What have we really learned about the nuclear equation of state from GW170817?

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What have we really learned about the nuclear EOS from GW170817?

Outline:

- What did we see?
- EM:
  - ejecta mass/velocity (how estimated, uncertainties, ...)
  - seeing colors (Ye, neutrinos, and remnant lifetime)
- What does it imply?
  - disk outflow dominates ejecta => rule out prompt-collapse (show Coughlin plot of disk mass as function of M/MTOV)
  - also high-Ye material => no prompt collapse
  - total energy => no long-lived NS

What have we really learned about the nuclear EOS from GW170817?

Outline:

- What did we see?
- Present "Vogt-Russel" theorem, but be cautious about it
- How well do we know Mtot?
  - show Mtot(q) plot
- High-spin???
  - Getting Mtot=3.3 requires q=0.315 => m1=2.51, m2=0.79Msun; population => despite N=1, Mchirp for 170817 amazingly consistent with Galactic distribution (it doesn't have to be). Would be very natural if so that q and spin also similar to Galactic distribution (a similar, dominant, stellar evolution pathway?). Chi_eff vs chi => both NSs should be rapidly spinning. How to form such a system?

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What did we see?

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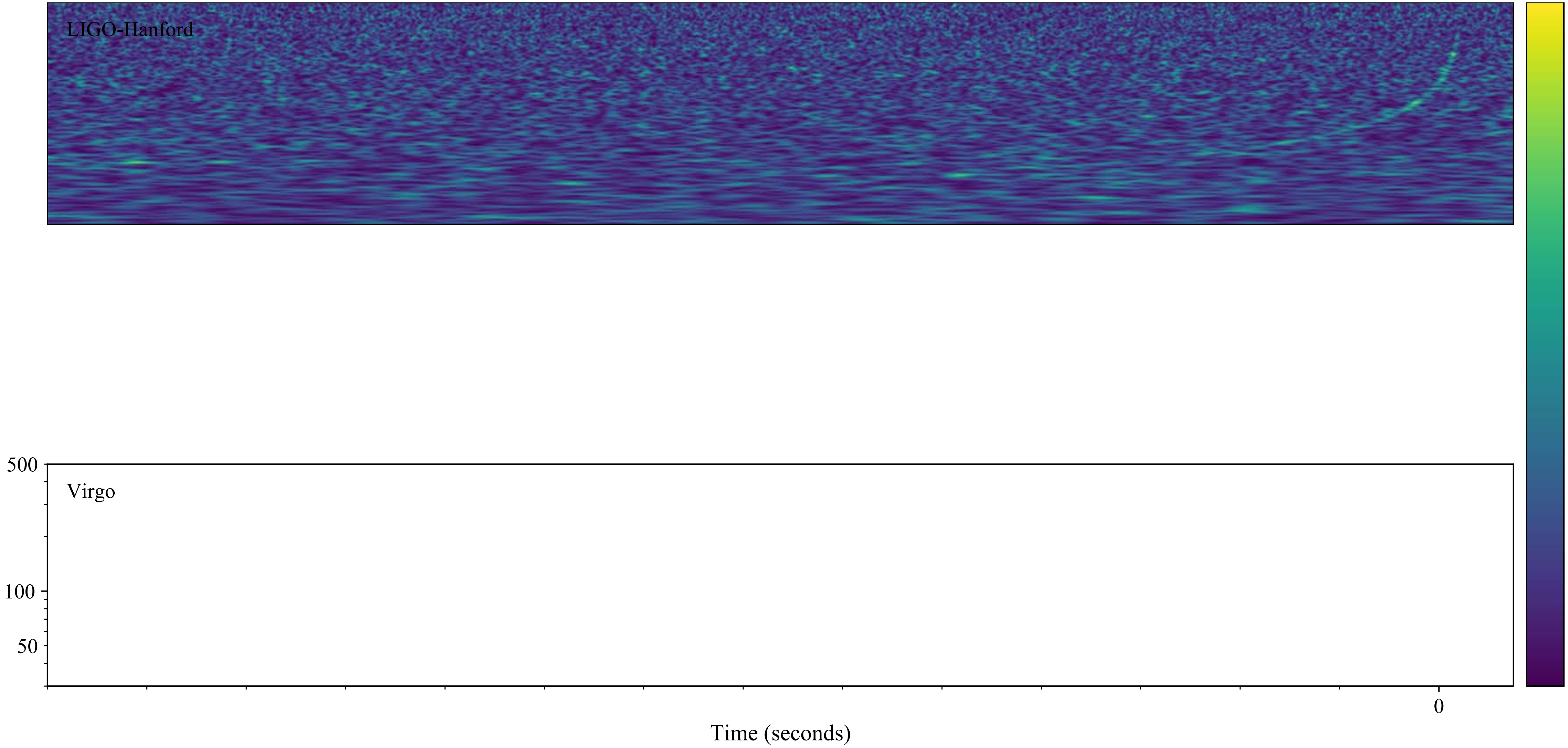
What did we see?

LIGO Virgo Collaboration (2017)



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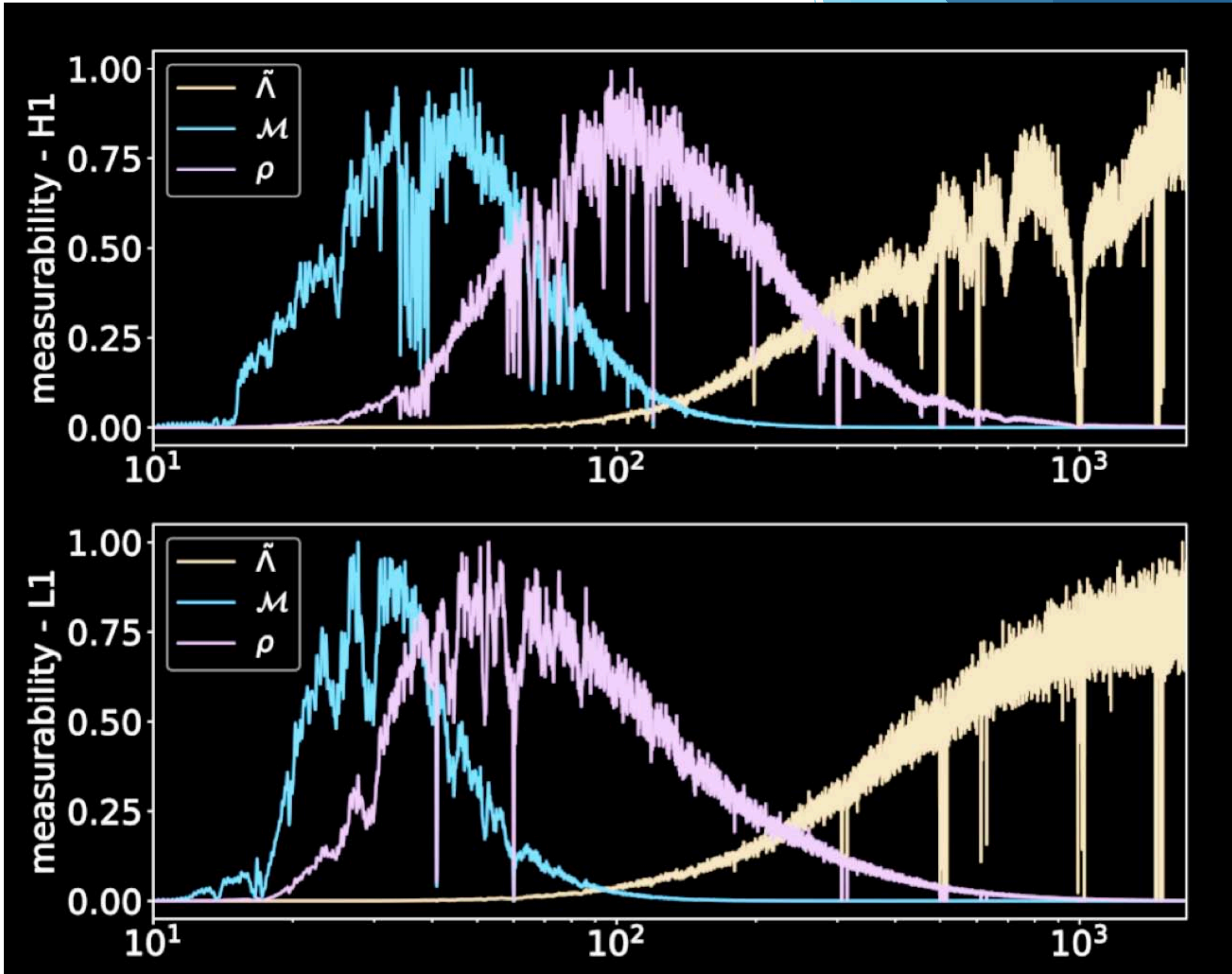

De et al. (2018)

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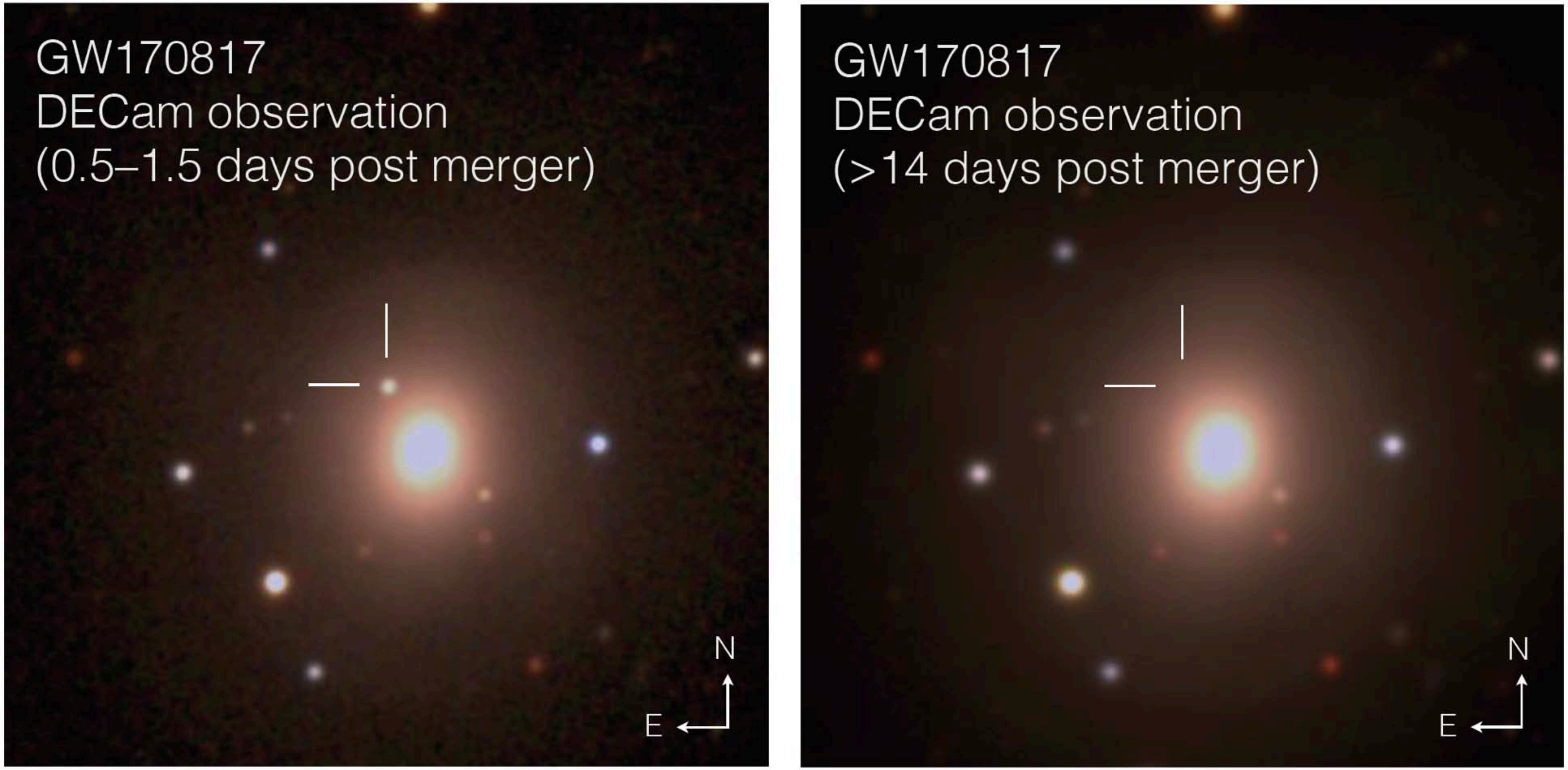
Soares-Santos et al. (2017)



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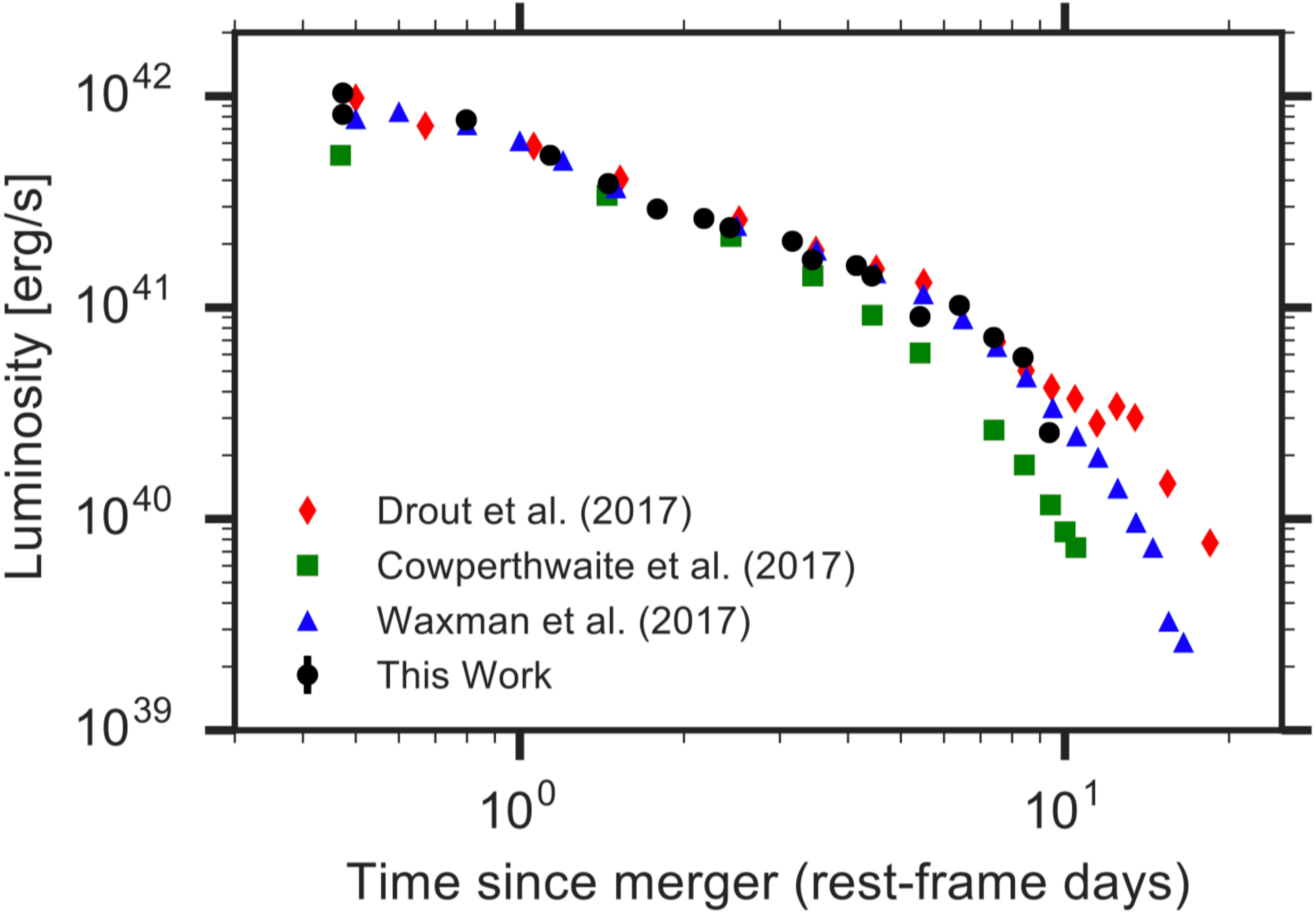
What did we see?

- bolometric eyes

$$L_{pk} \propto M_{ej}\dot{e}(t_{pk})$$

$$t_{pk} \sim \left(\frac{\kappa M_{ej}}{c v_{ej}}\right)^{1/2}$$

Arcavi (2018)



What did we see?

- seeing colors

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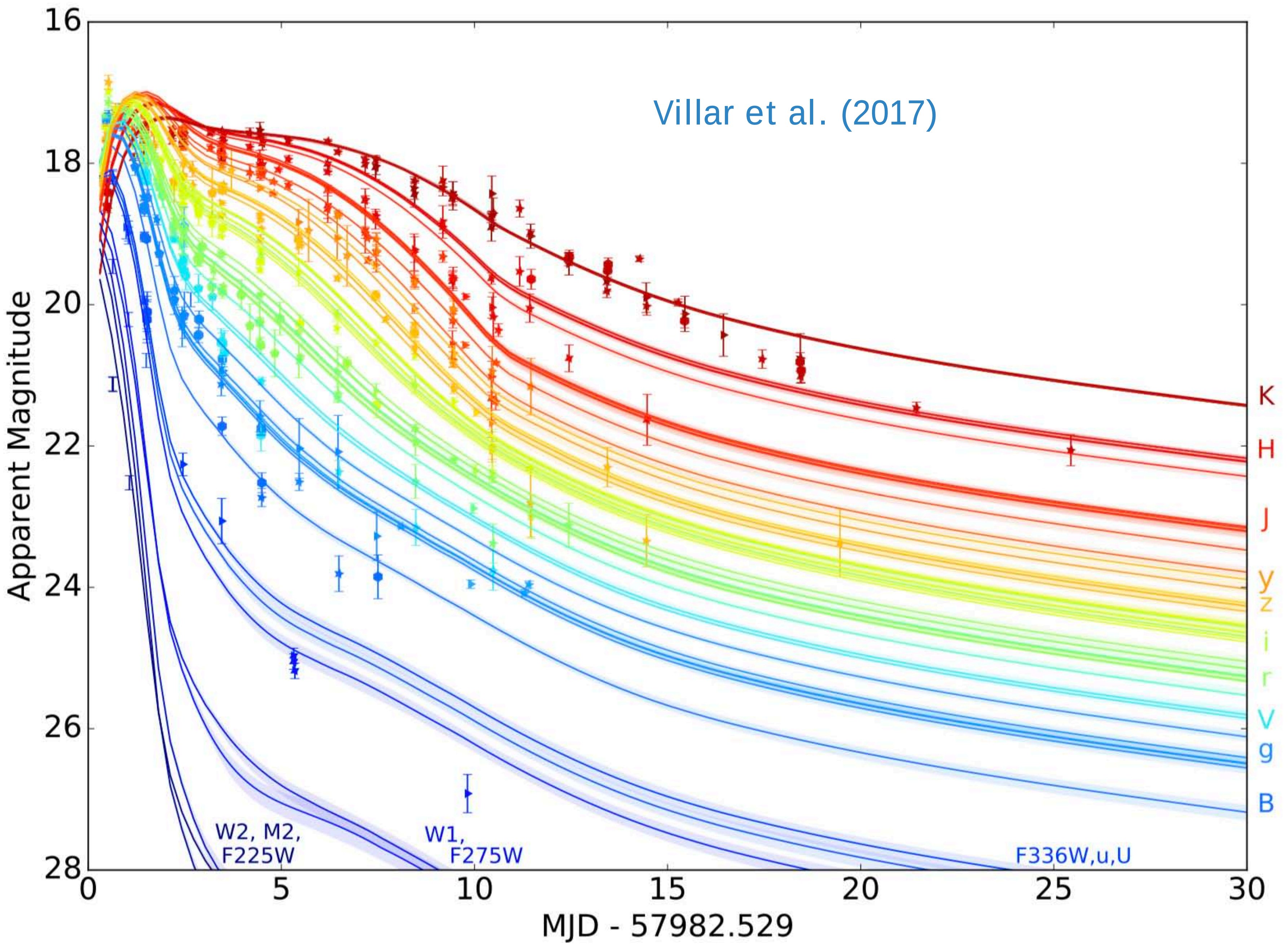

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What does it imply?

- assume BNS and not BHNS

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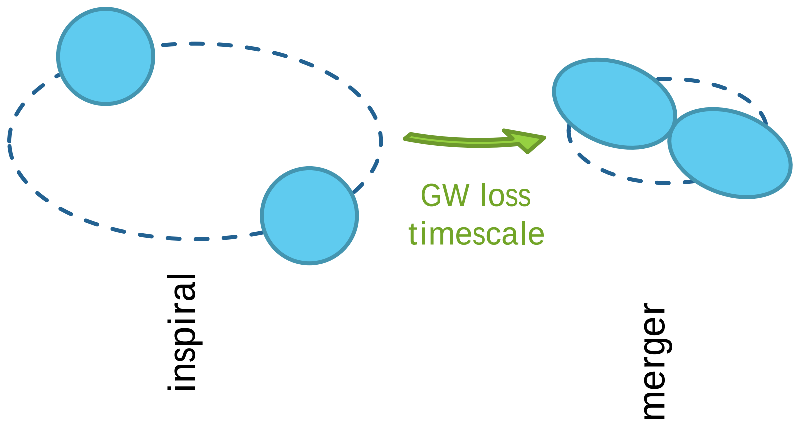
Merger Remnant:



schematics of a merger - outcome dependent on:

- binary mass
- NS EOS

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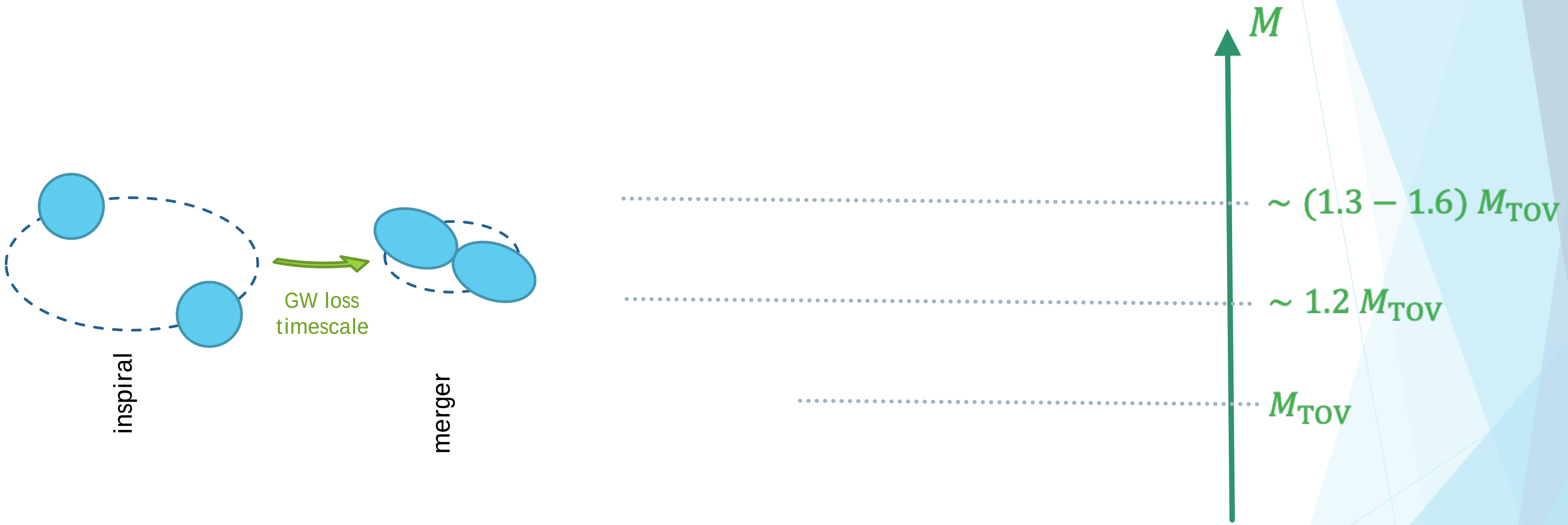

(see also Bartos+13)

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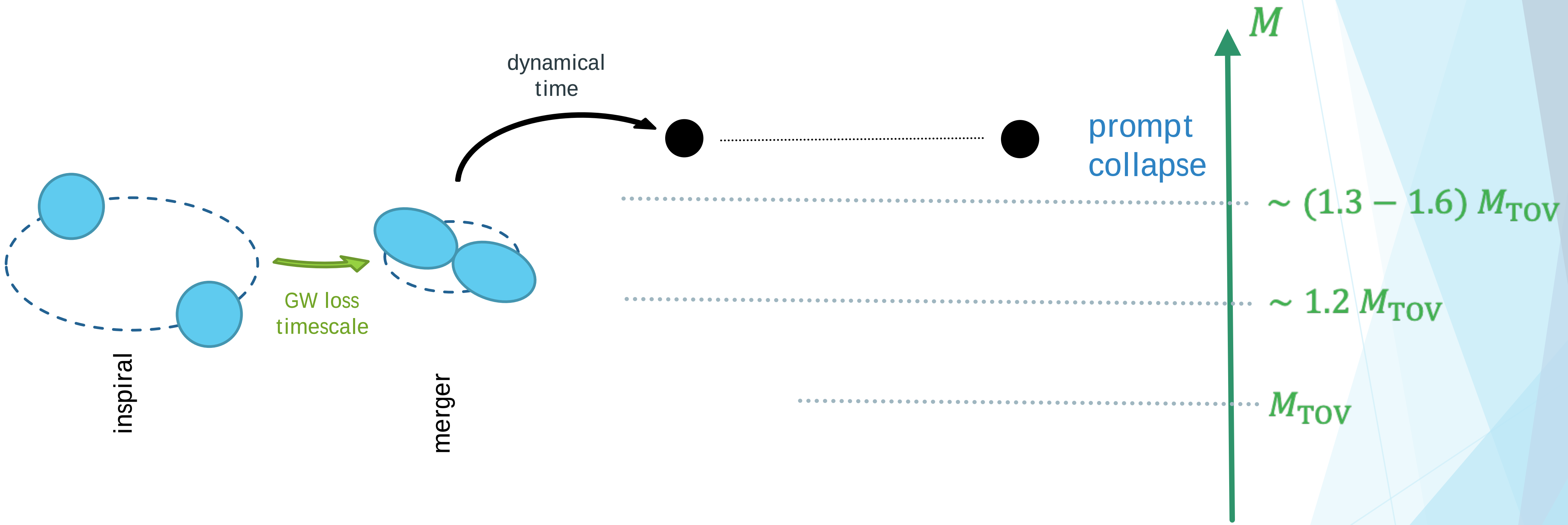

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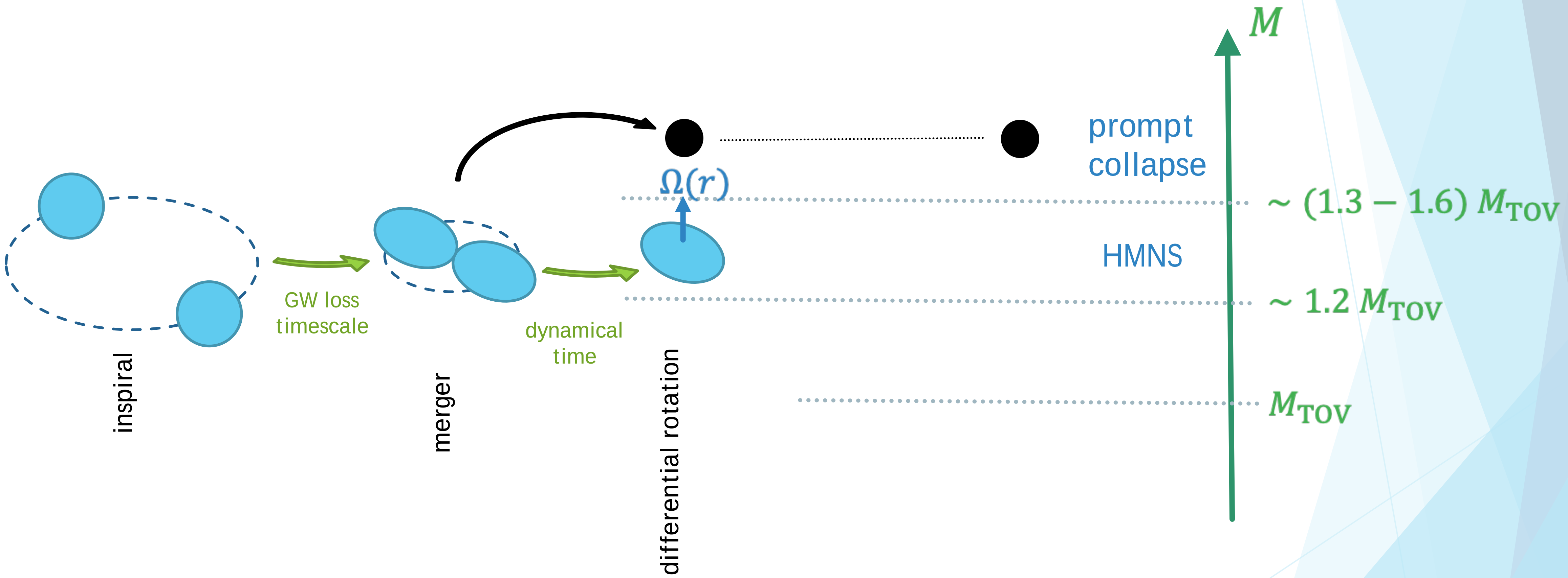

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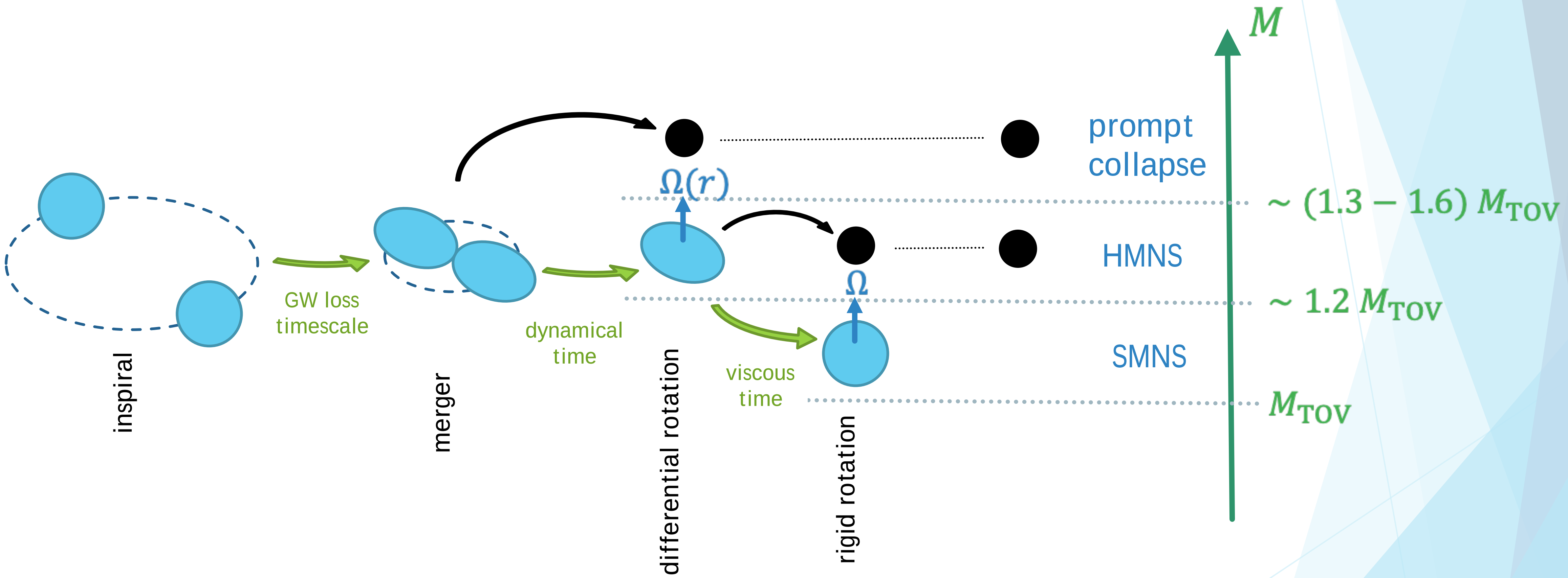

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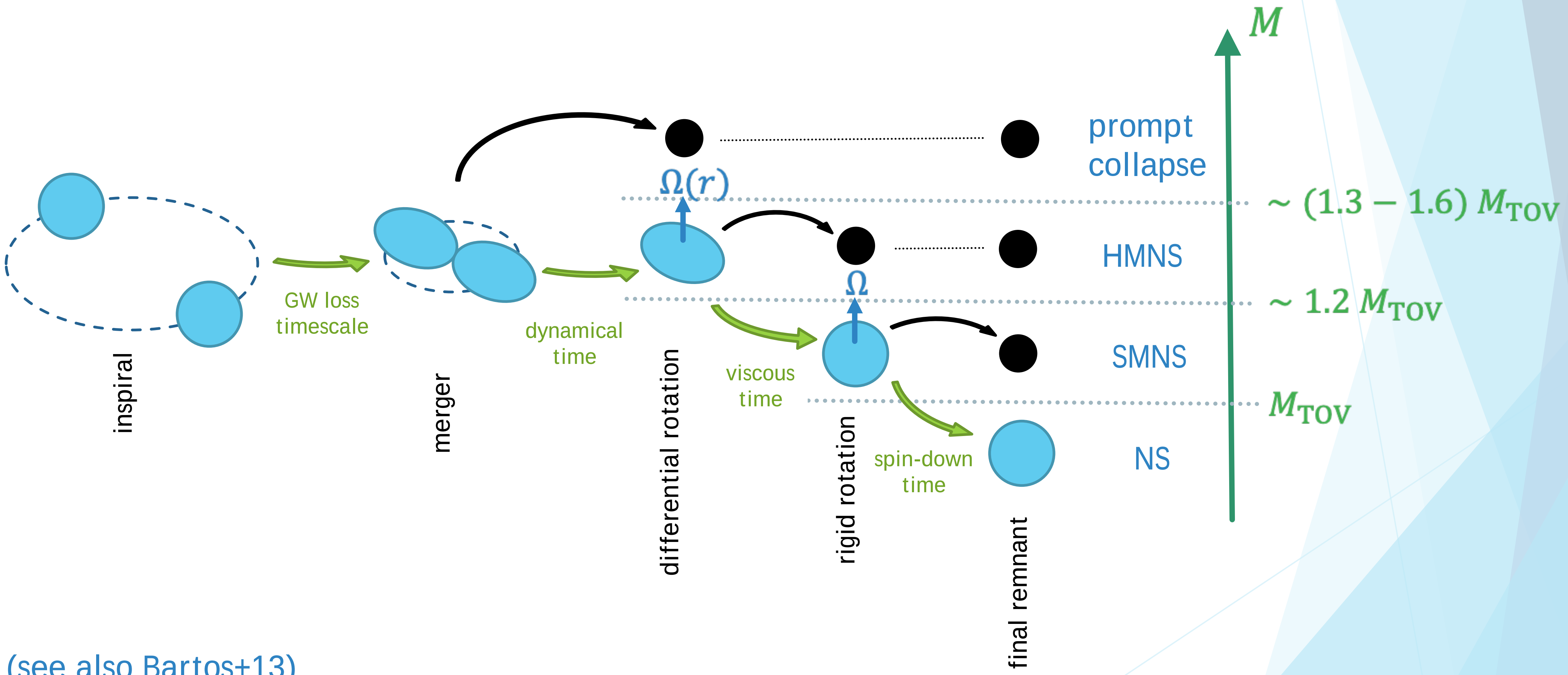

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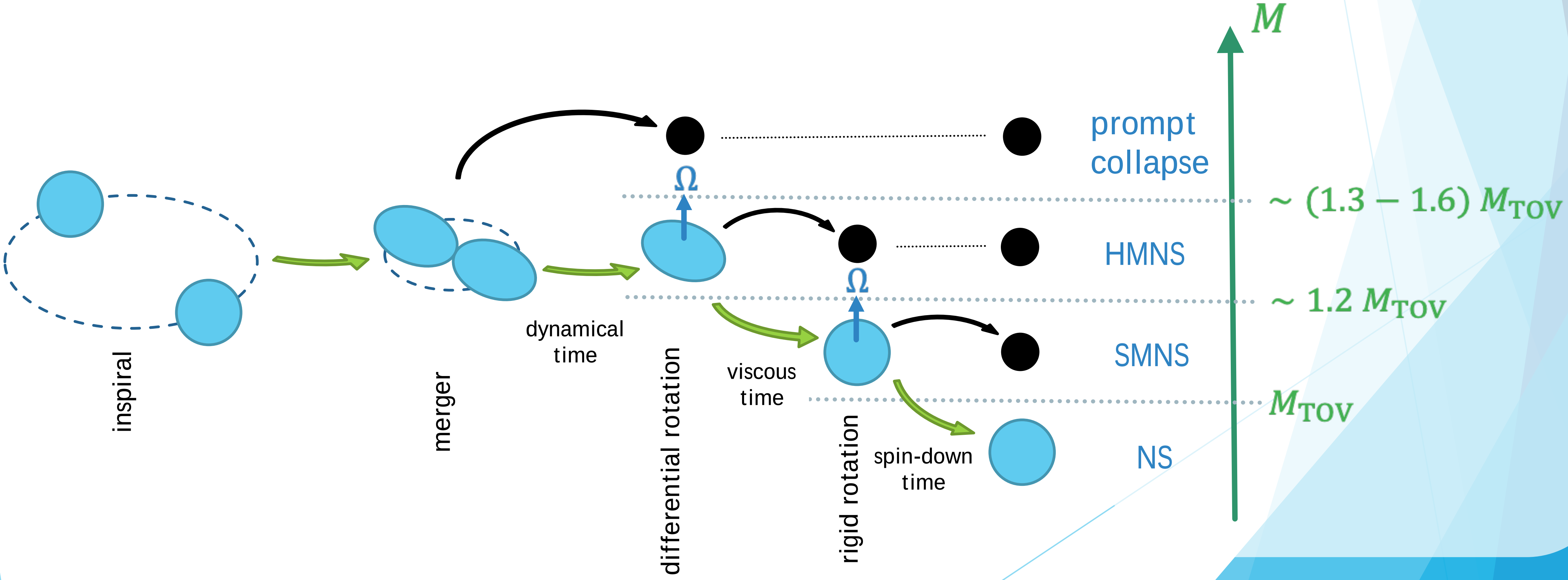
Multi-messenger EOS Constraints:

- how to use to constrain NS EOS?



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Multi-messenger EOS Constraints:

merger outcome $\Leftrightarrow M_{tot}/M_{TOV}$

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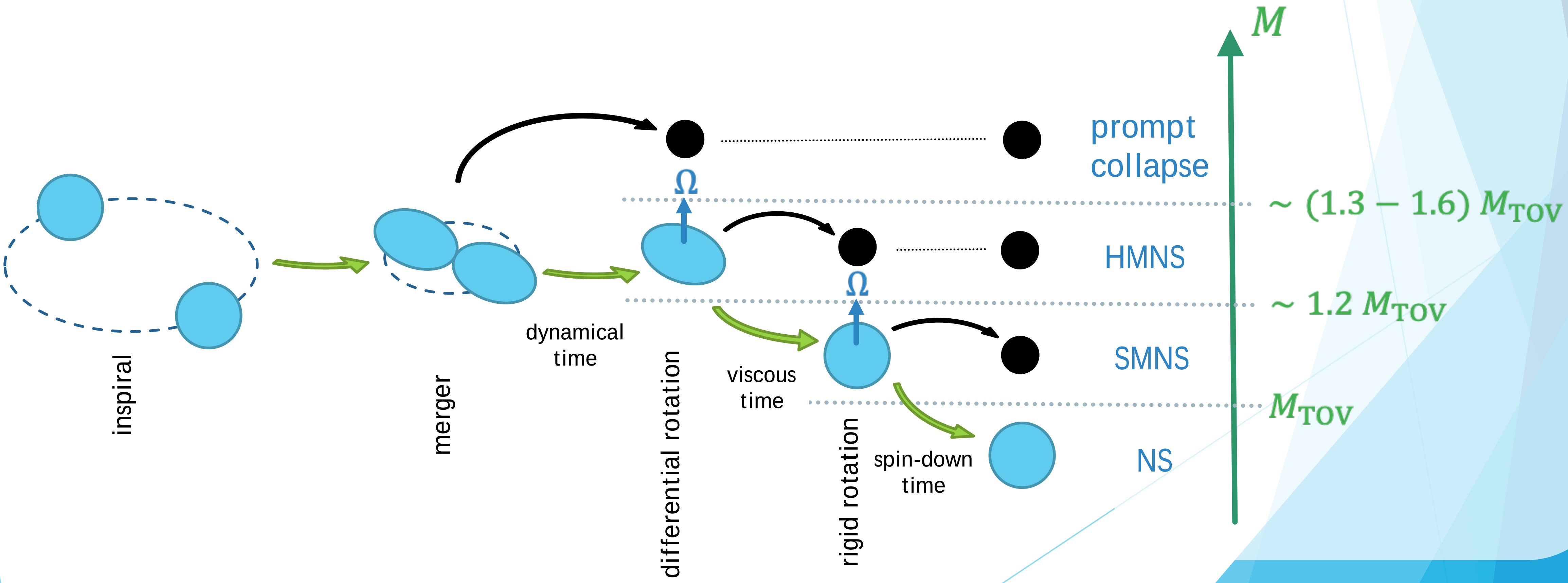

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Multi-messenger EOS Constraints:

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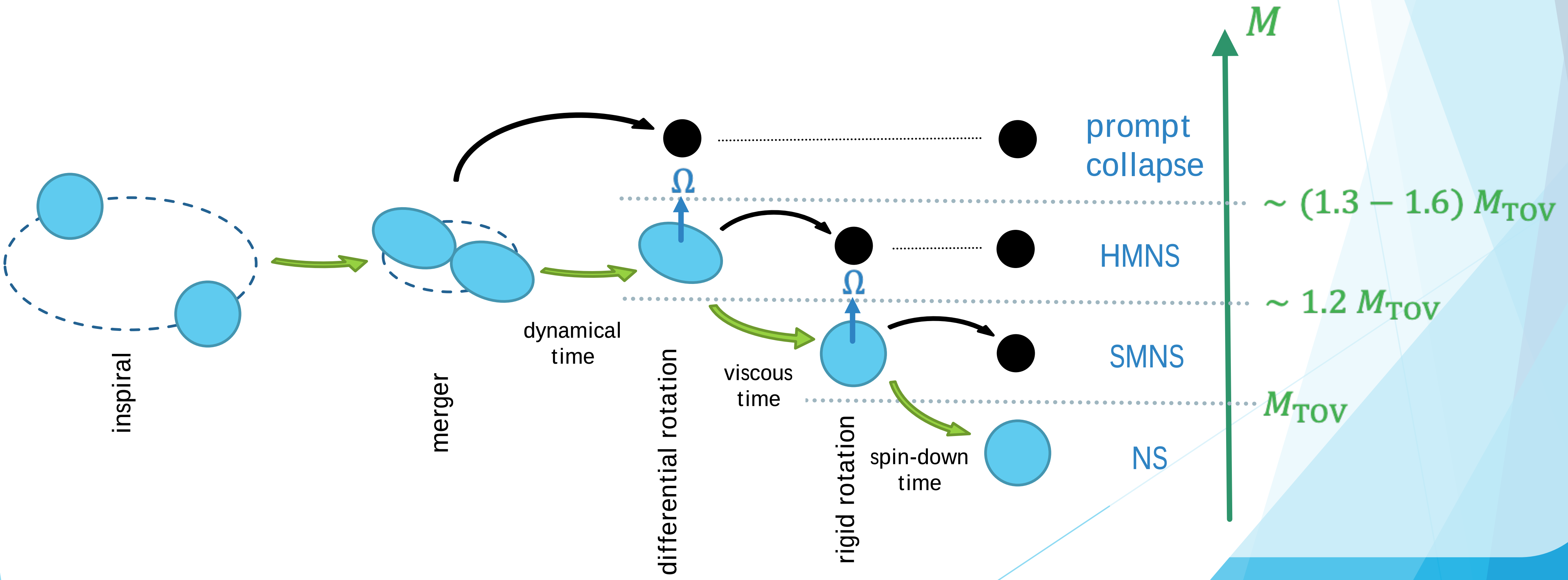
$$\underbrace{\text{merger outcome}}_{\text{EM}} \Leftrightarrow \underbrace{M_{\text{tot}}}_{\text{GW}}/\underbrace{M_{\text{TOV}}}_{\Rightarrow\text{EOS}}$$



What have we really learned about the nuclear EOS from GW170817?

Do we really know Mtot?

- GW signal $\Rightarrow$ total binary mass, $M_{\rm tot}$

- $M_{\rm tot} = M_{\rm chirp}\, q^{-3/5}(1+q)^{6/5}$

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

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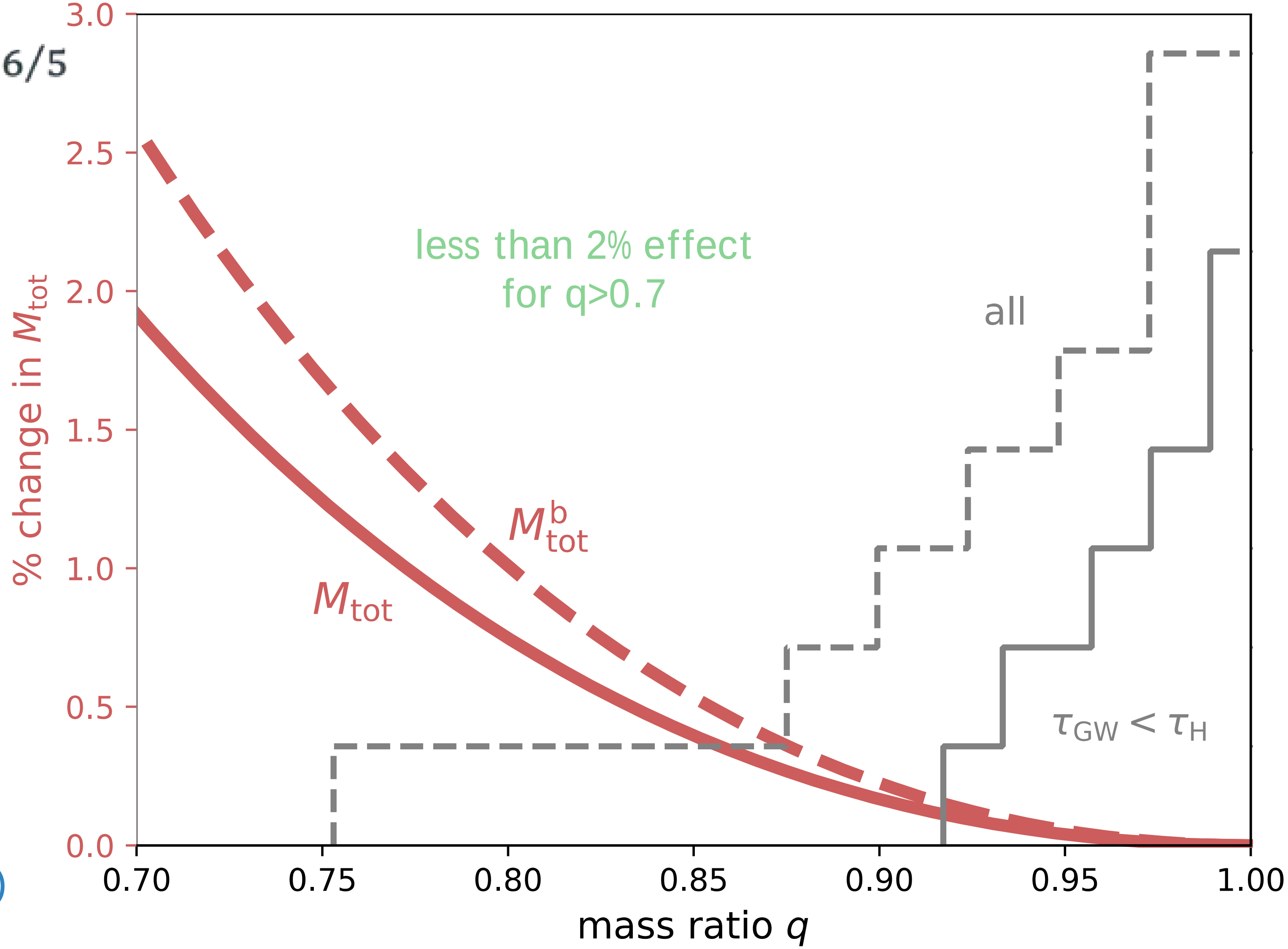
- $$M_{\rm tot} = \underbrace{M_{\rm chirp}}_{\text{precisely measured}} \underbrace{q^{-3/5}(1+q)^{6/5}}_{\text{f(q) weakly dependent on}}$$



BM & Metzger (2019)

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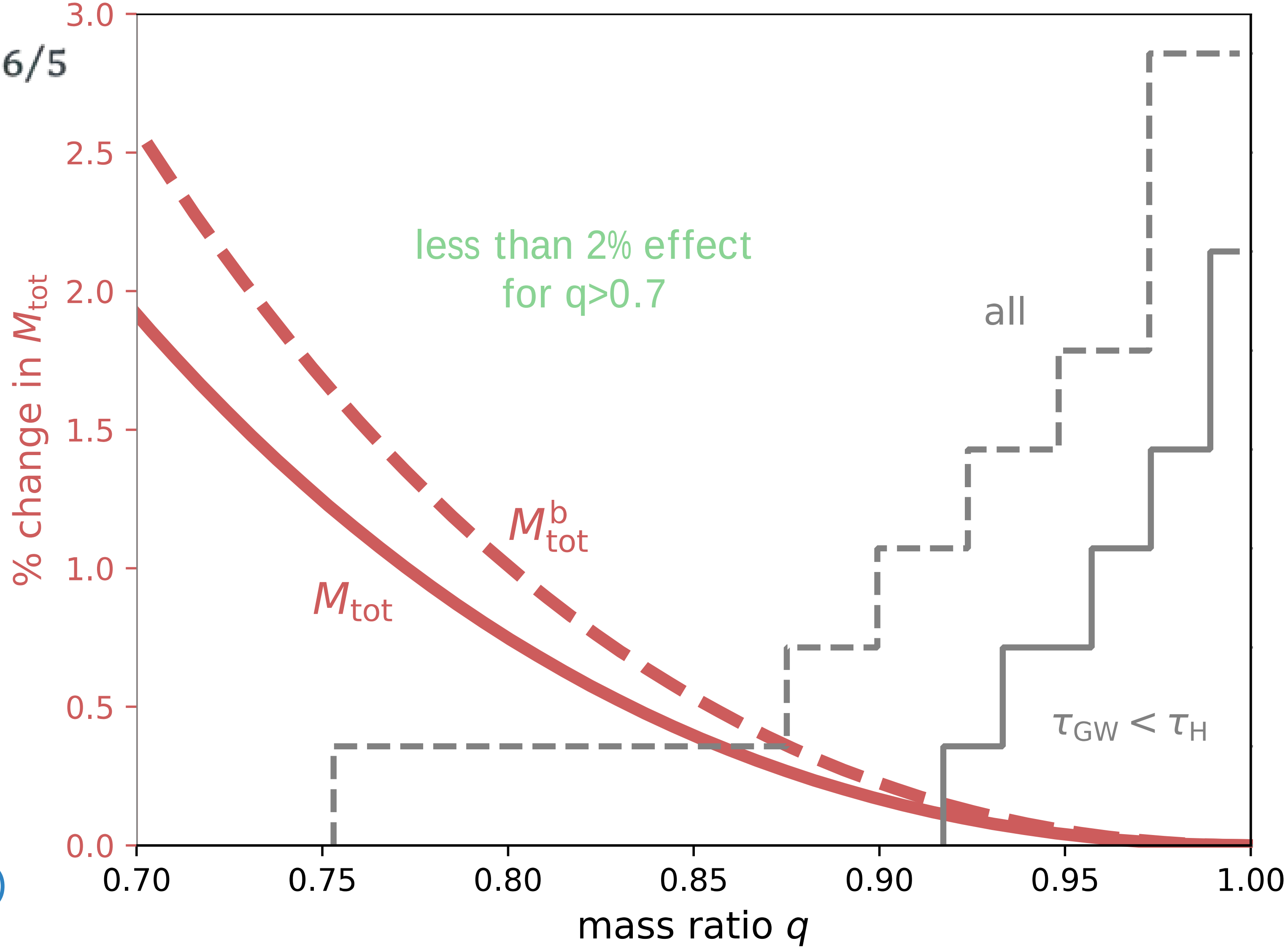
	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	$1.36–1.60\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$

LIGO Virgo Collaboration (2017)



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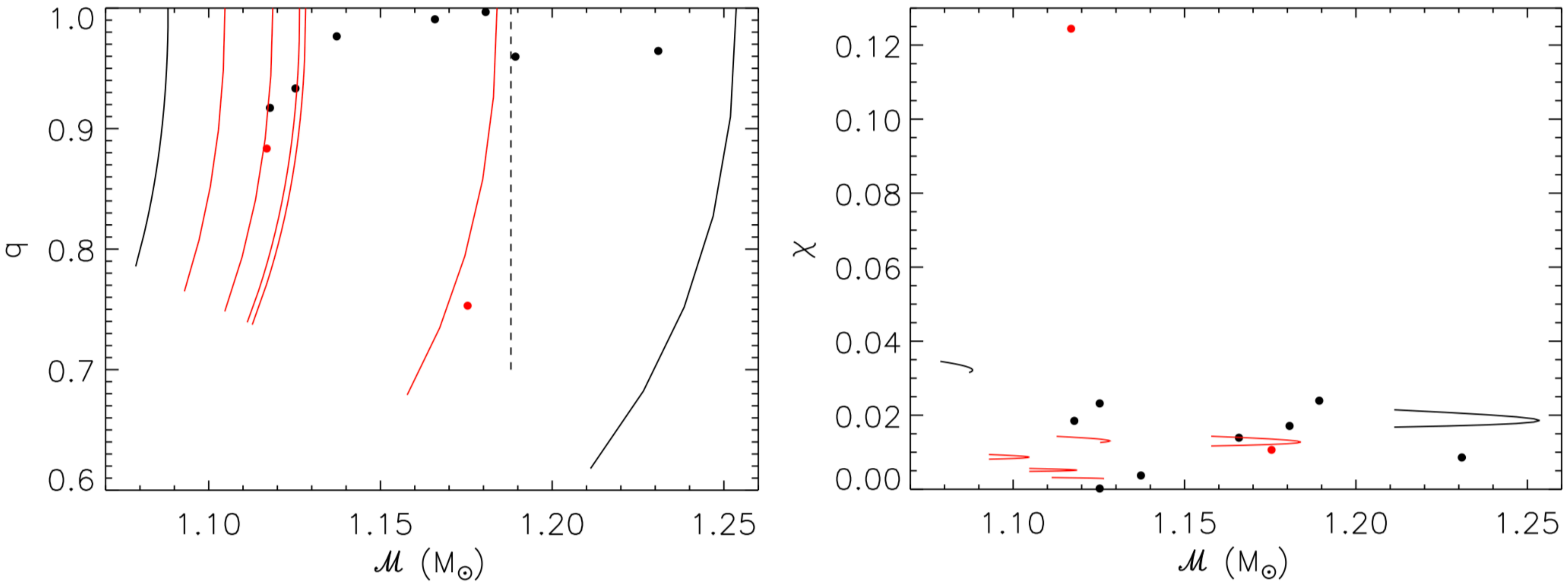
Zhao & Lattimer (2018)



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Do we really know Mtot?

- but what if high spin / low q?

- also if $M_{tot} > 2.9 M_\odot$ (only 6% higher) then $q < 0.53$ and $m_1 < 1 M_\odot$...

What have we really learned about the nuclear EOS from GW170817?

Remnant fate?

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- $\leftrightarrow$ EM signature

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

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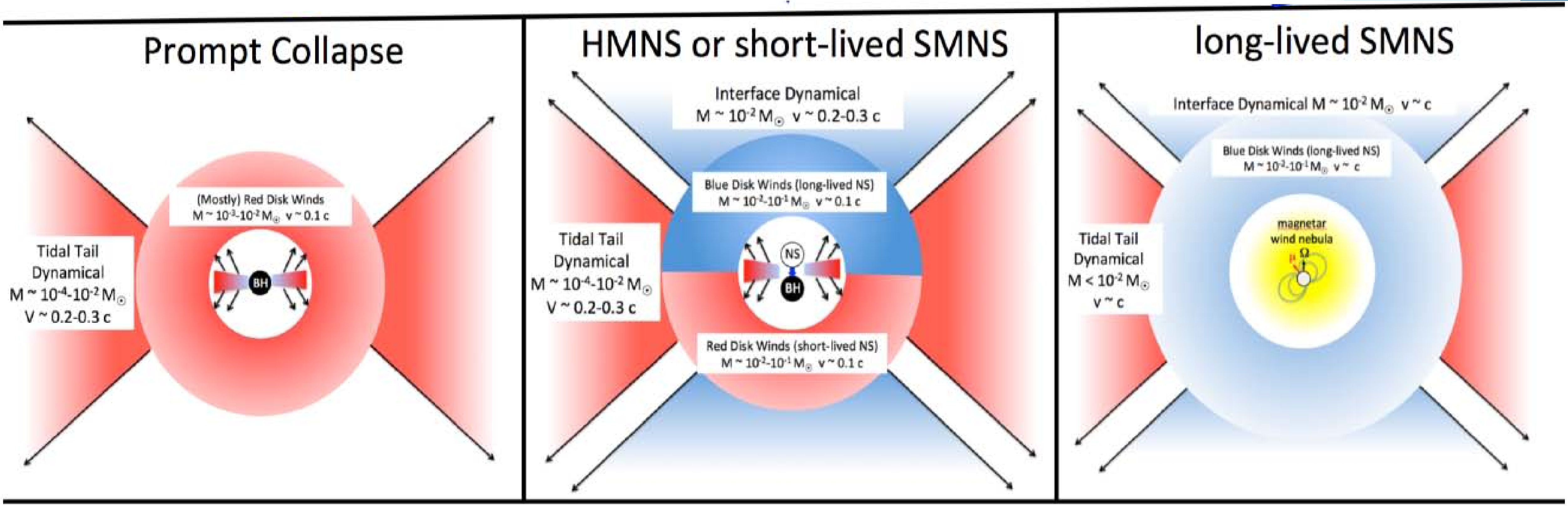

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Radice et al. (2018)

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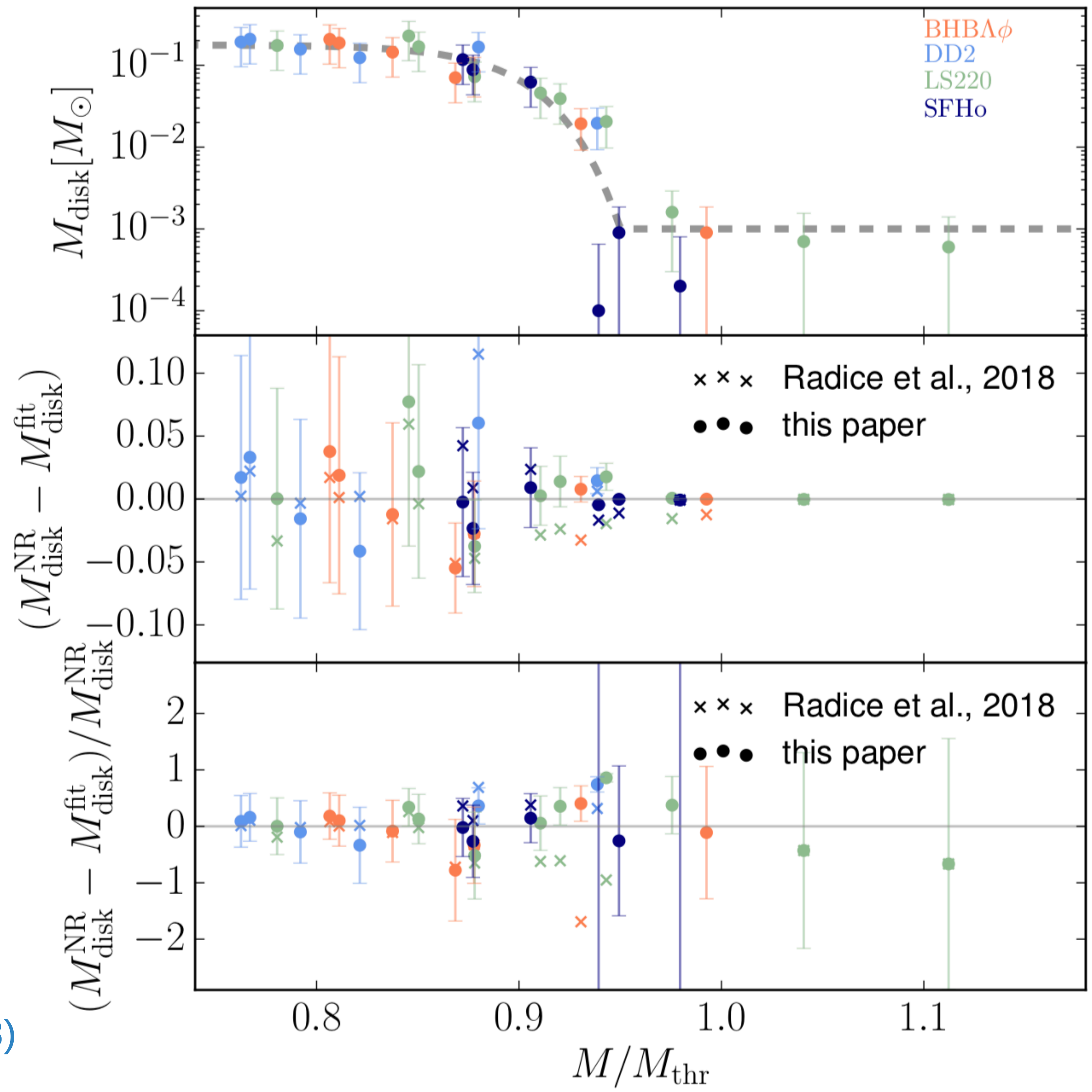

Coughlin, Dietrich, **BM**, Metzger (2018)

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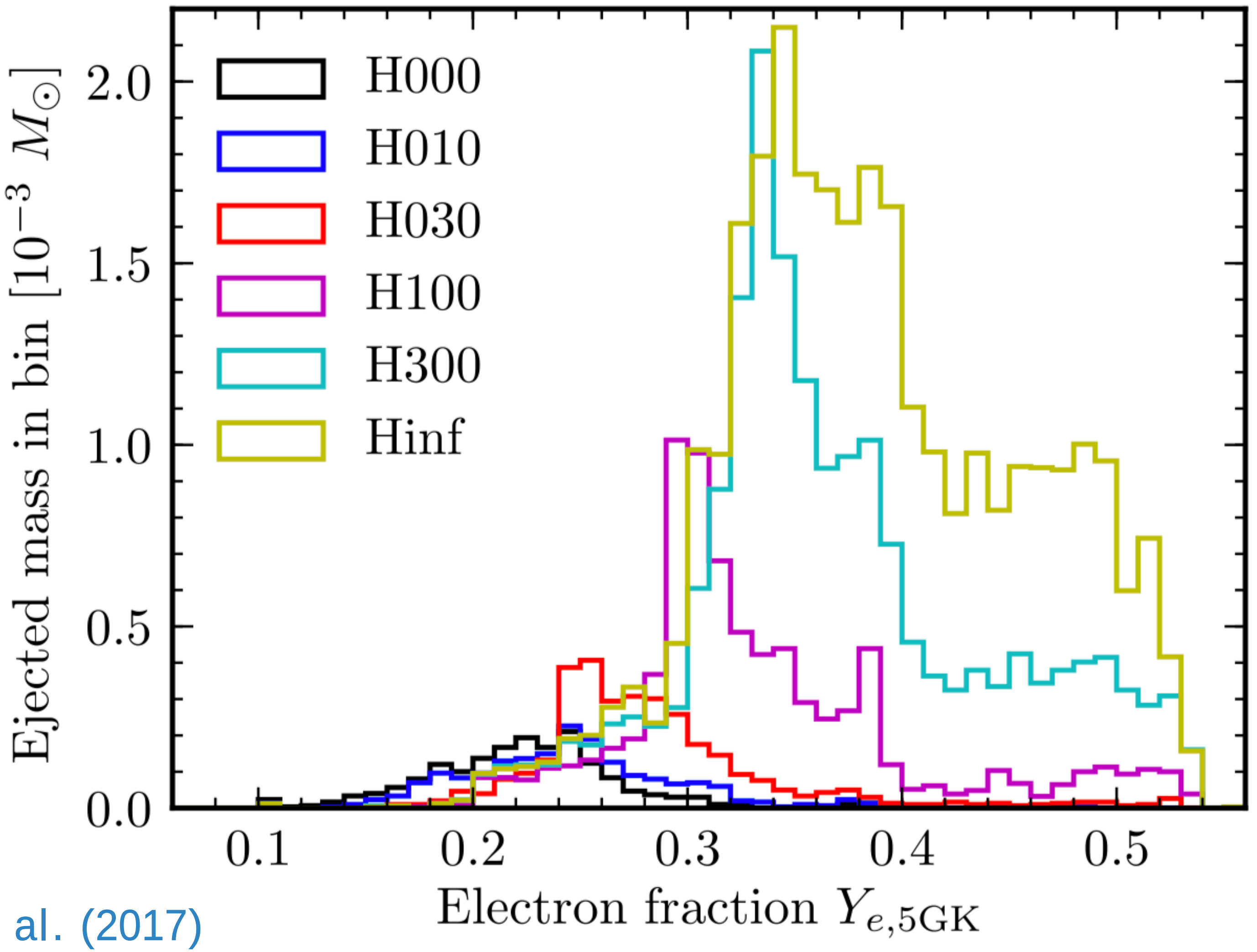
- blue kilonova implies remnant survived for some time



Lippuner et al. (2017)

What have we really learned about t

BM & Metzger (2019)

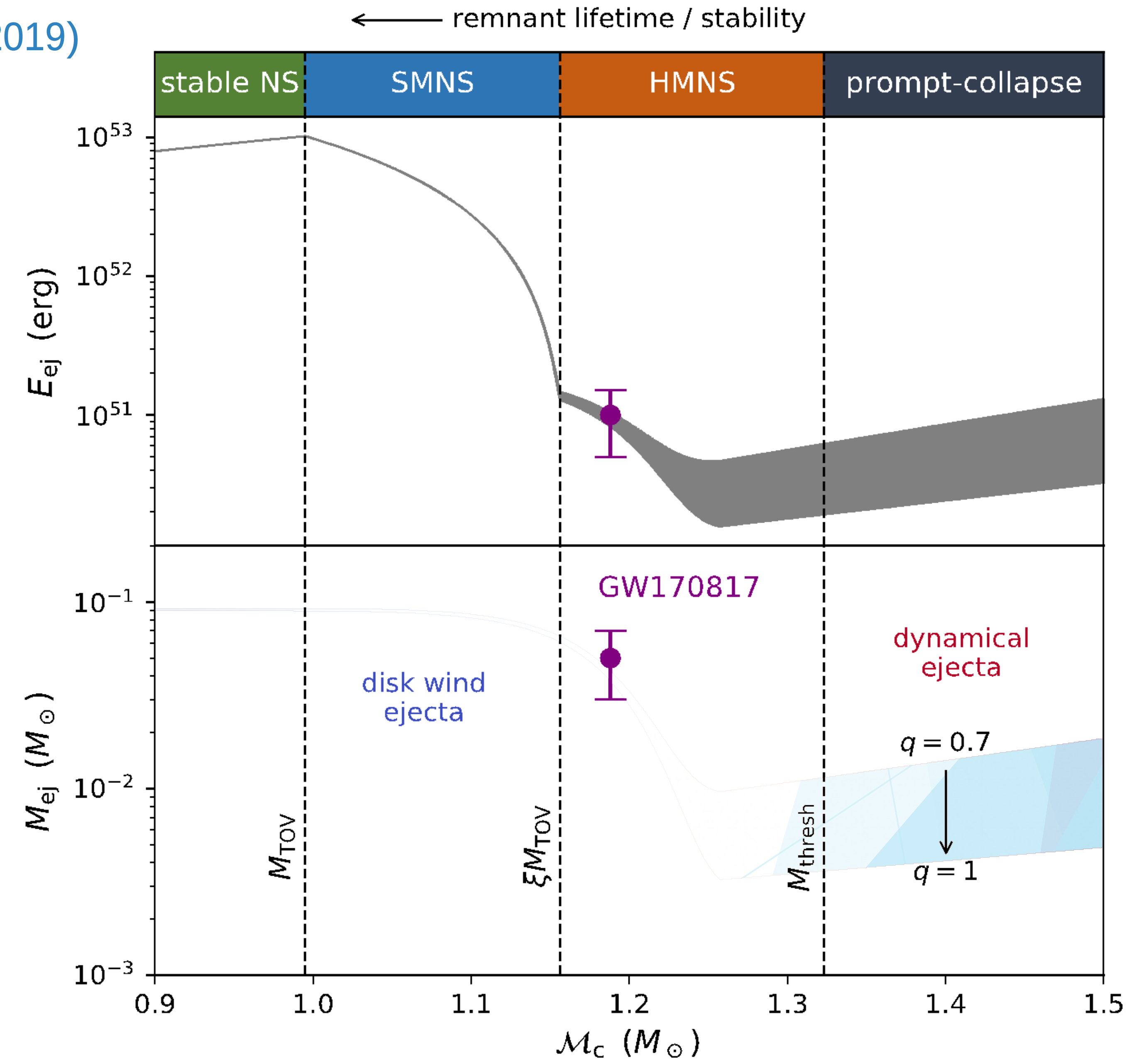
Remnant fate?

- remnant likely not SMNS

- energetics: if merger remnant maximally rotating

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

(Metzger, **BM**, Kasen, Quataert 2015)



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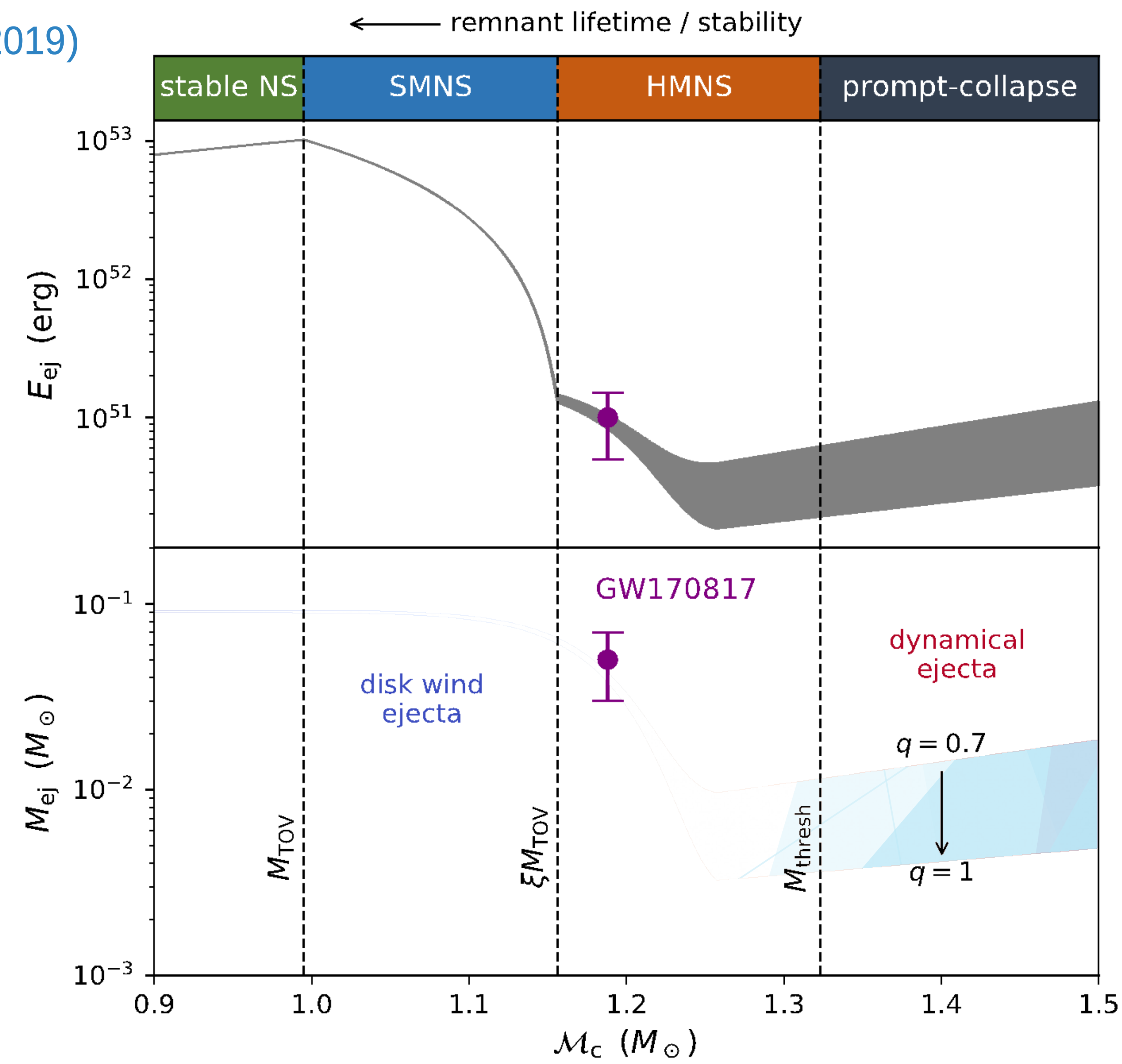
- jet formation (Ruiz+18,Rezolla+18)
- lack of X-rays (Pooley+18,BM+18)



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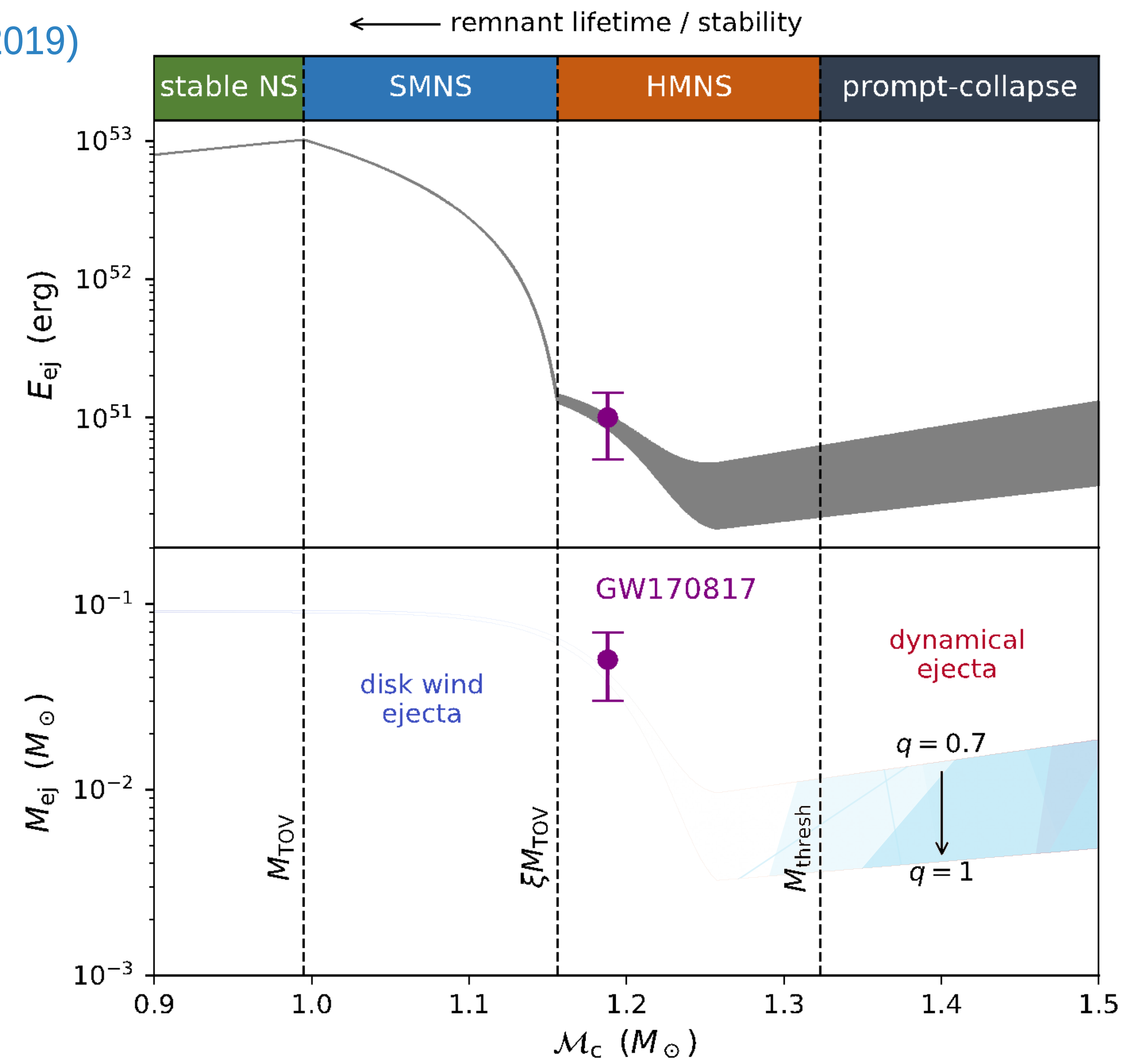
a “Voigt-Russel” theorem?

- to zeroth order merger outcome depends only on chirp mass



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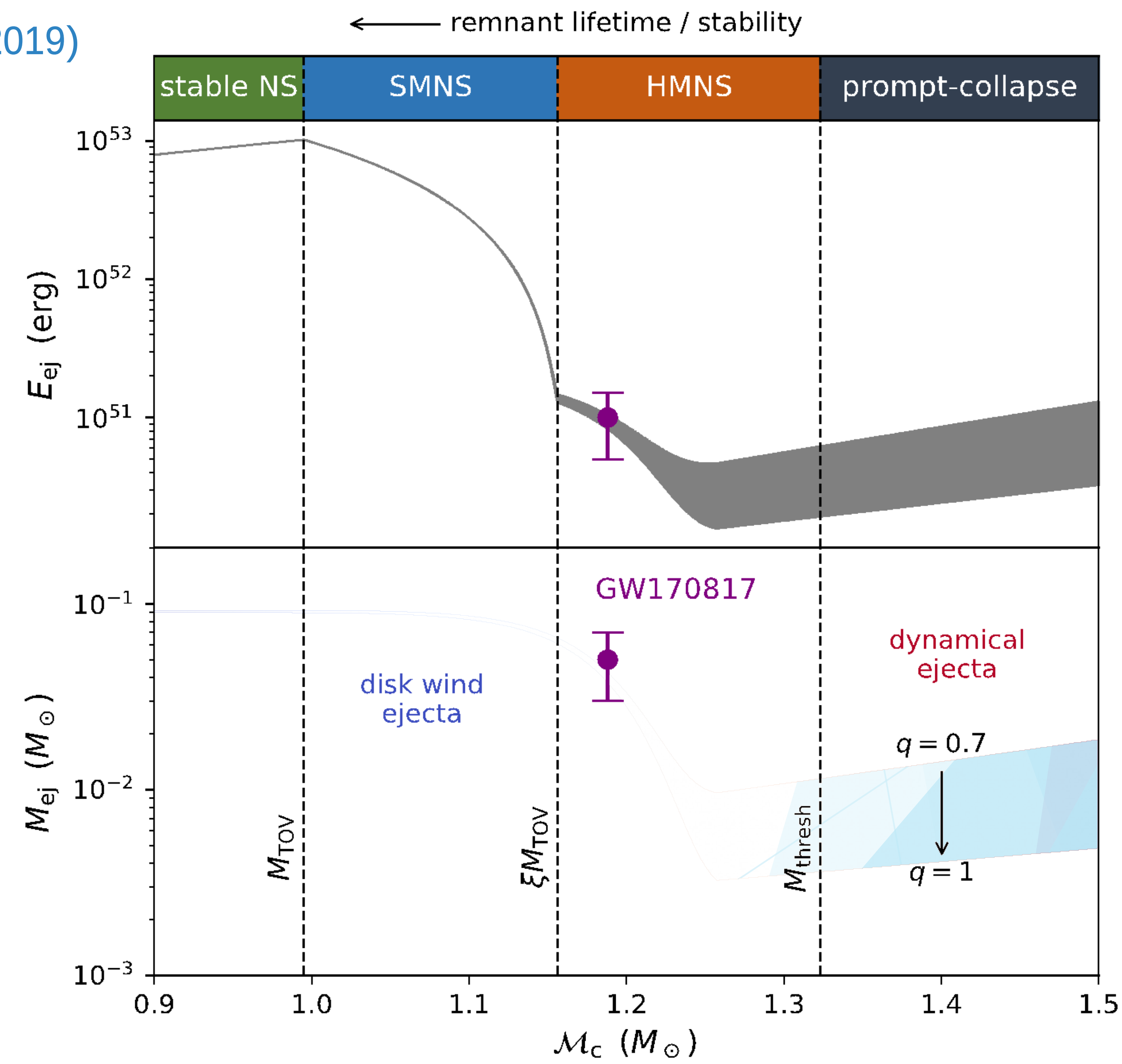
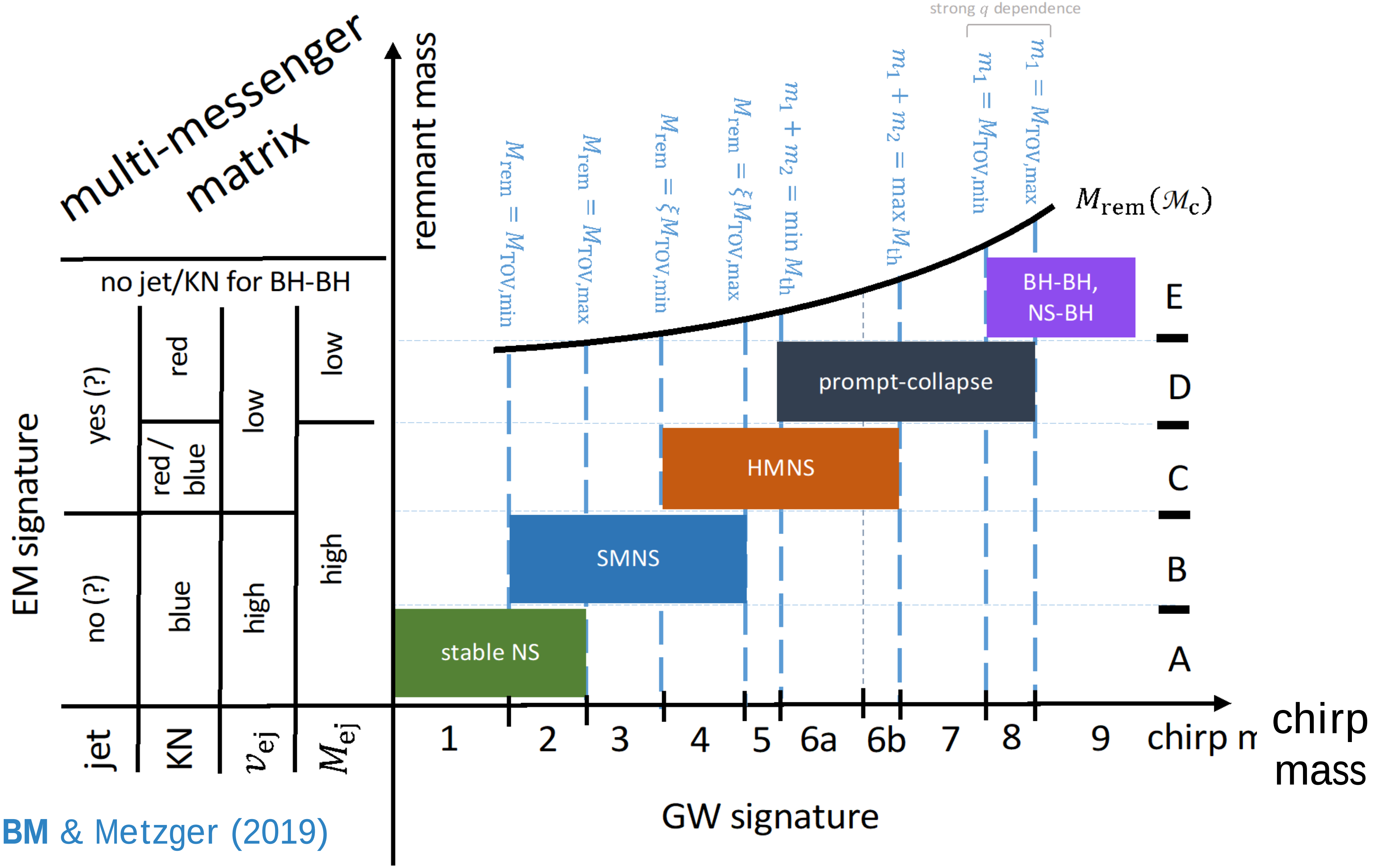


What have we really

Future Outlook:

- rich landscape

(bright future)



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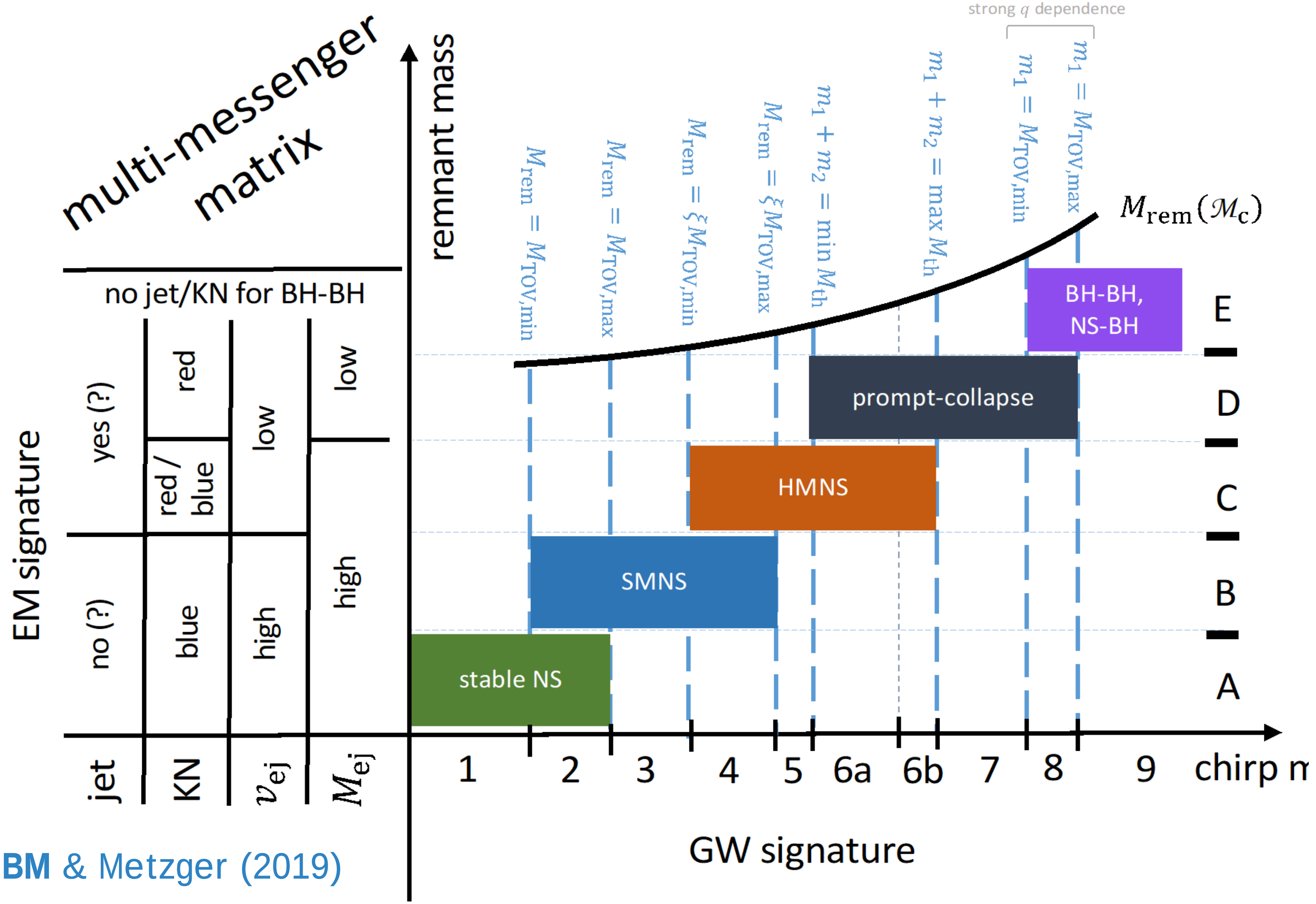

chirp
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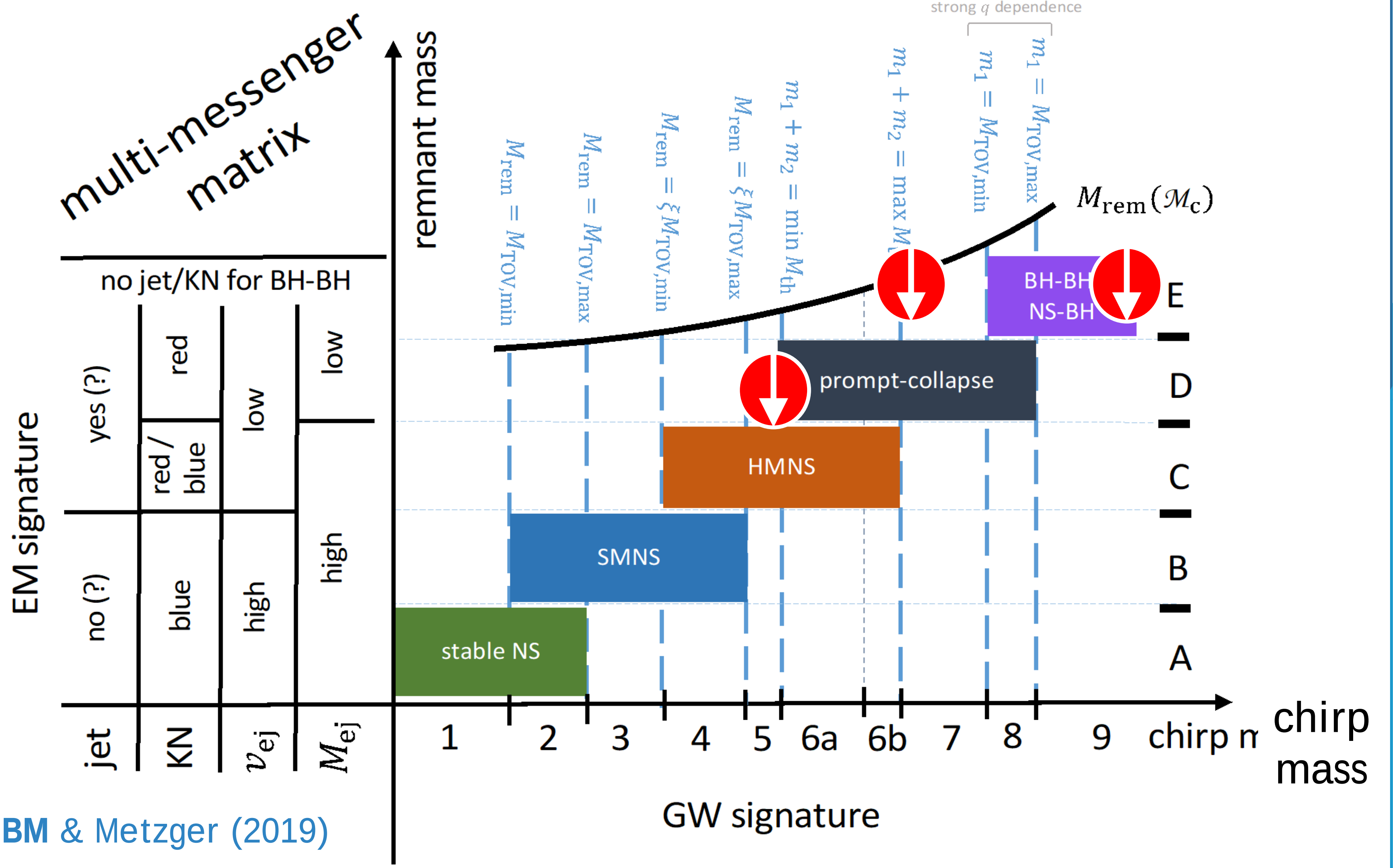

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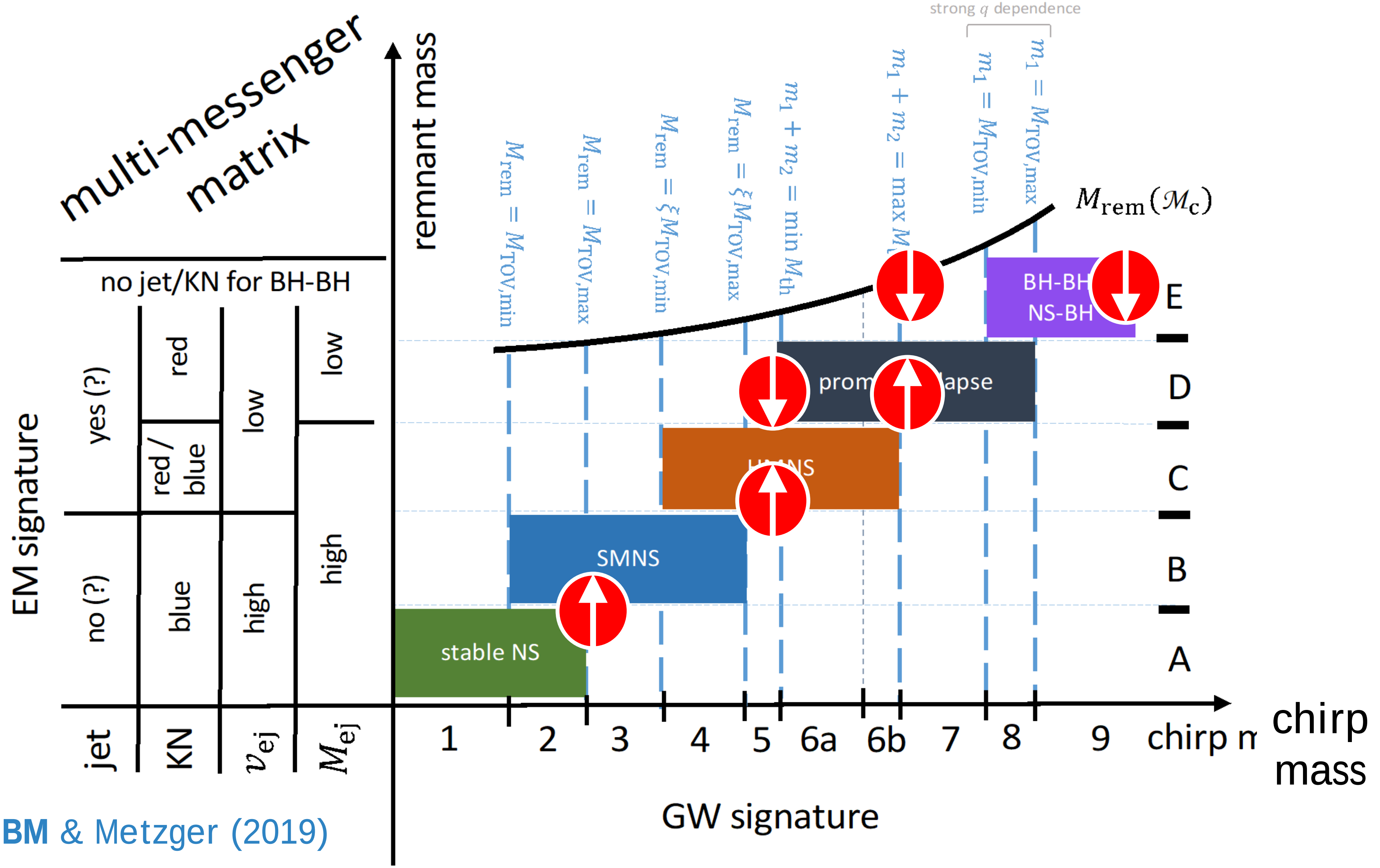

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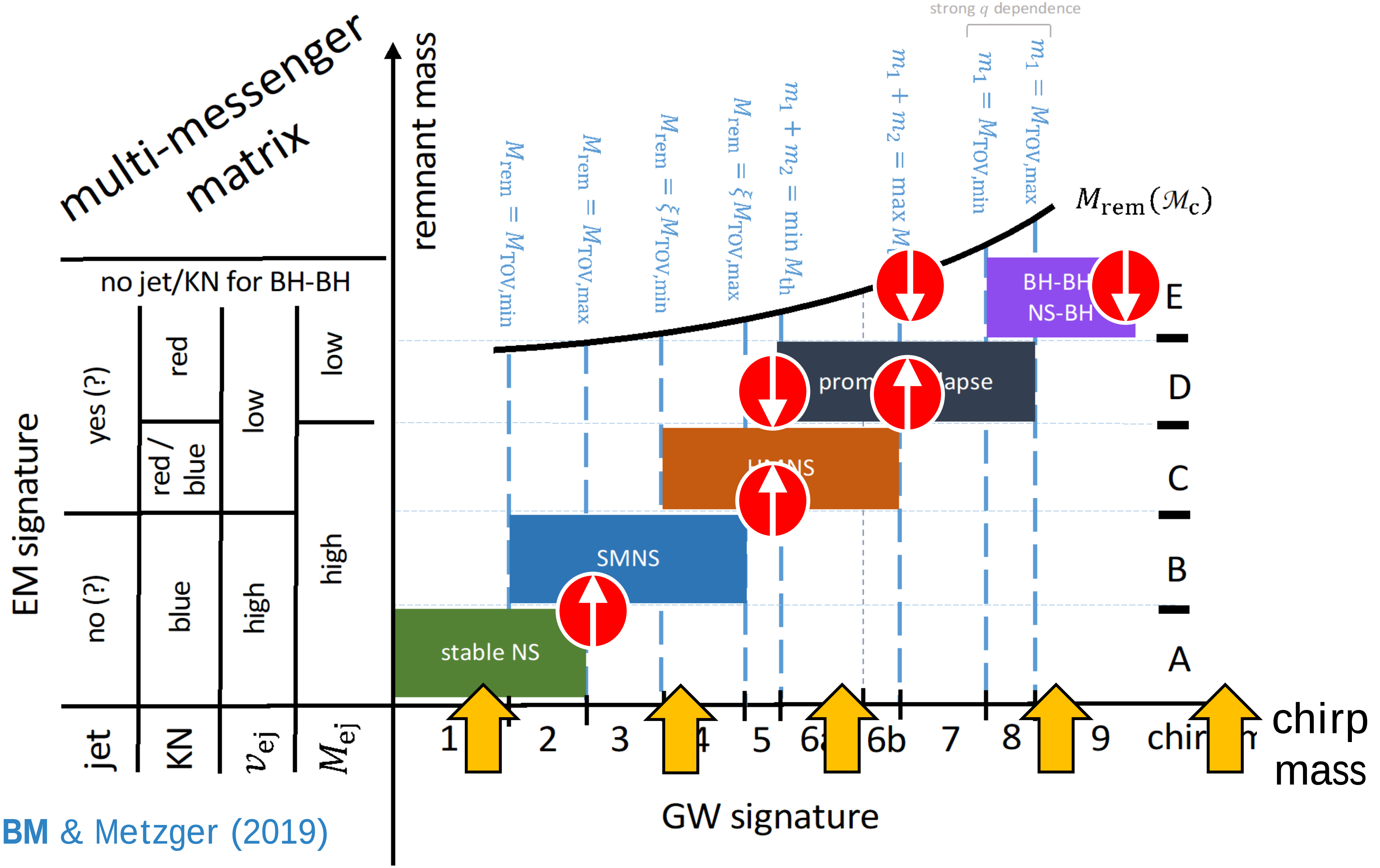

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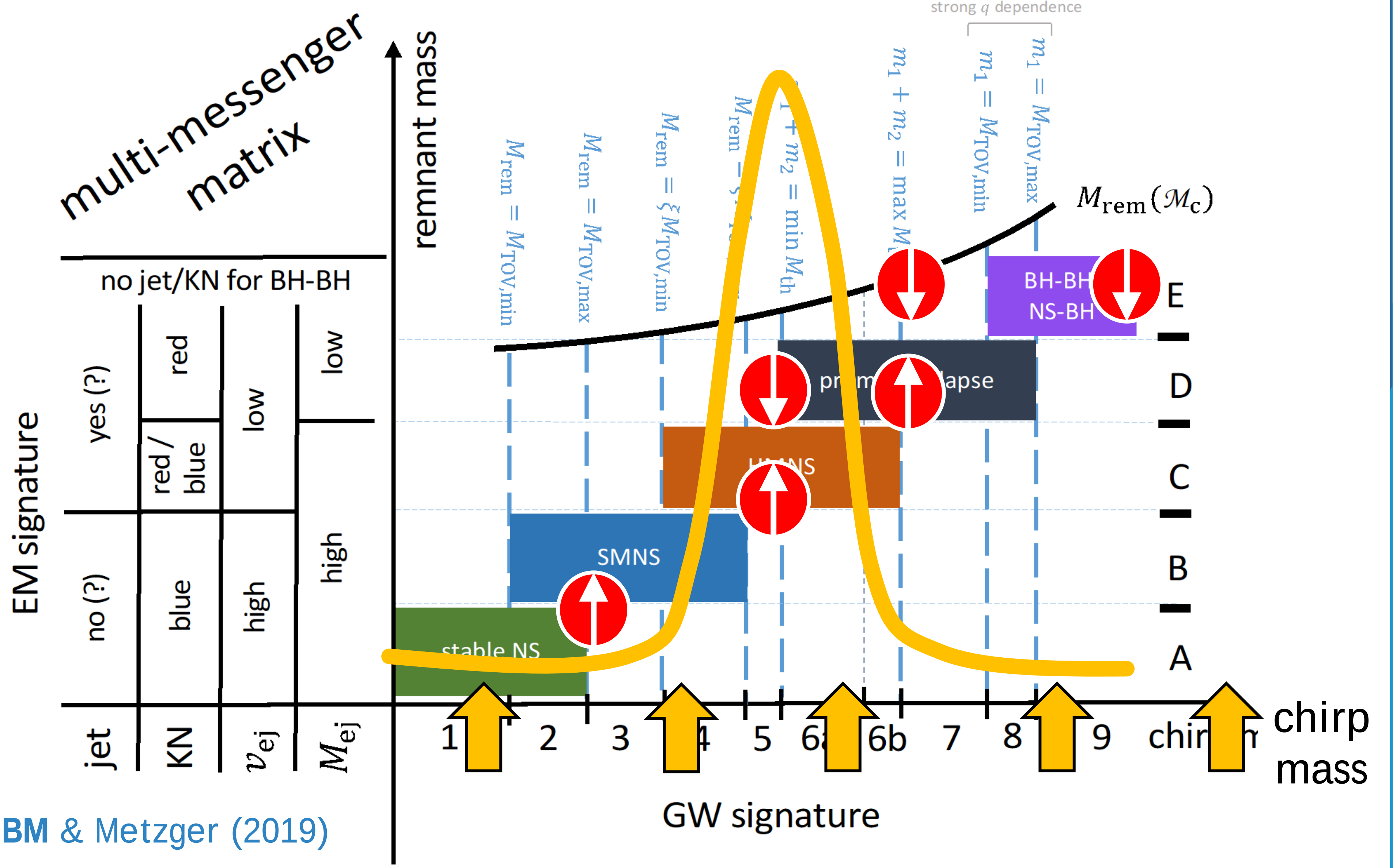

BM & Metzger (2019)

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Future Outlook:

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

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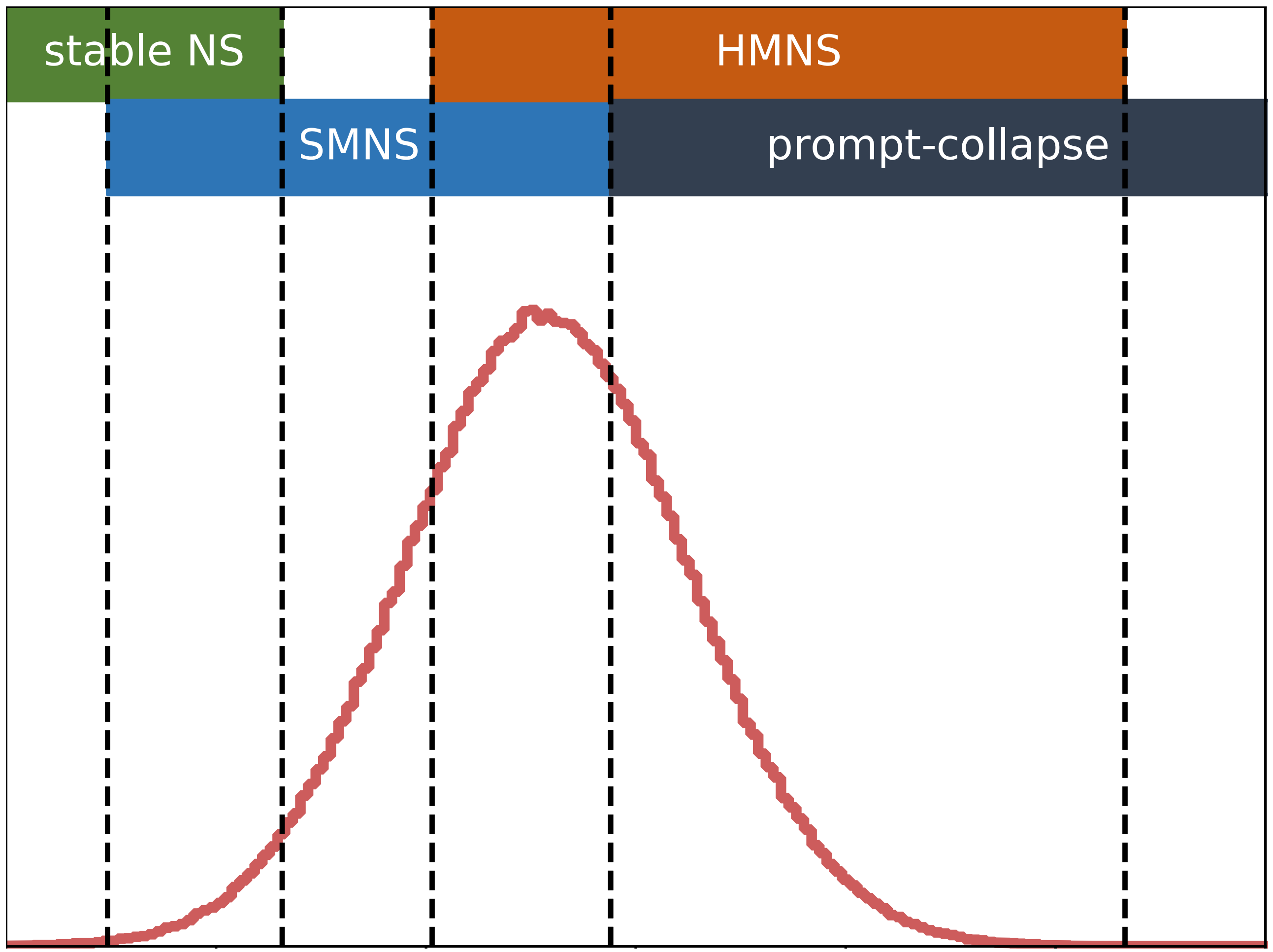

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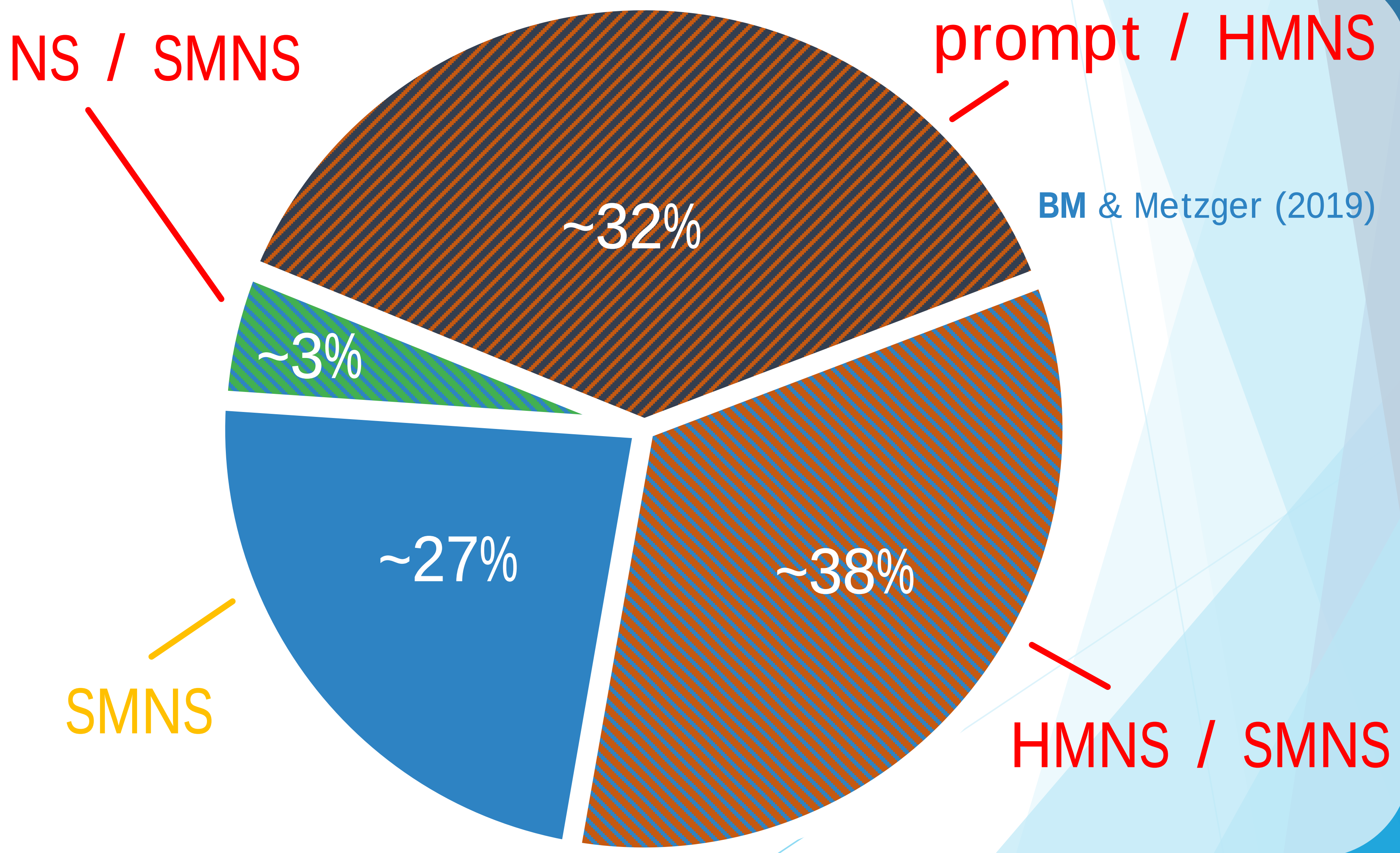

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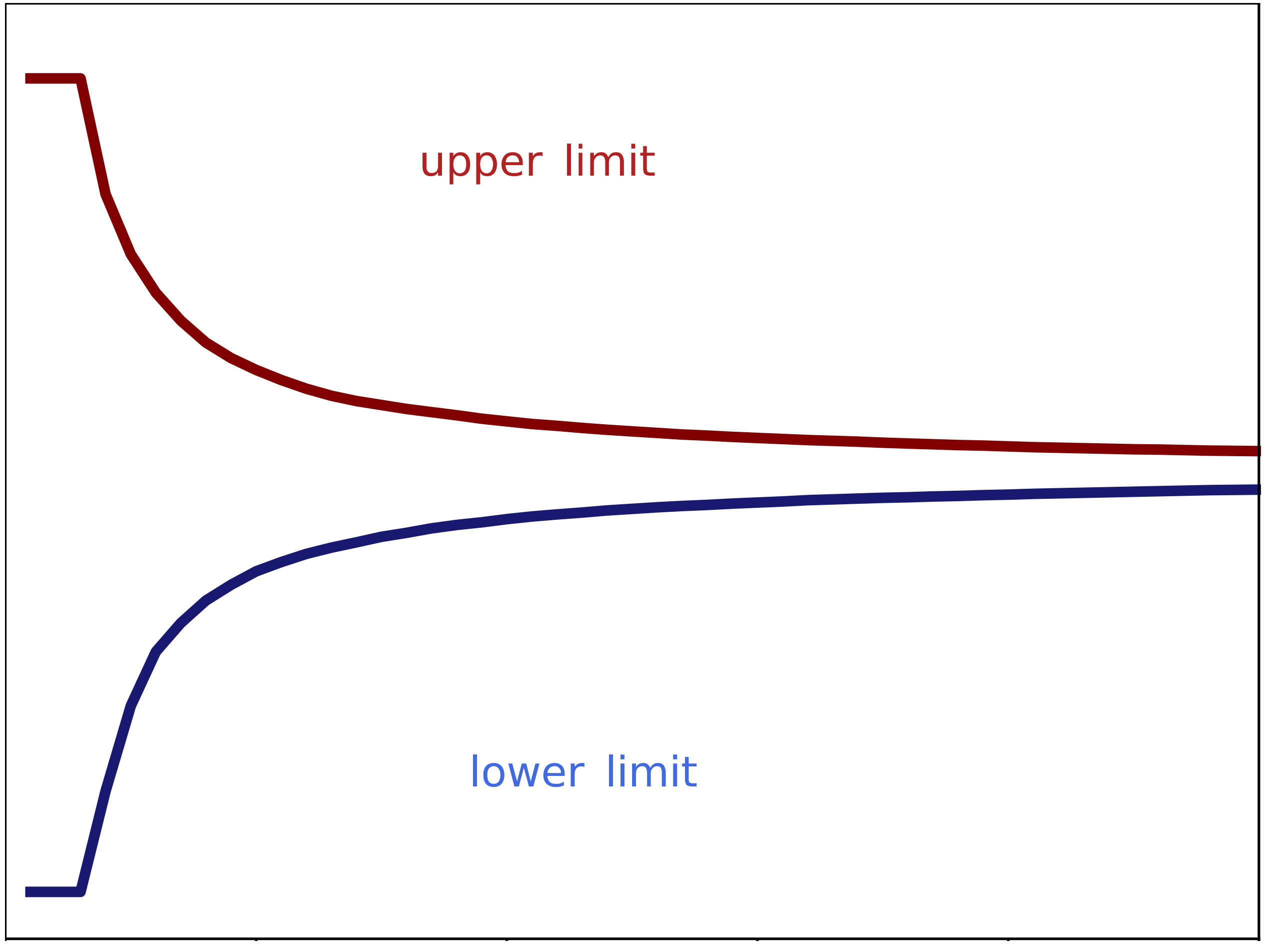


What have we really learned about the nuclear EOS from GW170817?

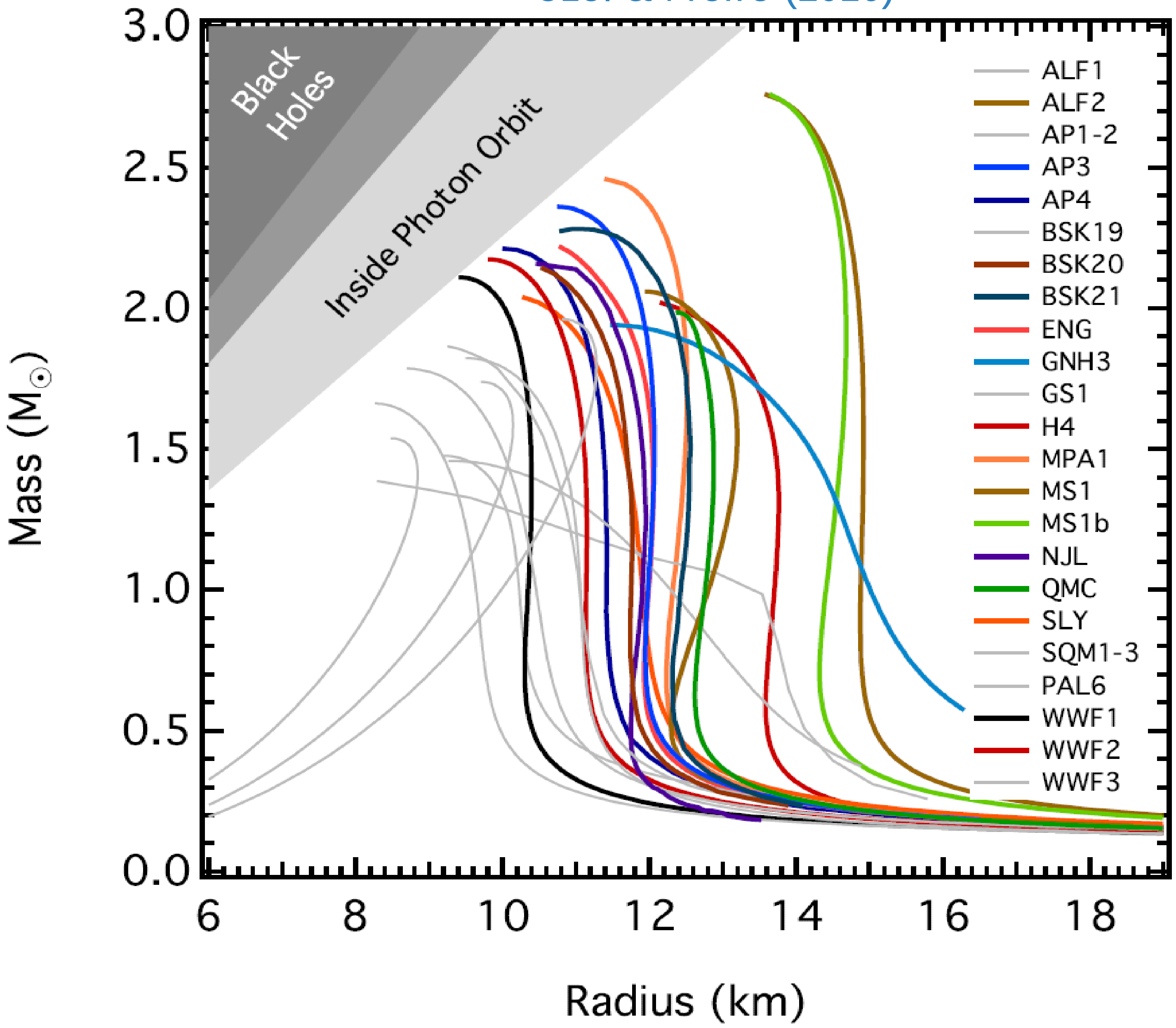
Summary of EOS Constraints:

- 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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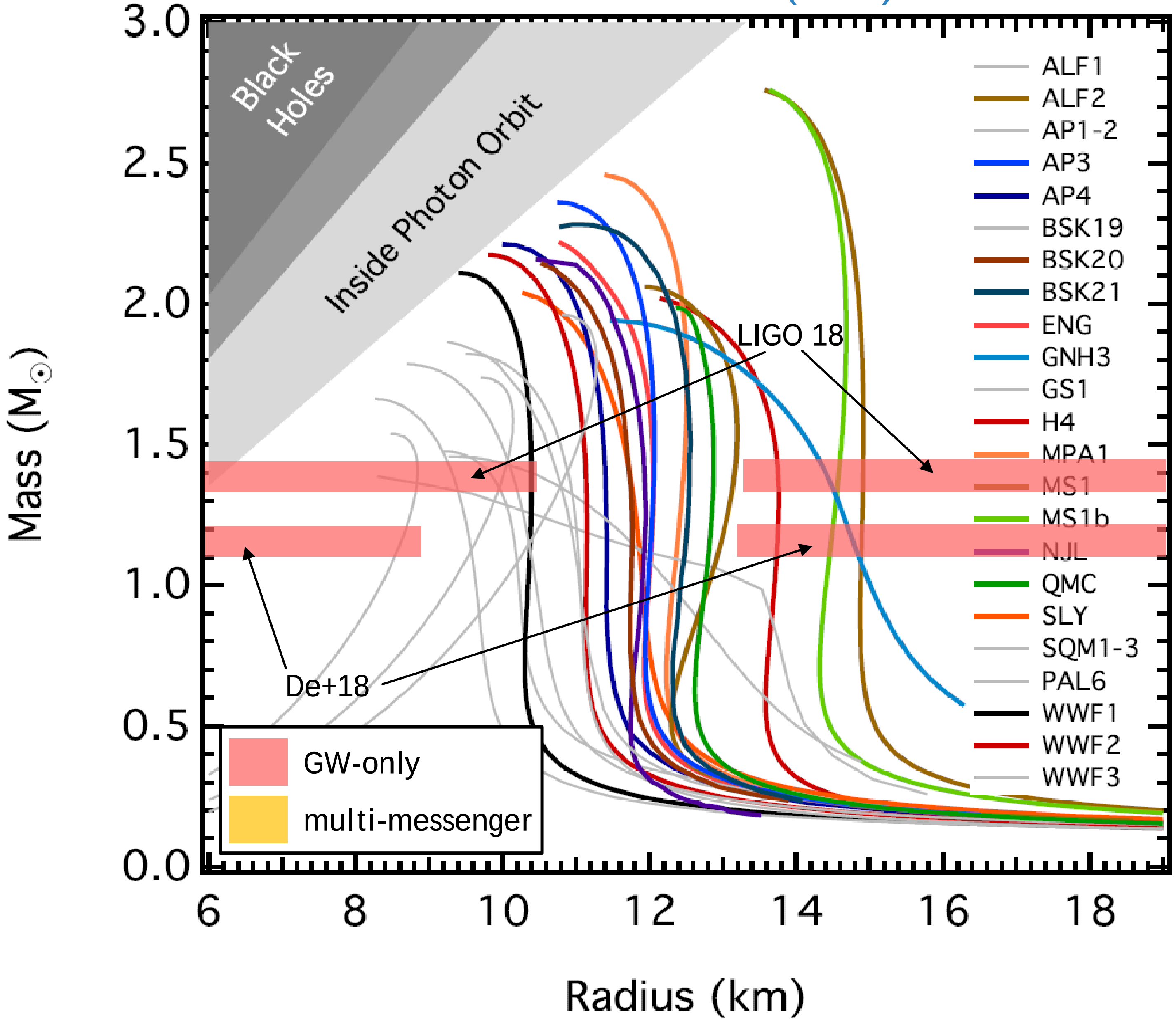

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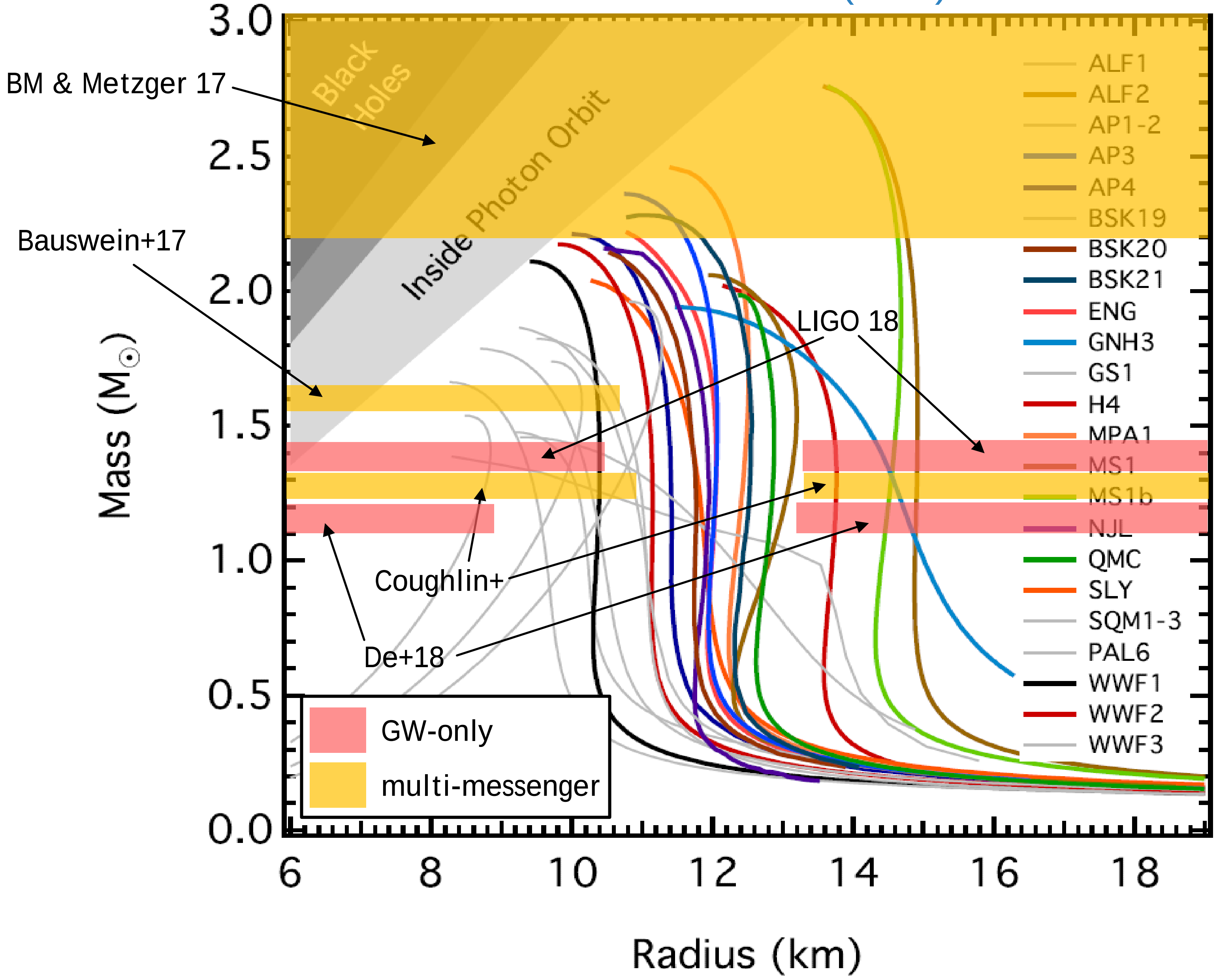

Backup Slides

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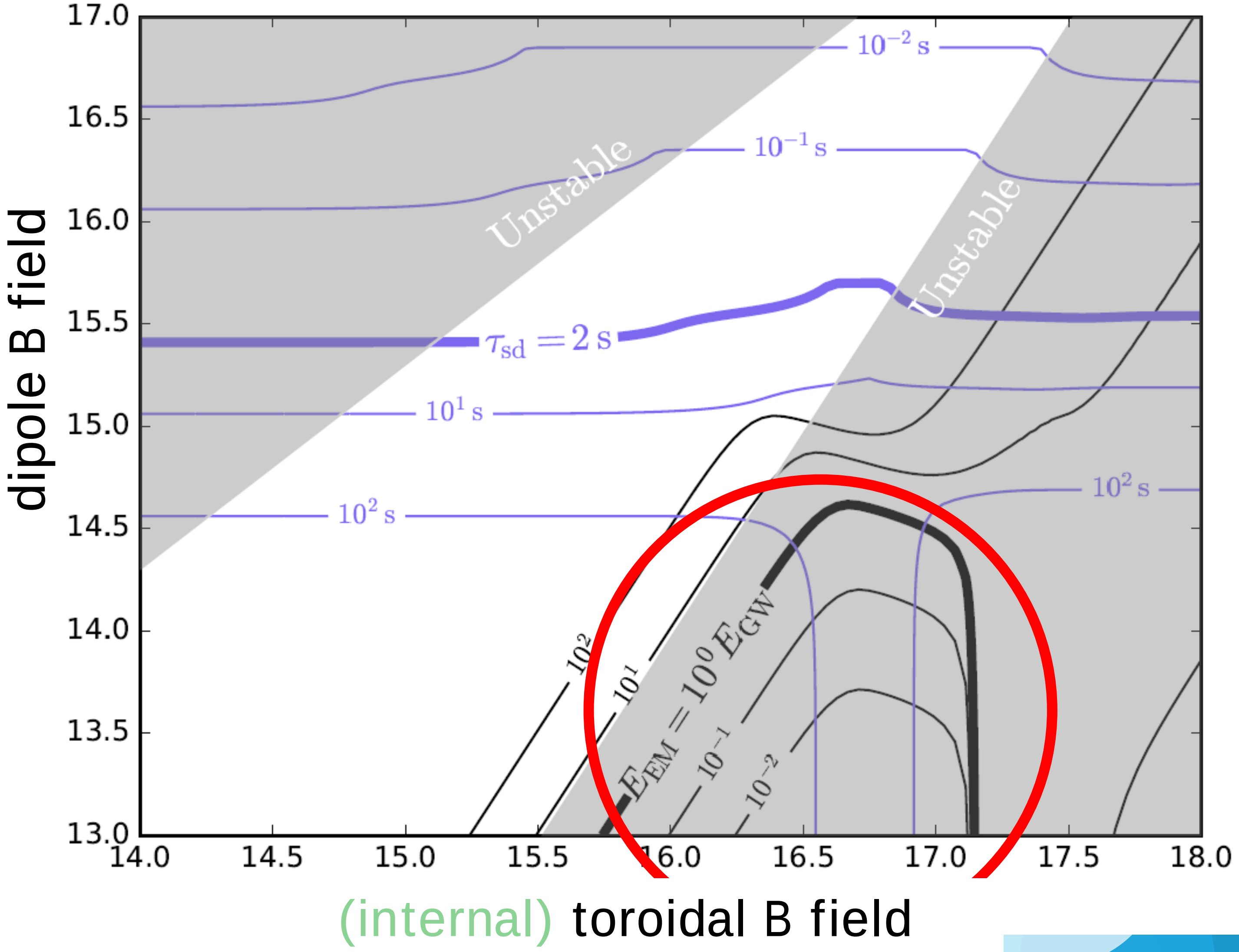
GW spin-down:

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

BM & Metzger (2017)



M_{TOV} Upper Limit:

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

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

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

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

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

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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)