

# **Populations of binary compact objects: exciting prospects with gravitational-wave astronomy**

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Institut d'Astrophysique de Paris

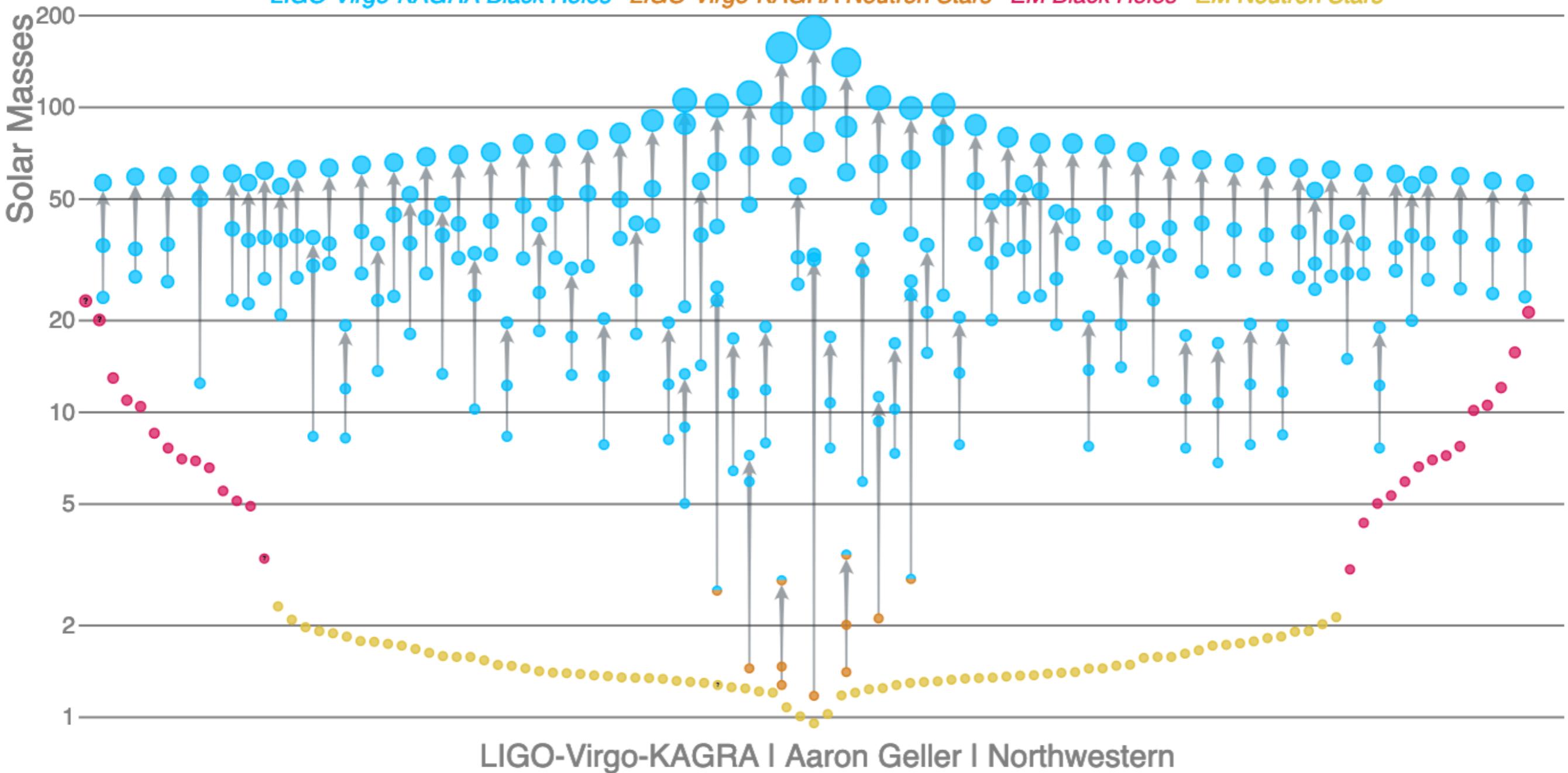
Sorbonne Université



**GWADW 2023, Isola d'Elba, 22 May 2023**

# Masses in the Stellar Graveyard

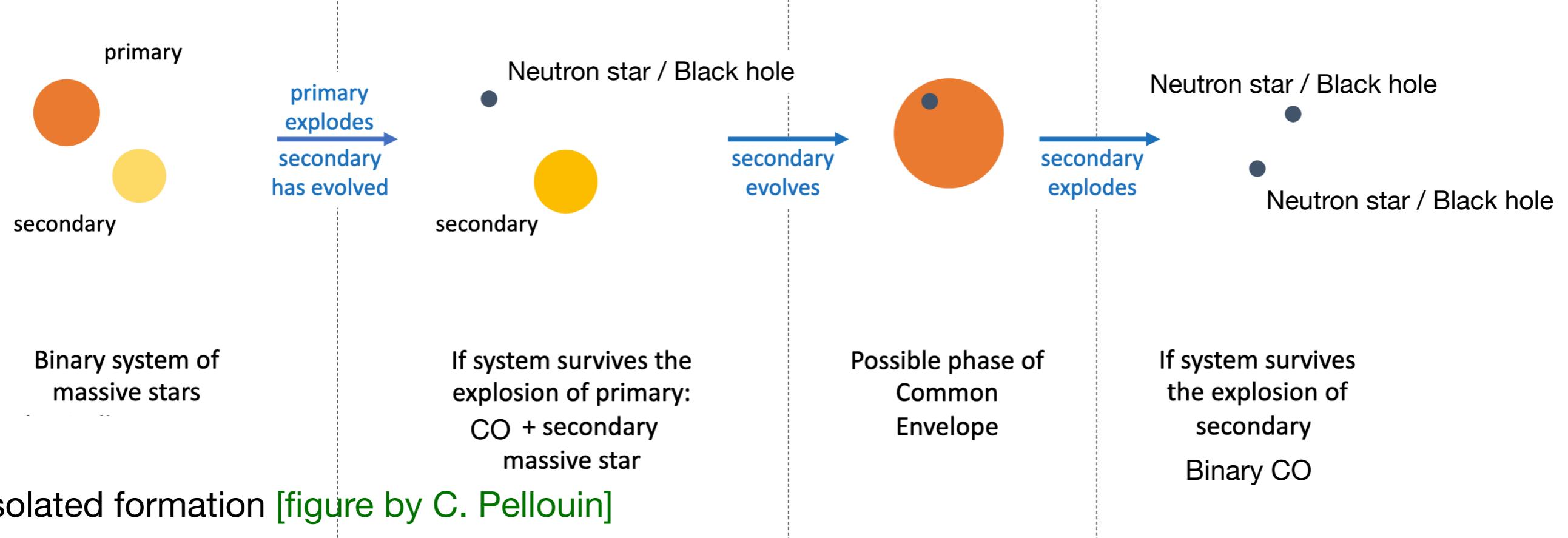
LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



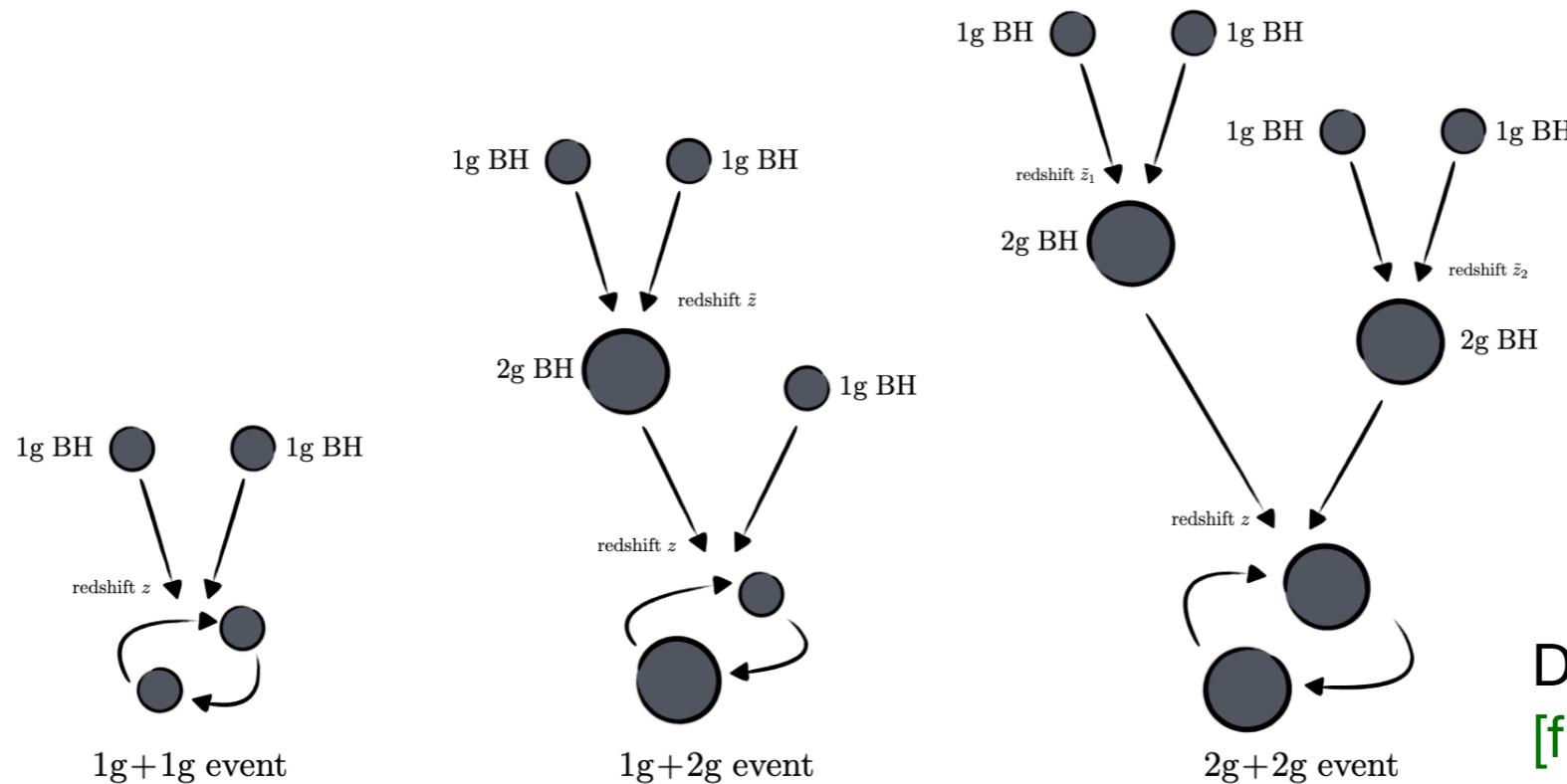
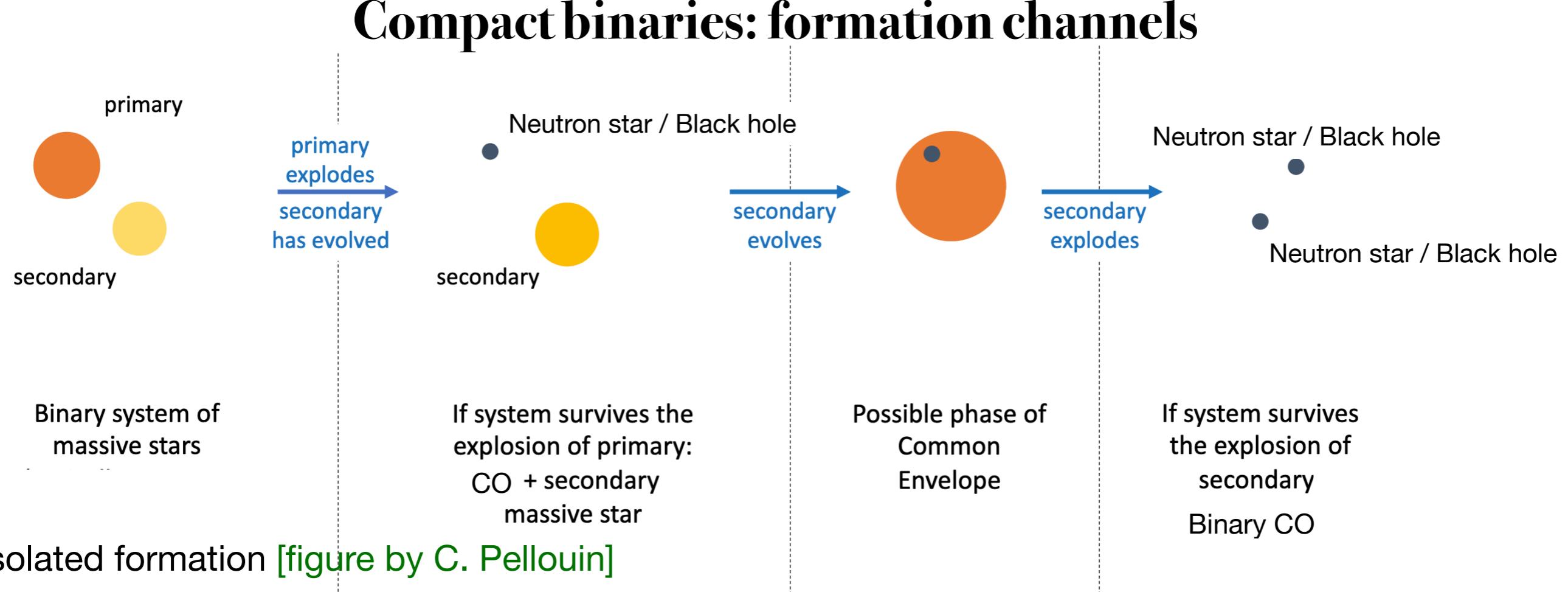
Abbott et al. 2019, PRX, 9, 031040; Abbott et al. 2021, PRX, 11, 021053;

Abbott et al. 2021, arXiv:2111.03606; Abbott et al. 2021, arXiv:2108.01045

# Compact binaries: formation channels

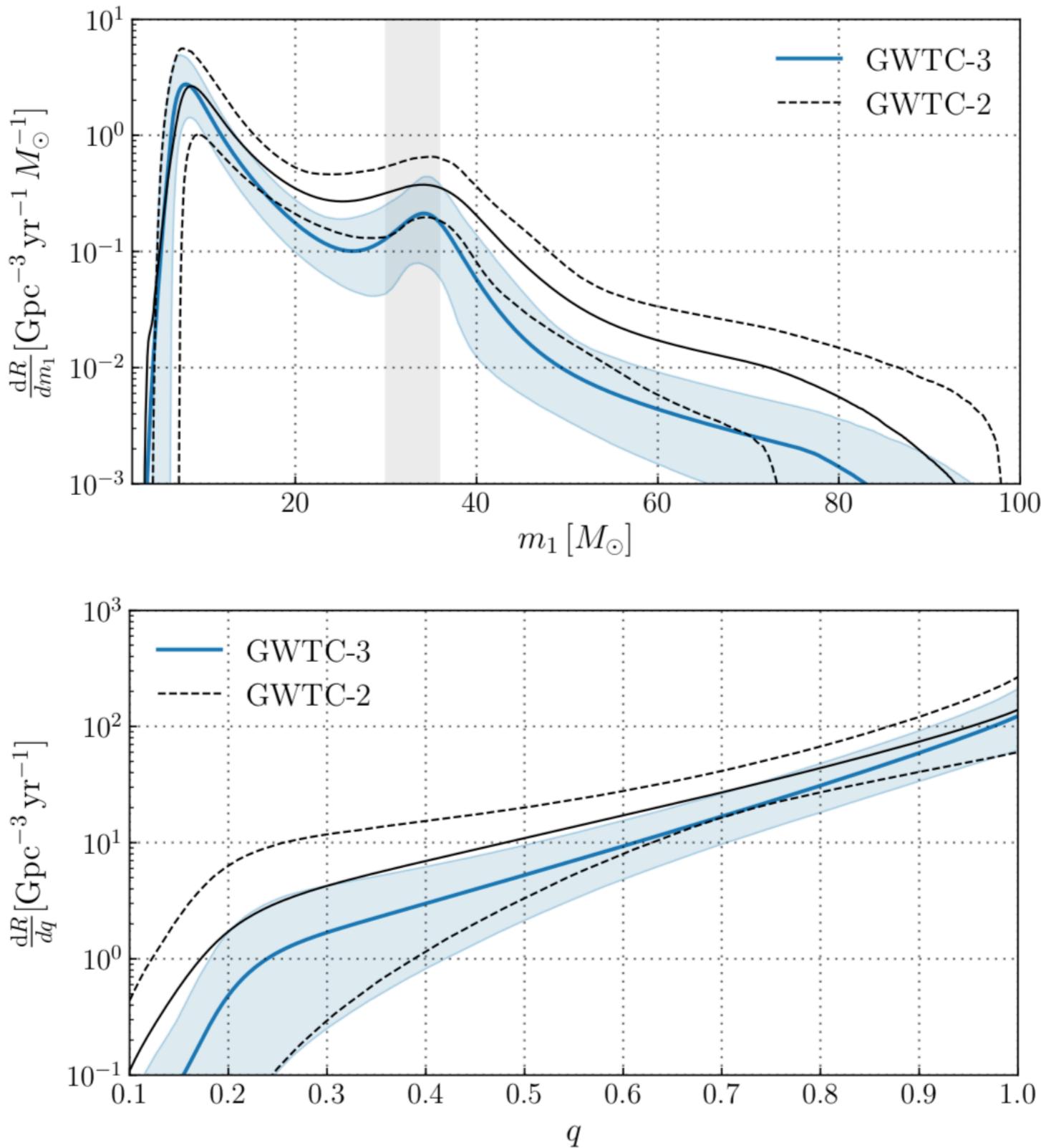


# Compact binaries: formation channels



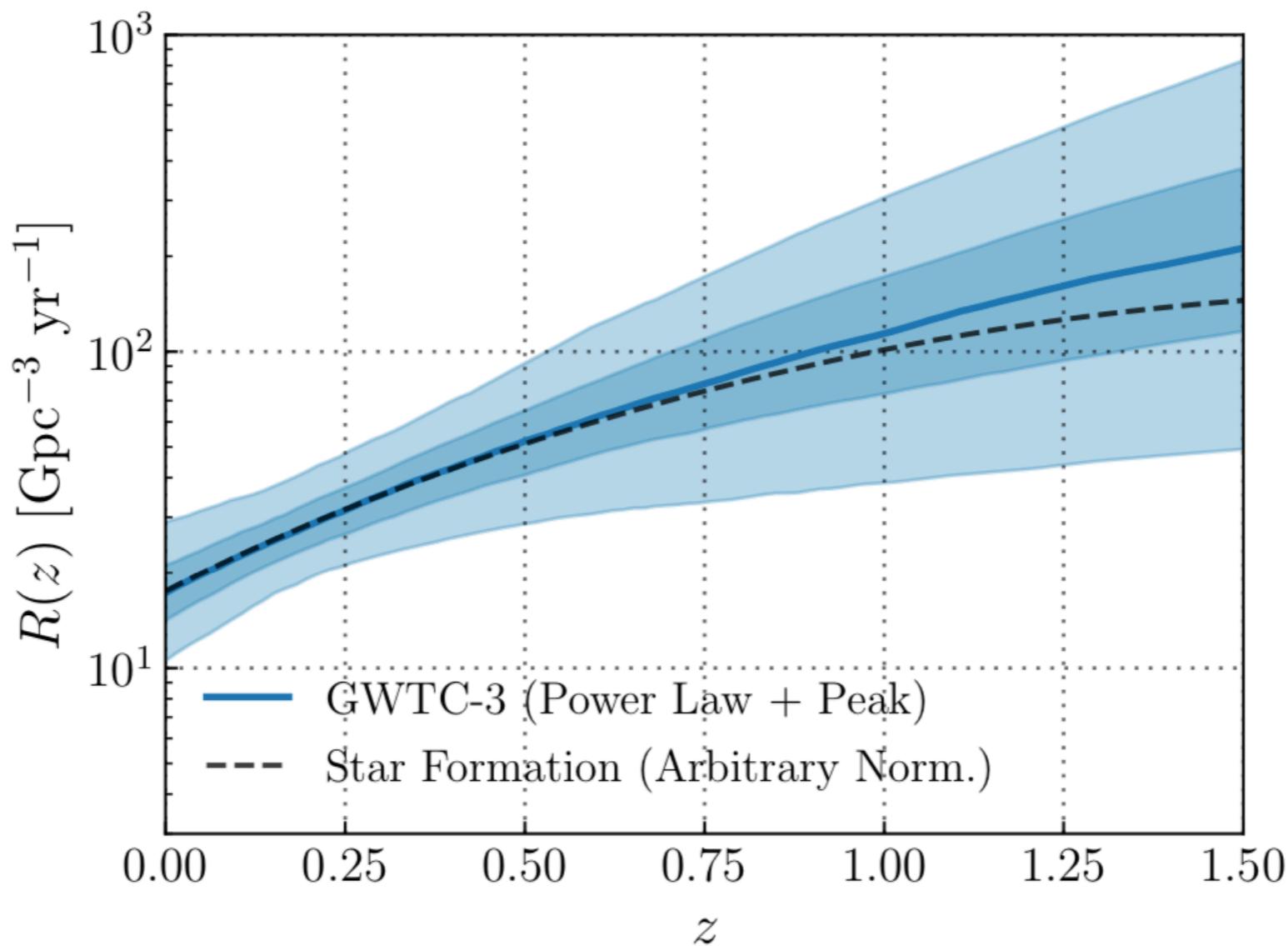
Dynamical formation  
[figure: Gerosa&Berti 2017]

# Black hole populations: mass distribution



[Abbott et al. 2023, PRX, 13, 011048]

# Black hole populations: merger rate evolution

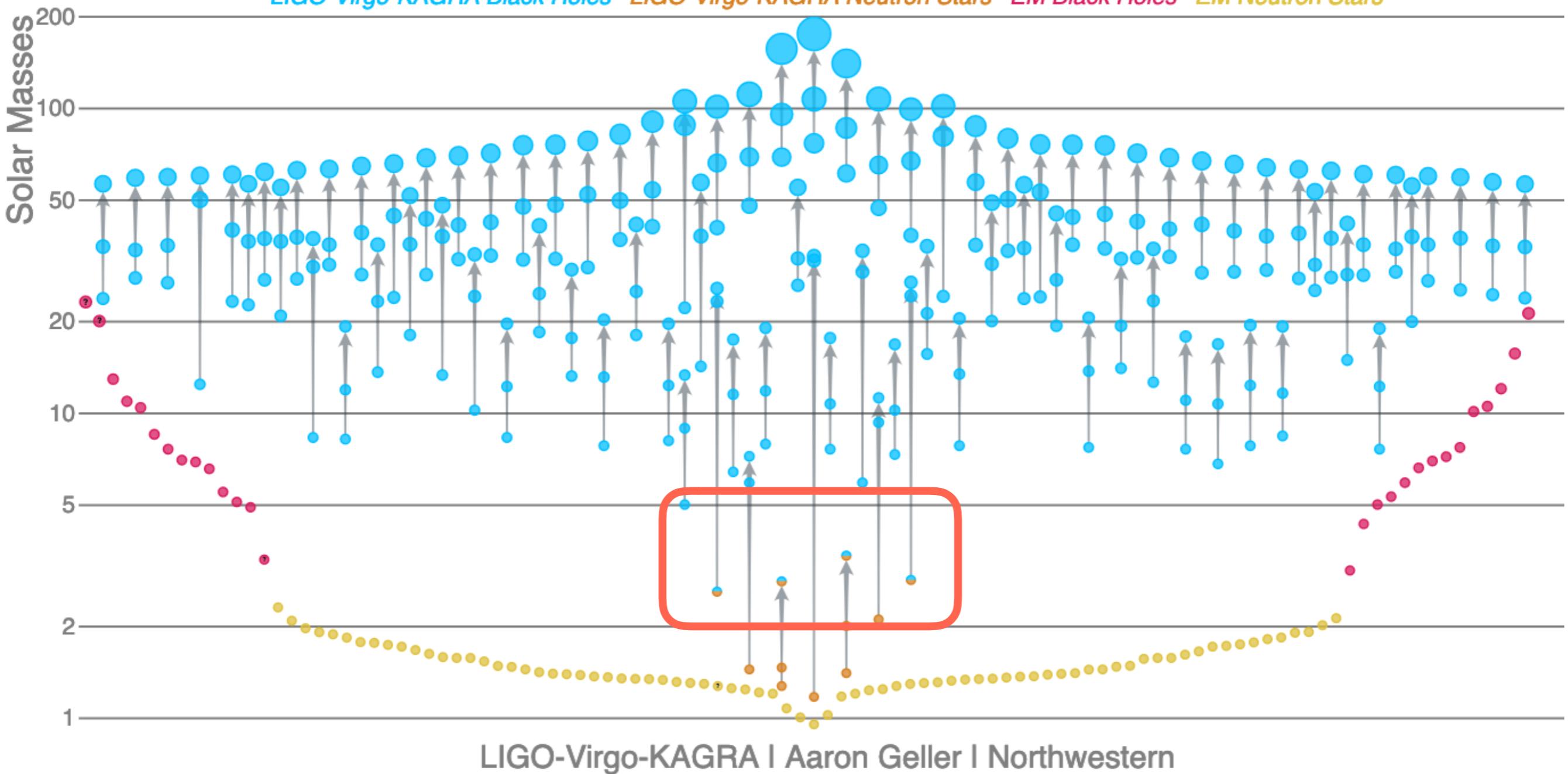


$$R_{BBH}(z = 0.2) = 17.3 - 45 \text{ Gpc}^{-3} \text{yr}^{-1}$$

[Abbott et al. 2023, PRX, 13, 011048]

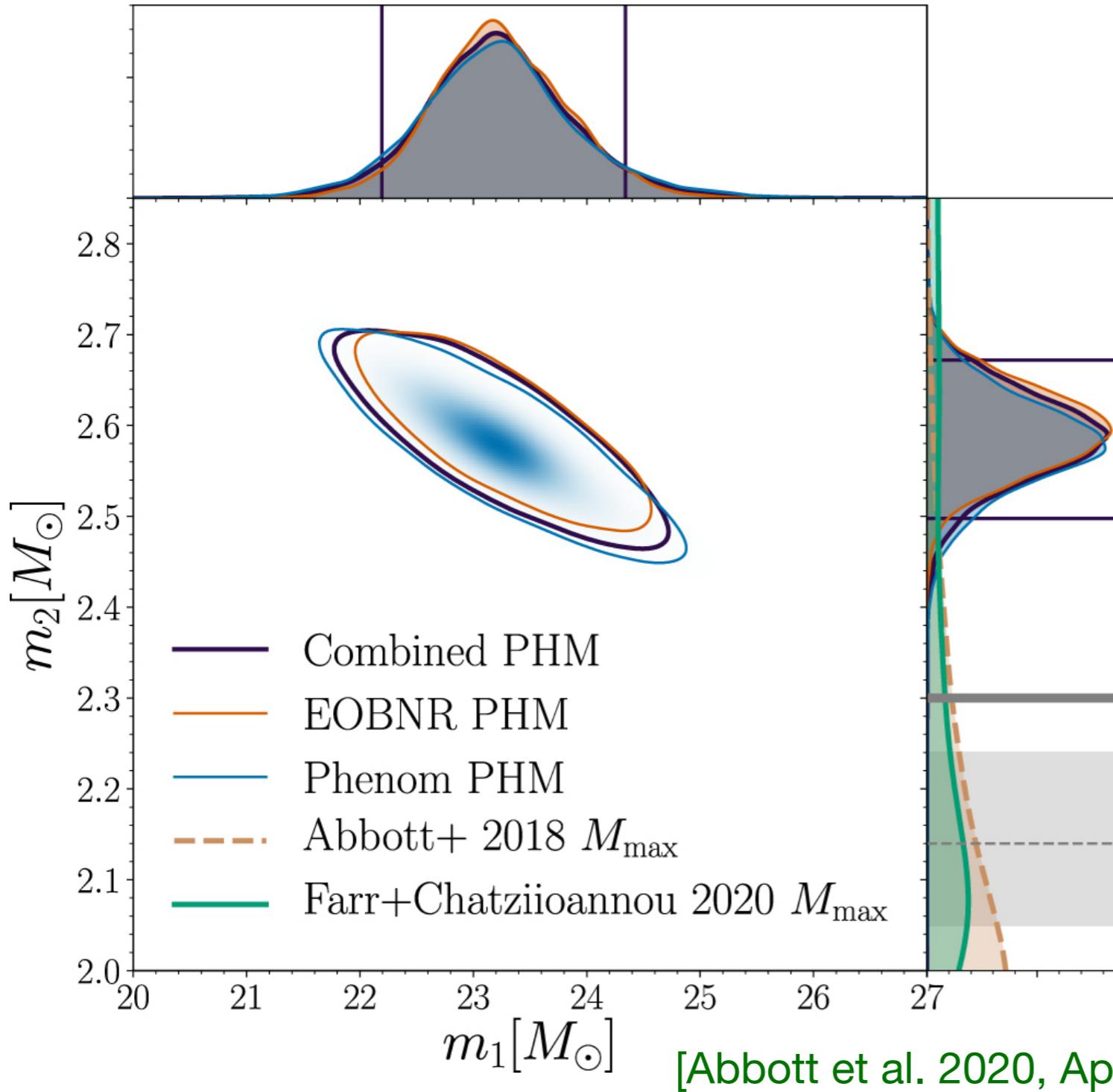
# Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



Abbott et al. 2019, PRX, 9, 031040; Abbott et al. 2021, PRX, 11, 021053;  
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# Black holes in the lower mass gap



**GW190814**

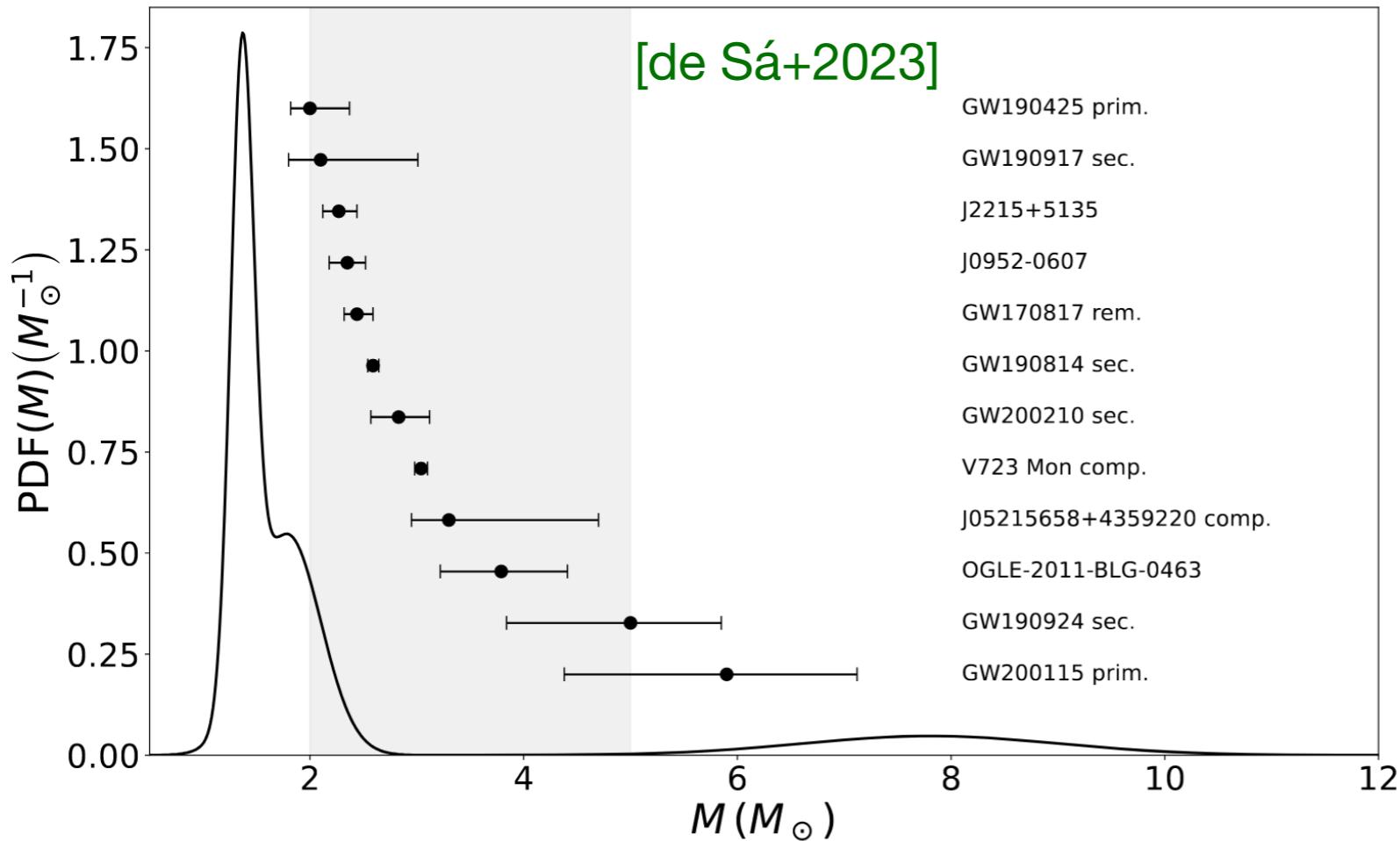
$$m_1 = 23.3^{+1.1}_{-1.0} \ M_{\odot}$$

$$m_2 = 2.59^{+0.08}_{-0.09} \ M_{\odot}$$

Heaviest neutron star?

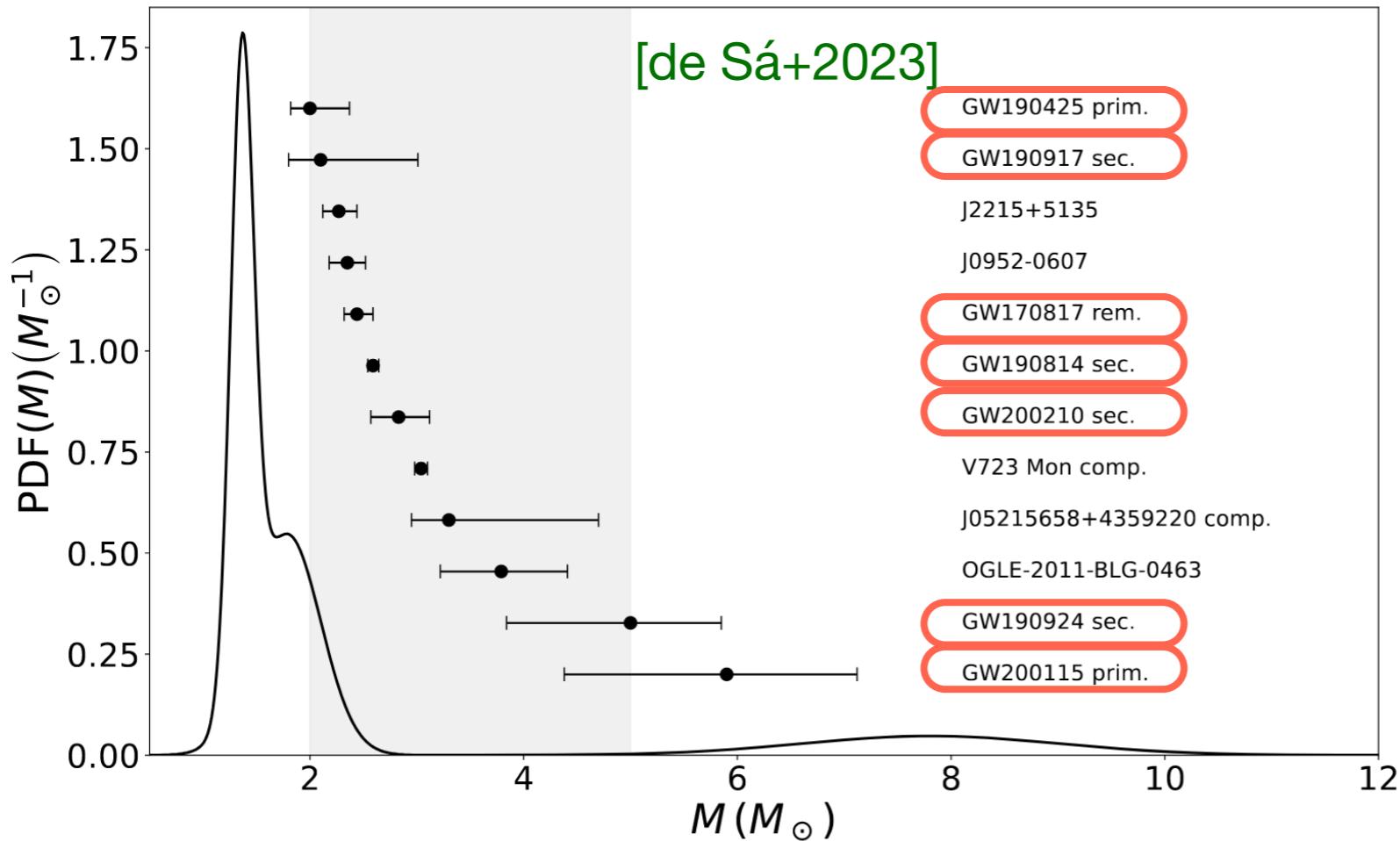
Lightest black hole?

# Black holes in the lower mass gap



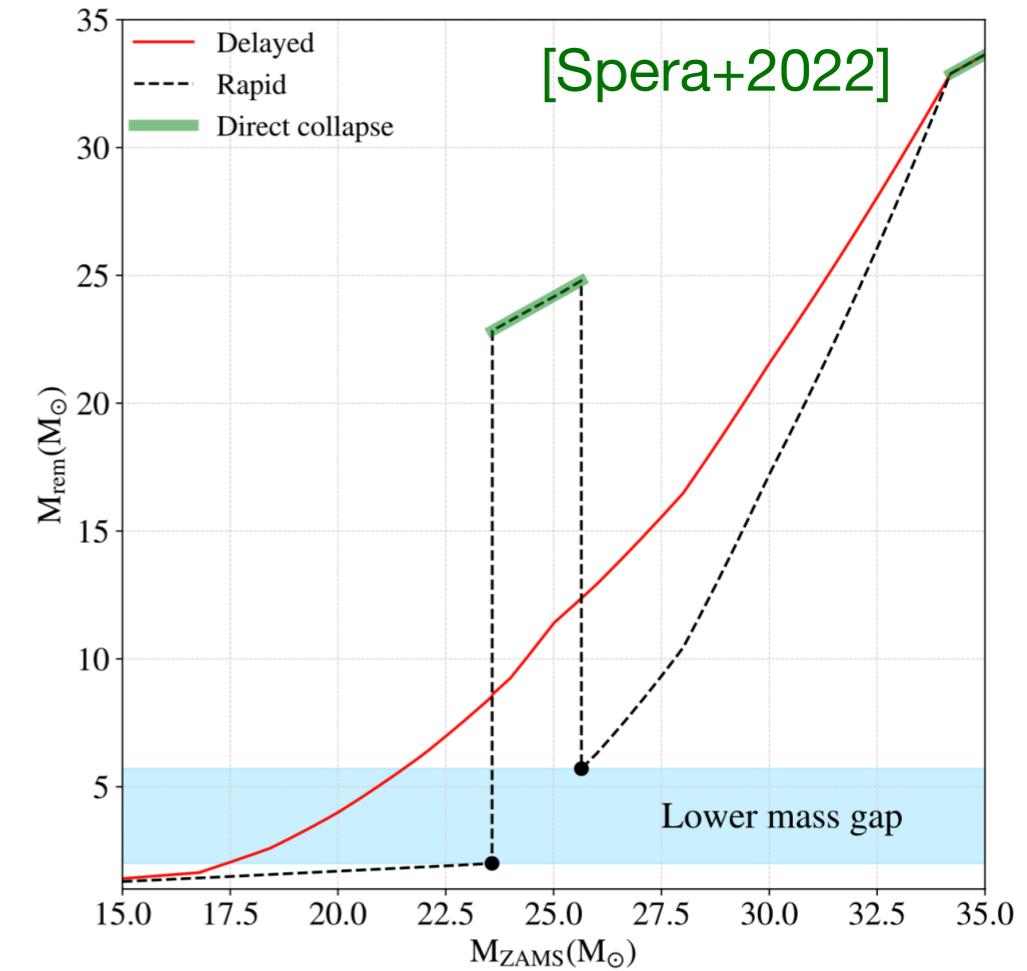
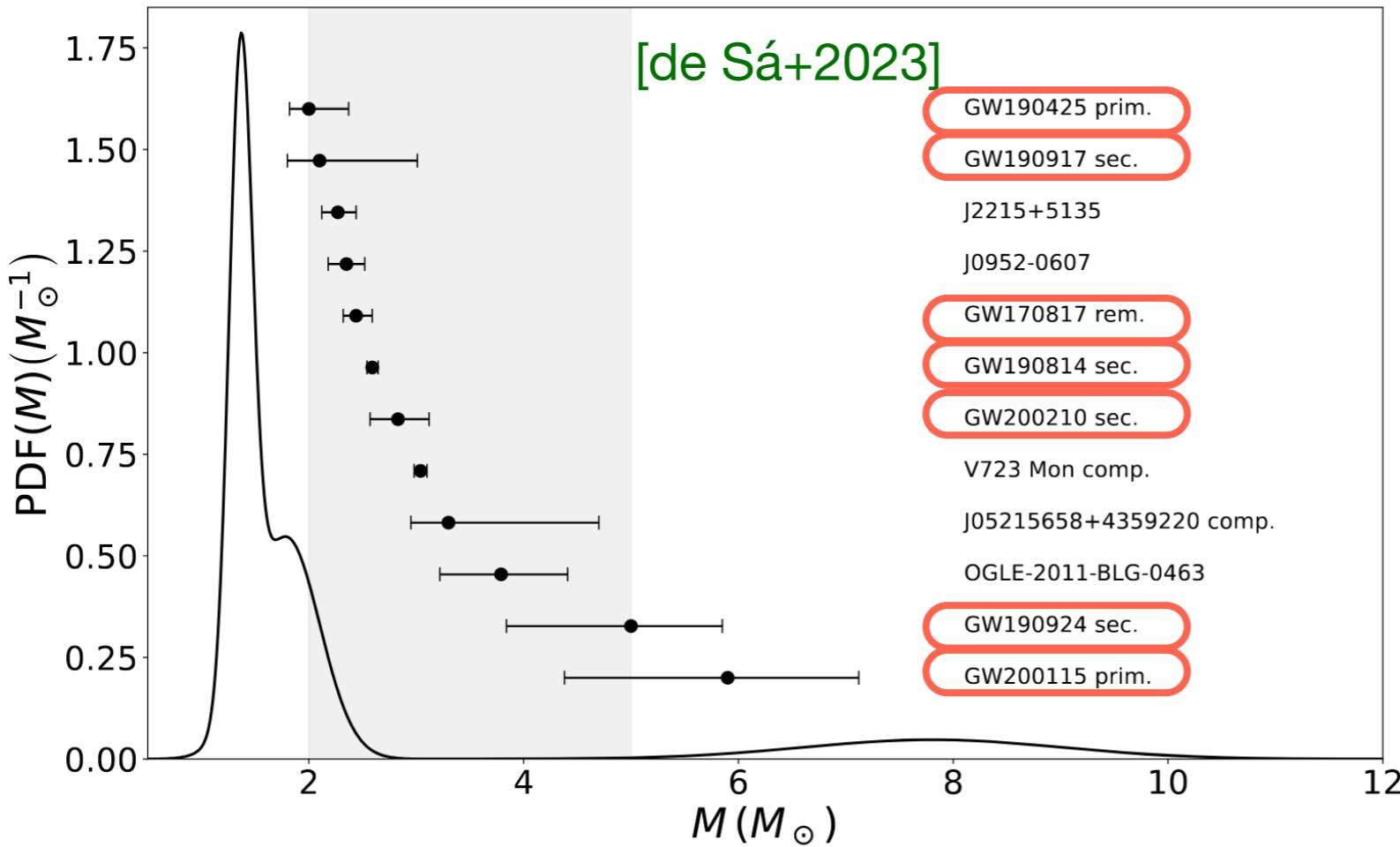
Is the mass gap real?  
Is it an observational effect?

# Black holes in the lower mass gap



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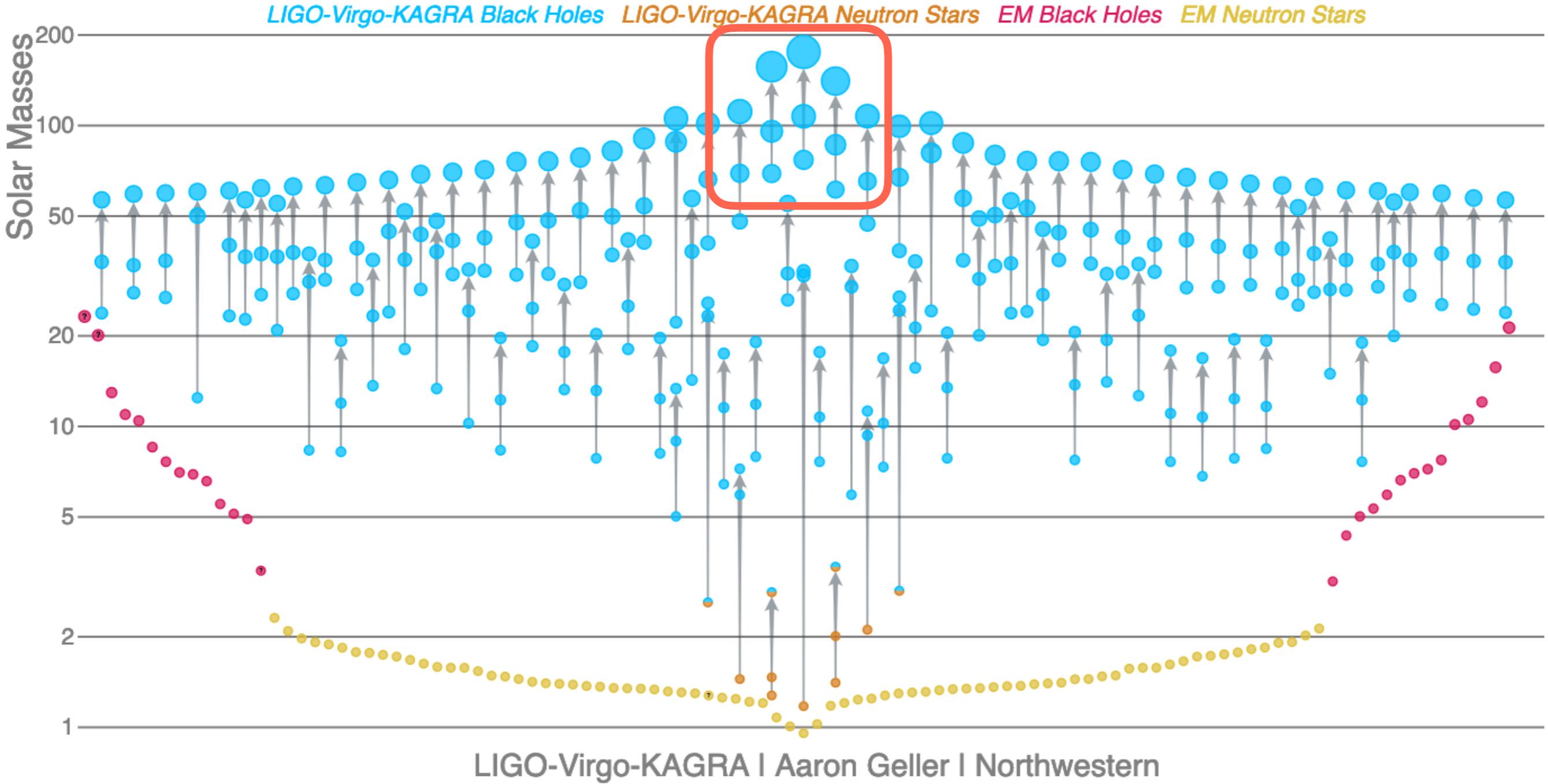
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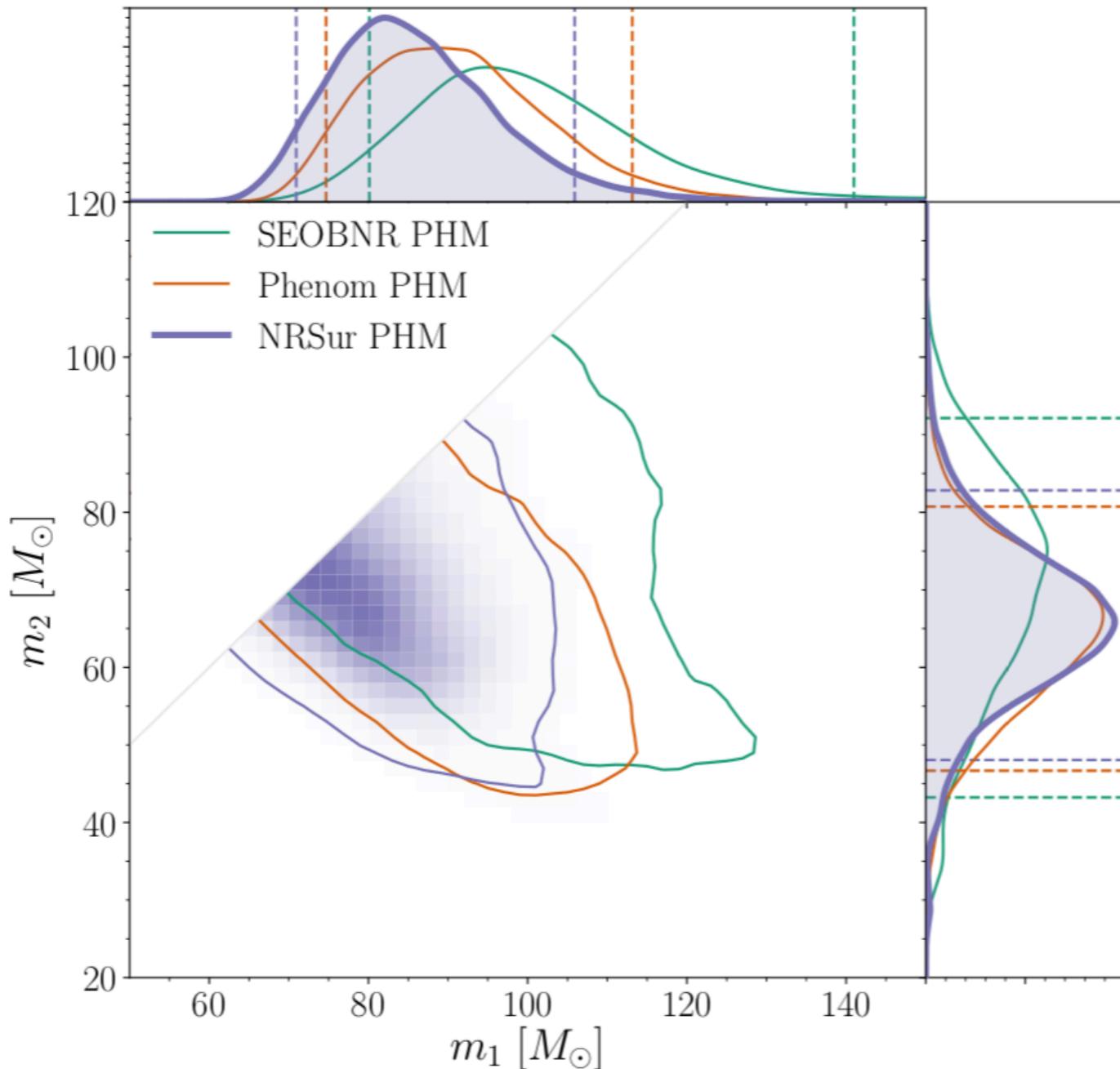
Implications for supernova  
explosion mechanism?

# Masses in the Stellar Graveyard



Abbott et al. 2019, PRX, 9, 031040; Abbott et al. 2021, PRX, 11, 021053;  
Abbott et al. 2021, arXiv:2111.03606; Abbott et al. 2021, arXiv:2108.01045

# Black holes in the upper mass gap



**GW190521**

$$m_1 = 85^{+21}_{-14} \ M_\odot$$

$$m_2 = 66^{+17}_{-18} \ M_\odot$$

Hierarchical merger?

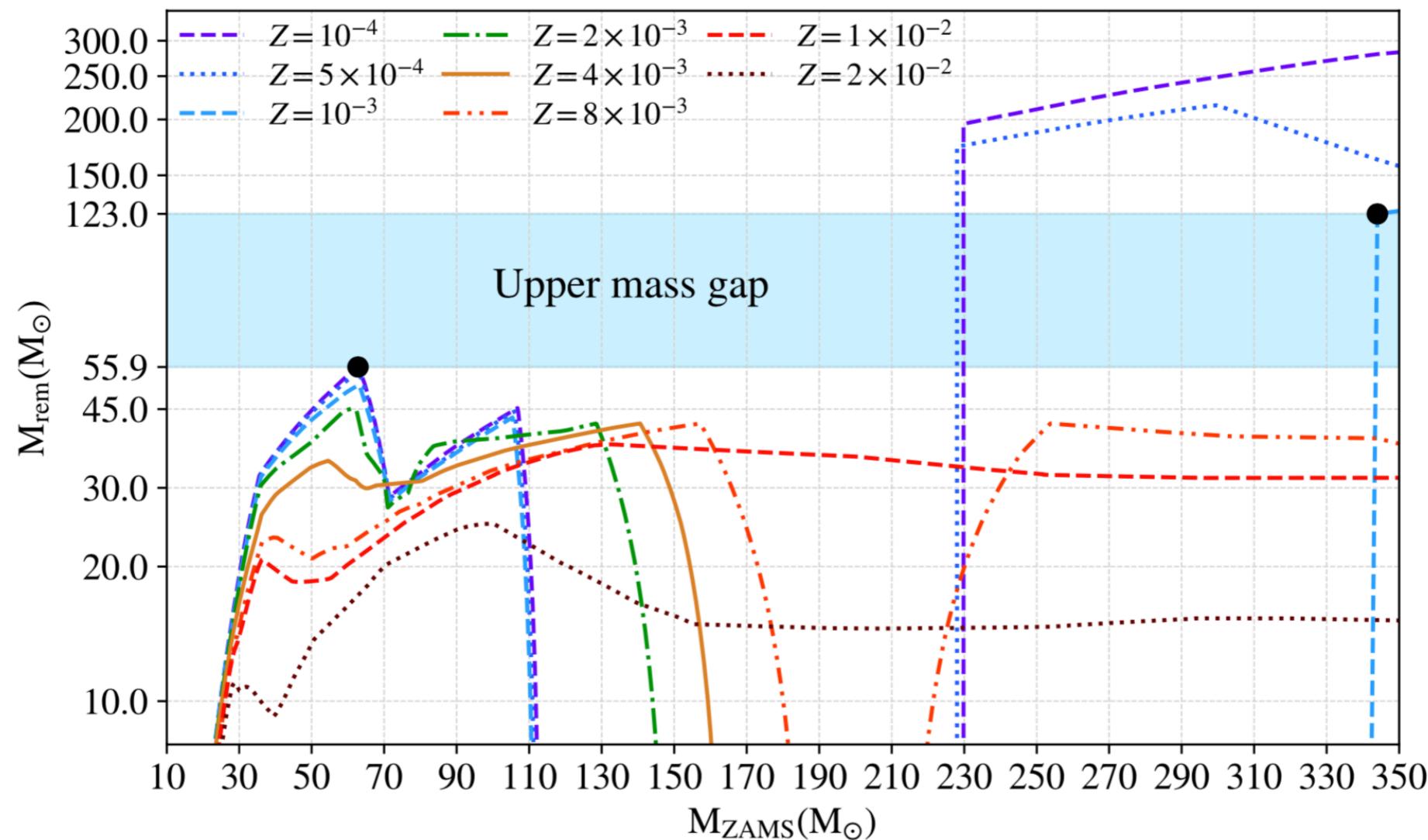
Black hole formed in the mass gap?

[Abbott et al. 2020, PRL 125, 101102]

[Abbott et al. 2020, ApJL, 900, 13]

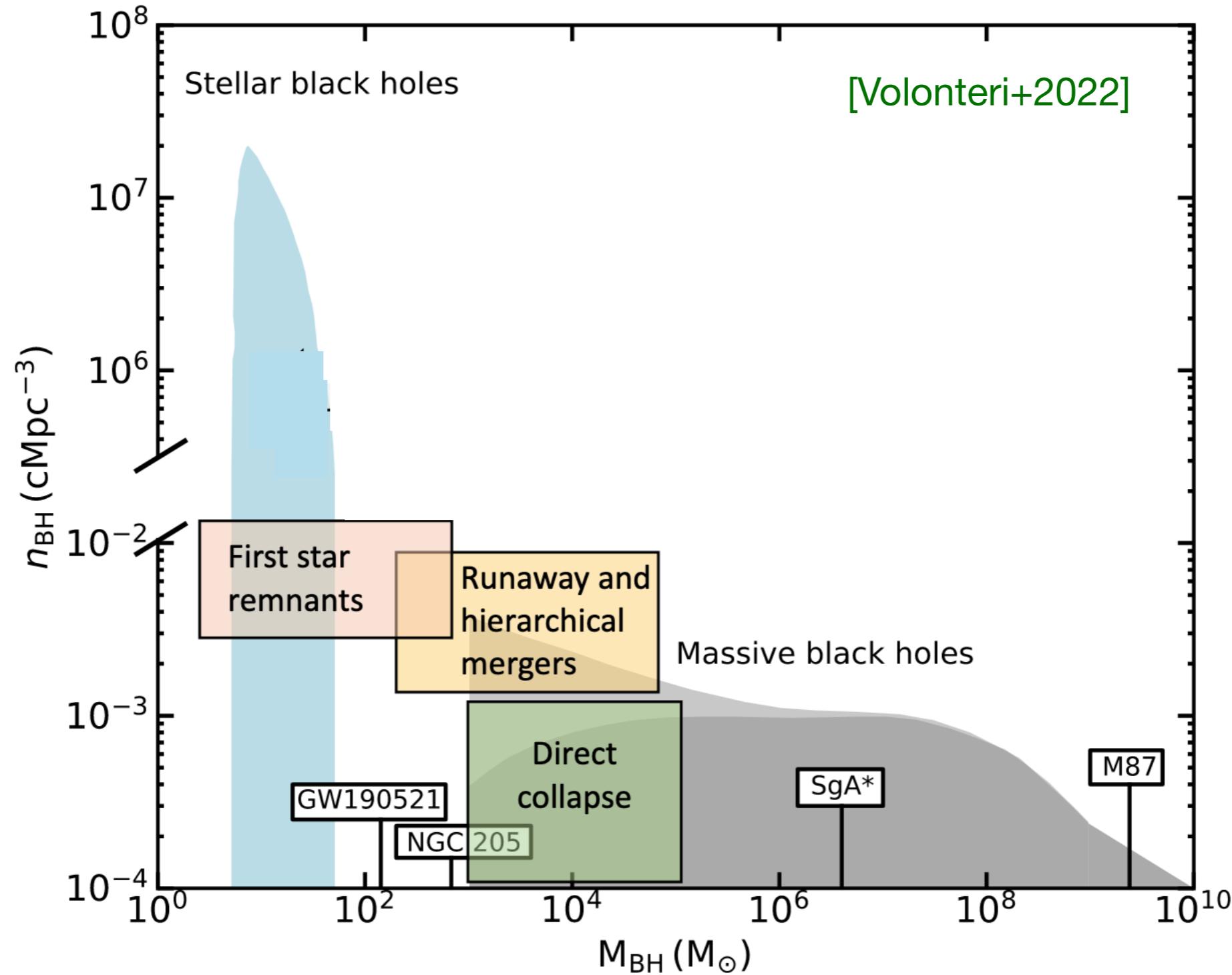
# Black holes in the upper mass gap

Stellar evolution theory predicts a gap caused by the pair instability  
GW190521: evidence for dynamical channel formation?

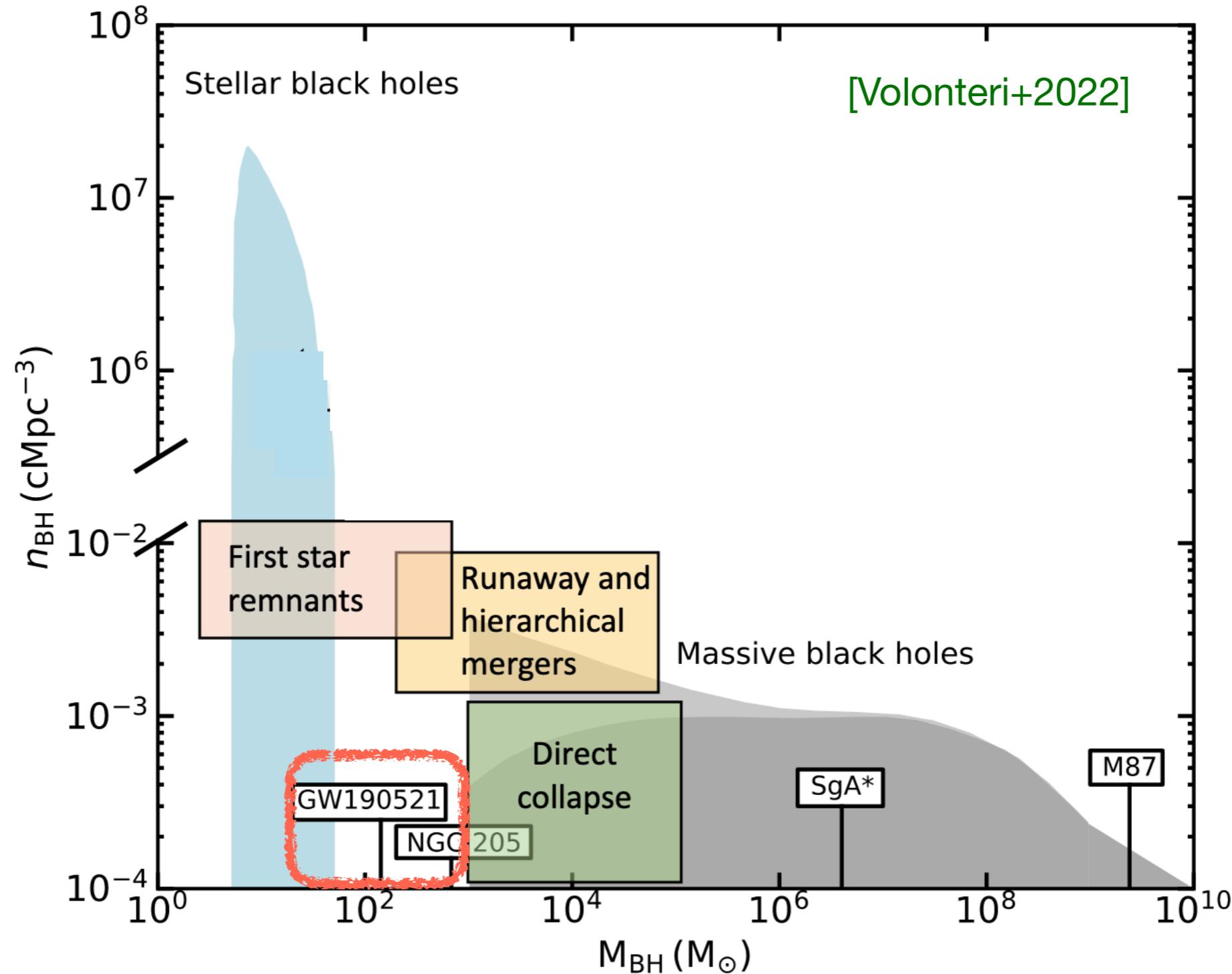


[Spera+2022]

# The link between stellar-mass and massive black holes?

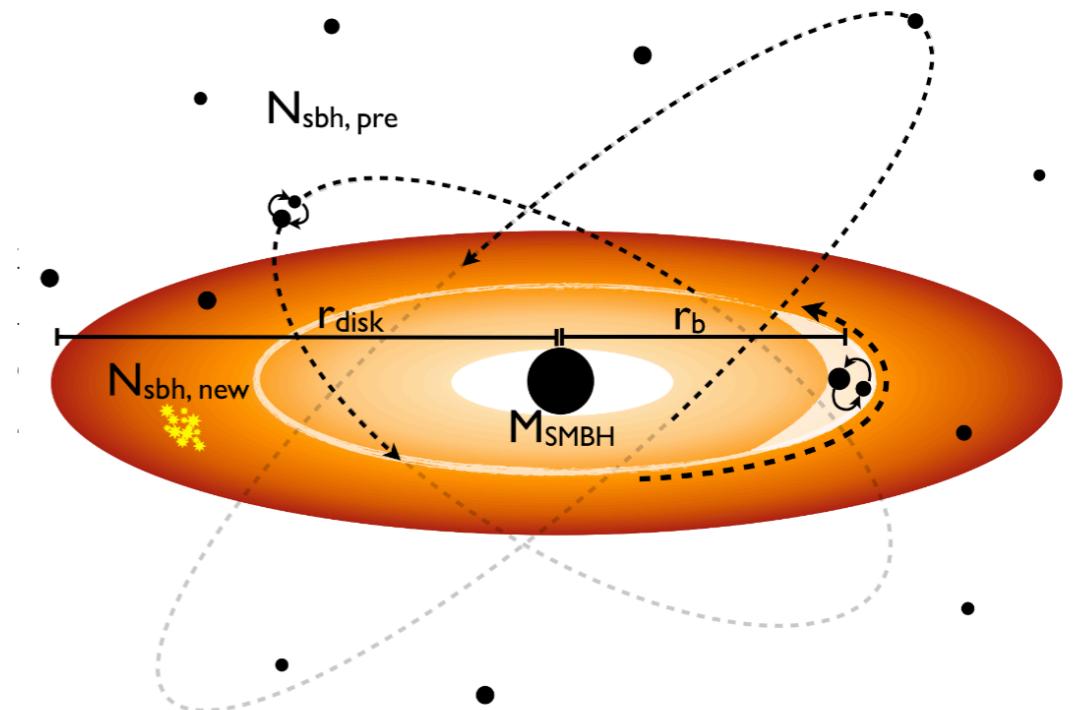
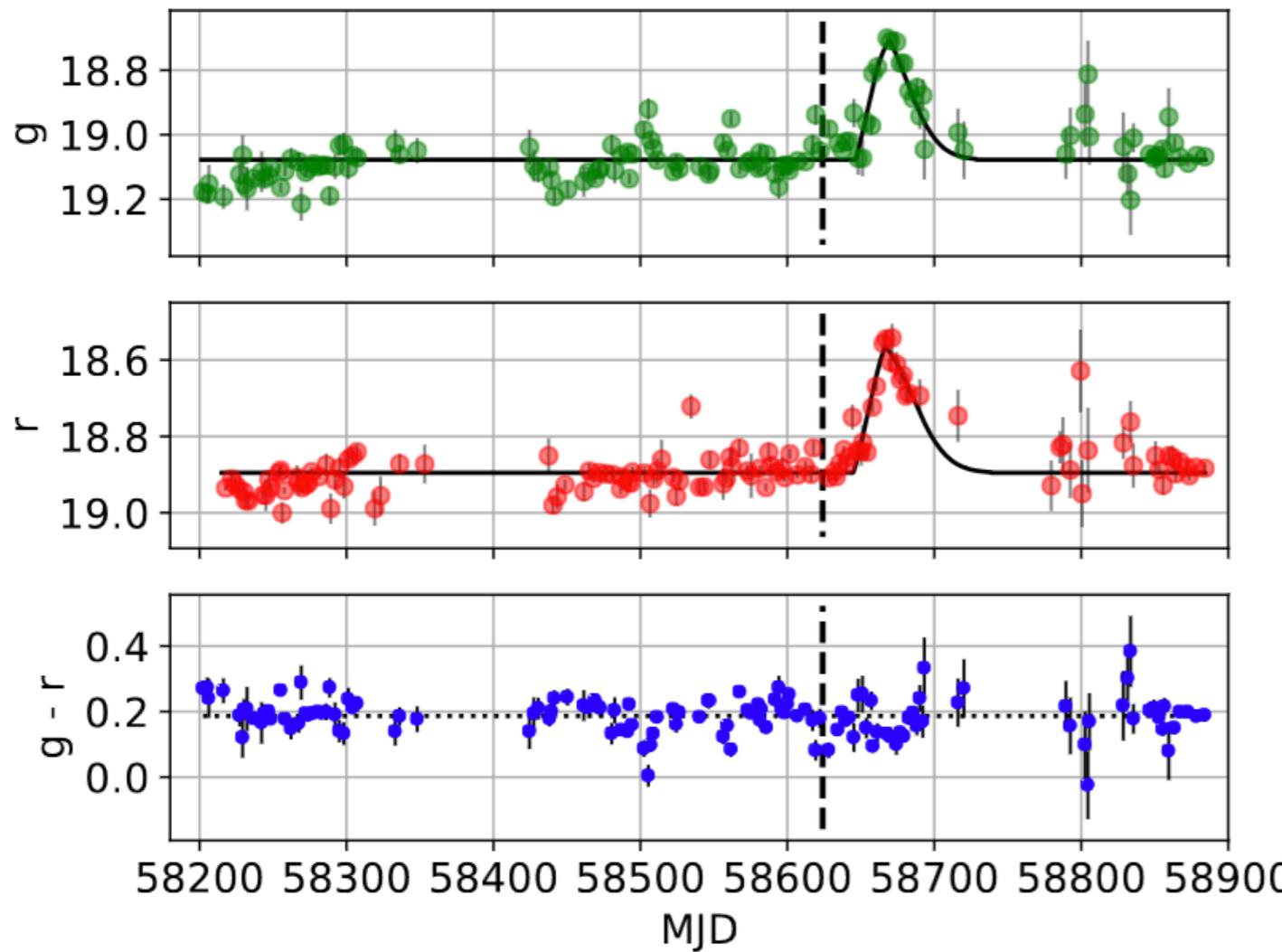


# The link between stellar-mass and massive black holes?



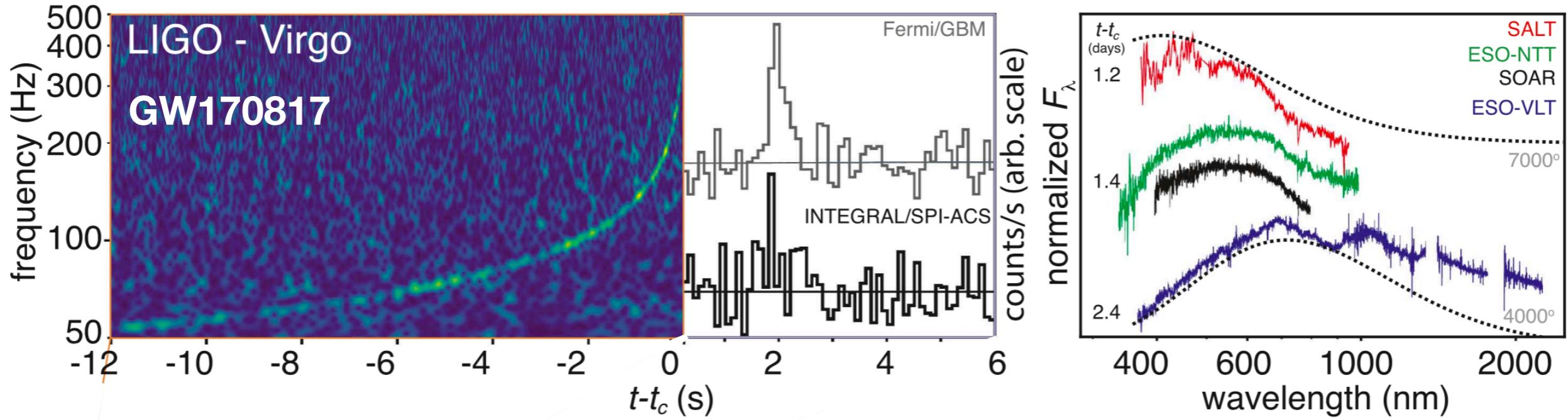
# Electromagnetic counterparts for intermediate black hole mergers?

Optical counterpart to GW190521:  
J124942.3+344929 ? [Graham+2020]

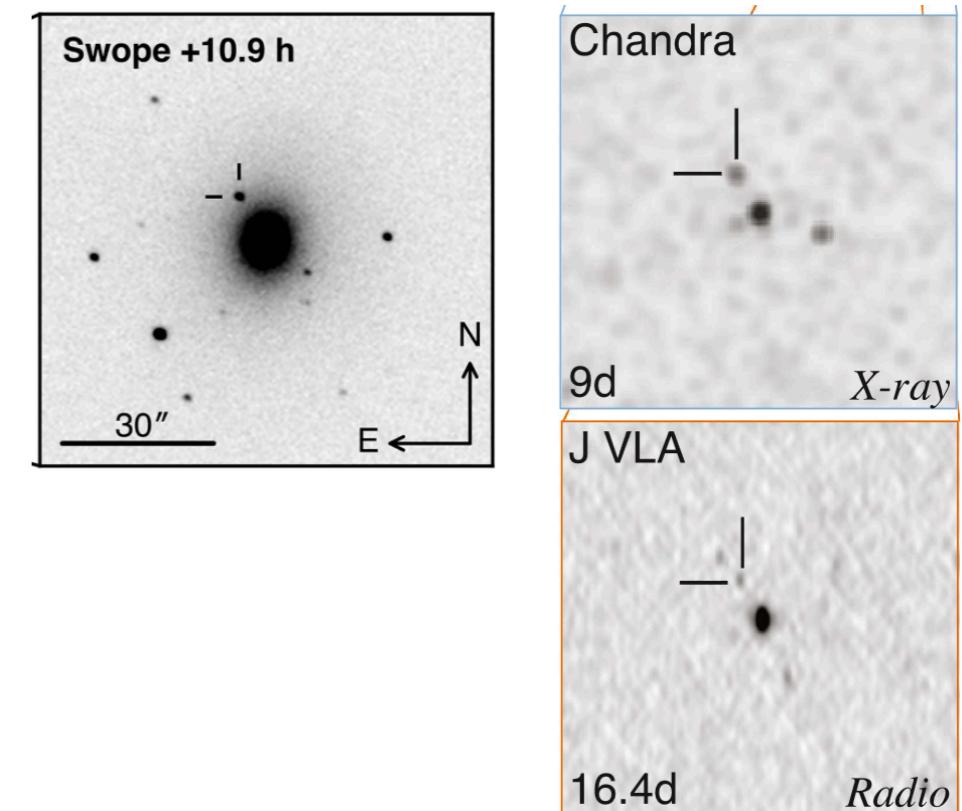


[Saavik Ford+2019:  
Astro2020 White Paper]

# Binary neutron stars: multi-messenger observations!

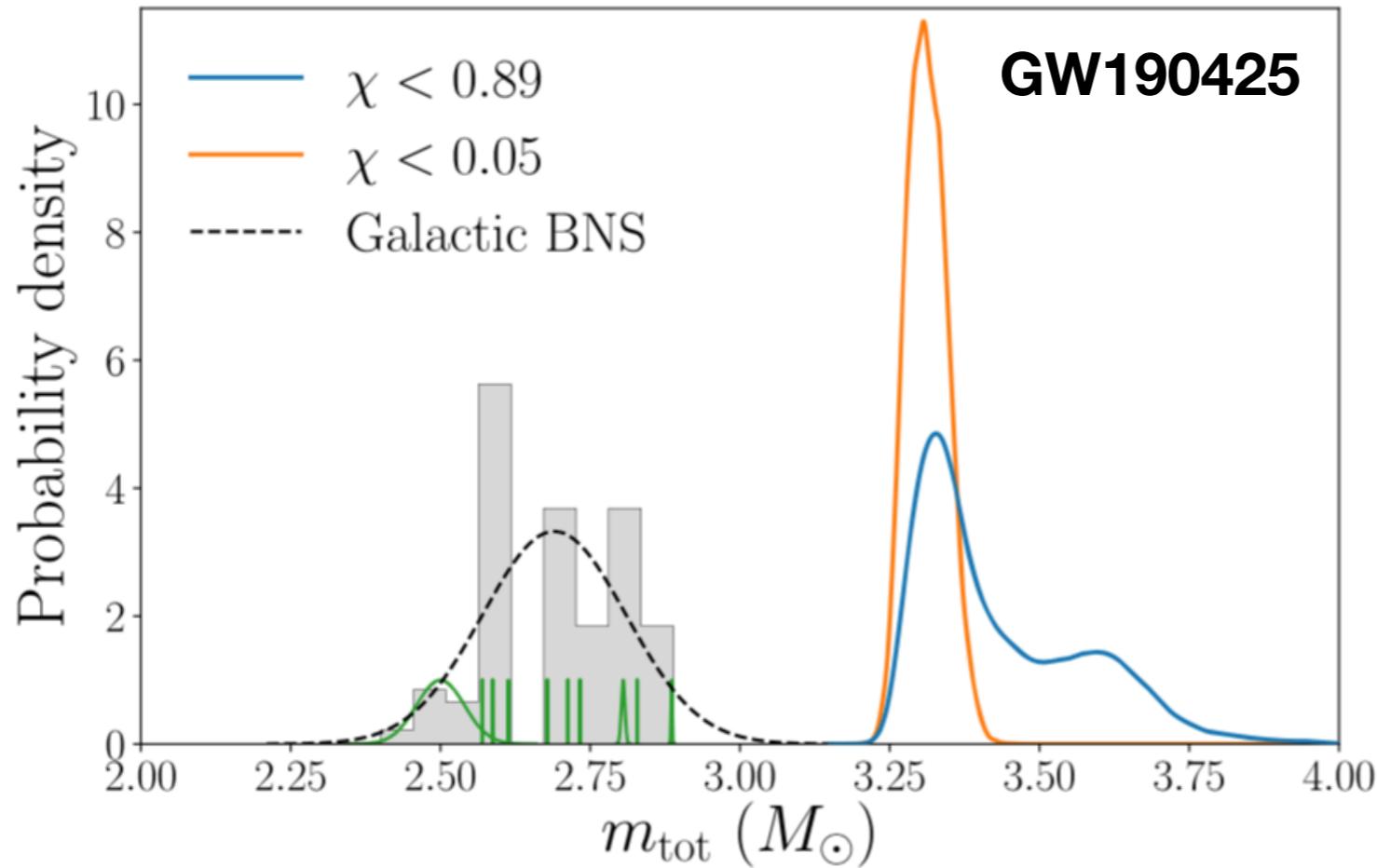


- GW+EM observations
- Connection between BNS merger and short gamma ray bursts (GRB)
- Kilonova: synthesis of heavy elements
- GRB: jet structure
- Identification of host galaxy



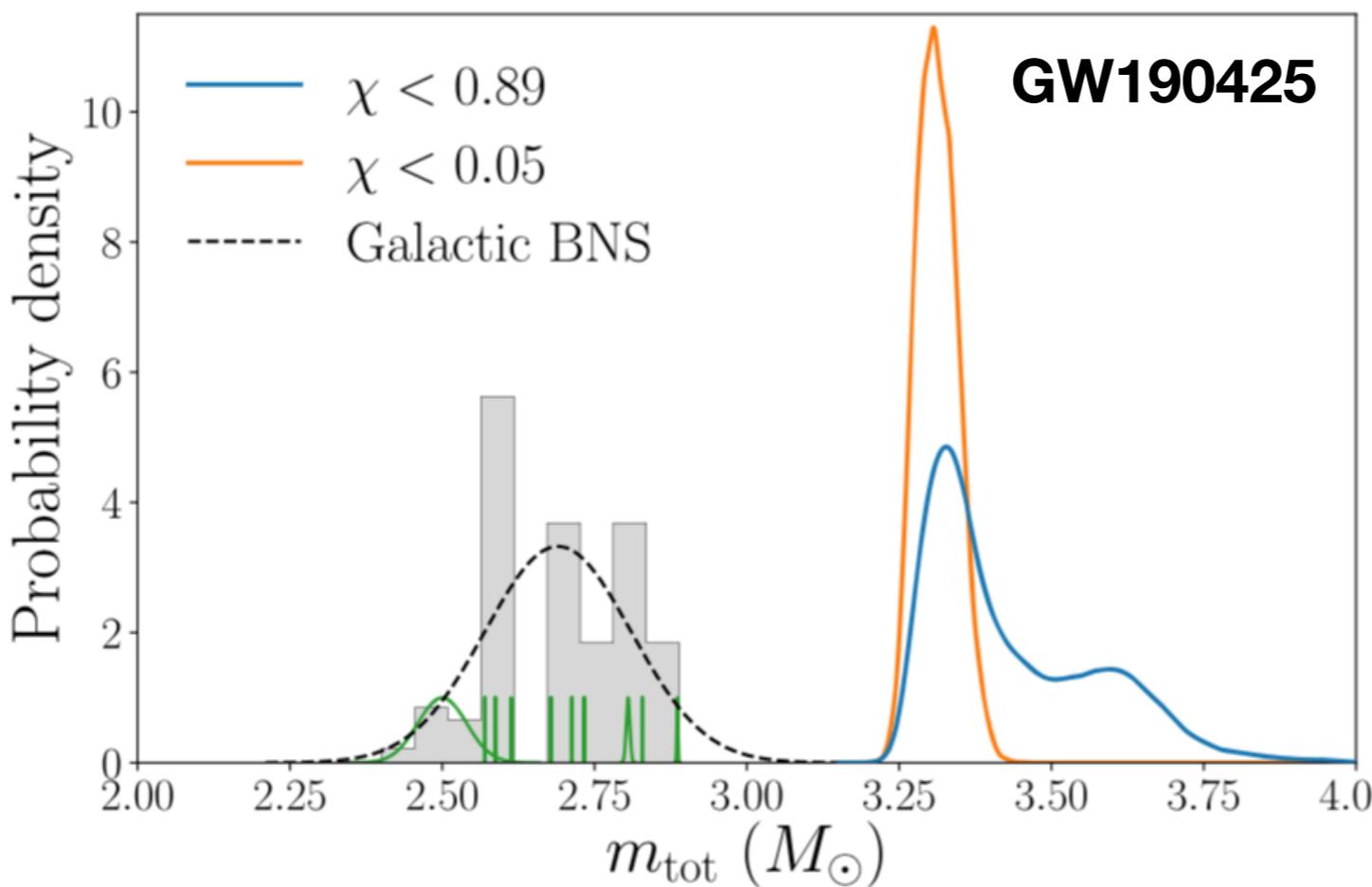
[Abbott et al. 2017, ApJ Letters, 848, 2]

# Binary neutron stars: masses

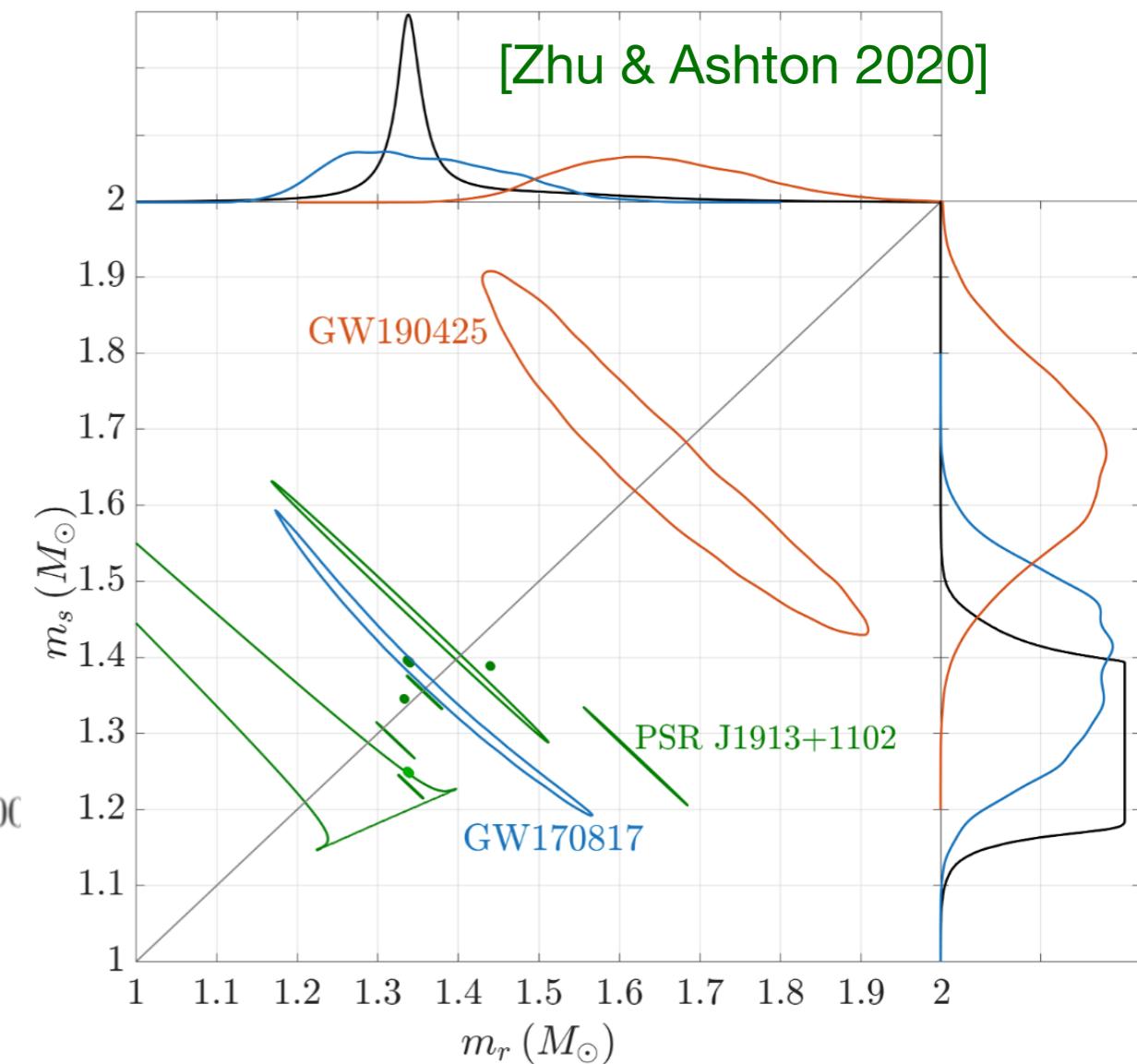


[Abbott et al. 2020, *Astrophys. J. Lett.* 892, L3]

# Binary neutron stars: masses



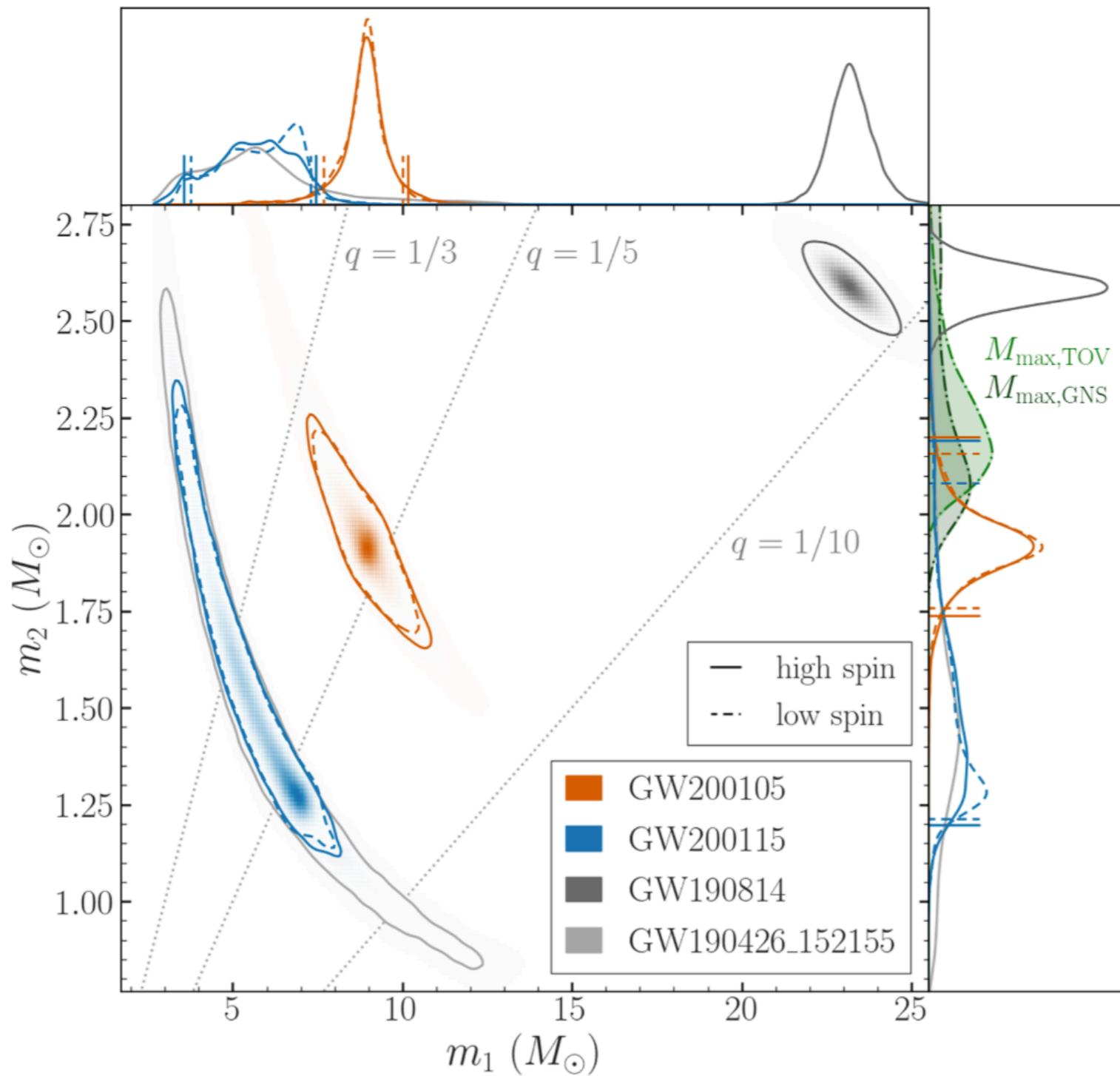
[Abbott et al. 2020, *Astrophys. J. Lett.* 892, L3]



How do binary neutron stars form?

What are the differences between GW sources and Galactic binaries?

# Neutron star-black hole: mixed binaries



**GW200115**

$$m_1 = 5.7^{+1.8}_{-2.1} M_{\odot}$$

$$m_2 = 1.5^{+0.7}_{-0.3} M_{\odot}$$

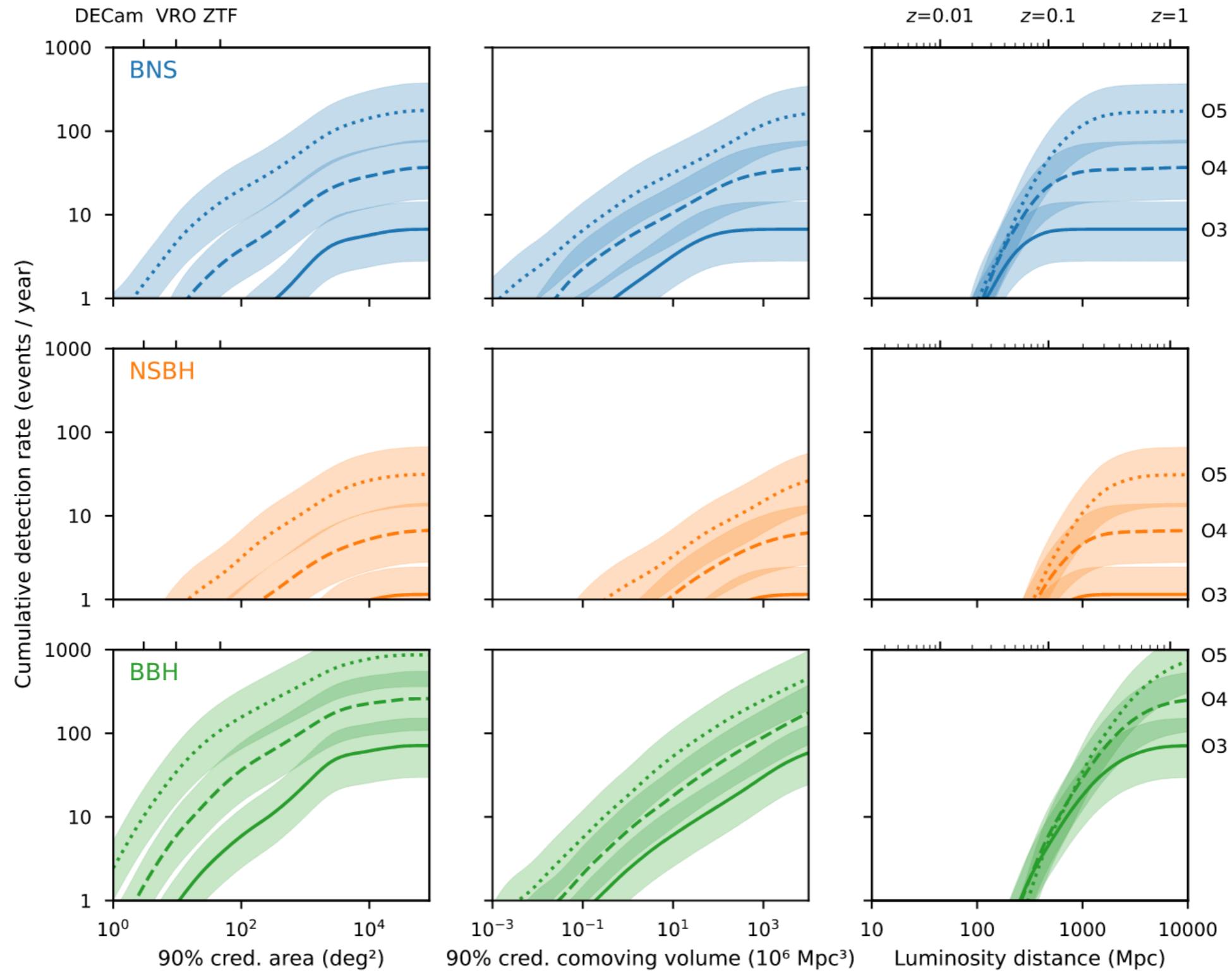
**GW200105**

$$m_1 = 8.9^{+1.2}_{-1.5} M_{\odot}$$

$$m_2 = 1.9^{+0.3}_{-0.2} M_{\odot}$$

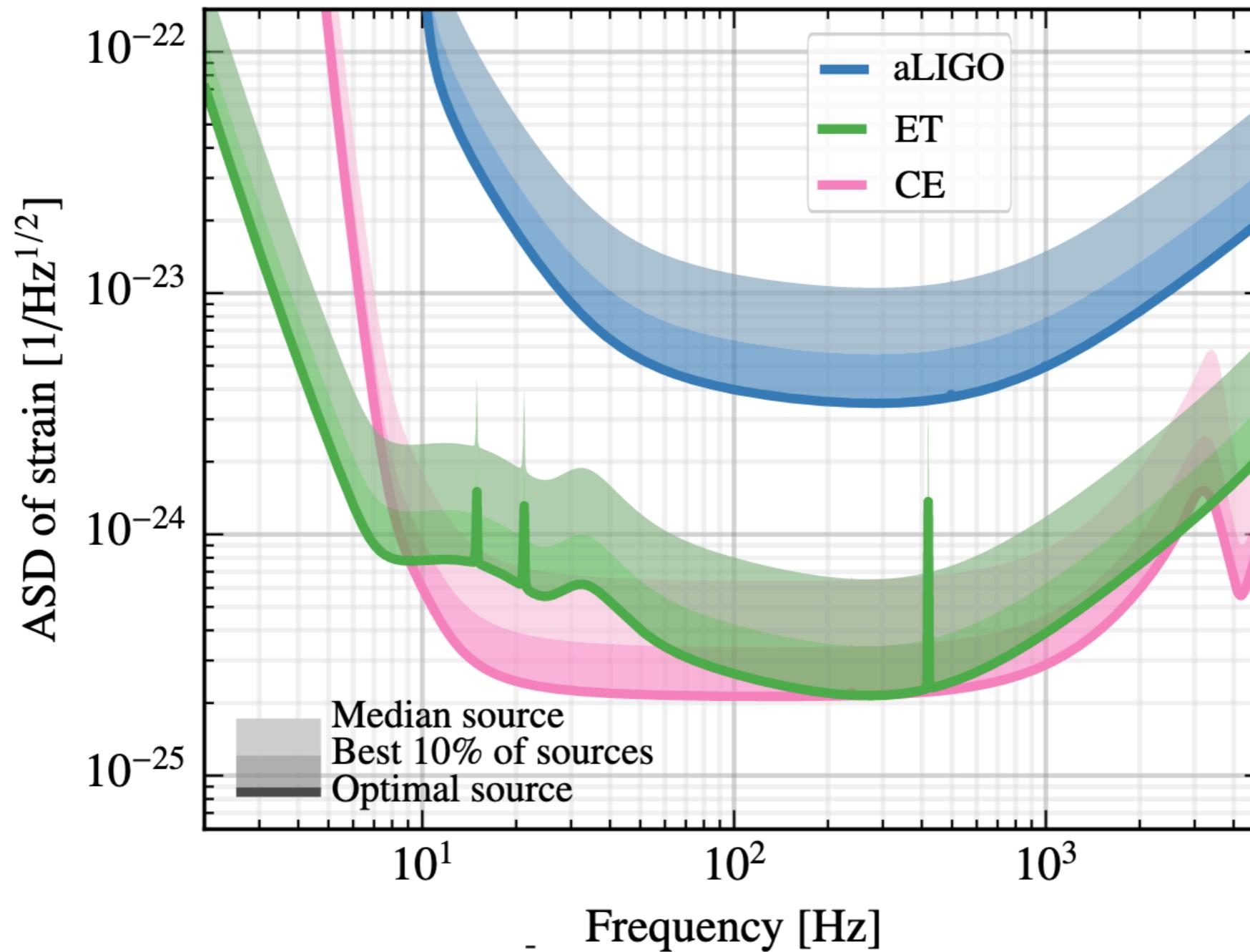
[Abbott et al. 2021, ApJL, 915, L5]

# Prospects for O4/O5 runs



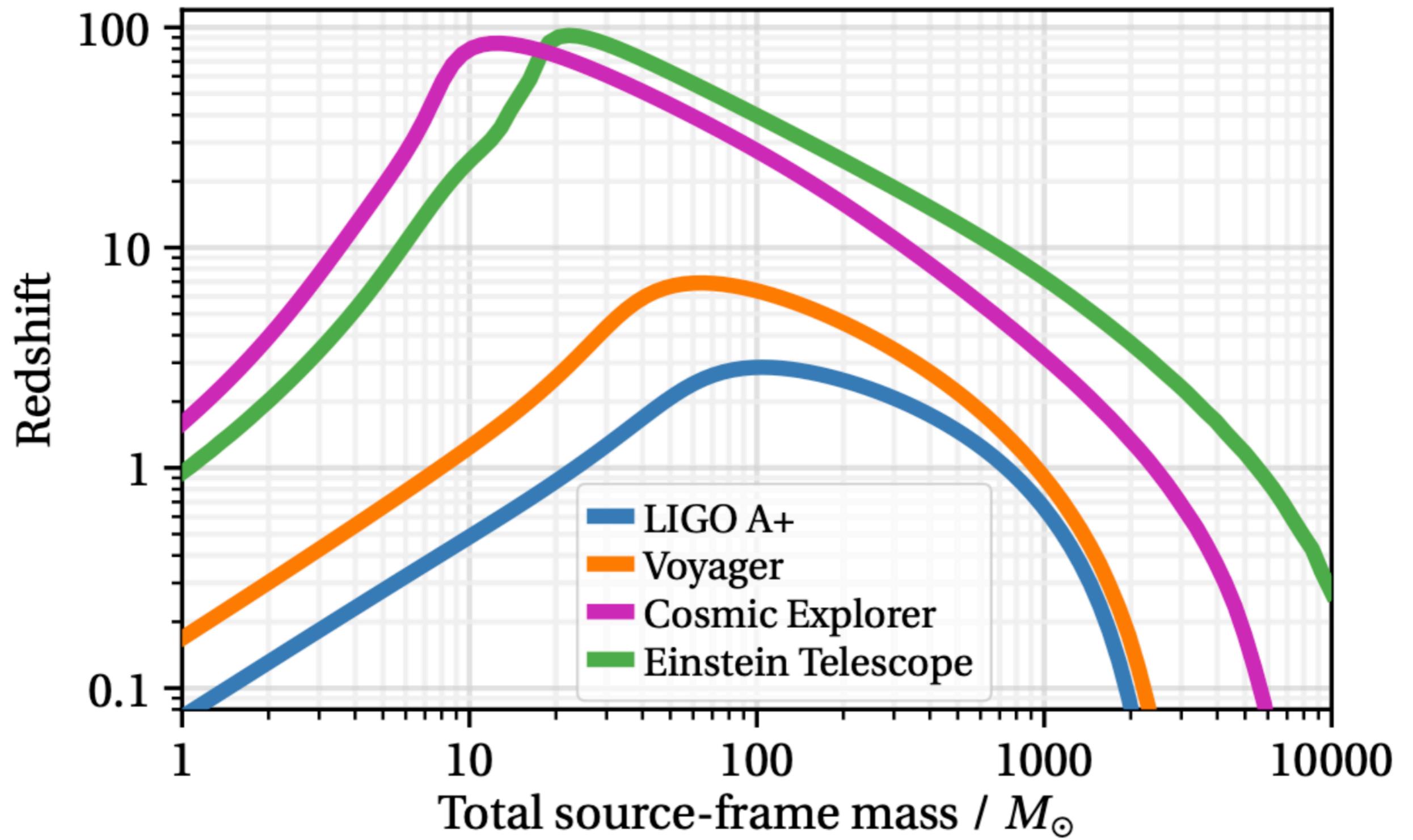
[LIGO Public User Guide: <https://emfollow.docs.ligo.org/userguide/capabilities.html>]

# Third generation detectors: Einstein Telescope and Cosmic Explorer



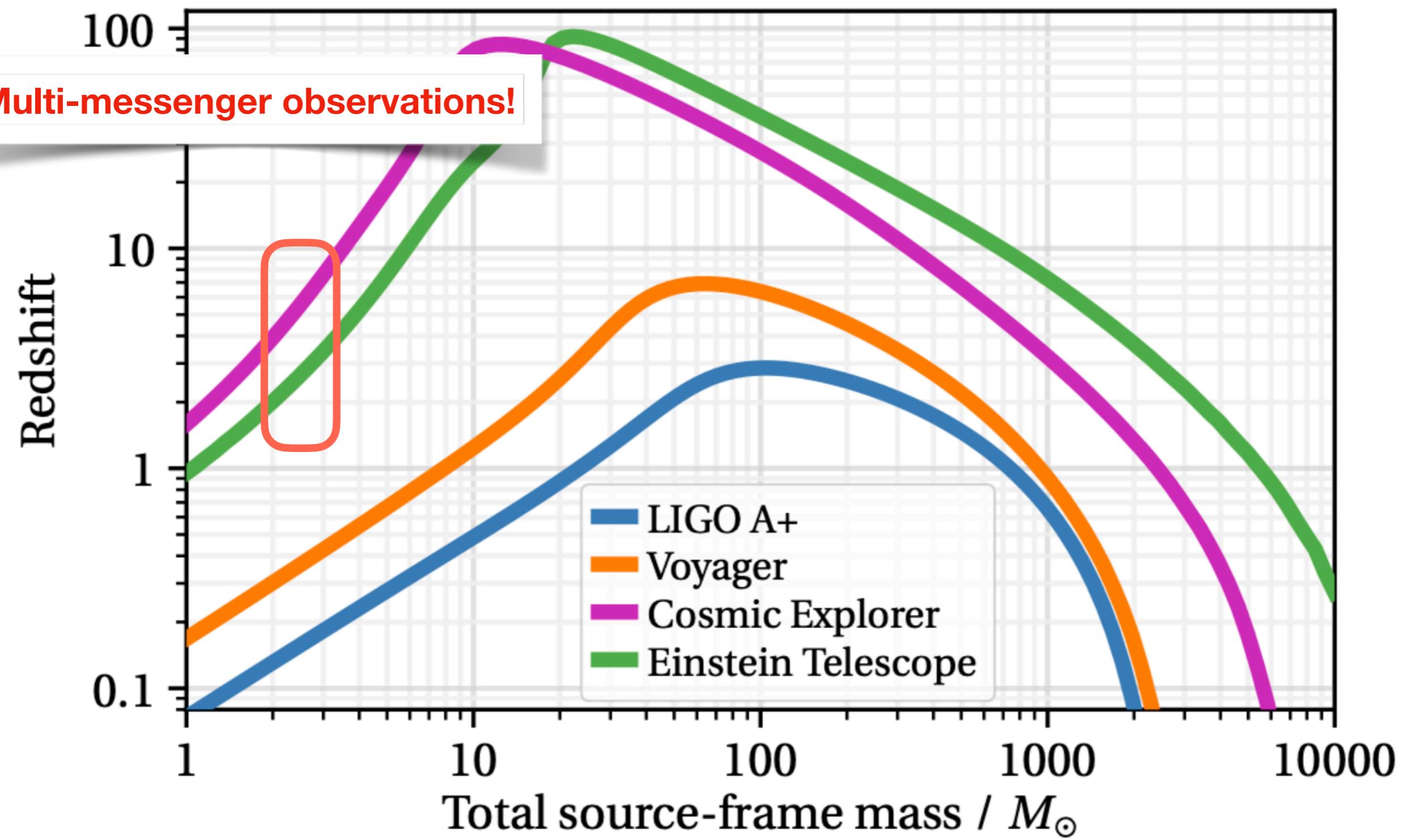
[Einstein Telescope Design Report Update 2020]

# Third generation detectors: Einstein Telescope and Cosmic Explorer



[Evans et al. 2021, Cosmic Horizon Study, arXiv:2109.09882]

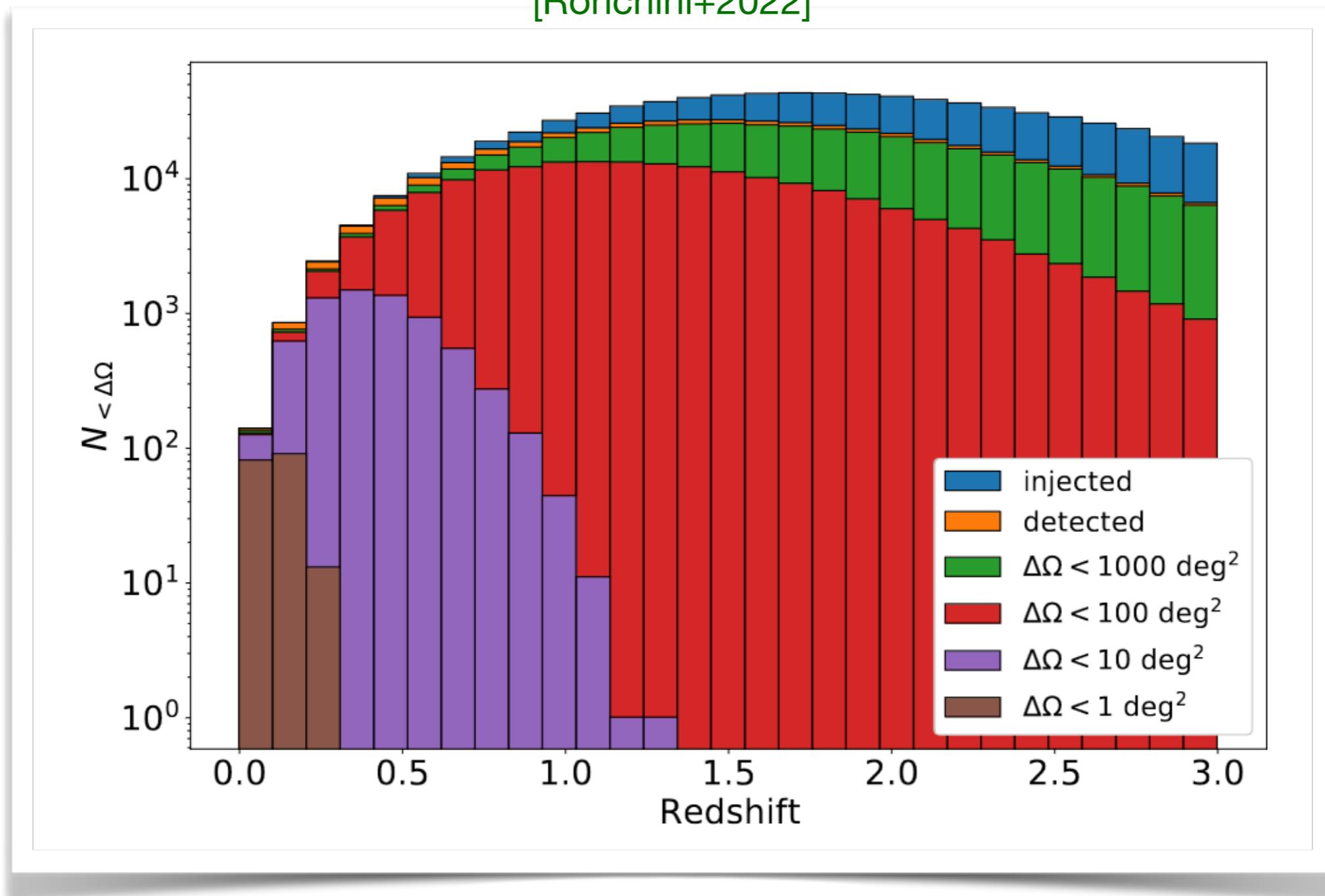
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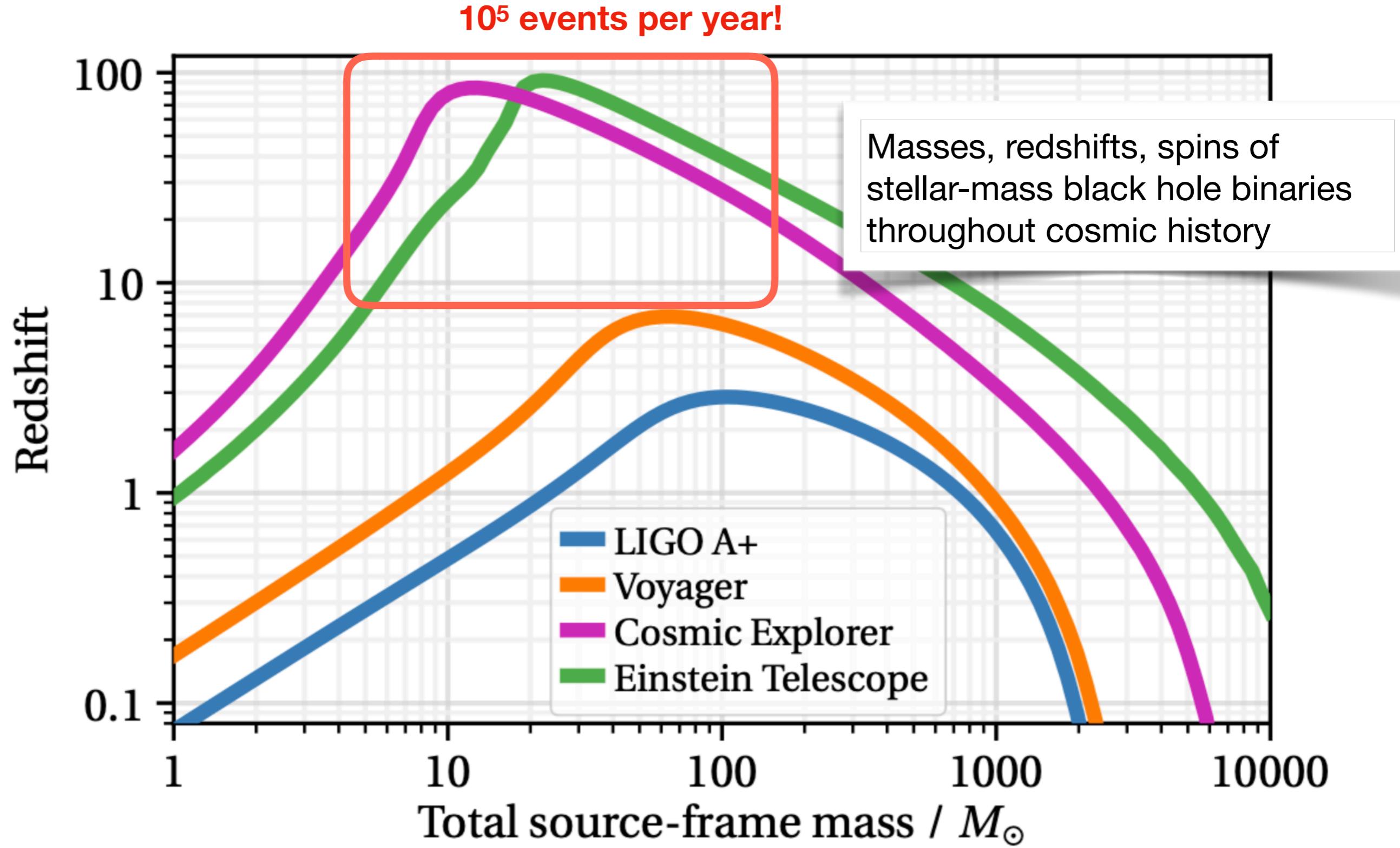
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[Ronchini+2022]

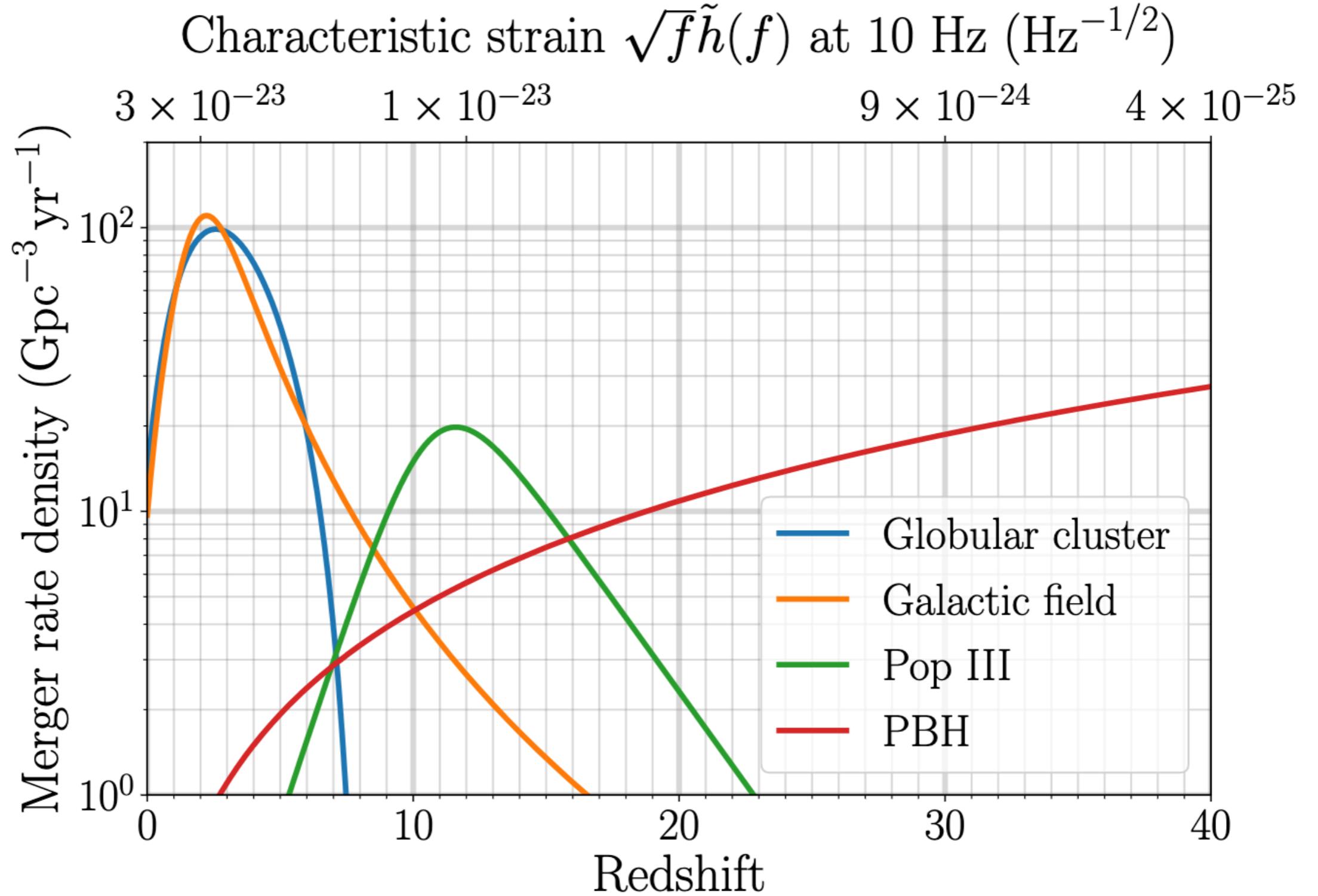


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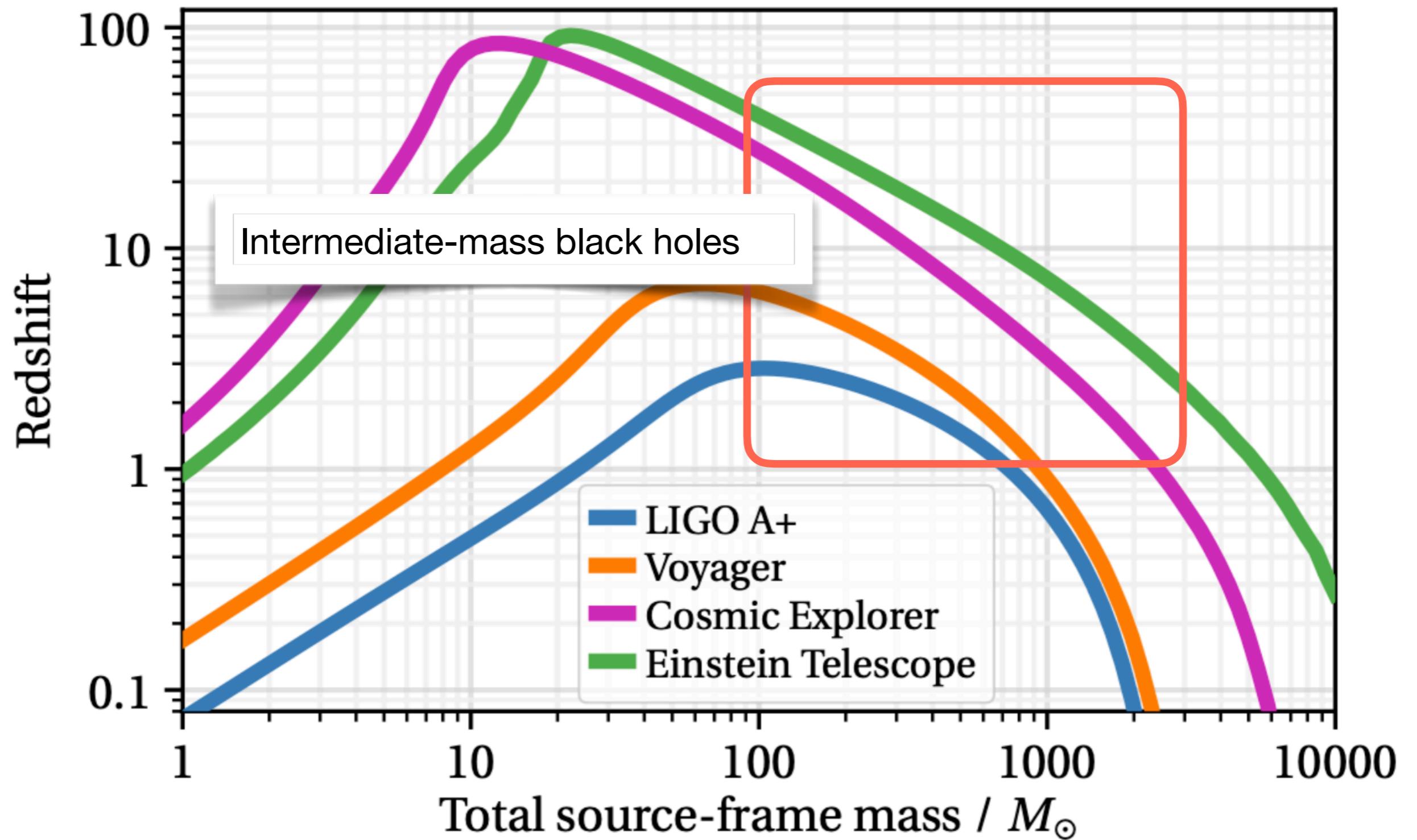
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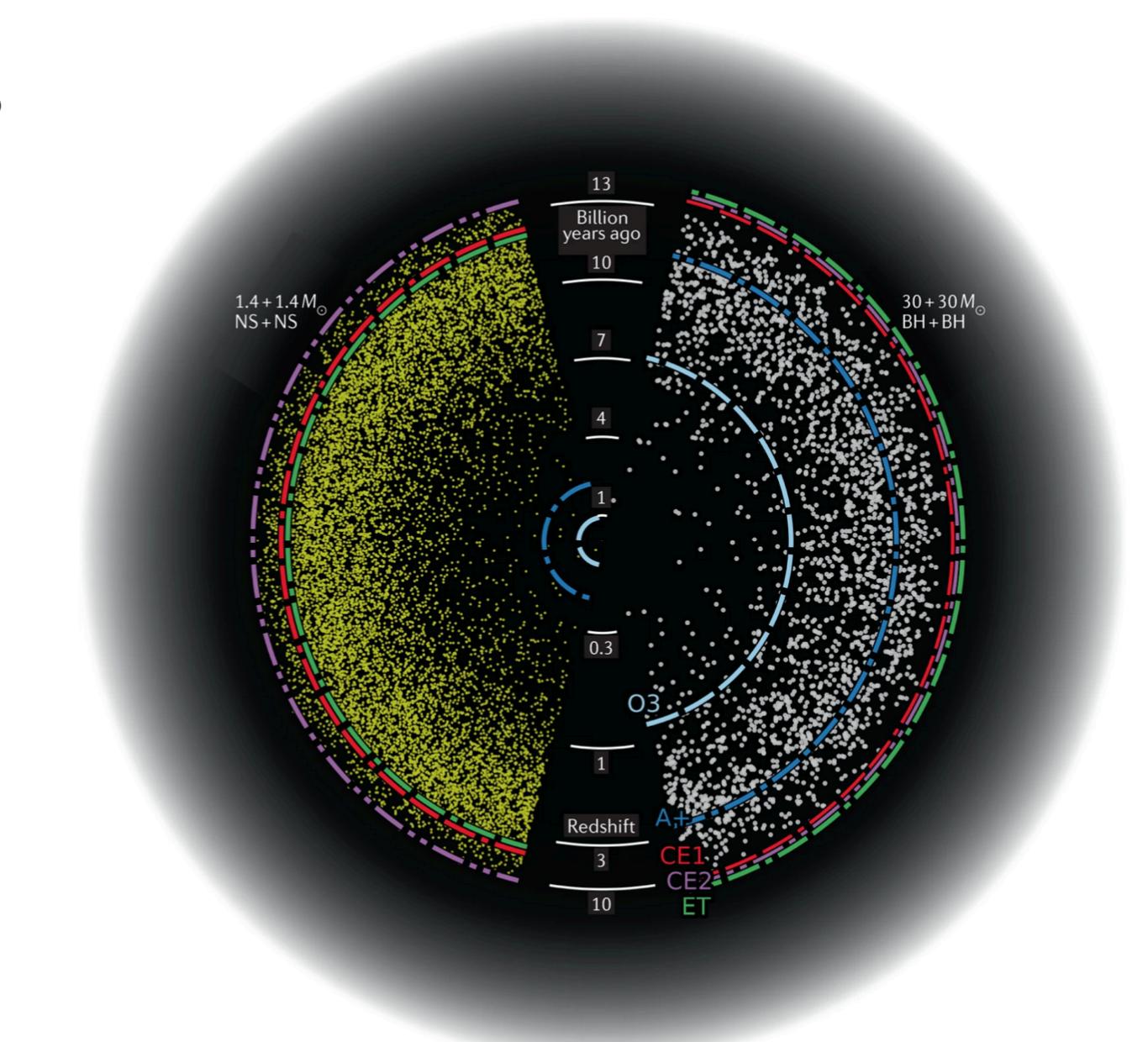
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# Some open questions: compact object binaries and stellar evolution

- How do massive stars end their lives?
- How do massive stellar binaries evolve?
- What are the seeds of (super-)massive black holes?
- Do black hole binaries form via the dynamical channel?
- What is the equation of state of neutron stars?
- Do primordial black holes exist?
- Do Galactic and extragalactic neutron stars form in the same way?
- Do the properties of binary compact objects evolve with redshift?
- ...



[Evans et al. 2021,  
Cosmic Horizon Study]

**Backup**

# Remnants of massive single stars

