The kilonova - short GRB connection in the Multi-Messenger era

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Credit: National Science Foundation/LIGO/Sonoma University/A. Simmonet

Swift & Short GRBs

Since 2005, with the advent of the *Swift* satellite, the discovery of short GRB afterglows and the identification of their host galaxies made possible to measure their distances and study their energy scales and environments.

To date, *Swift* detected ~150 short GRBs (~9/yr):

- ~15% with an extended emission

- ~75% with a X-ray afterglow detected

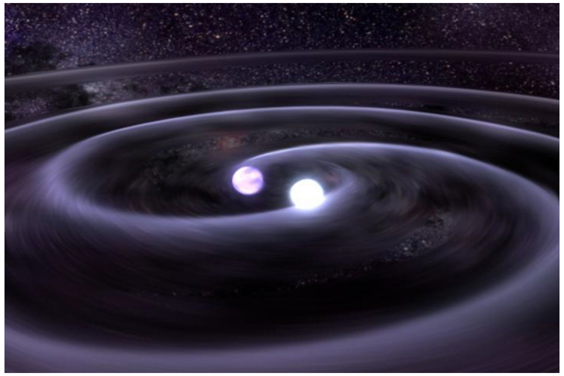
- ~15% with no X-ray afterglow detection in spite of prompt XRT slew

- ~35% with an optical afterglow detected

- ~5% with a radio afterglow detected

- ~25% with a redshift measurement (mainly from host galaxy spectroscopy -> importance of precise, arcsec, position for host galaxy association)

Berger 14
Fong+15
D'Avanzo15



A lot of science cases related to short GRBs
Main issue: the quest for progenitors

Compact object mergers: what we do expect

Diverse delay times:
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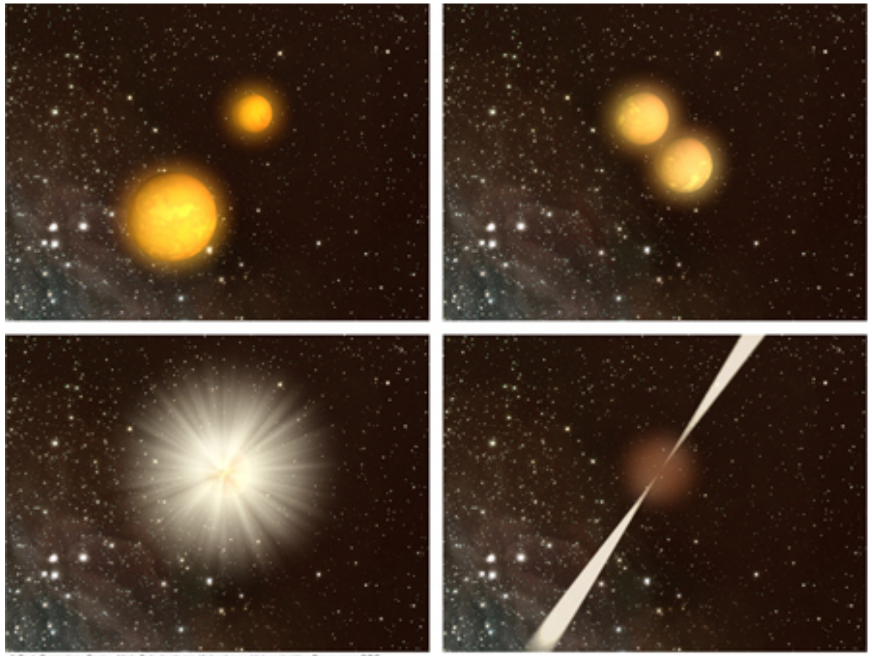
No associated supernova

Remnant (magnetar/BH?)

Emission geometry (jet?)

Kilonova association

Gravitational waves



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ESO PR Photo 32c/05 (October 6, 2005)

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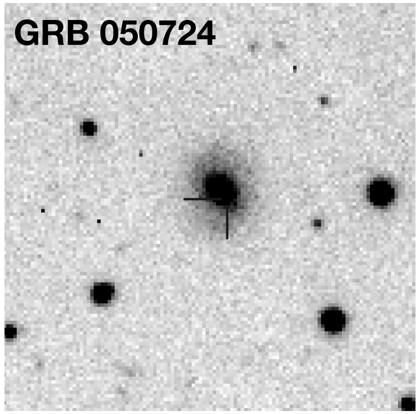
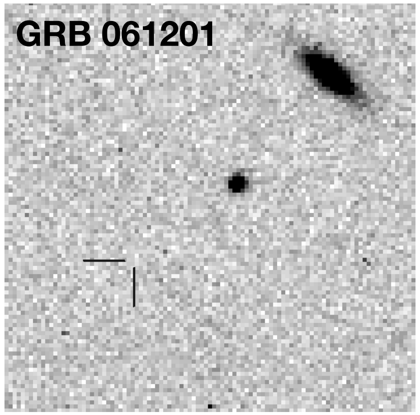
Barthelmy+05
Malesani+07
Stratta+07
PDA+09
Fong+13
Berger14



early type

late type



hostless

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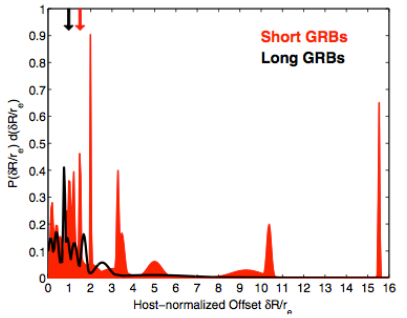
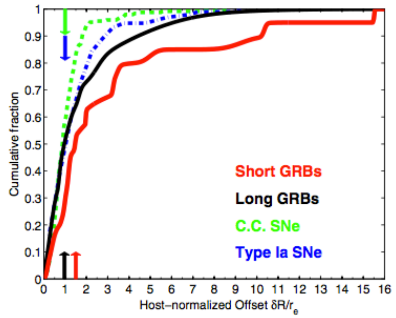
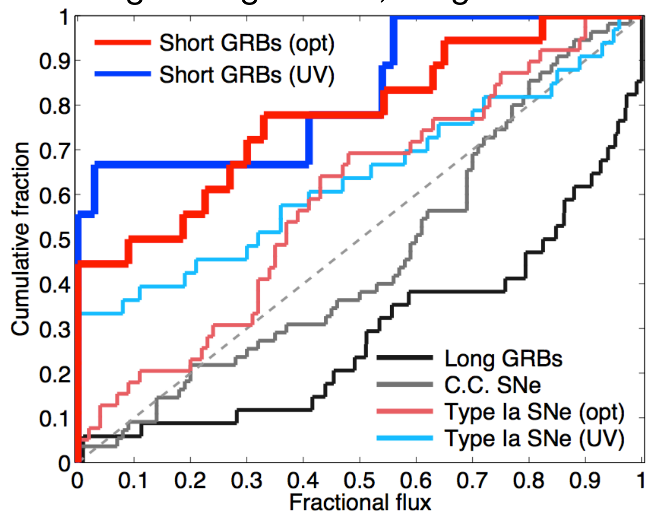
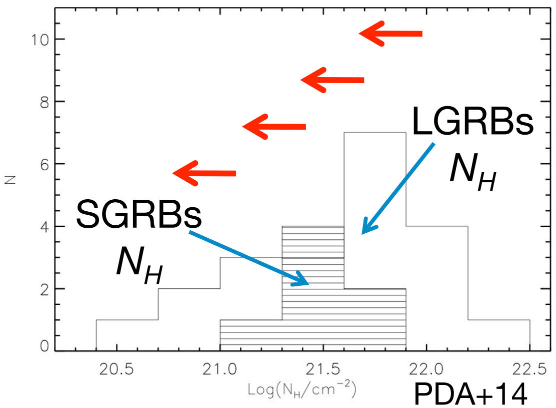


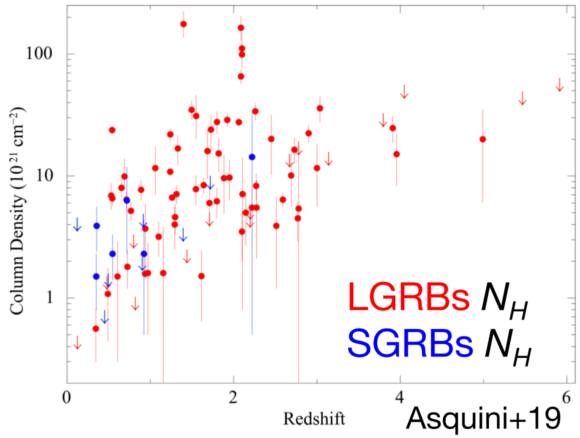


Fong & Berger 2013; Berger 2014





PDA+14



Asquini+19

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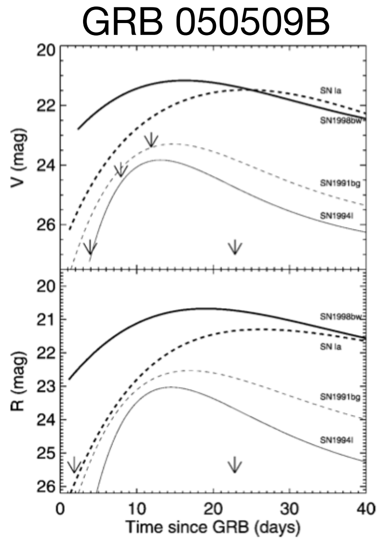
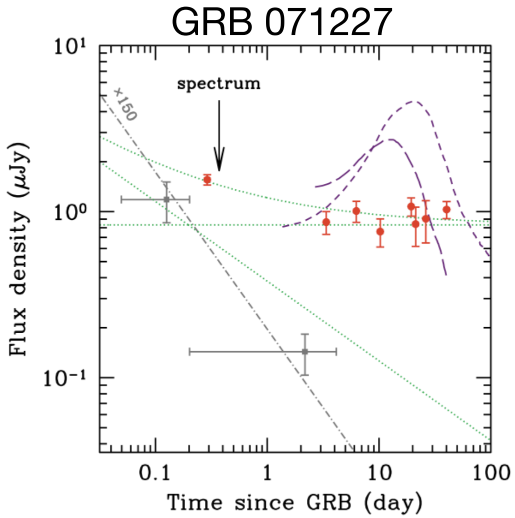
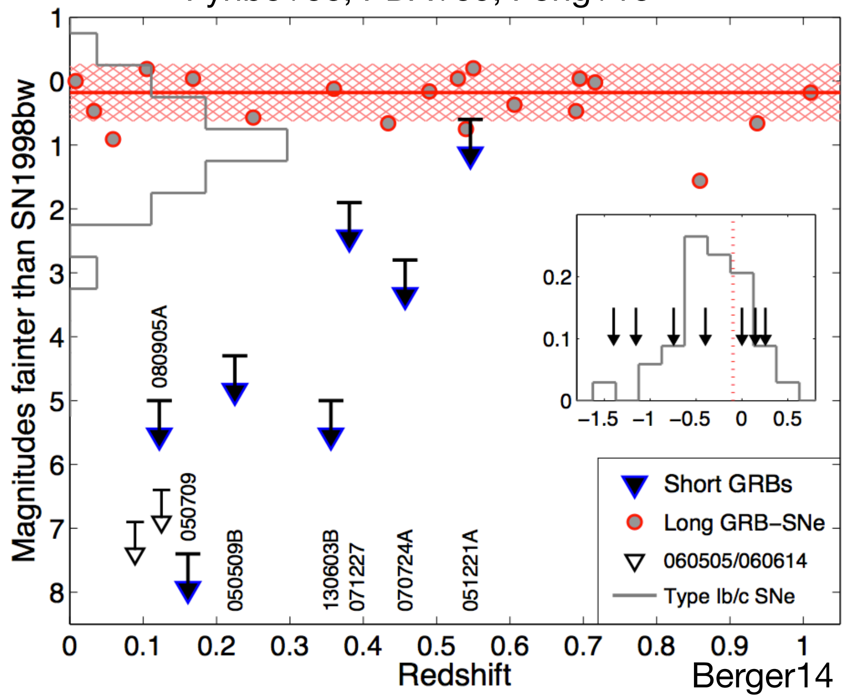




Hjorth+05; Covino+06; Della Valle+06; Fynbo+06; PDA+09; Fong+16



Berger14

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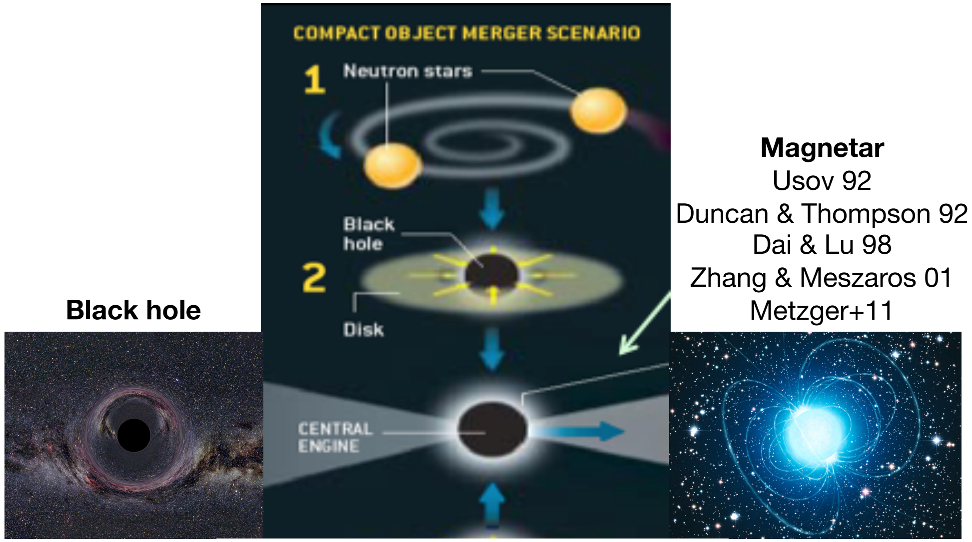

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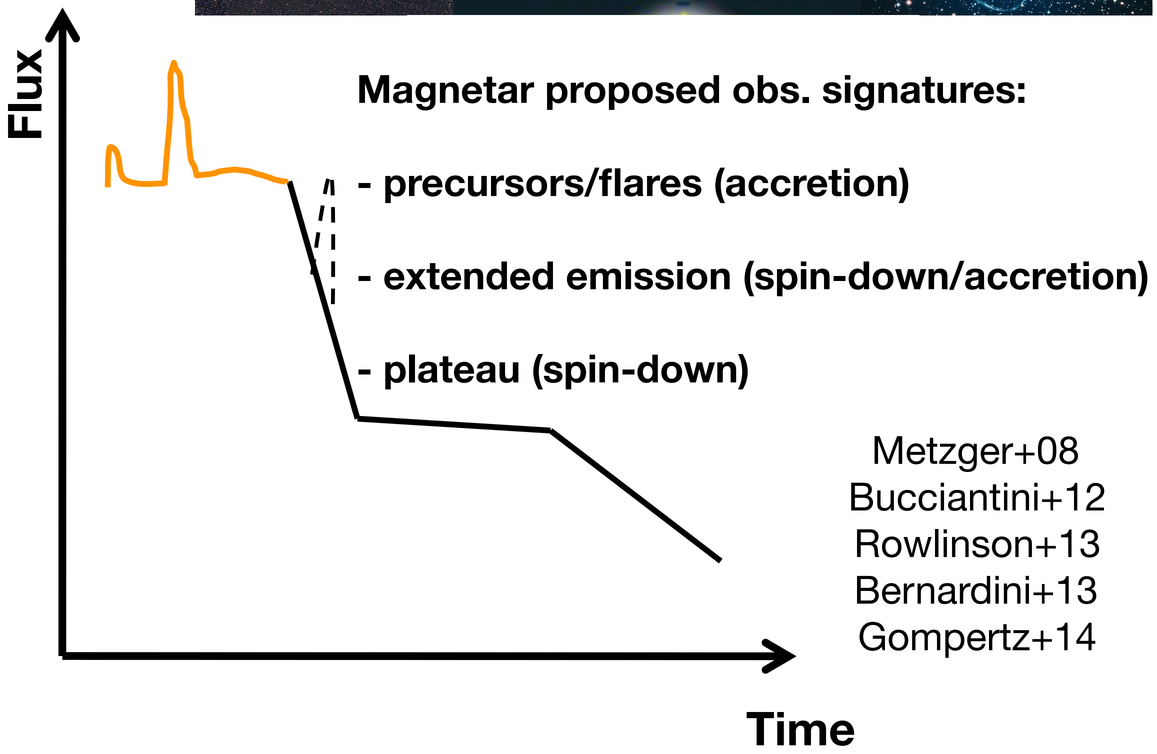
Maria Grazia Bernardini talk



Metzger+08
Bucciantini+12
Rowlinson+13
Bernardini+13
Gompertz+14

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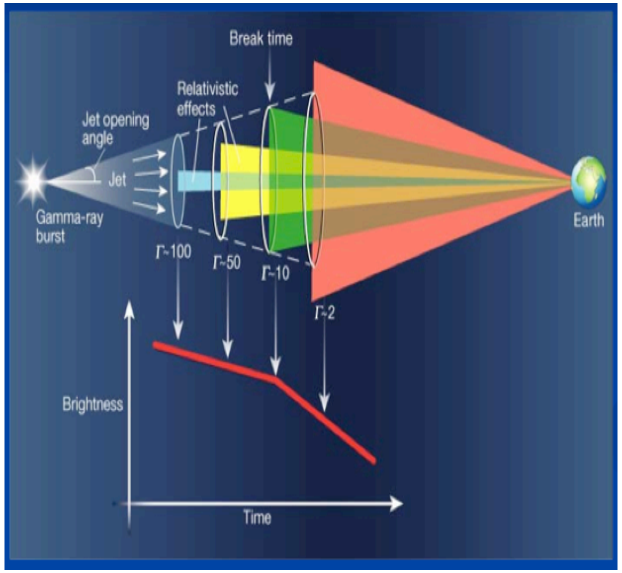
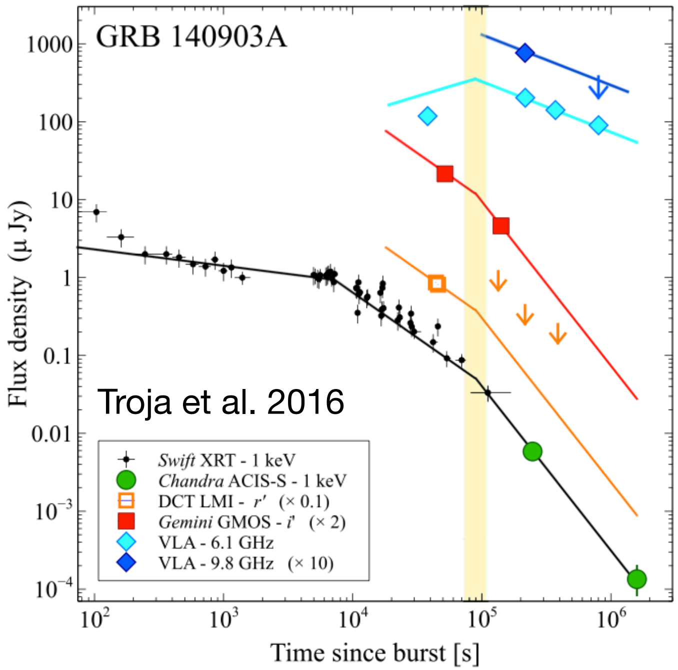


Short GRB Opening Angles

GRB	Band[a]	θ_j (deg)	$\delta t^b_{\rm last}$ (days)	Reference
050709	O	$\gtrsim 15^\circ$	16.2	1
050724A	X	$\gtrsim 25^\circ$	22.0	2
051221A	X	$6-7^\circ$	26.6	3
090426A	O	$5-7^\circ$	2.7	4
101219A	X	$\gtrsim 4^\circ$	3.9	5, This work
111020A	X	$3-8^\circ$	10.2	6
111117A	X	$\gtrsim 3-10^\circ$	3.0	7, 8
120804A	X	$\gtrsim 13^\circ$	45.9	9, This work
130603B	OR	$4-8^\circ$	6.5	10
140903A	X	$\gtrsim 6^\circ$	3.0	11, This work
140930B	X	$\gtrsim 9^\circ$	23.1	This work

$\langle\theta_{jet}\rangle \sim 10^o$ Fong et al. 2015



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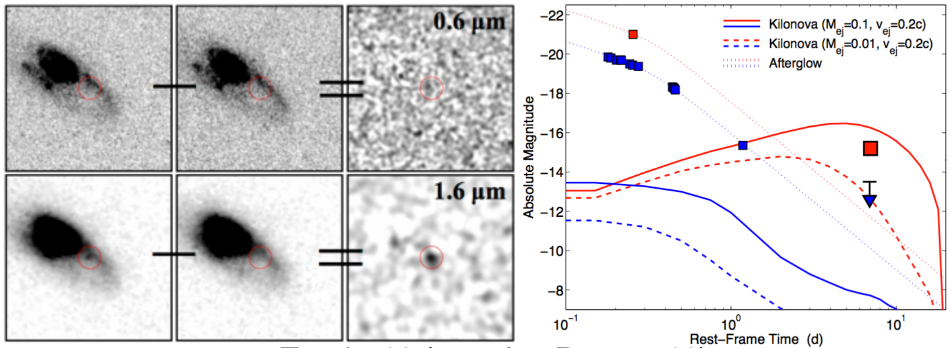
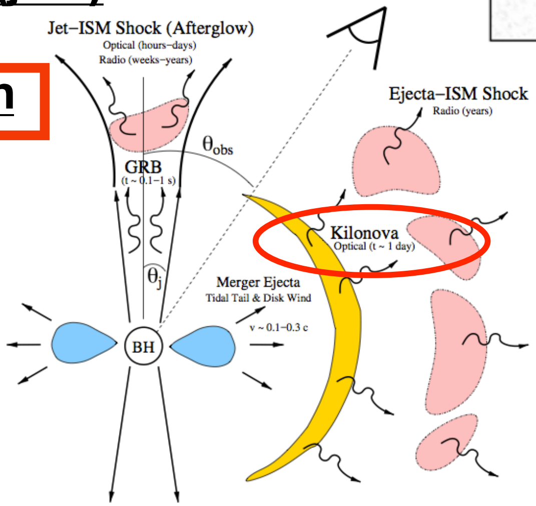
GRB 130613B (z=0.356)

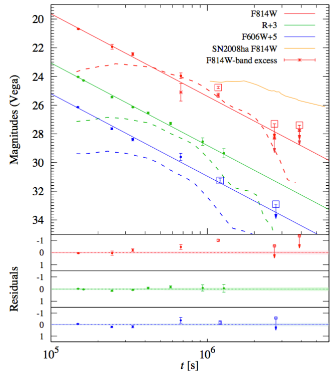


Tanvir+13 (see also Berger+13)

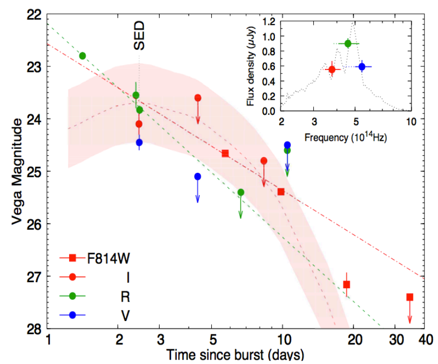


Metzger & Berger 2012

GRB 060614 (z=0.125)



GRB 050709 (z=0.160)



Yang+15; Jin+15; Jin+16

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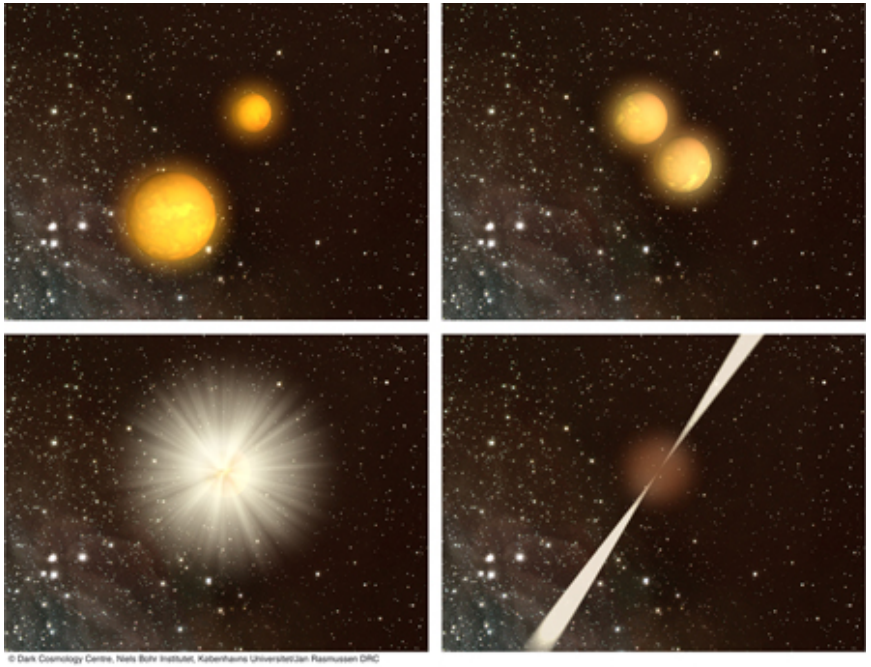

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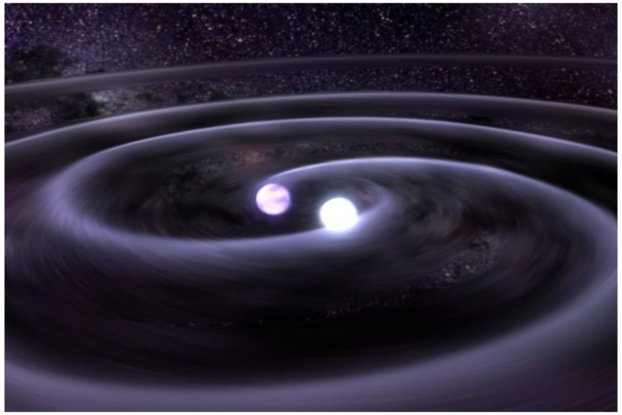

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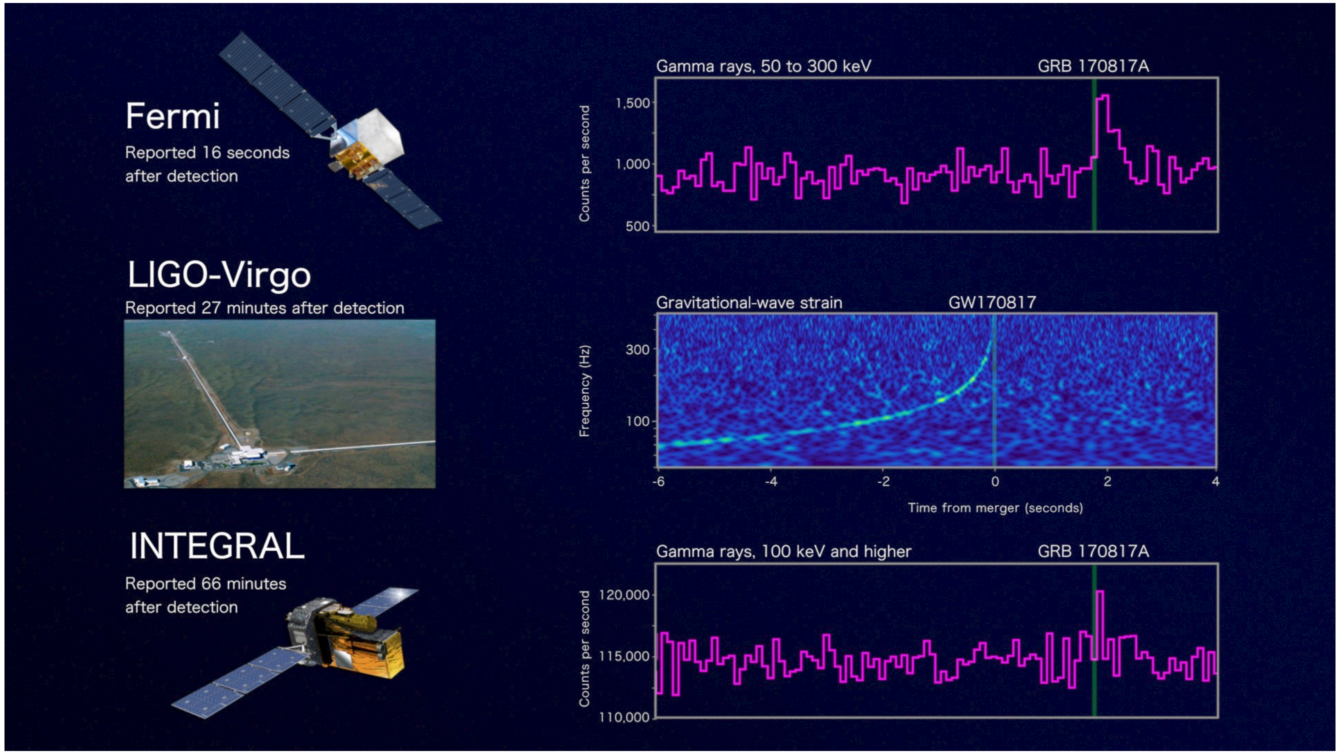

Goldstein+17; Savchenko+17
LVC + “partner astronomy groups” (2017)

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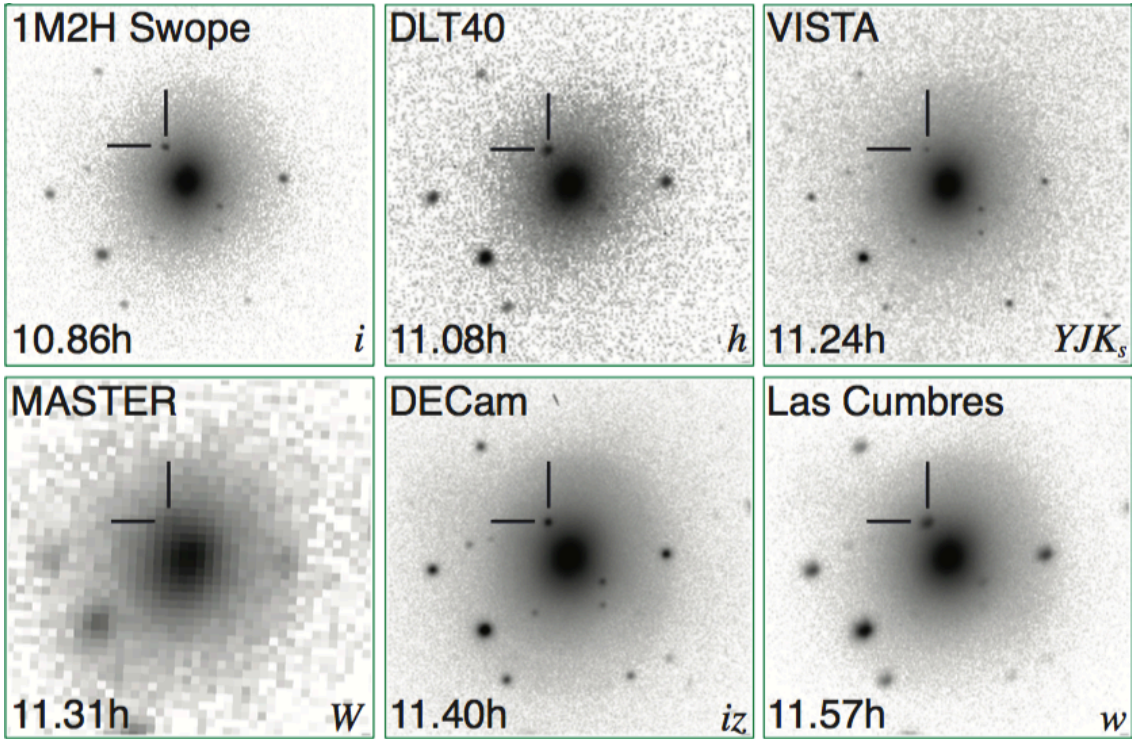
AT2017gfo



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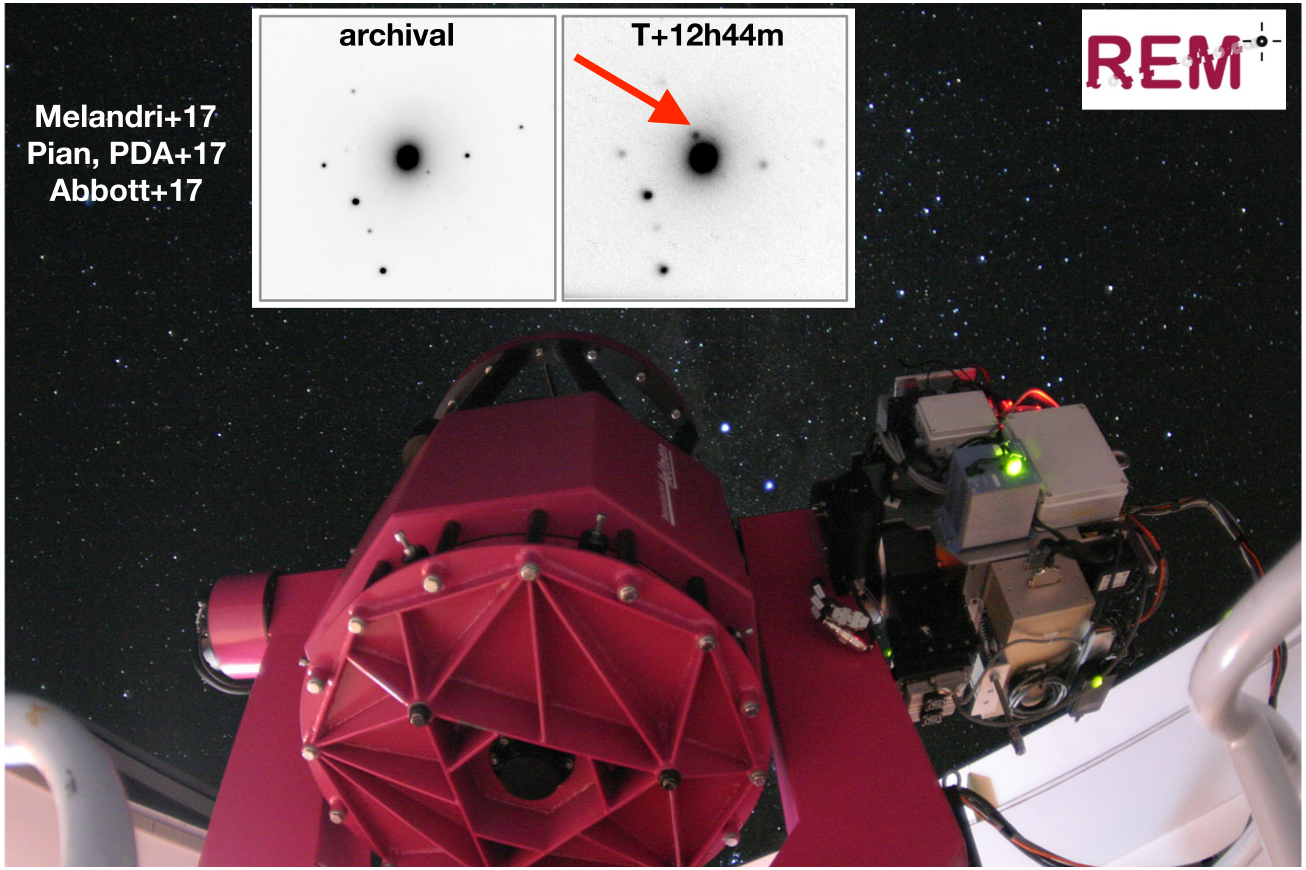
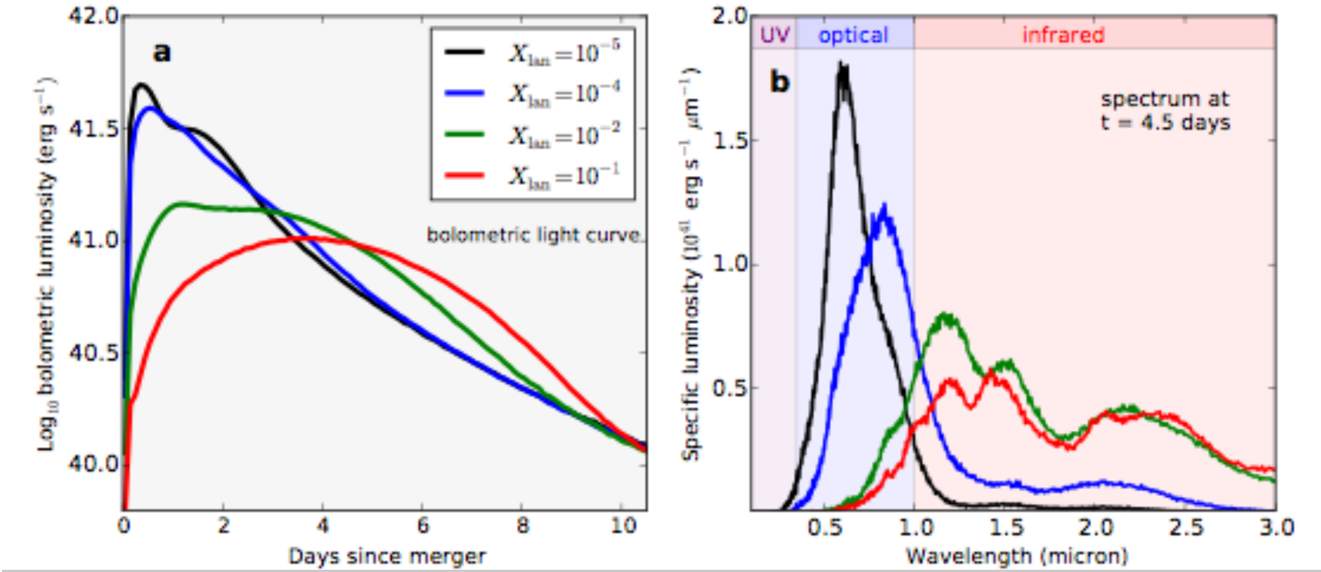
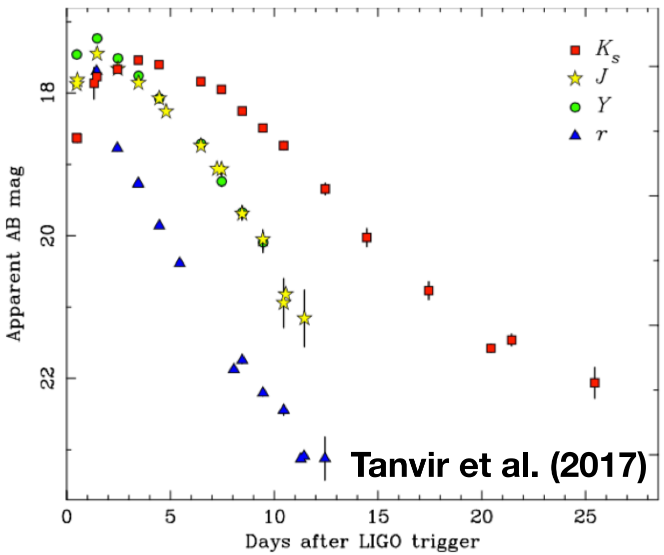


The GW 170817 kilonova components

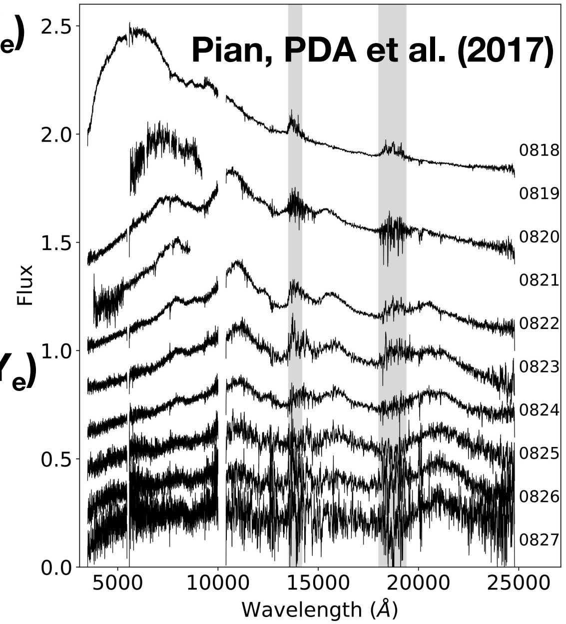
Kasen+17





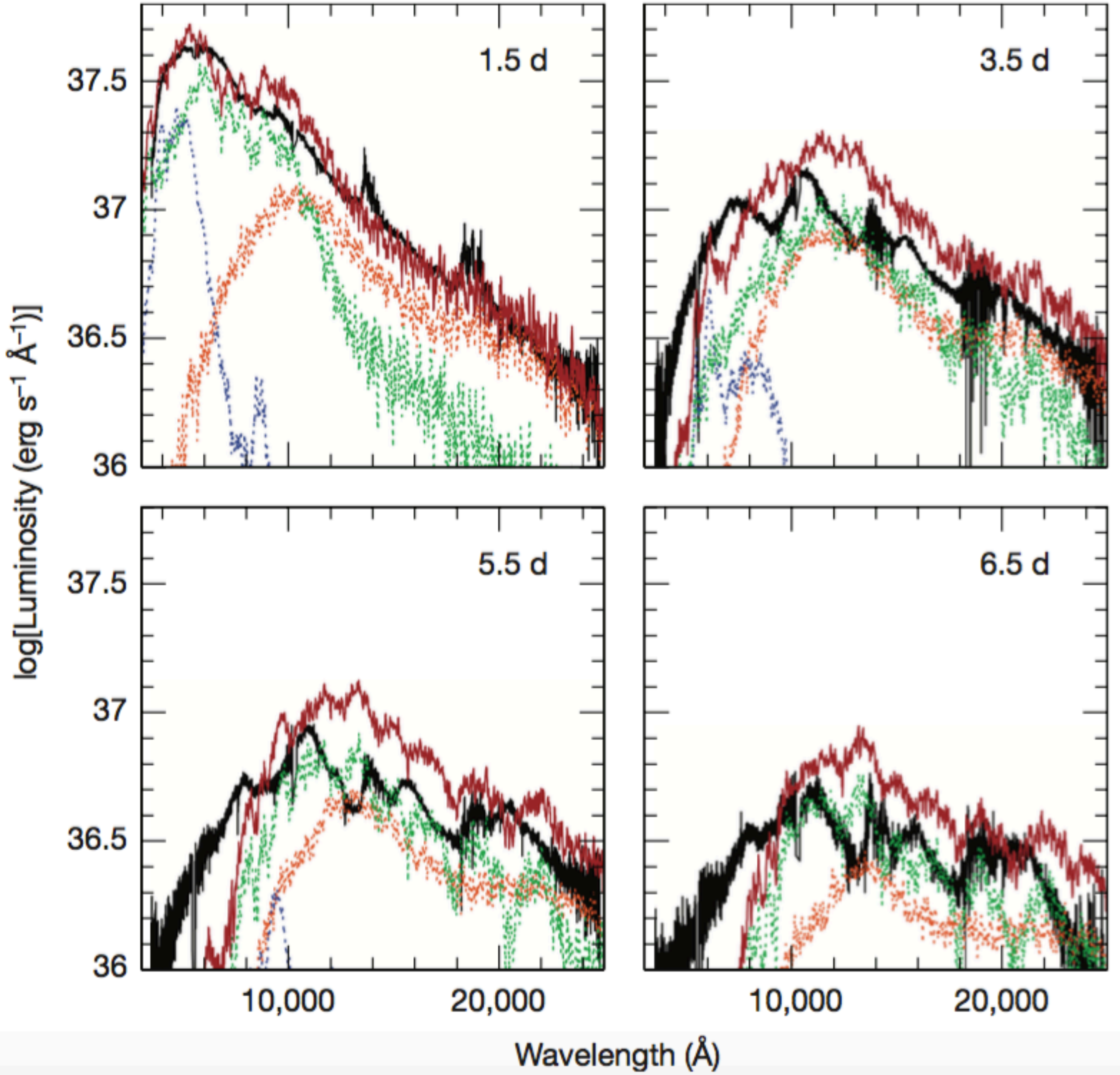
Neutron-rich ejecta (low e^- fraction Y_e)
Strong r-process
Very heavy elements (A>140)
Lanthanide rich
Higher opacity
Red KN, peak time~ 1 week

Neutron-rich ejecta (high e^- fraction Y_e)
Strong r-process
heavy elements (A<140)
Lanthanide poor
Lower opacity
Blue KN, peak time~ 1 day

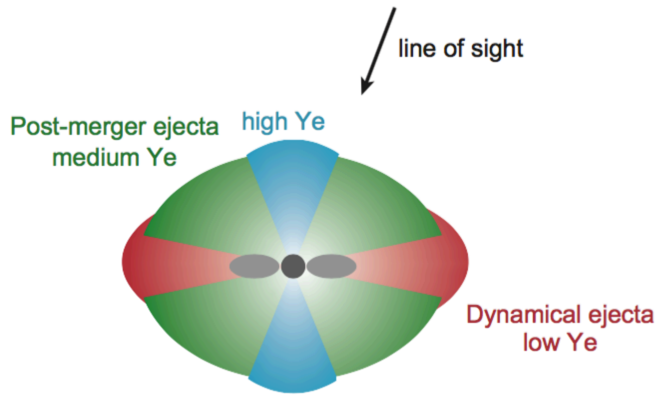


The GW 170817 kilonova components

Pian, PDA et al. (2017)



Tanaka et al. (2017)

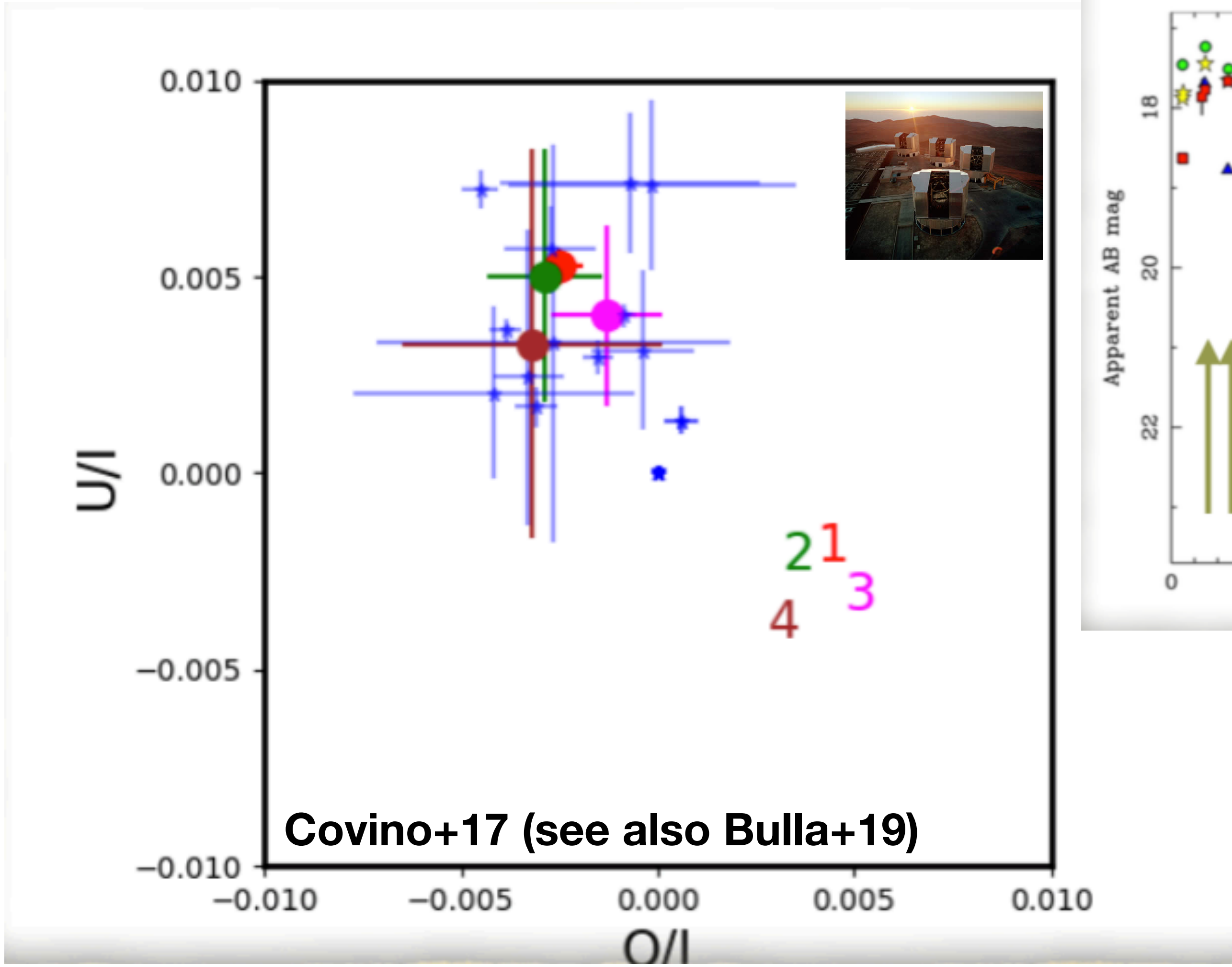


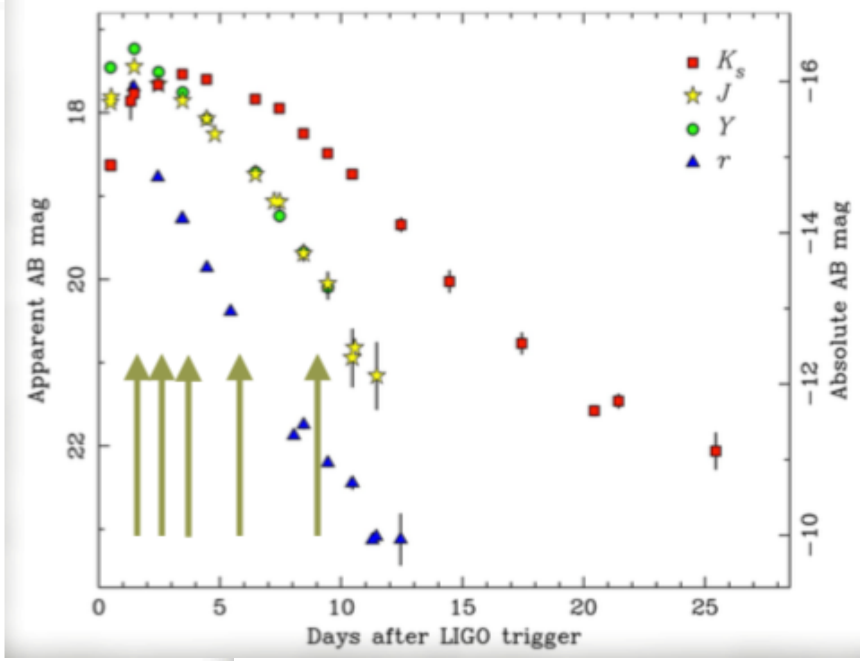
Three components Kilonova model with different velocity, composition and electron (proton) fraction (low Ye: lanthanide-rich; high Ye: lanthanide-poor)

Their sum and rescaling (red) can reproduce the observed spectra (black)

0.03-0.05 M_{Sun} ejected mass
Fast moving dynamical ejecta (0.2c) + slower wind (0.05c)

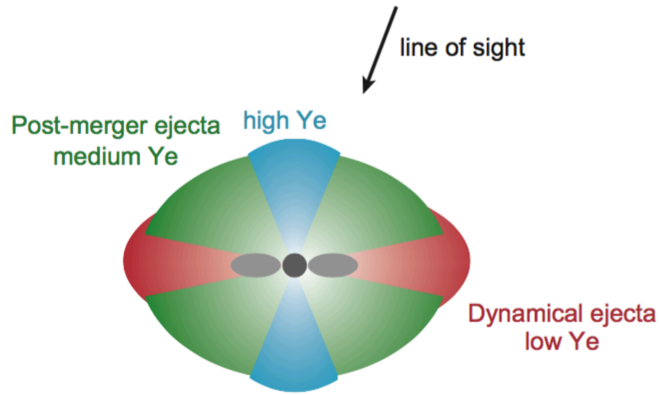
The GW 170817 kilonova polarimetry





P < 0.5% - 0.9% --> No polarisation

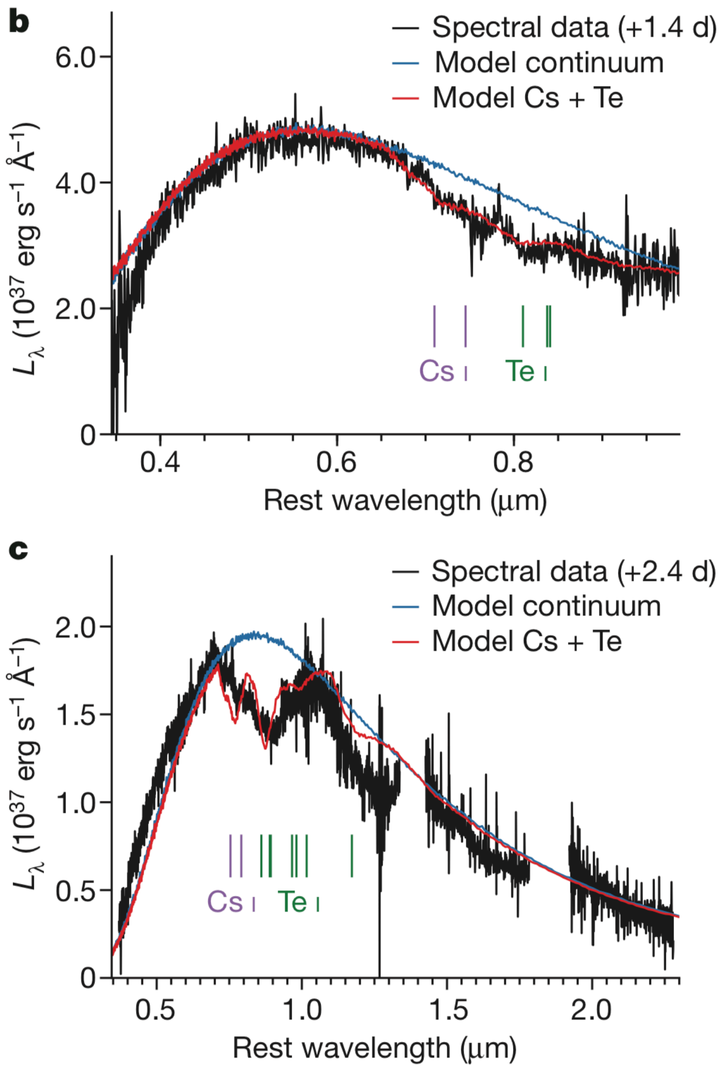
-Early time: rather symmetric emitting region (high latitude viewing angle)



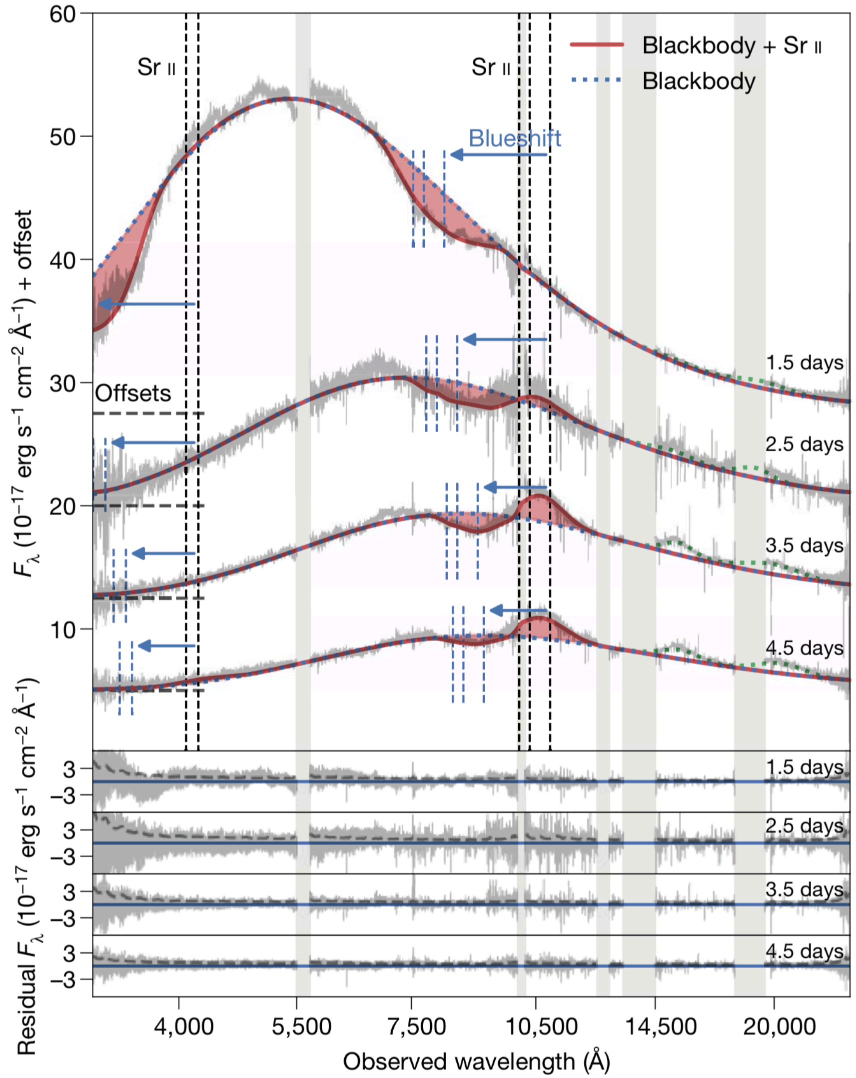
- late time: emission from Lanthanide-rich ejecta

Heavy elements (possible) signatures

Smartt et al. (2017)



Watson et al. (2019)



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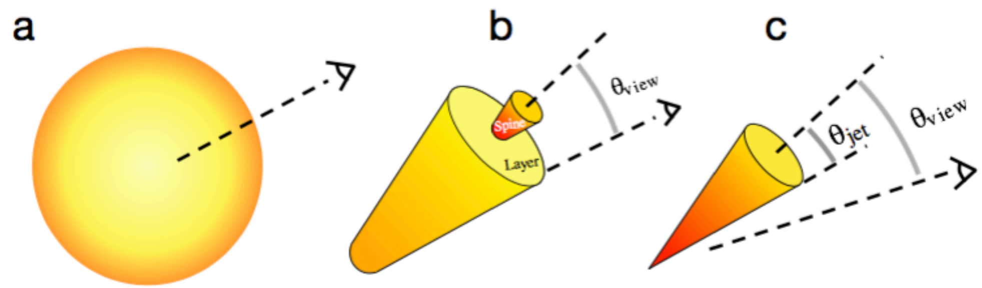

Salafia+17

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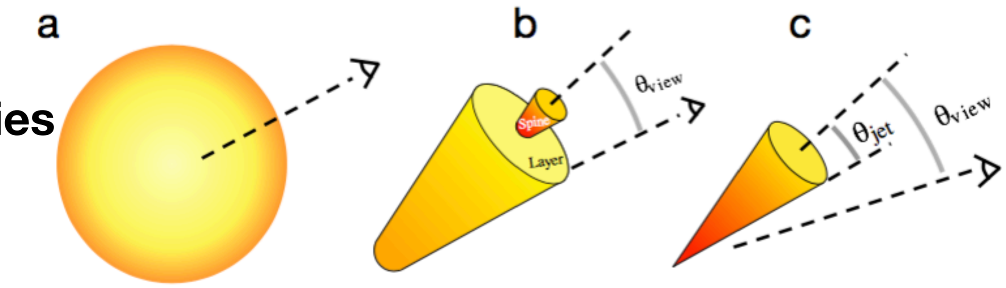

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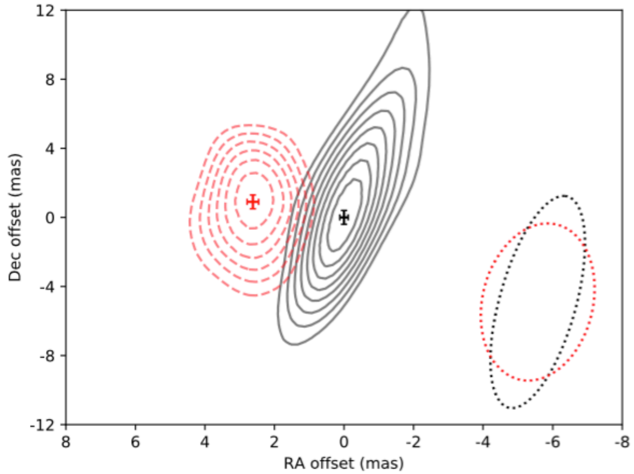

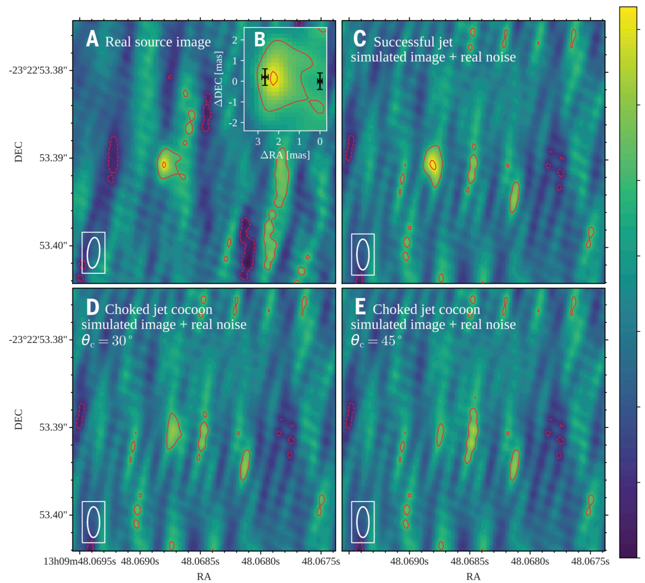

VLBI radio data:
- proper (superluminal) motion
- source size < 2 mas

-> structured jet with a relativistic core with θ_{jet} < 5 deg and θ_{view} ~ 20 deg (Mooley+18; Ghirlanda+19)

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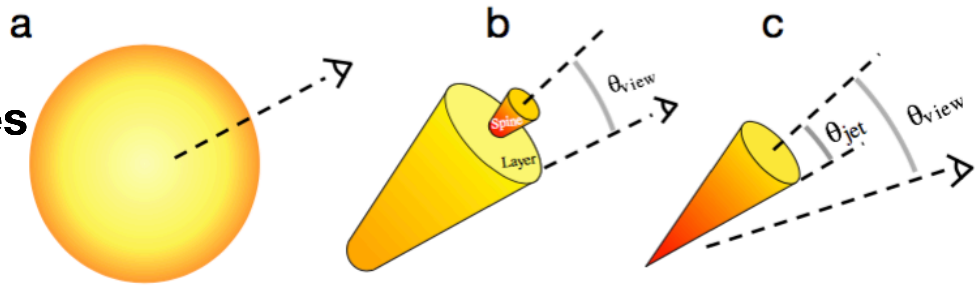

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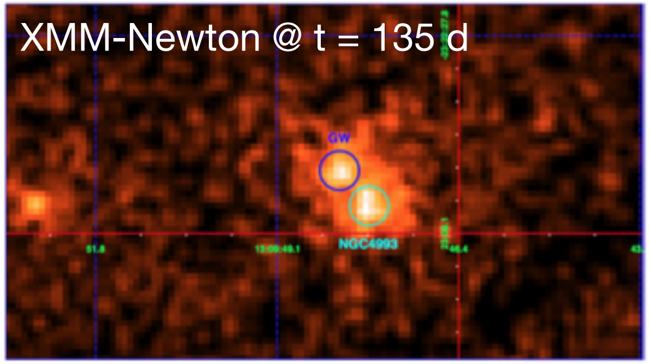
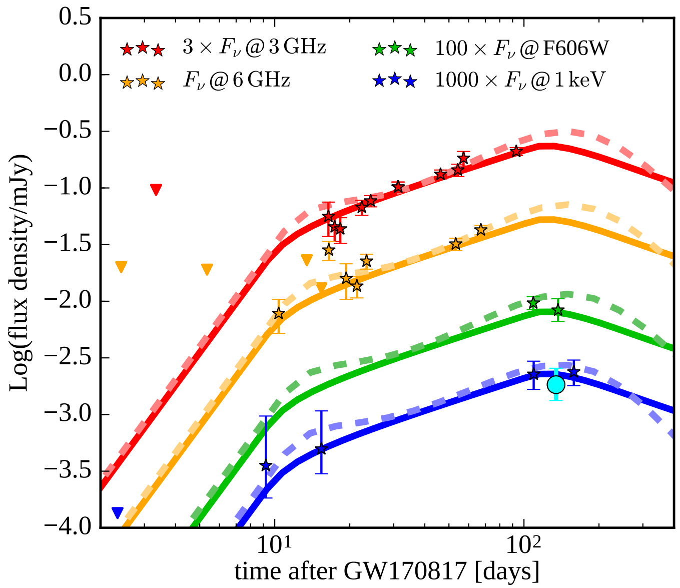
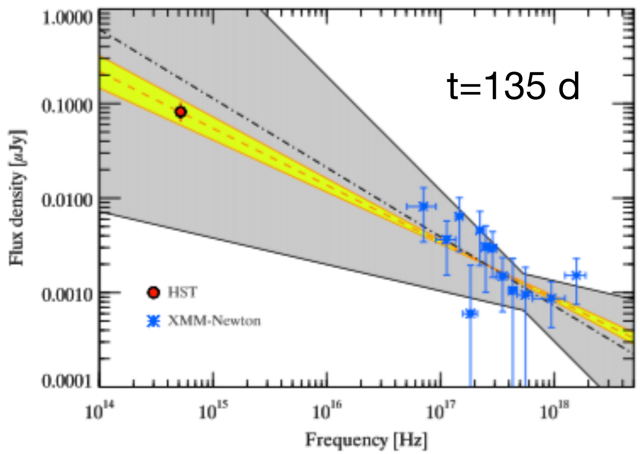




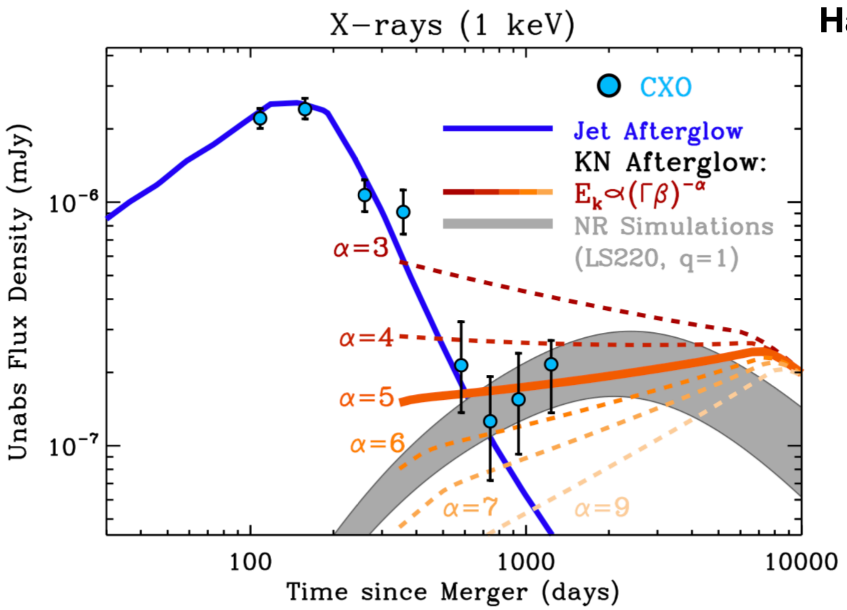
PDA+18

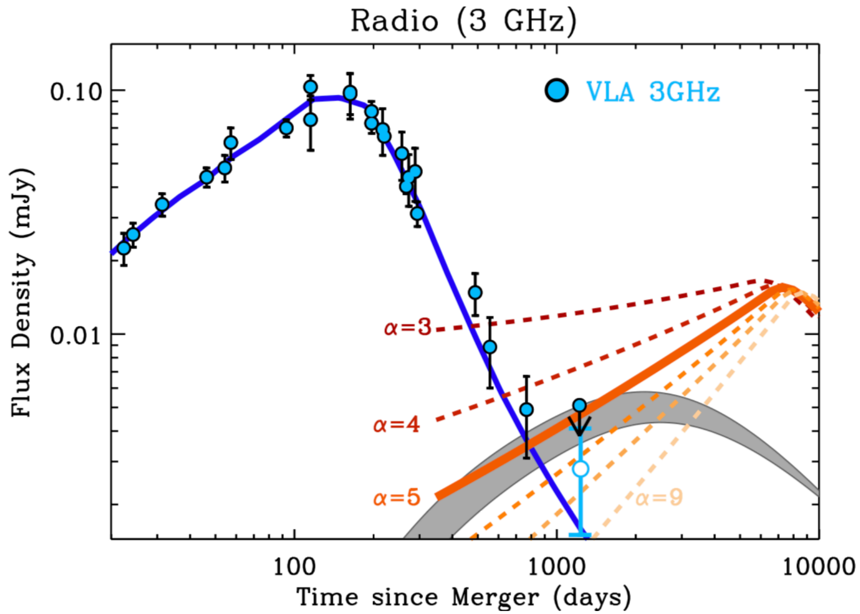


see also Troja+17, 18, 19, 20; Margutti+18; Alexander+18; Fong+19; Hajela+19

GRB170817A: a puzzling late time emission

Hajela+21





KN afterglow?

Accretion on compact remnant?

Magnetar?

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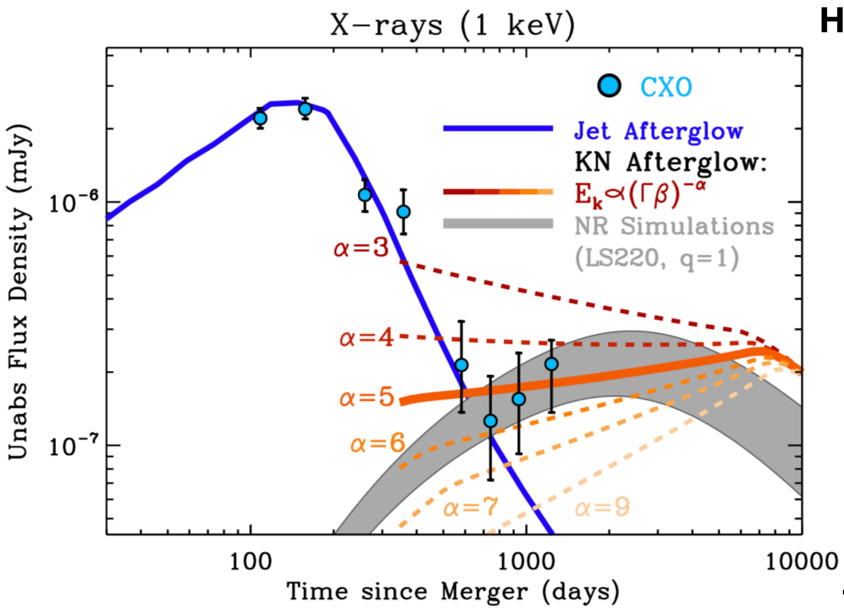
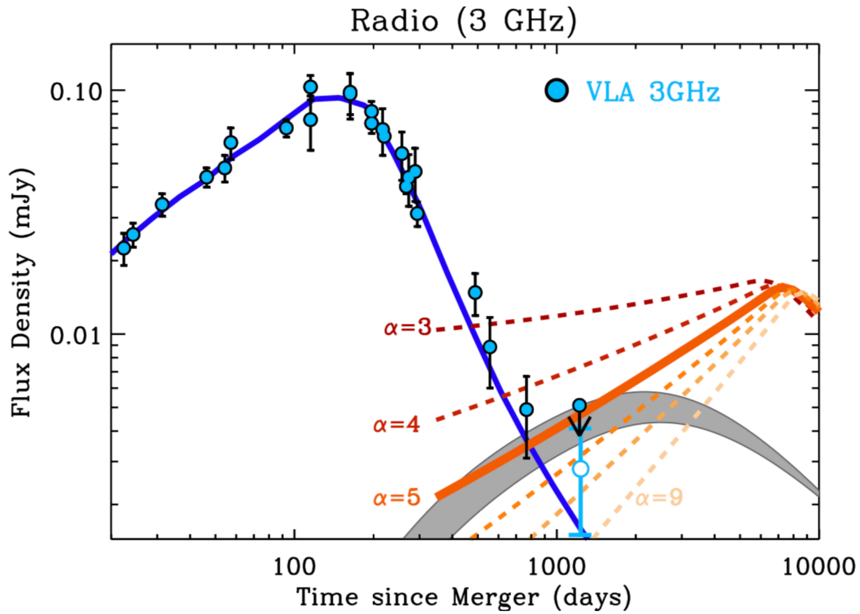
Hajela+21



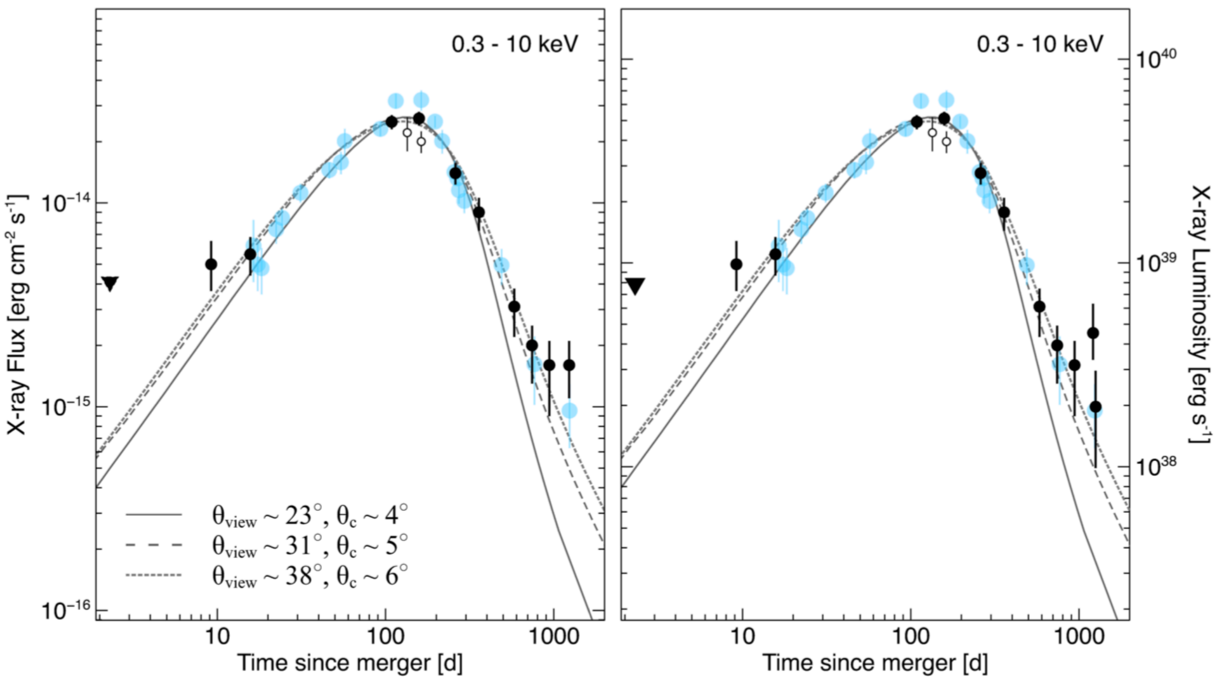


Troja+21

KN afterglow?

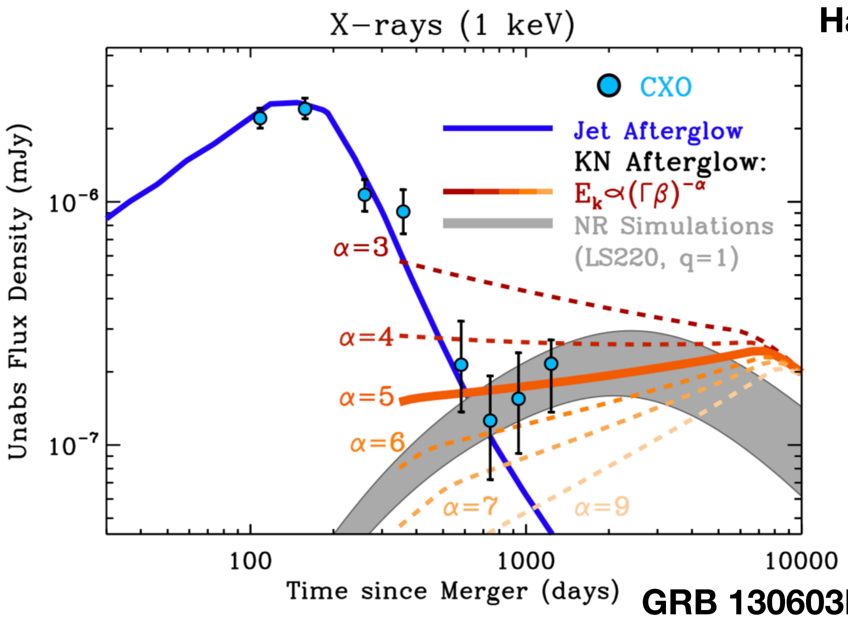
Accretion on compact remnant?

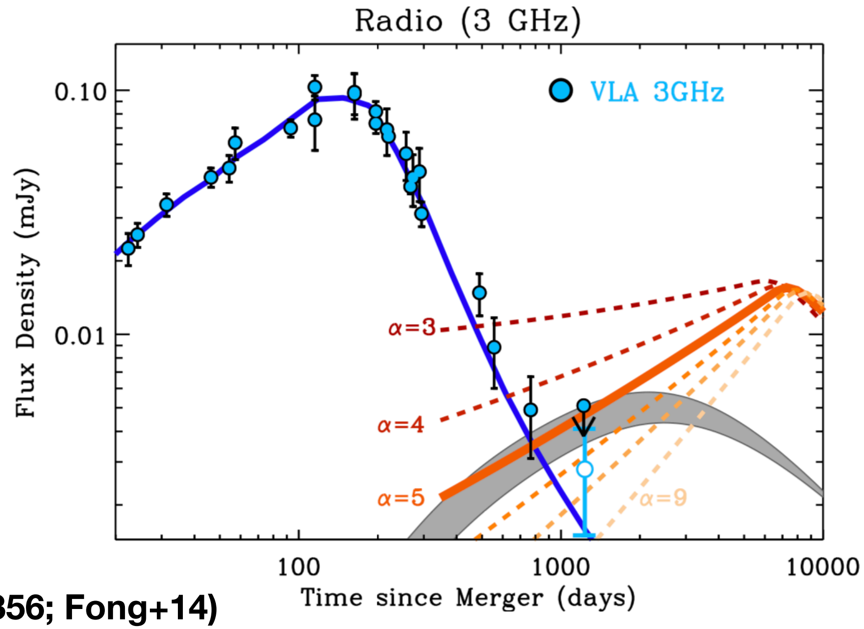
Magnetar?



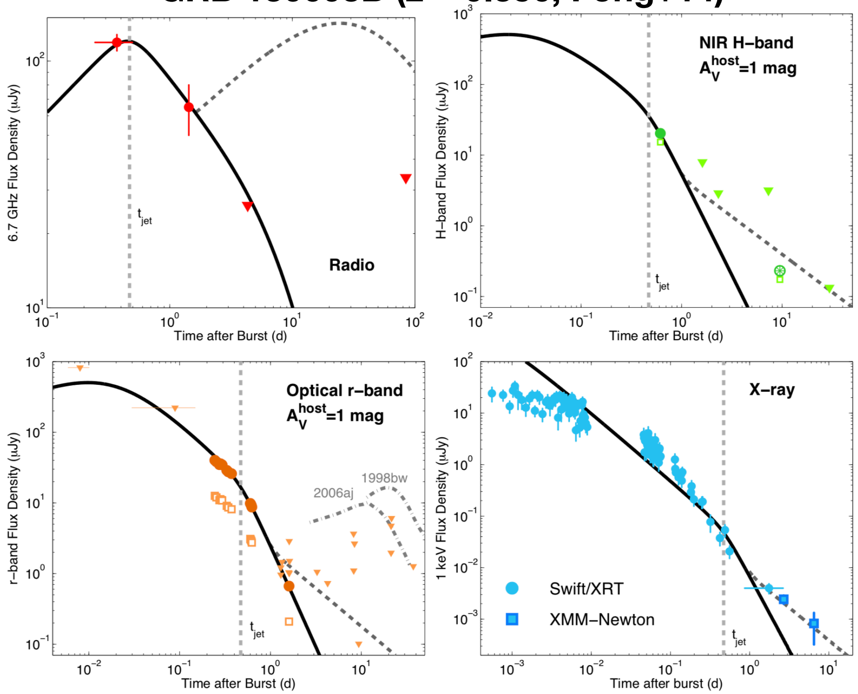
GRB170817A: a puzzling late time emission

Hajela+21





GRB 130603B (z = 0.356; Fong+14)



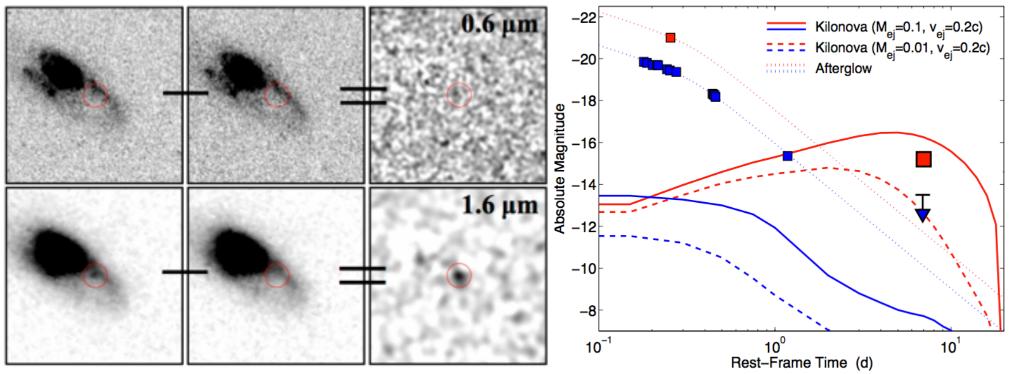
KN afterglow?

Accretion on compact remnant?

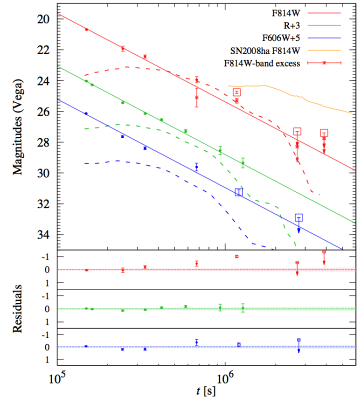
Magnetar?

Many (claimed) KNe

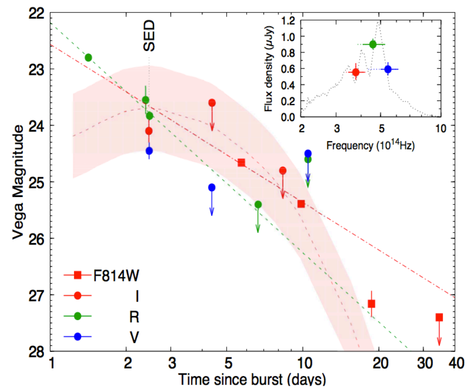
GRB 130613B (z=0.356) Tanvir+13; Berger+13



GRB 060614 (z=0.125)

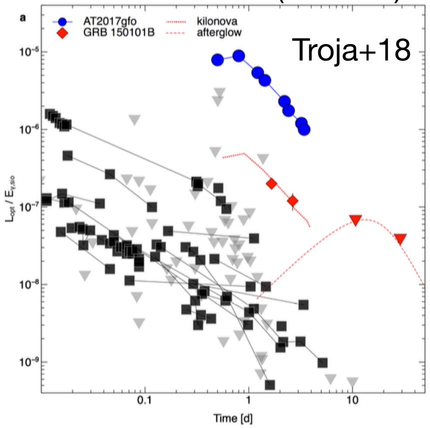


GRB 050709 (z=0.160)

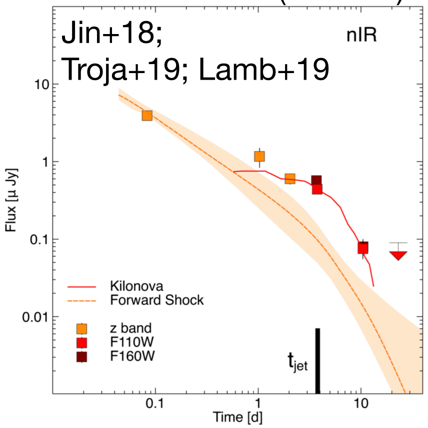


Yang+15; Jin+15; Jin+16

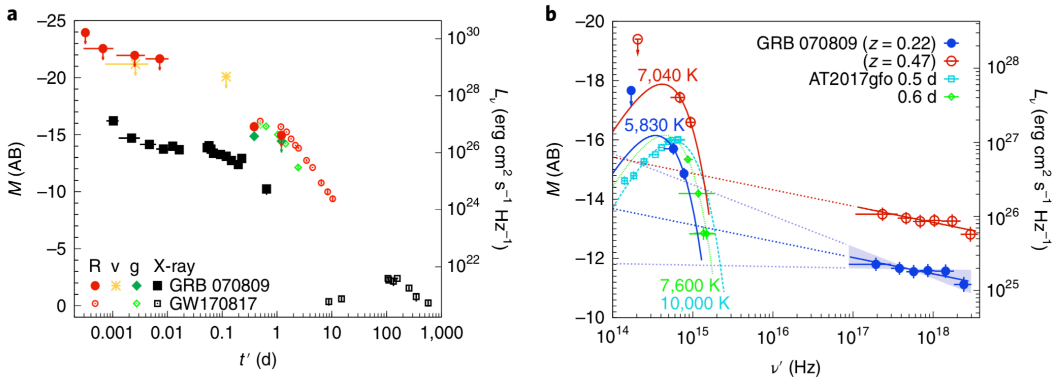
GRB 150101B (z=0.134)



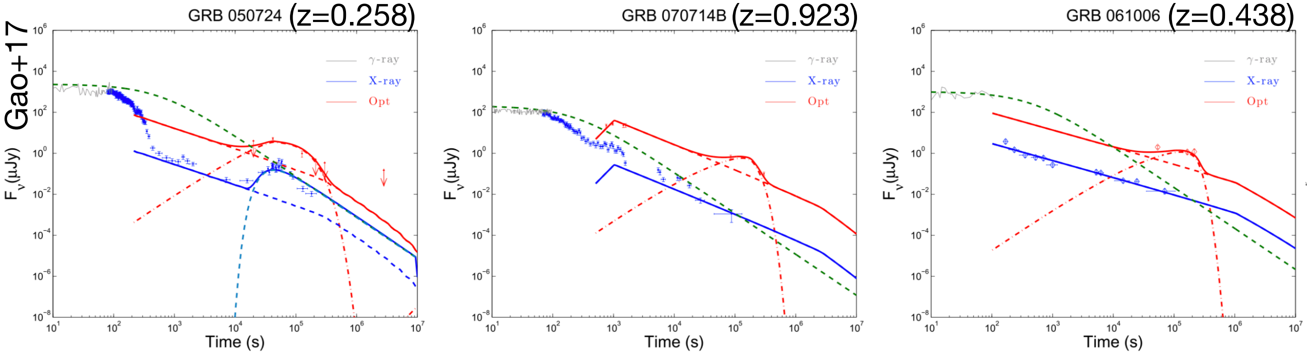
GRB 160821B (z=0.161)



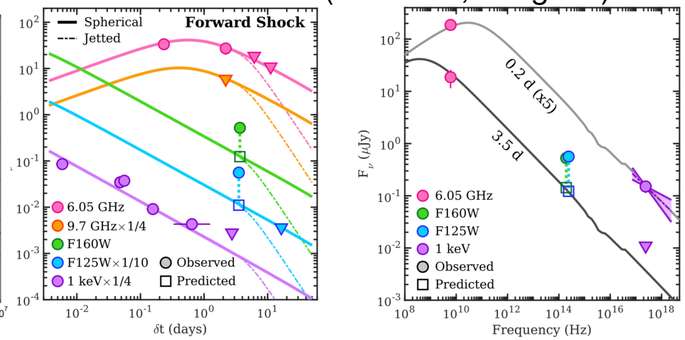
GRB 070809 (z=0.22 or z = 0.47; Jin+20)



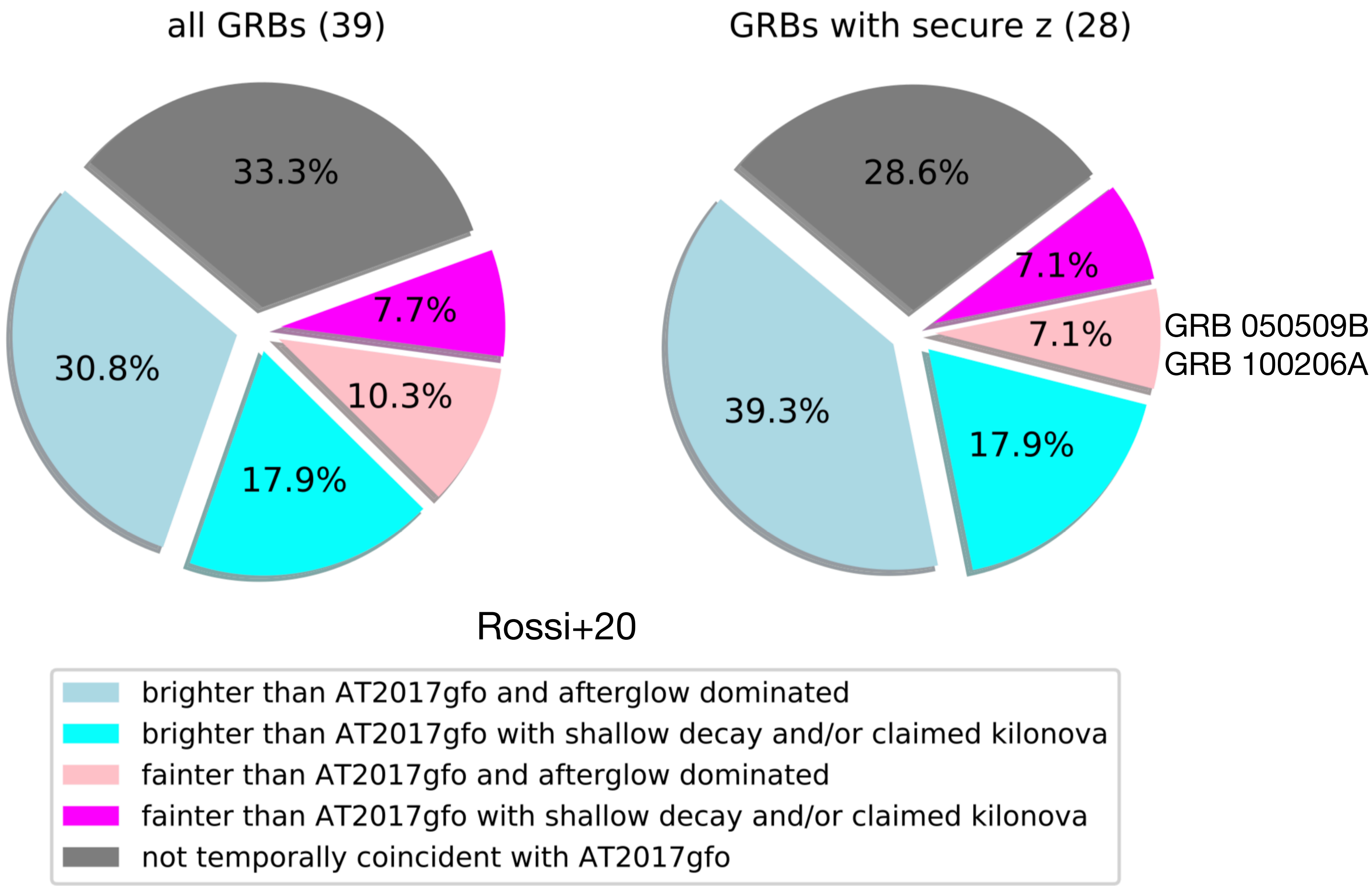
Gao+17



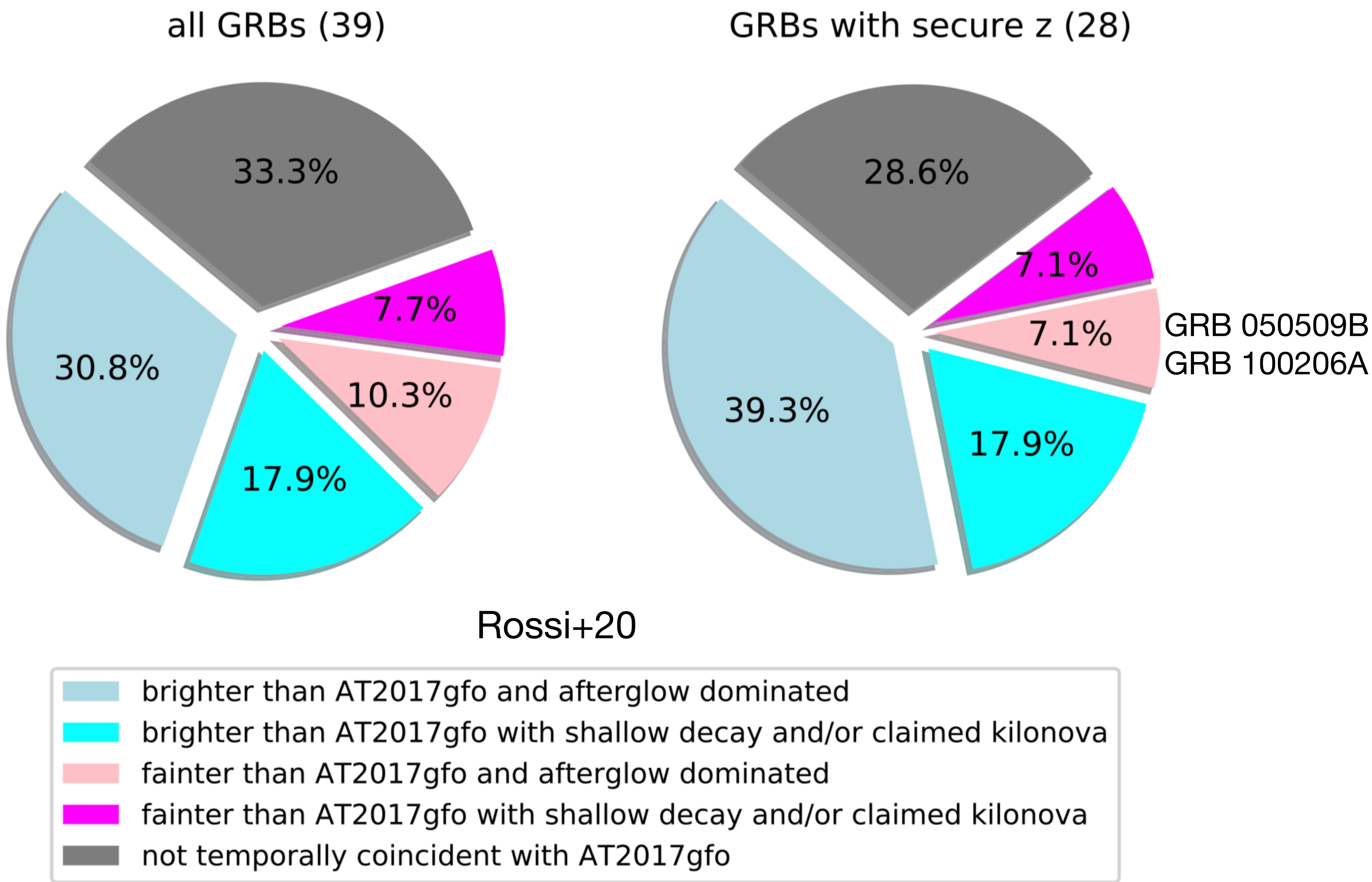
GRB 200522A (z=0.5536; Fong+20)



A KN for every short GRB?



A KN for every short GRB?



Another interesting finding of this work is that the luminosity of the blue KN component (when present) can vary significantly, while the red component seems to have always almost the same luminosity.

Searching for GRB 170817A – like events

von Kienlin+19

Talk by Andreas von Kienlin

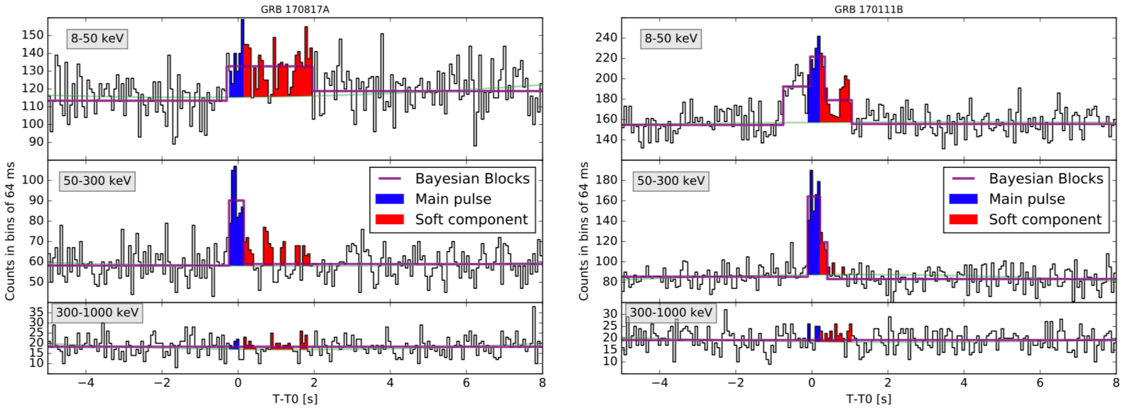


Figure 1. Left: composite light curves using NaI(Tl) detectors in the 8–50 keV (top panel), 50–300 keV (middle panel), and 300–1000 keV (bottom panel) energy ranges for GRB 170817A. Right: same, but for GRB 170111B. Blue marks the main pulse, red is the soft tail, and the procedure to find their span is given in Section 2.3. The observed pretrigger soft emission of GRB 170111B is later discussed in Section 4.

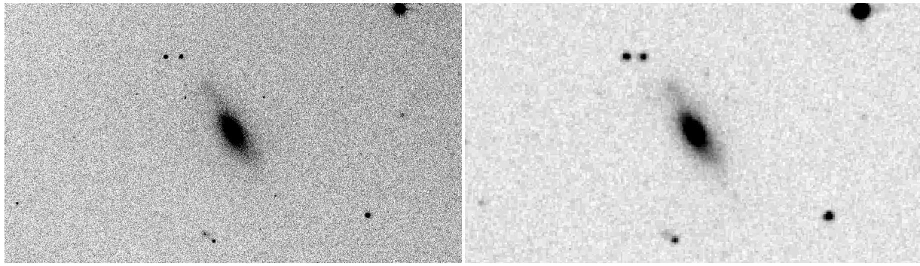
Table 2

Standard *Fermi*-GBM Burst Catalog Parameters of the Final Sample of 13 Candidate GRBs, which Includes the Reference GRB 170817A

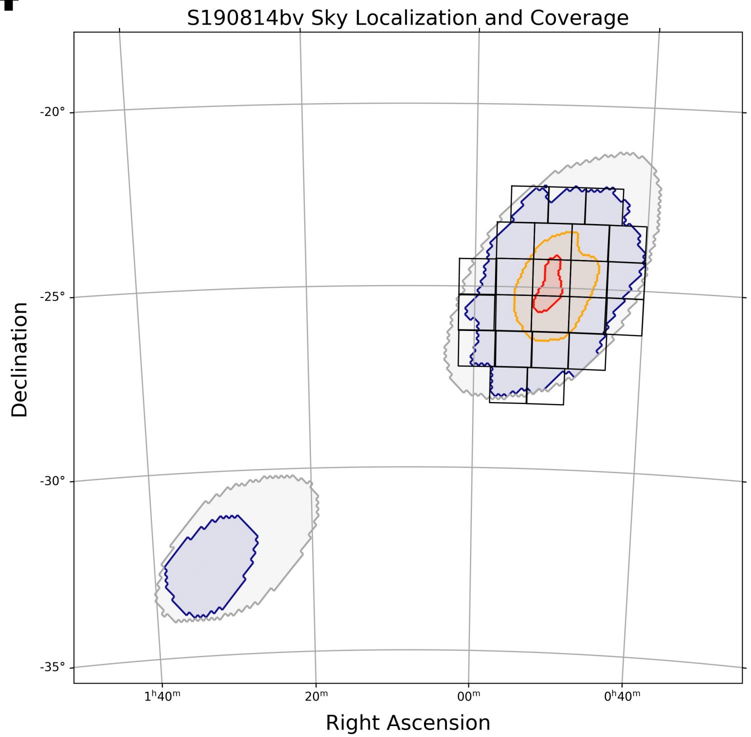
GRB Name	Trigger ID[a]	Time (UTC)	Durations T90 (s)	Durations T50 (s)	Localization R.A. (deg.)	Localization Decl. (deg.)	Localization Error (deg.)	Total Fluence (erg cm^{-2}) $\times 10^{-7}$	Peak Flux (64 ms) (ph cm^{-2} s^{-1})	Detect.[b]	References
GRB 081209A[c]	bn081209981	23:41:56.39	0.192 ± 0.143	0.128 ± 0.143	45.3	63.5	4.9	14.66 ± 1.49	25.4 ± 1.2	KW, S,[d] A	Golenetskii et al. (2008a, 2008b)
GRB 100328A[c]	bn100328141	03:22:44.60	0.384 ± 0.143	0.192 ± 0.091	155.9	47.0	4.8	10.01 ± 0.24	13.4 ± 0.8		Abadie et al. (2012)
GRB 101224A	bn101224227	05:27:13.86	1.728 ± 1.68	0.192 ± 0.286	285.9	45.7	0.1[e]	1.92 ± 0.27	6.7 ± 1.0	S	Krimm et al. (2010), Nugent & Bloom (2010), Xu et al. (2010), Golovnya et al. (2011)
GRB 110717A[c]	bn110717180	04:19:50.66	0.112 ± 0.072	0.032 ± 0.023	308.5	−7.9	7.5	2.51 ± 0.12	18.5 ± 1.8	KW, IA	*Fermi*-GBM Only
GRB 111024C[c]	bn111024896	21:30:02.24	0.960 ± 1.032	0.256 ± 0.143	91.2	−1.8	13.2	3.80 ± 0.16	7.4 ± 1.2	IA	*Fermi*-GBM Only
GRB 120302B[c]	bn120302722	17:19:59.08	1.600 ± 0.779	0.512 ± 0.466	24.1	9.7	13.9	1.19 ± 0.16	6.2 ± 1.5		*Fermi*-GBM Only
GRB 120915A[f]	bn120915000	00:00:41.64	0.576 ± 1.318	0.320 ± 0.091	209.4	67.3	5.9	5.06 ± 0.26	6.0 ± 0.9	IA, SW	*Fermi*-GBM Only
GRB 130502A	bn130502743	17:50:30.74	3.328 ± 2.064	2.304 ± 0.572	138.6	−0.1	0.0[e]	6.27 ± 0.35	6.6 ± 1.4	S, OT	Troja et al. (2013), Malesani et al. (2013), de Ugarte Postigo et al. (2013), Gorosabel et al. (2013), Breeveld & Troja (2013)
GRB 140511A[f]	bn140511095	02:17:11.56	1.408 ± 0.889	0.256 ± 0.181	329.8	−30.1	8.8	3.71 ± 0.32	9.4 ± 1.0		*Fermi*-GBM Only
GRB 150101B	bn150101641	15:23:34.47	0.08 ± 0.928	0.016 ± 0.023	188.0	−11.0	0.0[e]	2.38 ± 0.15	10.5 ± 1.3	S, IA, C, X, *z*	Troja et al. (2018), Burns et al. (2018), Fong et al. (2016)
GRB 170111B[f]	bn170111815	19:34:01.39	3.072 ± 1.318	0.32 ± 0.091	270.9	63.7	6.7	5.96 ± 0.12	7.6 ± 1.0		*Fermi*-GBM Only
GRB 170817A	bn170817529	12:41:06.47	2.048 ± 0.466	1.28 ± 0.405	197.5	−23.4	0.0[e]	2.79 ± 0.17	3.7 ± 0.9	L, *z*, C, IA, *HST* and more	Abbott et al. (2017a)
GRB 180511A[f]	bn180511364	08:43:35.79	0.128 ± 1.207	0.032 ± 0.045	250.4	−8.2	15.1	1.53 ± 0.21	9.2 ± 1.0	IA	*Fermi*-GBM Only

No luck during O3

Most promising event: GW 190814



GTC, VLT, LBT, WHT, TNG, NOT, LT, GROND coordinated observations of more than 70 galaxies, over multiple epochs within the 90% localization of the GW



Talk by Enrico Cappellaro

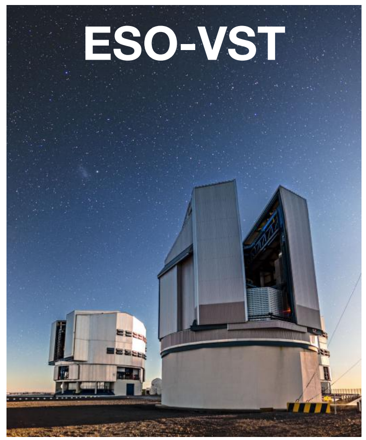
+

Wide-field observations (VST, VISTA, PS, ATLAS, GOTO)

ENGRAVE collaboration (Ackley+20)

5 VST epochs

Δt	r AB mag	Probability
+11.5 h	20.9	60.7%
+1.5 d	21.9	71.5%
+4.3 d	21.7	87.7%
+7.2 d	21.8	87.7%
+14.5 d	22.0	87.7%



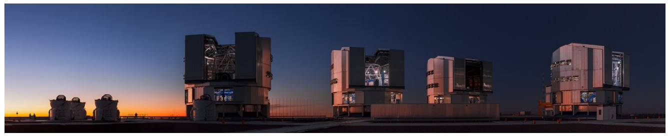
Looking towards O4

Search (& follow-up) European teams

Engrave

www.engrave-eso.org

Governing Council: M. Branchesi, E. Brocato, P. D'Avanzo, J. Hjorth, P. Jonker, E. Pian, S. Smartt (Chair), J. Sollerman, D. Steeghs, N. Tanvir.
Executive Committee: S. Covino, A. Levan (Chair), K. Maguire, D. Malesani, S. Vergani.



A collaboration of ~ 200 ESO scientists
Approved program during Oct 2018 – Mar 2020 fully covering O3. Time for EM counterparts **follow-up** on every useful **VLT** instrument + **ALMA**.

Talk by Enrico Cappellaro

GraWITA

Gravitational waves @ INAF

www.grawita.inaf.it

VIN ROUGE

www.star.le.ac.uk/nrt3/VINROUGE/

The **G**W **O**ptical
Transient **O**bserver
GOTO
www.goto-observatory.org

Pessto ESO

www.pessto.org

and more

Conclusions

- **GW 170717 / GRB 170817A / AT2017gfo results:**
  - Definition and consolidation of successful follow-up strategies
  - First EM counterpart (at all wavelengths)
  - First unambiguous observational evidence for a kilonova
  - Evidence for kilonovae as a heavy elements factory
  - `Smoking gun' for short GRB progenitors
  - Clues on short GRB outflow geometry and properties: first evidence for a structured jet

- **The search for SGRB/KN events (old and new events) looks promising**

- **No good events in O3, waiting for O4**

- **Still a number of open issues**
  - **how many KN types?**
  - **what is the origin of the blue component?**
  - **are KNe associated to every short GRB?**
  - **can KNe unveil the nature of the NS-NS remnant?**