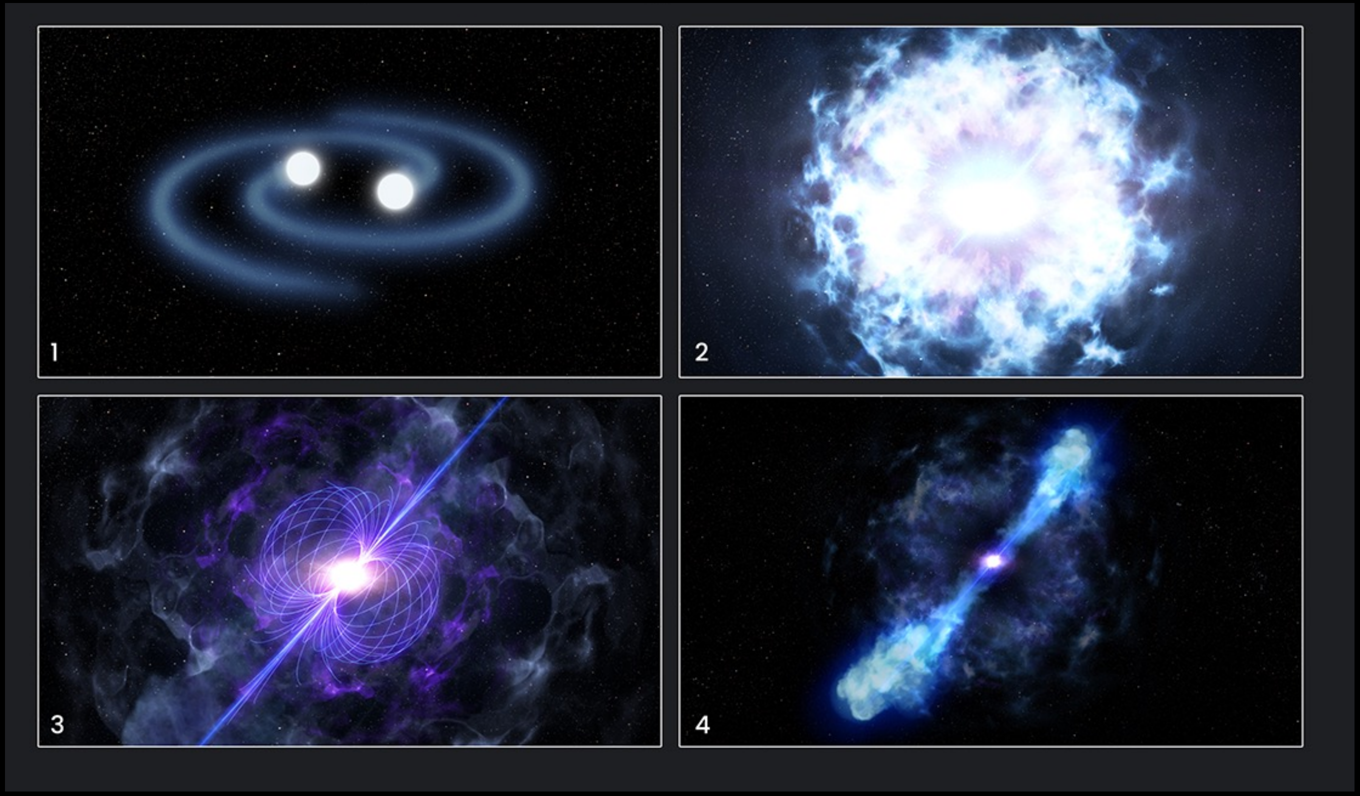
Observations of Kilonovae and theoretical implications



M. Della Valle

Capodimonte Observatory INAF-Napoli and Ariel University

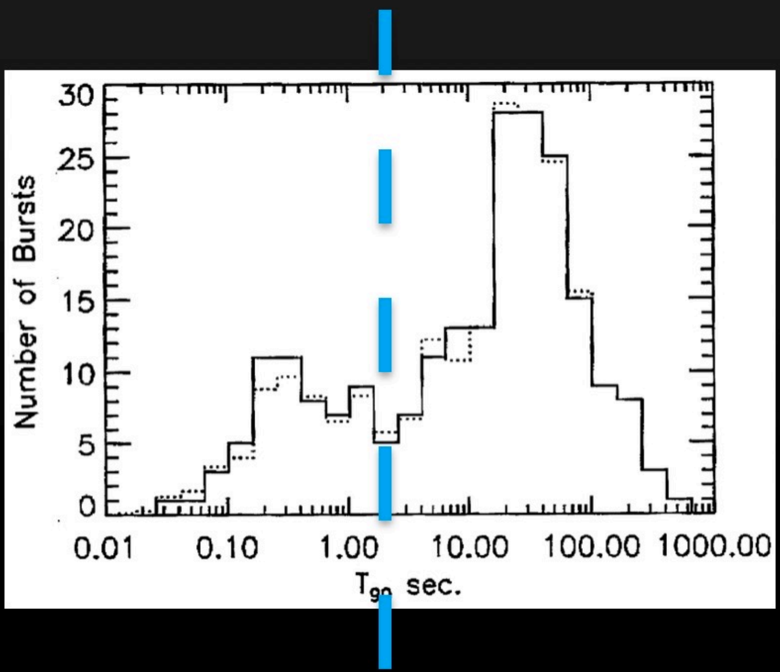
Vulcano Workshop 2022: Frontier Objects in AstroPhysics and Particle Physics
Elba, September 26th - October 1st

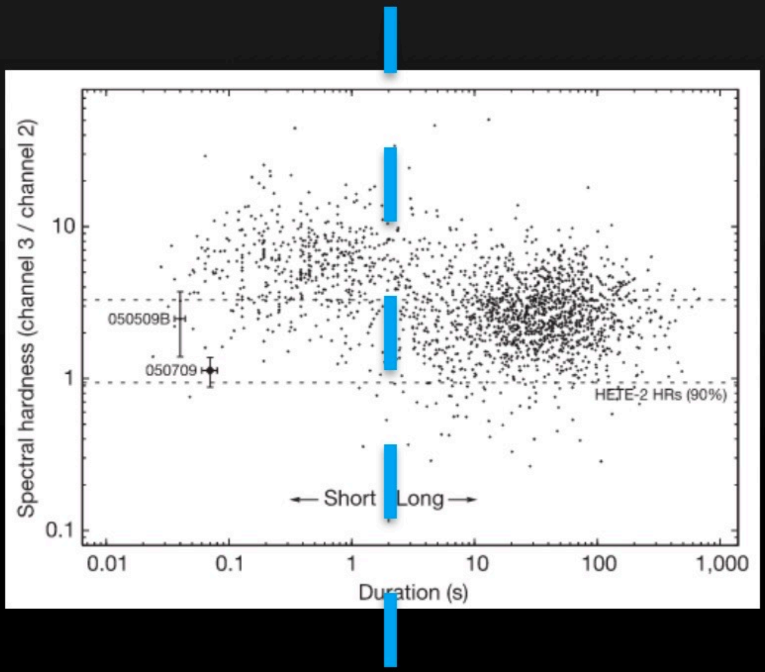
Summary

- GRBs background
- KN topics that are (relatively) well established
- KN open issues (post-merger remnant and rates)
- synergy with optical telescopes → O4 and O5
- Conclusions

Gamma-ray bursts

Two "families" of GRBs





Short and *Long* GRBs

(Kouveliotou+ 1993, Hjorth+ 2005)

<u>LONG GRBs (</u>ΔT~2s-1000s)

* Association with **bright (Ib/c)core-collapse SNe**

* Star-forming host galaxies

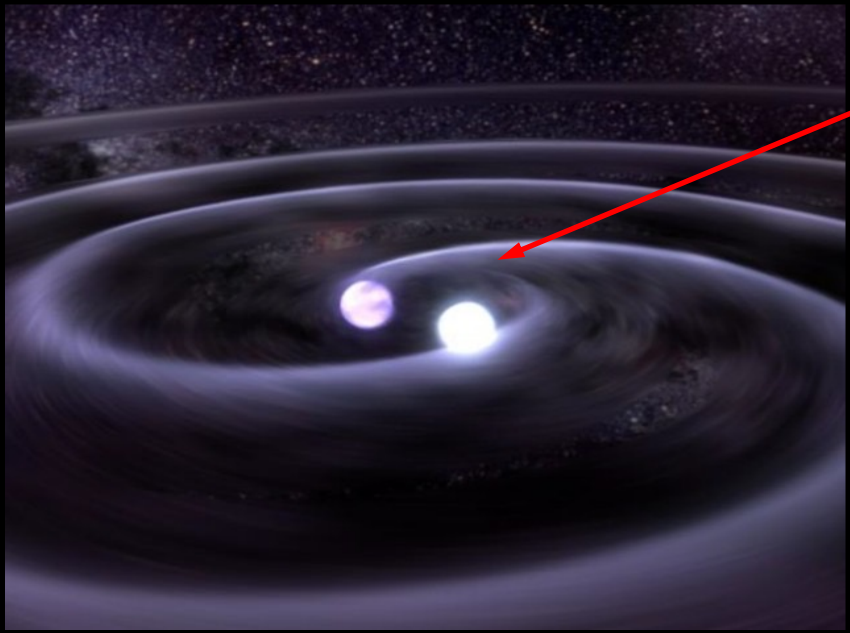
<u>SHORT GRBs (</u>ΔT <2s)

* Binary compact object mergers **(NS+NS; BH+NS)**

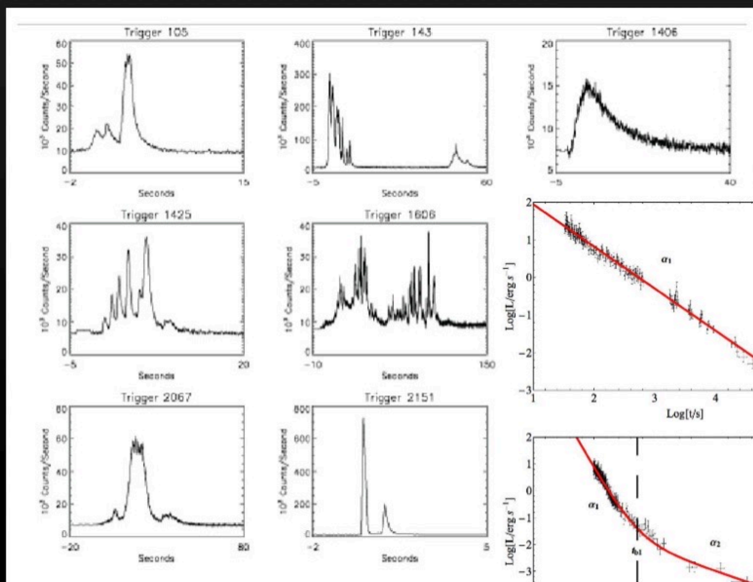
* Occur in all types of galaxies (Es → Spirals)

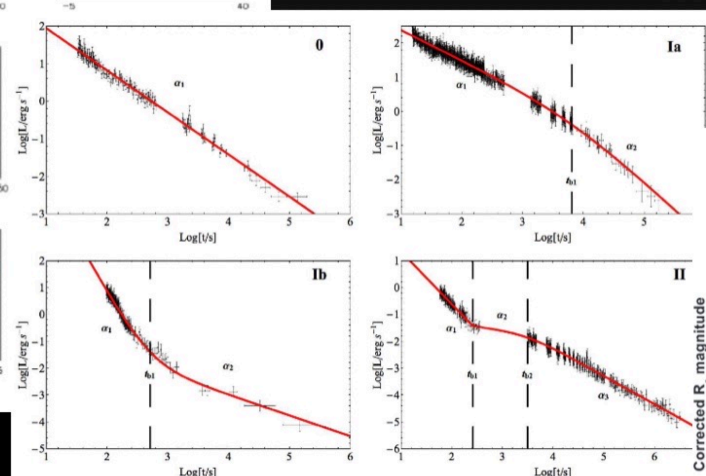
* Normally **not** associated with recent star formation regions

* Observed as kilonova events and detected also in GWs (170817)

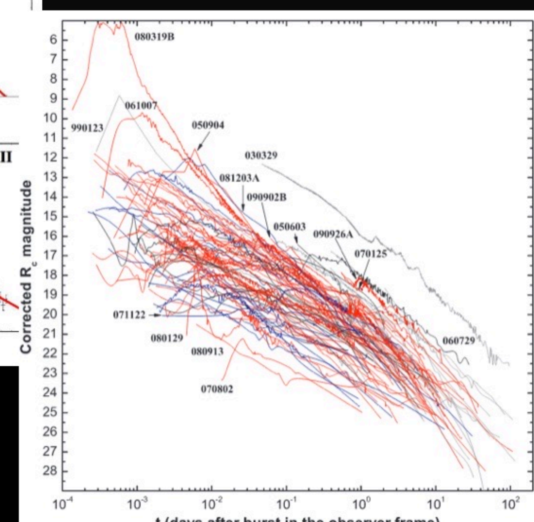


Gamma-ray bursts





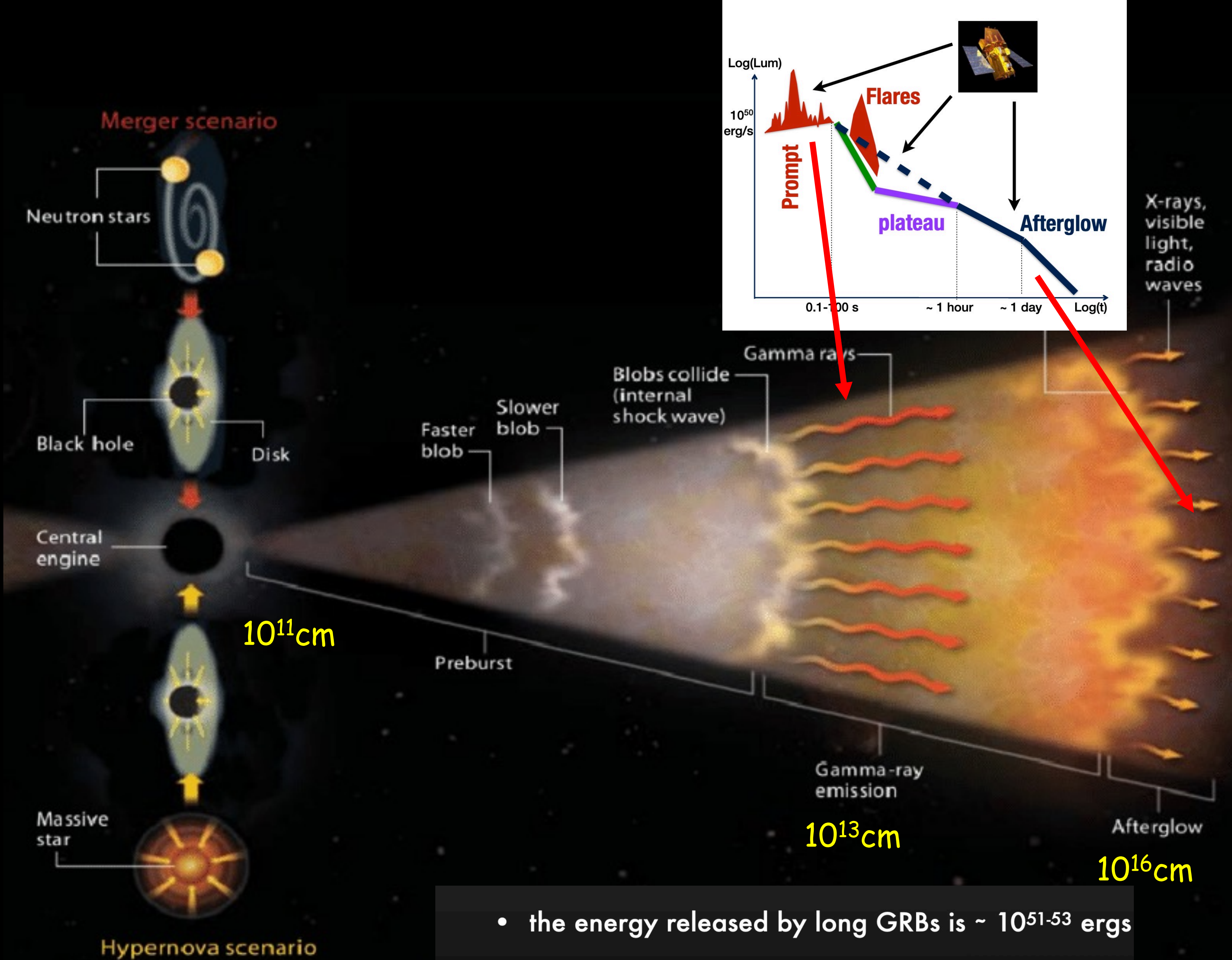
Optical wavelengths



The "prompt" emission
(10-1000 keV)

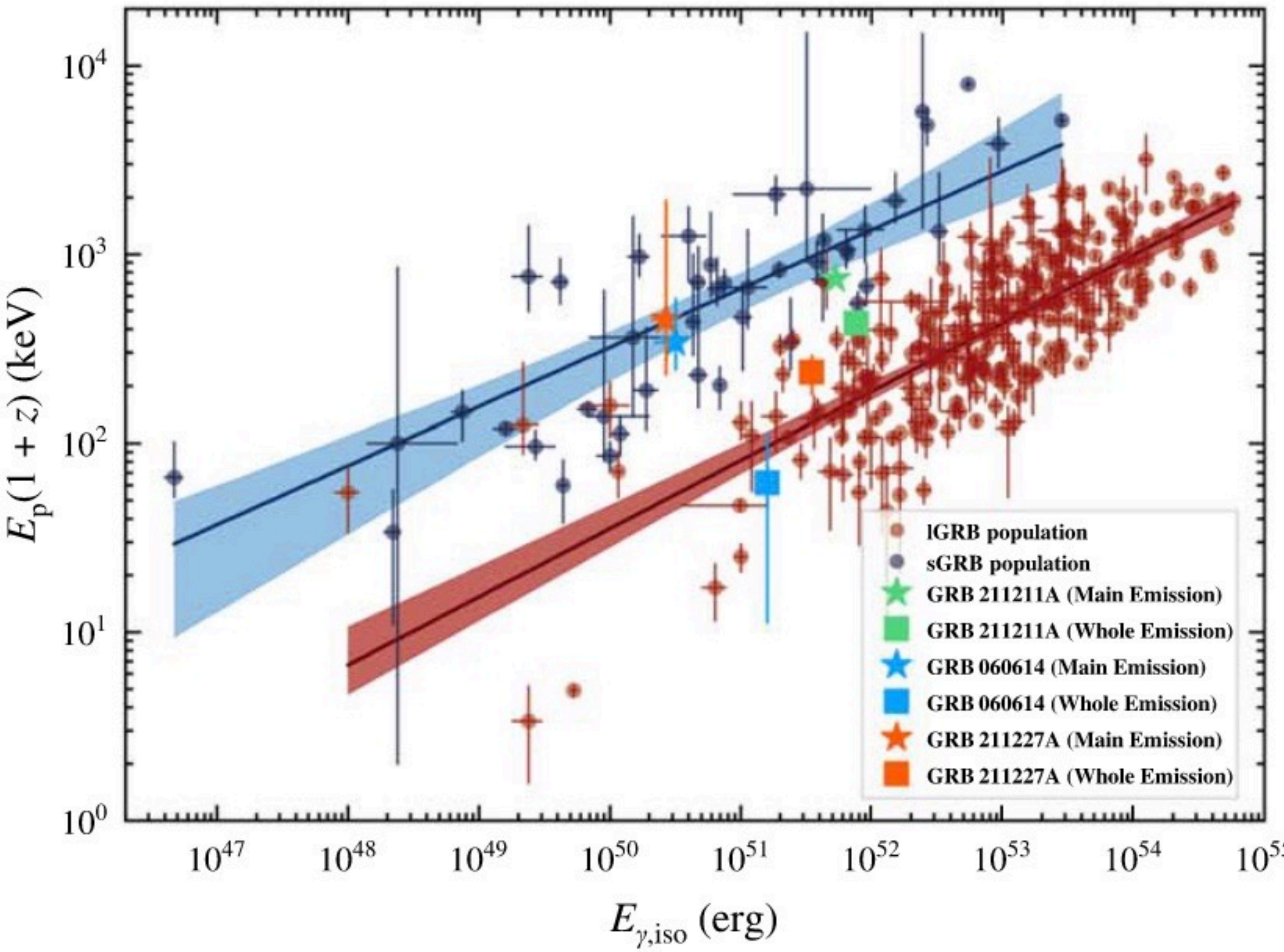
The "afterglow" emission
(0.3-10 keV)

courtesy of L. Izzo



- the energy released by long GRBs is ~ 10^{51-53} ergs
- collimated bi-polar (jet) relativistic emission

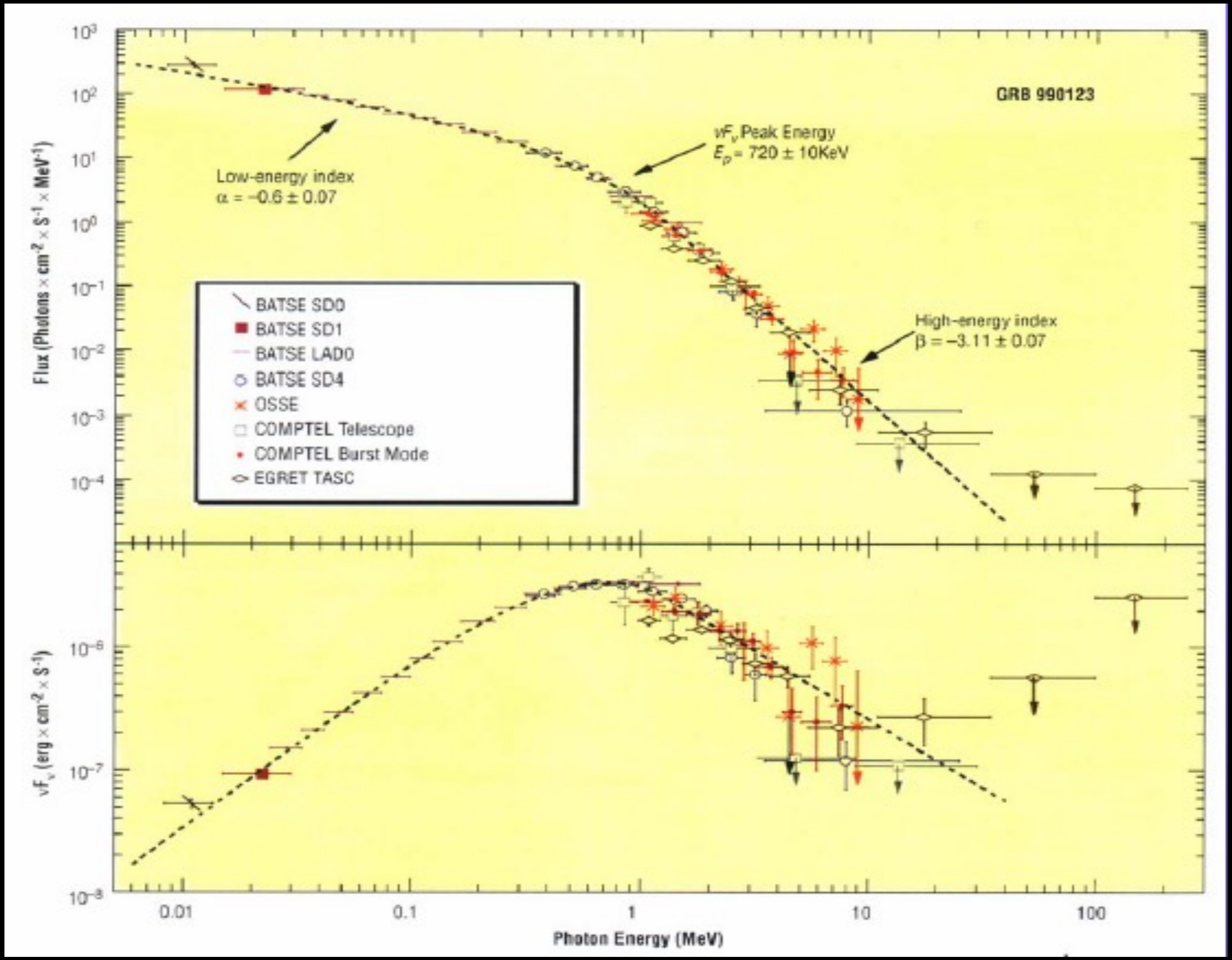
What is the engine?



Zhu et al. 2022

$E_{p,i} = E_p \times (1 + z)$

$$E_{\gamma,iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \quad \mathrm{erg}$$



Peak Energy:

It is the "color" of the GRB, i.e. the frequency at which the GRB emits the main bulk of the energy produced in the outburst

$\langle fb^{-1} \rangle \sim 500$ (Frail et al. 2001; Ghirlanda et al. 2013) ($\vartheta \sim 4^\circ$)

$\langle fb^{-1} \rangle \sim 75$ (Guetta et al. 2004) ($\vartheta \sim 9^\circ$)

$\langle fb^{-1} \rangle \lesssim 10$ (Guetta & DellaValle 2007) ($\vartheta > 25^\circ$) for sub-lum GRBs

$\langle fb^{-1} \rangle \lesssim 7$ (Pisani et al. 2016) ($\vartheta > 30^\circ$)

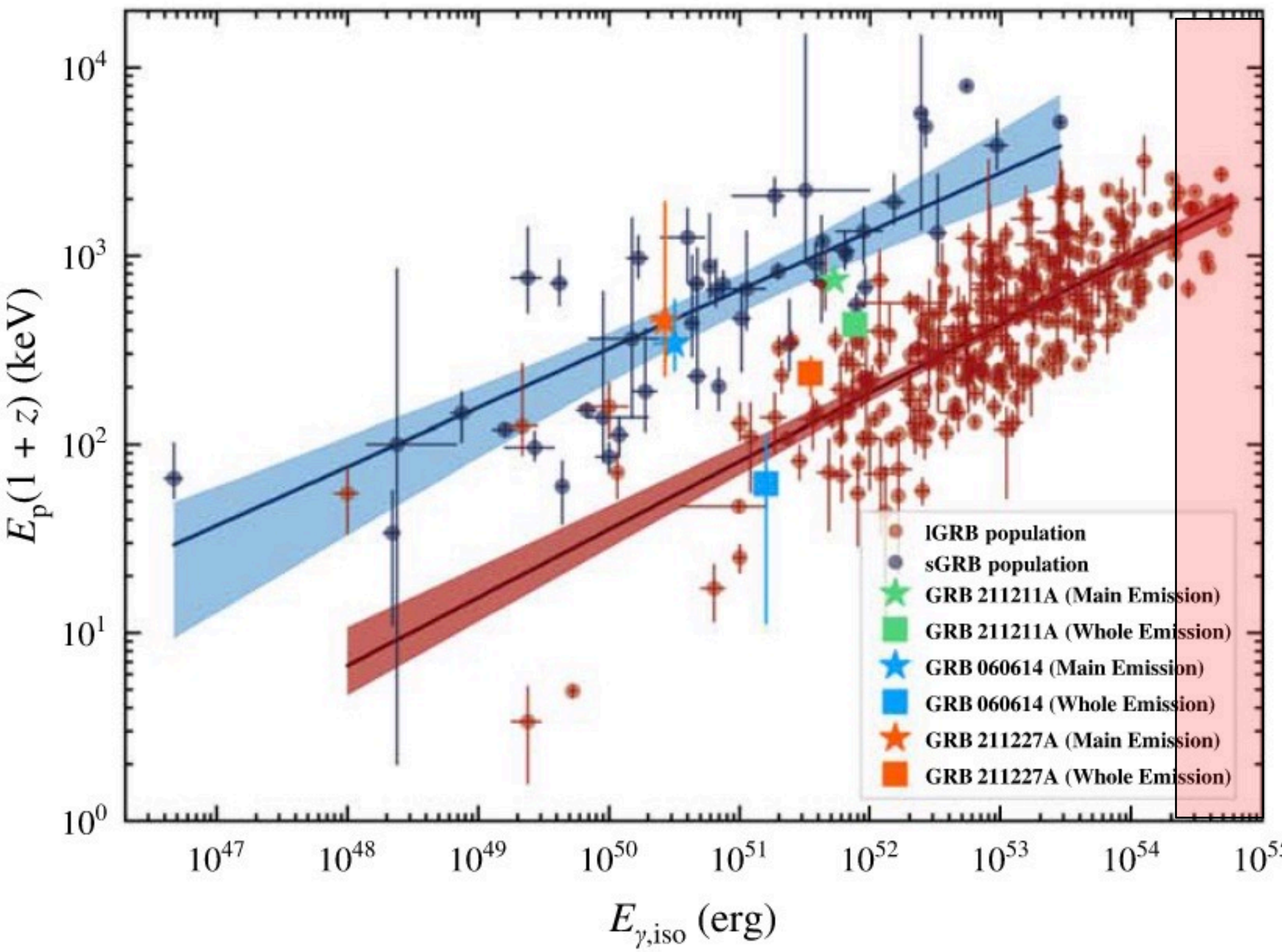
sGRB with Kilonova GW170817 (Ghirlanda et al. 2019) ($\vartheta \sim 4^\circ$)

The faster the narrower: characteristic bulk velocities and jet opening angles of gamma-ray bursts

G. Ghirlanda,[1★] G. Ghisellini,[1] R. Salvaterra,[2] L. Nava,[3] D. Burlon,[4] G. Tagliaferri,[1] S. Campana,[1] P. D'Avanzo[1] and A. Melandri[1]

[1] *INAF – Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy*
[2] *INAF – IASF Milano, via E. Bassini 15, I-20133 Milano, Italy*
[3] *APC Université Paris Diderot, 10 rue Alice Domon et Leonie Duquet, F-75205 Paris Cedex 13, France*
[4] *Sydney Institute for Astronomy, School of Physics, The University of Sydney, NSW 2006, Australia*

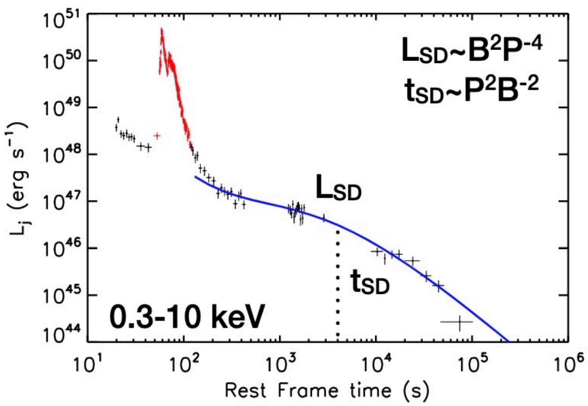
10^{50} 10^{52}



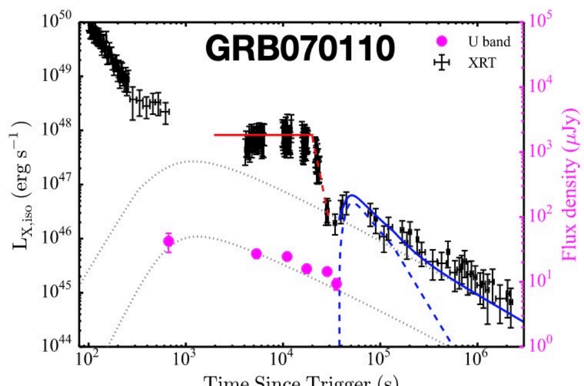
We can assume for a standard neutron star with mass $M \sim 1.4\ M_\odot$ the maximum rotation energy to be in the range 3×10^{52} erg (Lattimer & Prakash 2016) – 7×10^{52} erg (Haensel et al. 2009).

The most widely discussed models of central engines of GRBs are accreting magnetars (or in a few cases, accreting black holes).

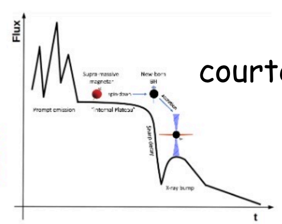
First evidence for magnetars: the GRB plateau



- magnetar **spin-down power** reproduce the **plateau** features
- **external or internal plateau**: long-lived magnetar or collapse to BH



Chen et al. 2017



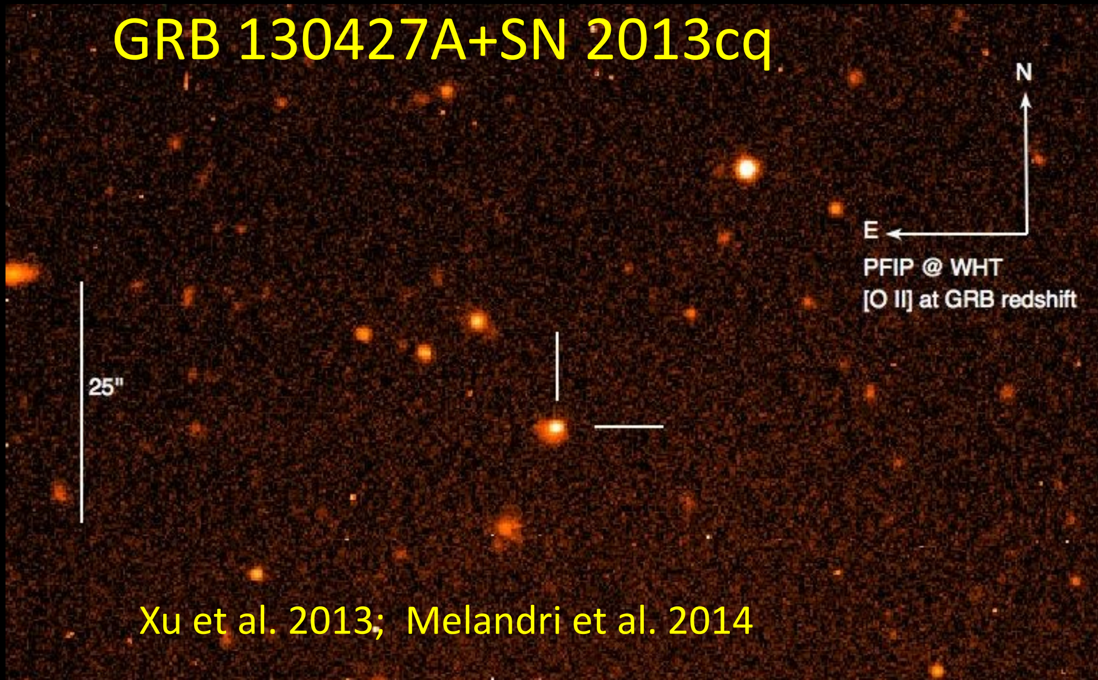
courtesy of MG Bernardini

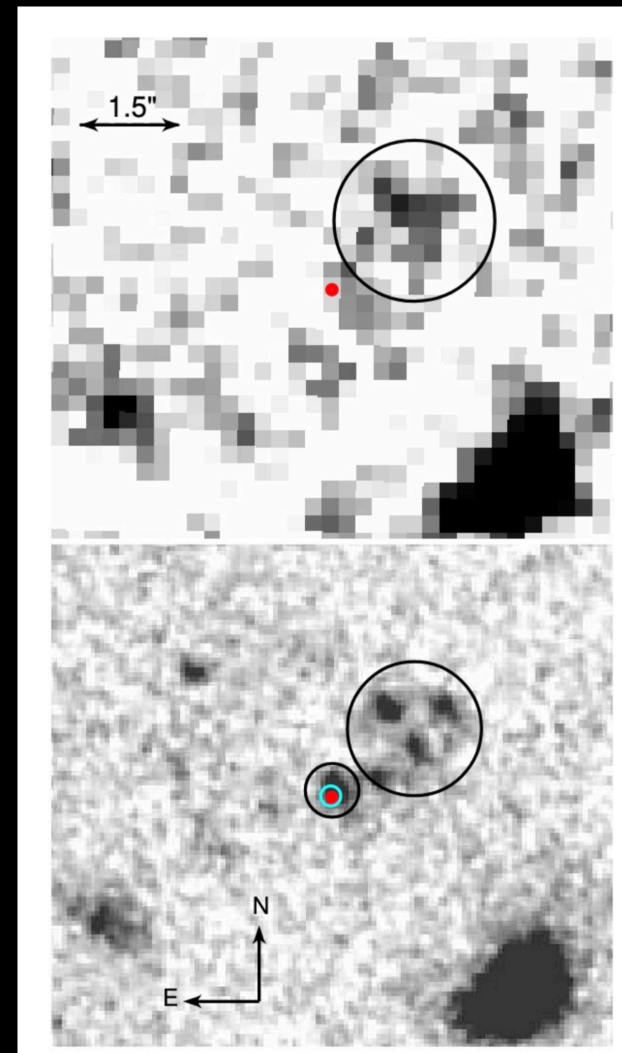
Wu et al. 2013
Yu et al. 2015
Gao et al. 2016
Chen et al. 2017

Dai & Lu 1998
Zhang & Meszaros 2001
Corsi & Meszaros 2009
Lyons et al. 2010
Dall'Osso et al. 2011

Metzger et al. 2011
Bernardini et al. 2012
Rowlinson et al. 2013, 2014
Lu & Zhang 2014
Lu et al. 2015

6

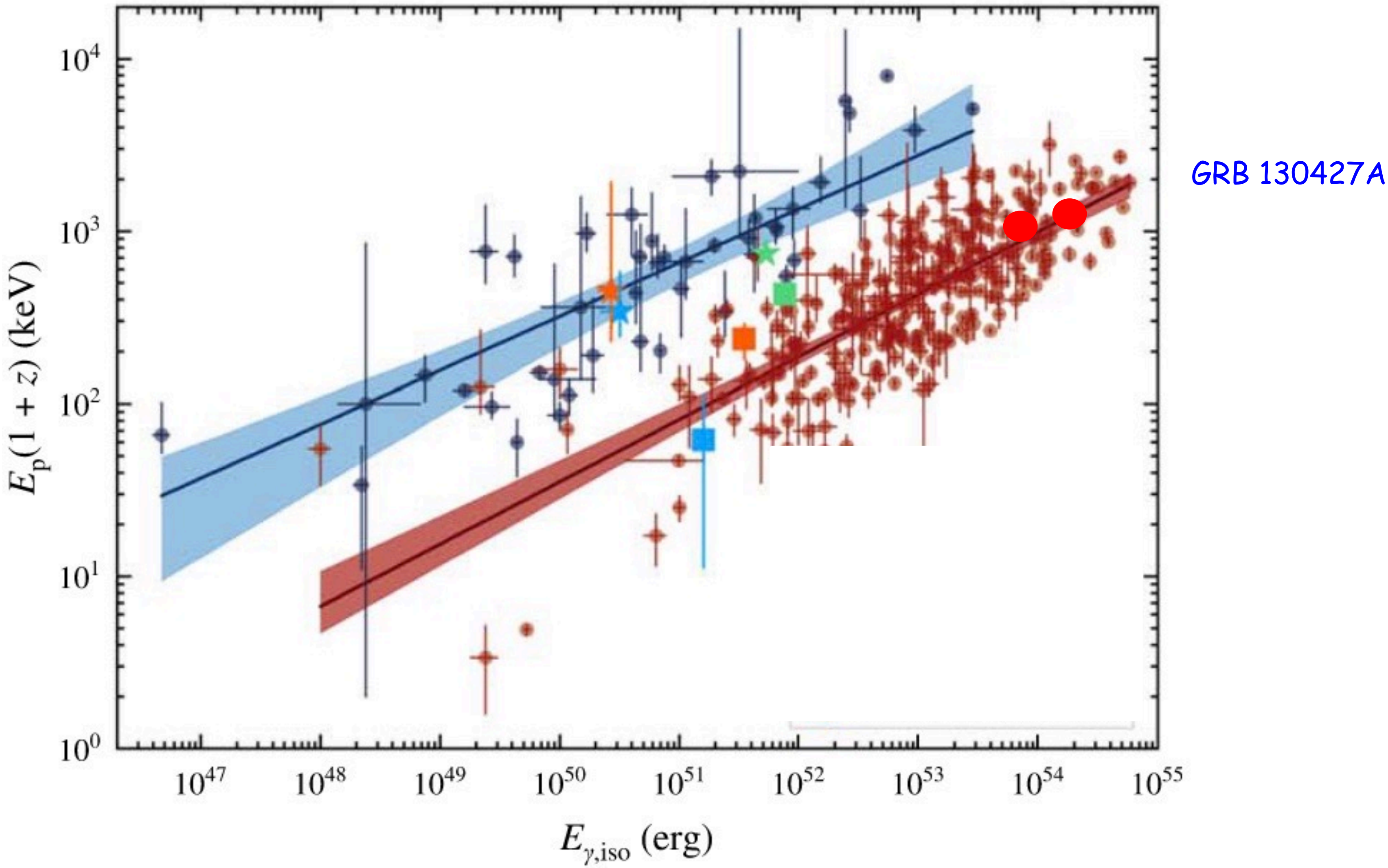




Astronomy & Astrophysics manuscript no. aaaaa ©ESO 2022
August 5, 2022

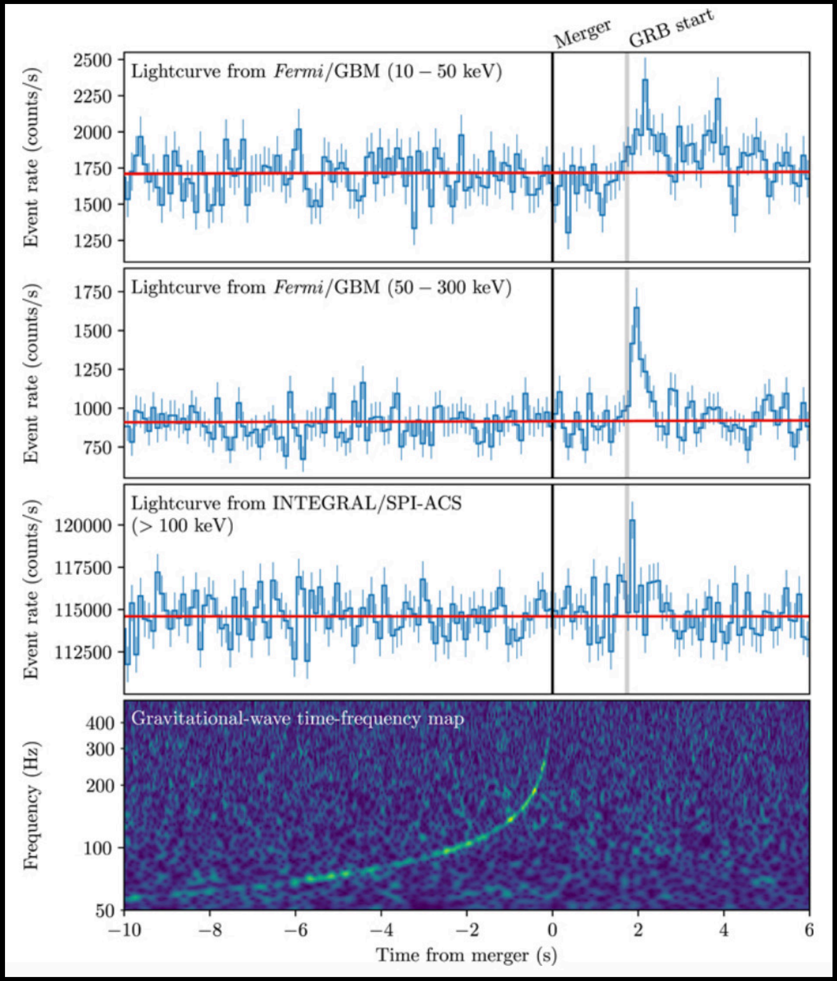
A blast from the infant Universe: the very high-z GRB 210905A ⋆

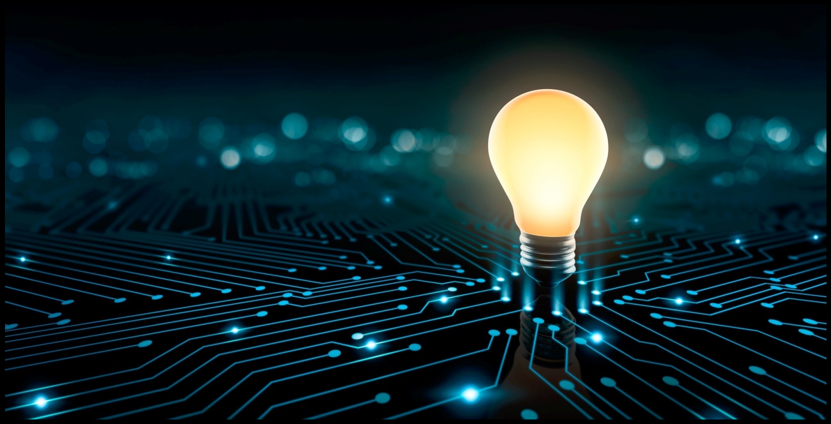
A. Rossi[1,⋆⋆], D. D. Frederiks[2], D. A. Kann[3], M. De Pasquale[4], E. Pian[1], G. Lamb[5], P. D'Avanzo[6], L. Izzo[7], A. J. Levan[8], D. B. Malesani[8,9,10], A. Melandri[6], A. Nicuesa Guelbenzu[11], S. Schulze[12], R. Strausbaugh[13], N. R. Tanvir[5], L. Amati[1], S. Campana[6], A. Cucchiara[13,14], G. Ghirlanda[5,15], M. Della Valle[16], S. Klose[11], R. Salvaterra[17], R. L. C. Starling[5], G. Stratta[1,18], A. E. Tsvetkova[2], S. D. Vergani[5,19,20], A. D'Aì[21], D. Burgarella[22], S. Covino[6], V. D'Elia[23,24], A. de Ugarte Postigo[25], H. Fausey[26], J. P. U. Fynbo[9,10], F. Frontera[1,27], C. Guidorzi[1,27,28], K. E. Heintz[9,10,29], N. Masetti[1,30], E. Maiorano[1], C. G. Mundell[31], S. R. Oates[32], M. J. Page[33], E. Palazzi[1], J. Palmerio[19], G. Pugliese[34,35], A. Rau[36], A. Saccardi[19], B. Sbarufatti[5,37], D. S. Svinkin[2], G. Tagliaferri[6], A. J. van der Horst[26,38], D. J. Watson[6,9,10], M. V. Ulanov[2], K. Wiersema[39], D. Xu[40,41], and J. Zhang (张洁莱)[42,43]

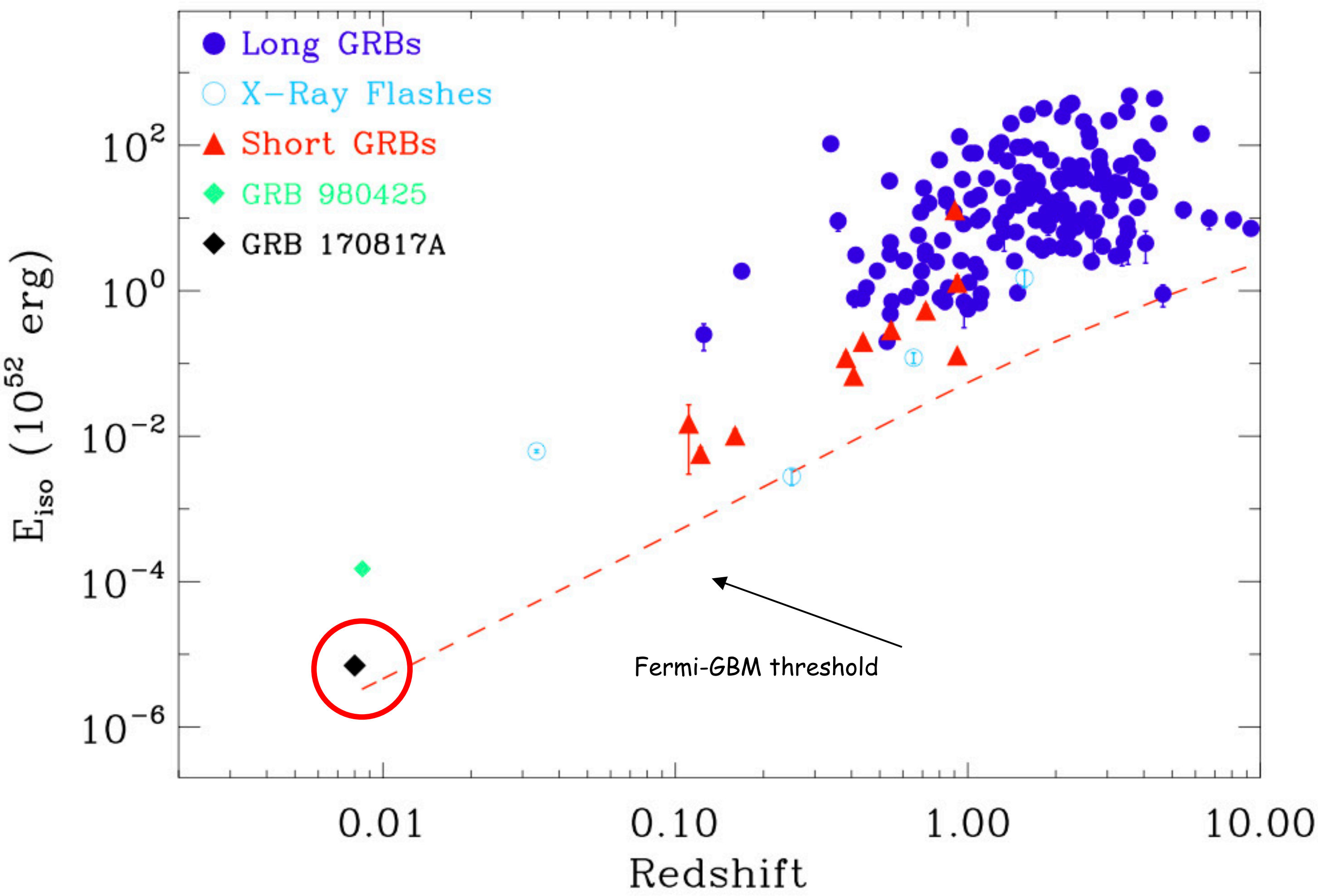


The rotational energy of a BH can reach up to 29% of its total mass, which exceeds that of neutron stars by a full order of magnitude. Indeed, rotating BHs of mass $M \sim 3M_\odot$ possess rotational energies up to $E_{rot} \sim 10^{54}$ erg. Therefore, an energy budget of $\sim 10^{53}$ erg can be conveniently extracted via the Blandford- Znajek mechanism, thereby suggesting that the central engines of some very energetic events may well be rotating BHs

Energy of GW 170817







D ~ 40 Mpc D_{max} ~ 49 Mpc MDV et al. 2018

GW170817: implications for the local kilonova rate and for surveys from ground-based facilities

Della Valle, M.[1,2,3]★ Guetta, D.[4], Cappellaro, E.[5], Amati, L.[6], Botticella. M.T.,[1] Branchesi, M.[7], Brocato, E.[8], Izzo. L.[2], Perez-Torres. M.A.[2,9], Stratta, G.[10],

ABSTRACT

We compute the local rate of events similar to GRB 170817A, which has been recently found to be associated with a kilonova (KN) outburst. Our analysis finds an observed rate of such events of $R_{KN} \sim 352^{+810}_{-281}$ Gpc^{-3}yr^{-1}. After comparing at their face values this density of sGRB outbursts with the much higher density of Binary Neutron Star (BNS) mergers of 1540^{+3200}_{-1220} Gpc^{-3}yr^{-1}, estimated by LIGO-Virgo collaboration, one can conclude, admittedly with large uncertainty that either only a minor fraction of BNS mergers produces sGRB/KN events or the sGRBs associated with BNS mergers are beamed and observable under viewing angles as large as $\theta \lesssim 40°$. Finally we provide preliminary estimates of the number of sGRB/KN events detected by future surveys carried out with present/future ground-based/space facilities, such as LSST, VST, ZTF, SKA and THESEUS.

One can conclude, admittedly with large uncertainty that either only a minor fraction of BNS mergers produces sGRB)/KN events or the sGRBs associated with BNS mergers are beamed and observable under viewing angles as large as $\theta \lesssim 40°$

PHYSICAL REVIEW LETTERS

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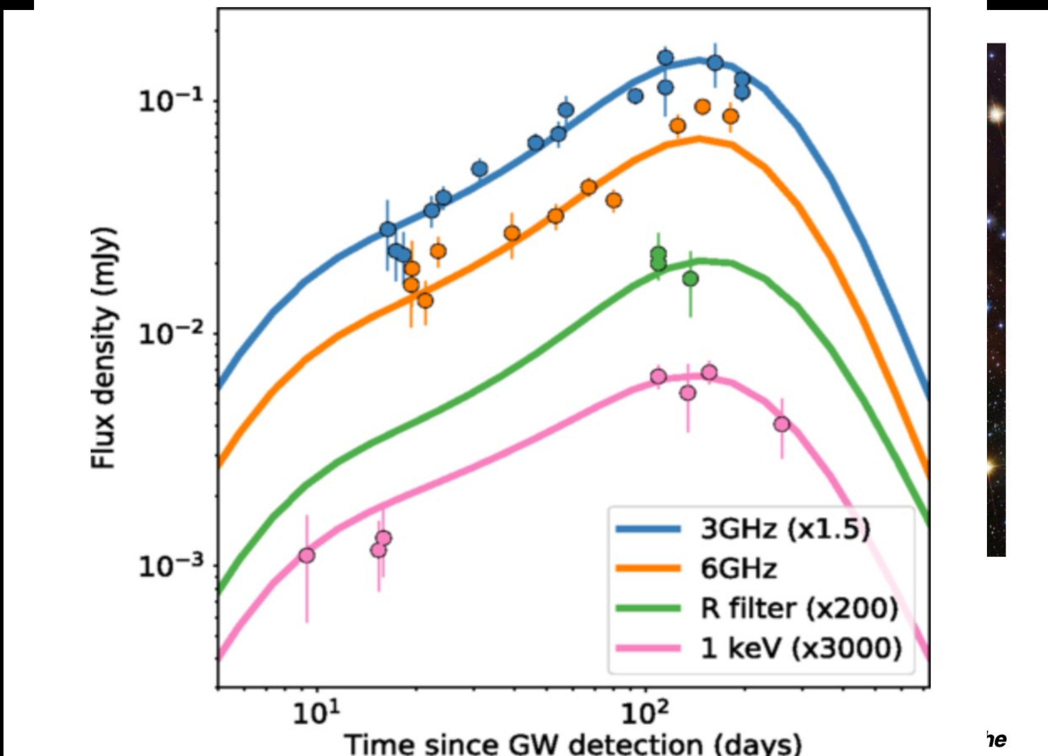
Featured in Physics Editors' Suggestion

Late Time Afterglow Observations Reveal a Collimated Relativistic Jet in the Ejecta of the Binary Neutron Star Merger GW170817

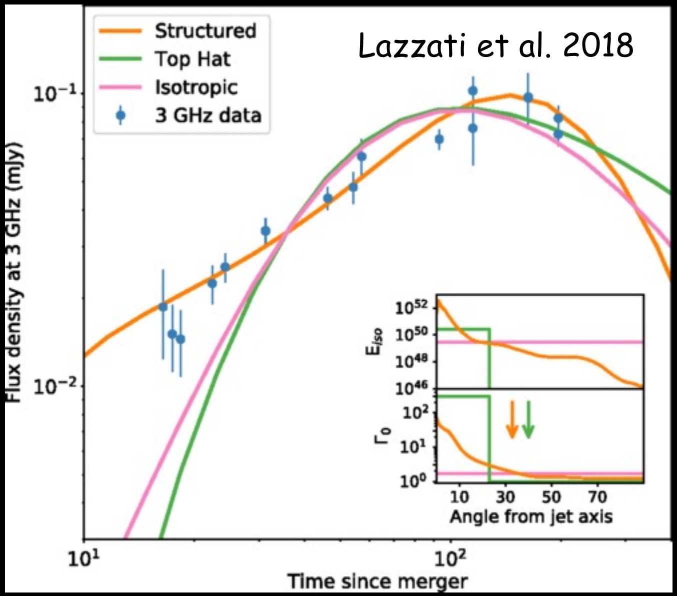
Davide Lazzati, Rosalba Perna, Brian J. Morsony, Diego Lopez-Camara, Matteo Cantiello, Riccardo Ciolfi, Bruno Giacomazzo, and Jared C. Workman

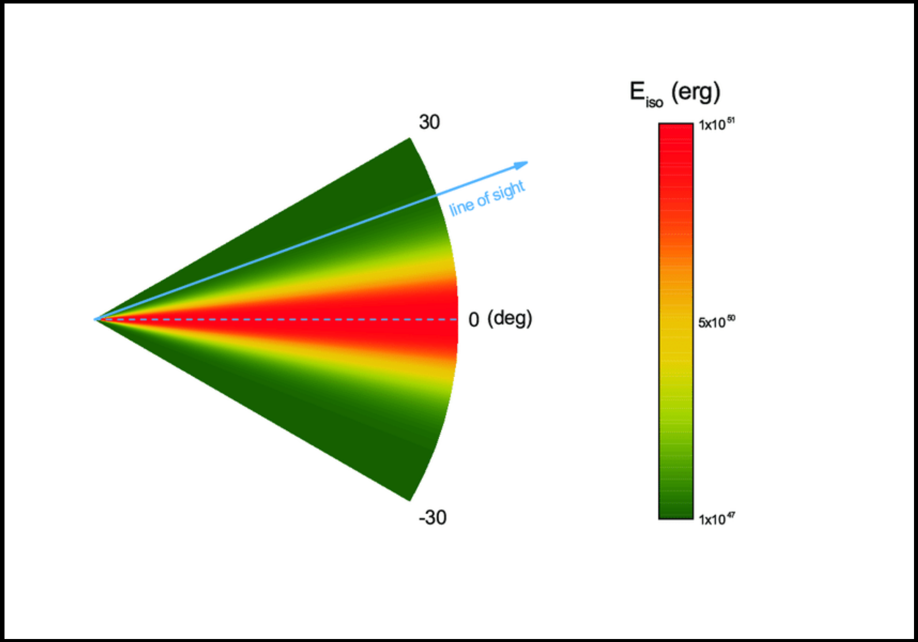
Phys. Rev. Lett. **120**, 241103 – Published 13 June 2018

The late appearance and increasing brightness of the multiwavelength afterglow of GW170817 allow these authors to constrain the geometry of its ejecta and thus reveal the presence of an off-axis jet pointing about 33° away from Earth. Confirmed by Troja et al. 2018 and Piro et al. 2019

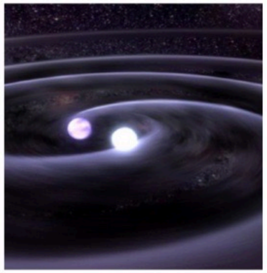


Lazzati et al. 2018


Structured
Top Hat
Isotropic
3 GHz data
Lazzati et al. 2018
Flux density at 3 GHz (mJy)
Time since merger
10^{-1}
10^{-2}
10^{1}
10^{2}
E_{iso}
Γ_0
10^{52}
10^{50}
10^{48}
10^{46}
10^{2}
10^{1}
10^{0}
10
30
50
70
Angle from jet axis


30
0 (deg)
-30
line of sight
E_{iso} (erg)
1×10^{51}
5×10^{50}
1×10^{47}

SGRB jets from BNS mergers



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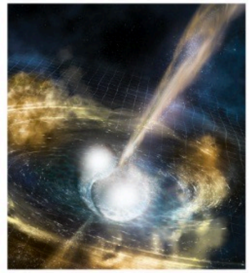


GW170817 GRB 170817A

??

jet launching mechanism?

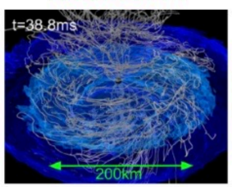
neutrino driven ✗ Just+2016 Perego+2017

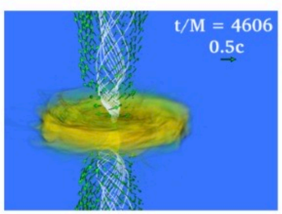
MHD driven ✓

→ need GRMHD simulations

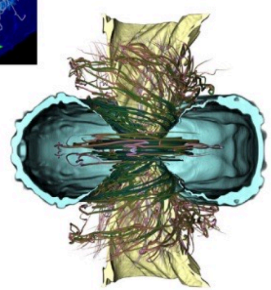
remnant/central engine nature?

Kiuchi+2014





Ruiz+2016



Kawamura+2016

BH + accretion disk

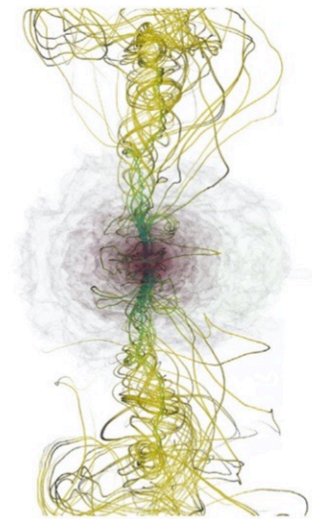
(Blandford-Znajek)

Ciolfi+2017

Ciolfi+2019

massive long-lived NS

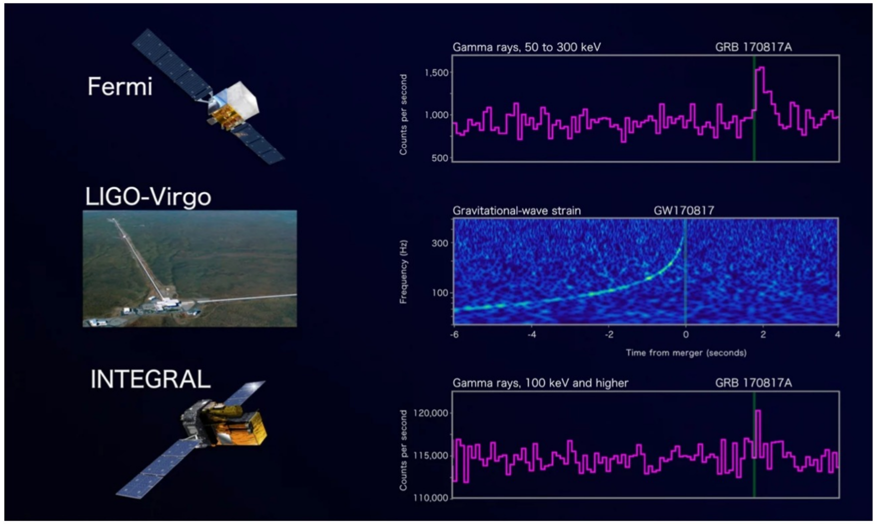
(magnetorotational)



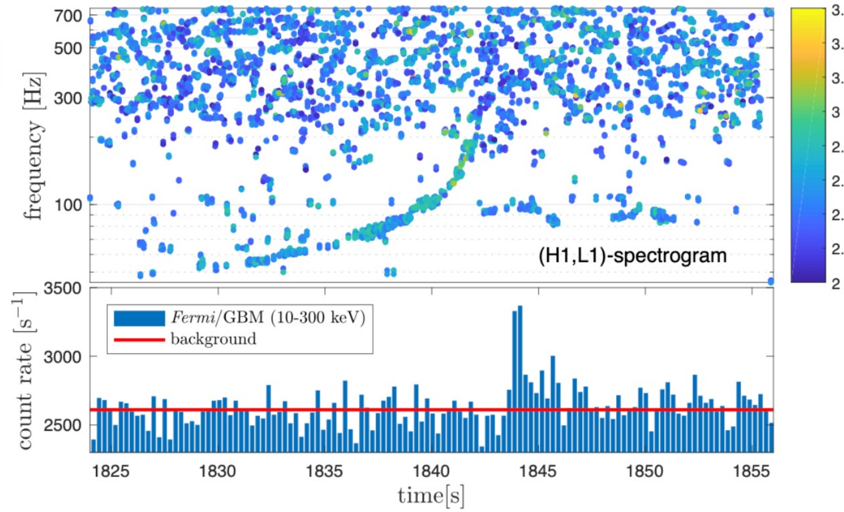
Ciolfi 2020a

courtesy of R. Ciolfi

GW170817-GRB170817A



https://www.mpg.de/11646260/neutron-star-merger-gravitational-waves



van Putten & Della Valle 2019 MNRAS 482 L46

JOURNAL ARTICLE

Observational evidence for extended emission to GW170817

Maurice H P M van Putten, Massimo Della Valle

Monthly Notices of the Royal Astronomical Society: Letters, Volume 482, Issue 1, January 2019, Pages L46–L49, https://doi.org/10.1093/mnrasl/sly166
Published: 04 September 2018 **Article history** ▾

THE ASTROPHYSICAL JOURNAL LETTERS

Multi-messenger Extended Emission from the Compact Remnant in GW170817

Maurice H. P. M. van Putten[1], Massimo Della Valle[2,3], and Amir Levinson[4]

Published 2019 April 25 •
The Astrophysical Journal Letters, Volume 876, Number 1

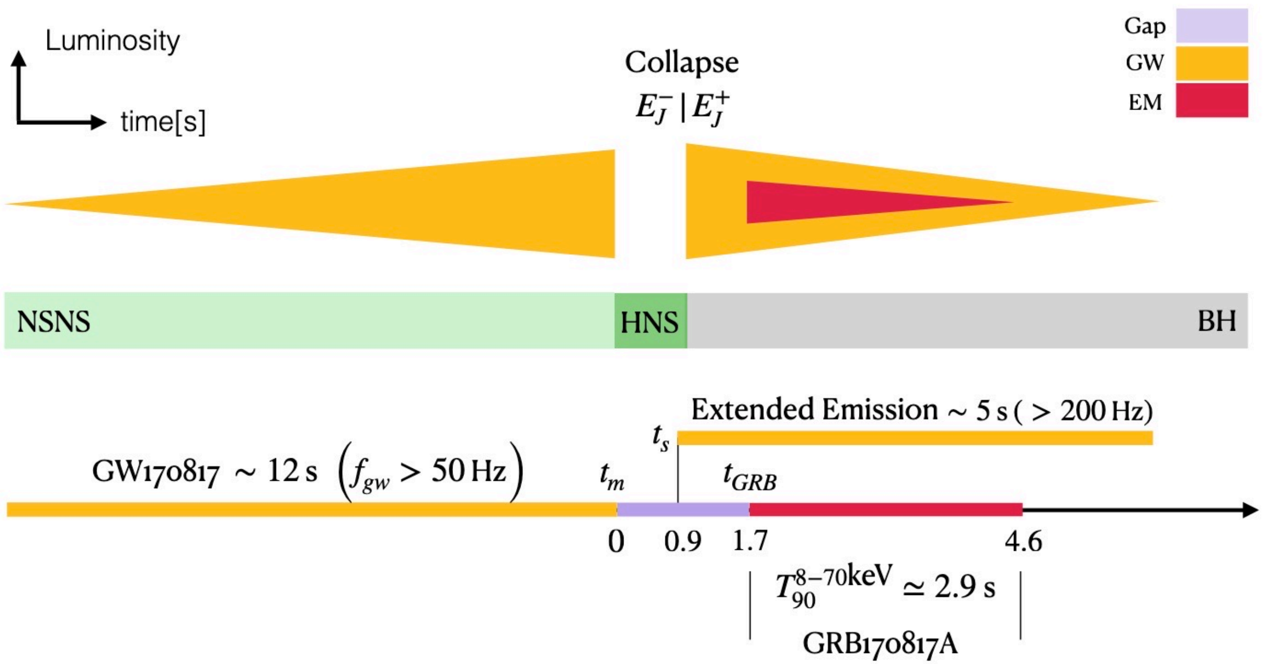
Astronomy & Astrophysics manuscript no. output ©ESO 2022
September 21, 2022

Central engine of GRB170817A: neutron star versus Kerr black hole by multimessenger calorimetry and event timing

Maurice H.P.M. van Putten[1] and Massimo Della Valle[2] submitted

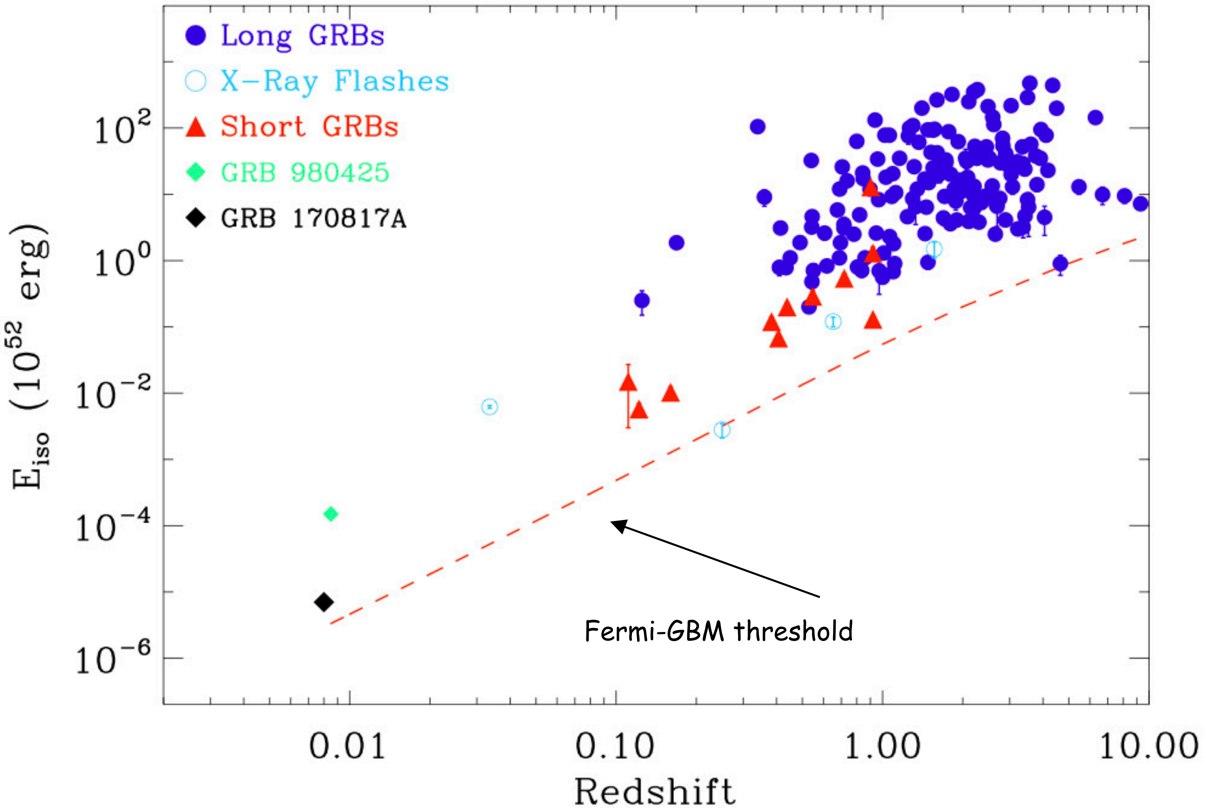
	Lifetime HNS, start-time descending branch	Duration GRB170817A, time-scale of descent	References
EM	$t_w = (0.98 \pm 0.3)$ s	$T_{90}^{(8-70)\mathrm{keV}} = (2.9 \pm 0.3)$ s	Gill et al. (2019); Pozanenko et al. (2018)
GW	$t_s = (0.92 \pm 0.083)$ s	$\tau_s = (3.0 \pm 0.09)$ s	this work

Received 2019 January 12; revised 2019 April 2; accepted 2019 April 4; published 2019 May 14



Post-merger output E_{GW} ~ 1% Mc^2 which is comparable with the whole E_J of the hyper-massive neutron star in the immediate aftermath of GW170817, yet it is consistent with E_J rejuvenated in gravitational collapse to a Kerr black hole.

Empirical constraints on the KN rate with the GW170817

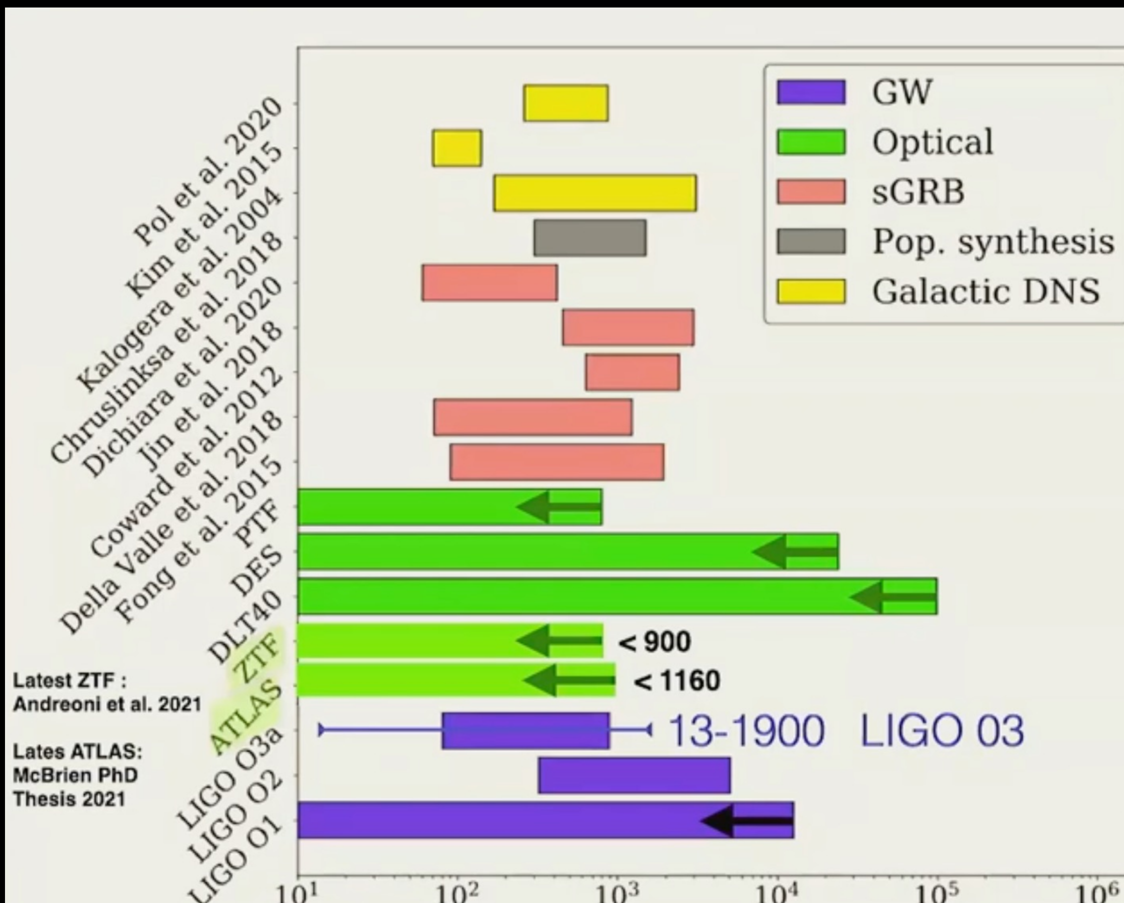


$$352^{+810}_{-281}\ \mathrm{Gpc}^{3}\ \mathrm{yr}^{-1}$$

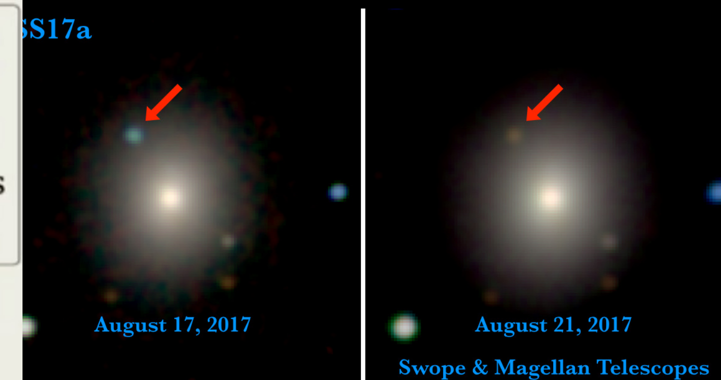
MDV et al. 2018

Kilonova rate ~ 300 $Gpc^{-3}\,yr^{-1}$

factor ~ 3 uncertainty



courtesy of S. Smartt

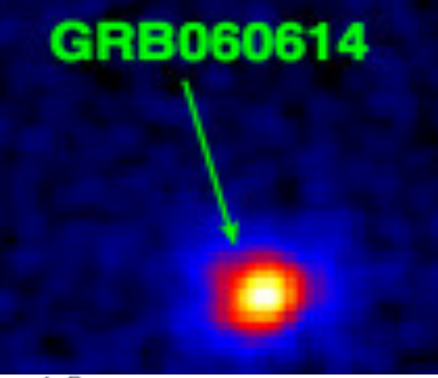


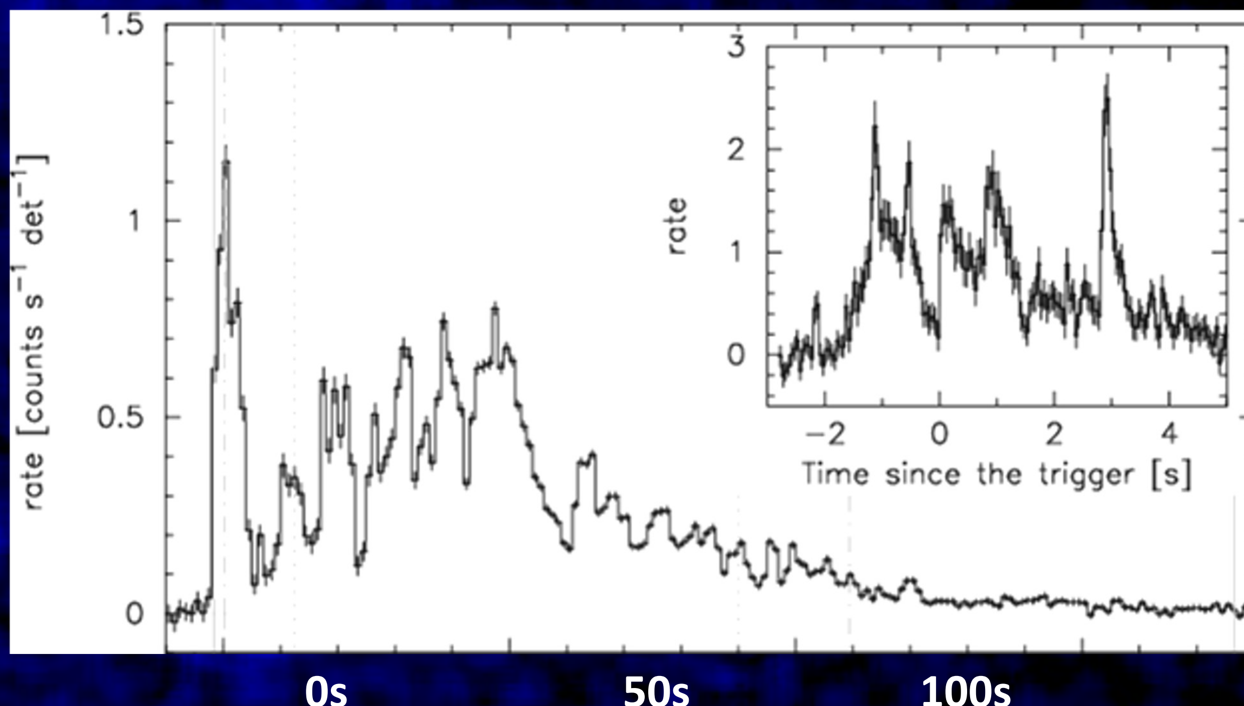
1 event per decade within 50 Mpc (D_{max} 49 Mpc)

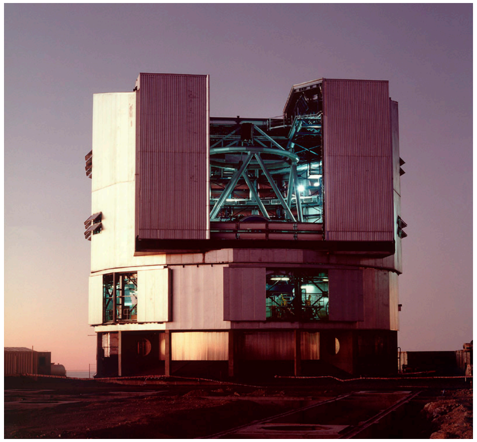
The Lightning without Thunder

Low redshift:
***z* = 0.125**

SN search!





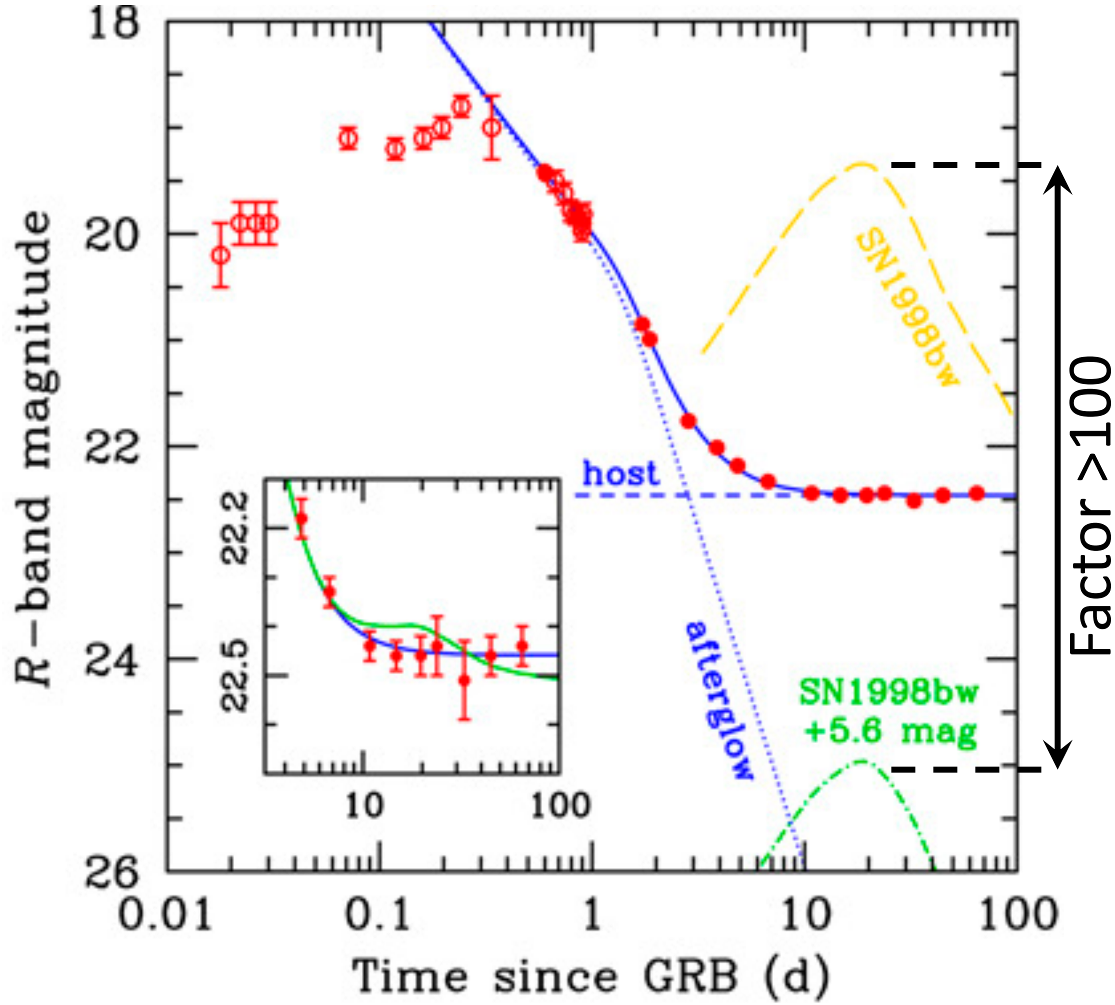


Late time:

host galaxy contribution (no variation)

Upper limit:

M_V > -13.5 (3σ)

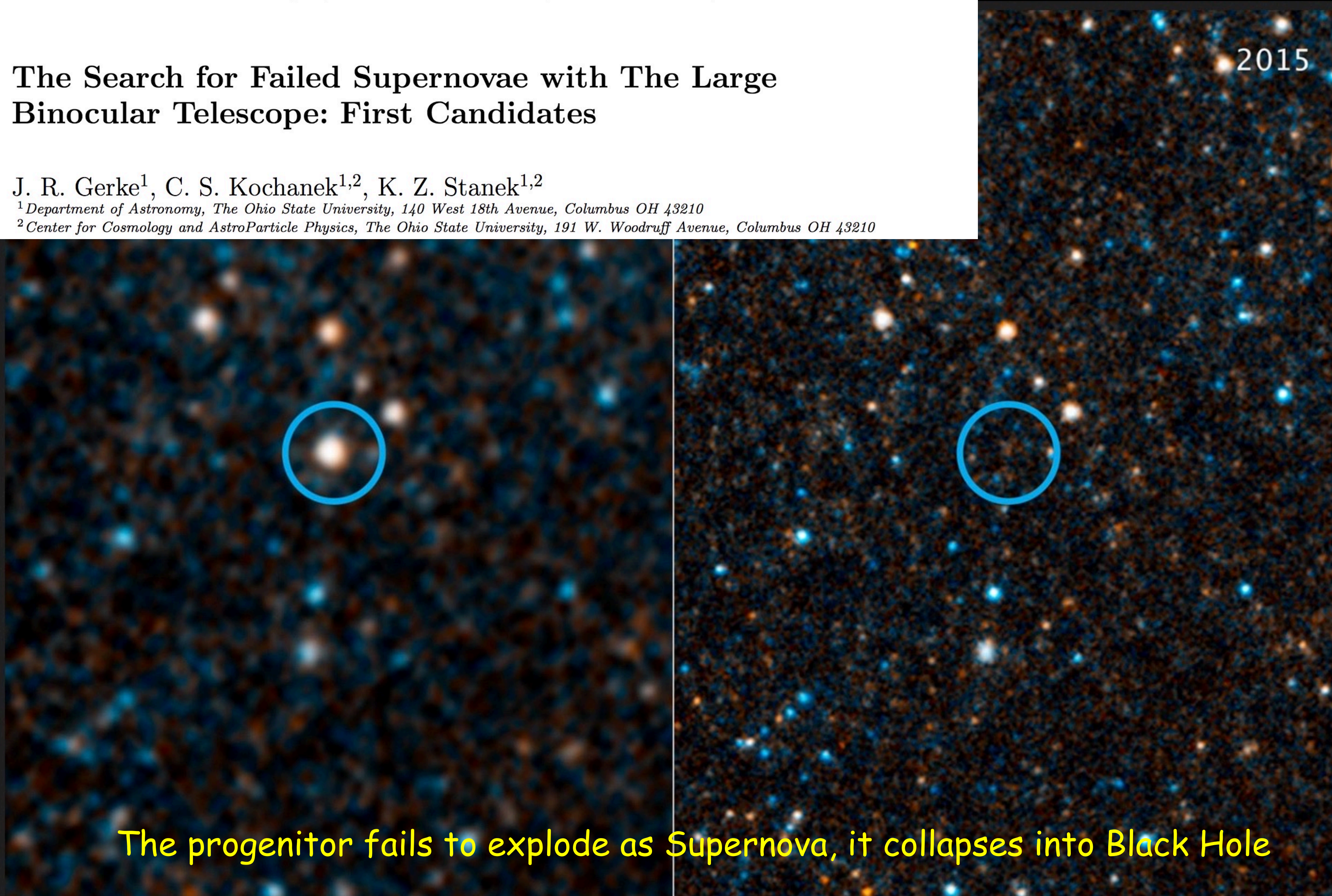


Della Valle et al. 2006 (see also Gal-Yam et al. 2006 – Fynbo et al. 2006)

Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 10 April 2015 (MN LaTeX style file v2.2)

The Search for Failed Supernovae with The Large Binocular Telescope: First Candidates

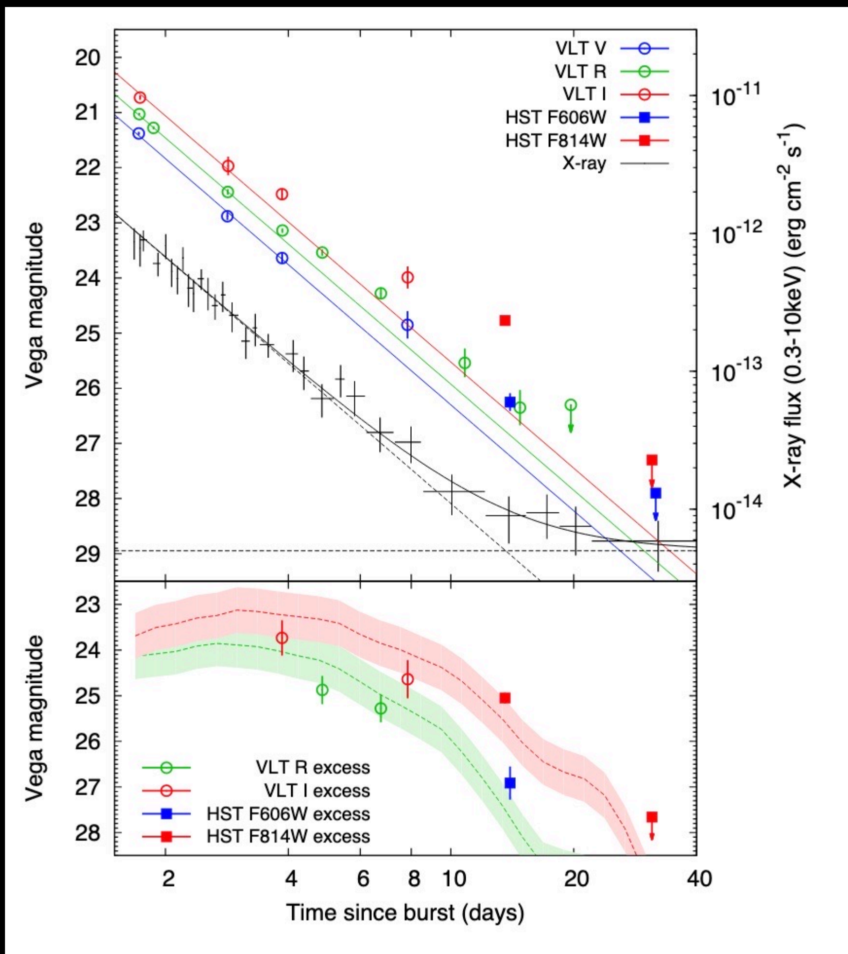
J. R. Gerke[1], C. S. Kochanek[1,2], K. Z. Stanek[1,2]
[1] *Department of Astronomy, The Ohio State University, 140 West 18th Avenue, Columbus OH 43210*
[2] *Center for Cosmology and AstroParticle Physics, The Ohio State University, 191 W. Woodruff Avenue, Columbus OH 43210*



THE LIGHTCURVE OF THE MACRONOVA ASSOCIATED WITH THE LONG-SHORT BURST GRB 060614

Zhi-Ping Jin[1], Xiang Li[1,2], Zach Cano[3], Stefano Covino[4], Yi-Zhong Fan[1], and Da-Ming Wei[1]
[1] Key Laboratory of dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Science, Nanjing, 210008, China.
[2] University of Chinese Academy of Sciences, Yuquan Road 19, Beijing, 100049, China.
[3] Centre for Astrophysics and Cosmology, Science Institute, University of Iceland, 107 Reykjavik, Iceland.
[4] INAF/Brera Astronomical Observatory, via Bianchi 46, I-23807 Merate (LC), Italy.

Draft version June 17, 2018



Monthly Notices of the Royal Astronomical Society
MNRAS **441,** 3444–3453 (2014) doi:10.1093/mnras/stu802

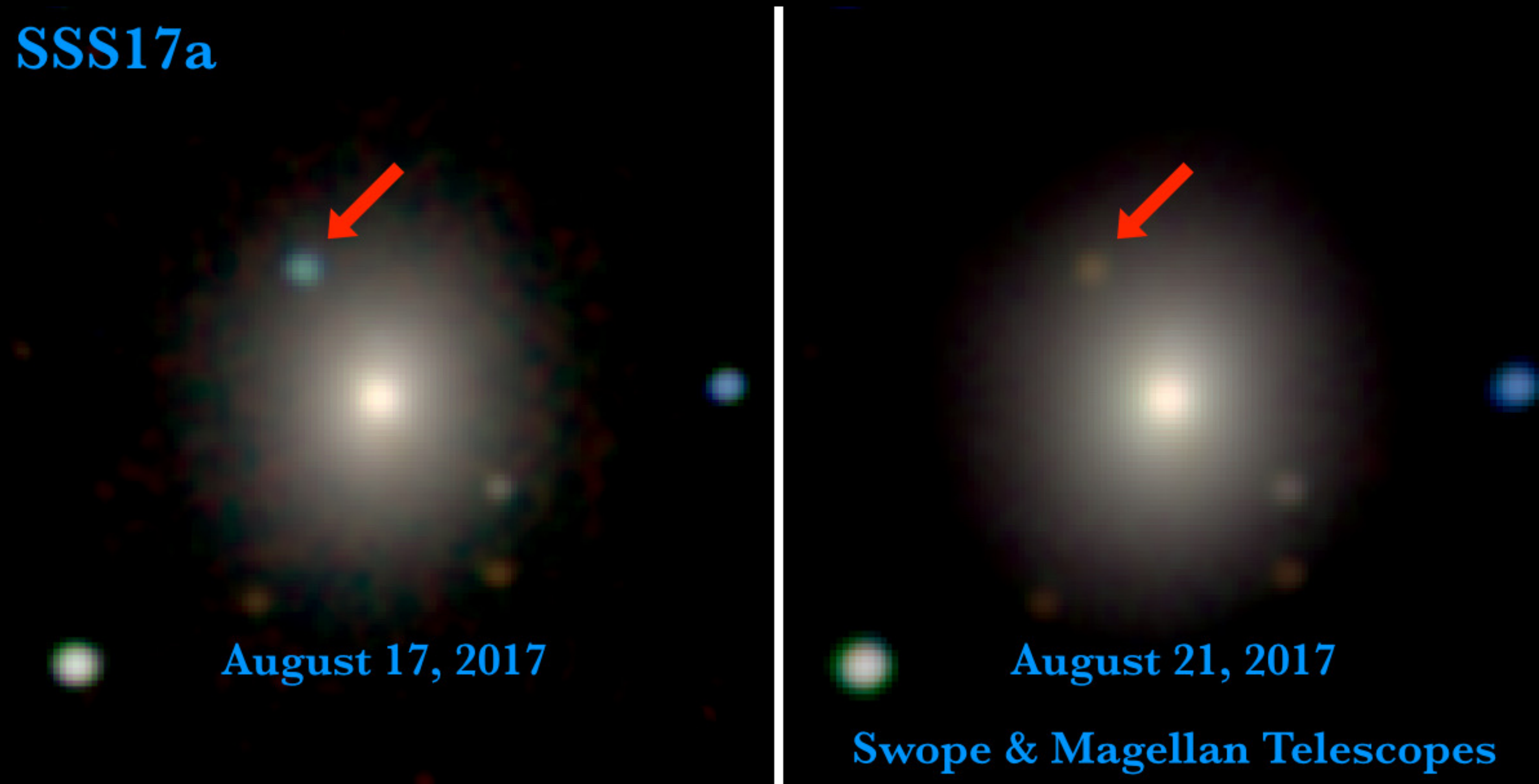
Red or blue? A potential kilonova imprint of the delay until black hole formation following a neutron star merger

Brian D. Metzger[1]★ and Rodrigo Fernández[2,3]

NIR excess due to r-process nucleosynthesis that take place in binary neutron star mergers and forming lanthanides (atomic numbers 57 to 71)

The dashed lines are KN model lightcurves generated from numerical simulation for the ejecta from a BH–NS merger, with a velocity ~ 0.2c and mass M_{ej} ~ $0.1M_{\odot}$, by Tanaka et al. (2014).

The green and red lines are in R and I bands, and shadows represent a 2σ uncertainties. The KN models are in agreement with the observed data.

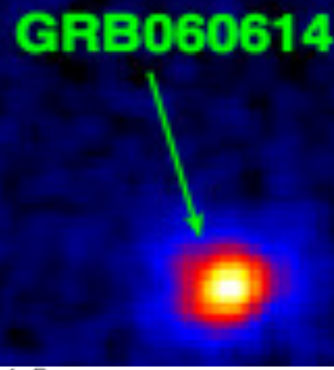

SSS17a
August 17, 2017
August 21, 2017
Swope & Magellan Telescopes

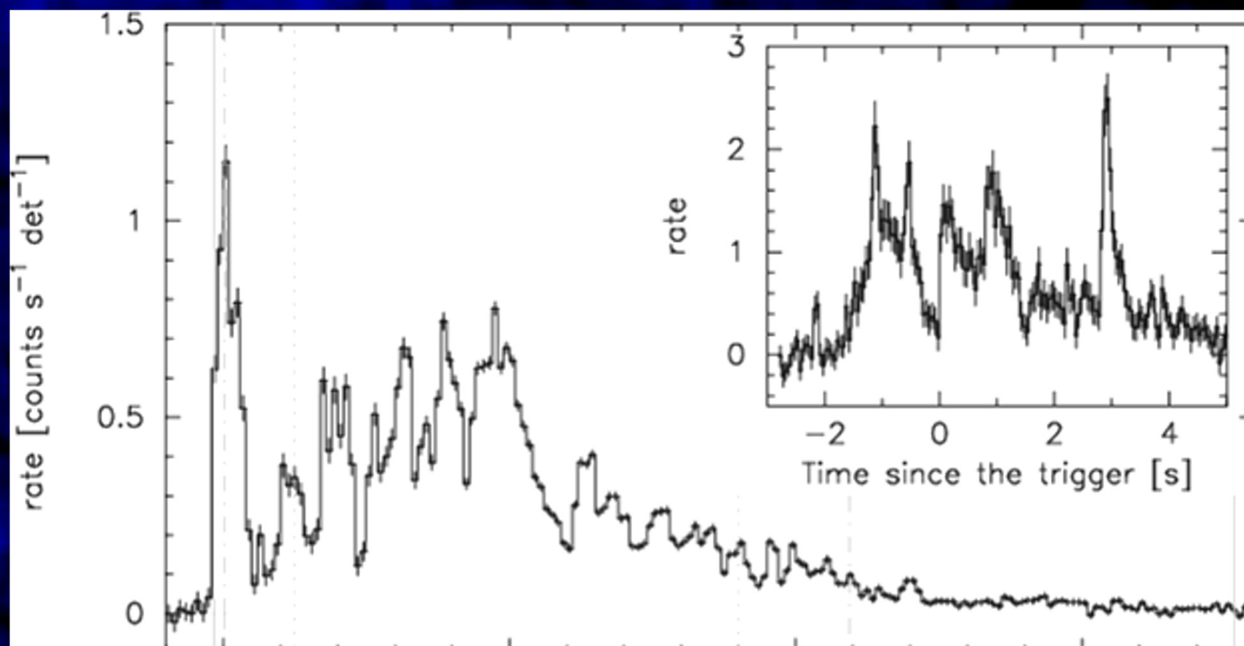
The Lightning without Thunder

may well be a new class of GW sources: KNe !

Low redshift:
***z* = 0.125**

SN search!

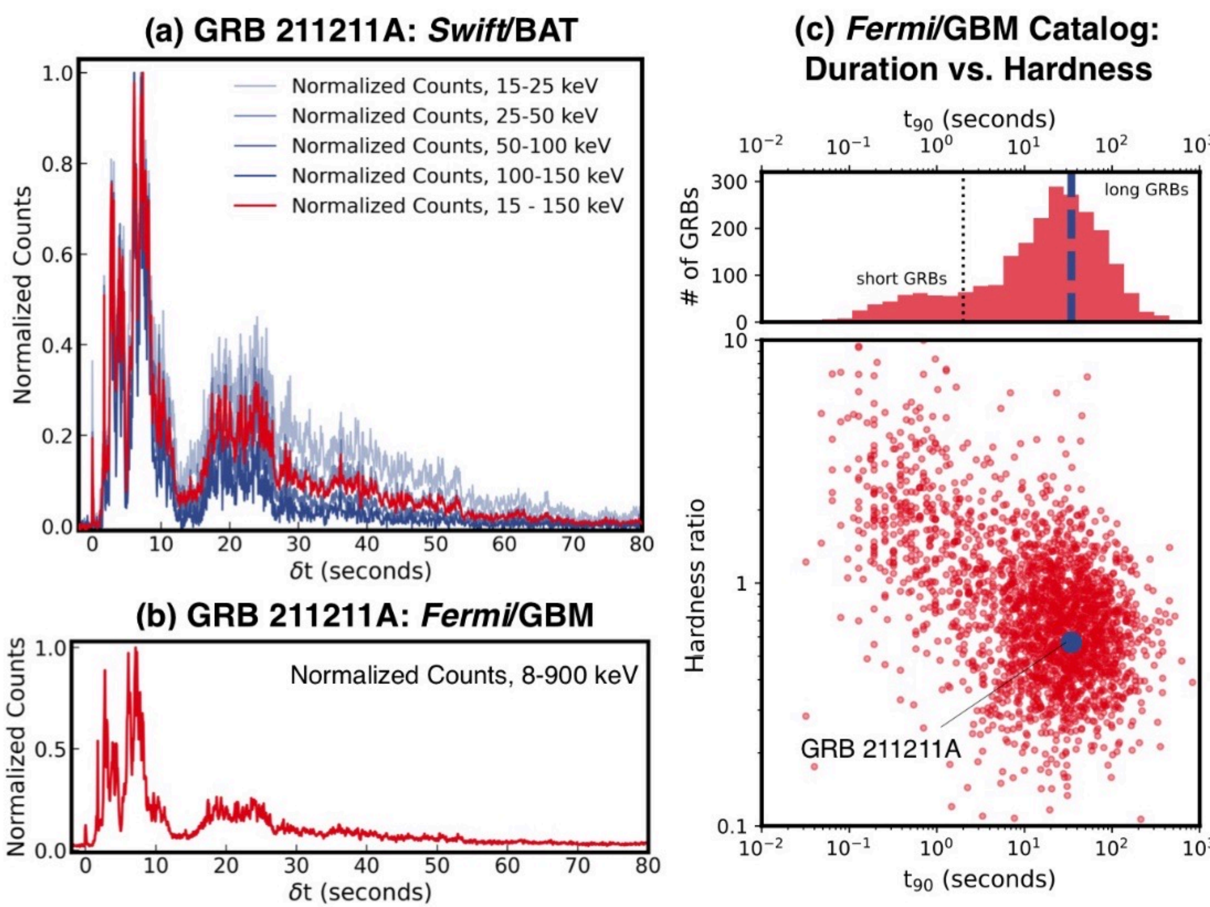


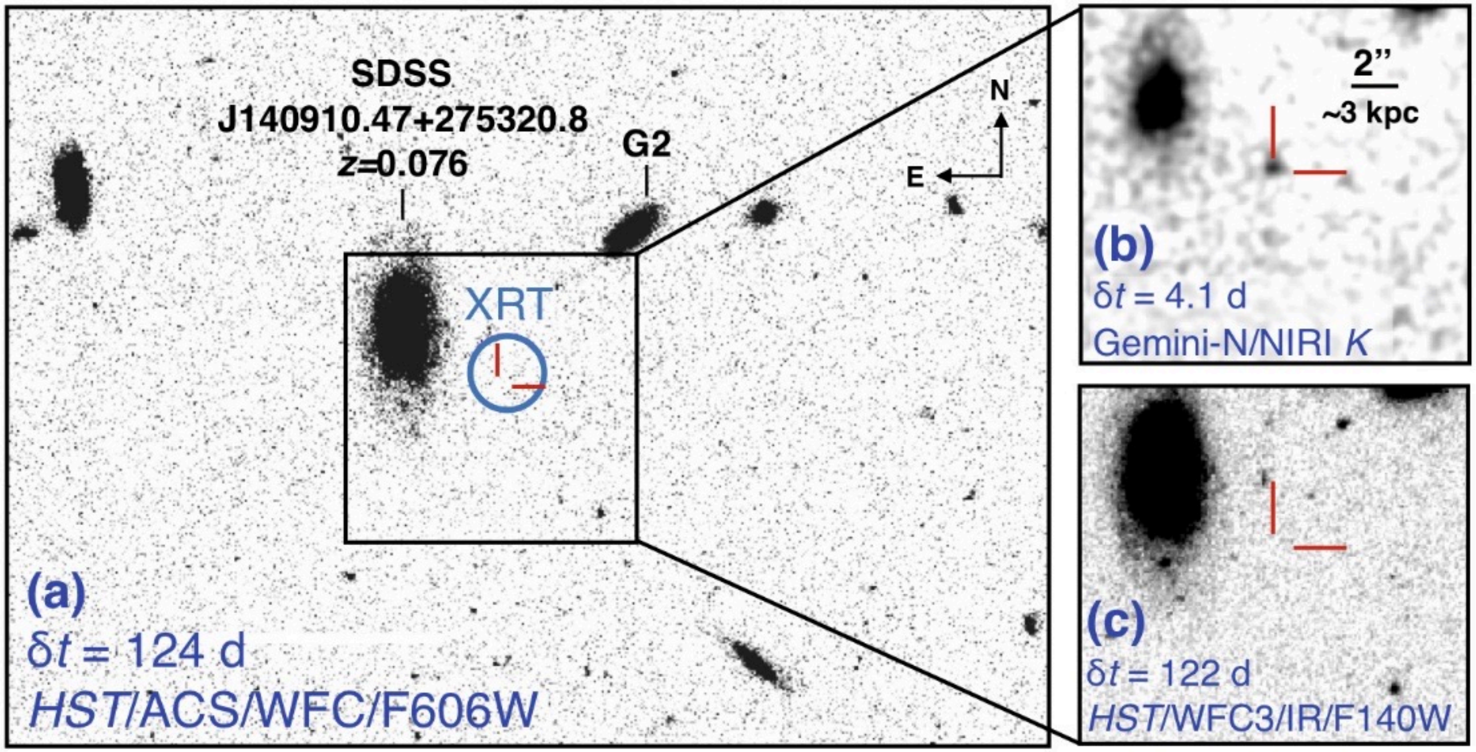


0s 50s 100s

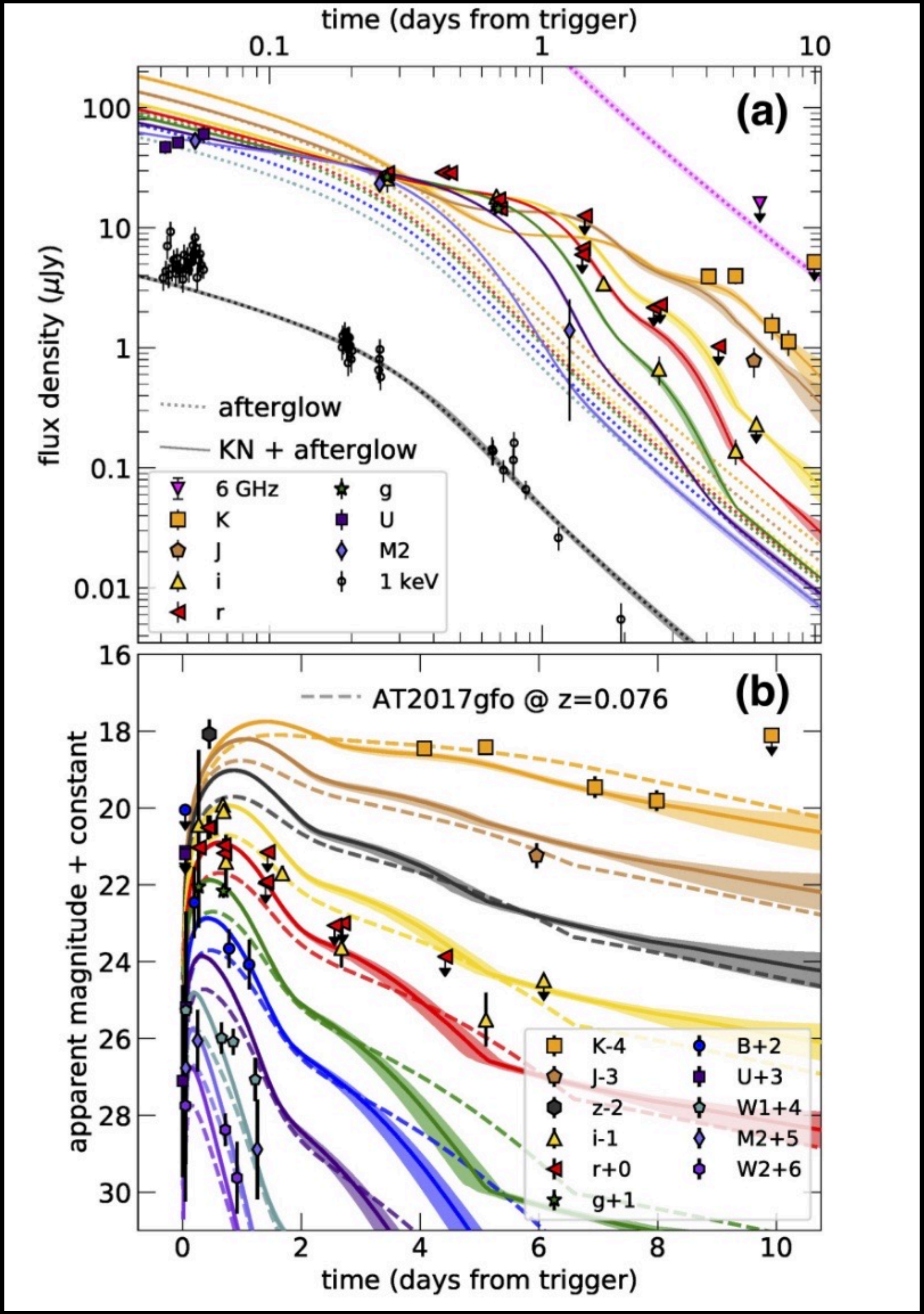
A Kilonova Following a Long-Duration Gamma-Ray Burst at 350 Mpc

Rastinejad et al. 2022
Troja et al. 2022
Yang et al. 2022





the absence of any fainter, underlying host galaxy in late-time Hubble Space Telescope (HST) imaging provide compelling evidence that GRB 211211A originated in SDSS J140910.47+275320.8



Kilonova and afterglow models (solid lines) and the afterglow model alone (dotted lines)

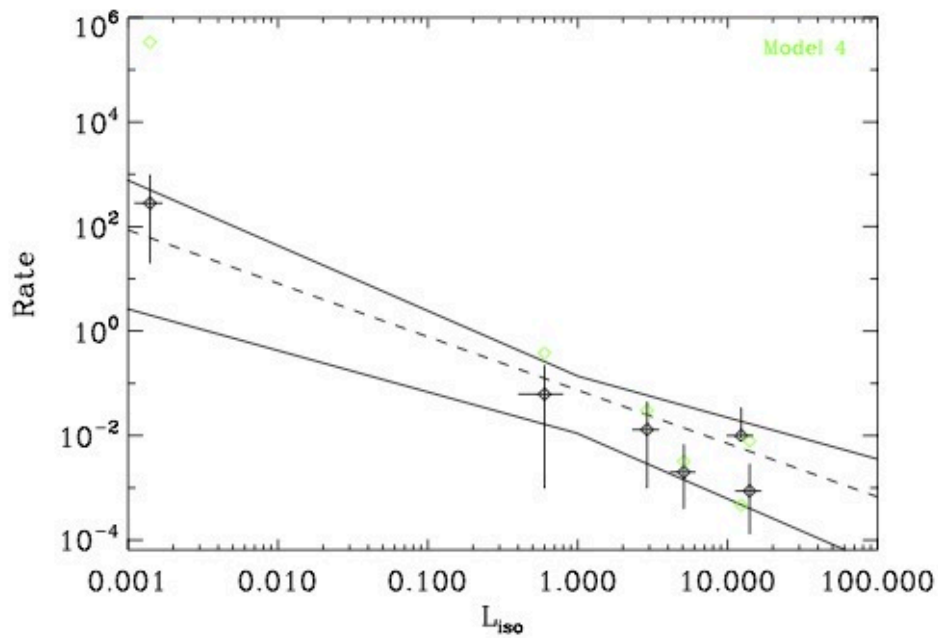
The NIR detections are ≈ 4 magnitudes brighter than predicted by the afterglow model and require a kilonova component to fit.

Plot models tuned to AT 2017gfo from shifted to the redshift of GRB 211211A (dashed lines).

The detection of NIR excess strongly supports the detection of the r-process in the ejecta, responsible to power the KN event

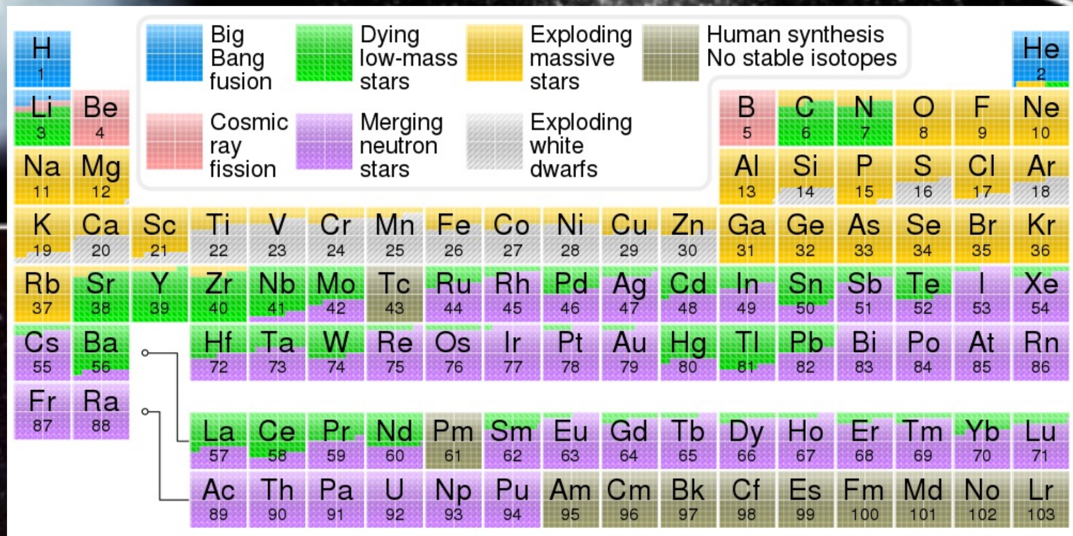
GRB	peak flux ph/cm^2	Distance Mpc	E$_{iso}$ 10^{50}erg	L$_{iso}$ 10^{50}erg/sec	Rate Gpc^{-3}yr^{-1}
050709	34	769	0.28	5.1	0.002
060614	11.5	585	8.6	2.9	0.013
070809	1.2	1083	0.53	0.60	0.061
170817A	0.74	41	4.3×10^{-4}	1.4×10^{-3}	280
130306B	6.4	1960	20	14	0.00087
211211A	155	344	115.	12.3	0.001

(Guetta, DV and Amati 2023)



Data are satisfactory fitted by the luminosity function proposed by Guetta and Piran in 2006, which is described by a sGRBs population that doesn't follow the SFR, rather it follows a distribution of delay times, after the SFR, characterized by: $\Delta t \sim$ 10 - 100 millions years

KNe and the chemical evolution of galaxies



The majority of heavy nuclei beyond the iron peak originate from neutron captures. The neutron capture on a heavy seed, such as Fe can occur slowly or rapidly, relative to the β-decay process. Therefore we are dealing with s-process and r-process.

Most r-process elements can be produced in core-collapse supernovae (Woosley 1996, Wheeler et al.1998,) .

More recently KNe are believed to be responsible of forming lanthanides, characterized by atomic numbers 57 to 71 during BNS mergers (Korobkin et al. 2012, Rosswog 2013, Hotokezaka et al. 2013) .

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **500,** 1071–1086 (2021) doi:10.1093/mnras/staa3340
Advance Access publication 2020 October 29

Predicted rates of merging neutron stars in galaxies

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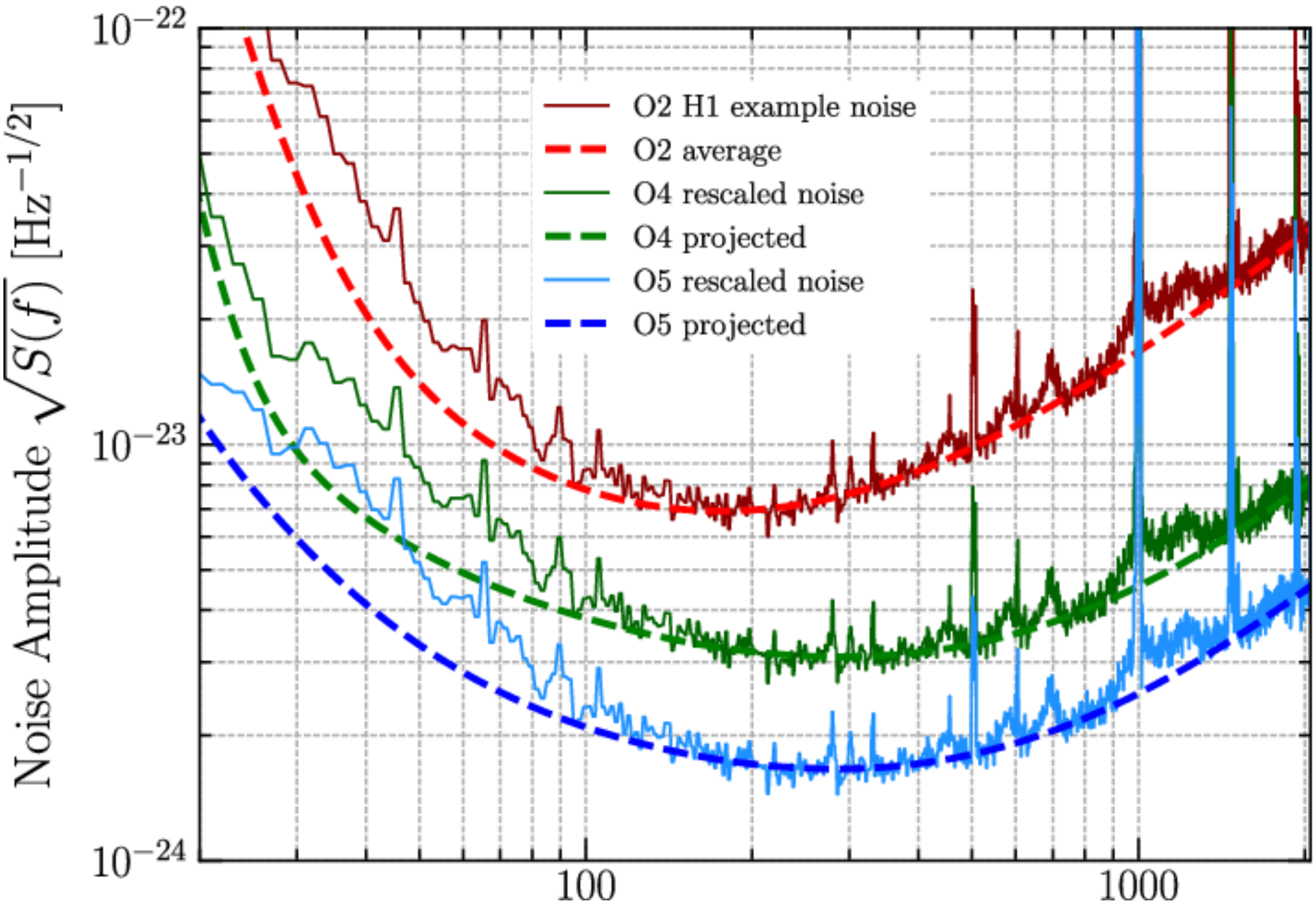
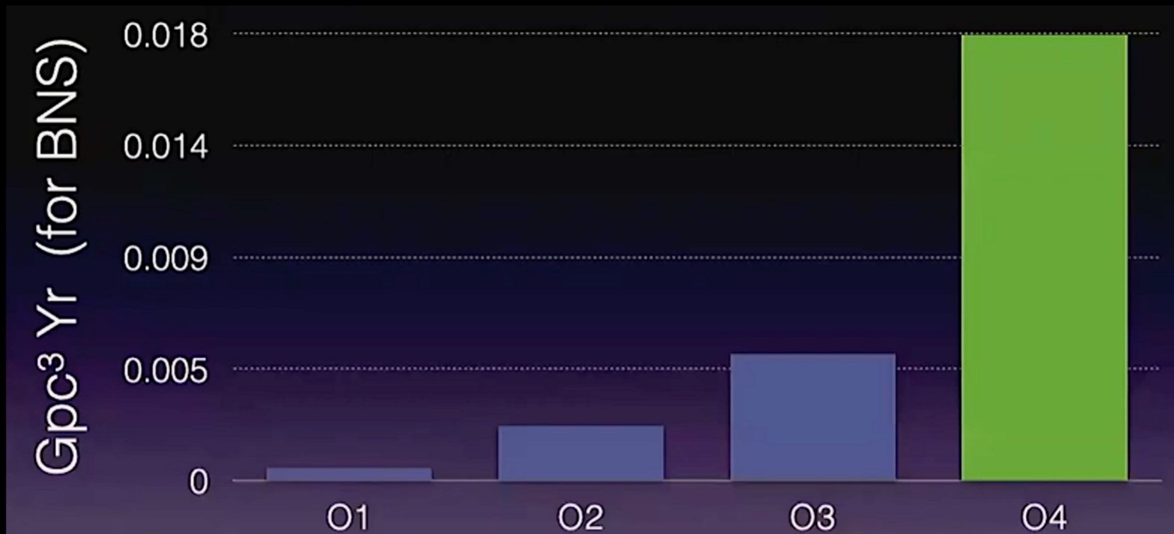
In this paper the authors have computed for the first time, the rate of BNS mergers in galaxies of different morphological types, such as Ellipticals, Spirals and Irregulars by assuming only BNS mergers as producers of such elements.

Particularly the [Eu/Fe] vs. [Fe/H] in the Milky Way can be reproduced by assuming BNS mergers as the only Eu producers if a constant total delay time (stellar lifetime plus gravitational time delay) of 10 Myr is adopted.

When more KNe will be observed (i.e. rate will be improved) we'll be in the position to disentangle the degeneracy between the SN and KN contributes to the chemical evolution of the galaxies.

What are the consequences of KN rate on O4 and O5?





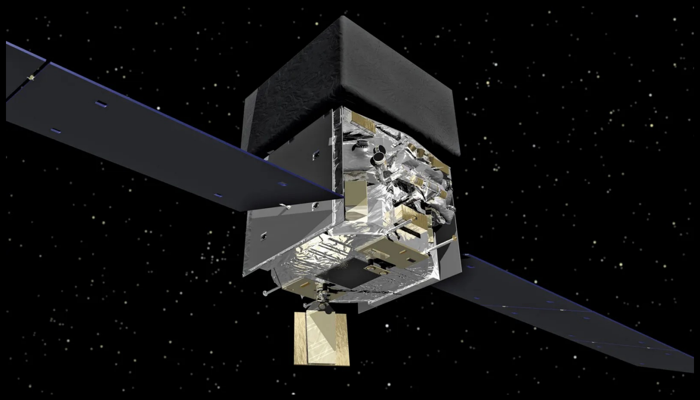
D	BNS per year	Comment
100 Mpc	1	GW170817 is once per decade event
175 Mpc	4 - 7	Most likely for O4 ?
300 Mpc	30	Game changing number : O5 + Rubin Observatory ToO

O4 volume > 2 (O1+O2+O3)

D (Mpc)	KN per yr	caption
100	~1	Based on 300 yr^{-1}
175	5-7	+ O4
300	~30	+O5

Conclusions

The potential of Multi-Messenger astronomy has not yet been fully exploited. To date, only one EM counterpart of a GW source has been revealed. The main reason for this is the inherently low rates of GW events that can be detected simultaneously by high-energy satellites and ground-based facilities. For O4 we expect an improvement in the number of BNS merger detections.



Conclusions cont'd

The main change in this area will come with O5, in synergy with the Vera Rubin Observatory, in 2025. LSST will patrol thousands of deg^2 with three visits per night in 6 filters, down to a significantly fainter range of magnitudes than that achieved by the current optical investigations (eg. ZTF, Pan-STARRS, ATLAS). The sampled volume will be ~ 40 times larger than O4. From all of this, **I expect:**

i) a significant increase in the number of KN detections both in GWs and in optical/NIR: >10 or even >> 10
ii) the detection of a few post-merger signals which will allow to disentagle among different compact remnants (NSs, metastable HNSs and BHs)
iii) decreasing the uncertainty on the KN rates by an order of magnitude
iv) Hubble constant measurements with GW standard sirens (see Holz & Hughes 2005) will approach the accuracy of SNe-Ia and CMB measures.