GRBs from NS+BH coalescences: expected rates and properties

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Coalescing compact binaries

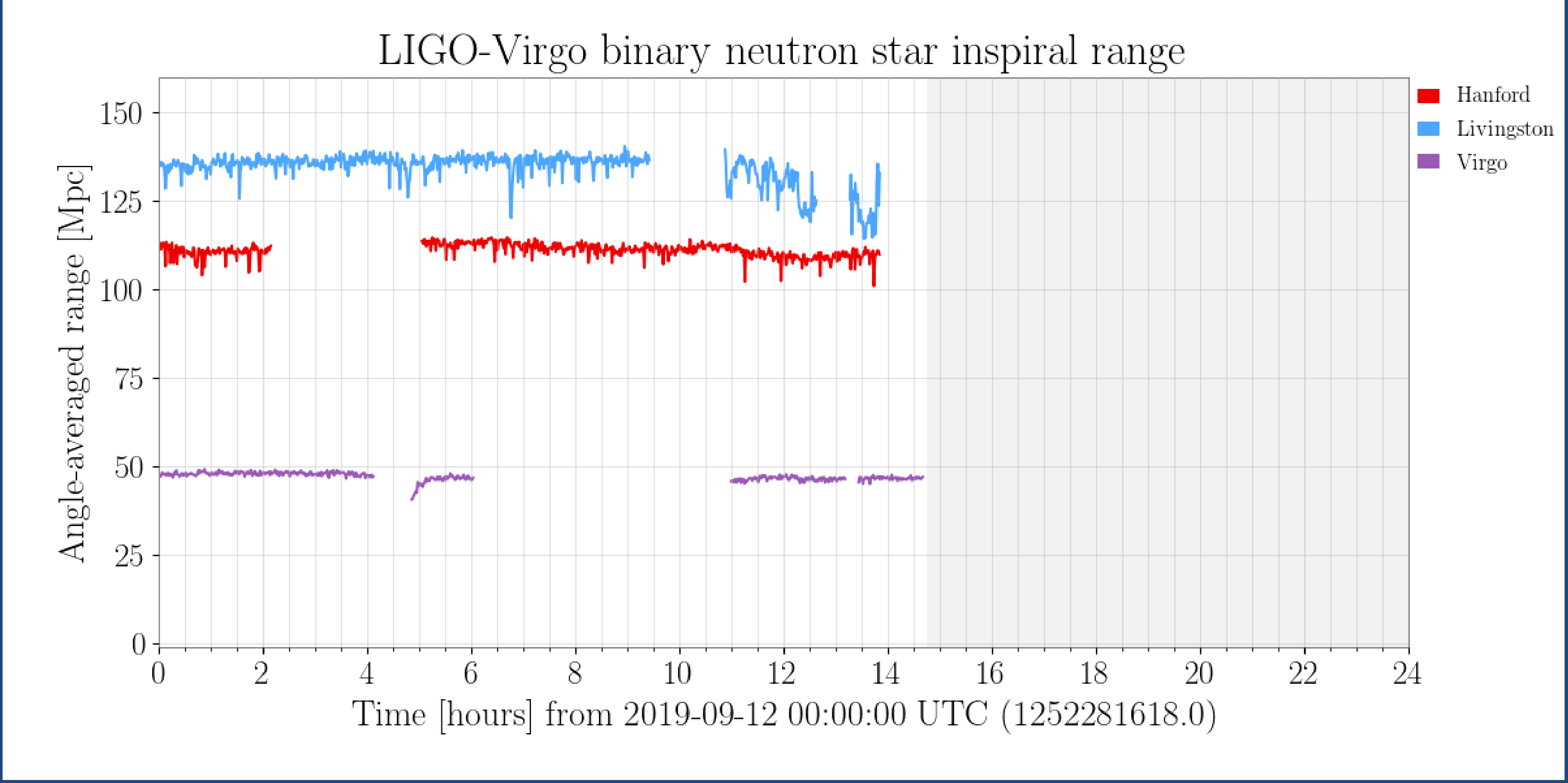
- Waveform from two coalescing point-like masses is determined by a combination of component masses (the chirp mass)

$$M_{ch} = (\mu^3 M^2)^{1/5}$$

$$h \sim M_{ch}^{5/3} f^{2/3} / r$$

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right)^{3/5}$$

Current Detection horizon



$D_h \sim M_{chirp}^{5/6}$

https://www.gw-openscience.org/

LVC O3 detections

- 25 triggers, 20 BH+BH, 3 NS+NS, 2 NS+BH

  https://gracedb.ligo.org

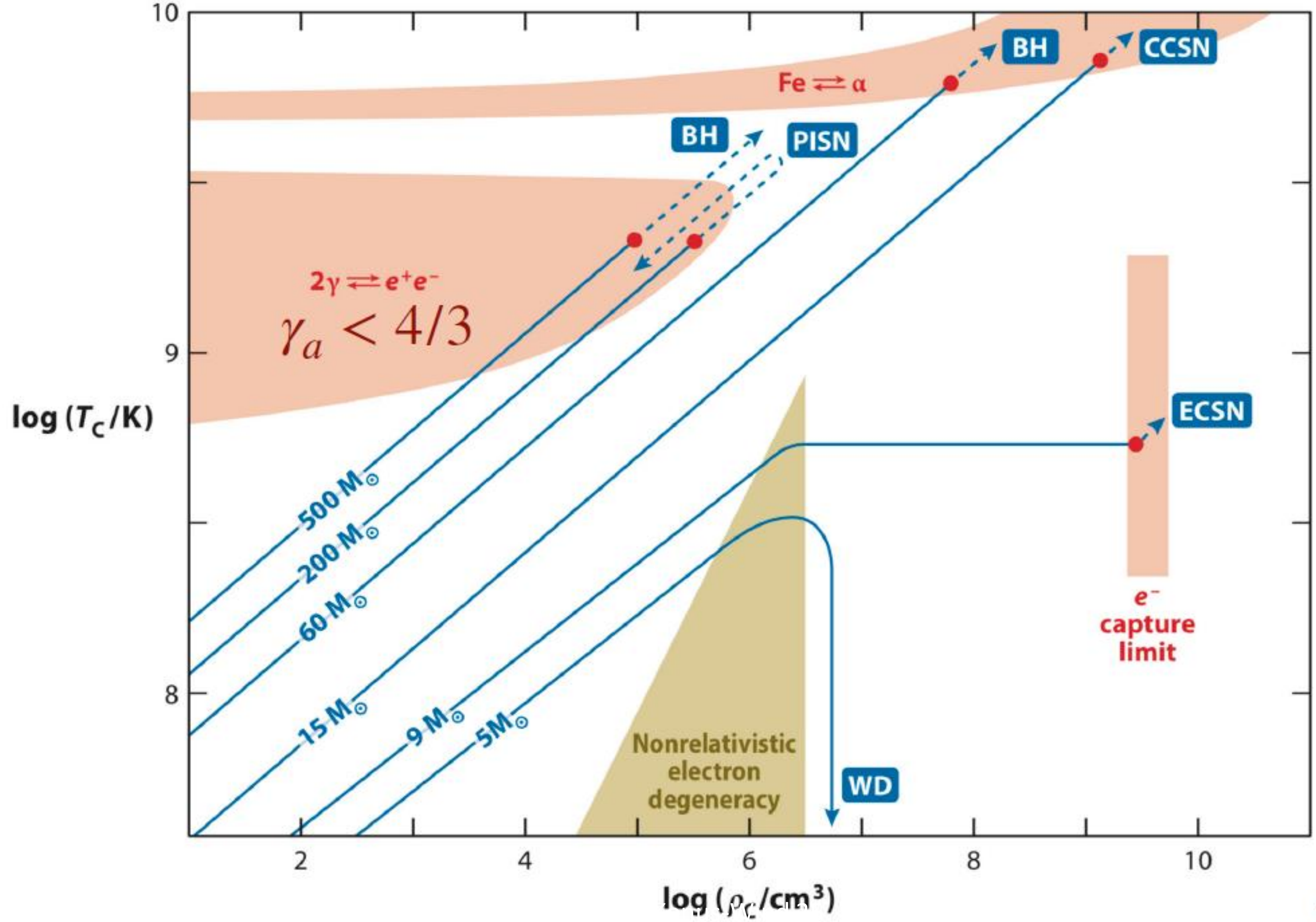
- No electromagnetic counterparts so far

https://gracedb.ligo.org

Astrophysical binary BHs

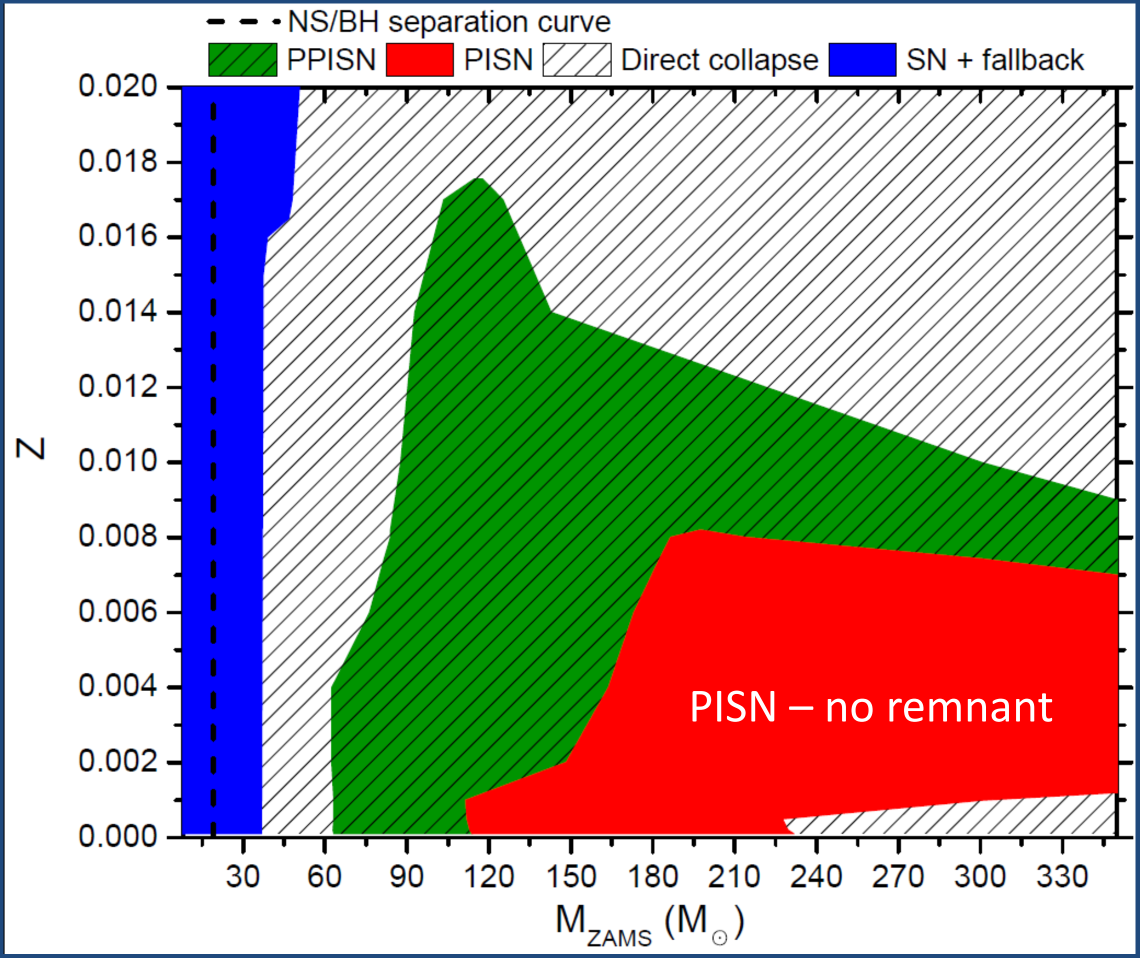
- BH formation
  - Initial ZAMS mass
  - Initial rotation
  - Possible kick
- BH in binaries
  - From massive binary systems
  - In dense stellar clusters (dynamical)
  - Primordial BHs

BH formation from stars (solar metallicity)



Langer (2012)

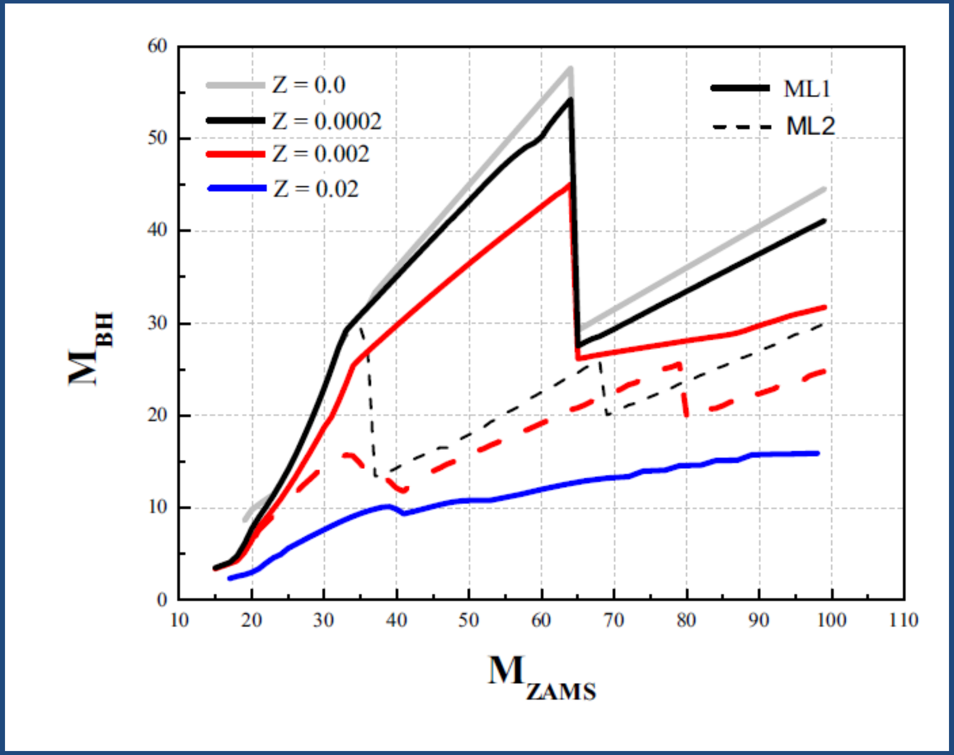
BH from massive stars



Spera,Mapelli 2017

Pair instability SNe (PISNe, Fowler & Hoyle 1964), pulsational PISNe (PPISNe) (Woosley 2017)

Dependence on the metallicity and stellar wind mass loss



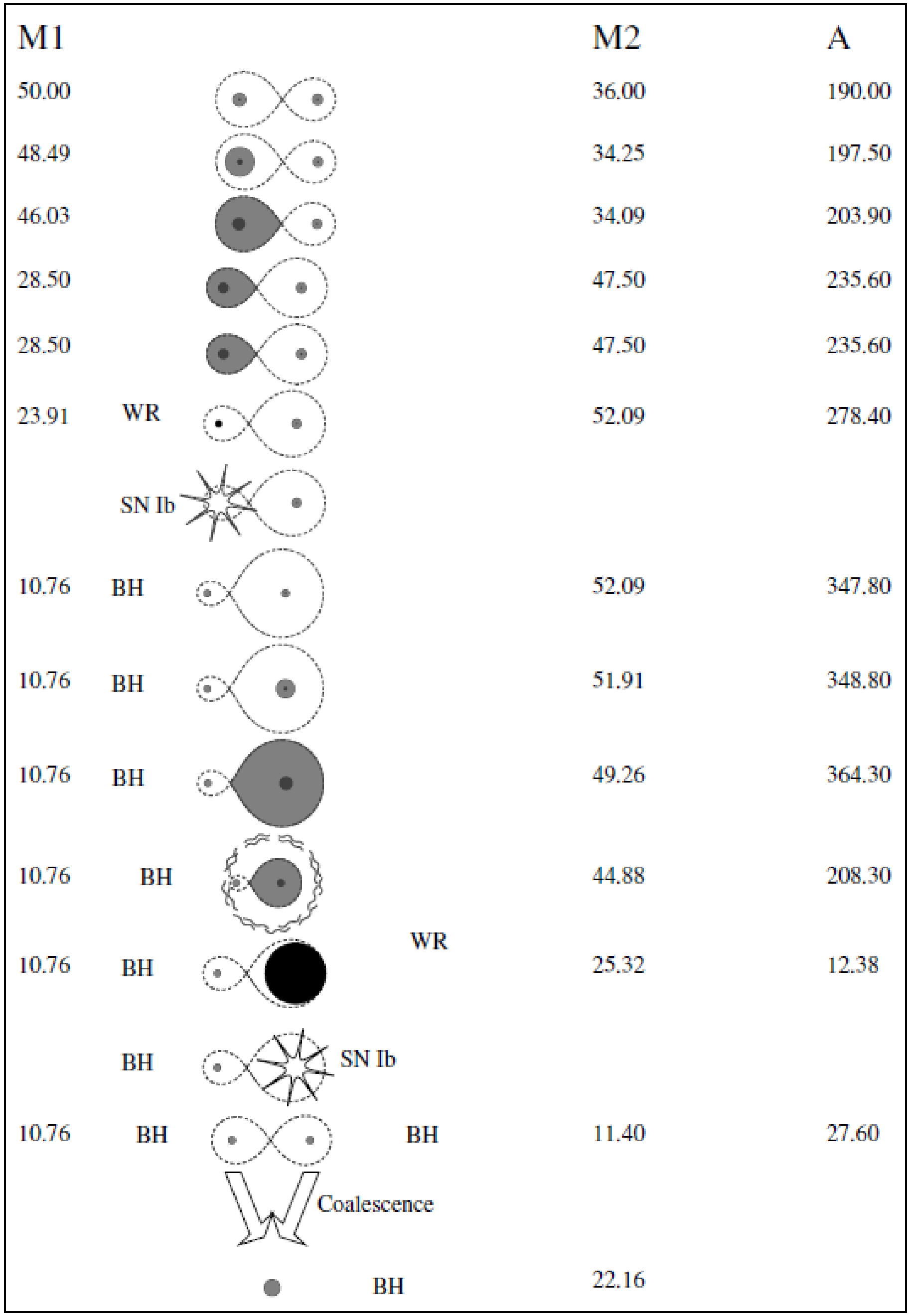
Fryer et al 2012, Giacobbo et al. 2018

Additional effects in binaries:

- Initial spin misalignment
- Tidal synchronization of the envelope
- Common envelope phase
- Star formation and metallicity history in galaxies

$$\Psi\left(z, \frac{Z}{Z_\odot}\right) = \psi(z)\Phi(Z/Z_\odot).$$

$$\Phi(Z/Z_\odot) = \frac{\hat{\Gamma}[0.84, (Z/Z_\odot)^2\, 10^{0.3z}]}{\Gamma(0.84)}$$



- Initial ZAMS mass
- Fraction of collapsed mass

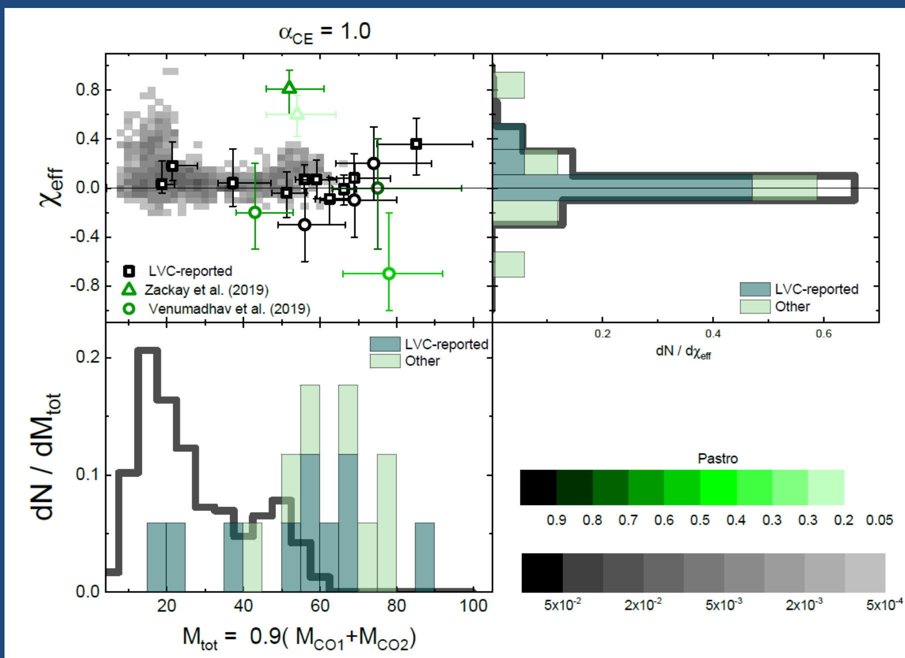
$$k_{BH} = M_{BH}/M_*$$

- Possible kick

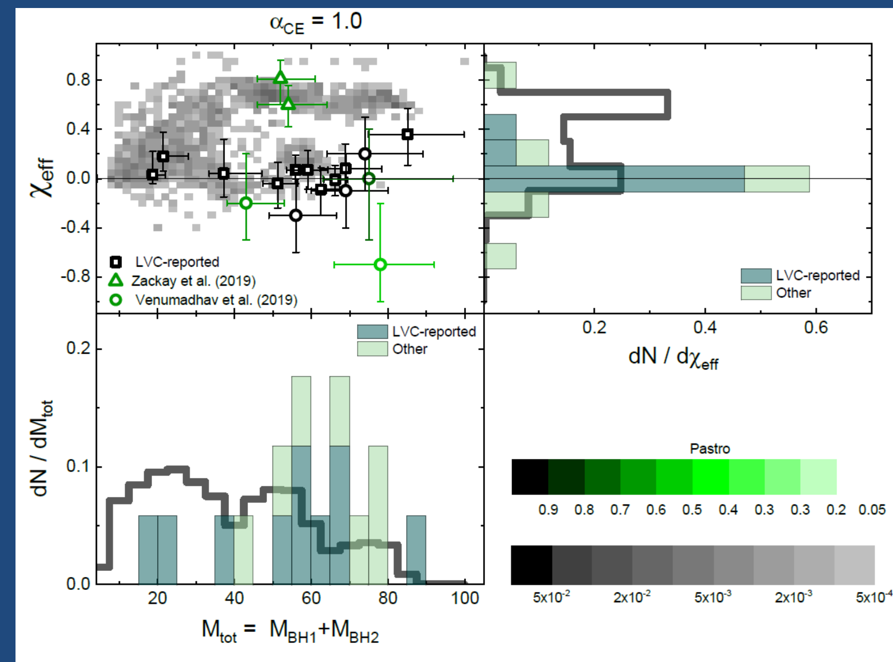
$$\frac{w_{BH}}{w_{NS}} = \frac{M_* - M_{BH}}{M_* - M_{OV}} = \frac{1 - k_{BH}}{1 - M_{OV}/M_*}$$

Tutukov, Yungelson 1993 MNRAS)
Lipunov, Postnov, Prokhorov 1997 MNRAS)

Mass and spin distributions before coalescence



Without fallback

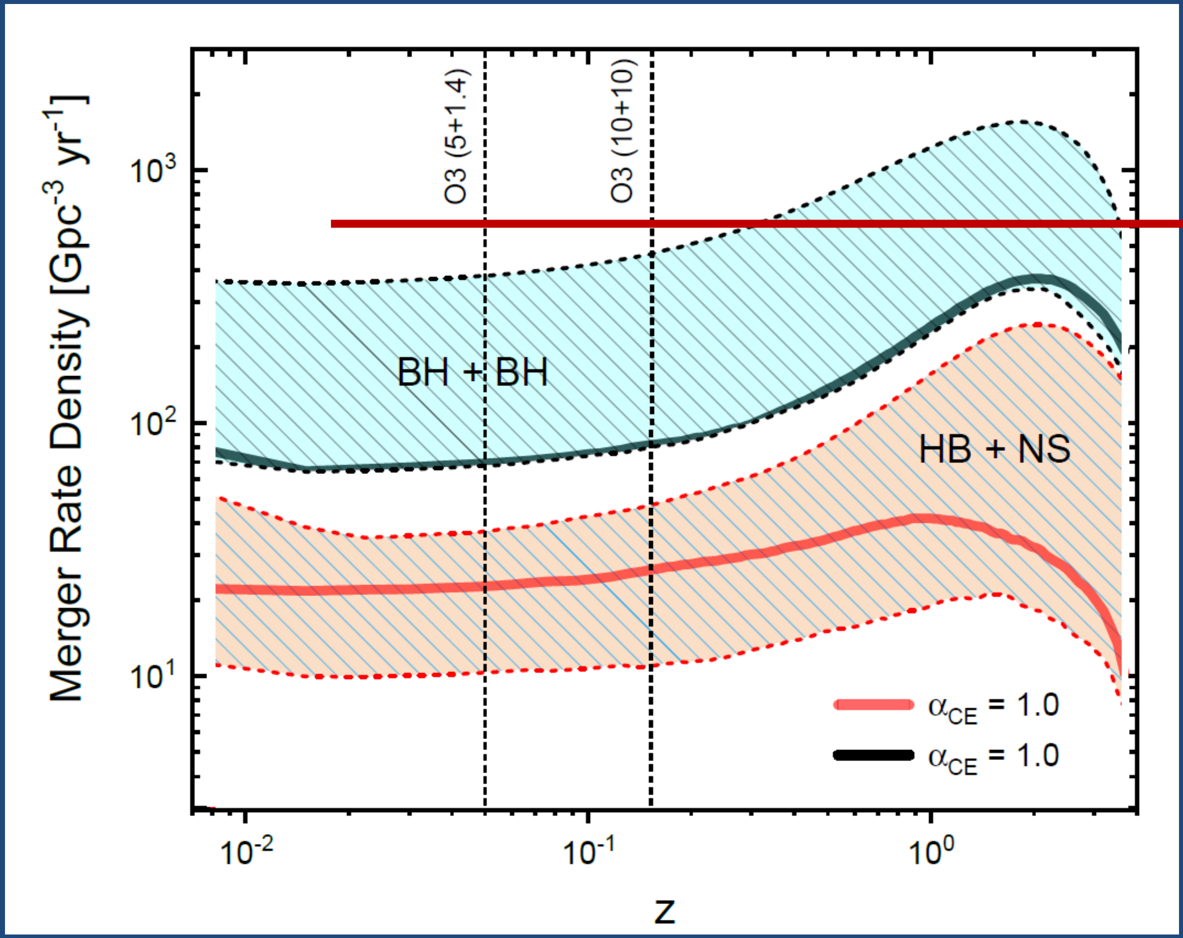


+ fallback from envelope

PK+ 2019, Physics-Uspekhi (2019, No 11, in press)

MNRAS 483, 3288–3306 (2019)

BH+NS systems

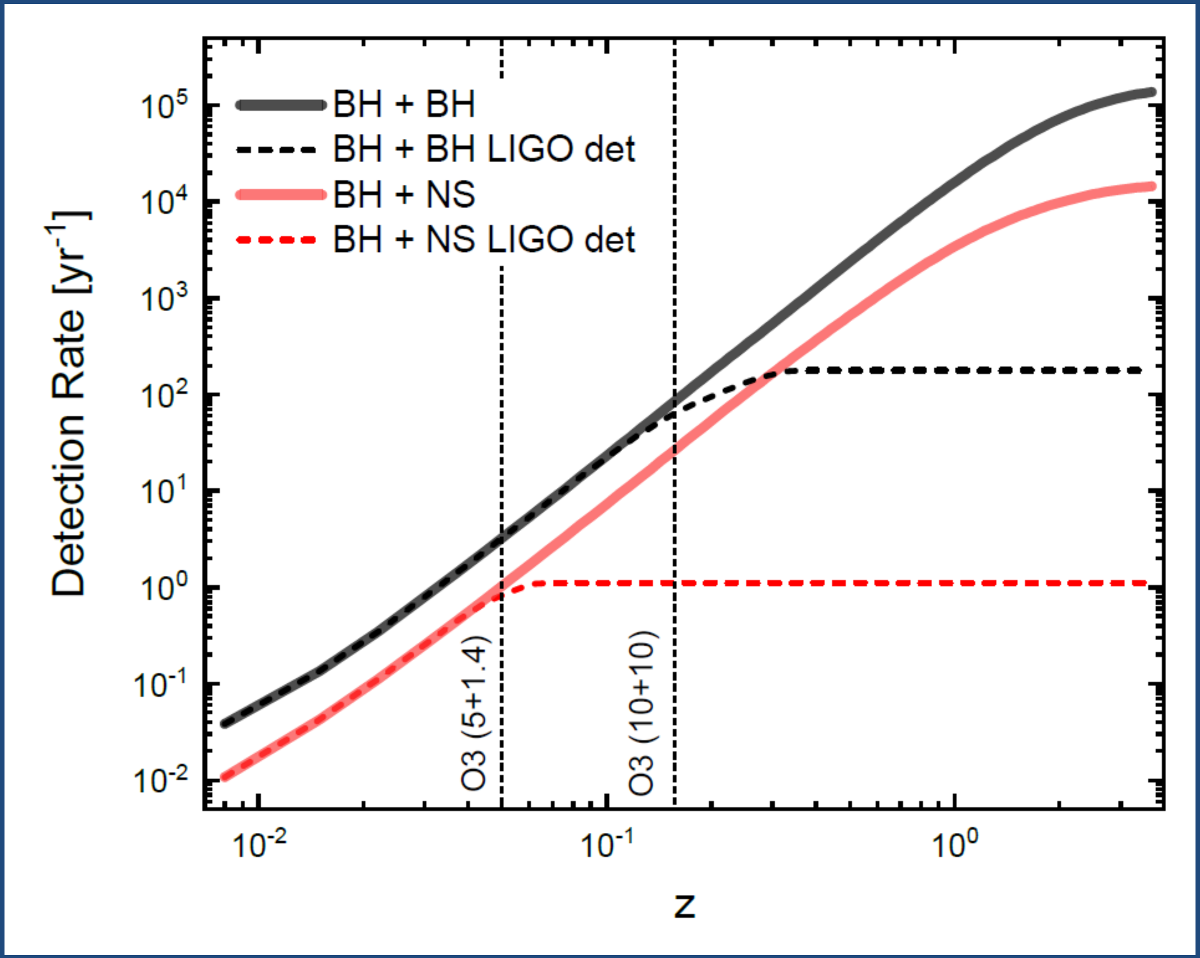


NS+BH upper limit
610 Gpc^{-3} yr^{-1}

1811.12907

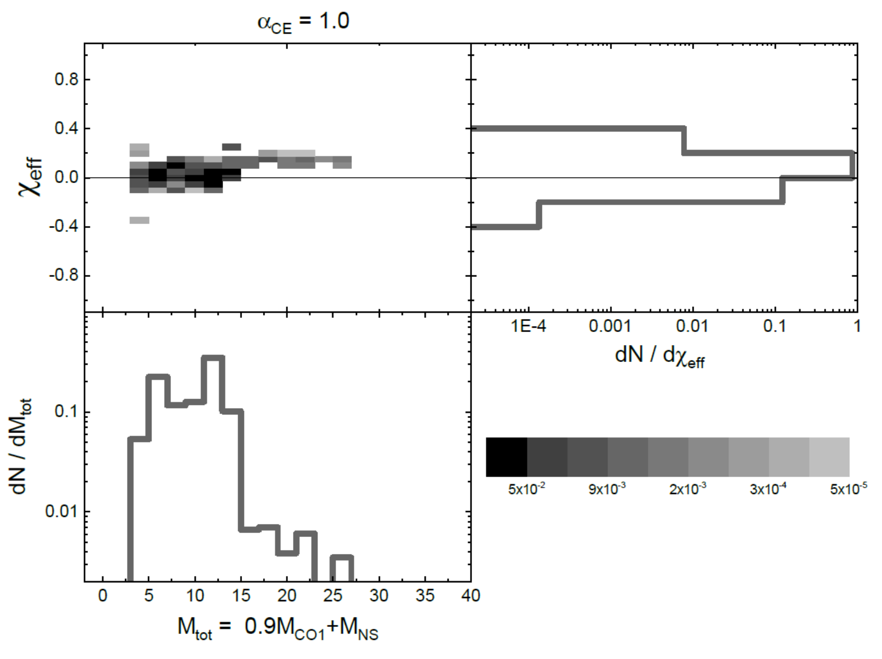
PK+ 2019, Physics-Uspekhi (2019, No 11, in press); 1907.04218

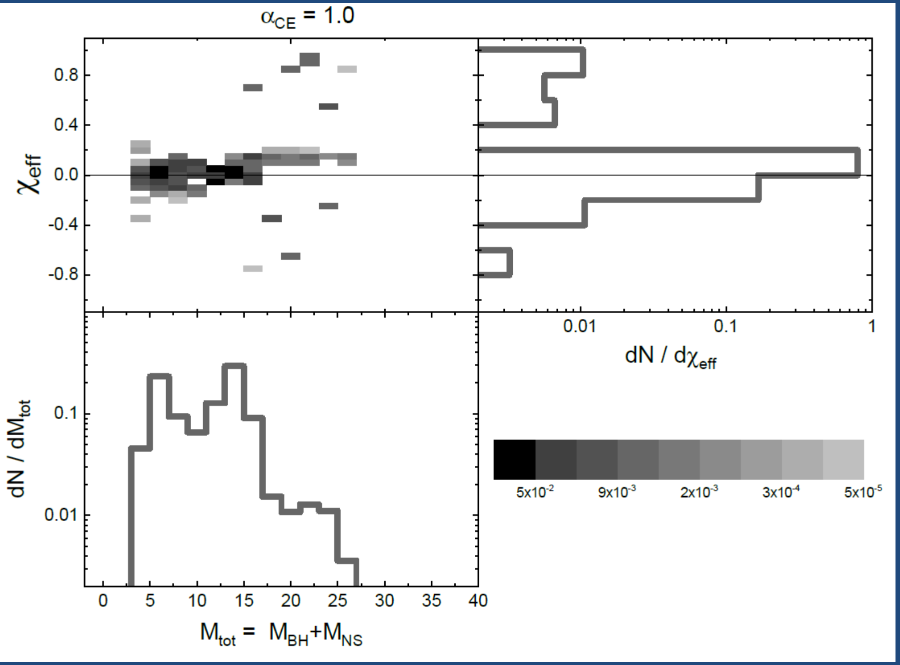
Detection rate BH+BH, BH+NS



1907.04218

Effective spin/total mass distribution for BH+NS coalescing binaries





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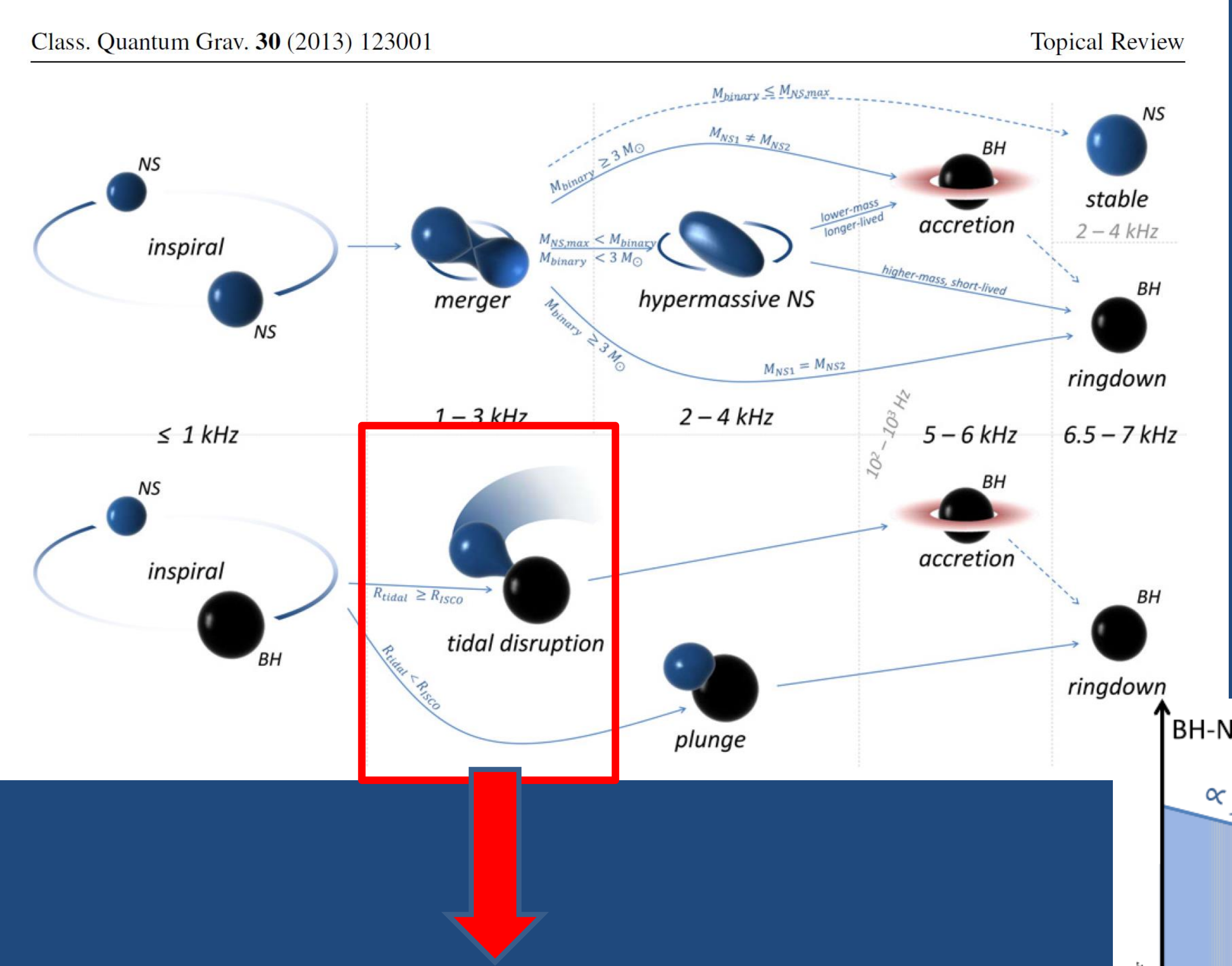
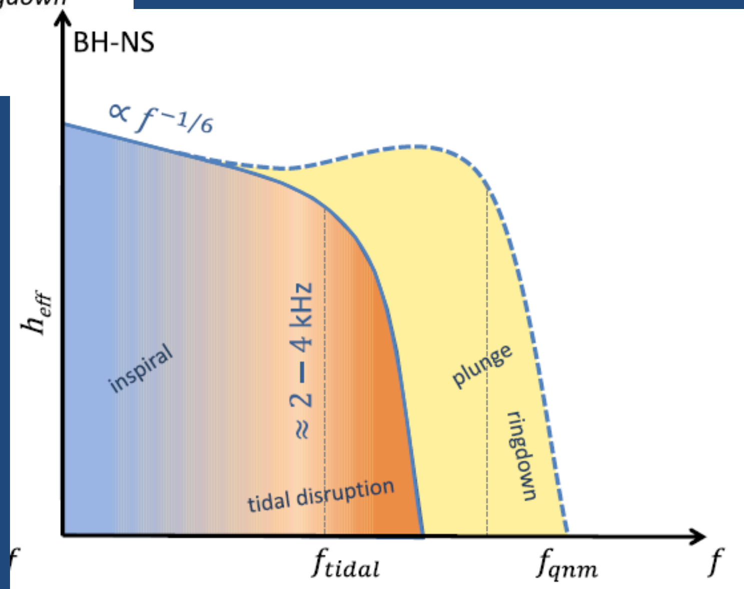
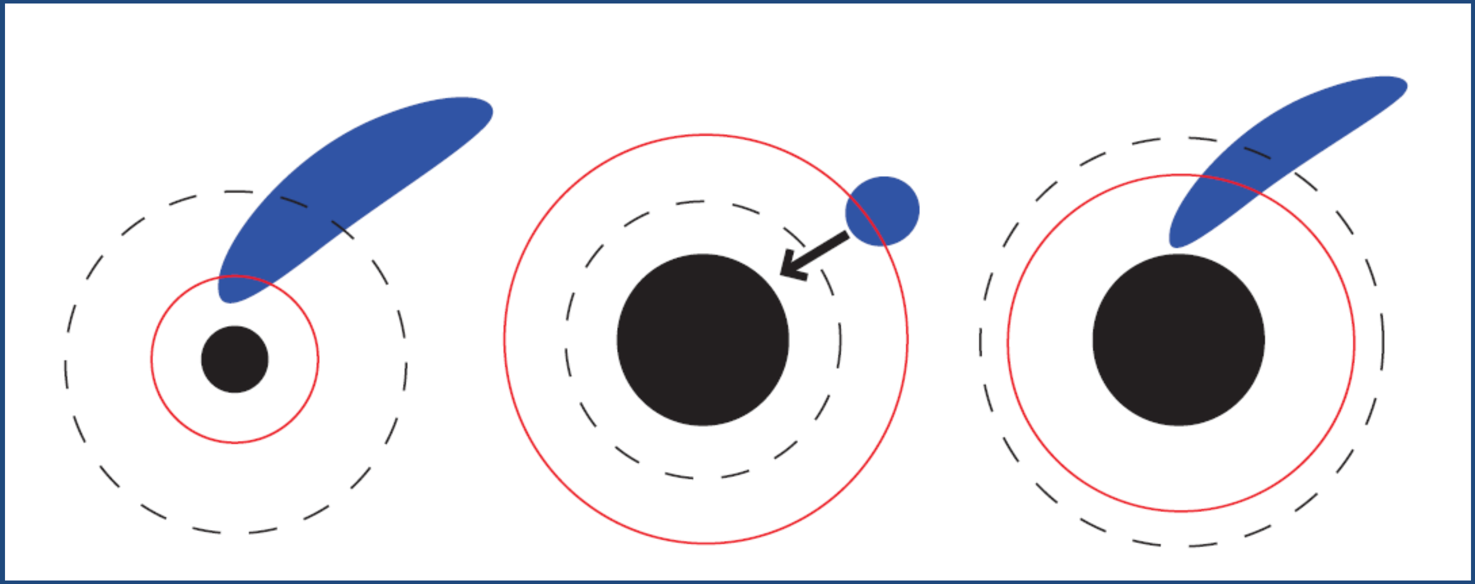
sGRB from NS+BH



sGRB-favorable





$R_{tid} > R_{ISCO}$ $R_{tid} < R_{ISCO}$ $R_{tid} \sim R_{ISCO}$

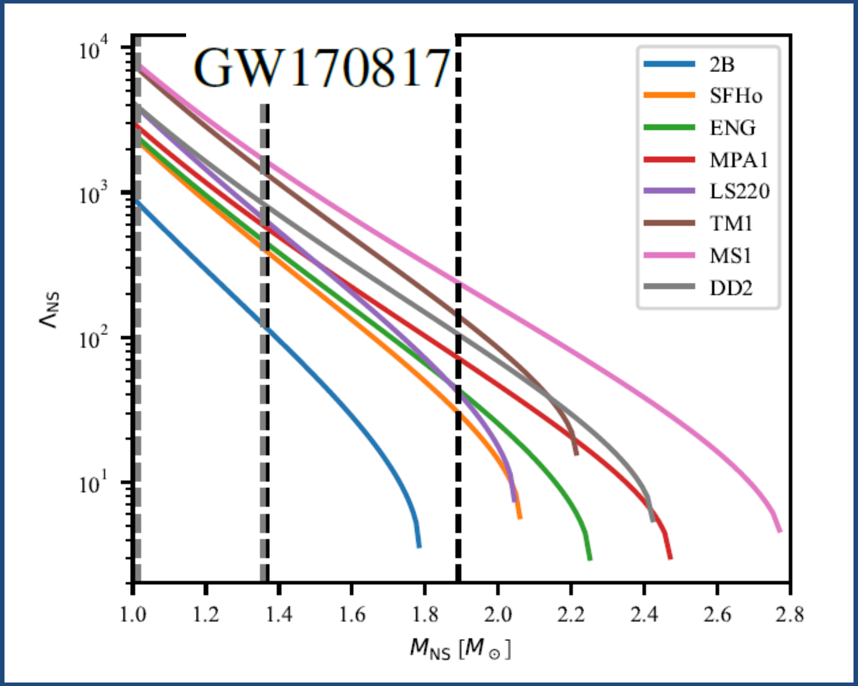
Kyotoku+'11

Mass shedding and tidal disruption

$$r_{\rm ISCO}/M = 3 + Z_2 \mp \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)}$$

$$Z_1 \equiv 1 + (1 - \chi_1^2)^{1/3} \times \left[(1 + \chi_1)^{1/3} + (1 - \chi_1)^{1/3}\right]$$

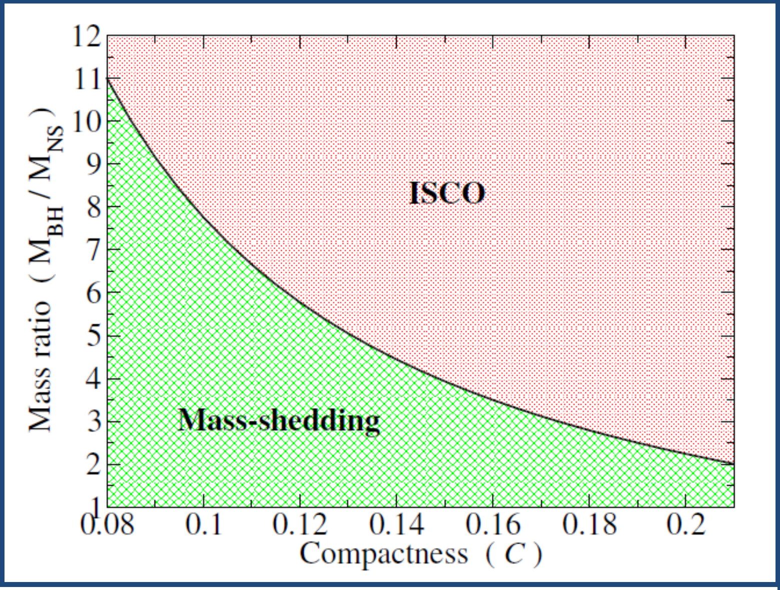
$$Z_2 \equiv \sqrt{3\chi_1^2 + Z_1^2}$$

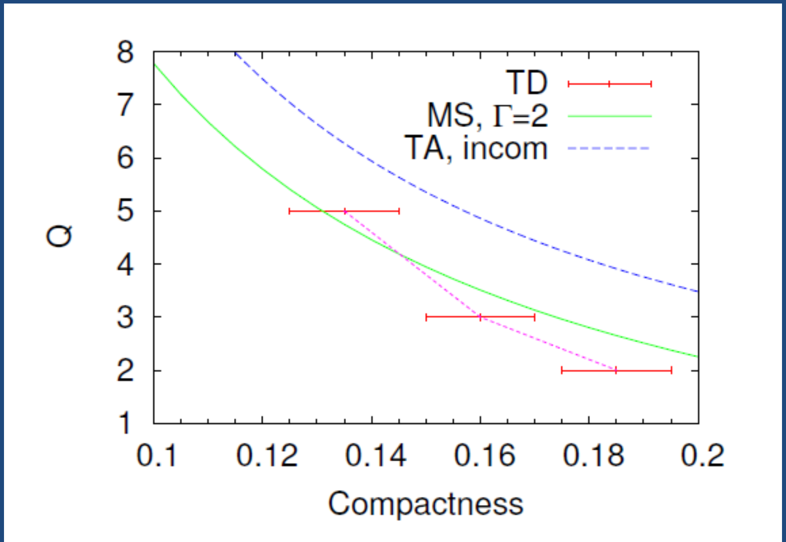


Barbieri+ 1908.08822

- $R_{tid} \sim R_{ns}(M_{bh}/M_{ns})^{1/3}$
  Mass shedding if
  $R_{tid} > R_{ISCO}$
- Depends on NS compactness $C = M_{ns}/R_{ns}$ (EOS)
- **Tidal parameter $\Lambda = 2k_2/(3C^5)$**
- Depends on the BH spin

Mass ratio for tidal disruption

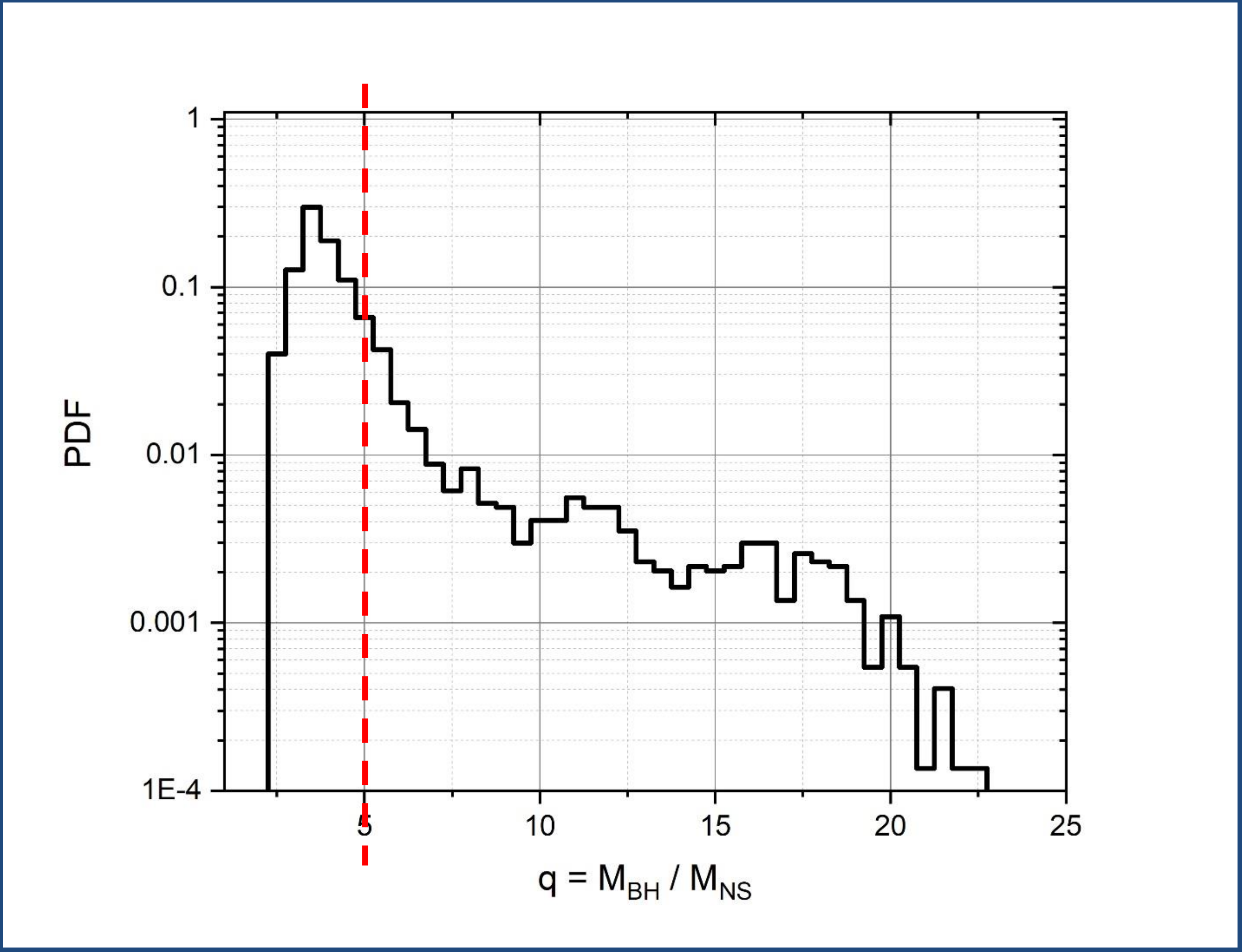




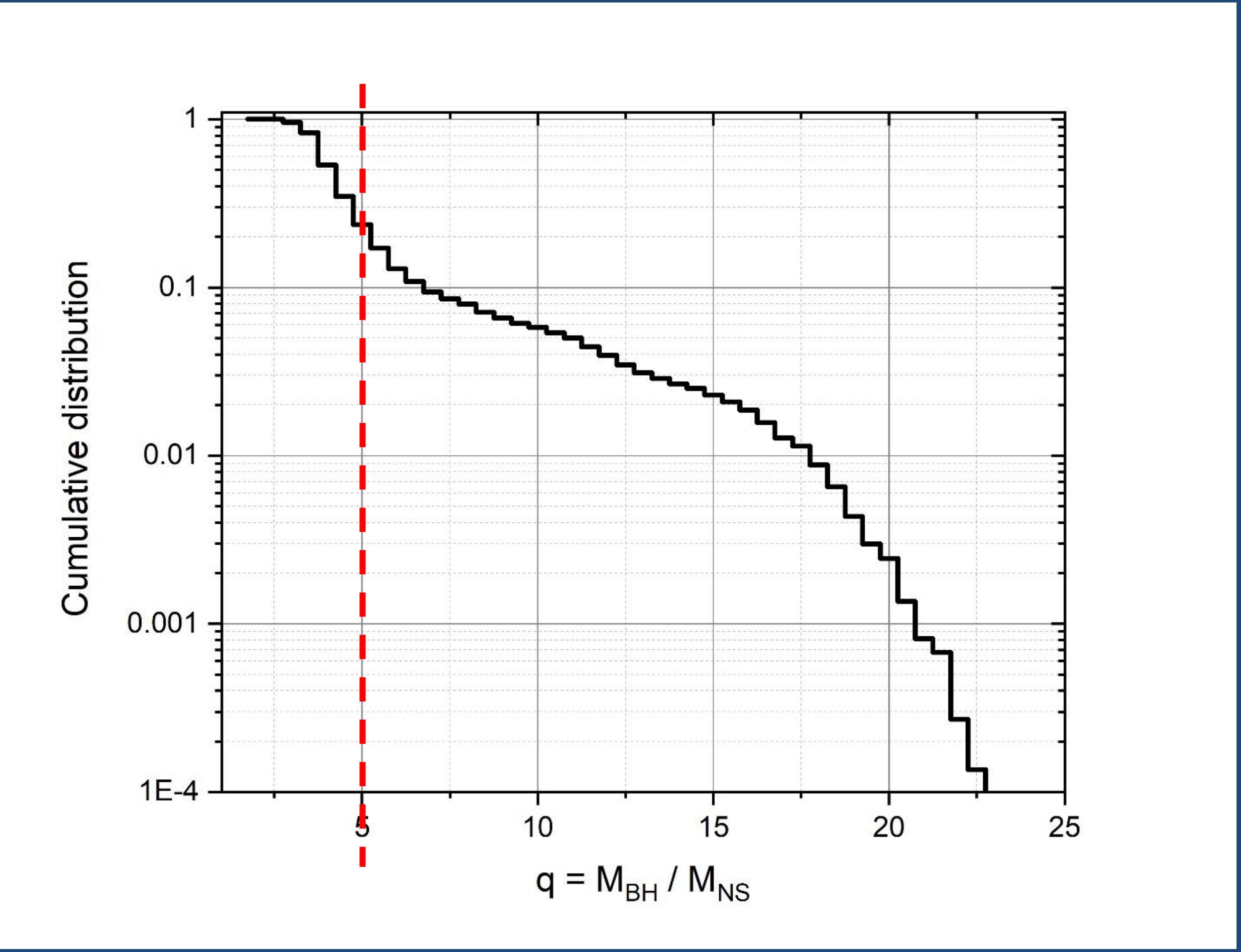
- Approximately the same as for the mass shedding
- For a=0: q_{cr}~3-5
- For a→1: q_{cr} ~5-7

Shibata, Taniguchi '11

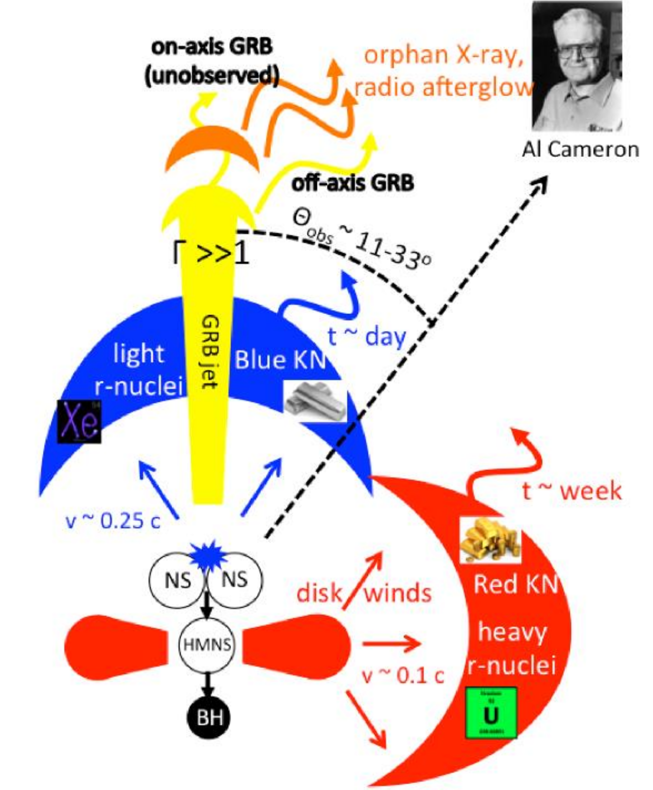
Coalescing BH/NS mass ratio



Coalescing BH/NS mass ratio



- A substantial (>50%) fraction of NS+BH mergings is expected to occur in the tidal disruption regime favoring disk formation around a rotating BH



Mass ejection

- ‘Dynamical’ (merger) + ‘viscous’ (disc)

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

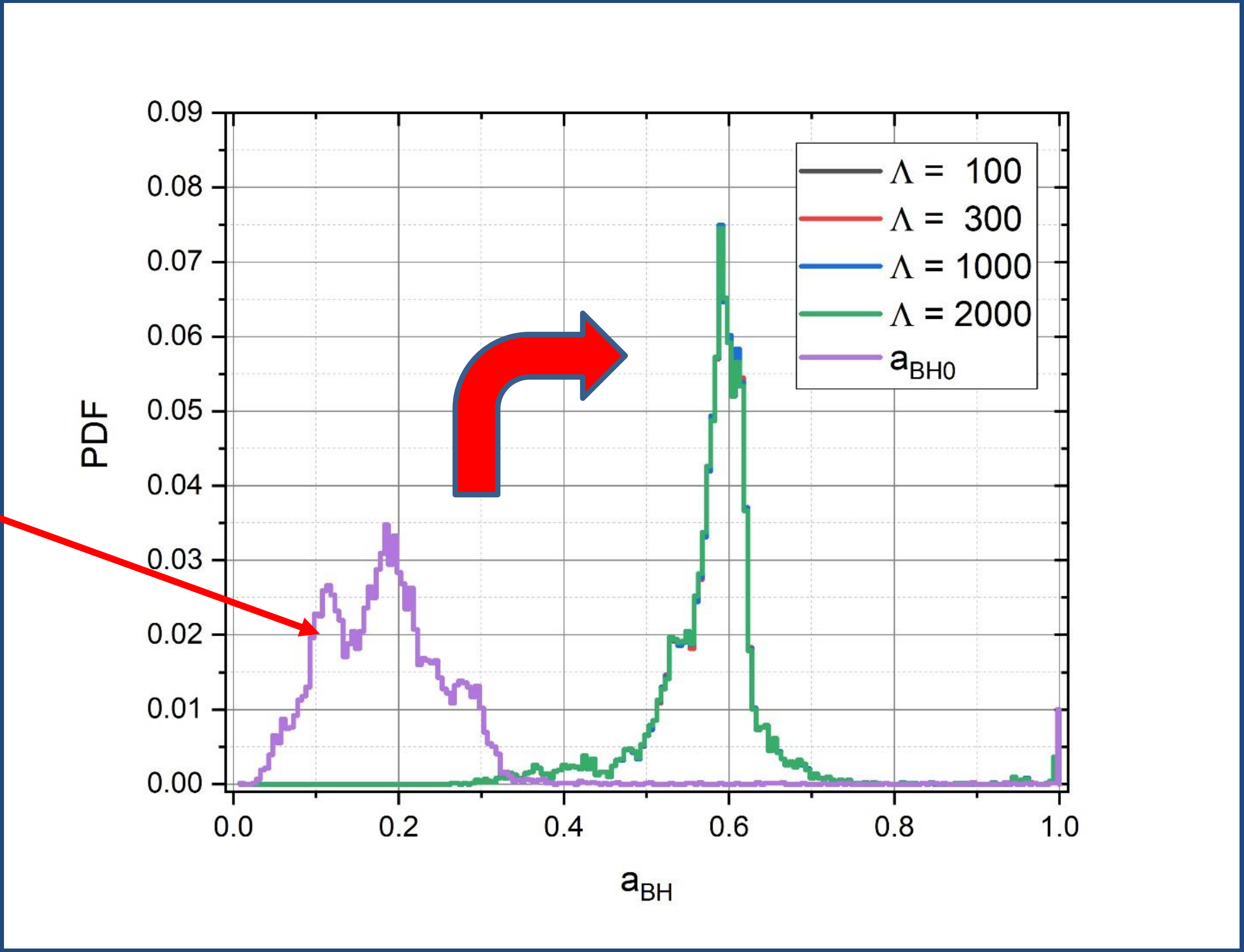
Type of binary	Remnant	$M_{\rm ej,dyn}$	$M_{\rm ej,vis}$	$Y_{e,\rm dyn}$	$Y_{e,\rm vis}$	$\langle v_{\rm ej}\rangle$
Low-m BNS	SMNS	$O(10^{-3})$	$O(10^{-2})$	0.05–0.5	0.3–0.5	0.15
Mid-m BNS (stiff EOS)	HMNS	$O(10^{-3})$	$O(10^{-2})$	0.05–0.5	0.2–0.5	0.15
Mid-m BNS (soft EOS)	HMNS	$\sim 10^{-2}$	$O(10^{-2})$	0.05–0.5	0.2–0.5	0.20
High-m BNS ($q \sim 1$)	BH	$< 10^{-3}$	$< 10^{-3}$	—	—	—
High-m BNS ($q \ll 1$)	BH	$O(10^{-3})$	$\lesssim 10^{-2}$	0.05–0.1	0.05–0.3	0.30
BH-NS	BH	0–0.1	0–0.1	0.05–0.1	0.05–0.3	0.30

1908.02350

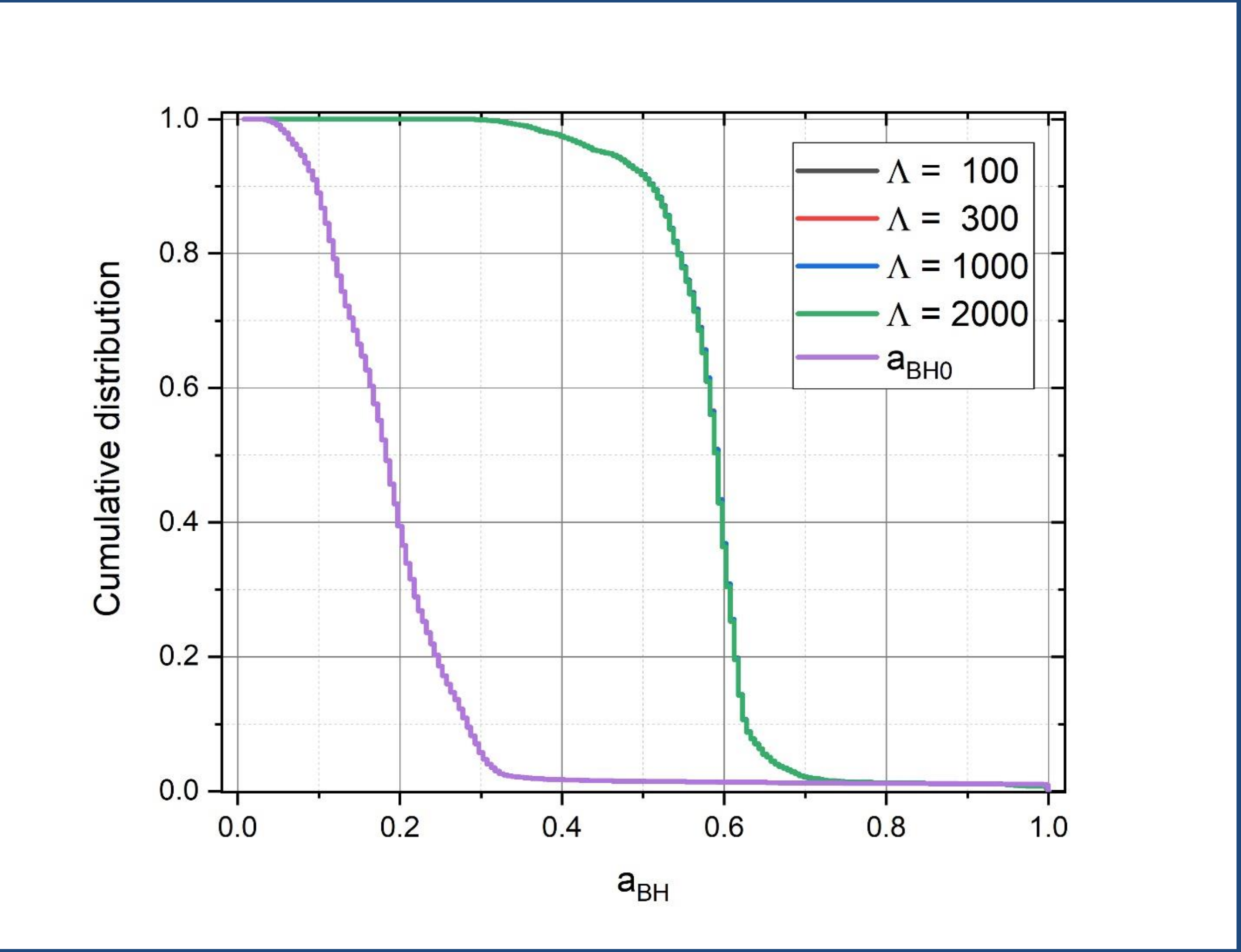
- **Mass ejection depends on the total mass M before the coalescence, binary mass ratio, component spins and tidal deformation (EOS)**
- Final BH mass and spin, emitted GW energy → from numerical relativity simulations (Jimenez-Forteza+’18)
- Account for NS EOS → from NR simulations of BH+NS mergings (Zappa+’19)

Final spin of BH

Initial BH spin from population synthesis (PK+'19)

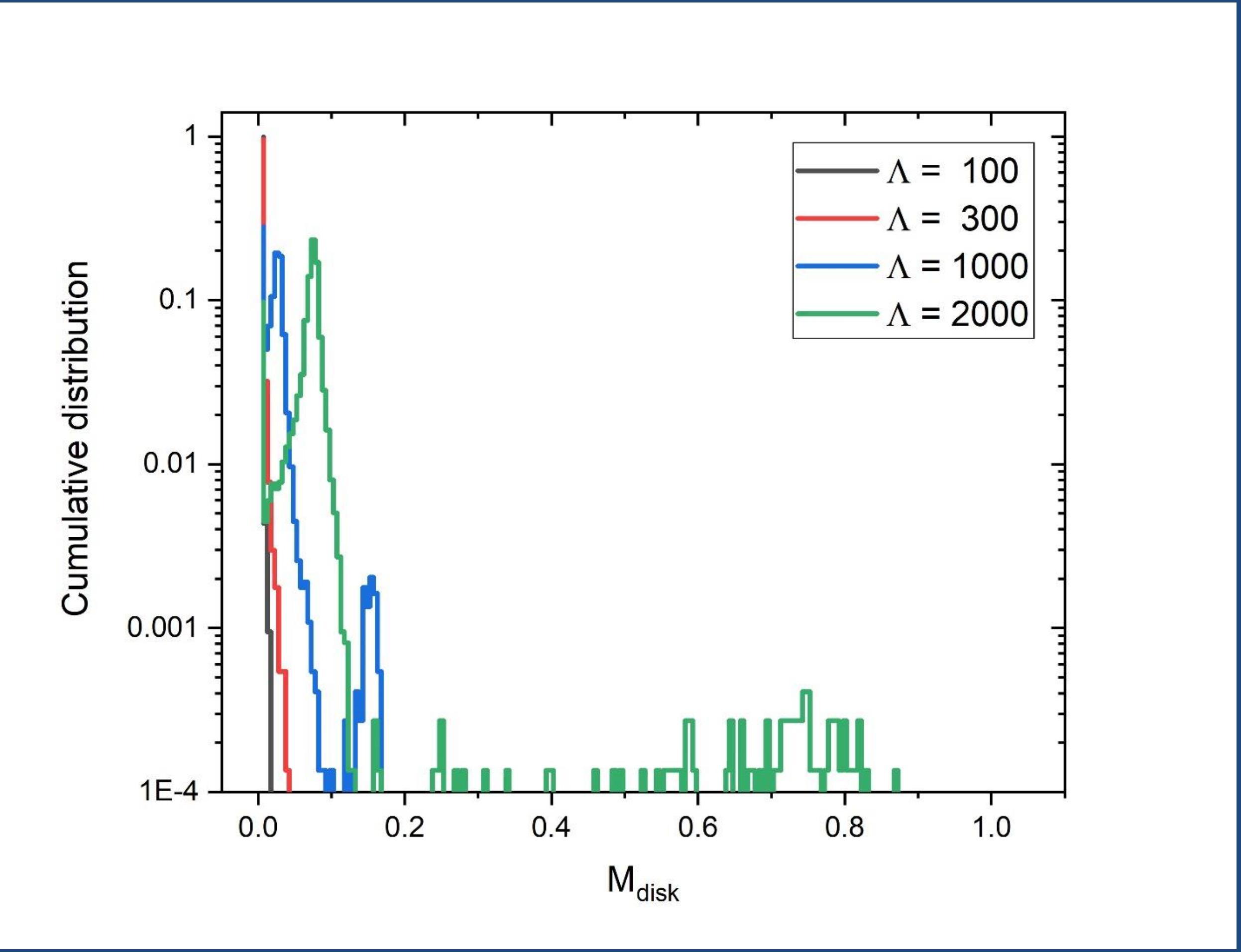


Final spin of BH

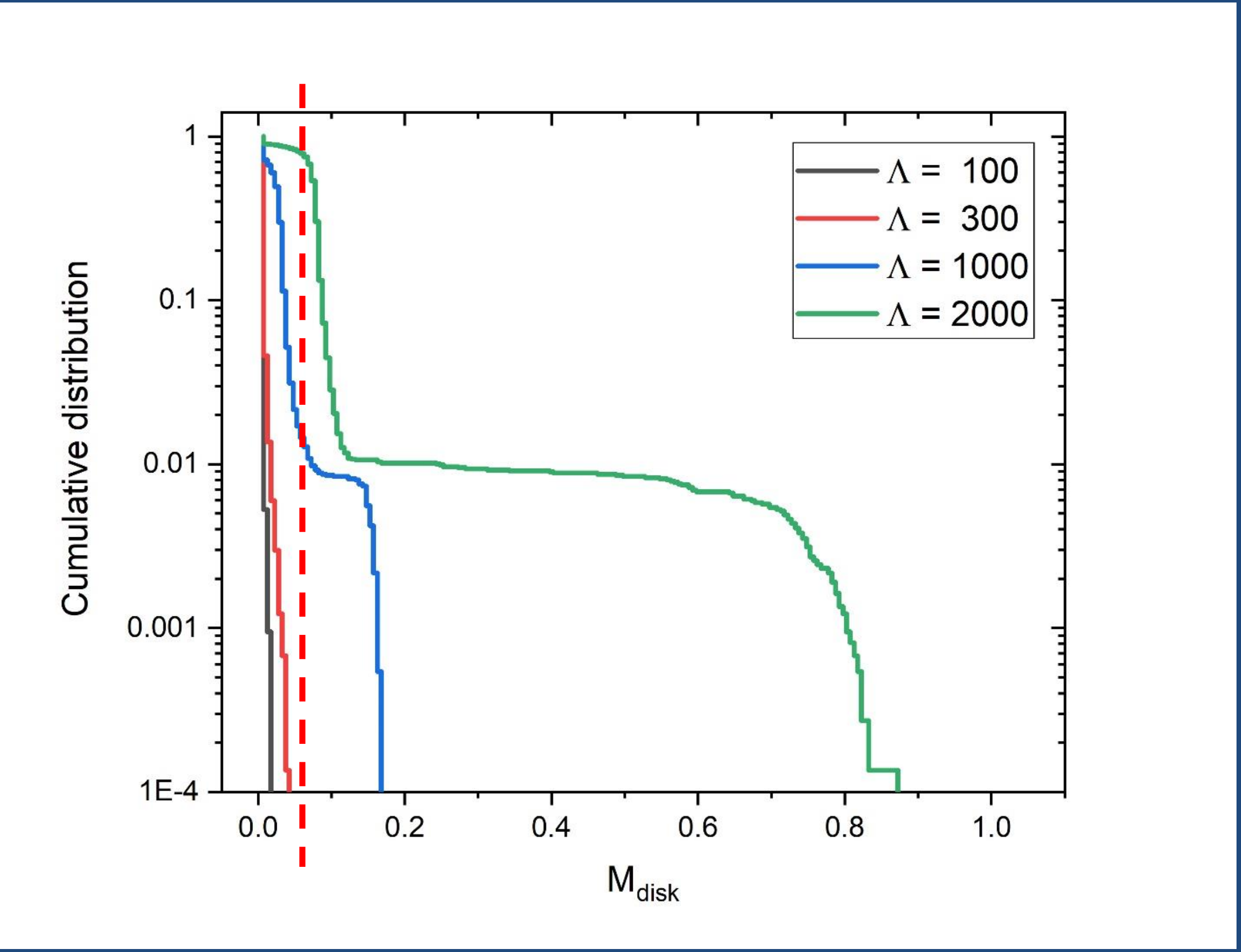


- Final BH spin is almost insensitive to uncertain NS EOS!

Residual disk mass from tidally disrupted NS (q<5)



Residual disk mass

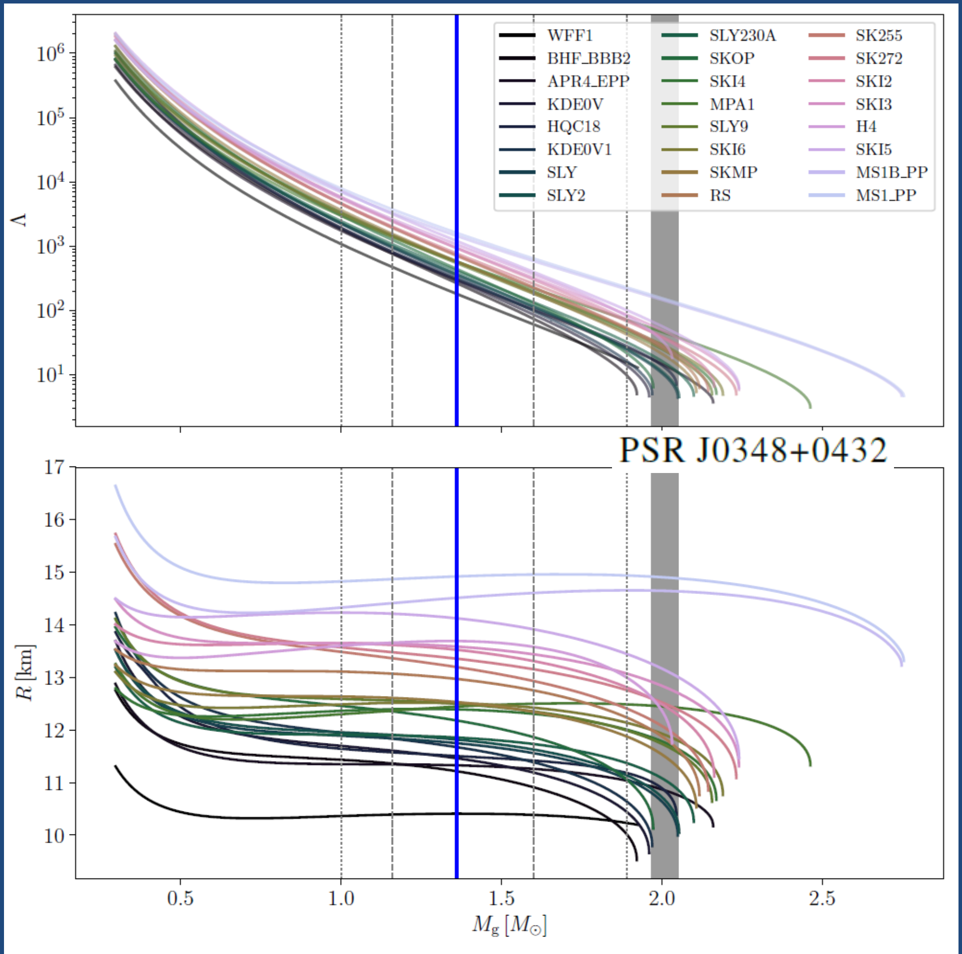


- M_{disk} is determined by the mass ratio
- Strongly depends on NS EOS!
- Only large deformations (hard EOS) with **Λ>1000** can give rise to interesting disk masses

Constraints from GW170817:

~200<Λ< ~1600

NS equation of state constraints



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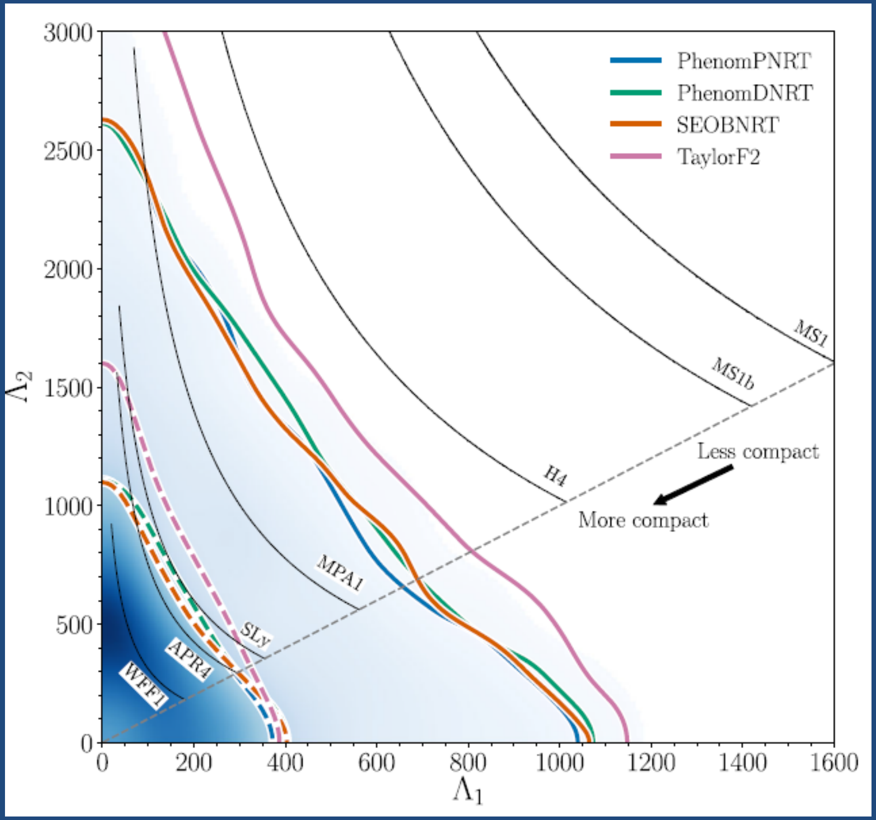
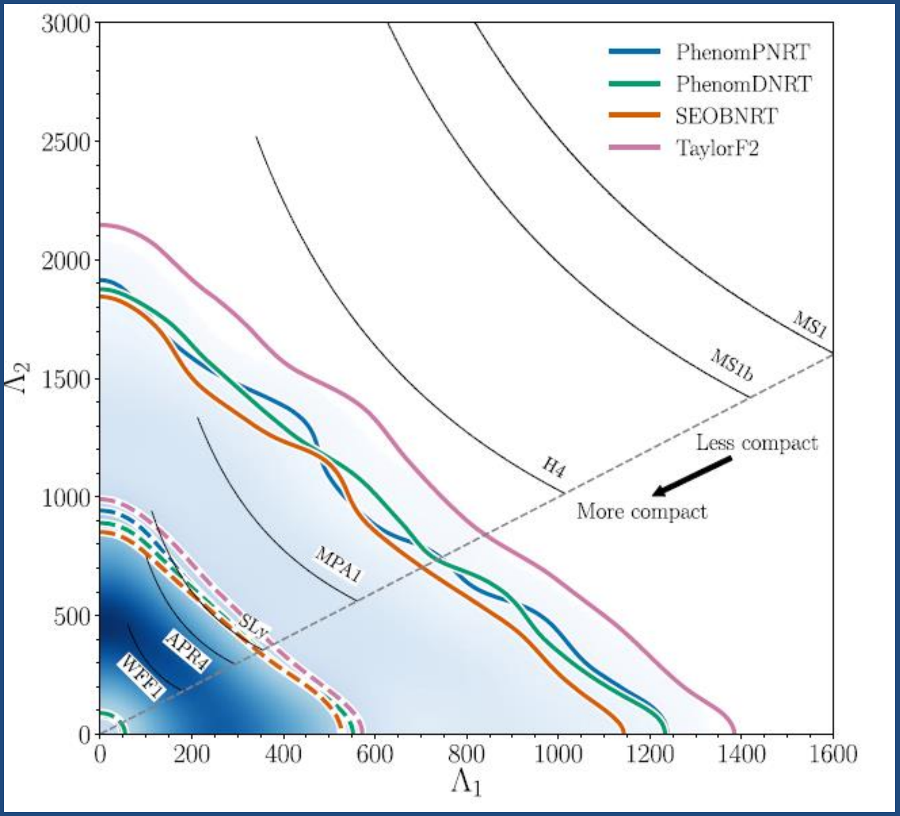
Tidal deformation

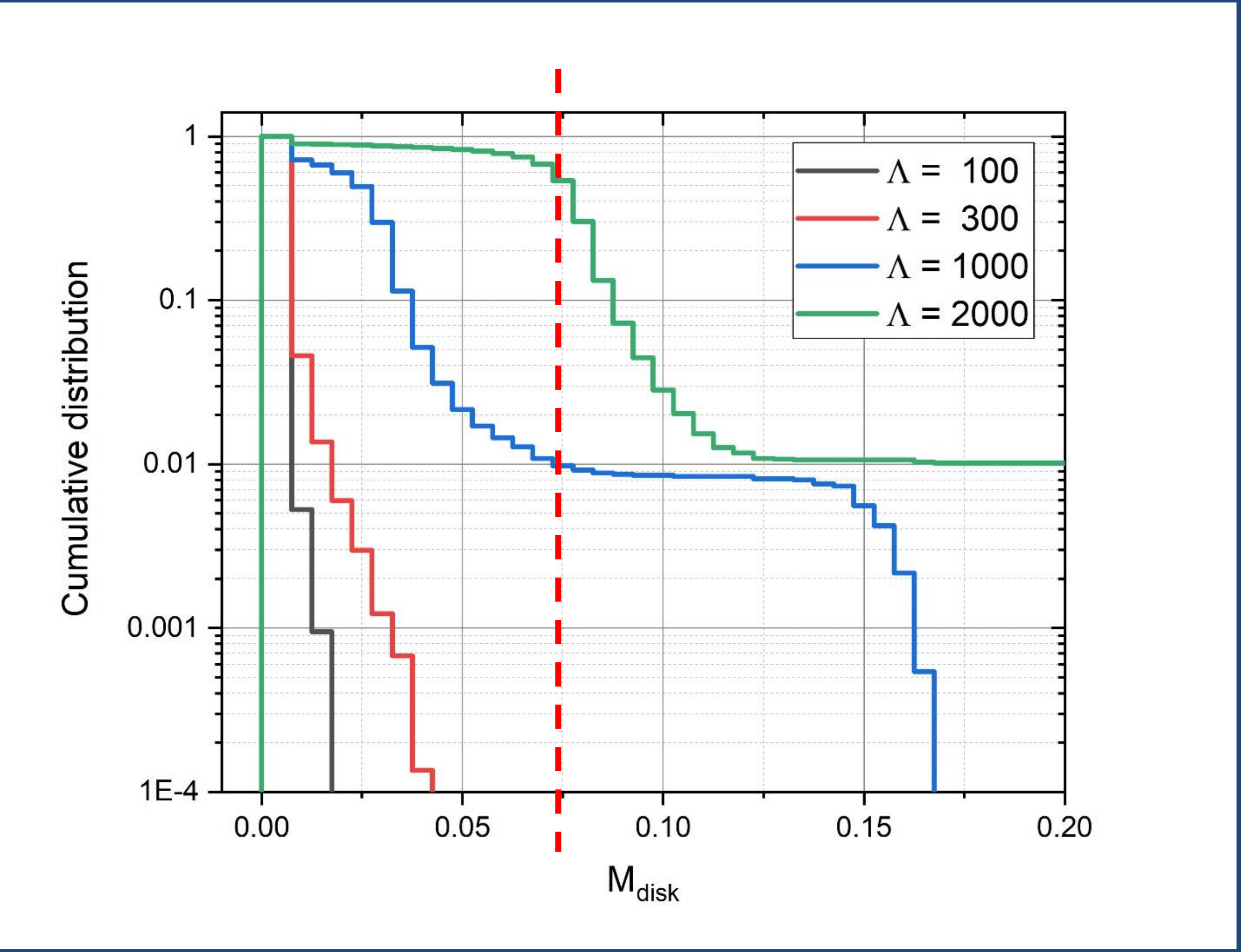




$$\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$$

1805.11579

Residual disk mass



BZ jet

$$L_{BZ} \sim B_d{}^2 M^2 \Omega_H^2 f(\Omega_H)$$

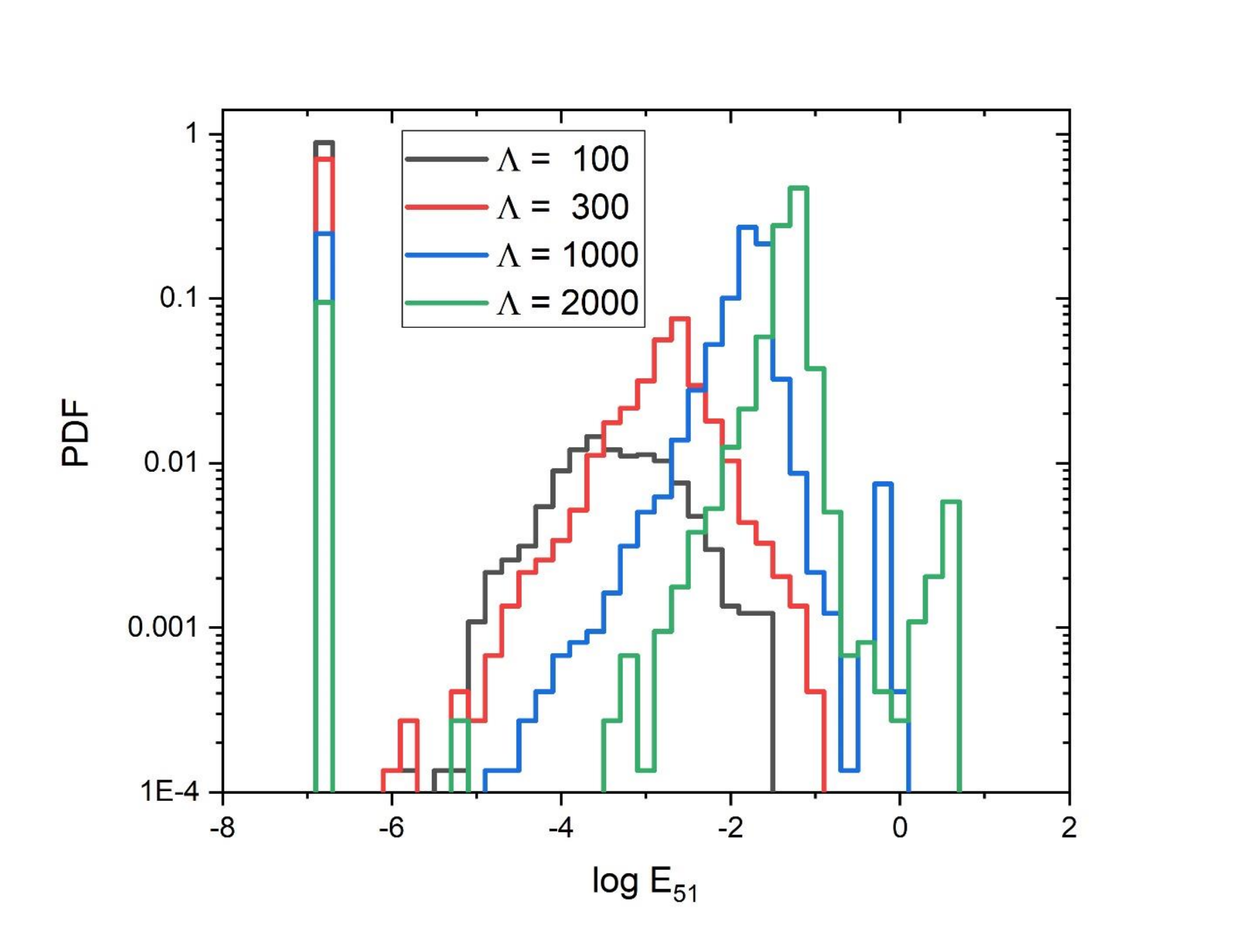
$$B^2 \sim \dot{M}_{accr} / M^2$$

$$\dot{M}_{accr} \sim M_{disk} / t_{accr}$$

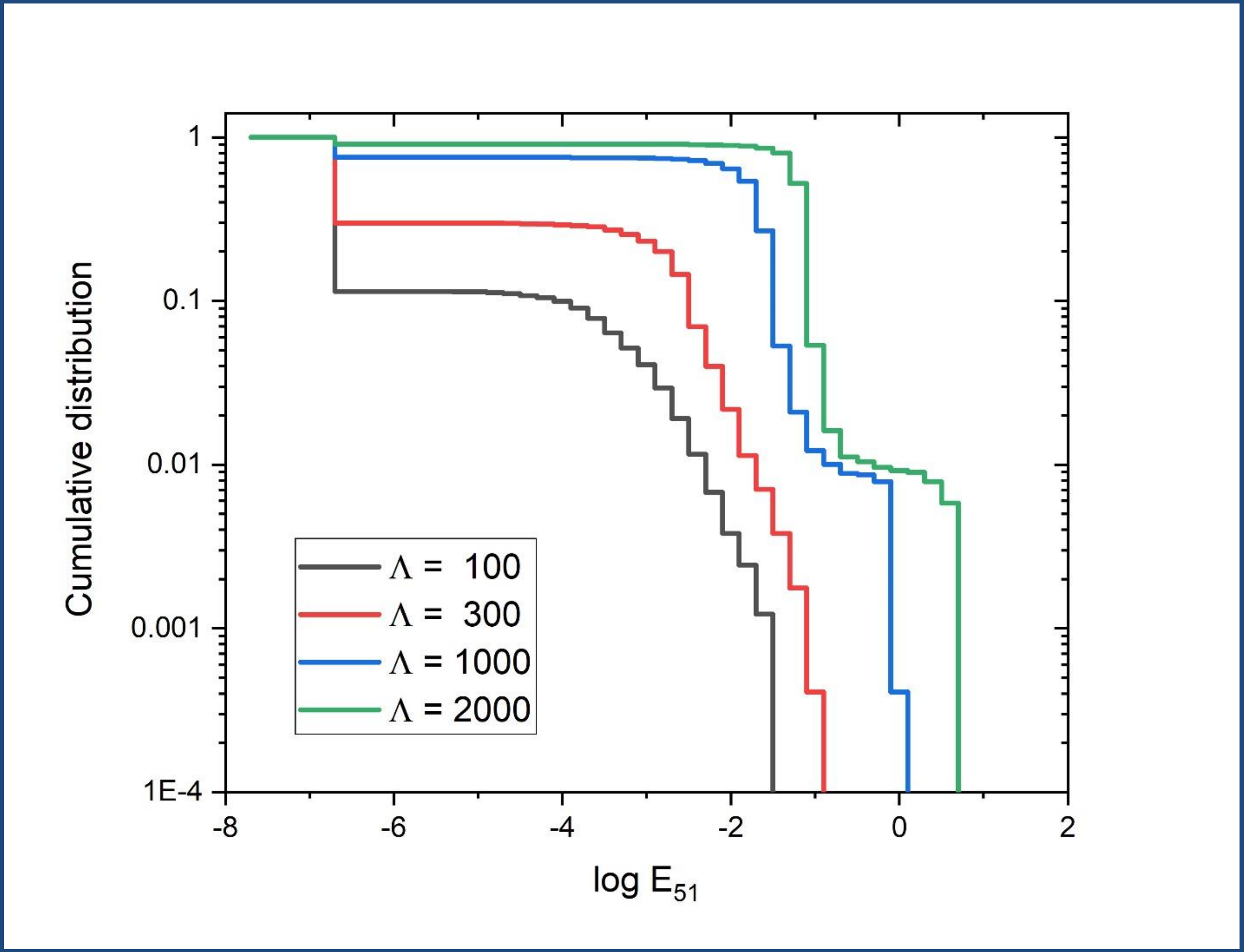
$$E_{BZ} = \varepsilon M_{disk} \Omega_H^2 f(\Omega_H)$$

$$\varepsilon = 0.015 \quad (Barberi + '19)$$

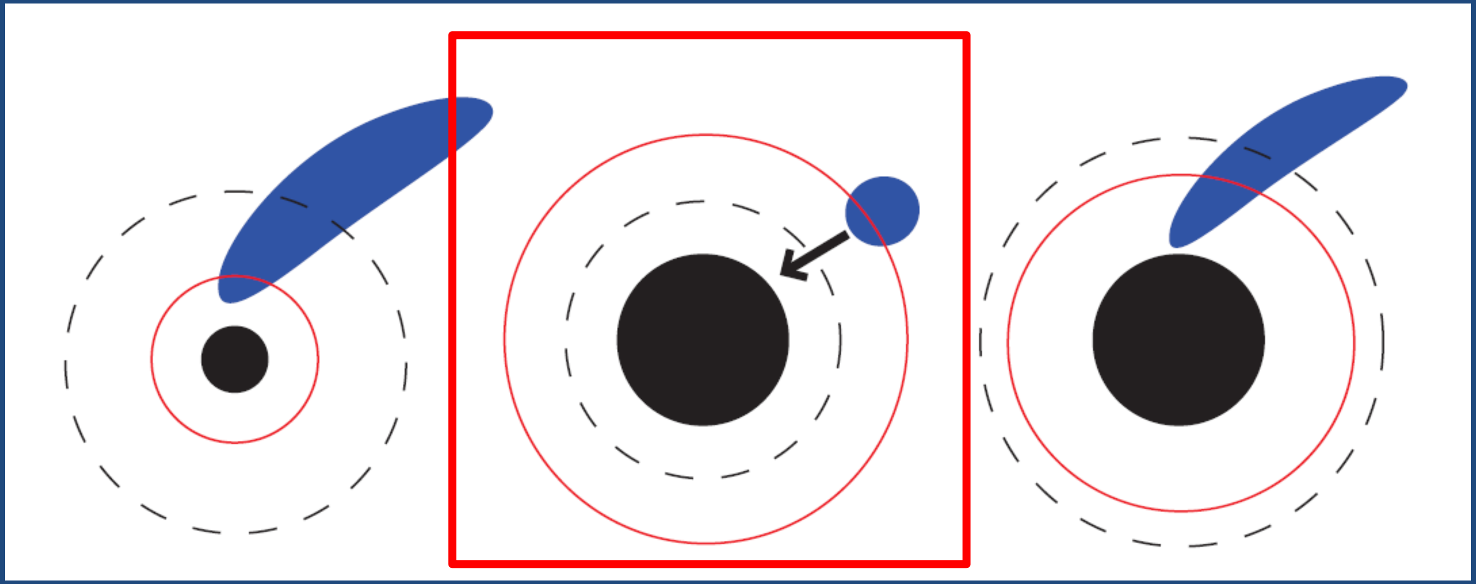
BZ jet kinetic energy



BZ jet kinetic energy



NS plunging into BH (q>5)



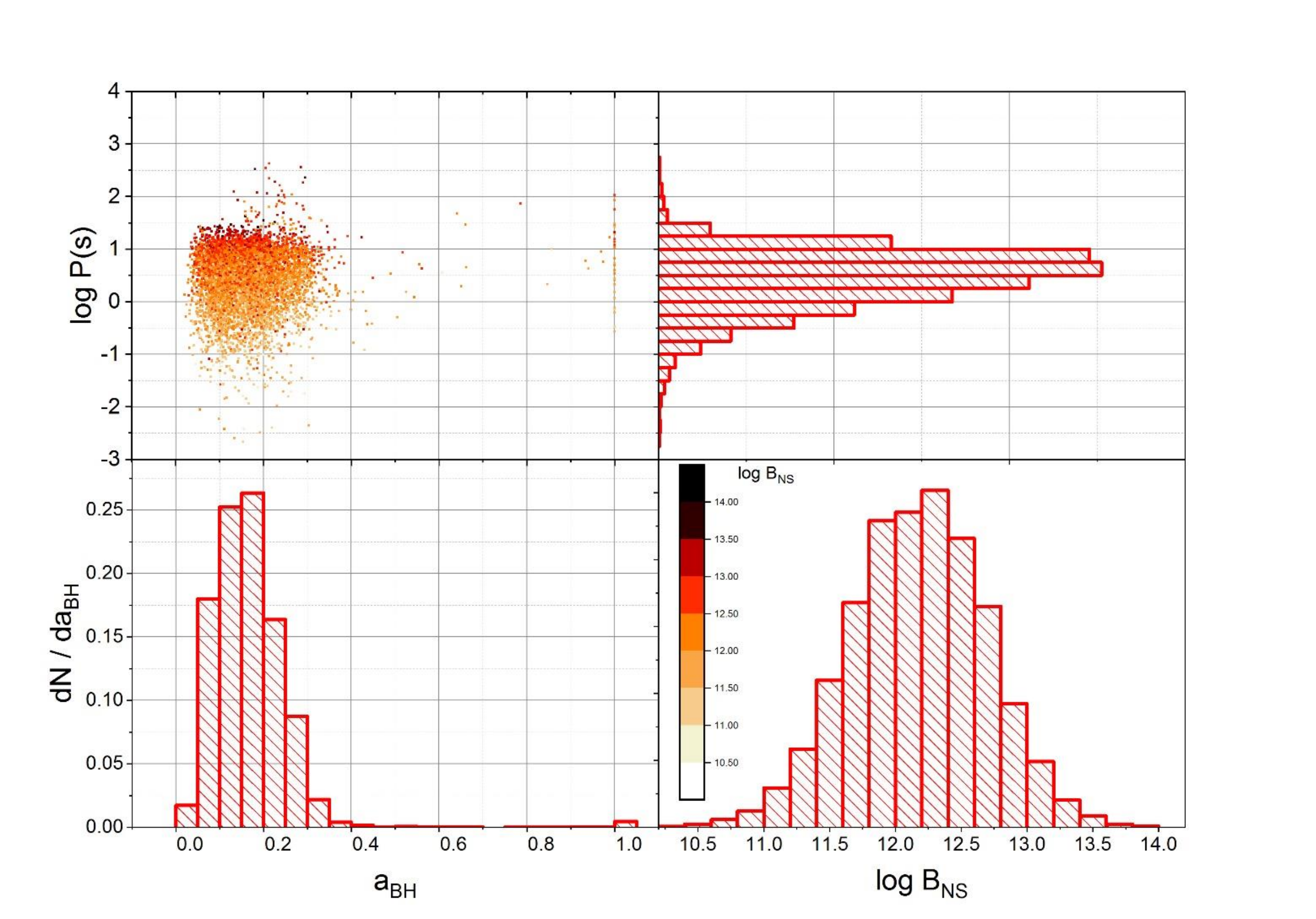
NS plunging into BH (q>5)

- A rotating BH in a magnetic field can acquire electric charge (Wald 1974)

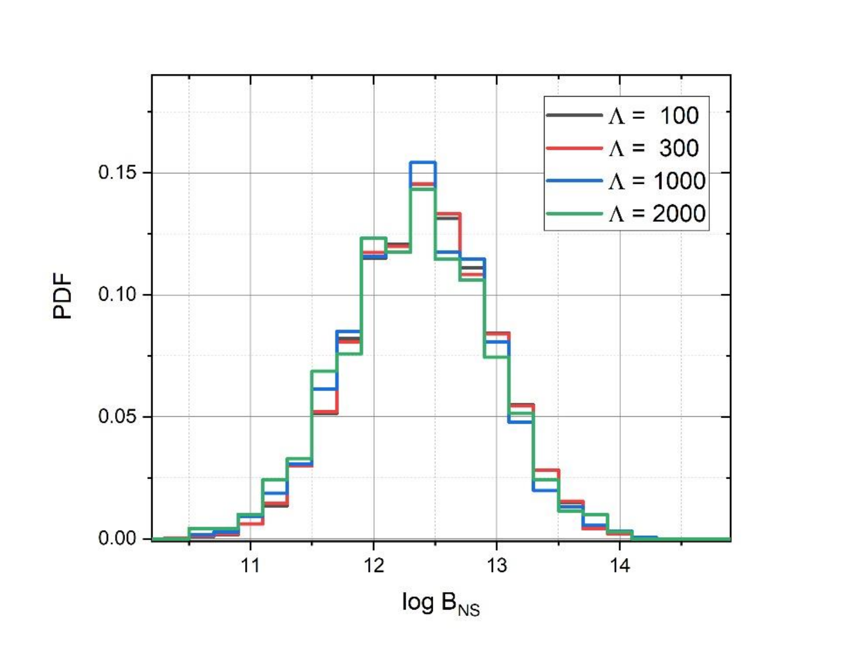
$$Q_{\mathrm{W,max}} \simeq \frac{2G}{c^3} J \times B_{\mathrm{S,NS}} = \frac{2G^2}{c^4} a M^2 B_{\mathrm{S,NS}}$$
$$= 4.4 \times 10^{24} a \left(\frac{M}{10 M_\odot} \right)^2 \frac{B_{\mathrm{S,NS}}}{10^{12}\mathrm{G}} \text{ e.s.u.},$$

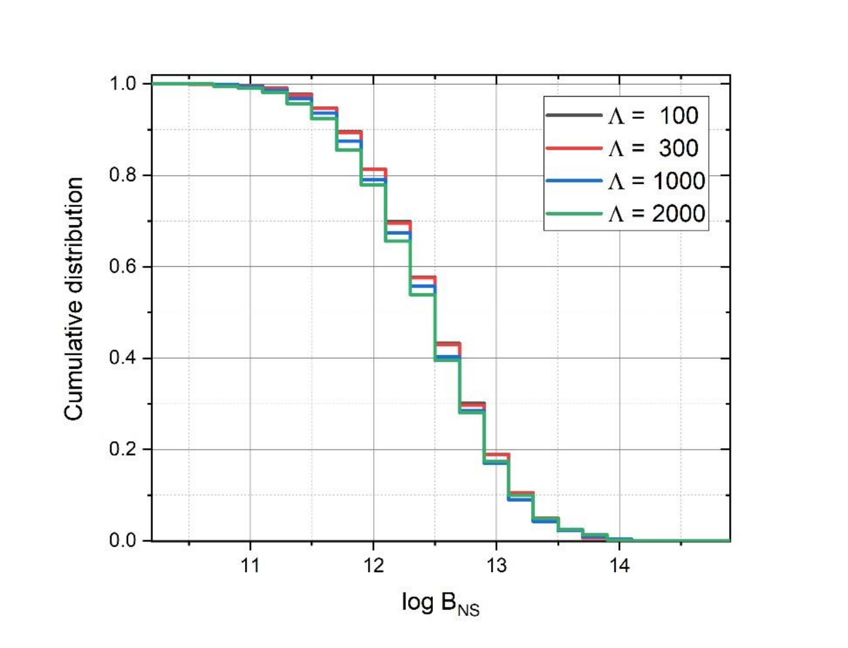
- There can be EM emission associated with charged BH (Levin+’18, Shu-Quing Zhong+’19…)

NS rotation and magnetic field before the coalescence

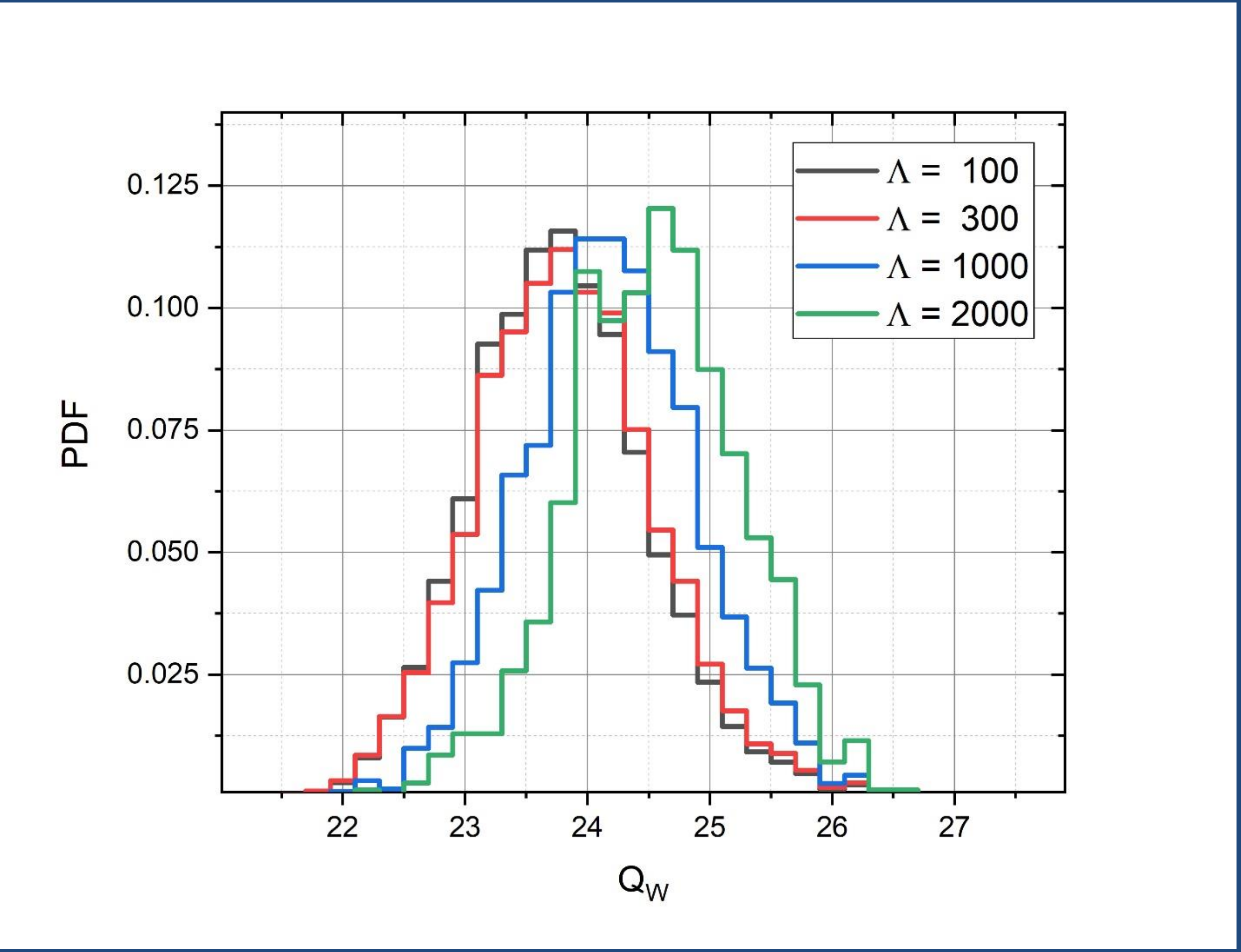


NS magnetic field for plunged NS

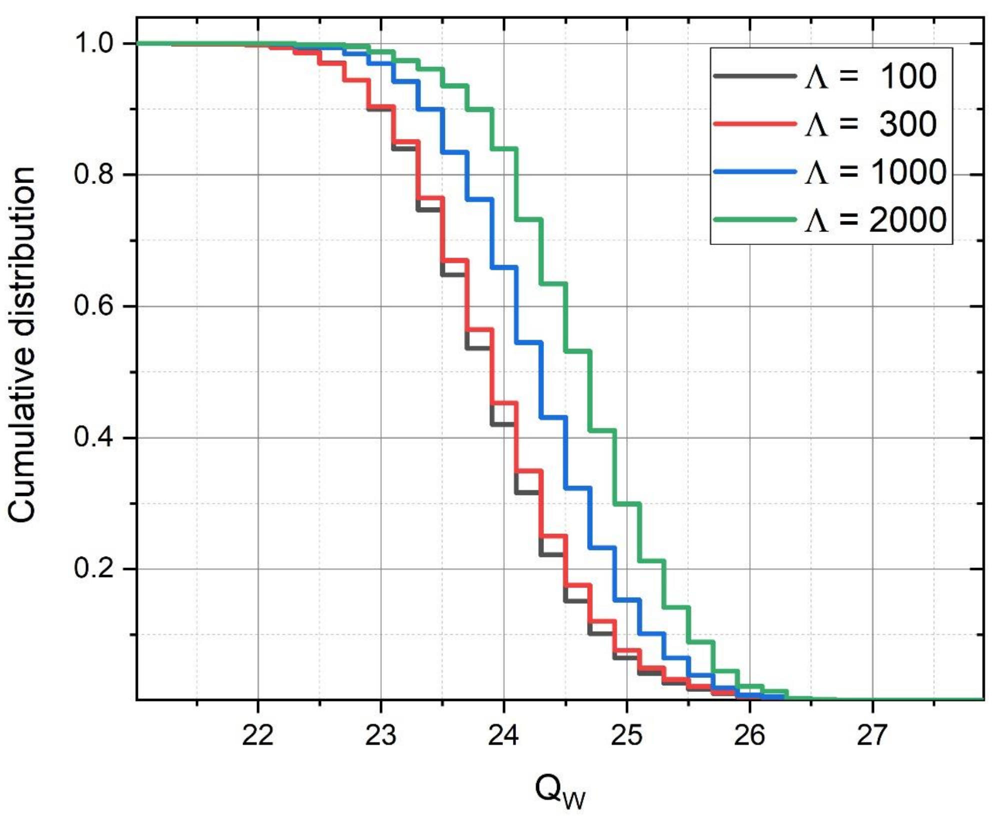




Wald BH charge



Wald BH charge



Conclusions

- NS+BH rate is one order of magnitude smaller than BH+BH rate, ~ a few is expected within LVC O3 detection horizon (as of 13/09/19, 2 out of 25 detections)
- Disk formation form NS tidal disruption mostly depends on (uncertain) NS EOS
- **1-10 % of NS+BH coalescences with tidally disrupted NS can launch relativistic BZ jets and produce short (likely subluminous) GRBs**
- More exotic (but less secure) mechanisms of EM radiation from high-mass-ratio NS+BH plunges are not excluded