Multiwavelength Electromagnetic Counterparts of Gravitational Wave Events

Edo Berger *(Harvard University)*

KITP – Merging Visions – June 2019

Multiwavelength Electromagnetic Counterparts of Gravitational Wave Events

Edo Berger *(Harvard University)*

KITP − Merging Visions − June 2019

Outline

- EM counterparts: Why and what?
- GW170817 from γ-rays to radio
- EM follow-up in Observing Run 3
- The importance of BNS merger host galaxies

Soares-Santos et al. 2017, Cowperthwaite et al. 2017, Nicholl et al. 2017, Chornock et al. 2017, Margutti et al. 2017, Alexander et al. 2017, Blanchard et al. 2017, Fong et al. 2017, Villar et al. 2017, Cantiello et al. 2018, Margutti et al. 2018, Alexander et al. 2018, Villar et al. 2018, Safarzadeh et al. 2019a,b,c, Hosseinzadeh et al. 2019

Electromagnetic Counterparts: Why & What

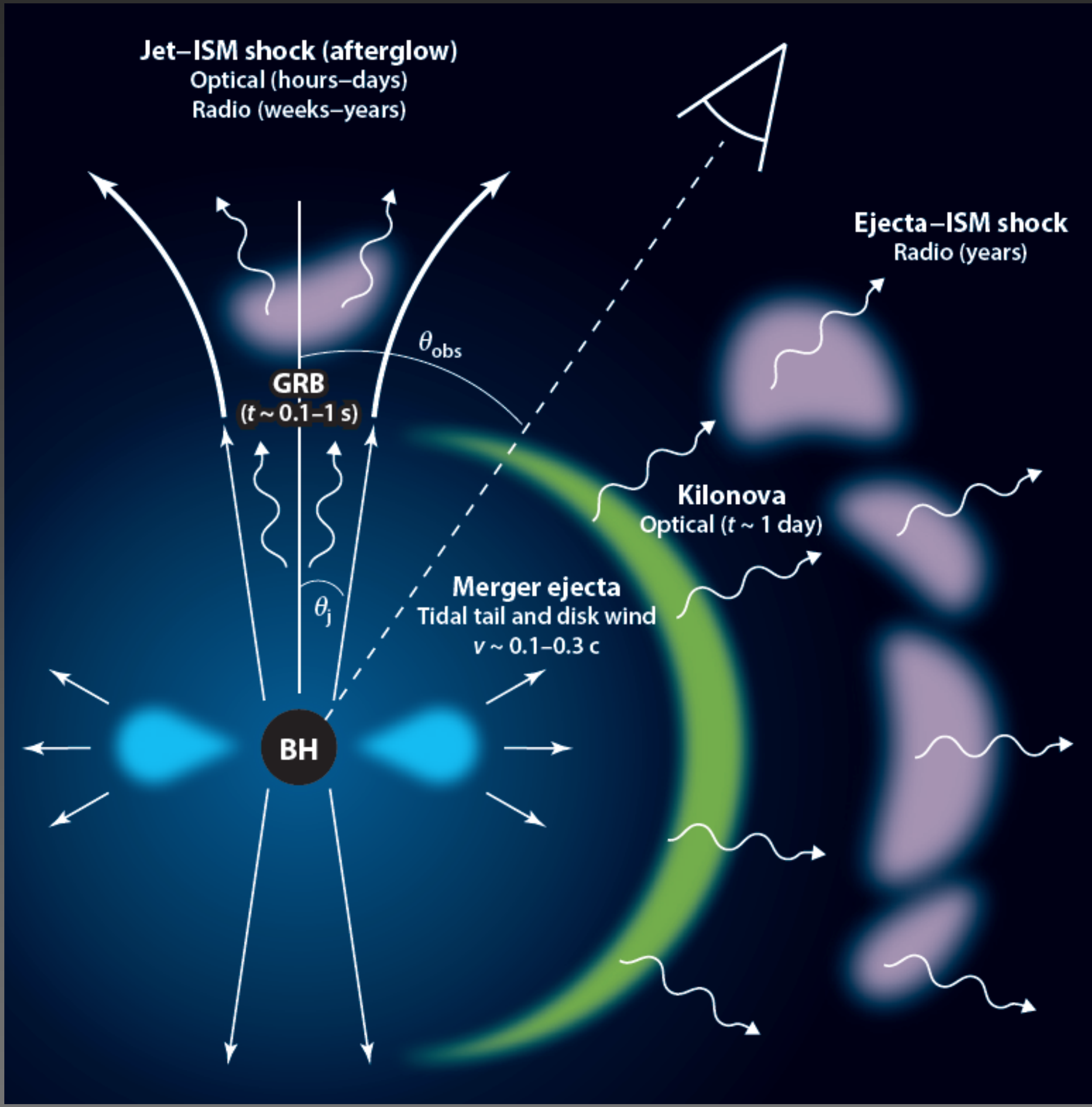
- Precise position
- Precise distance / *z*
- Host / context
- Behavior of matter
- Nature of remnant

Electromagnetic Counterparts: Why & What

- Precise position
- Precise distance / z
- Host / context
- Behavior of matter
- Nature of remnant

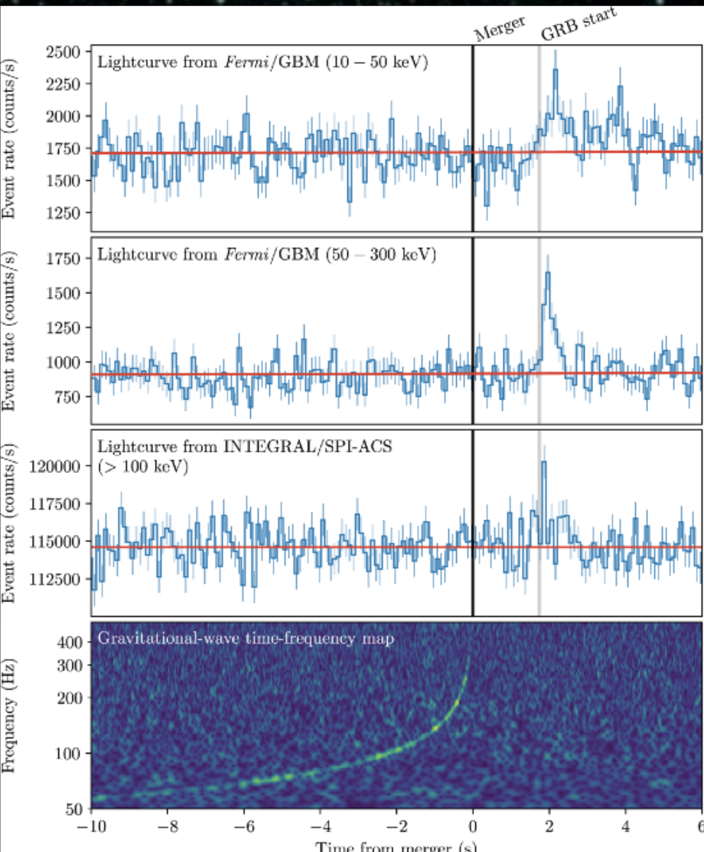
Predicted EM emission beamed and isotropic, relativistic and non-relativistic, multi-λ.

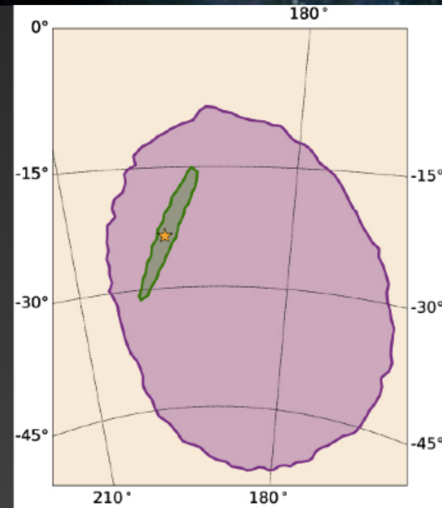
(short GRB, kilonova, ejecta/ISM interaction, speculative components)



Metzger & EB 2012

GW170817: GW & γ-Rays





$A \approx 30$ deg^2

$d \approx 25\text{–}50$ Mpc

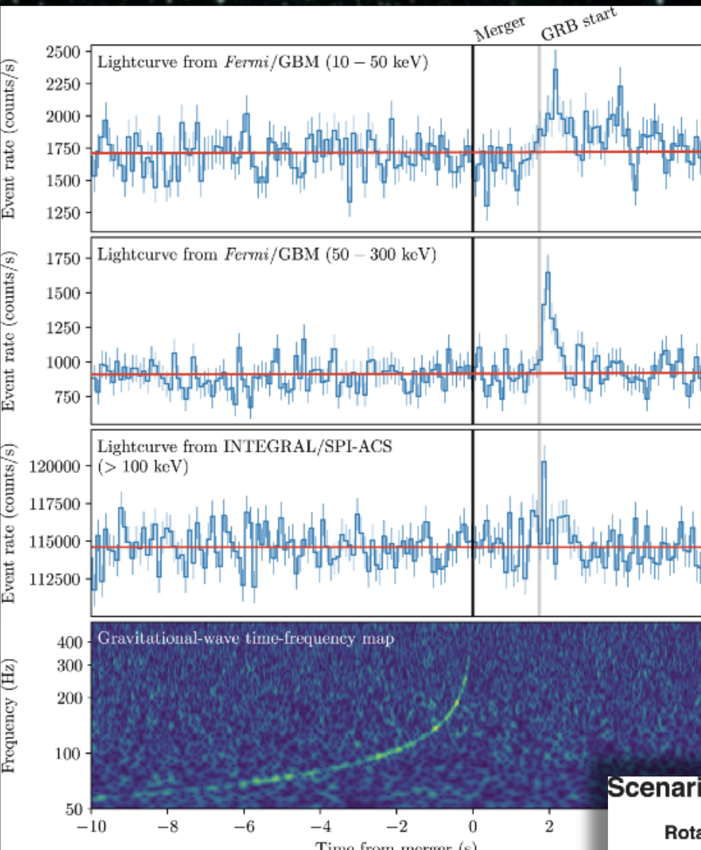
Abbott et al. 2017

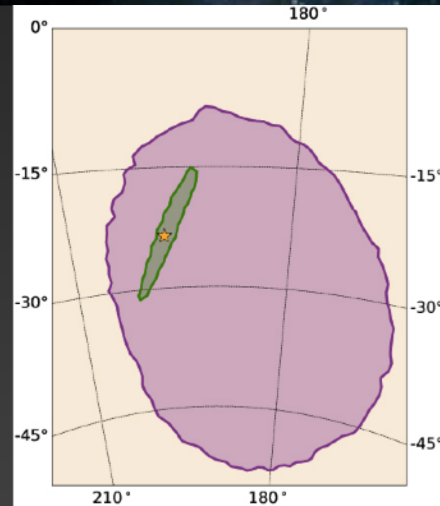
$M_1 \approx 1.4\text{–}1.6\ M_\odot$

$M_2 \approx 1.2\text{–}1.4\ M_\odot$

$M_{tot} \approx 2.74\ M_\odot$

GW170817: GW & γ-Rays



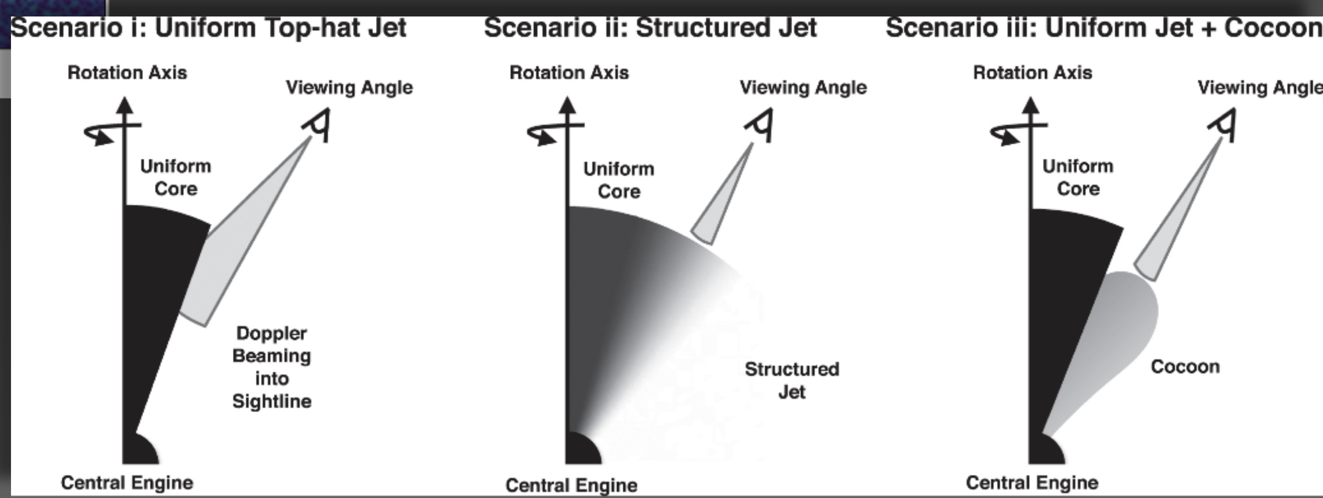


Weak γ-ray emission ($\sim10^5$ times lower than typical short GRBs) is difficult to uniquely interpret in isolation

$A \approx 30$ deg^2
$d \approx 25{-}50$ Mpc

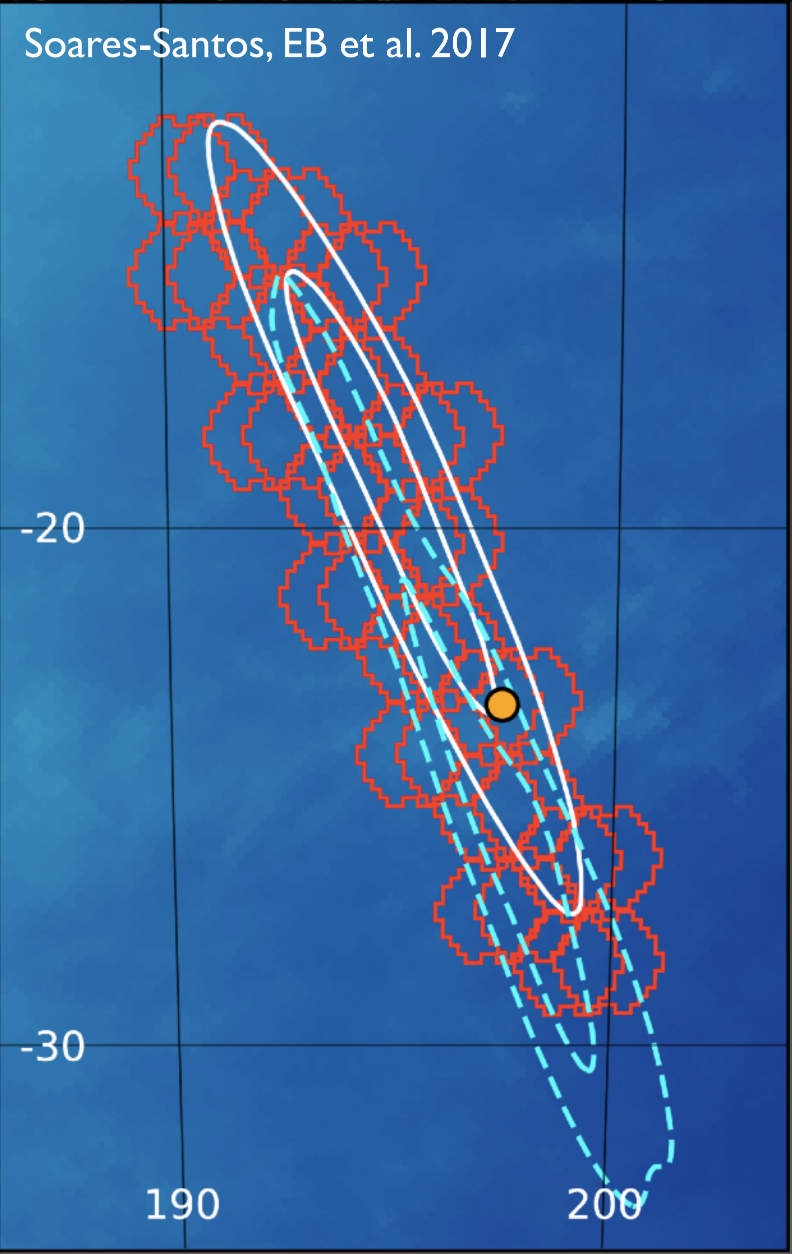
Abbott et al. 2017

$M_1 \approx 1.4{-}1.6\ M_\odot$
$M_2 \approx 1.2{-}1.4\ M_\odot$
$M_{tot} \approx 2.74\ M_\odot$

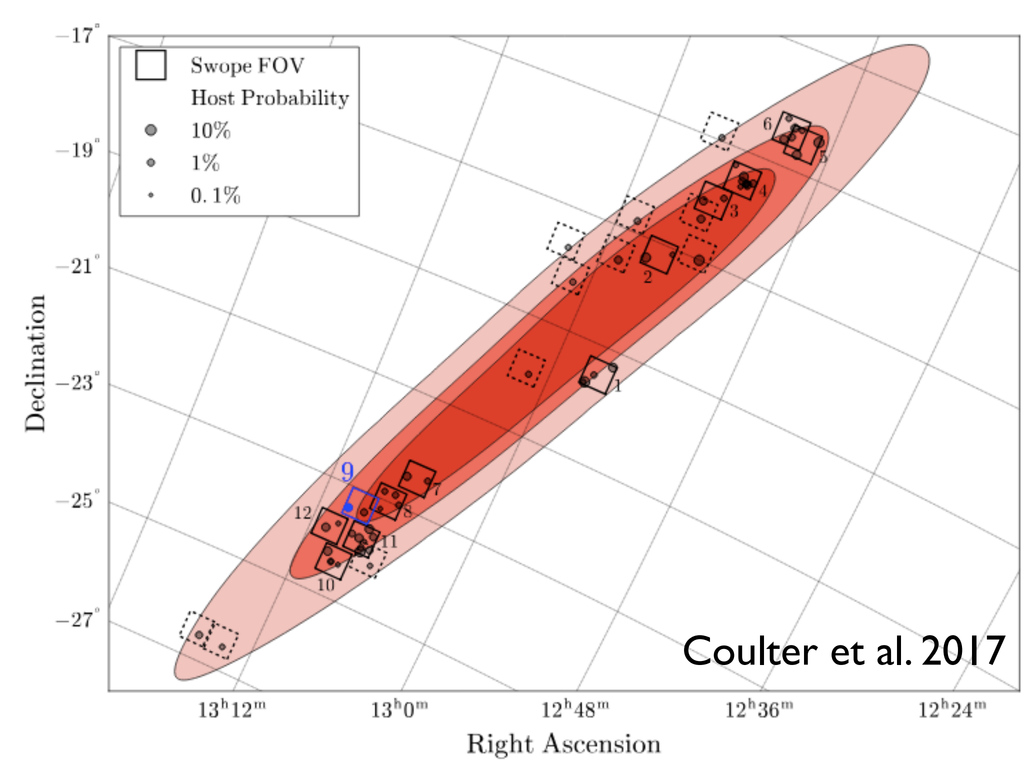


GW170817: Optical Counterpart

Soares-Santos, EB et al. 2017

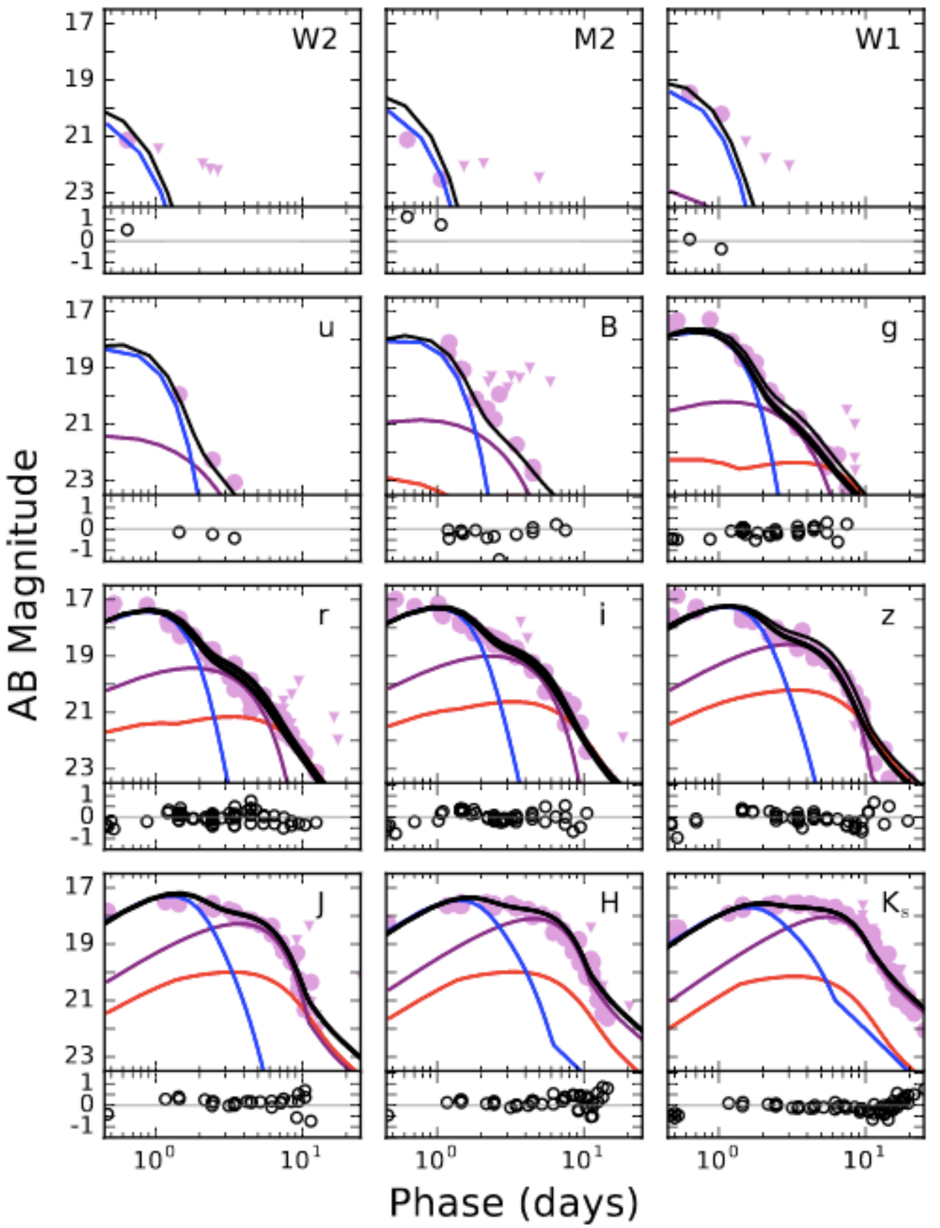


Optical counterpart identified rapidly in wide-field and galaxy-targeted searches (scalable?)



Coulter et al. 2017

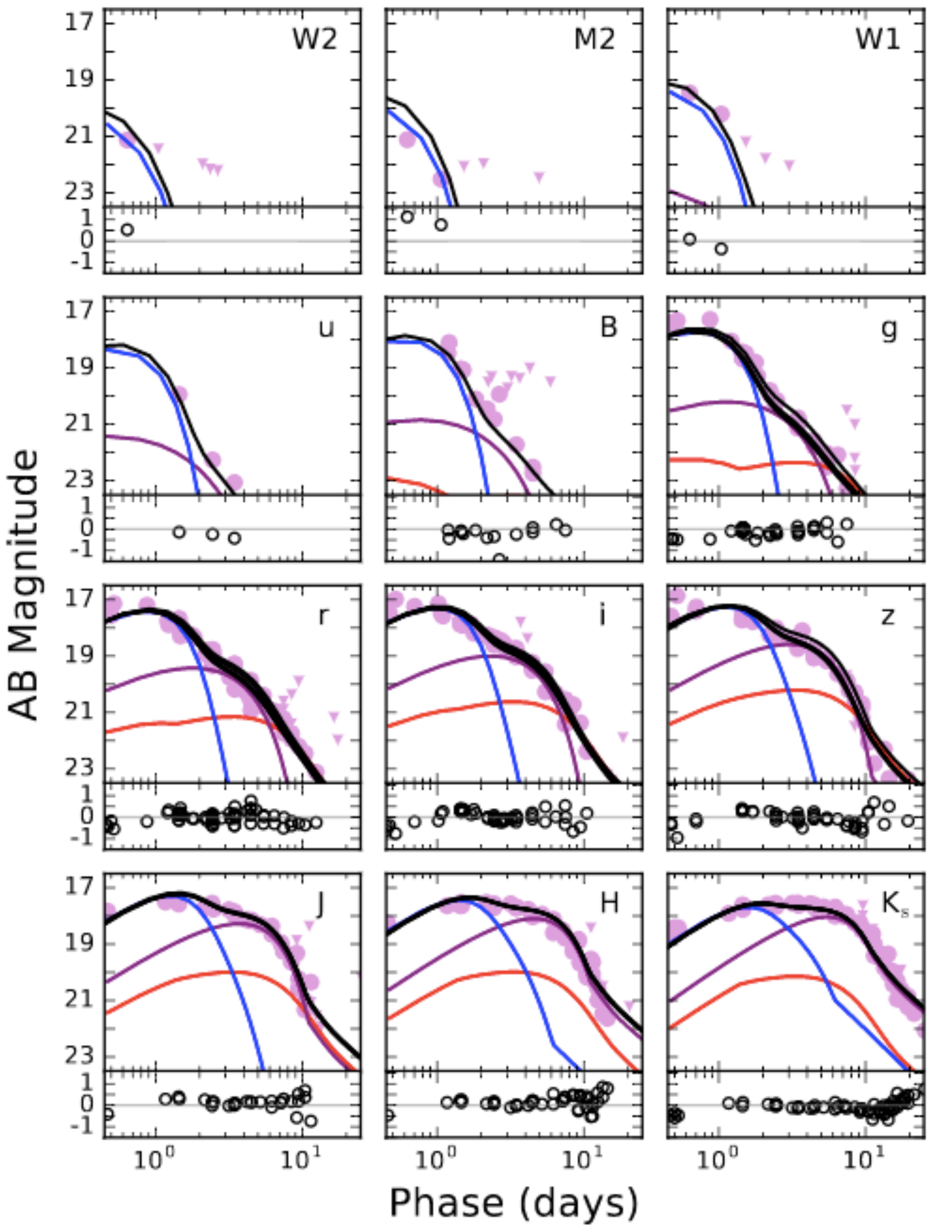
GW170817: UV/Optical/IR Kilonova



A range of ejecta properties with different *r*-process nucleosynthetic yields, velocity, ejecta mass, (*geometry?*)

Villar, EB et al. 2017

GW170817: UV/Optical/IR Kilonova



A range of ejecta properties with different *r*-process nucleosynthetic yields, velocity, ejecta mass, (*geometry?*)

Low-opacity (low X_{lan}) ejecta

$M_{ej} \approx 0.02\ M_{\odot}\ /\ v_{ej} \approx 0.3c$

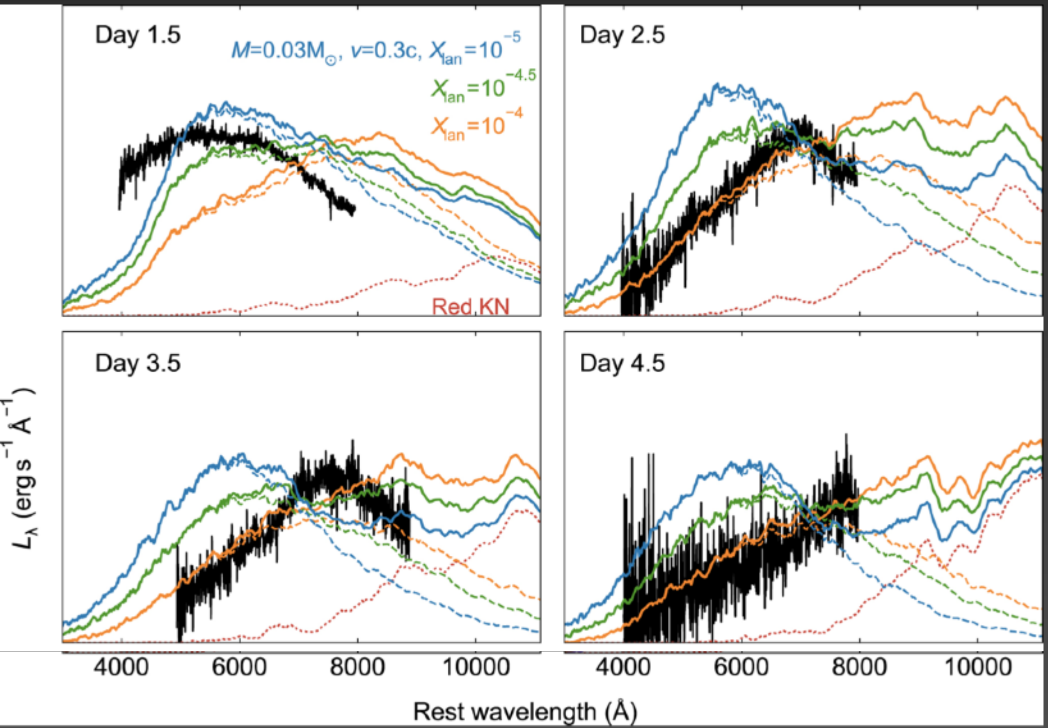
High-opacity (high X_{lan}) ejecta

$M_{ej} \approx 0.05\ M_{\odot}\ /\ v_{ej} \approx 0.1c$

Villar, EB et al. 2017

GW170817: UV/Optical/IR Kilonova

Nicholl, EB et al. 2017



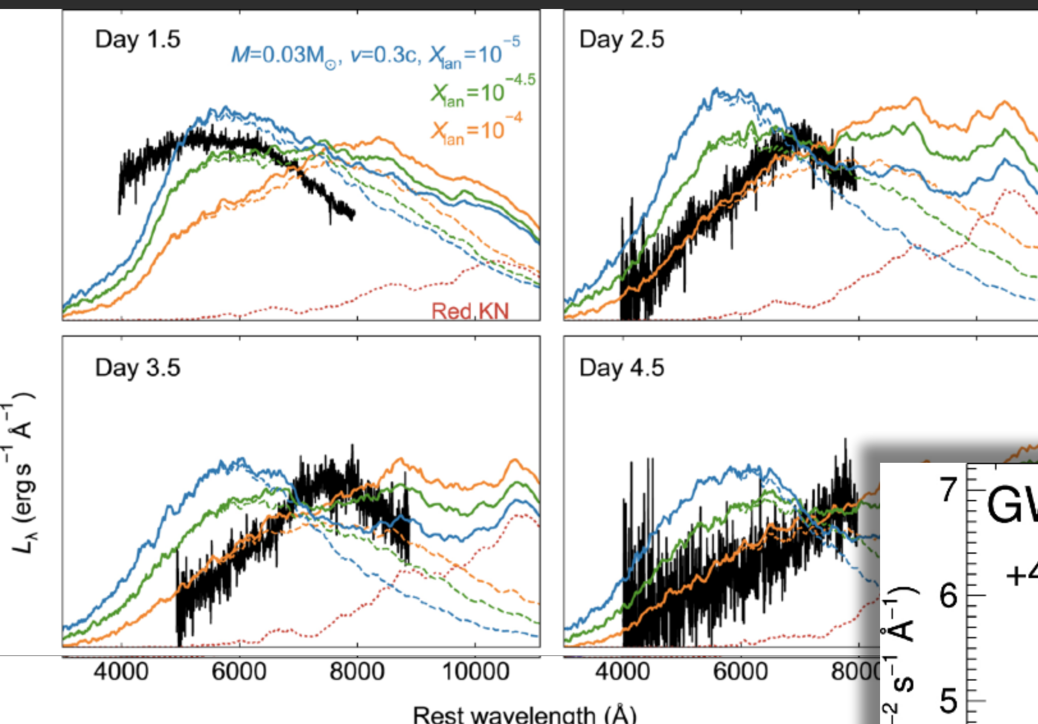
Optical spectra featureless (high velocity)

M_{ej} ~ 0.03 $M_{\odot}$ / v_{ej} ~ 0.3c

$X_{lan} \lesssim 10^{-5}$ (1 day) / $\sim 10^{-4}$ (2−4 days)

GW170817: UV/Optical/IR Kilonova

Nicholl, EB et al. 2017

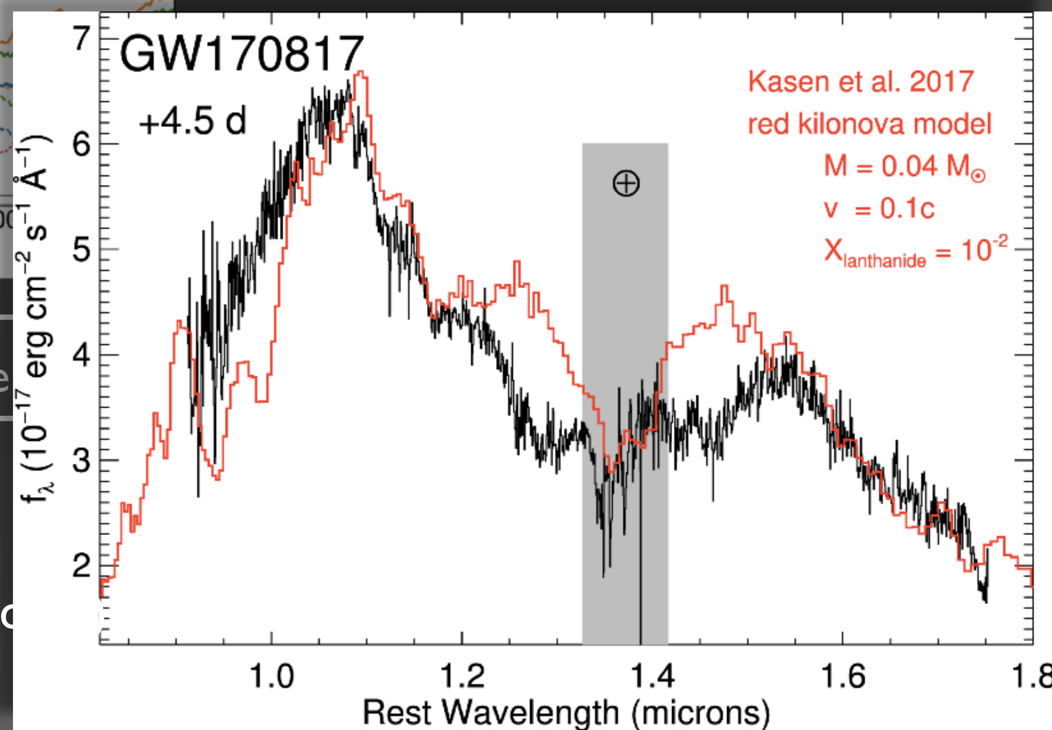


NIR spectra show distinct features (lower velocity)

M_{ej} ~ 0.04 $M_\odot$ / v_{ej} ~ 0.1c

X_{lan} ~ 10^{-2} (5−10 days)

Chornock, EB et al. 2017



Optical spectra featureless (high ve

M_{ej} ~ 0.03 $M_\odot$ / v_{ej} ~ 0.3c

X_{lan} ≲ 10^{-5} (1 day) / ~10^{-4} (2−4 d

GW170817: UV/Optical/IR Kilonova

- Direct (spectroscopic) evidence for *r*-process nucleosynthesis
- $M_{ej} \times R_{BNS}$ accounts for Galactic *r*-process production rate
- $M_{ej,lan\text{-}rich} / M_{ej,lan\text{-}poor} \approx R_{MW,A>140} / R_{MW,A<140}$

GW170817: UV/Optical/IR Kilonova

- Direct (spectroscopic) evidence for *r*-process nucleosynthesis
- $M_{ej} \times R_{BNS}$ accounts for Galactic *r*-process production rate
- $M_{ej,lan\text{-}rich} \,/\, M_{ej,lan\text{-}poor} \approx R_{MW,A>140} \,/\, R_{MW,A<140}$

- Lanthanide-poor ejecta $v \approx 0.3c \Rightarrow$ collision interface $\Rightarrow$ NS-NS
  (breaks ambiguity from GW data)

Nicholl, EB et al. 2017

GW170817: UV/Optical/IR Kilonova

- Direct (spectroscopic) evidence for *r*-process nucleosynthesis
- $M_{ej} \times R_{BNS}$ accounts for Galactic *r*-process production rate
- $M_{ej,lan\text{-}rich} / M_{ej,lan\text{-}poor} \approx R_{MW,A>140} / R_{MW,A<140}$

- Lanthanide-poor ejecta $v \approx 0.3c \Rightarrow$ collision interface $\Rightarrow$ NS-NS (breaks ambiguity from GW data)

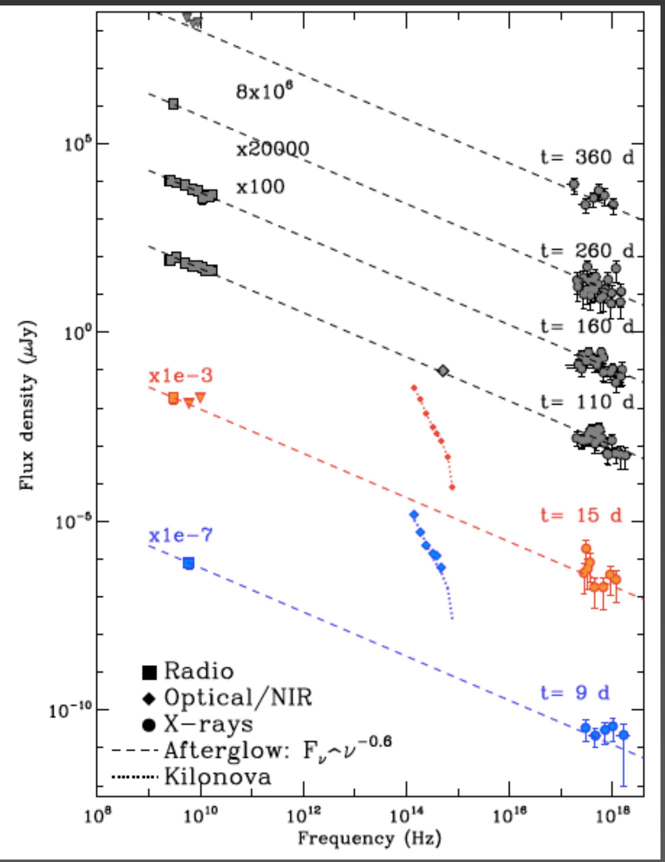
Nicholl, EB et al. 2017

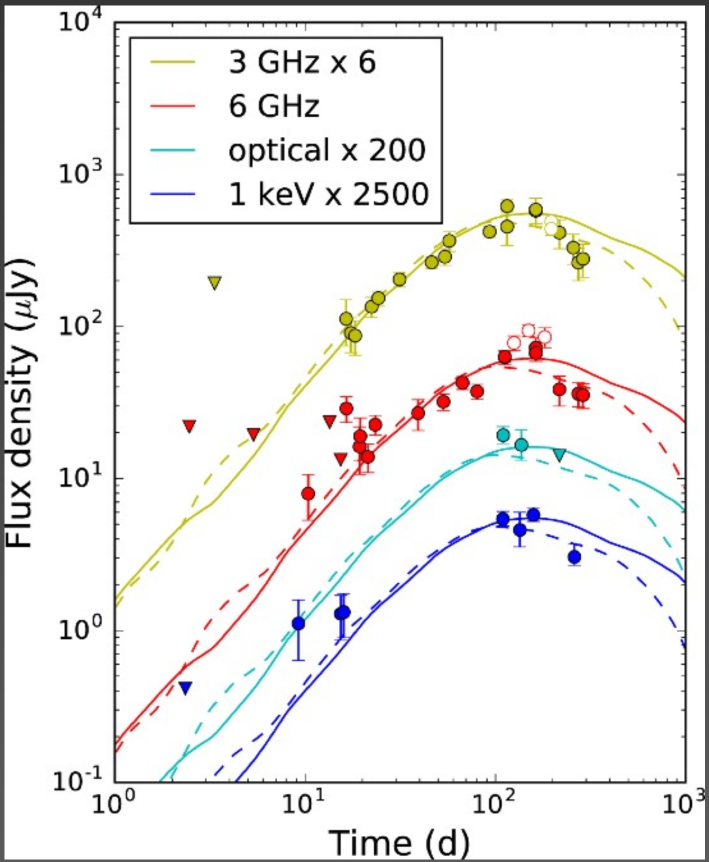
- Lanthanide-rich ejecta $v \approx 0.1c \Rightarrow$ accretion disk wind
- High lanthanide fraction $\Rightarrow$ short HMNS phase ($\lesssim$0.1 sec) $\Rightarrow$ final state is BH (breaks ambiguity from GW data)

Chornock, EB et al. 2017

GW170817: Radio/X-ray Off-Axis Jet

Radio, X-ray, and late optical emission from a single component: synchrotron emission from an off-axis structured jet

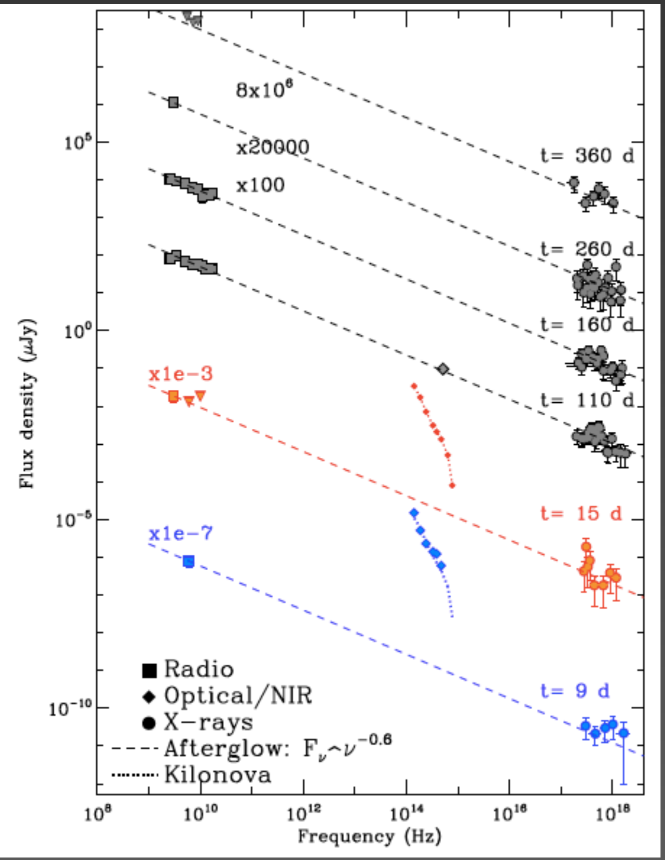


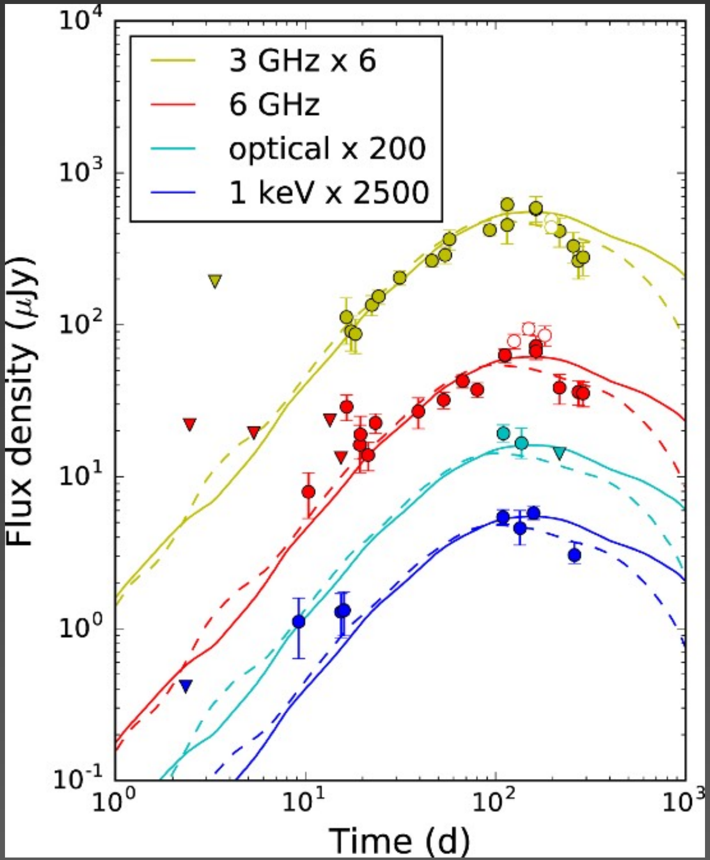


Alexander, EB et al. 2017,2018; Margutti, EB et al. 2017,2018

GW170817: Radio/X-ray Off-Axis Jet

Radio, X-ray, and late optical emission from a single component: synchrotron emission from an off-axis structured jet





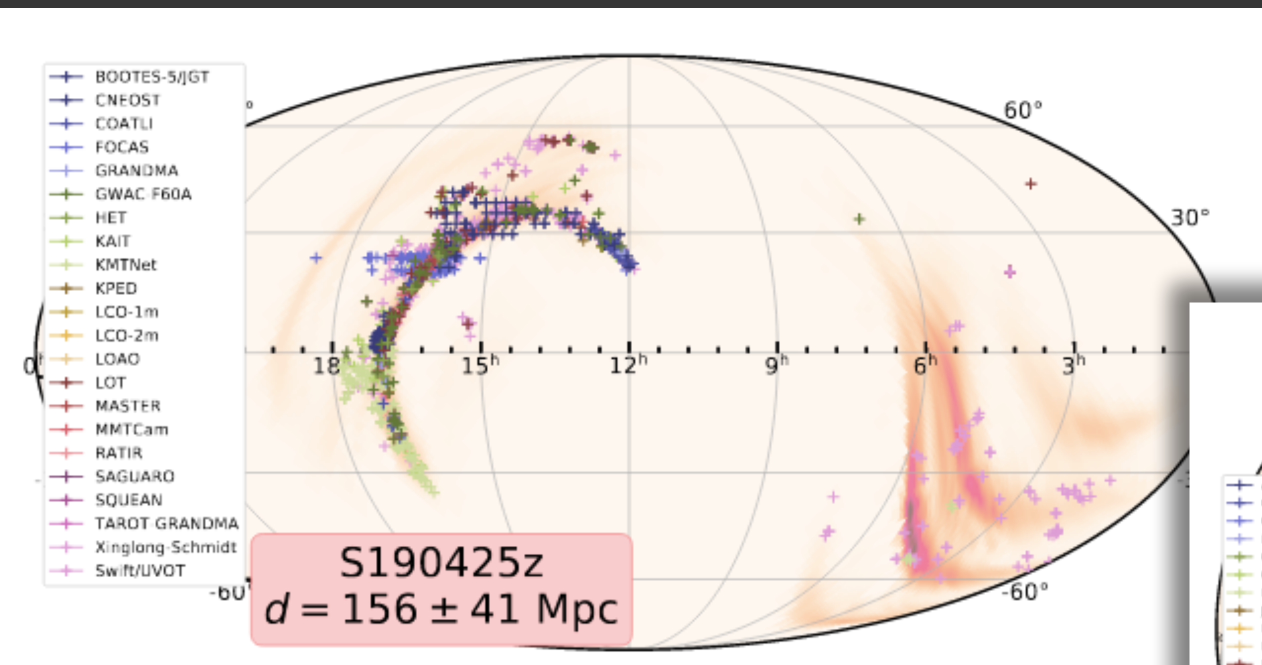
Radio/X-ray observations in the next few years should reveal emission from the kilonova ejecta, providing an independent measure of the ejecta mass and velocity

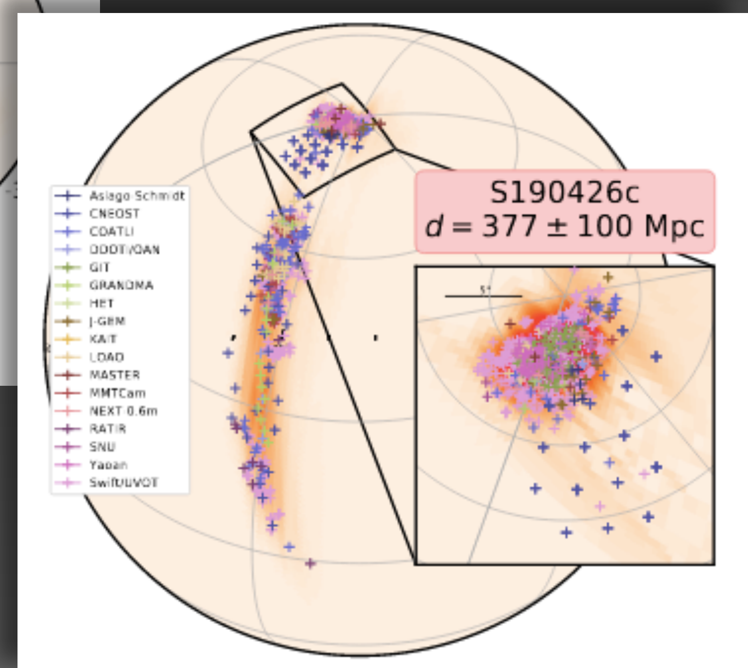
Alexander, EB et al. 2017,2018; Margutti, EB et al. 2017,2018

O3 Events: S190425z & S190426c

S190425z: BNS at ~155 Mpc, 7460 deg^2 (FAR: 1 in 70,000 years)

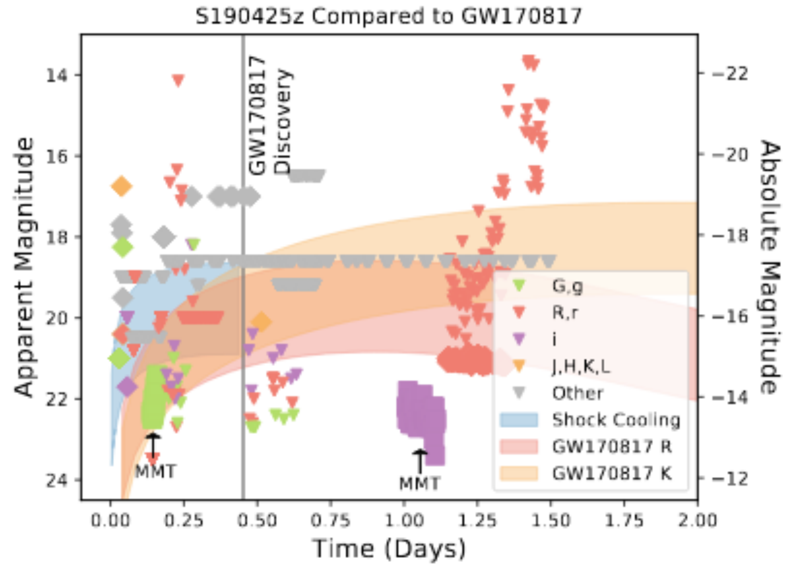
S190426c: NS-BH/BNS at ~375 Mpc, 1130 deg^2 (FAR: 1 in 1.7 years)

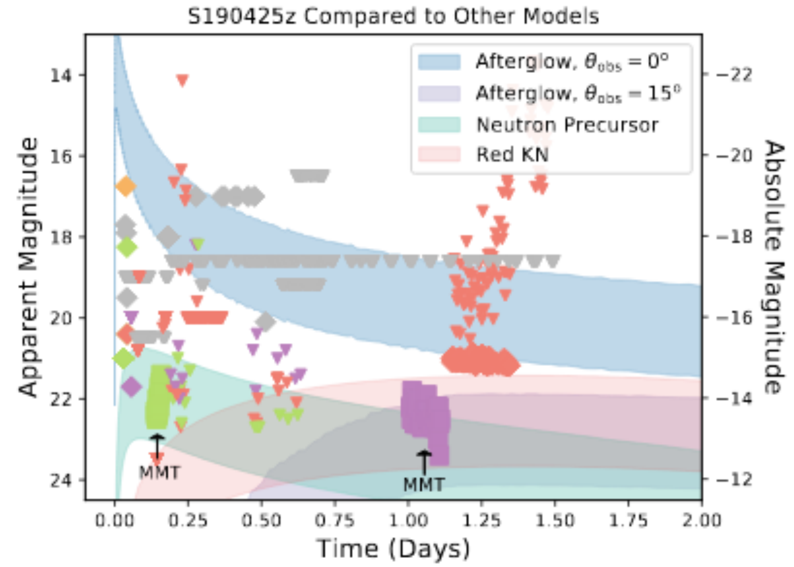




Hosseinzadeh, EB et al. 2019

O3 Events: S190425z & S190426c

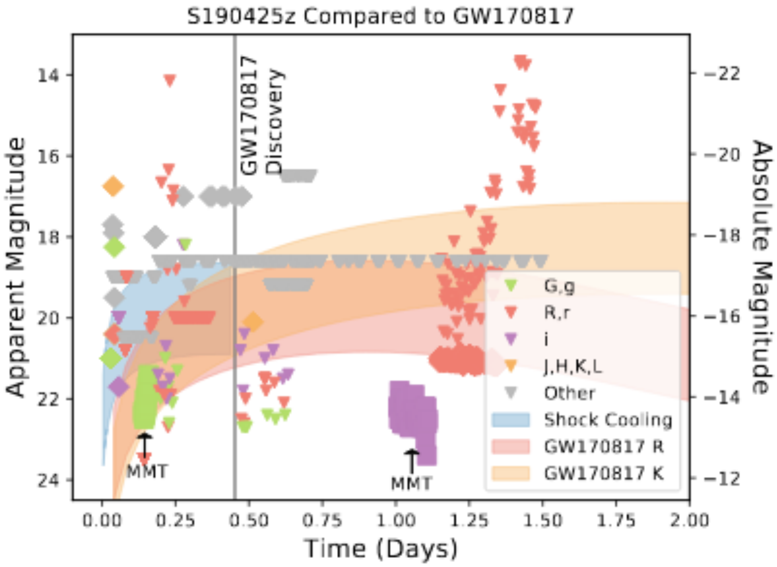


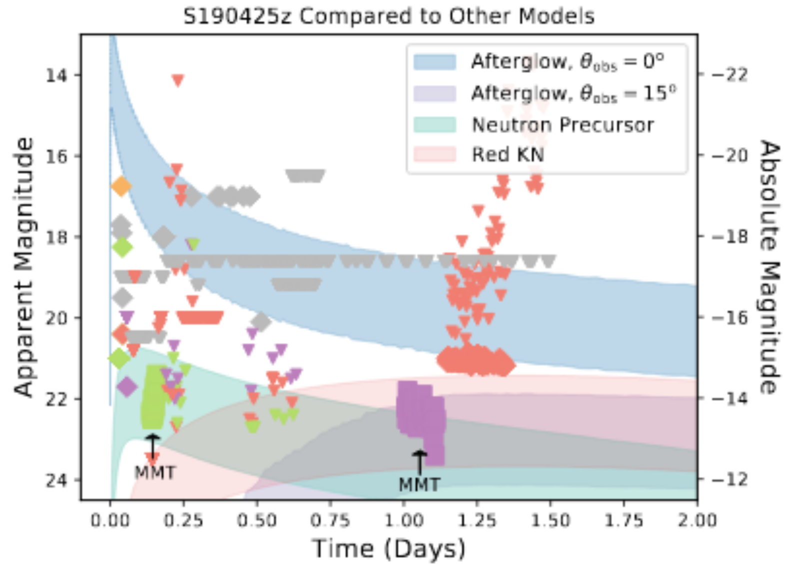


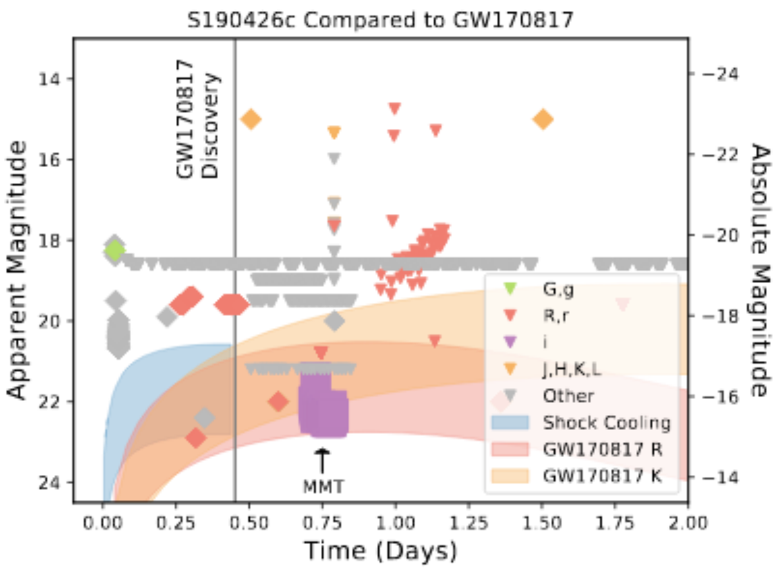
Comparison to GW170817

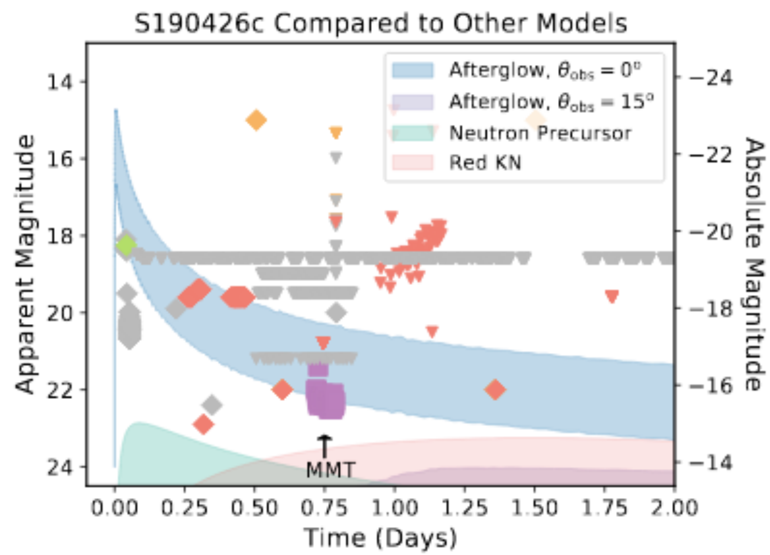
Other models

O3 Events: S190425z & S190426c

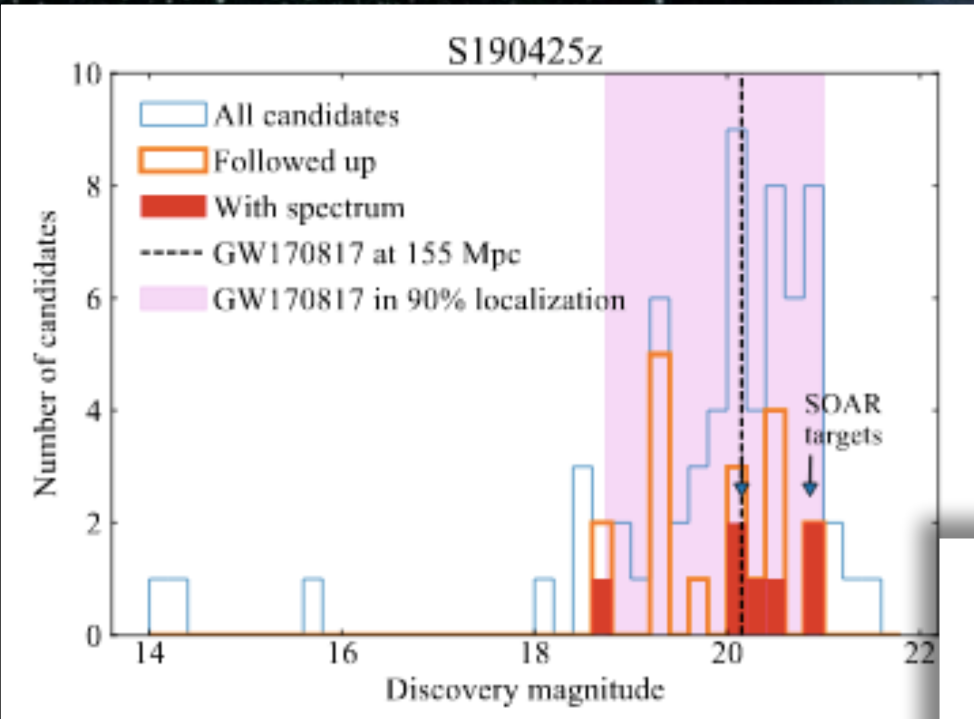




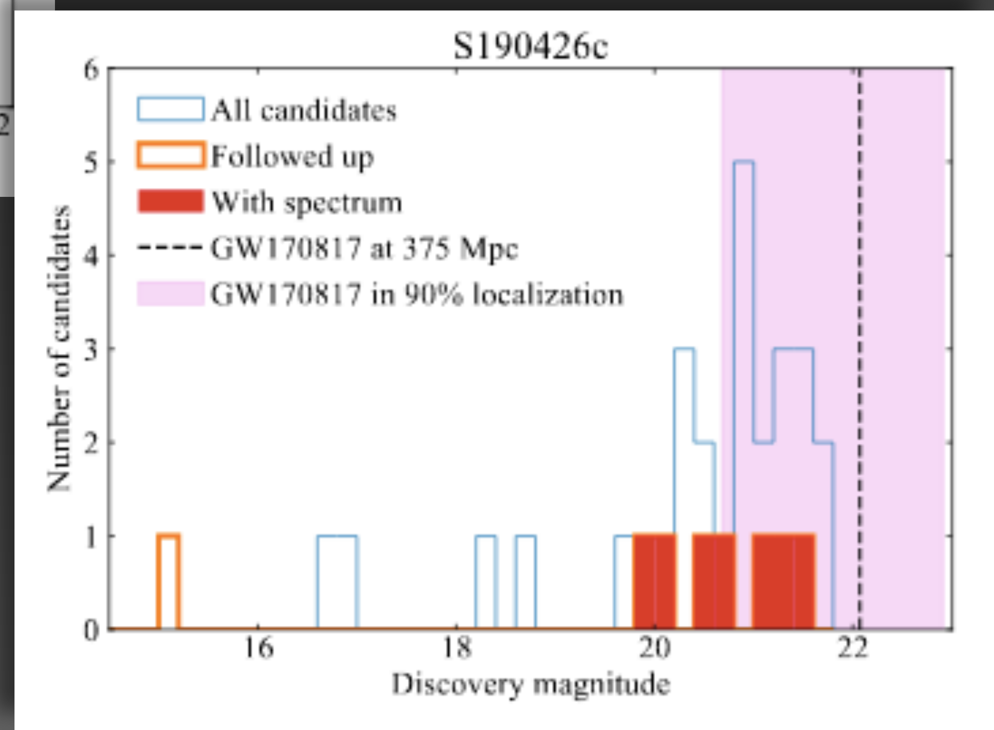




O3 Events: S190425z & S190426c

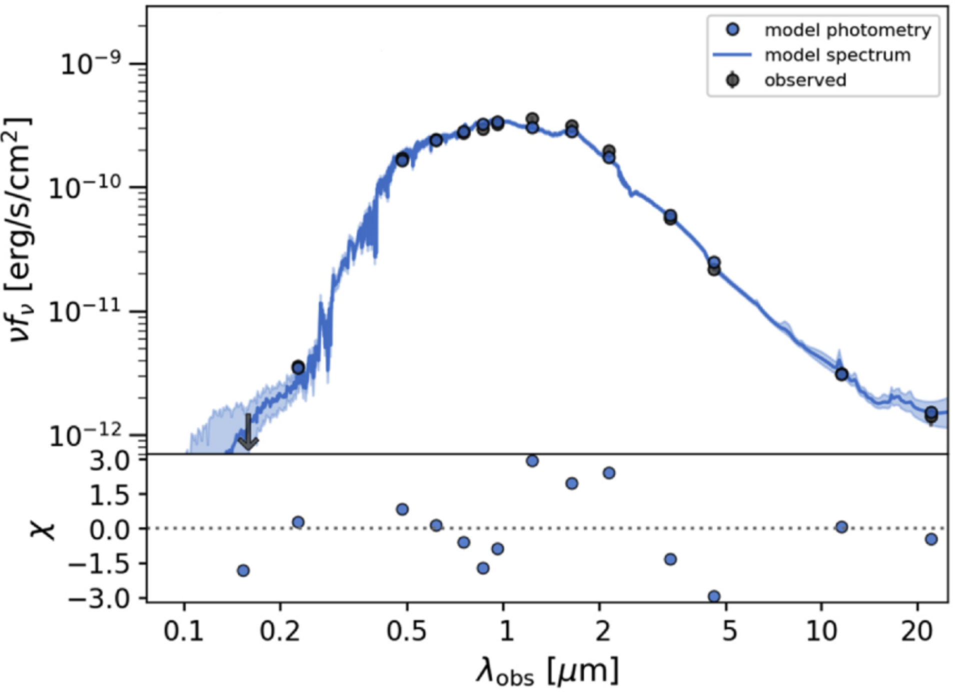


Dozens of transients were announced within the localization regions, and about 10% were spectroscopically classified (all normal supernovae)



GW170817: Host Galaxy

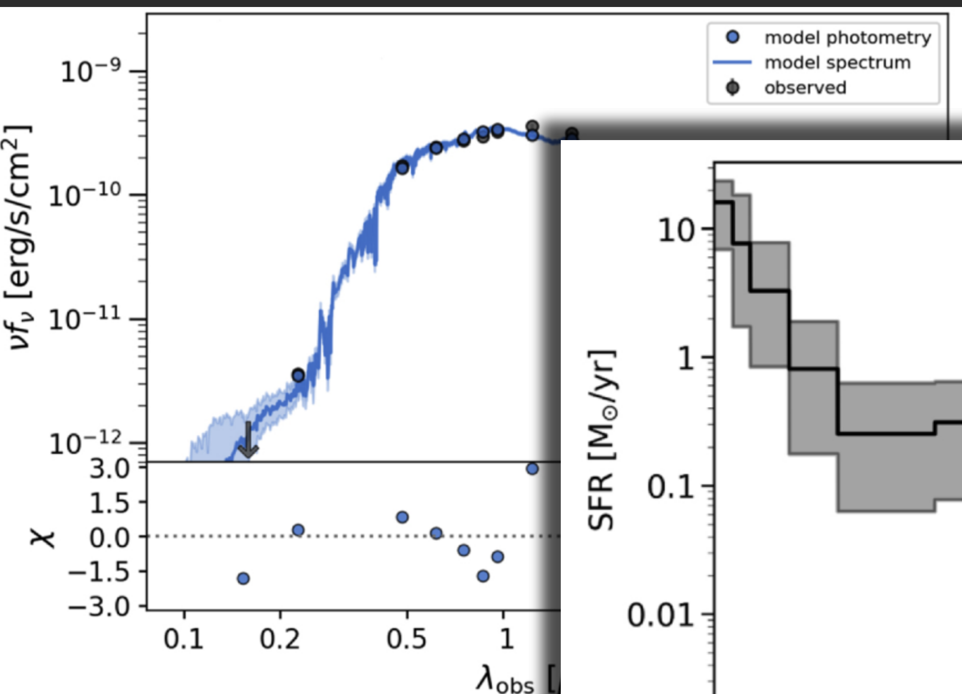
Blanchard, EB et al. 2017

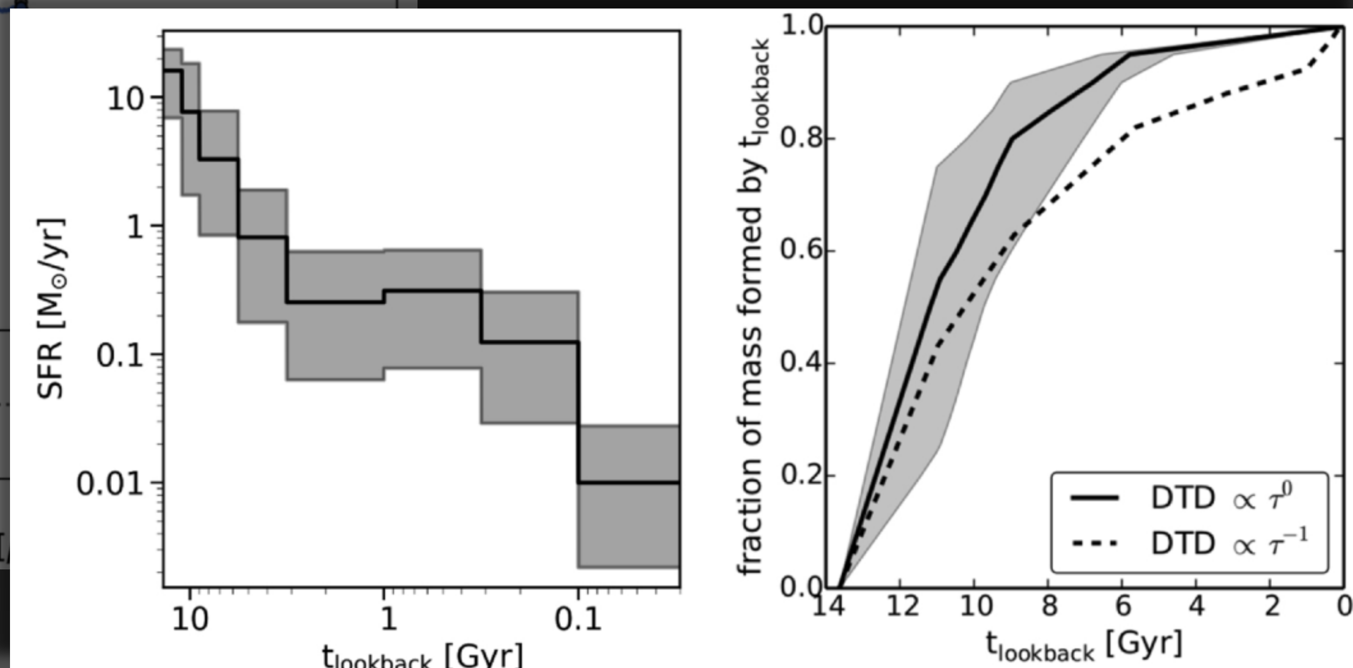


GW170817: Host Galaxy

Blanchard, EB et al. 2017

$\langle \tau_{merger} \rangle \approx 11$ Gyr

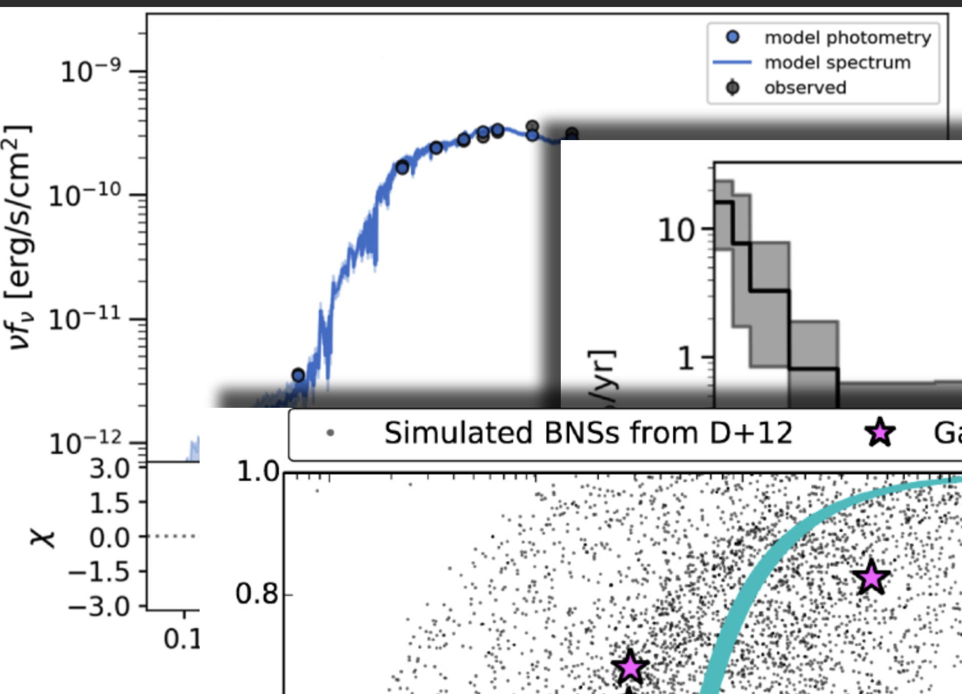


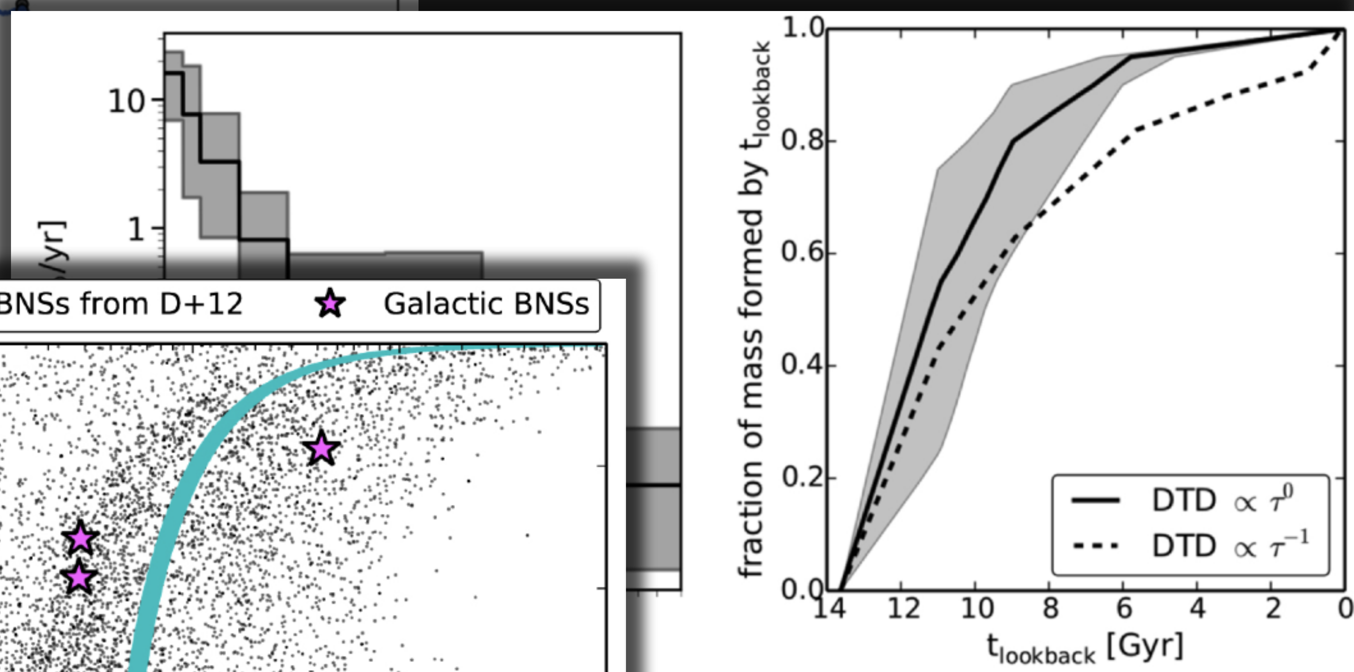


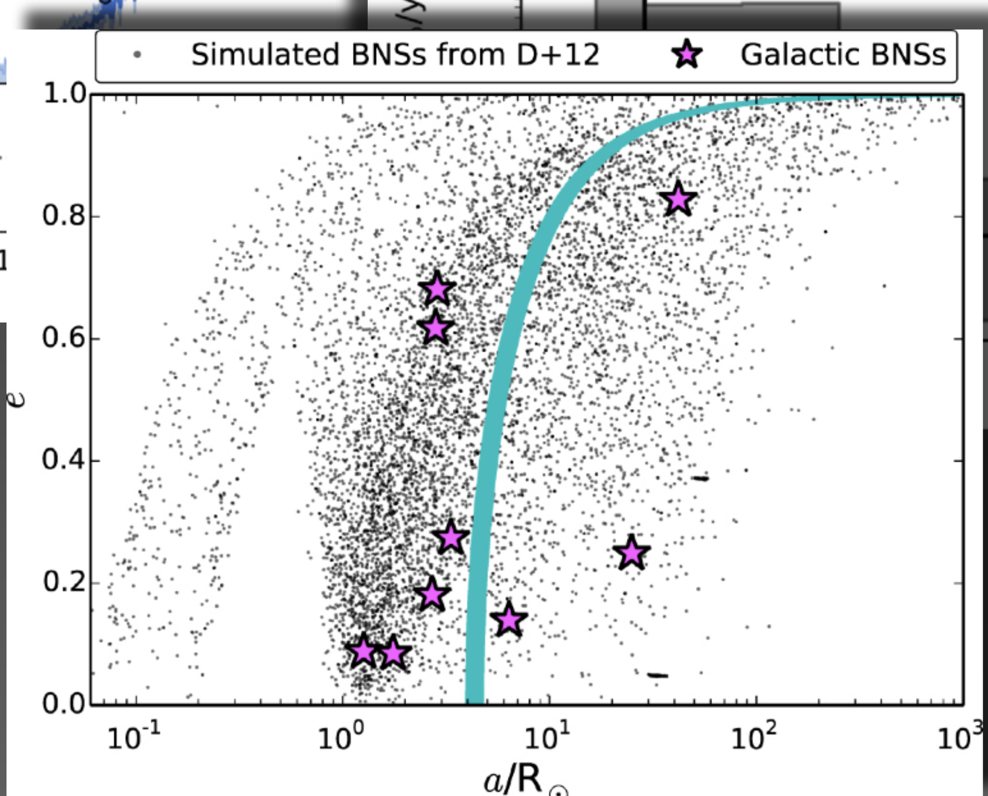
GW170817: Host Galaxy

Blanchard, EB et al. 2017

$\langle \tau_{merger} \rangle \approx 11$ Gyr

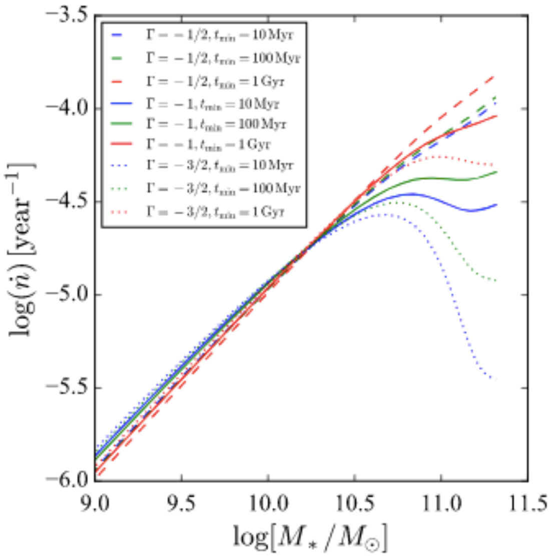


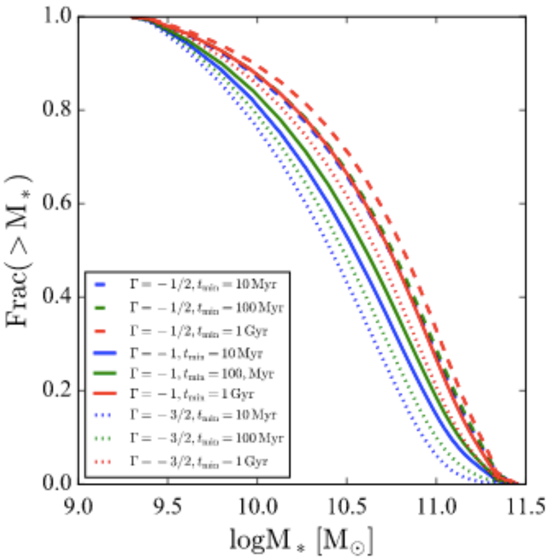




$\langle R_{initial} \rangle \approx 4.5\ R_\odot$

Host Galaxies: Delay Time Distribution

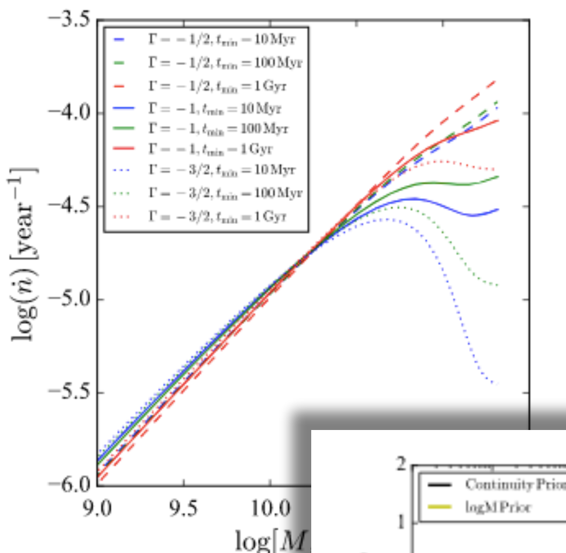




The SFH of galaxies correlates with stellar mass ⇒ convolution with different DTDs leads to different host galaxy stellar mass distributions

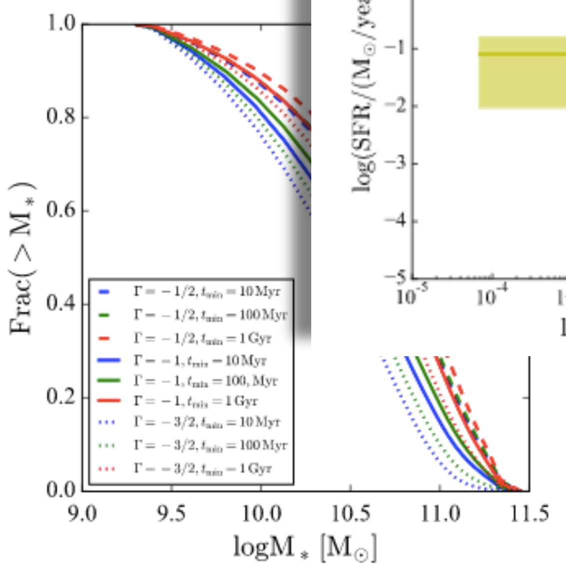
Safarzadeh & EB 2019a

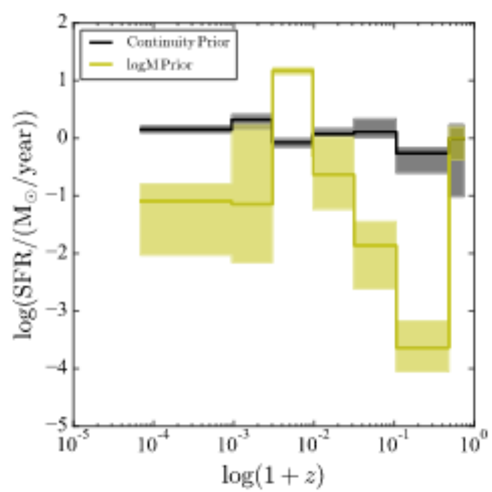
Host Galaxies: Delay Time Distribution

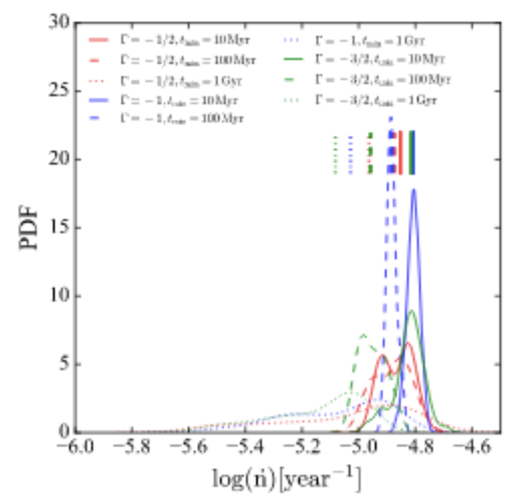


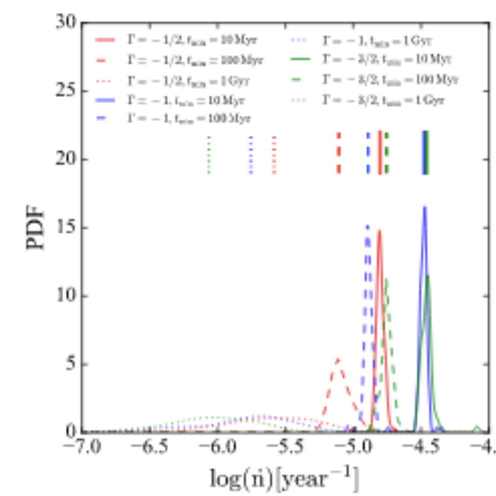
The SFH of galaxies correlates with stellar mass ⇒ convolution with different DTDs leads to different host galaxy stellar mass distributions

Safarzadeh, EB, et al. 2019c





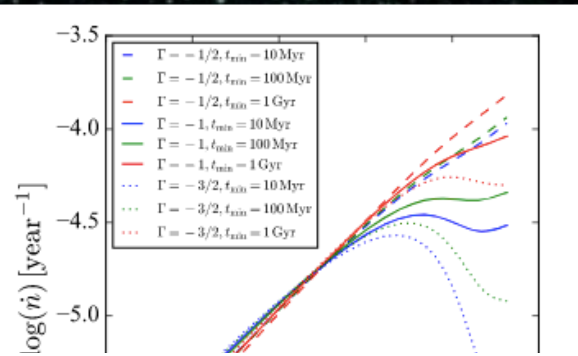




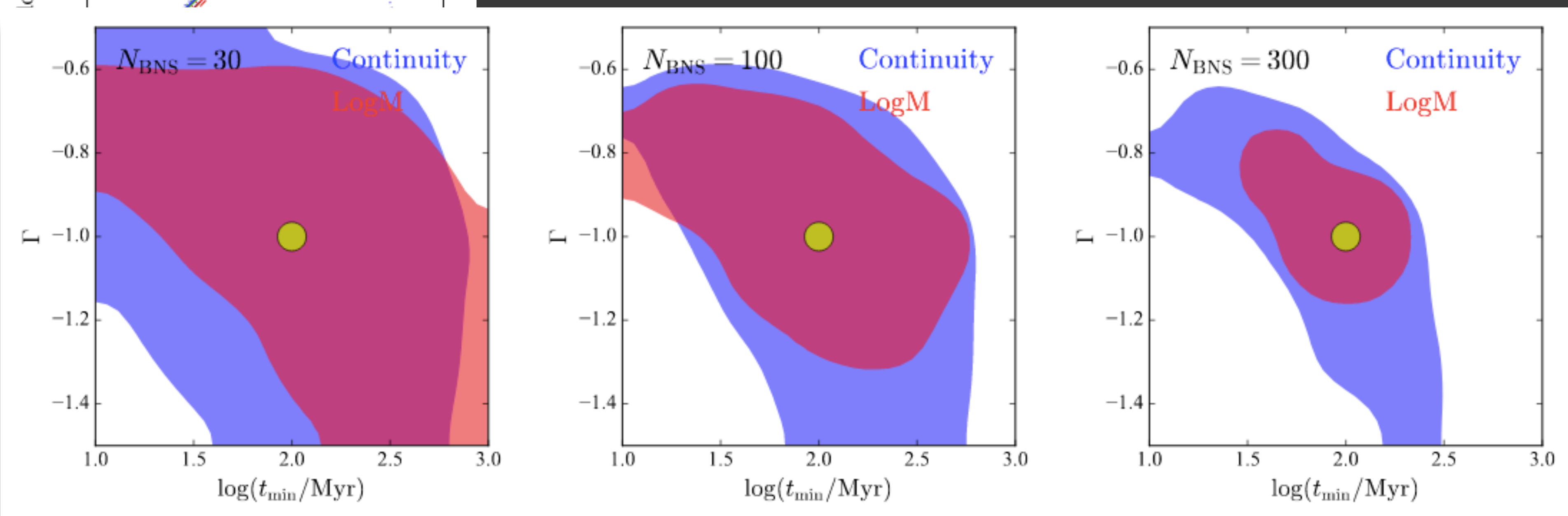
Instead of using stellar mass as a proxy, we can determine the SFH of each galaxy and infer the DTD from the combined sample

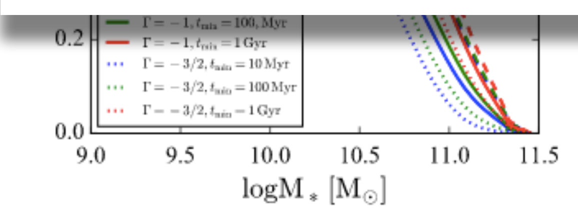
Safarzadeh & EB 2019a

Host Galaxies: Delay Time Distribution



The SFH of galaxies correlates with stellar mass ⇒ convolution with different DTDs leads to different host galaxy stellar mass distributions

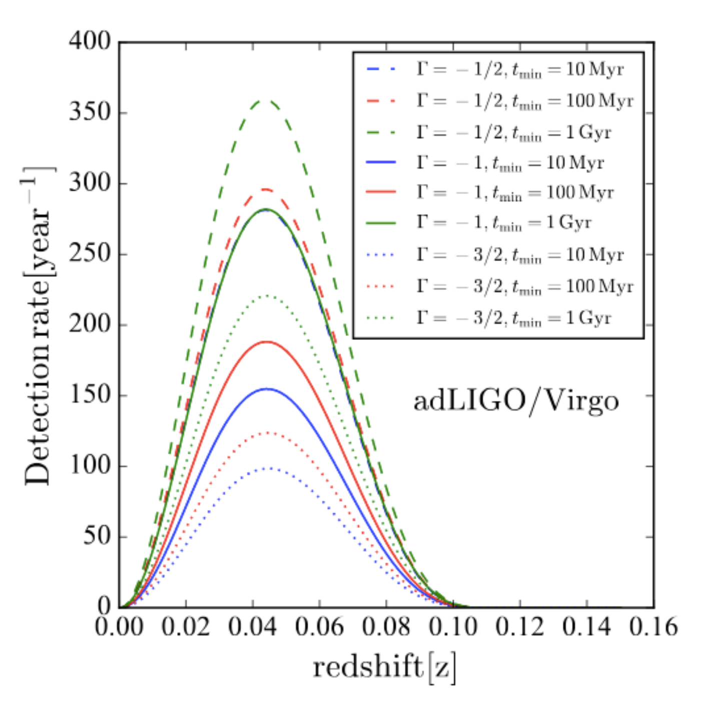




Instead of using stellar mass as a proxy, we can determine the SFH of each galaxy and infer the DTD from the combined sample

Safarzadeh & EB 2019a

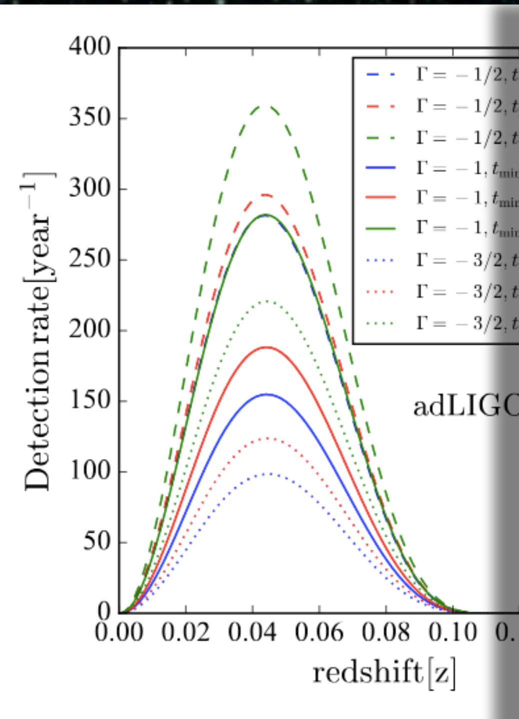
Redshifts: Delay Time Distribution



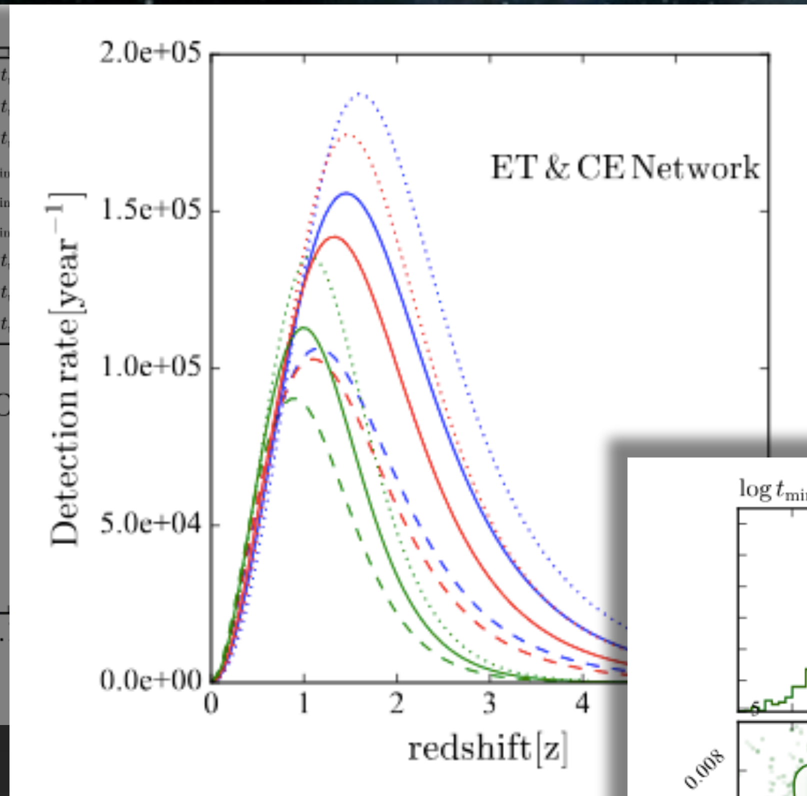
Safarzadeh, EB, et al. 2019b

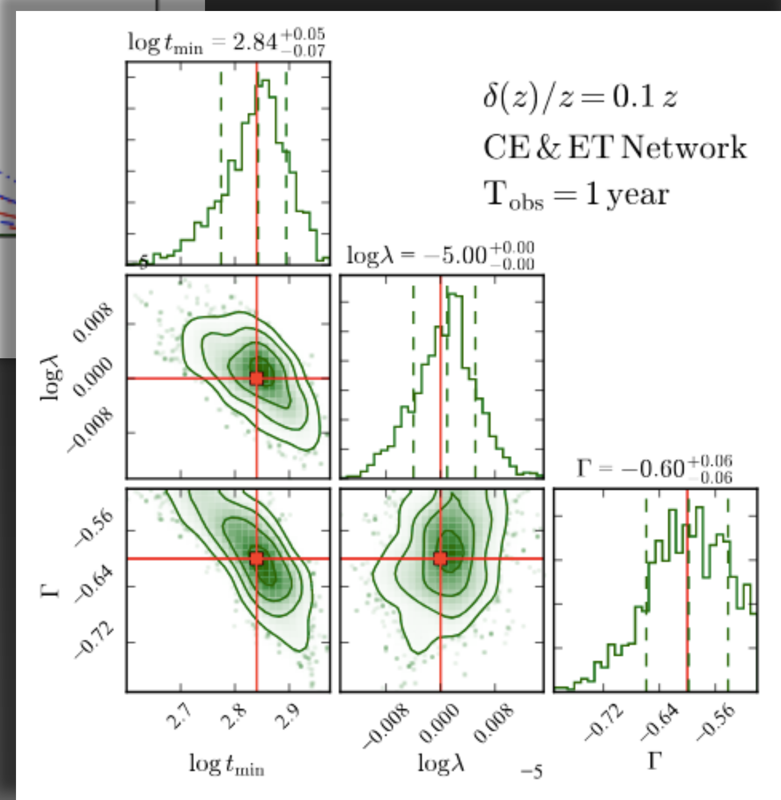
Existing detectors only sensitive to z ~ 0 ⇒ DTD degenerate with mass efficiency

Redshifts: Delay Time Distribution



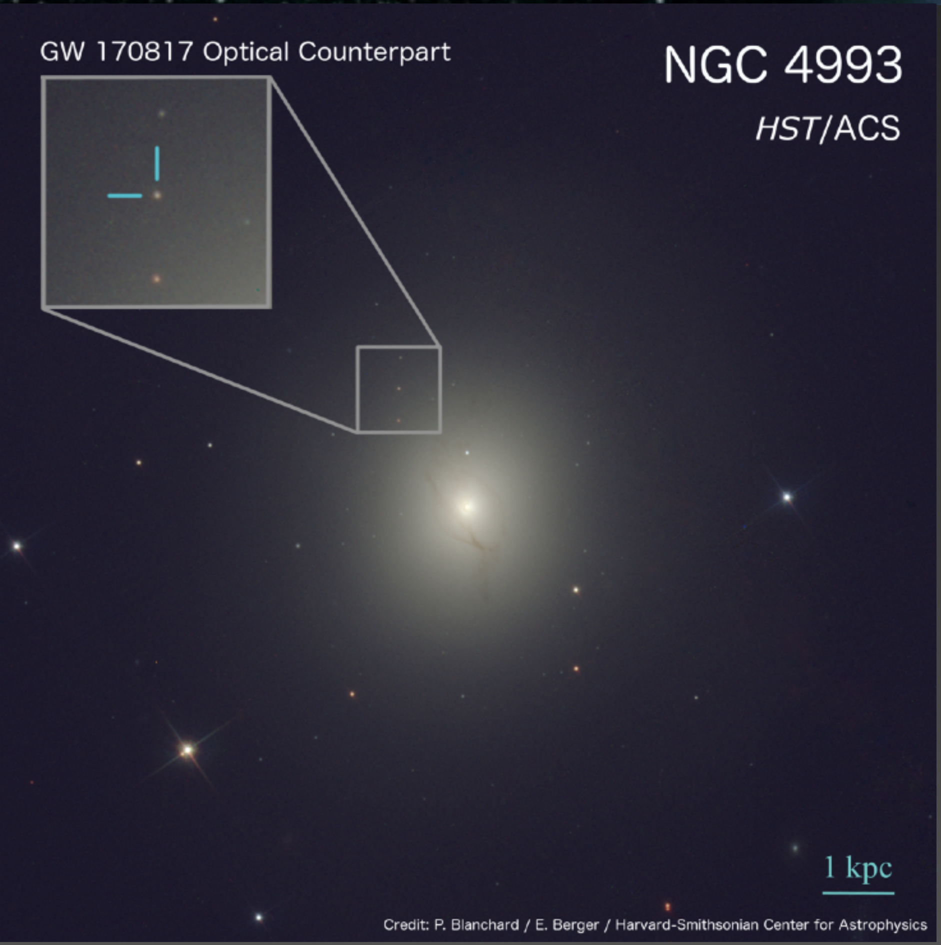
Safarzadeh, EB, et al. 2019b





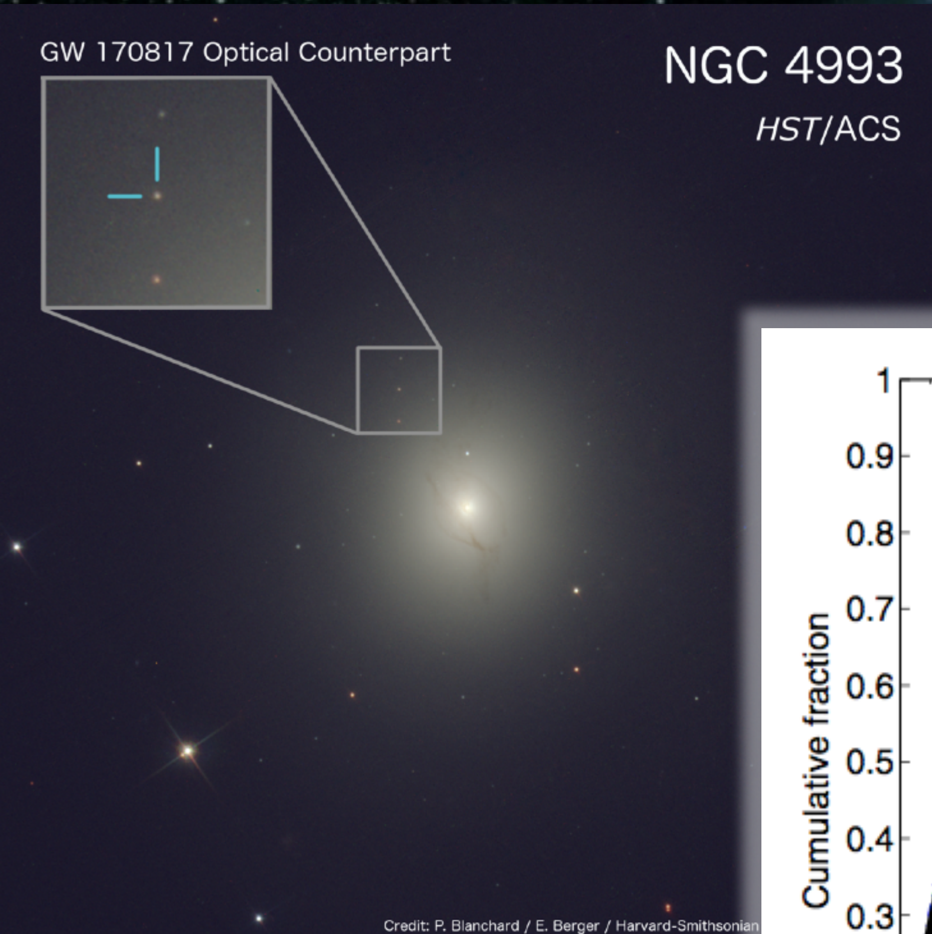
The DTD is imprinted on the redshift distribution for 3G detectors, even with δz/z=0.1z

Host Galaxies: Offsets/Kicks



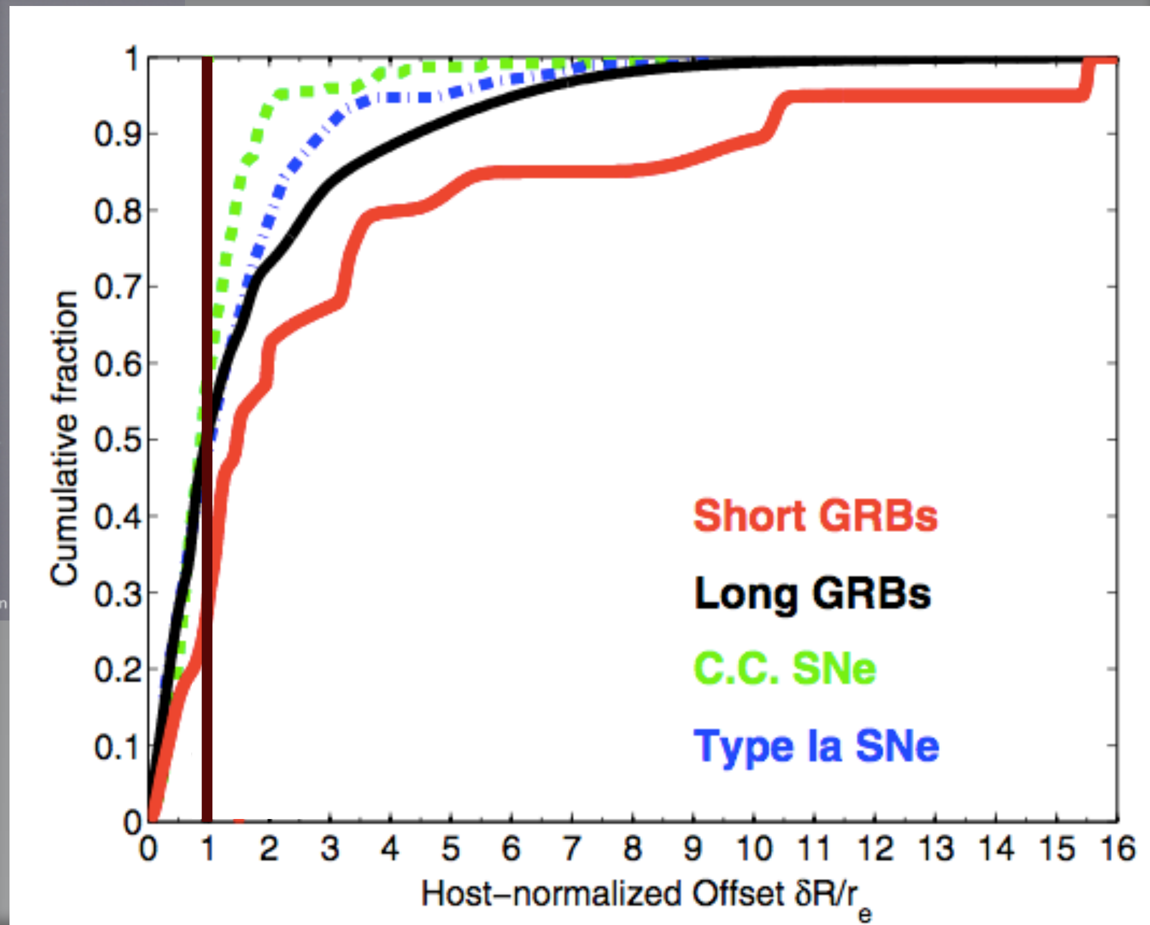
Blanchard, EB et al. 2017

Host Galaxies: Offsets/Kicks



Blanchard, EB et al. 2017

Fong & EB 2015



Summary

Summary

- EM counterparts are essential for a complete interpretation of BNS/NS-BH mergers, and for access to fundamental physics, nucleosynthesis, cosmology
- The optical band remains the most promising route to rapid precise localizations
- Events like GW170817 will provide the most detailed view of mergers (but are likely to be rare)
- Host galaxies hold a key to the delay time distribution, kicks, and hence formation channels of BNS and NS-BH systems