Prompt Counterparts to GW Detections
Outline

Prompt GW-EM Observations

Theoretical Expectations

Implications & Prospects
Prompt GW-EM Observations
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We only have up to 3 GW-EM cases related to CBC merger

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Case #1: No Doubtly GW+GRB

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Abbott et al. 2017, PRI, 119, 161101

<table>
<thead>
<tr>
<th>Primary mass $m_1$, $m_2$, $M$</th>
<th>$1.39_{-0.35}^{+0.60}$ $M_\odot$, $1.37_{-0.18}^{+0.39}$ $M_\odot$, $1.188_{-0.204}^{+0.236}$ $M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ratio $m_2/m_1$</td>
<td>$0.71_{-0.35}^{+0.60}$</td>
</tr>
<tr>
<td>Total mass $m_{tot}$</td>
<td>$2.74_{-0.18}^{+0.39}$ $M_\odot$, $2.87_{-0.40}^{+0.35}$ $M_\odot$</td>
</tr>
<tr>
<td>Radiated energy $E_{rad}$</td>
<td>$&gt;0.025 M_\odot c^2$</td>
</tr>
<tr>
<td>Luminosity distance $D_L$</td>
<td>$40^{+8}_{-4}$ Mpc</td>
</tr>
<tr>
<td>Viewing angle $\theta$</td>
<td>$\leq 38^\circ$</td>
</tr>
<tr>
<td>Using NGC 4993 location</td>
<td>$\leq 28'$</td>
</tr>
<tr>
<td>Combined dimensionless tidal deformability $\Lambda$</td>
<td>$\leq 800$</td>
</tr>
<tr>
<td>Dimensionless tidal deformability $\Lambda/1.4M_\odot$</td>
<td>$\leq 800$</td>
</tr>
</tbody>
</table>
Case #2: GW + Possible GRB(?)

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### Low-spin prior (x < 0.05) vs High-spin prior (x < 0.89)

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<tr>
<th>Metric</th>
<th>Low-spin</th>
<th>High-spin</th>
</tr>
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<tbody>
<tr>
<td>Primary mass m₁</td>
<td>1.62 – 1.88 M☉</td>
<td>1.61 – 2.52 M☉</td>
</tr>
<tr>
<td>Secondary mass m₂</td>
<td>1.45 – 1.69 M☉</td>
<td>1.12 – 1.68 M☉</td>
</tr>
<tr>
<td>Chirp mass M</td>
<td>1.44^{+0.02}_{-0.01} M☉</td>
<td>1.44^{+0.02}_{-0.01} M☉</td>
</tr>
<tr>
<td>Detector-frame chirp mass</td>
<td>1.486^{+0.009}_{-0.009} M☉</td>
<td>1.487^{+0.009}_{-0.009} M☉</td>
</tr>
<tr>
<td>Mass ratio m₂/m₁</td>
<td>0.8 – 1.0</td>
<td>0.4 – 1.0</td>
</tr>
<tr>
<td>Total mass mₜot</td>
<td>3.3^{+0.4}_{-0.4} M☉</td>
<td>3.4^{+0.4}_{-0.4} M☉</td>
</tr>
<tr>
<td>Effective inspiral spin parameter χₚeff</td>
<td>0.015^{+0.01}_{-0.01}</td>
<td>0.058^{+0.01}_{-0.01}</td>
</tr>
<tr>
<td>Luminosity distance Dₗ</td>
<td>160^{+70}_{-50} Mpc</td>
<td>150^{+60}_{-50} Mpc</td>
</tr>
<tr>
<td>Combined dimensionless tidal deformability λ</td>
<td>≤ 600</td>
<td>≤ 1100</td>
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</table>

**Very Low S/N**

No spectral confirmation
Case #3: sub-threshold GW + GRB

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Both GW and EM are identified as sub-threshold by LVC/Fermi GCN Circulars, Yang+19, Goldstein+19

A sharp GRB with typical GRB spectrum

Theoretical Expectations
What GW Events can produce prompt EM Counterparts?

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NS-NS merger

Paczynski 1986

Eichler et al 1989

LETTERS TO NATURE

Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars

David Eichler*, Mario Livio†, Tsvi Piran‡ & David N. Schramm§

* Department of Physics, Bar Ilan University, Beer Sheva, Israel, and Astronomy Program, University of Maryland, College Park, Maryland 20742, USA
† Department of Physics, The Technion, Haifa, Israel
‡ Racah Institute for Physics, Hebrew University, Jerusalem, Israel, and Princeton University Observatory, Princeton, New Jersey 08544, USA
§ Departments of Physics and Astrophysics, University of Chicago, 5640 Ellis Avenue, Chicago, Illinois 60637, USA, and the Fermilab Astrophysics Center, Batavia, Illinois 60510, USA

Neutron-star collisions occur inevitably when binary neutron stars spiral into each other as a result of damping of gravitational radiation. Such collisions will produce a characteristic burst of gravitational radiation, which may be the most promising source of a detectable signal for proposed gravity-wave detectors. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant 1. However, the rates of these neutron-star collisions are highly uncertain 2. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process). In addition, these collisions should produce neutrino bursts 3 and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed γ-ray burst afterglows and γ-ray burst rate may be a test for these collisions that are both significant and consistent with other estimates.
\[ M_{\text{max}} = M_{\text{TOV}}(1 + \alpha P^3) \]

- \( M_L \): gravitational mass of the merger remnant
- \( M_{\text{TOV}} \): maximum mass for non-rotating NS
- \( M_{\text{max}}(P_l) \): maximum mass for rotating NS with initial period \( P_l \).
If final product is a BH:

A Short GRB
+ Beamed X-ray + Optical + radio afterglow
+ Kilonova in Multi-wavelength and time scale

See also talks by Kasliwal & Murphy

Metzger & Berger (2012)
If final product is a stable NS (magnetar): 

Three zones

Jet zone:
- short GRB + multiwavelength afterglow
- + X-ray from magnetar wind dissipation

Free zone:
- no GRB/ or weak GRB 170718A-like GRB,
- X-ray from magnetar wind dissipation only

Trapped zone:
- no GRB unless at nearby universe
- X-rays initially trapped by the dynamical ejecta,
- eventually become free at photosphere radius.
- Emitted X-ray is essentially the Wien tail of the merger-nova photosphere emission.

X-rays radiation is produced isotropically via magnetar wind dissipation.
Magnetar Case 1: 170817A-like GRB+AG+KN
Magnetar Case 2: No GRB, Spin-Down Powered X-ray transient

\[ L_{X,\text{free}}(t) = \eta L_{sd} = \frac{\eta B_p^2 R^6 \Omega^4(t)}{6 c^3} \]
Magnetar Case 3: No GRB, X-ray Trapped, then becomes free

\[ L_{X,\text{trapped}}(t) = e^{-\frac{\eta B_p^2 R^6 \Omega^4(t)}{6c^3}} + (\nu X L_{\nu,X})_{bb} \]
## What GW Events can produce prompt EM Counterparts?

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NS-BH Merger

A matter of mass ratio \( q = \frac{M_{BH}}{M_{NS}} \)
NS-BH Merger

A matter of mass ratio \( q = \frac{M_{\text{BH}}}{M_{\text{NS}}} \)

Not-too-large \( q \) (e.g., \( q < 5 \)):

- Black Hole + disk + jet central engine
- \( \rightarrow \) traditional short GRB + kilonova + AG
NS-BH Merger

A matter of mass ratio $q = \frac{M_{BH}}{M_{NS}}$

Not-too-large $q$ (e.g., $q<5$):

Black Hole + disk + jet central engine
$\rightarrow$ traditional short GRB + kilonova + AG

A large $q$ (e.g., $q>5$):

NS would plunge into the BH as a whole
so no matter for accretion disk to form
$\rightarrow$ NO traditional short GRB

BUT alternative models can still lead to a GRB (see next).
What GW Events can produce prompt EM Counterparts?

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BH-BH Merger

...was thought to be no EM-associated before GW150914

Connaughton et al. 2016; Zhang, B. 2016
BH-BH Merger (and Large-q NS-BH Merger)

Most popular alternative model for producing a GRB: **charged** compact binary coalescence (cCBC):

a burst can be produced by:
1. **electric and magnetic dipole radiation**
2. magnetic reconnection
3. BZ mechanism

Recent theoretical development:
Zhang 2019, Dai 2019, Pan & Yang 2019; Zhong et al. 2019
Implications & Prospects
Goal:
Maximize the physical information from the observations
Best Case: Detailed GW constraints + luxury EM observations

GW:
merger masses, angles, distance, energies, tidal deformability, final product, EOS

EM:
jet structure, speed, opening angle, viewing angle, cocoon structure, heavy element production, emission radius engine types (NS vs BH)

ALL:
event rate, populations, fundamental physics (e.g. WEP, LIV etc)

See also talks by Kasliwal, Murphy, Sari, Nissanke ...
But what about:

GW190425

GBM-190816
But what about:

Not much to do if the EM signal is only tentative w/o spectroscopic confirmation
But what about:

Not much to do if the EM signal is only tentative w/o spectroscopic confirmation

EM becomes important when it can be spectroscopically confirmed, and can even help validate the GW event
GBM-190816 as an example

EM becomes important when it can be spectroscopically confirmed, and can even help validate the GW event.
Fermi GBM-190816: A sub-threshold GRB candidate **potentially** associated with a sub-threshold LIGO/Virgo compact binary merger candidate

L1 and V1 identified a **possible** compact binary merger candidate at 2019-08-16 21:22:13.027 UTC (GPS Time: 1250025751.027).

GBM-190816:

1. Duration: approximately 0.1 s
2. Hard spectral template
3. The lighter compact object may have a mass < 3 $M_\odot$.
4. FAR ~ $1.2 \times 10^{-4}$

**Distance from GW: 428 +/- 143 Mpc**

**GCN #25406, GCN #25406, Golastein +19**
GW: Sub-threshold Event Gives $q$

**Information:**
1. L1 and V1 data are available at that time.
2. LVC identified a possible CBC candidate at 2019-08-16 21:22:13.027 UTC.
3. The network S/N of this sub-threshold event is below the threshold of GW analysis pipelines, which is 12.
4. The luminosity distance of the event is constrained to 362±151 Mpc.
5. The lighter compact object of this CBC event may have a mass < 3 $M_{\odot}$.

**Assumptions:**
1. One compact object of this CBC event is an NS with a mass of 1.4 $M_{\odot}$.
2. The sensitivity of the L1 detector in O3 is twice of that in O1.
3. The S/N of the event is 8 and mostly contributed by L1.

**Constraints:**
Follow the FINDCHIRP pipeline (Allen et al. 2012). The mass ratio lies in $q \sim [2.142, 5.795]$. 
Excited Community

(But Nothing in optical, High-E, neutrinos, X-ray)

Search by

INTEGRAL/SPI-ACS, ANTARES, HAWC, IceCube, Zwicky, AGILE, Fermi-LAT, MAXI/GSC

A wise man once said nothing.
**EM: Burst Confirmation**

**Bayesian Block (BB)** (Scargle et al. 2013):

Signal appears in various conditions.

The significance level of the burst S/N reached 3.95.
Multi-wavelength light curves

Pulse evolution and structure
EM: Burst Confirmation

Precise Duration

\[ T_{90} = 0.112^{+0.185}_{-0.085} \text{s} \]

starts at \( T_{90,1} = 0.032^{+0.025}_{-0.065} \text{s} \)

ends at \( T_{90,2} = 0.143^{+0.17}_{-0.11} \text{s} \)

A homework in GWCLASS2019
**f parameter**


\[ f = 2.58 \pm 0.37, \text{ typical as a short GRB} \]

\( f \): the ratio between the peak flux and the average background flux

\( f_{\text{eff}} \): the ratio between the peak flux of a pseudo-burst and the average background flux.

However, there is a non-negligible probability (\( p \sim 0.03 \)) of being the "tip of iceberg" of a longer short burst.
Spectral Analysis

<table>
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<th>Time Interval</th>
<th>CPL</th>
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<td>$t_1$</td>
<td>$t_2$</td>
</tr>
<tr>
<td>0.032</td>
<td>0.143</td>
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**Observed Properties**

- $T_{90}$ (s): 0.112$^{+0.185}_{-0.085}$
- Peak energy $E_p$ (keV): 94.84$^{+11.64}_{-17.94}$
- Total fluence (erg cm$^{-2}$): 7.38$^{+6.35}_{-2.51} \times 10^{-8}$
- Distance (Mpc): 428 + / − 143
- Isotropic energy $E_{\gamma,iso}$ (erg): 1.65$^{+3.81}_{-1.16} \times 10^{48}$
- Luminosity $L_{\gamma,iso}$ (erg s$^{-1}$): 1.47$^{+3.40}_{-1.04} \times 10^{49}$
- $f$ parameter: 2.58 + / − 0.37

EM: Burst Confirmation

EM: Burst Confirmation

GBM-190816 as a short GRB

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<tr>
<td>Isotropic energy $E_{\gamma, \text{iso}}$ (erg)</td>
<td>$1.14^{+3.18}_{-0.85} \times 10^{48}$</td>
</tr>
<tr>
<td>Luminosity $L_{\gamma, \text{iso}}$ (erg s$^{-1}$)</td>
<td>$1.92^{+2.84}_{-0.86} \times 10^{49}$</td>
</tr>
<tr>
<td>$f$ parameter</td>
<td>$2.58 + / - 0.37$</td>
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If it looks like a duck, walks like a duck and quacks like a duck, then it just may be a duck.

(Walter Reuther)
Burst confirmed.
Concidence established.

GW signal happens 1.57 s before the burst
How to use the observed EM info?
Traditional NS-BH CBC: Constraints on Model Parameters

Total mass of the matter left outside $M_{\text{out}}$:

$$M_{\text{out}} = M_{\text{NS}}^b \left( \max \left( \frac{1 - 2\rho}{\eta^{1/3}} - \beta \bar{R}_{\text{ISCO}} \rho + \gamma, 0 \right) \right)^\delta$$

The dimensionless ISCO radius follows

$$\bar{R}_{\text{ISCO}} = R_{\text{ISCO}} c^2 / G M_{\text{BH}} = 3 + Z_2 - \text{sgn} (\chi_{\text{BH}}) \sqrt{(3 - Z_1) (3 + Z_1 + 2Z_2)}$$

Dynamical ejecta mass $M_{\text{dyn}}$

$$M_{\text{dyn}} = M_{\text{NS}}^b \left\{ \max \left[ a_1 q^n (1 - 2C_{\text{NS}}) / C_{\text{NS}} - a_2 q^n \bar{R}_{\text{ISCO}} (\chi_{\text{eff}}) + a_3 (1 - M_{\text{NS}} / M_{\text{NS}}^b) + a_4, 0 \right] \right\}$$

The disc mass $M_{\text{disc}}$

$$M_{\text{disc}} = M_{\text{out}} - M_{\text{dyn}}$$

The kinetic energy of the jet can be calculated by

$$E_{\text{K, jet}} = \epsilon (1 - \xi_w) M_{\text{disc}} c^2 \Omega^2_h f(\Omega_h)$$

The dimensionless spin of the final BH remnant

$$\chi_{\text{BH}, f} = \frac{\chi_{\text{BH}} M_{\text{BH}}^2 + \bar{l}_z (\bar{R}_{\text{ISCO}}, \chi_{\text{BH}, f}) M_{\text{BH}} M_{\text{NS}}}{M^2}$$

The orbital angular momentum per unit mass of a test particle orbiting the BH remnant at the ISCO

$$l_z (\bar{R}_{\text{ISCO}}, \chi_{\text{BH}, f}) = \text{sgn} (\chi_{\text{BH}, f}) \frac{\bar{r}_{\text{ISCO}}^2 - 2 \text{sgn} (\chi_{\text{BH}, f}) R_{\text{ISCO}} + \chi_{\text{BH}, f}^2}{\sqrt{\bar{r}_{\text{ISCO}}^2 - 3 \bar{r}_{\text{ISCO}} + 2 \text{sgn} (\chi_{\text{BH}, f}) \chi_{\text{BH}, f} R_{\text{ISCO}} + \chi_{\text{BH}, f}^2}}$$

we assume a Gaussian-shape structured jet with an angular distribution of the kinetic energy and Lorentz factor $\Gamma$ following

$$\frac{dE}{d\Omega}(\theta) = E_c e^{-\left(\theta/\theta_{0, i}\right)^2}, \quad \Gamma(\theta) = (\Gamma_c - 1) e^{-\left(\theta/\theta_{0, i}\right)^2} + 1$$

At the viewing angle $\theta_v$, the isotropic gamma-ray radiation energy can be estimated as

$$E_{\gamma, \text{iso}} (\theta_v) \approx \eta_f \int \frac{D_p^3}{\Gamma} \frac{dE}{d\Omega} d\Omega$$

$$E_{\gamma, \text{iso}} \approx E_{\gamma, \text{iso}}(M_{\text{NS}}, q, \epsilon, \xi, \eta, \Gamma, \theta_{\text{jet}}, \theta_{\text{obs}}, \Lambda_{\text{N}})$$

Yang+19
NS-BH Merger with Tidal Disruption: Constraints on Model Parameters

Yang+19
If q is too large...
cCBC with Constant Charge
(Plunging NS-BH Merger)

Electric dipole radiation luminosity
\[ L_{e,dip} = \frac{1}{6} \frac{c^5}{G} \left( \hat{q}_1^2 + \hat{q}_2^2 \right) \left( \frac{r_s(m_1)}{a} \right)^2 \left( \frac{r_s(m_2)}{a} \right)^2 \]

Magnetic dipole radiation luminosity
\[ L_{B,dip} = \frac{196}{1875} \frac{c^5}{G} \left( \hat{q}_1 m_1 + \hat{q}_2 m_2 \right)^2 \left( \frac{r_s(m)}{a} \right)^4 \left( \frac{r_s(M)}{a} \right)^{11} \]

Isotropic EM luminosity, assuming \( \eta_y \sim 1 \)
\[ L_{\gamma,iso} = \eta_\gamma \left( L_{e,dip} + L_{B,dip} \right) \]

For an NS-BH merger system: Under the following simplest assumptions: (1) only the NS carries a constant charge; (2) the NS mass is 1.4 \( M_\odot \); (3) \( a = a_{\text{min}} = r_s(m_{\text{BH}}) + 2.4 r_s(m_{\text{NS}}) \) (\( r_{\text{NS}} = 2.4 r_s \) for neutron star) at the merger time; (4) mass-ratio \( q \) lies in [2.142, 5.795]. \( q_{\text{NS}} \) lies in \([1.25, 1.50] \times 10^{-4}\). \( B_{15}/P_{-3} \) should fall in the range of \([0.28, 0.34]\). Implying that the neutron star has to be a millisecond magnetar. Disfavored.

Absolute charge \( Q_{\text{NS}} \) lies in \([1.75, 2.11] \times 10^{26}\) e.s.u
For a charged BH-BH system: Under the following simplest assumptions: (1) the lighter BH has a mass of $2.8 \, M_\odot$, (2) only the lighter BH carries a constant dimensionless charge. We constrain: $q_{BH}^{\text{BH}}$ lies in $[5.97, 10.32] \times 10^{-5}$. The demanded dimensionless charge is comparable to the one required to explain the putative γ-ray event GW150914-GBM.

Absolute charge $Q_{NS}$ lies in $[1.67, 2.89] \times 10^{26}$ e.s.u

**Electric dipole radiation luminosity**

$$L_{e,dip} = \frac{1}{6} \frac{c^5}{G} \left( \hat{q}_1^2 + \hat{q}_2^2 \right) \left( \frac{r_s(m_1)}{a} \right)^2 \left( \frac{r_s(m_2)}{a} \right)^2$$

**Magnetic dipole radiation luminosity**

$$L_{B,dip} = \frac{196}{1875} \frac{c^5}{G} \left( \frac{\hat{q}_1 m_1 + \hat{q}_2 m_2}{M} \right)^2 \times \left( \frac{r_s(\mu)}{a} \right)^4 \left( \frac{r_s(M)}{a} \right)^{11}$$

**Isotropic EM luminosity, assuming $\eta_\gamma \sim 1$**

$$L_{\gamma,iso} = \eta_\gamma (L_{e,dip} + L_{B,dip})$$
with a large q (e.g., >5):

Charged CBC must at work to produce the observed GRB

Case 1: Constant Charge —
Contrived conditions needed for a BH to carry very large charge.
Charged CBC must at work to produce the observed GRB

Case 1: Constant Charge —
Contrived conditions needed for a BH to carry very large charge.

Case 2: Increasing Charge —
(Dai 2019)

with a large q (e.g., >5):
A BH is immersed in the magnetic field of the NS and gains charge via the Wald mechanism (Wald 1974).

BH may reach the maximal Wald charge when it could transit from the electro-vacuum state to the force-free state.

At this point, four possible pre-merger mechanisms generate $\gamma$-ray emission:

1. first and second magnetic dipole radiation
2. second magnetic dipole radiation,
3. electric dipole radiation,
4. magnetic reconnection close to BH’s equatorial plane.

And two possible post-merger mechanisms:

1. magnetic reconnection at polar regions
2. BZ mechanism.

Dai 2019, Zhong, S.-Q. et al 2019
Following Dai (2019) and Zhong et al. (2019), we calculate that the sub-threshold GRB could be produced by the pre-merger magnetic reconnection or the post-merger BZ mechanism if the NS’ surface magnetic field \( \log(B_{S,NS}/G) > 13.4 \) and \( \log(B_{S,NS}/G) \sim 13.5 - 14.5 \), respectively.

Given the following conditions:

1. The radiative efficiency \( \eta_V = 1 \),
2. The mass ratio \( q = 5.5 \),
3. The minimal separation between the BH and the NS \( a_{\text{min}} = 2GM_{BH}/c^2 + r_{NS} \), and the NS mass \( M_{NS} = 1.4 M_\odot \) and its radius \( r_{NS} = 12 \) km.

Seems more reasonable
Charged CBC must at work to produce the observed GRB

Case 1: Constant Charge —
**Contrived conditions** needed for a BH to carry very large charge.

Case 2: Increasing Charge —
Seems possible.
The GW-GRB Time Delay
GW

GRB 170817A
Duration: 2 s
Delay: 1.7s

GBM-190816
Duration: 0.1 s
Delay: 1.57s

What a coincidence!
What can cause the delay?

(1) \( \Delta t_{\text{jet}} \),

*delay time to launch a clean relativistic jet. Includes three parts:*

①. The waiting time \( \Delta t_{\text{wait}} \) for a central object (BH) to form,

②. The accretion time scale \( \Delta t_{\text{acc}} \),

③. time \( \Delta t_{\text{clean}} \) for the jet to become clean.

In the case GBM-180916, at least one BH exists in the pre-merger system so

\( \Delta t_{\text{wait}} \) is 0.

\( \Delta t_{\text{clean}} \sim 0 \) (BH)

\( \Delta t_{\text{acc}} \) is typically \( \sim 10 \) ms.

So \( \Delta t_{\text{jet}} \) is at most 0.01 s.
What can cause the delay?

(1) $\Delta t_{\text{jet}}$

*delay time to launch a clean relativistic jet. Includes three parts:*

① The waiting time $\Delta t_{\text{wait}}$ for a central object (BH) to form,
② The accretion time scale $\Delta t_{\text{acc}},$
③ Time $\Delta t_{\text{clean}}$ for the jet to become clean.

In the case GBM-180916, at least one BH exists in the pre-merger system so $\Delta t_{\text{wait}}$ is 0.
$\Delta t_{\text{clean}} \sim 0$ (BH)
$\Delta t_{\text{acc}}$ is typically $\sim 10$ ms.
*So $\Delta t_{\text{jet}}$ is at most 0.01 s.*

(2) $\Delta t_{\text{bo}}$

*delay time for the jet to break out from the surrounding medium.*
For an NS-BH central engine, $\Delta t_{\text{bo}}$ is typically *10 ms to 100 ms.*
What can cause the delay?

(1) $\Delta t_{\text{jet}}$,  
*delay time to launch a clean relativistic jet. Includes three parts :*  
   1. The waiting time $\Delta t_{\text{wait}}$ for a central object (BH) to form,  
   2. The accretion time scale $\Delta t_{\text{acc}}$,  
   3. time $\Delta t_{\text{clean}}$ for the jet to become clean.  
In the case GBM-180916, at least one BH exists in the pre-merger system so $\Delta t_{\text{wait}}$ is 0.  
$\Delta t_{\text{clean}} \sim 0$ (BH)  
$\Delta t_{\text{acc}}$ is typically $\sim 10$ ms.  
So $\Delta t_{\text{jet}}$ is at most 0.01 s.

(2) $\Delta t_{\text{bo}}$  
*delay time for the jet to break out from the surrounding medium.*  
For an NS-BH central engine, $\Delta t_{\text{bo}}$ is typically 10 ms to 100 ms.

(3) $\Delta t_{\text{GRB}}$,  
*delay time for the jet to reach the energy dissipation and GRB emission site.*  
$\Delta t_{\text{GRB}} = \frac{R}{2c\Gamma^2}$.  
<— should mostly account for the delay
GRB 170817A & GBM-190816


“Oversold” cocoon model, seems ruled out

Structured jet: Zhang & Meszaros (2002); Rossi et al. (2002)

B.-B. Zhang et al 2018

R = \Delta t \Gamma c

Yang et al 2019
Summary

- We currently have (up to) 3 prompt CBC GW-EM association cases.
- Prompt observation of EM signal in GW event is crucial in understanding the physical nature of the merger process.
- Encourage prompt EM following up and coverage of the GW events.
Thanks!

GW-EM Evolved Missions in China:
SVOM,
LAMOST,
SkyMapper,
DESI, CLAUDS,
Mephisto,
FAST,
TNTS,
ASTS, ZTF
Chinese Space Station Survey
HXTM,
SVOM/SVOM-GWAC,
Einstein Probe,
GECAM, …
(See talk by Shuang-Nan Zhang)