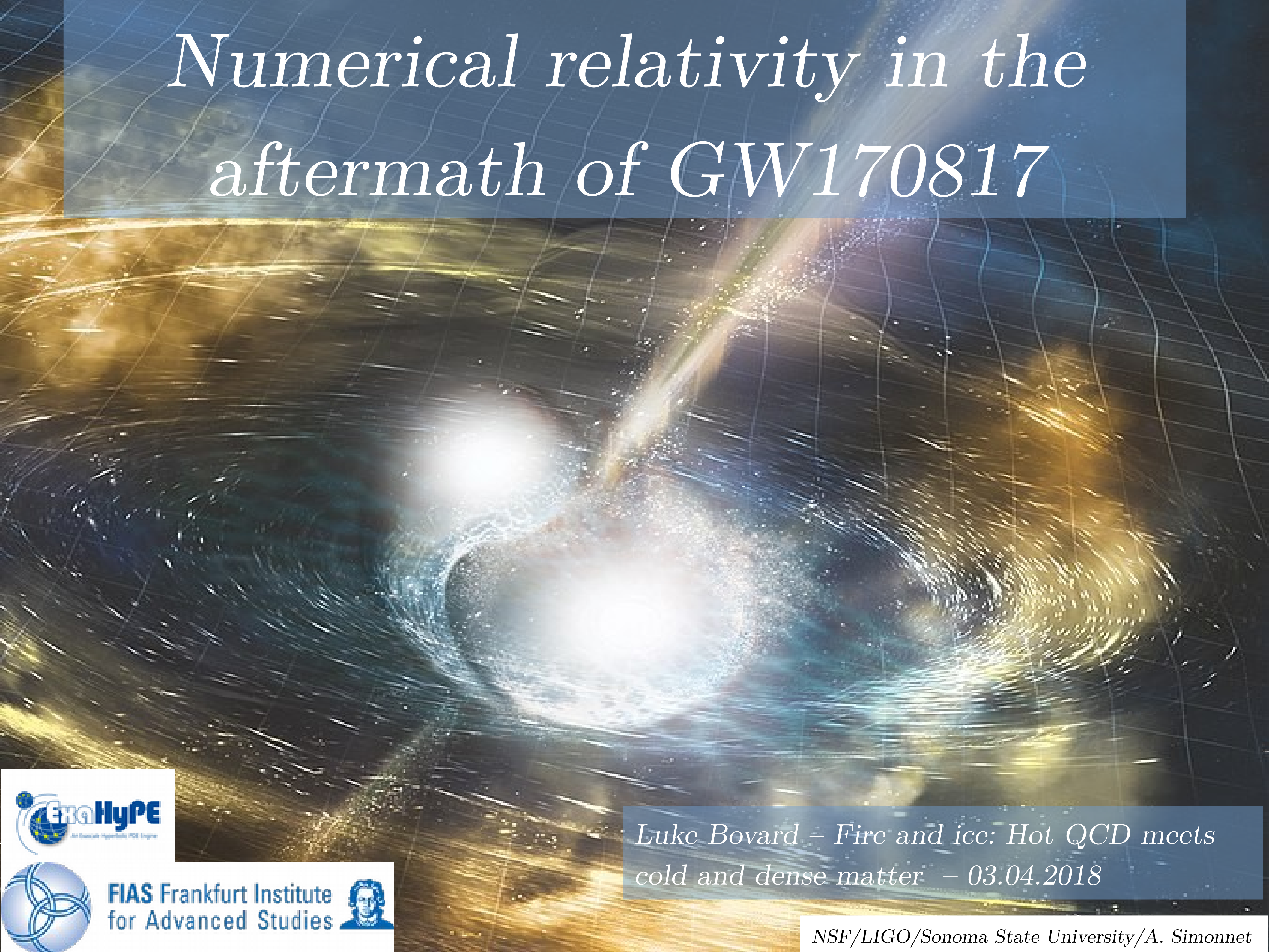


Numerical relativity in the aftermath of GW170817

Luke Bovard – Fire and ice: Hot QCD meets cold and dense matter – 03.04.2018

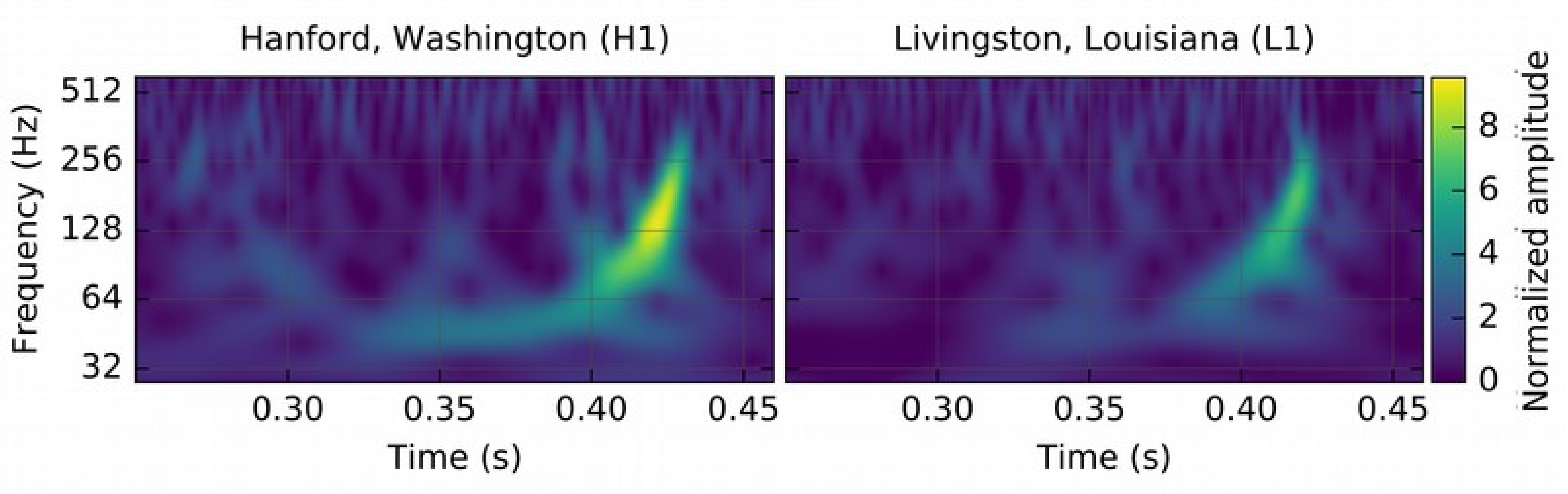
ExaHyPE

FIAS Frankfurt Institute for Advanced Studies

NSF/LIGO/Sonoma State University/A. Simonnet

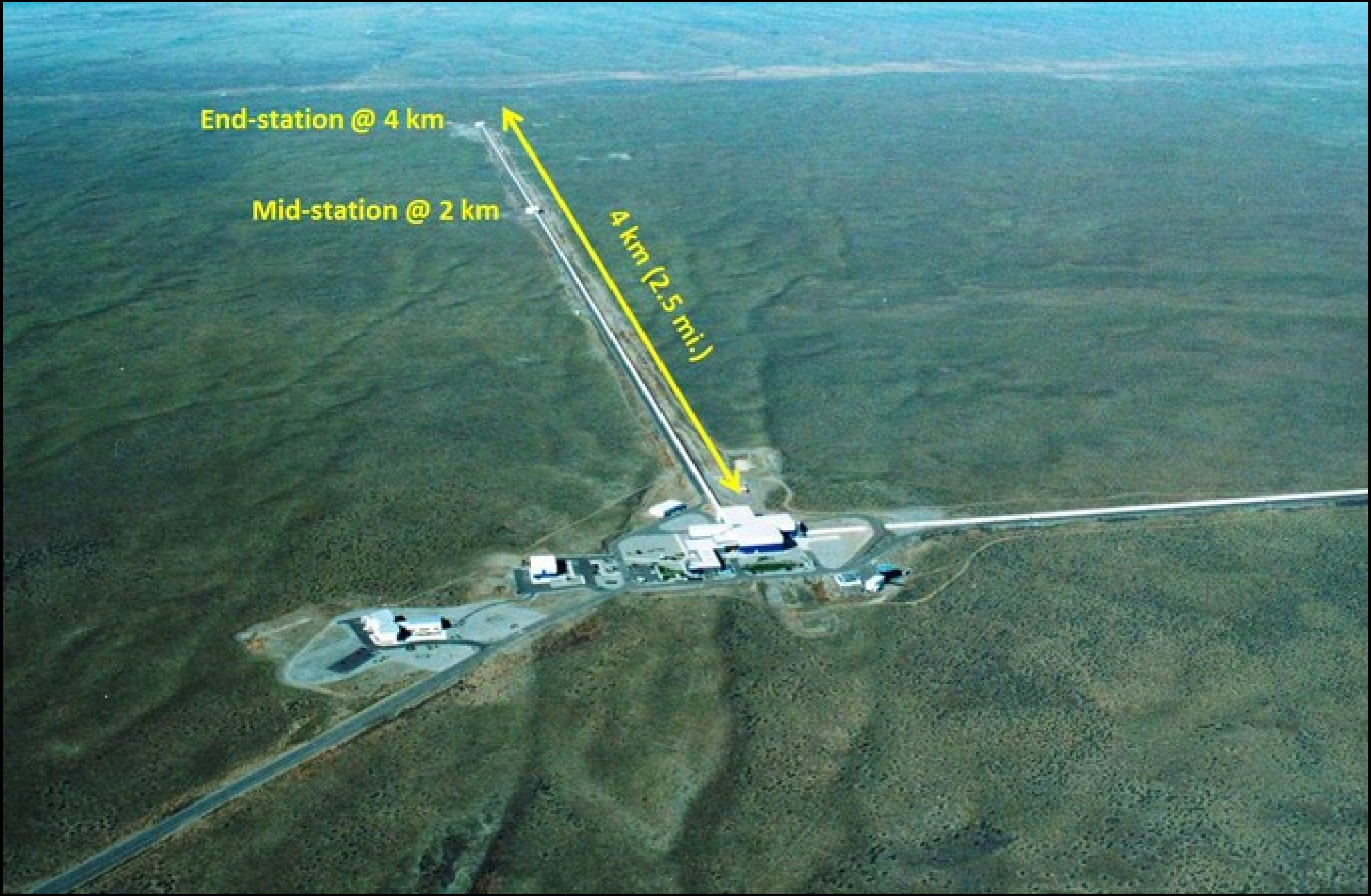
Gravitational Waves

- *Distortions of spacetime predicted by Einstein in 1916*
- *Indirectly observed in the Hulse-Taylor binary in 1974*
- *Directly observed from a merger of binary black holes on September 14th, 2015 by LIGO*

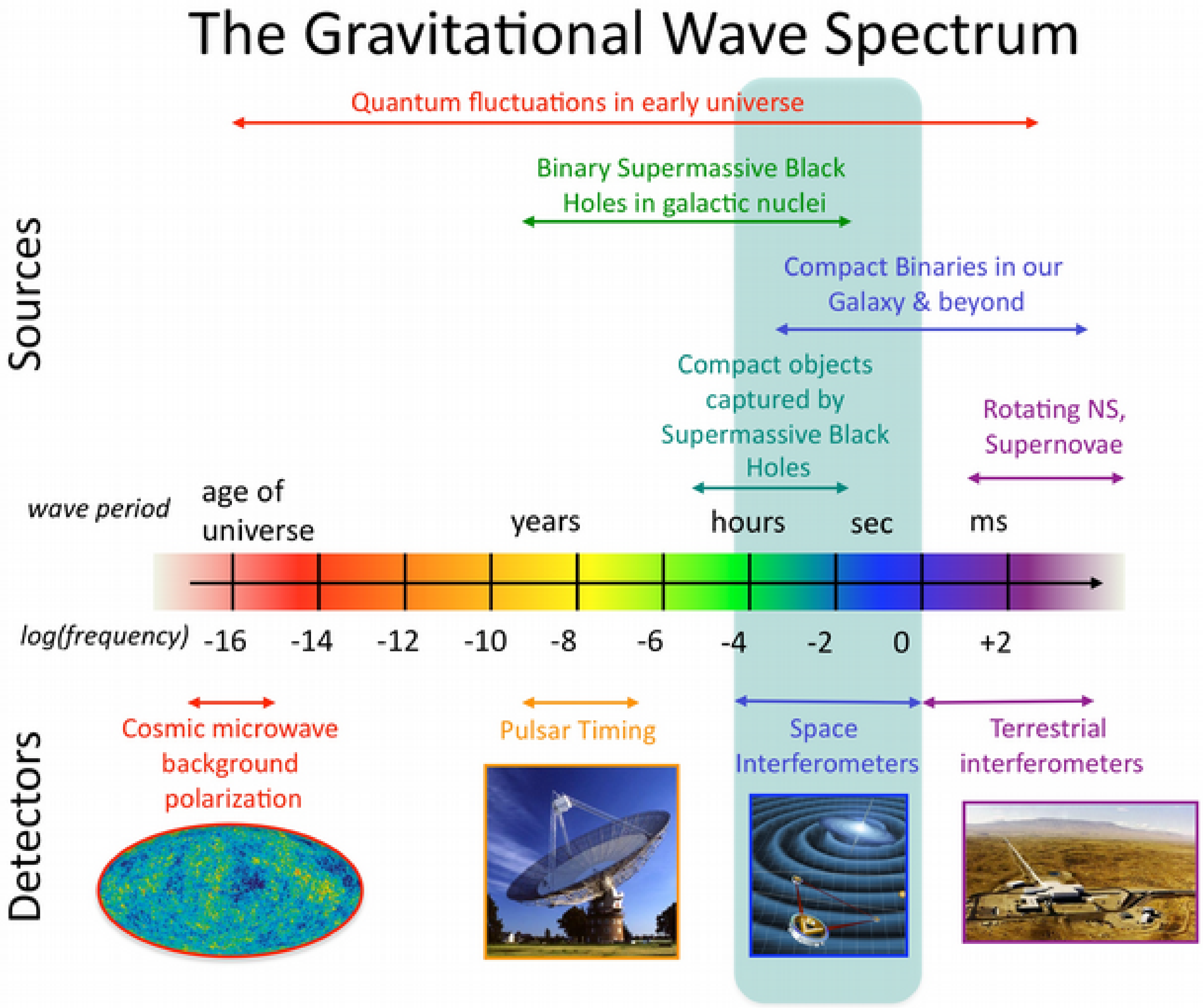


(Abbott 2016)

$$\mathit{strain}\ h \sim \Delta L/L \sim 10^{-21}$$



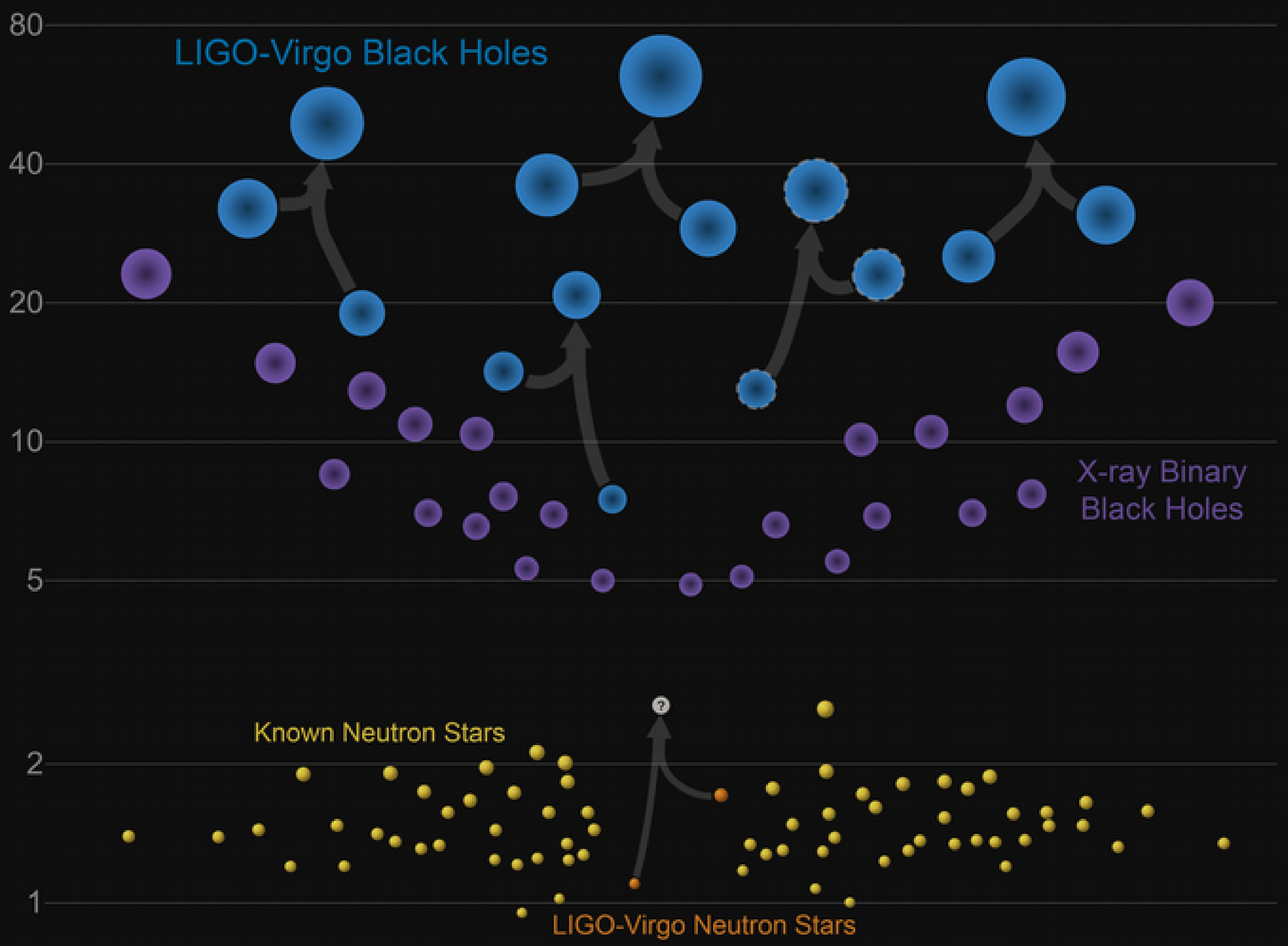
Animation created by T. Pyle, Caltech/MIT/LIGO Lab



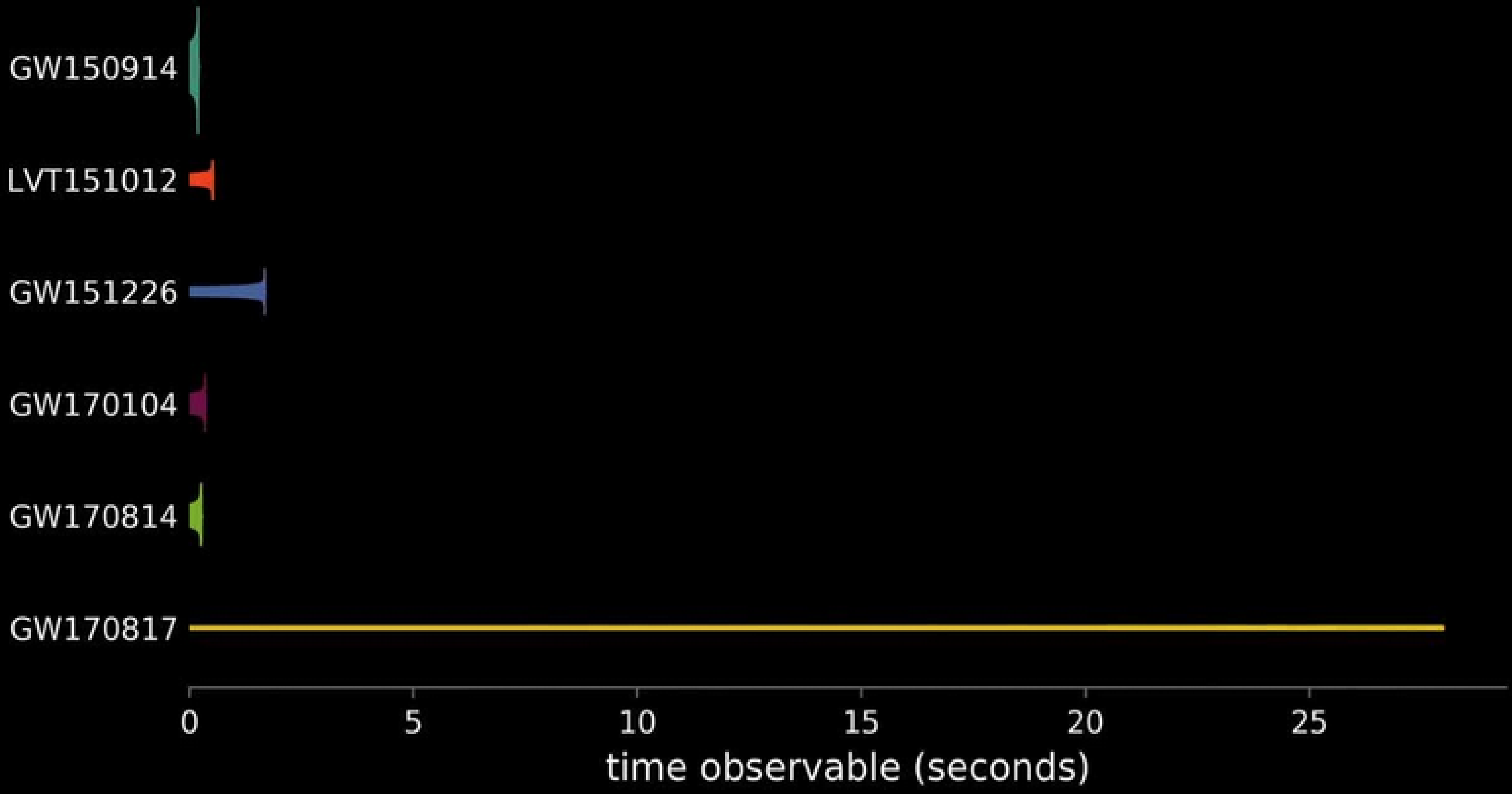
NASA Goddard Space Flight Center

Masses in the Stellar Graveyard

in Solar Masses



Caltech/MIT/LIGO

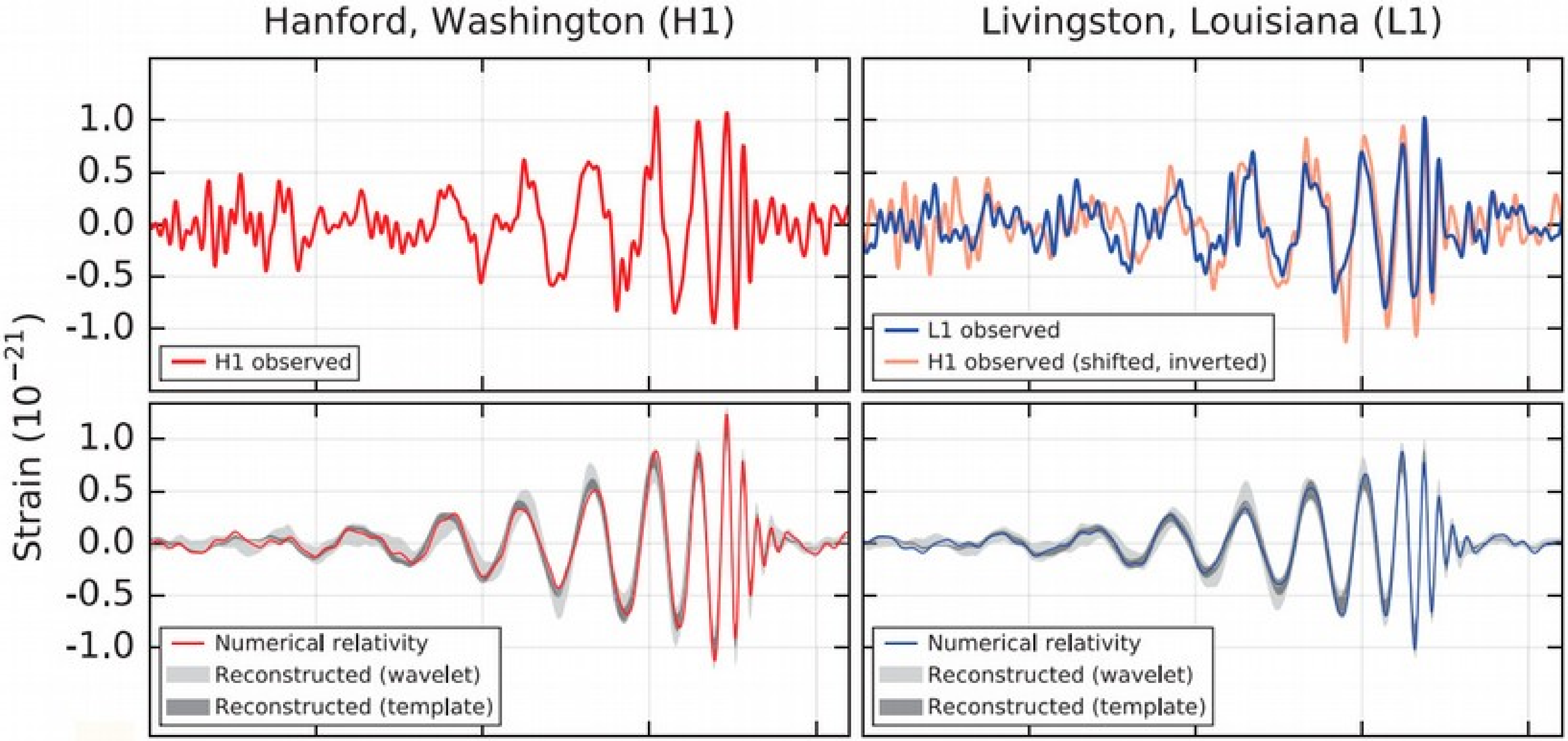


LIGO/University of Oregon/Ben Farr

Caltech/MIT/LIGO

BH-BH in NR

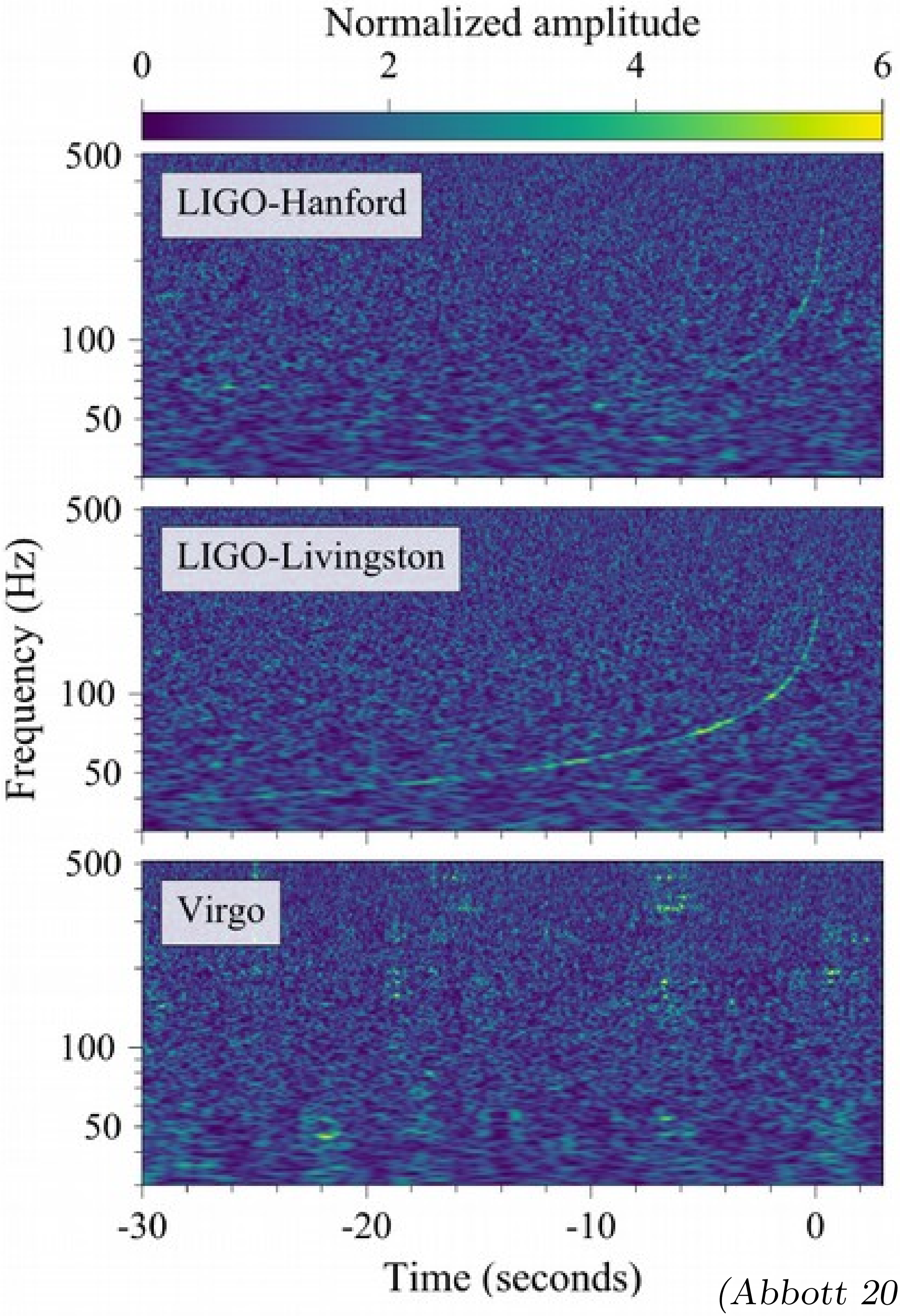
(Abbott 2016)



NR simulations of BH-BH mergers agree perfectly with observations

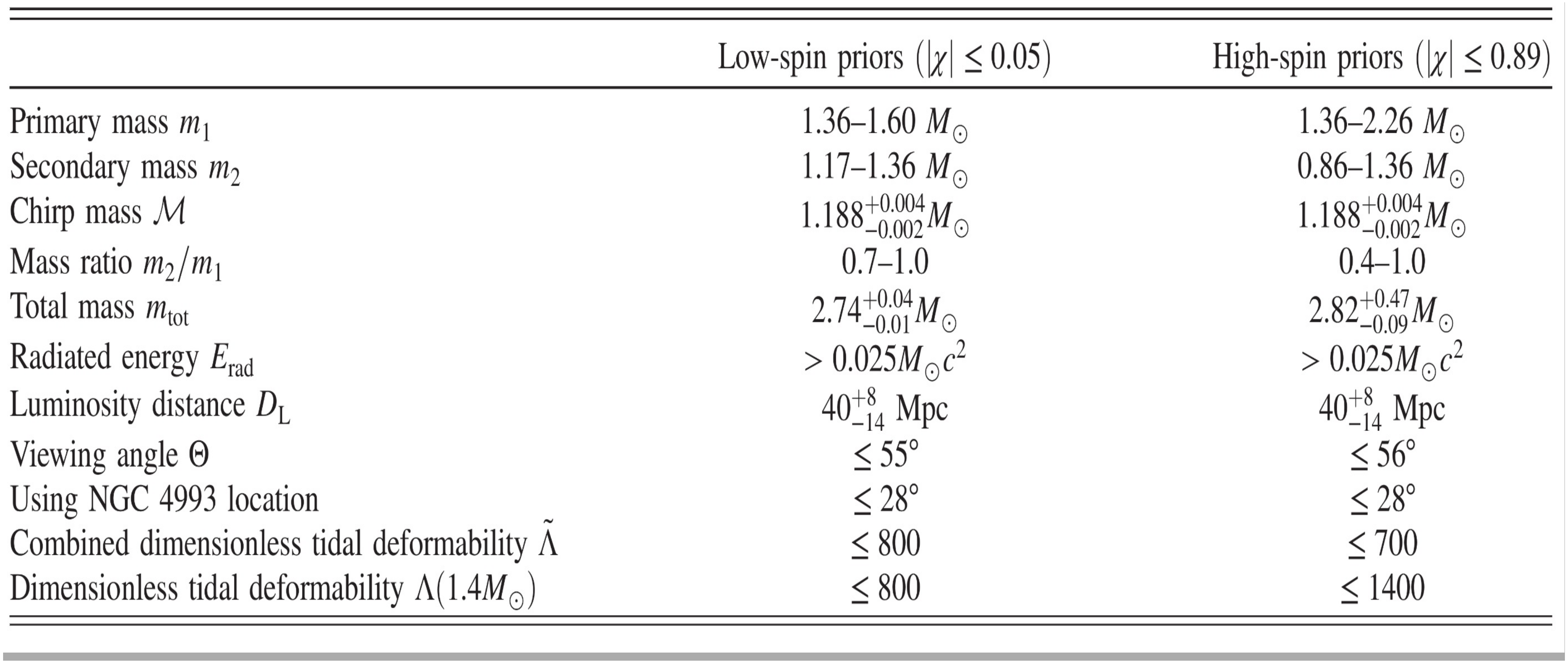
GW170817

- *On August 17th, 2017 LIGO detected a NS-NS merger*
- *Not just in the GW spectrum! EM counterpart also observed*
- *Waveform only inspiral*
- *Still can constrain EOS*



(Abbott 2017)

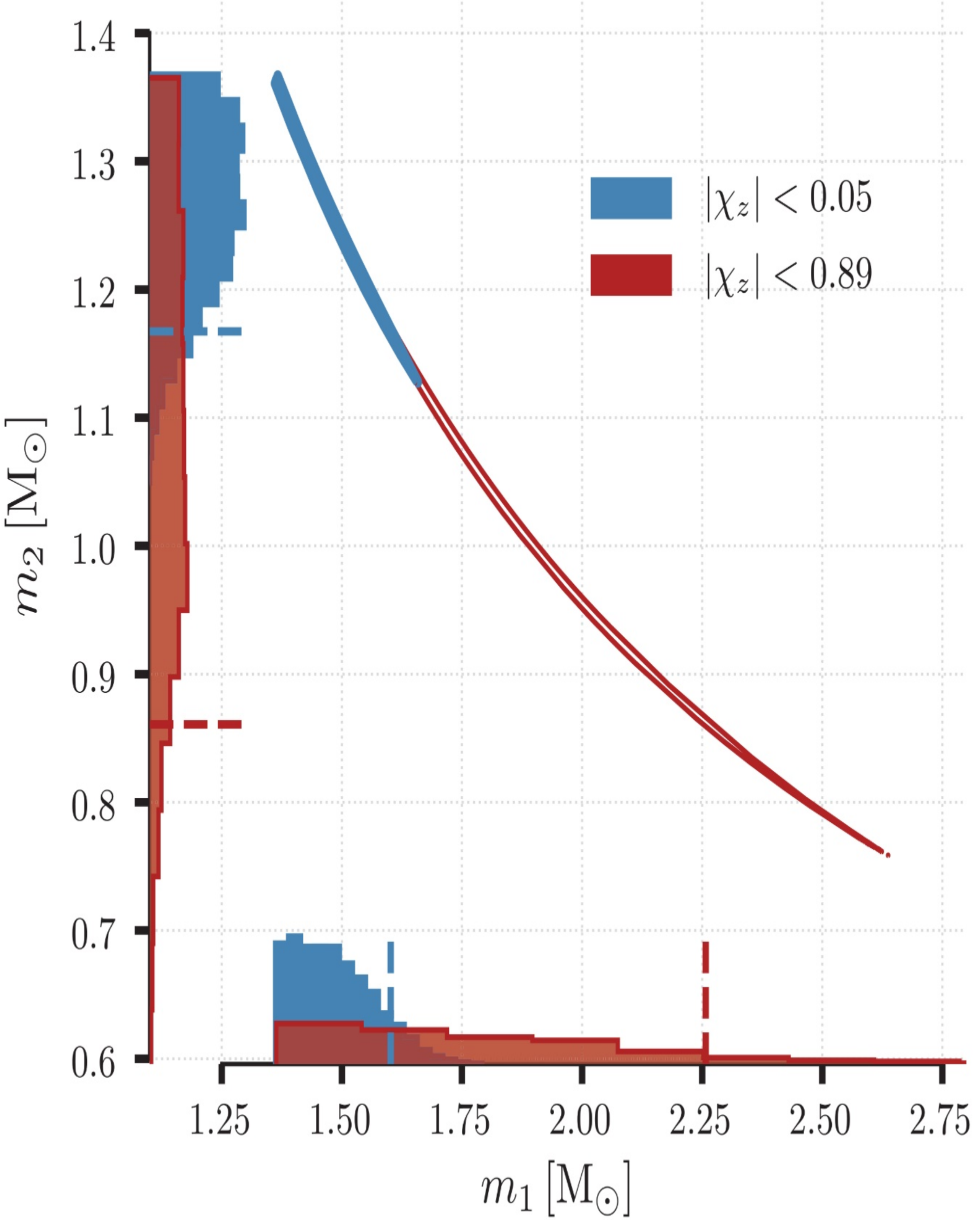
GW170817



	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–$1.60\ M_\odot$	1.36–$2.26\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$	0.86–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

(Abbott 2017)

GW170817

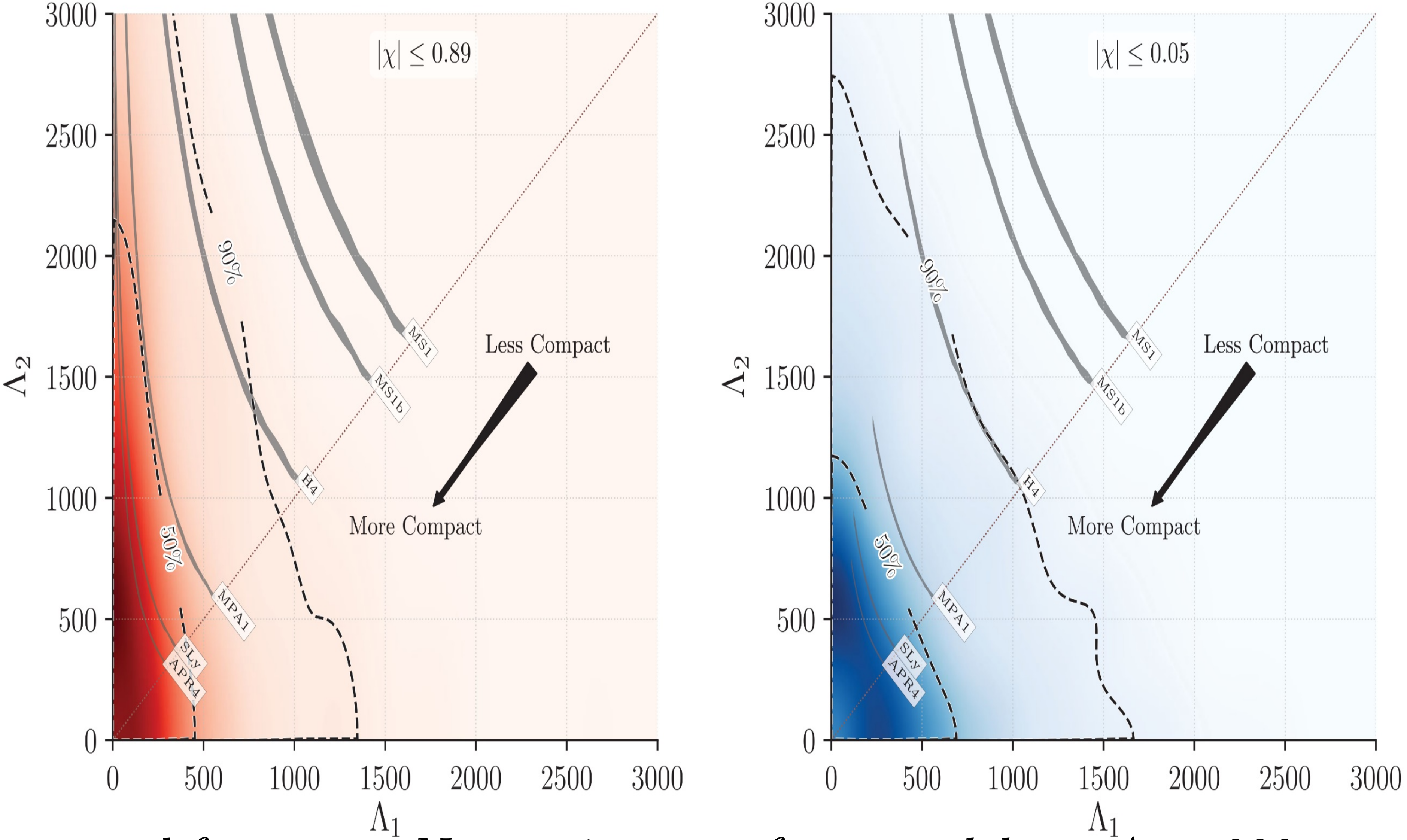


(Abbott 2017)

(Abbott 2017)

Tidal Deformability

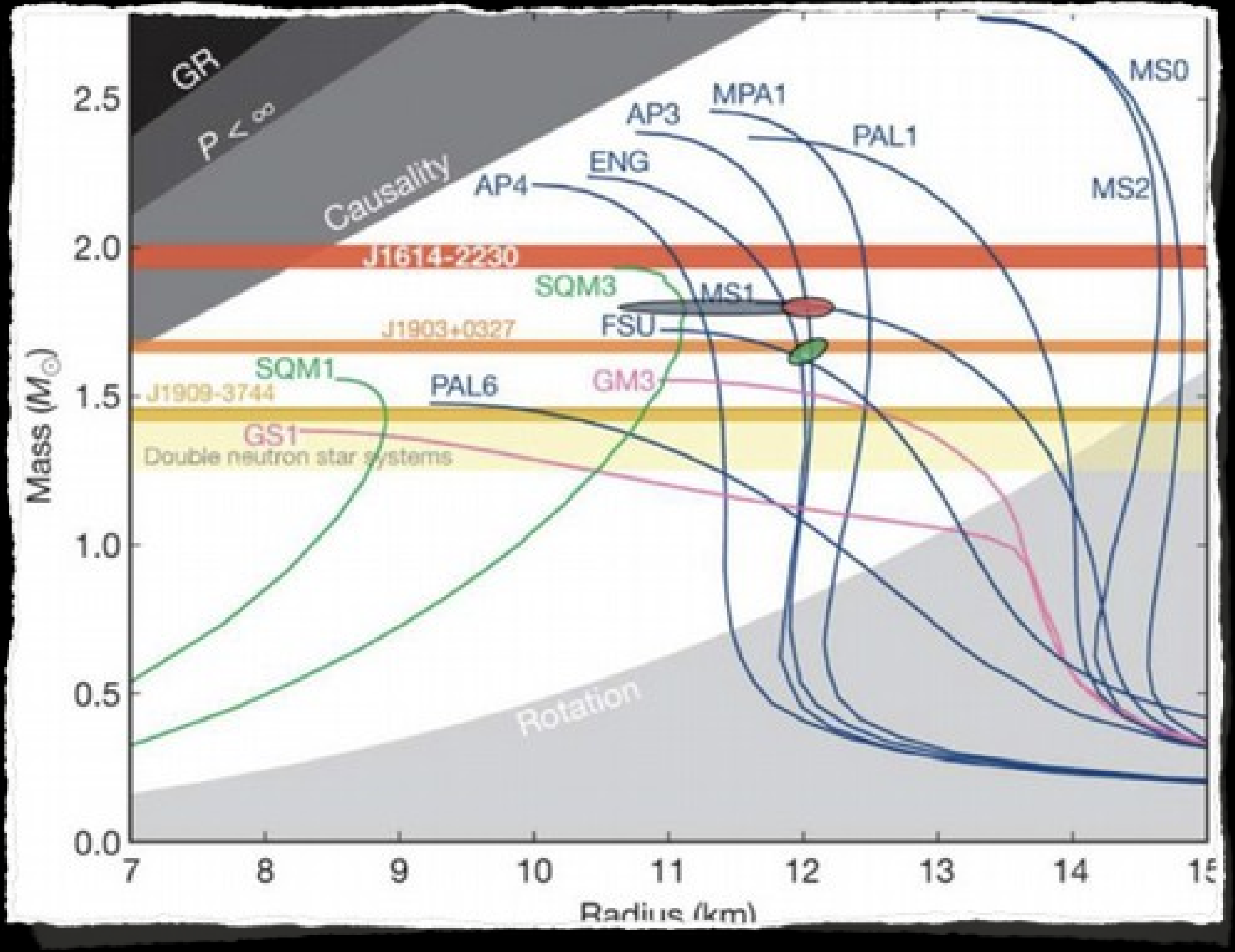
$$\Lambda = \frac{\lambda}{\bar{M}^5} = \frac{16}{3}\kappa_2^T$$



Computed from post-Newtonian waveform models → $\Lambda \leq 800$

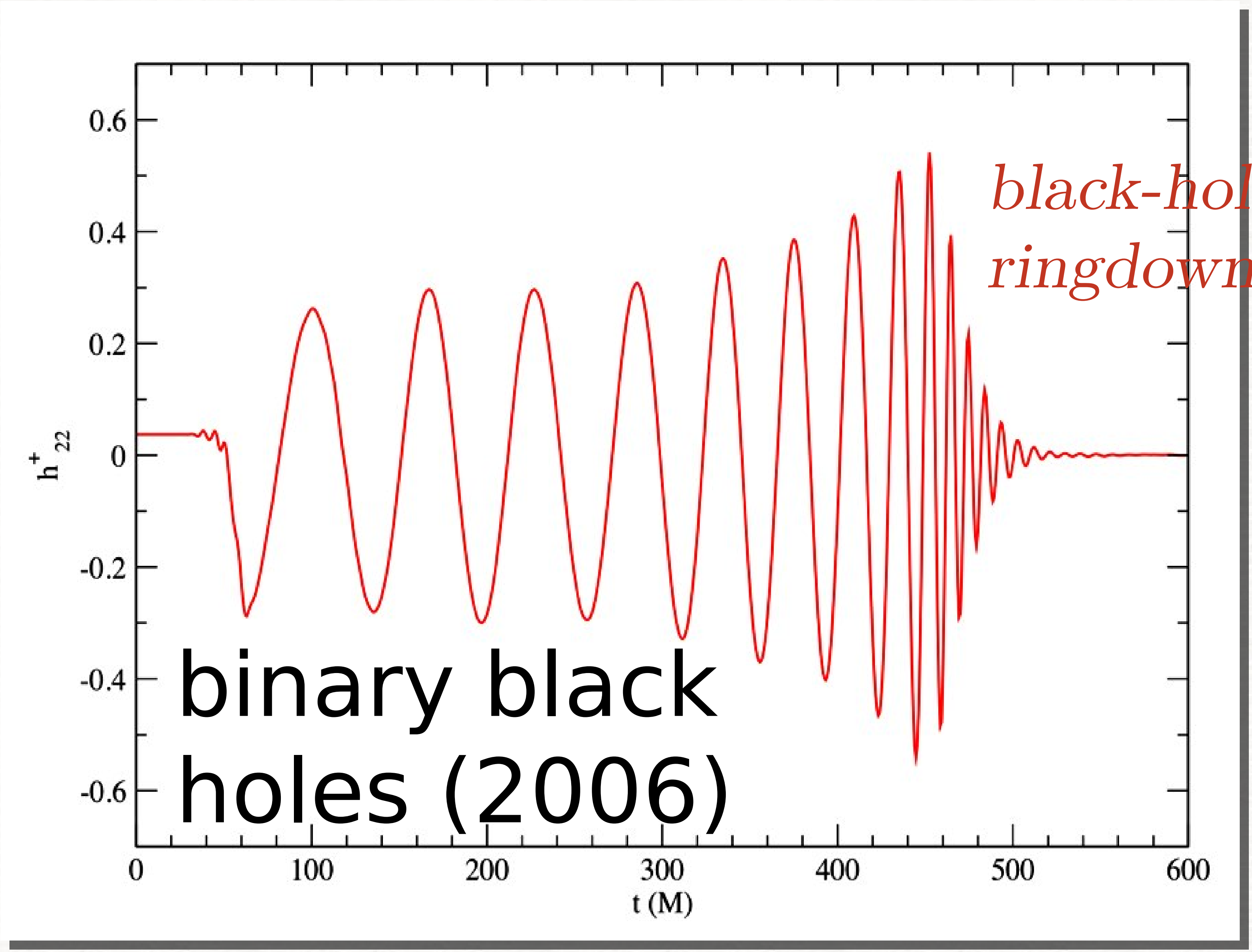
See talks later today for more details!

How to constrain the EOS



Slides courtesy of Luciano Rezzolla

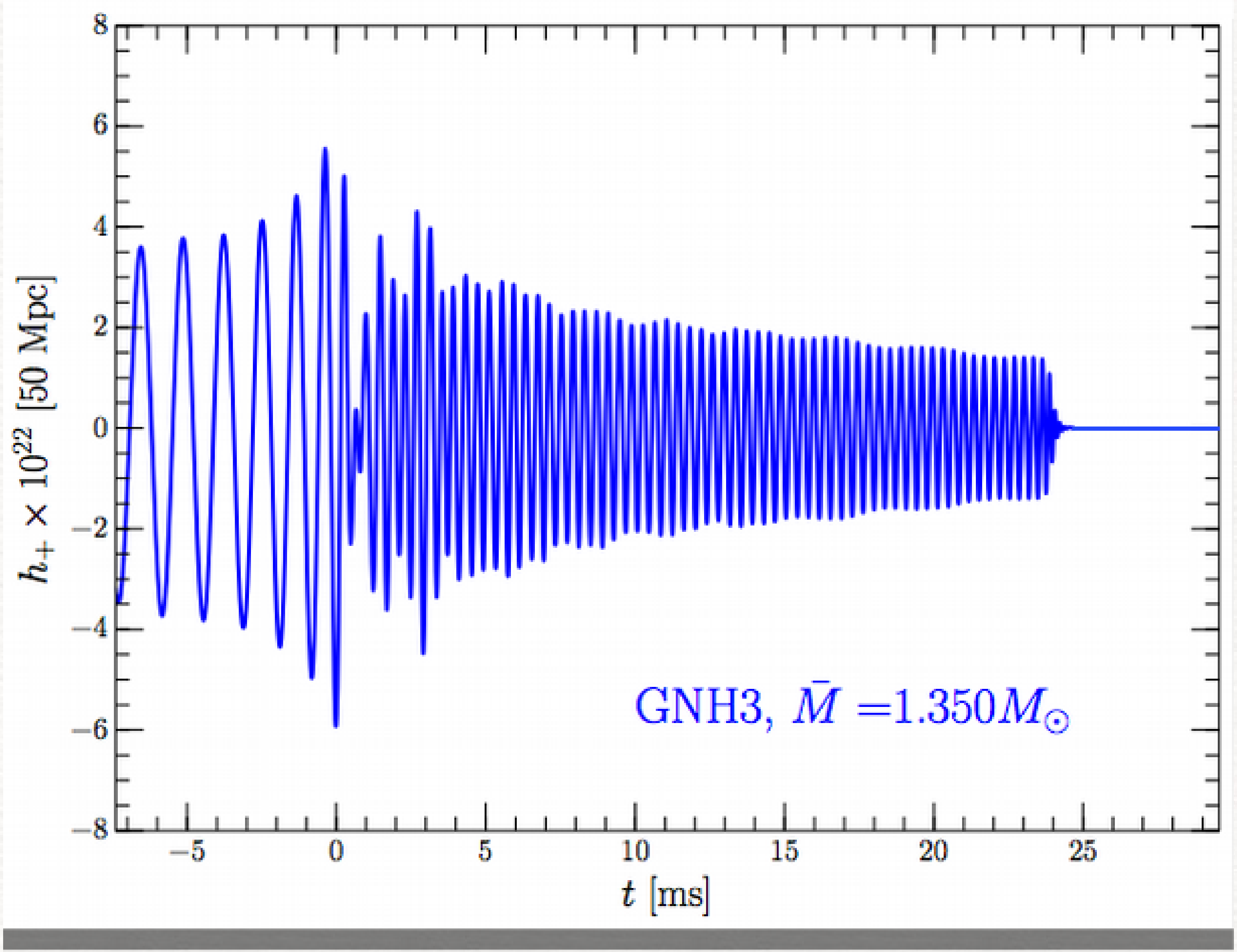
Anatomy of the GW signal



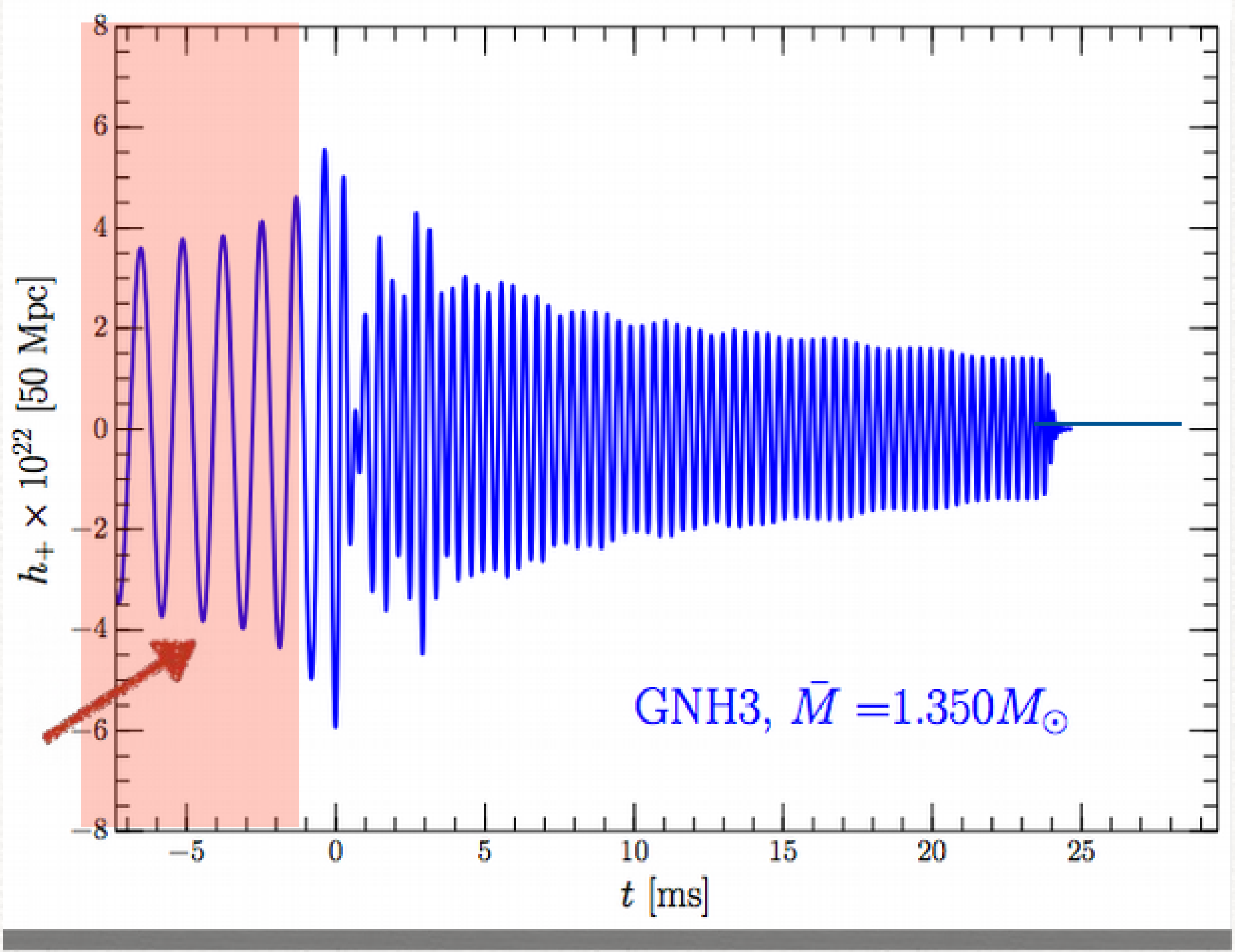
black-hole ringdown

binary black holes (2006)

Anatomy of the GW signal



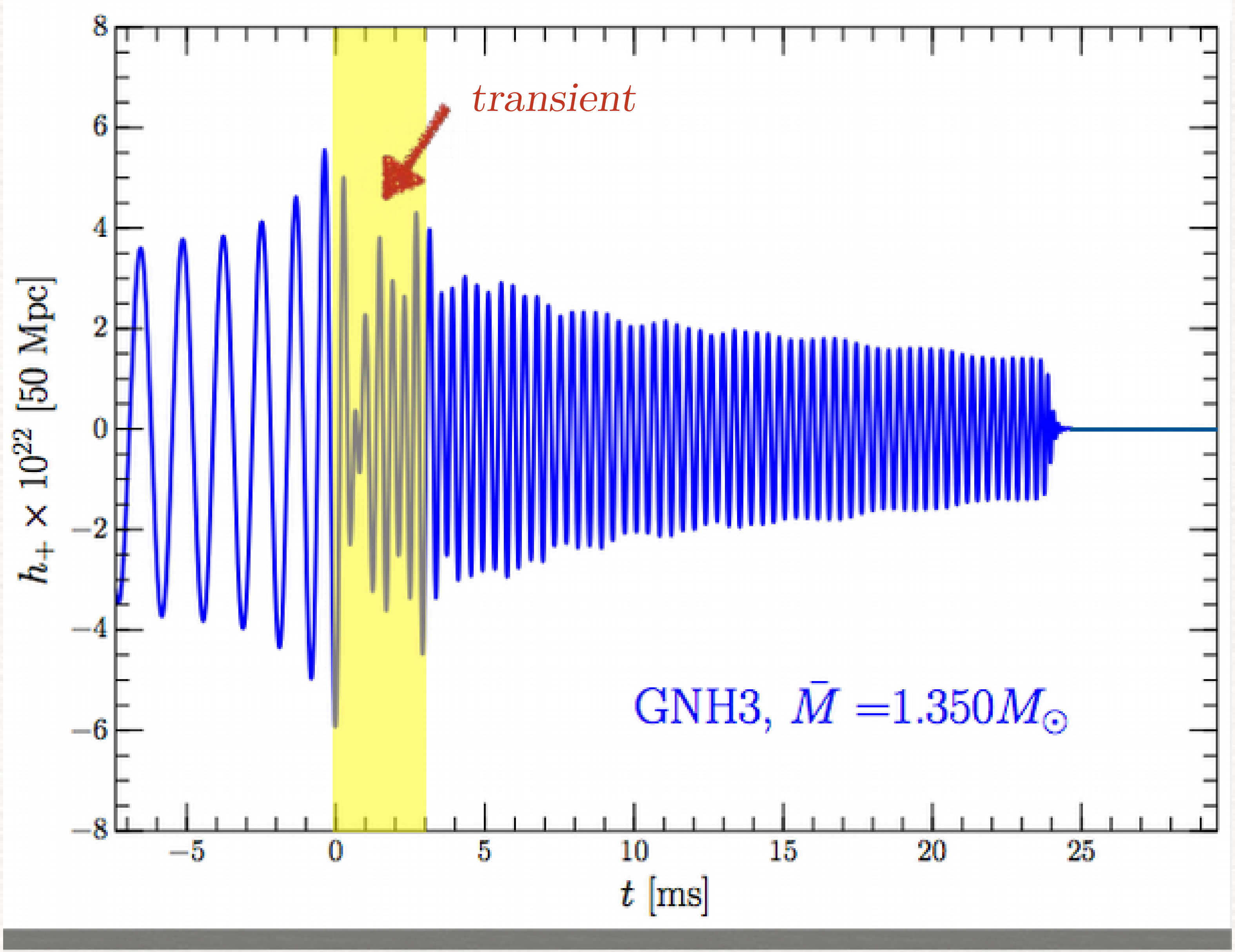
Anatomy of the GW signal



Chirp signal

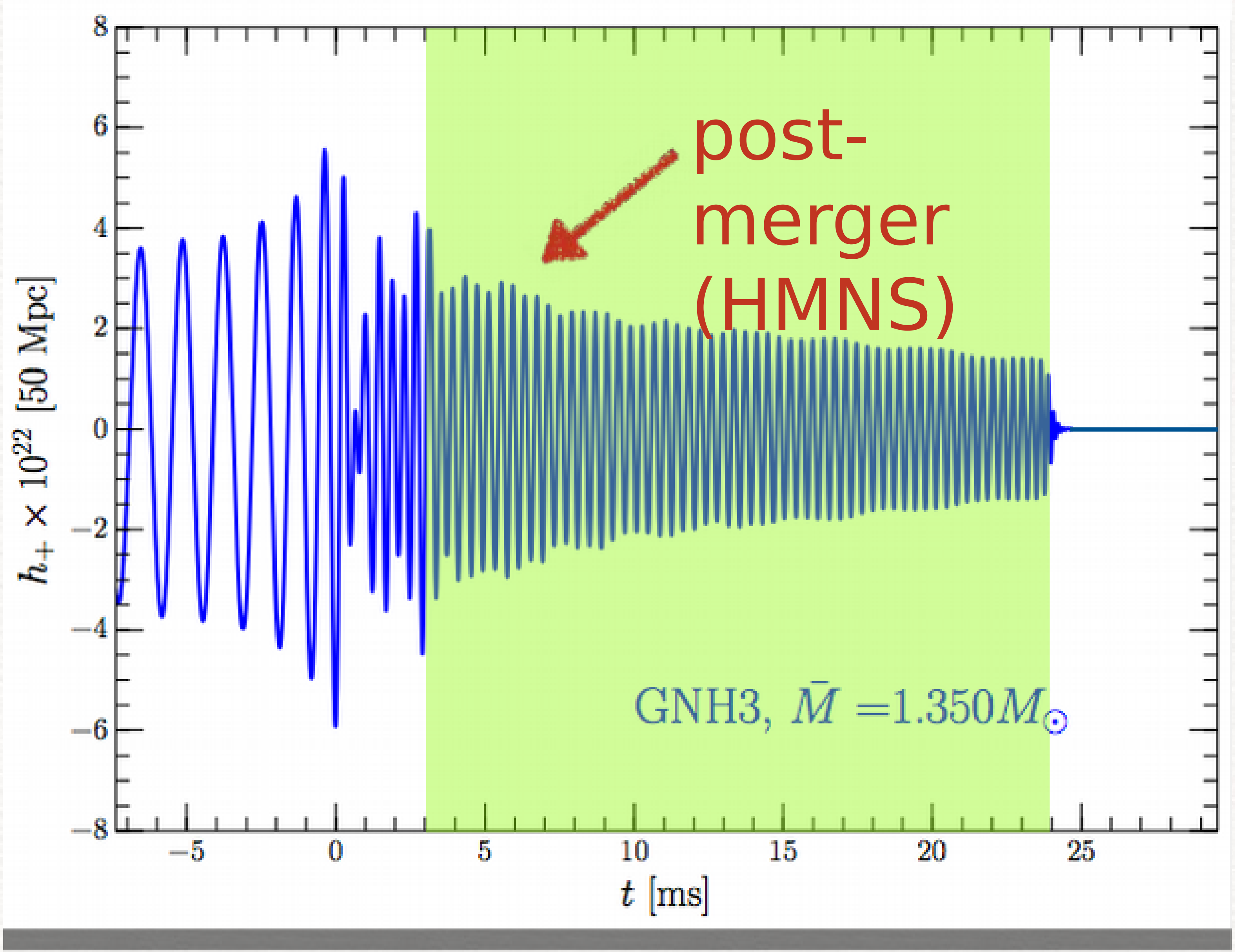
Inspiral: *well approximated by PN/EOB; tidal effects important*

Anatomy of the GW signal



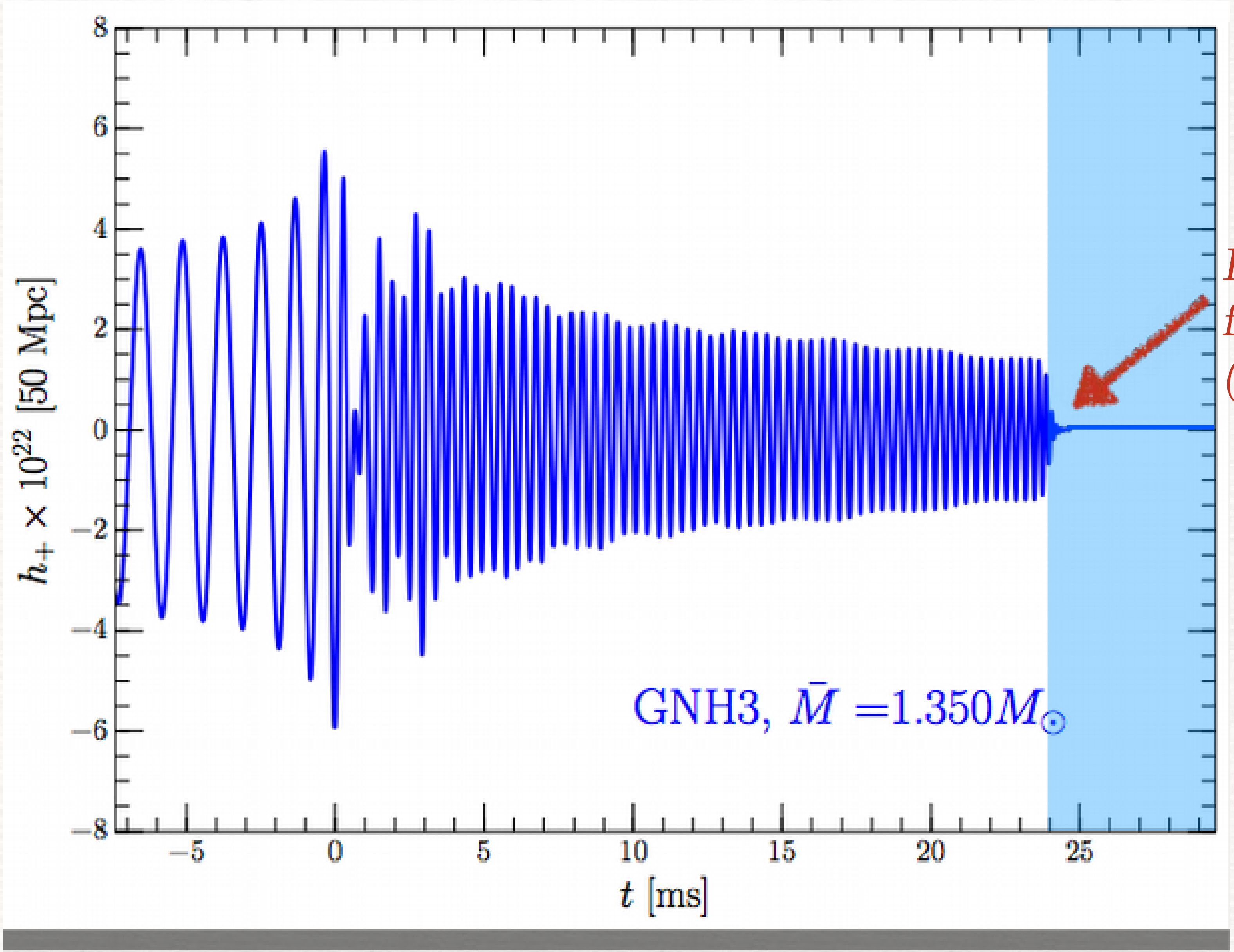
Merger: highly nonlinear but analytic description possible

Anatomy of the GW signal



post-merger: quasi-periodic emission of bar-deformed HMNS

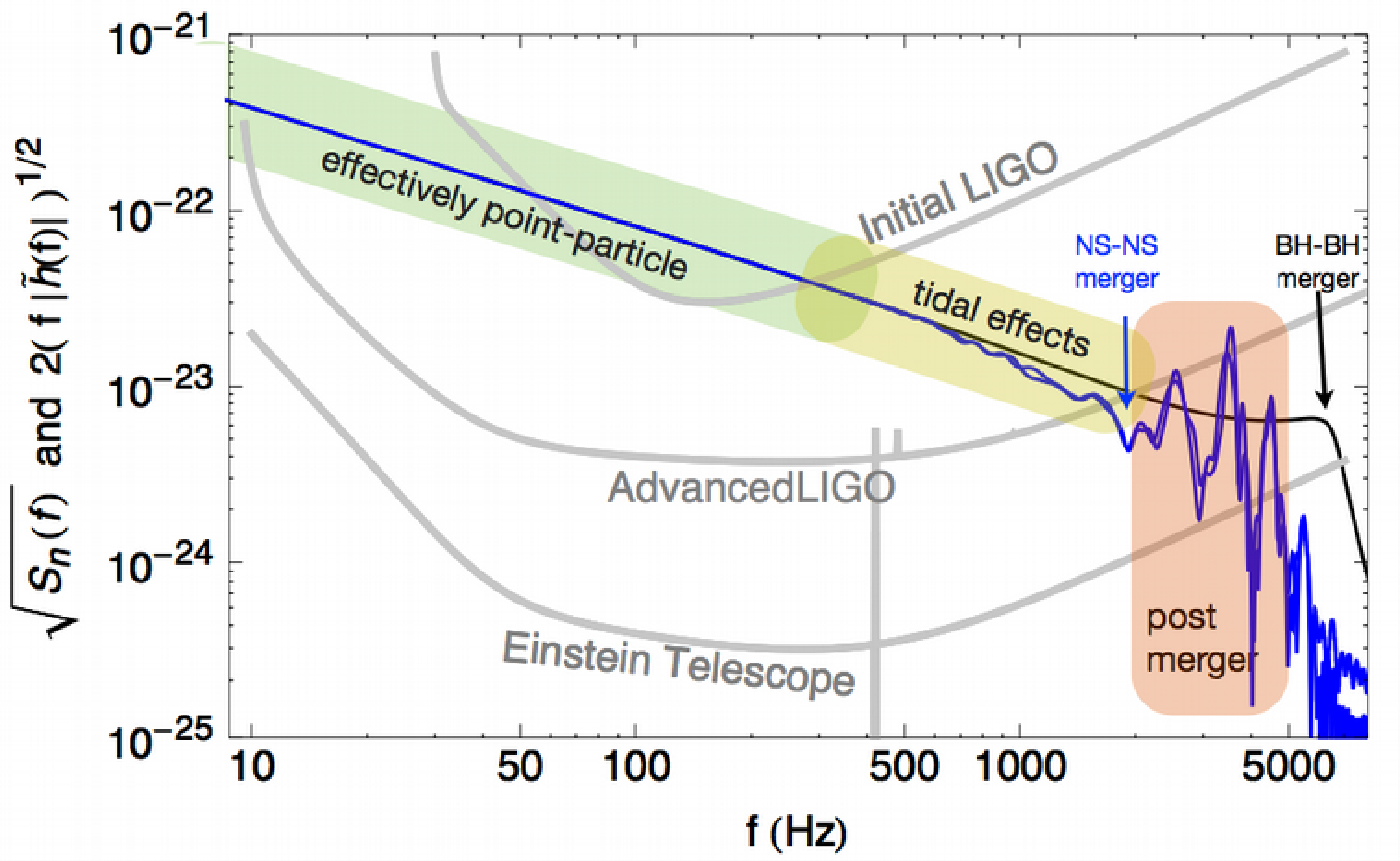
Anatomy of the GW signal



Black-hole formation (ringdown)

Collapse-ringdown: signal essentially shuts off.

A BNS merger in frequency space



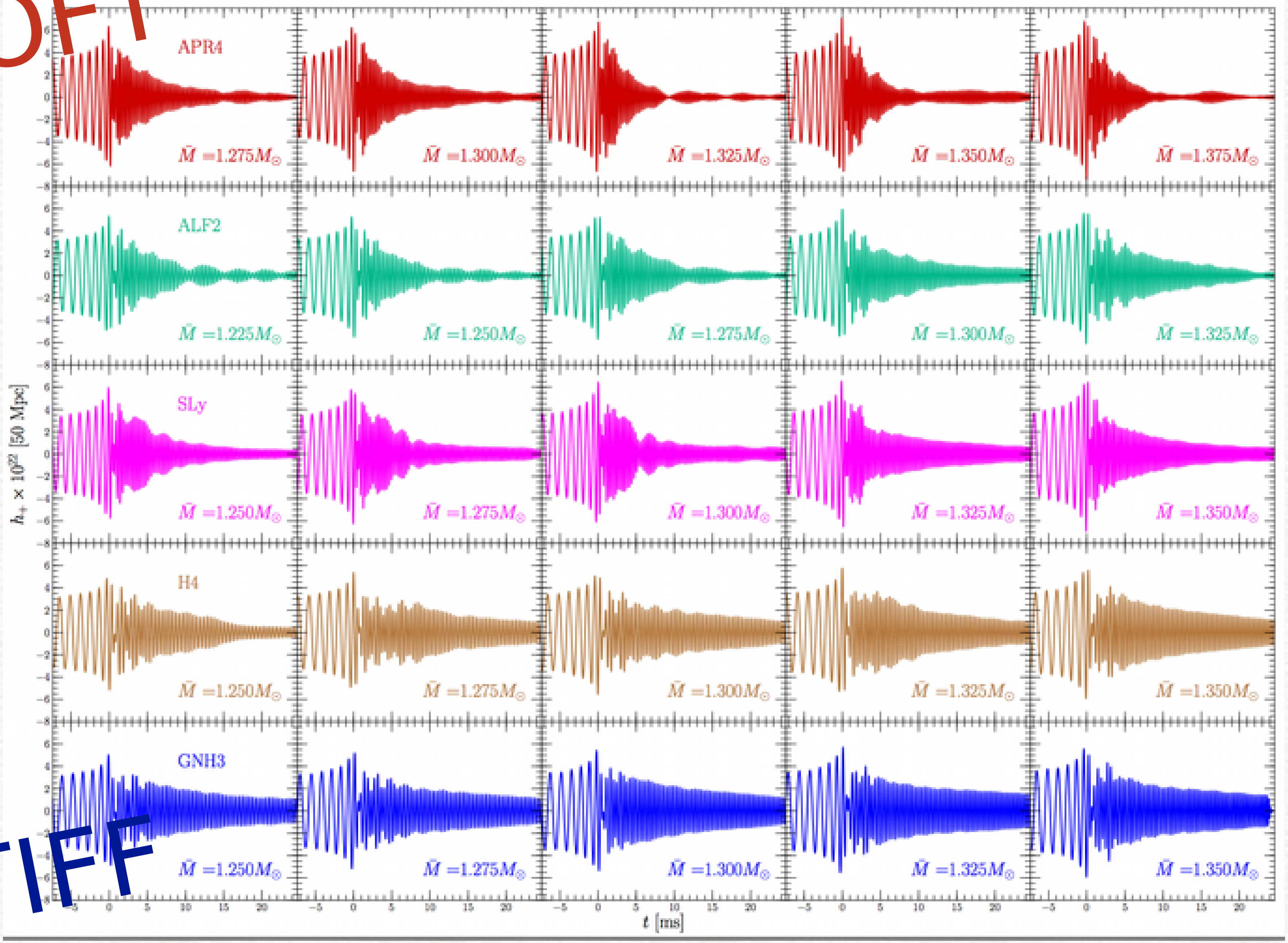
100 Mpc

Read et al. (2013)

What we can do nowadays

Takami, LR, Baiotti (2014, 2015), LR+ (2016)

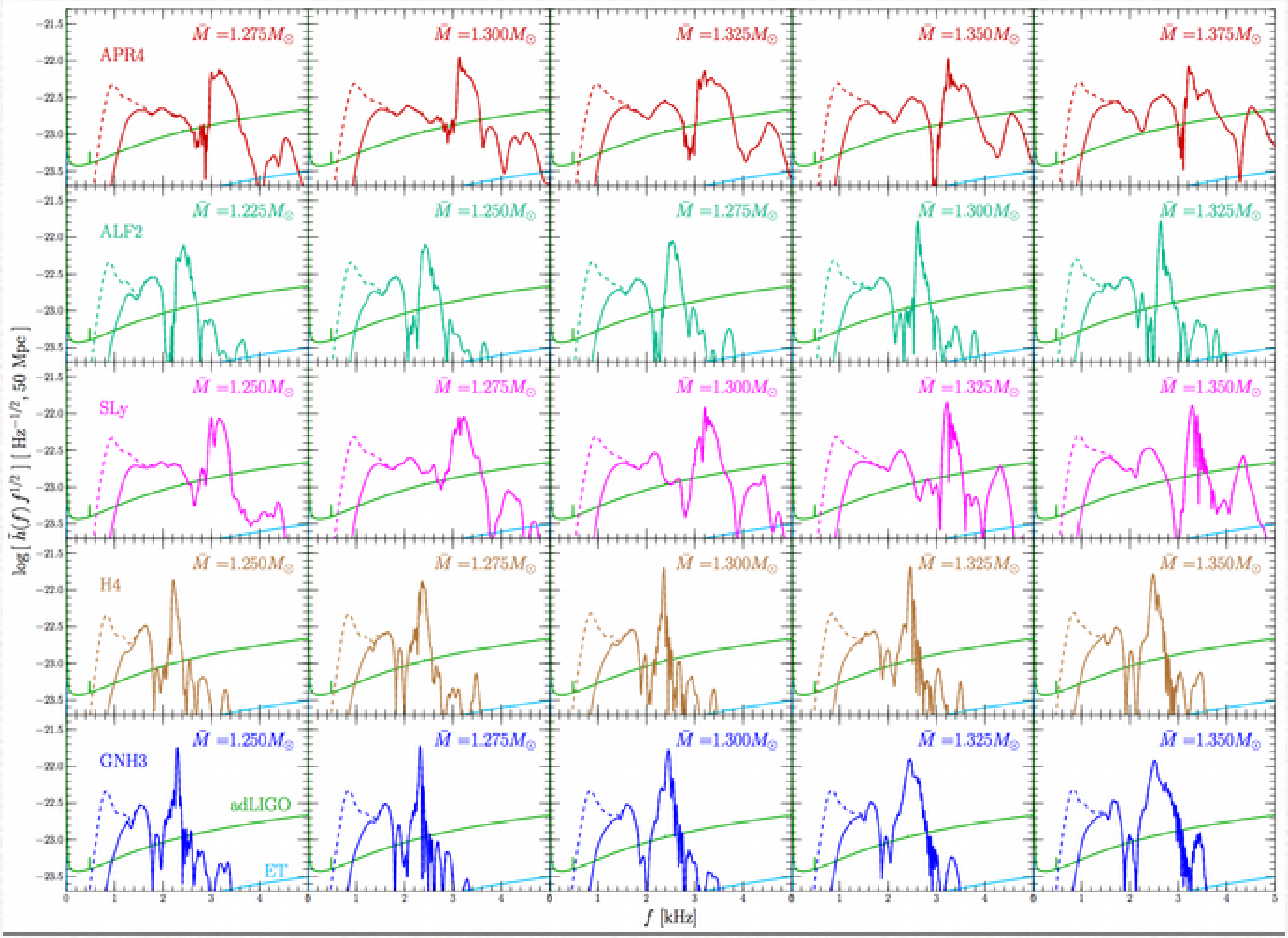
SOFT



STIFF

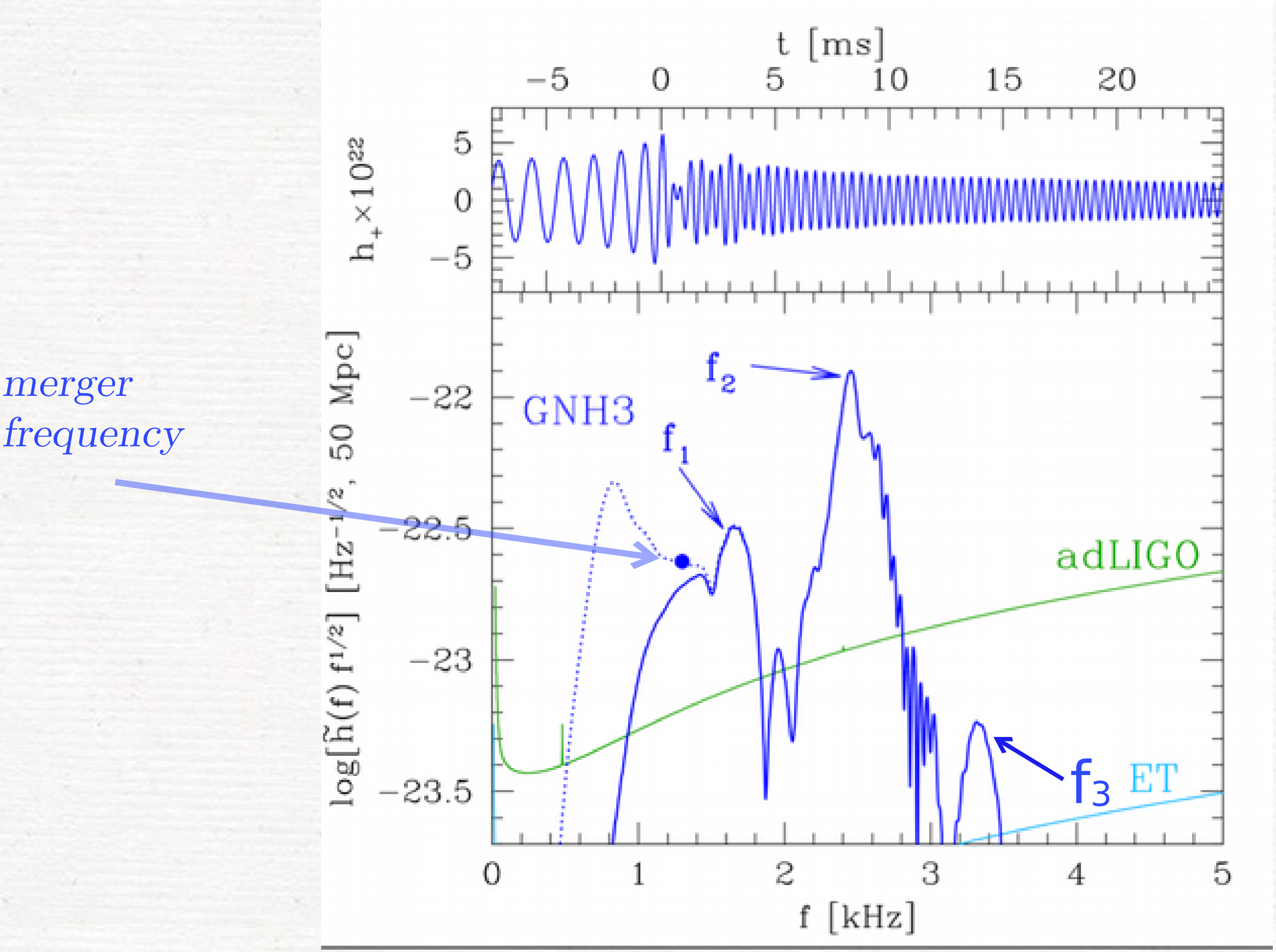
Extracting information from the EOS

Takami, LR, Baiotti (2014, 2015), LR+ (2016)



A new approach to constrain the EOS

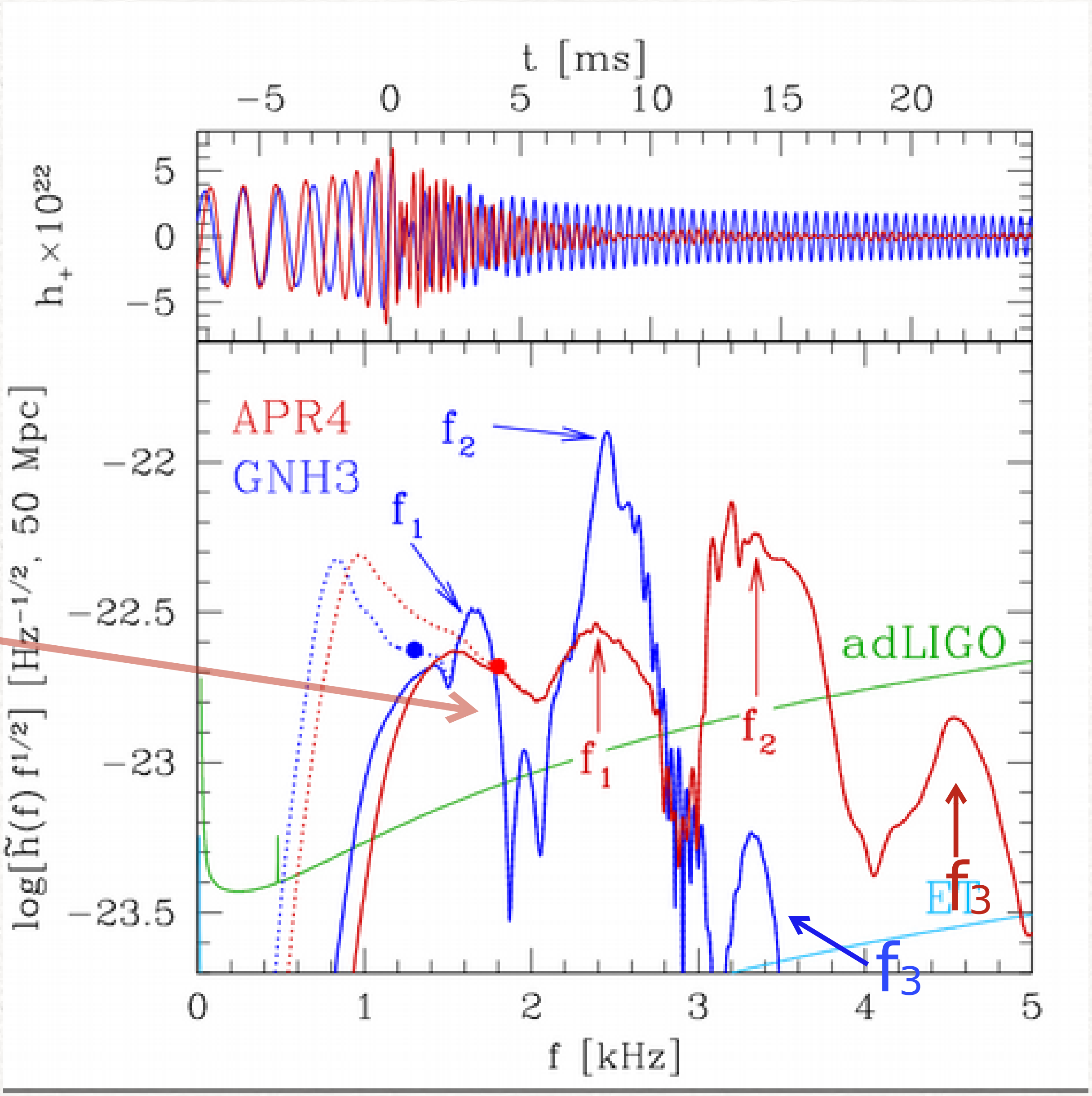
Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 ...



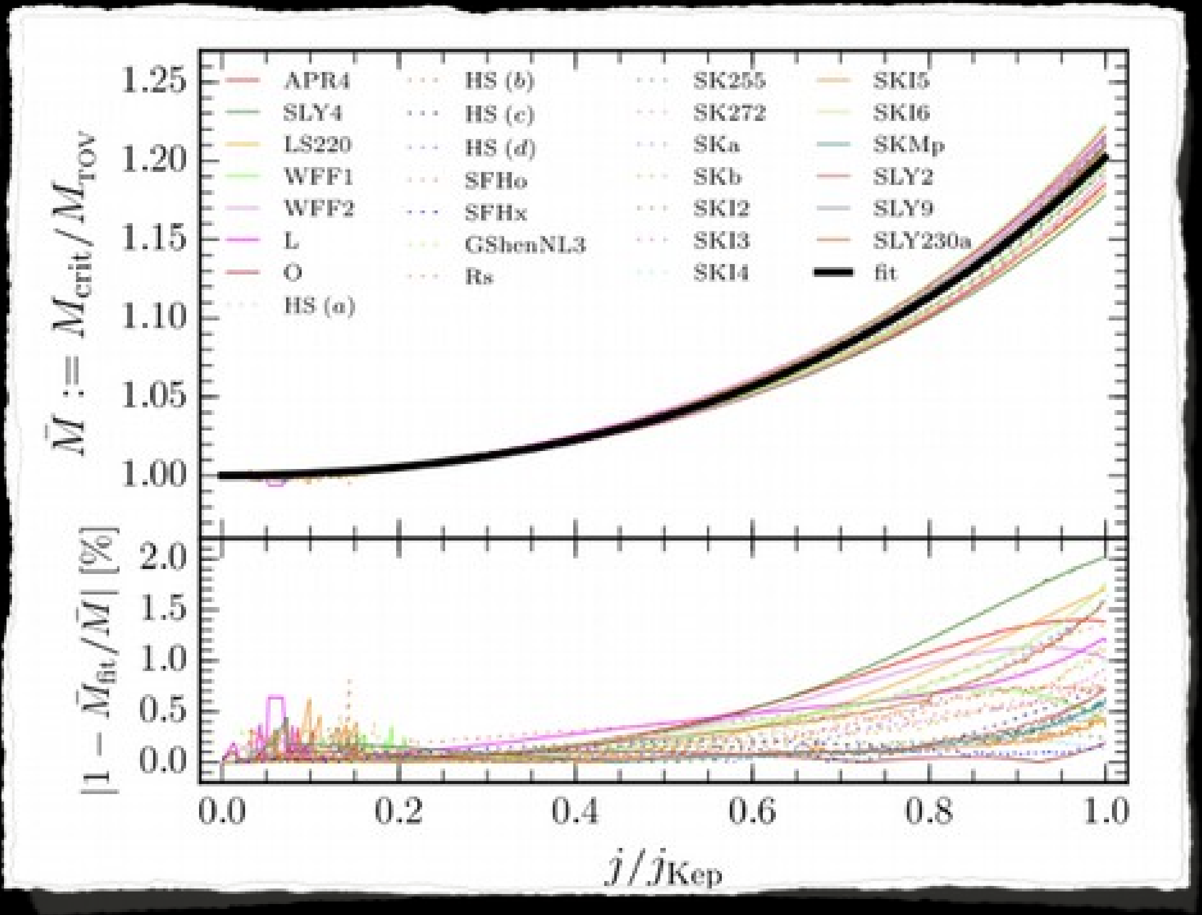
A spectroscopic approach to the EOS

Oechslin+2007, Baiotti+2008, Bauswein+ 2011, 2012, Stergioulas+ 2011, Hotokezaka+ 2013, Takami 2014, 2015, Bernuzzi 2014, 2015, Bauswein+ 2015, Clark+ 2016, LR+2016, de Pietri+ 2016, Feo+ 2017, Bose+ 2017 ...

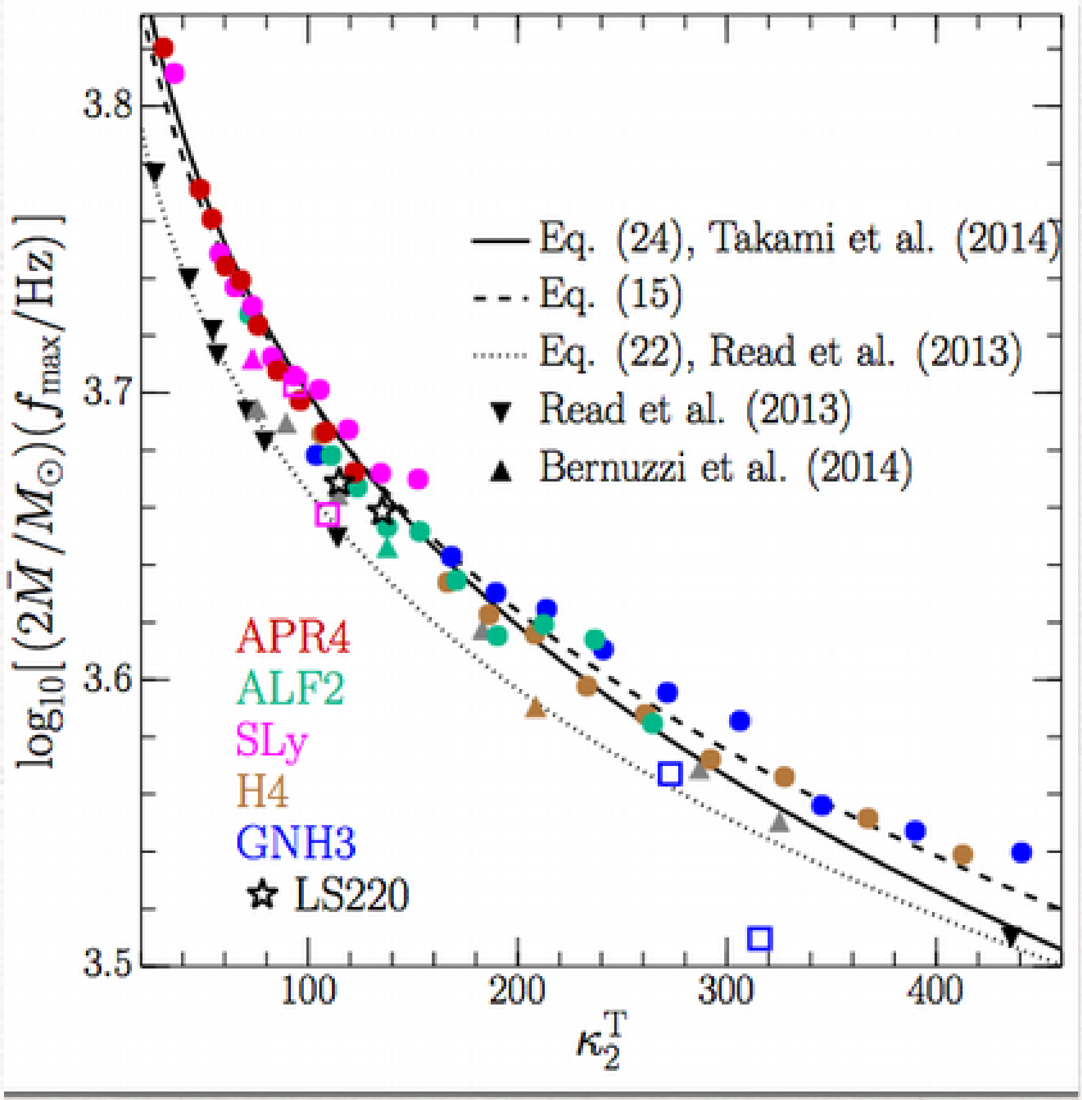
merger frequency



Quasi-universal behaviour



Quasi-universal behaviour: inspiral

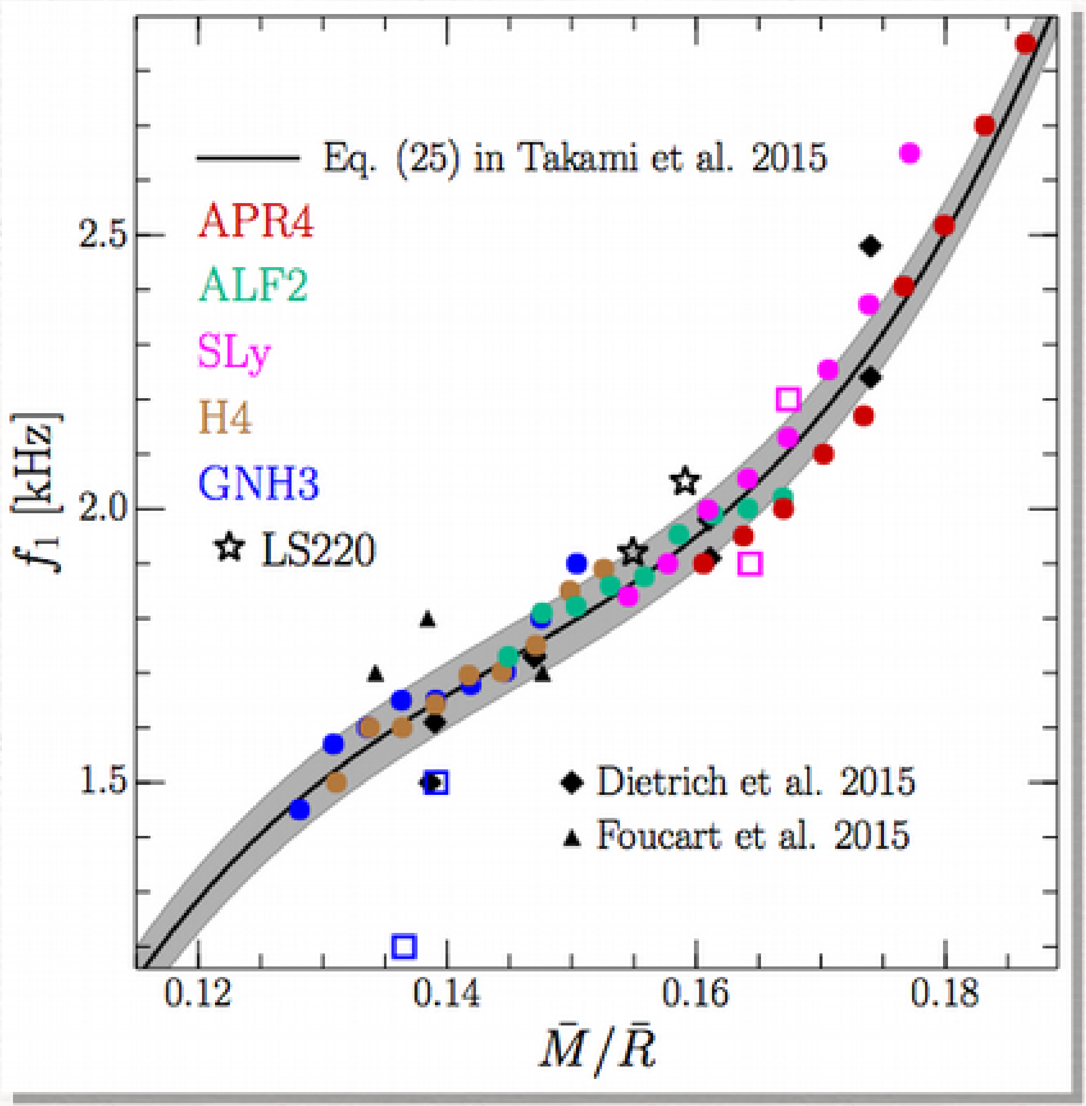


"surprising" result: quasi-universal behaviour of GW frequency at amplitude peak (Read+2013)

Many other simulations have confirmed this (Bernuzzi+ 2014, Takami+ 2015, LR+2016) .

Quasi-universal behaviour in the inspiral implies that once $f_{\rm max}$ is measured, so is tidal deformability

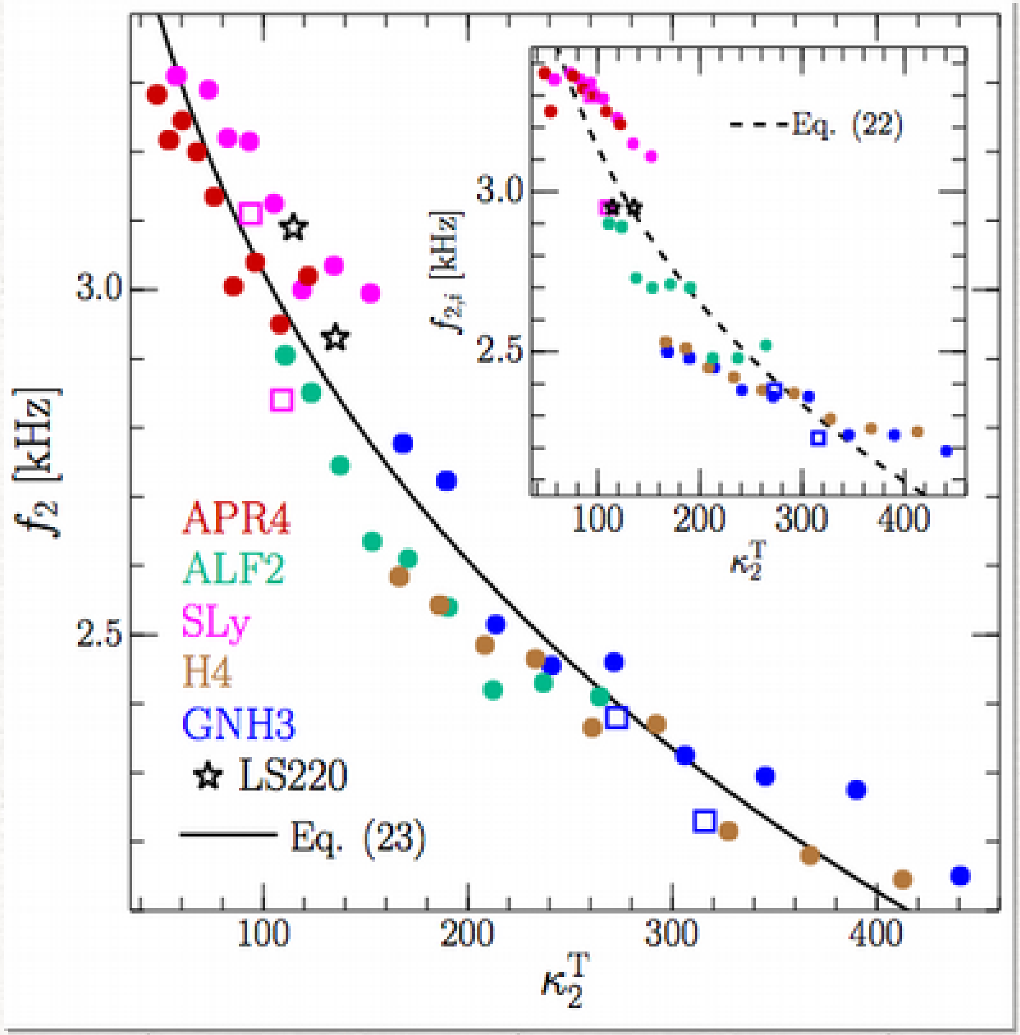
Quasi-universal behaviour: post-merger



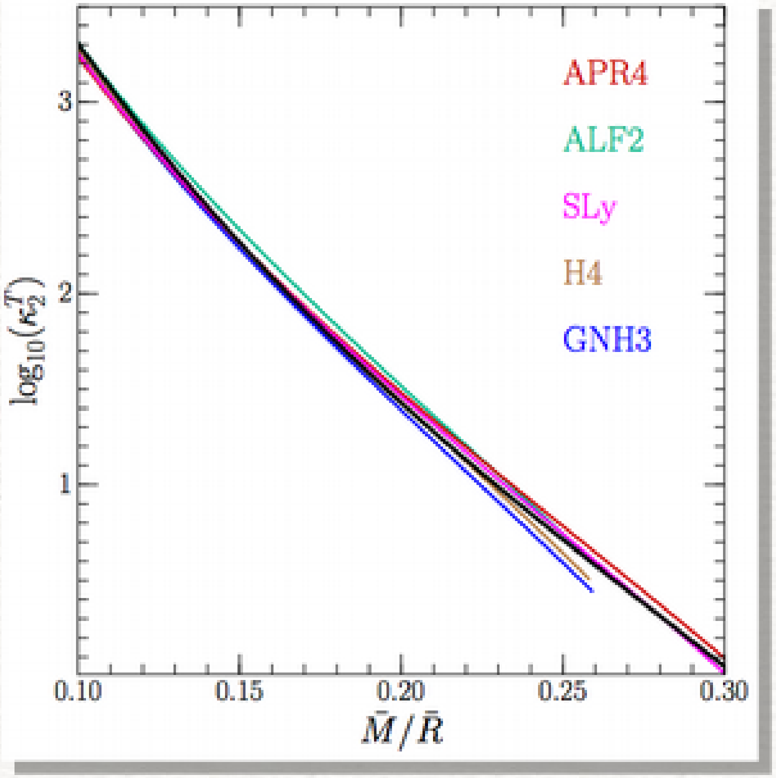
We have found quasi-universal behaviour: i.e., the properties of the spectra are only weakly dependent on the EOS.

This has profound implications for the analytical modelling of the GW emission: "what we do for one EOS can be extended to all EOSs."

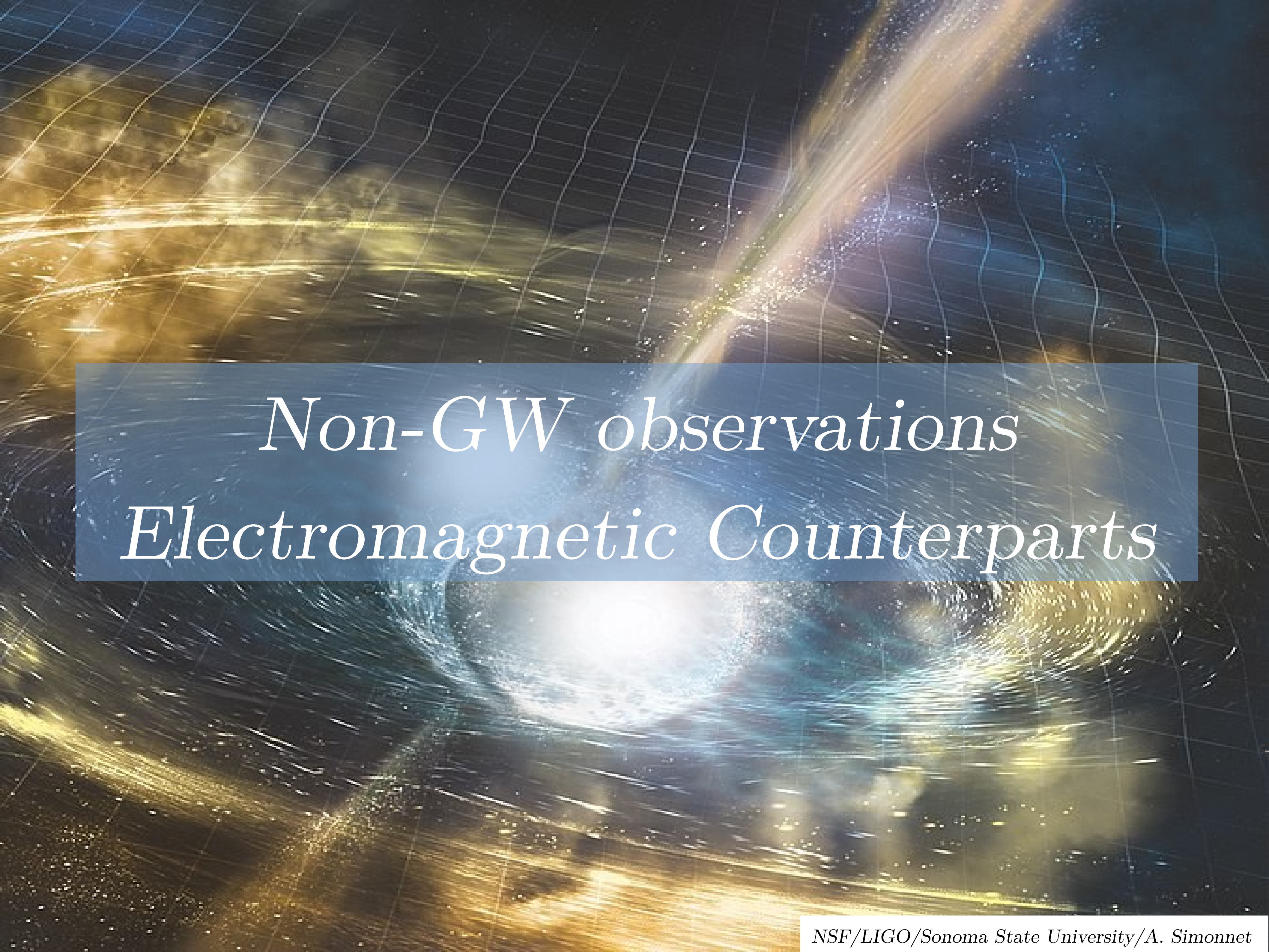
Quasi-universal behaviour: post-merger



- Correlations with Love number found also for high frequency peak f_2.
- This and other correlations are weaker but equally useful.



- Important correlation also between compactness and deformability



Non-GW observations

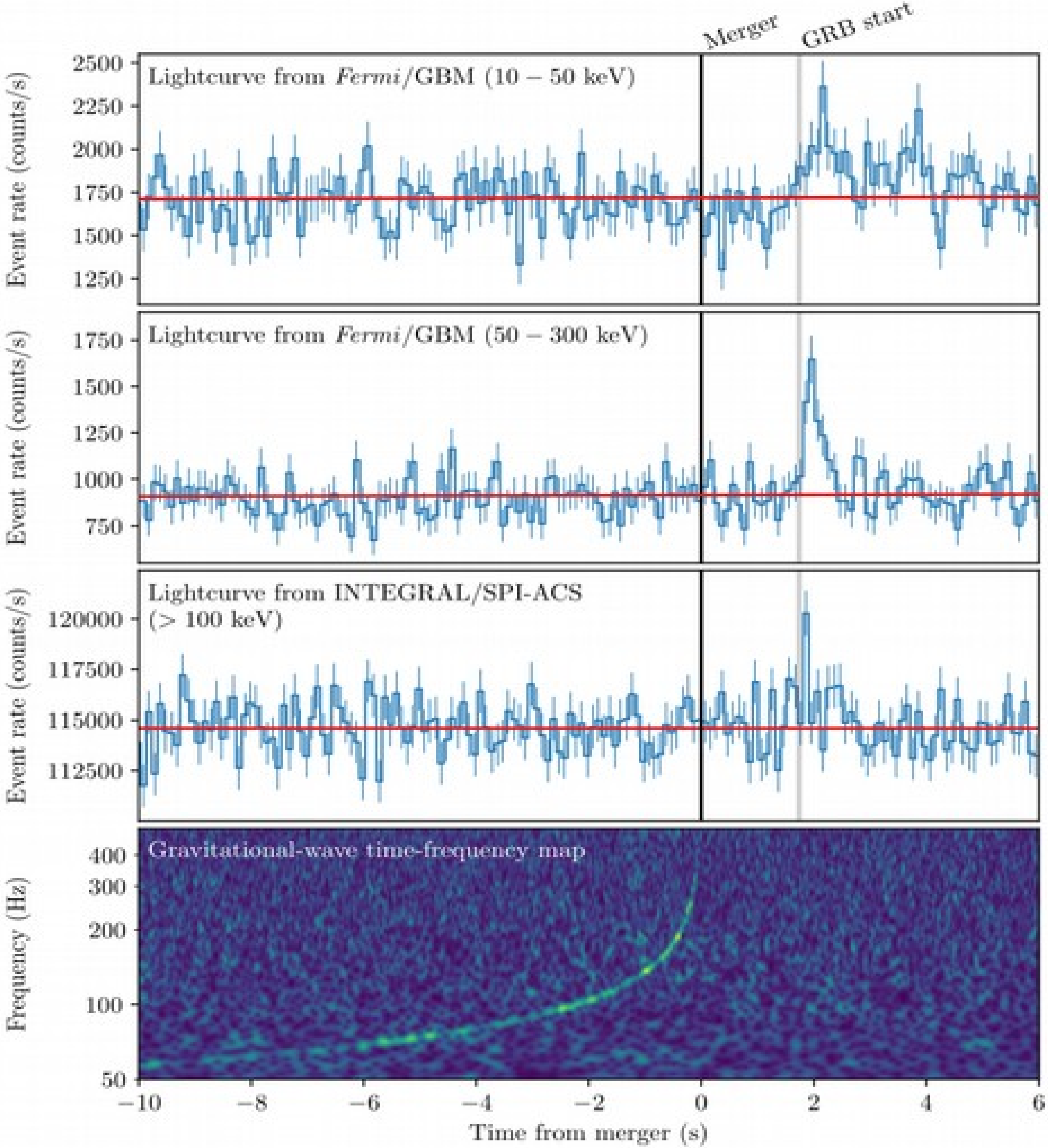
Electromagnetic Counterparts

NSF/LIGO/Sonoma State University/A. Simonnet

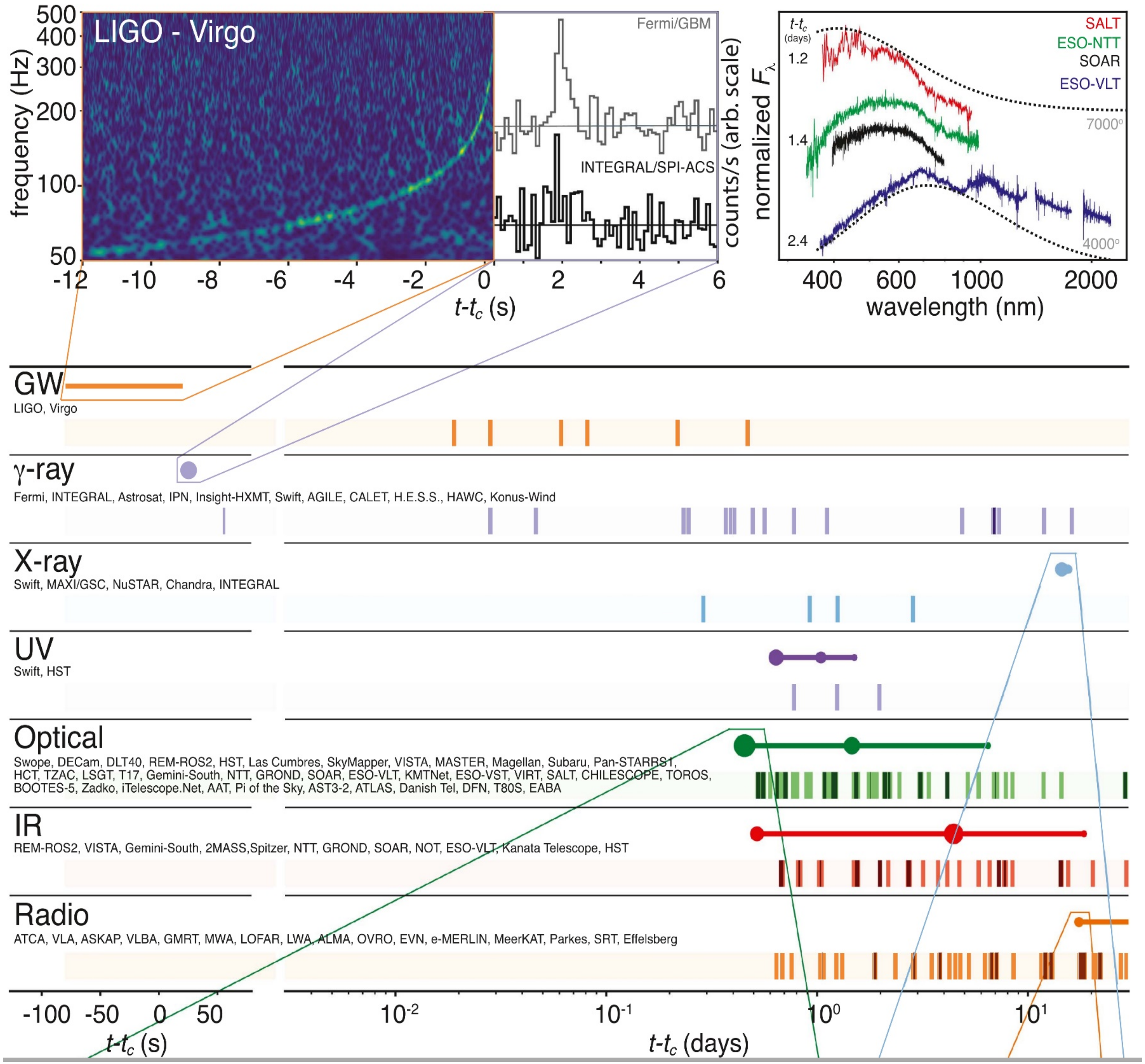
Electromagnetic Counterparts

- ***What can we learn about the EOS from E&M follow-up?***

- ***Observational channels***
    - *SGRBs*
    - *r-process*
    - *kilonova*



(Abbott et al. 2017 ApJL)



(*Abbott et al. 2017 ApJL*)

Abbott et al. 2017

EOS constraints?

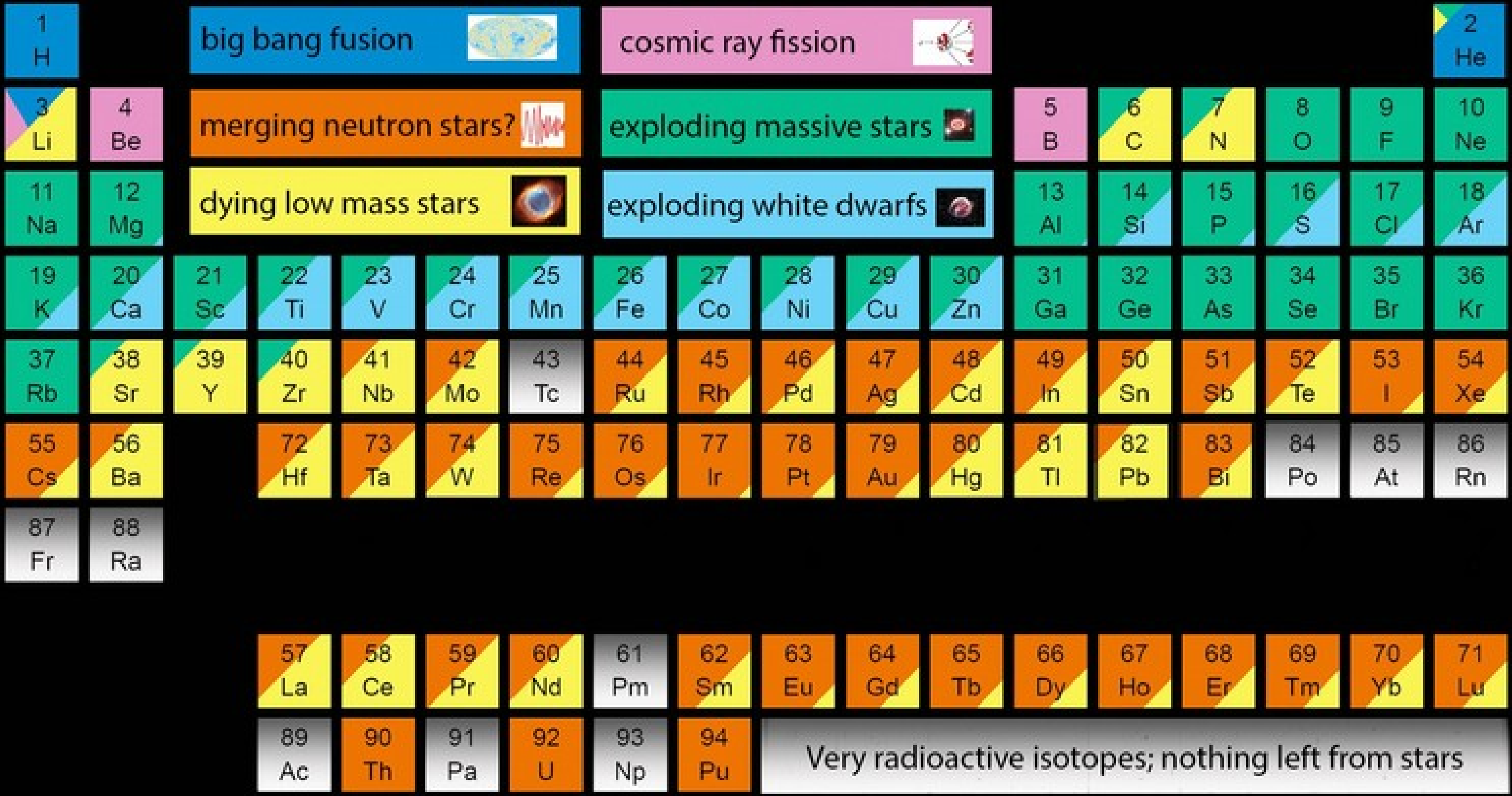
What object could power the SGRB?

- *merger remnant collapsed to a rotating BH with disk that powered the SGRB (Shibata et al. 2006)*

- *merger formed a rapidly rotating, strongly magnetized NS (millisecond magnetar) with an accretion disk (Metzger et al. 2008)*

- *Not very constraining, better can be done: see talks later today*

The Origin of the Solar System Elements



big bang fusion

cosmic ray fission

merging neutron stars?

exploding massive stars

dying low mass stars

exploding white dwarfs

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	Very radioactive isotopes; nothing left from stars								

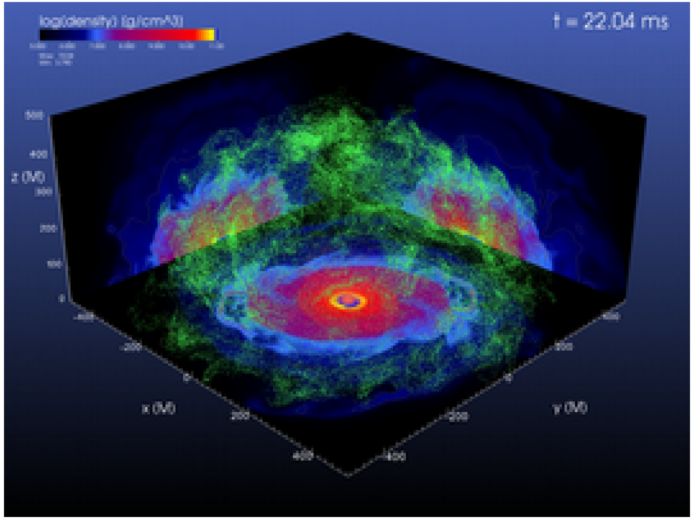
Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

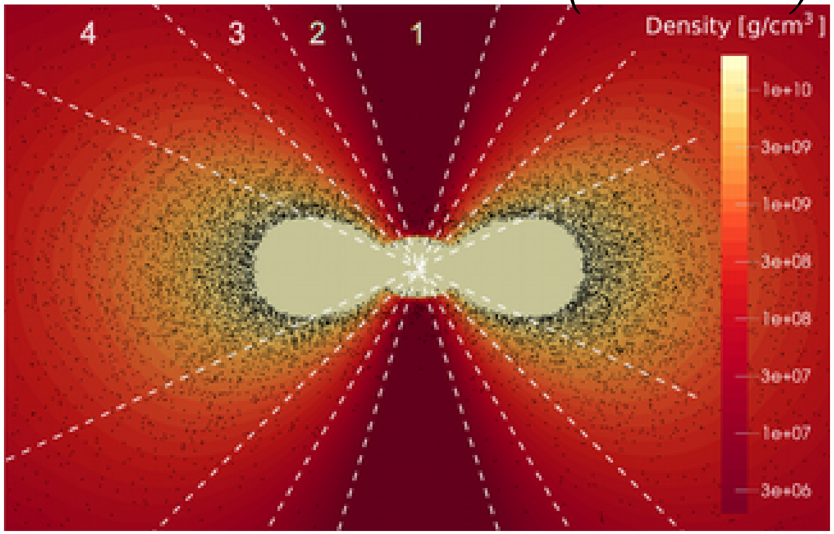
Categories of ejecta

Martin et al. 2015,
Fujibayashi 2017

Dynamic ejecta ~ O(10 ms)

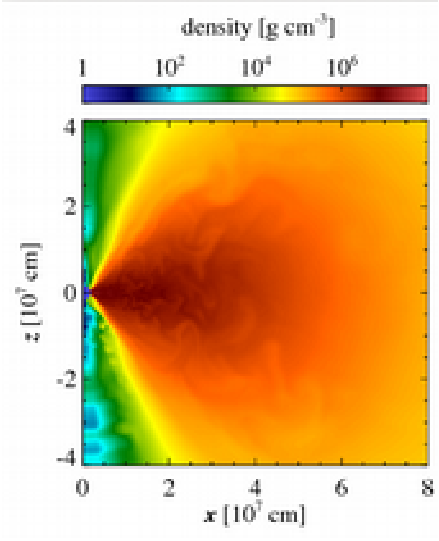


Neutrino wind ~ O(100 ms)



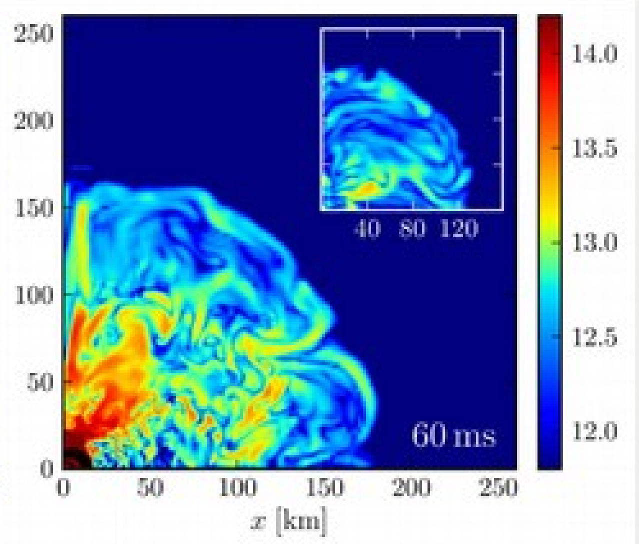
Bovard 2017

Viscous Heating ~ O(1 s)

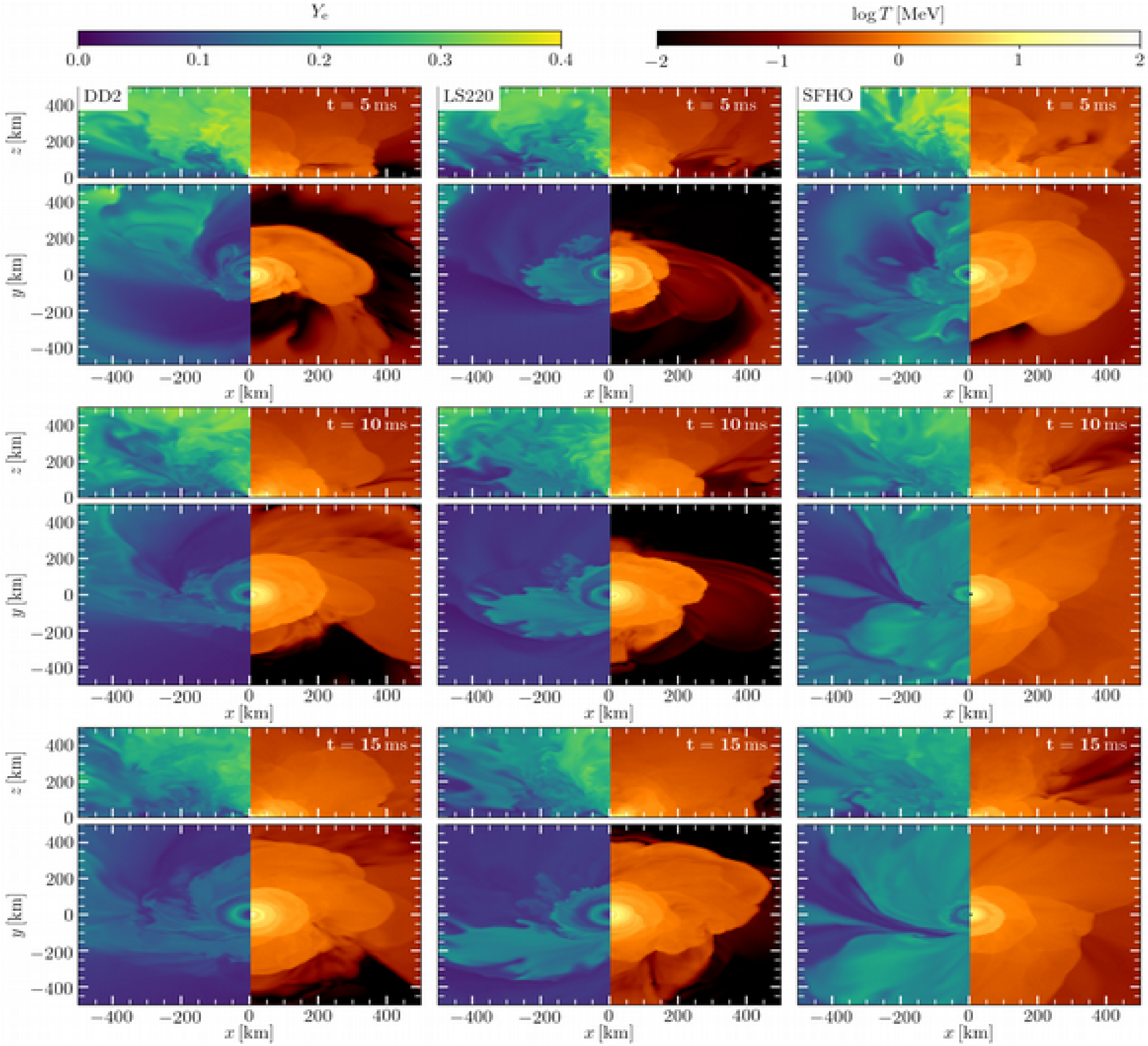


Fernández & Metzger 2013

Magnetic driven wind~ O(50 ms)



Siegel et al. 2014



Temperature

~ 0.01–100 MeV

Electron fraction

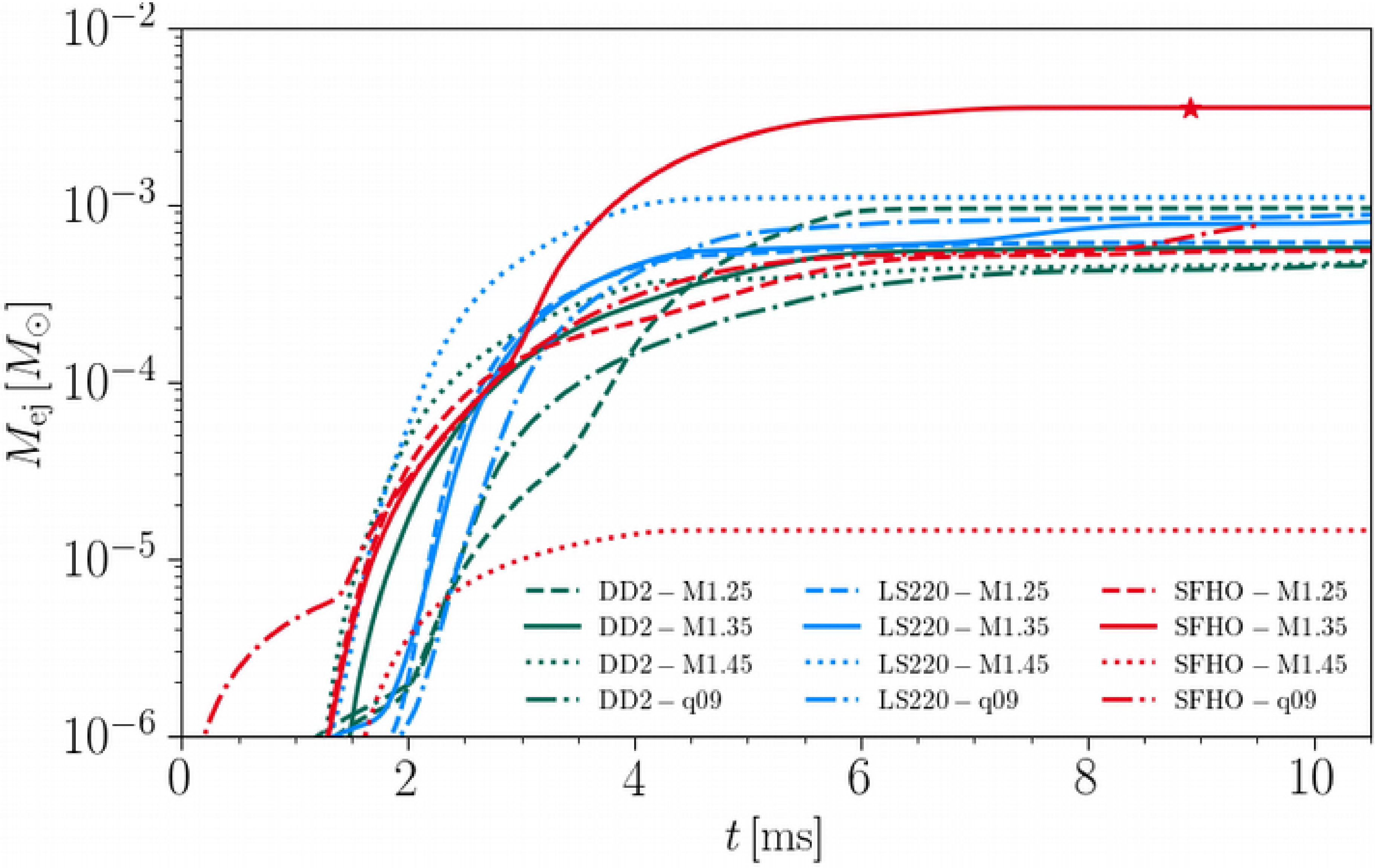
~ 0.0 – 0.5

Density

$\sim 10^3 - 10^{15}$ g/cm^3

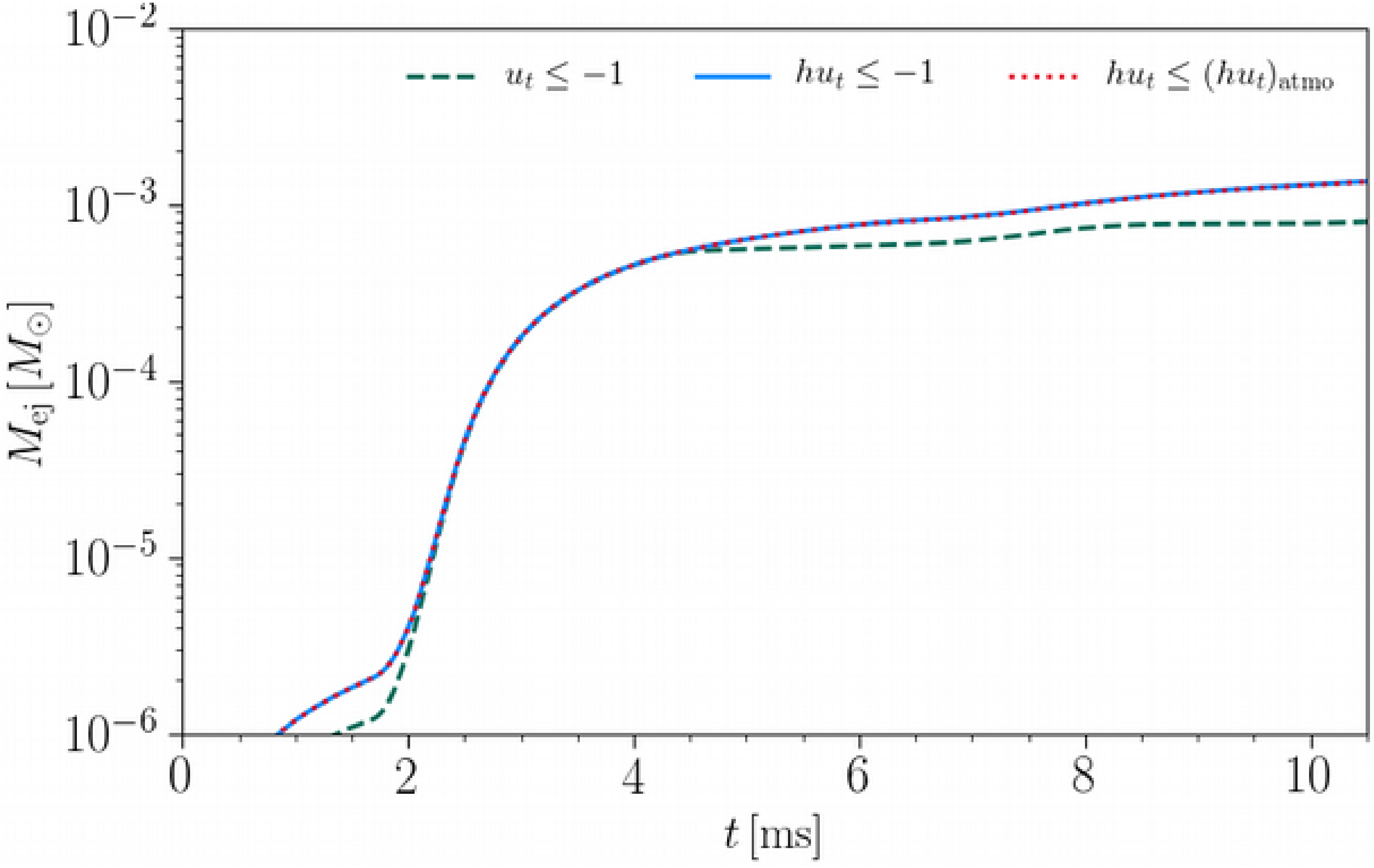
(Bovard et al. 2017)

Mass ejection



(Bovard et al. 2017)

Mass ejection

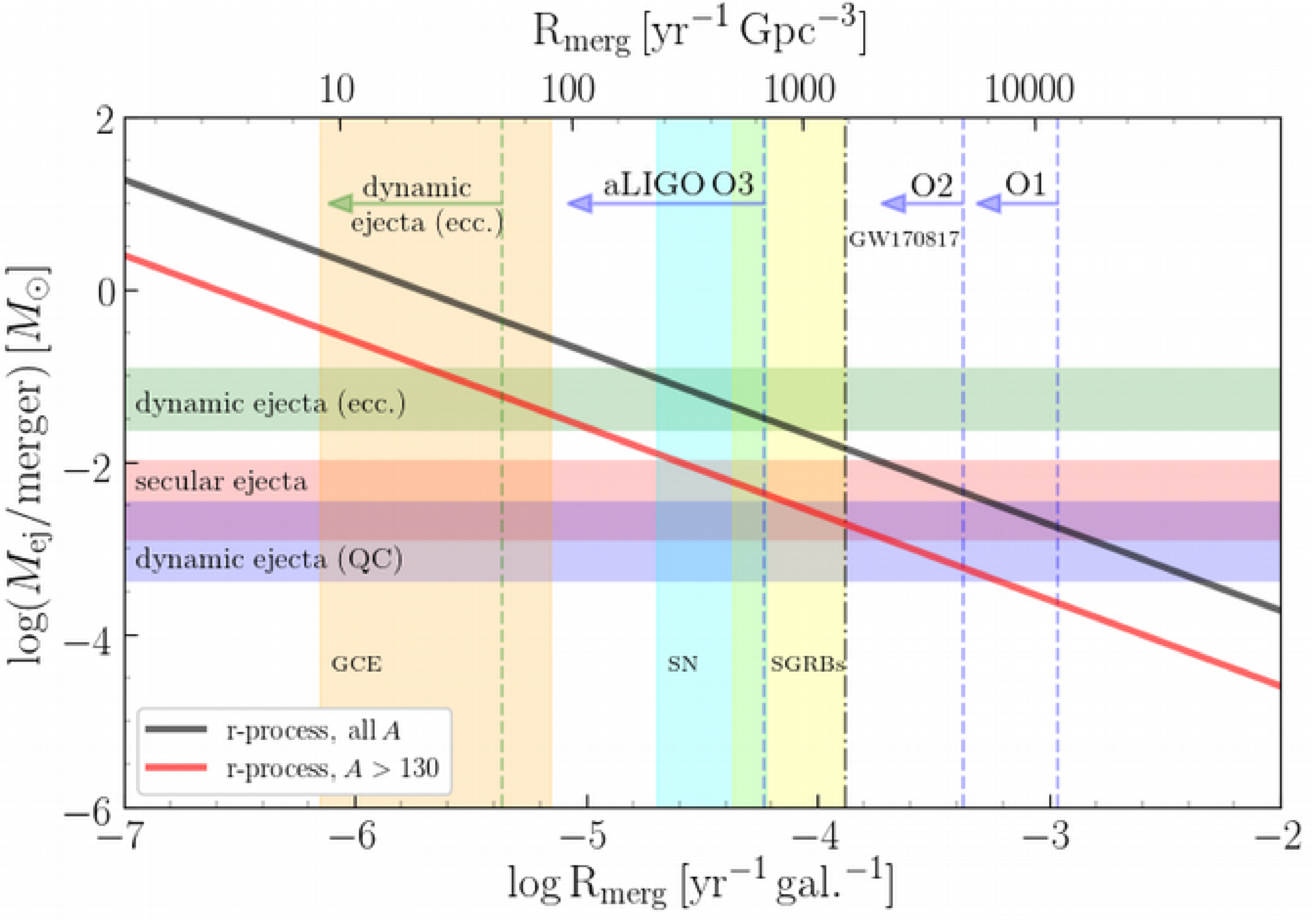


Changing selection criteria can change mass ejection by factor of 3

(Bovard et al. 2017)

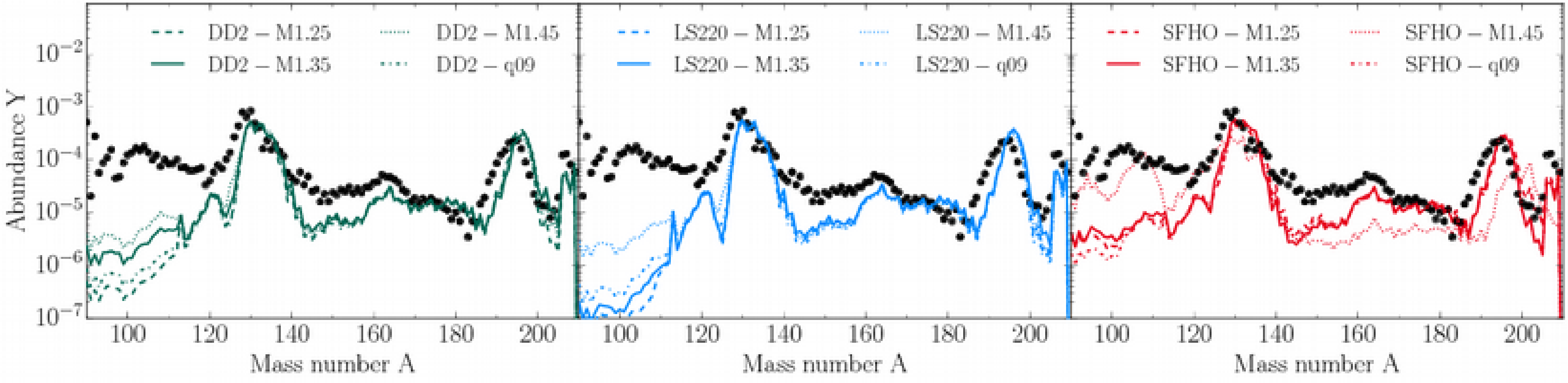
(Bovard et al. 2017)

Detectability



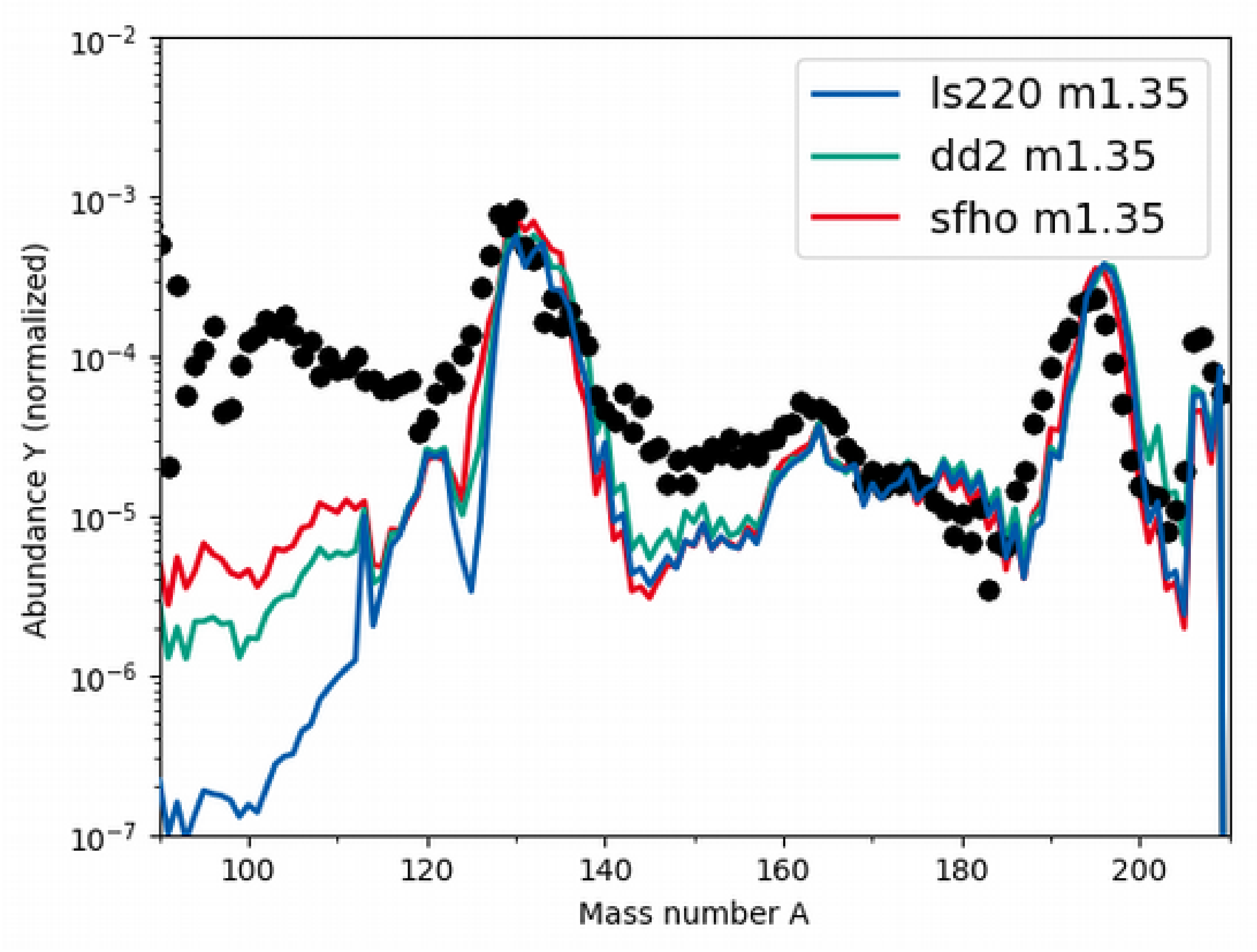
adapted from Hotokezaka 2015, Rosswog 2017

Nucleosynthesis



(Bovard et al. 2017)

Nucleosynthesis



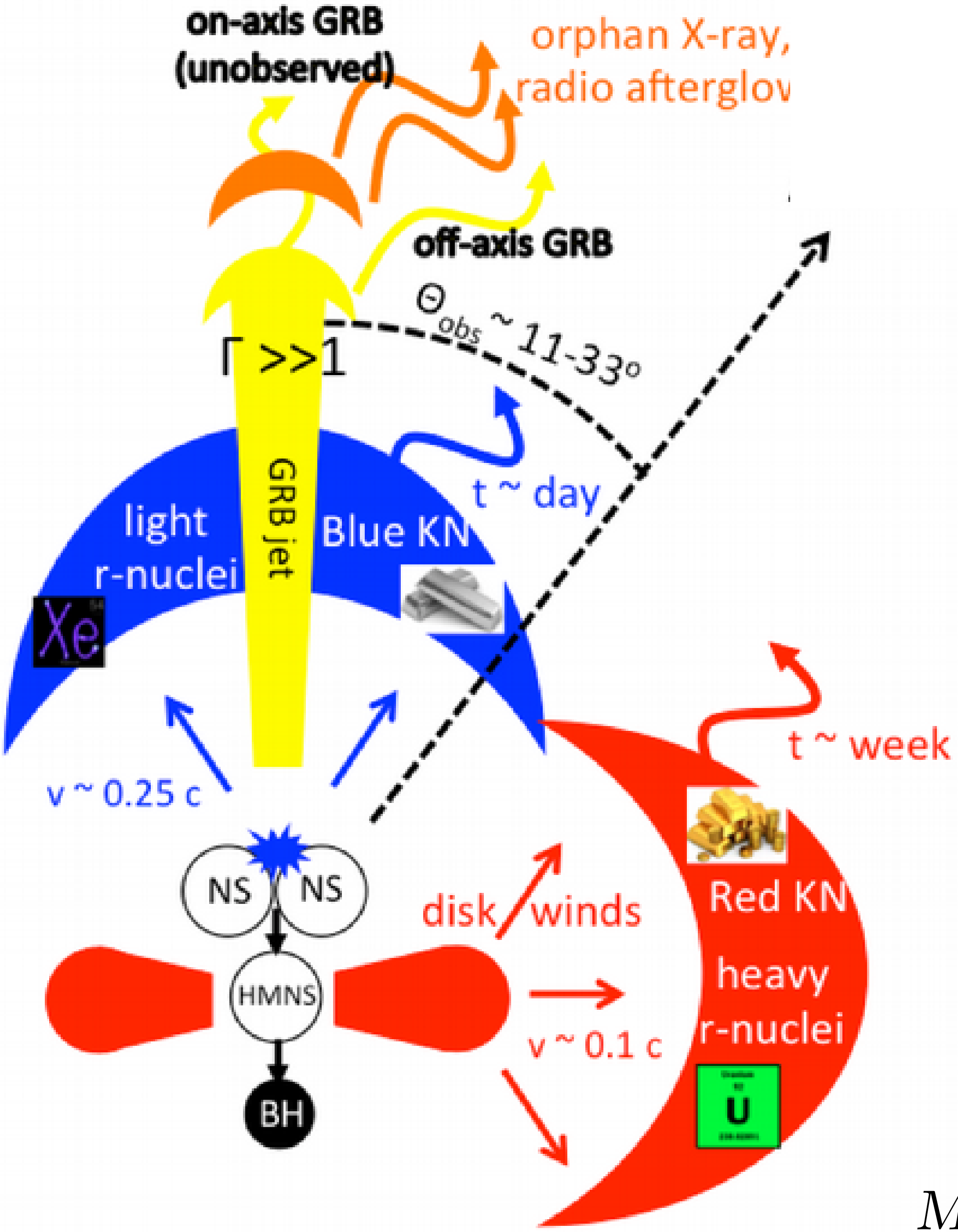
r-process is robust against changes in EOS, initial masses, mass ratio

(Bovard et al. 2017)

Kilonova

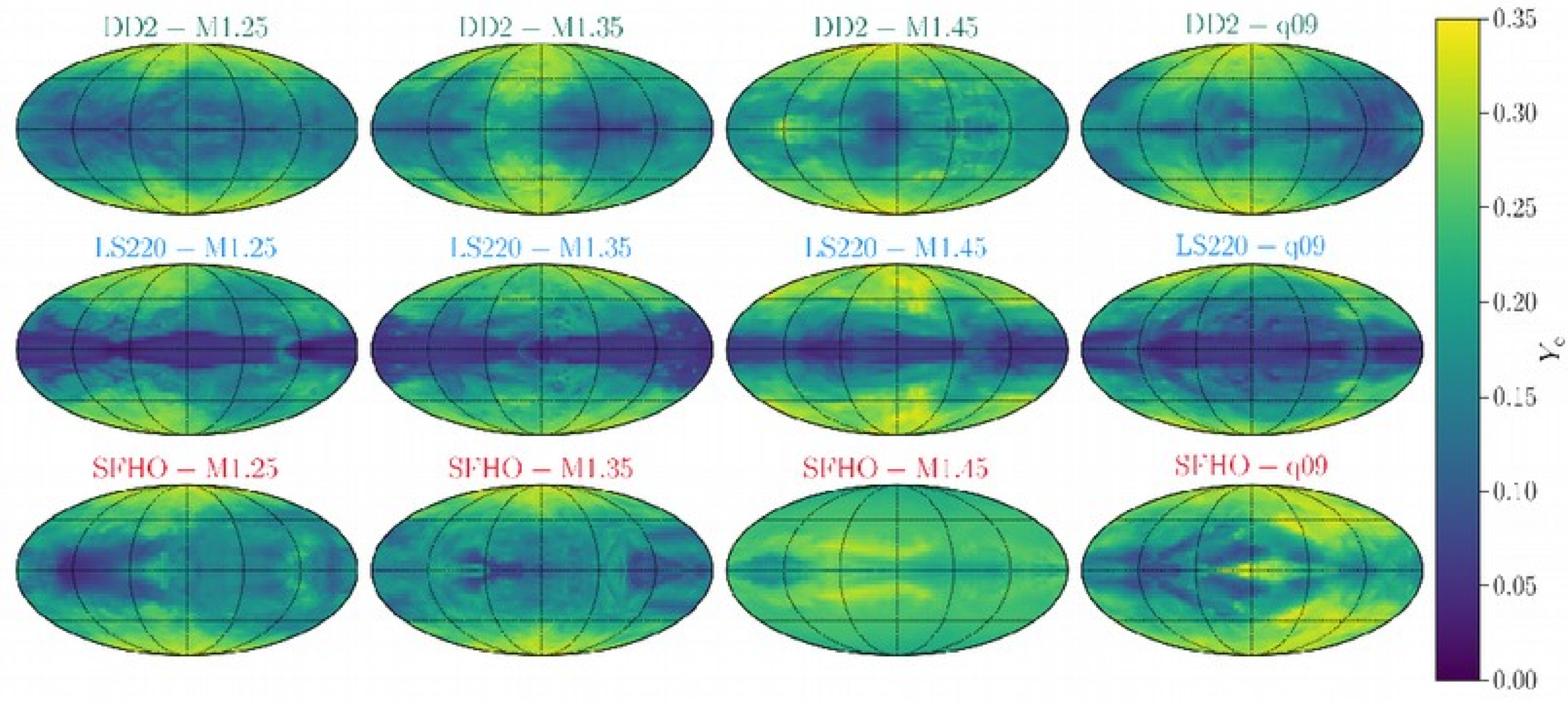
- *Where do the heavy elements come from? Rapid neutron capture (r-process) is main formation channel*
- *Need neutron rich astrophysical site for main source of r-process: supernovas (some) or neutron star mergers (confirmed)*
- *r-process material undergoes radioactive decay (Li & Paczyński 1998) and emits radiation in a* ***kilonova***

- *Modeling still has a long way to go (see reviews by Metzger 2017, Tanaka 2016)*



Metzger 2017

Angular Ye distribution

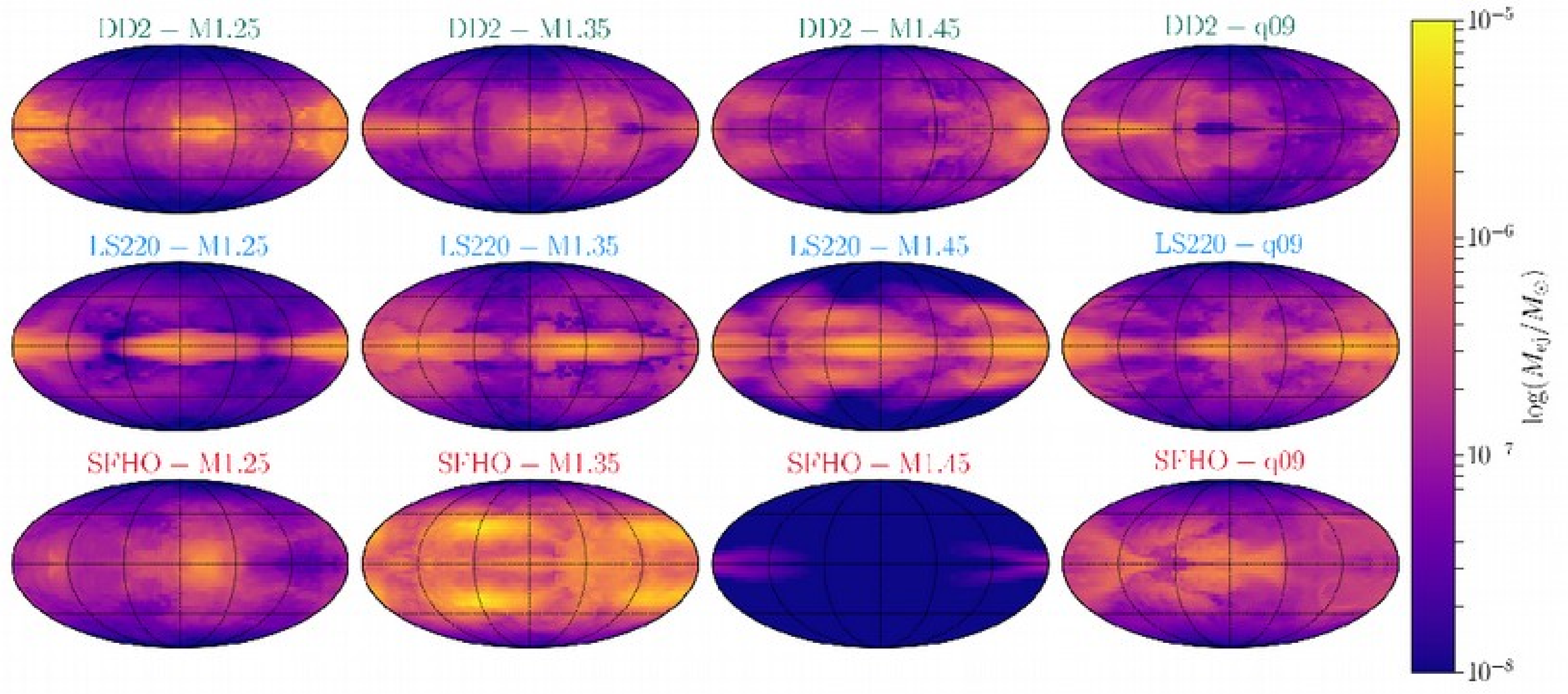


Electron fraction distribution directly influences kilonova light-curve

(Bovard et al. 2017)

Angular mass distribution

(Bovard 2017)



(Bovard et al. 2017)

Kilonova estimates

$$t_{\rm peak} = 4.9\ {\rm days} \times \left(\frac{M_{ej}}{10^{-2}M_\odot}\right)^{\frac{1}{2}} \left(\frac{\kappa}{10{\rm cm}^2{\rm g}^{-1}}\right)^{\frac{1}{2}} \left(\frac{v_{\rm ej}}{0.1}\right)^{-\frac{1}{2}},$$

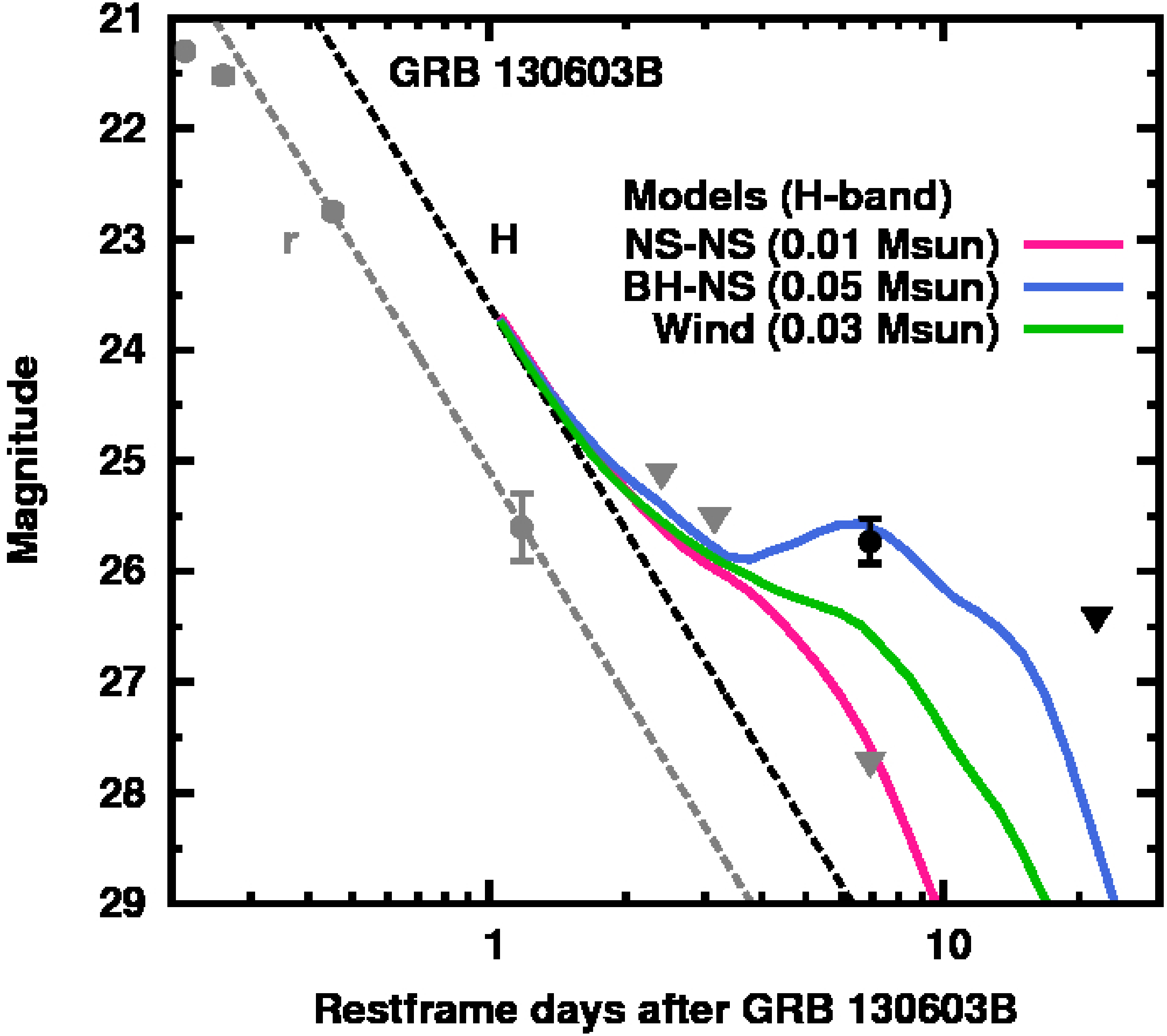
$$L_{\rm peak} = 2.5 \cdot 10^{40}{\rm erg\,s}^{-1} \times \left(\frac{M_{ej}}{10^{-2}M_\odot}\right)^{1-\frac{\alpha}{2}} \left(\frac{\kappa}{10{\rm cm}^2{\rm g}^{-1}}\right)^{-\frac{\alpha}{2}} \left(\frac{v_{\rm ej}}{0.1}\right)^{\frac{\alpha}{2}},$$

$$T_{\rm peak} = 2200{\rm K} \times \left(\frac{M_{ej}}{10^{-2}M_\odot}\right)^{-\frac{\alpha}{8}} \left(\frac{\kappa}{10{\rm cm}^2{\rm g}^{-1}}\right)^{-\frac{\alpha+2}{8}} \left(\frac{v_{\rm ej}}{0.1}\right)^{\frac{\alpha-2}{8}}.$$

Grossman et al. 2014

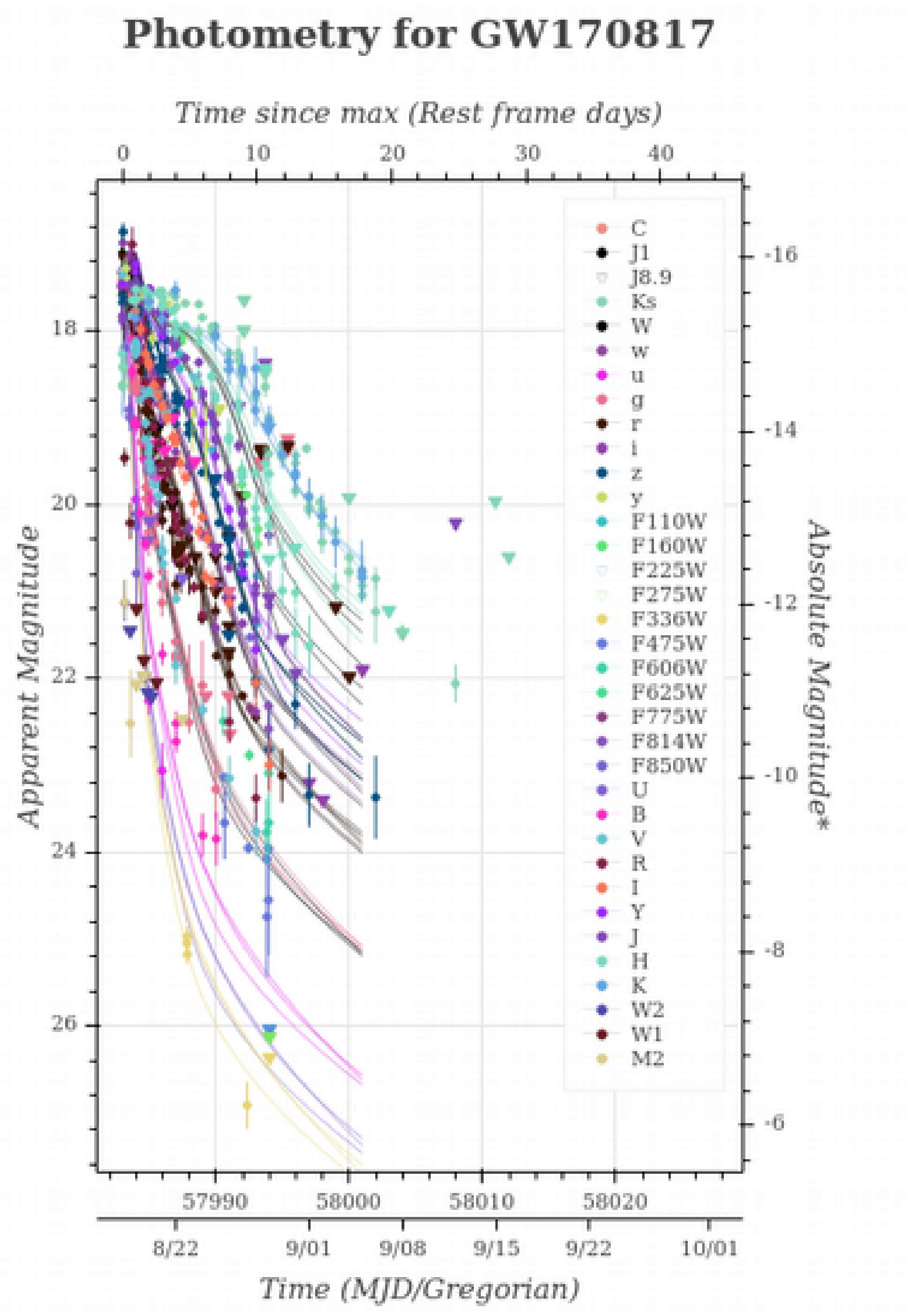
- $\alpha = 1.3$

Kilonova observations before GW170817



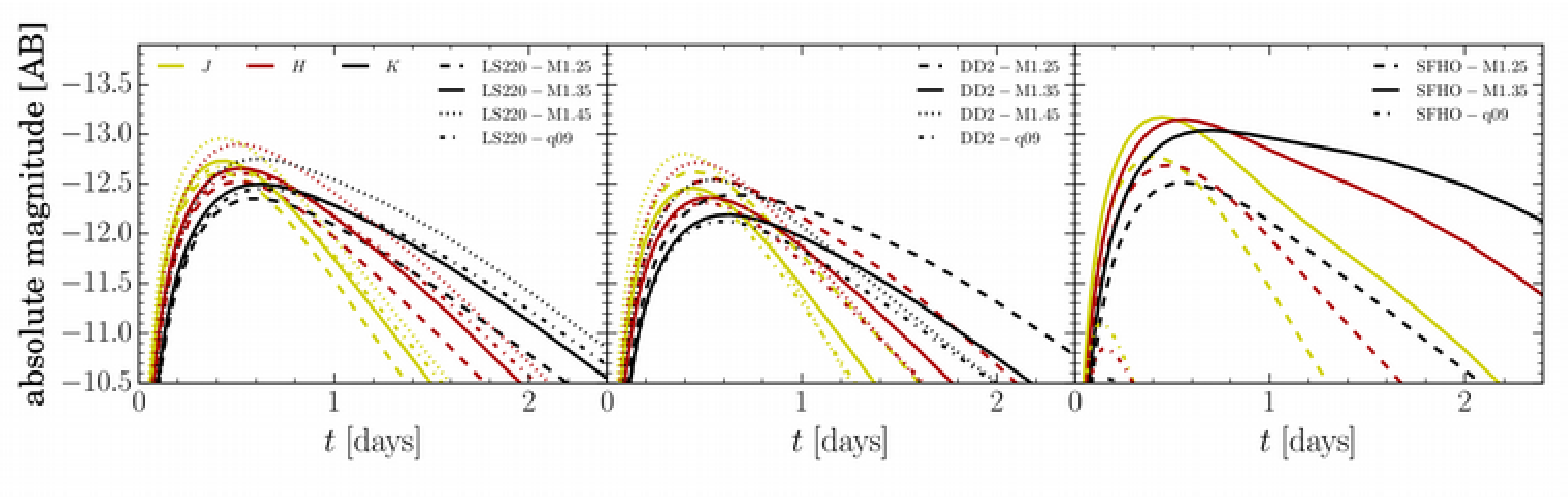
(Tanaka 2016)

Kilonova observations after GW170817



kilonova.space

Kilonova



Kilonova light curves depends sensitively on initial mass, mass ratio, EOS

(Bovard et al. 2017)

Kilonova properties

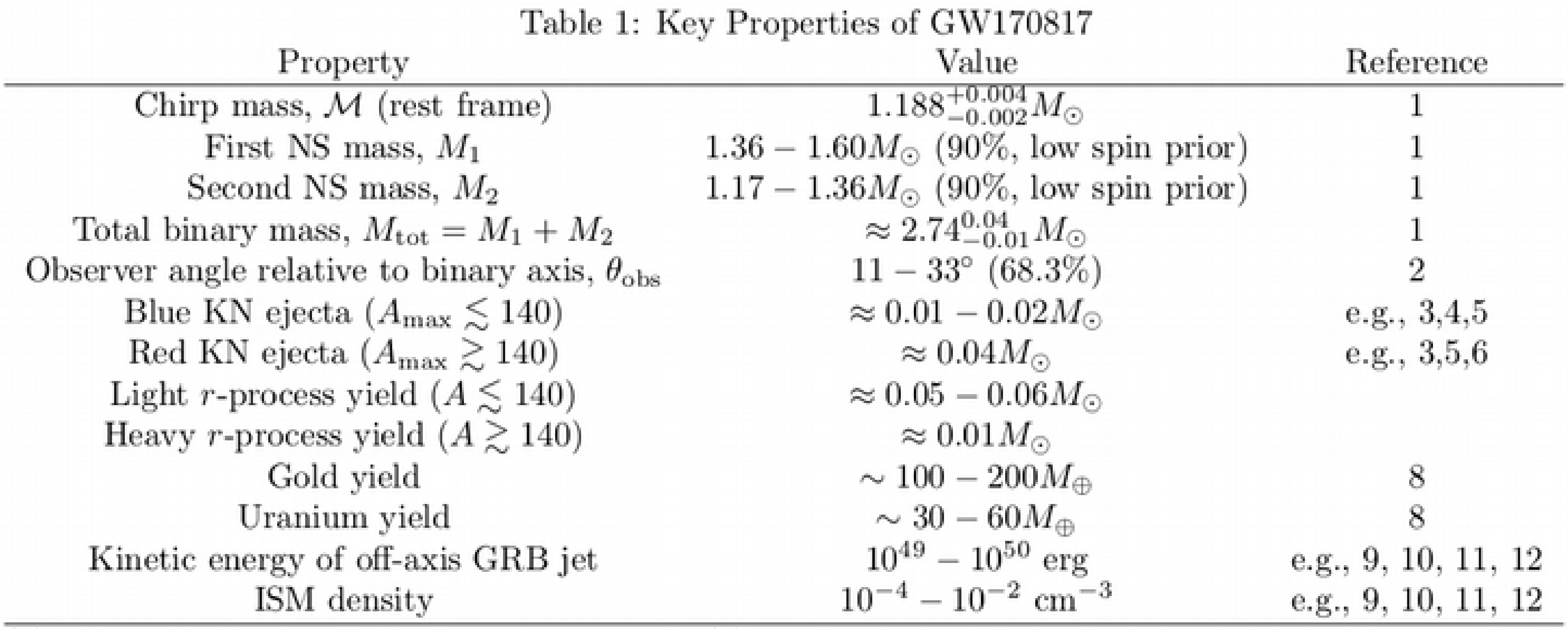
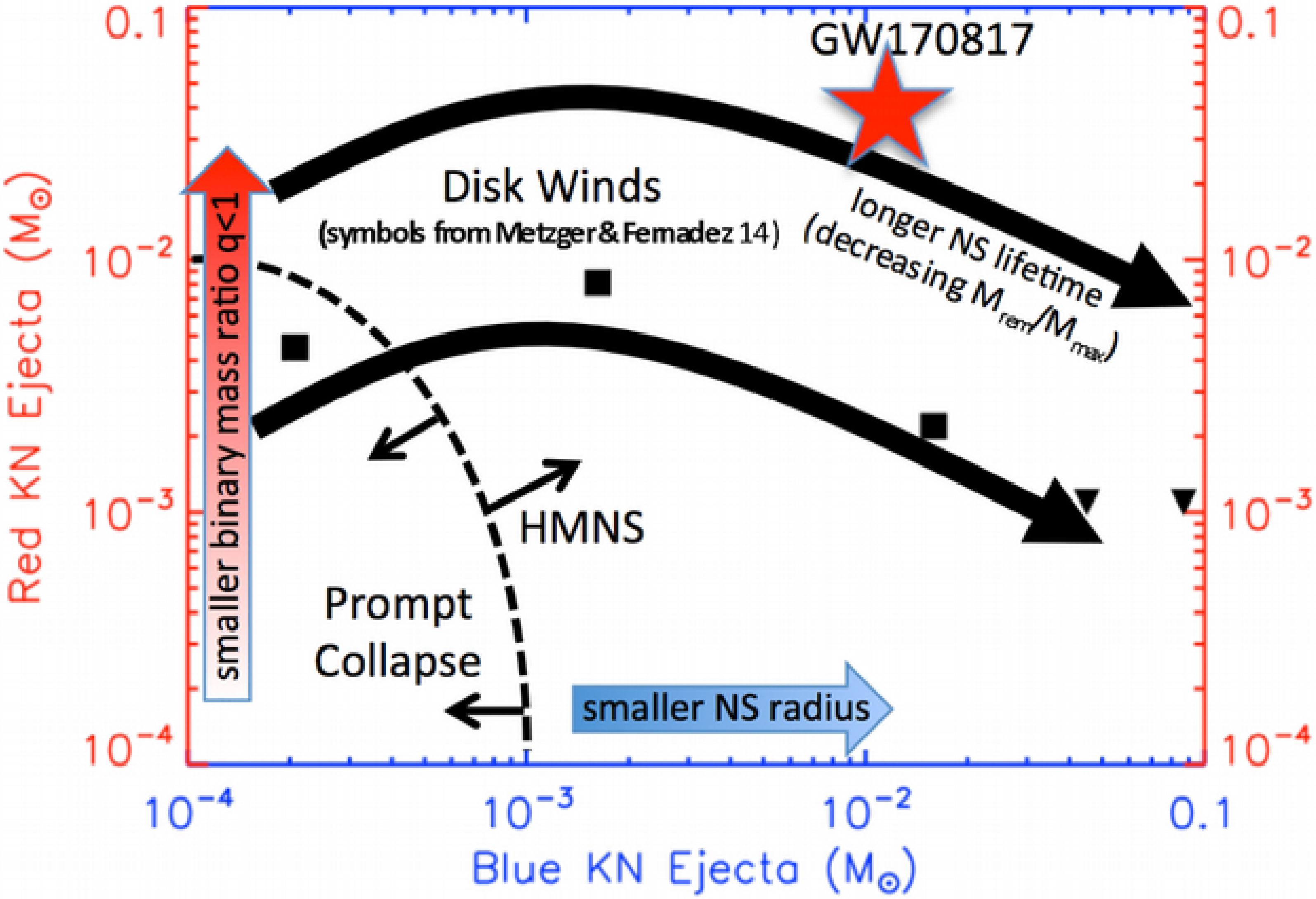


Table 1: Key Properties of GW170817

Property	Value	Reference
Chirp mass, $\mathcal{M}$ (rest frame)	$1.188^{+0.004}_{-0.002} M_\odot$	1
First NS mass, M_1	$1.36 - 1.60 M_\odot$ (90%, low spin prior)	1
Second NS mass, M_2	$1.17 - 1.36 M_\odot$ (90%, low spin prior)	1
Total binary mass, $M_{\rm tot} = M_1 + M_2$	$\approx 2.74^{0.04}_{-0.01} M_\odot$	1
Observer angle relative to binary axis, $\theta_{\rm obs}$	$11 - 33^\circ$ (68.3%)	2
Blue KN ejecta ($A_{\rm max} \lesssim 140$)	$\approx 0.01 - 0.02 M_\odot$	e.g., 3,4,5
Red KN ejecta ($A_{\rm max} \gtrsim 140$)	$\approx 0.04 M_\odot$	e.g., 3,5,6
Light r-process yield ($A \lesssim 140$)	$\approx 0.05 - 0.06 M_\odot$	
Heavy r-process yield ($A \gtrsim 140$)	$\approx 0.01 M_\odot$	
Gold yield	$\sim 100 - 200 M_\oplus$	8
Uranium yield	$\sim 30 - 60 M_\oplus$	8
Kinetic energy of off-axis GRB jet	$10^{49} - 10^{50}$ erg	e.g., 9, 10, 11, 12
ISM density	$10^{-4} - 10^{-2}$ cm^{-3}	e.g., 9, 10, 11, 12

Metzger 2017

Ejecta requirements



Metzger 2017

WAGER II: What year will the first EM-GW detection you believe will be?

- 2017: 0
- 2018: Albino
- 2019: Mansi, Bruno, Shibata, Oliver, Luke, Cristine, Stephan, Siegel, Tominaga, Brian
- 2020:Kasen, Rodrigo, Yong, Gabriel, Phil, Francois, Edo, Masaomi, Kenta, Eddie, Meng
- Next Decade: Tsvi, Sasha
- Never: 0

Conclusions

- *GW170817 has opened the door to gravitational wave multi-messenger astronomy providing multiple channels to constrain the EOS*

- *With 1 observation, already can constrain the EOS through inspiral, but post-merger is where things really get interesting!*

- *GW170817 tells us we need sophisticated microphysics (e.g. advanced neutrino evolution schemes) and long term evolution in our simulations to interpret observations → feed input into kilonova models*

- *More fully temperature-dependent EOSs are needed to better explore parameter space in NR simulations*