NS Merger Remnants and the nuclear EOS

[special focus on multi-messenger methods]

Ben Margalit,
Einstein Fellow at UC Berkeley

YITP, Kyoto

September 25th 2019

NS Merger Remnants and the nuclear EOS

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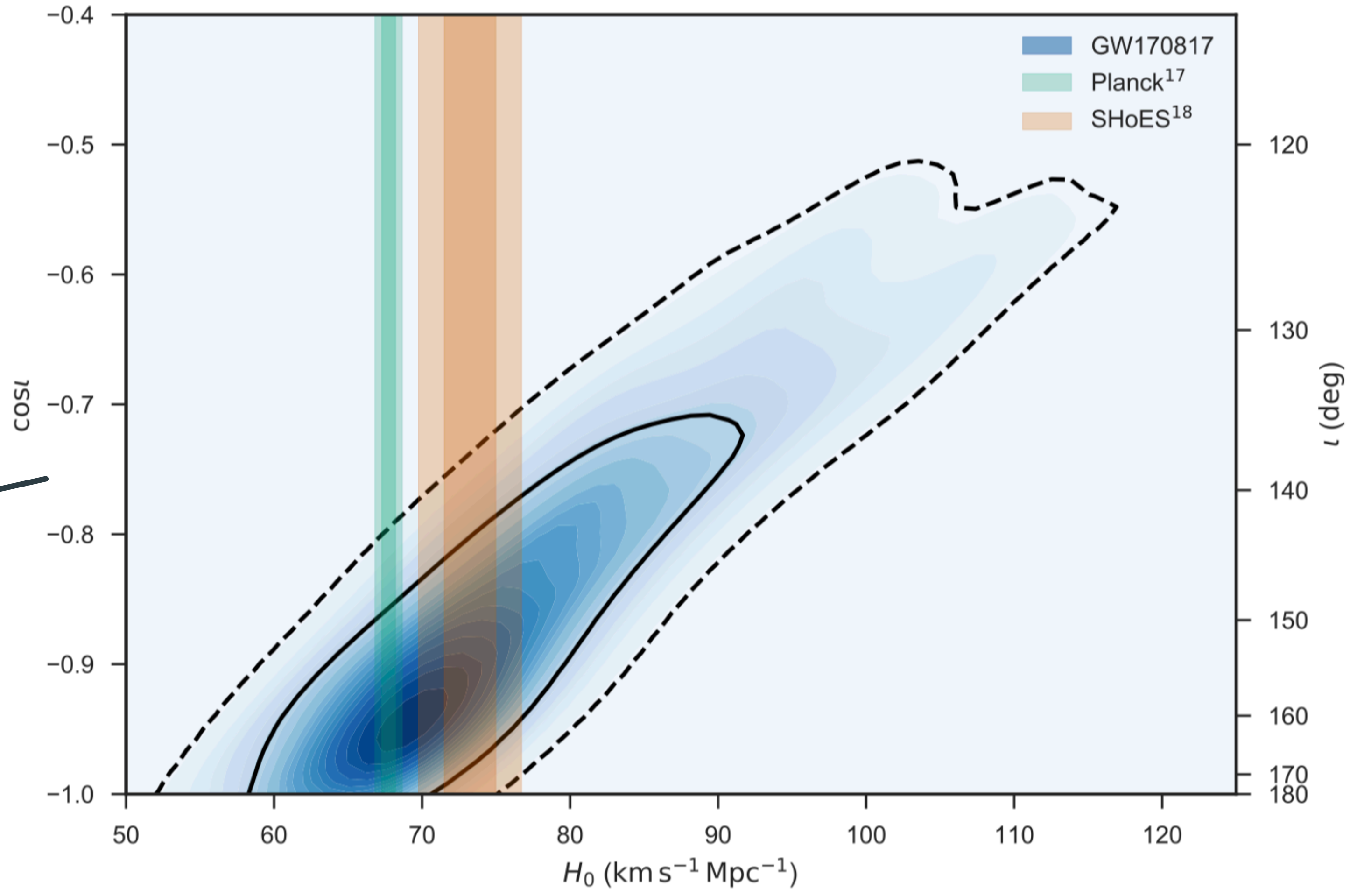
[and multi-messenger astrophysics]

Binary NS Merger Science:

- or Why study them?
  - GW sources for LIGO, Virgo, …
  - progenitors of GRBs, kilonovae
  - r-process nucleosynthesis
  - constraining NS EOS (LIGO17, …)
  - ‘standard sirens’ / H0 (Schutz86, LIGO17, Guidorzi+17)
  - tests of GR, e.g. speed of gravitational waves (LIGO17)
  - binary stellar evolution, NS formation channels

LIGO + (2017)



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[and multi-messenger astrophysics]

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multi-messenger

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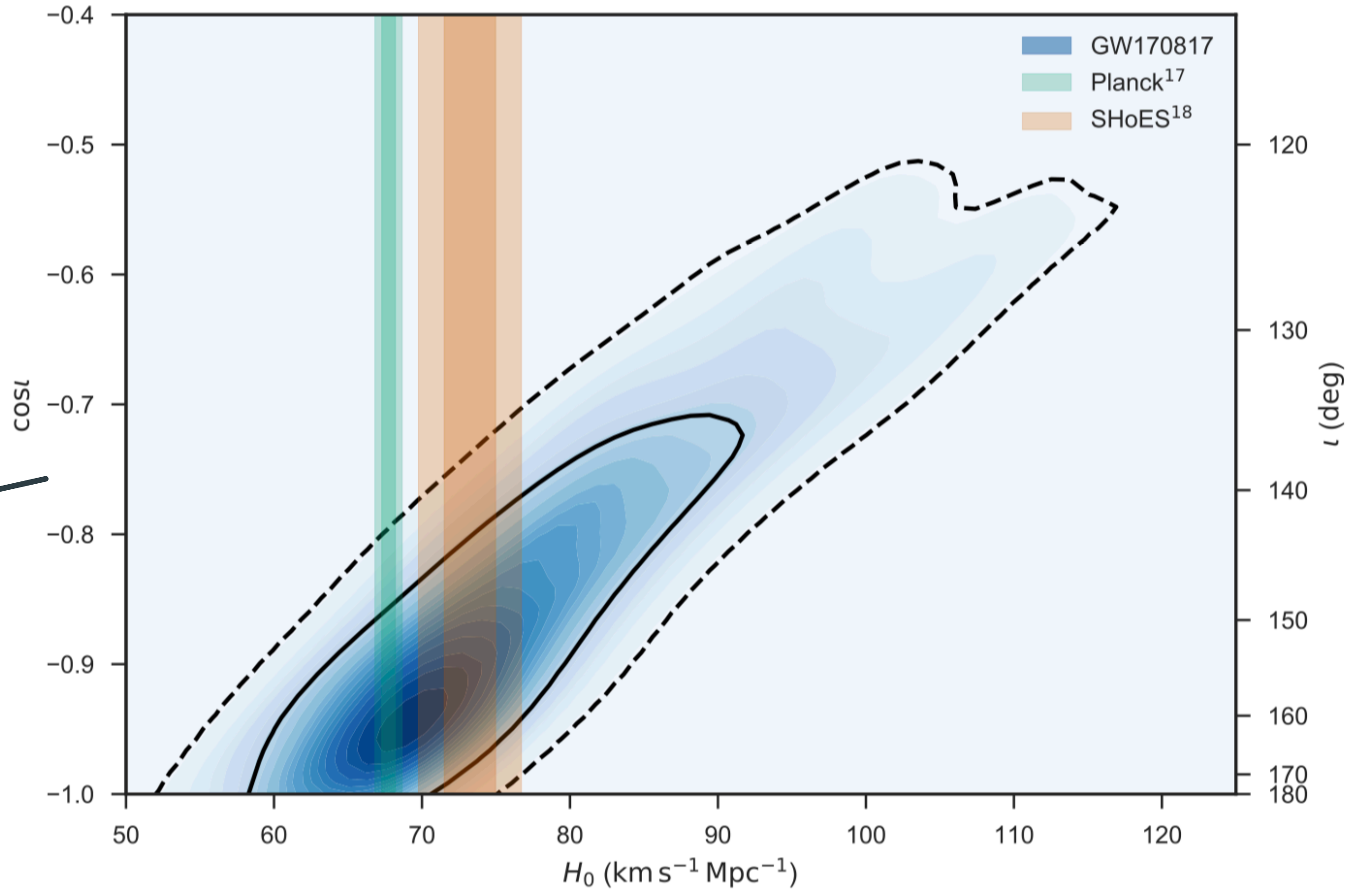

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A Vogt-Russell Theorem for BNS mergers?

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- Conjecture:

["only" ≡ to leading order]

"merger outcome depends only on total mass"

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A Vogt-Russel Theorem for BNS mergers?

- Conjecture:

  ["only" ≡ to leading order]

  "merger outcome depends only on total mass"

- neglects:
  - mass ratio [assume close to $q \approx 1$, and only secondary affect]
  - spins [assume low spin $\chi \ll 1$]
  - eccentricity [assume $e \approx 1$]
  - initial magnetic field [assume not dynamically important]

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[and multi-messenger astrophysics]

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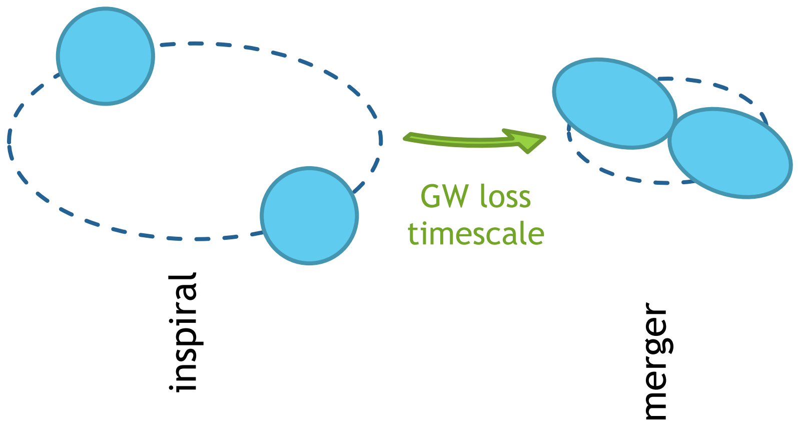
Merger Remnant:



schematics of a merger - outcome dependent on:

- binary mass
- NS EOS

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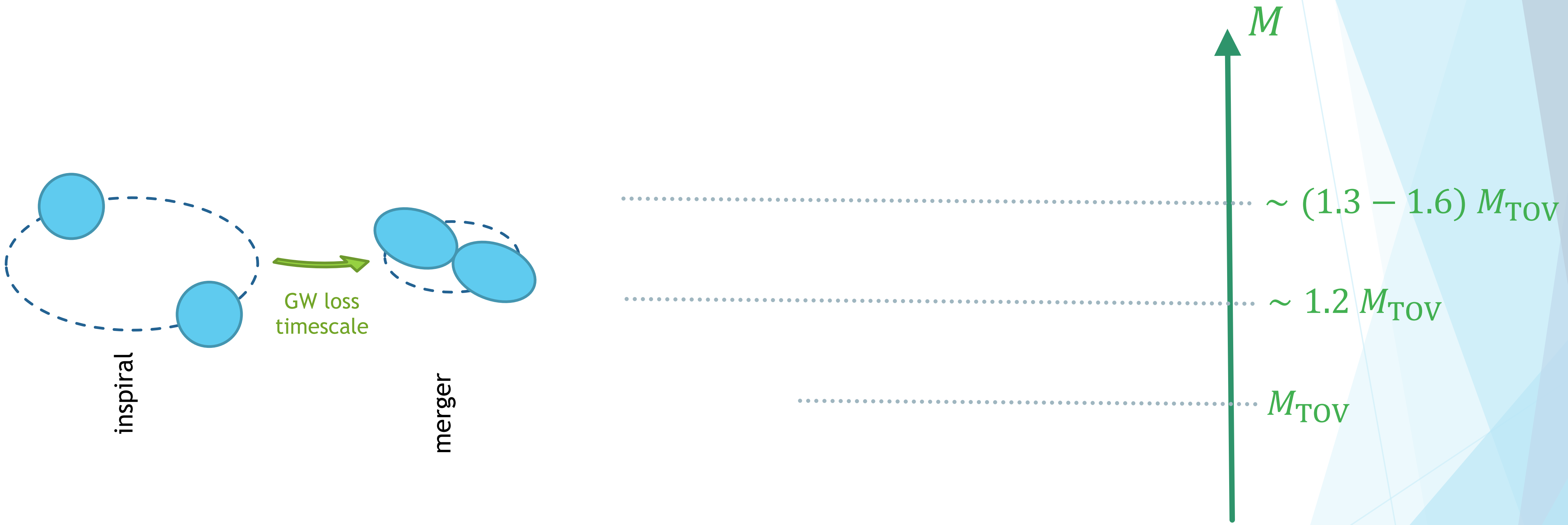

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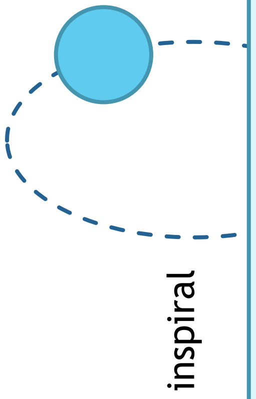
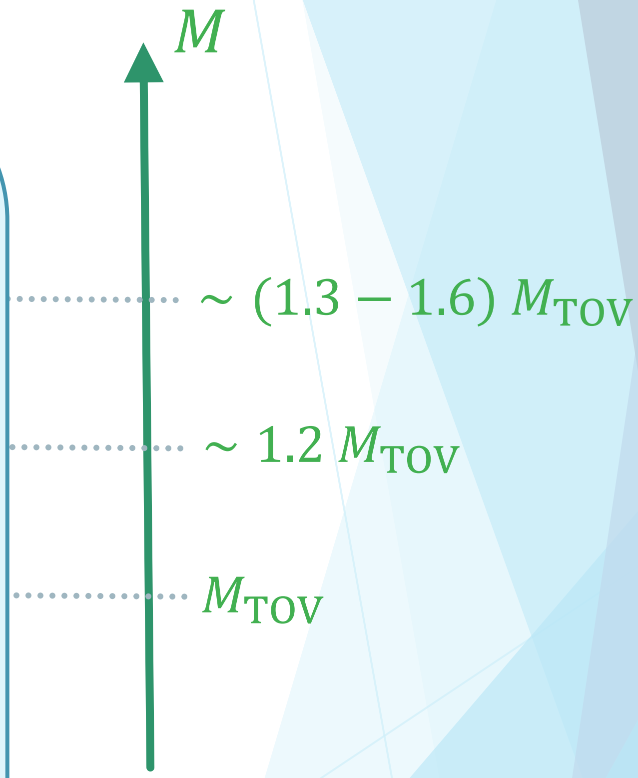


reminder:

$M_{\rm TOV}$ = maximum mass of cold, non-rotating NS

$$\frac{dP}{dr} = -\frac{G}{r^2}\left(m + 4\pi r^3 \frac{P}{c^2}\right)\left(\rho + \frac{P}{c^2}\right)\left(1 - \frac{2Gm}{c^2 r}\right)^{-1}$$

where $m = \int 4\pi r^2 \rho \, dr$



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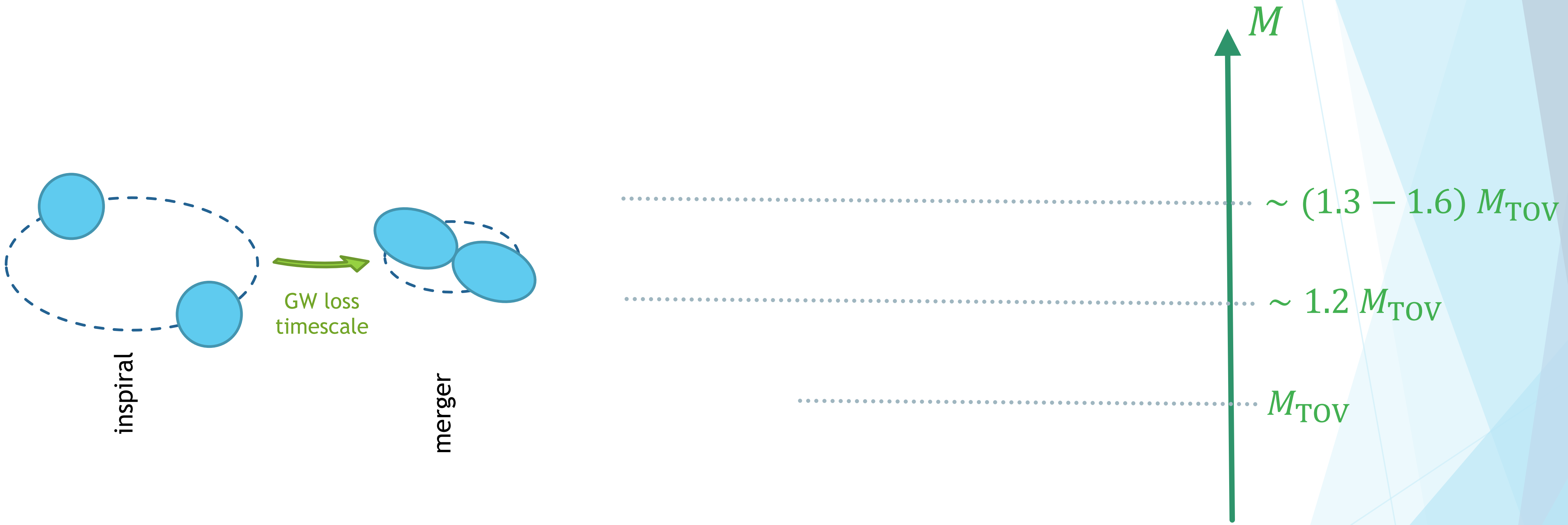

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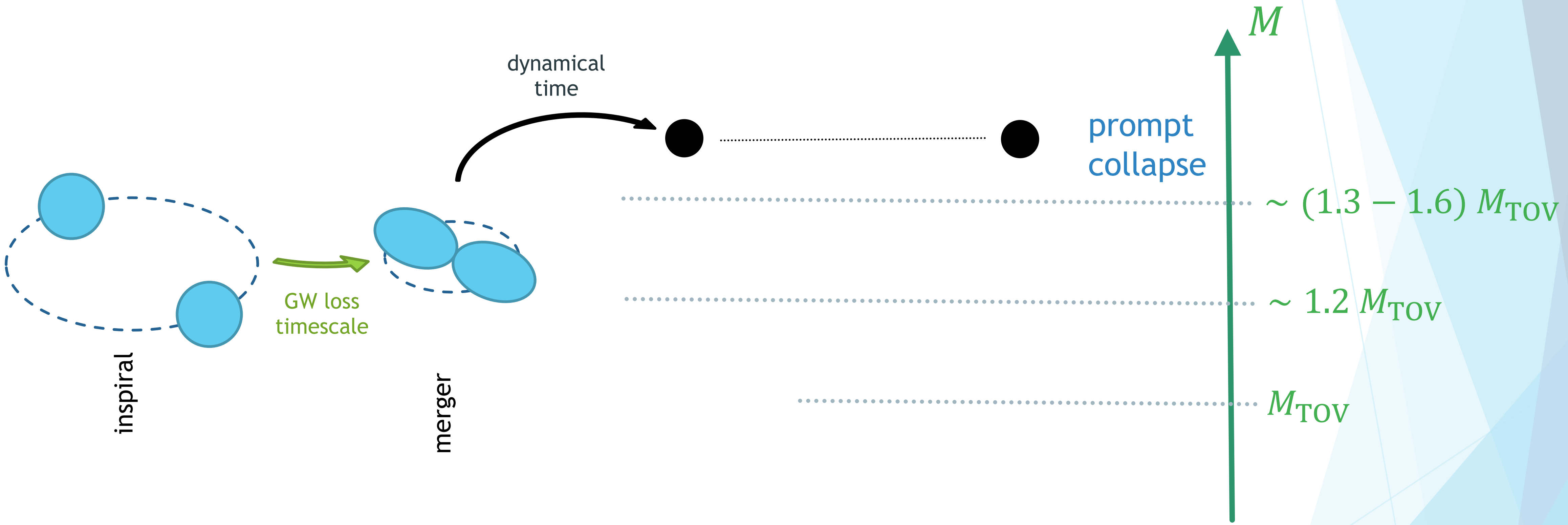

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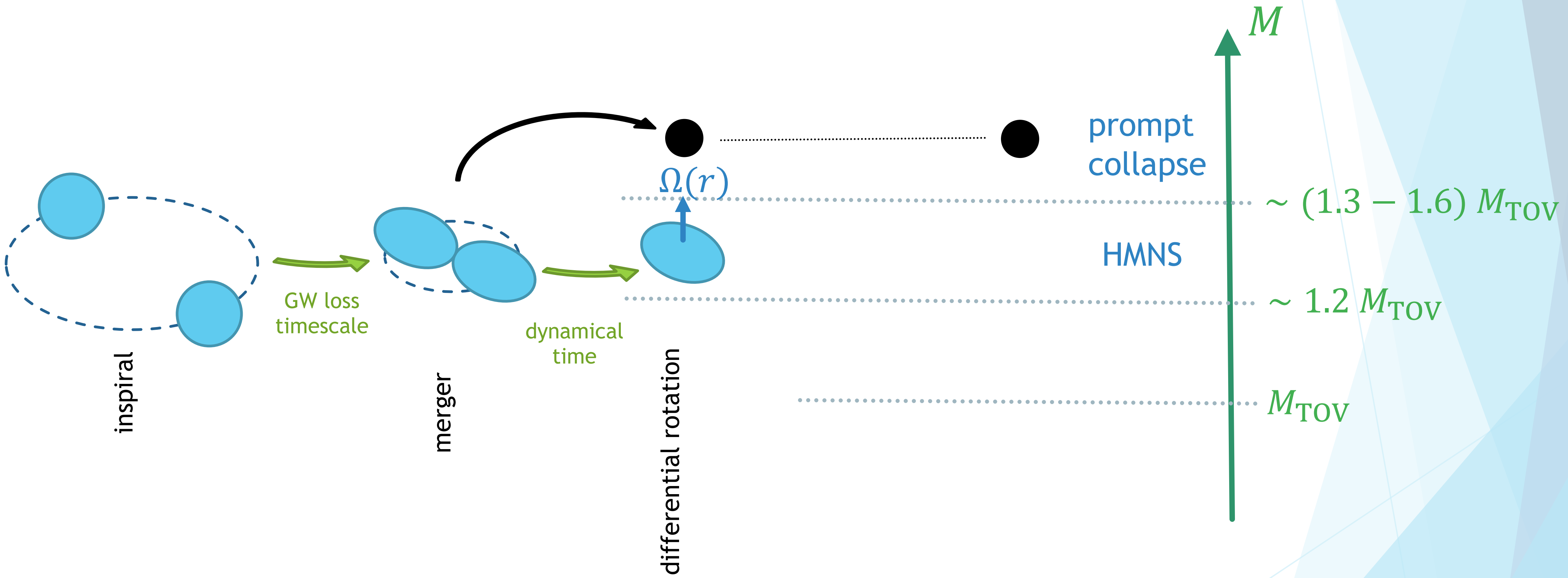

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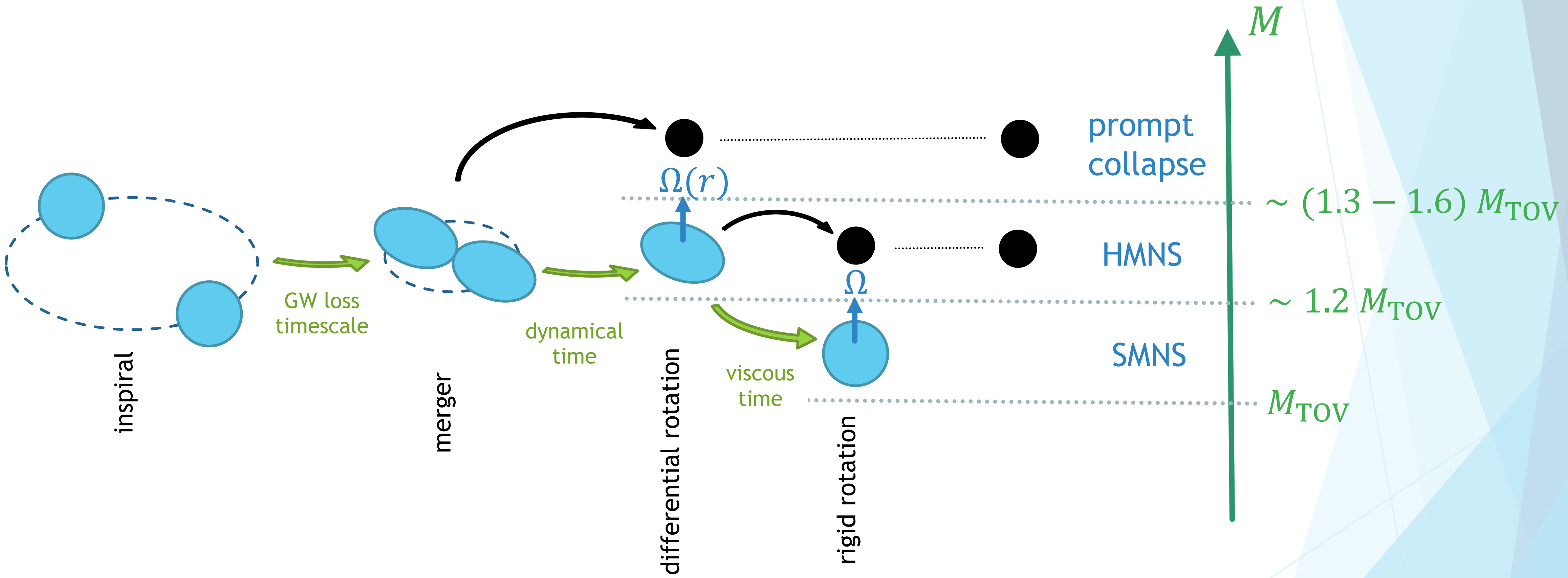

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[and multi-messenger astrophysics]

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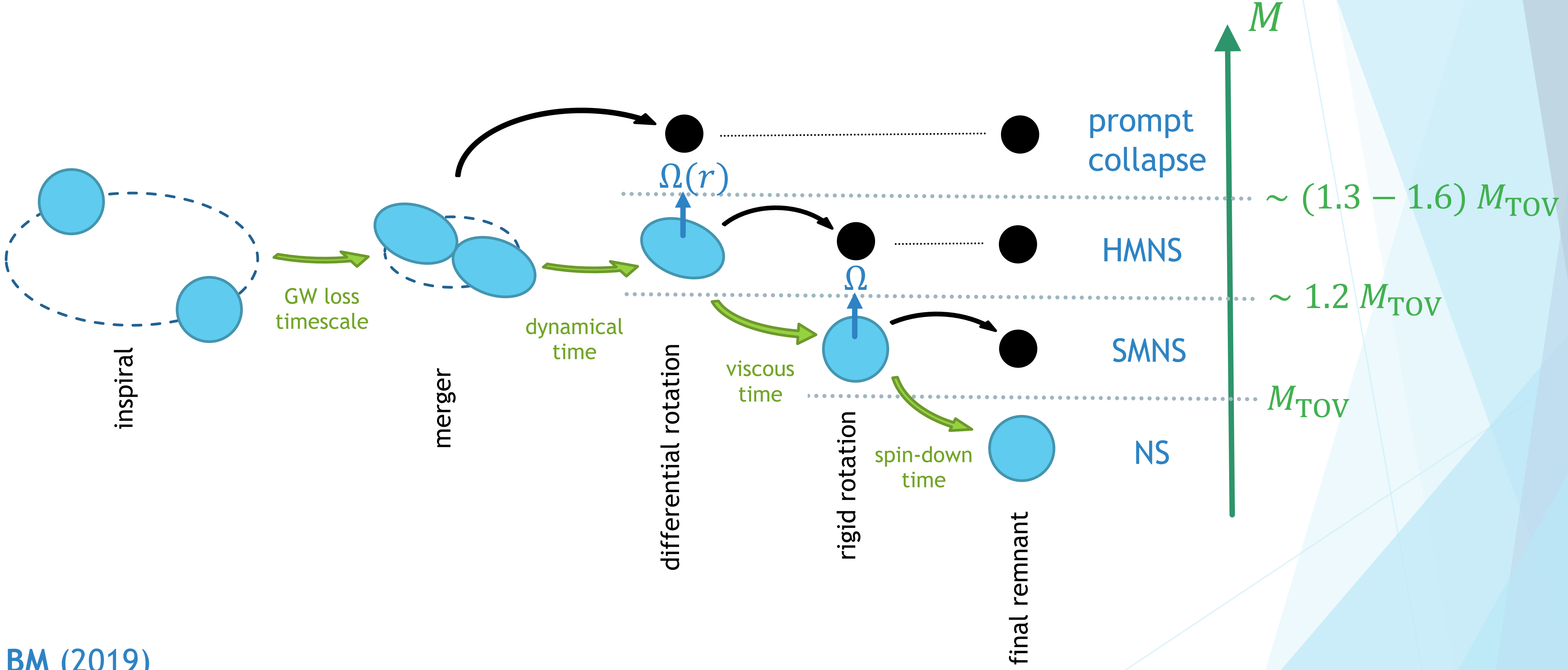

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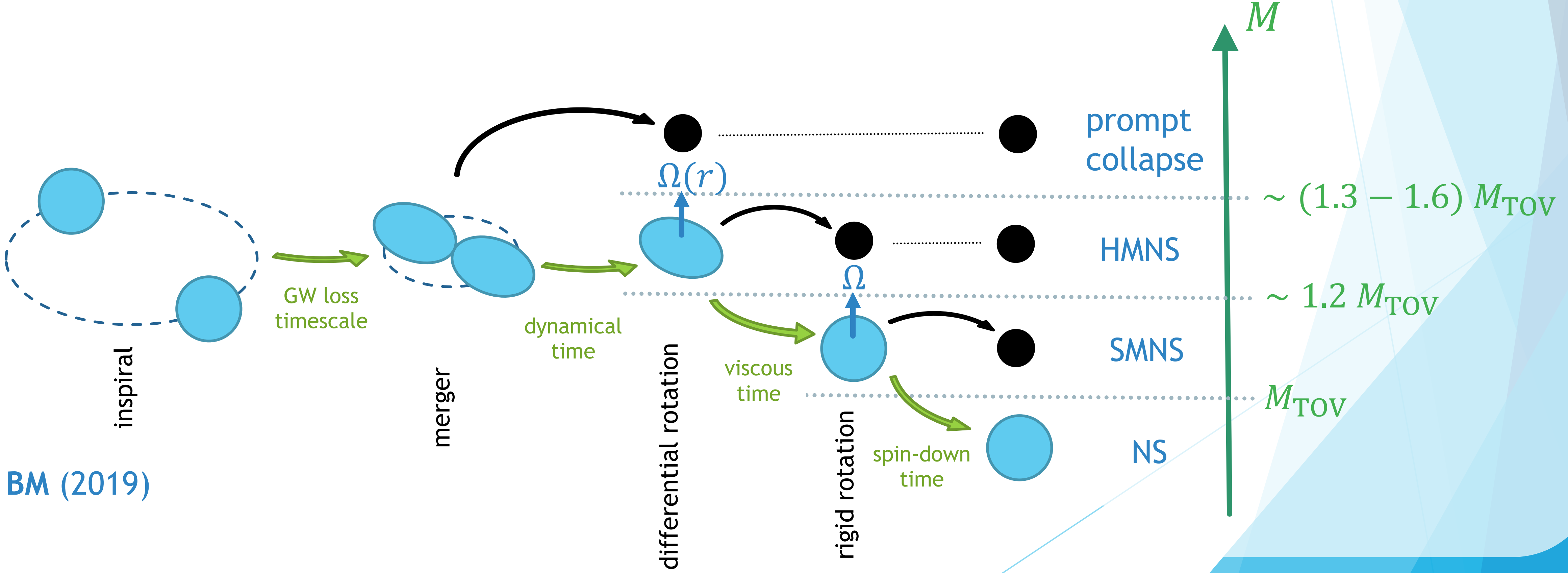
Multi-messenger EOS Constraints:

- how to use to constrain NS EOS?



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Multi-messenger EOS Constraints:

merger outcome ⇔ $M_{\rm tot}/M_{\rm TOV}$

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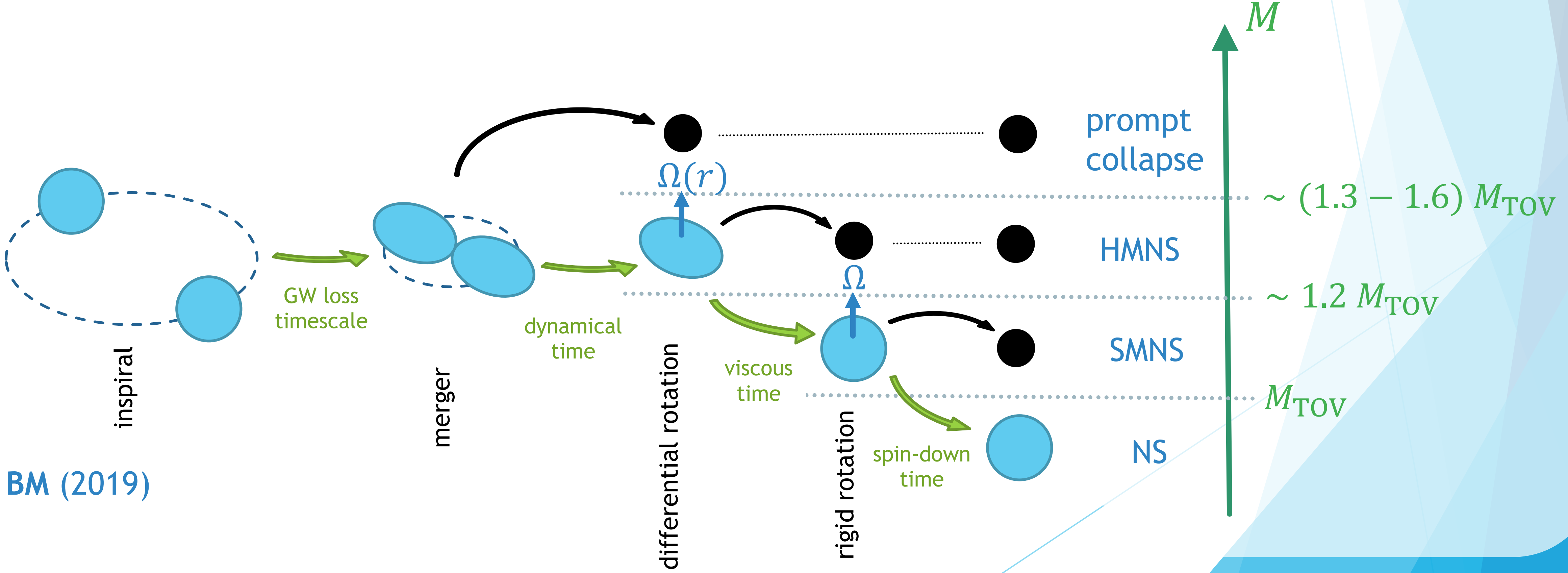

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Multi-messenger EOS Constraints:

- GW signal ⇒ total binary mass, $M_{\rm tot}$
- $M_{\rm tot} = M_{\rm chirp}\, q^{-3/5}(1+q)^{6/5}$

merger outcome ⇔ $M_{\rm tot}/M_{\rm TOV}$

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precisely measured (Biscoveanu+19)

f(q) weakly dependent on q

merger outcome ⇔ $M_{\rm tot}/M_{\rm TOV}$

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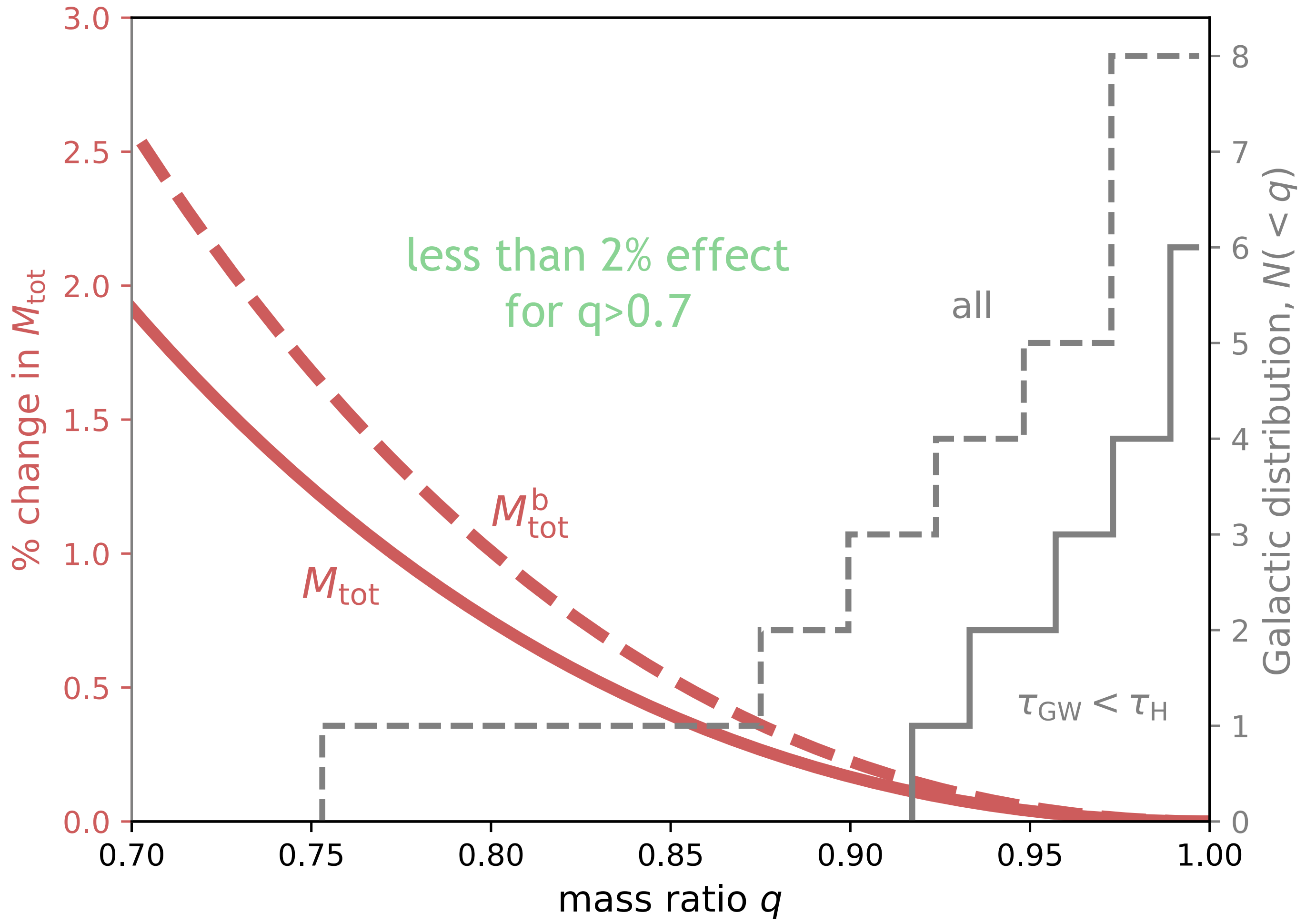

BM & Metzger (2019)

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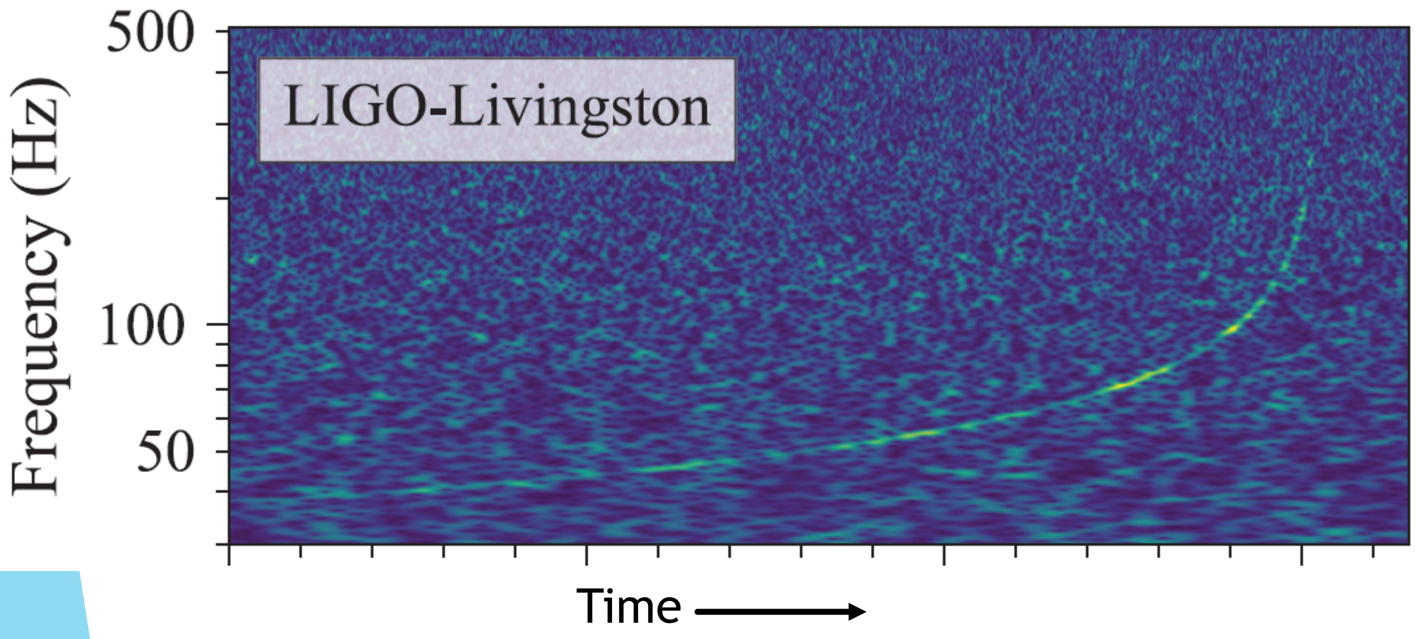

	Low-spin priors ($\lvert\chi\rvert \le 0.05$)
Primary mass m_1	1.36–1.60 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$

LIGO Virgo (2017)

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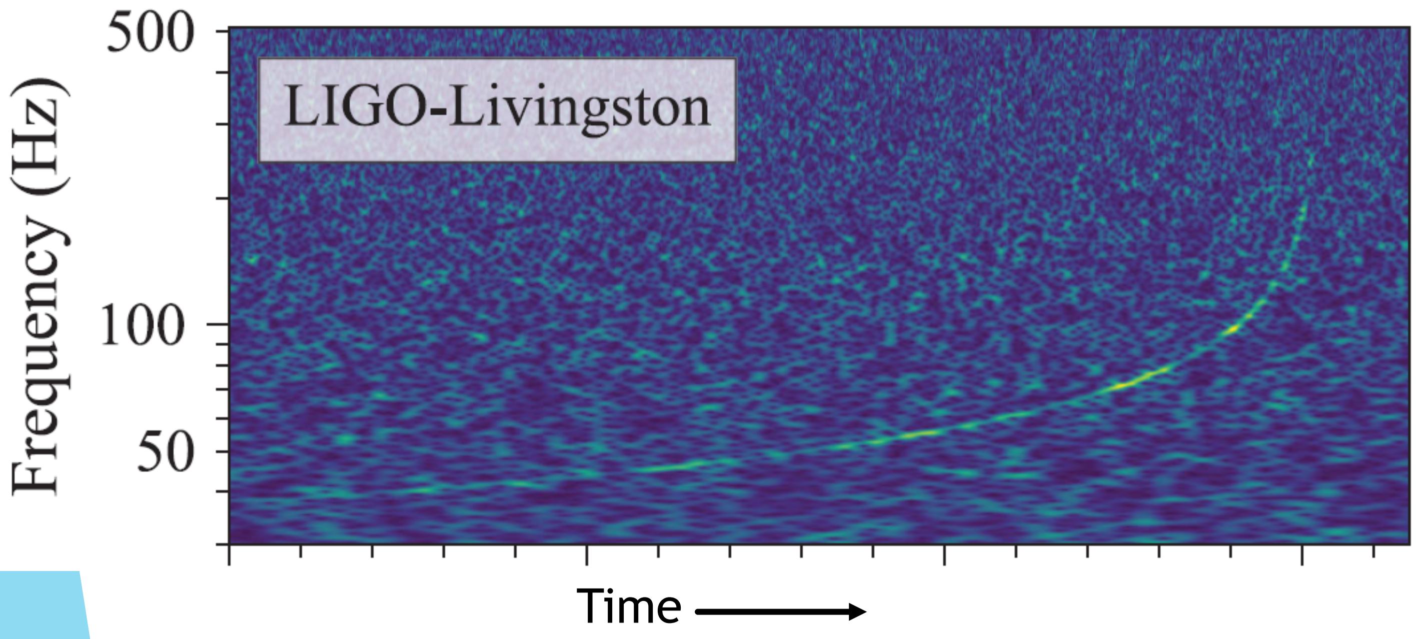
GW (for $M_{\rm tot}$)



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LIGO Virgo (2017)

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Multi-messenger EOS Constraints:

- justification for low-spin prior
  [as well as $q \approx 1$]

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[and multi-messenger astrophysics]

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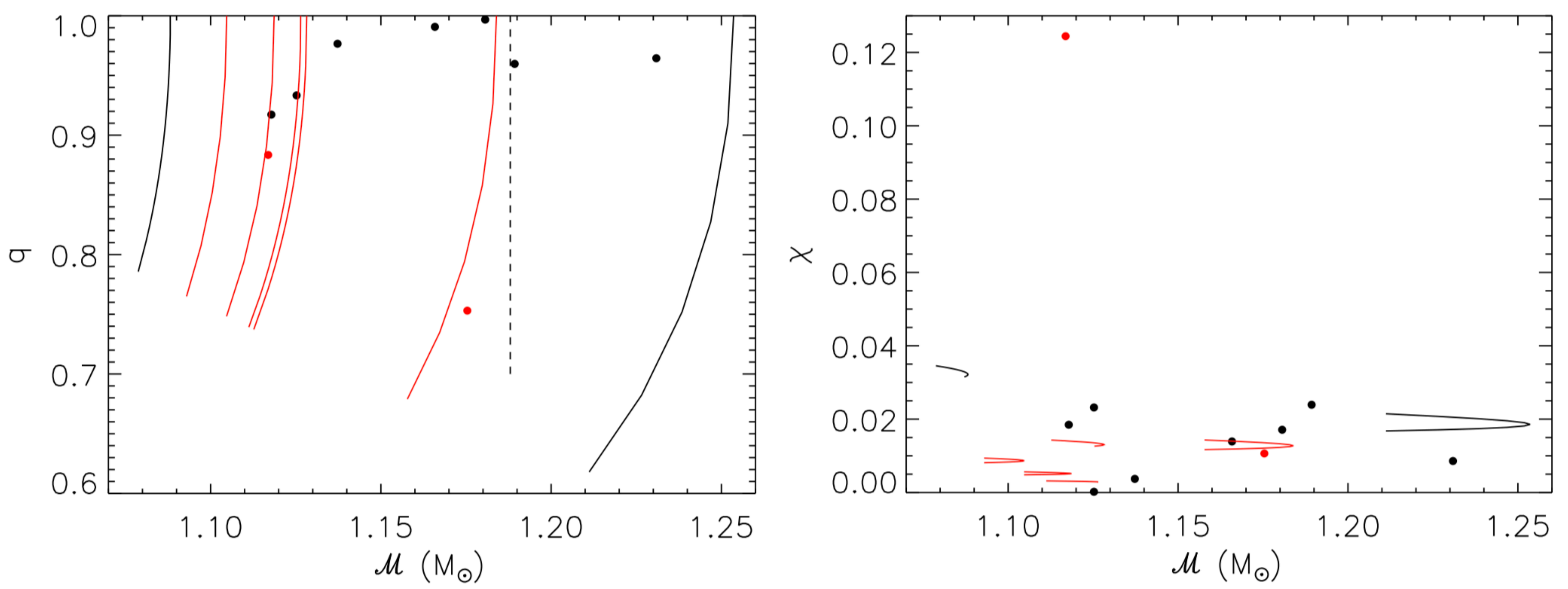
Multi-messenger EOS Constraints:

- justification for low-spin prior
  [as well as $q \approx 1$]

Zhao & Lattimer (2018)



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Multi-messenger EOS Constraints:

merger outcome $\Leftrightarrow$ $\underbrace{M_{\rm tot}}_{\text{GW}}/M_{\rm TOV}$

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Multi-messenger EOS Constraints:

- EM signature ⇒ remnant fate

  (Bauswein+13; Metzger&Fernandez14; Metzger&Piro14; Kasen+15; …)

merger outcome ⇔ $\underbrace{M_{\rm tot}}_{\rm GW}/M_{\rm TOV}$

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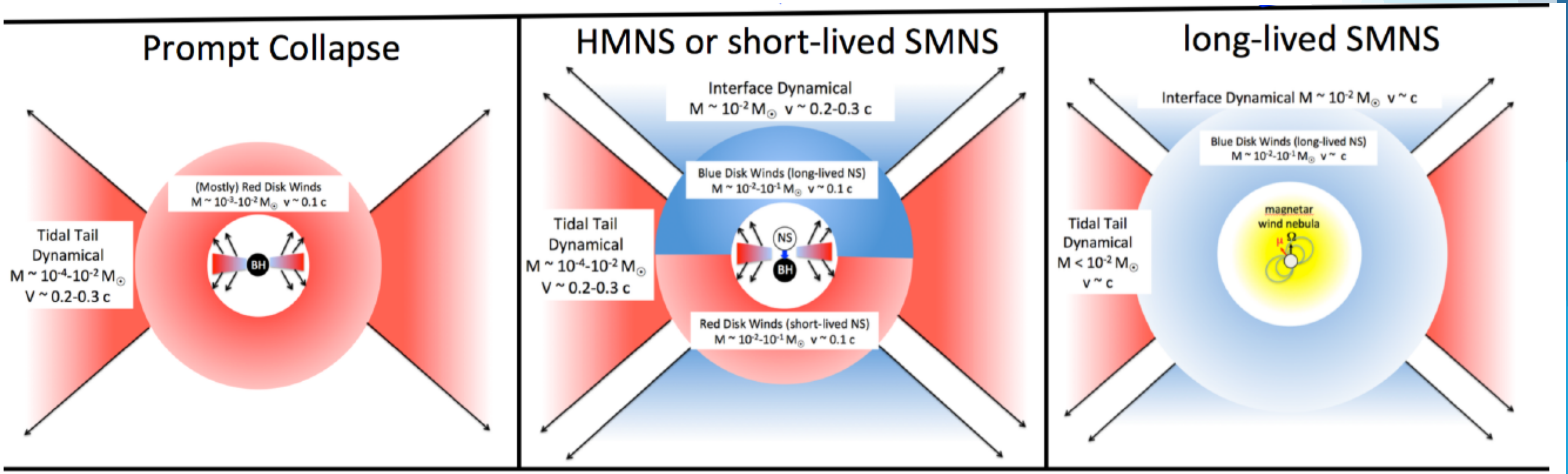
GW

BM & Metzger (2017)



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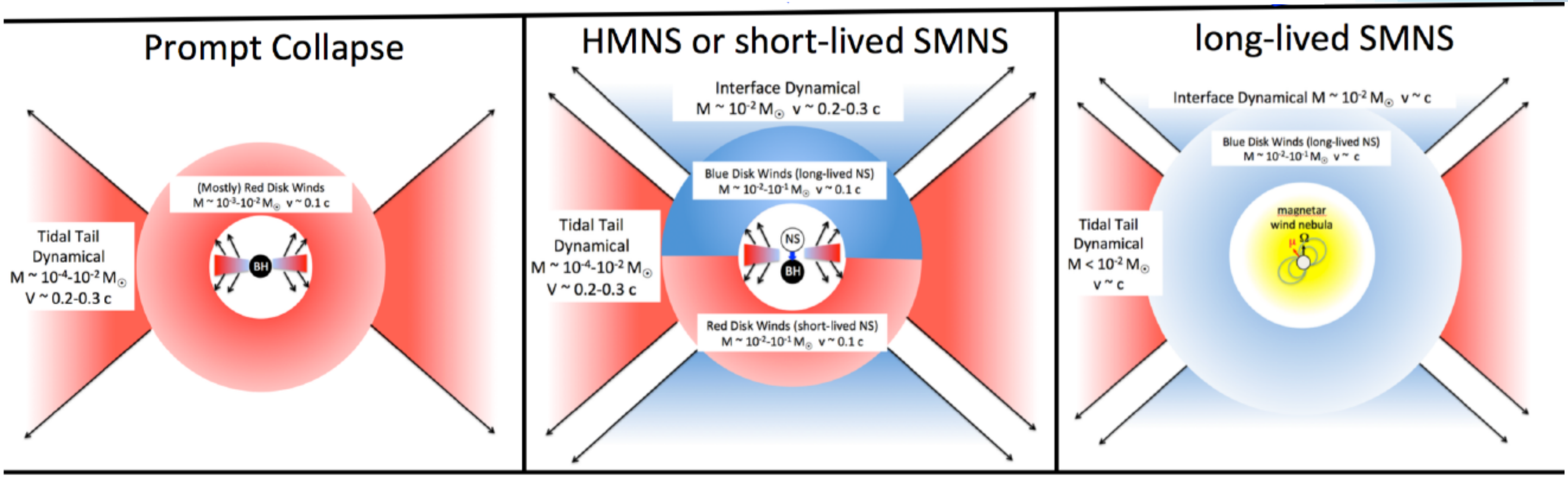
merger outcome ⇔ $M_{\rm tot}/M_{\rm TOV}$

EM (merger outcome) — GW ($M_{\rm tot}$)

BM & Metzger (2017)



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EM GW ⇒EOS

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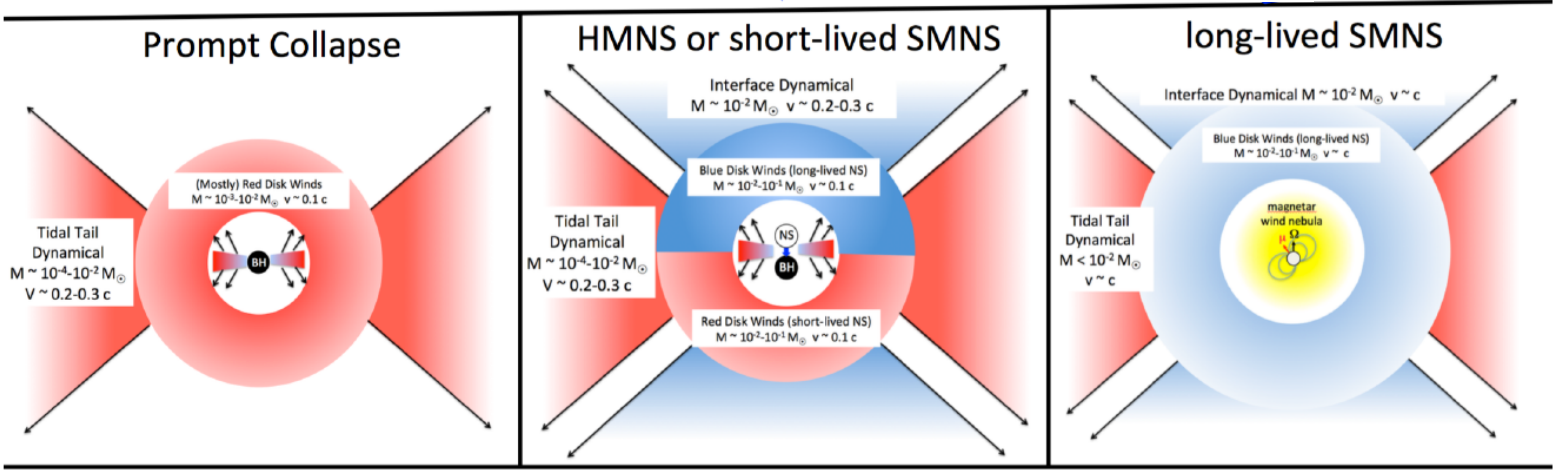

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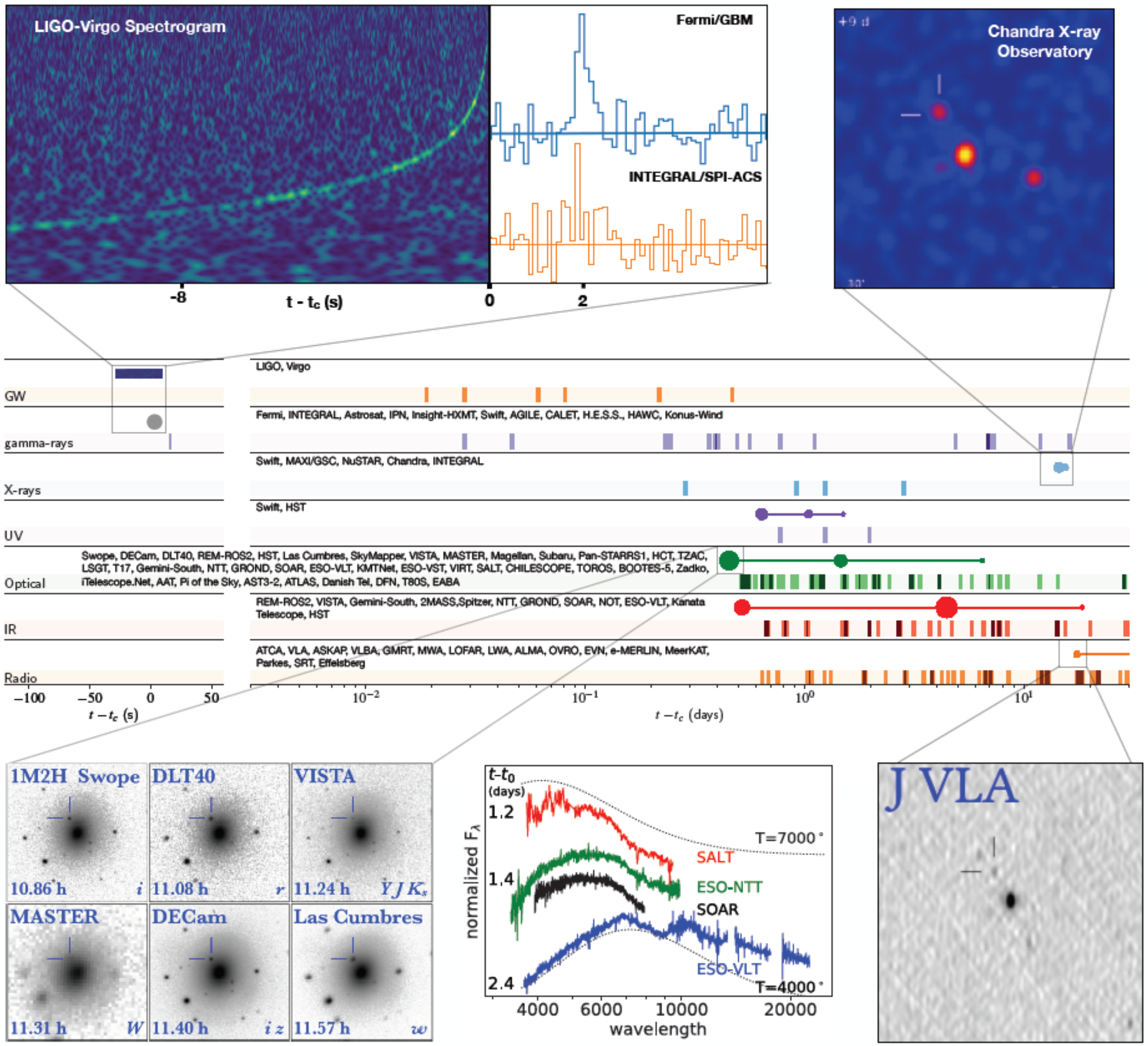
Application to GW170817:



LIGO + (2017)

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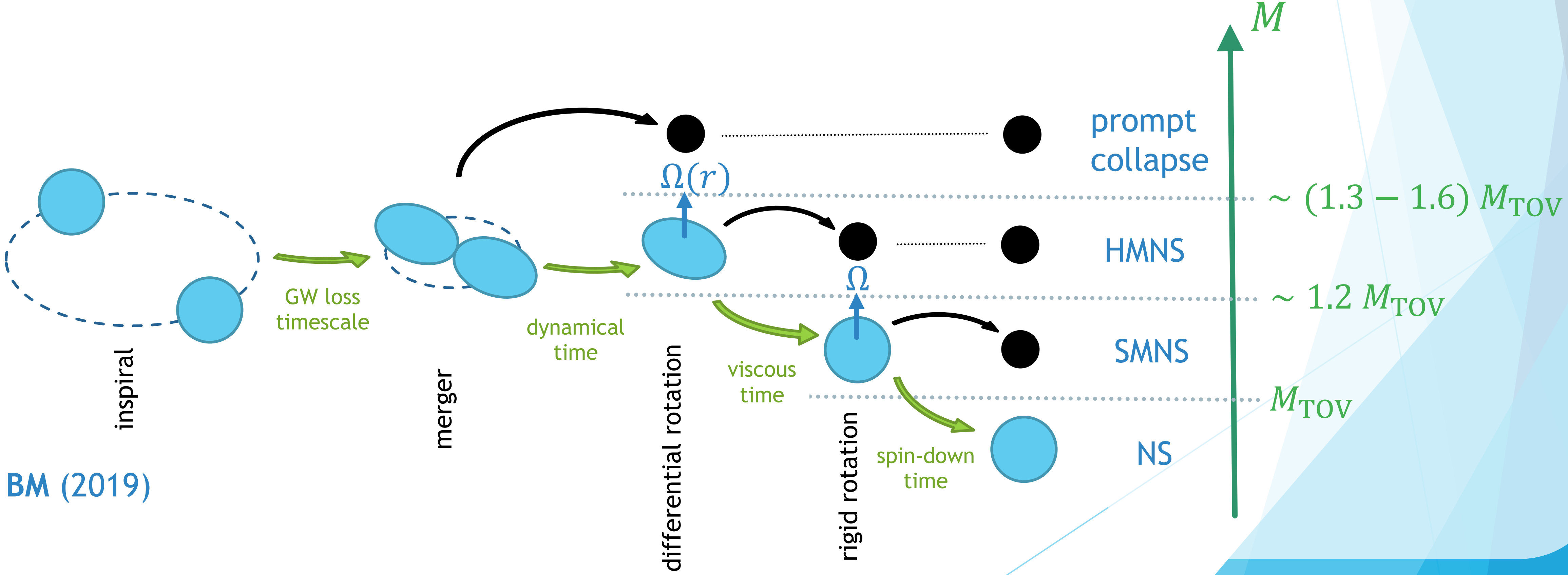
Application to GW170817: (I) remnant fate



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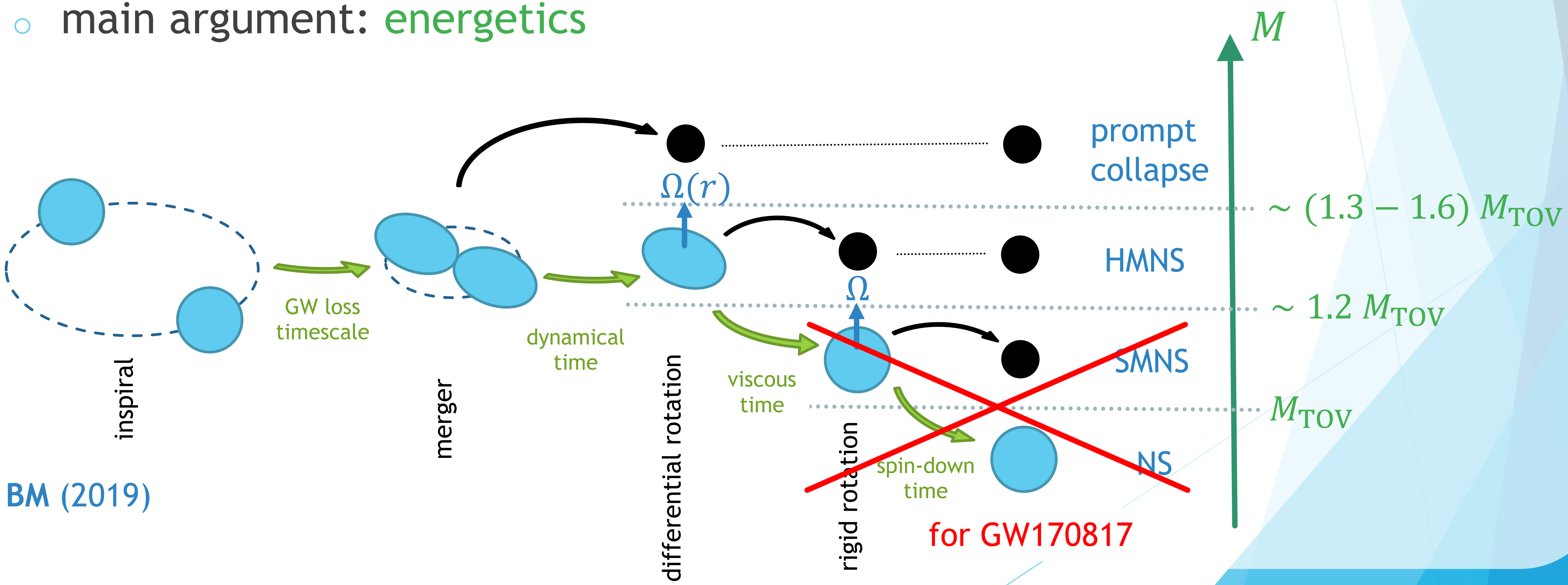
Application to GW170817: (I) remnant fate

- rule out long-lived SMNS or stable NS remnant
- main argument: energetics



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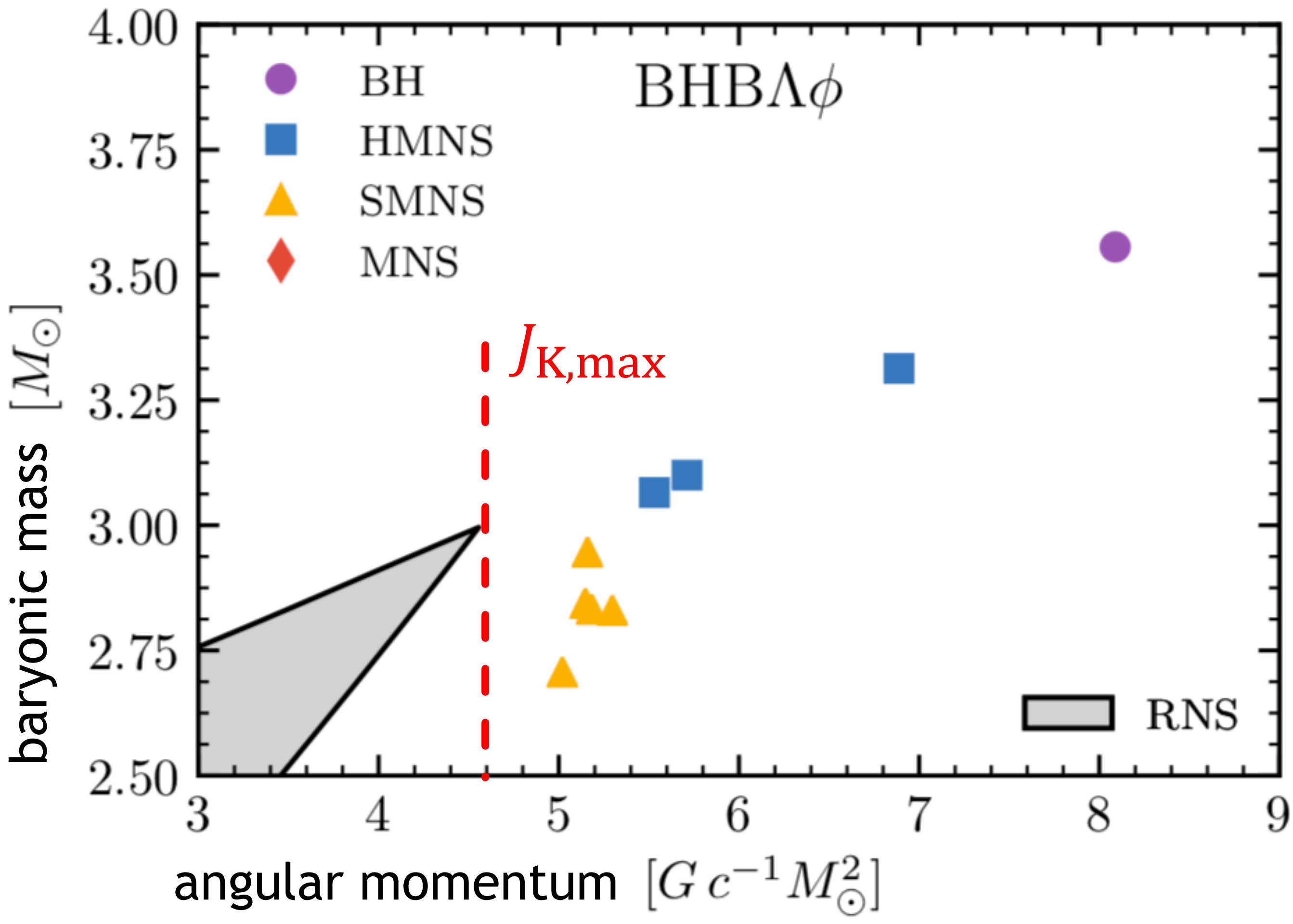
Application to GW170817: (II) energetics

- $J_{\text{remnant}} \sim J_{\text{orbital}} > J_{\text{K, max}}$

Radice+ (2018)



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Application to GW170817: (II) energetics

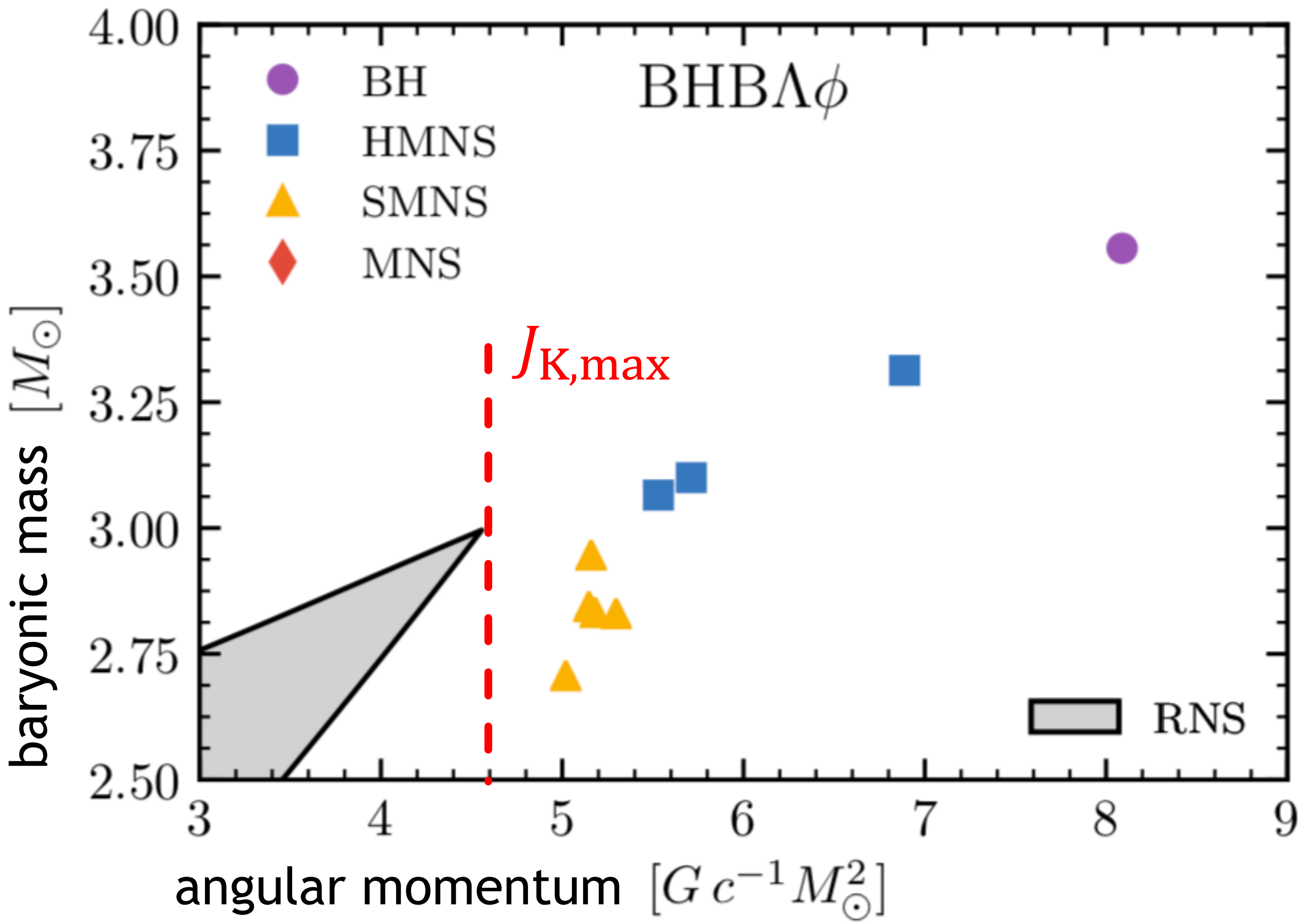
- $J_{\text{remnant}} \sim J_{\text{orbital}} > J_{\text{K, max}}$

⇒ merger remnant maximally rotating

$$E_{\text{rot}} = \frac{1}{2} I\Omega^2 \sim 10^{53} \text{ erg !}$$

(Metzger, **BM**+15)

Radice+ (2018)



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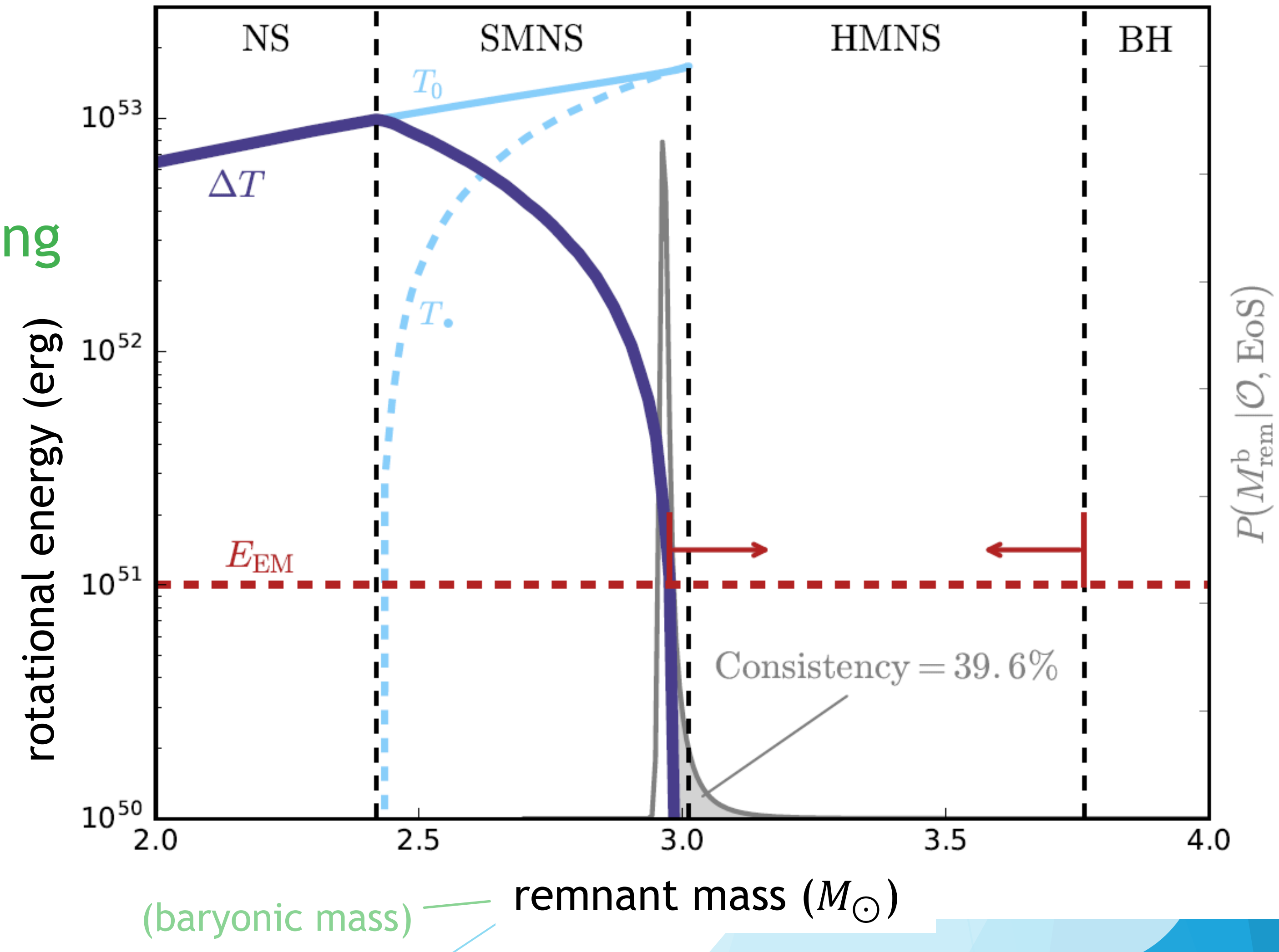
BM & Metzger (2017)



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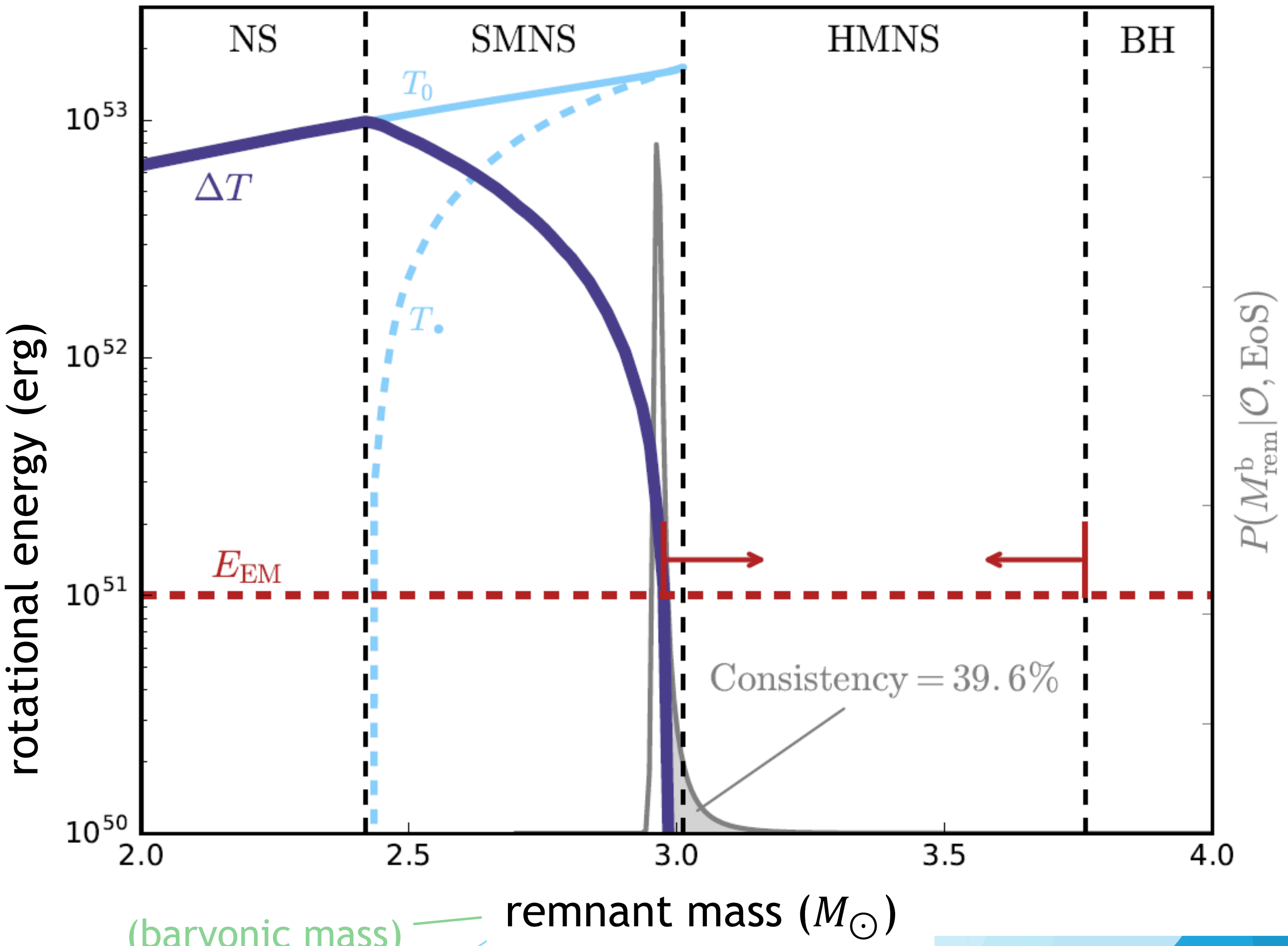

(baryonic mass)

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Application to GW170817: (II) energetics

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(Metzger, **BM**+15)

- for stable remnant: tapped by magnetic-dipole spin-down ($\dot{E} \sim \mu^2\Omega^4/c^3$)

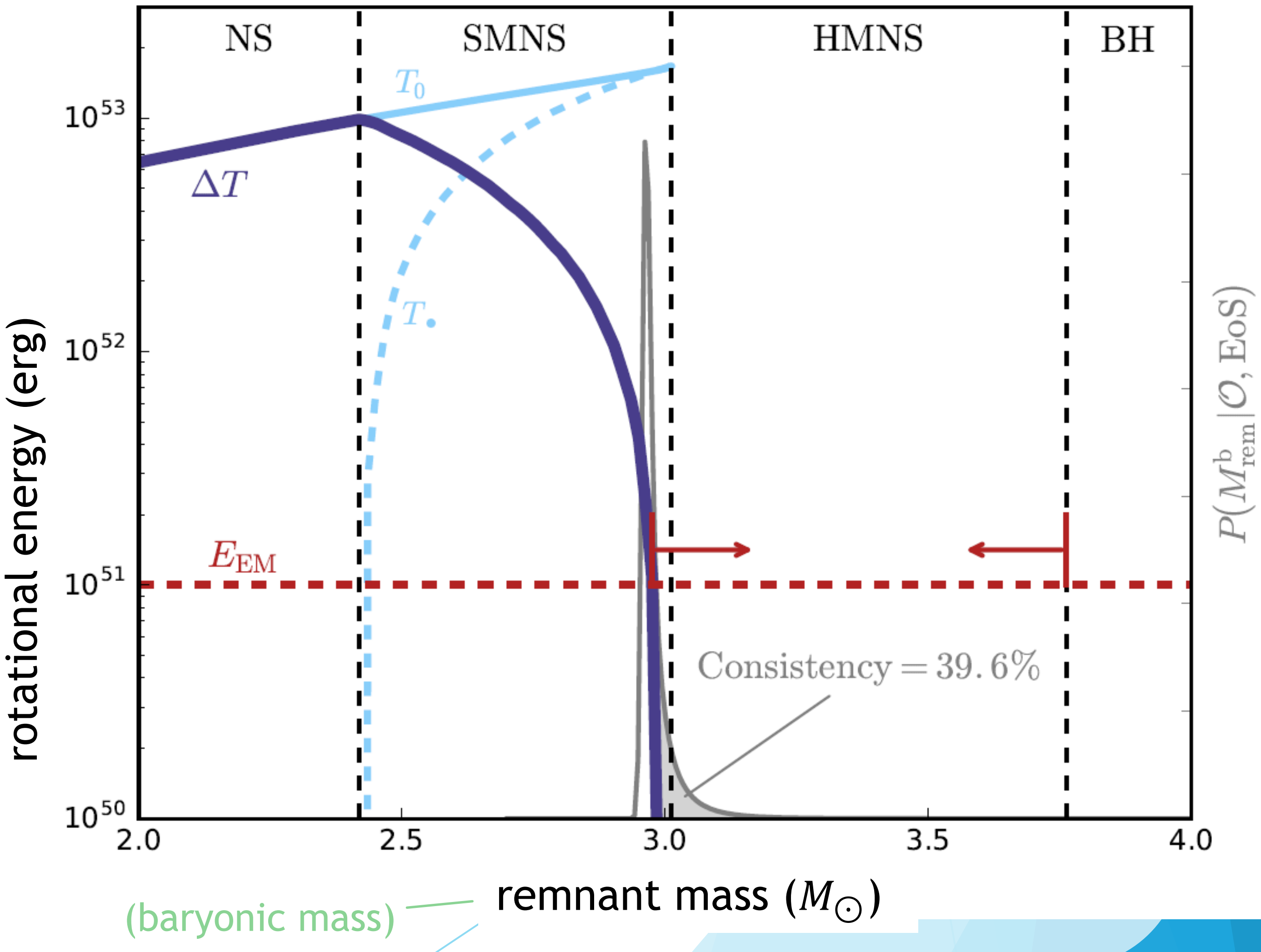
(Kiuchi+14, Metzger&Piro14, Siegel&Ciolfi16, …)

- inconsistent with GW170817 kilonova + afterglow

(unless high ellipticity invoked)

(e.g. Ai+18)

BM & Metzger (2017)



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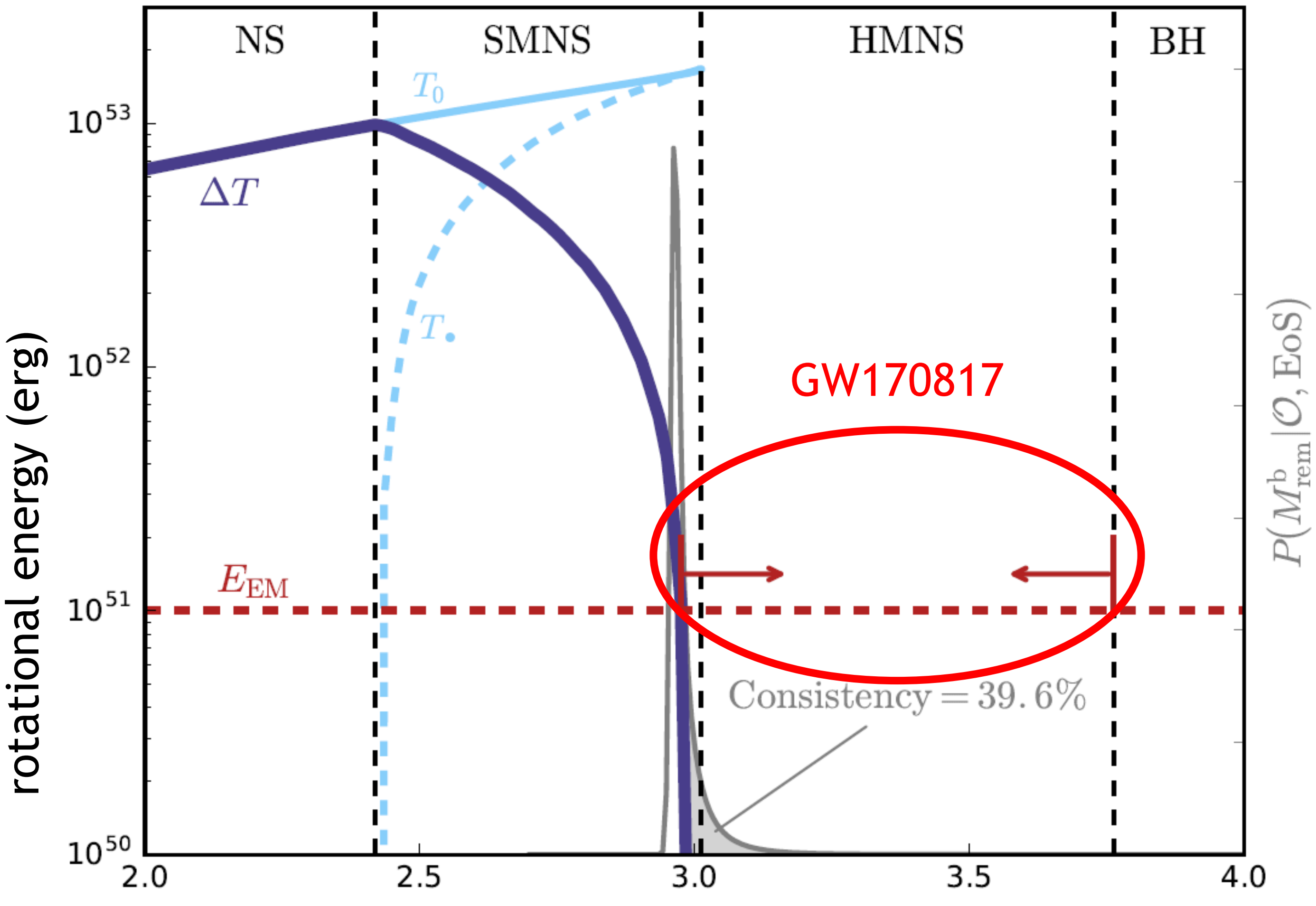

(baryonic mass) remnant mass ($M_\odot$)

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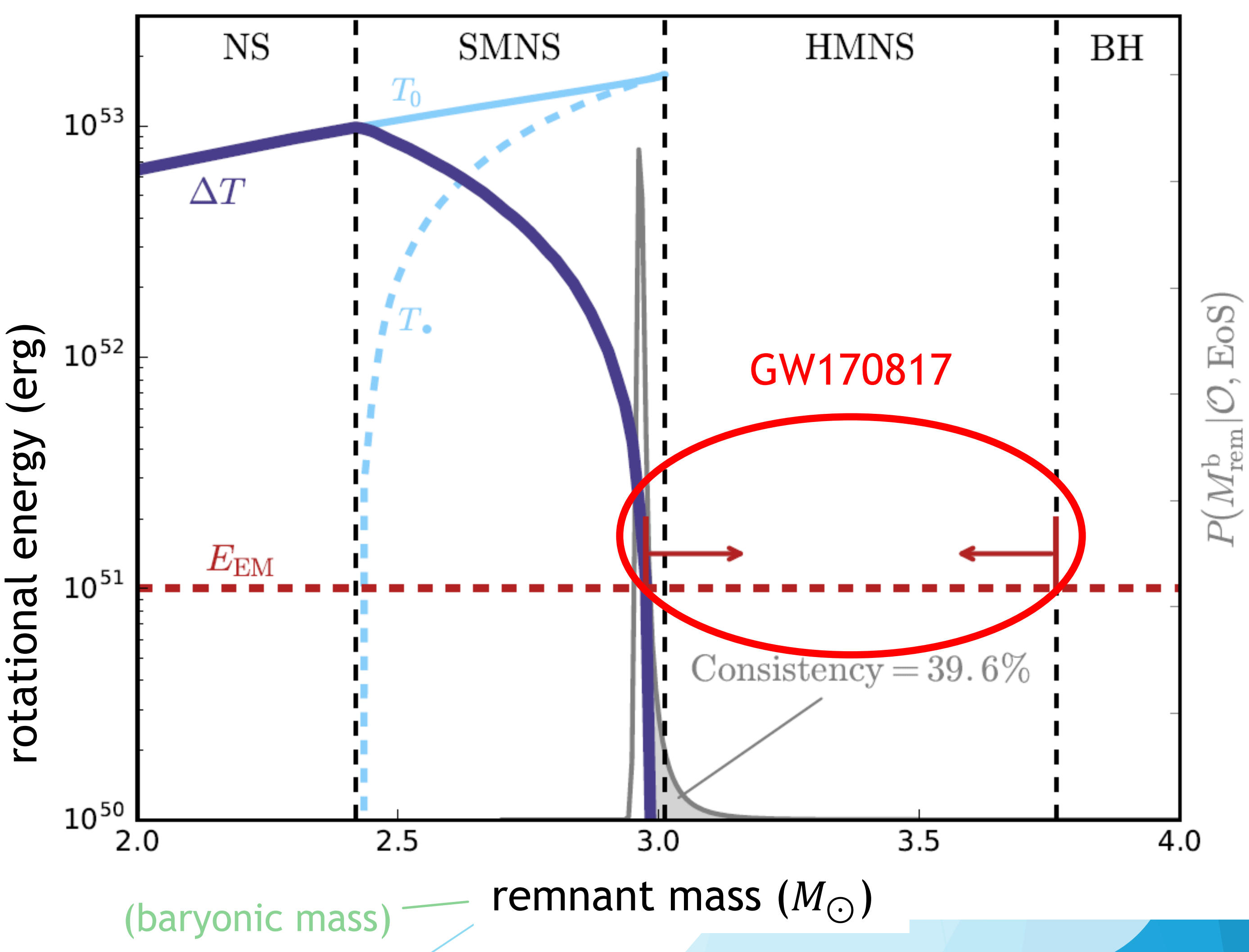
Application to GW170817: (II) energetics

- rule out NS or SMNS remnant

BM & Metzger (2017)



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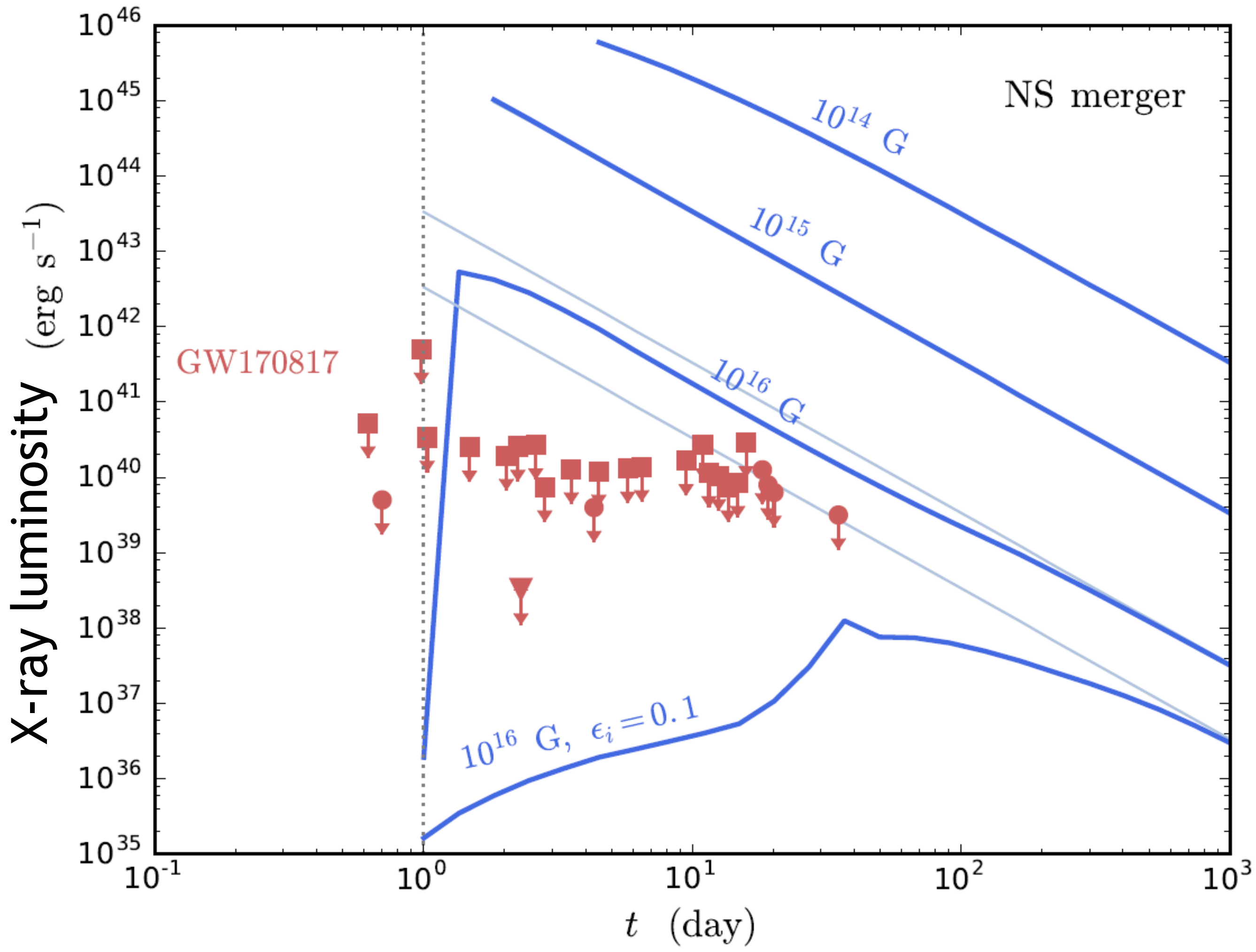
Application to GW170817: (II) energetics

- rule out NS or SMNS remnant
- also strengthened by:
  - observed GRB $\lesssim 2\text{s}$ post merger
  - lack of X-rays from NS spindown

(**BM**+18b, Pooley+18)

BM + (2018b)



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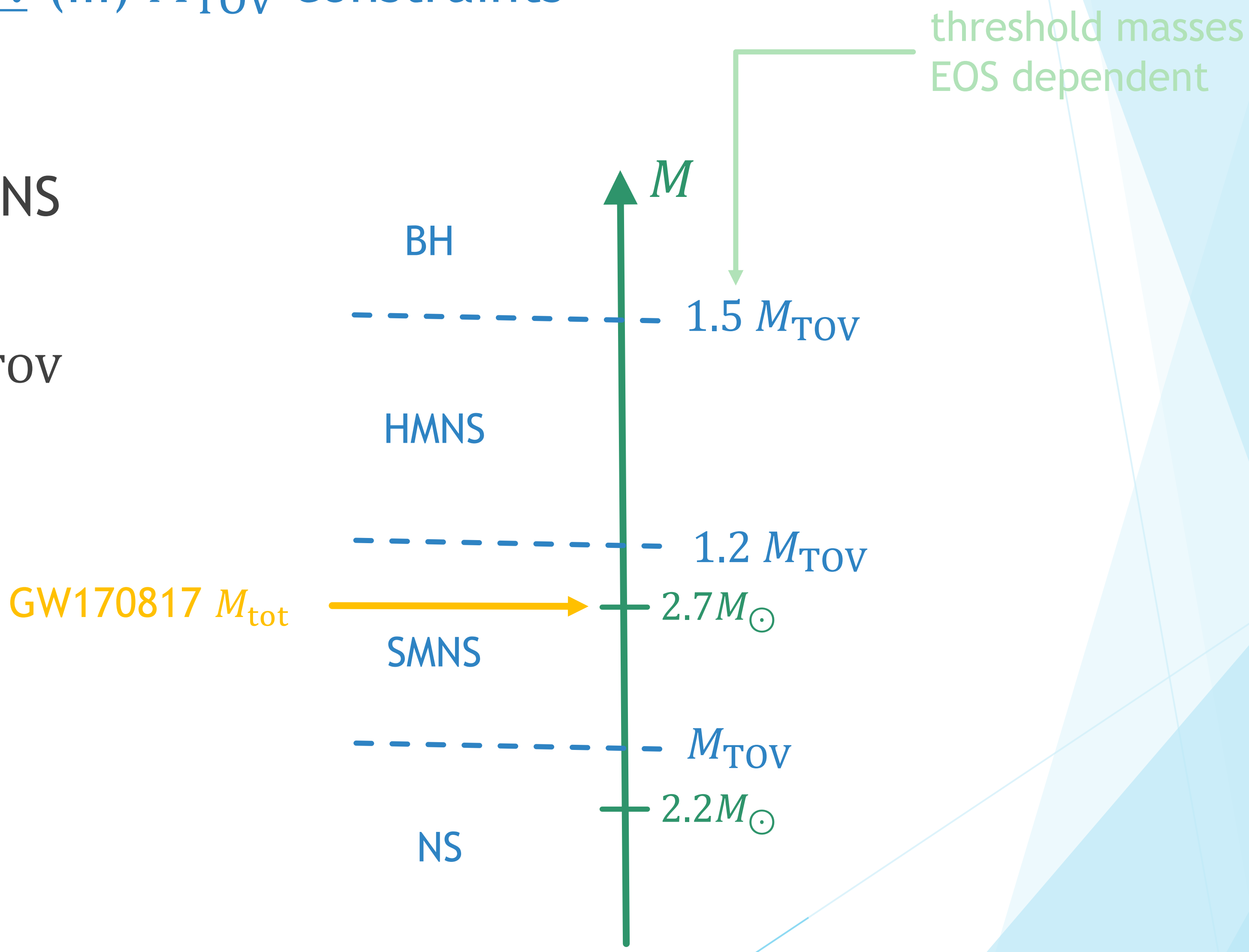
Application to GW170817: (III) M_{TOV} constraints

- ruling out long-lived NS

  ⇒ upper limit on M_{TOV}



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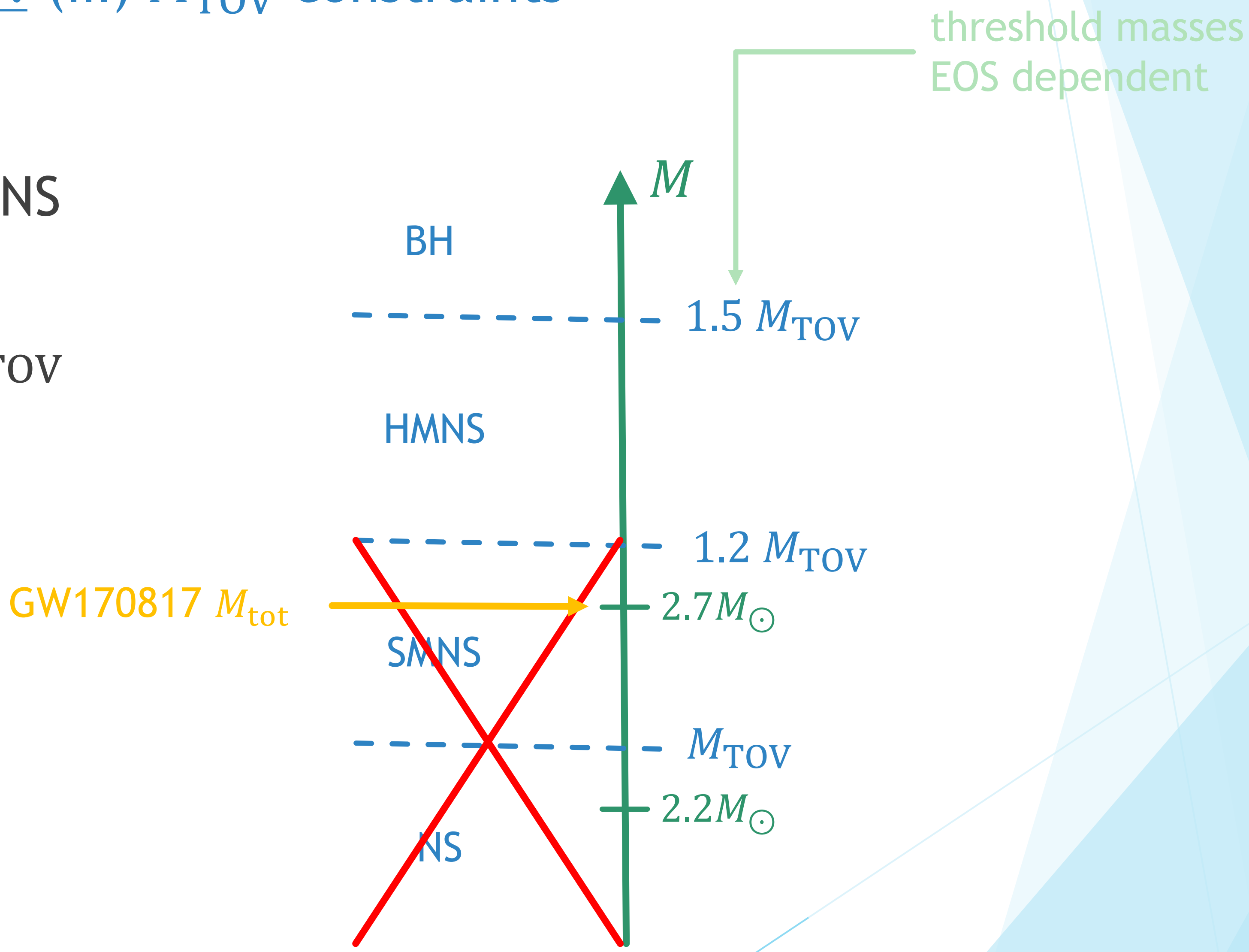

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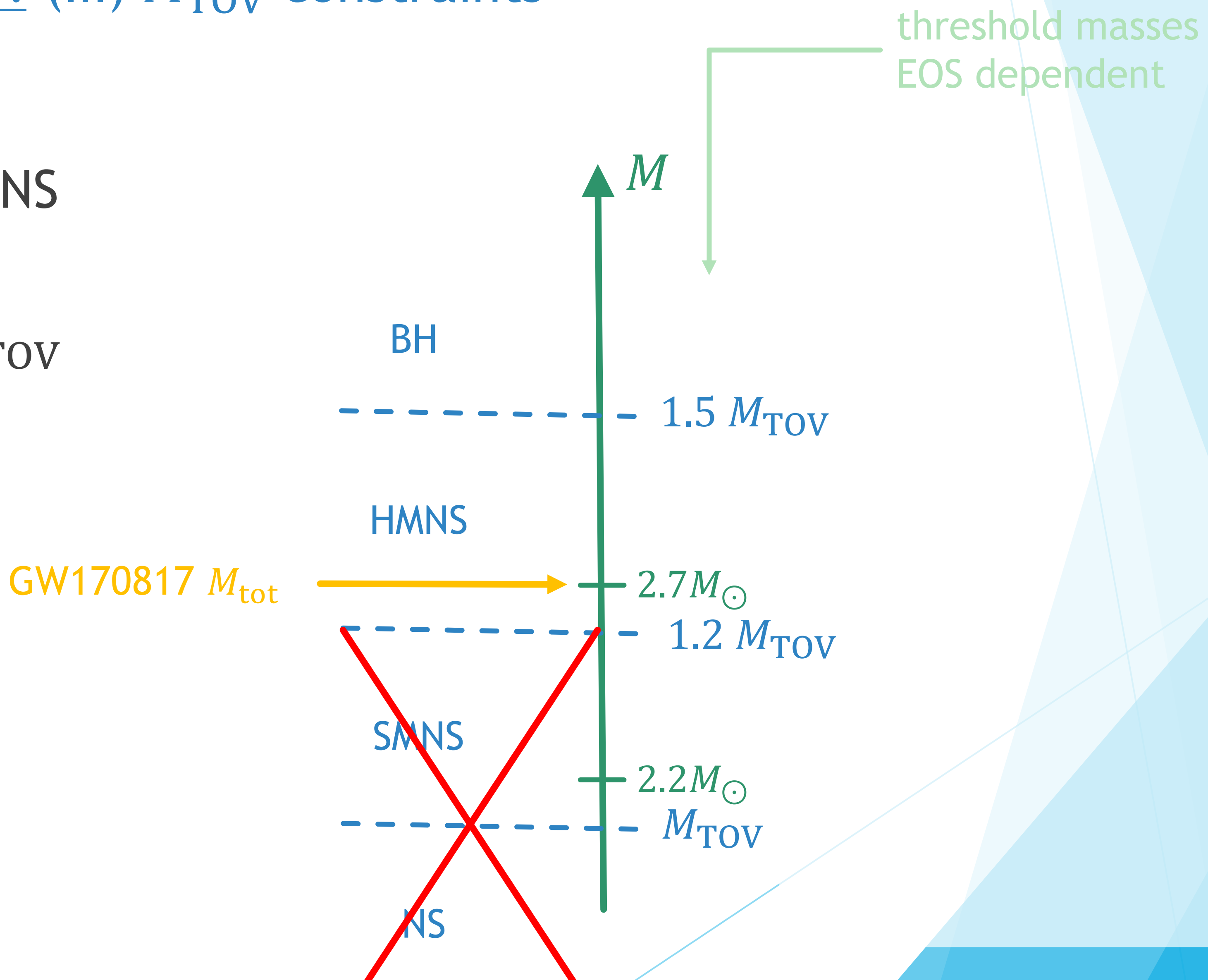

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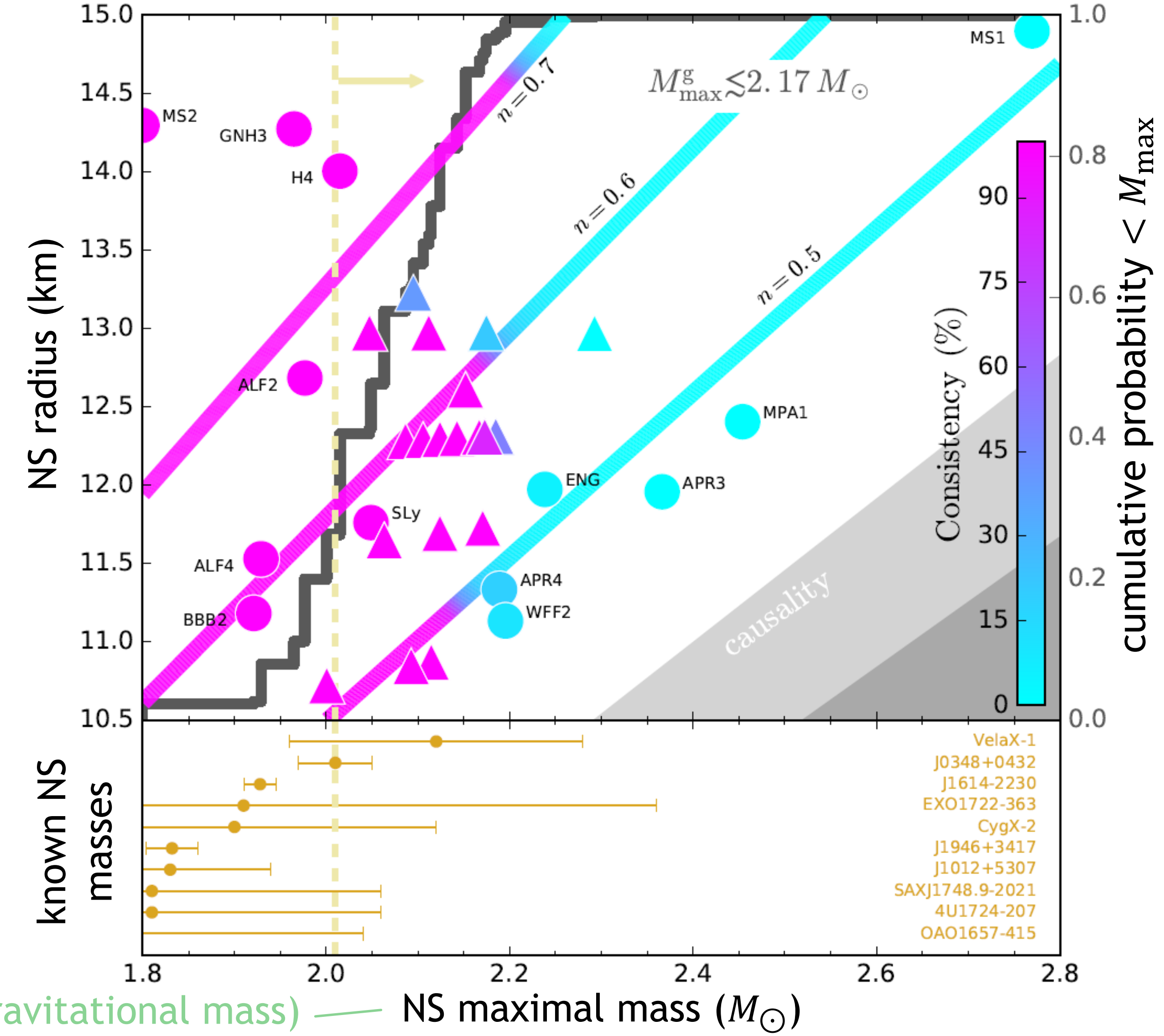
Application to GW170817: (III) $M_{\rm TOV}$ constraints

- find $M_{\rm TOV} \lesssim 2.2 M_\odot$ (BM&Metzger17)

BM & Metzger (2017)



(gravitational mass)

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  [but see Shibata+19]

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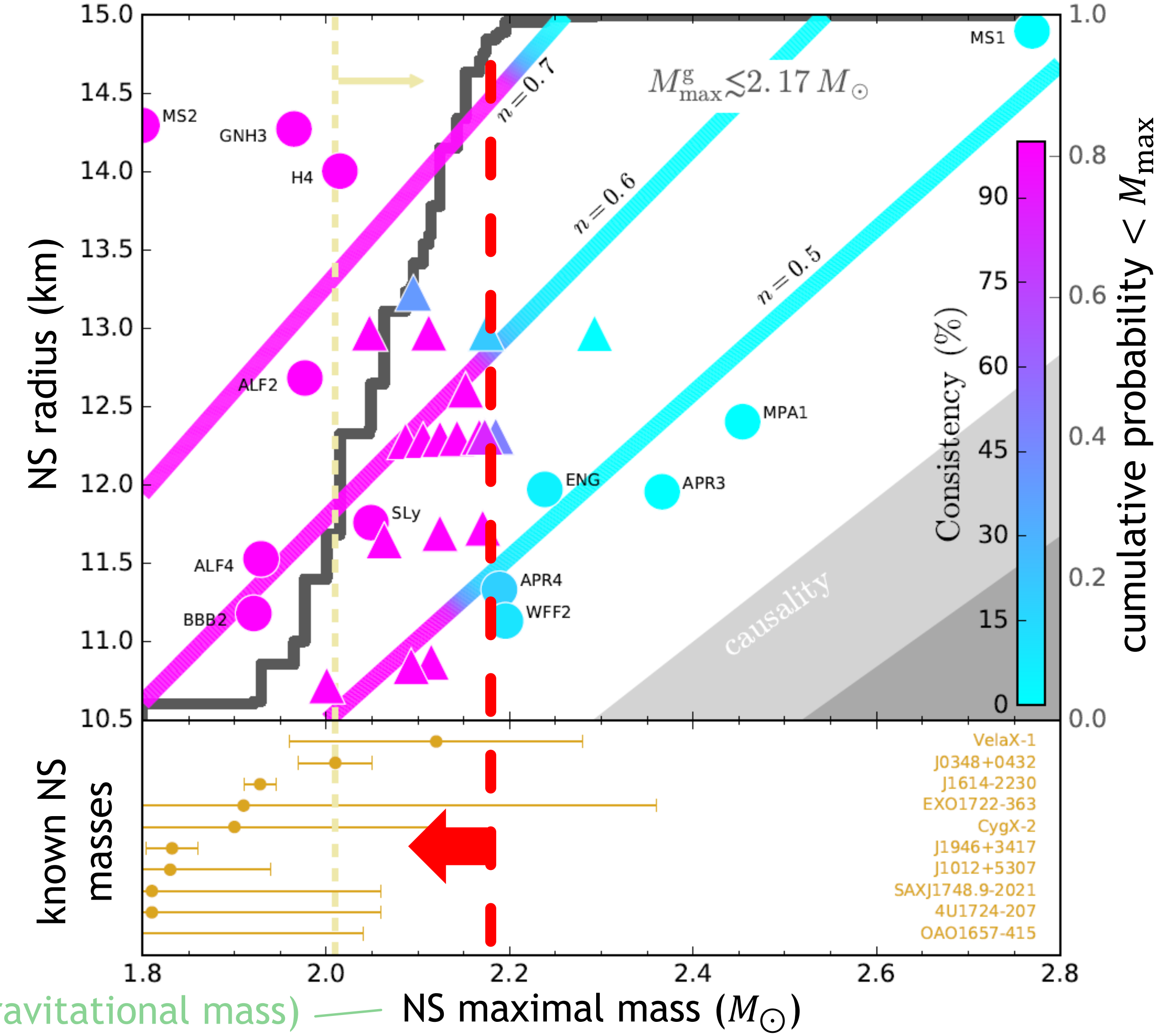

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Application to GW170817: (III) $M_{\rm TOV}$ constraints

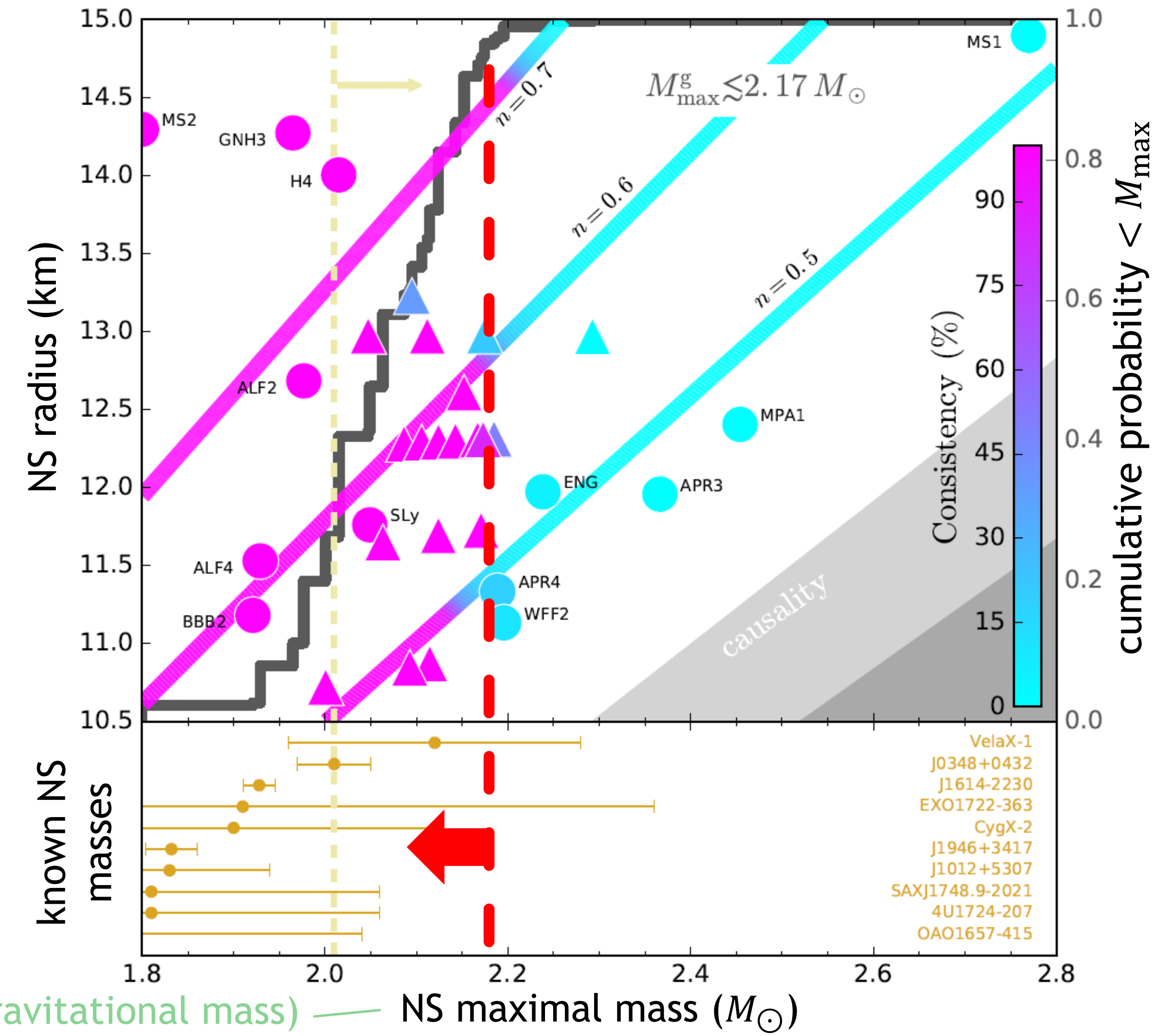
- find $M_{\rm TOV} \lesssim 2.2 M_\odot$ (BM&Metzger17)

  [but see Shibata+19]

- relies only on qualitative categorization (HMNS / SMNS / …)

- not sensitive to quantitative kilonova modeling uncertainties

BM & Metzger (2017)



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Application to GW170817: (IV) $R_{\rm ns}$ constraints

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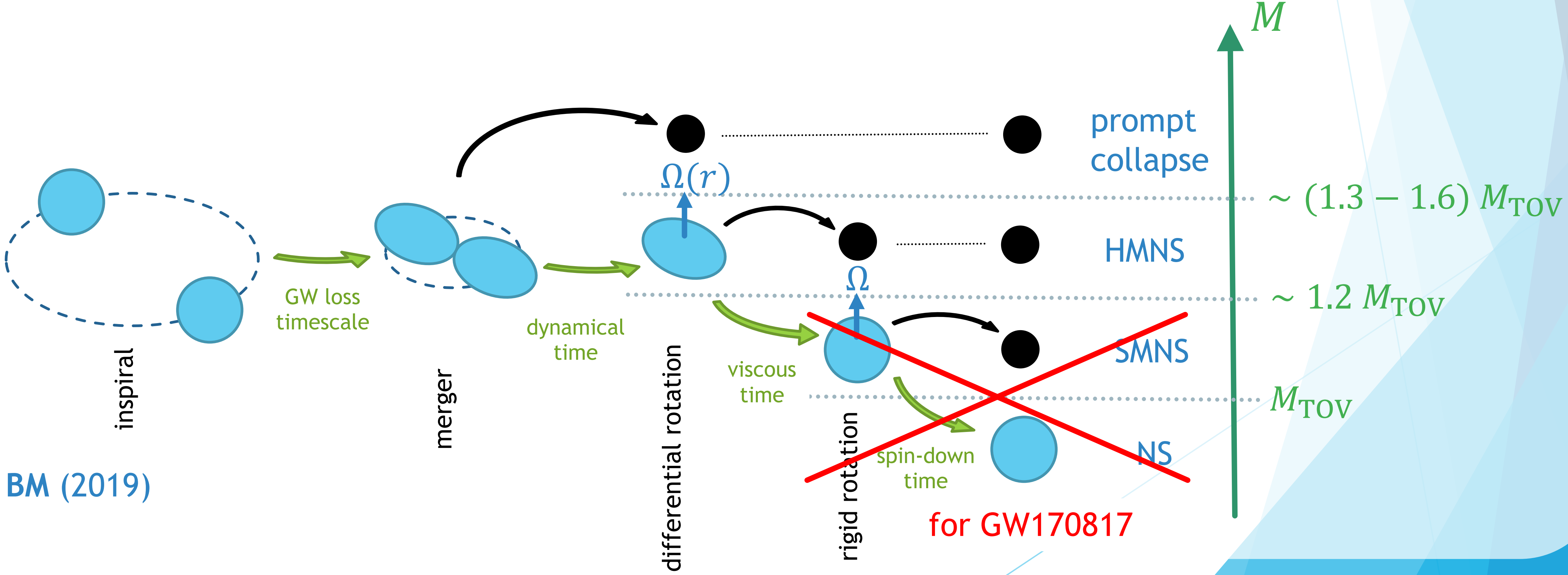
Application to GW170817: (IV) R_{ns} constraints



BM (2019)

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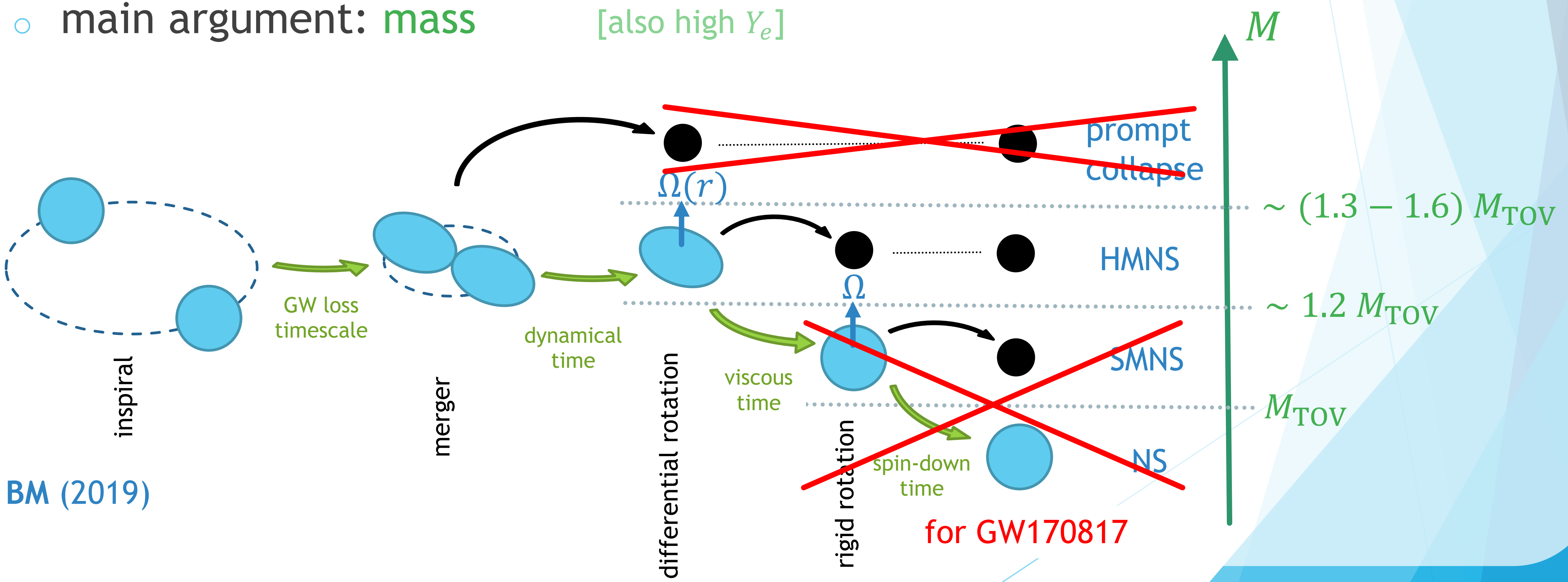
Application to GW170817: (IV) $R_{\rm ns}$ constraints

- rule out prompt-collapse
- main argument: mass [also high Y_e]



BM (2019)

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Application to GW170817: (IV) $R_{\rm ns}$ constraints

- GW170817 ejecta likely dominated by disk outflows

  (e.g. Siegel & Metzger 2017)

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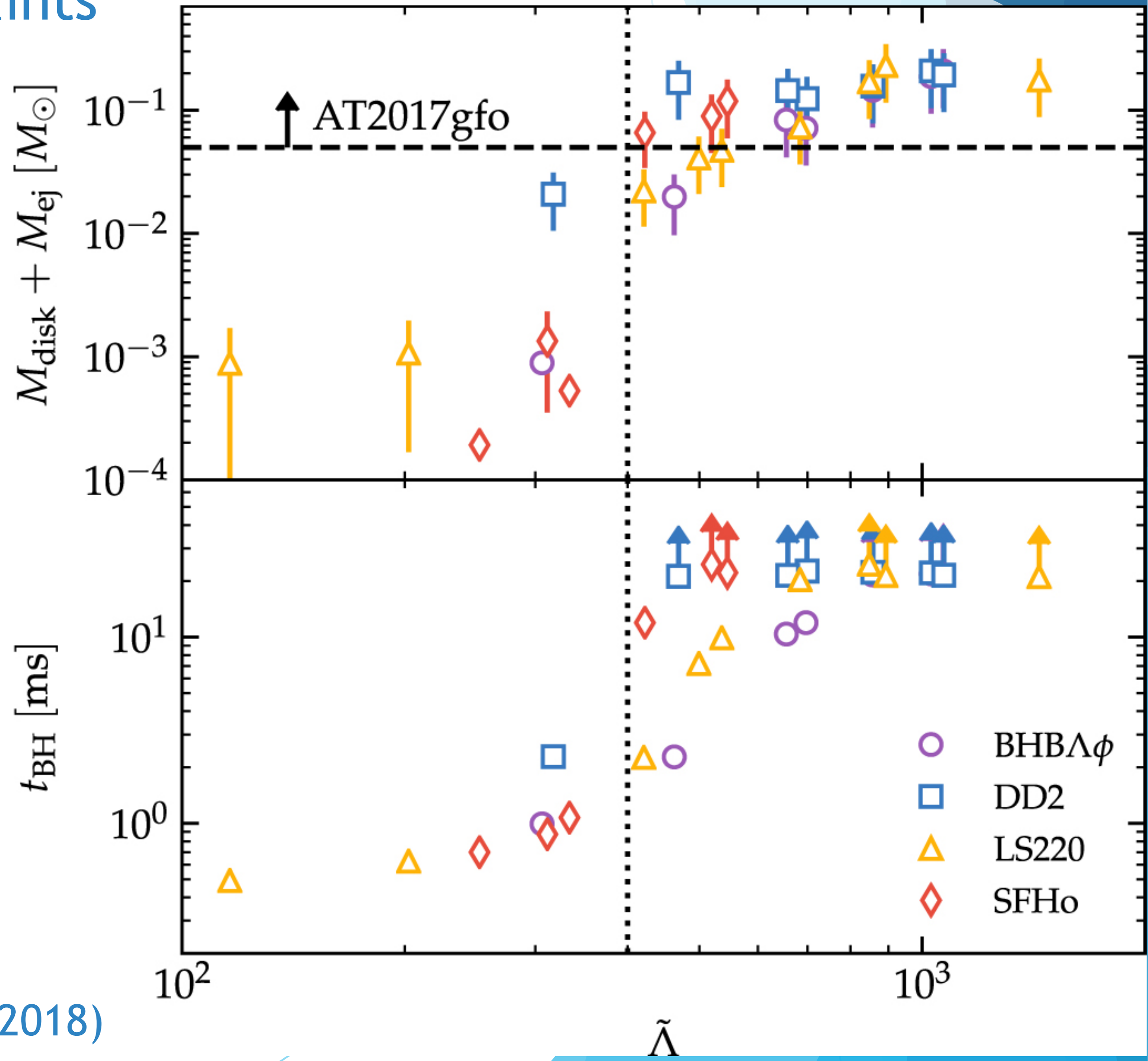

Radice + (2018)

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Application to GW170817: (IV) $R_{\rm ns}$ constraints

- GW170817 ejecta likely dominated by disk outflows

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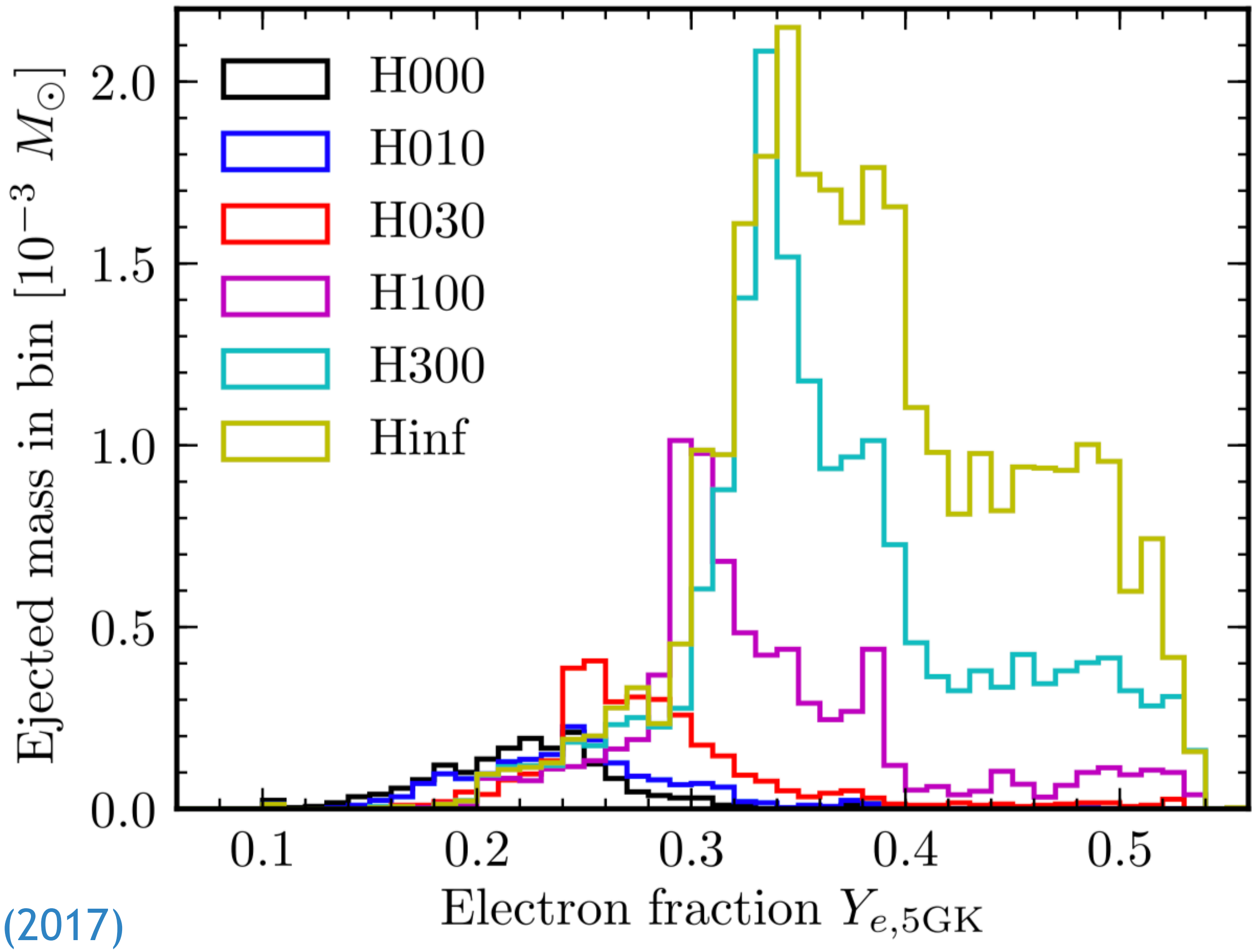
- disk mass increases sharply if remnant survives $\gtrsim$ couple ms

- blue kilonova also suggests remnant survived for some time



Lippuner + (2017)

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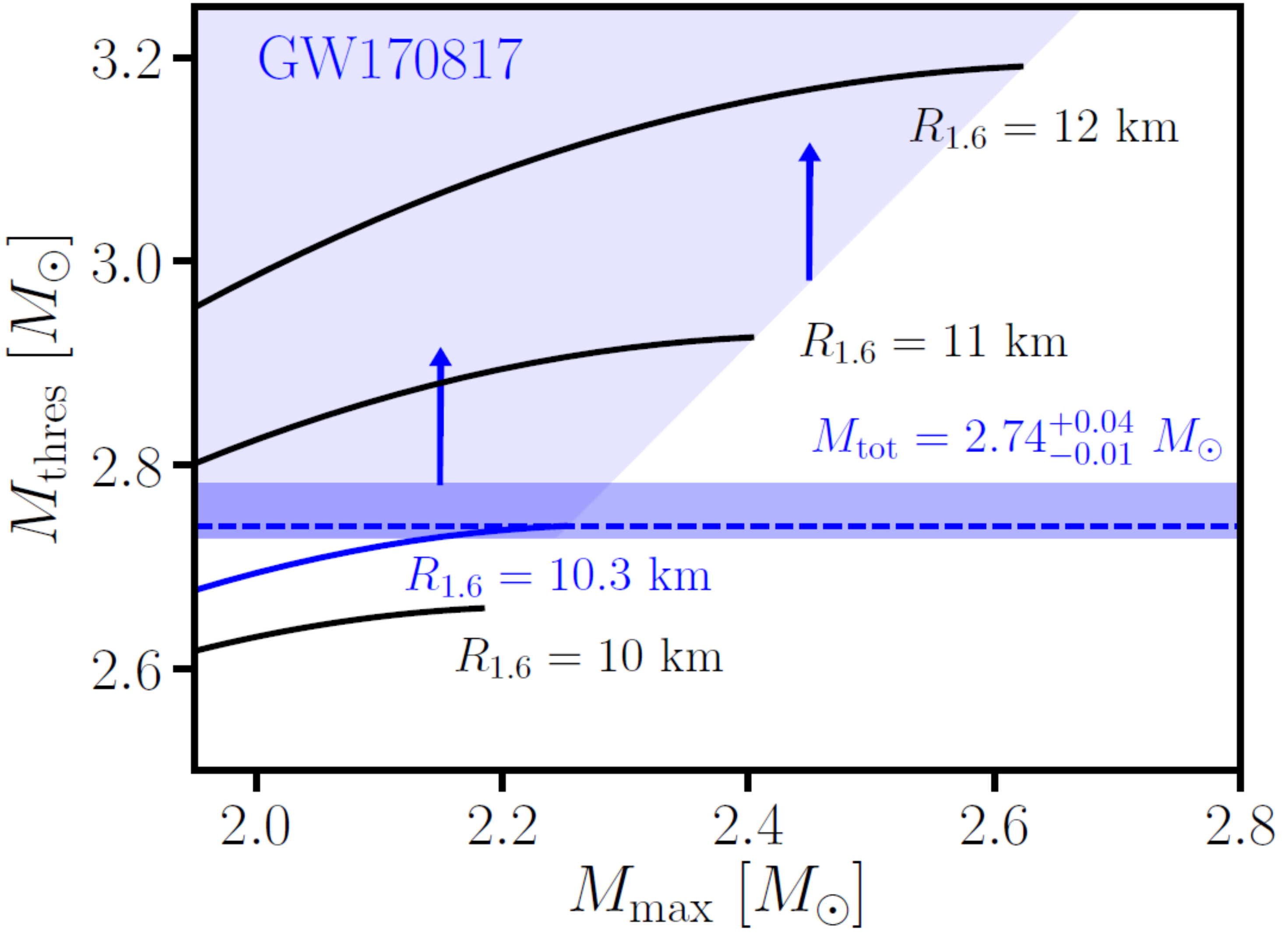
Application to GW170817: (IV) $R_{\rm ns}$ constraints

Bauswein + (2017)

- prompt-collapse threshold:

$$M_{\rm thres} \approx f\left(\frac{M_{\rm TOV}}{R_{1.6}}\right) \times M_{\rm TOV}$$

(Bauswein+13; but see Kiuchi+19)



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- prompt-collapse threshold:

$$M_{\rm thres} \approx f\left(\frac{M_{\rm TOV}}{R_{1.6}}\right) \times M_{\rm TOV}$$

(Bauswein+13; but see Kiuchi+19)

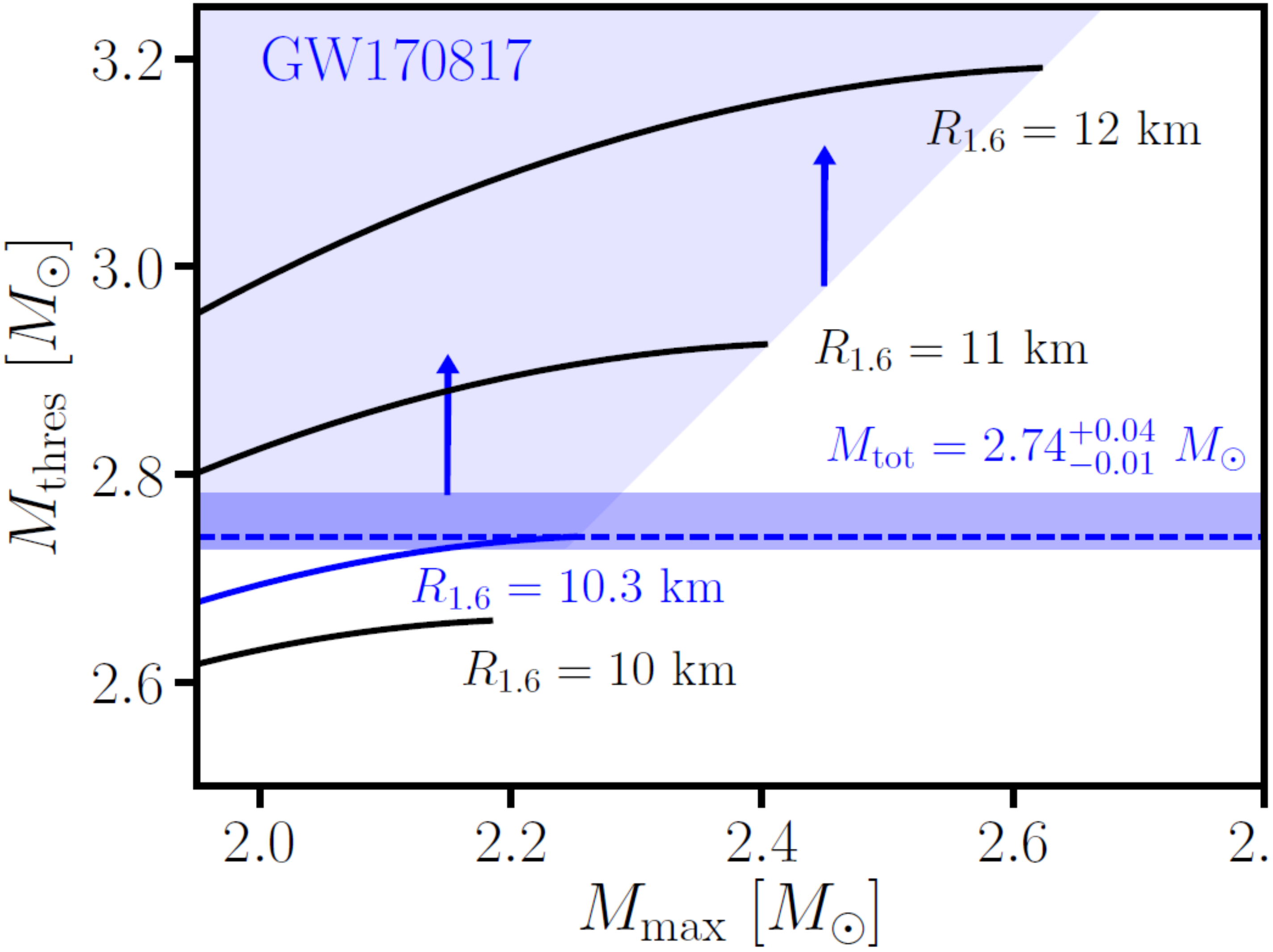
- $M_{\rm thres} > M_{\rm GW170817} \simeq 2.74 M_{\odot}$

+ causality

$\Rightarrow \quad R_{1.6} > 10.3\ \mathrm{km}$

(Bauswein+17)

Bauswein + (2017)



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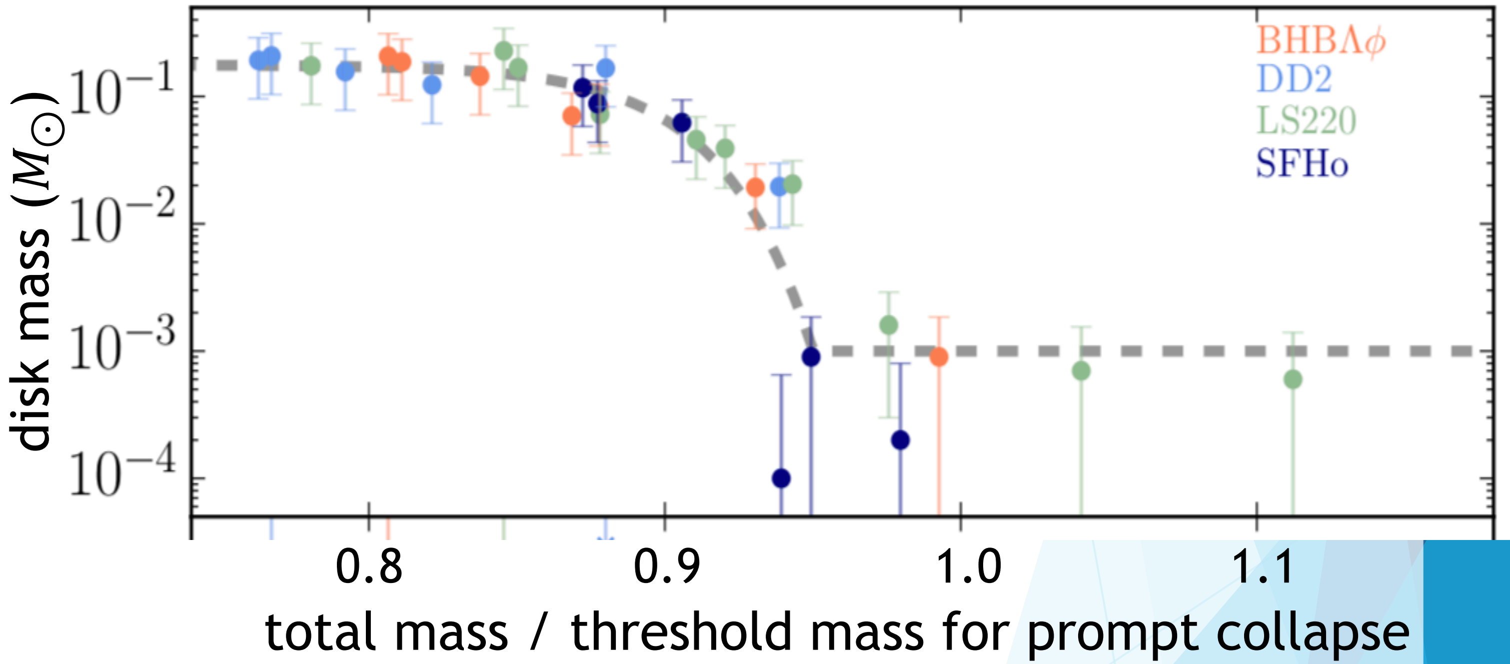
Additional Multi-Messenger Constraints:

(but model dependent)

- additional constraints from fitting kilonova ejecta properties
  - identify ejecta source (dynamical / disk winds)
  - ejecta mass & velocity depend on binary parameters and EOS

Coughlin, Dietrich, **BM** + (2019)



(see also Radice+18; Radice&Dai19)

NS Merger Remnants and the nuclear EOS

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[and multi-messenger astrophysics]

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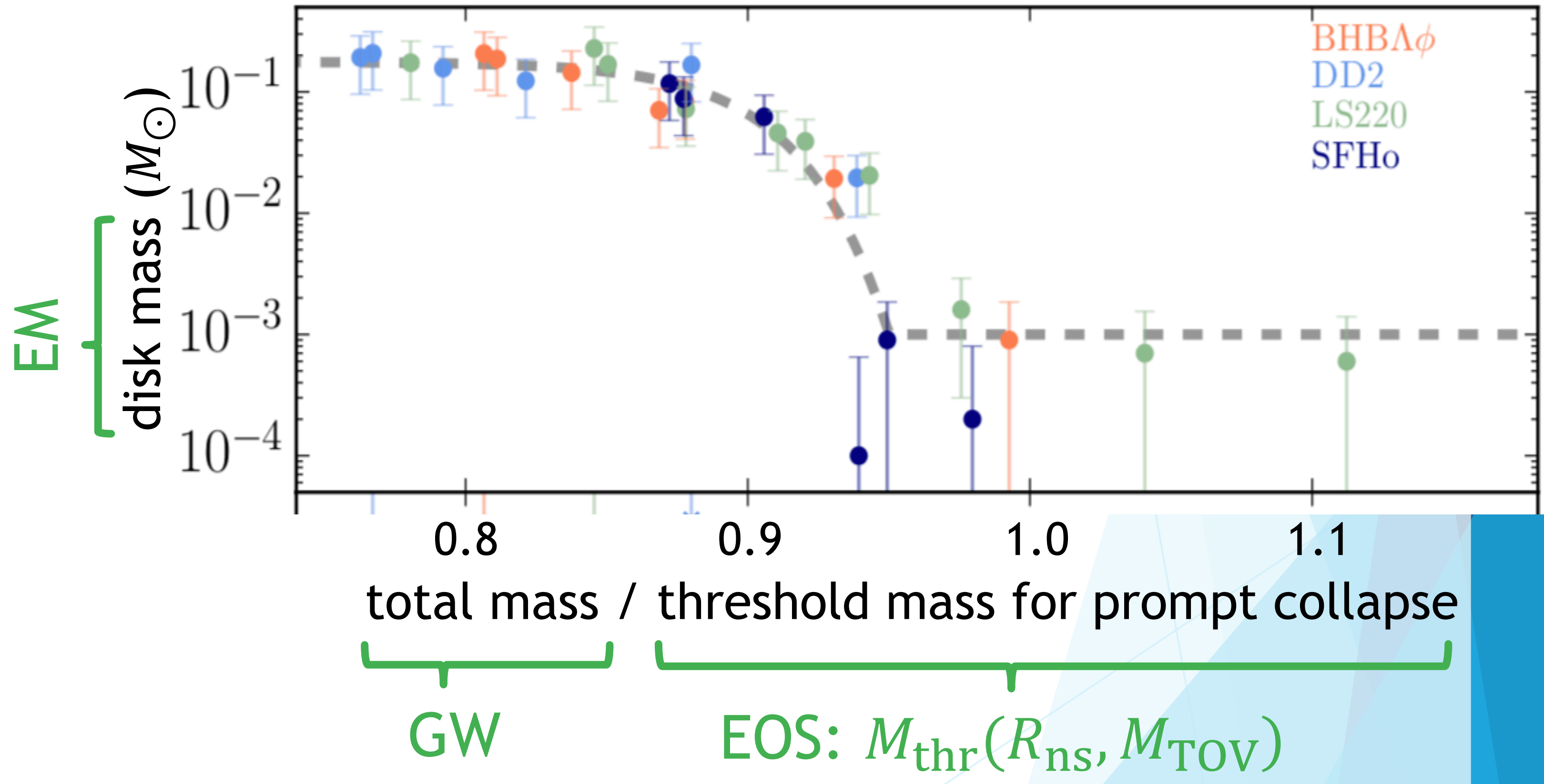

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Future Outlook:

- rich landscape

(bright future)

NS Merger Rem

BM & Metzger (2019)

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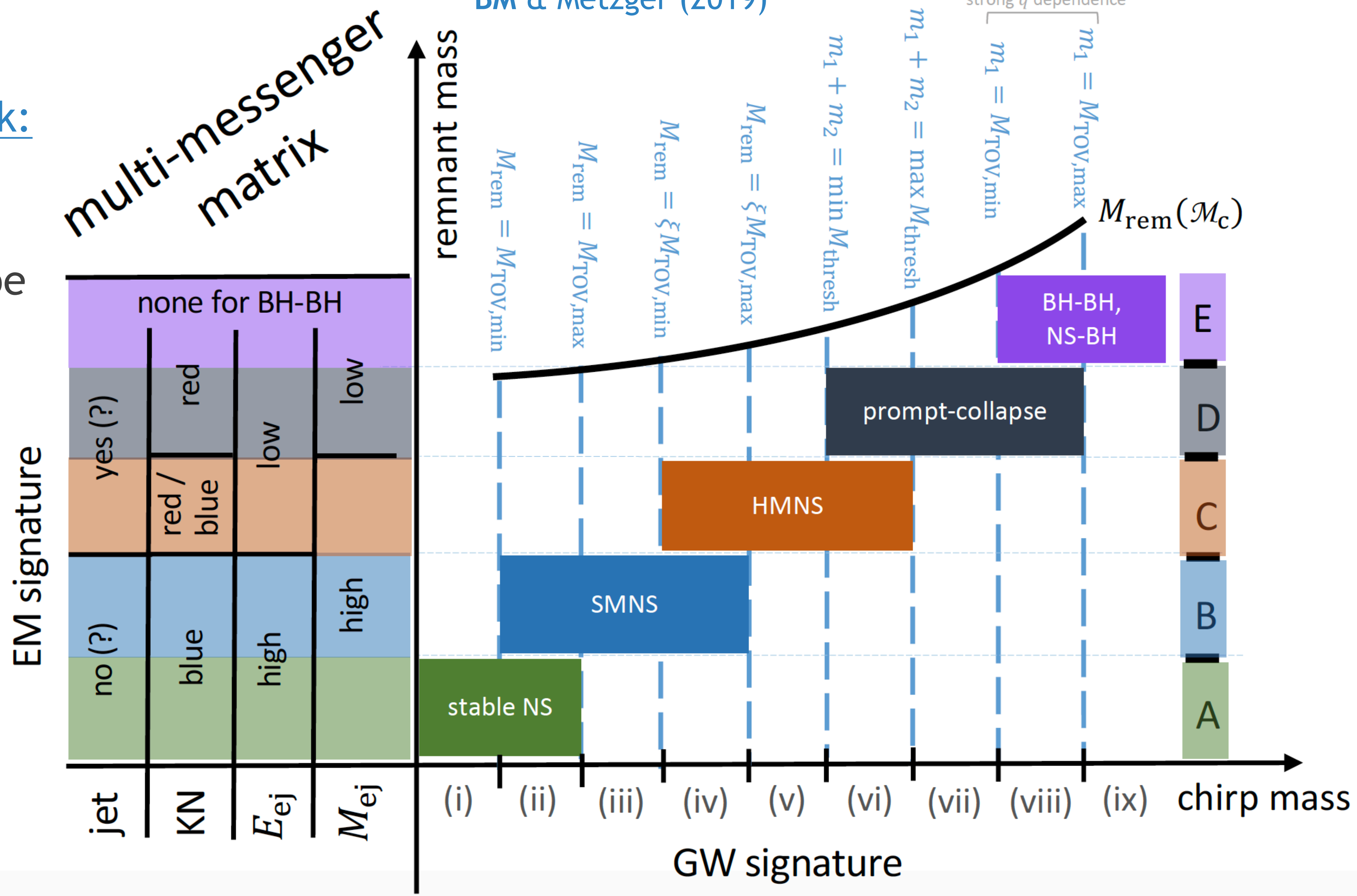

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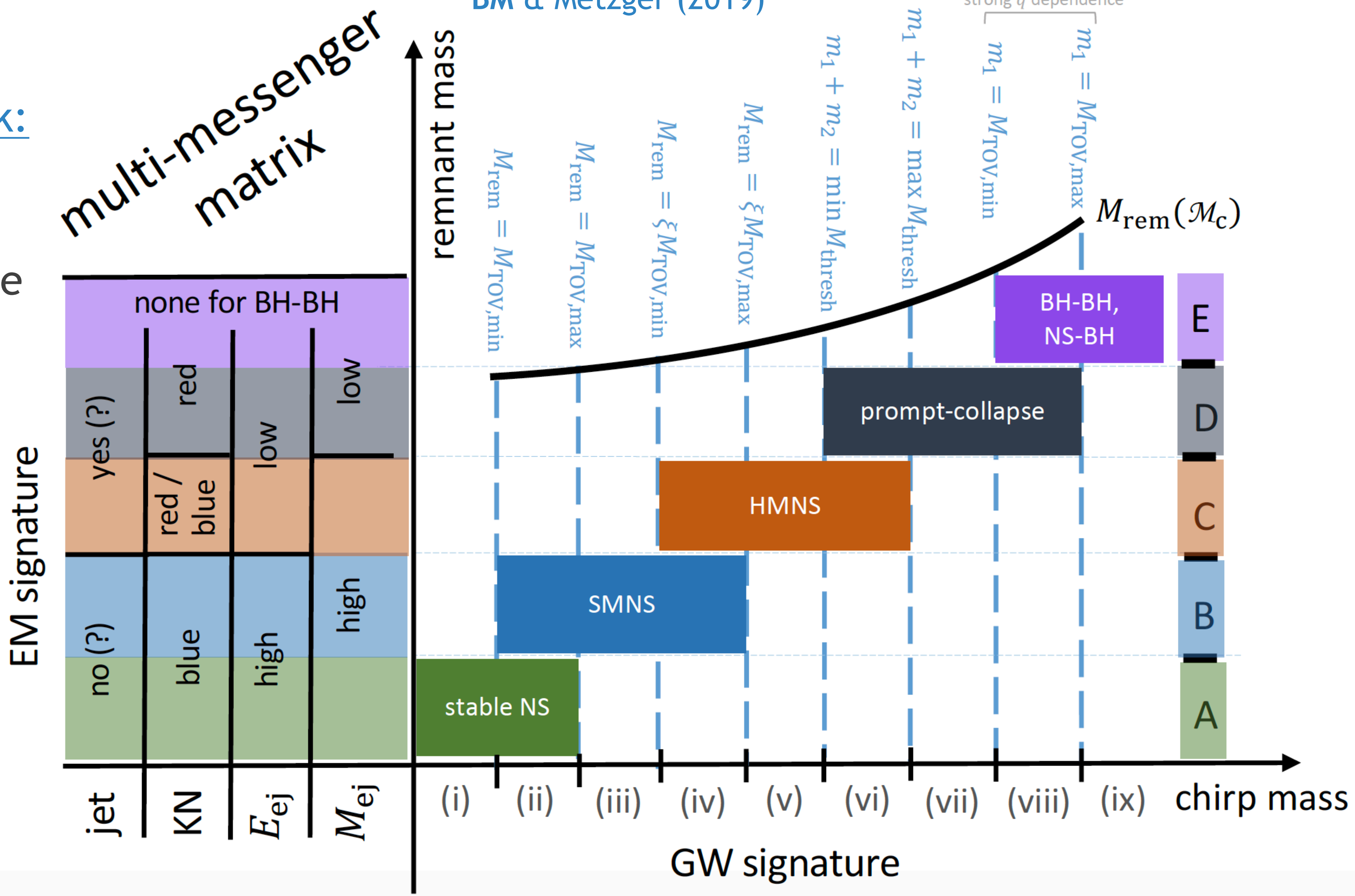

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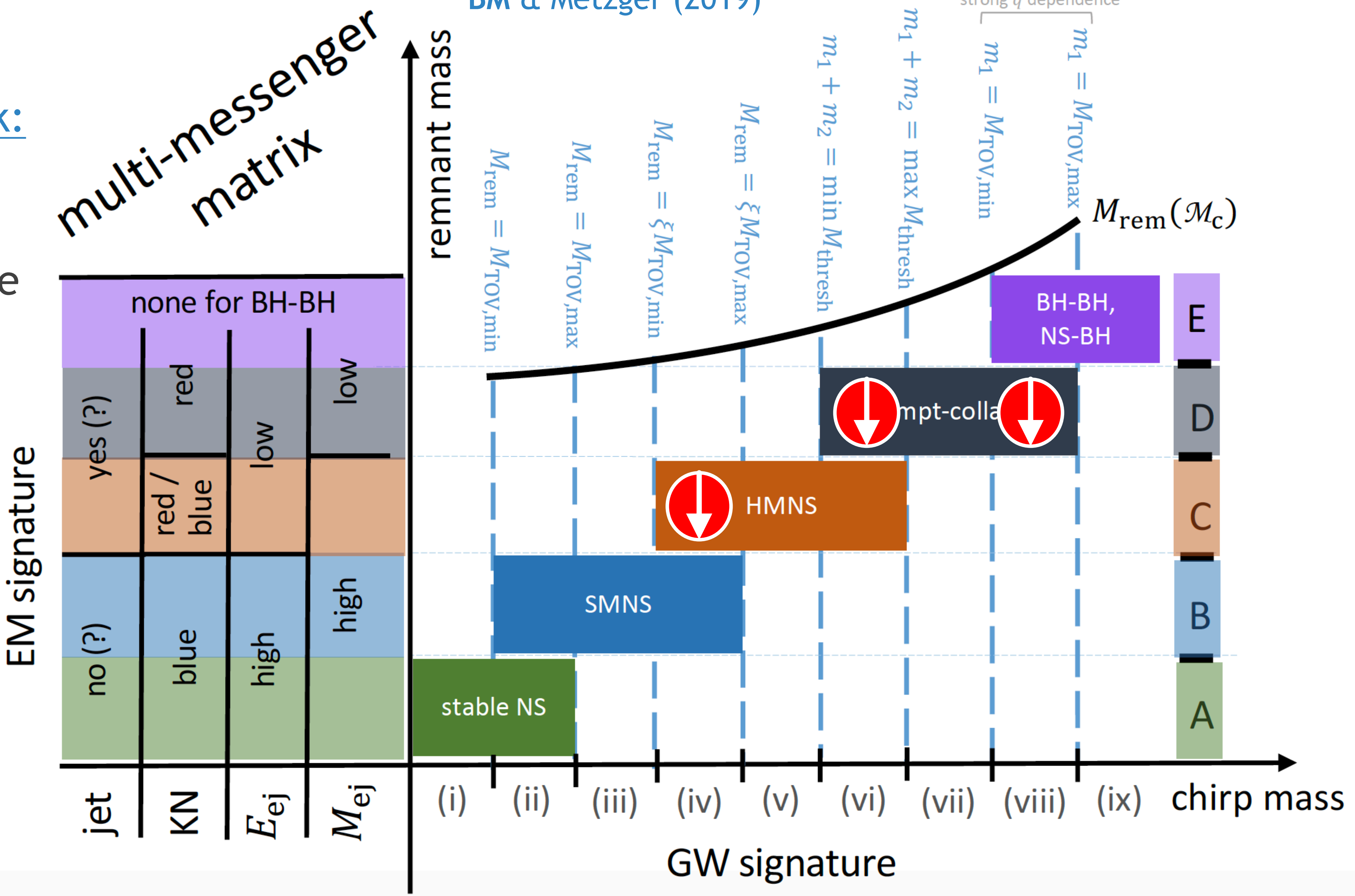

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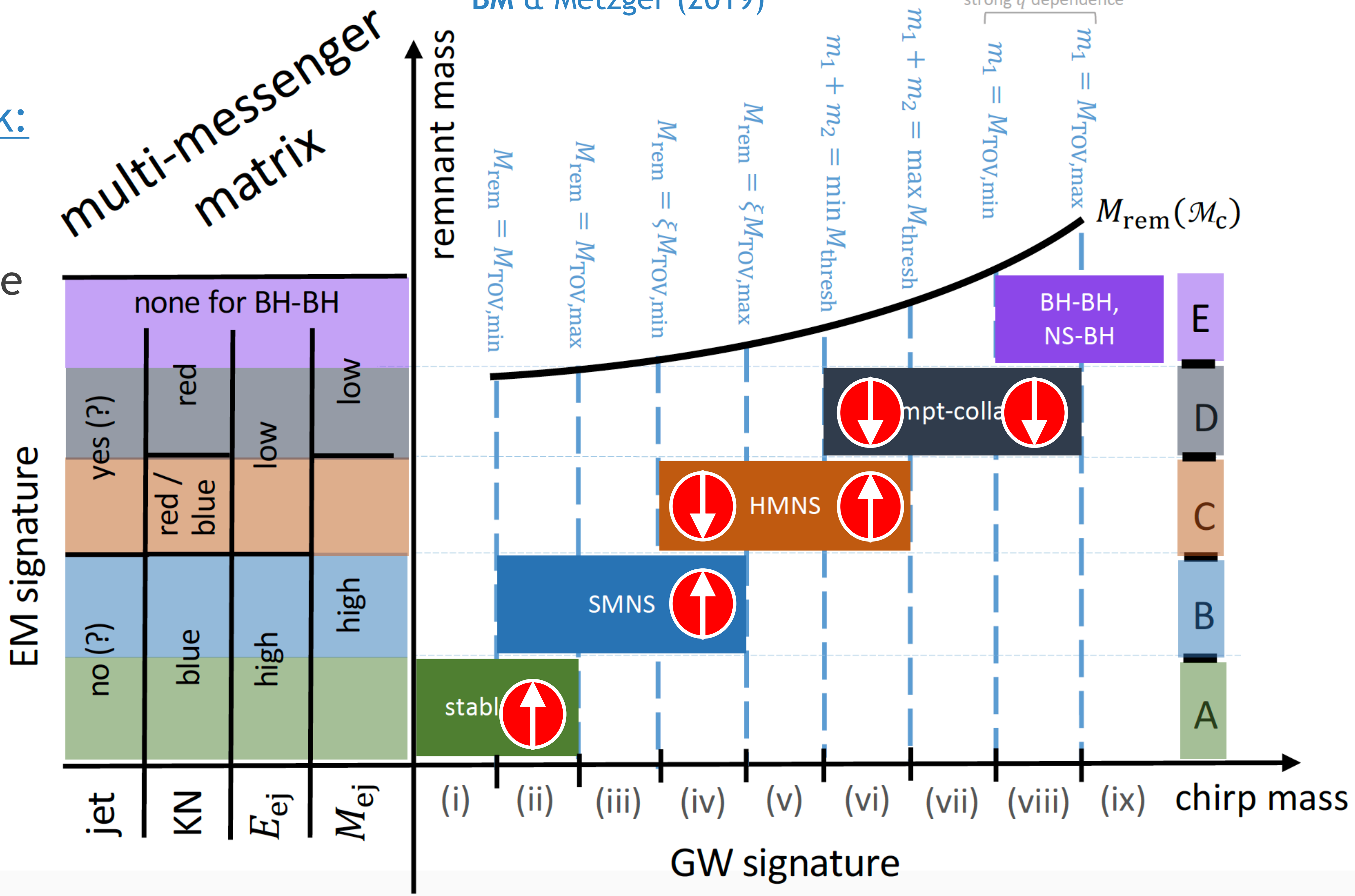

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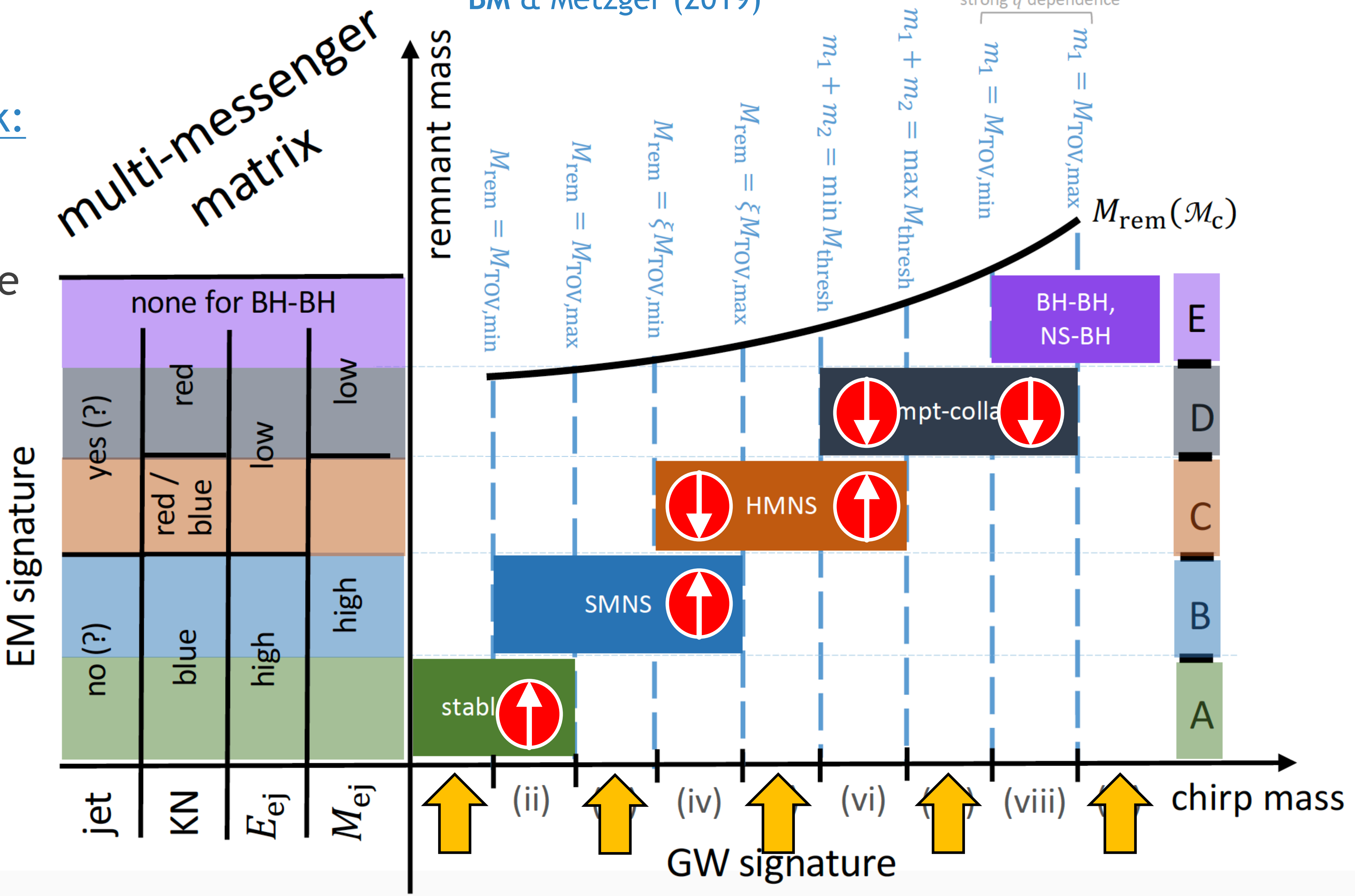

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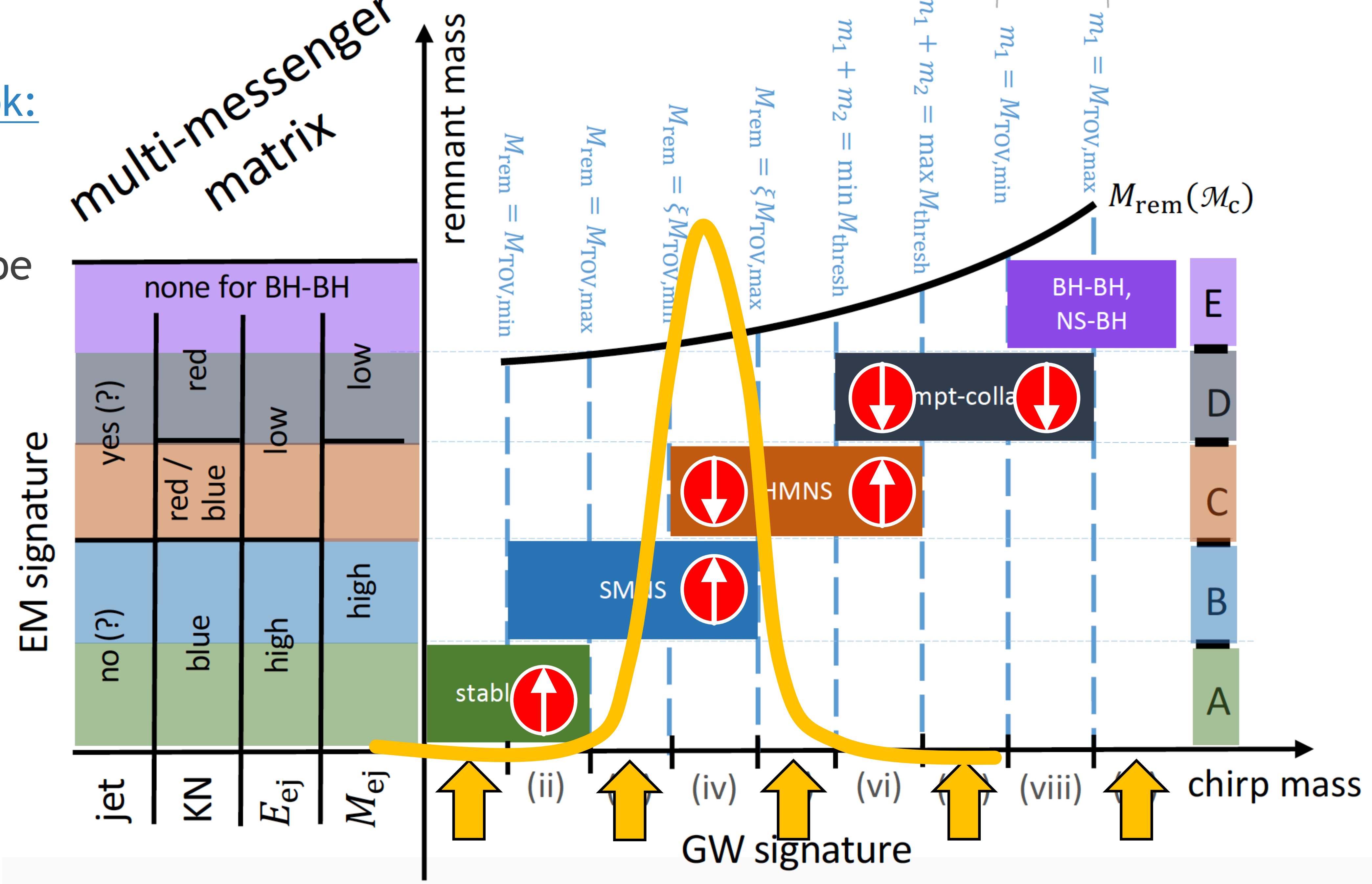

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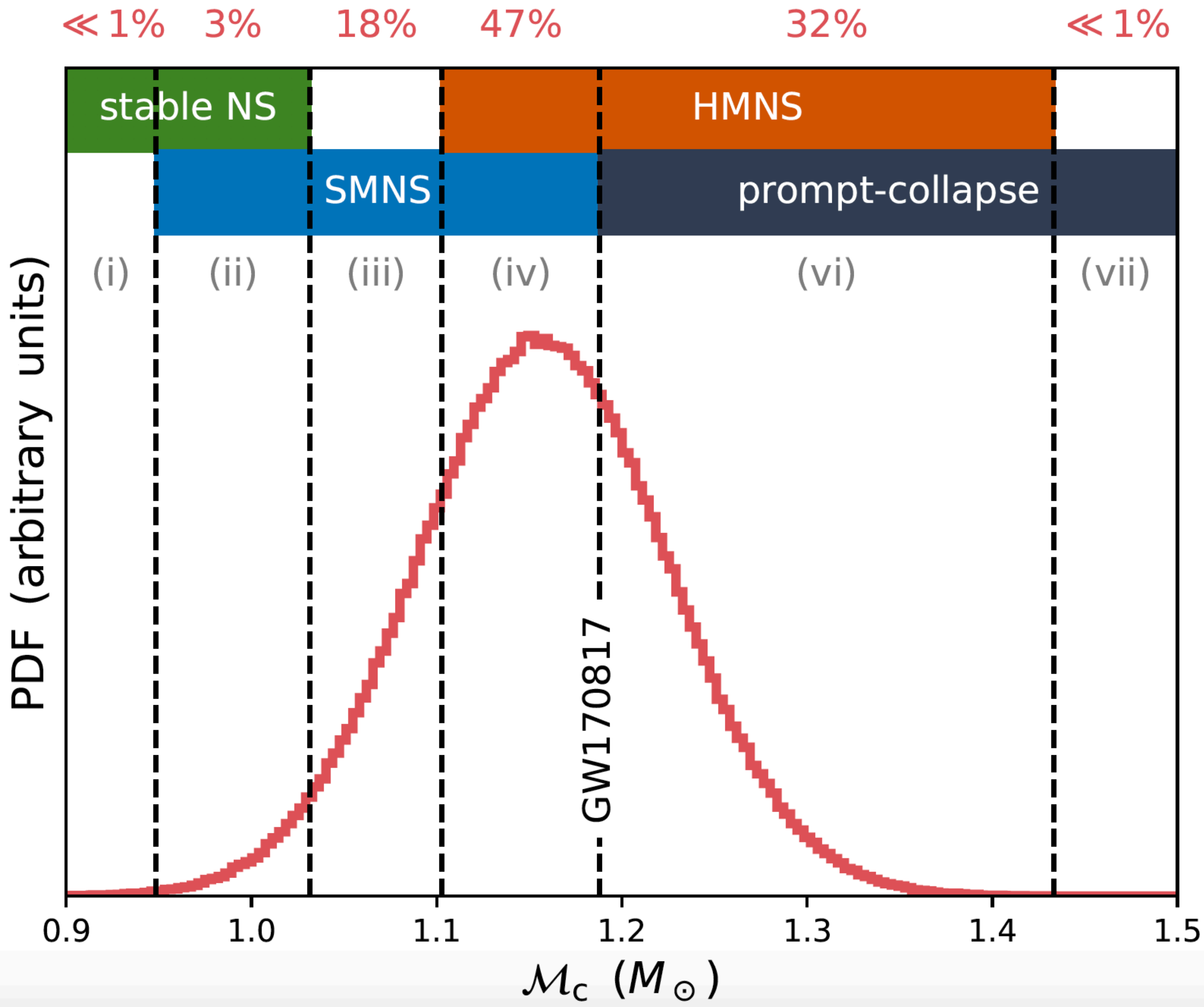
Future Outlook:

- for Galactic distribution of binary NSs (Kiziltan+13)

EOS learning opportunities & predictions!

BM & Metzger (2019)



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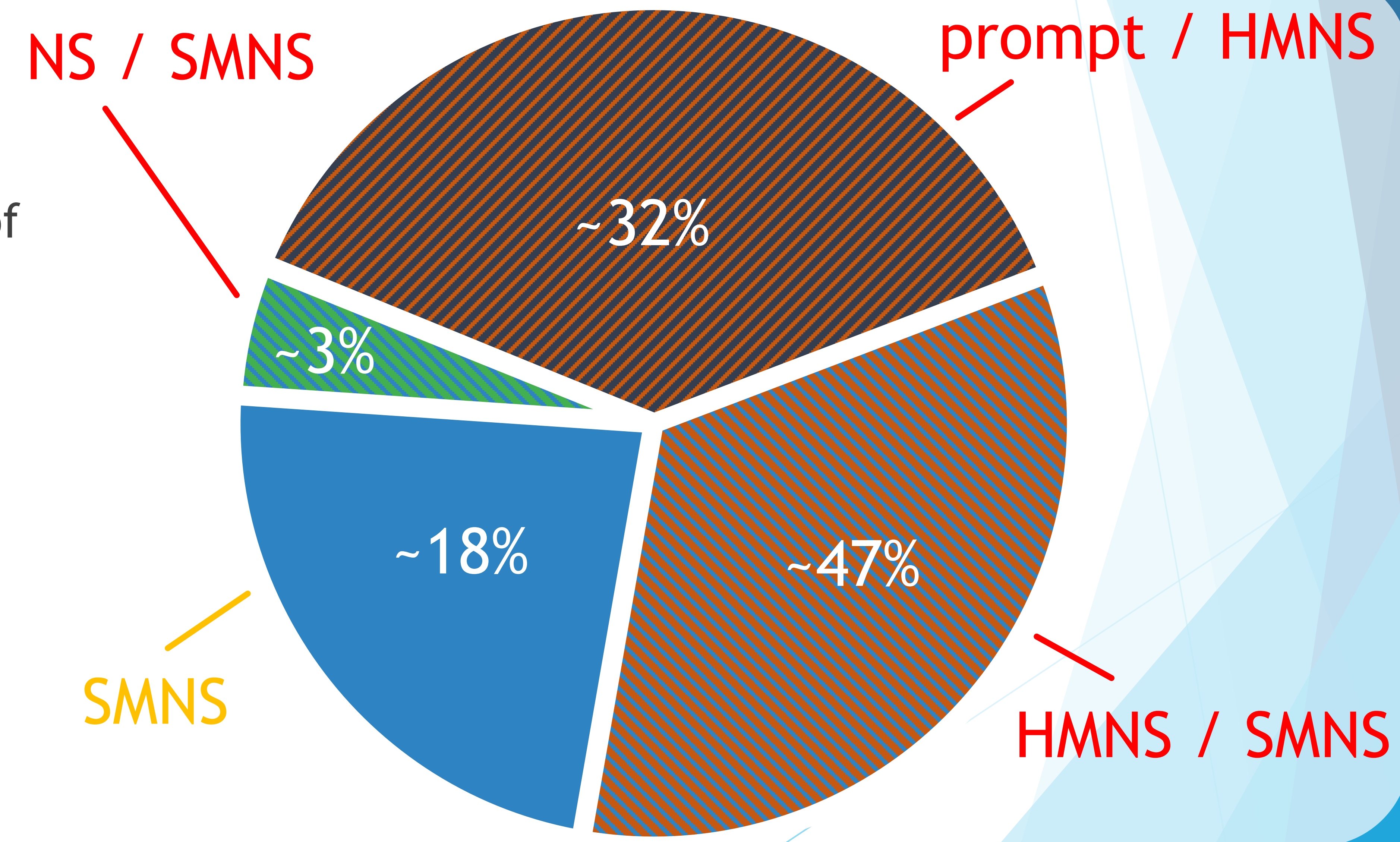

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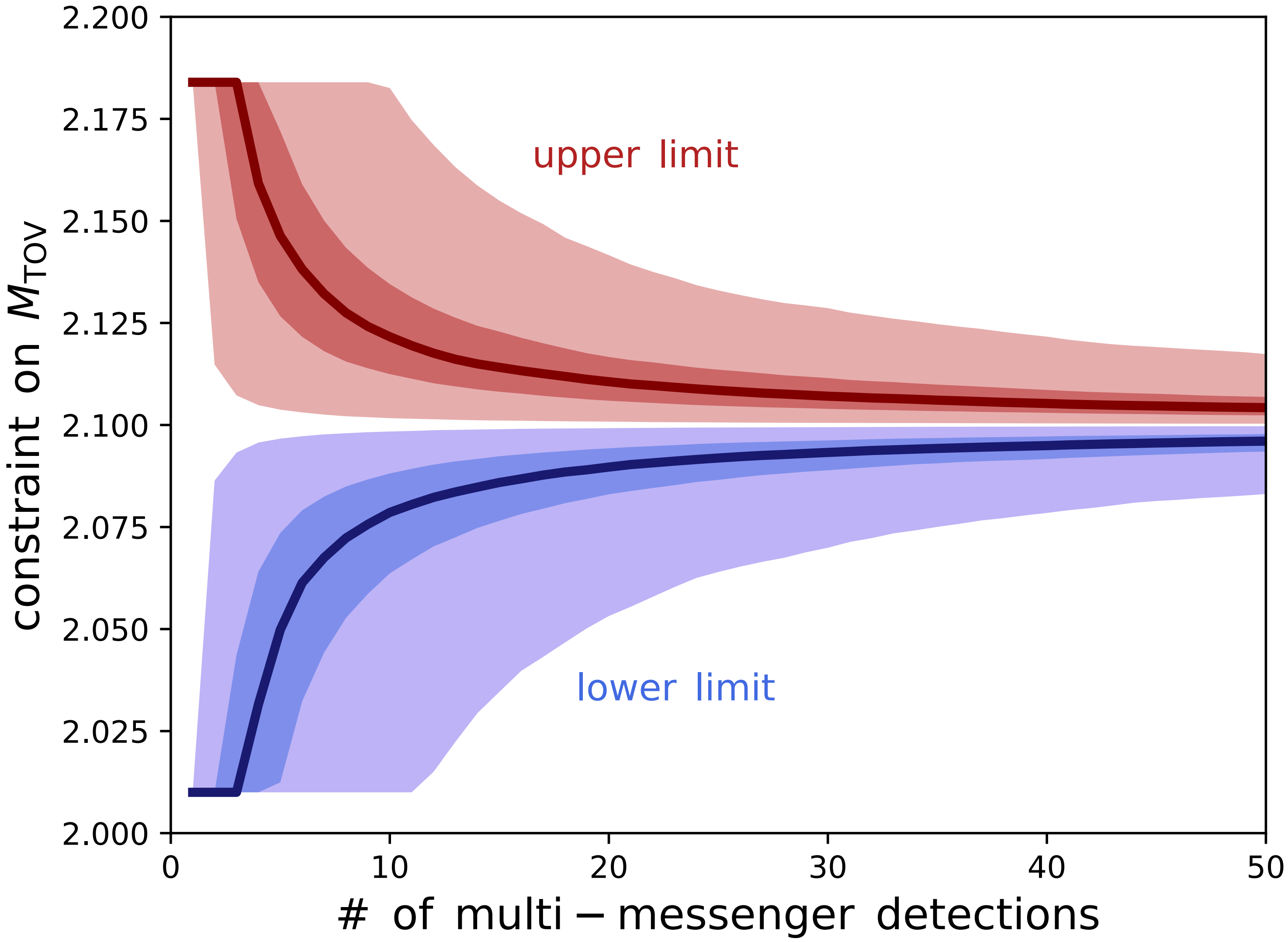

NS Merger Remnants and the nuclear EOS

[and multi-messenger astrophysics]

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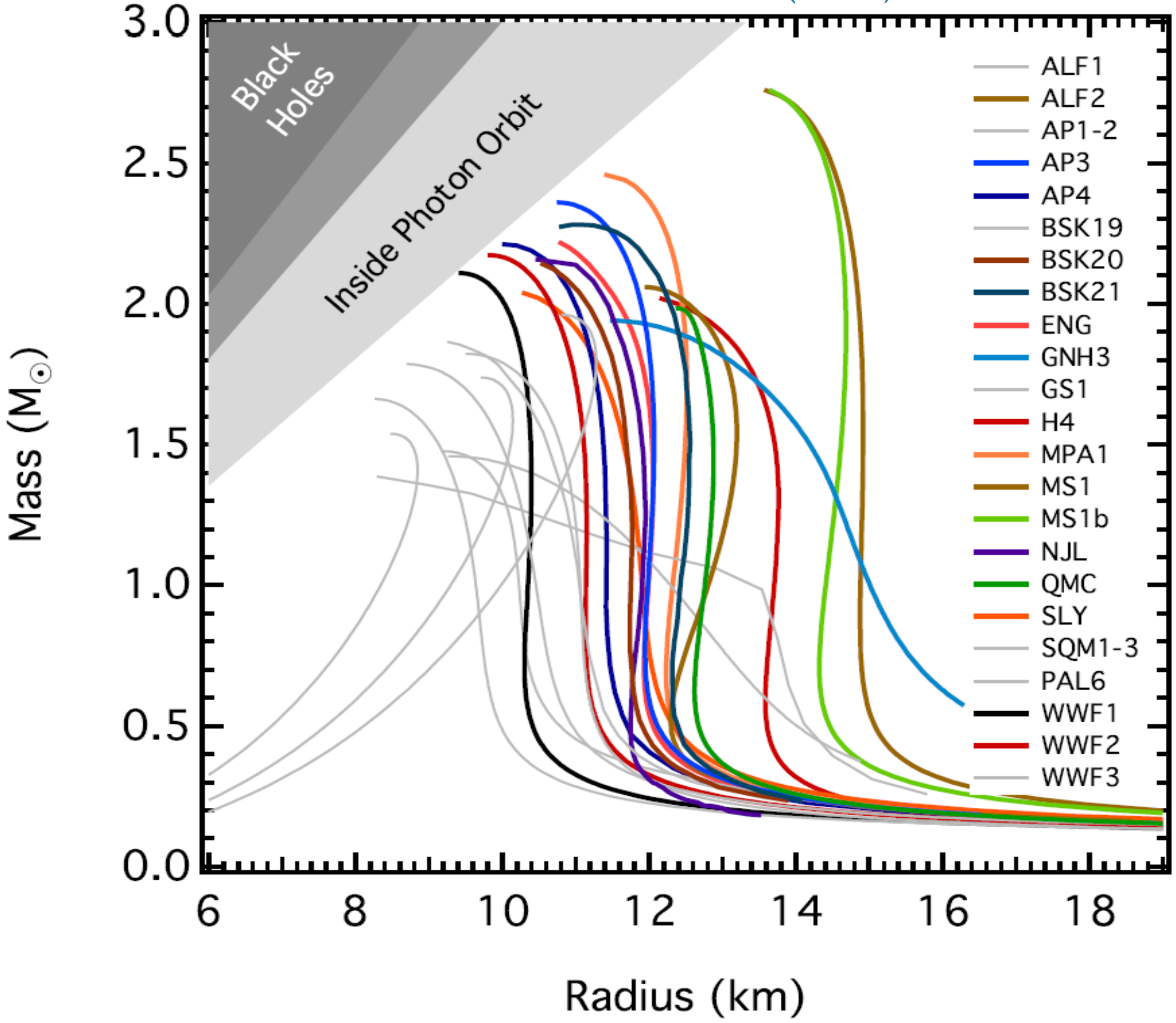
Summary of EOS Constraints:

- multi-messenger methods complementary to GW-only constraints

  (tidal deformability, post-merger signals, …)

- future multi-messenger observations can further constrain EOS

Ozel & Freire (2016)



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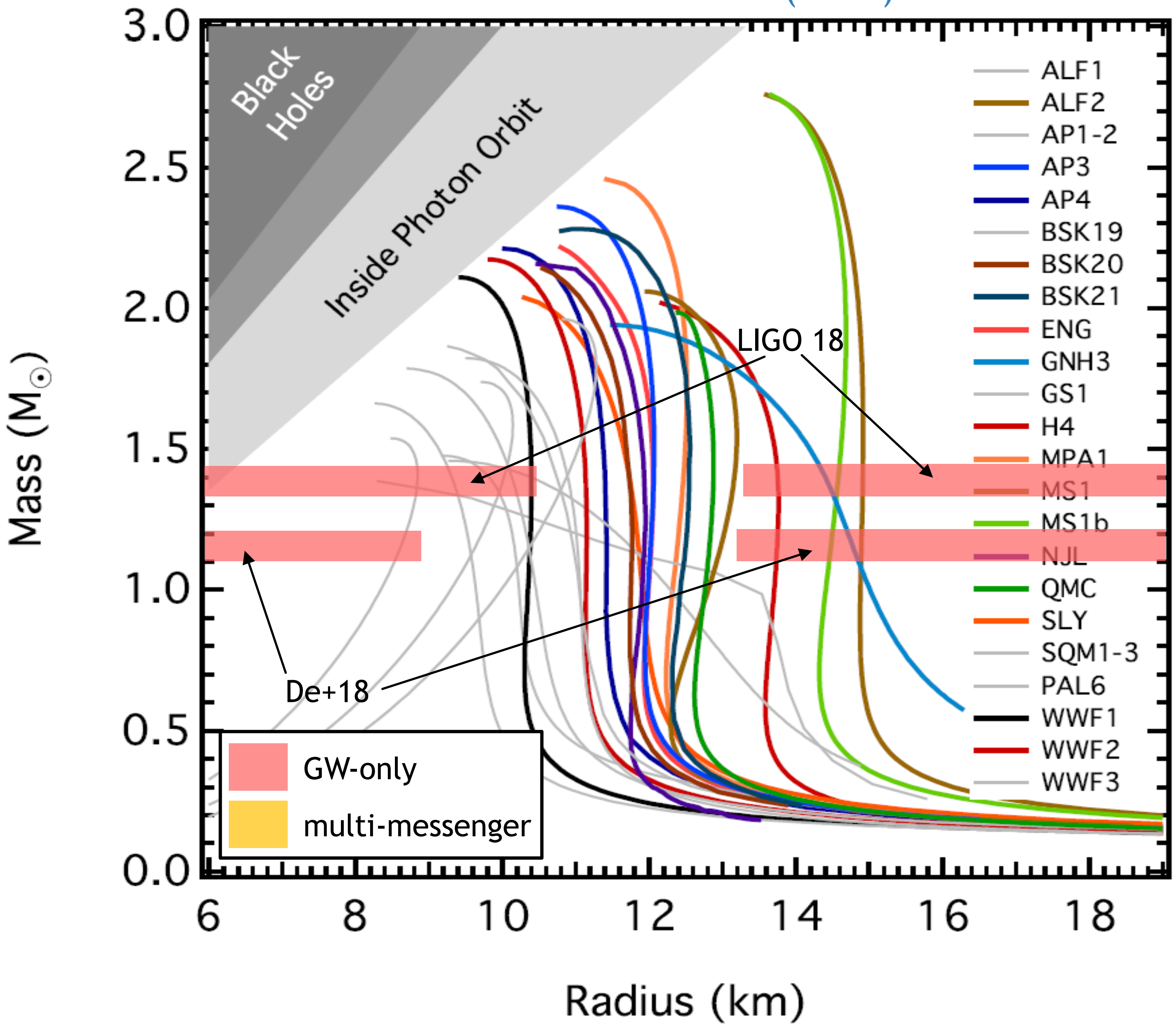

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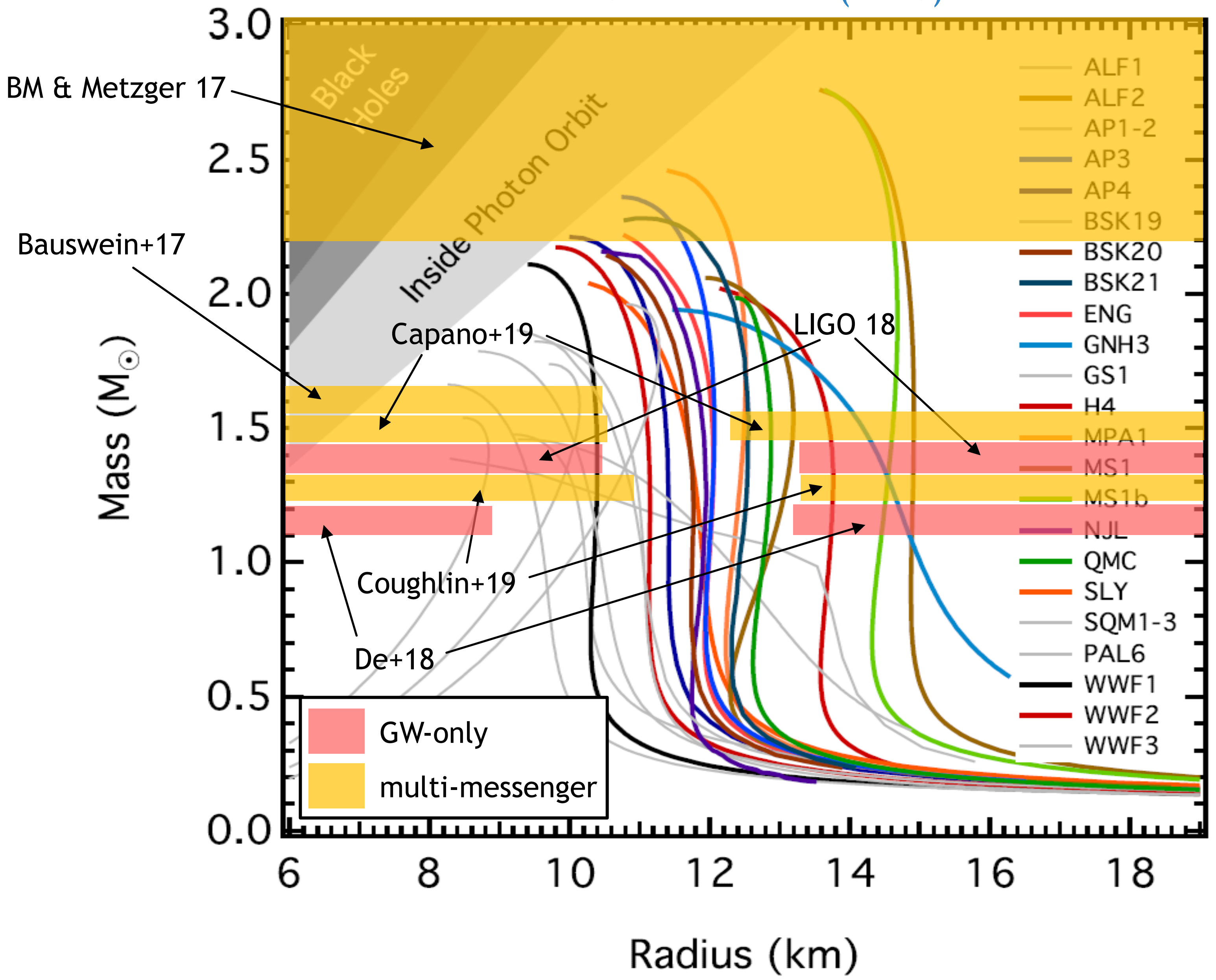

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Other implications:

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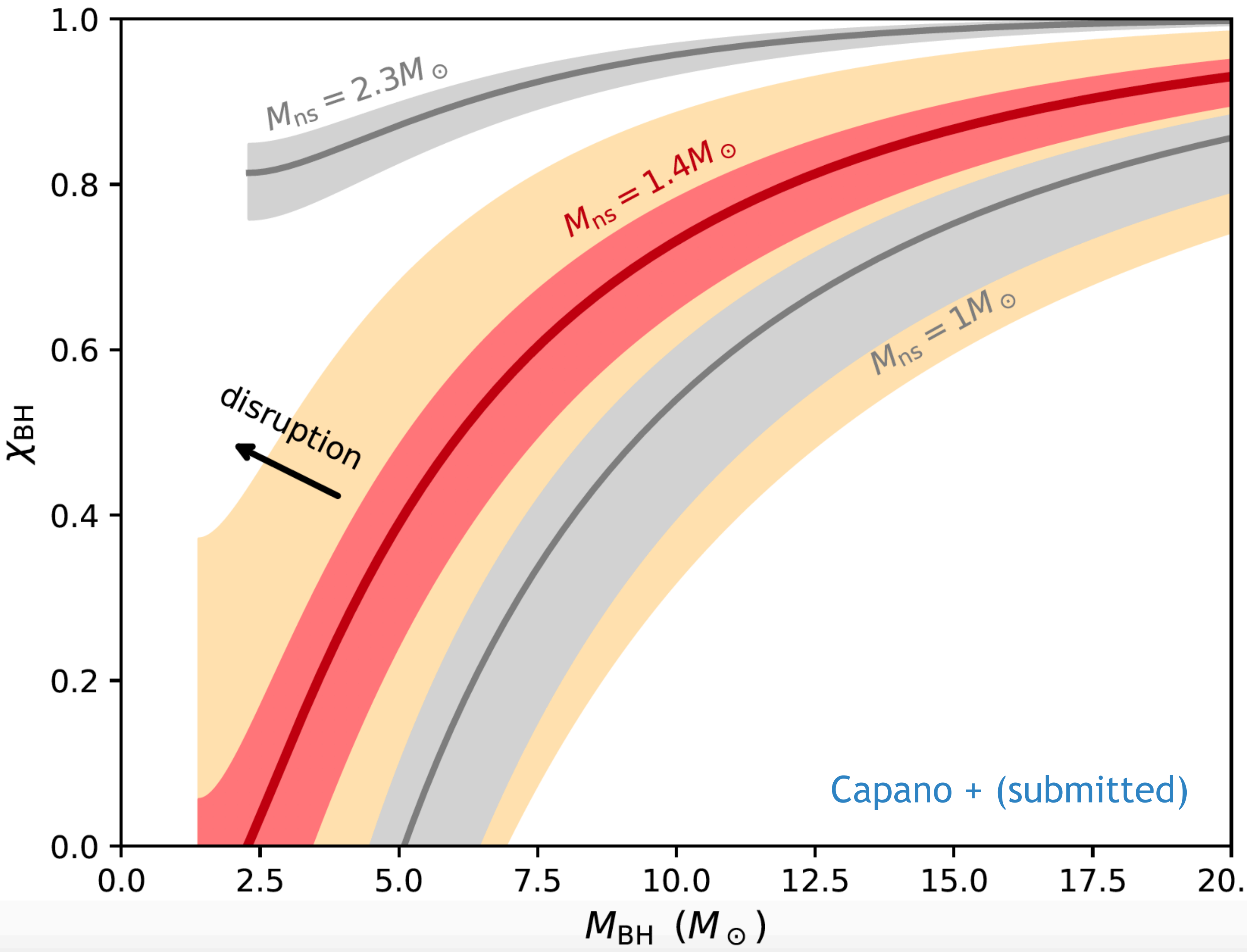
Other implications:

- small R_{ns} implies BH-NS mergers may not disrupt NS!

  [unless high BH spin]

c.f. Foucart+17



NS Merger Remnants and the nuclear EOS

[and multi-messenger astrophysics]

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Other implications:

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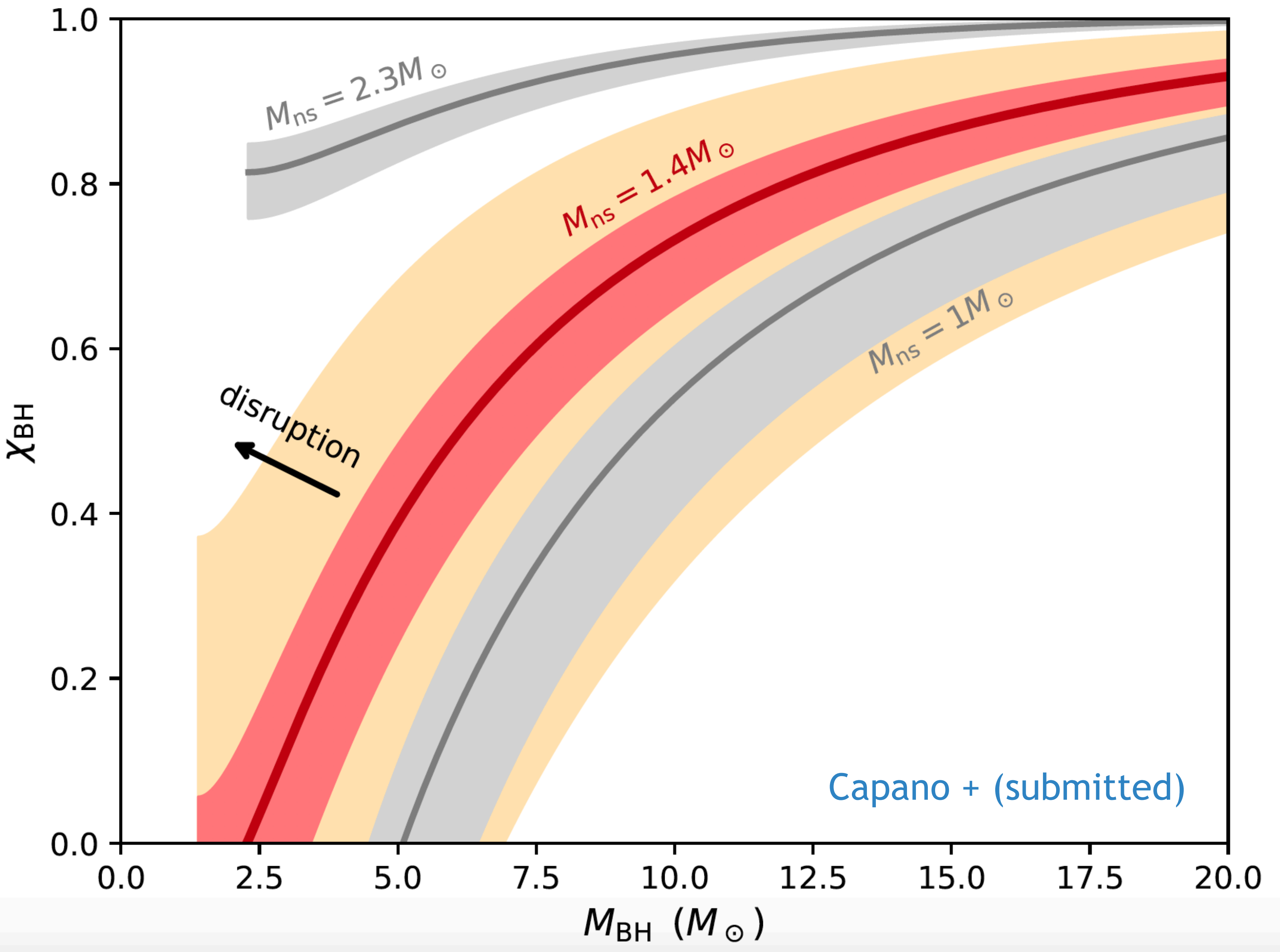
- no kilonova / GRB counterpart ?!

c.f. Foucart+17



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Other implications:

- merger remnant also has implications to GRB models

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  - magnetar models (require SMNS / stable NS remnant)
  - the 'time reversal' scenario (requires SMNS remnant)
    (Ciolfi&Siegel15; Rezzolla&Kumar15)

[though may encounter other difficulties; **BM+15**]

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  - the 'time reversal' scenario (requires SMNS remnant)
    (Ciolfi&Siegel15; Rezzolla&Kumar15)

    [though may encounter other difficulties; **BM**+15]

- radio follow-up of GRBs already constrains scenarios
  (Bower&Metzger14; Fong+16; Horesh+16)

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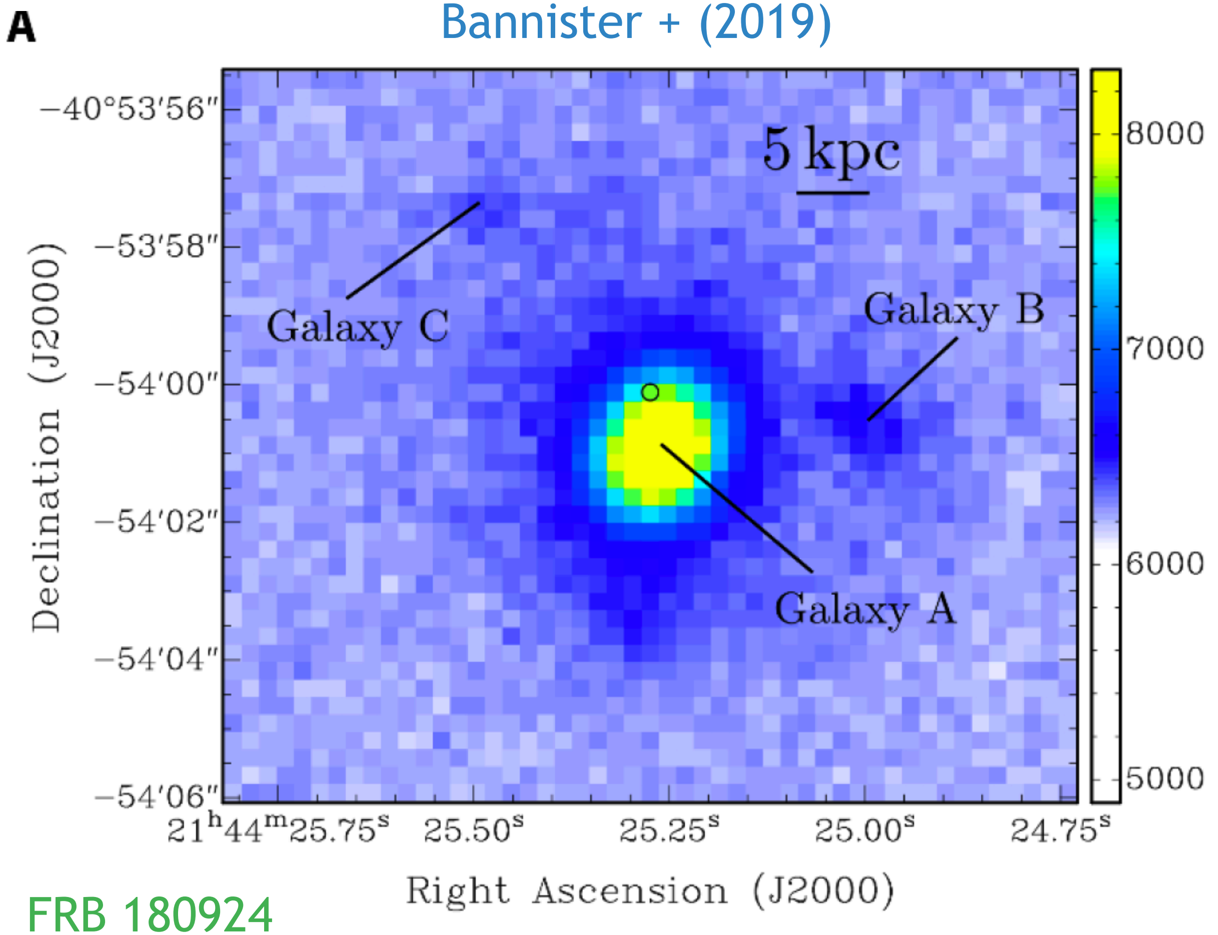
FRBs from BNS mergers?

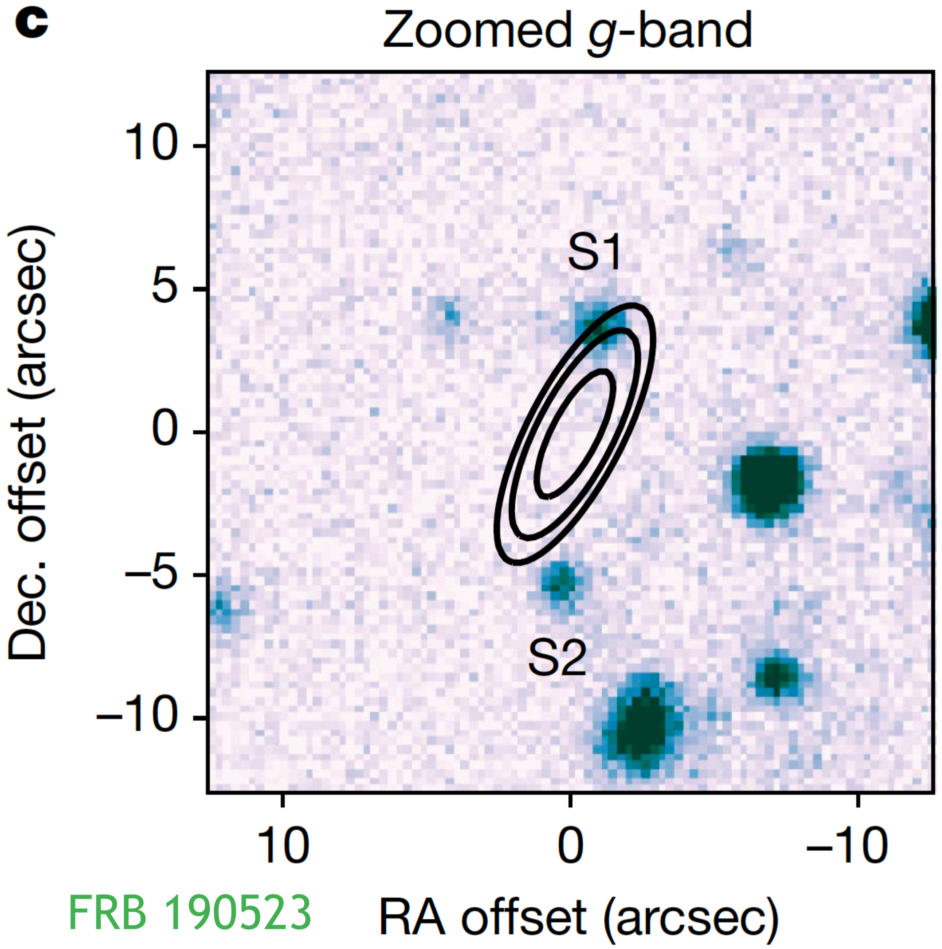
- new localizations in tension with standard magnetar models

Bannister + (2019)



FRB 180924

Ravi + (2019)



FRB 190523

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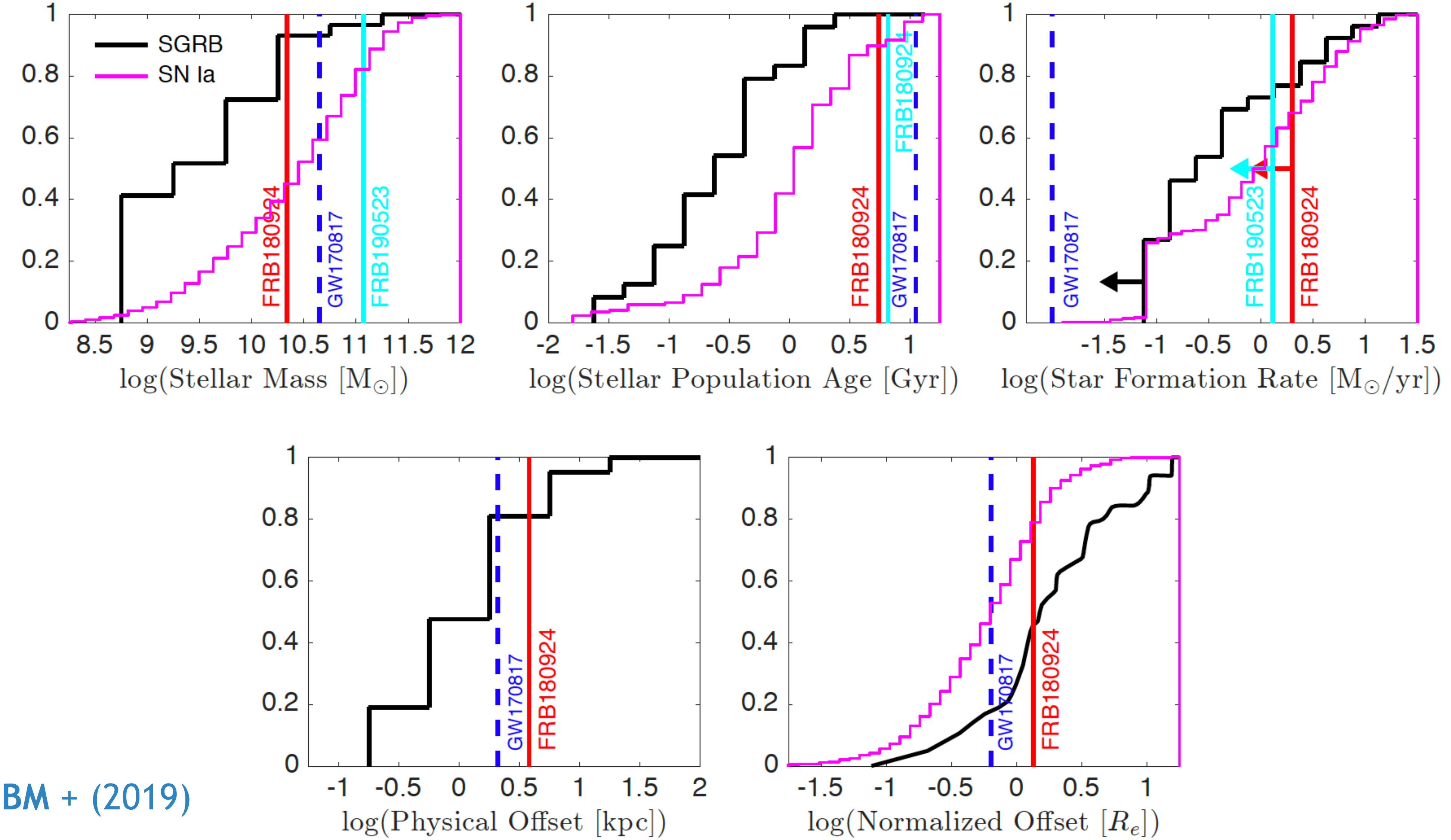
FRBs from BNS mergers?



BM + (2019)

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FRBs from BNS mergers?

- can potentially form FRB-producing magnetars in (small subset) of BNS mergers

(BM+19)

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- could be most massive NSs
  ⇒ direct-Urca cooled ?

  [high ambipolar diffusion rate ↔ $\dot{E}$]

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FRBs from BNS mergers?

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  [high ambipolar diffusion rate ↔ $\dot{E}$]

- another potential probe of EOS

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Extra Slides

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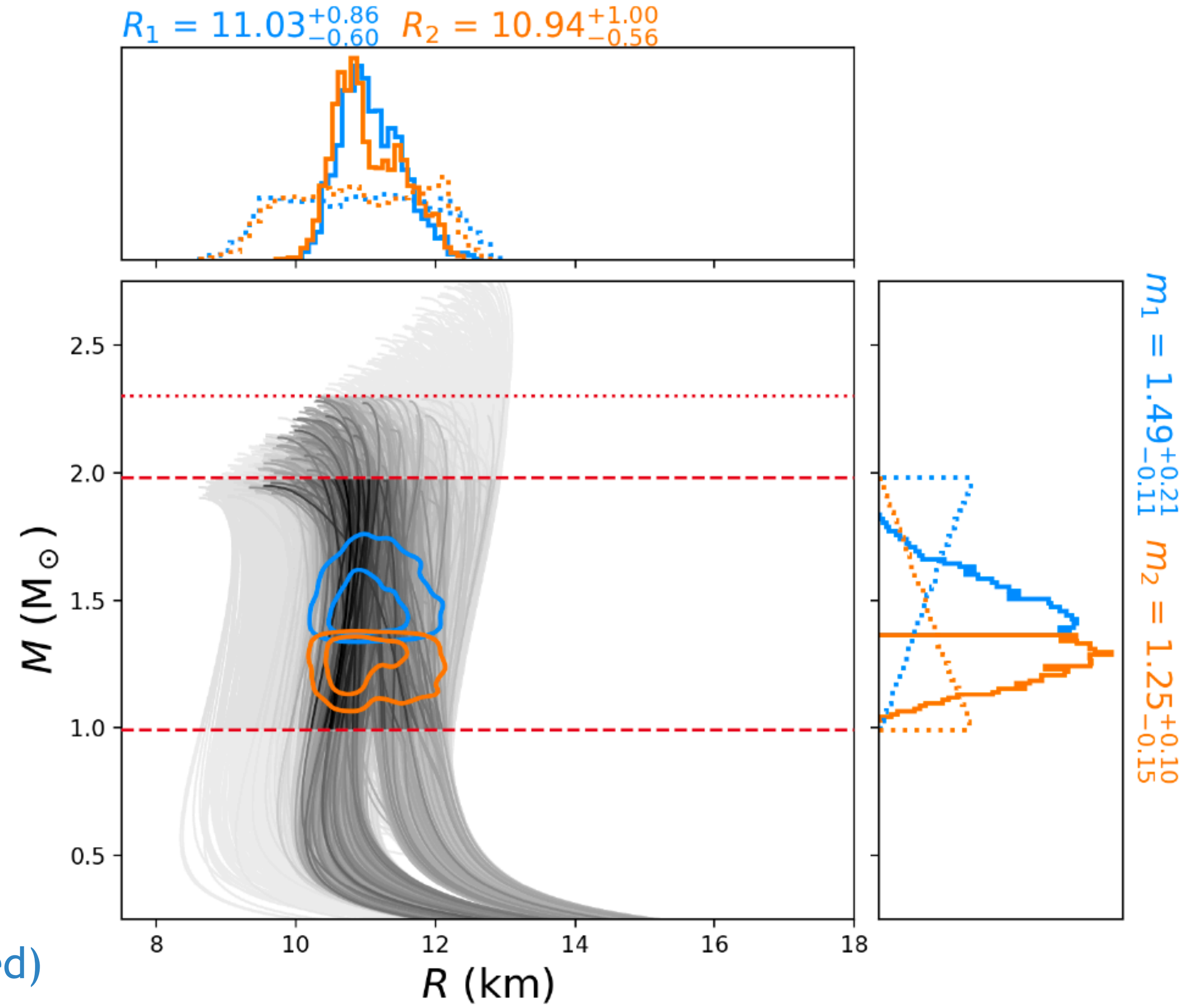
Application to GW170817: (IV) $R_{\rm ns}$ constraints

- Using chiral effective field theory EOSs



Capano + (submitted)

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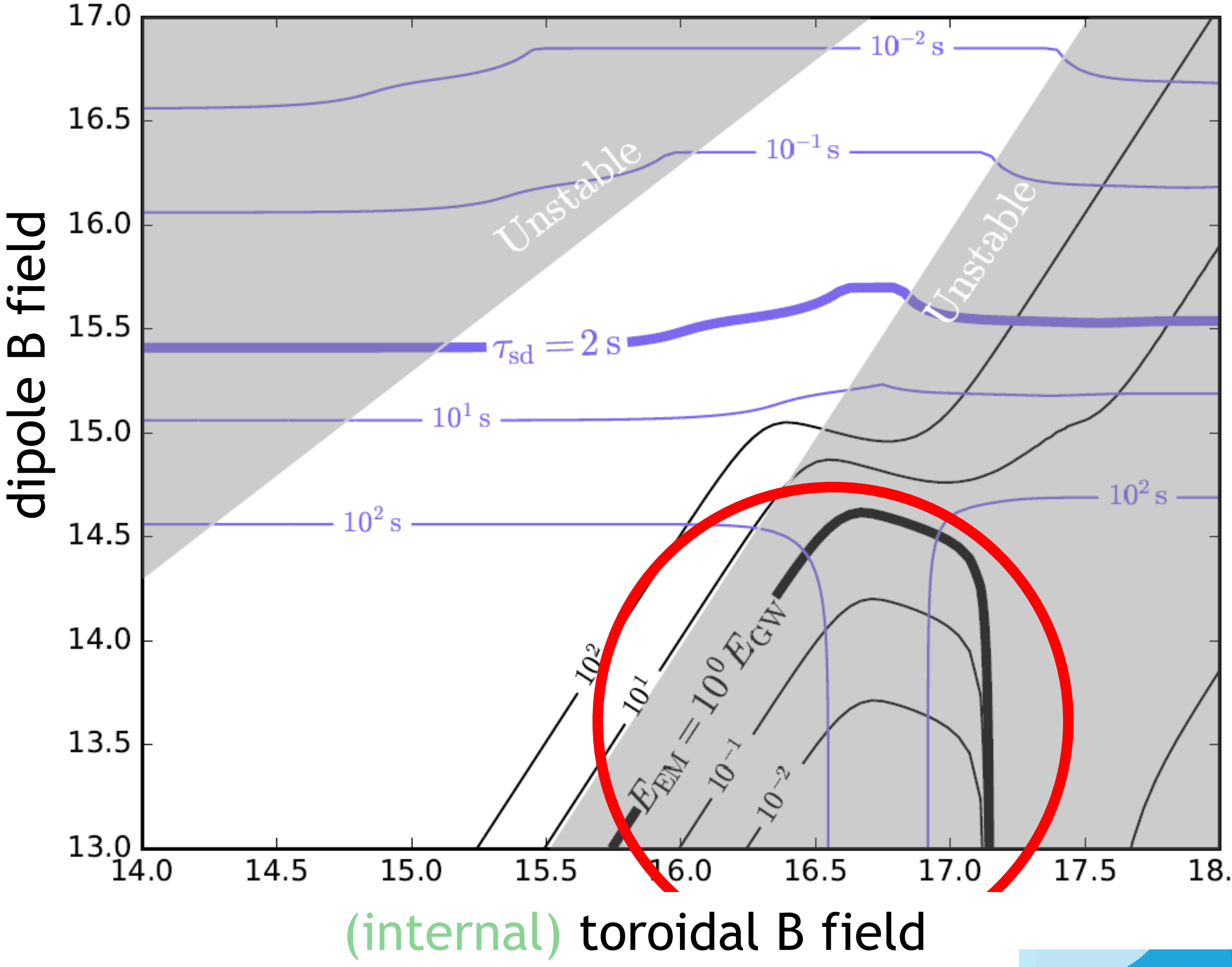
GW spin-down:

- GW spindown unlikely:
  - requires unstable $B_t \gtrsim 100 B_d$ (Braithwaite09)
  - $\tau_{sd} \sim 100s$, in tension with GRB
  - GW spindown not detected by LIGO (though not constraining)

BM & Metzger (2017)



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$M_{\rm TOV}$ Upper Limit:

- analytic estimate of result:
  - $M^{\rm b} \approx M^{\rm g} + 0.075(M^{\rm g})^2$ (Timmes+96)

    $$\Rightarrow M^{\rm b}_{\rm remnant} \lesssim M^{\rm b}_{\rm tot} \lesssim 3.06 M_\odot$$

  - $M^{\rm b}_{\rm smns} \approx \xi M^{\rm b}_{\rm TOV}$, where $\xi \approx 1.18$ (Lassotta+98)

  - demand: $M^{\rm b}_{\rm smns} \lesssim M^{\rm b}_{\rm remnant}$

$$\Rightarrow M^{\rm g}_{\rm TOV} \lesssim \frac{1}{0.15}\left(\sqrt{1 + 0.3\xi^{-1} M^{b}_{\rm remnant}} - 1\right) \lesssim 2.2 \mathrm{M}_\odot$$

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[and multi-messenger astrophysics]

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EOS Constraints using only GWs:

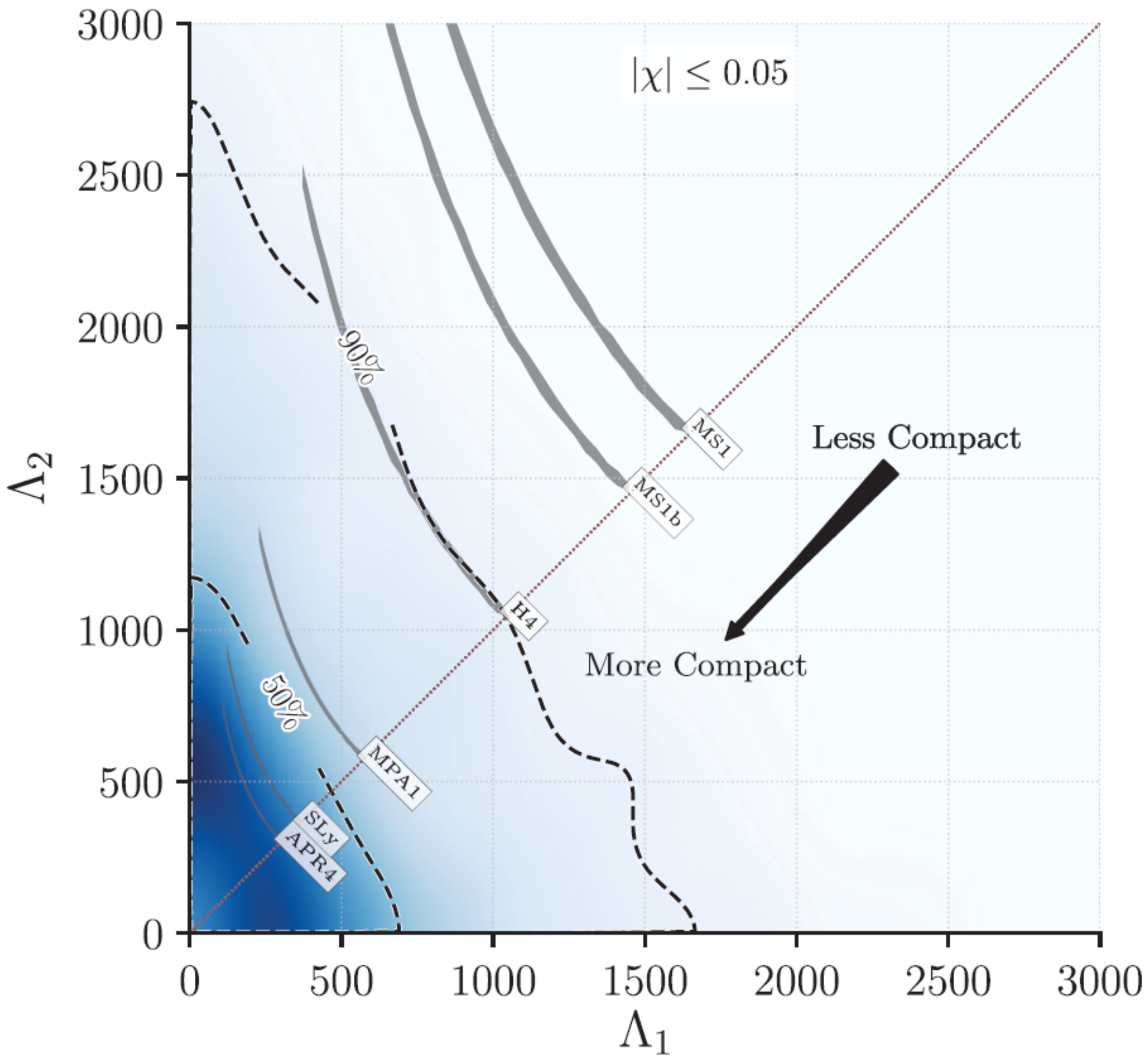
- traditional paradigm:
  measure finite size corrections to GW waveform

- tidal deformability: $$\Lambda = \frac{2}{3} k_2 \left(\frac{GM}{Rc^2}\right)^{-5}$$

  $[k_2 \approx 0.05 - 0.15,\ Q_{ij} = -\Lambda \varepsilon_{ij}]$

- additionally – post-merger GW signals

LIGO (2017)



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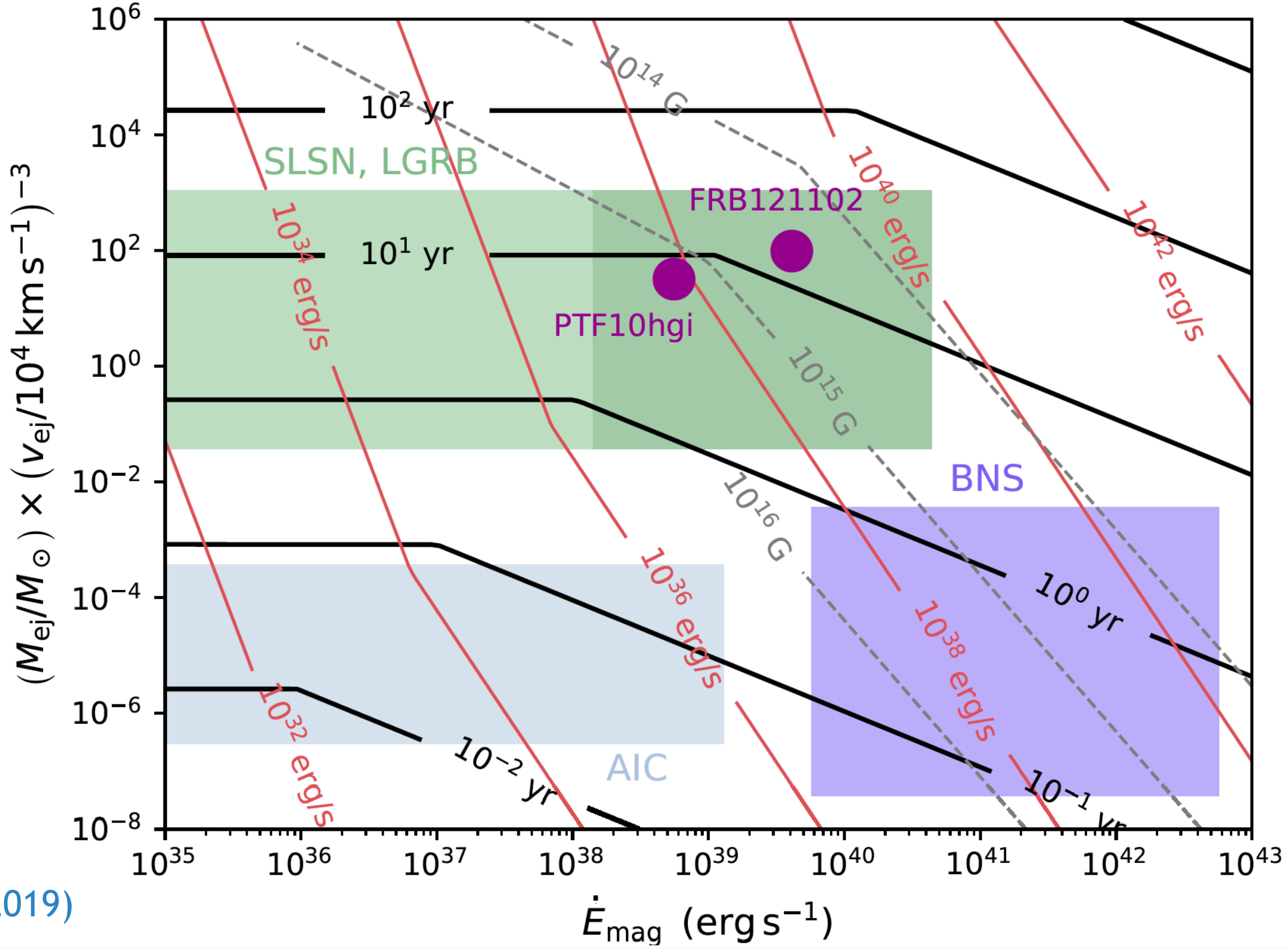
FRB persistent emission:

- nebular radio emission depends on ambient ejecta and engine activity



BM + (2019)