Gravitational waves: from theory to discoveries

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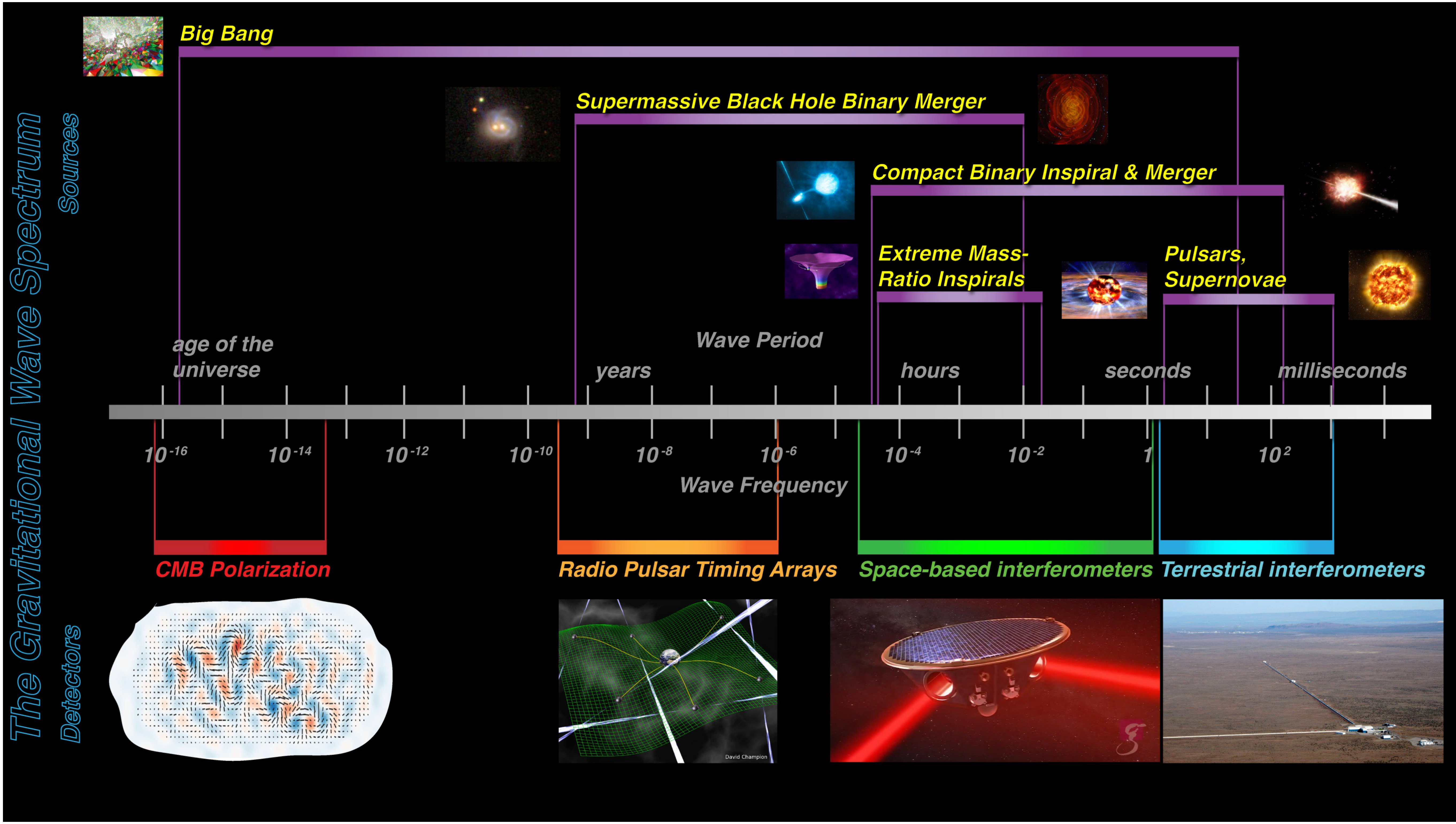
The Transient Universe, Cargèse, May 2023

Outline

- GW theory
  - Introduction to General Relativity, Einstein equation
  - Black holes
  - Gravitational waves
- GW sources
  - Formation of stellar-mass compact binaries
  - LIGO/Virgo observations and binary black hole populations
  - Formation of massive compact binaries
  - Other transient sources
  - Continuous sources and stochastic backgrounds

Overview of GW sources



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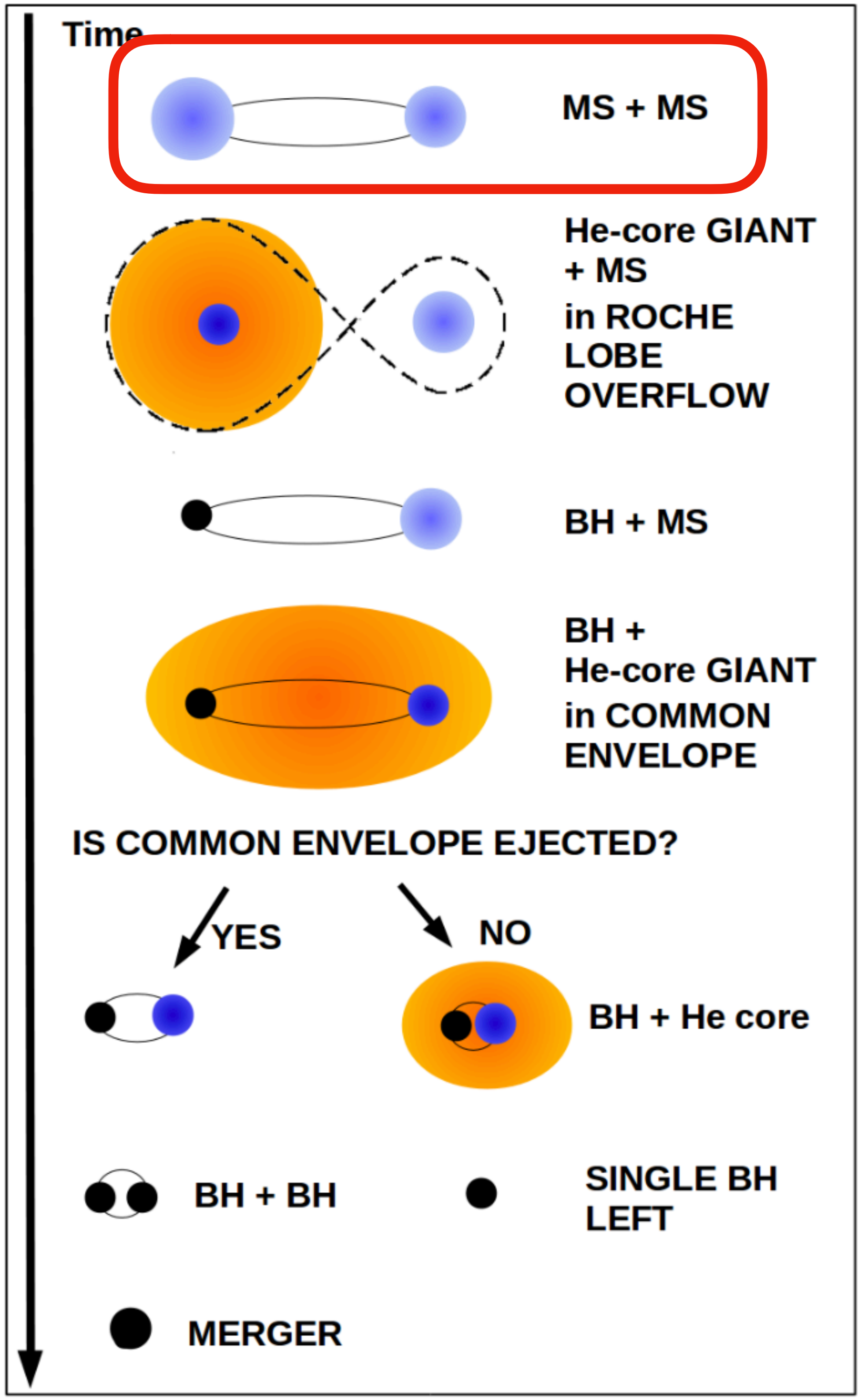
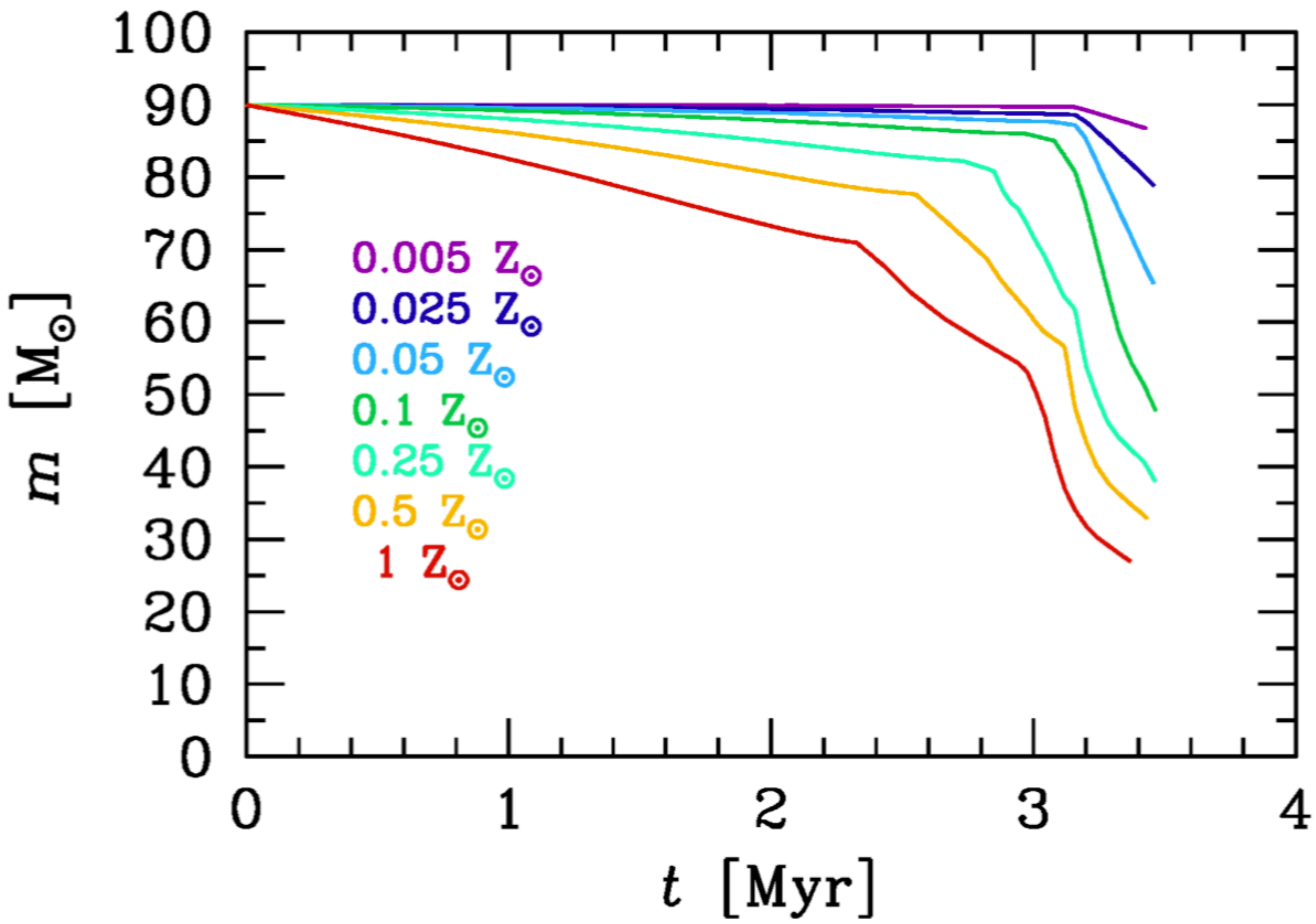
Compact binaries: isolated formation channel



Mapelli, arXiv:2105.12455

Stellar winds



Mapelli, arXiv:2106.00699

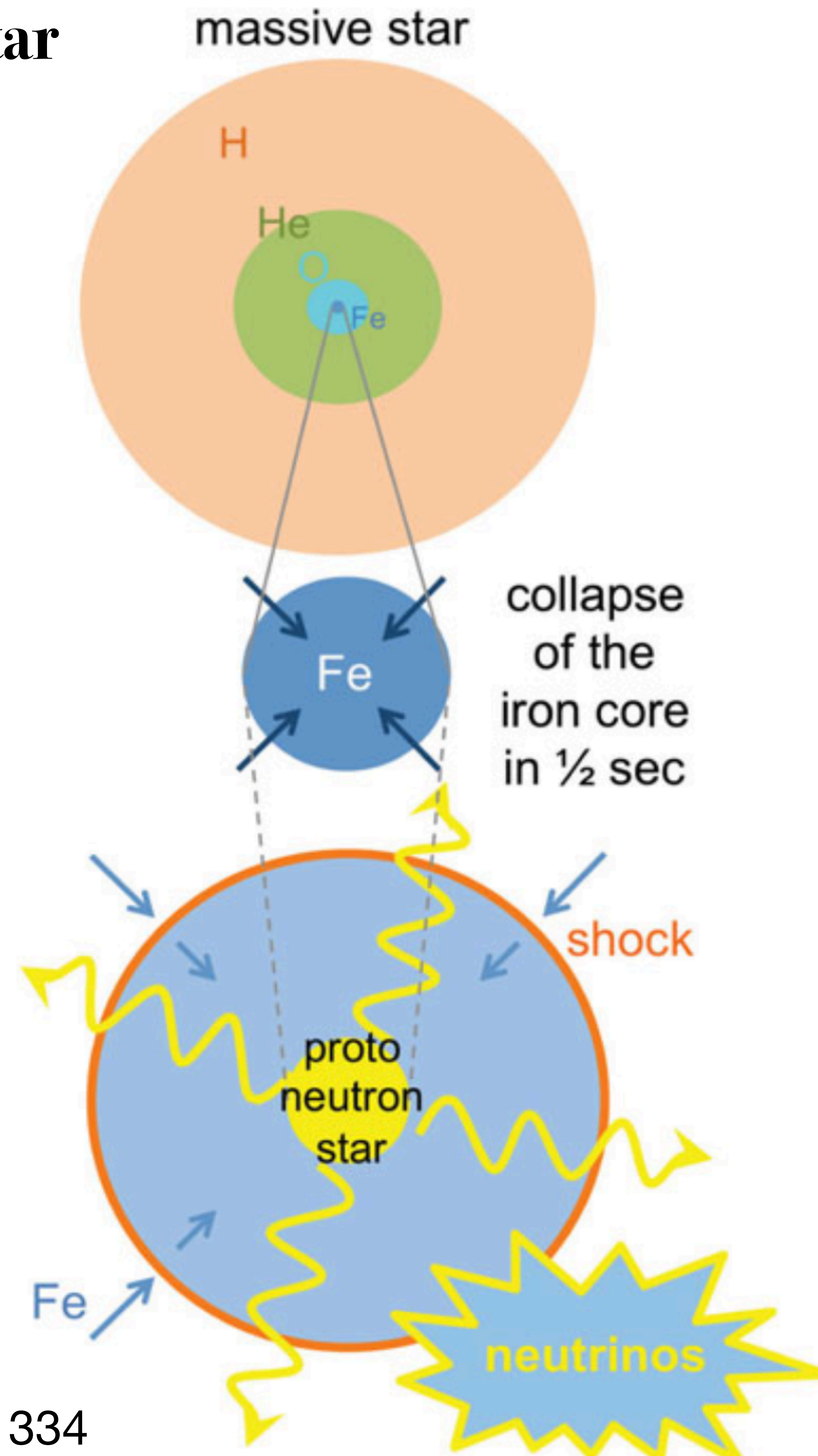
$$\dot{m} \propto Z^{\alpha}$$

$$\alpha = 0.5 - 1$$

$$\Gamma_e = \frac{\kappa_e L}{4\pi c G m}$$

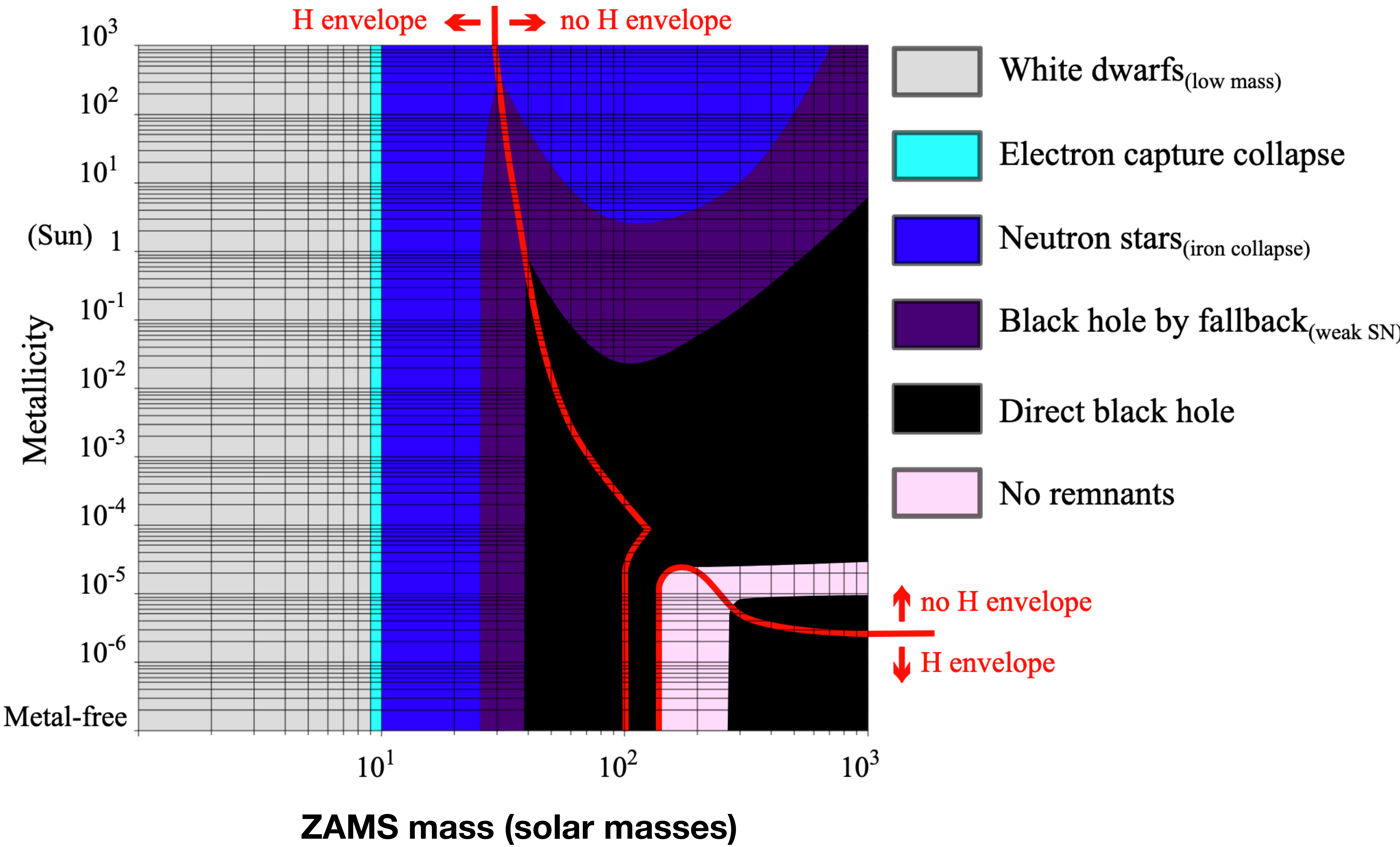
$$\alpha = \begin{cases} 0.85 \quad if \quad \Gamma_e < 2/3 \\ 2.45 - 2.4\Gamma_e \quad if \quad 2/3 \leq \Gamma_e \leq 1 \\ 0.05 \quad if \quad \Gamma_e \geq 1 \end{cases}$$

Collapse to a neutron star



Foglizzo et al., arXiv:1501.01334

The fate of massive stars



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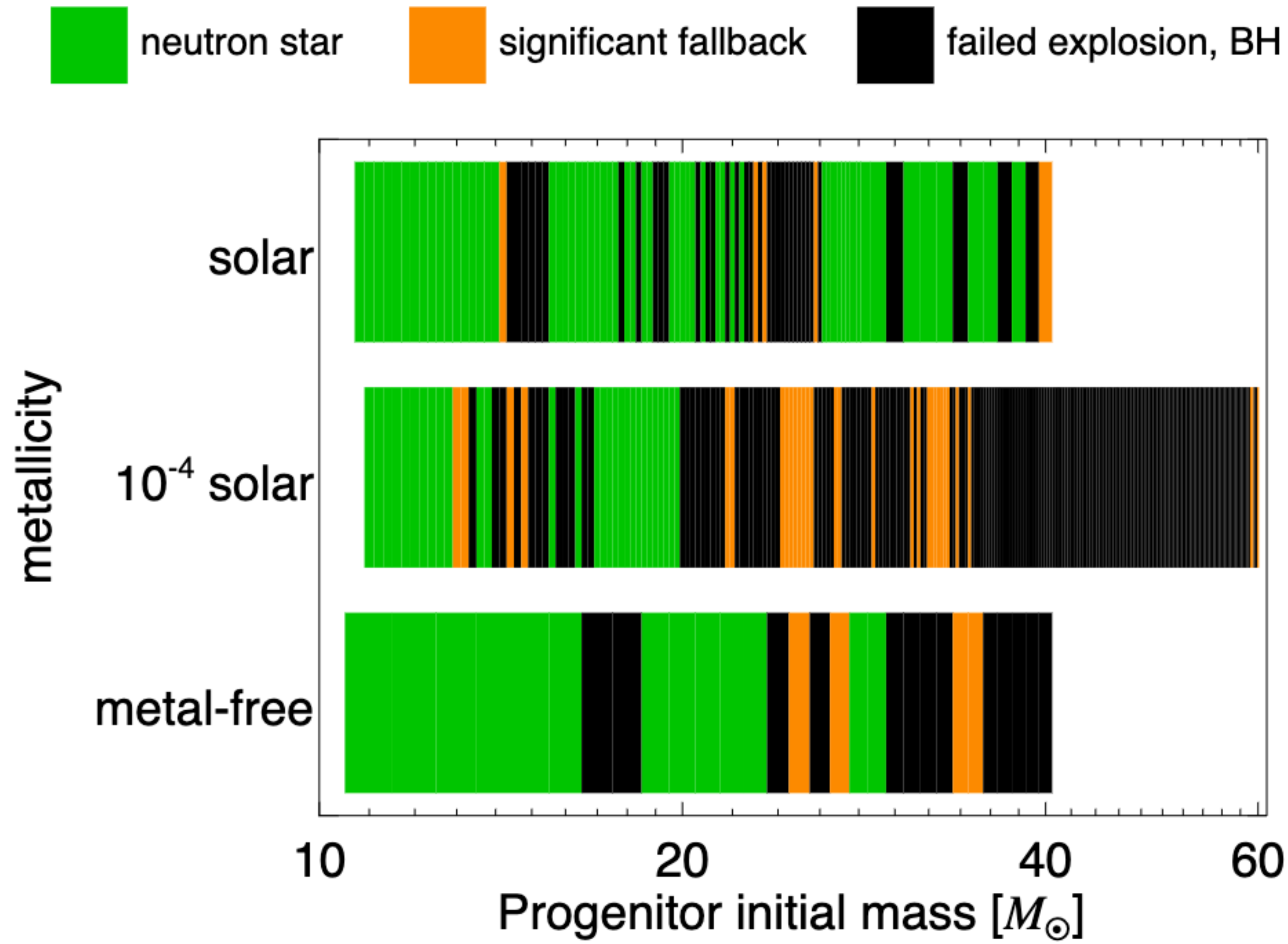
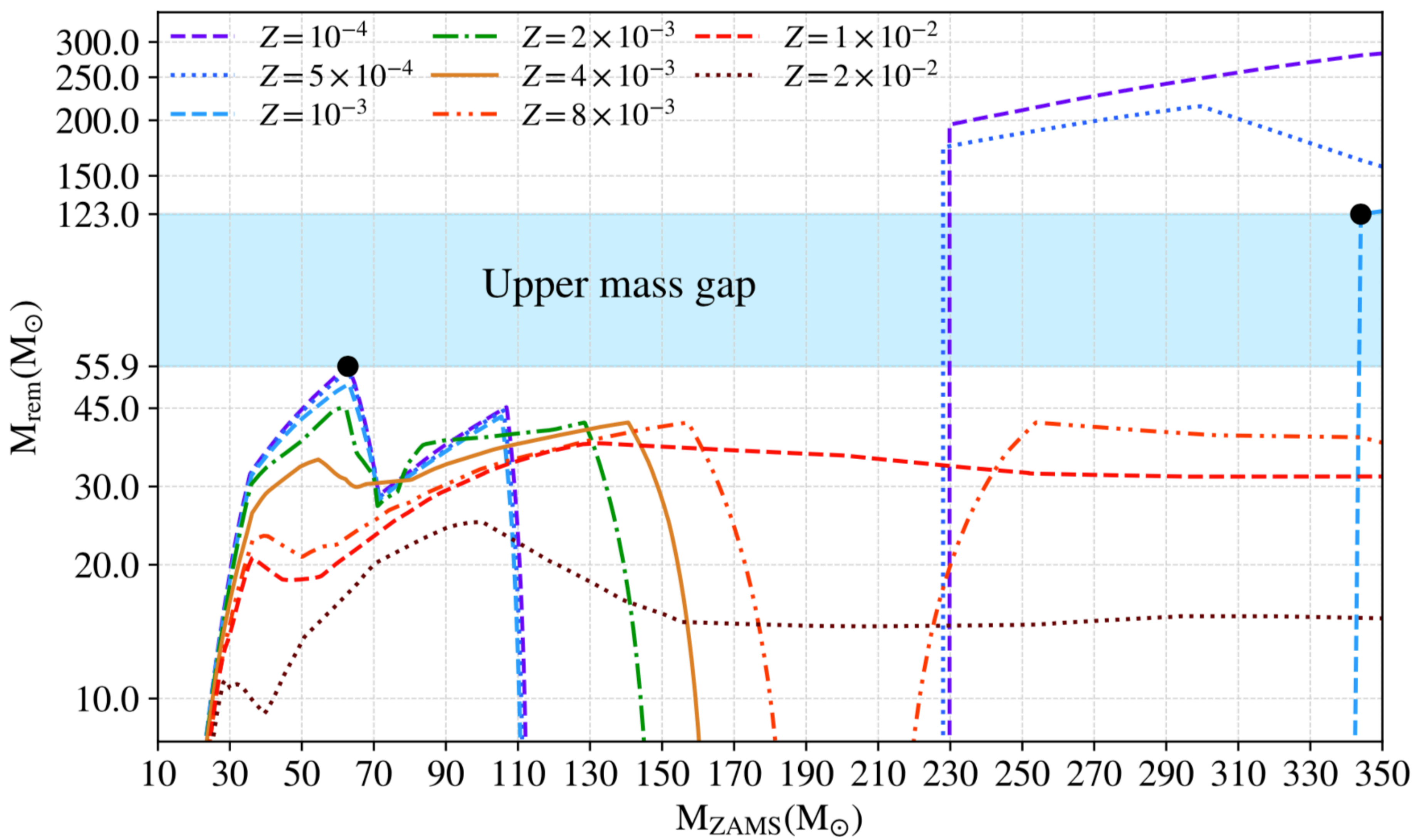


Pejcha & Thompson (2015)

Collapse to a compact object

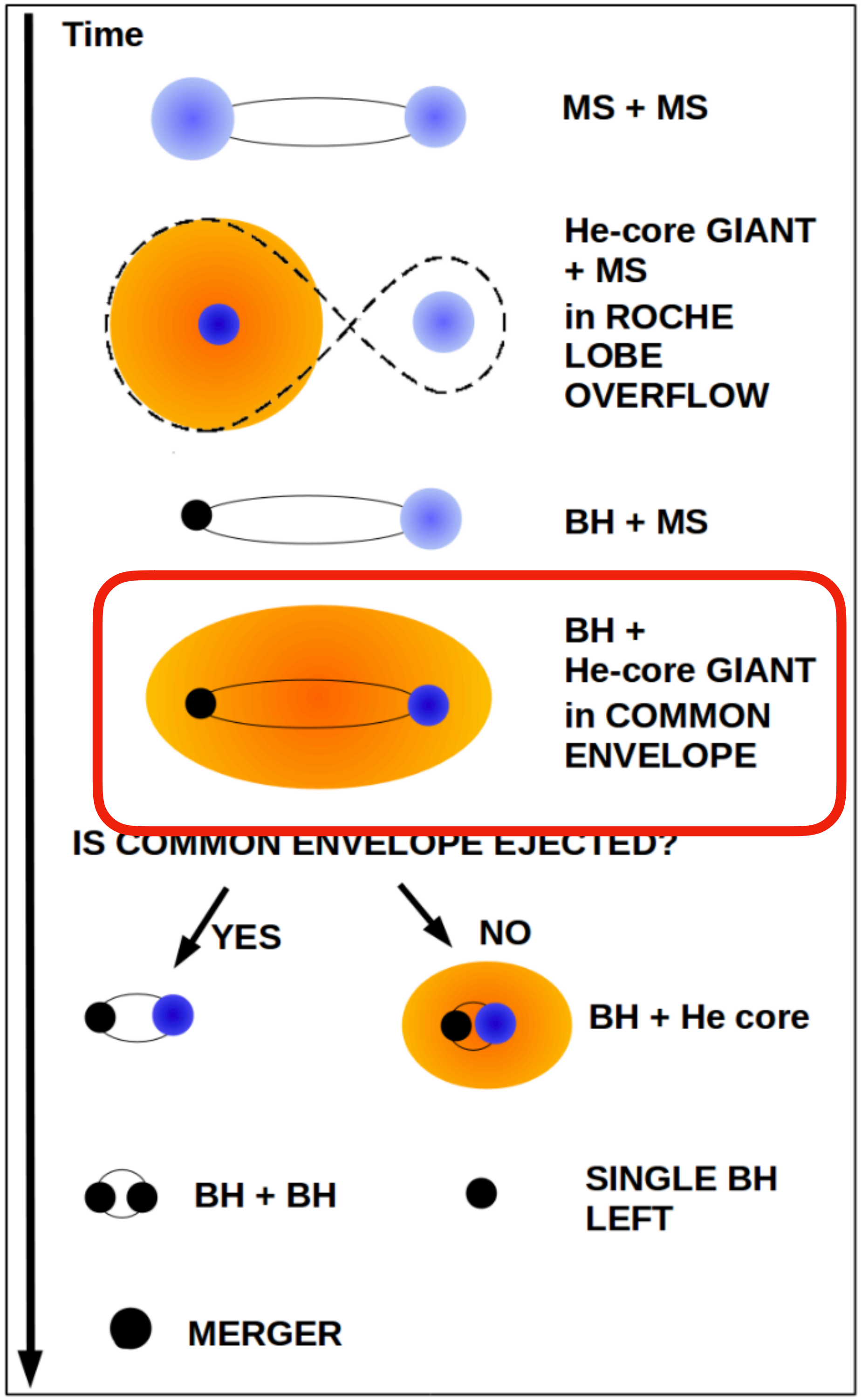
Pair-instability supernova (PISN):

electron-positron pairs remove pressure from the star -> contraction -> runaway oxygen/silicon burning -> disruption of the star



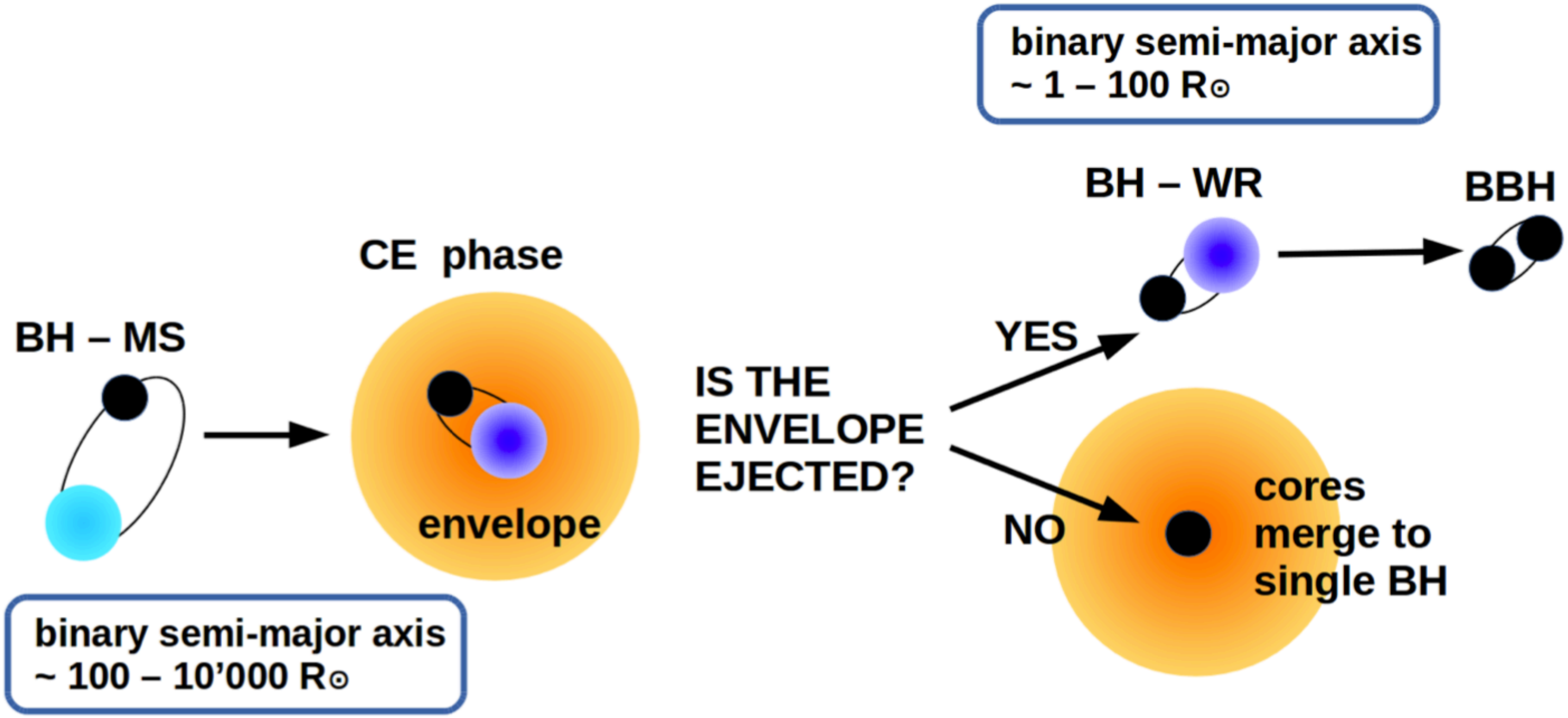
[Spera+2022]

Compact binaries: isolated formation channel



Mapelli, arXiv:2105.12455

Common envelope

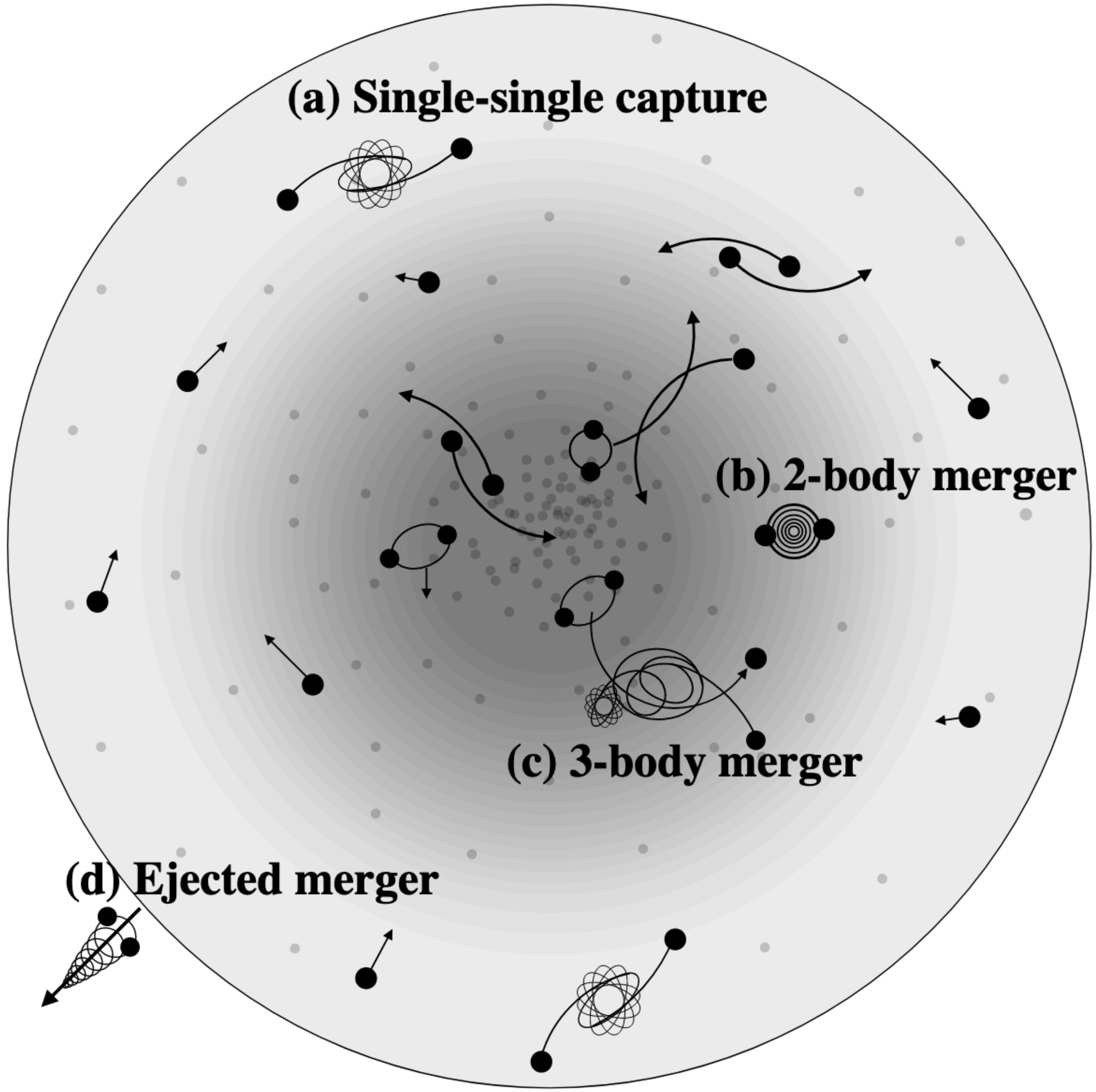


Mapelli, arXiv:2106.00699

$\alpha - \lambda$ formalism: Envelope binding energy $$E_{env} \simeq -\frac{1}{\lambda}\frac{G m_1 m_{env,1}}{R_1}$$

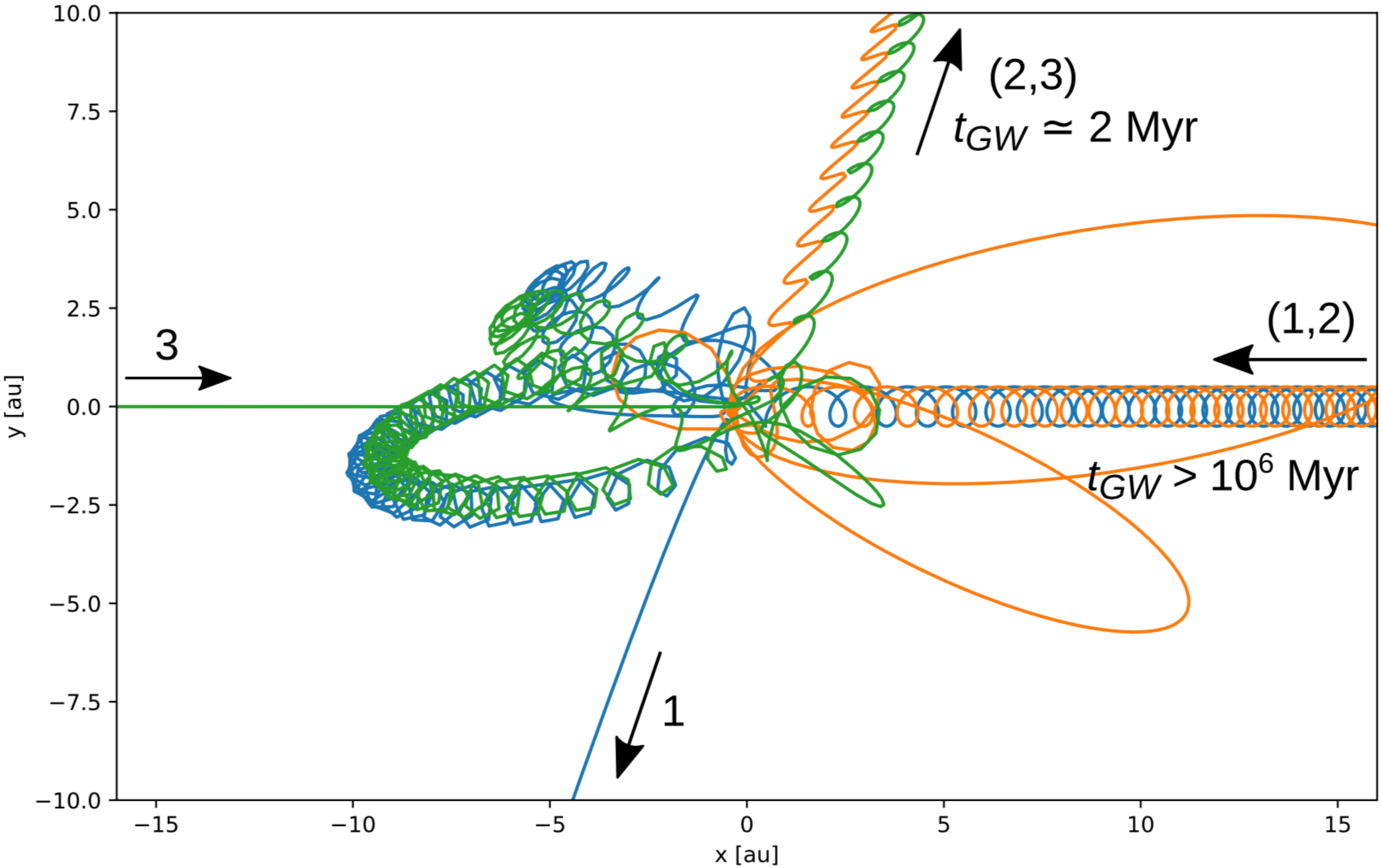
Fraction of orbital energy used to unbind the envelope $$\Delta E_{orb,un} \simeq -\alpha \frac{G m_{c,1} m_{BH}}{2}\left(\frac{1}{a_f} - \frac{1}{a_i}\right)$$

Compact binaries: isolated formation channel



[Samsing+2020]

Compact binaries: isolated formation channel



[Spera+2022]

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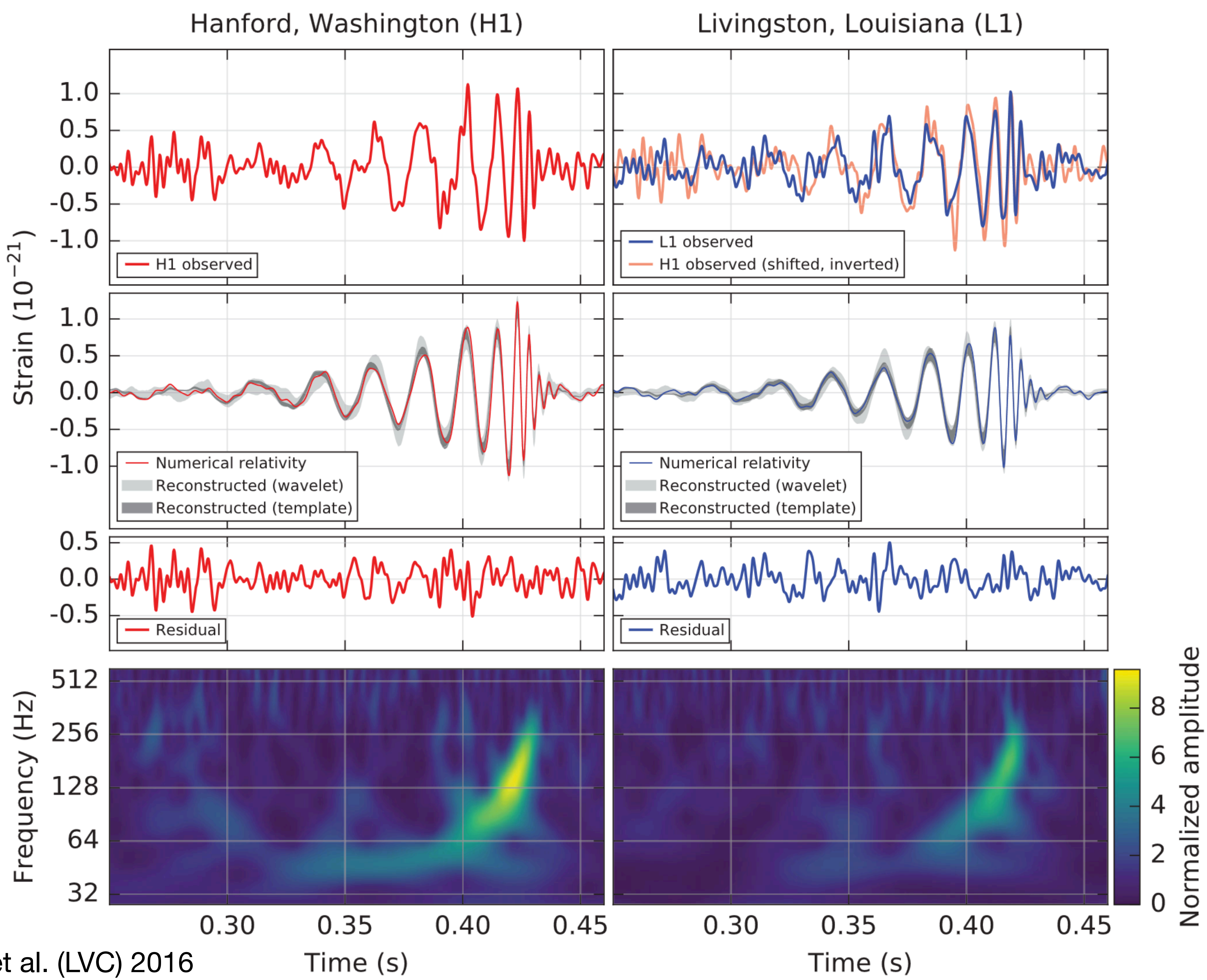
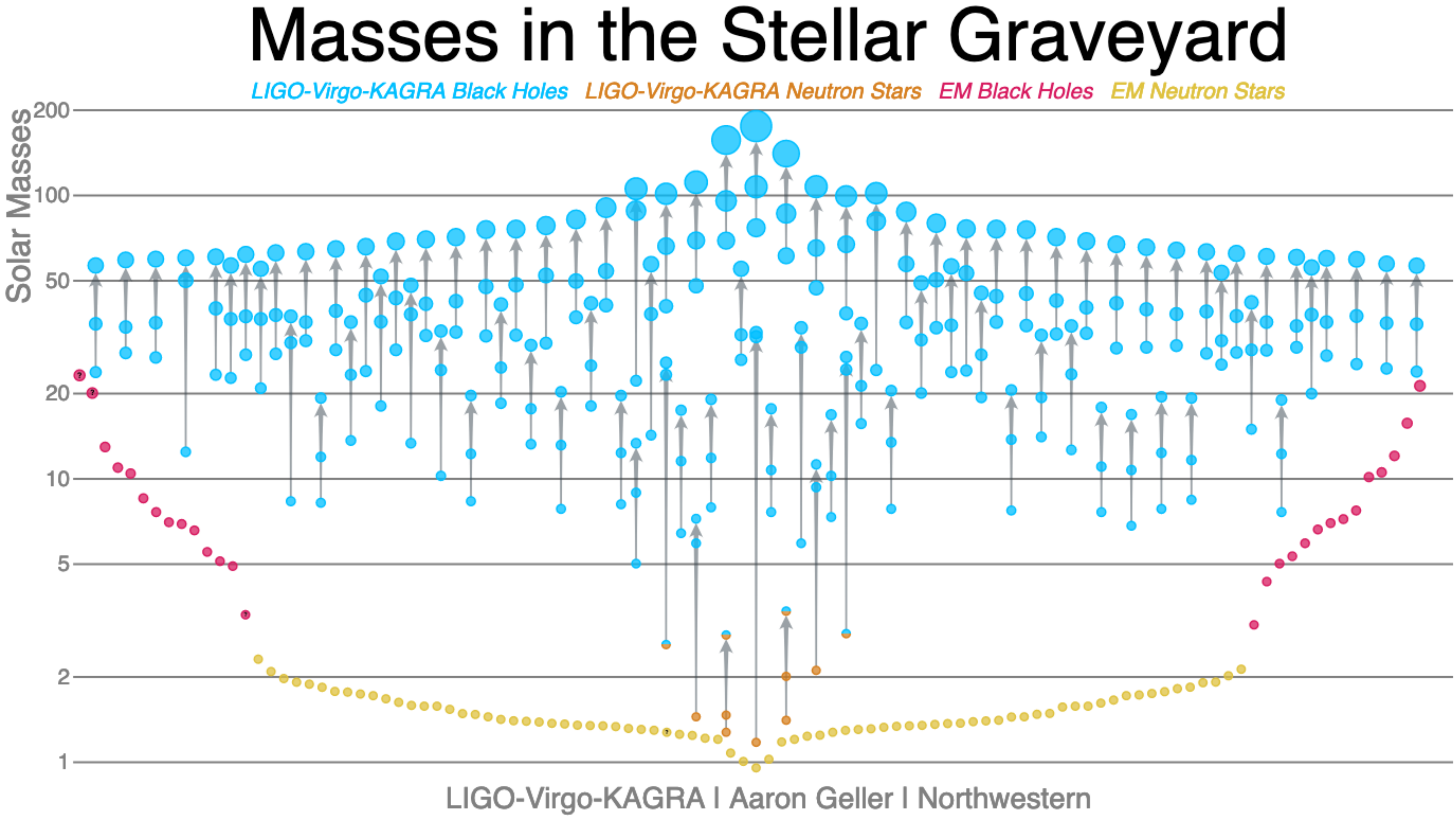
Detection of gravitational waves: GW150914

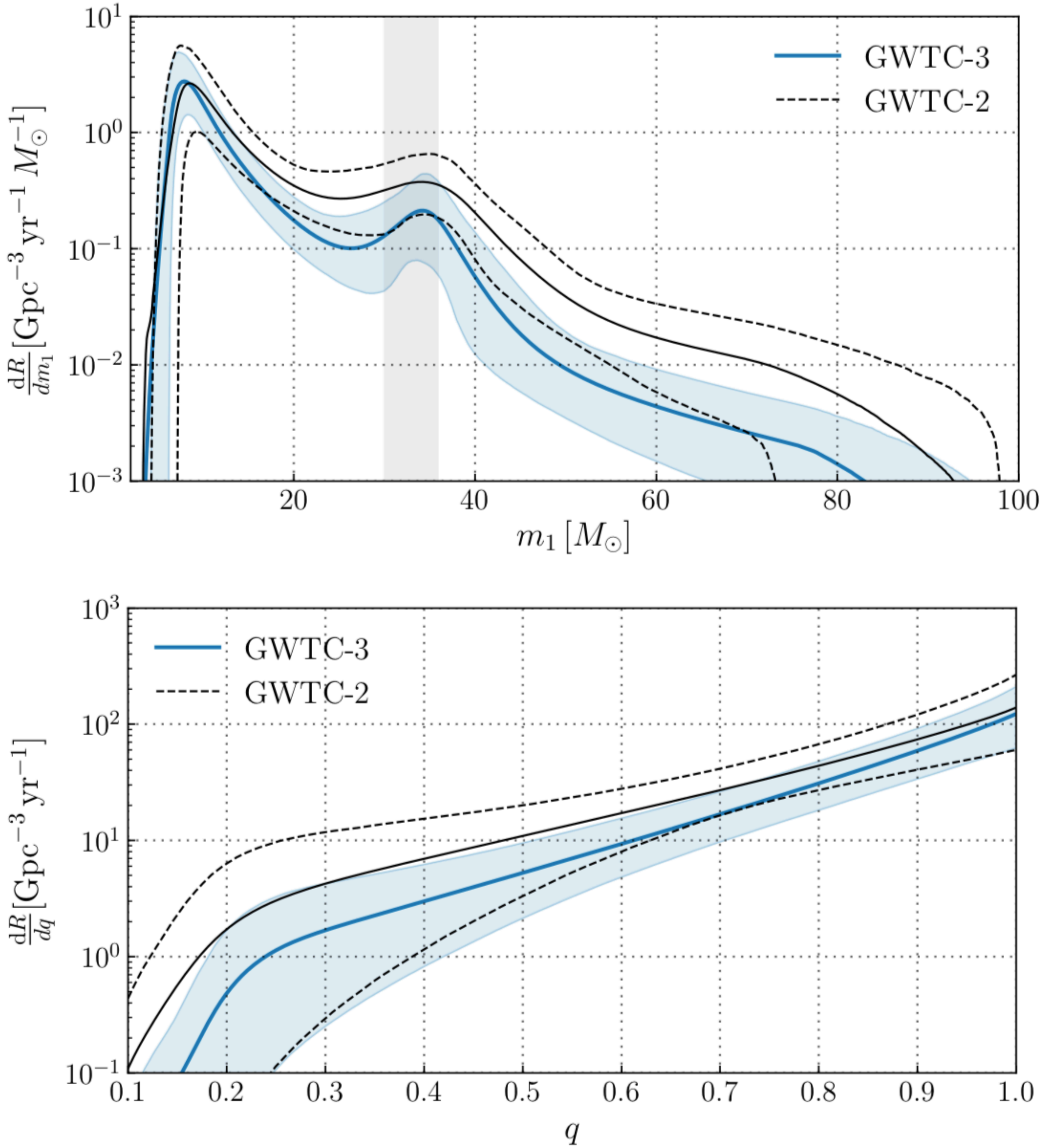


Abbott et al. (LVC) 2016



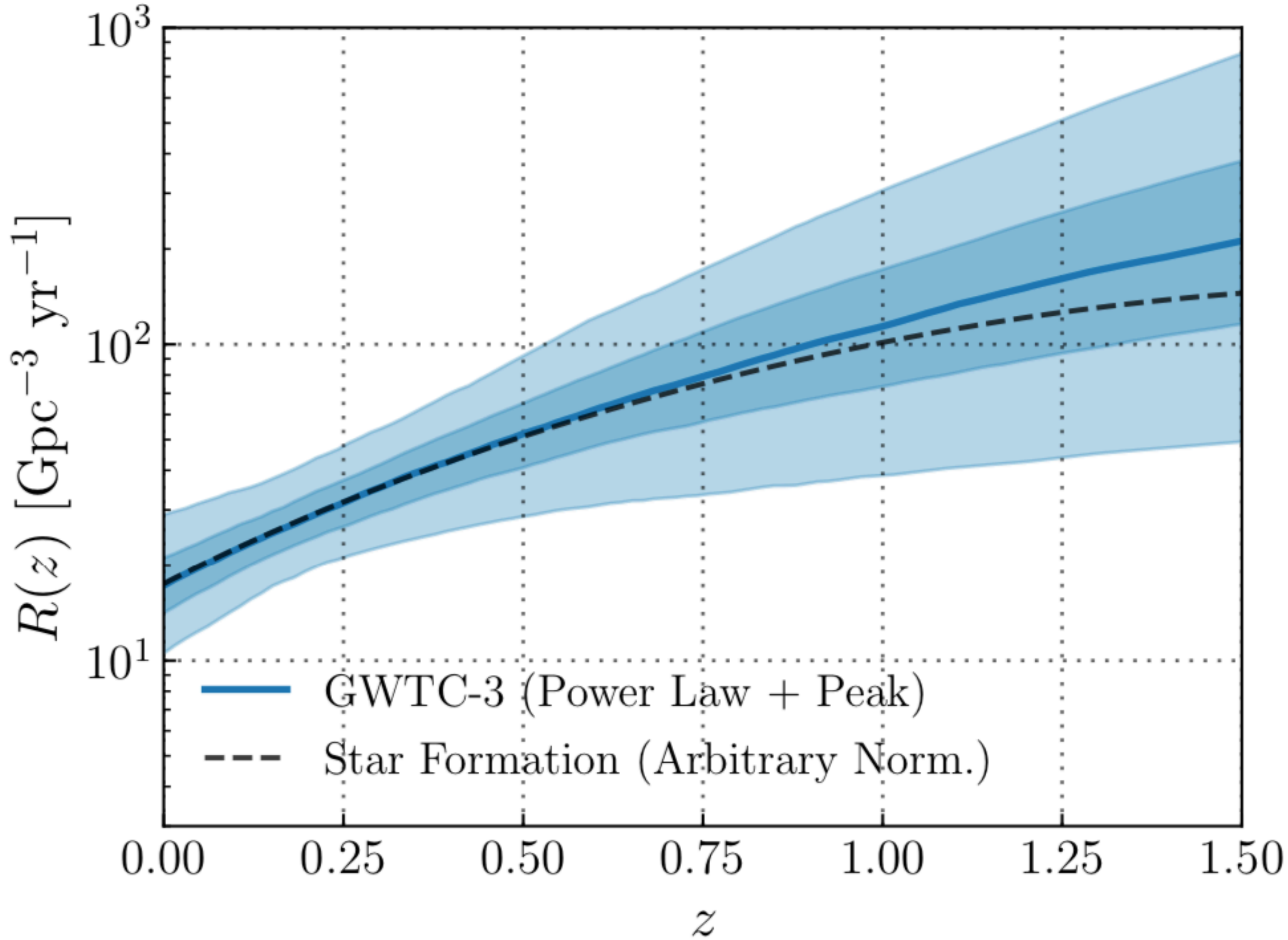
Abbott et al. 2019, PRX, 9, 031040; Abbott et al. 2021, PRX, 11, 021053;
Abbott et al. 2021, arXiv:2111.03606; Abbott et al. 2021, arXiv:2108.01045

Black hole populations: mass distribution



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

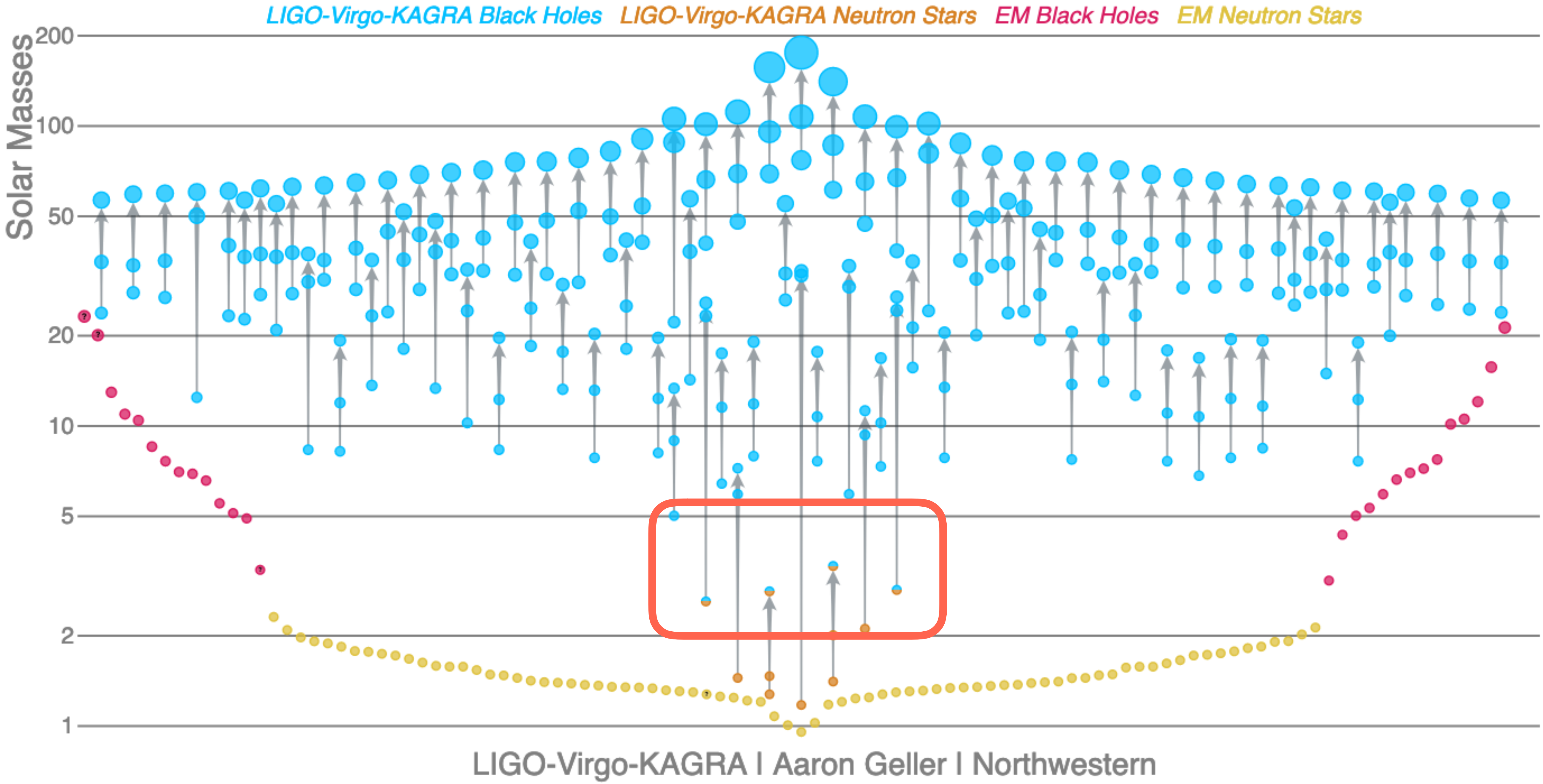
Black hole populations: merger rate evolution



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

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

Masses in the Stellar Graveyard



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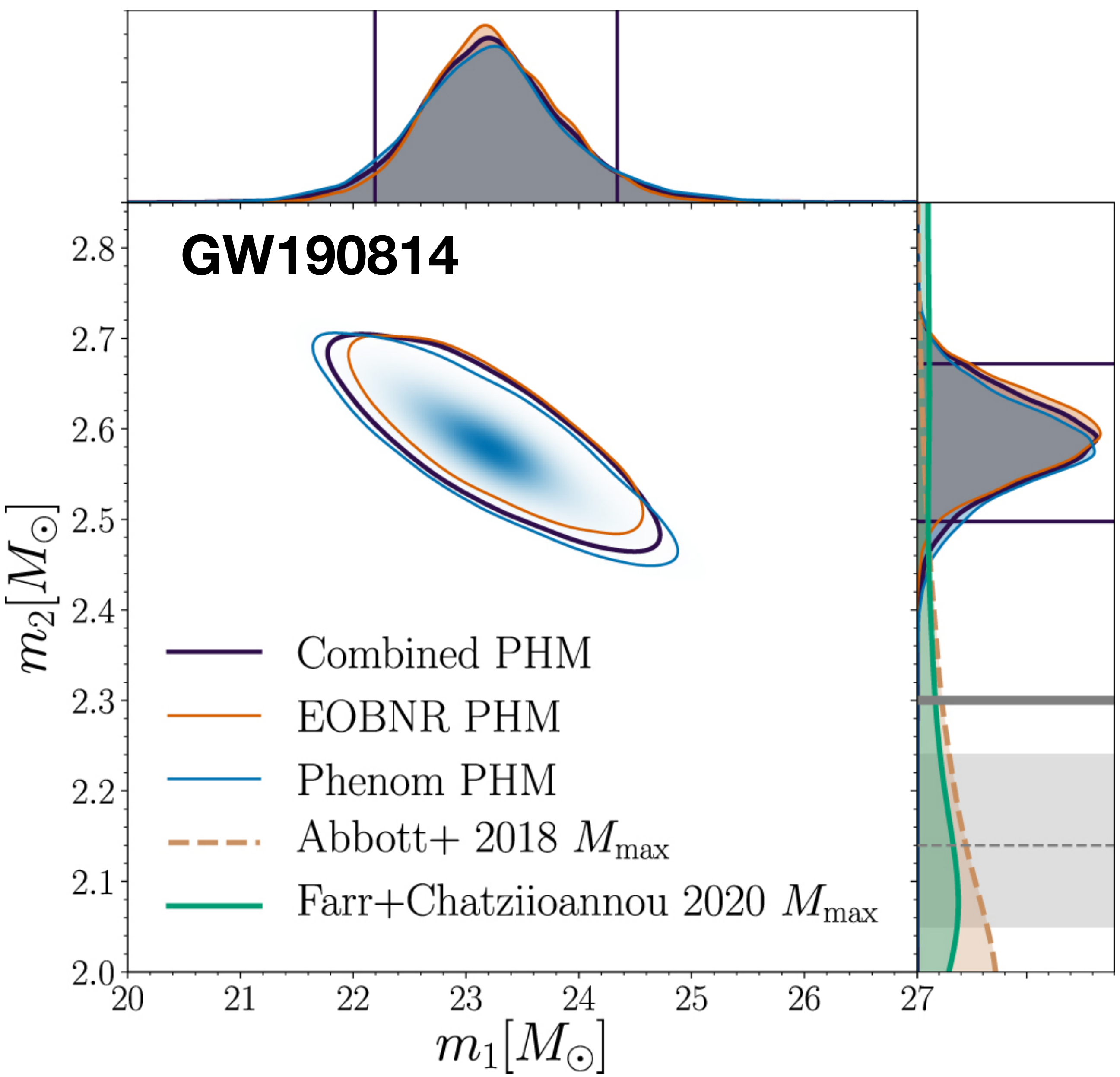
Black holes in the lower mass gap

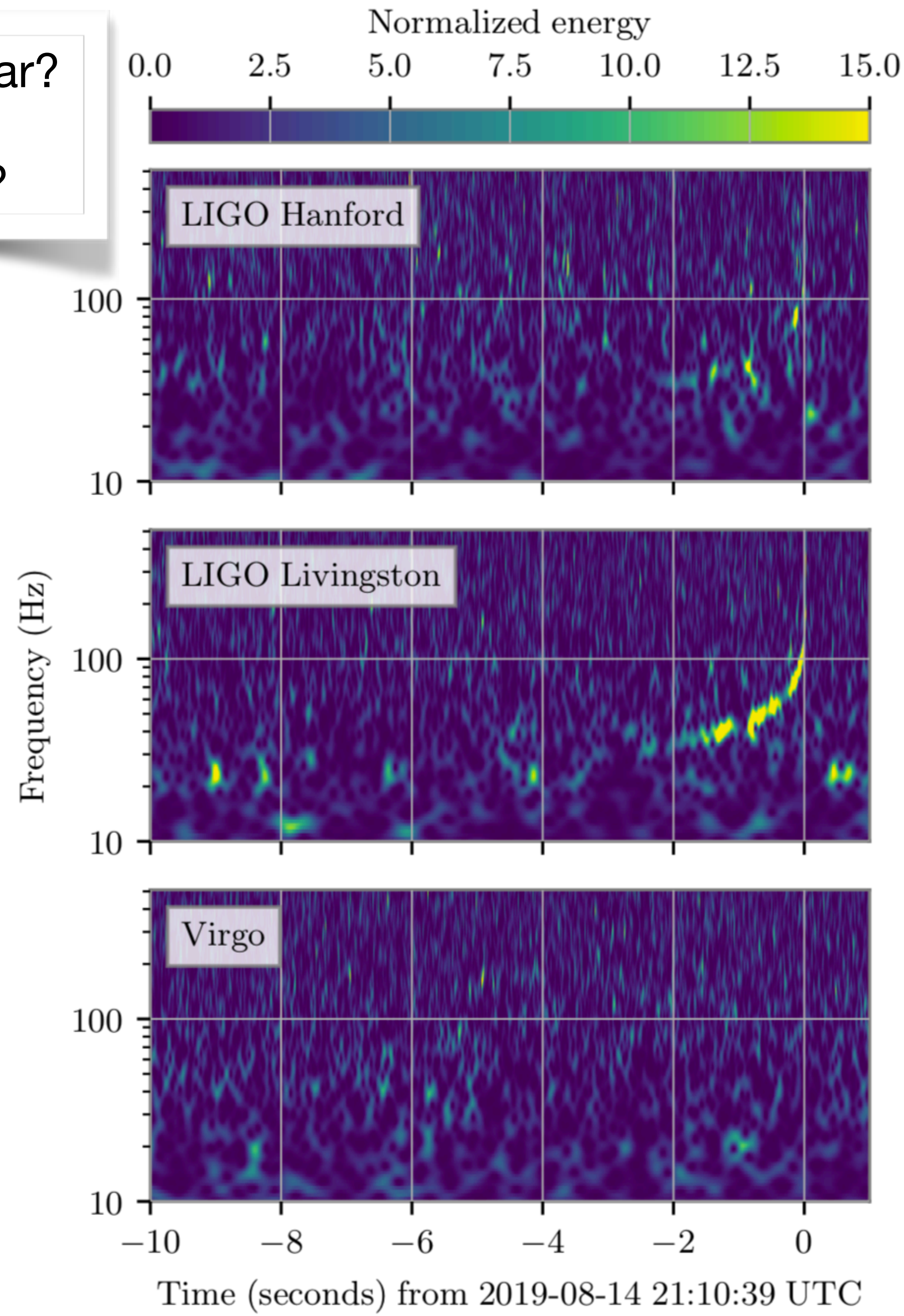
$$m_1 = 23.3^{+1.1}_{-1.0}\ M_\odot$$

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

Heaviest neutron star?

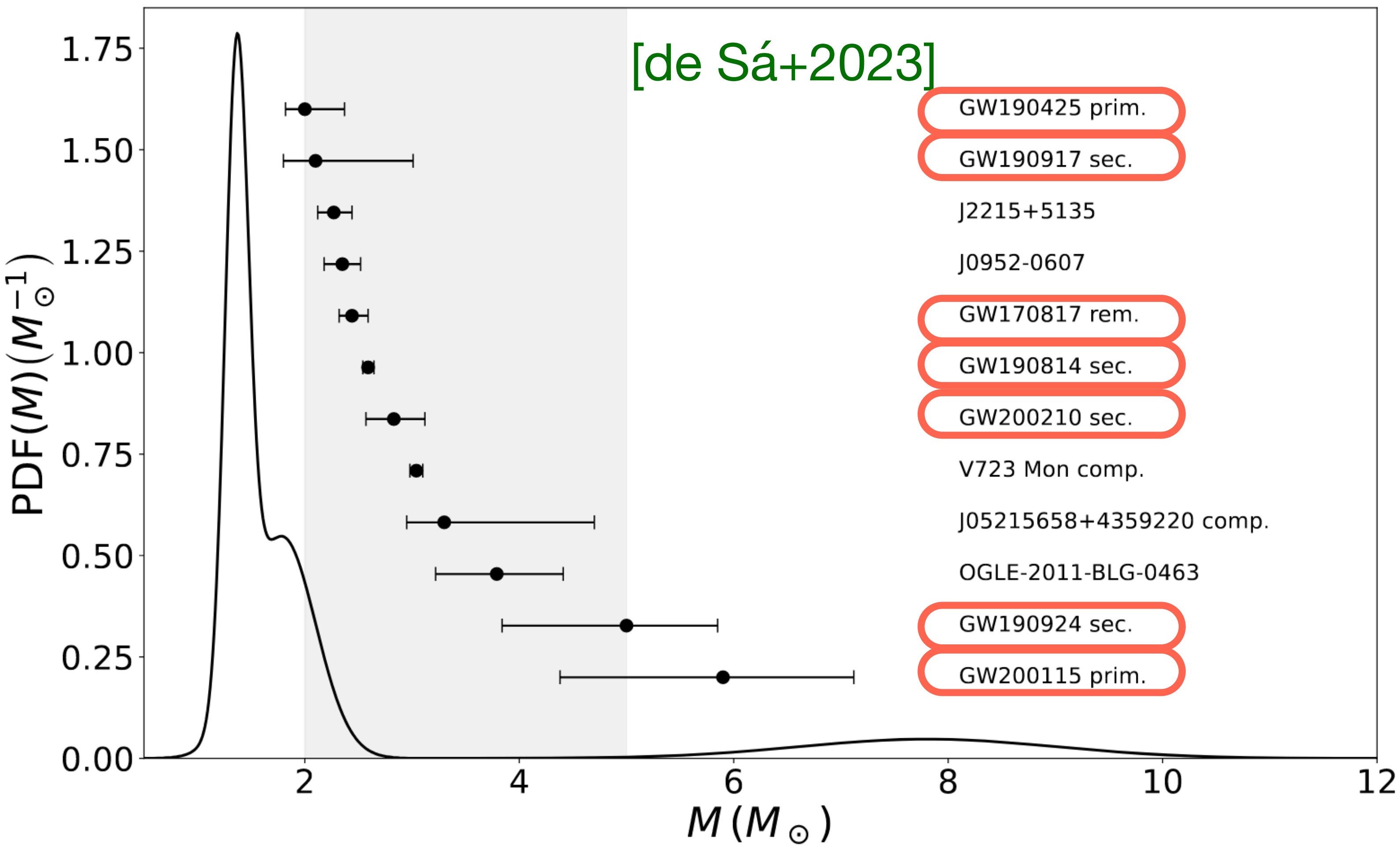
Lightest black hole?

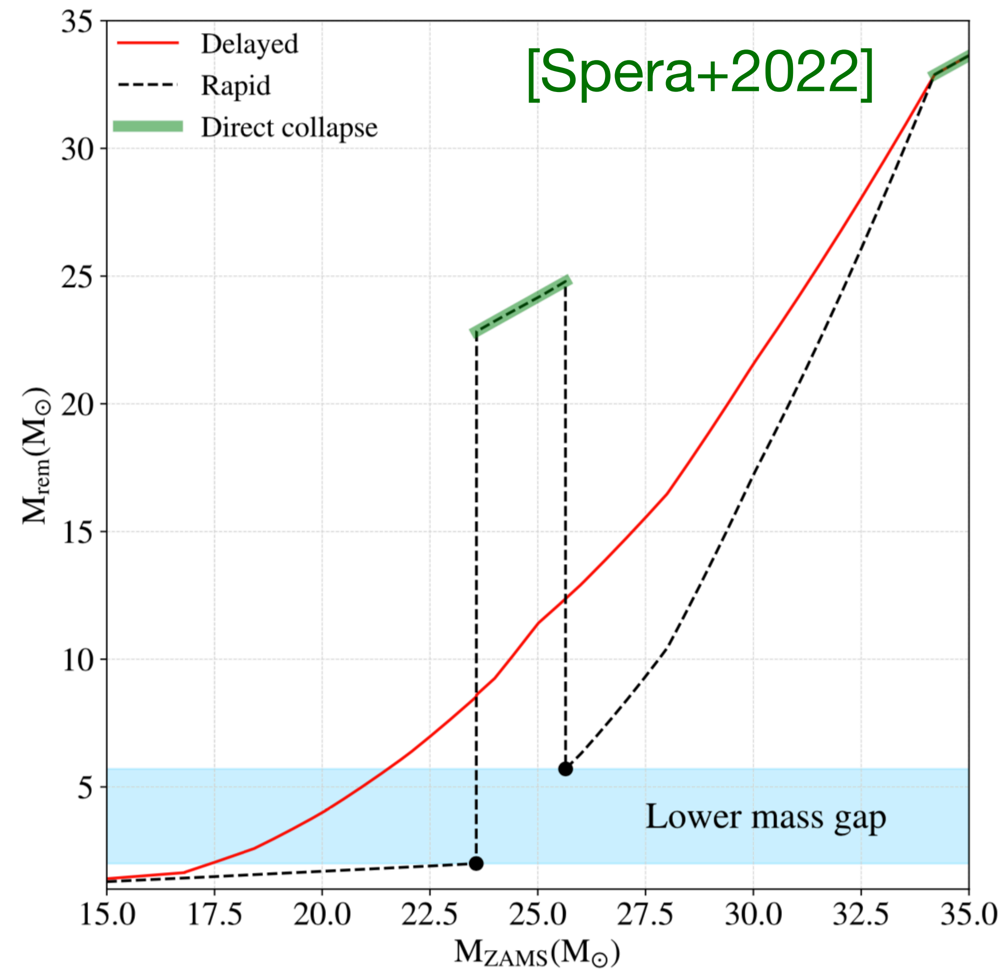




[Abbott et al. 2020, ApJL, 896, 44]

Black holes in the lower mass gap

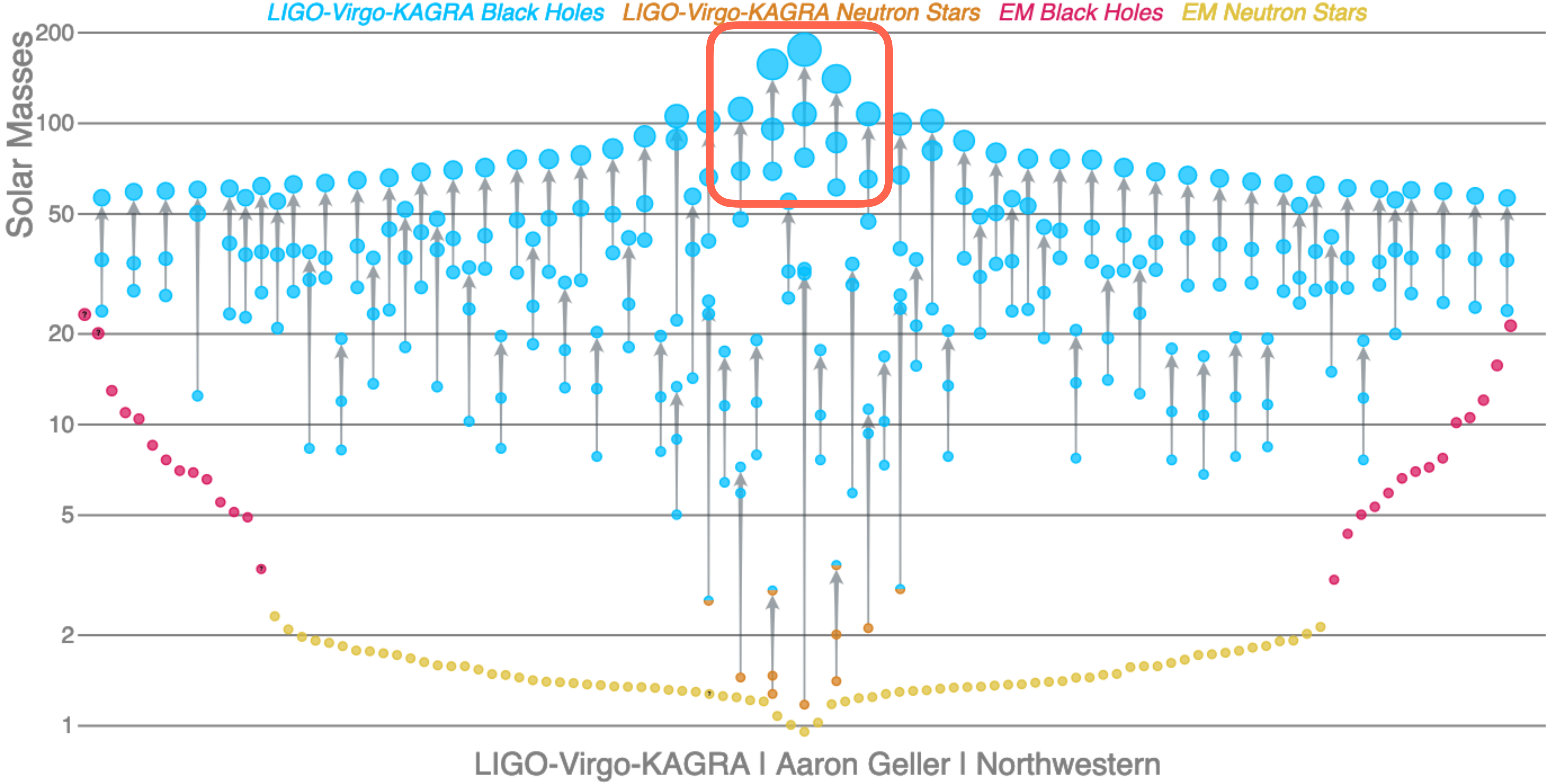




Is the mass gap real?
Is it an observational effect?

Implications for supernova explosion mechanism?

Masses in the Stellar Graveyard



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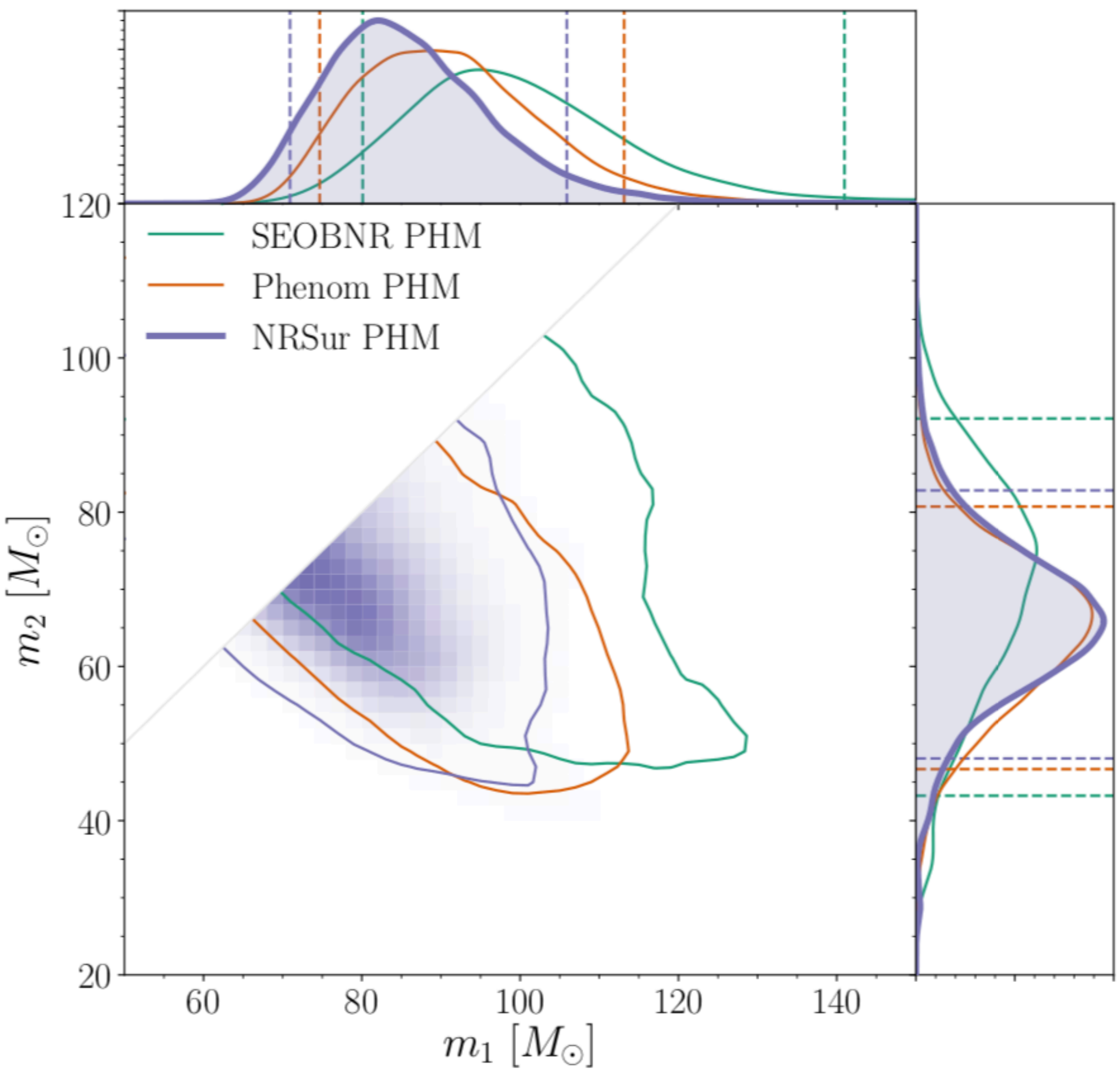
Black holes in the upper mass gap



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

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

GW190521

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

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

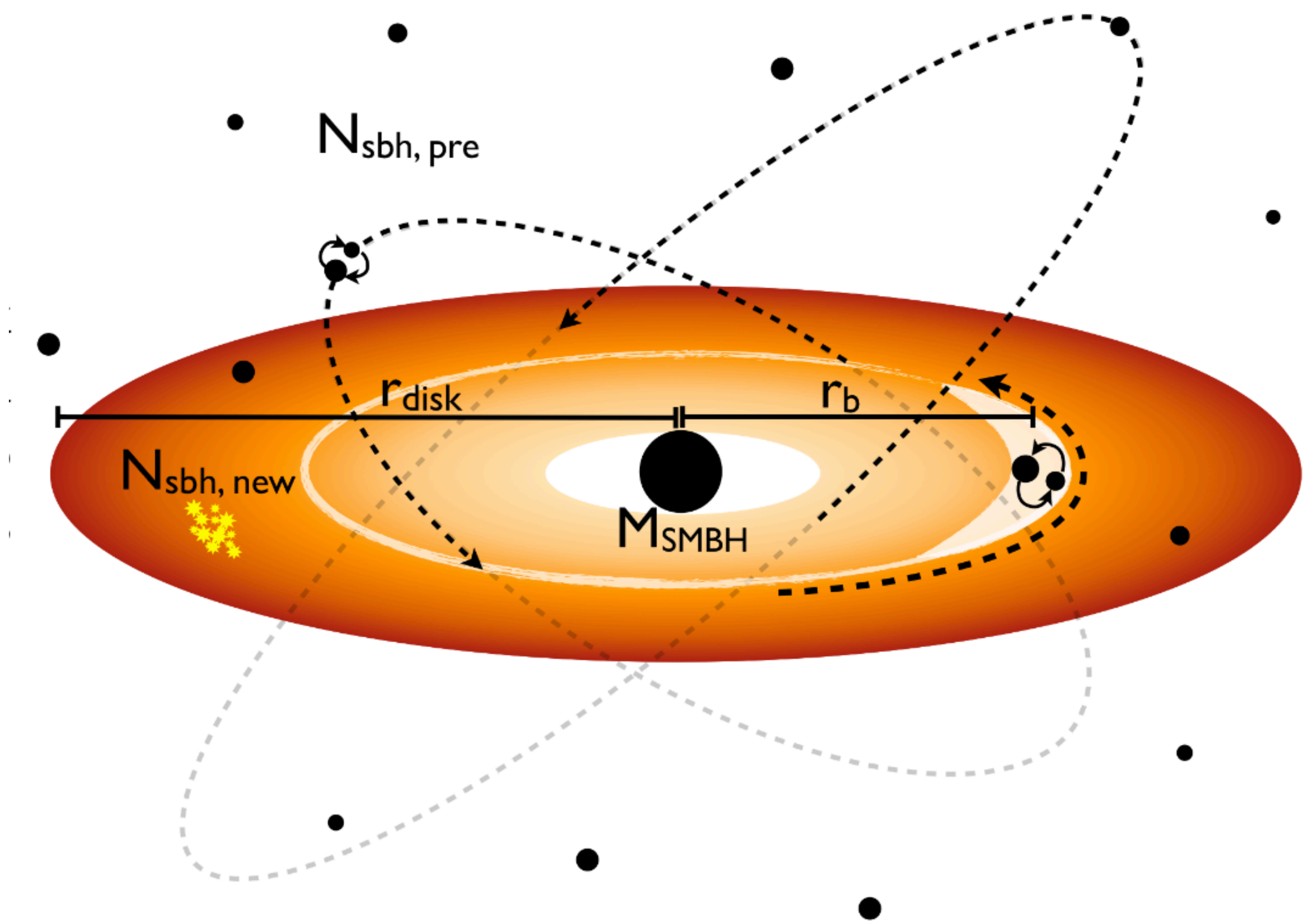
Hierarchical merger?

Black hole formed in the mass gap?

BBH mergers in AGN disks?

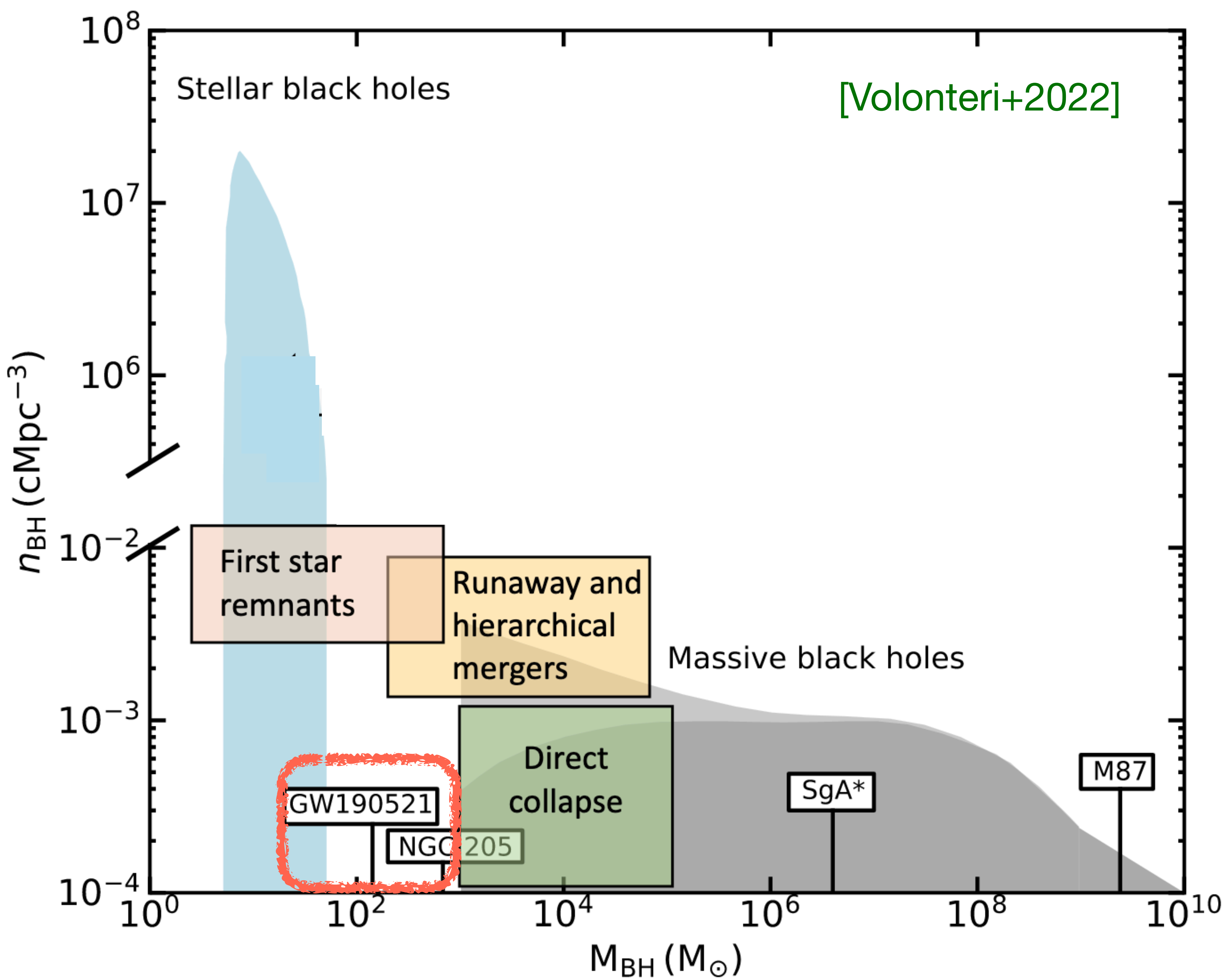
- AGN + gaseous disk + distribution of BHs
- Some BHs get trapped in the disk
- Torques from gas: BHs migrate within the disk and merge
- BH can grow by gas accretion —> IMBH

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



[Saavik Ford+2019: Astro2020 White Paper]

The link between stellar-mass and massive black holes?



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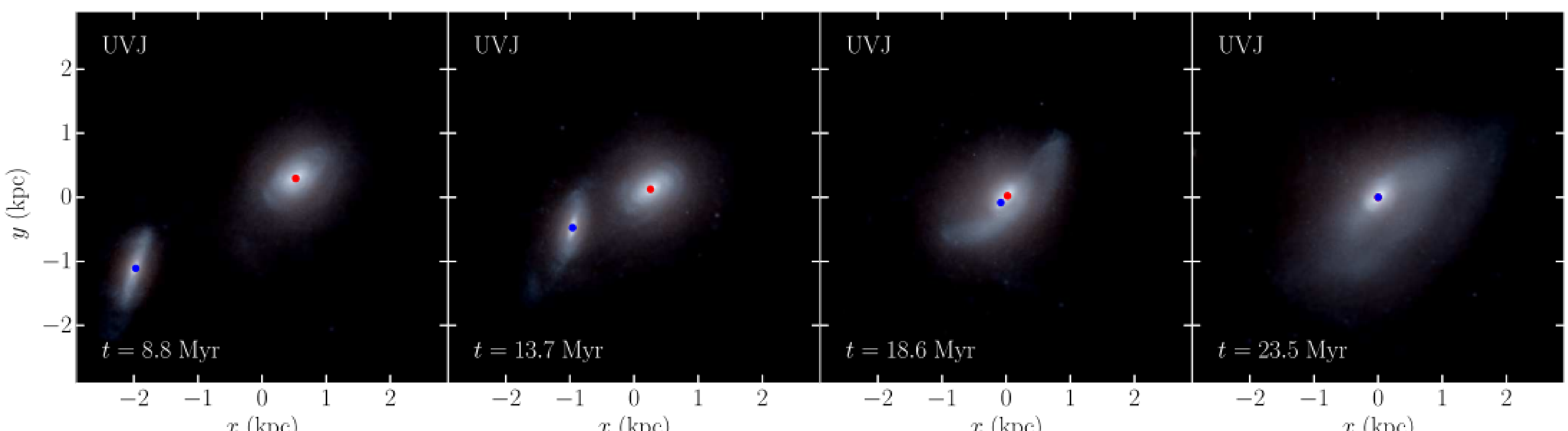
Massive black hole binaries $M_{BH} \sim 10^5 - 10^9 M_\odot$

Evolution of massive BH binaries:

- **Seed BHs** grow through accretion in galactic centers
- Two galaxies that host BHs merge ***(10-100 kpc)***
- Dynamical friction of BHs with surrounding gas —> bound BH binary ***(kpc)***
- Orbit decay through interactions with surrounding gas and stars ***(pc)***
- Emission of GW —> merger ***(milli-pc)***

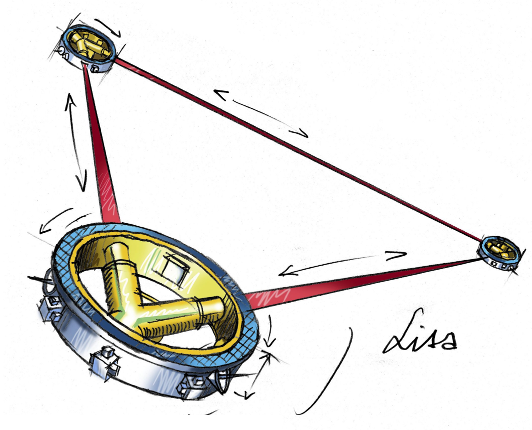


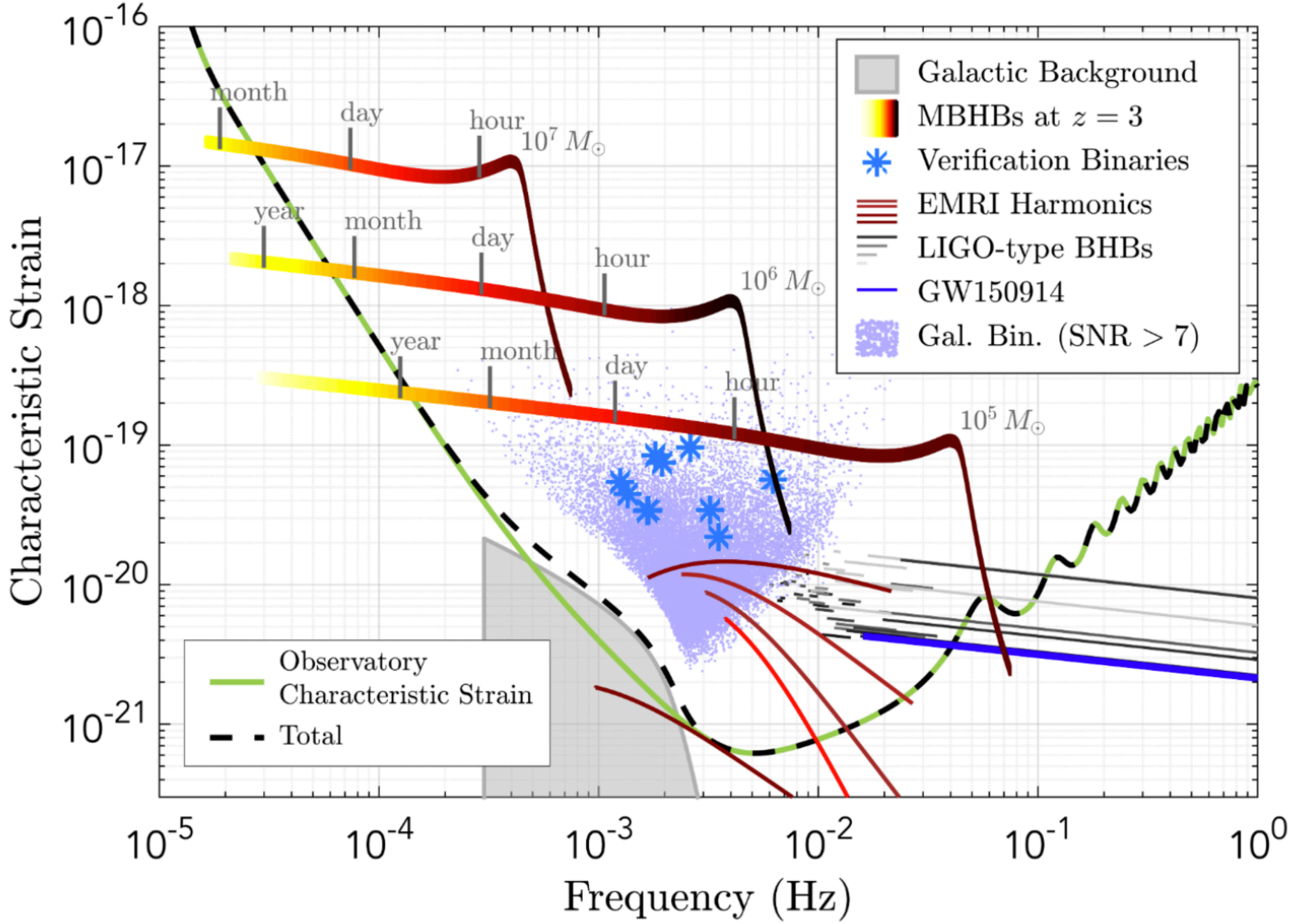
[Khan et al. (2016)]

A variety of GW sources with LISA

Astrophysics with LISA [2203.06016]

Cosmology with LISA [2204.05434]





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Extreme mass-ratio inspirals

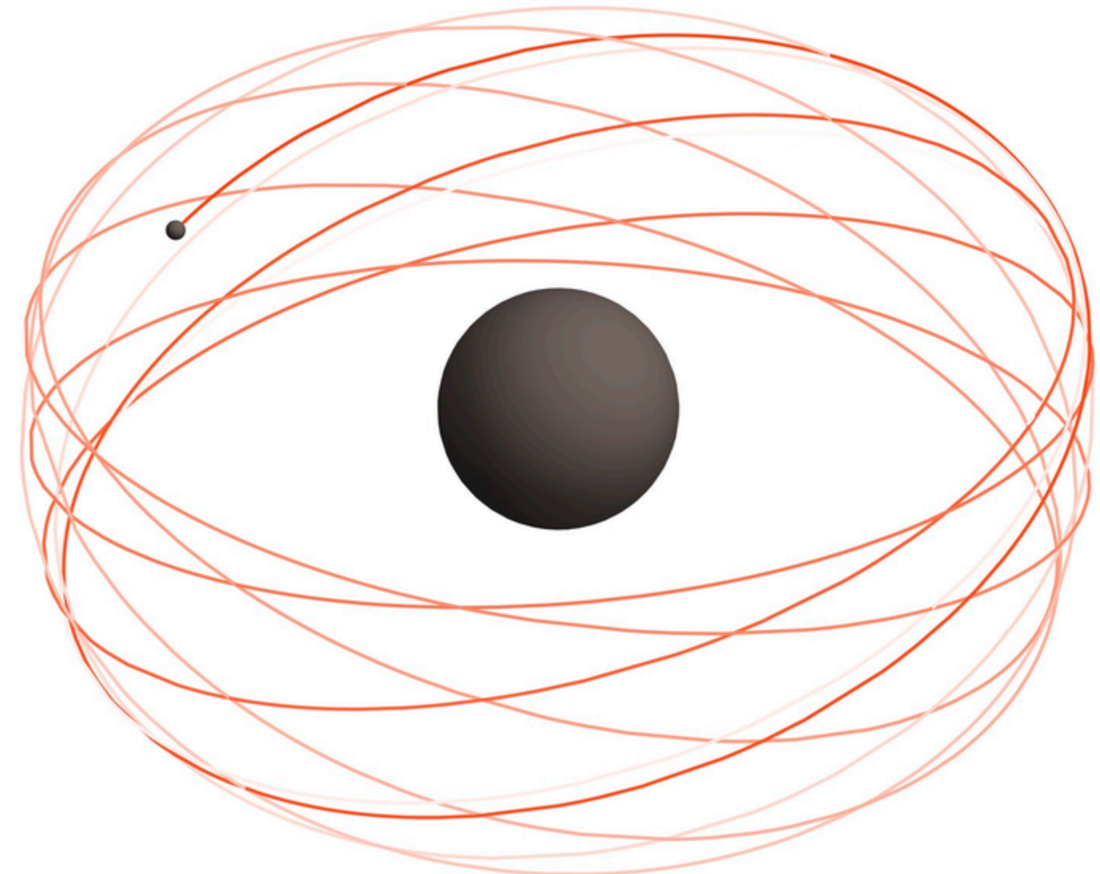
Stellar-mass black holes orbiting massive black holes

Population models: massive black hole formation

+ capture rates of stellar-mass black holes

Waveform models: long-lived source, need

extreme accuracy

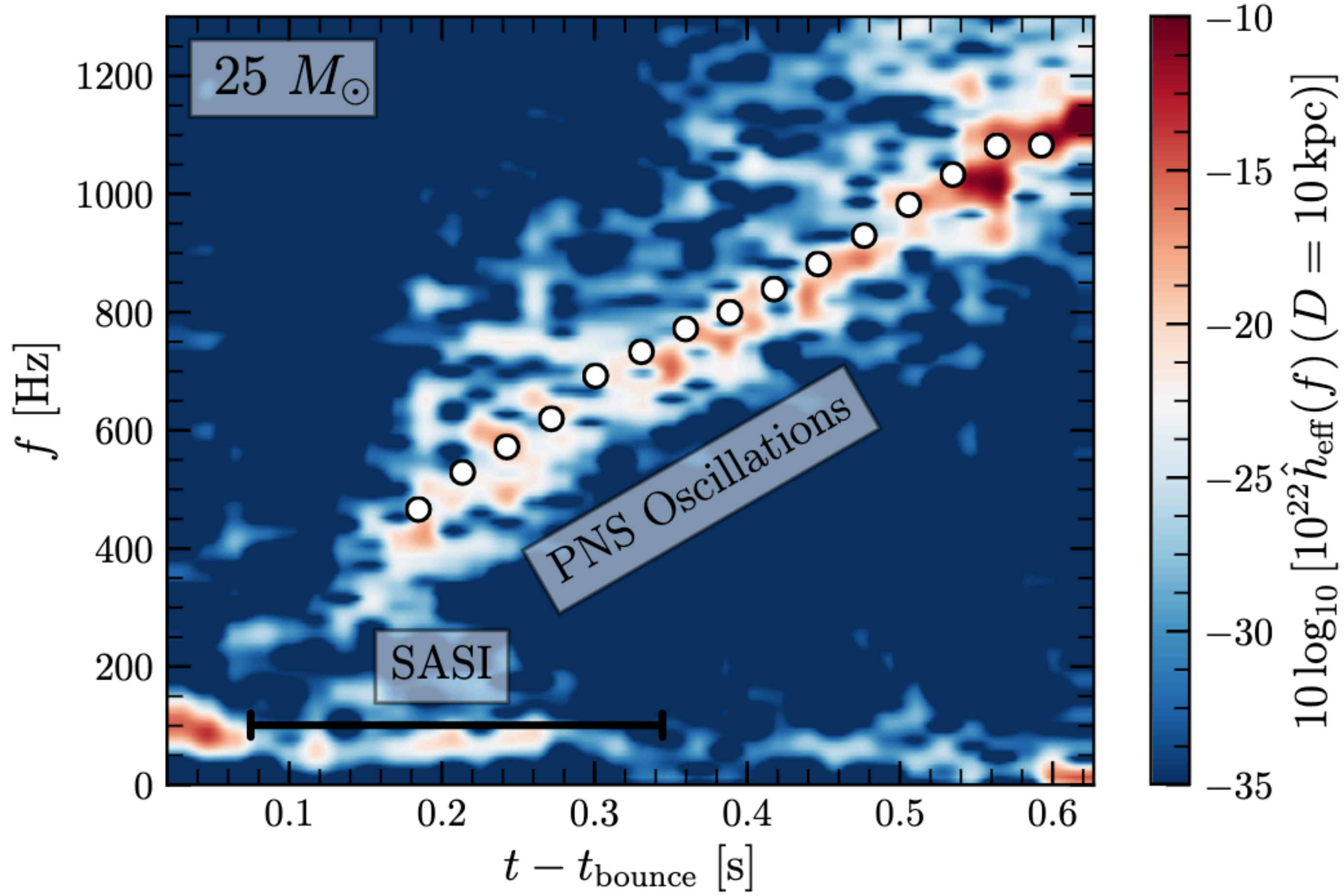


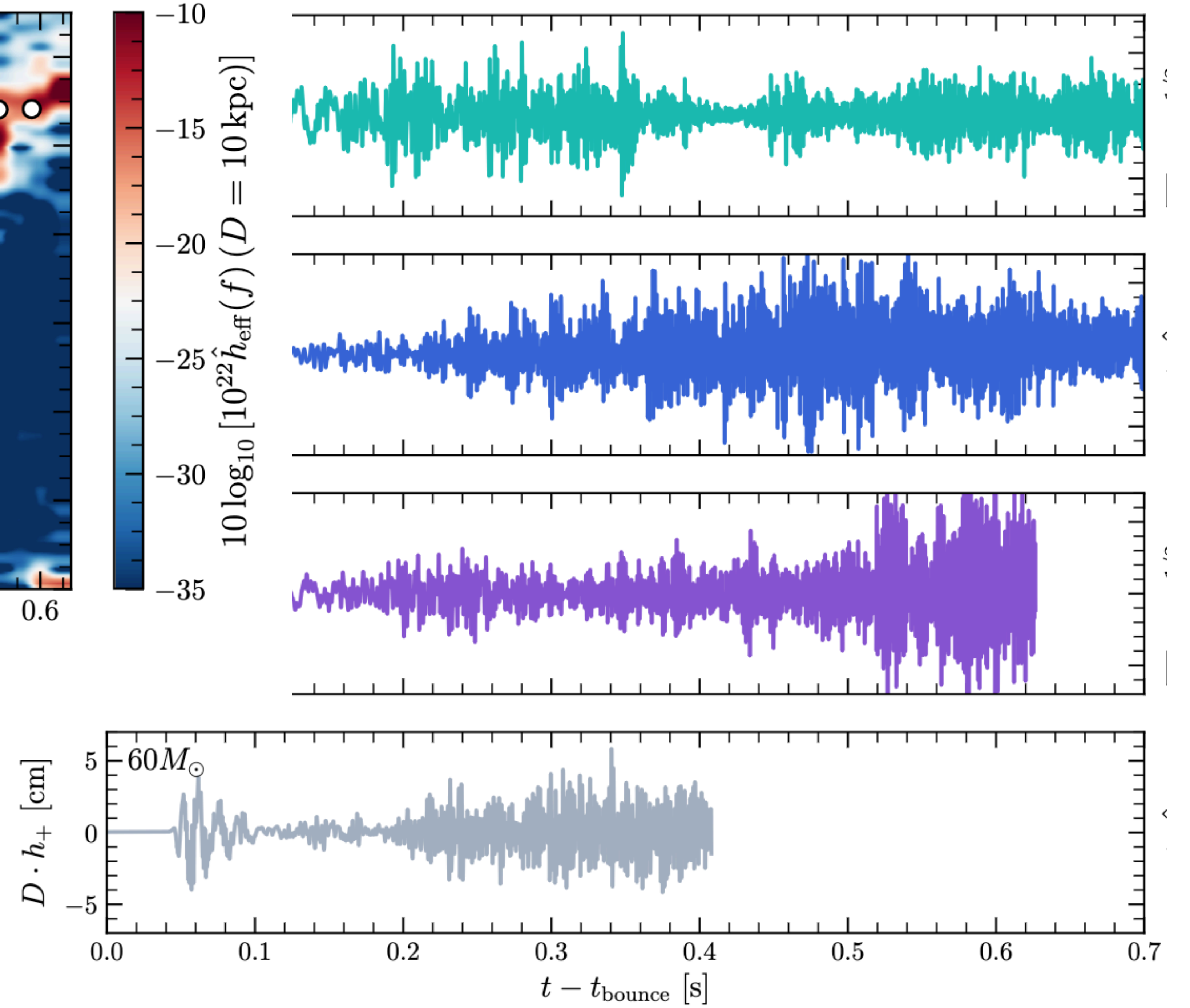
Credit: N. Franchini

Core-collapse supernovae

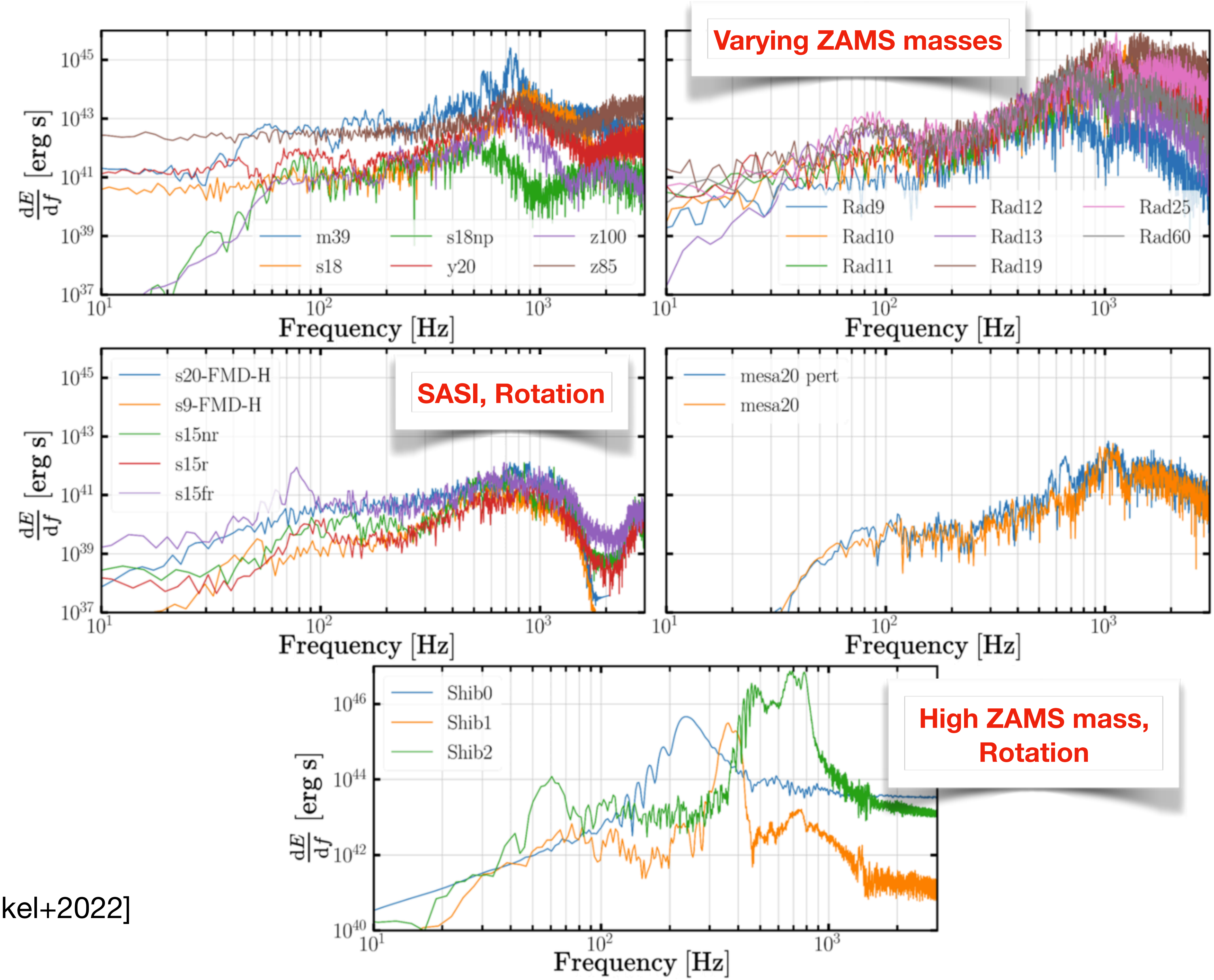
Need compact sources, relativistic motion

$$L_{GW} \sim \frac{G}{c^5}\dddot{Q}^2 \sim \frac{c^5}{G}\left(\frac{GM}{Rc^2}\right)^2\left(\frac{v}{c}\right)^6$$





[Radice+2019]


Varying ZAMS masses
SASI, Rotation
High ZAMS mass, Rotation
$\frac{dE}{df}$ [erg s]
Frequency [Hz]
m39
s18
s18np
y20
z100
z85
Rad9
Rad10
Rad11
Rad12
Rad13
Rad19
Rad25
Rad60
s20-FMD-H
s9-FMD-H
s15nr
s15r
s15fr
mesa20 pert
mesa20
Shib0
Shib1
Shib2

[Finkel+2022]

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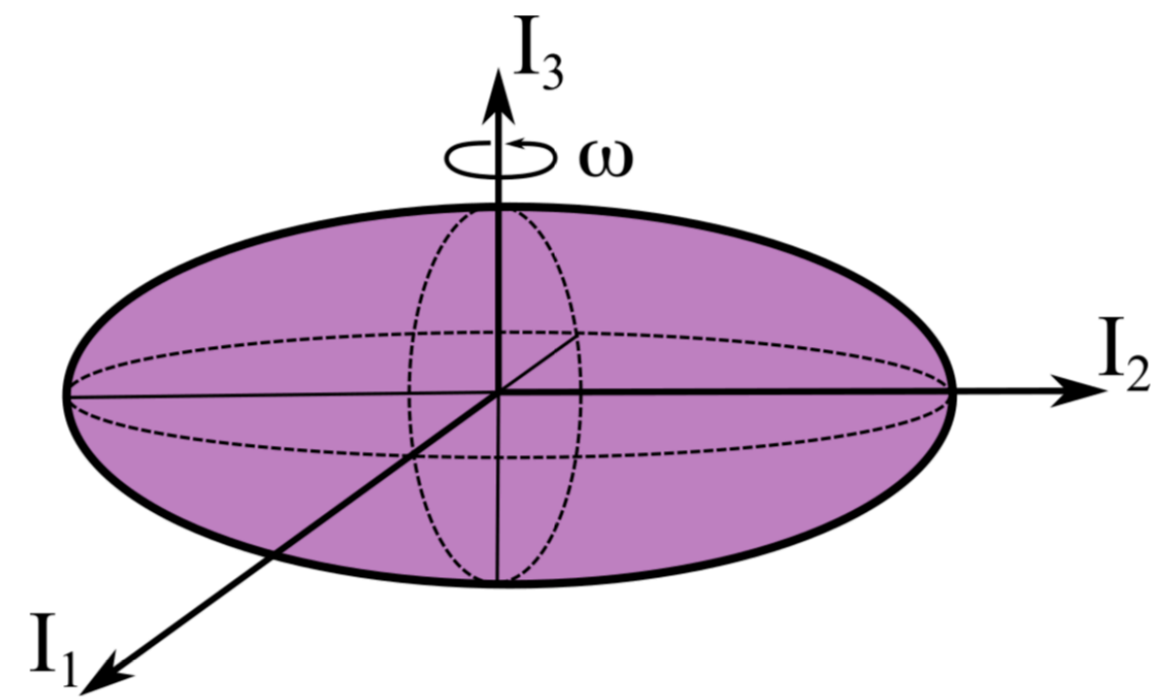
Rotating neutron stars

Triaxial star

$$h \simeq \frac{4\pi^2 G}{c^4} \frac{I_3 f_{GW}^2 \epsilon}{r}$$

$$\epsilon = \frac{I_1 - I_2}{I_3}$$

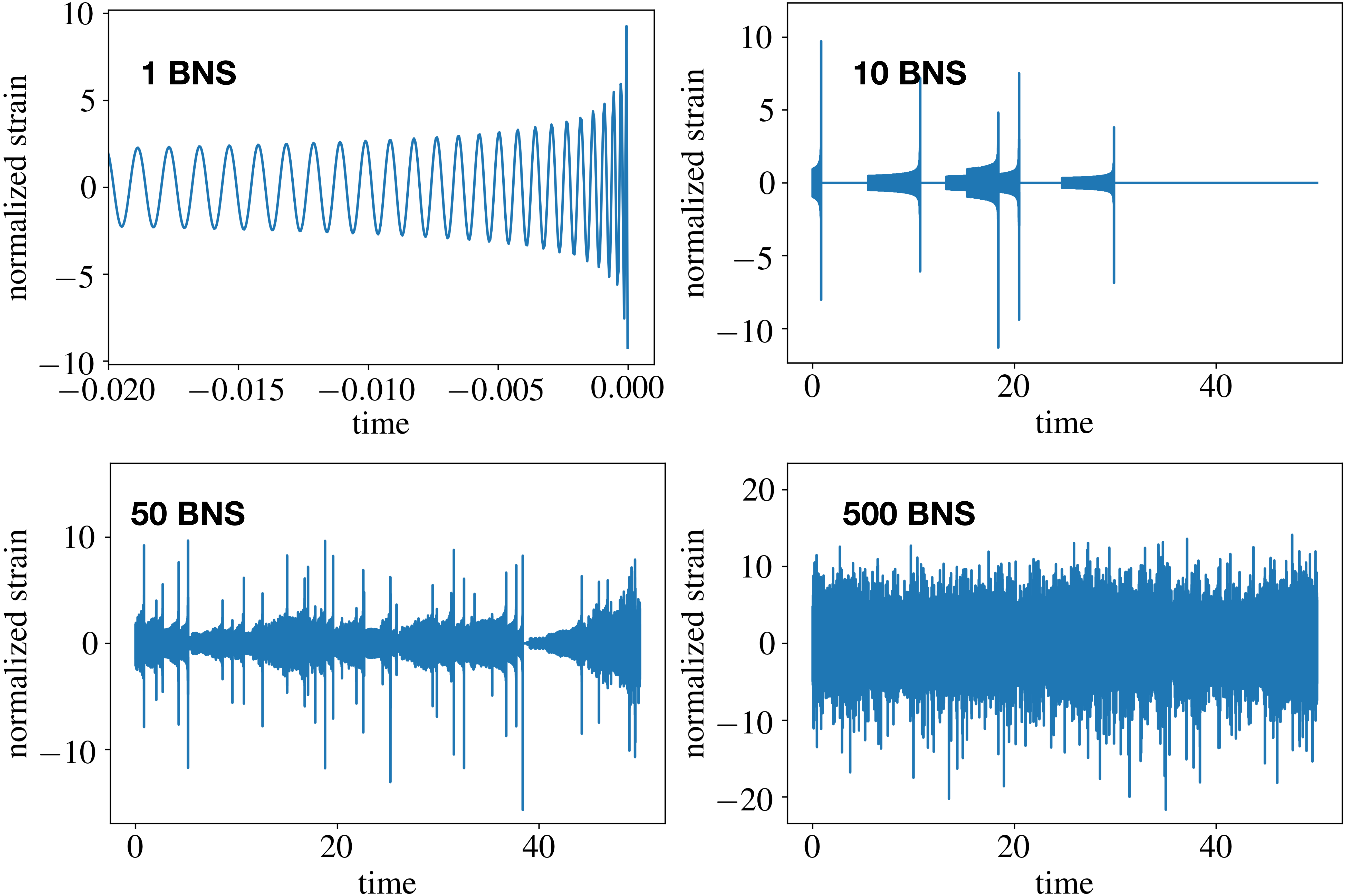


Sieniawska & Bejger (2019)

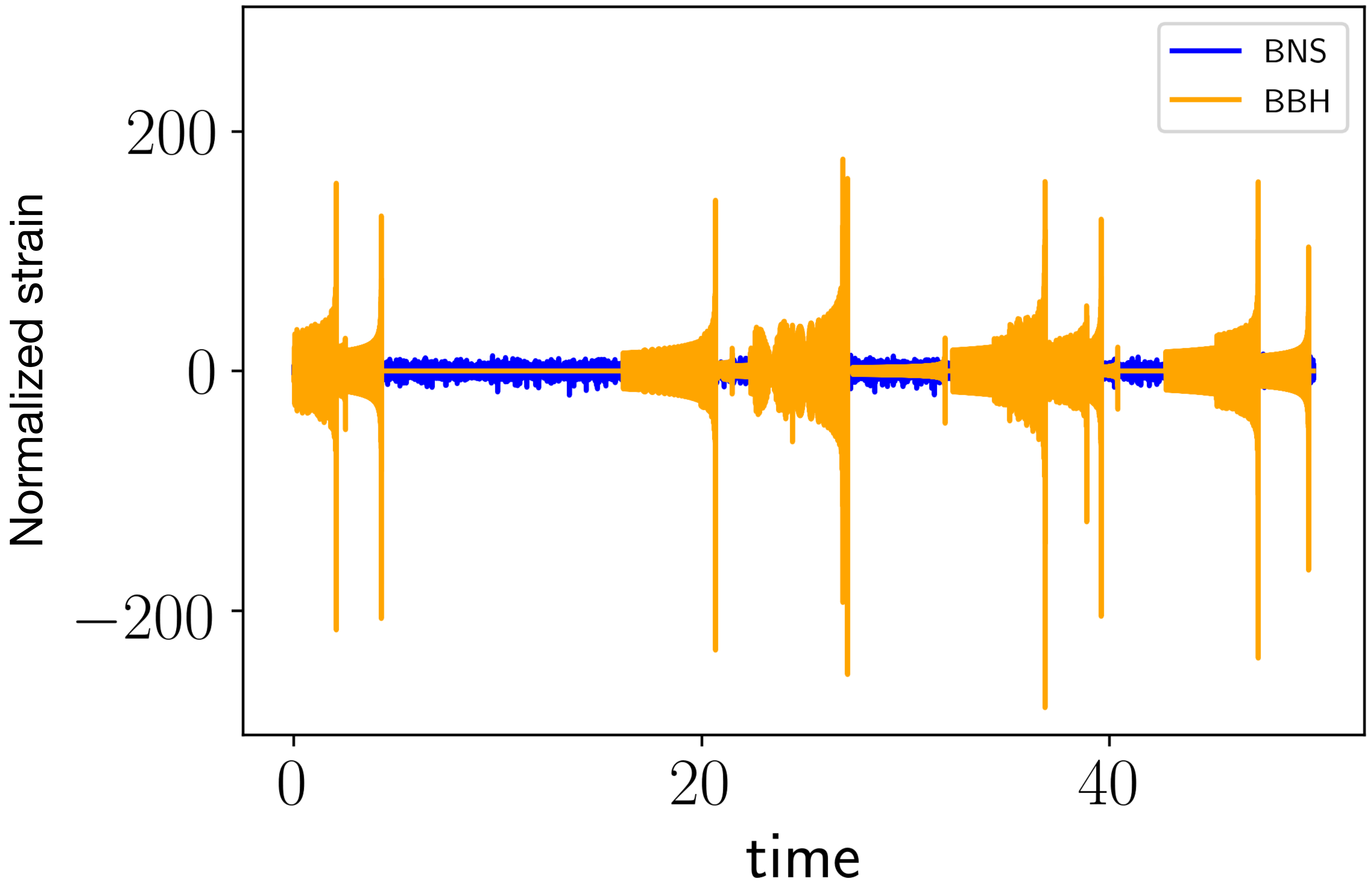
Many mechanisms lead to continuous waves from neutron stars:

oscillations, deformability due to magnetic stresses, free precession…

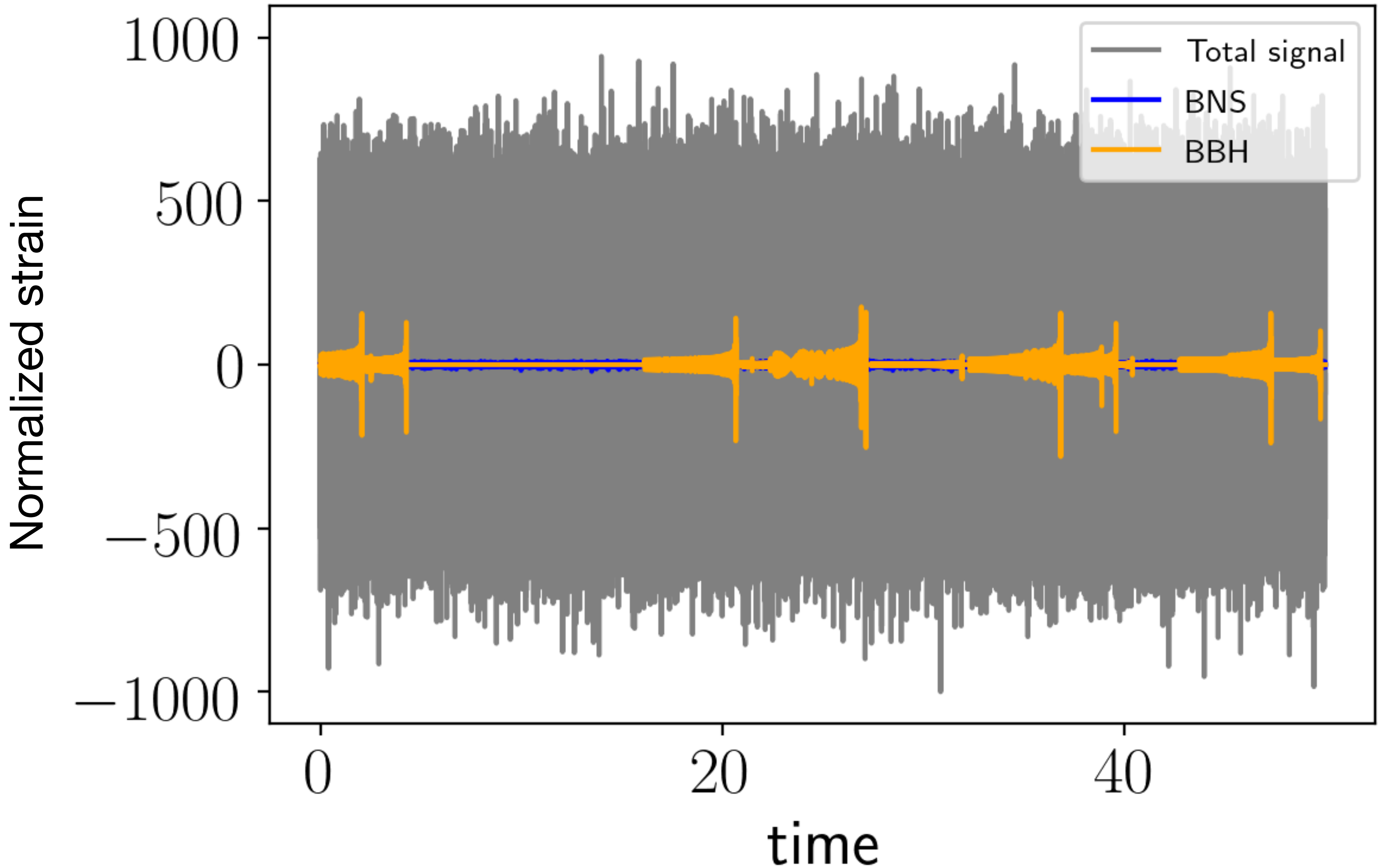
Incoherent superposition of deterministic signals



Combination of stochastic signals



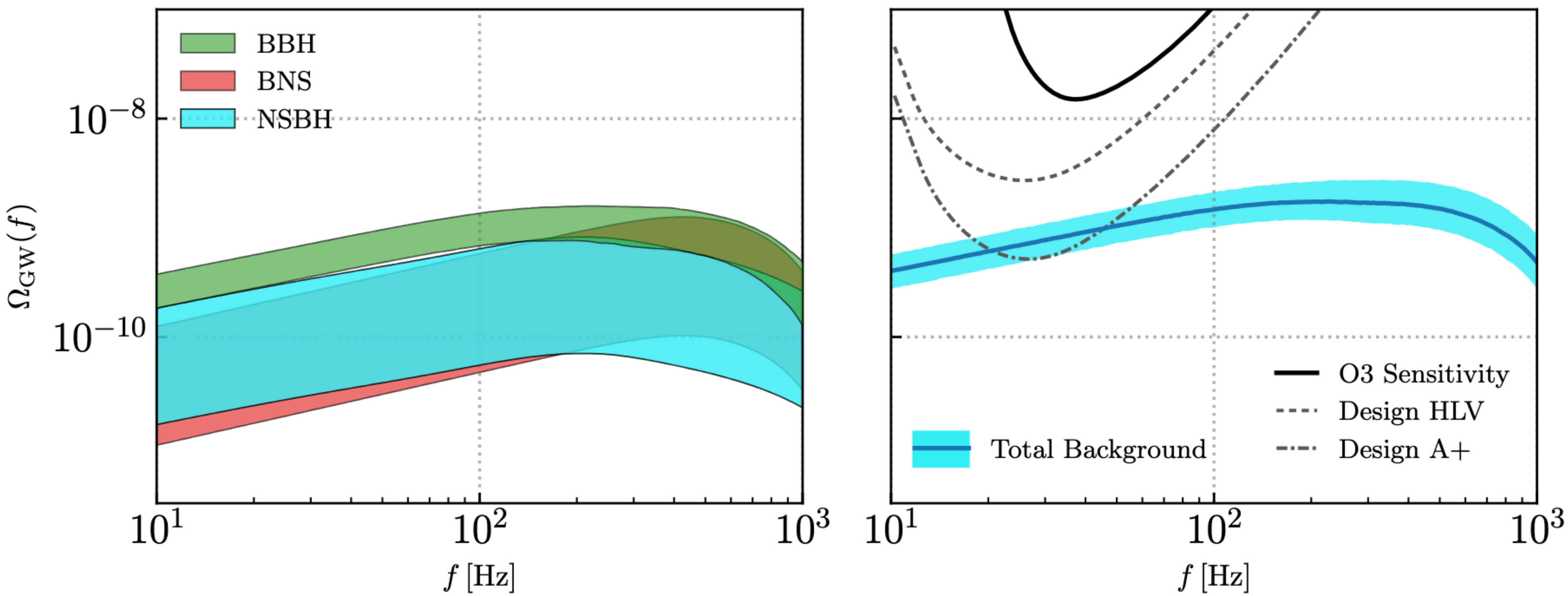
Signal is buried in noise!

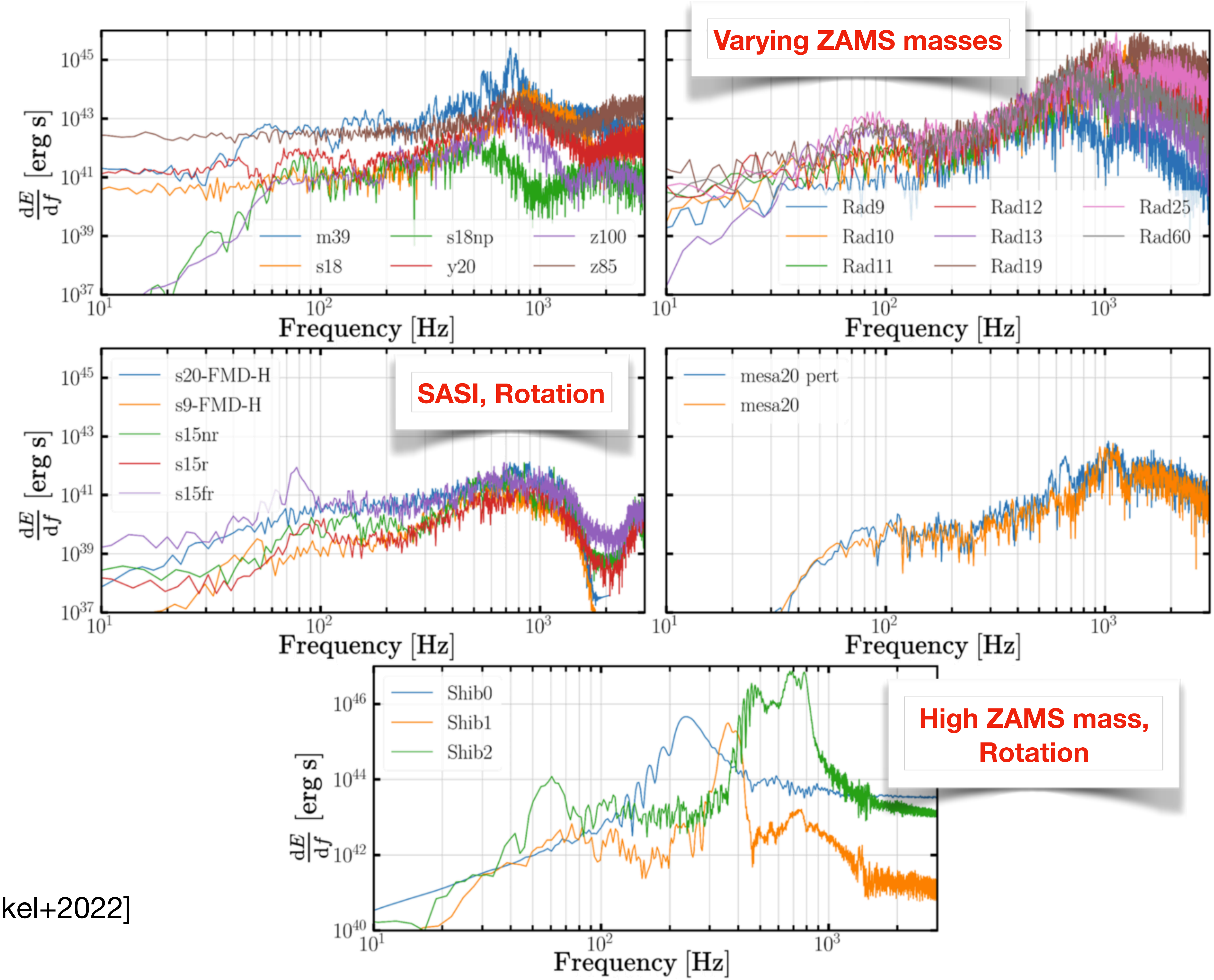


In the inspiral phase: $\Omega_{GW}(f) \propto \frac{dE}{d\ln f} \propto f^{2/3}$

Stochastic background from compact binaries

[LVK 2021]

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SASI, Rotation
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m39
s18
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Rad9
Rad10
Rad11
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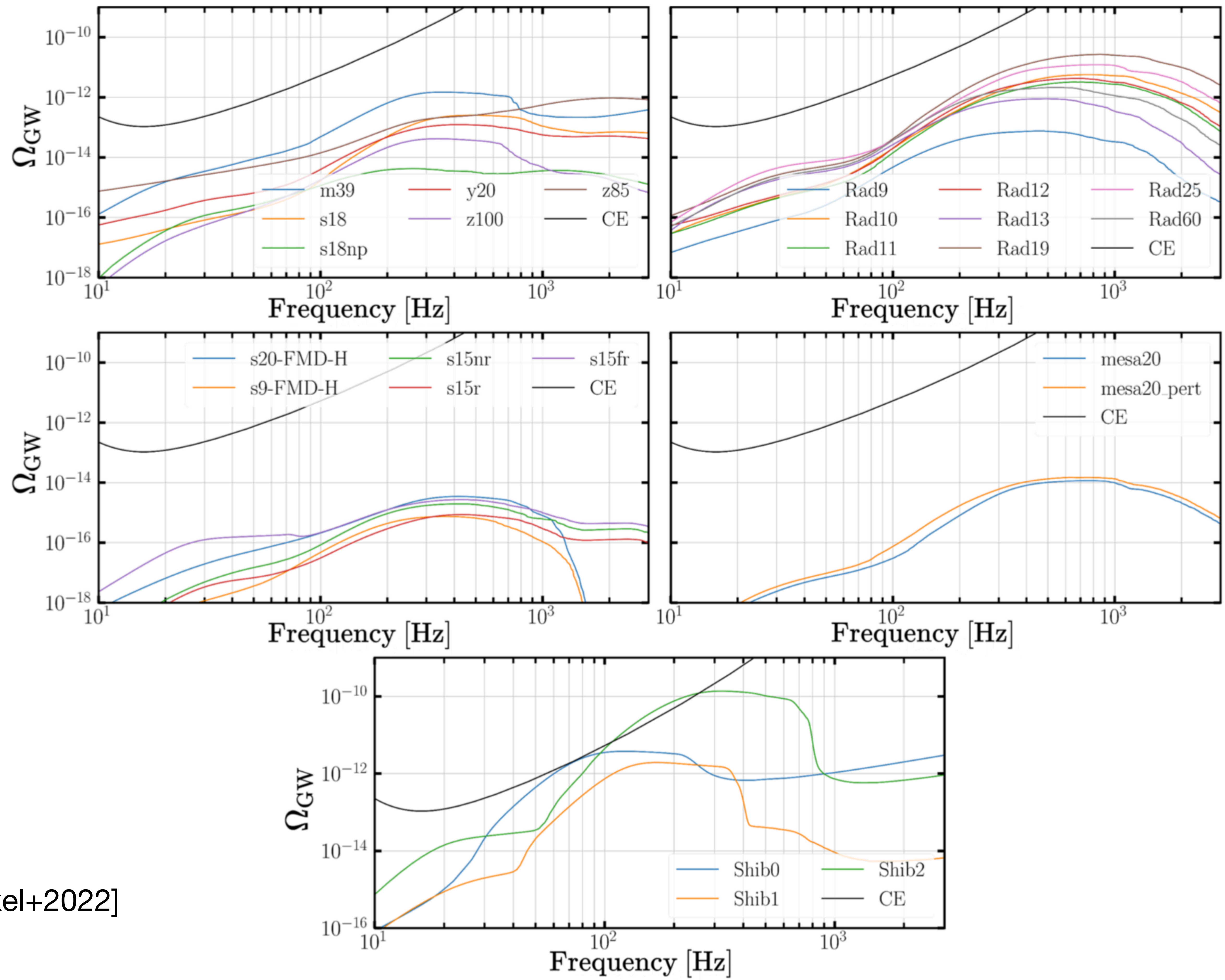
Rad13
Rad19
Rad25
Rad60
s20-FMD-H
s9-FMD-H
s15nr
s15r
s15fr
mesa20 pert
mesa20
Shib0
Shib1
Shib2
$\frac{dE}{df}$ [erg s]
Frequency [Hz]
10^{1}
10^{2}
10^{3}
10^{37}
10^{39}
10^{41}
10^{43}
10^{45}
10^{40}
10^{42}
10^{44}
10^{46}

[Finkel+2022]

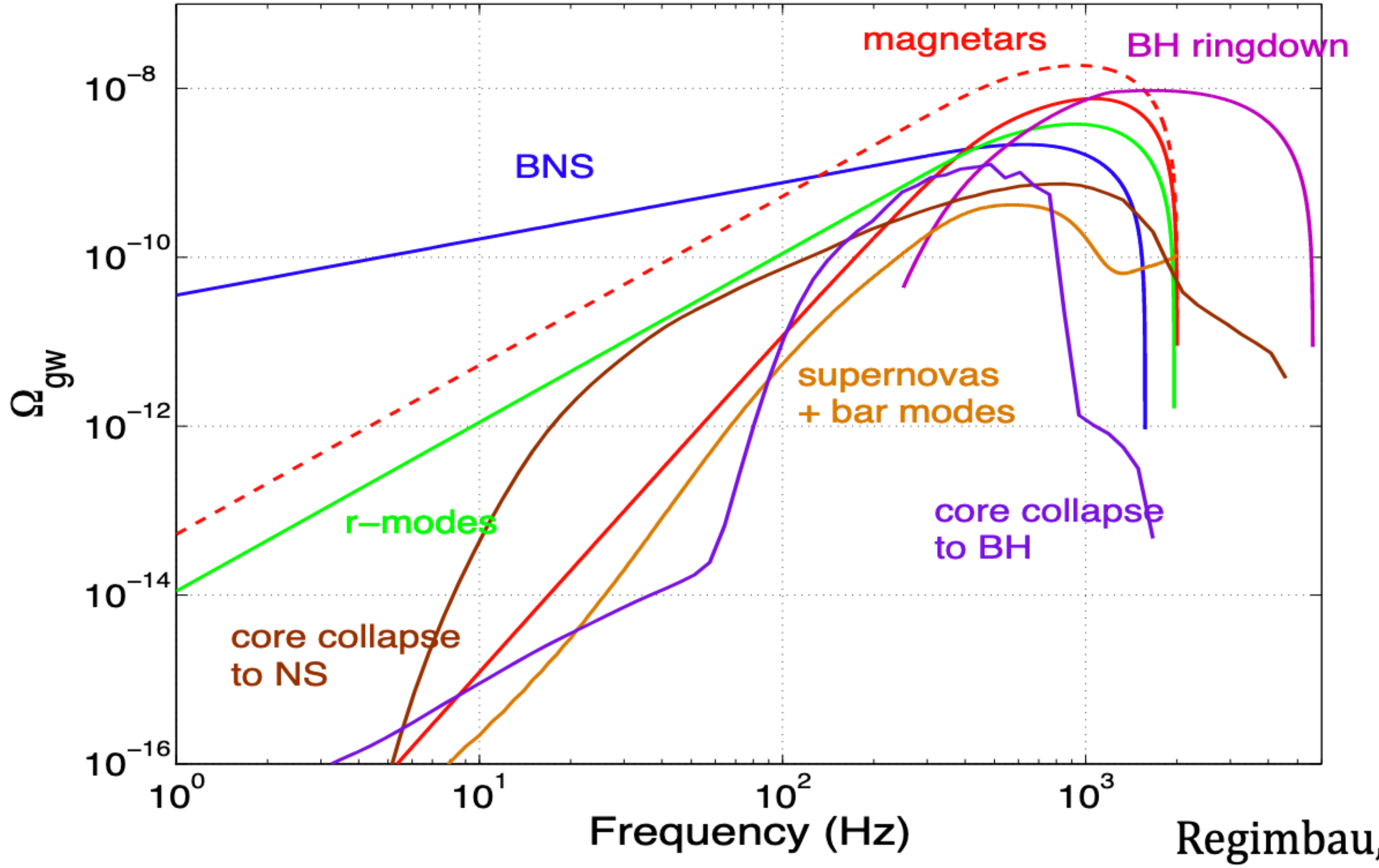


Ω_{GW}
Frequency [Hz]
m39
s18
s18np
y20
z100
z85
CE
Rad9
Rad10
Rad11
Rad12
Rad13
Rad19
Rad25
Rad60
s20-FMD-H
s9-FMD-H
s15nr
s15r
s15fr
mesa20
mesa20_pert
Shib0
Shib1
Shib2

[Finkel+2022]

Rotating neutron stars

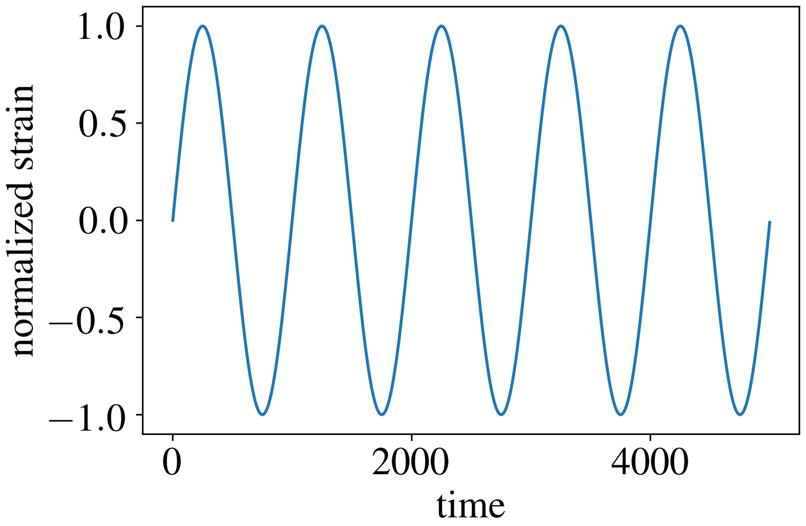
- Rotating neutron stars with a triaxial shape
- In magnetars: strong distortion of the shape (depending on the EOS)

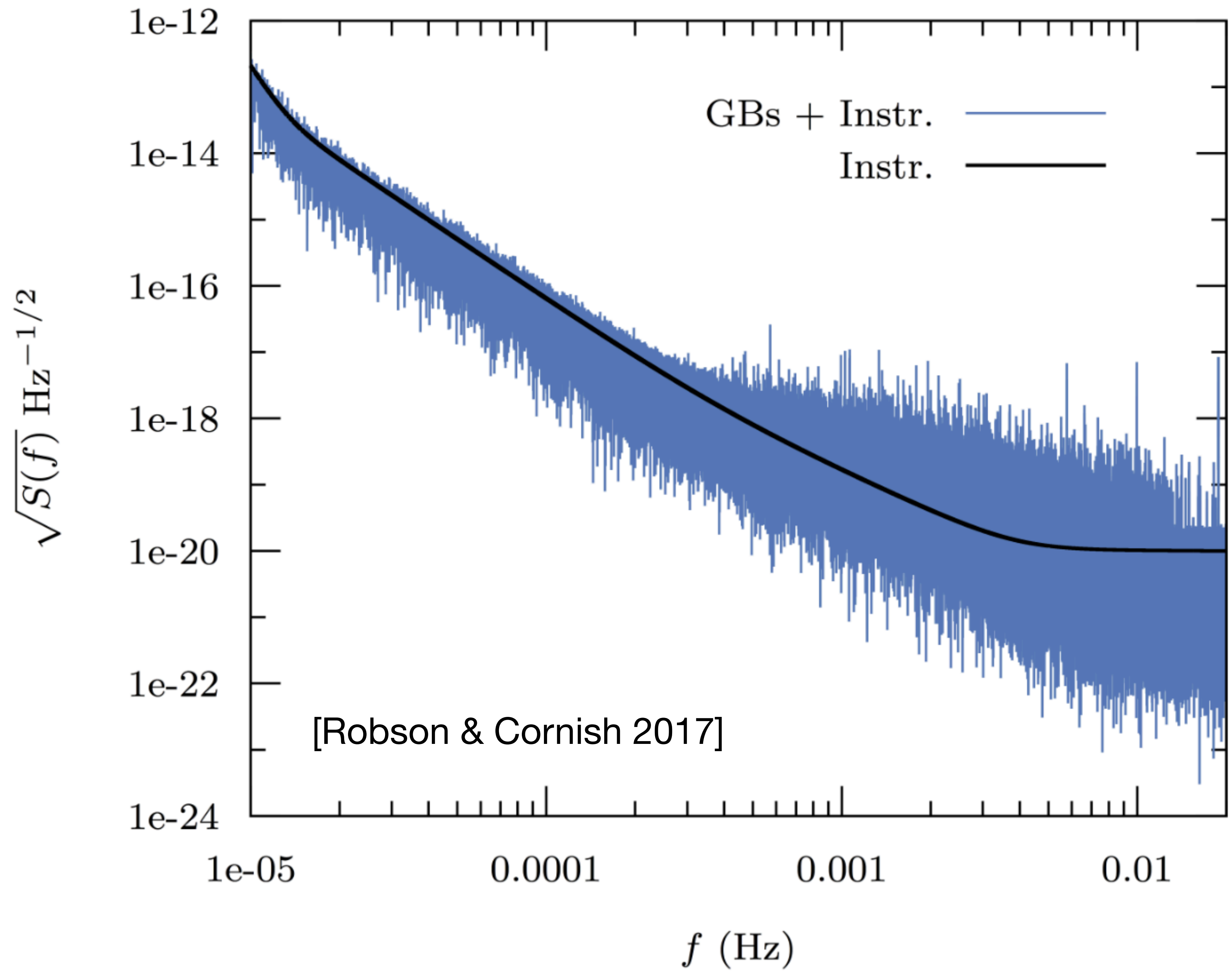


Regimbau, arXiv:1101.2762

Double white dwarfs

- A few millions of double white dwarf systems in the Milky Way
- Monochromatic sources in LISA band
- Confusion noise dominates instrument noise in the mHz band



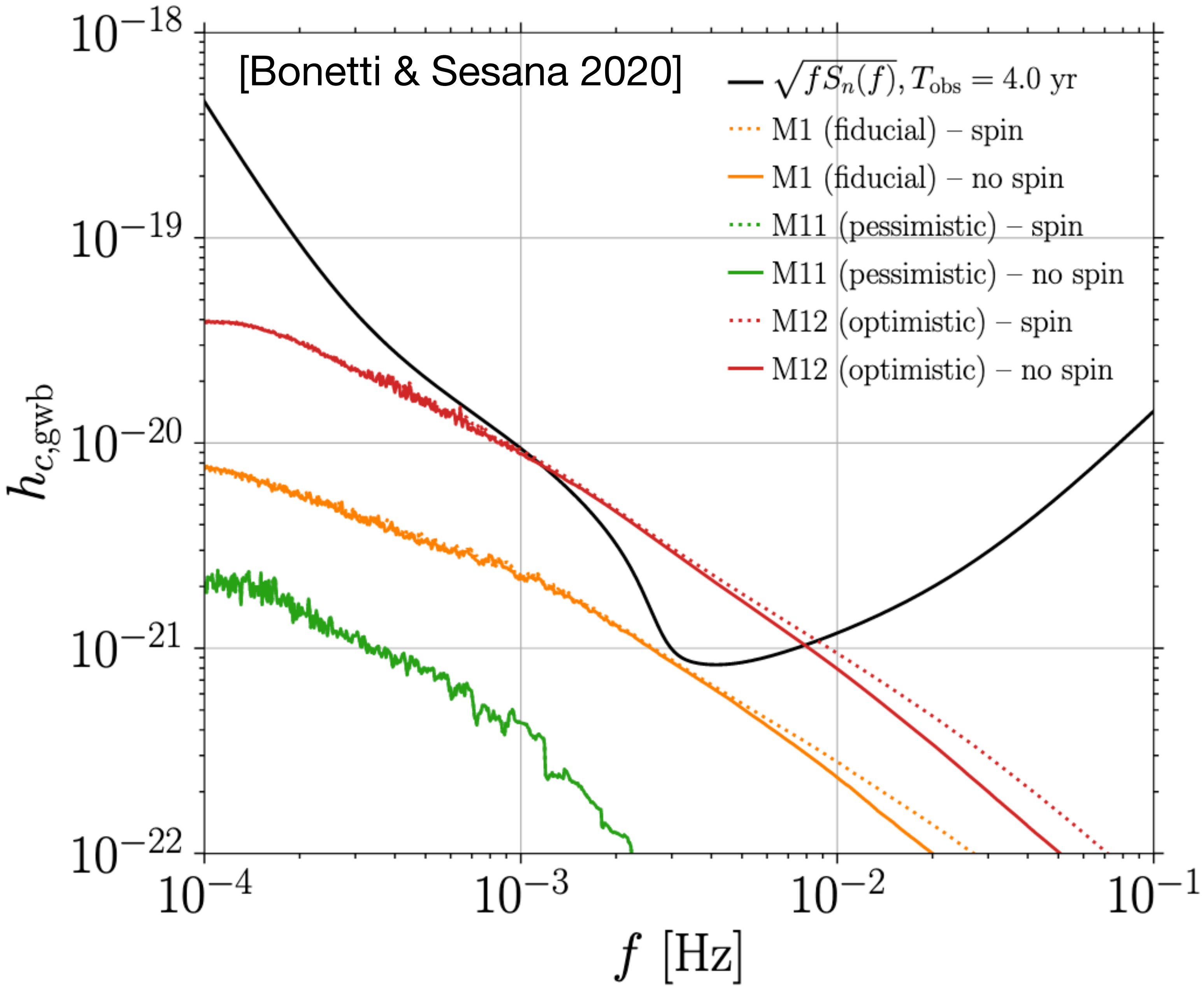


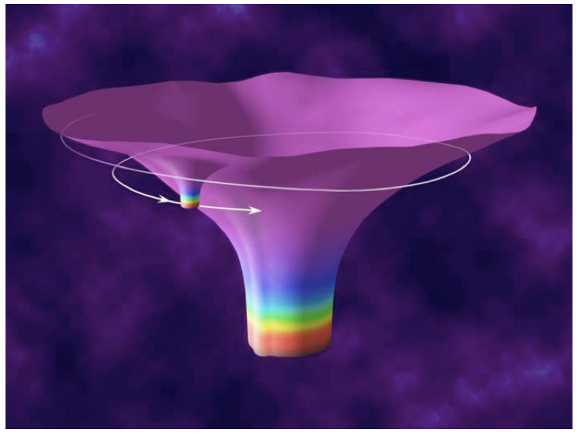
Extreme mass ratio inspirals

- Stellar-mass black holes orbiting massive black holes
- Expected to form in dense galactic centers
- LISA detection rates: $1 - 10^4\ yr^{-1}$ [Babak+2017]

$$M_{BH} \sim 10^5 - 10^7 M_\odot$$

$$m_{BH} \sim 10 - 50 M_\odot$$

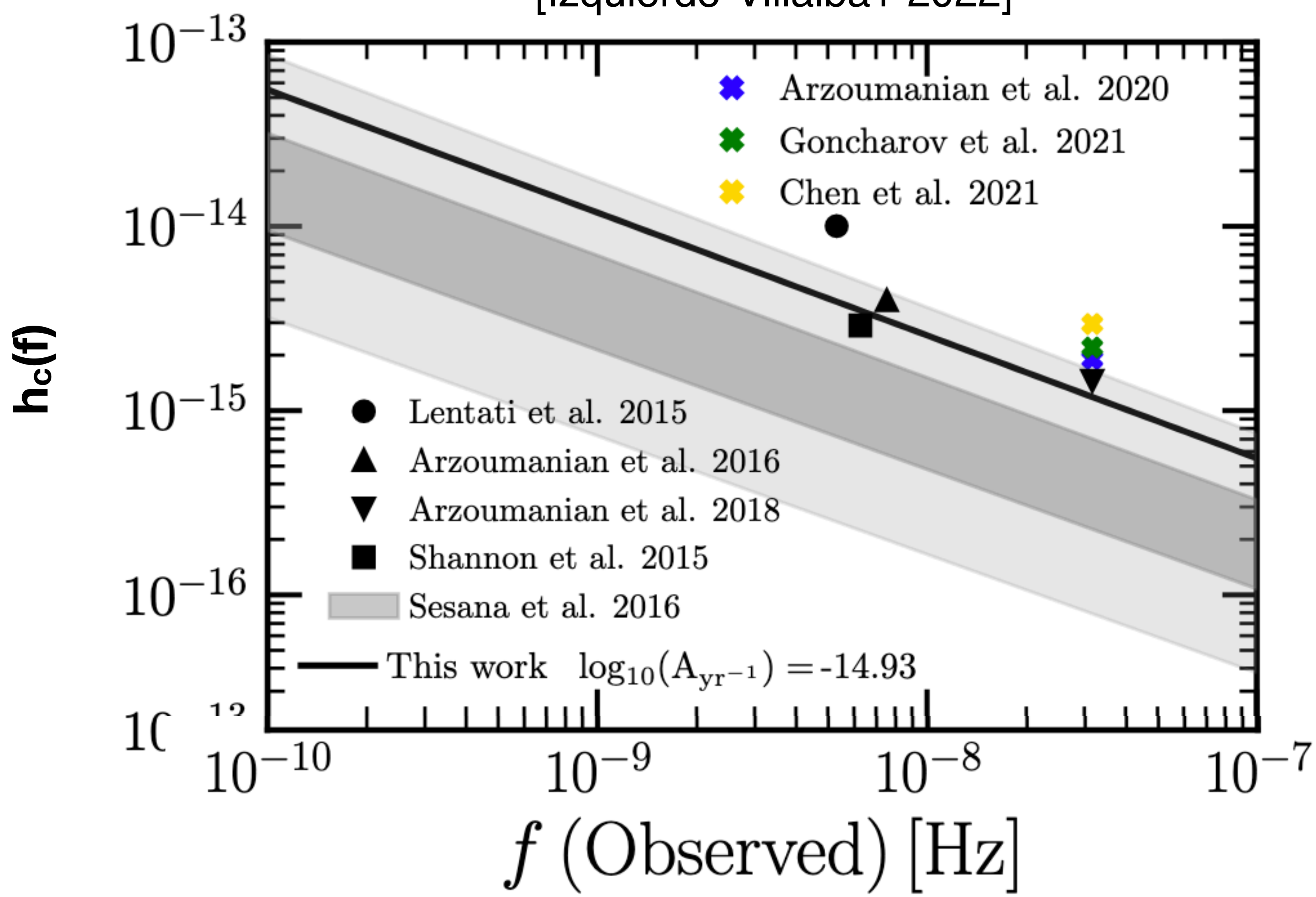




Pulsar Timing Arrays

- **Tentative detection of a correlated signal by NANOGrav, PPTA, EPTA**
- Evidence for a common-spectrum process, but not the correlation expected from GW
- Consistent with signal from black hole binaries
- Consistent with cosmological signals (primordial black holes, cosmic strings…)

[Izquierdo-Villalba+ 2022]



Gravitational-wave astronomy is fun!