Prompt Counterparts to GW Detections

Binbin Zhang
Nanjing University

Transients 2020, Feb 3 – 7 , 2020 • Cape Town

Outline

Prompt GW-EM Observations

Theoretical Expectations

Implicaitons & Prospects

Prompt GW-EM Observations

Current GW-EM Zoo

Case	Type	EM	Ref.
GW150914-GBM/ GW150914	BH-BH	low S/N EM	Connaughton+15
GRB170817A/GW170817/ AT2017gfo	NS-NS	Definitely Beautiful!	Abbott+17
S190510g	NS-NS	13 optical EM candidtes, NONE confirmed	Andreoni+19a
S190814bv	BH-NS	Deep search yeild nothing confirmed in EM	Andreoni+19b Dobie+19, etc
GW190425/S190425z	NS-NS	13 optical candiates **INTEGRAL/ACS candidate** (none confirmed)	Abbott+19 Coughlin+19a Antier+19, Pozanenko+19
S190426c, S190510g, S190901ap, S190910h	NS-?	deep search, some candiates, nothing confirmed	Coughlin+19b Goldstein+19
"I-OGC 151030"	NS-NS	found by 3rd party, sub-threshold, high FAR, GW NOT confirmed by LIGO	Nitz+19
GBM-190816	BH-?	Both GW and EM are identified as sub- threshod by LVC/Fermi	GCN Circulars, Yang+19

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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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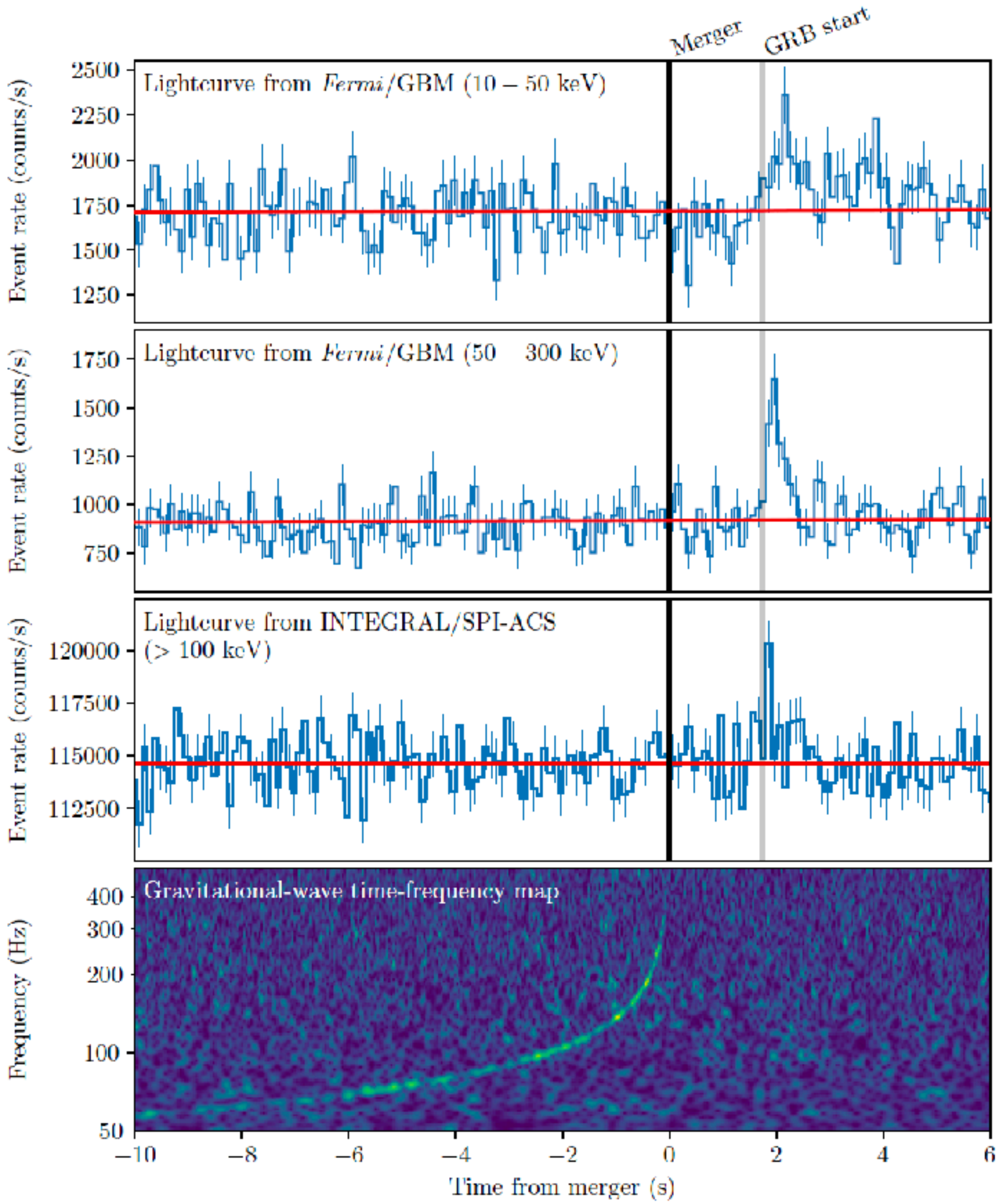
Abbott et al. 2017, PRL, 119, 161101

	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_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_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



Case #2: GW + Possible GRB(?)

Case	Type	EM	Ref.
GRB170817A/ GW170817/ AT2017gfo	NS-NS	Definitely Beautiful!	Abbott+17
GW190425/ S190425z	NS-NS	13 optical candiates INTEGRAL/ACS candidate (none confirmed)	Abbott+19 Coughlin+19 Antier+19, Pozanenko+19
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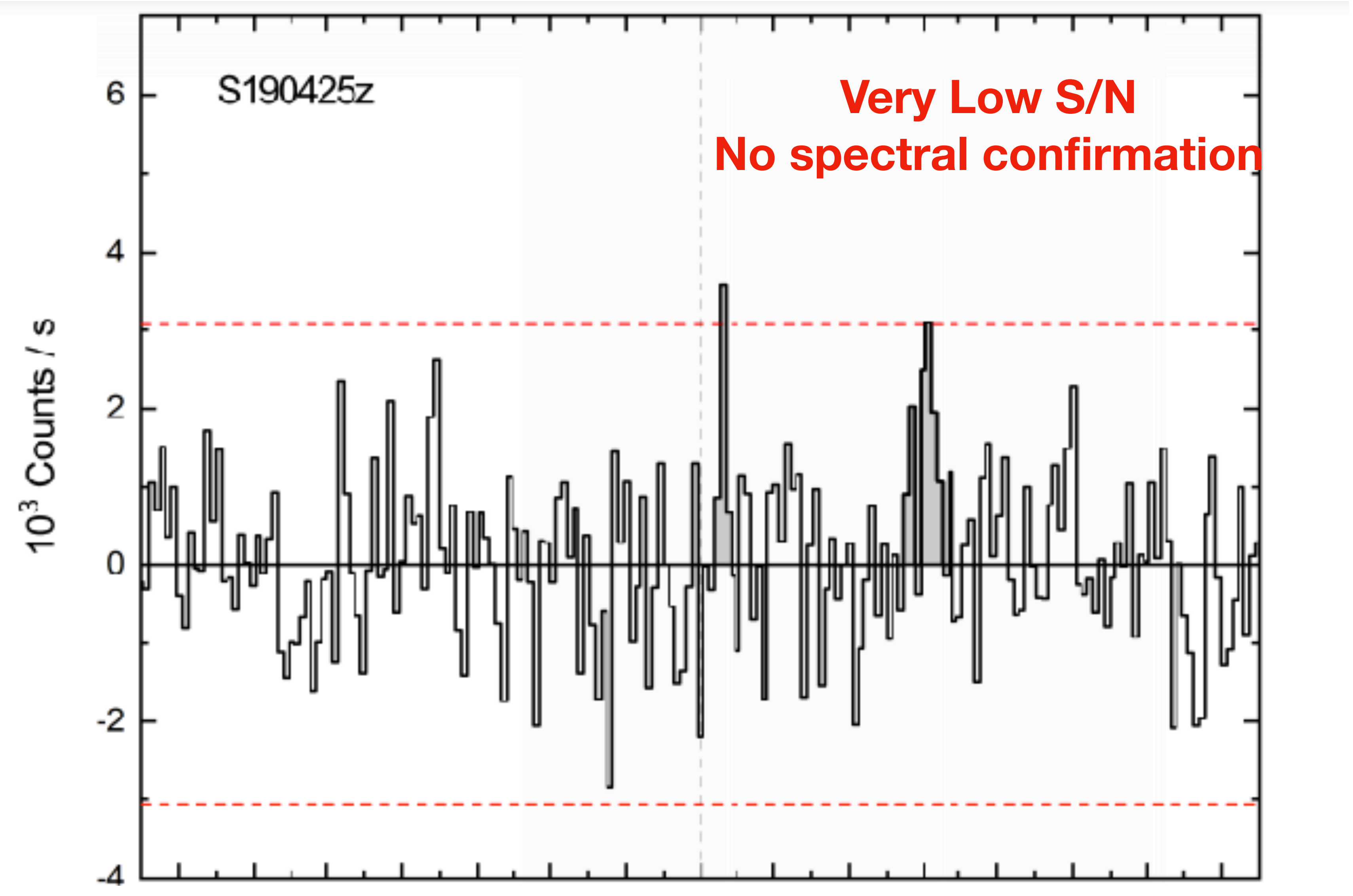
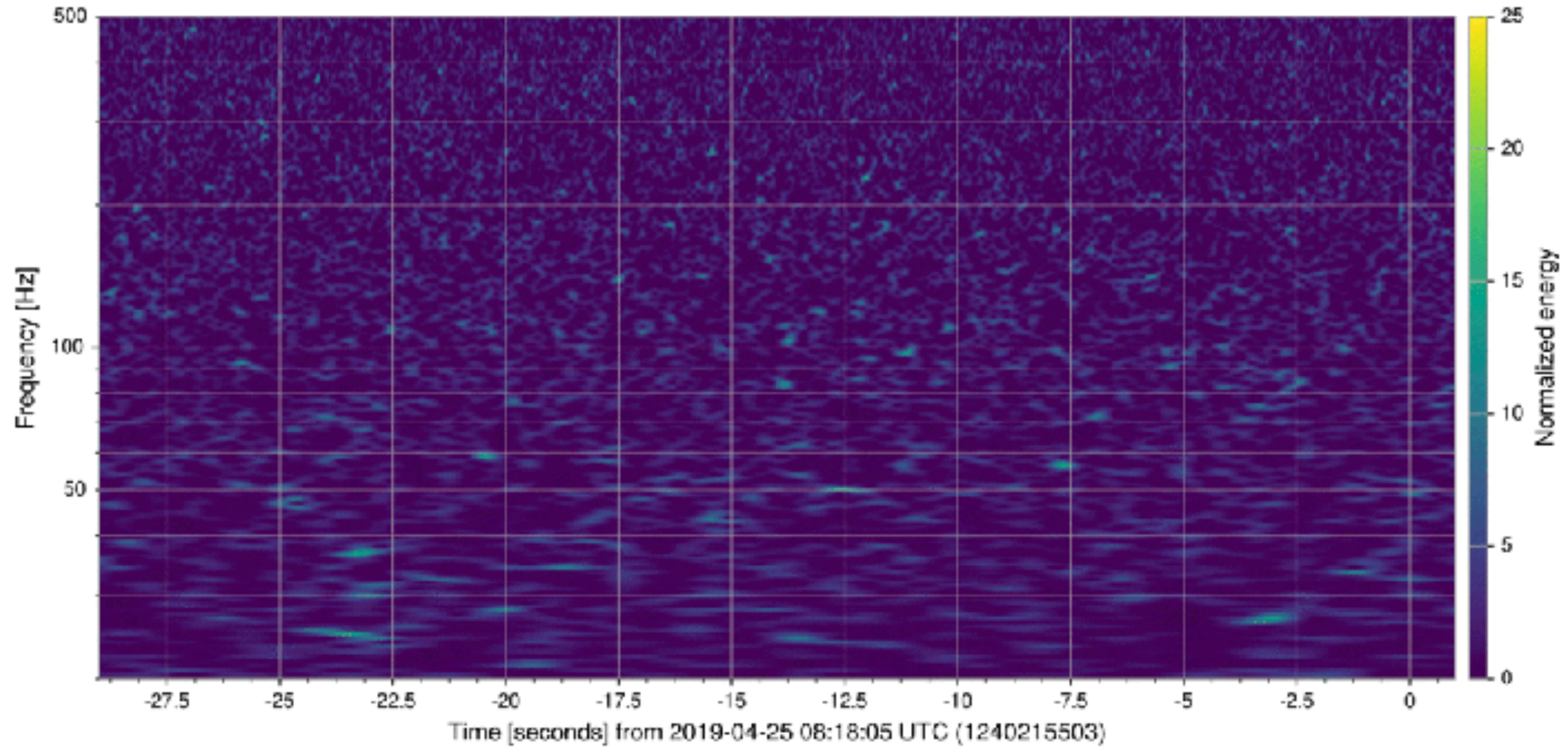


	Low-spin prior ($\chi < 0.05$)	High-spin prior ($\chi < 0.89$)
Primary mass m_1	$1.62 - 1.88\ M_\odot$	$1.61 - 2.52\ M_\odot$
Secondary mass m_2	$1.45 - 1.69\ M_\odot$	$1.12 - 1.68\ M_\odot$
Chirp mass $\mathcal{M}$	$1.44^{+0.02}_{-0.02}\ M_\odot$	$1.44^{+0.02}_{-0.02}\ M_\odot$
Detector-frame chirp mass	$1.4868^{+0.0003}_{-0.0003}\ M_\odot$	$1.4873^{+0.0008}_{-0.0006}\ M_\odot$
Mass ratio m_2/m_1	0.8 – 1.0	0.4 – 1.0
Total mass m_{tot}	$3.3^{+0.1}_{-0.1}\ M_\odot$	$3.4^{+0.3}_{-0.1}\ M_\odot$
Effective inspiral spin parameter χ_{eff}	$0.013^{+0.01}_{-0.01}$	$0.058^{+0.11}_{-0.05}$
Luminosity distance D_L	161^{+67}_{-73} Mpc	159^{+69}_{-71} Mpc
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 600	≤ 1100



Case #3: sub-threshold GW + GRB

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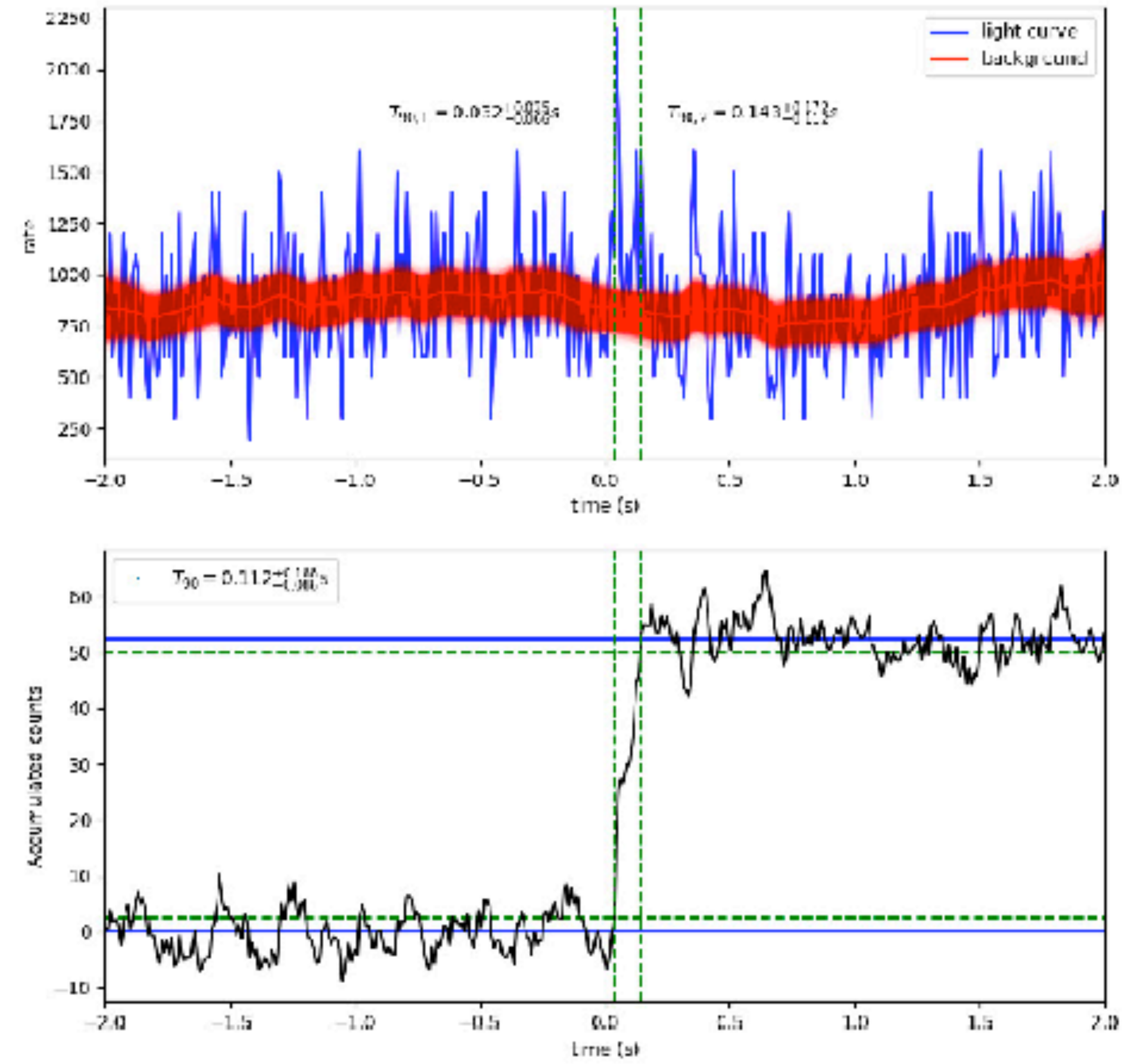
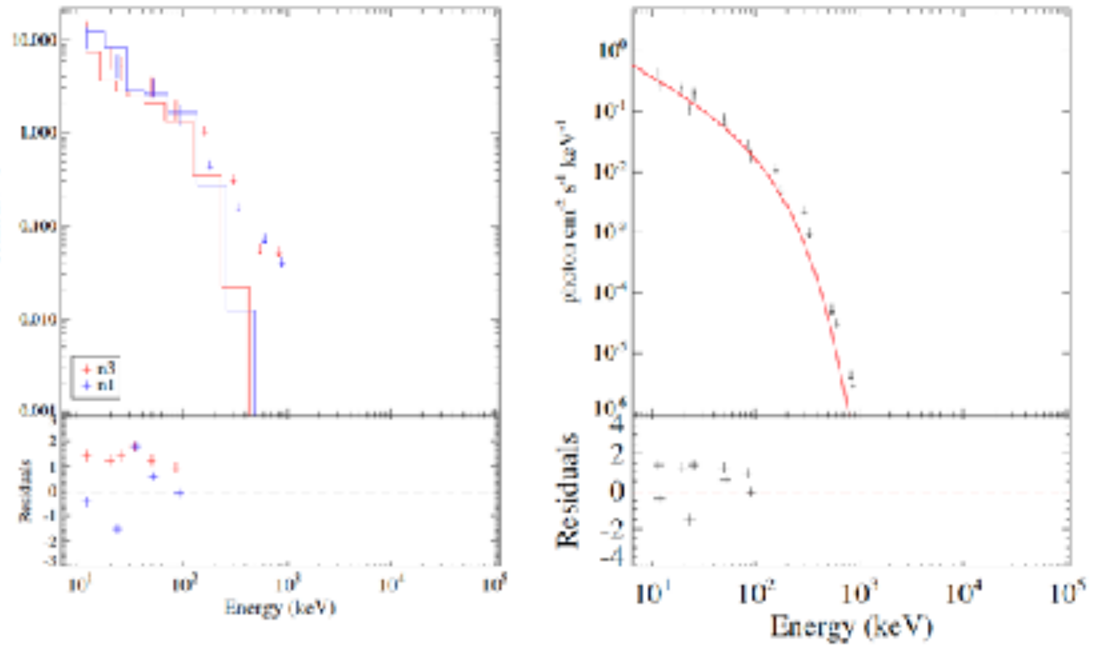
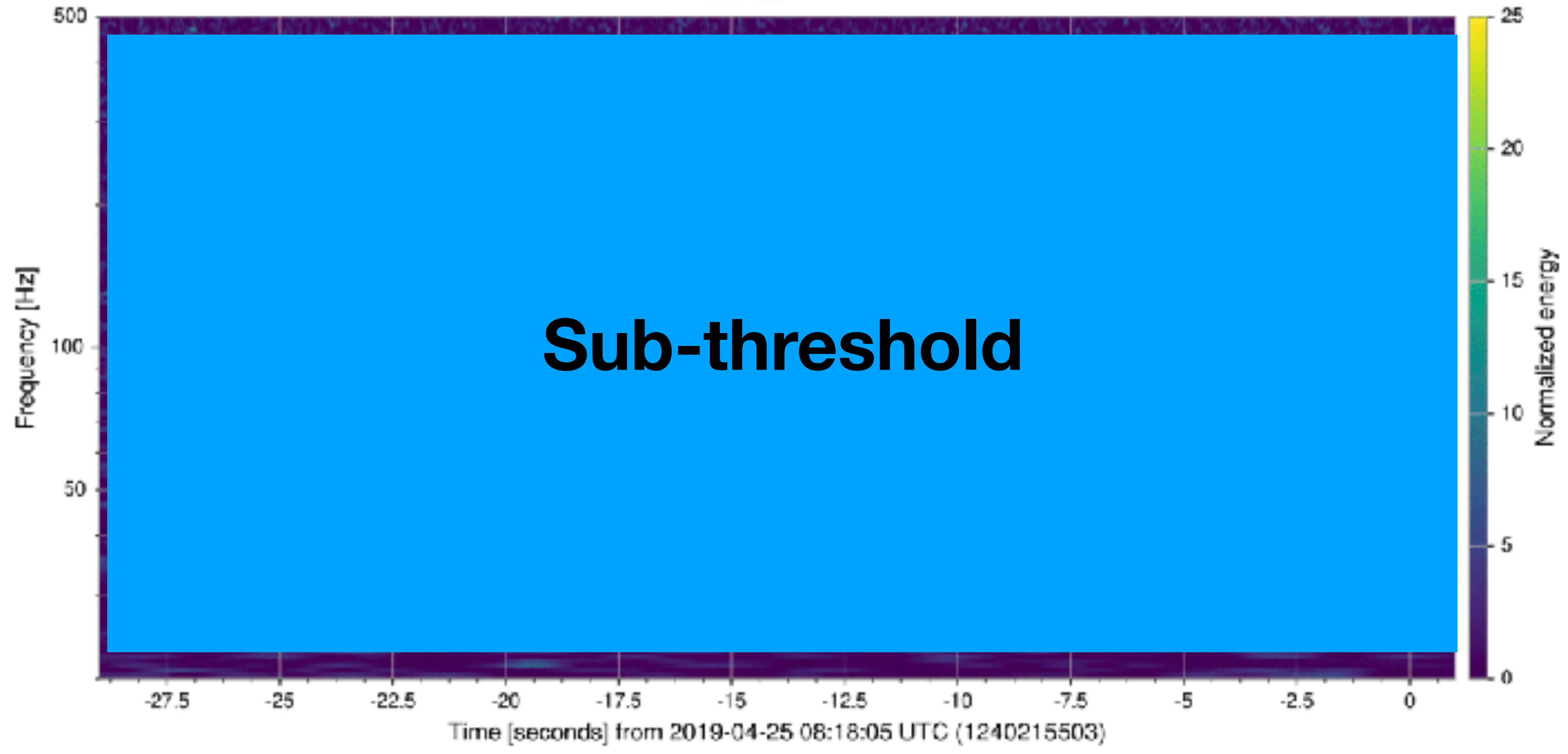


Observed Properties	
T_{90} (s)	$0.112^{+0.185}_{-0.085}$
Peak energy E_p (keV)	$94.84^{+114.64}_{-17.94}$
Total fluence(erg cm^{-2})	$7.38^{+6.35}_{-2.51} \times 10^{-8}$
Distance (Mpc)	$428 + / - 143$
Isotropic energy $E_{\gamma,iso}$ (erg)	$1.65^{+3.81}_{-1.10} \times 10^{48}$
Luminosity $L_{\gamma,iso}$ (erg s^{-1})	$1.47^{+3.40}_{-1.04} \times 10^{49}$
f parameter	$2.58 + / - 0.37$
Assumed Parameters	
Jet core angle $\theta_{c,j}$	assumed 5° (16°)
Viewing angle θ_v	$10^{\circ} - 19^{\circ}$ $(18^{\circ} - 24^{\circ})$
Γ_c	assumed 100
m_2 $(M_{\odot})$	assumed 1.4 (for NS-BH system)
	assumed 2.8 (for BH-BH system)
Derived Constrains	
q from GRB	varies
q from GW	$3.44^{+4.84}_{-1.30}$
m_1 $(M_{\odot})$	varies
Intrinsic duration(s)	1.57
Charge of BH (e.s.u.)	$2.23^{+0.87}_{-0.06} \times 10^{26}$ (for NS-BH system)
	$2.58^{+2.10}_{-0.51} \times 10^{26}$ (for BH-BH system)

A sharp GRB with typical GRB spectrum





Yang et al 2019, ApJ submitted

Theoretical Expectations

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NS-NS merger	Yes
NS-BH Merger	Maybe (Mass/Model dependent)
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NS-NS merger

THE ASTROPHYSICAL JOURNAL, 308 L43–L46, September 15

GAMMA-RAY BURSTERS AT COSMOLOGICAL DISTANCES

BOHDAN PACZYŃSKI
Princeton University Observatory
Received 1986 May 12; accepted 1986 June 23

ABSTRACT

We propose that some, perhaps most, gamma-ray bursters are at cosmological distances, like quasars, with a redshift $z \approx 1$ or $z \approx 2$. This proposition requires a release of supernova-like energy of about 10^{51} ergs within less than 1 s, making gamma-ray bursters the brightest objects known in the universe, many orders of magnitude brighter than any quasars. This power must drive a highly relativistic outflow of electron-positron plasma and radiation from the source. The emerging spectrum should be roughly a black body with no annihilation line, and a temperature $T \approx (\dot{E}/4\pi r_0^2 \sigma)^{1/4}$. As an example the spectrum would peak at about 8 MeV for the energy injection rate of $\dot{E} = 10^{51}$ ergs s^{-1} and for the injection radius $r_0 = 10$ km.

We propose that three gamma-ray bursts, all with identical spectra, detected from B1900+14 by Mazets, Golenetskii, and Gur'yan and reported in 1979, were all due to a single event multiply imaged by a gravitational lens. The time intervals between the successive bursts, 10 hr to 3 days, were due to differences in the light travel time

Subje

On various occasions very energetic phenomena that involved bare neutron stars were suggested for a variety of reasons. Haensel and Schaeffer (1982) calculated models of neutron stars with a phase transition in their structure leading to a release of 10^{48} ergs in a small fraction of a second and noticed a possibility of even more powerful events. Ostriker (1979) considered the fate of the inner cores of globular clusters where the dominant constituents may be neutron stars. From time to time neutron stars will collide, releasing up to 10^{53} ergs per event. The binary radio pulsar PSR 1913+16 will coalesce with its neutron star companion within about 10^8 yr as a result of gravitational radiation losses (Taylor and Weisberg 1982). The final stage is likely to be very violent, and again of the order of 10^{52} or 10^{53} ergs will be released. In all of these cases the details of a violent energy release are not known, and it is not clear at all that a significant fraction of energy will be radiated in the gamma-ray region. But it is not unreasonable to expect that some of these, or perhaps some other rare phenomena may generate enough gamma-ray energy. The frequency of events required by the available observations is very low: perhaps 1000 bursts per year per 10^{11} galaxies.

Paczynski 1986

LETTERS TO NATURE

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

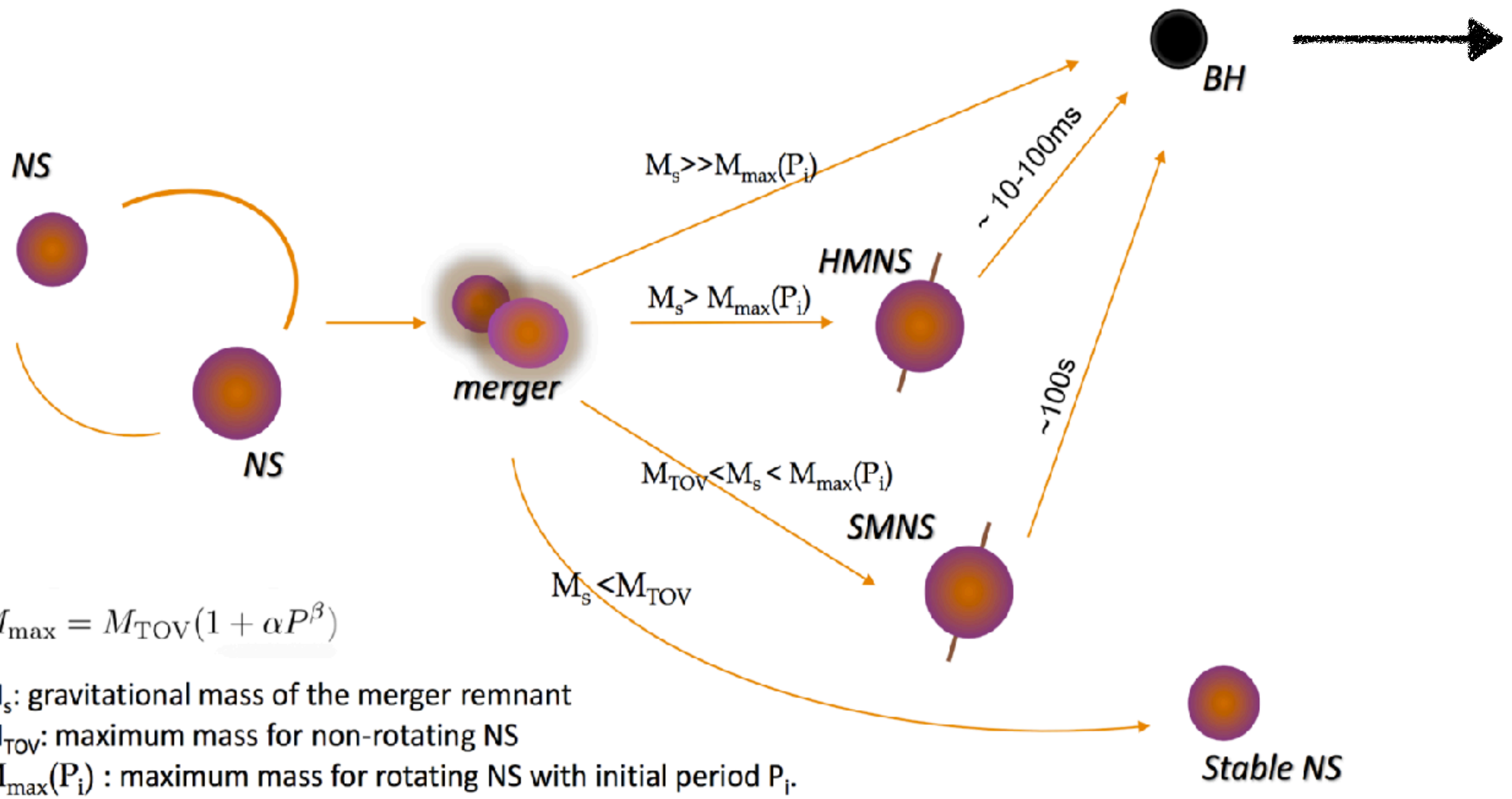
David Eichler*, Mario Livio†, Tsvi Piran‡ & David N. Schramm§

* Department of Physics, Ben Gurion 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 NASA/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[1]. Such signals are sufficiently unique and robust for them to have been proposed as a means of determining the Hubble constant[2]. However, the rate of these neutron-star collisions is highly uncertain[3]. Here we note that such events should also synthesize neutron-rich heavy elements, thought to be formed by rapid neutron capture (the r-process)[4]. Furthermore, these collisions should produce neutrino bursts[5] and resultant bursts of γ-rays; the latter should comprise a subclass of observable γ-ray bursts. We argue that observed r-process abundances and γ-ray-burst rates predict rates for these collisions that are both significant and consistent with other estimates.

Eichler et al 1989

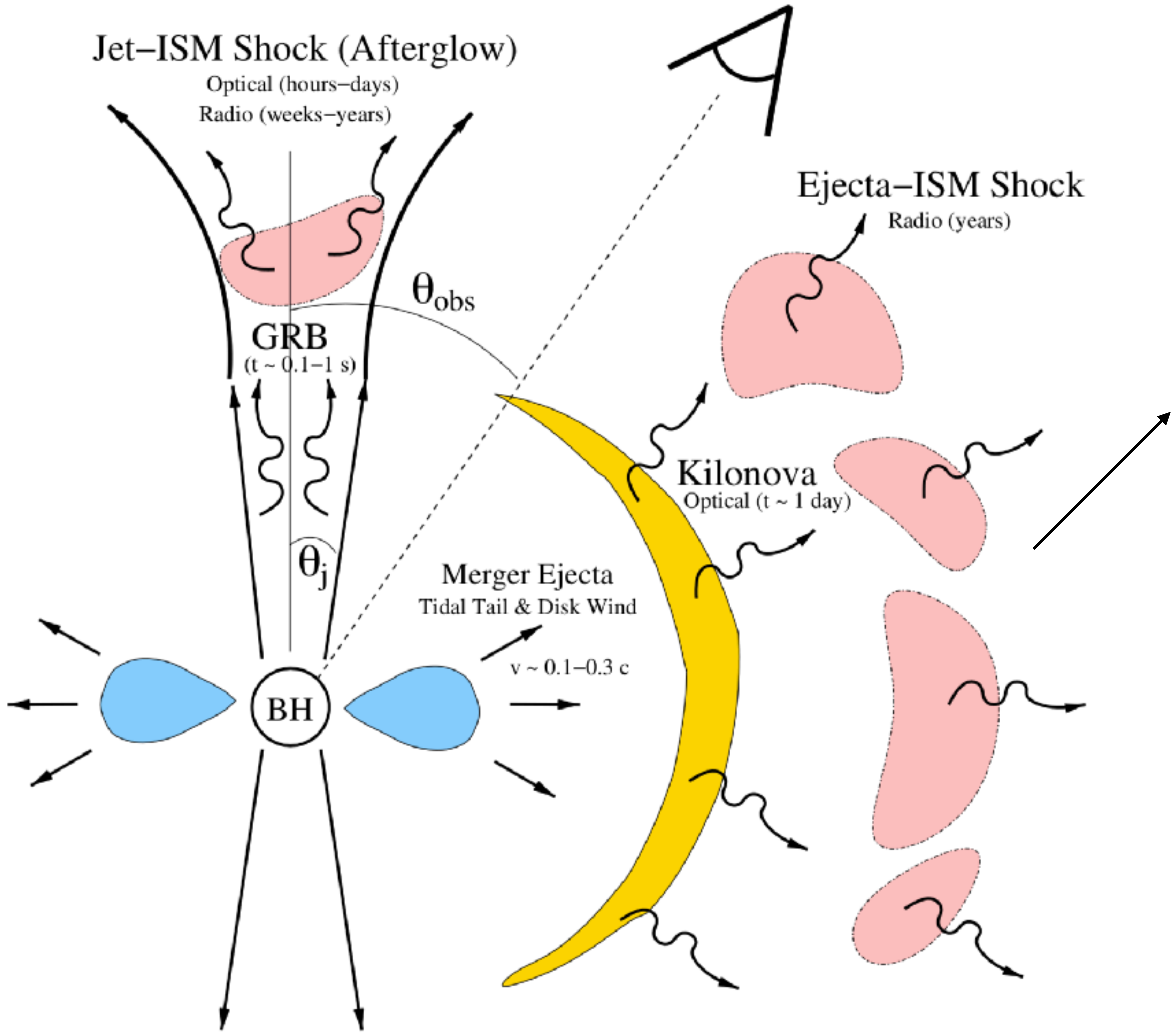
NS-NS Merger Chart



$$M_{\max} = M_{\mathrm{TOV}}(1 + \alpha P^{\beta})$$

M_s: gravitational mass of the merger remnant
M_{TOV}: maximum mass for non-rotating NS
$M_{max}(P_i)$: maximum mass for rotating NS with initial period P_i.

If final product is a BH :



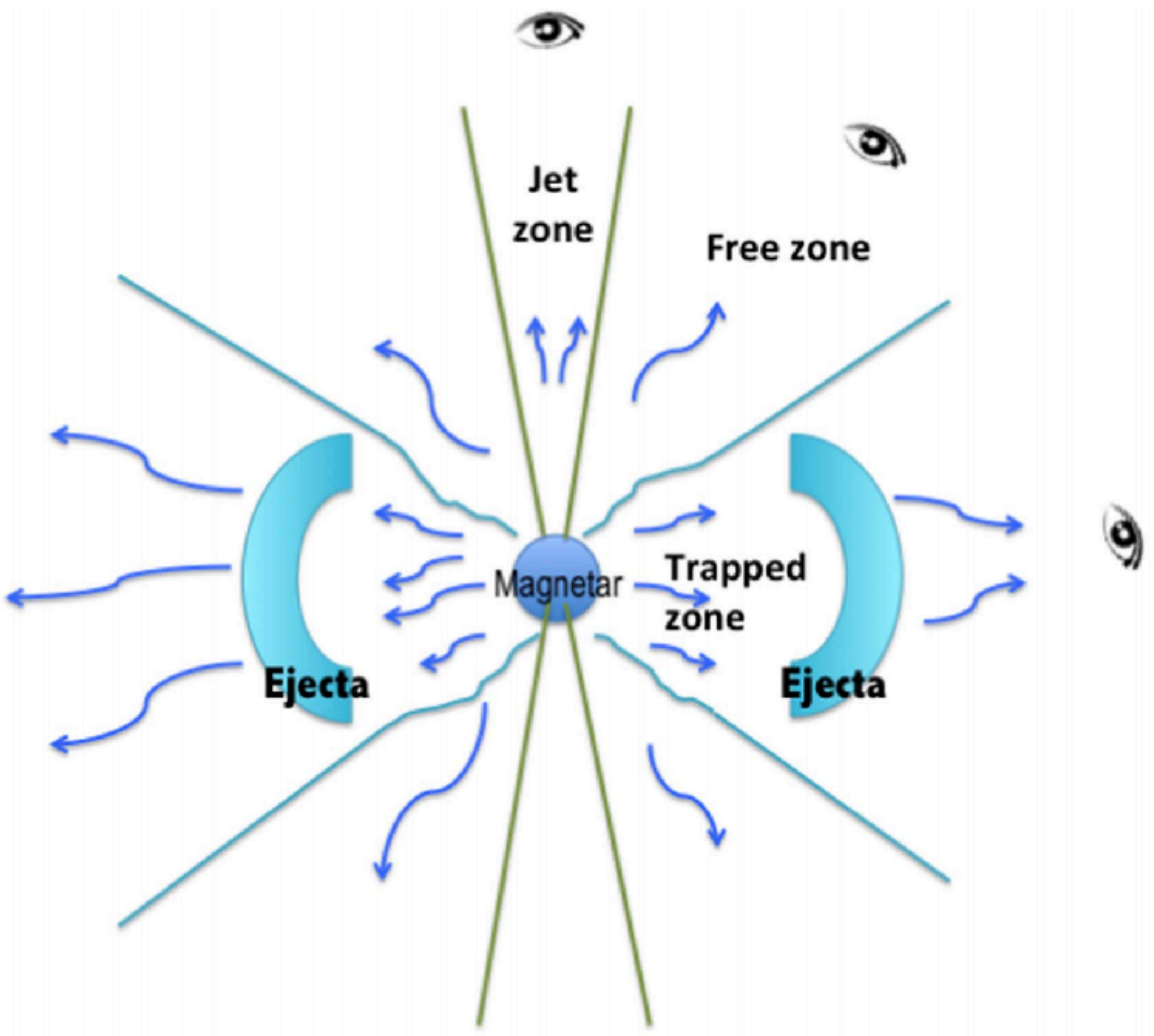
Metzger & Berger (2012)

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

See also talks by Kasliwal & Murphy

If final product is a stable NS (magnetar) :

Three zones



Sun, H+2017

X-rays radiaion is produced isotropically via magnetar wind dissipation

Jet zone:

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

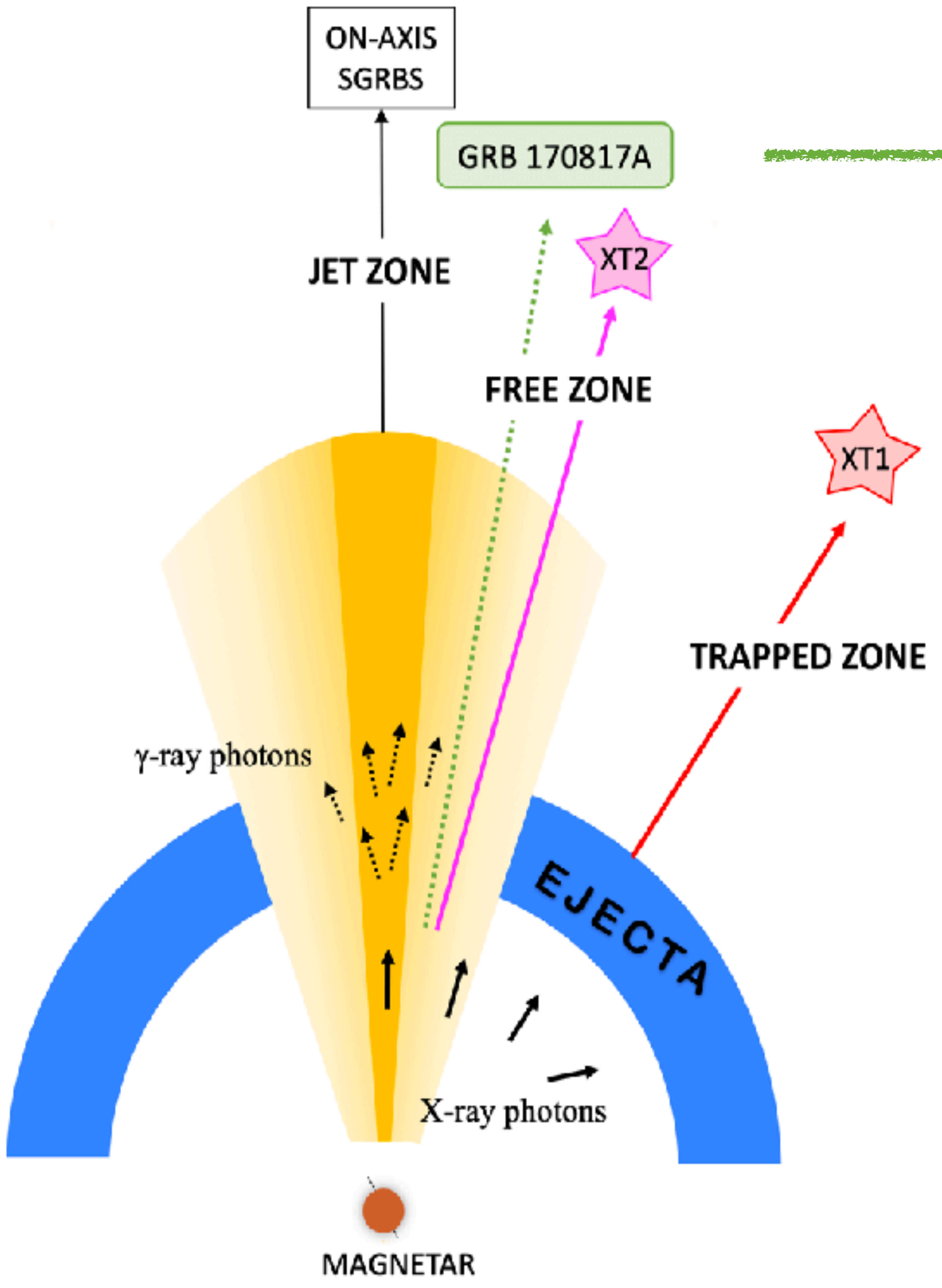
Free zone:

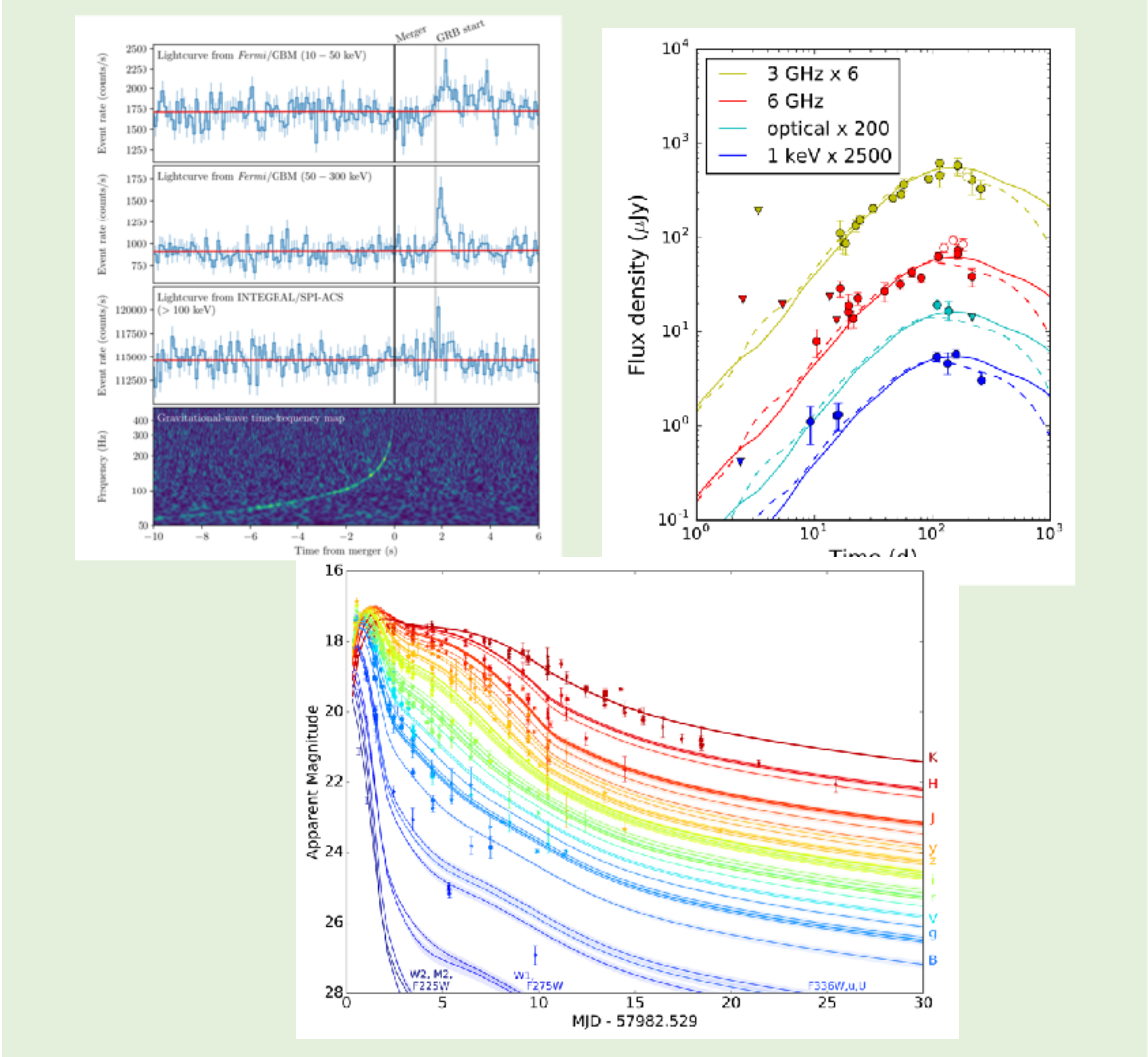
no GRB/ or weak GRB 170718A-like GRB ,
X-ray from magnetar wind dissipation only

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.

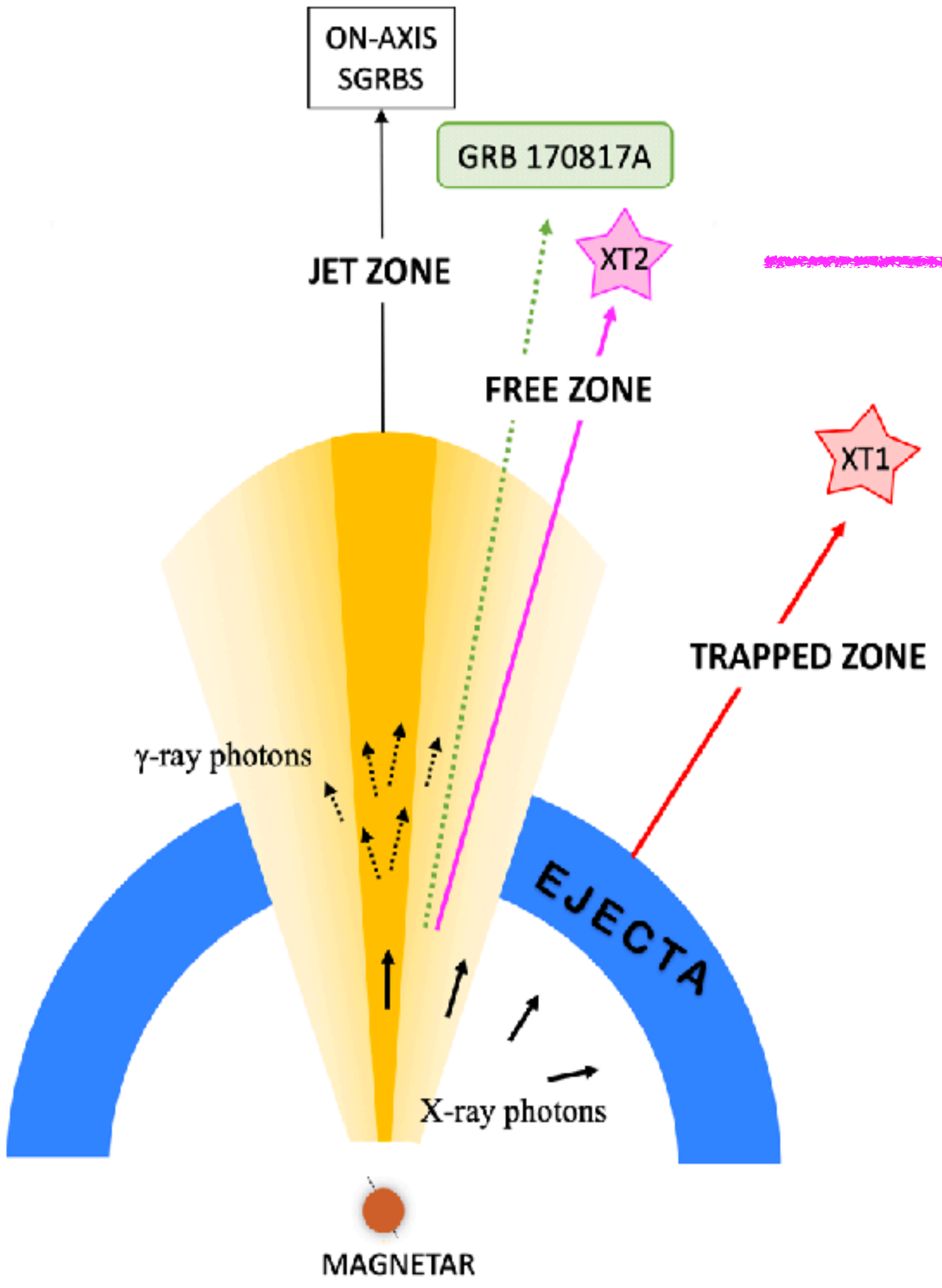
Magnetar Case 1: 170817A-like GRB+AG+KN



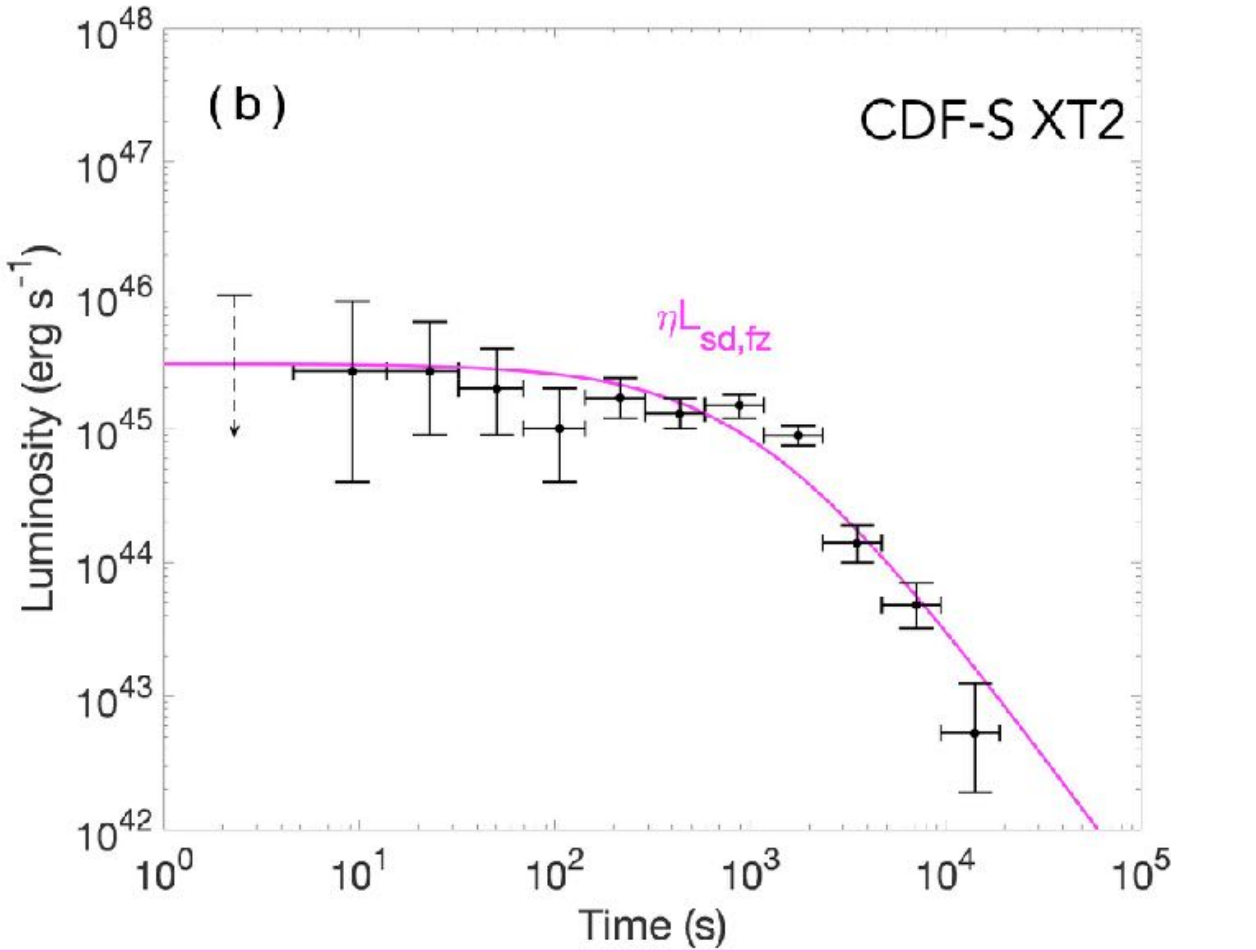


Sun, H+2017

Magnetar Case 2: No GRB , Spin-Down Powerd X-ray transient



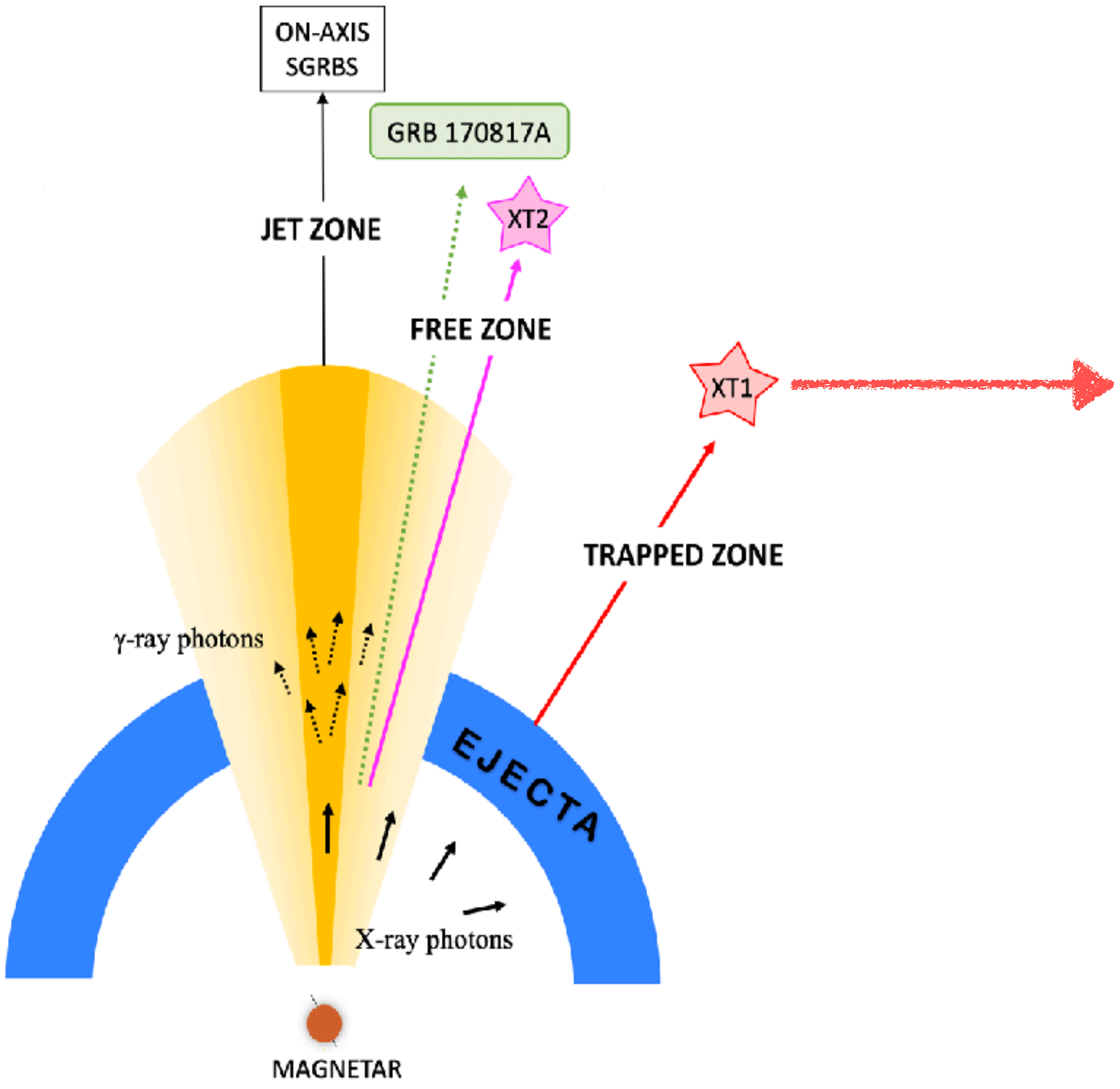
Sun, H+2017

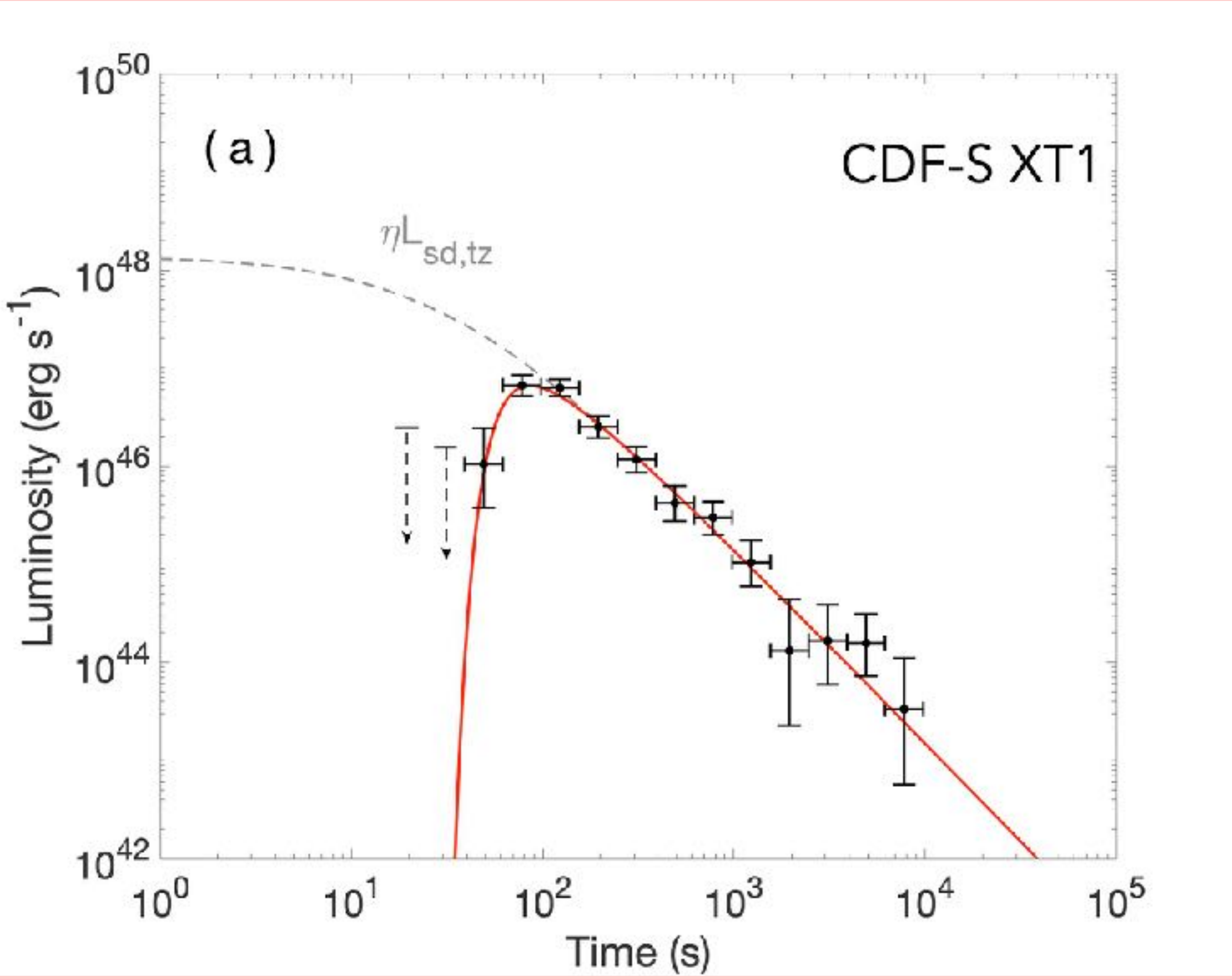


$$L_{X,\mathrm{free}}(t) = \eta L_{\mathrm{sd}} = \frac{\eta B_p^2 R^6 \Omega^4(t)}{6c^3}$$

Xue et al 2019, Nature

Magnetar Case 3: No GRB , X-ray Trapped, then becomes free





$$L_{\mathrm{X,trapped}}(t) = e^{-\tau}\frac{\eta B_p^2 R^6 \Omega^4(t)}{6c^3} + (\nu_{\mathrm{X}} L_{\nu,\mathrm{X}})_{\mathrm{bb}}$$

Sun, H+17, 19

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NS-BH Merger

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

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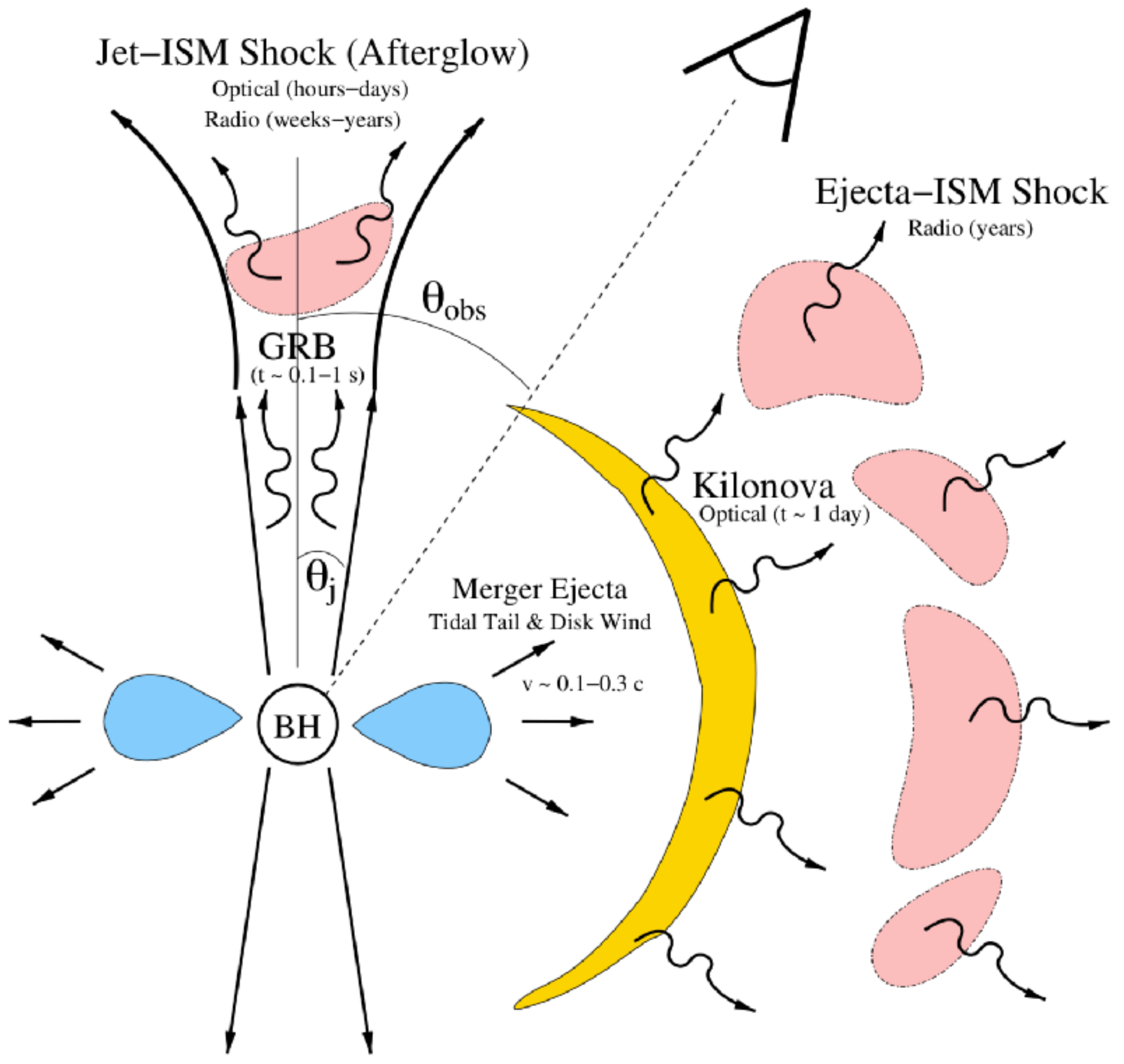
Not-too-large q (e.g., q< 5) :

Black Hole+ disk + jet central engine
—> traditional short GRB + kilonova+ AG



NS-BH Merger

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

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Black Hole+ disk + jet central engine
—> 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 accreation disk to form
——> NO traditional short GRB

BUT alternative models can still lead to a GRB (see next).

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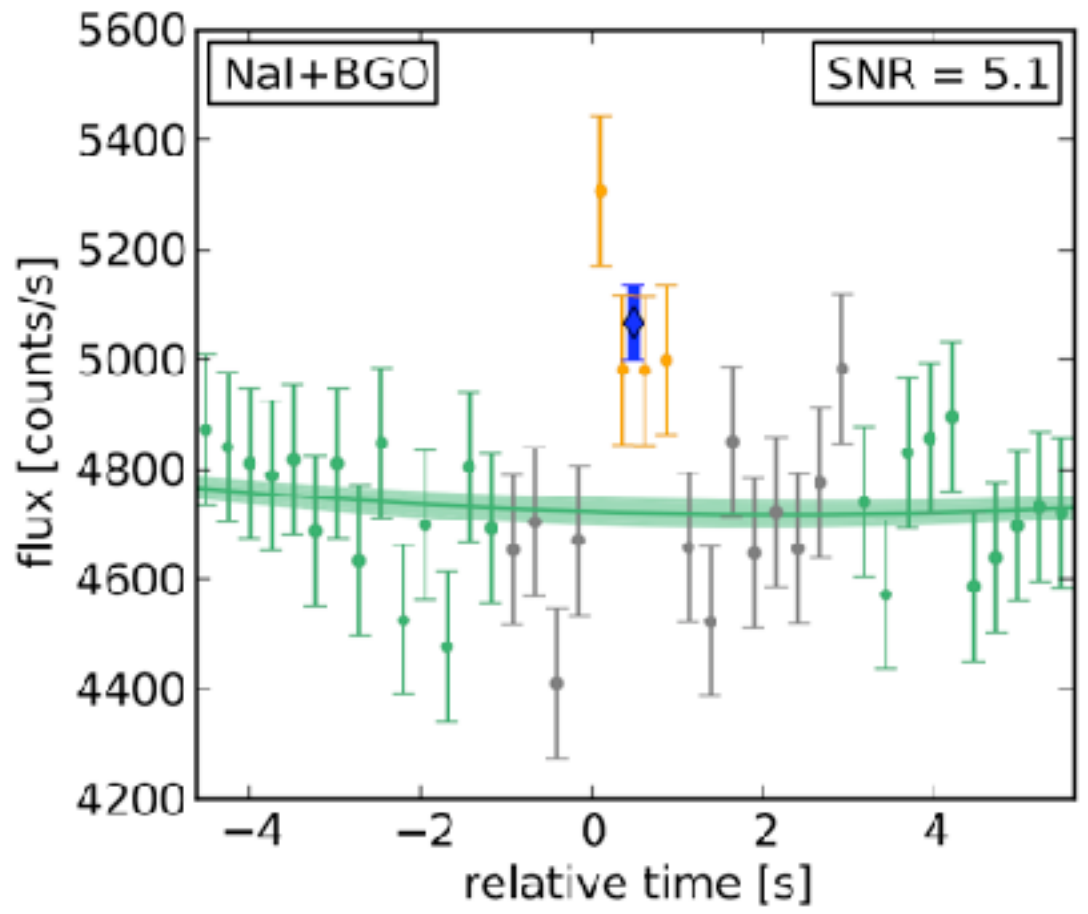
BH-BH Merger

…was thought to be no EM-associated before GW150914

The Astrophysical Journal Letters, 826:L6 (19pp), 2016 July 20 doi:10.3847/2041-8205/826/1/L6

FERMI GBM OBSERVATIONS OF LIGO GRAVITATIONAL-WAVE EVENT GW150914

V. Connaughton[1], E. Burns[2], A. Goldstein[3,20], L. Blackburn[4,5], M. S. Briggs[6,7], B.-B. Zhang[7,8], J. Camp[9], N. Christensen[10], C. M. Hui[3], P. Jenke[7], T. Littenberg[1], J. E. McEnery[9], J. Racusin[9], P. Shawhan[11], L. Singer[9,20], J. Veitch[12], C. A. Wilson-Hodge[3], P. N. Bhat[7], E. Bissaldi[13,14], W. Cleveland[1], G. Fitzpatrick[7], M. M. Giles[15], M. H. Gibby[15], A. von Kienlin[16], R. M. Kippen[17], S. McBreen[18], B. Mailyan[7], C. A. Meegan[7], W. S. Paciesas[1], R. D. Preece[6], O. J. Roberts[18], L. Sparke[19], M. Stanbro[6], K. Toelge[14], and P. Veres[7]



The Astrophysical Journal Letters, 827:L31 (5pp), 2016 August 20 doi:10.3847/2041-8205/827/2/L31

MERGERS OF CHARGED BLACK HOLES: GRAVITATIONAL-WAVE EVENTS, SHORT GAMMA-RAY BURSTS, AND FAST RADIO BURSTS

Bing Zhang
Department of Physics and Astronomy, University of Nevada, Las Vegas, NV 89154, USA; zhang@physics.unlv.edu
Received 2016 March 22; revised 2016 July 12; accepted 2016 July 12; published 2016 August 16

ABSTRACT

The discoveries of GW150914, GW151226, and LVT151012 suggest that double black hole (BH–BH) mergers are common in the universe. If at least one of the two merging black holes (BHs) carries a certain amount of charge, possibly retained by a rotating magnetosphere, the inspiral of a BH–BH system would drive a global magnetic dipole normal to the orbital plane. The rapidly evolving magnetic moment during the merging process would drive a Poynting flux with an increasing wind power. The magnetospheric activities during the final phase of the merger would make a fast radio burst (FRB) if the BH charge can be as large as a factor of $\hat{q} \sim (10^{-9}–10^{-8})$ of the critical charge Q_c of the BH. At large radii, dissipation of the Poynting flux energy in the outflow would power a short-duration high-energy transient, which would appear as a detectable short-duration gamma-ray burst (GRB) if the charge can be as large as $\hat{q} \sim (10^{-5}–10^{-4})$. The putative short GRB coincident with GW150914 recorded by *Fermi* GBM may be interpreted with this model. Future joint GW/GRB/FRB searches would lead to a measurement or place a constraint on the charges carried by isolate BHs.

Connaughton et al. 2016; Zhang, B. 2016

BH-BH Merger (and Large-q NS-BH Merger)

Most popoular 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

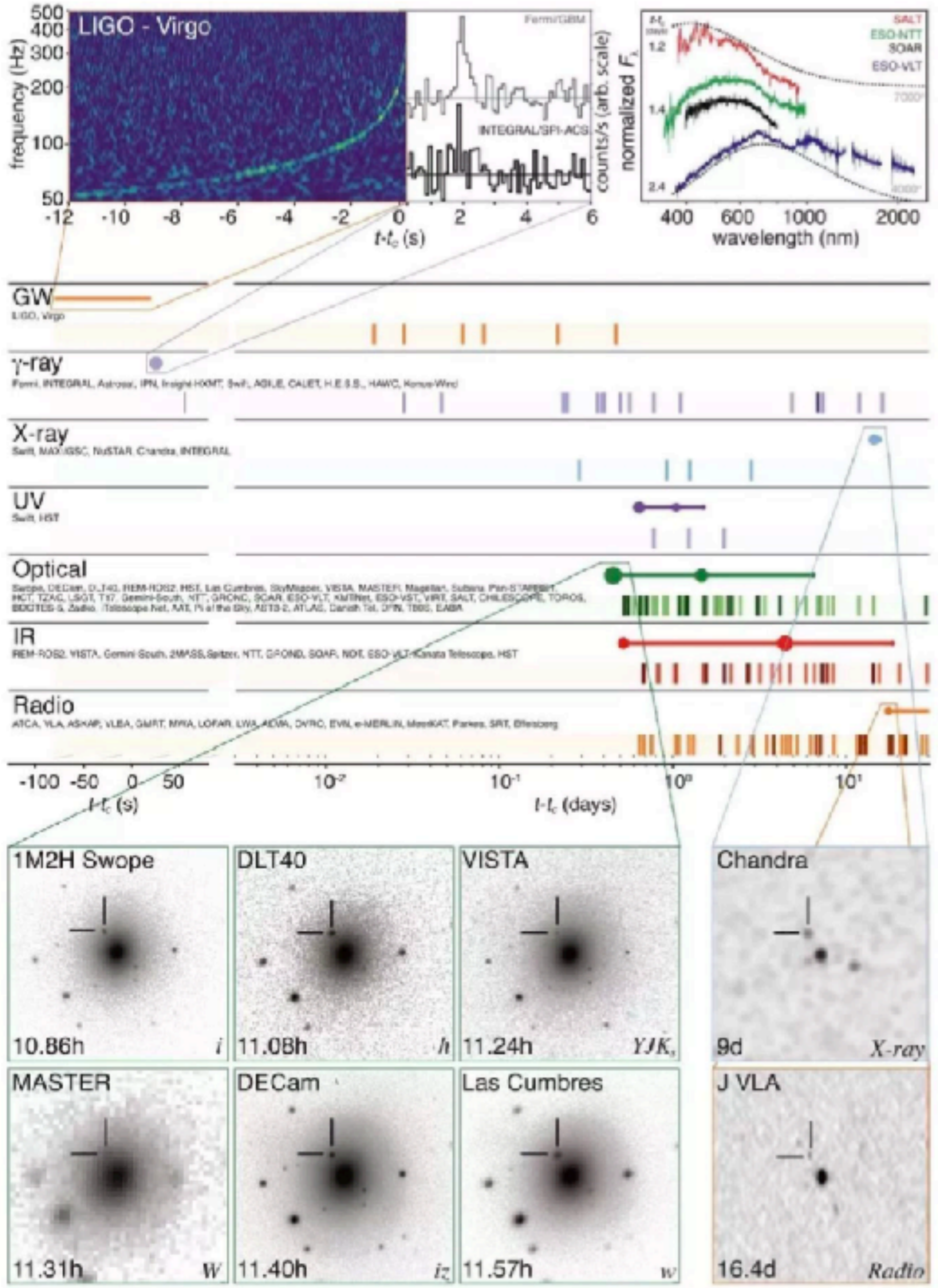
Recent theoretical development:
Zhang 2019, Dai 2019, Pan & Yang 2019; Zhong et al. 2019

Implicaitons & Prospects

Goal:

Maximize the physical information from the observations

Best Case:
Detailed GW constraints + luxury EM obsevations



GW：

merger masses, angles, distance,
eneregies, tidal deformbility,
final product, EOS

EM：

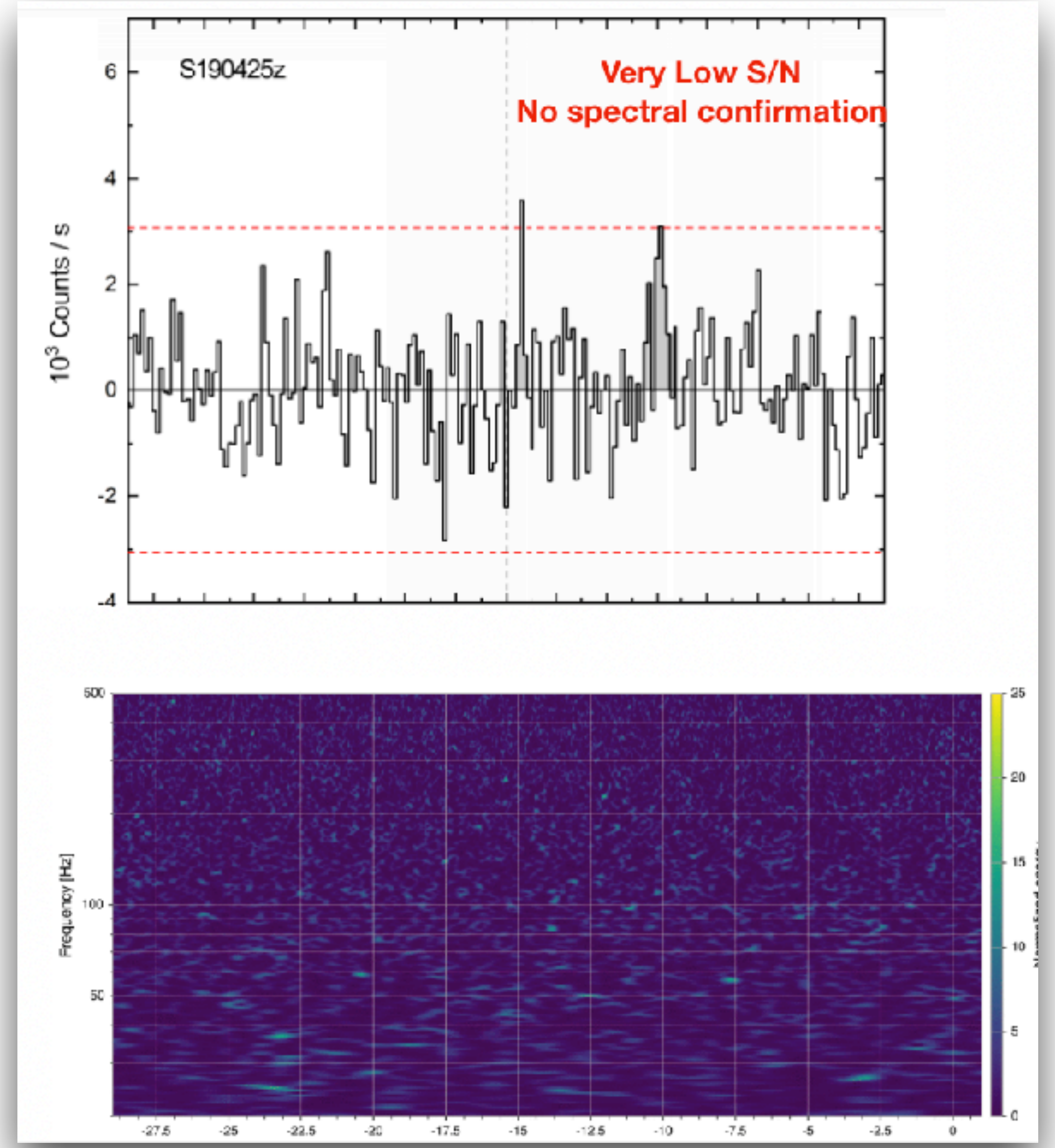
jet structure, speed, openning angle,
viewing angle, cocoon structure,
heavy element production, emission radius
engine types (NS vs BH)

ALL：

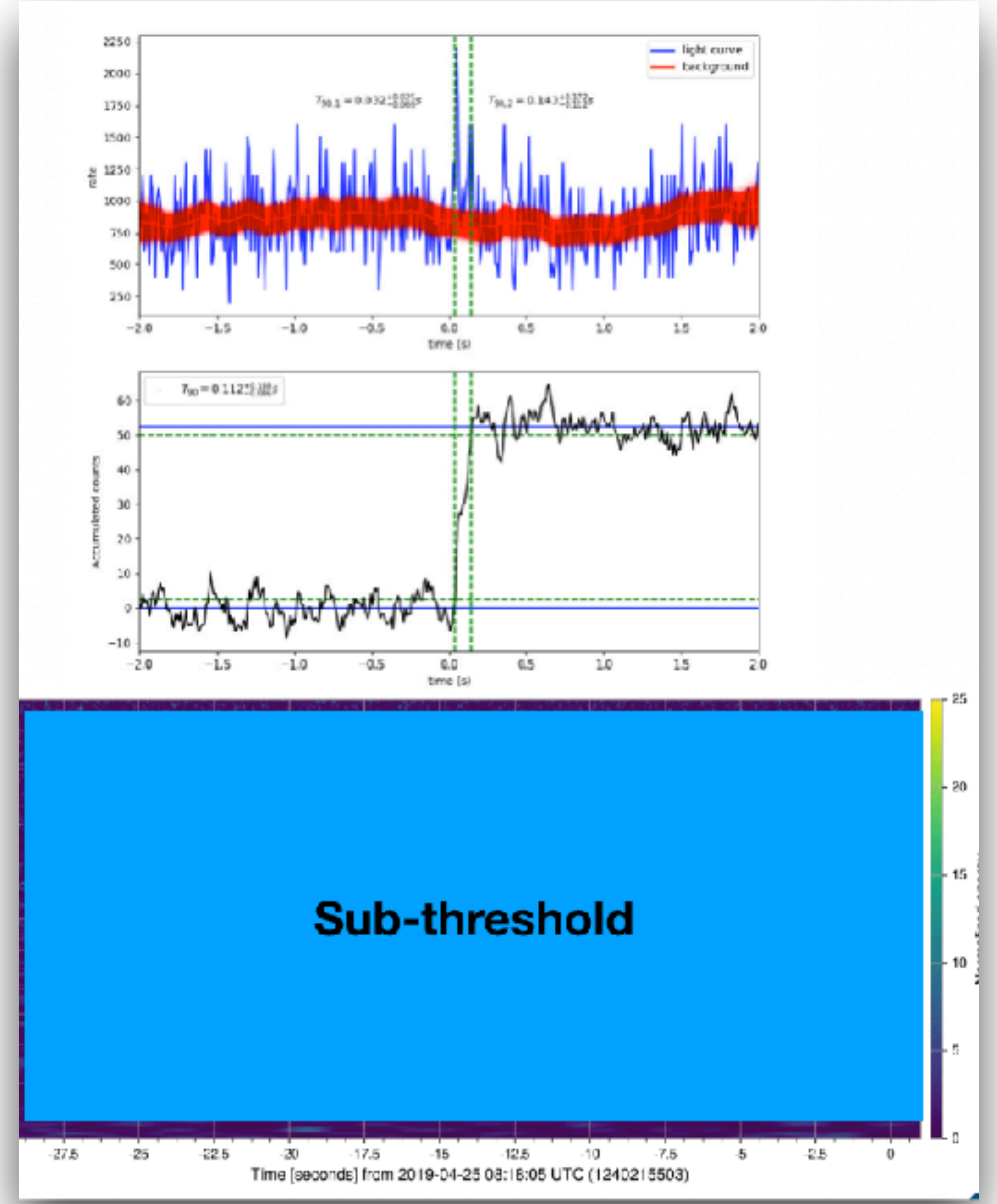
event rate, populations,
foundamental physics (e.g WEP, LIV etc)

See also talks by Kasliwal, Murphy, Sari, Nissanke …

But what about:

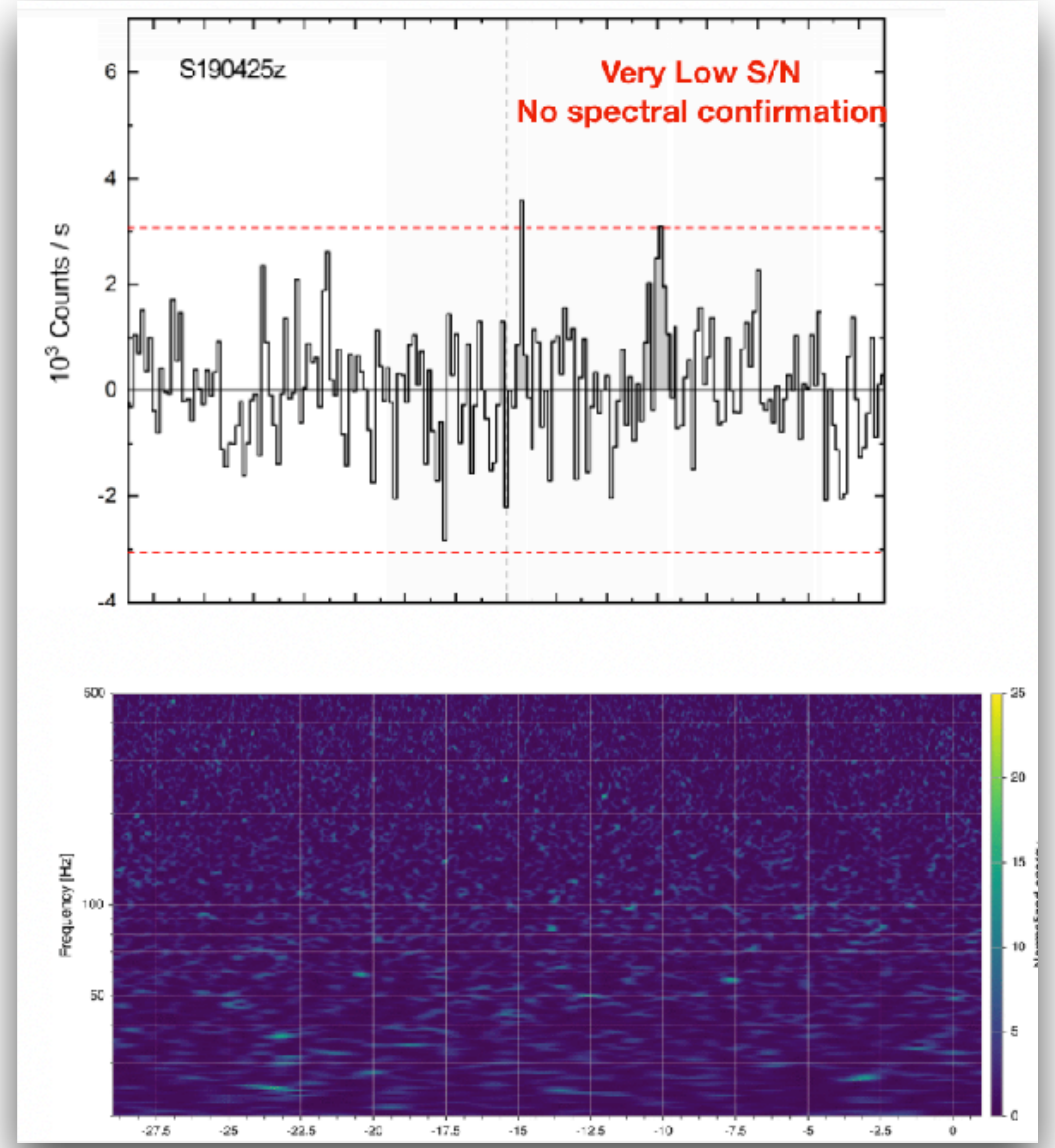


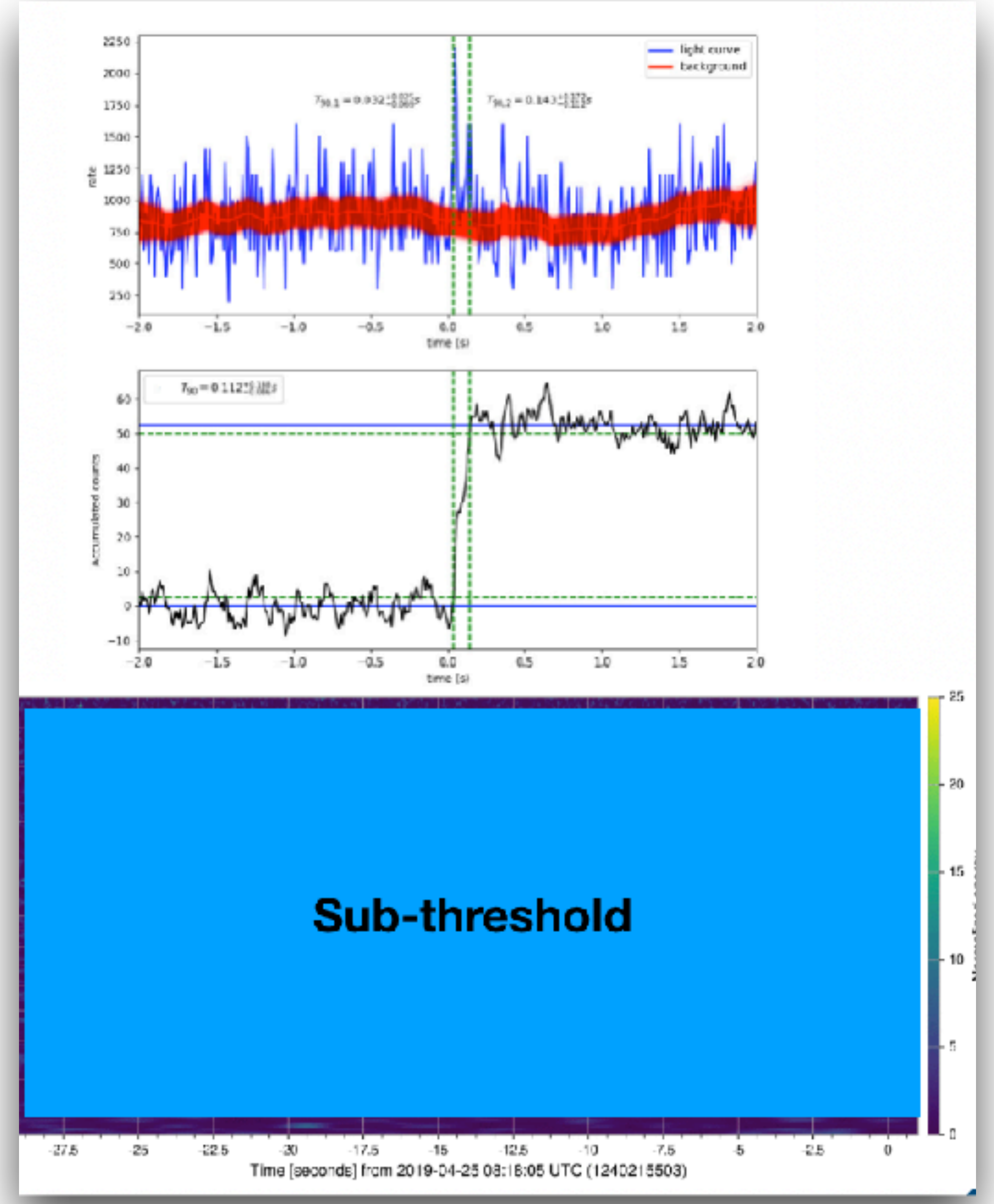
GW190425



GBM-190816

But what about:





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

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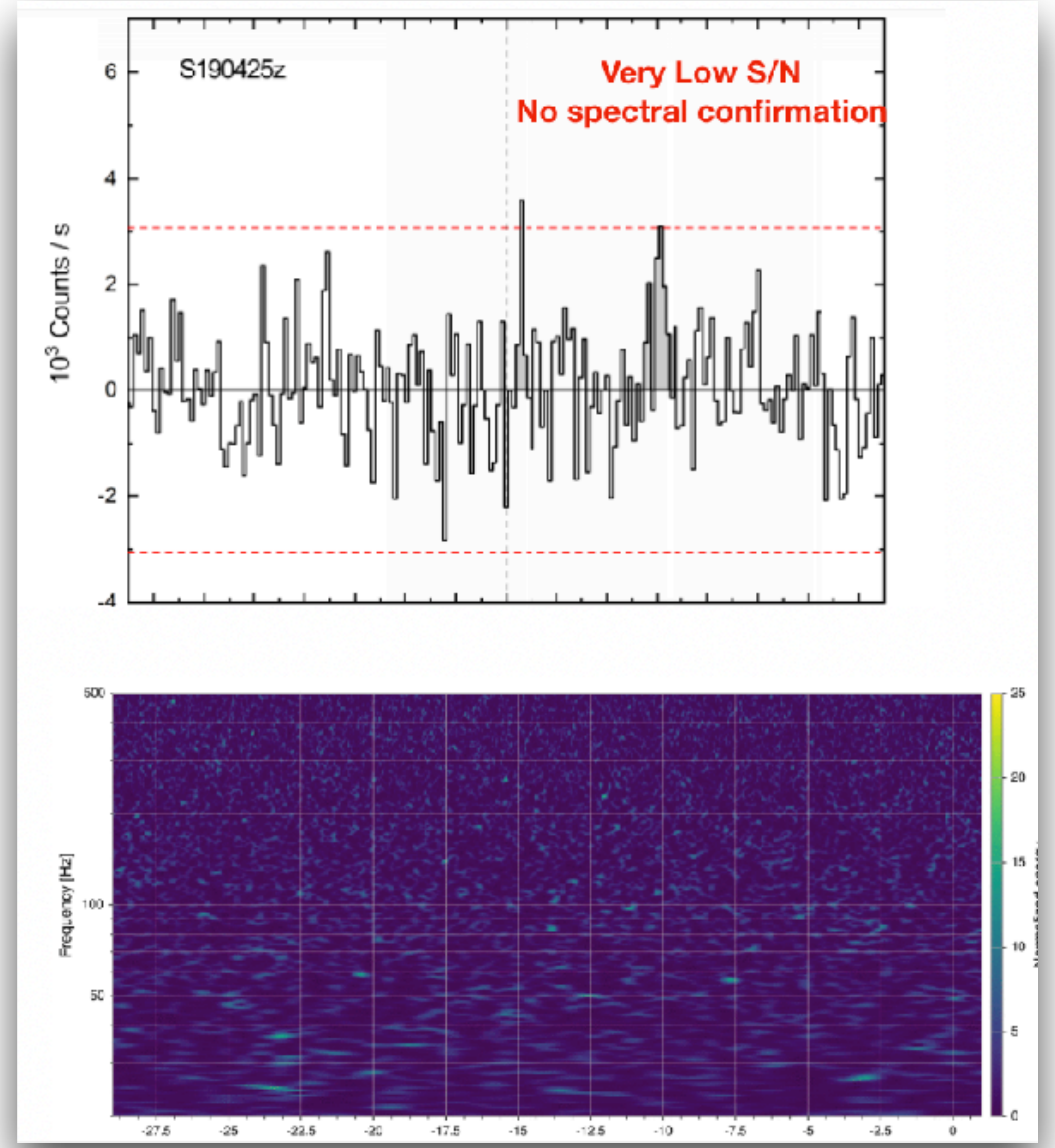
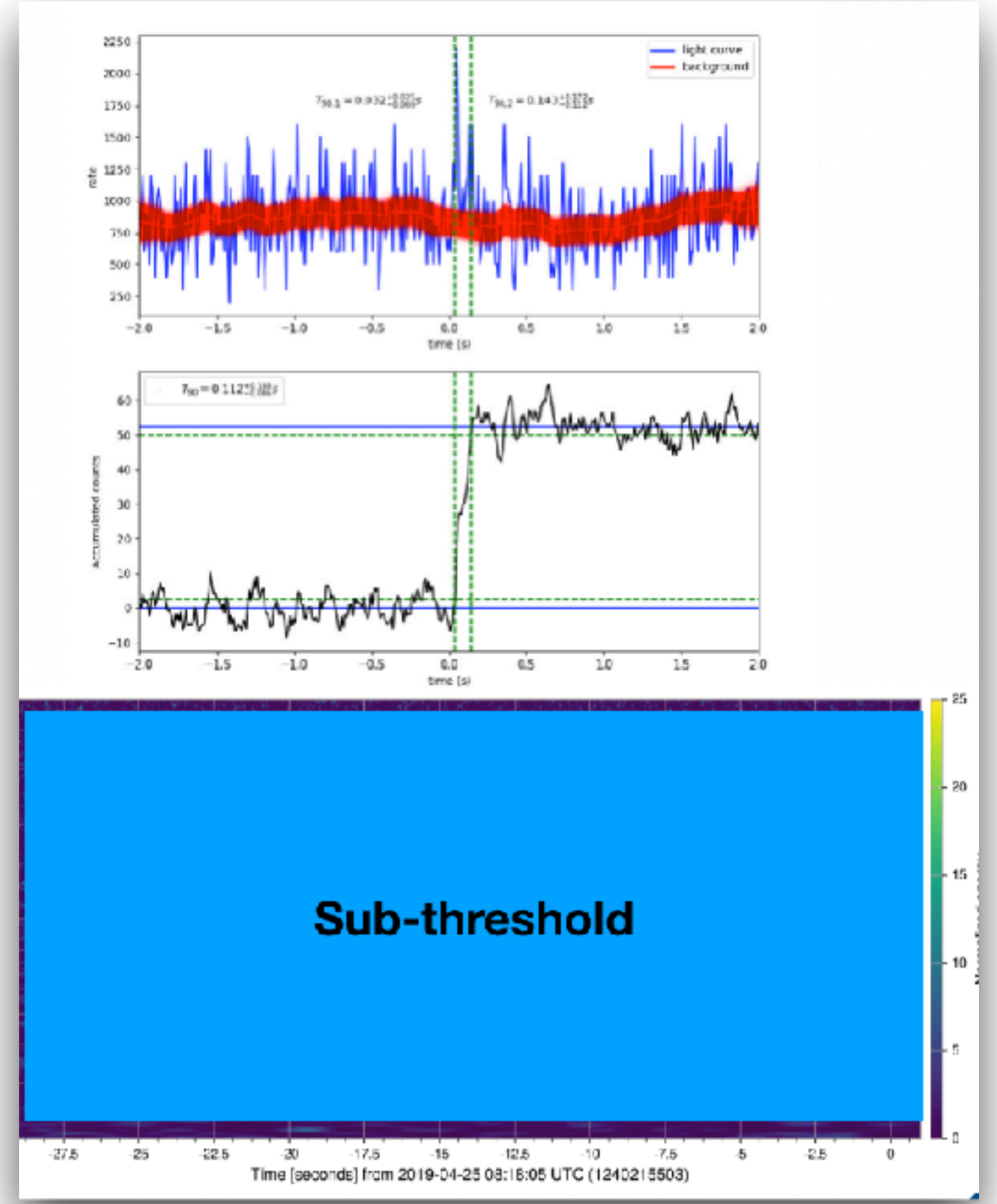
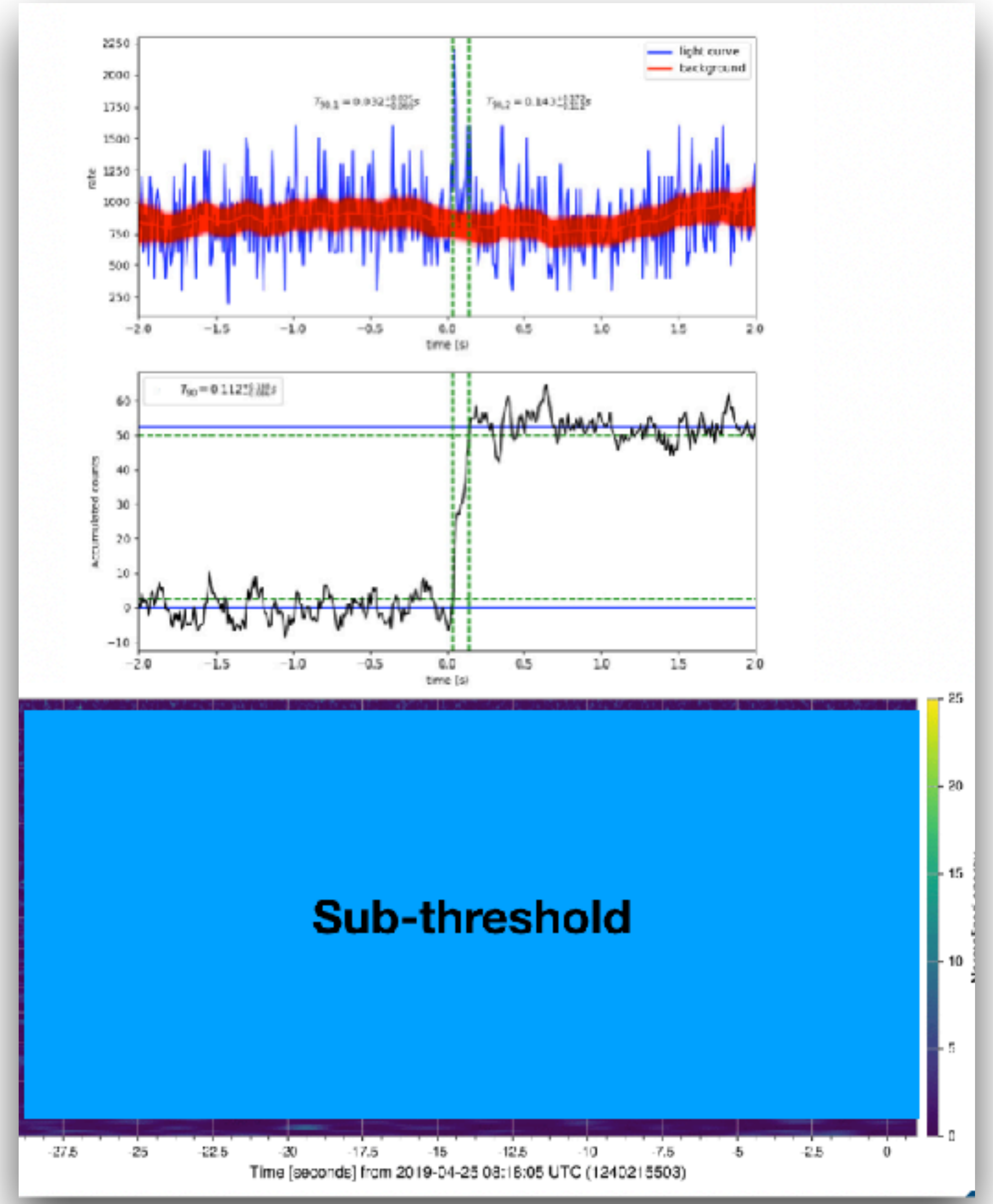


Not much to do if the EM signal is only tentative w/o spectroscopic confirmation



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

Limited GW Info

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).

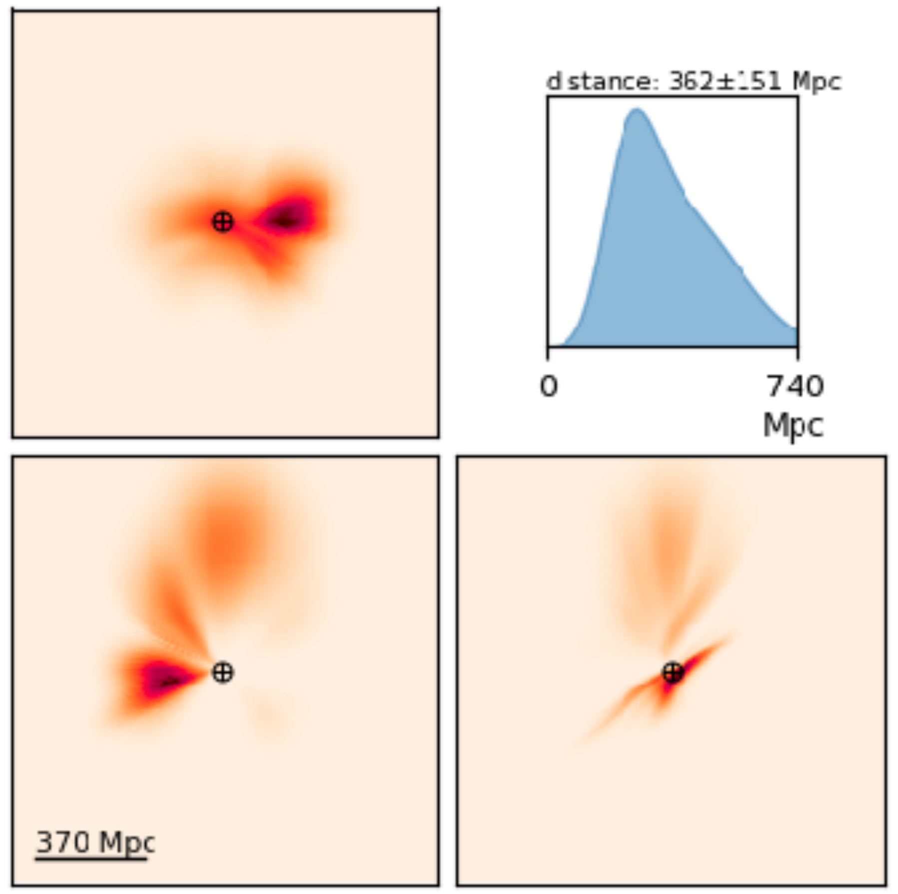
GBM-190816:

①. Duration: approximately 0.1 s

②. Hard spectral template

③. The lighter compact object may have a mass < 3 $M_\odot$.

④. FAR ~ 1.2×10^{-4}



Distance from GW: 428 +/- 143 Mpc

GCN #25406, GCN #25406, Golastein +19

GW: Sub-thrshold Event Gives q

Information:

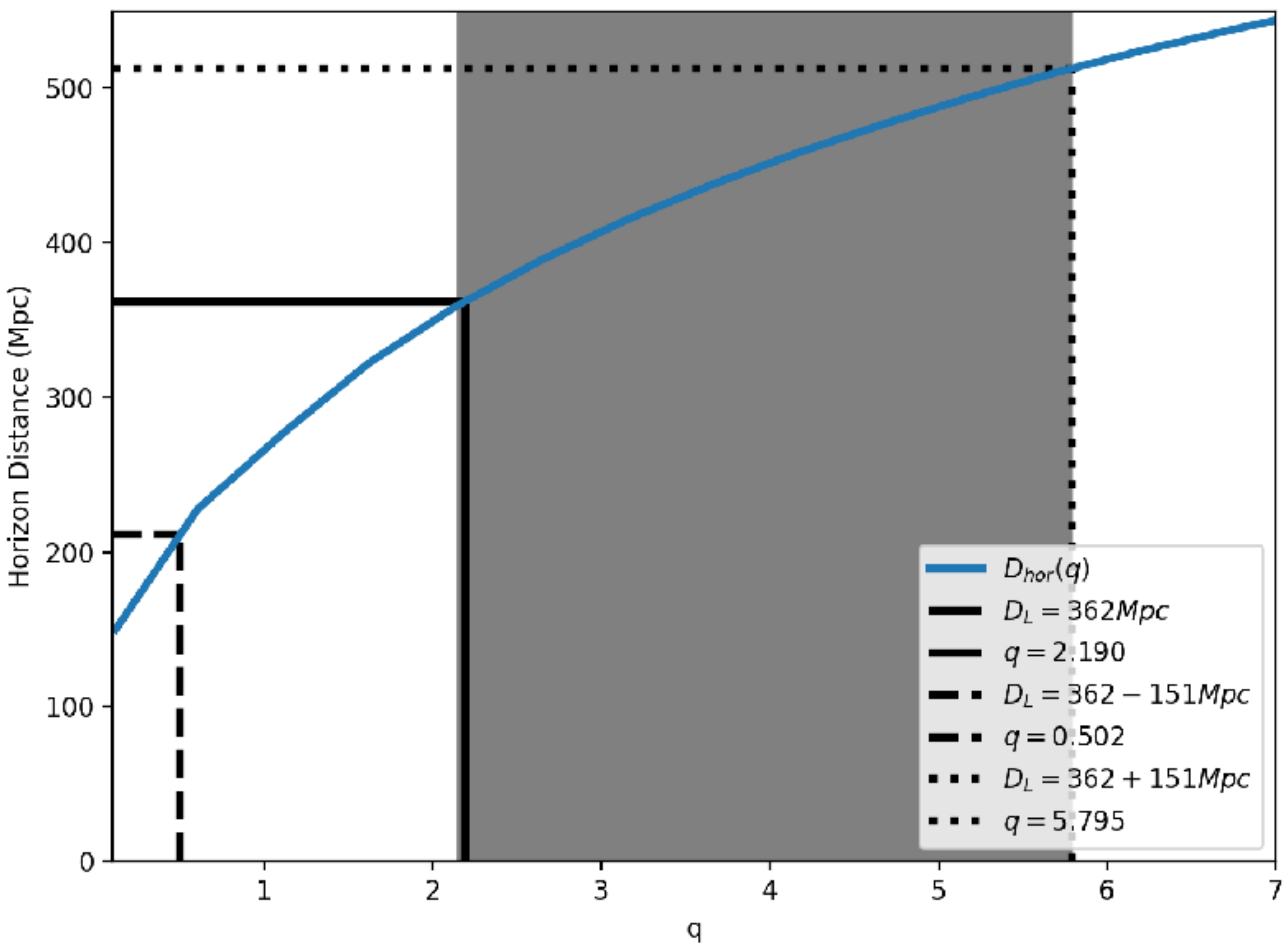
1. L1 and V1 data are available at that time.
2. LVC identified a possible CBC candidate at 2019-08-16 21:22:13.027 UTC.
3. The network S/N of this sub-threshold event is below the threshold of GW analysis pipelines, which is 12.
4. The luminosity distance of the event is constrained to 362±151 Mpc
5. 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 ~ [2.142, 5.795]**

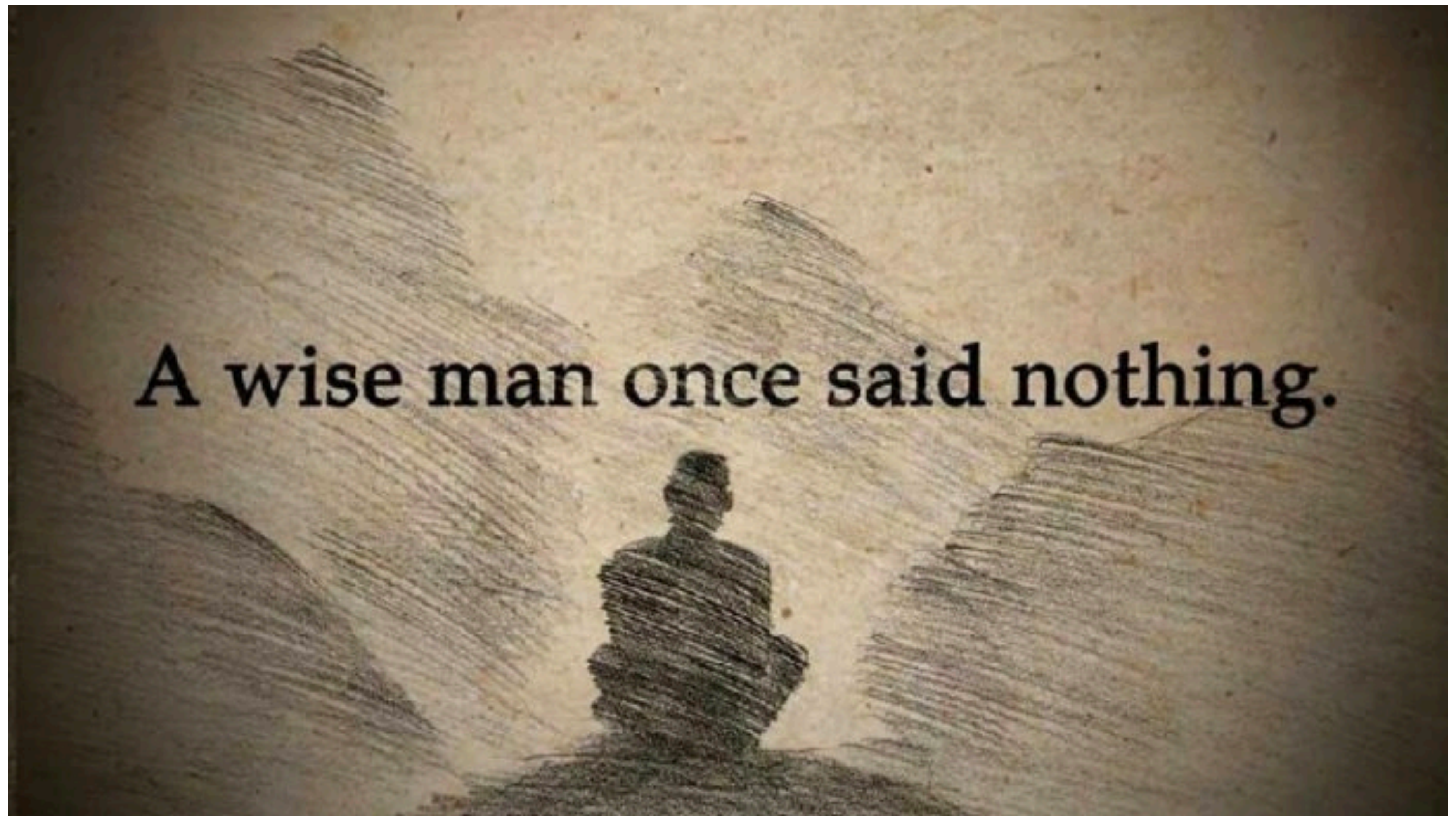


Excited Community

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

Search by

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

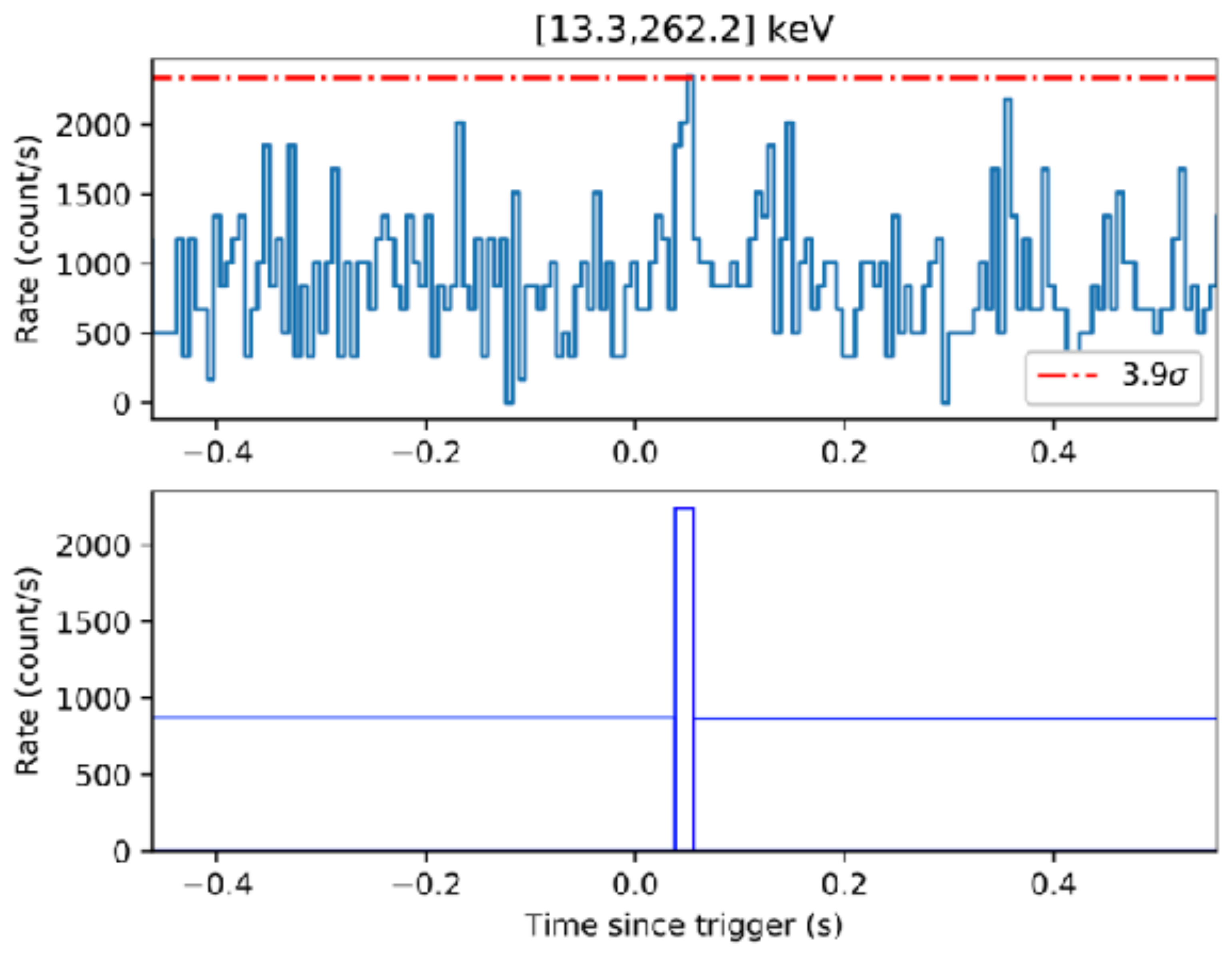


EM: Burst Confirmation

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

Signal appears in various conditions.

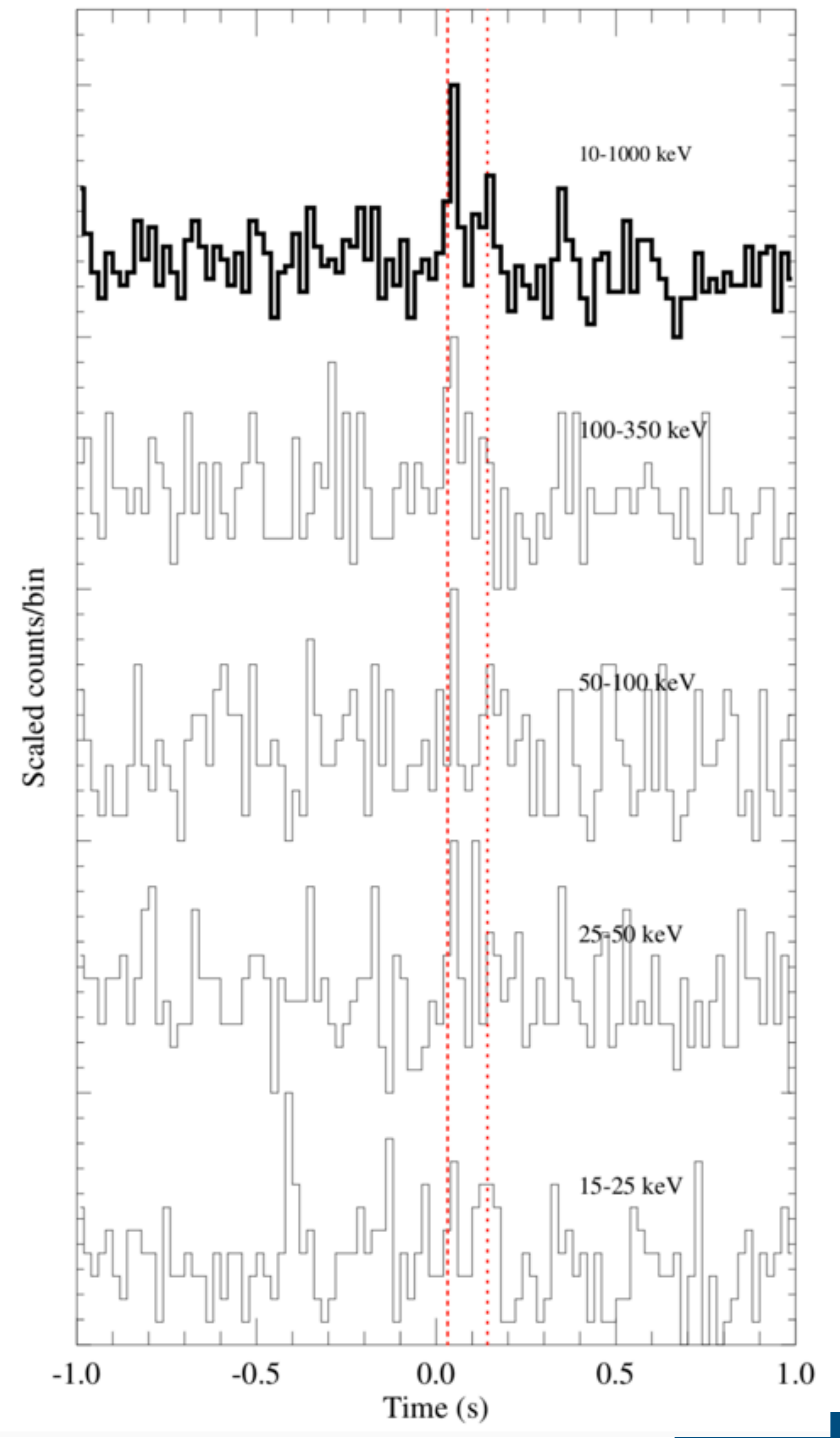
The significance level of the burst S/N reached 3.95.



EM: Burst Confirmation

Multi-wavelegth light curves

Pulse evolution and struture



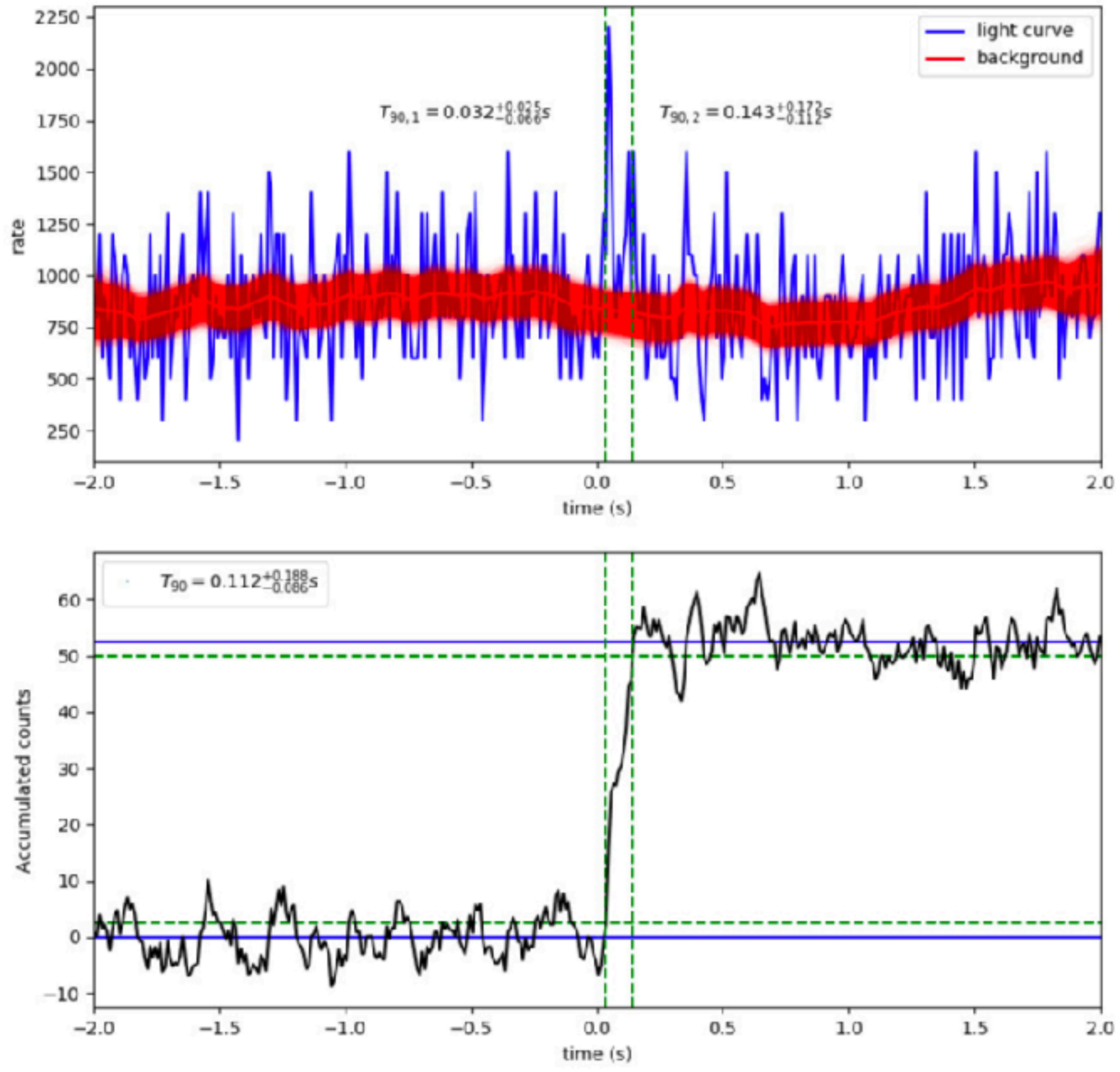
EM: Burst Confirmation

Precise Duration

$T_{90} = \quad 0.112^{+0.185}_{-0.085}\, s$

starts at $T_{90,1} = \quad 0.032^{+0.025}_{-0.065}\, s$

ends at $T_{90,2} = \quad 0.143^{+0.17}_{-0.11}\, s$



A homework in GWCLASS2019

EM: Burst Confirmation

f parameter

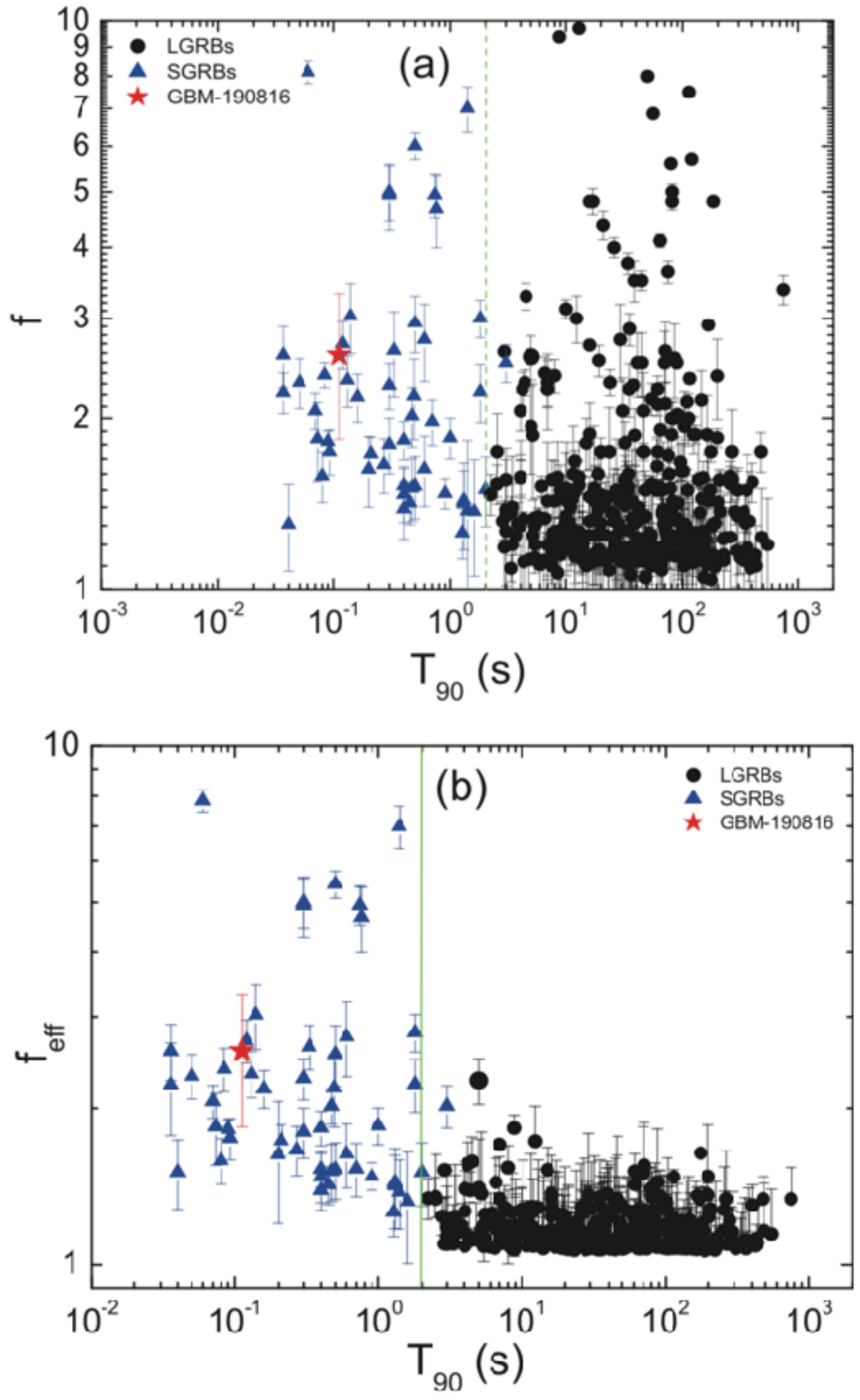
(a.k.a : tip-of-iceberg effect, Lü, H.-J. et al. 2012)

f = 2.58 ± 0.37, typical as a short GRB

f: the ratio between the peak flux and the average background flux

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

However, there is a non-negligible probability (p ~ 0.03.) of being the ”tip of iceberg” of a longer short burst.

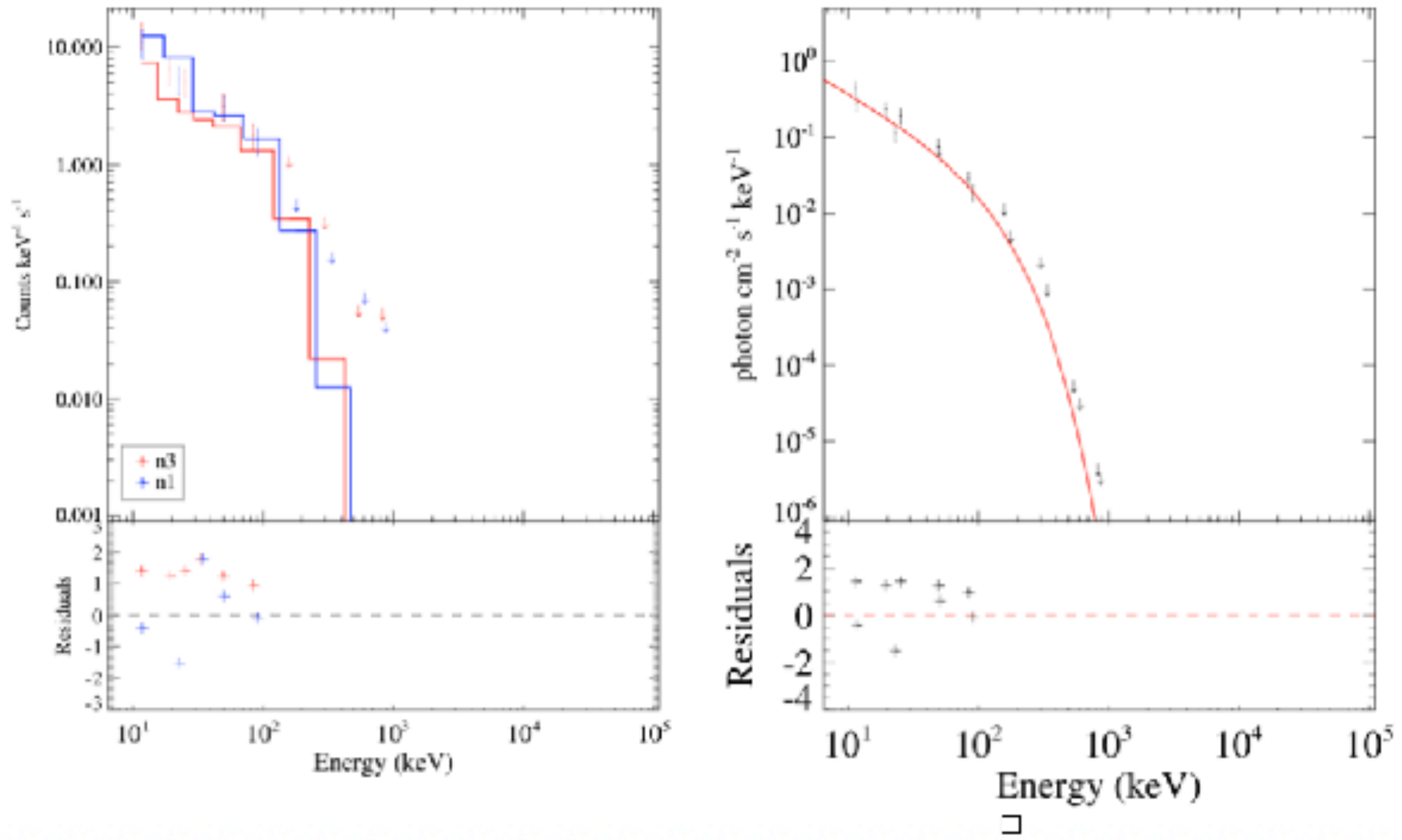


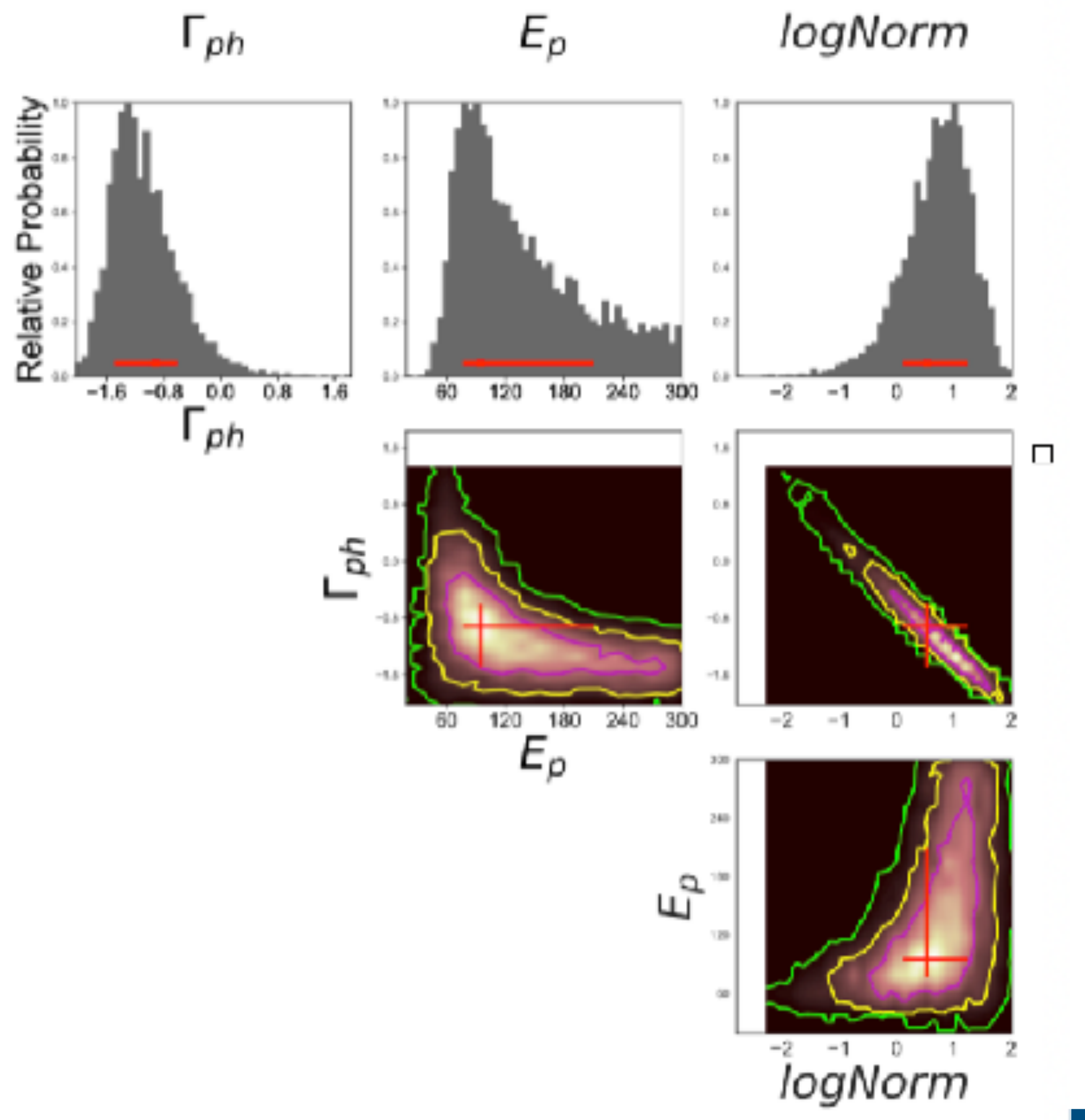
EM: Burst Confirmation

Spectral Analysis

Time Interval		CPL			
t_1	t_2	$\Gamma_{\rm ph}$	$E_{\rm p}$	$logNorm$	PGSTAT/dof
0.032	0.143	$-0.92^{+0.32}_{-0.58}$	$94.84^{+114.64}_{-17.94}$	$0.53^{+0.72}_{-0.41}$	130.1/227

Observed Properties	
T_{90} (s)	$0.112^{+0.185}_{-0.085}$
Peak energy $E_{\rm p}$ (keV)	$94.84^{+114.64}_{-17.94}$
Total fluence(erg cm^{-2})	$7.38^{+6.35}_{-2.51} \times 10^{-8}$
Distance (Mpc)	**428 + / − 143**
Isotropic energy $E_{\gamma,\rm iso}$ (erg)	$\mathbf{1.65^{+3.81}_{-1.16} \times 10^{48}}$
Luminosity $L_{\gamma,\rm iso}$ (erg s^{-1})	$\mathbf{1.47^{+3.40}_{-1.04} \times 10^{49}}$
f parameter	2.58 + / − 0.37





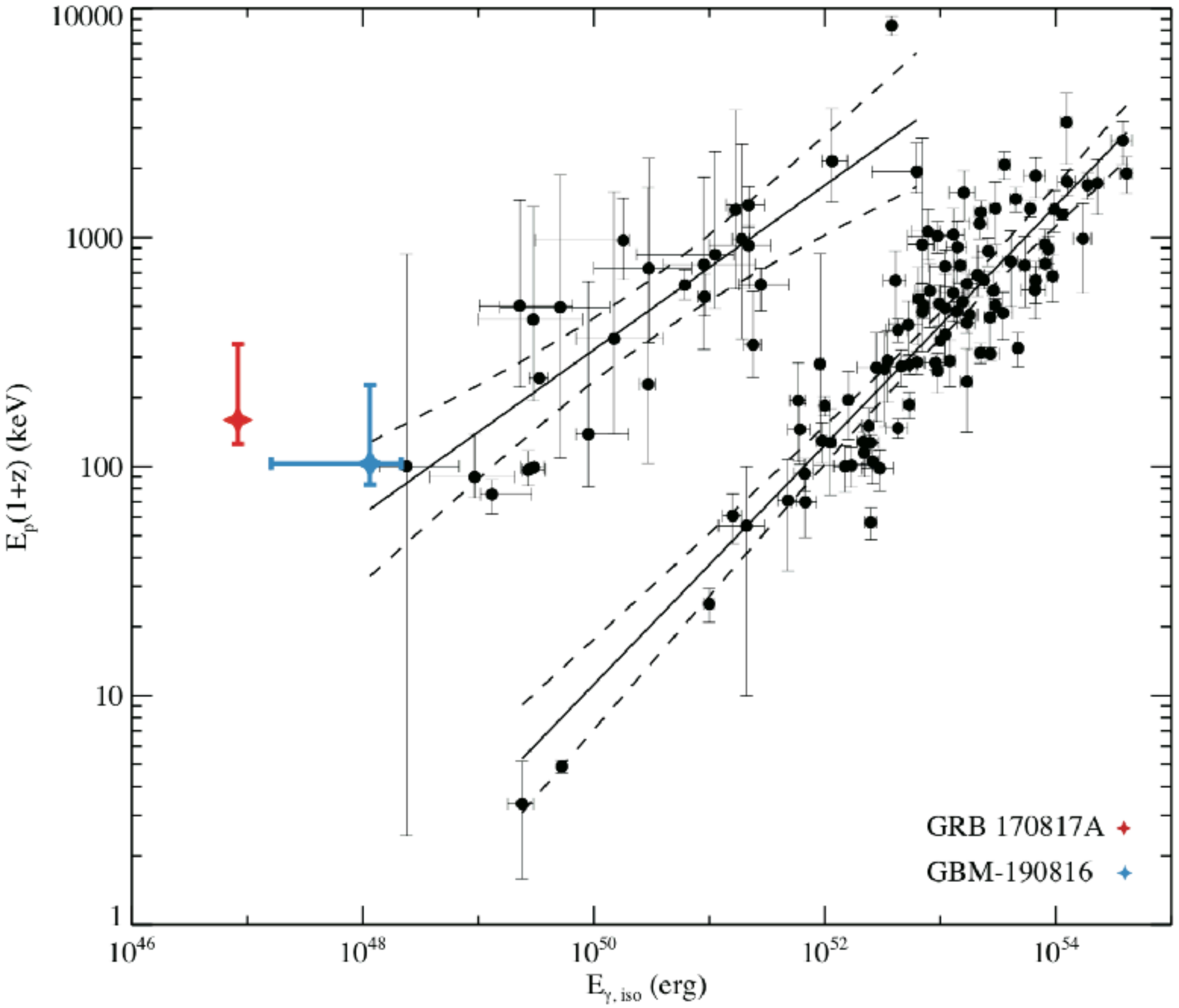
EM: Burst Confirmation

GBM-190816 as a short GRB

Observed Properties	
T_{90} (s)	$0.112^{+0.185}_{-0.085}$
Peak energy E_p (keV)	$94.84^{+114.64}_{-17.94}$
Total fluence(erg cm^{-2})	$7.38^{+6.35}_{-2.51} \times 10^{-8}$
Distance (Mpc)	362 +/− 151
Isotropic energy $E_{\gamma,\mathrm{iso}}$ (erg)	$1.14^{+3.18}_{-0.89} \times 10^{48}$
Luminosity $L_{\gamma,\mathrm{iso}}$ (erg s^{-1})	$1.02^{+2.84}_{-0.80} \times 10^{49}$
f parameter	2.58 + / − 0.37

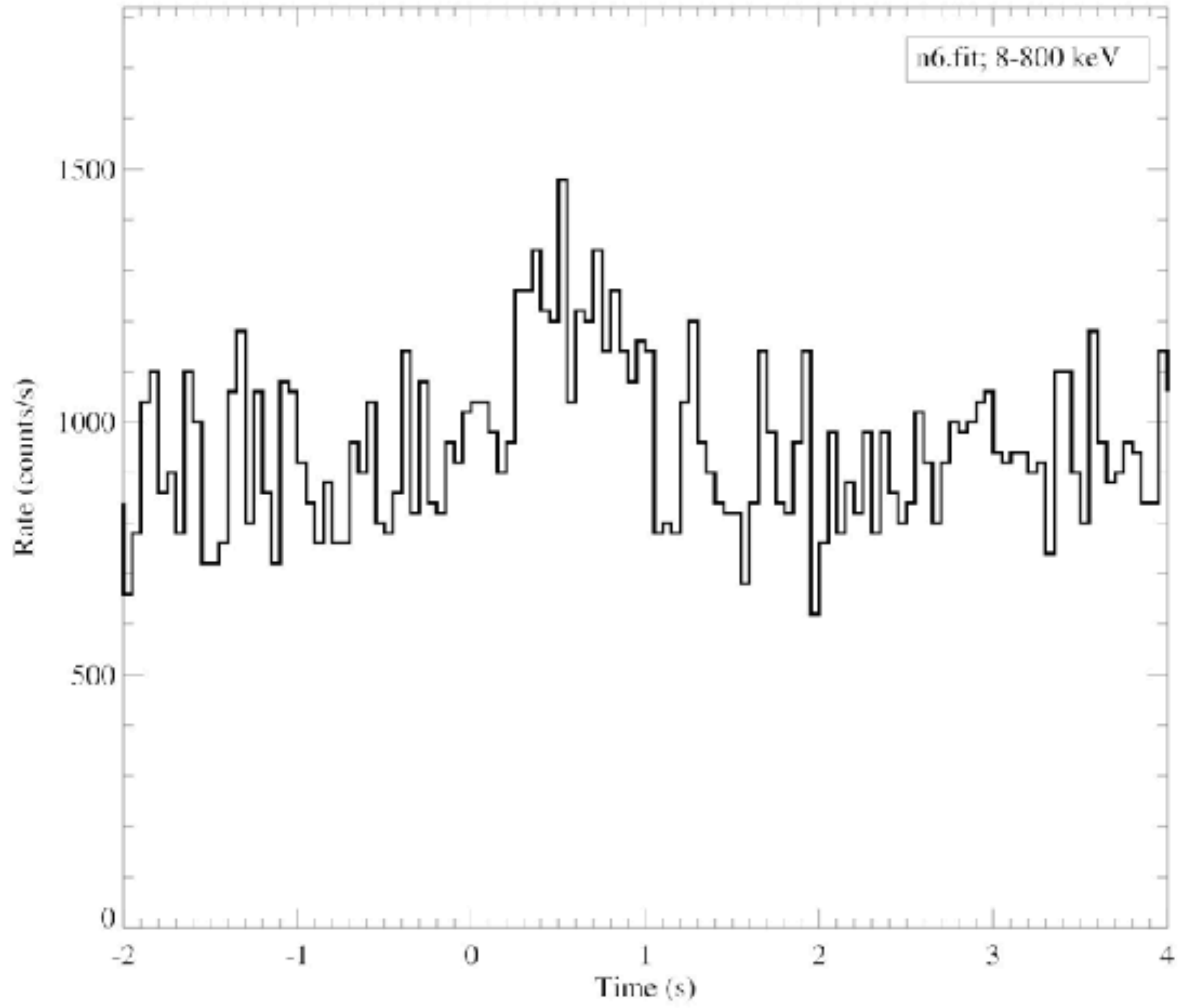
If it looks like a duck, walks like a duck and quacks like a duck, then it just may be a duck.

(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_{out}:

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

The dimensionless ISCO radius follows

$$\tilde{R}_{\rm ISCO} = R_{\rm ISCO}c^2/GM_{\rm BH} = 3 + Z_2 - {\rm sgn}\left(\chi_{\rm BH}\right)\sqrt{\left(3-Z_1\right)\left(3+Z_1+2Z_2\right)}$$

Dynamical ejecta mass M_{dyn}

$$M_{\rm dyn} = M_{\rm NS}^{\rm b}\left\{\max\left[a_1 q^{n_1}\left(1-2C_{\rm NS}\right)/C_{\rm NS} - a_2 q^{n_2}\tilde{R}_{\rm ISCO}\left(\chi_{\rm eff}\right) + a_3\left(1 - M_{\rm NS}/M_{\rm NS}^{\rm b}\right) + a_4, 0\right]\right\}$$

The disc mass M_{disc}

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

The kinetic energy of the jet can be calculated by

$$E_{\rm K,jet} = \epsilon\left(1-\xi_{\rm w}\right)M_{\rm disc}c^2\Omega_{\rm H}^2 f\left(\Omega_{\rm H}\right)$$

The dimensionless spin of the final BH remnant

$$\chi_{\rm BH,f} = \frac{\chi_{\rm BH}M_{\rm BH}^2 + l_z\left(\bar{r}_{\rm ISCO}, \chi_{\rm BH,f}\right)M_{\rm BH}M_{\rm NS}}{M^2}$$

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

$$l_z\left(\bar{r}_{\rm ISCO}, \chi_{\rm BH,f}\right) = {\rm sgn}\left(\chi_{\rm BH,f}\right)\frac{\bar{r}_{\rm ISCO}^2 - 2\,{\rm sgn}\left(\chi_{\rm BH,f}\right)\chi_{\rm BH,f}\sqrt{\bar{r}_{\rm ISCO}} + \chi_{\rm BH,f}^2}{\sqrt{\bar{r}_{\rm ISCO}}\left(\bar{r}_{\rm ISCO}^2 - 3\bar{r}_{\rm ISCO} + 2\,{\rm sgn}\left(\chi_{\rm BH,f}\right)\chi_{\rm BH,f}\sqrt{\bar{r}_{\rm ISCO}}\right)^{1/2}}$$

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

$$\frac{dE}{d\Omega}(\theta) = E_{\rm c}e^{-\left(\theta/\theta_{\rm c,j}\right)^2}, \quad \Gamma(\theta) = \left(\Gamma_{\rm c}-1\right)e^{-\left(\theta/\theta_{\rm c,j}\right)^2} + 1$$

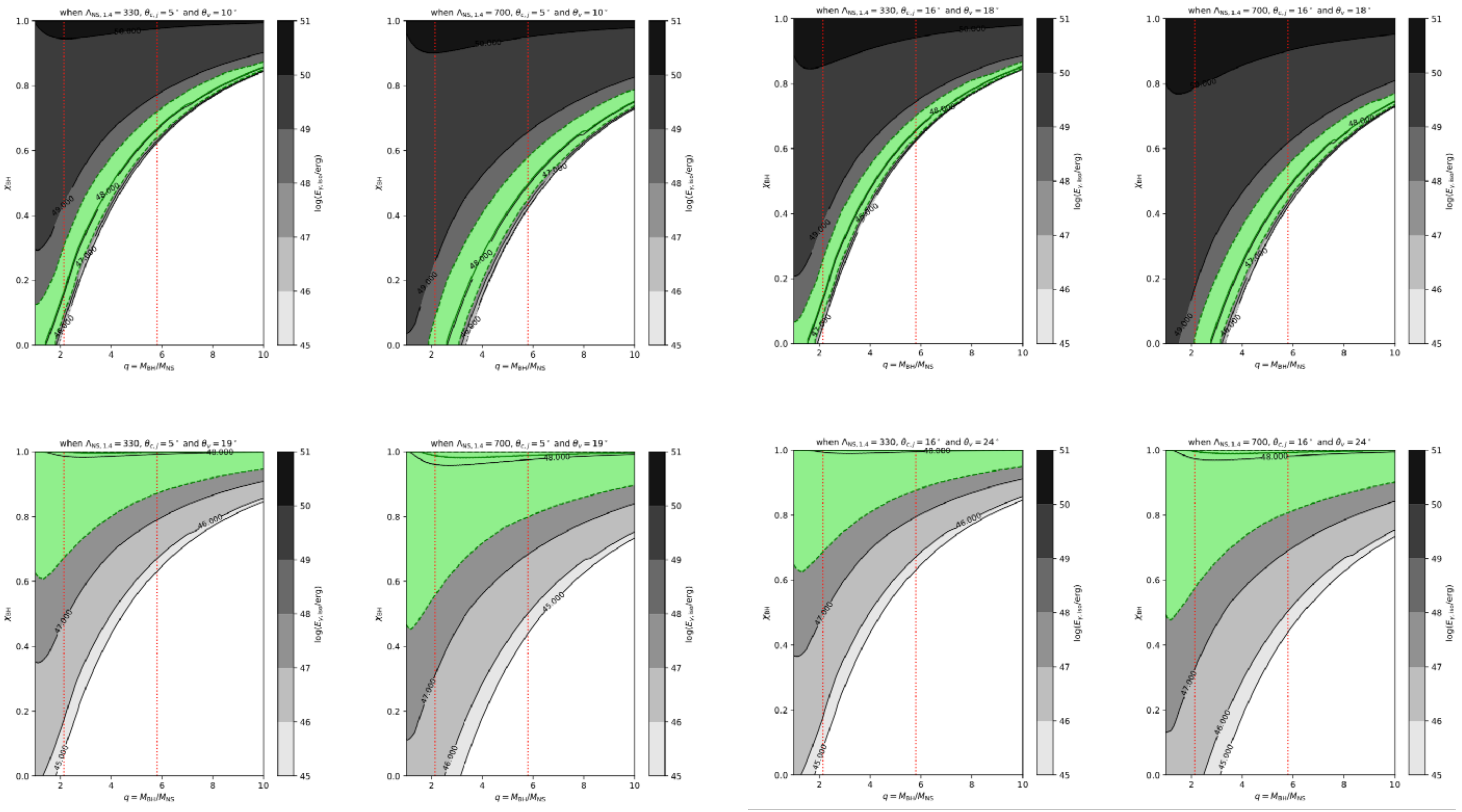
At the viewing angle θ_v, the isotropic gamma-ray radiation energy can be estimated as

$$E_{\gamma,iso}\left(\theta_v\right) \simeq \eta_\gamma\int\frac{D_{\rm p}^3}{\Gamma}\frac{dE}{d\Omega}d\Omega$$

$E_{iso} = E_{iso}(M_{NS}, q, \varepsilon, \xi_w, \eta_\gamma, \Gamma_c, \theta_{jet}, \theta_{obs}, \Lambda_N \ldots)$

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

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

Magnetic dipole radiation luminosity

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

Zhang, B. 2016, 2019

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

$$L_{\gamma,\rm iso} = \eta_\gamma\left(L_{\rm e,dip} + L_{\rm B,dip}\right)$$

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) $a = a_{min} = r_s(m_{BH}) + 2.4 r_s(m_{NS})$ ($r_{NS} = 2.4\, r_s$ for neutron star) at the merger time; (4) mass-ratio q lies in [2.142, 5.795]. **$\hat{q}_{NS}$ lies in [1.25, 1.50] $\times 10^{-4}$.**

$$\hat{q}_{\rm NS} \simeq \frac{3\Omega B_p R^3}{2c\sqrt{G}M}\cos\alpha = (4.4\times 10^{-4}) B_{15} P_{-3}^{-1} R_6^3 M_{1.4}^{-1}\cos\alpha$$

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_{NS} lies in [1.75, 2.11] $\times 10^{26}$ e.s.u

cCBC with Constant Charge (BH-BH Merger)

Electric dipole radiation luminosity

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

Magnetic dipole radiation luminosity

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

Zhang, B. 2016, 2019

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

$$L_{\gamma,\rm iso} = \eta_\gamma\left(L_{\rm e,dip} + L_{\rm B,dip}\right)$$

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 constrains: **$\hat{q}_{BH}$ 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

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.

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.

Case 2: Increasing Charge —
(Dai 2019)

cCBC with Increasing Charge (NS/BH-BH Merger)

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 γ-ray emission:

①first and second magnetic dipole radiation

②second magnetic dipole radiation,

③electric dipole radiation,

④magnetic reconnection close to BH's equatorial plane.

And two possible post-merger mechanisms:

①magnetic reconnection at polar regions

②BZ mechanism.

Dai 2019, Zhong, S.-Q. et al 2019

cCBC with Increasing Charge (Plunging NS-BH Merger)

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.

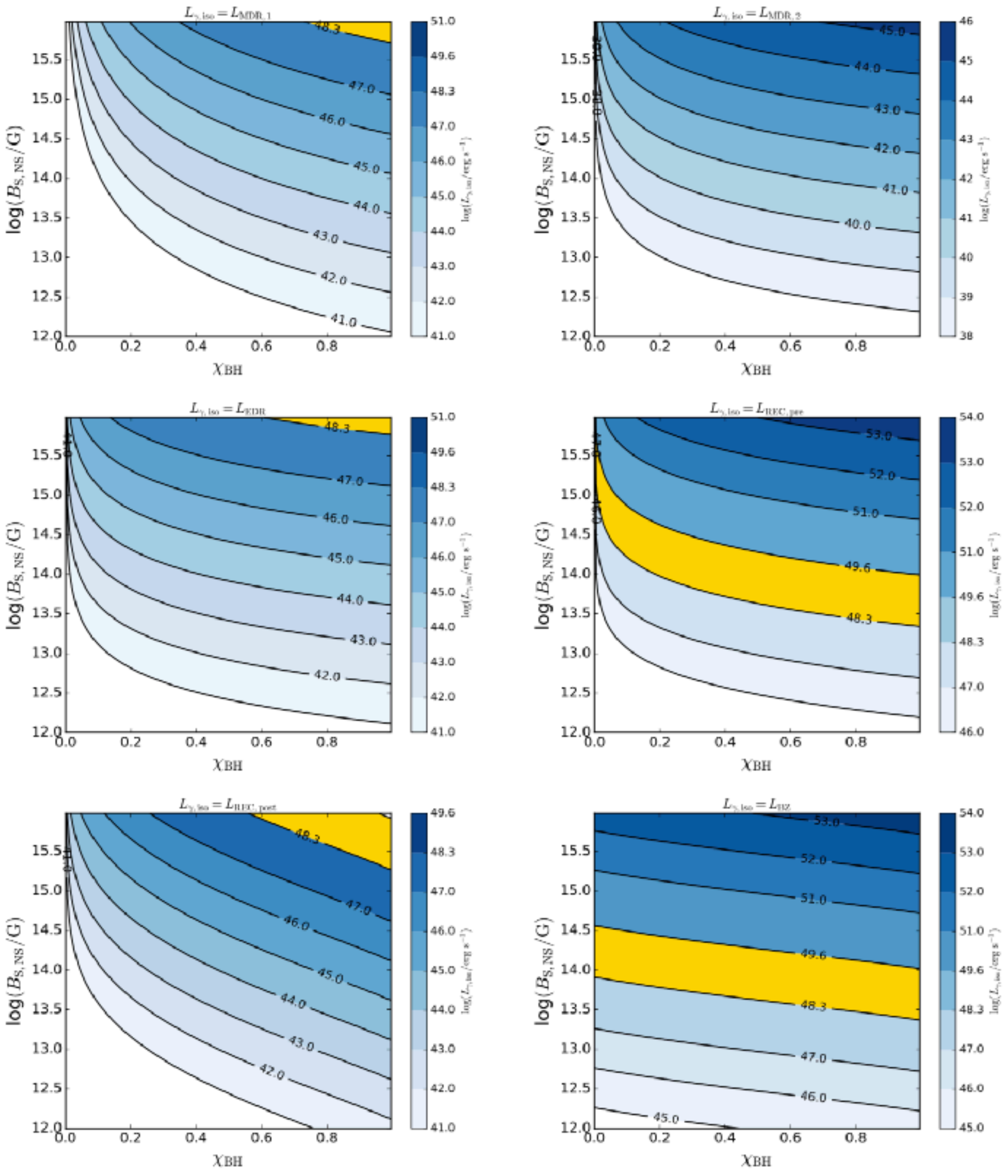
Given the following conditions:

①. The radiative efficiency $\eta_\gamma = 1$,

②. The mass ratio $q = 5.5$,

③. The minimal separation between the BH and the NS $a_{min} = 2GM_{BH}/c^2 + r_{NS}$, and the NS mass $M_{NS} = 1.4\ M_\odot$ and its radius $r_{NS} = 12$ km.

Seems more reasonable



with a large q (e.g, >5):

Charged CBC must at work to produce the observed GRB

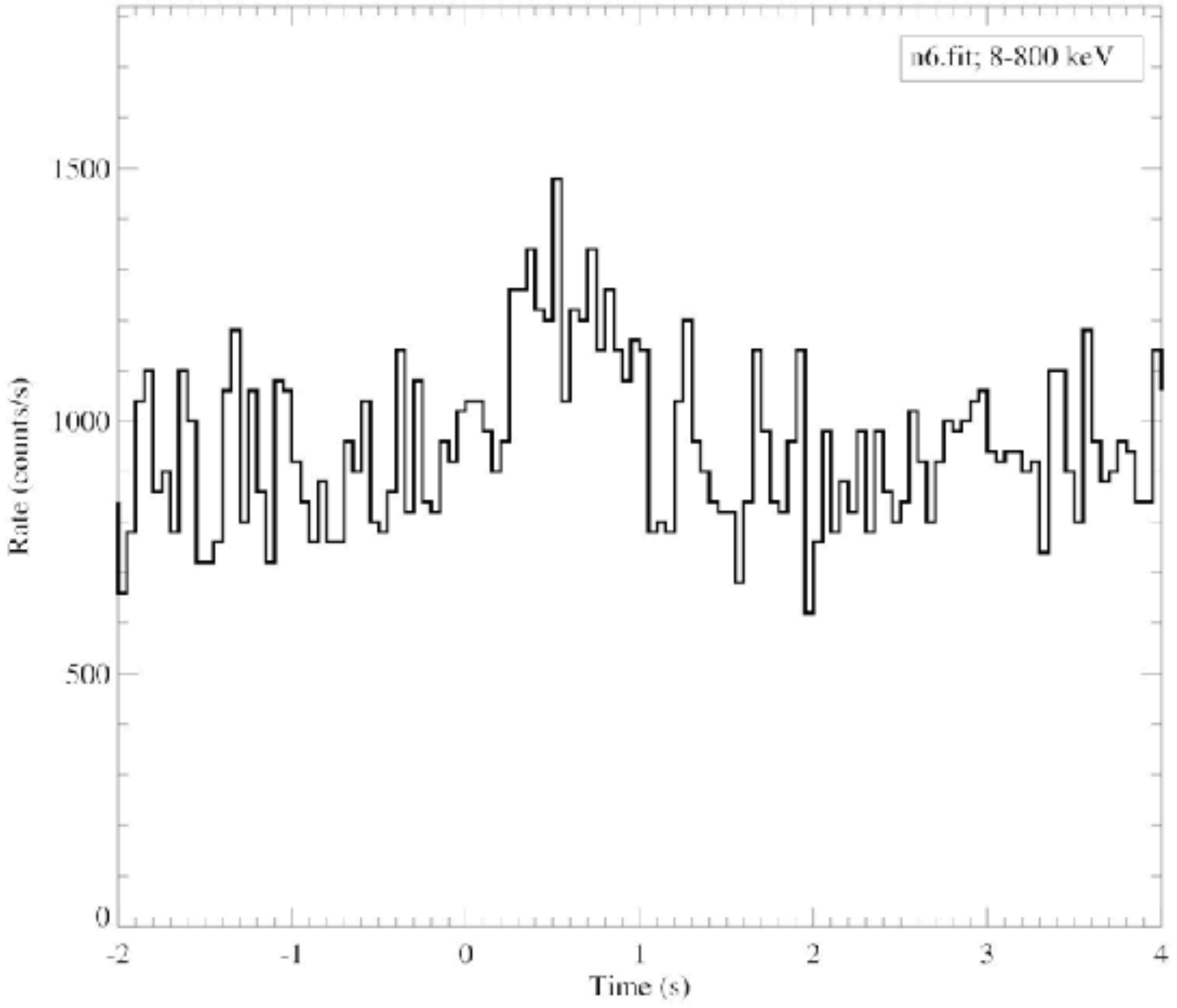
Case 1: Constant Charge —
Contrived conditions needed for a BH to carry very large charge.

Case 2: Increasing Charge —
Seems possible.

The GW-GRB Time Delay

GW

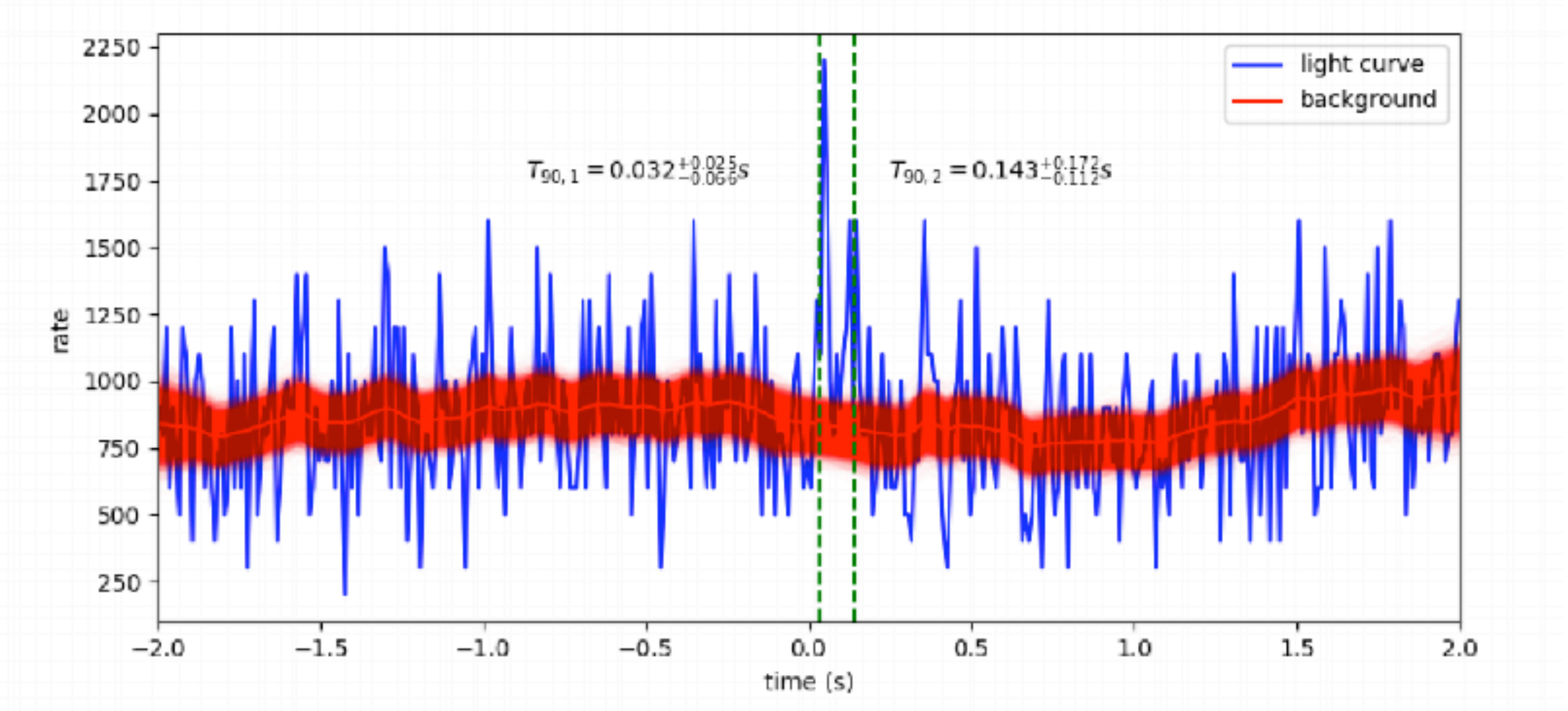
GRB 170817A
Duration: 2 s
Delay: 1.7s



GW

GBM-190816

Duration: 0.1 s
Delay: 1.57s



What can cause the delay?

(1) **Δt_{jet},**

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

①.The waiting time Δt_{wait} for a central object (BH) to form,

②. The accretion time scale Δt_{acc},

③. time Δt_{clean} for the jet to become clean.

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

Δt_{wait} is 0.

Δt_{clean} ~ 0 (BH)

Δt_{acc} is typically ~ 10 ms.

So Δt_{jet} is at most 0.01 s.

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(2) **Δt_{bo}**

delay time for the jet to break out from the surrounding medium.

For an NS-BH central engine, **Δt_{bo}** is typically **10 ms to 100 ms.**

What can cause the delay?

(1) **Δt_{jet},**

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

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③. time Δt_{clean} for the jet to become clean.

In the case GBM-180916, at least one BH exists in the pre-merger system so Δt_{wait} is 0.

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

Δt_{acc} is typically $\sim$ 10 ms.

So Δt_{jet} is at most 0.01 s.

(2) **Δt_{bo}**

delay time for the jet to break out from the surrounding medium.

For an NS-BH central engine, **Δt_{bo}** is typically **10 ms to 100 ms.**

(3) **Δt_{GRB},**

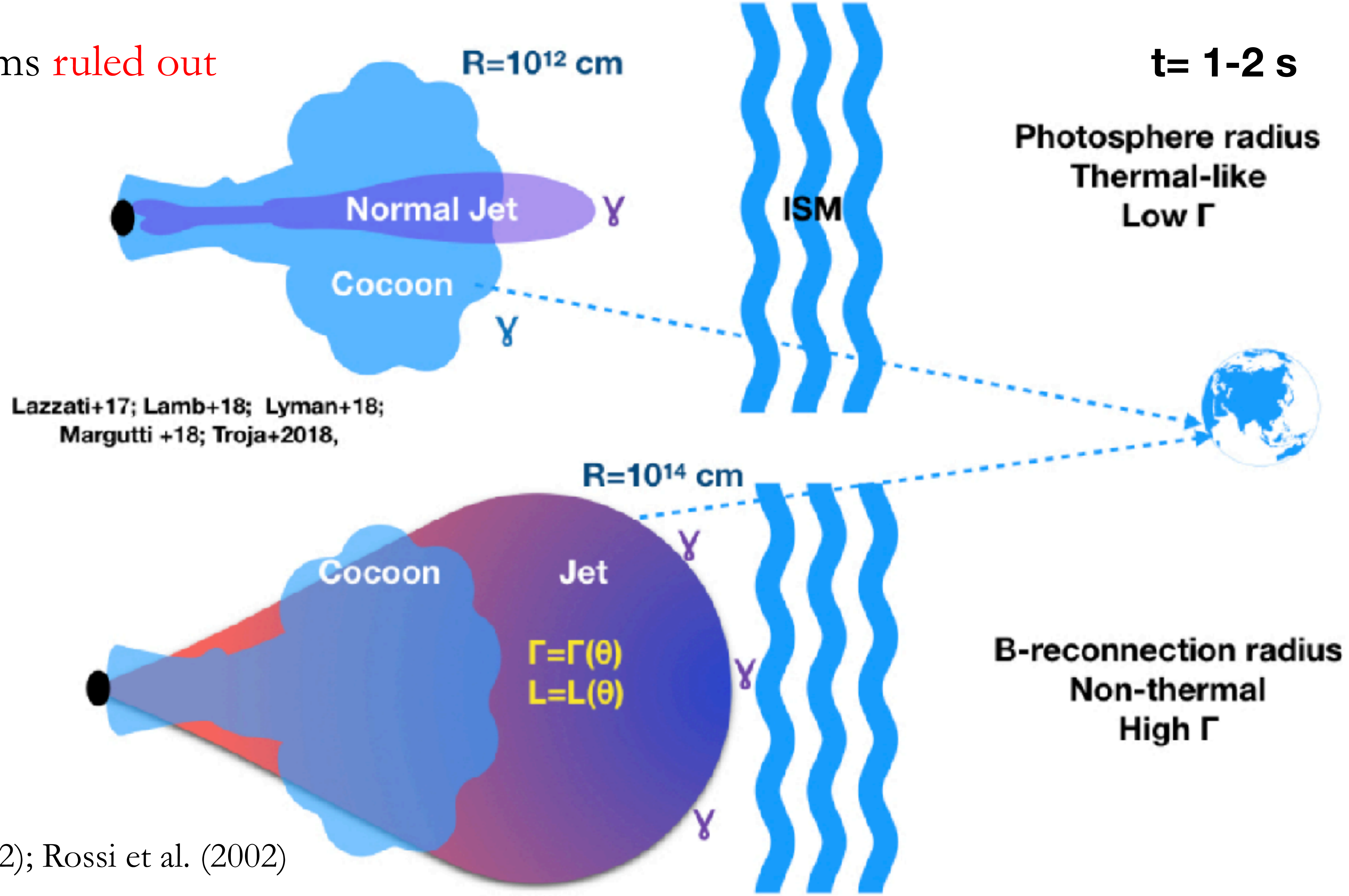
delay time for the jet to reach the energy dissipation and GRB emission site.

$\Delta t_{GRB} = R/2c\Gamma^2$. <— should mostly account for the delay

GRB 170817A & GBM-190816

Abbott et al. 2017, ApJL, 848, L13; Mooley et al. 2018, Nature, 554, 207;
B.-B. Zhang et al. 2018, Nature Communications, 9, 447

“Oversold” cocoon model, seems ruled out

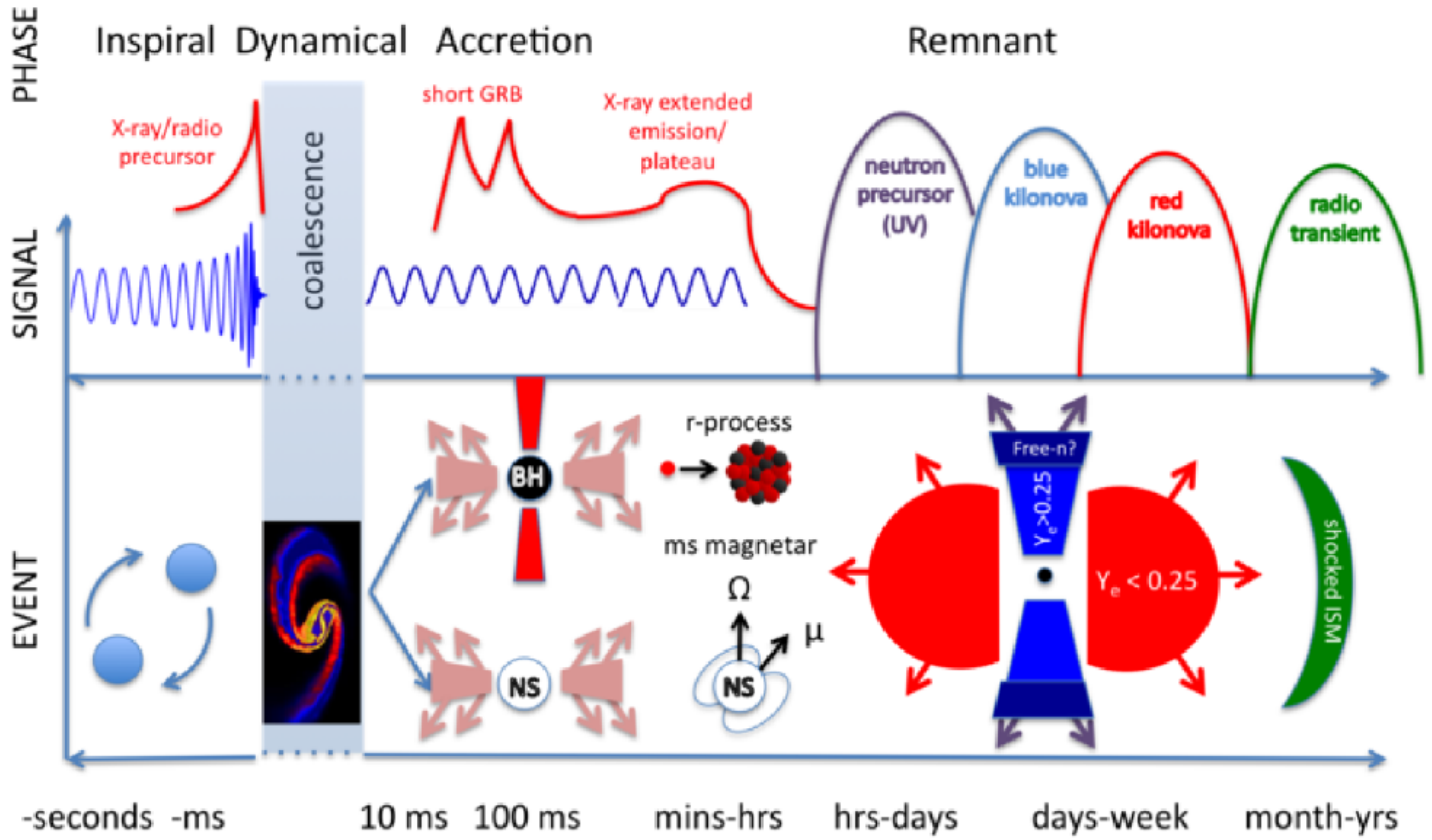


Structured jet: Zhang & Meszaros (2002); Rossi et al. (2002)

B.-B. Zhang et al 2018 $R = \Delta t \Gamma^2 c$ 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 undertanding the physical nauture 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)