VIRGO PROMETEO GROUP

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

CLAUDIO BARBIERI - PHD STUDENT

ELECTROMAGNETIC COUNTERPARTS OF BLACK HOLE – NEUTRON STAR MERGERS

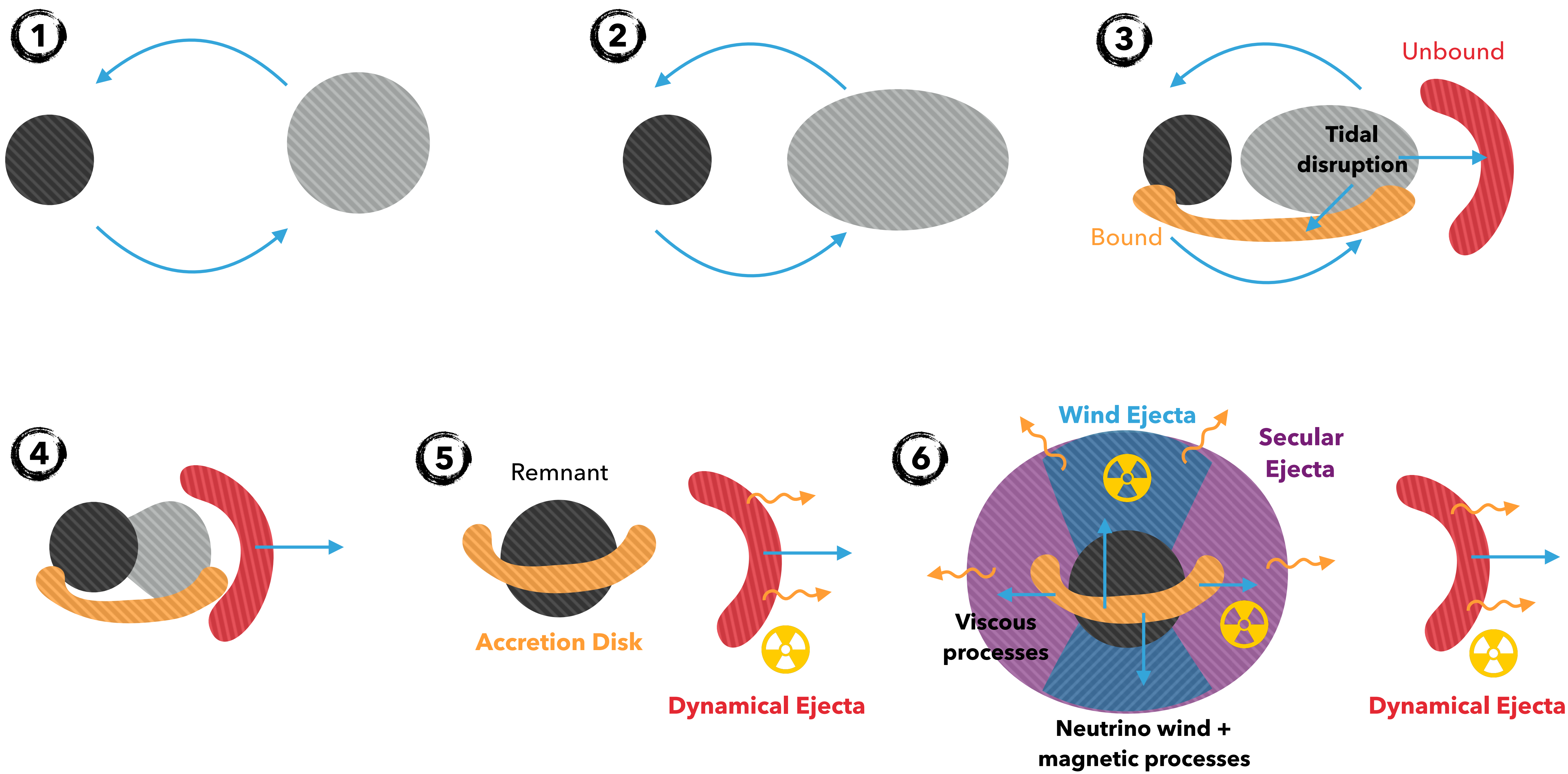
The first compact star merger event – Implications for nuclear and particle physics, Trento, October 14-18 2019

1

E.M. COUNTERPARTS

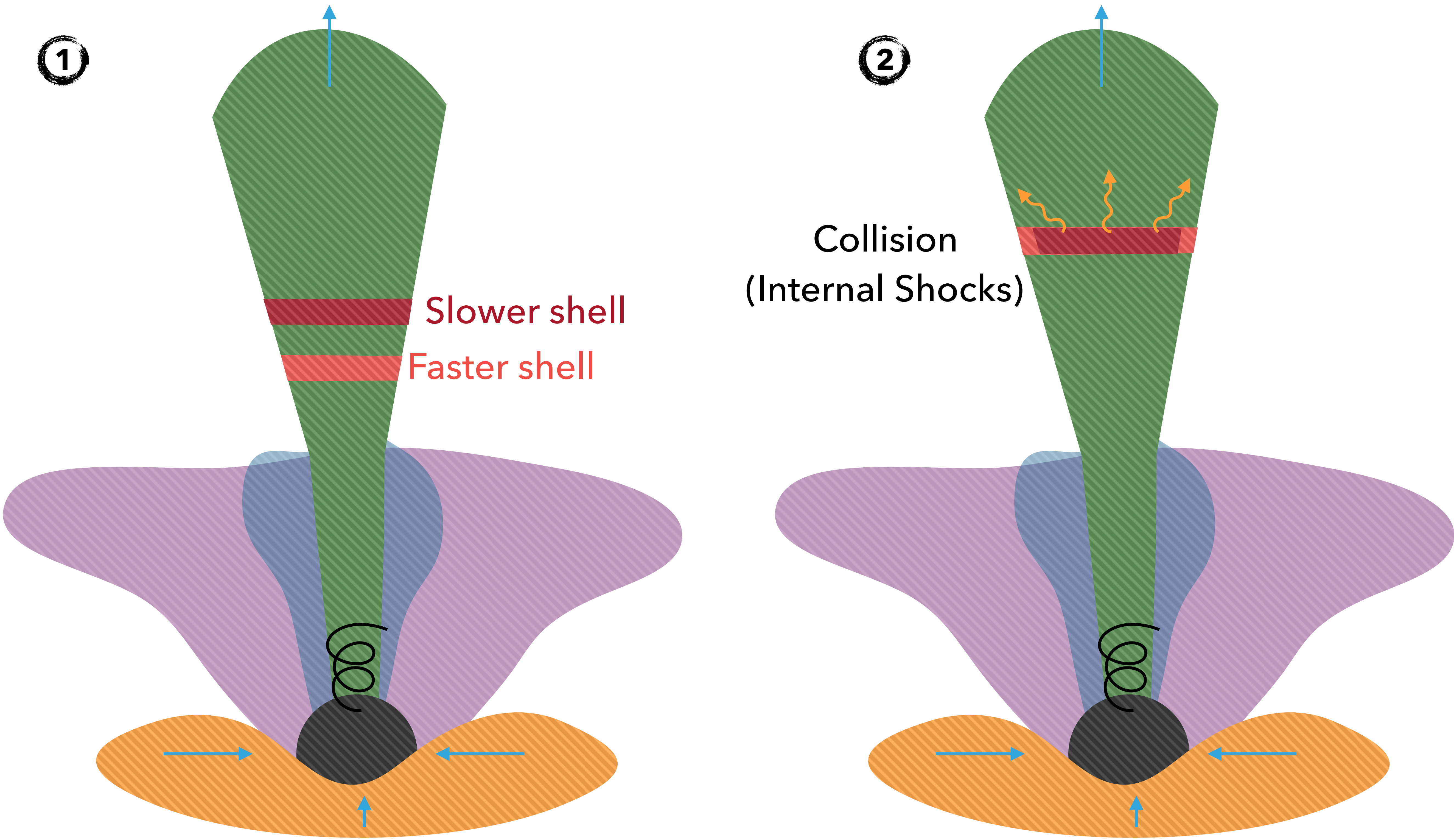
KILONOVA

- The NS releases neutron-rich ejecta -> r-processes produce heavy elements far from the “valley of stability” -> radioactive decay -> **kilonova** emission.



GRB PROMPT

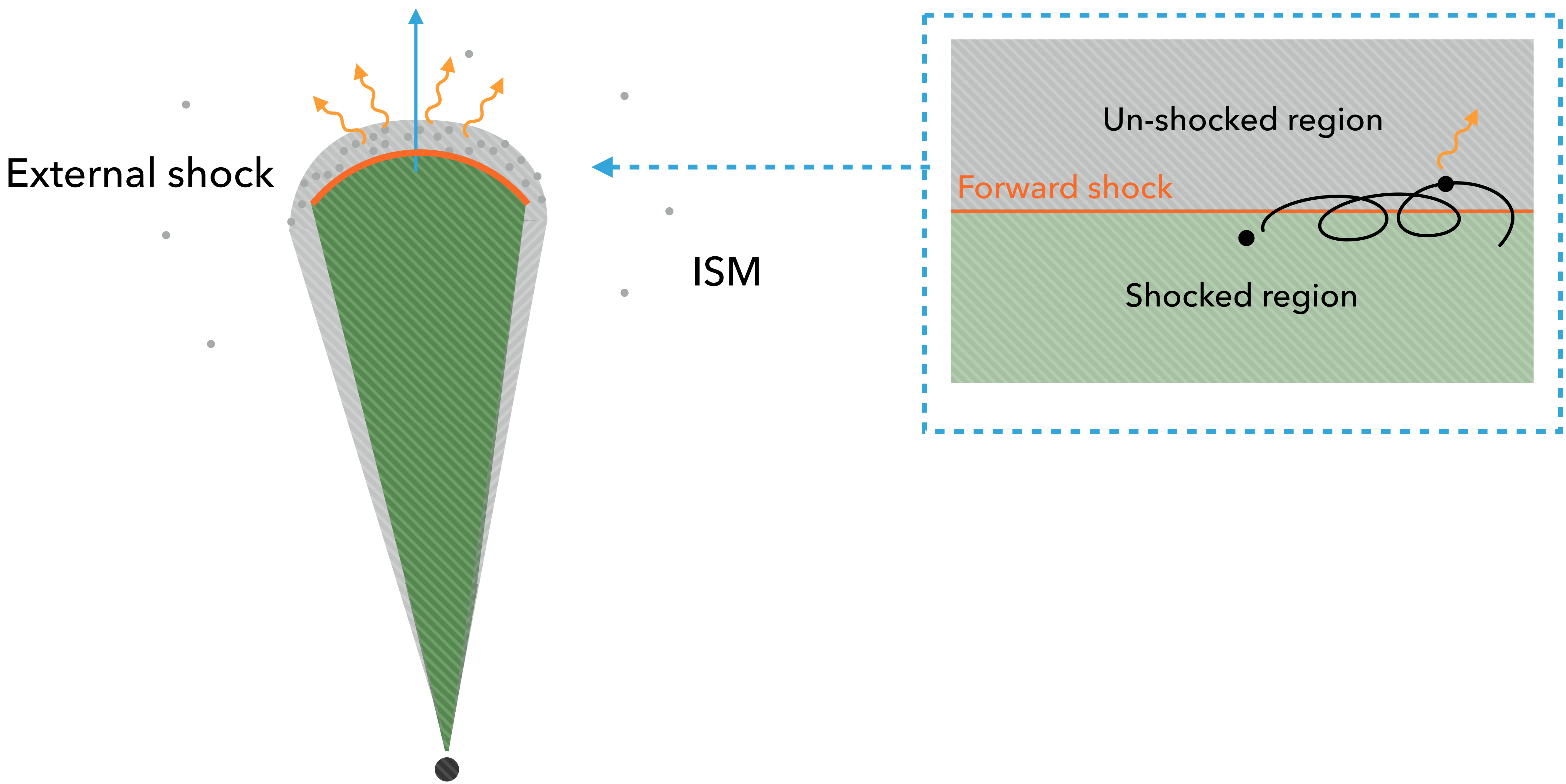
- The disc accretes onto the remnant BH -> Relativistic jet launch (Blandford-Znajek).
- Internal Shocks and/or magnetic reconnection -> **GRB Prompt** emission.



Jet - Environment interaction -> **Salafia, Barbieri et al. 19**, Submitted to A&A, (arXiv:1907.07599)

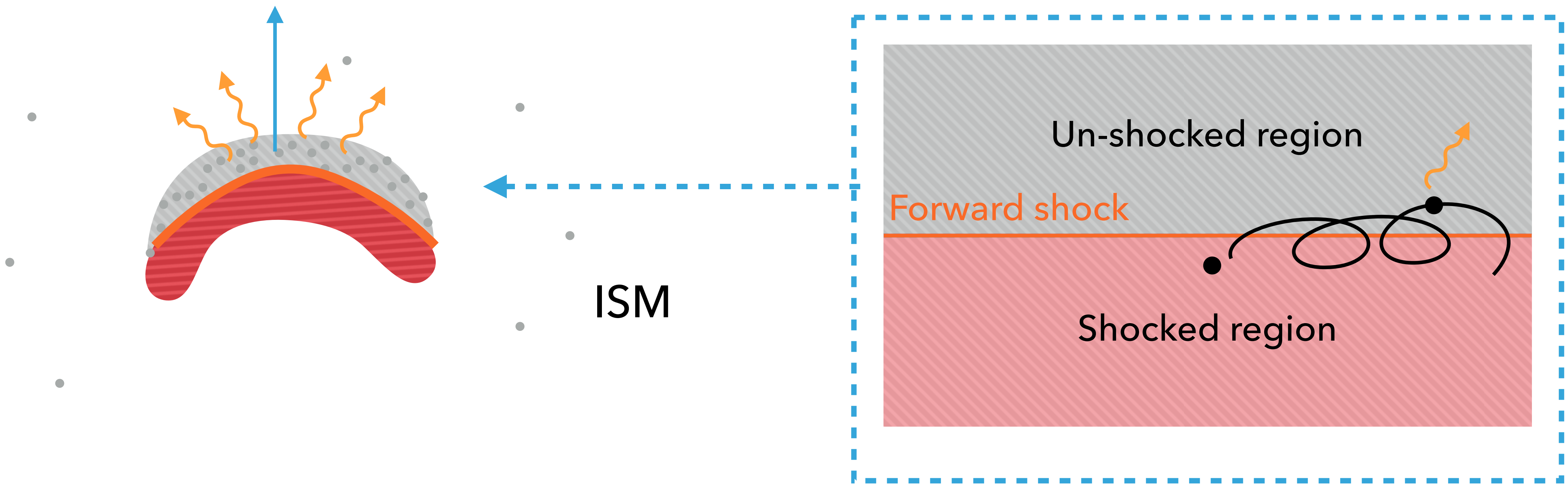
GRB AFTERGLOW

- The jet propagates into the Interstellar Medium (ISM). When it decelerates, a forward shock is formed. ISM electrons are accelerated (Fermi process) and produce synchrotron radiation: the **GRB afterglow**.



KILONOVA RADIO REMNANT

- Same as GRB afterglow. When the dynamical ejecta decelerates through interaction with ISM, a forward shock forms and synchrotron radiation is produced.



2

HOW TO CALCULATE GW SIGNAL AND LIGHT CURVES

GW SIGNAL AND E.M. COUNTERPARTS OF BHNS MERGERS

Binary parameters

$$M_{\rm BH},\ \chi_{\rm BH},\ M_{\rm NS},\ \Lambda_{\rm NS}({\rm or\ EoS}), d_{\rm L},\ \theta_{\rm v}$$

GW modeling

Merger Result

GW waveform

$$M^{\rm f}_{\rm BH},\ \chi^{\rm f}_{\rm BH},\ M_{\rm disk},\ M_{\rm ejecta}, v_{\rm ejecta}$$

GRB modeling

KN modeling

GRB Afterglow

GRB Prompt

Kilonova

Kilonova Radio Remnant

Observational conditions

Observational conditions

GW SNR

E.M. Counterpart Observation

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GW SIGNAL AND SNR IN O3 NETWORK

Using pycbc

$$M_{\rm BH},\ M_{\rm NS},\ d_{\rm L},\ \theta_{\rm v} \xrightarrow{\text{Taylor F2 approximant}} \tilde{h}_+,\ \tilde{h}_\times$$

$$\alpha,\ \delta,\ \psi,\ T \longrightarrow \text{Interferometer antenna pattern} \quad p^{\rm i}_+,\ p^{\rm i}_\times$$

$$\tilde{h}^{\rm i}_{\rm obs} = p^{\rm i}_+ \times \tilde{h}_+ + p^{\rm i}_\times \times \tilde{h}_\times$$

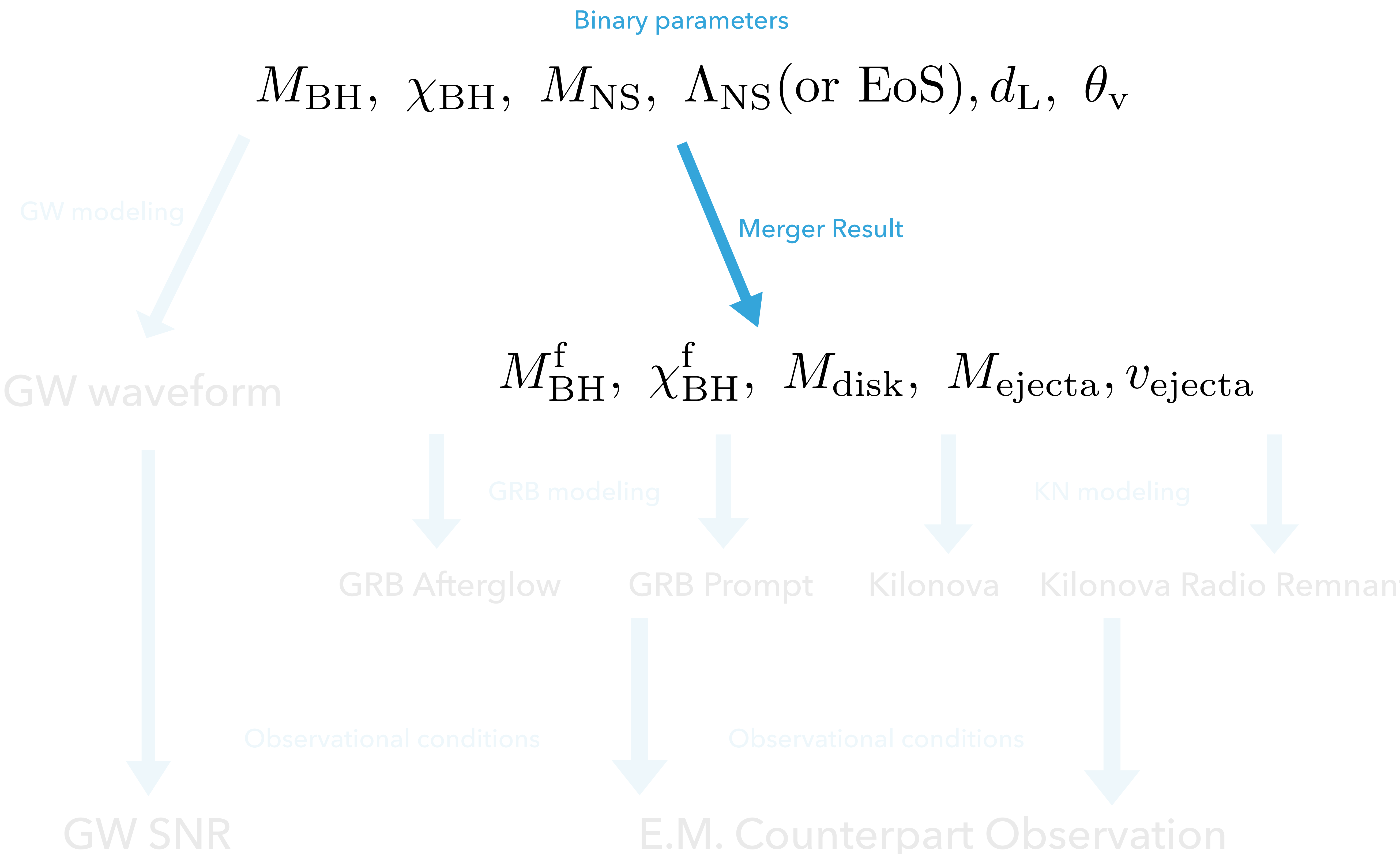
$$\mathrm{SNR}^{\rm i} = \sqrt{\int \frac{4\nu|\tilde{h}^{\rm i}_{\rm obs}|^2}{\mathrm{PSD}^{\rm i}} d\nu}$$

$$\mathrm{SNR}^{\rm Network} = \sqrt{\sum_{\rm i} (\mathrm{SNR}^{i})^2}$$

$$\text{Detection} : \mathrm{SNR}^{\rm Network} \geq 12$$

https://www.gssi.it/communication/news-events/item/1982-la-prima-volta-di-ligo-virgo-l-astronomia-gravitazionale-diventa-realta

GW SIGNAL AND E.M. COUNTERPARTS OF BHNS MERGERS



MERGER RESULT

$M_{\rm BH},\ M_{\rm NS},\ \chi_{\rm BH},\ \Lambda_{\rm NS}$

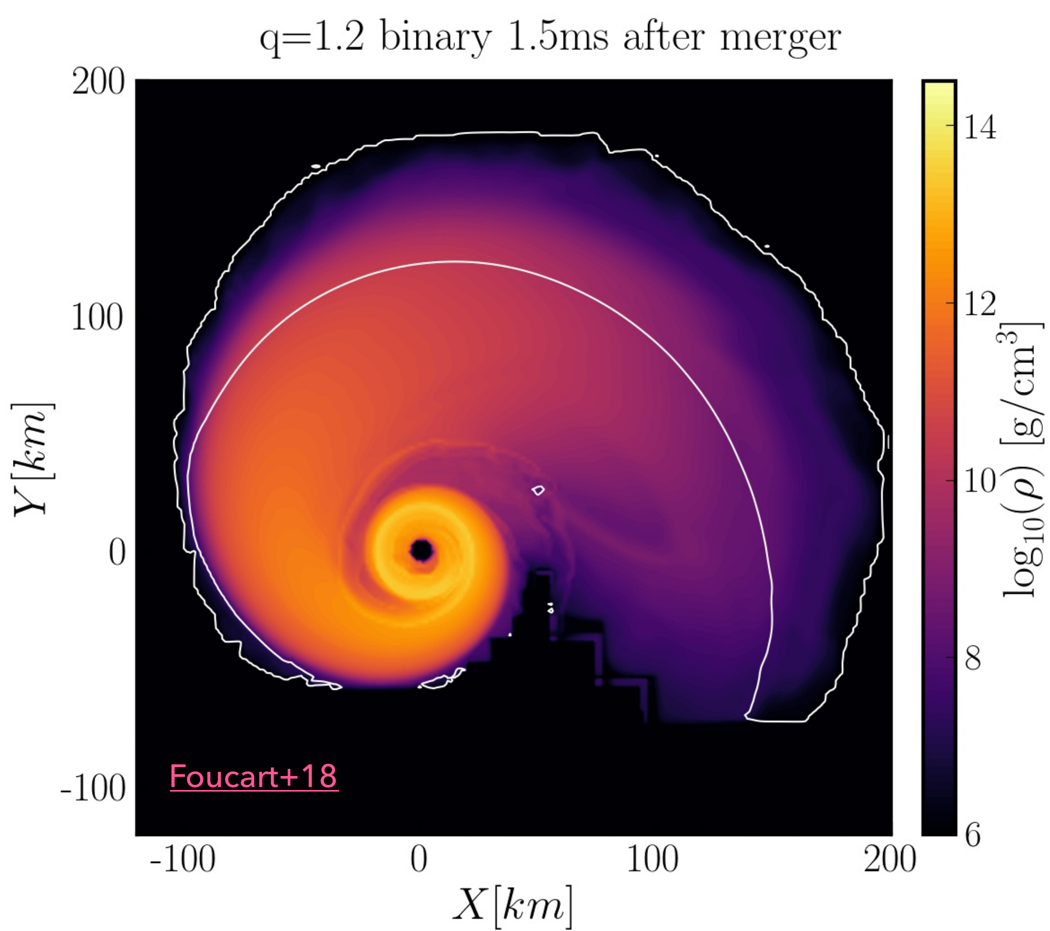
Kawaguchi+16 → $M_{\rm dyn}$

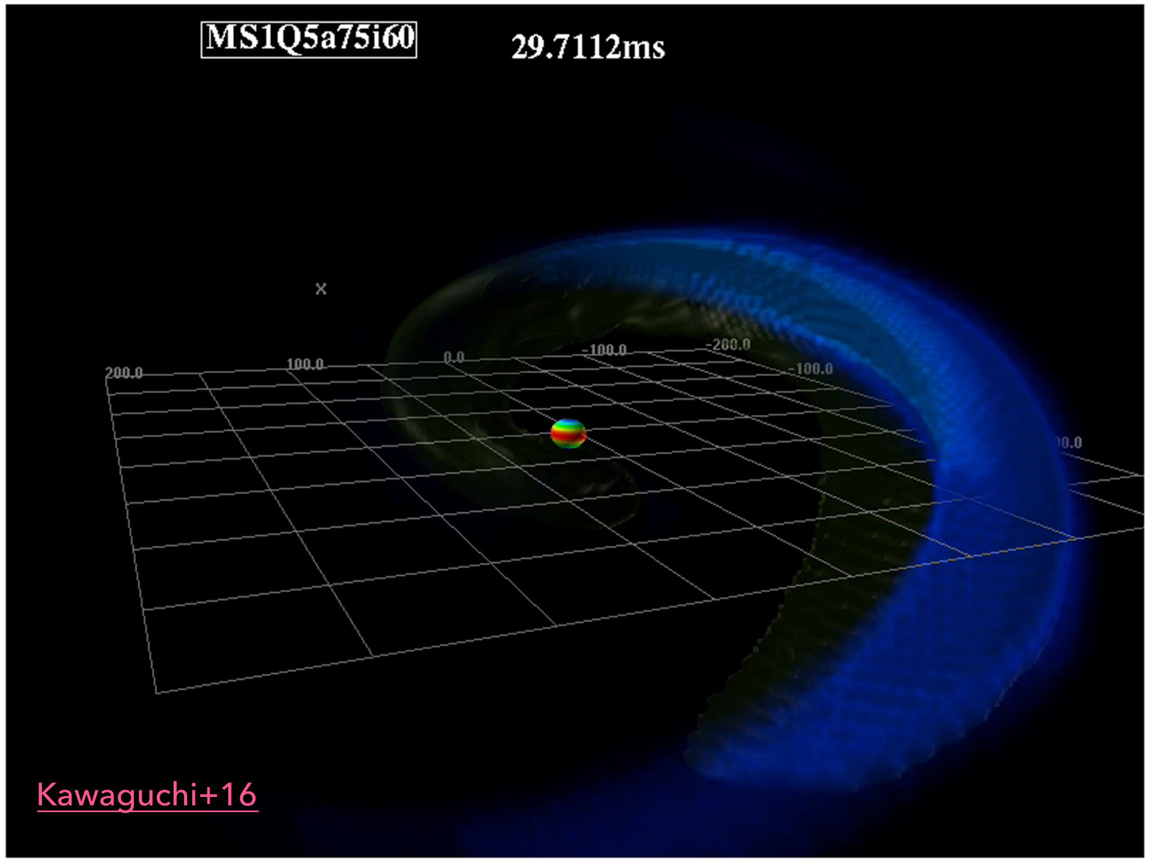
Foucart+18 → $M_{\rm out}$

Pannarale+13 → $M^{\rm f}_{\rm BH},\ \chi^{\rm f}_{\rm BH}$

$M_{\rm BH},\ M_{\rm NS}$ Kawaguchi+16 → $v_{\rm dyn}$

$$M_{\rm disk} = M_{\rm out} - M_{\rm dyn}$$





GW SIGNAL AND E.M. COUNTERPARTS OF BHNS MERGERS

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Kilonova

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Observational conditions

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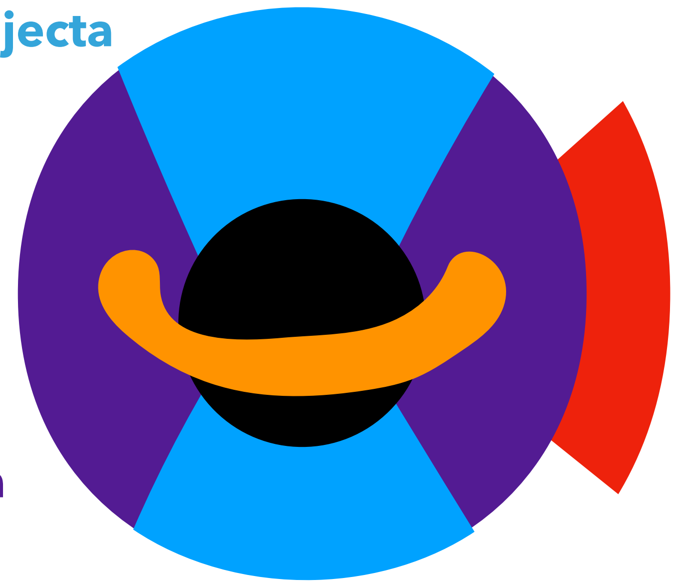
KILONOVA AND GRB AFTERGLOW LIGHT CURVES



$M_{\rm disk},\ d_{\rm L},\ \theta_{\rm v}$ → **Perego+17** → Wind ejecta KN, Secular ejecta KN

$\xi_{\rm w} = 0.01,\ v_{\rm w} = 0.1\ c,\ k_{\rm w} = 1\ {\rm cm}^2/{\rm g},\ \theta < \pi/3\ {\rm rad}$

$\xi_{\rm s} = 0.2,\ v_{\rm s} = 0.1\ c,\ k_{\rm s} = 5\ {\rm cm}^2/{\rm g},\ \ \propto \sin^2\theta$

$M_{\rm dyn},\ d_{\rm L},\ \theta_{\rm v}$ → **Barbieri+19** → Dynamical ejecta KN

$k_{\rm d} = 15\ {\rm cm}^2/{\rm g},\ \phi = \pi\ {\rm rad}, \theta \gtrsim 1.3\ {\rm rad}$

Kawaguchi+16, Fernandez+17

$M_{\rm disk},\ \chi^{\rm f}_{\rm BH}$ → **Barbieri+19, Salafia+19** → GRB Afterglow

$\epsilon_{\rm e} = 0.1,\ \epsilon_{\rm B} = 0.01,\ p = 2.3,\ \theta_{\rm c} = 0.1\ {\rm rad},\ n = 10^{-3}{\rm cm}^{-3}$

3

TAKE-HOME MESSAGES

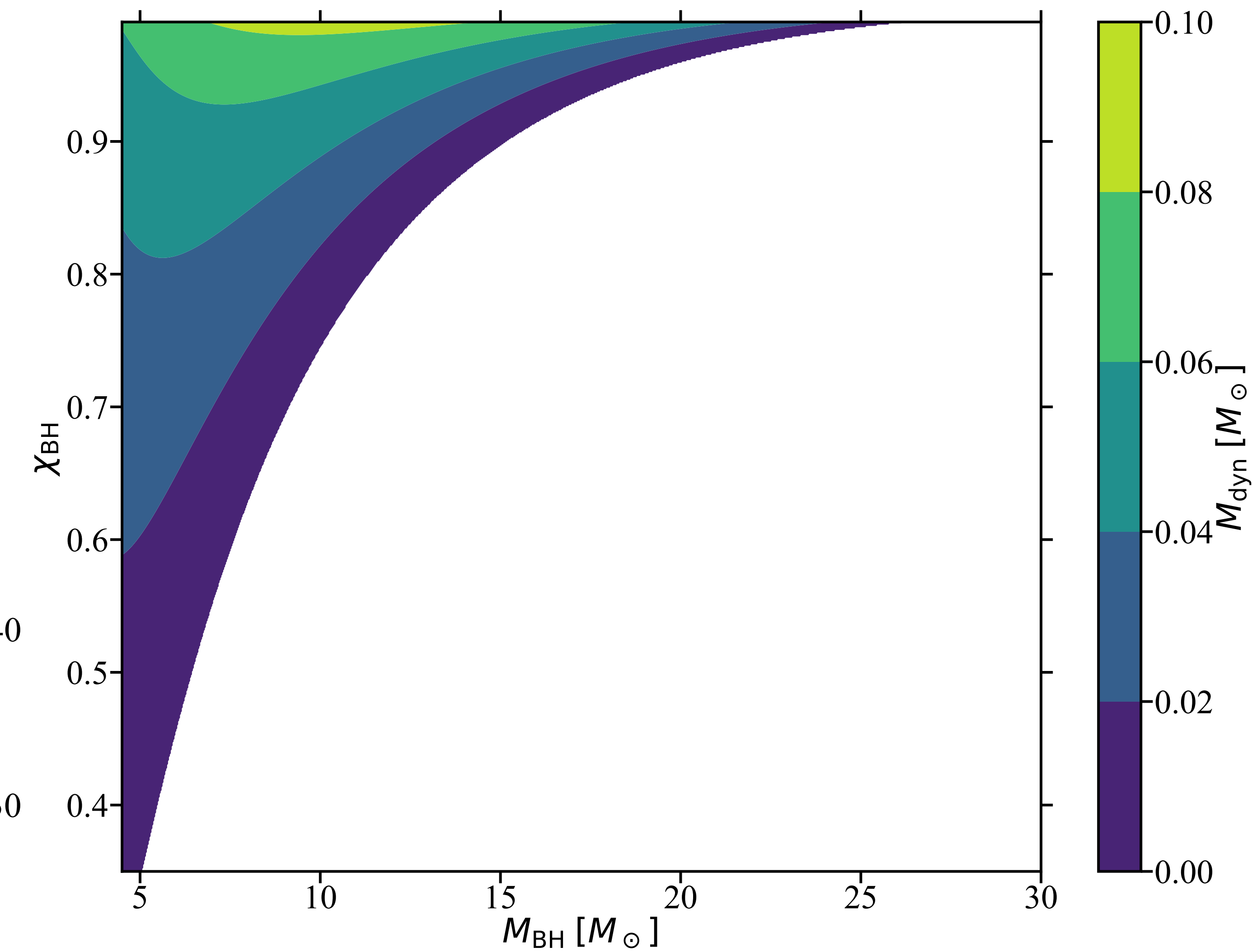
3

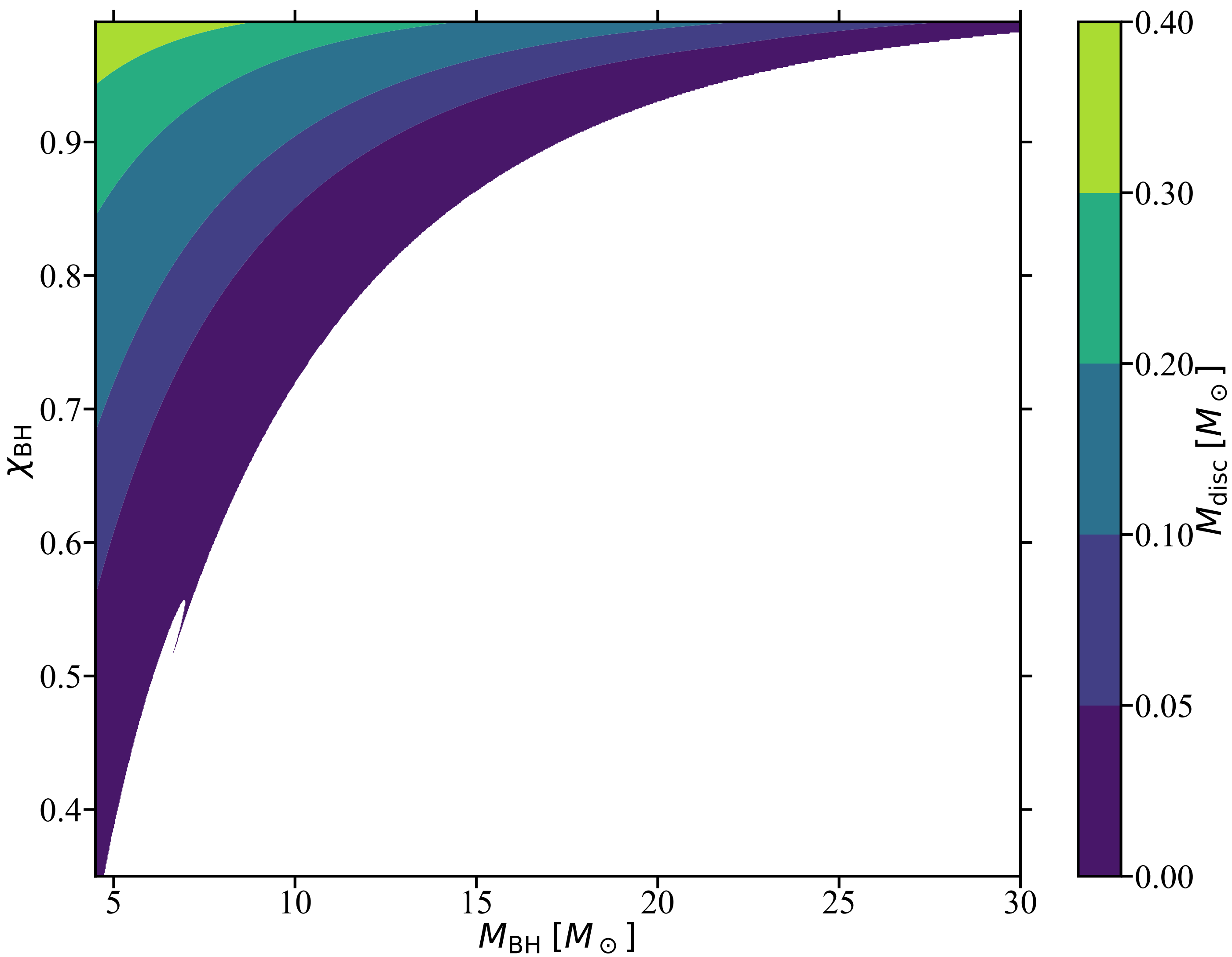
TAKE-HOME MESSAGES

1) EM counterparts dependence on the BH properties

EM COUNTERPARTS DEPENDENCE ON THE BH PROPERTIES

Barbieri et al. 19 [1], Published on A&A, (DOI 10.1051/0004-6361/201935443) "Light curve models of BHNS mergers: steps towards a multi-messenger parameter estimation"





EM COUNTERPARTS DEPENDENCE ON THE BH PROPERTIES

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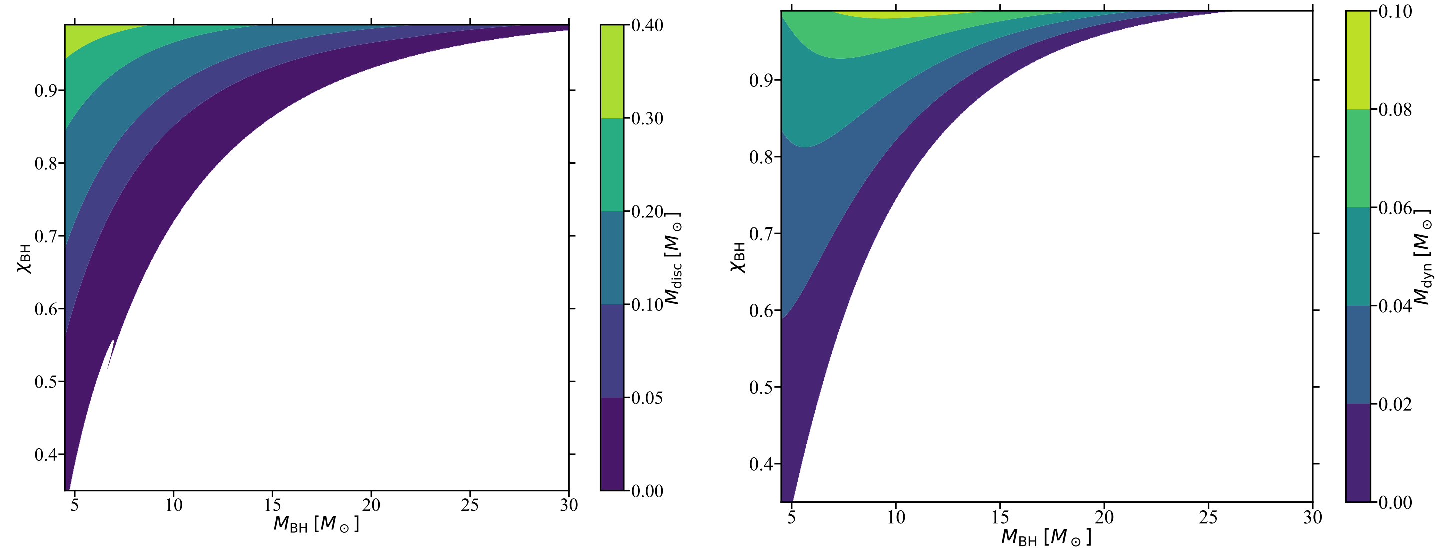

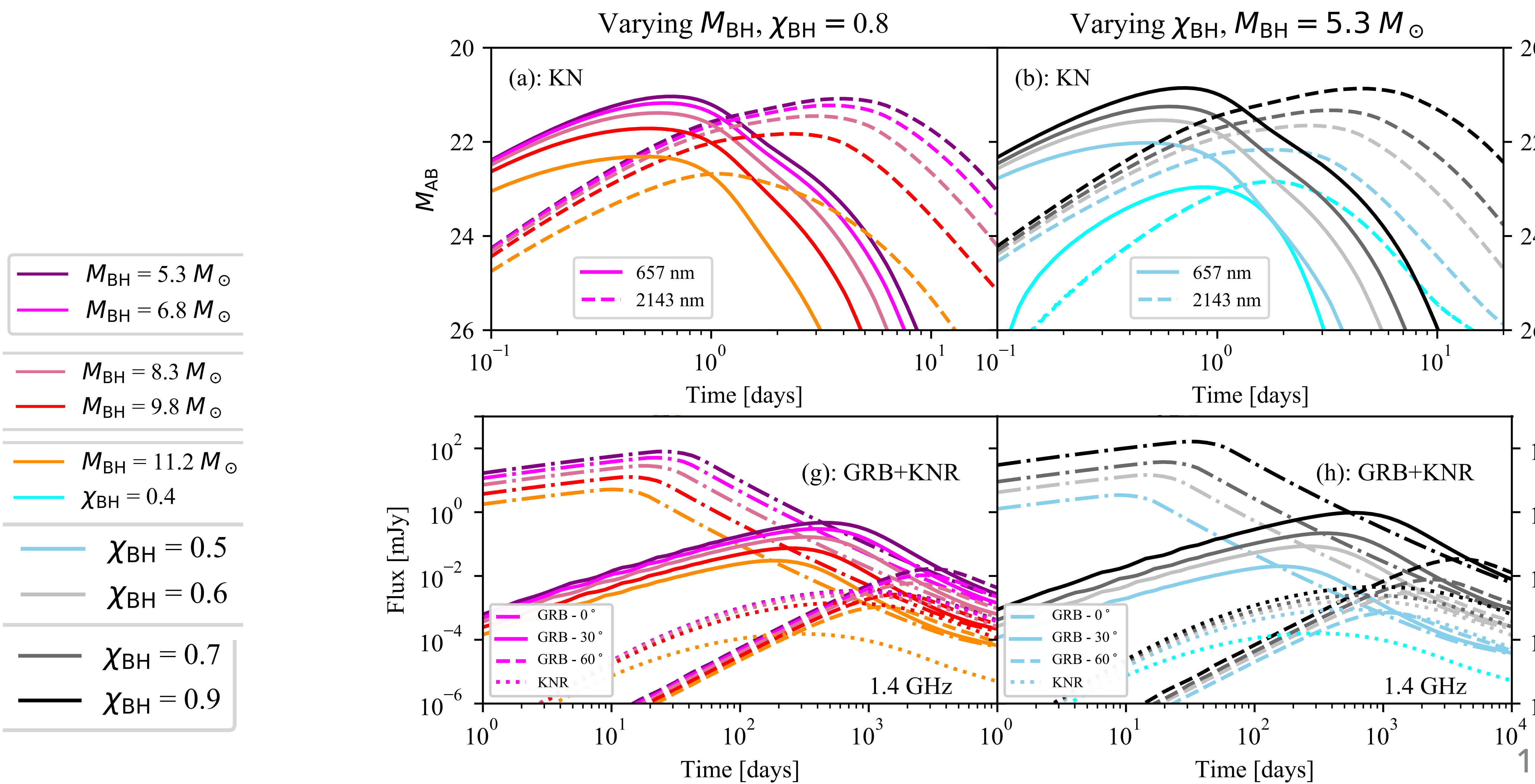

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TAKE-HOME MESSAGES

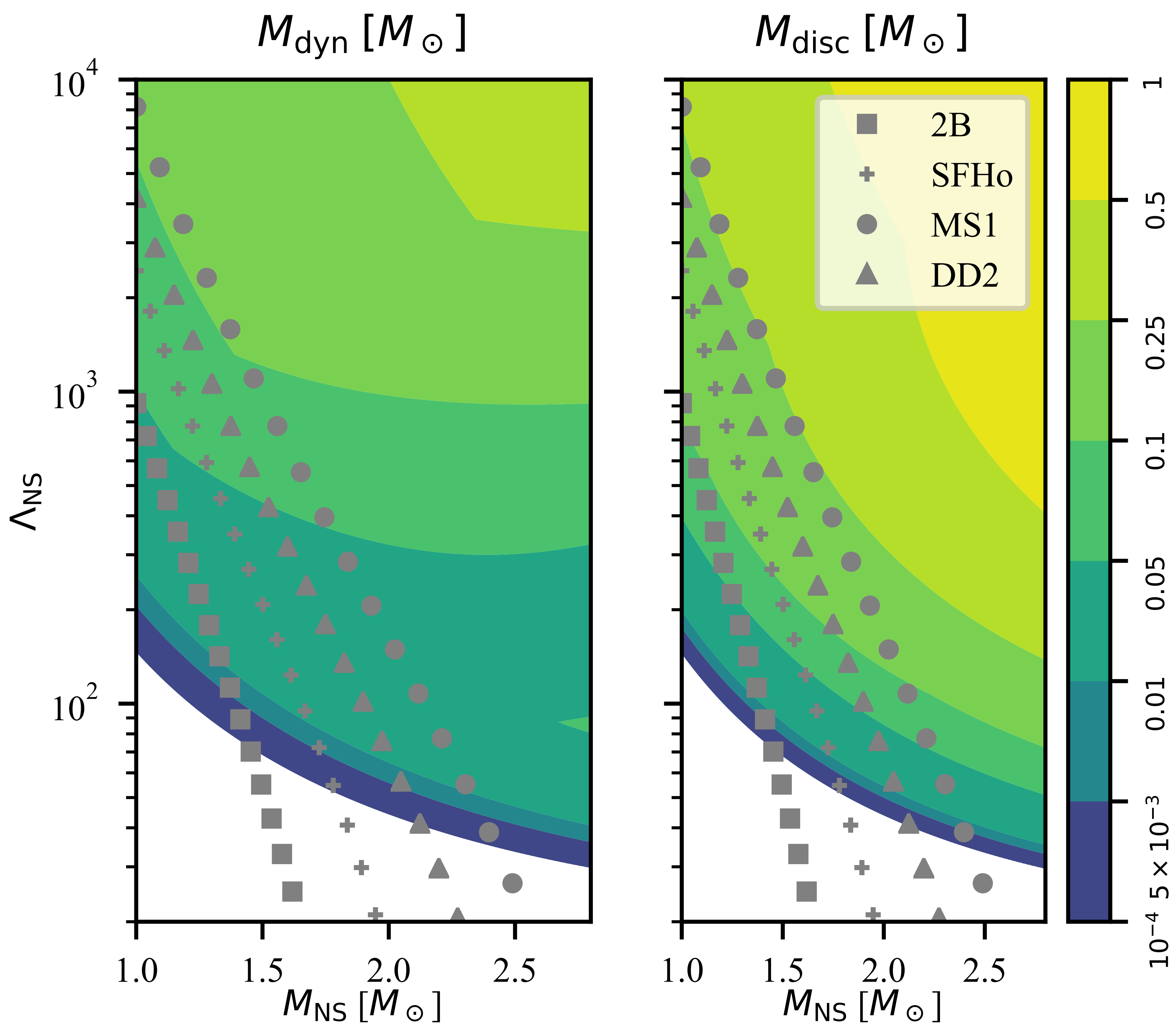
1) EM counterparts dependence on the BH properties

2) EM counterparts dependence on the NS properties

EM COUNTERPARTS DEPENDENCE ON THE NS PROPERTIES

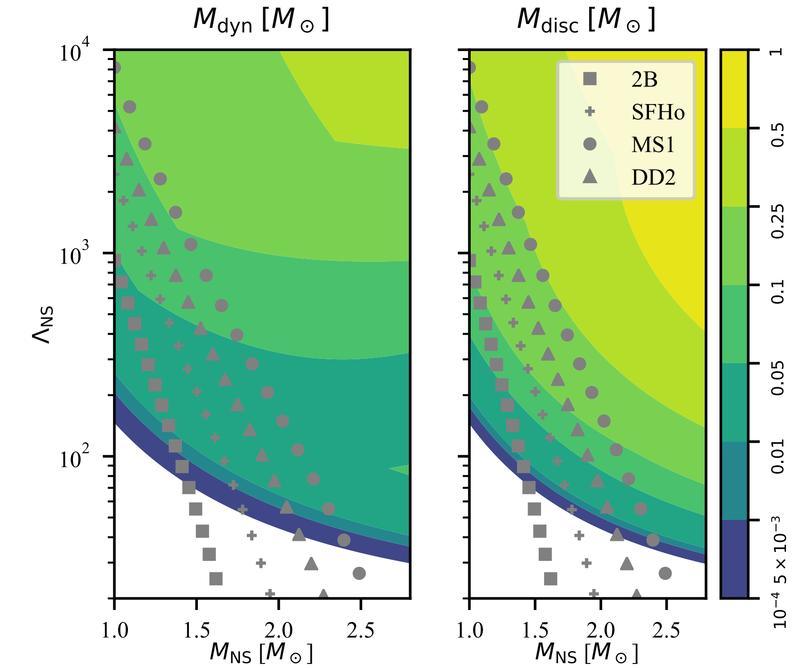
Barbieri et al. 19 [2], Submitted to EPJA, (arXiv:1908.08822)

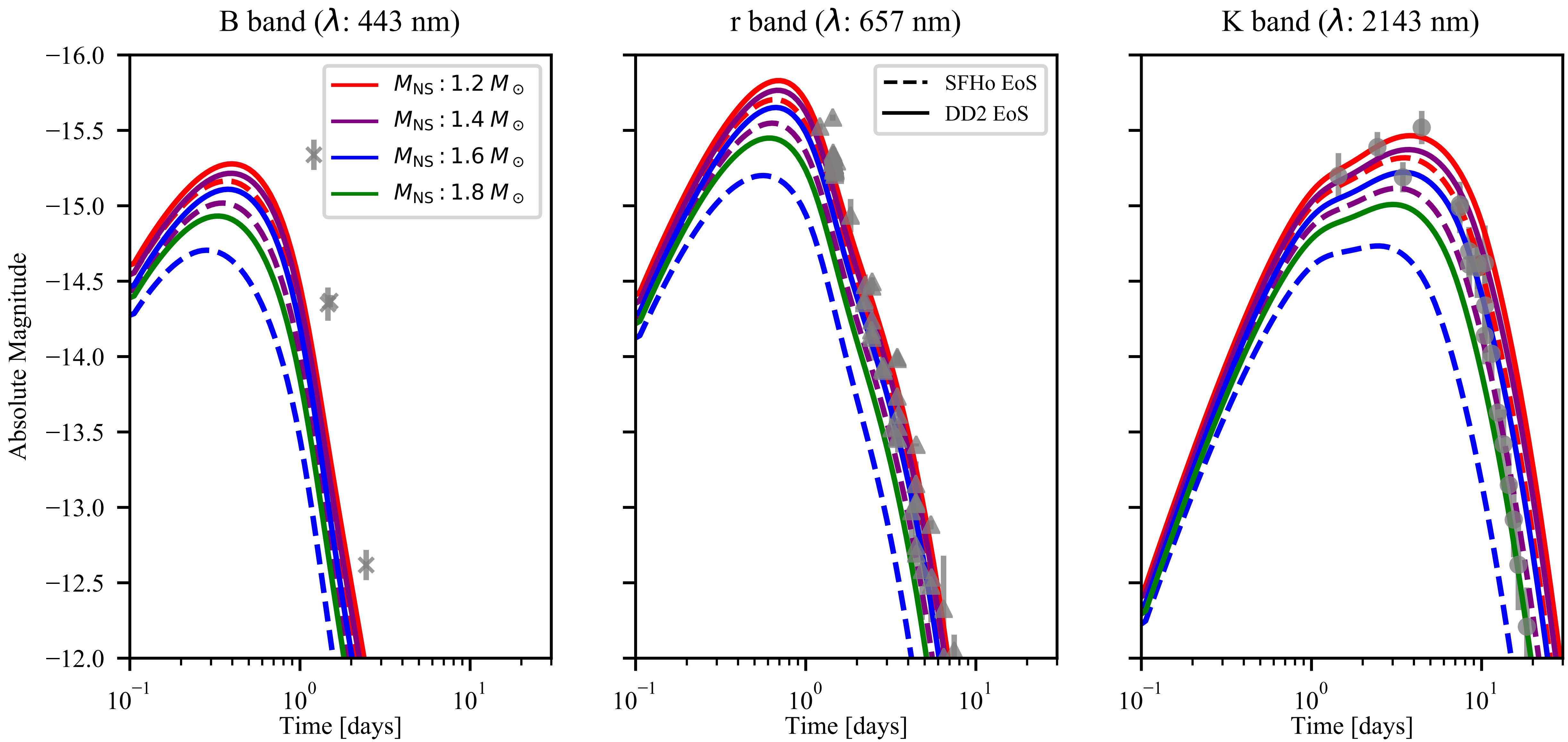
"EM counterparts of BH-NS mergers: dependence on the NS properties"



EM COUNTERPARTS DEPENDENCE ON THE NS PROPERTIES

Barbieri et al. 19 [2]





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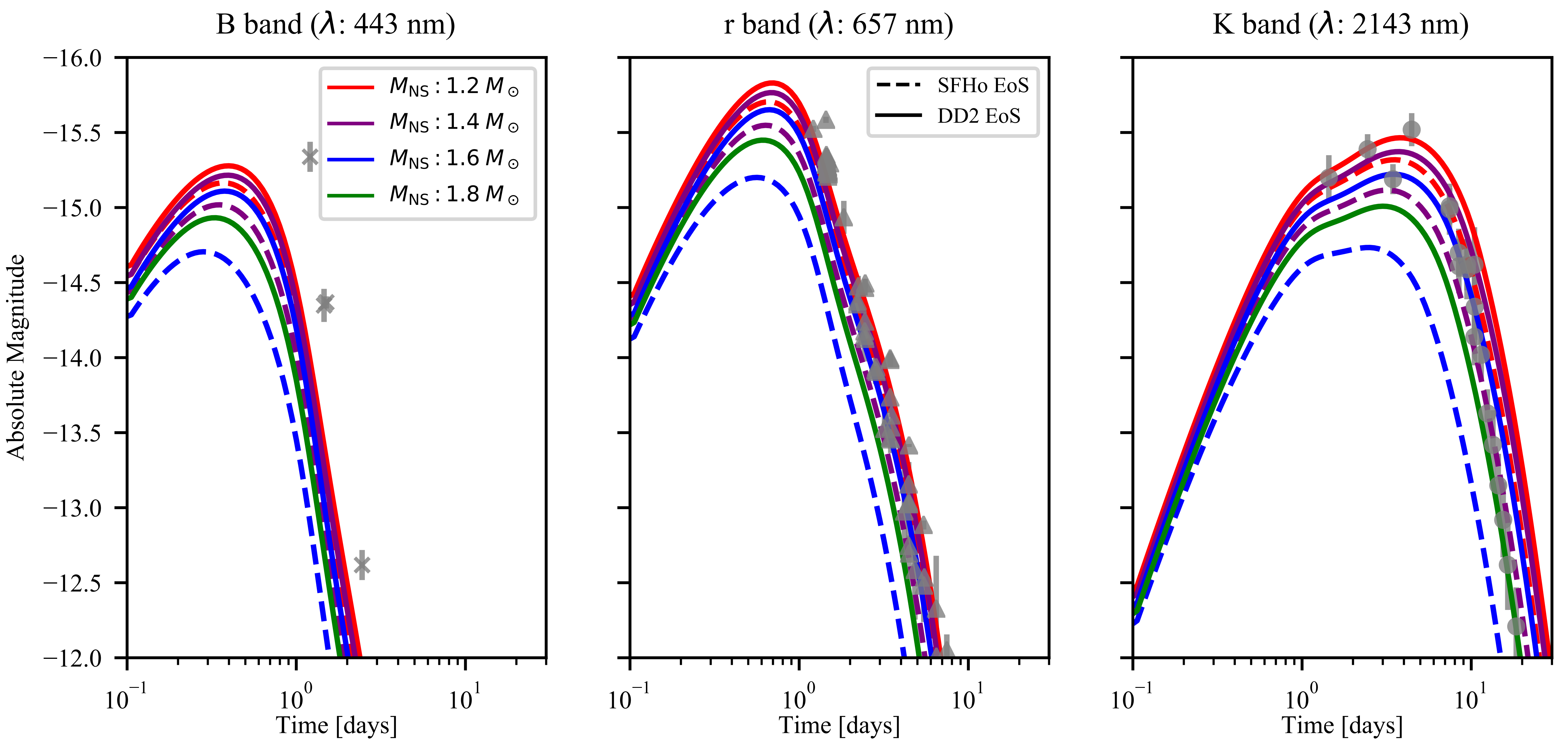
TAKE-HOME MESSAGES

1) EM counterparts dependence on the BH properties
2) EM counterparts dependence on the NS properties
3) BHNS can “mimick” NSNS kilonovae

BHNS CAN "MIMICK" NSNS KILONOVAE

Barbieri et al. 19 [2]



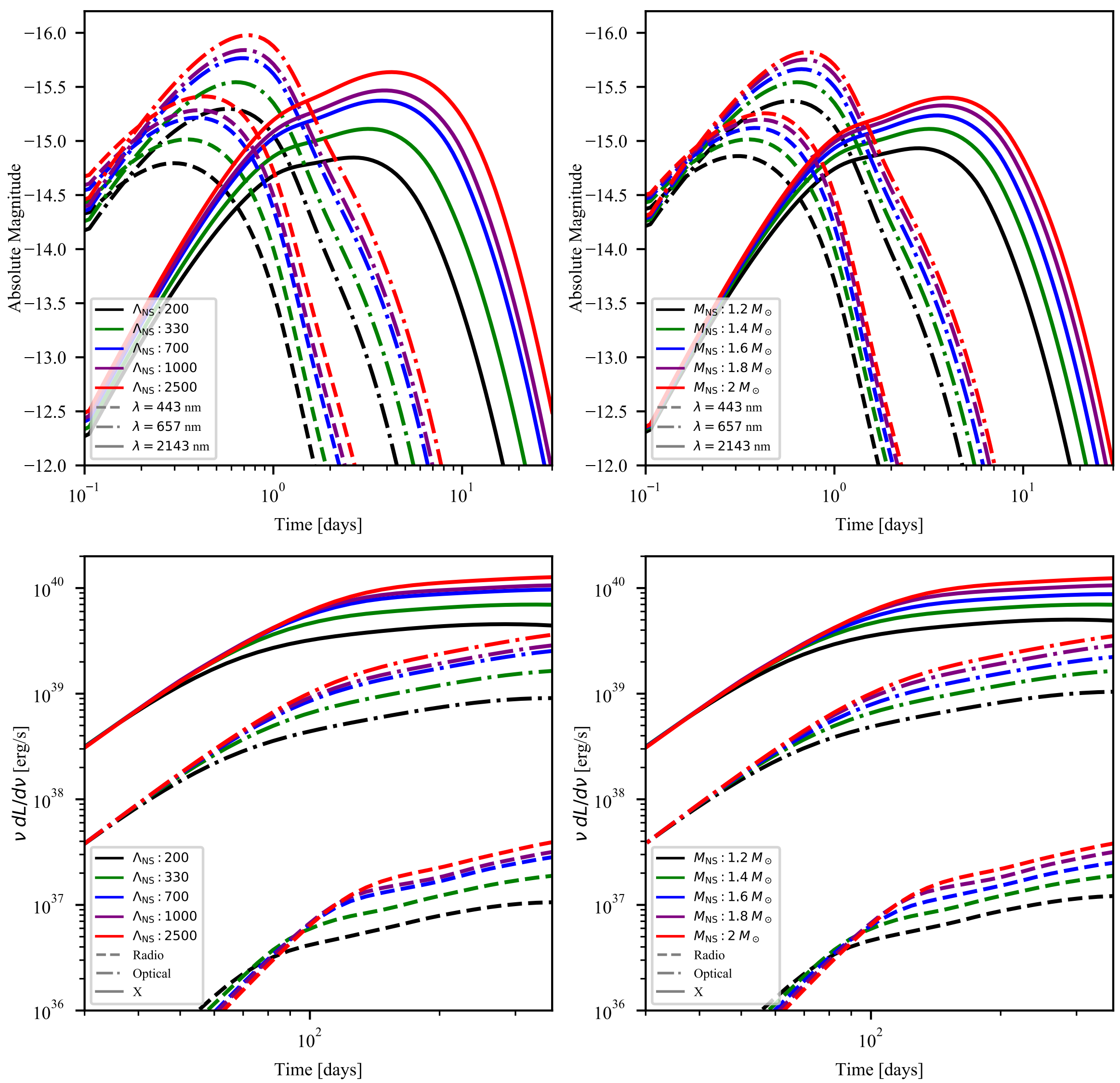
TAKE-HOME MESSAGES

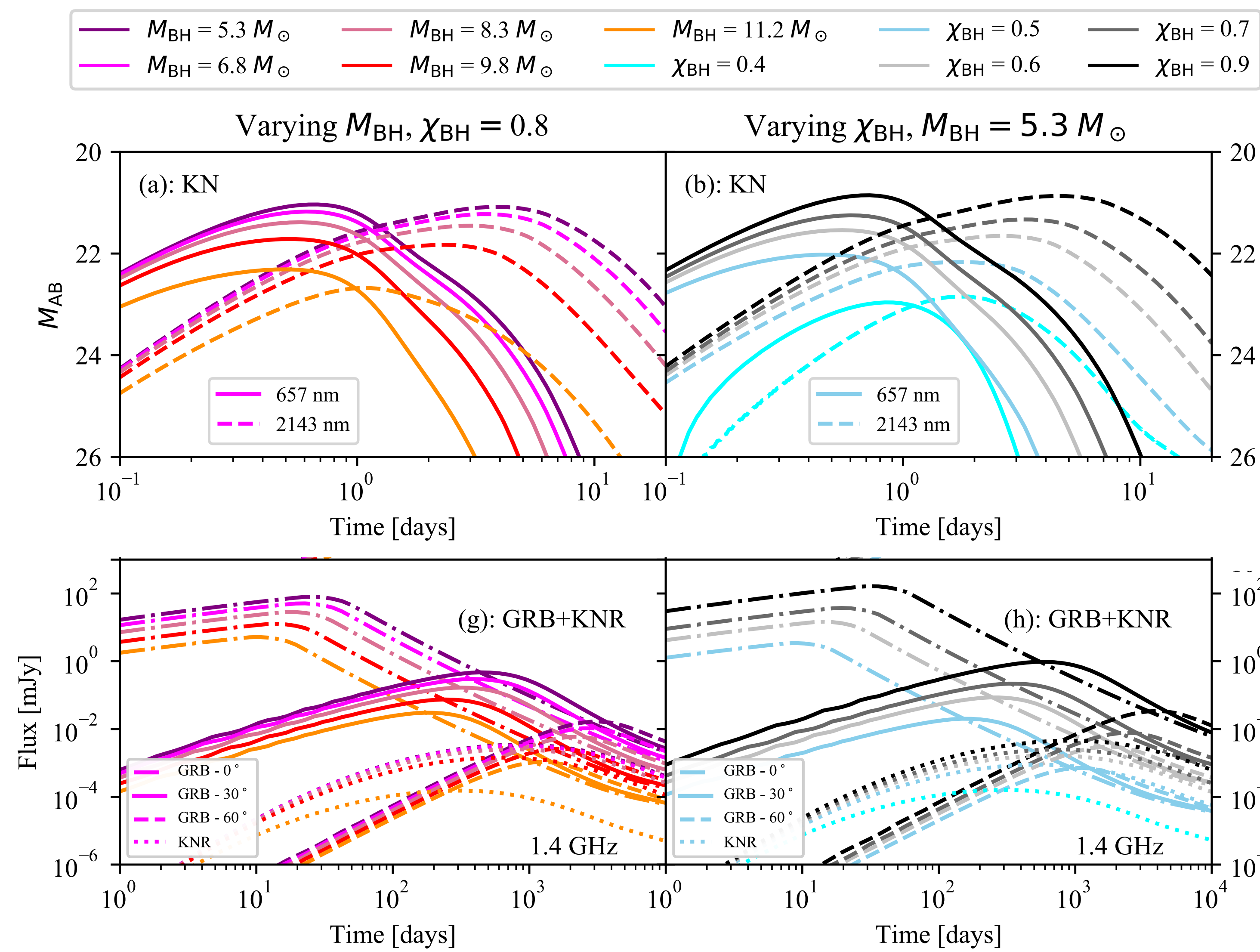
1) EM counterparts dependence on the BH properties
2) EM counterparts dependence on the NS properties
3) BHNS can “mimick” NSNS kilonovae
4) Light curves degeneracy

LIGHT CURVES DEGENERACY

Barbieri et al. 19 [1,2]

- Light curves display a large **degeneracy** introduced by different combinations of binary parameters. Through the EM observations alone it is not possible to constrain the intrinsic binary parameters.





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1) EM counterparts dependence on the BH properties

2) EM counterparts dependence on the NS properties

3) BHNS can “mimick” NSNS kilonovae

4) Light curves degeneracy

5) Power of multi-messenger astronomy

POWER OF MULTI-MESSENGER ASTRONOMY

GW signal detection

↓

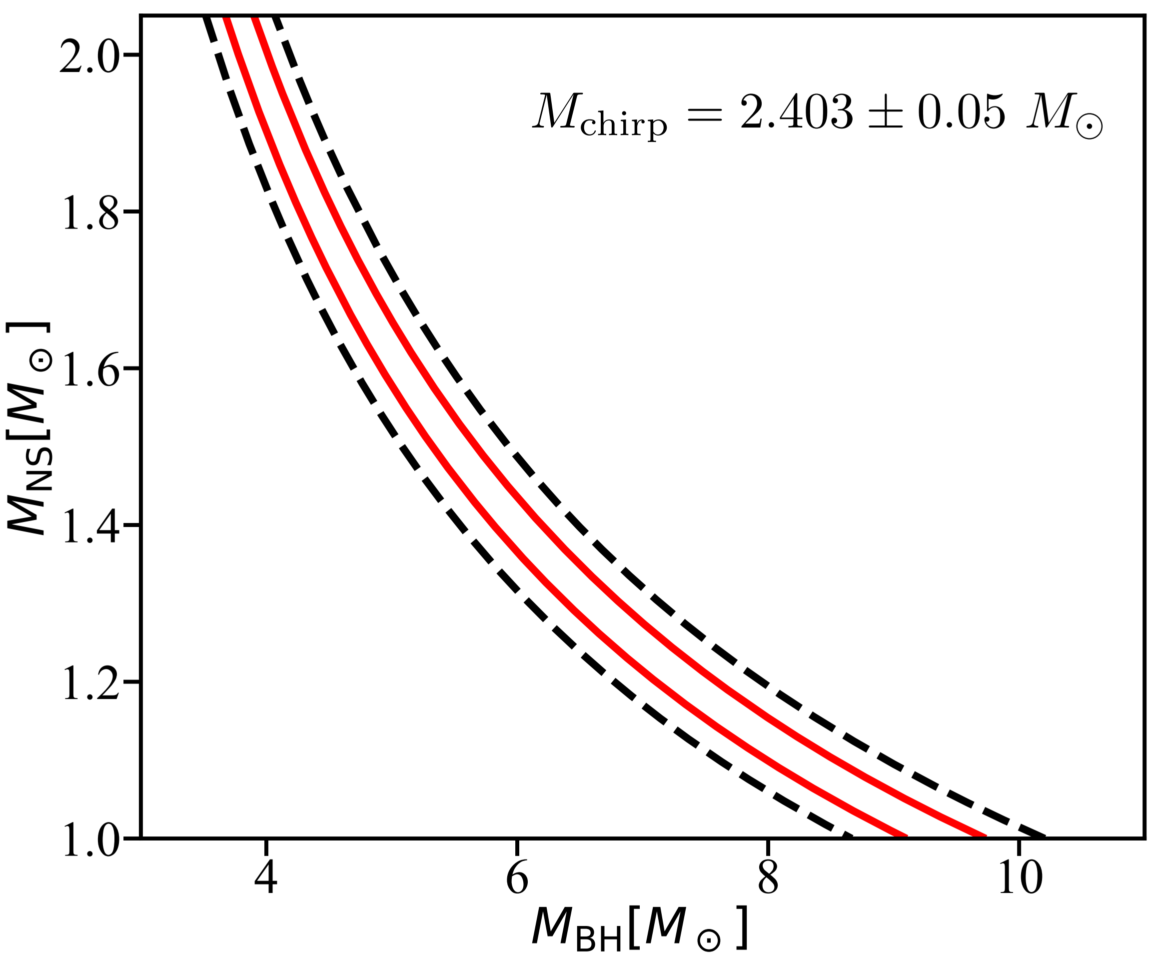
Estimated M_{chirp} -> M_{BH}, M_{NS} posteriors

↓

EM observation

↓

EM PE using M_{BH}, M_{NS} posteriors as ***priors***

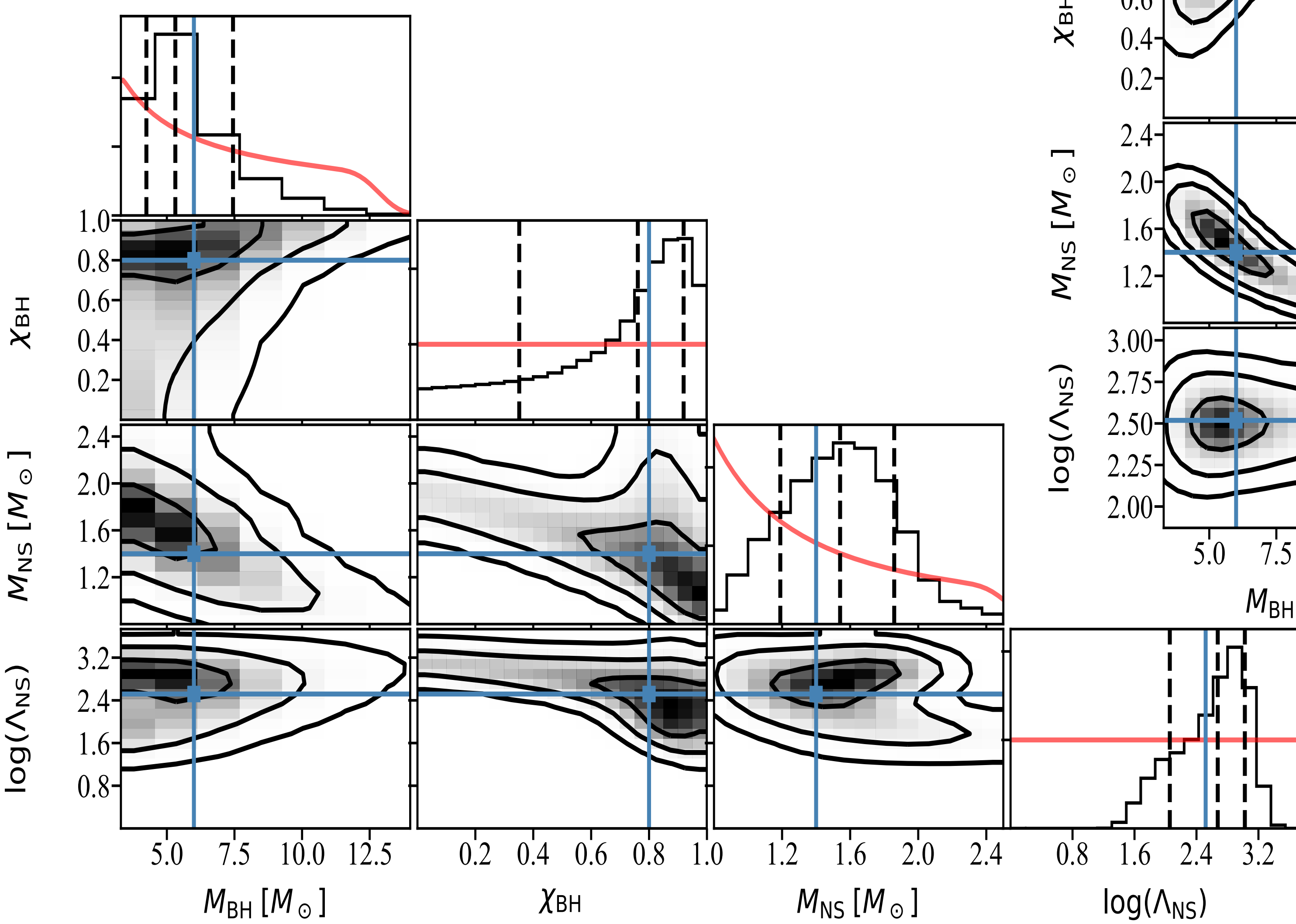


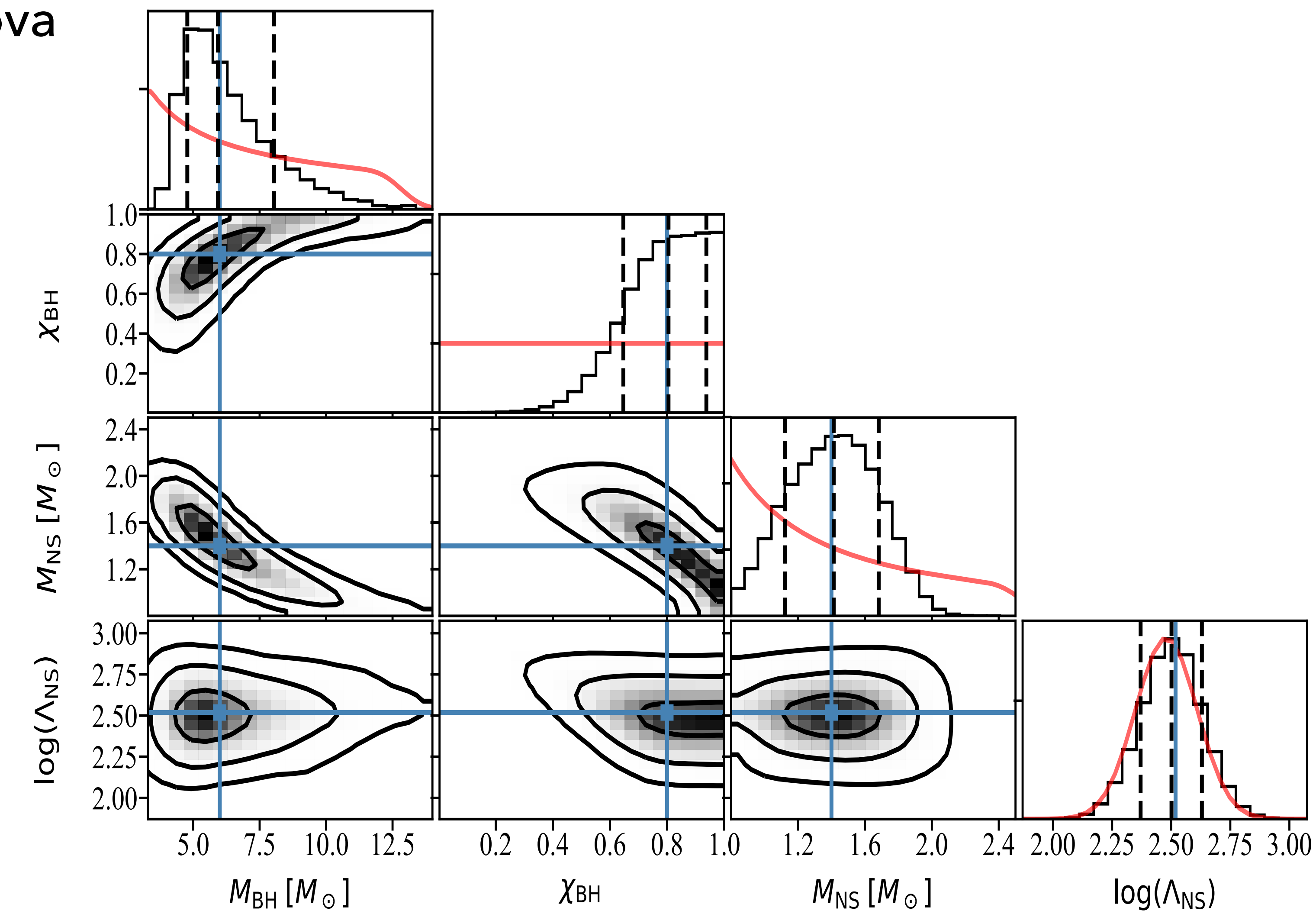
POWER OF MULTI-MESSENGER ASTRONOMY

Barbieri et al. 19 [1]

- How the info from an EM counterpart can complement that from the GW signal? Proof-of-concept **multi-messenger PE** -> observation and modeling of the kilonova can break the degeneracies, leading to <u>better constraints</u> on i.e. the BH spin.

	log-flat prior on Λ_{NS}	log-normal prior on Λ_{NS}
M_{BH} [$M_\odot$]	$5.6^{+1.9}_{-1.3}$	$6.1^{+2.0}_{-1.3}$
χ_{BH}	$0.7^{+0.2}_{-0.3}$	$0.8^{+0.1}_{-0.2}$
M_{NS} [$M_\odot$]	$1.5^{+0.4}_{-0.3}$	$1.4^{+0.3}_{-0.3}$
$\log(\Lambda_{NS})$	$2.7^{+0.3}_{-0.6}$	$2.5^{+0.2}_{-0.1}$





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1) EM counterparts dependence on the BH properties

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5) Power of multi-messenger astronomy

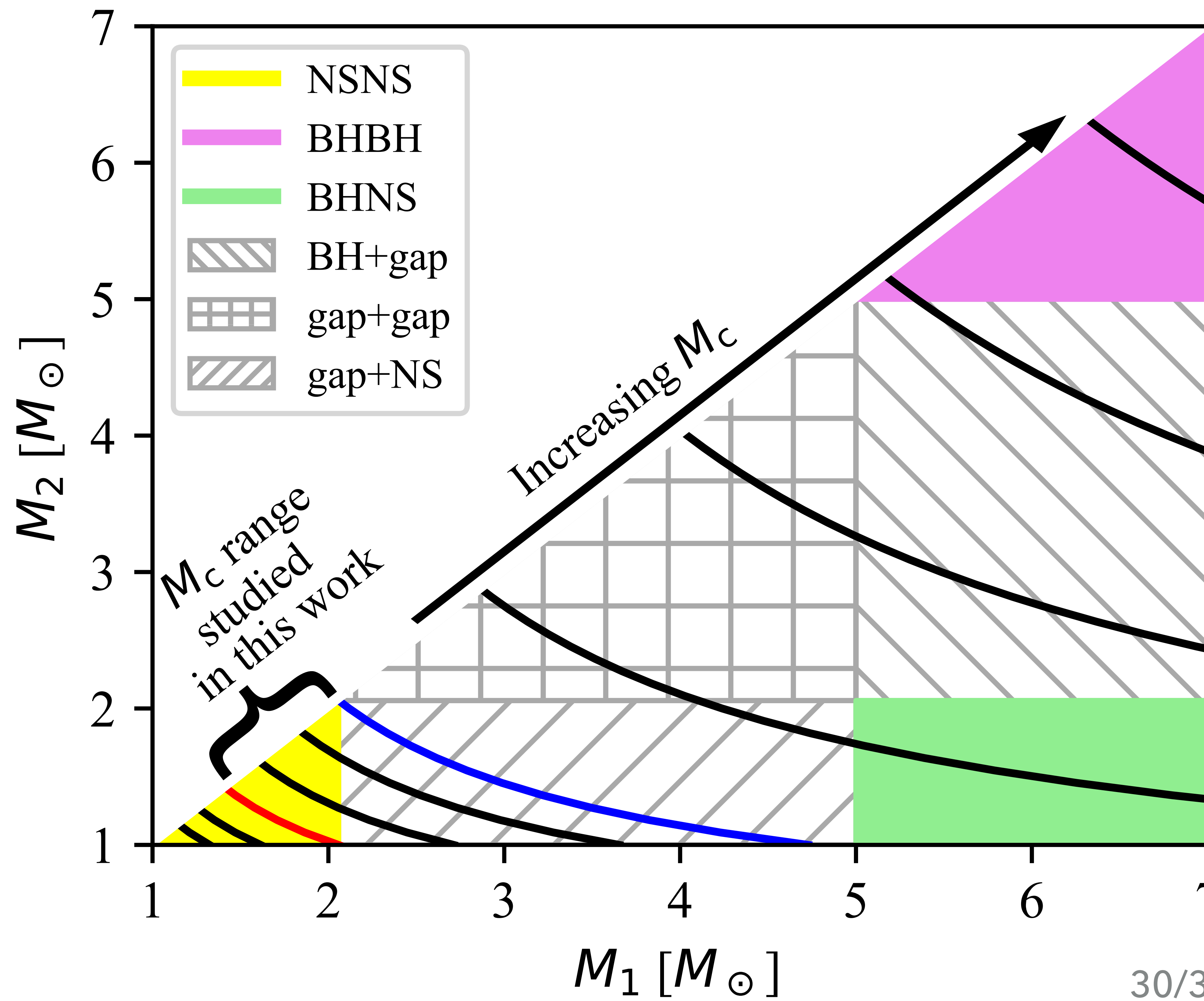
6) Differences between NSNS and BHNS with the same M_{chirp}

DIFFERENCES BETWEEN NSNS AND BHNS WITH THE SAME M_{CHIRP}

Barbieri et al. 19 [3], in preparation

- If BH and NS mass distributions are adjacent, there exist a range of "ambiguous" M_{chirp} values compatible with both NSNS and BHNS.
- How to distinguish?

"Ambiguous" M_{chirp} range for SFHo EoS: [1.233,1.792] $M_{\odot}$

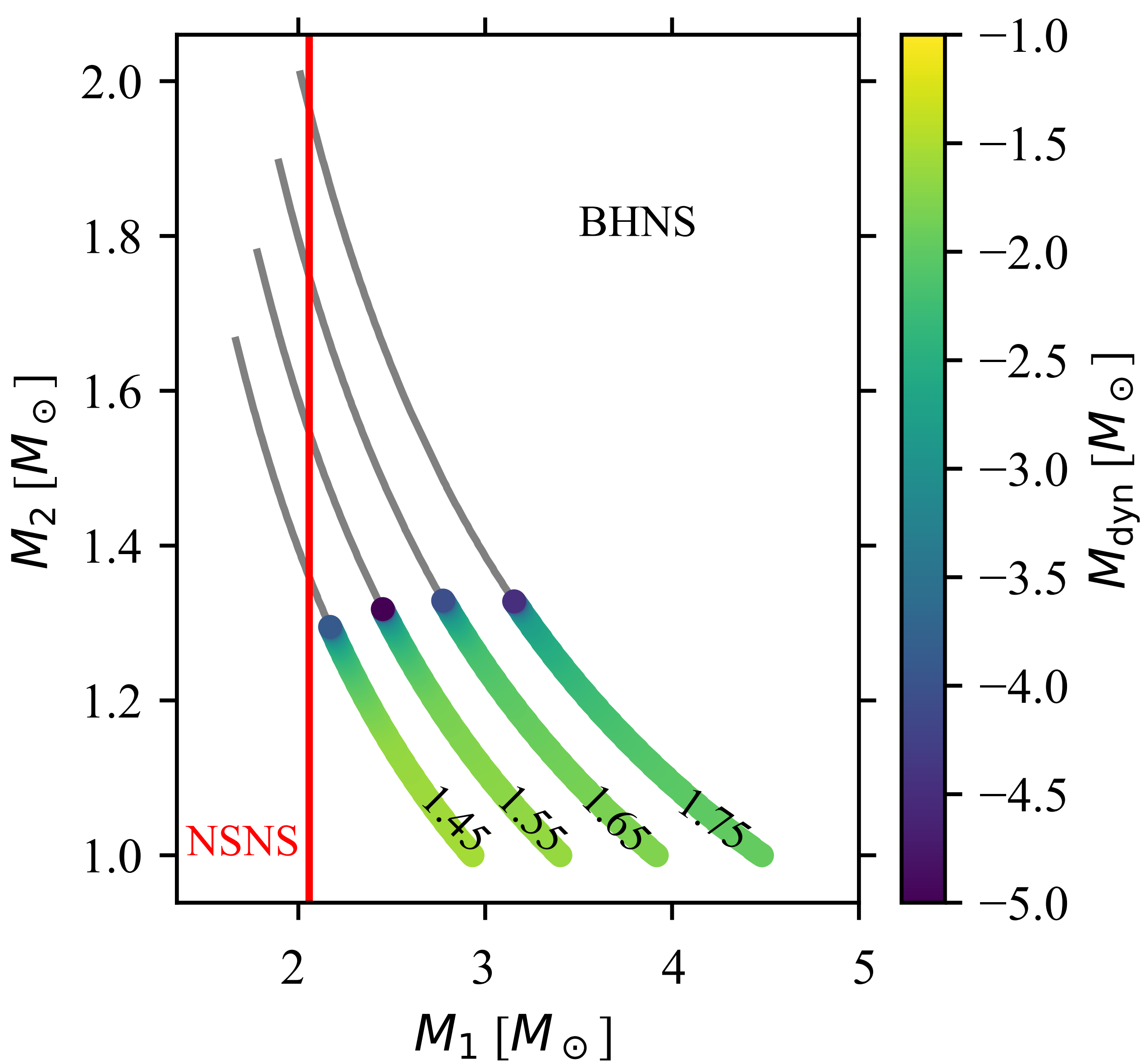


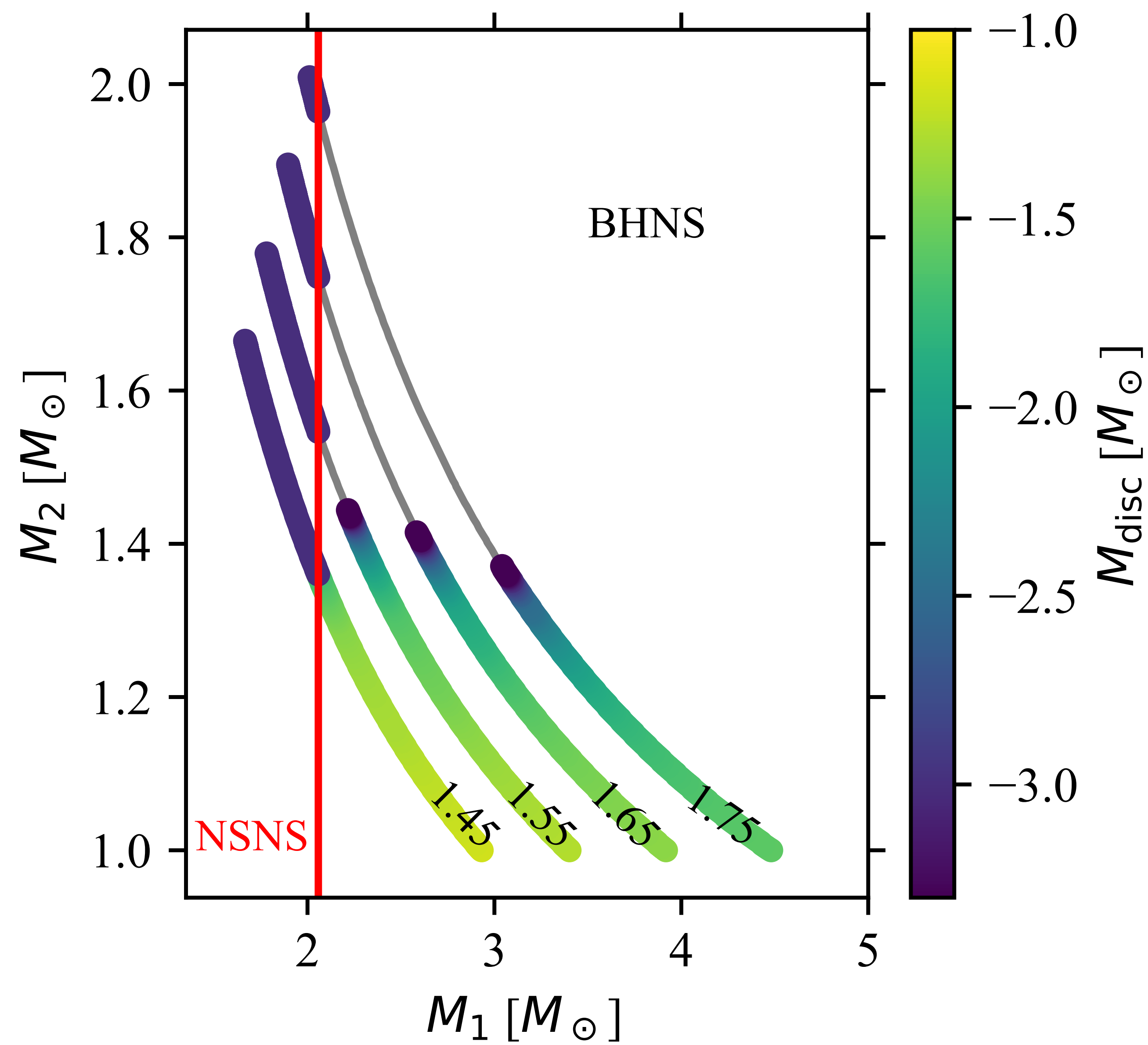
DIFFERENCES BETWEEN NSNS AND BHNS WITH THE SAME M_{CHIRP}

Barbieri et al. 19 [3]

- Differences of the ejecta
- Non-spinning BH!

NSNS ejecta properties:
Radice+18





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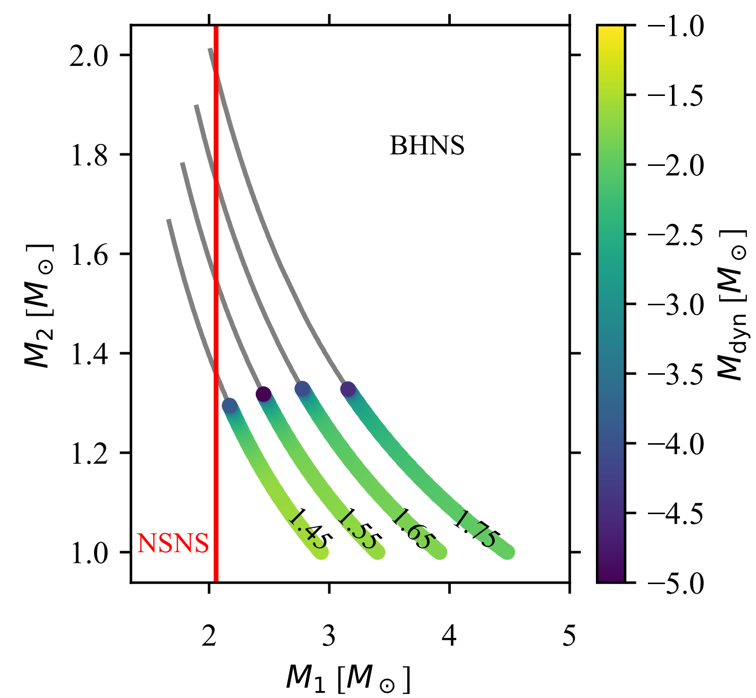
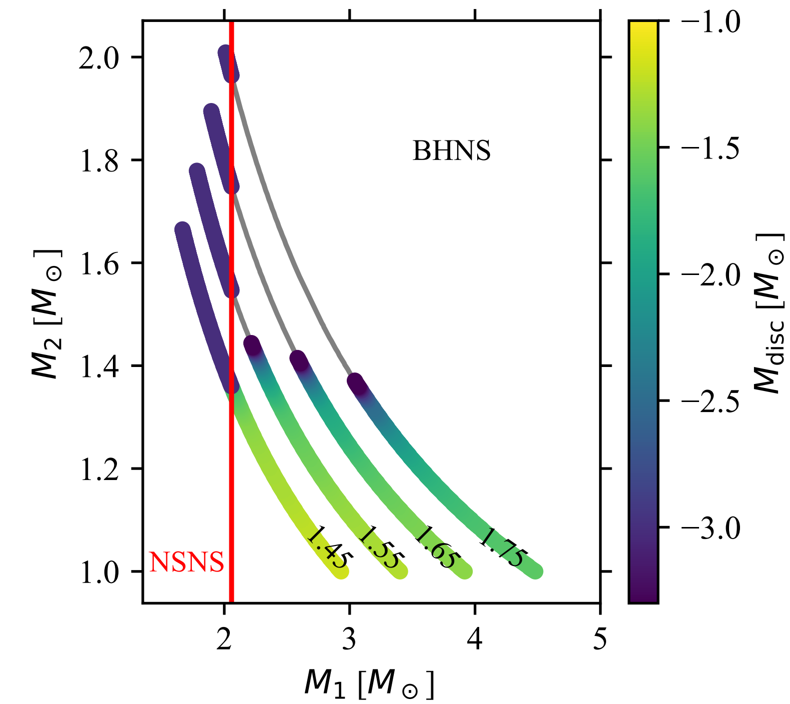
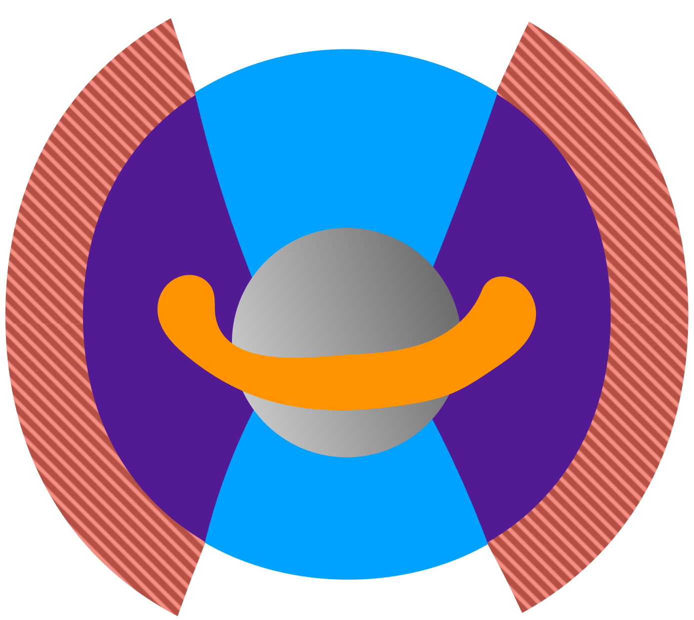


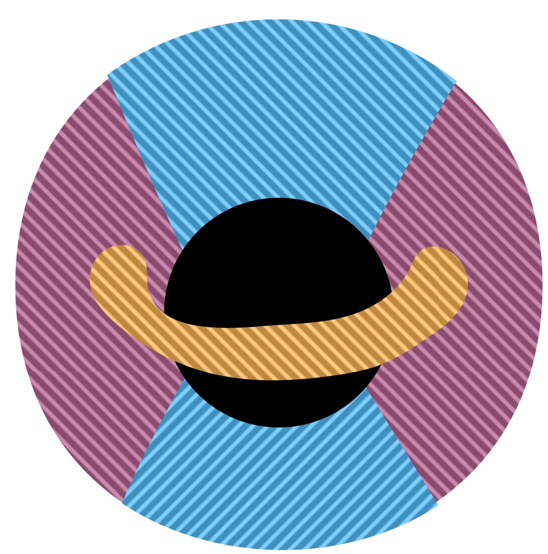


I) 1.46 $M_\odot$ NS - 1.27 $M_\odot$ NS (GW170817-like), M_{chirp} = 1.18 $M_\odot$



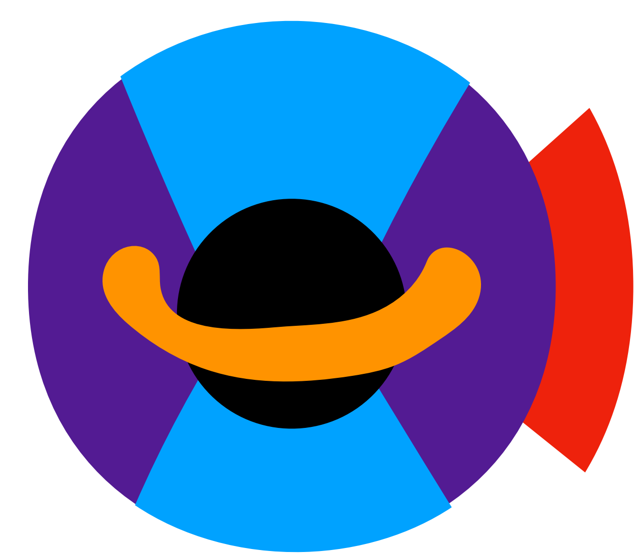
Dynamical Ejecta: ~10^{-3} $M_\odot$
Accretion Disc: ~3×10^{-2} $M_\odot$
Wind Ejecta: ~3×10^{-3} $M_\odot$
Secular Ejecta: ~10^{-2} $M_\odot$

II) 2 $M_\odot$ NS - 1.6 $M_\odot$ NS, M_{chirp} = 1.55 $M_\odot$



Dynamical Ejecta: Absent
Accretion Disc: ~10^{-3} $M_\odot$
Wind Ejecta: ~3×10^{-5} $M_\odot$
Secular Ejecta: ~10^{-4} $M_\odot$

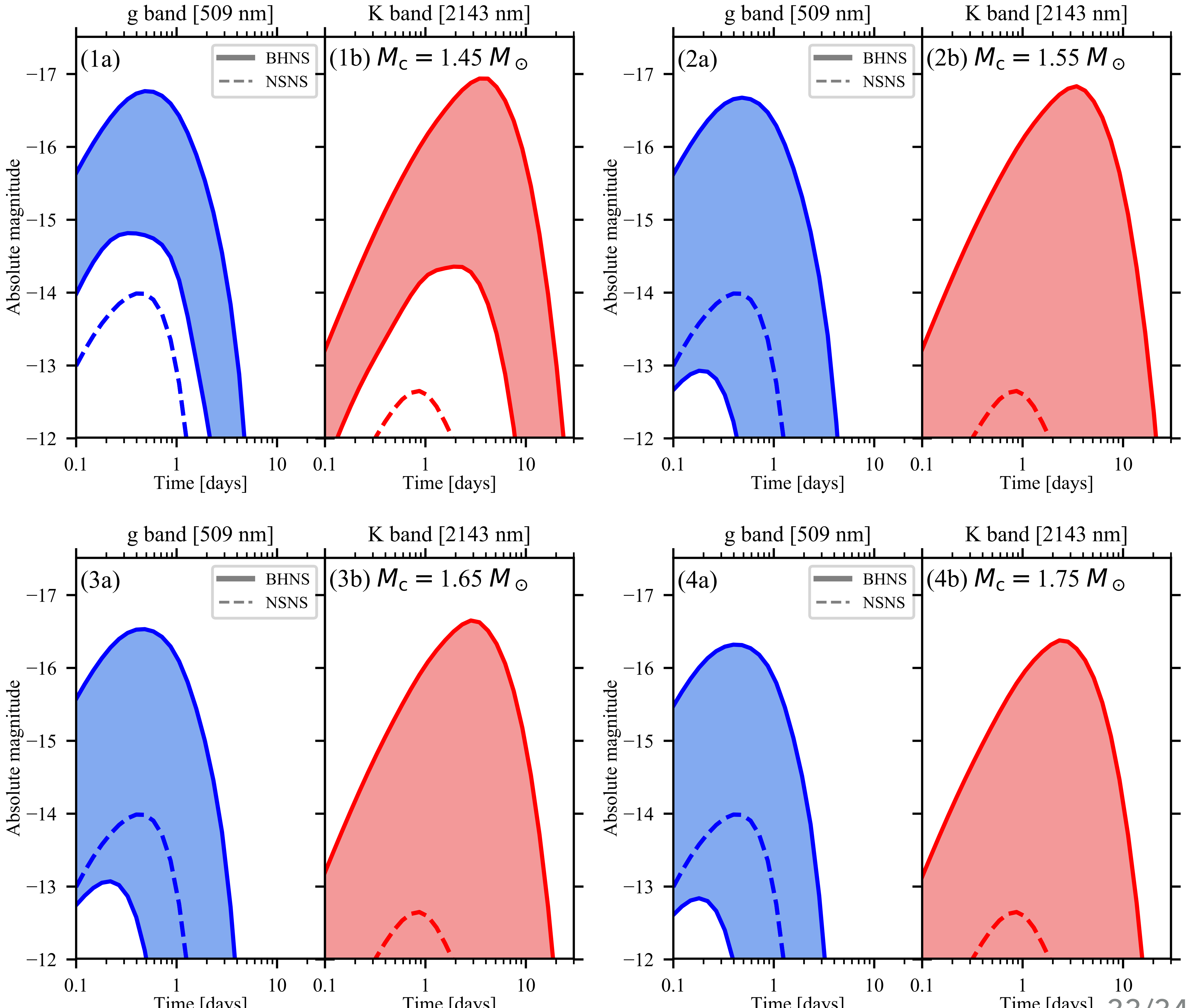
III) 3 $M_\odot$ BH - 1.1 $M_\odot$ NS, M_{chirp} = 1.55 $M_\odot$



Dynamical Ejecta: ~10^{-2} $M_\odot$
Accretion Disc: ~3×10^{-2} $M_\odot$
Wind Ejecta: ~3×10^{-4} $M_\odot$
Secular Ejecta: ~10^{-2} $M_\odot$

DIFFERENCES BETWEEN NSNS AND BHNS WITH THE SAME M_{CHIRP}

Barbieri et al. 19 [3]



- **Differences of the kilonova**
- Non-spinning BH!

THANK YOU

FOR THE ATTENTION!

Low spins ?

- LVC detections of ten BHBH mergers indicate that the effective spins cluster around ~ 0.

Large spins ?

- Belczynski+17, Arca Sedda+19: high natal spins for BHs below 20-30 $M_\odot$
- Galactic binaries : X-ray bright sources -> spins above 0.85

- Galactic binaries: transient -> large spread of spins from 0 to above 0.95

$$\chi_{\rm eff} = \frac{M_1\chi_1\cos\theta_1 + M_2\chi_2\cos\theta_2}{M_1 + M_2}$$

Isolated binaries or dynamically formed?