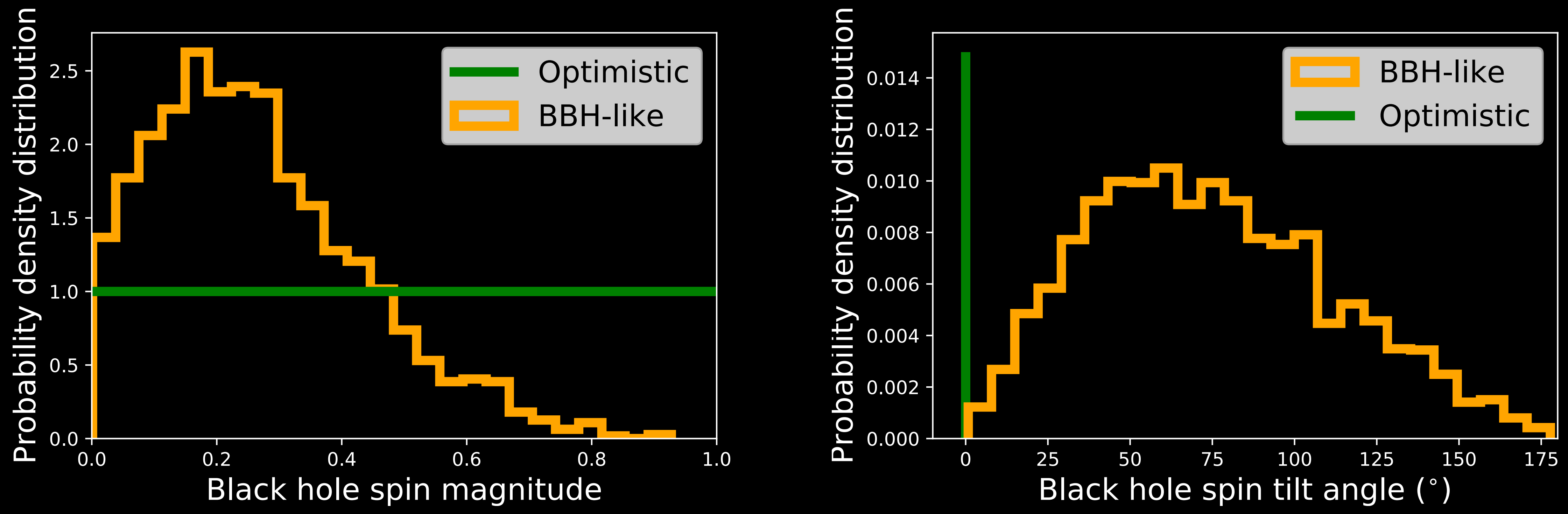

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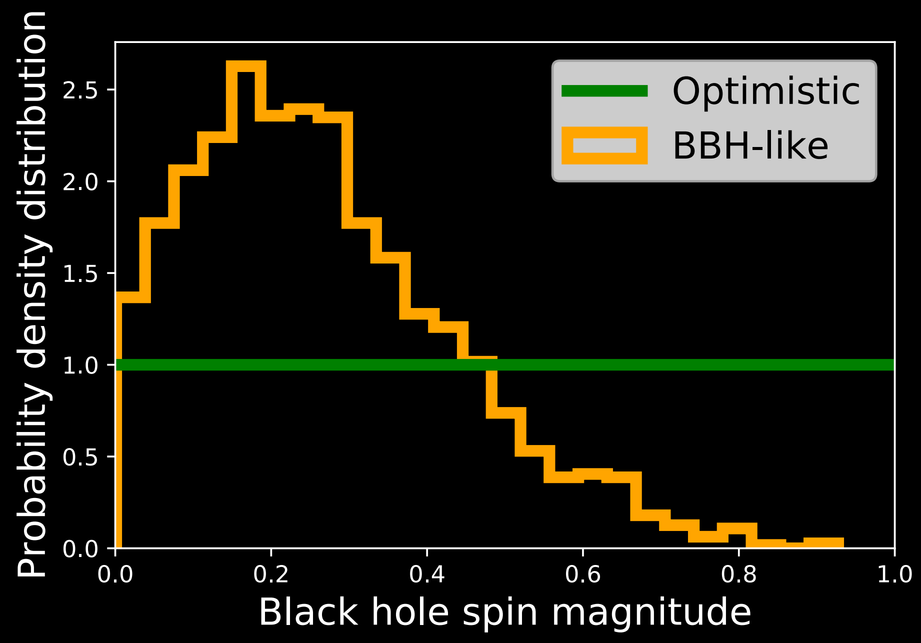

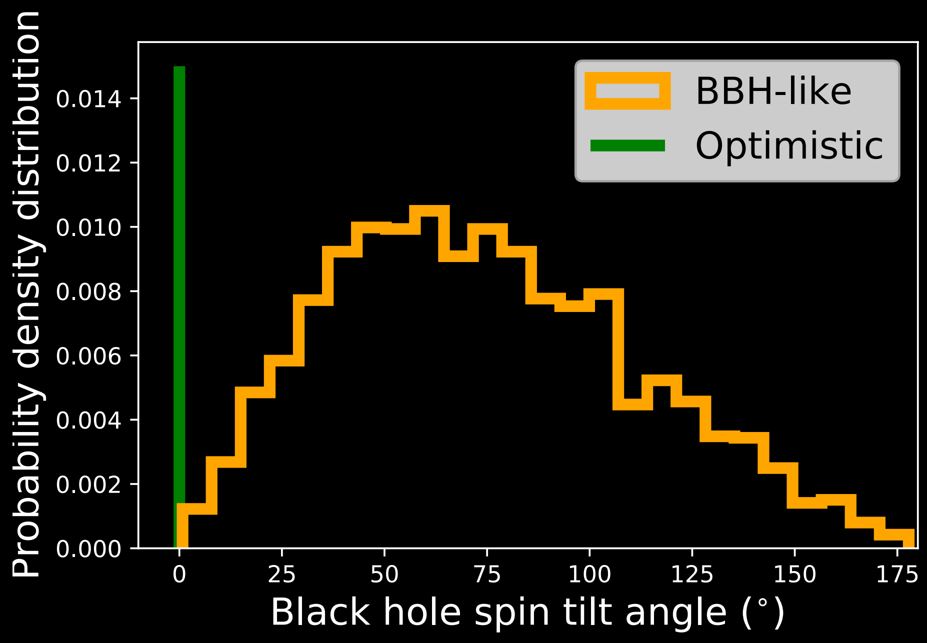

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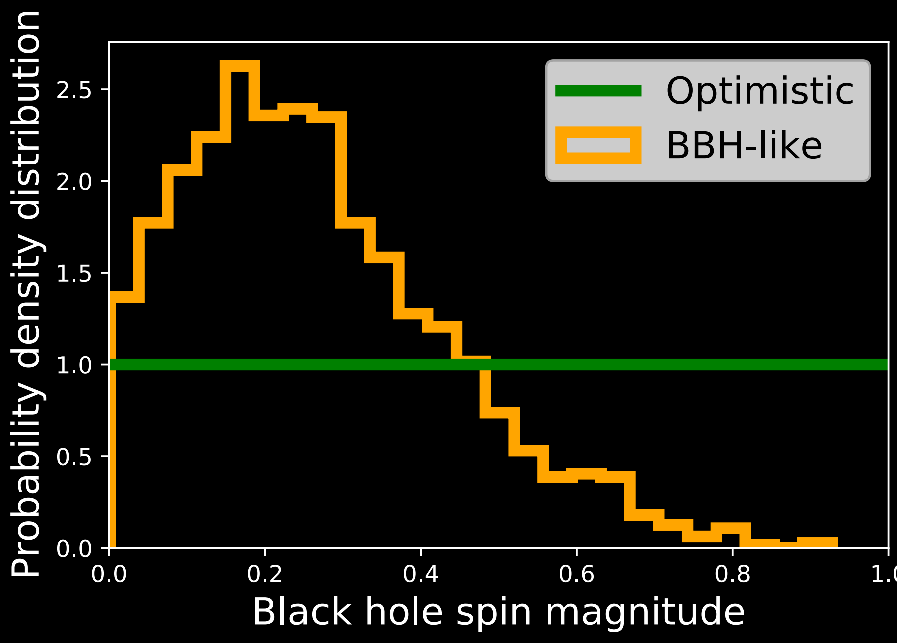

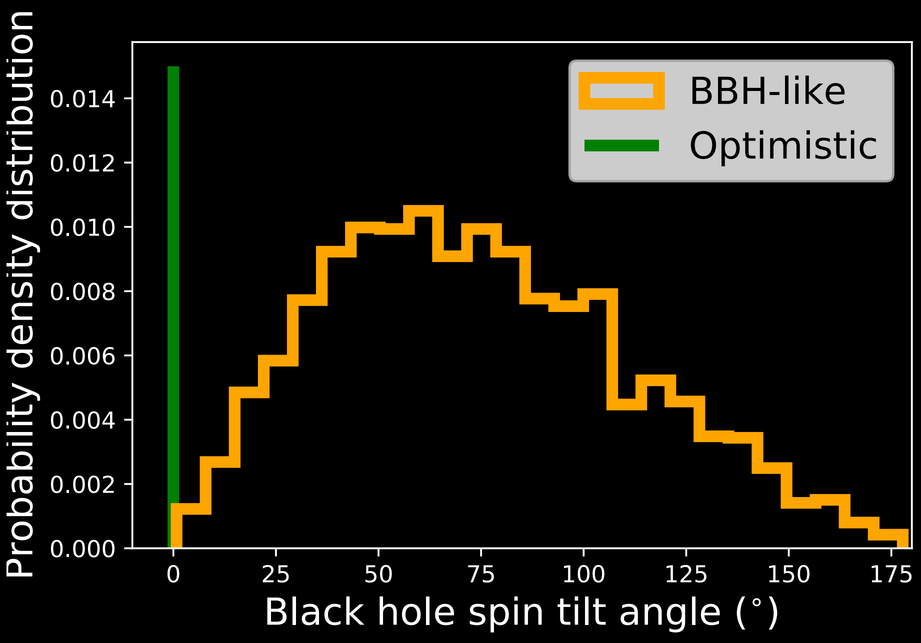

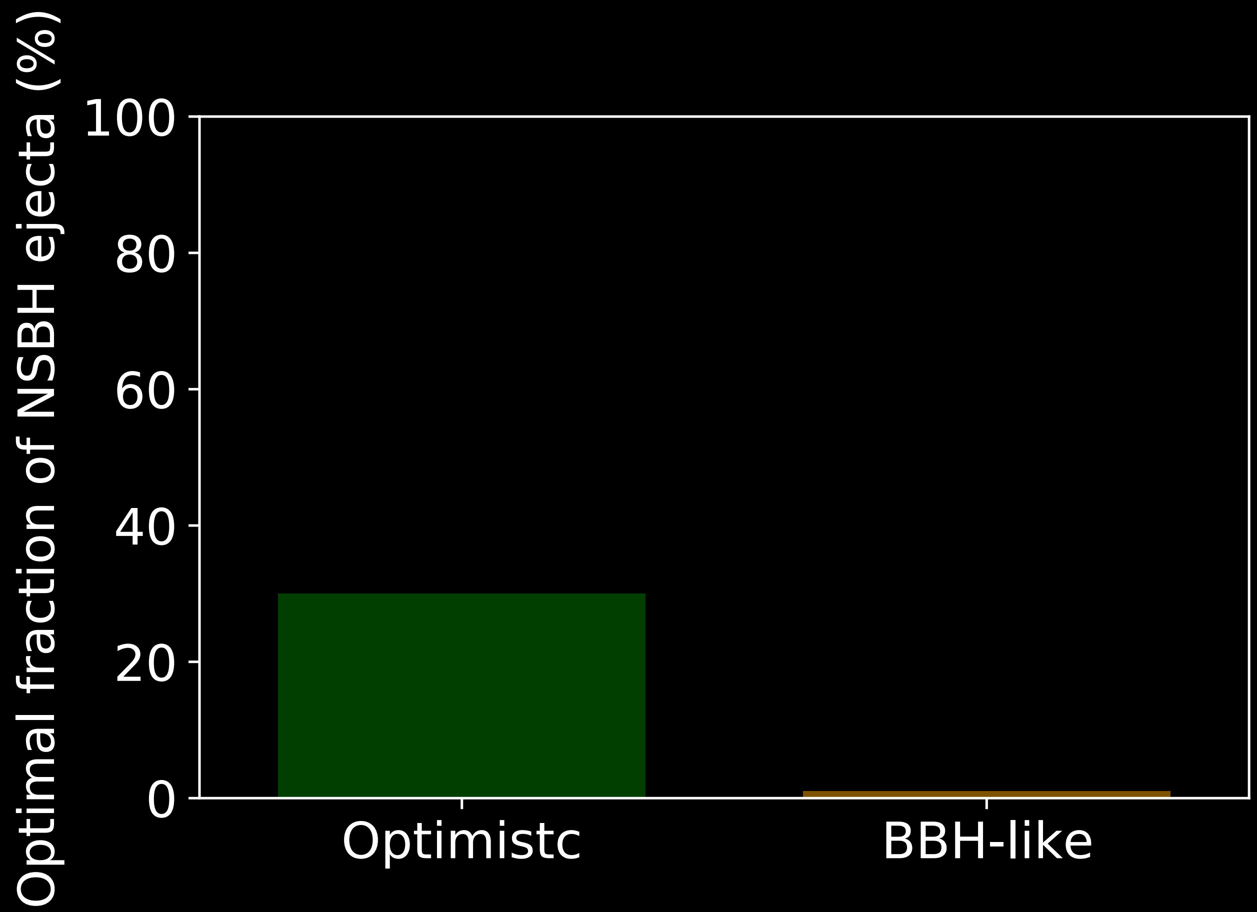

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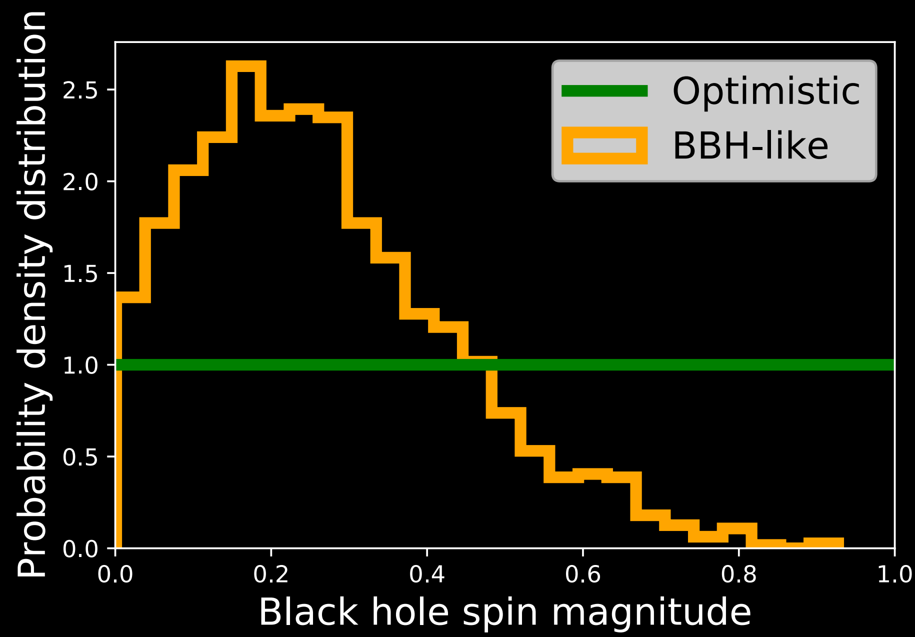

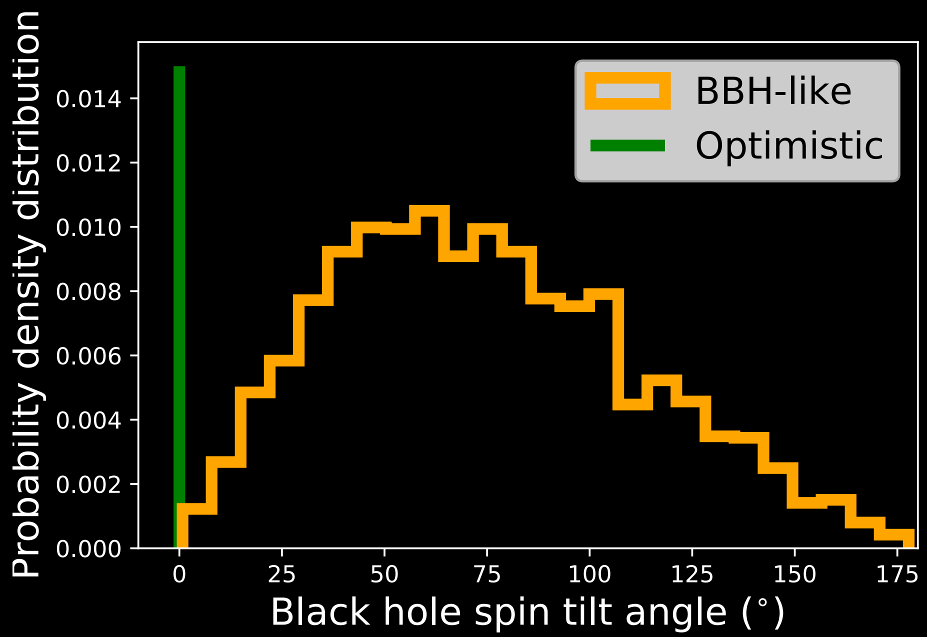

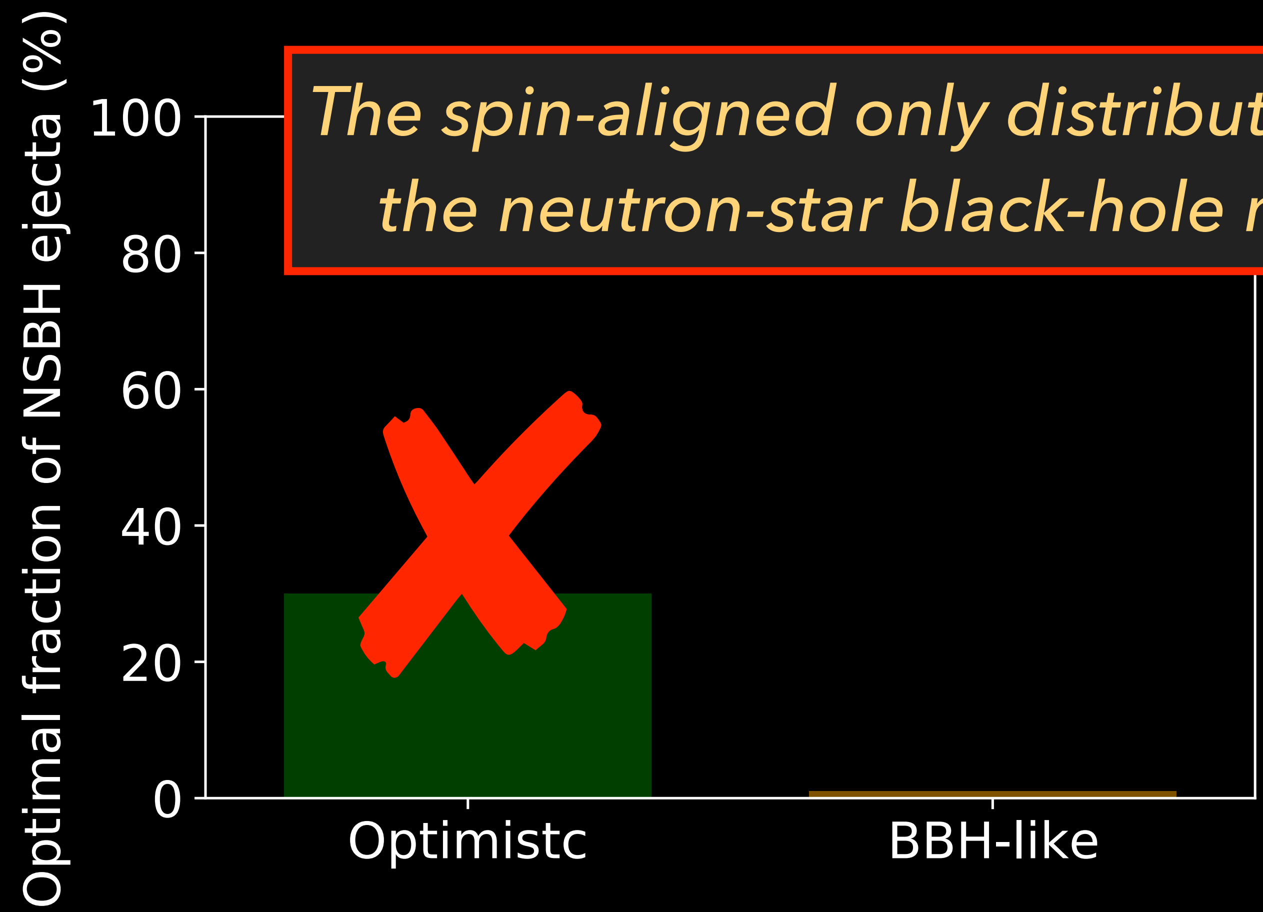

The spin-aligned only distribution is inconsistent with the neutron-star black-hole merger observations.

Chen, Vitale & Foucart, 2107.02714, ApJL (2021)

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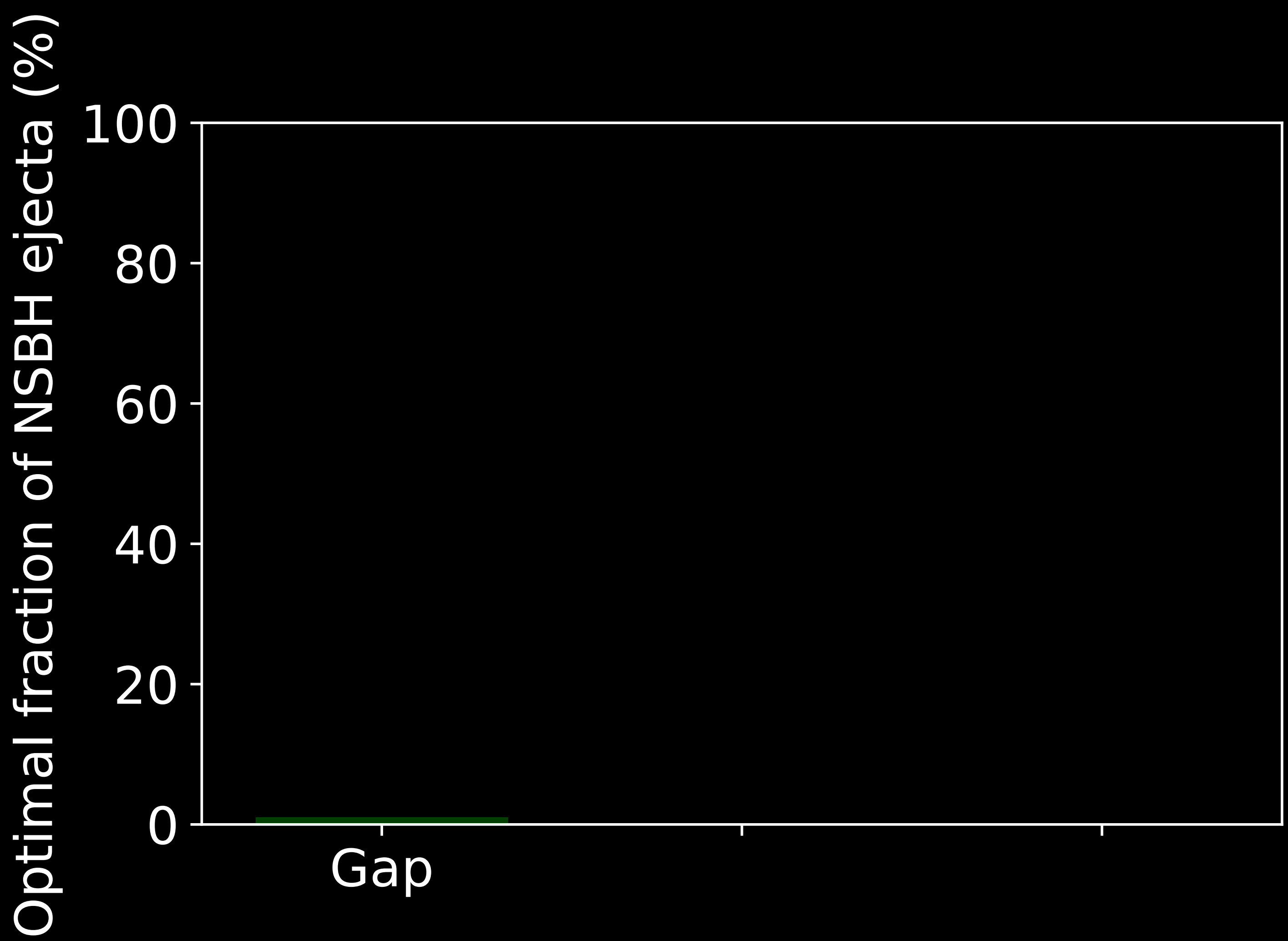

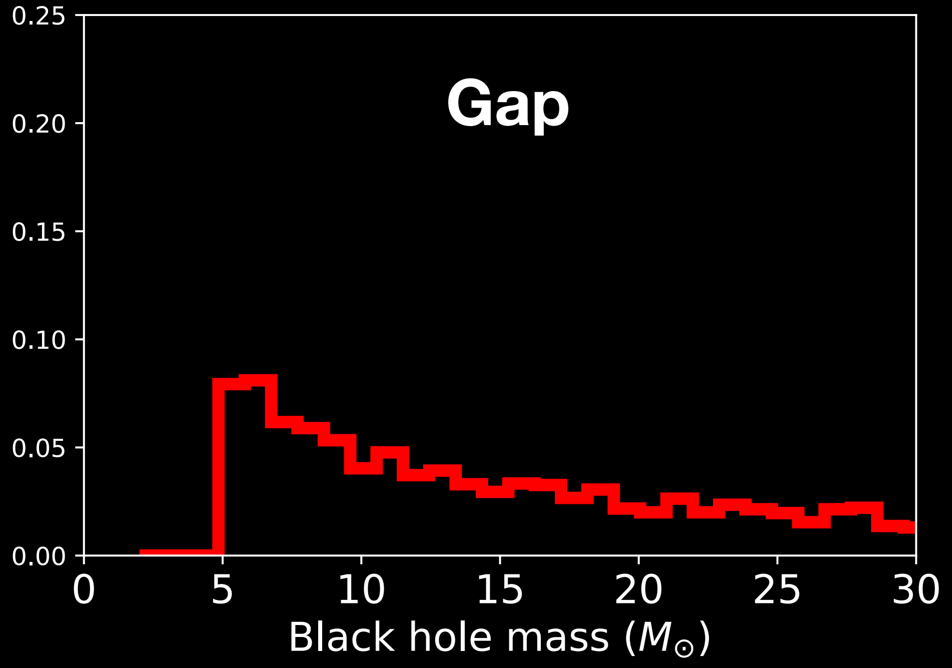

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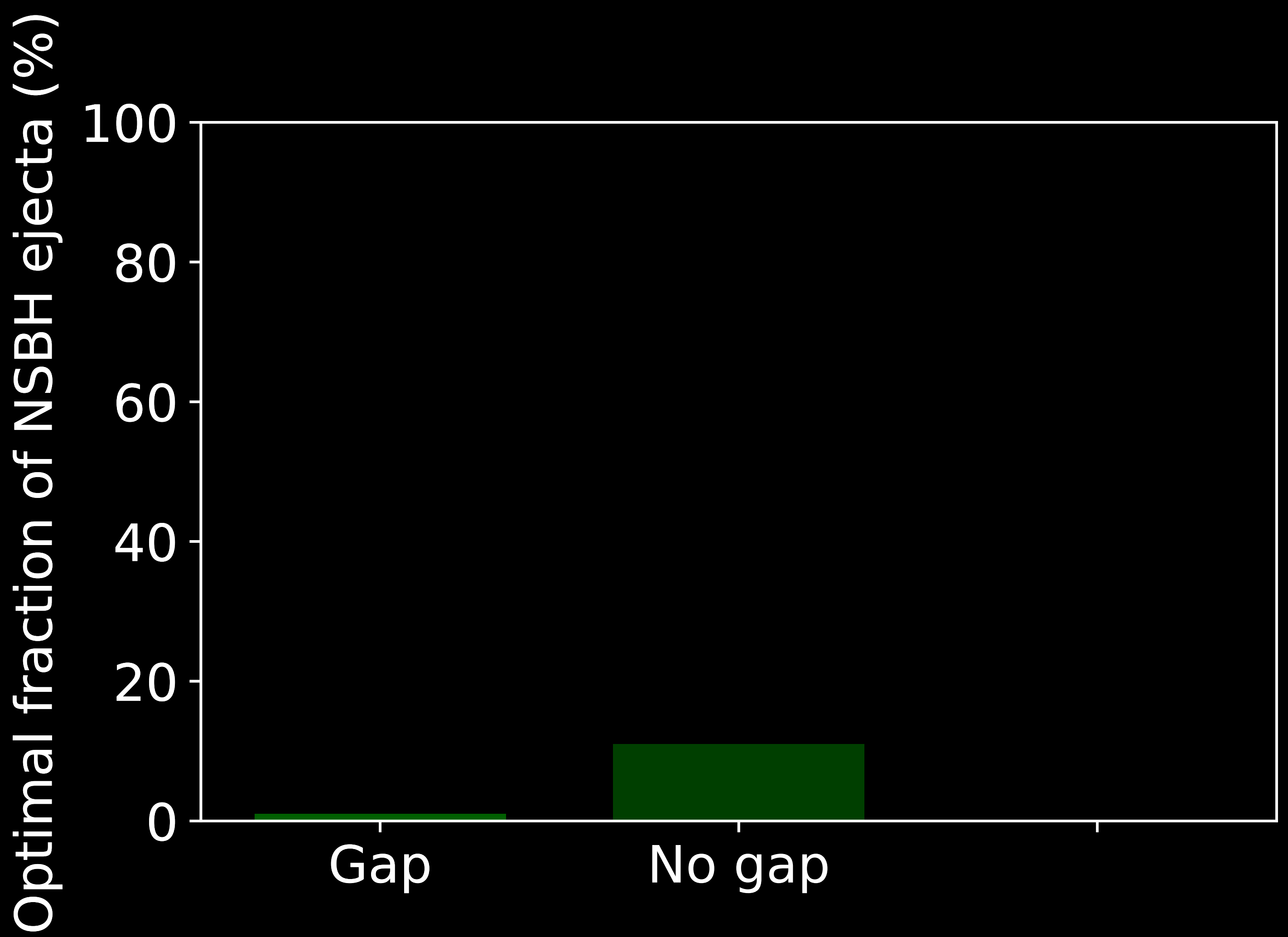

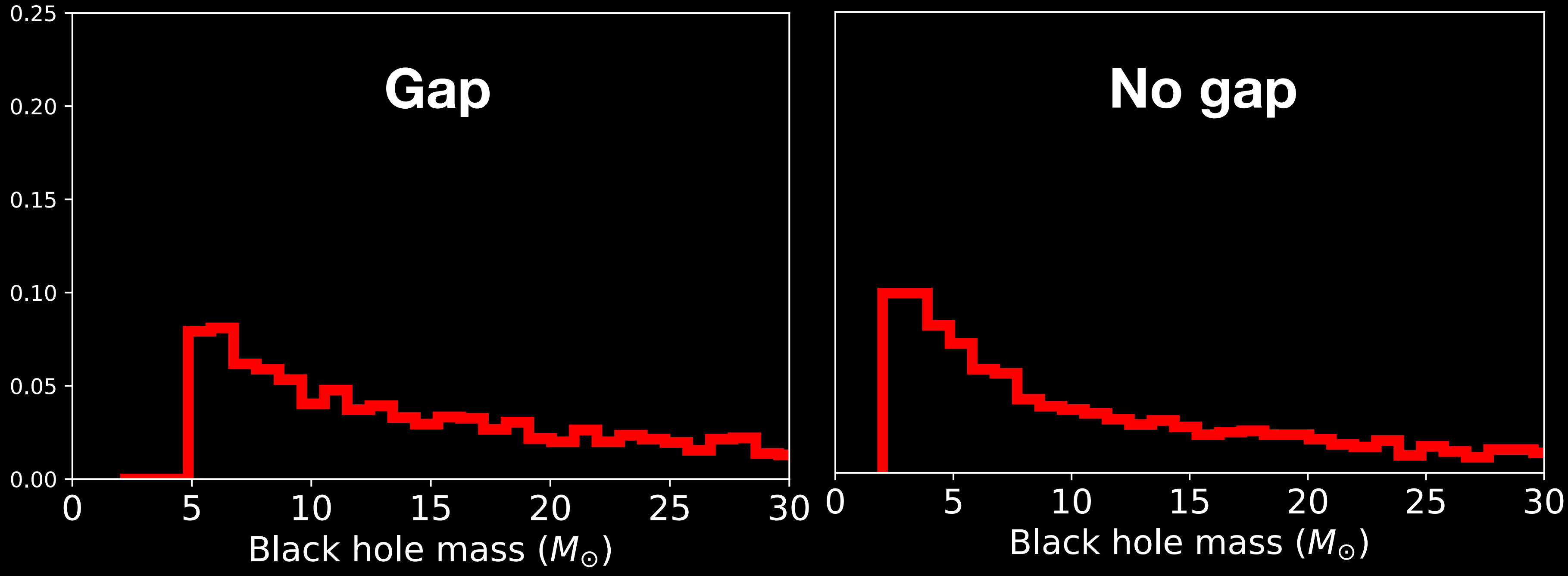

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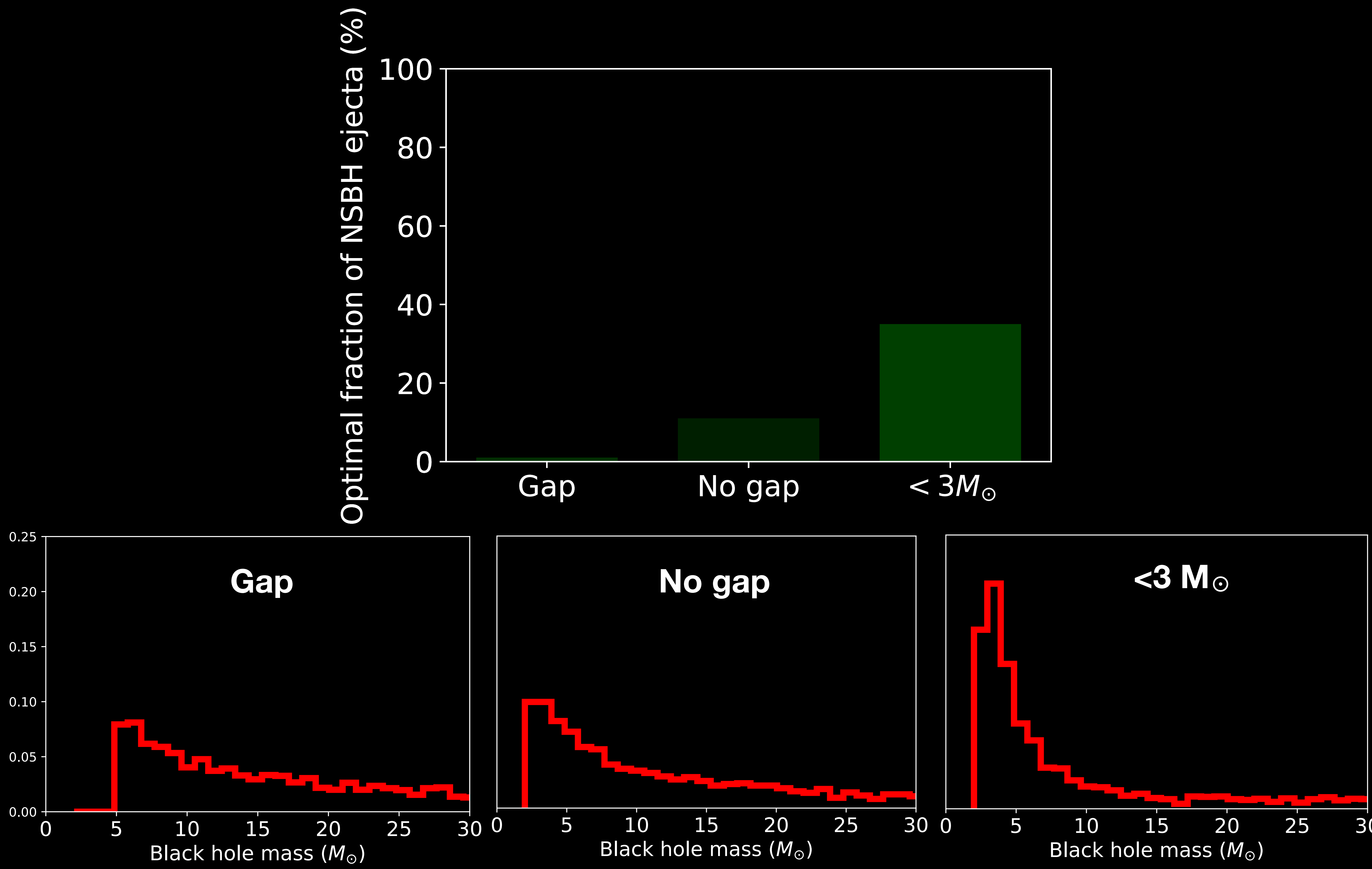

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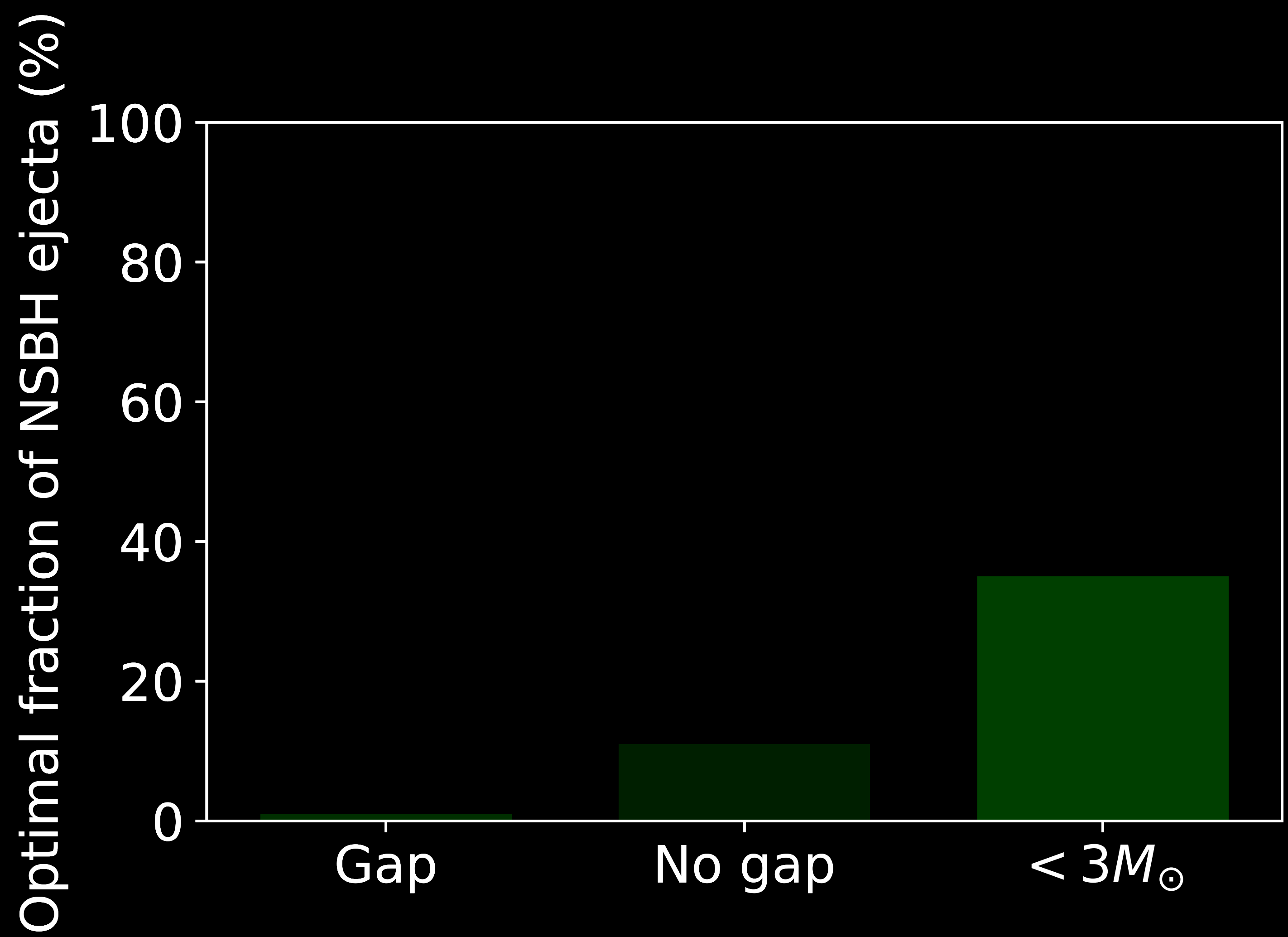
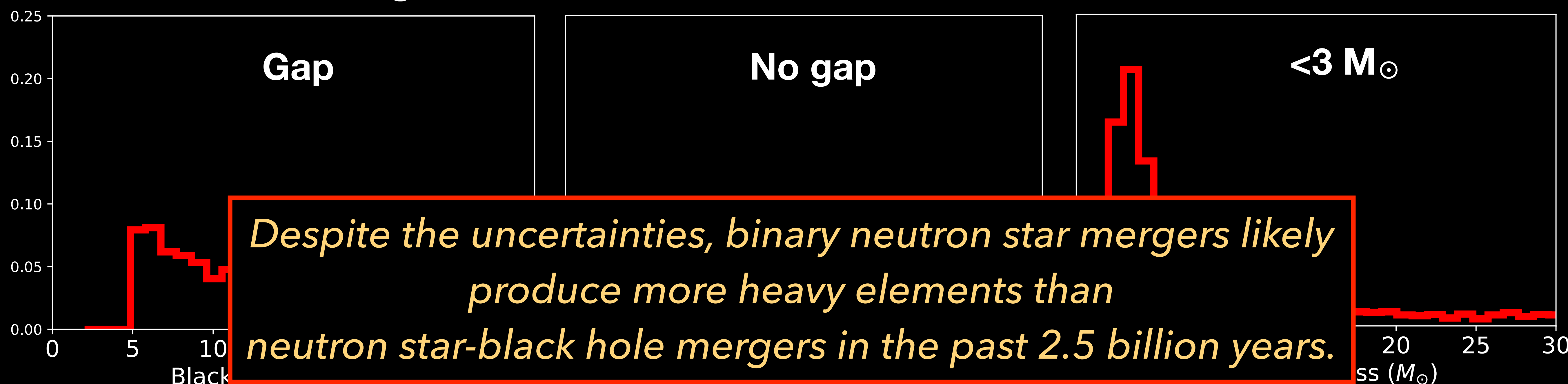




Despite the uncertainties, binary neutron star mergers likely produce more heavy elements than neutron star-black hole mergers in the past 2.5 billion years.

Reconstructing the heavy-element production history

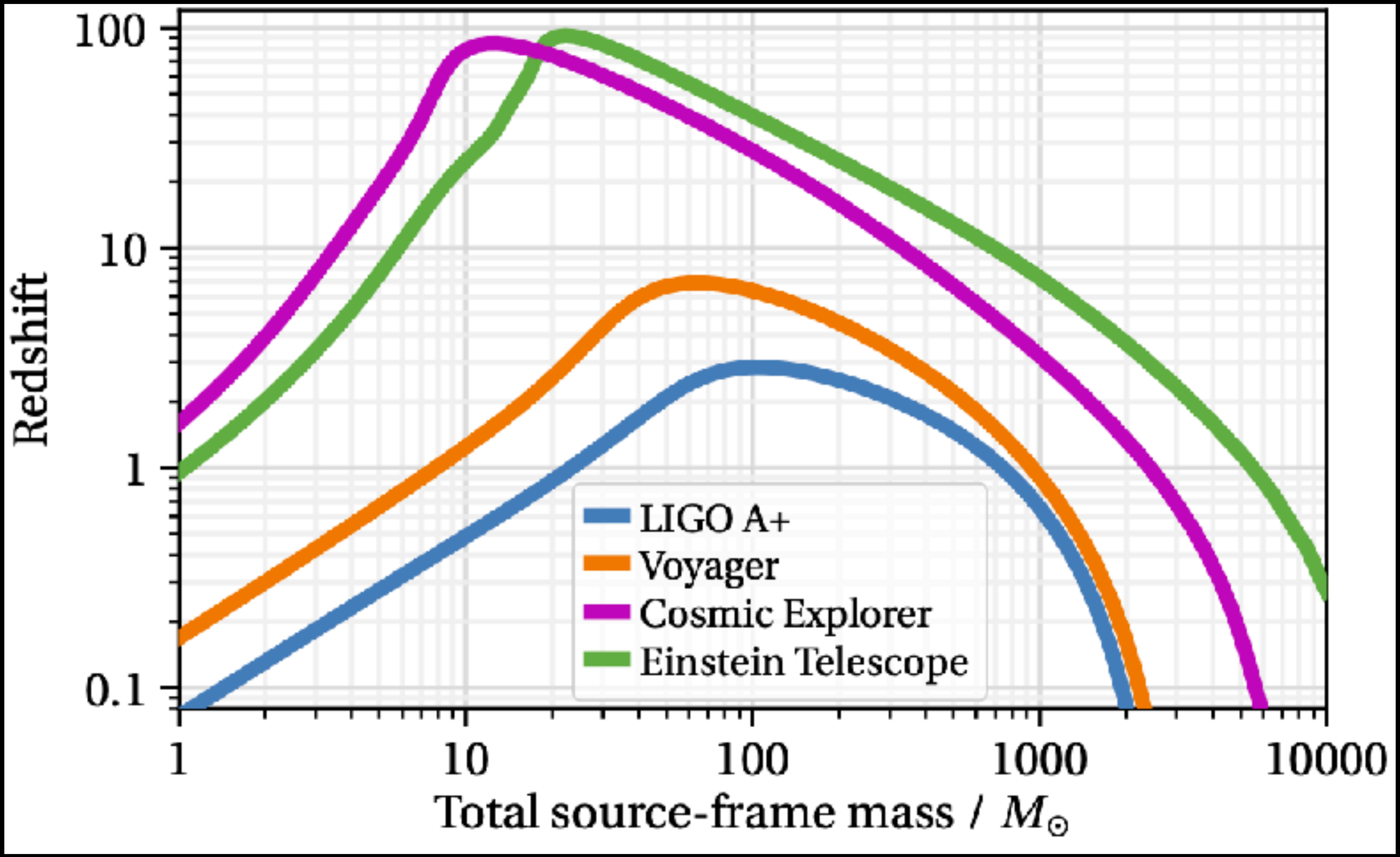
-The Solar system is 4.6 billion years old.

Wallner et al., Nature Communications (2015)

-The r-process element enriched stars in Reticulum II ultra-faint dwarf galaxy are >10 billion years old.

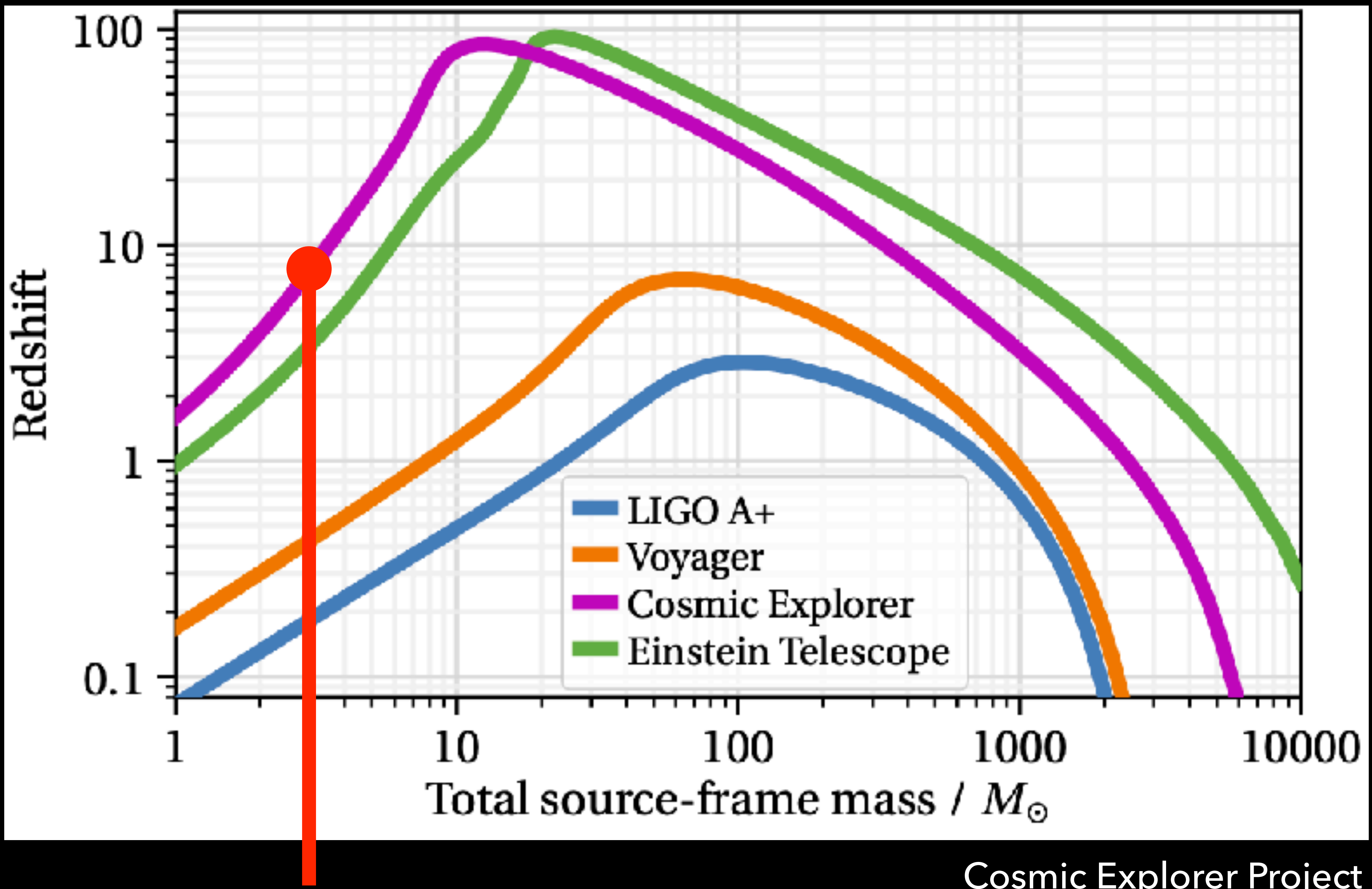
Credit: Y. Beletsky (Carnegie Observatories)

Reconstructing the heavy-element production history



Cosmic Explorer Project

Reconstructing the heavy-element production history



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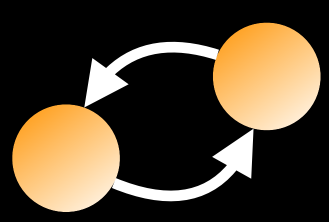

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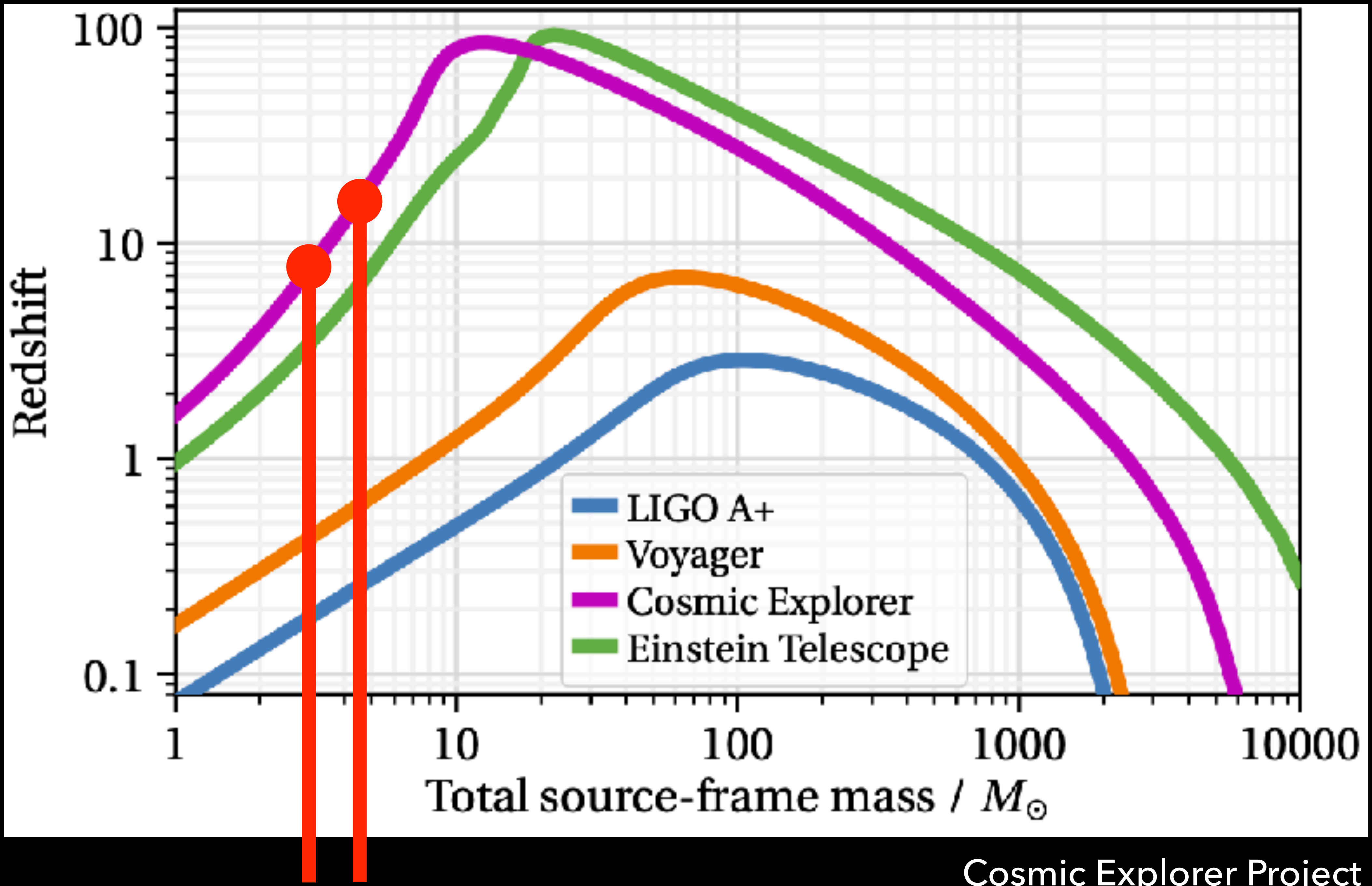
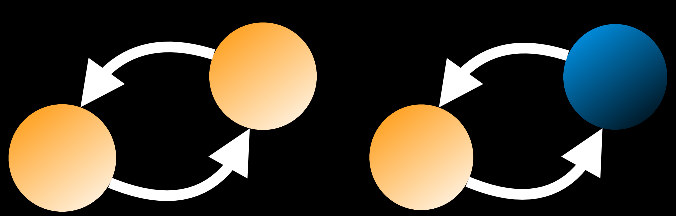
Reconstructing the heavy-element production history



Cosmic Explorer Project



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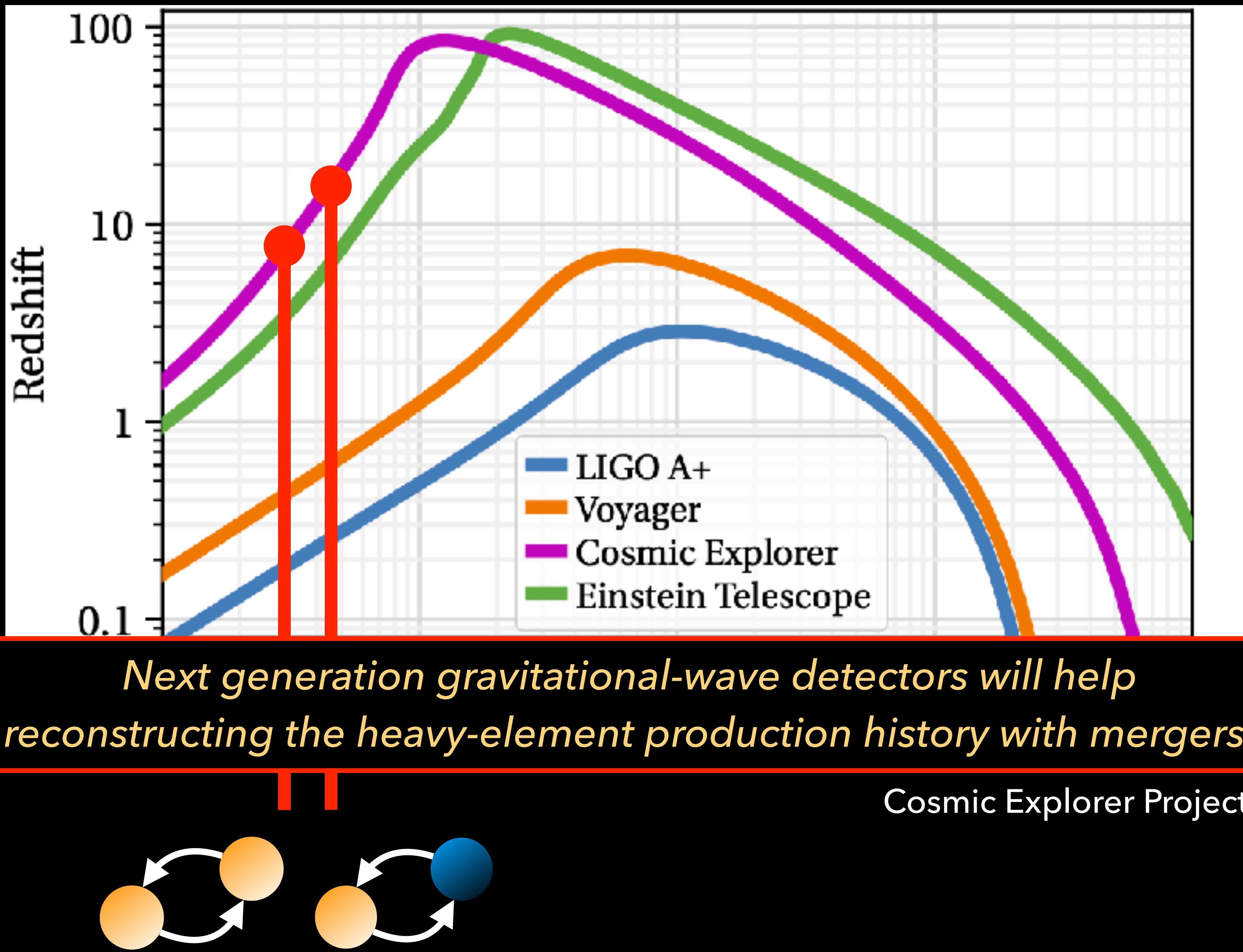

Next generation gravitational-wave detectors will help reconstructing the heavy-element production history with mergers.

Cosmic Explorer Project

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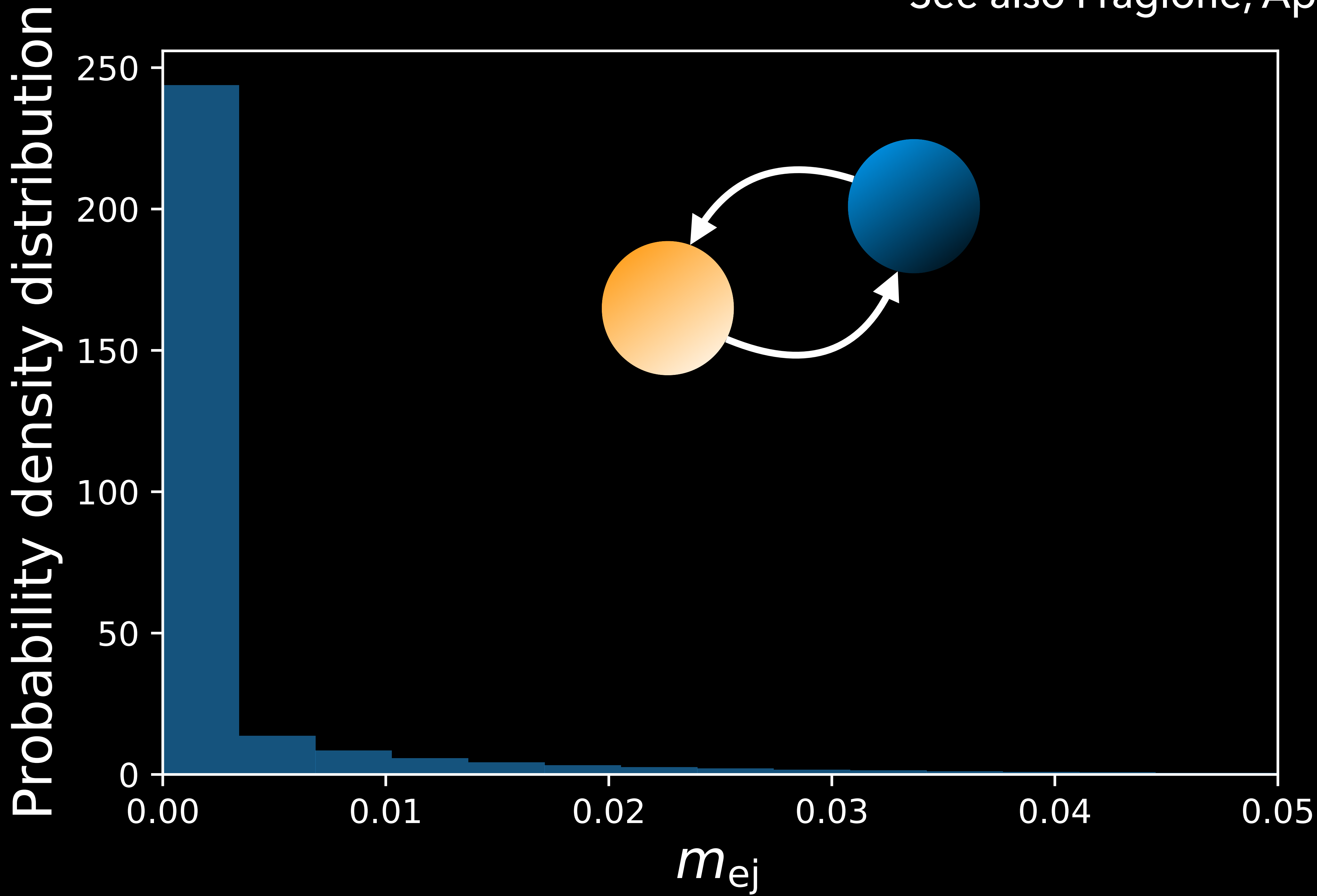
Further implications on the electromagnetic emissions

See also Fragione, ApJL (2021)



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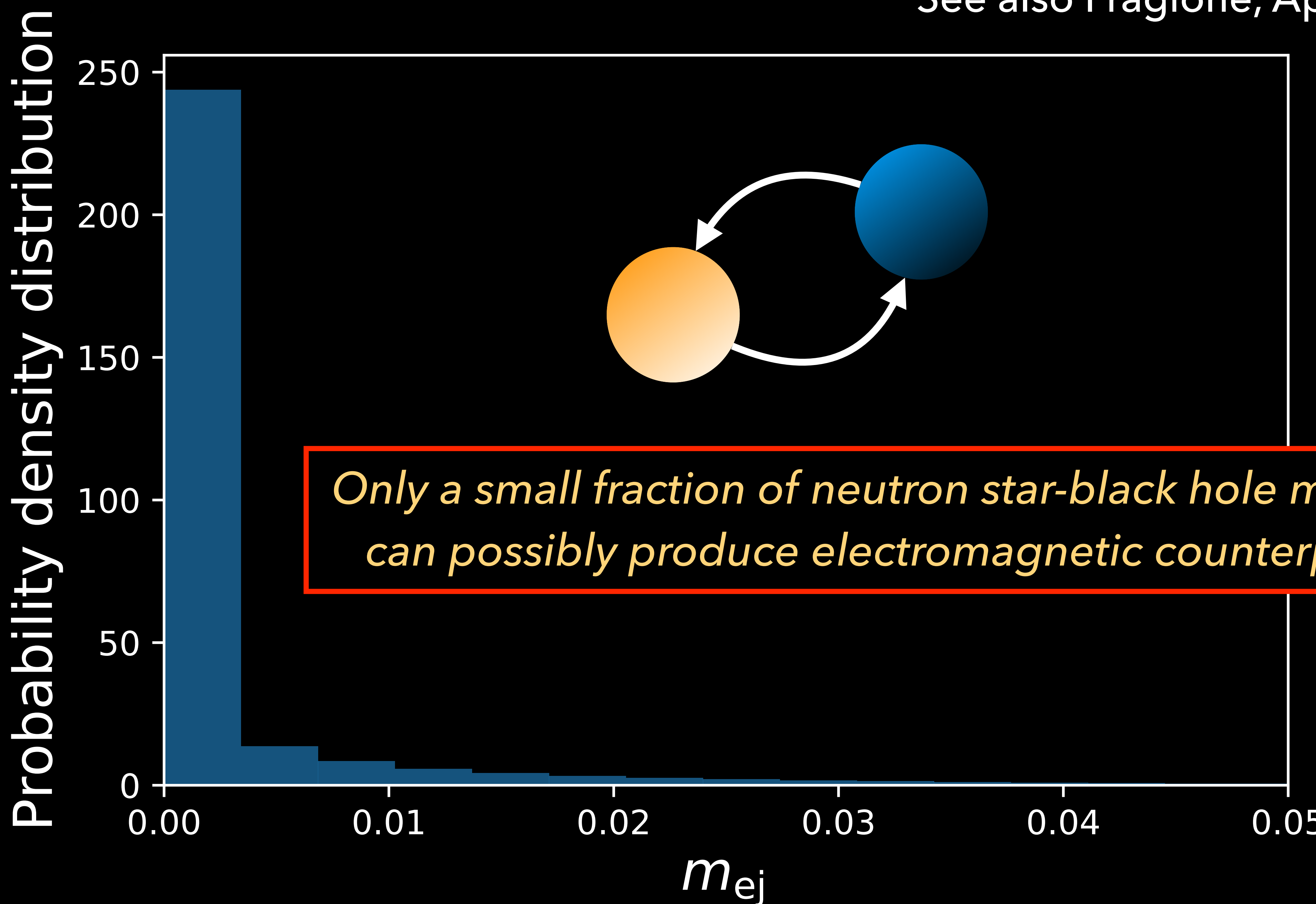
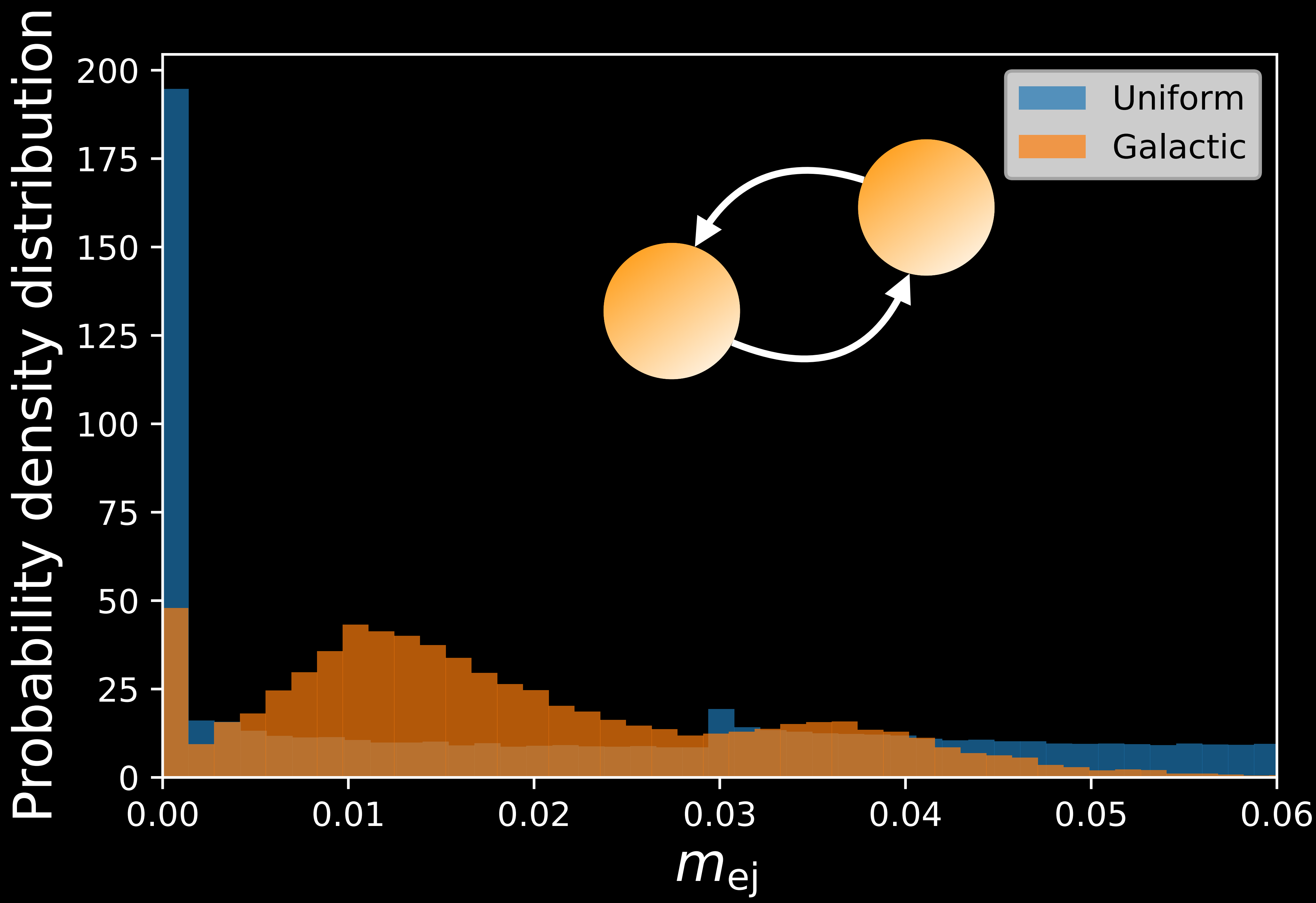


Only a small fraction of neutron star-black hole mergers can possibly produce electromagnetic counterparts.

Further implications on the electromagnetic emissions



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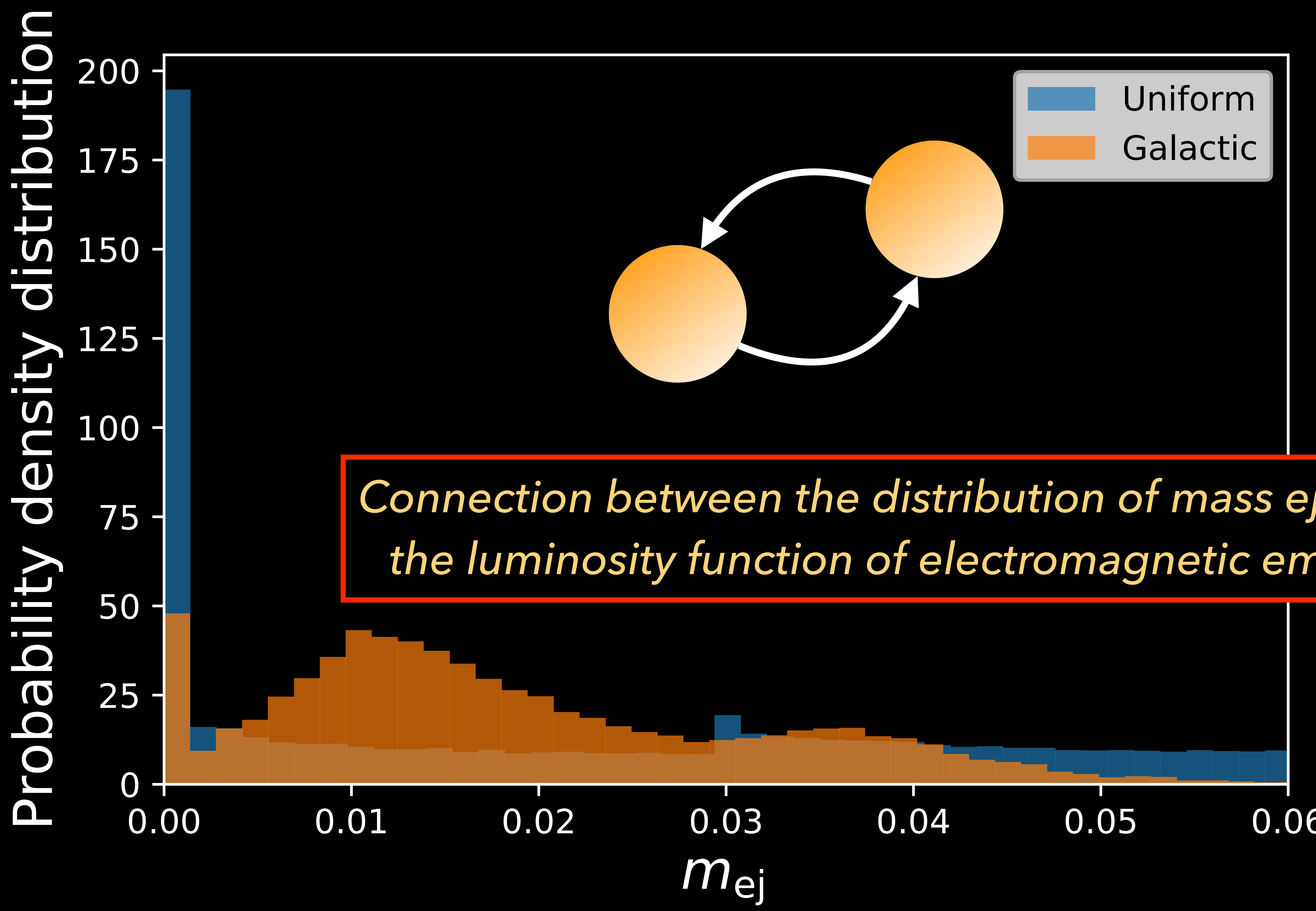
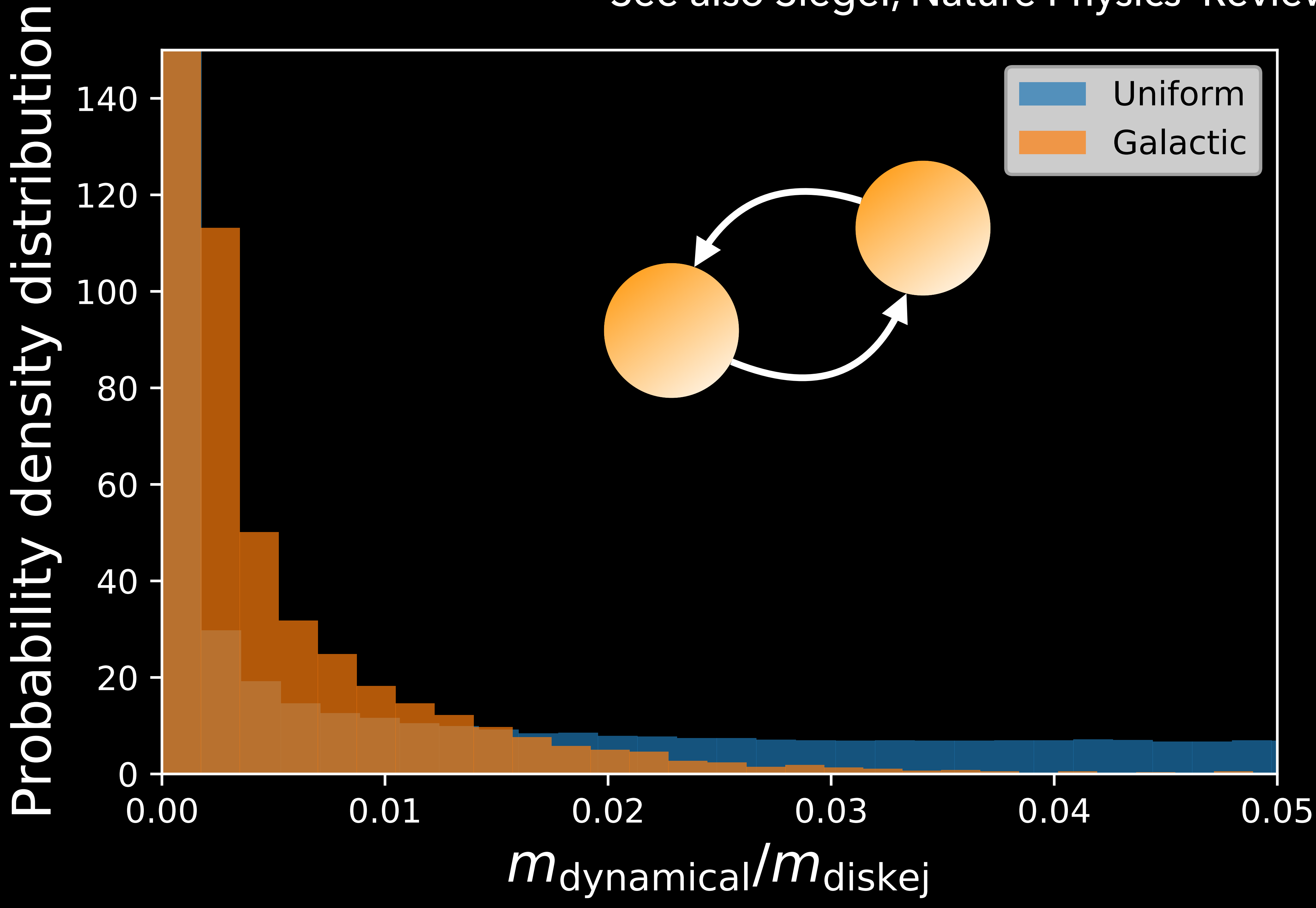


Connection between the distribution of mass ejecta with the luminosity function of electromagnetic emissions.

Relative ratio of different ejecta

See also Siegel, Nature Physics Reviews (2022)



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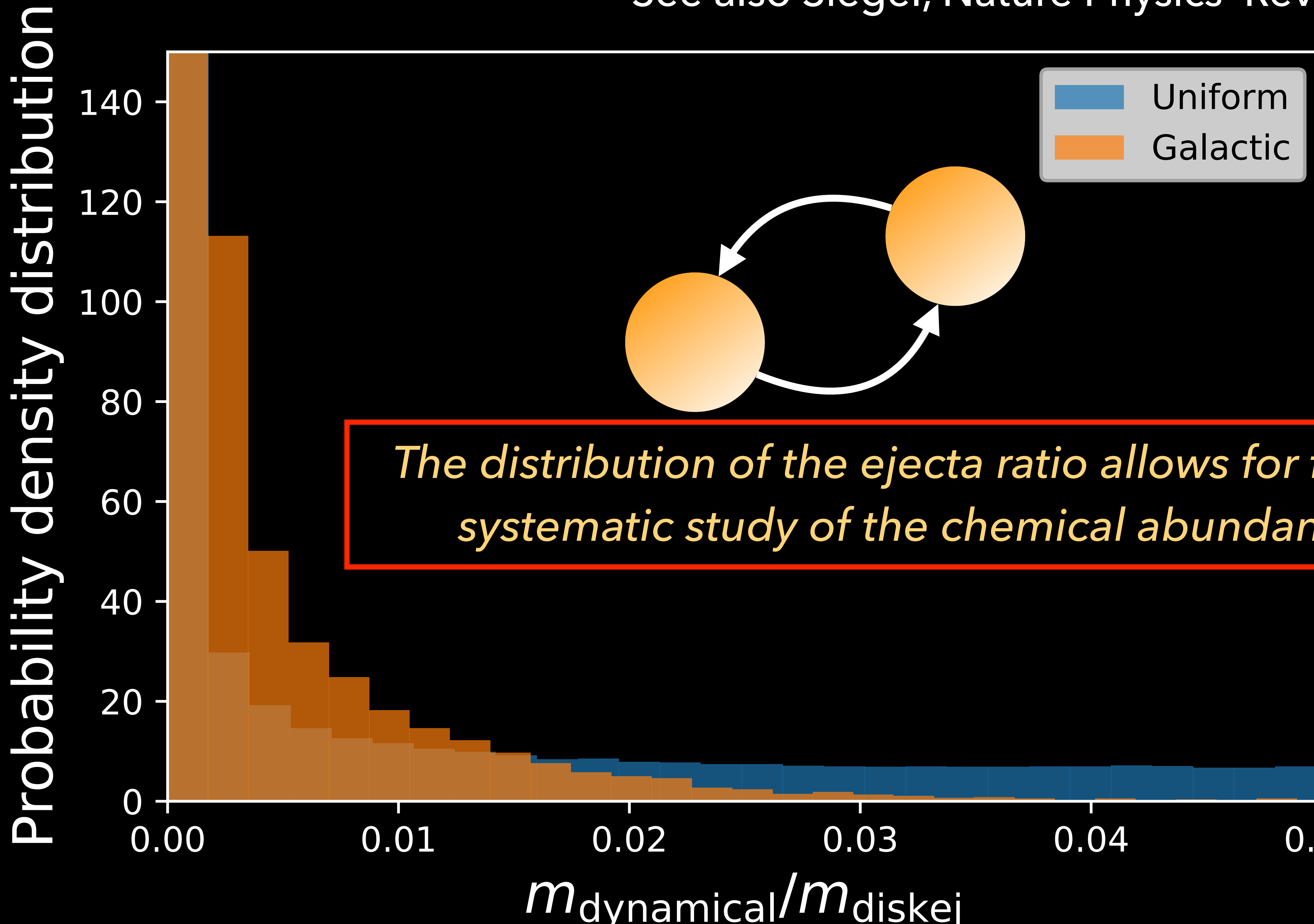

The distribution of the ejecta ratio allows for further systematic study of the chemical abundance.

Summary

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-With a few years of Advanced LIGO-Virgo observations (O4+O5), the convergence of mass/spin/astrophysical rate distributions of mergers will allow for interesting constraints on the total amount of ejecta.

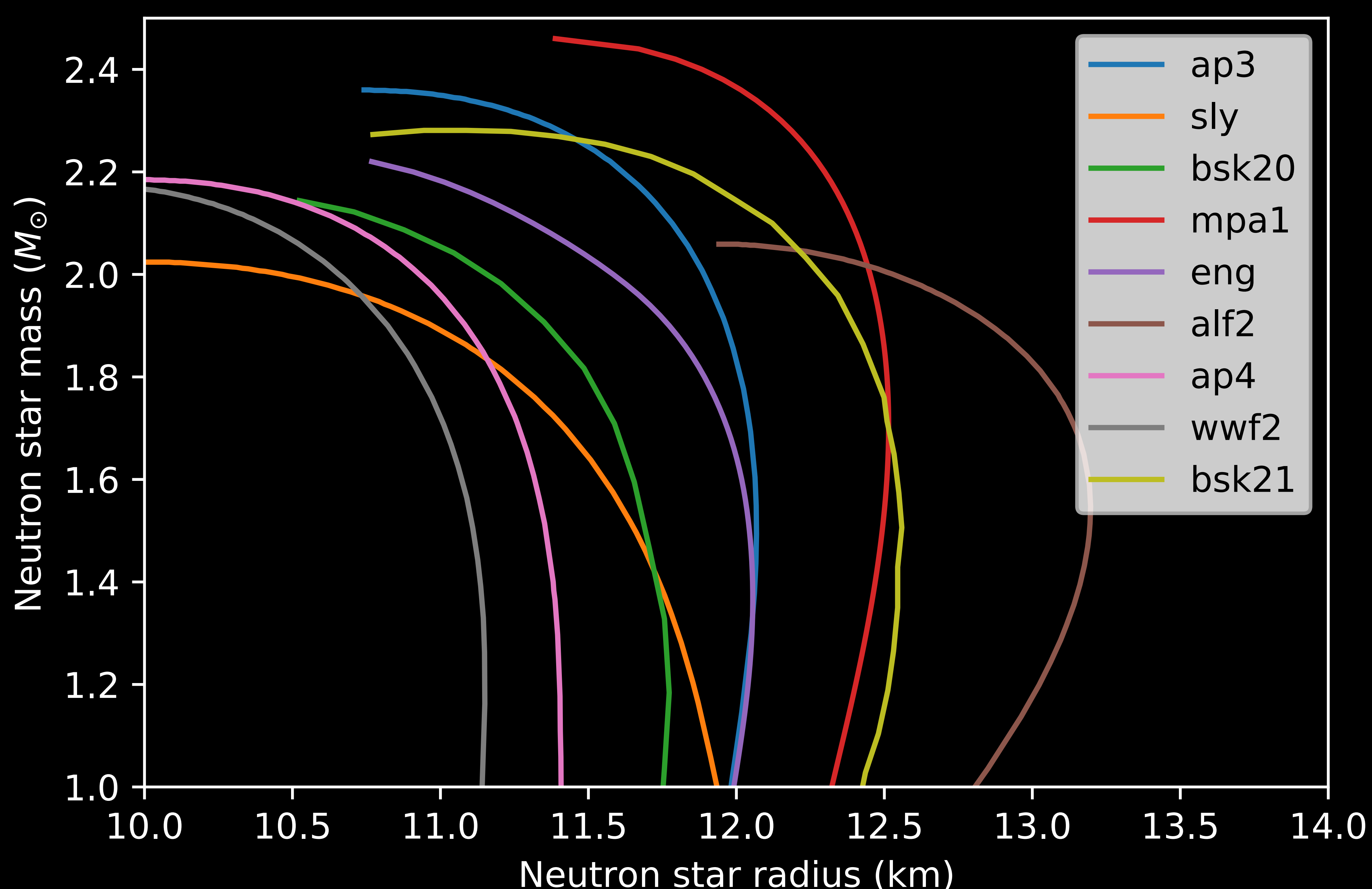
-Higher redshift gravitational-wave observations (2.5G+) will reconstruct the production history of heavy elements from mergers.

-Electromagnetic observations and numerical simulations will jointly provide deeper insight into the chemical abundance of the ejecta.

Thank you!

Measurement of neutron star equation-of-state

-Combination of gravitational-wave, radio and x-ray observations.



Ozel et al. (2016), Bagdanov et al. (2016), Ozel&Freire (2016),Raaijmakers et al.(2020)

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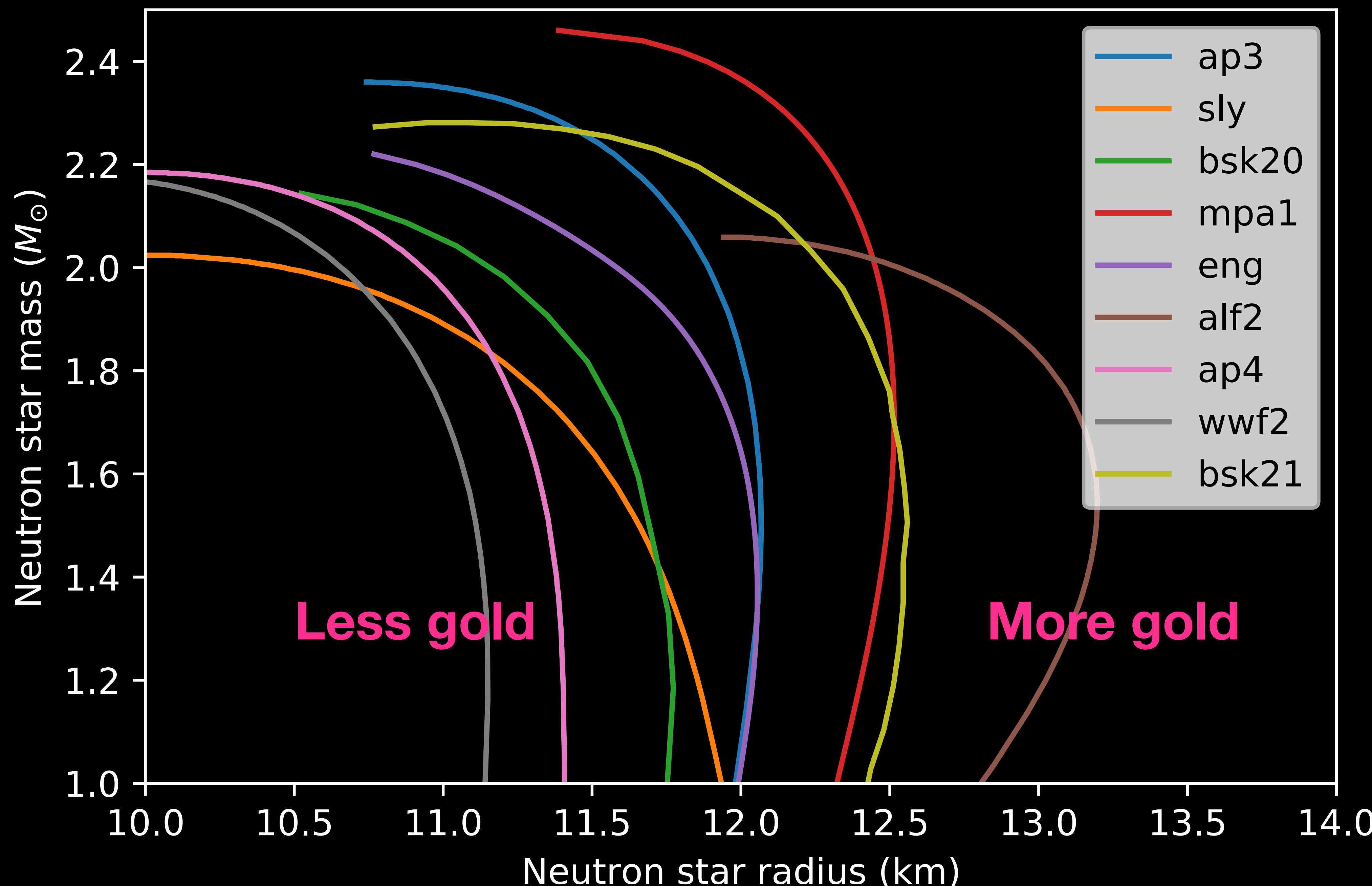

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