SUSSP73 – St Andrews

Multi-messenger astrophysics

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University of Leicester

The plan

Me (mainly on potential EM emission from compact binary mergers)

- Short duration gamma-ray bursts
- Prospects for X-ray/gamma-ray
- Kilonova emission
- Prospects for nIR follow-up

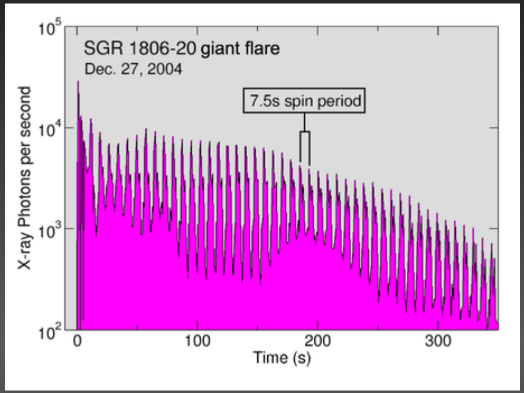
Stephen Smartt (mainly on observing strategies, results to-date and future developments)

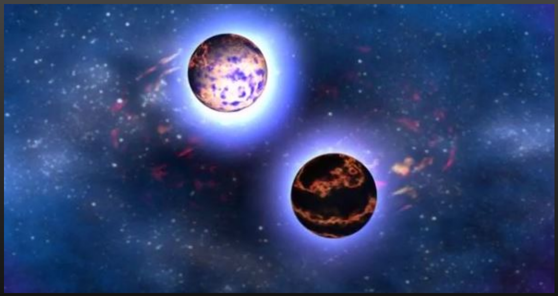
- Survey strategies and instruments
- Optical to NIR, efforts to date
- Prospects for LIGO, LIGO+VIRGO, LIGO+VIRGO+India
- Outlook for 2020+

Potential GW sources

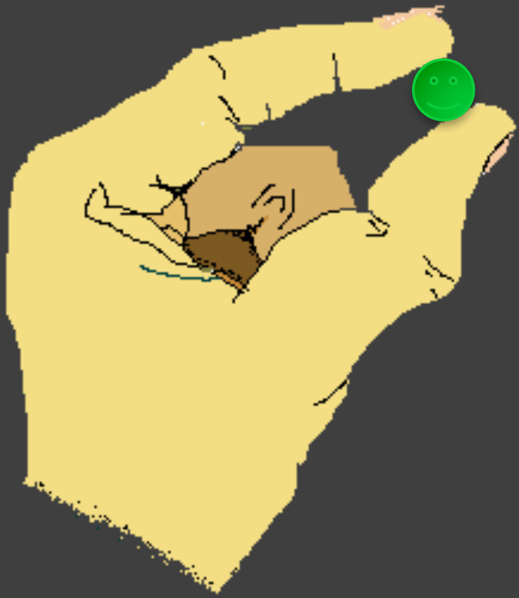
Large time-varying mass-quadrupole:

- Core collapse
- Neutron star reconfiguration
- Binaries involving compact objects
  - NS+NS
  - NS+BH
  - BH+BH
  - SMBH+…
  - WD+…





Huge gravitational fields leads to high energies.



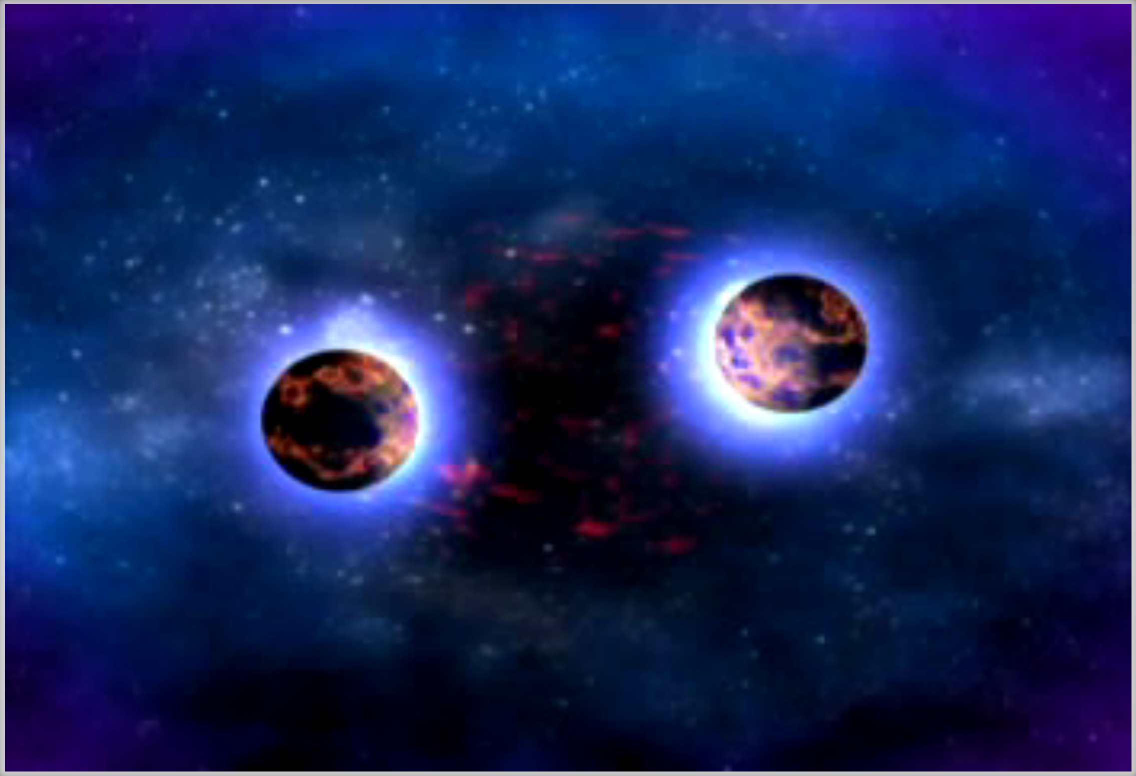
Huge gravitational fields leads to high energies.

~1.4 $M_\odot$

$$PE = \frac{GMm}{R} \approx 10^{13}\ \mathrm{J}$$

~10^4 m

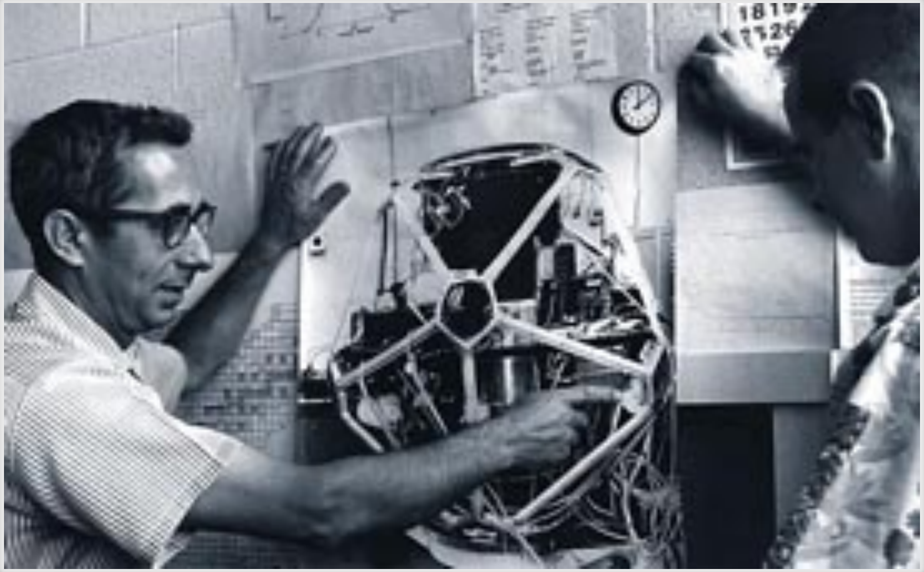
Two neutron stars colliding…

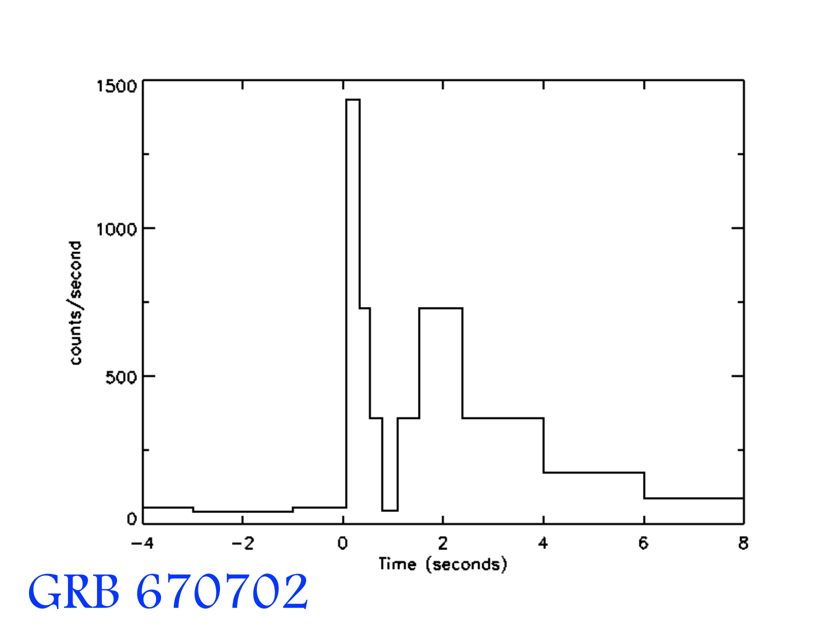


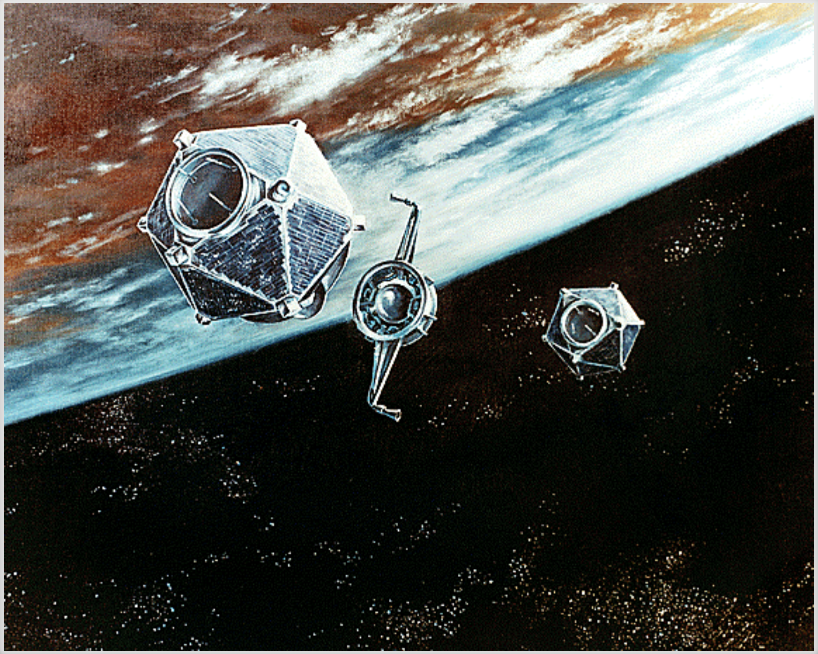
$$BE = \frac{GM^2}{R} \approx 10^{47}\ \mathrm{J} \equiv 10^{54}\ \mathrm{erg}$$

→ Very large energy reservoir (if it can be tapped)

Gamma-ray bursts (golden anniversary)

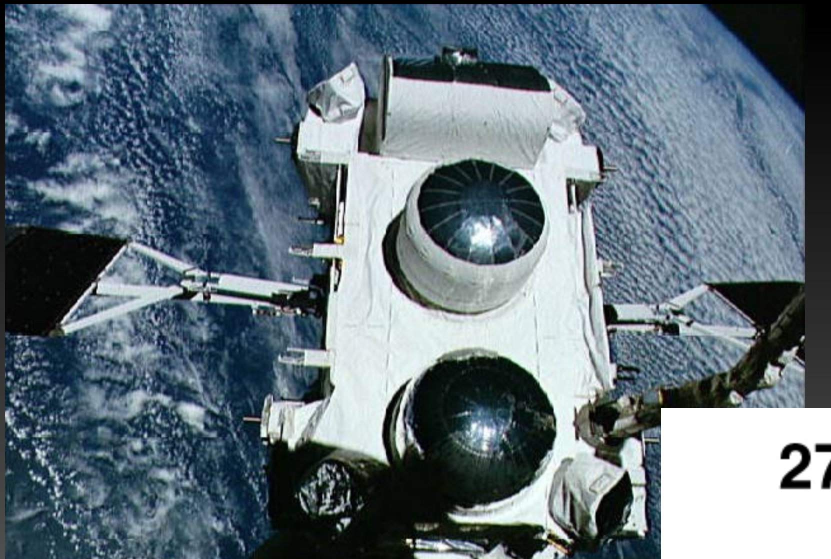


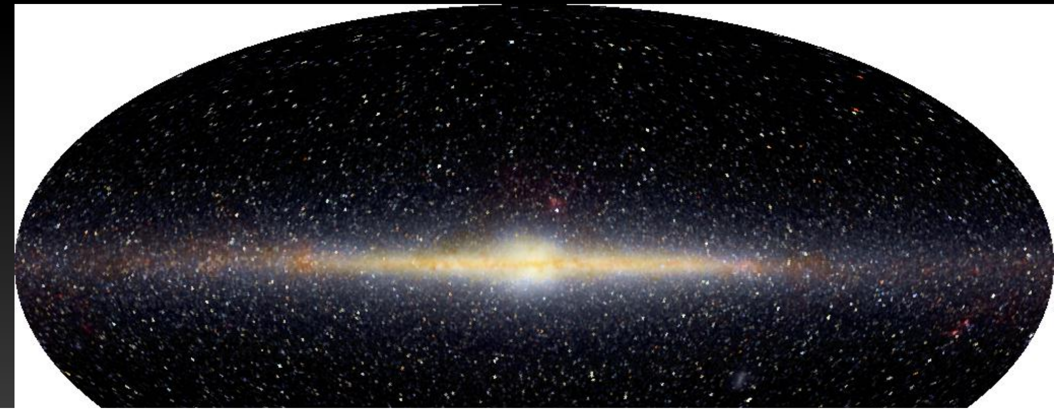


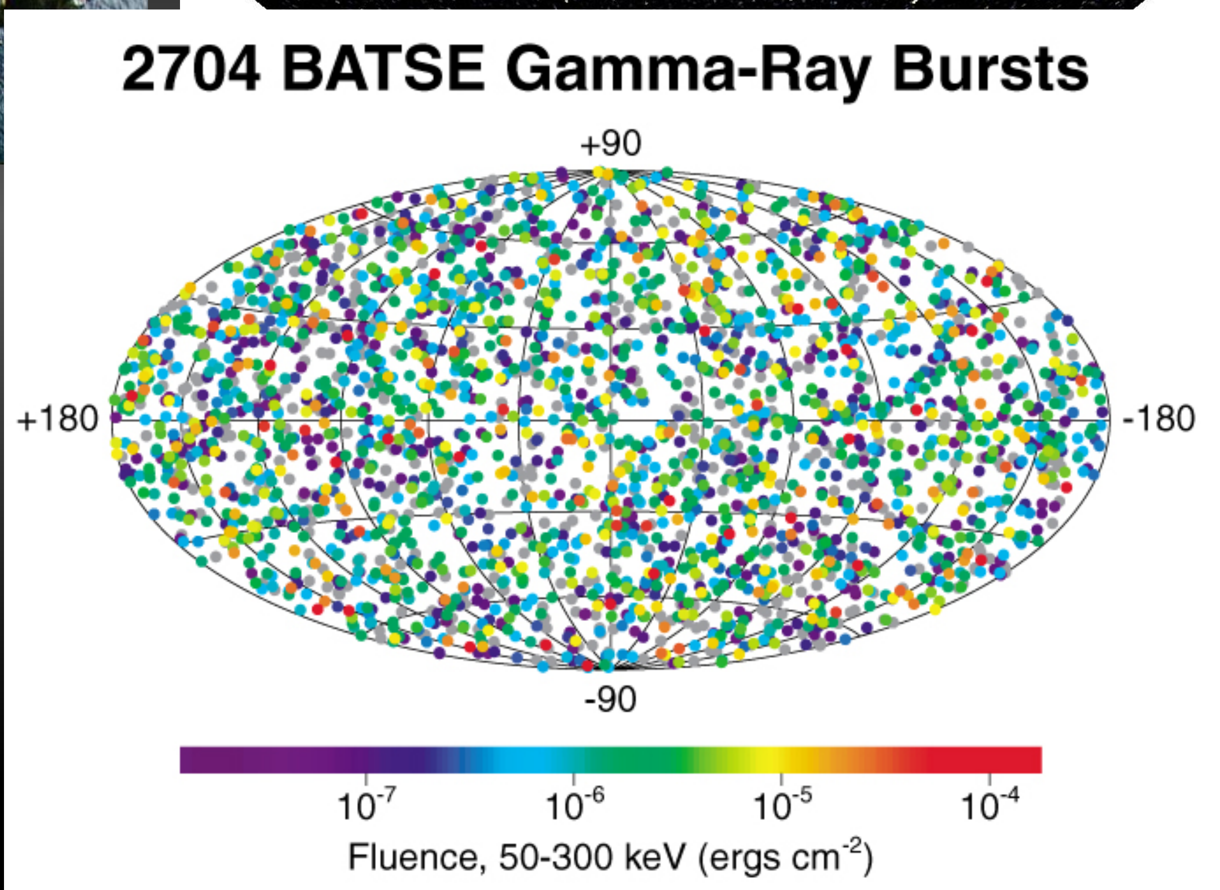


First known GRB detected 2nd July 1967 by US Vela 4 satellites.

Strong & Klebesadel 1976



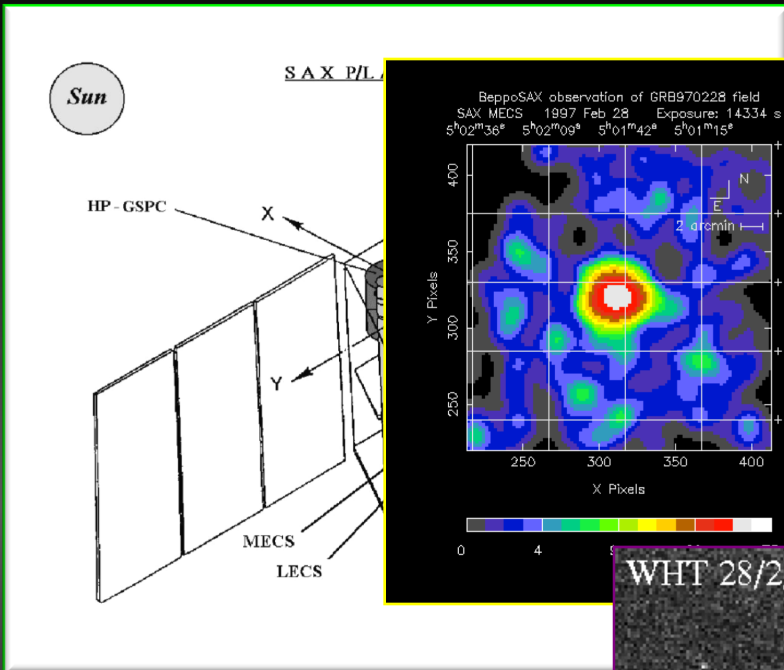


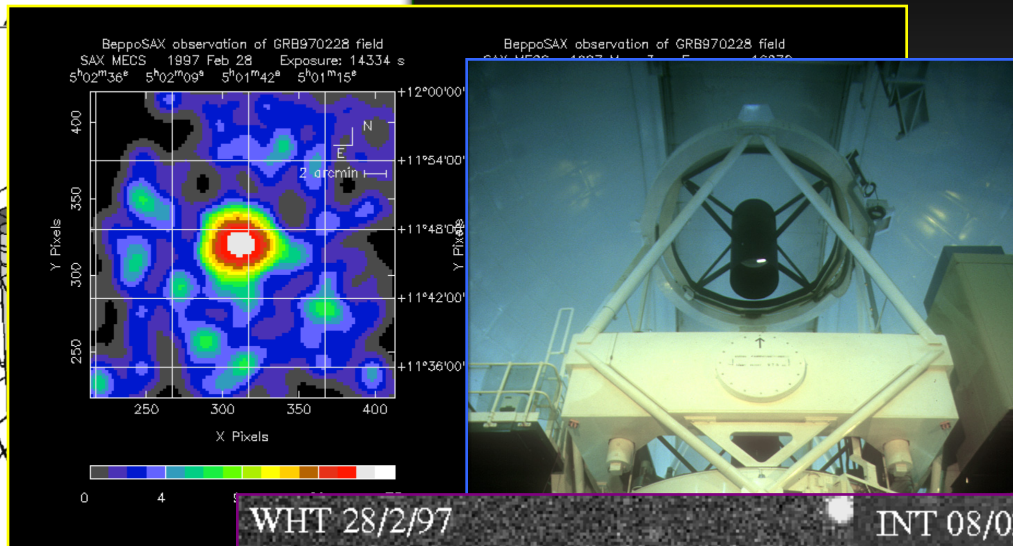


Compton GRO 1991-1999

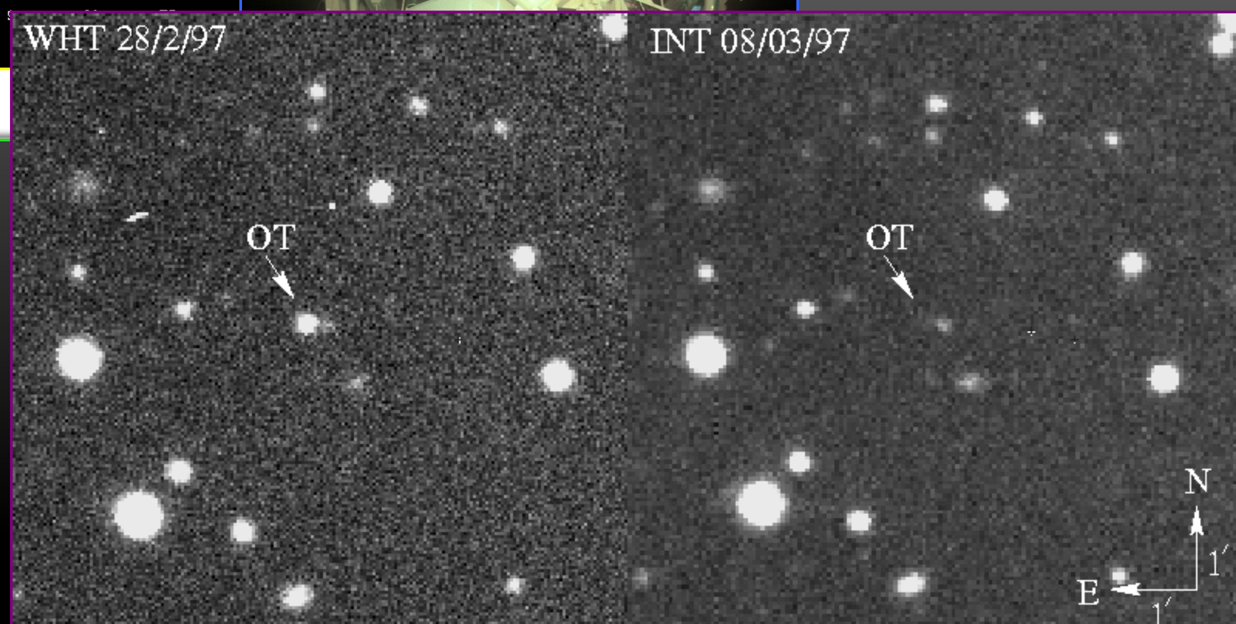
Finds that the bursts are spread over the whole sky. Still can't solve the mystery of their origin.

1997 - BeppoSAX and GRB afterglows



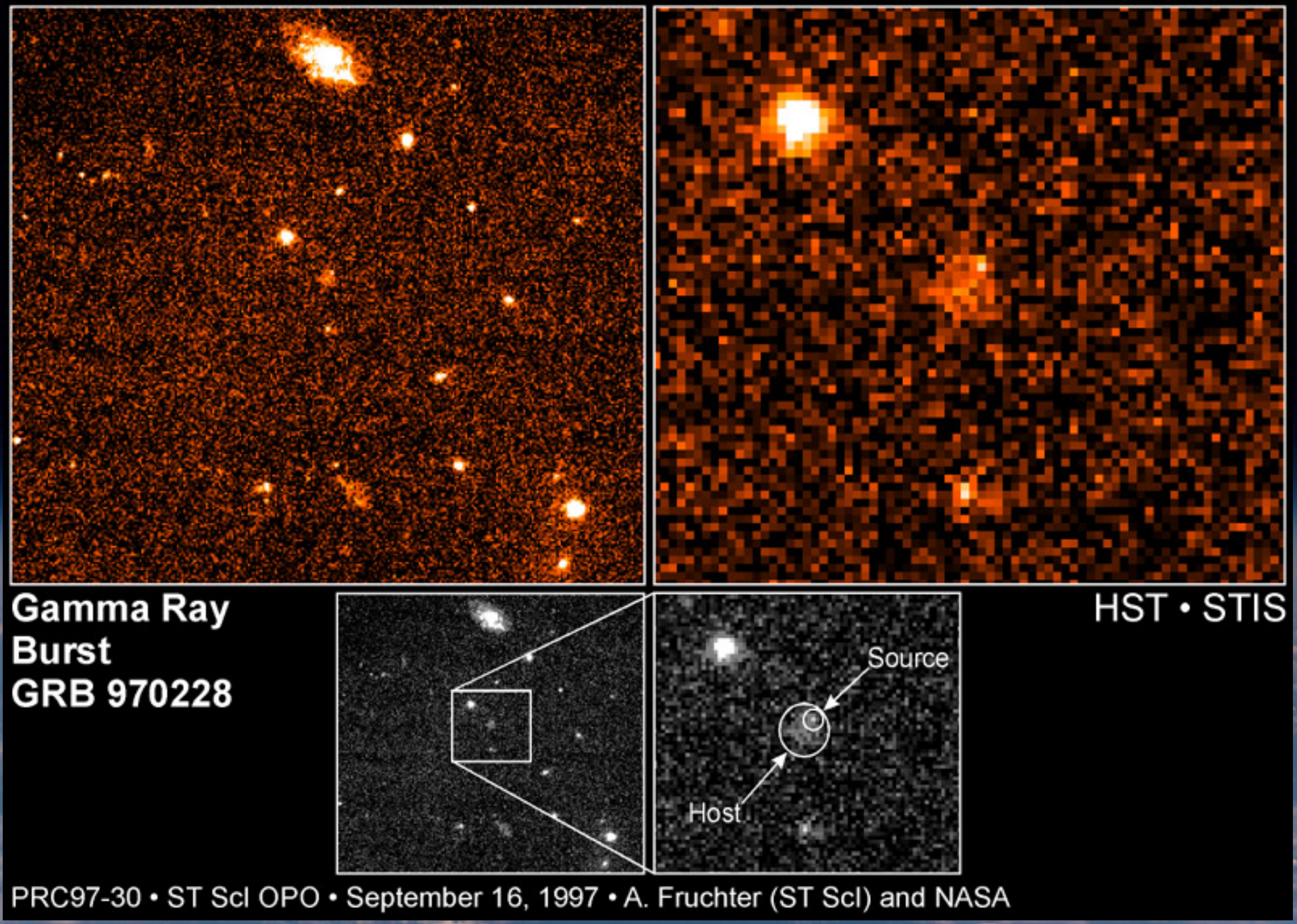


BSAX able to see X-ray afterglows and hence provide few arcmin error circles.



First optical afterglow found for GRB 970228

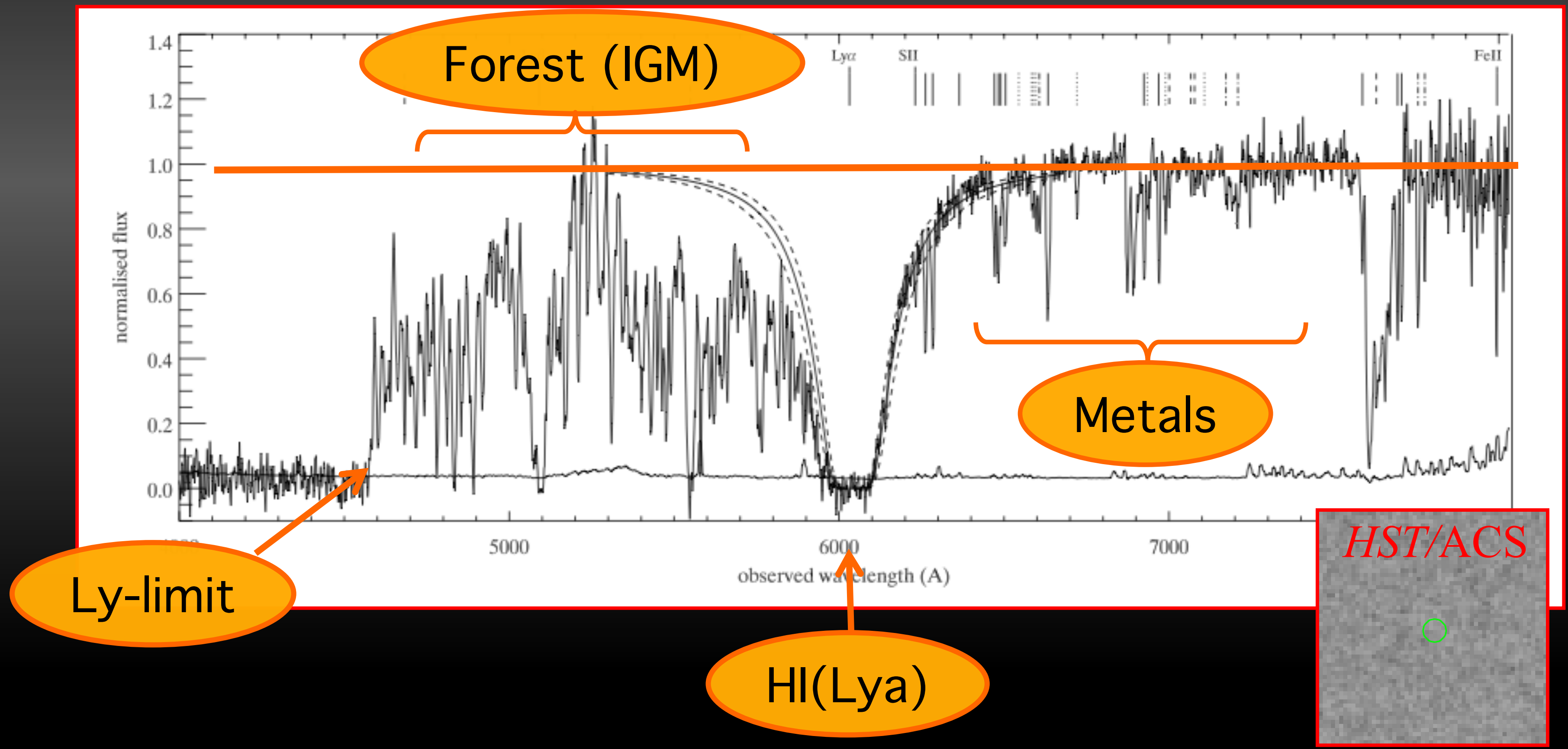
Later HST observations reveal host galaxy at z=0.65, which is about half way across observable universe!



GRBs by far the most luminous objects known!

Afterglow spectra contain much information

Redshift, abundances, HI, dust, dynamics etc. even for very faint hosts. E.g. GRB 050730: faint host (R>28.5), but z=3.97, [Fe/H]=~2 and low dust, from afterglow spectrum (Chen et al. 2005; Starling et al. 2005).



Max radiative energy (if isotropic) comparable to NS-NS or core-collapse.

$$E_{\text{iso}} \sim 10^{54}\ \text{erg}$$
$$\sim 10^{60}\ \gamma\text{'s}$$

Rapid variability of prompt emission (in some bursts) suggests compact progenitor.

$$d < ct_{\text{var}} \sim 10^{-2} c\ \text{m}$$

Compactness and non-thermal spectrum resolved if emission produced through dissipation after ultra-relativistic expansion.

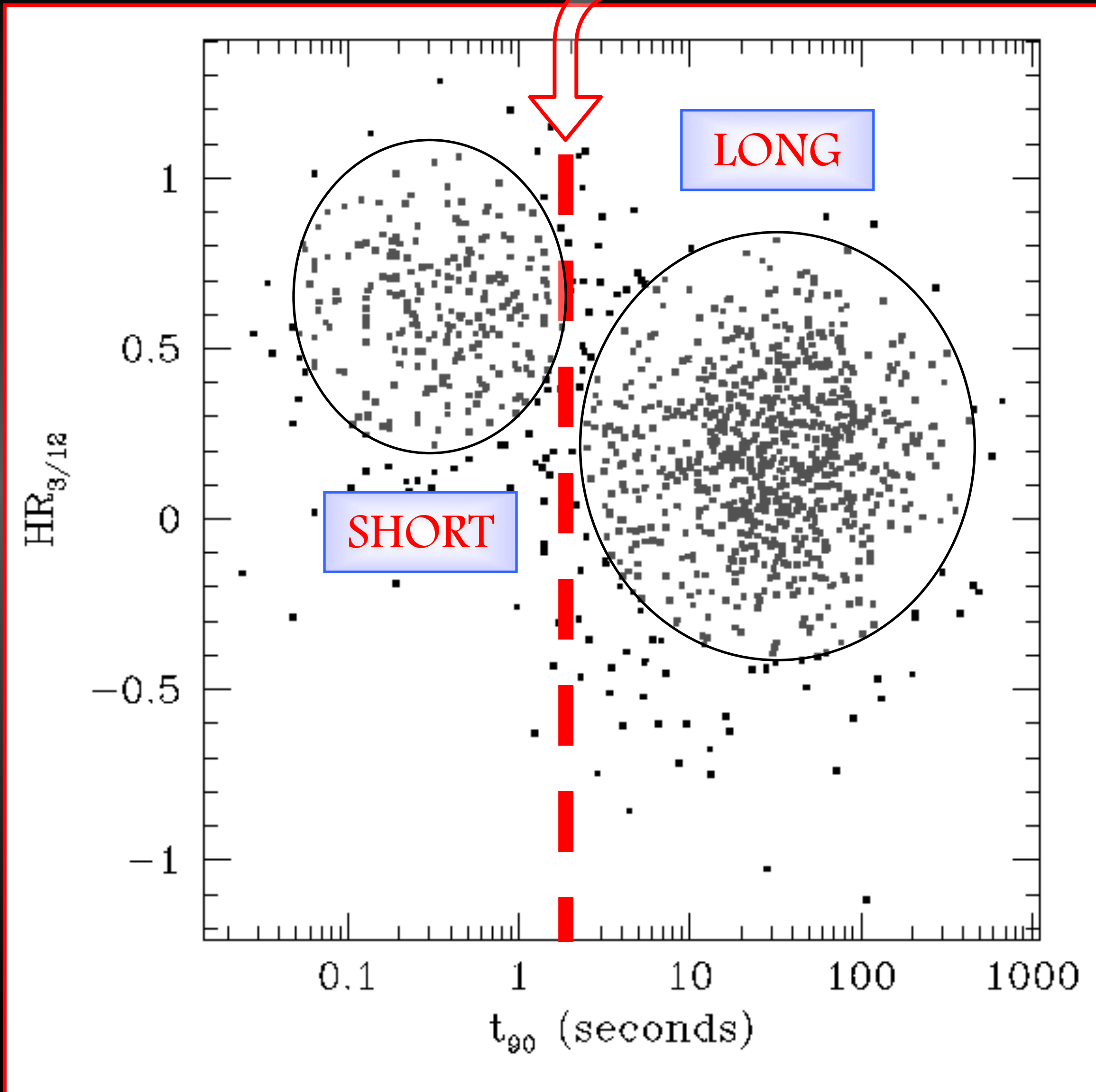
$$\tau_{\gamma\gamma} \sim \frac{10^{13}}{\Gamma^5}$$
$$\Longrightarrow \Gamma \sim 300$$

Requires low baryon pollution.

$$E = \Gamma M c^2$$
$$\Rightarrow M_{\text{iso}} \sim 10^{-3}\ \text{M}_\odot$$

Two populations

$T_{90}=2$ s



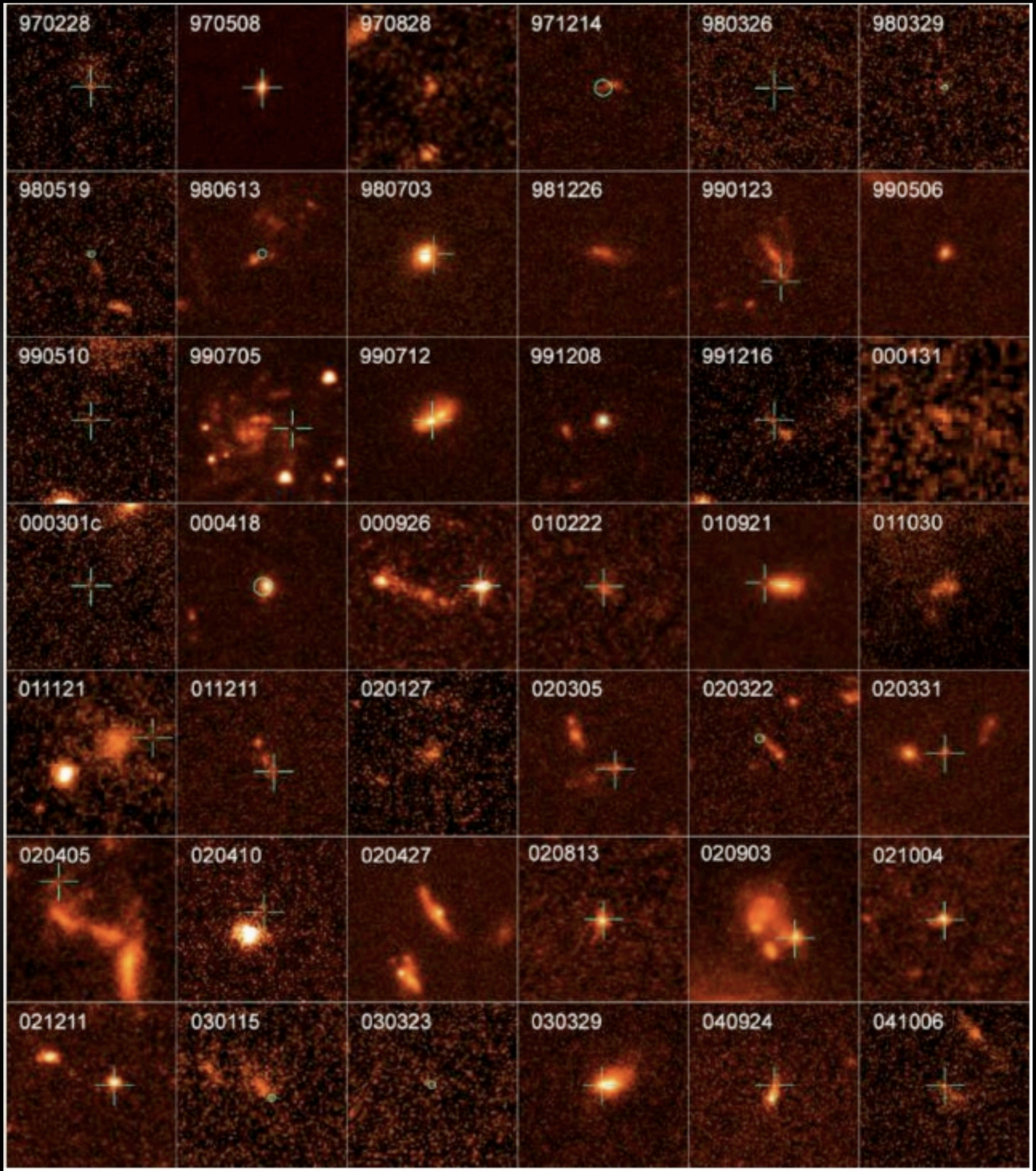
- Obviously overlap
- Detector dependent
- Redshift dependent (in complicated ways)

Kouveliotou et al. 1993
Mazets et al. 1982

Long-GRB hosts

Actively star forming, typically low luminosity, irregular, low(ish) metallicity.

Generally trace brightest regions of star formation, suggestive of short-lived (<~10 Myr) massive star progenitor.

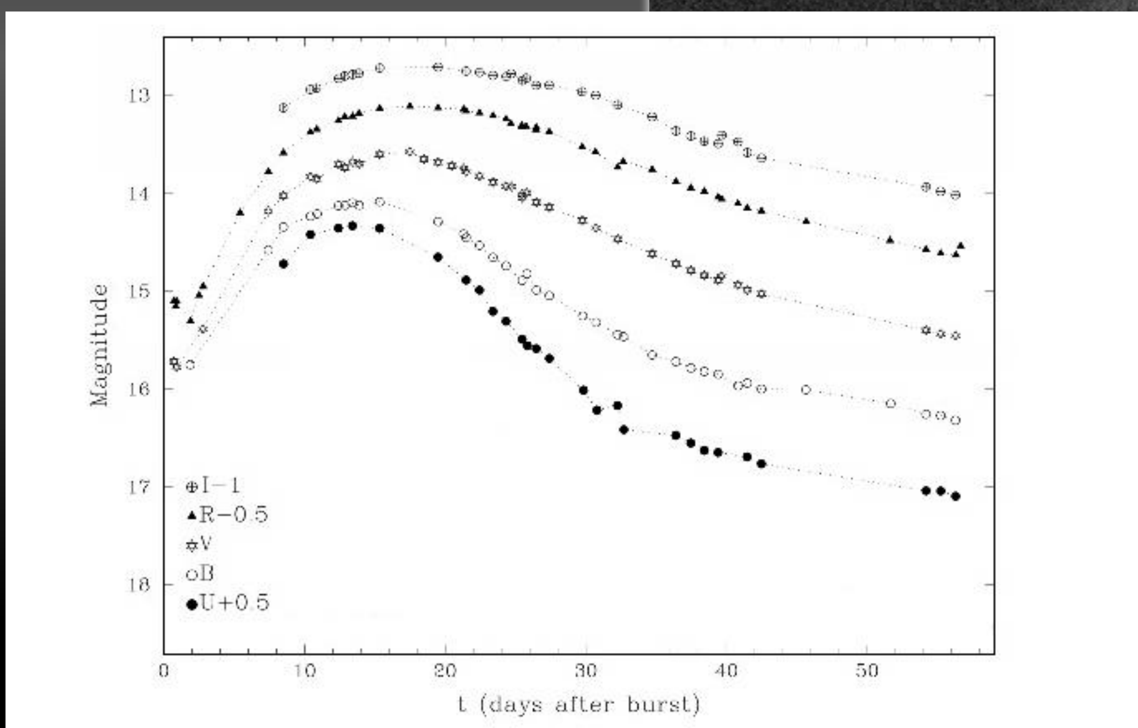


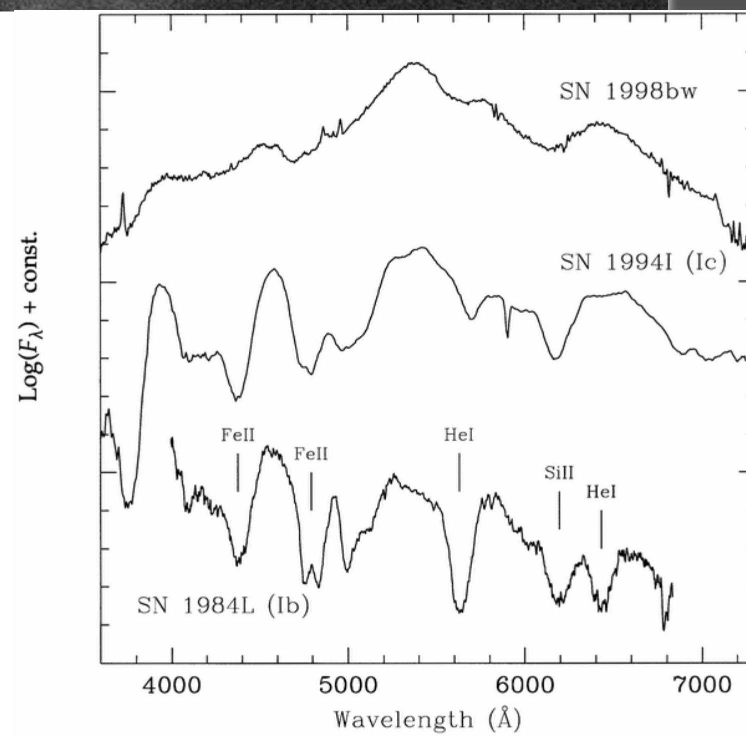
Fruchter et al. 2006

GRB 980425/SN98bw

Galama et al. 1998

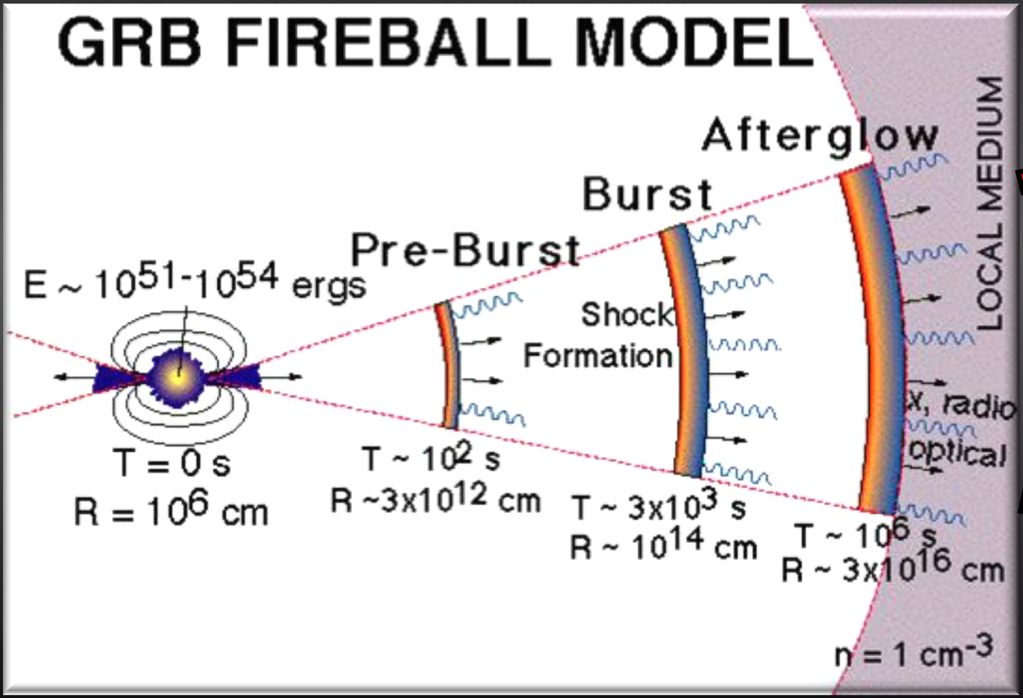
Type Ic with broad lines indicative of expansion velocities >~20000 km/s

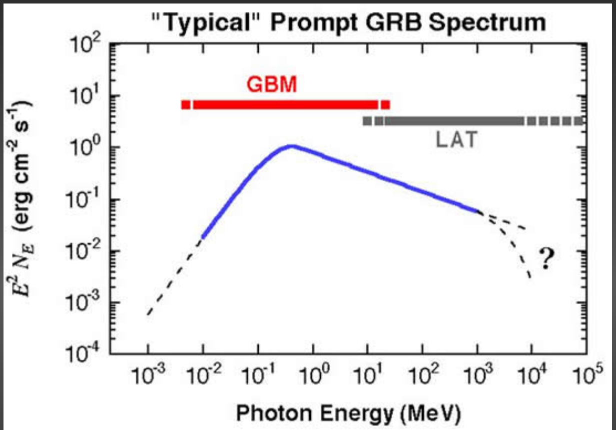


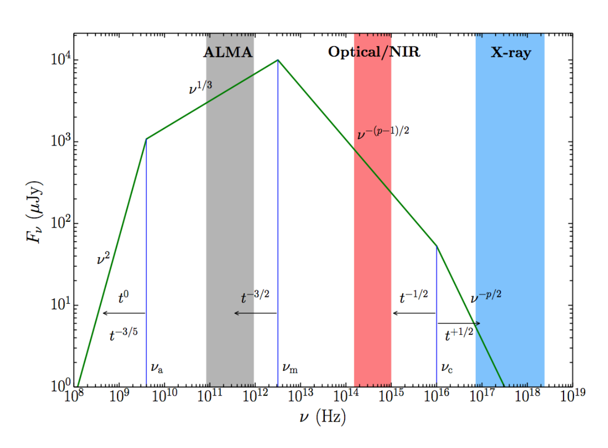


Relativistic fireball

"Standard picture" ultra-relativistic jet produces prompt emission via internal shocks from shell collisions within jet, and afterglow emission via shocking of ambient medium.

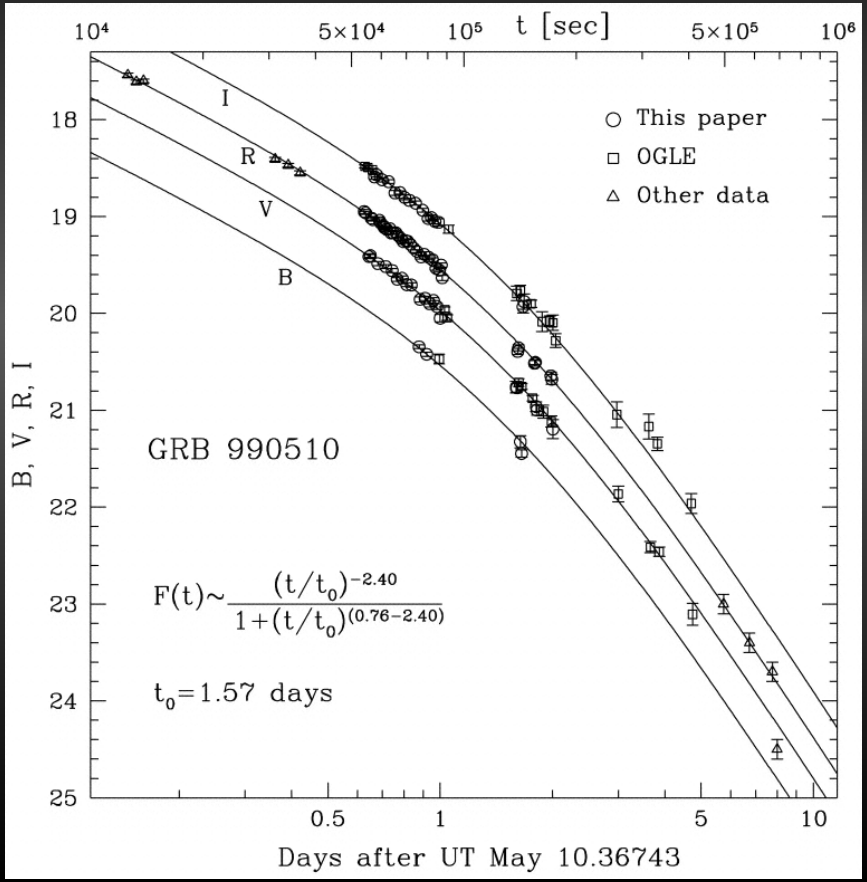






Why do we think long-GRBs are jetted?

- Although we don't understand them well, we know jets are common in accreting astrophysical systems.
- Easier to conceive of a jet solving baryon loading problem by clearing material to side.
- Alleviates the efficiency problem – total energy requirement reduced by 2-3 orders of magnitude.
- Some GRB light curves show achromatic breaks, a predicted signature of a (decelerating) jetted source with opening angles >~few degrees.



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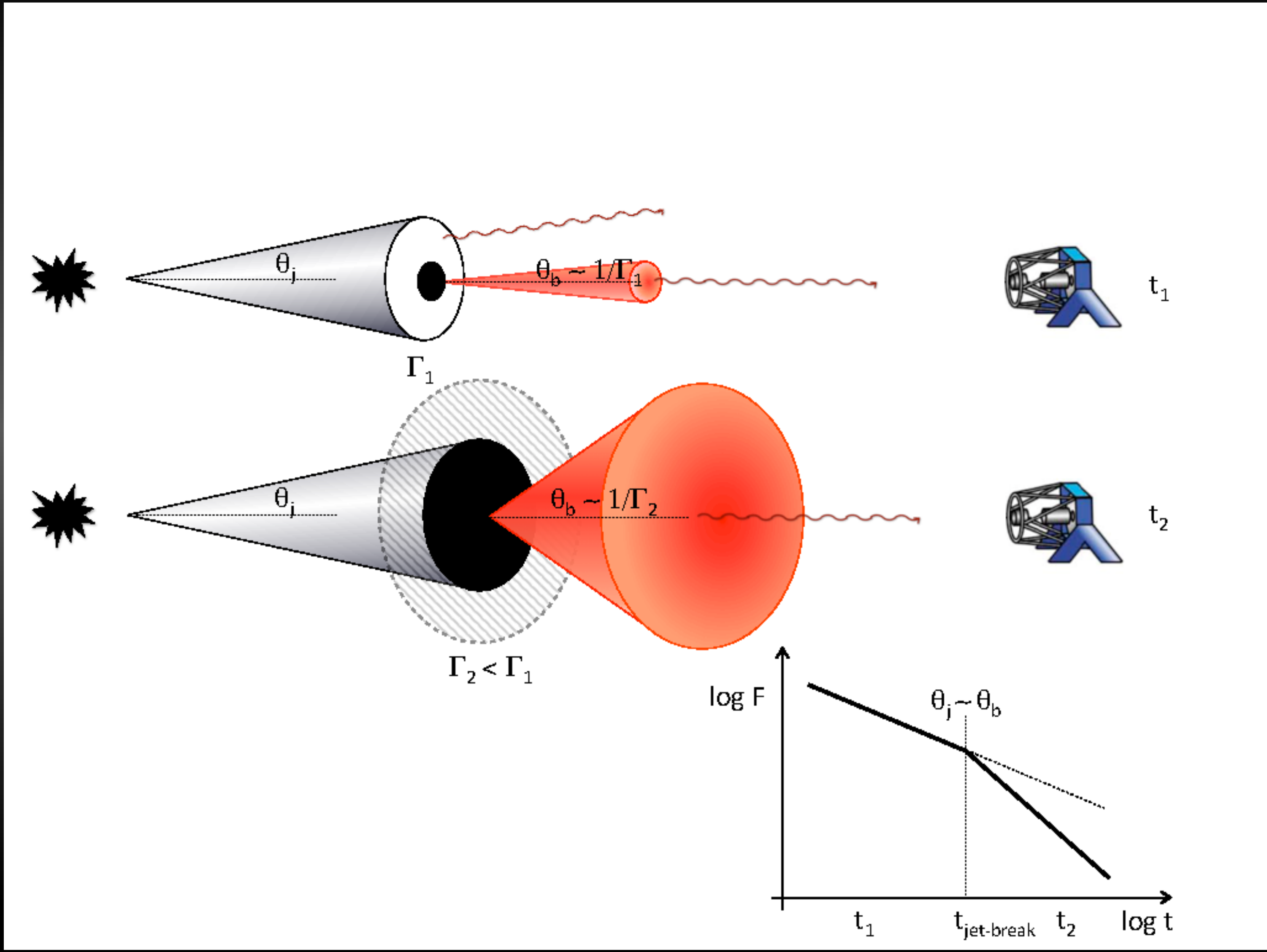
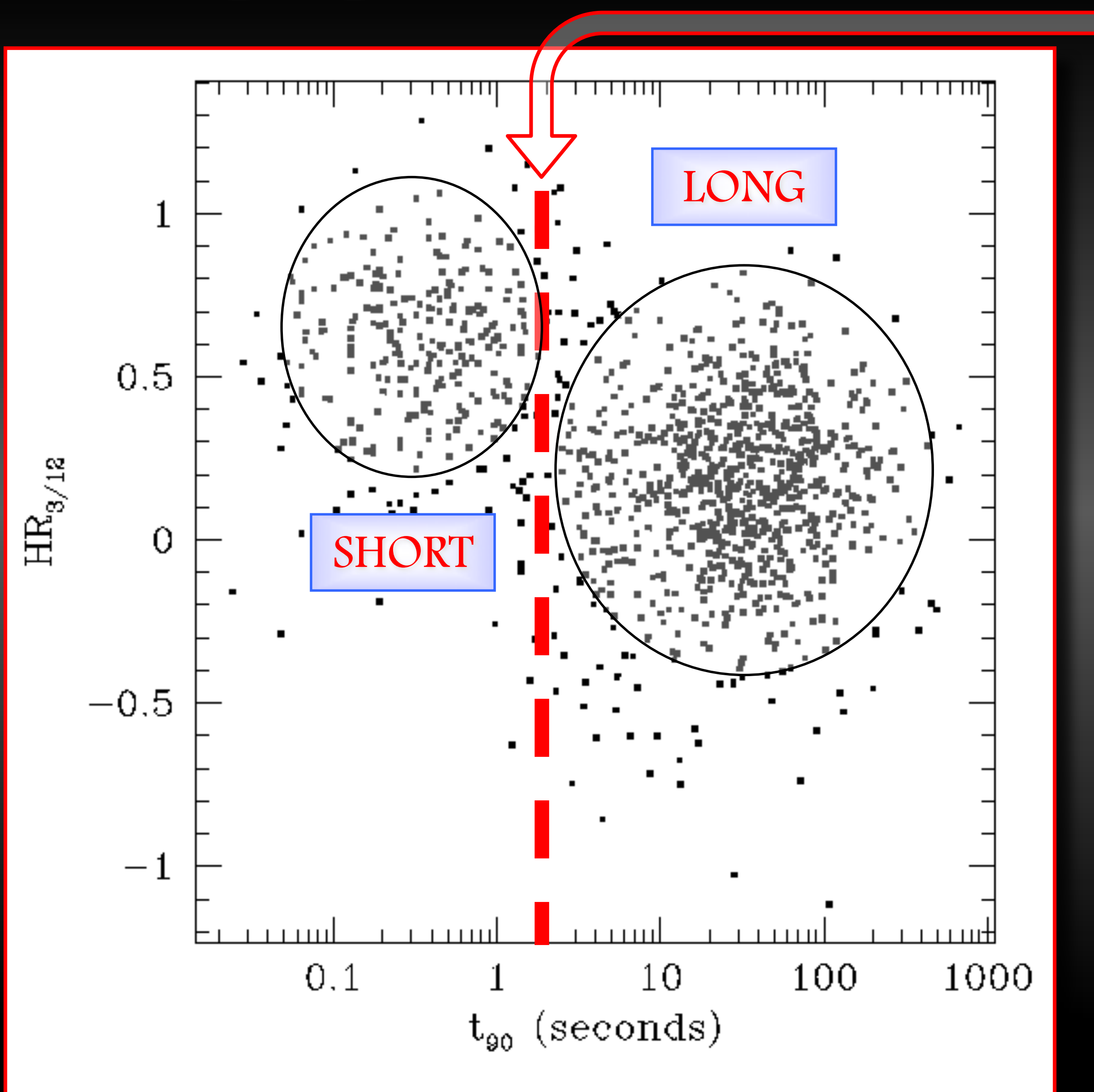


Two populations

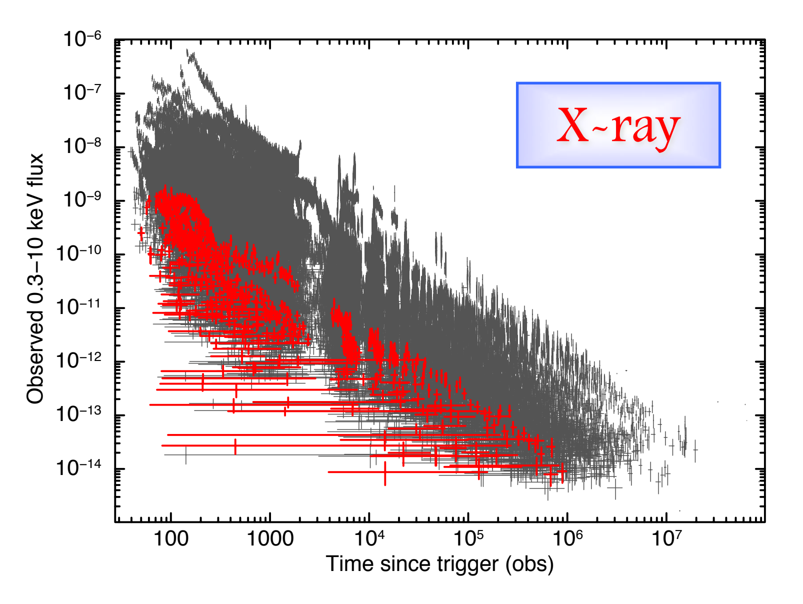


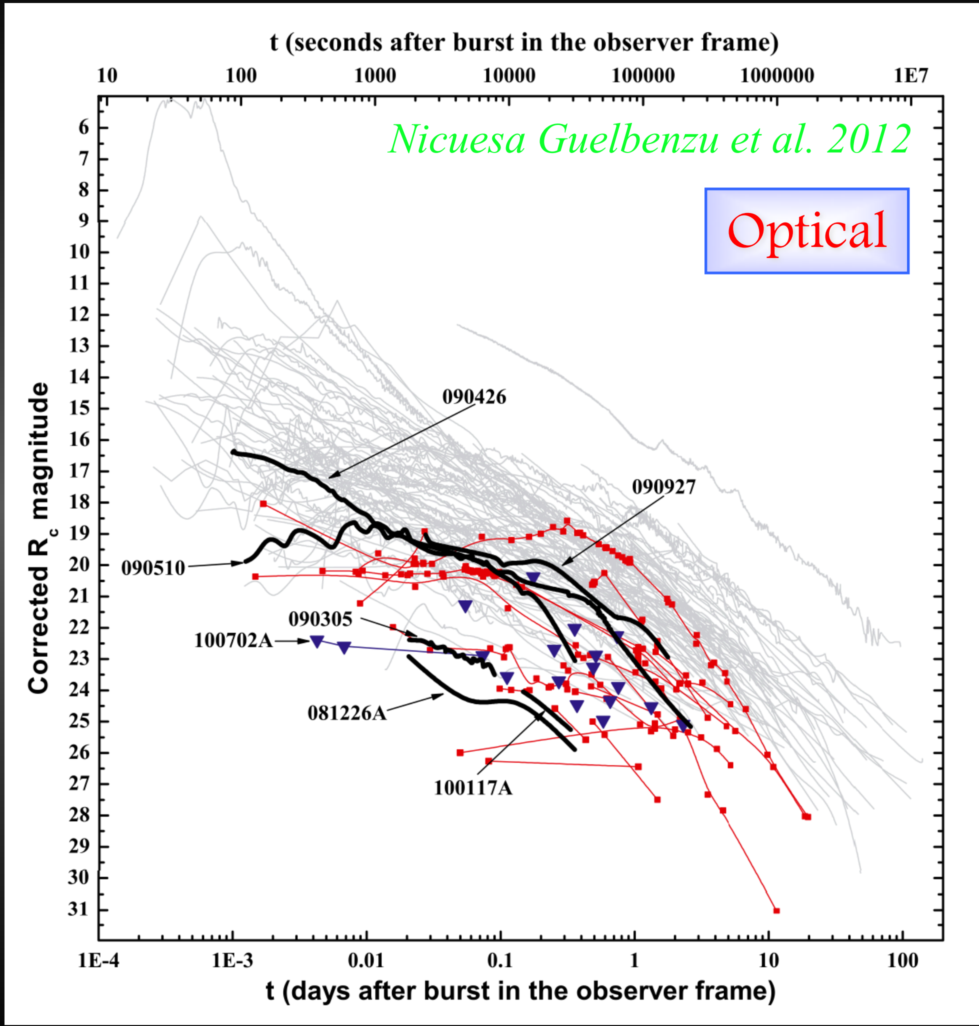
What about the short-duration events?

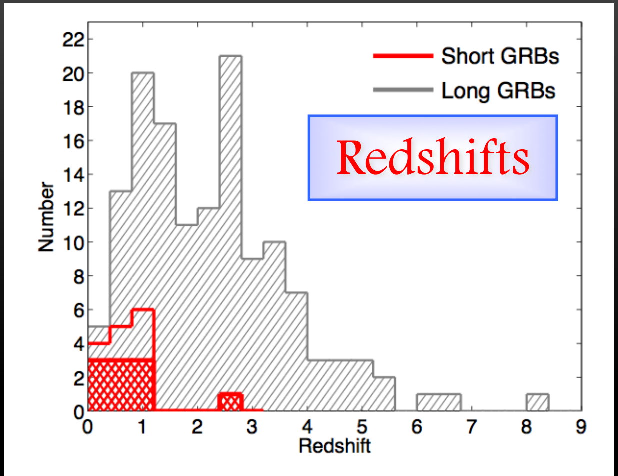
Kouveliotou et al. 1993
Mazets et al. 1982

Short~duration bursts

Rarer and fainter => slow progress



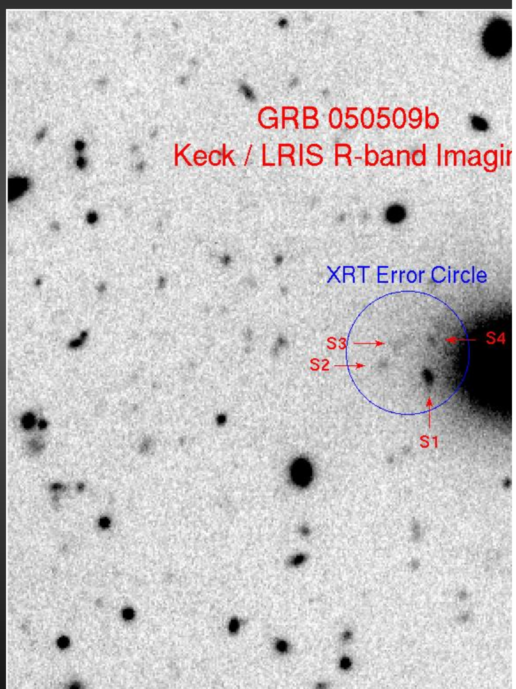


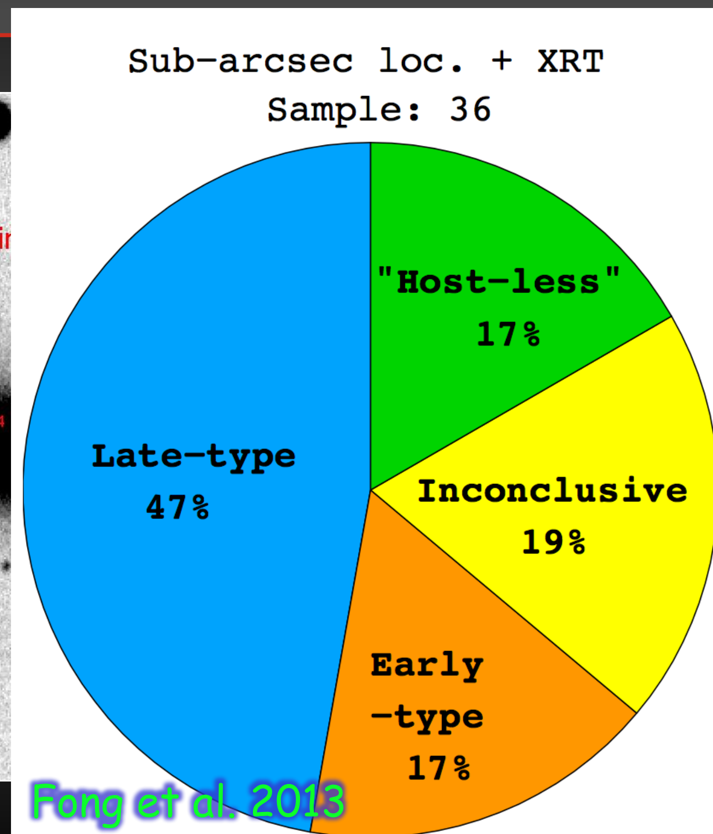


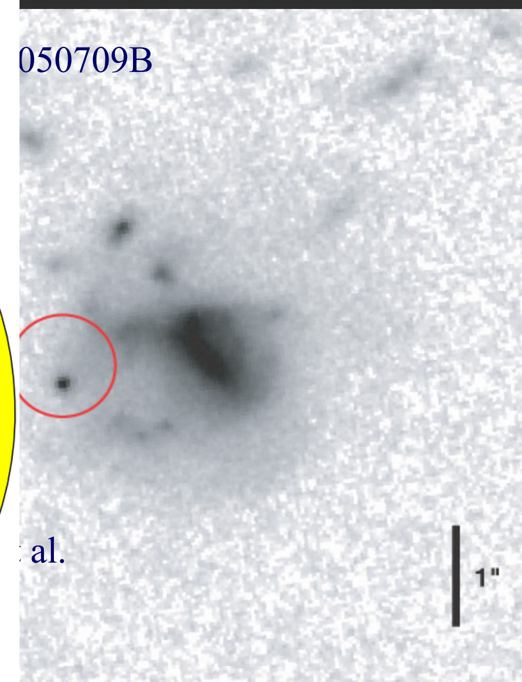
Redshifts nearly all from host galaxies

Short-duration bursts

Host galaxies span a much larger range of stellar populations than long-GRBs.







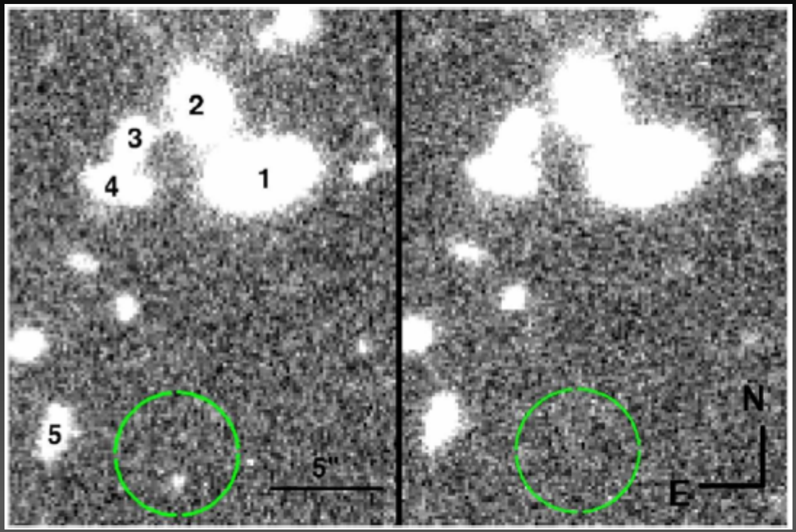
Consistent with NS compact binaries, with long merger times.

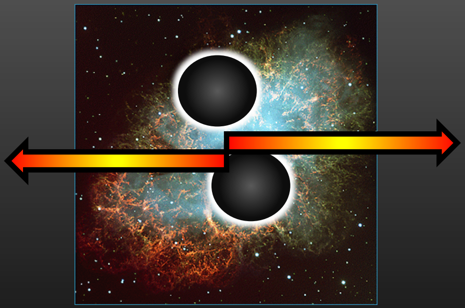
Short-hard GRBs - compact binary mergers?

Sometimes apparently far from their host.

e.g. GRB090515 afterglow R~26.5 at 2 hours post burst. No obvious host.

Rowlinson et al. 2010

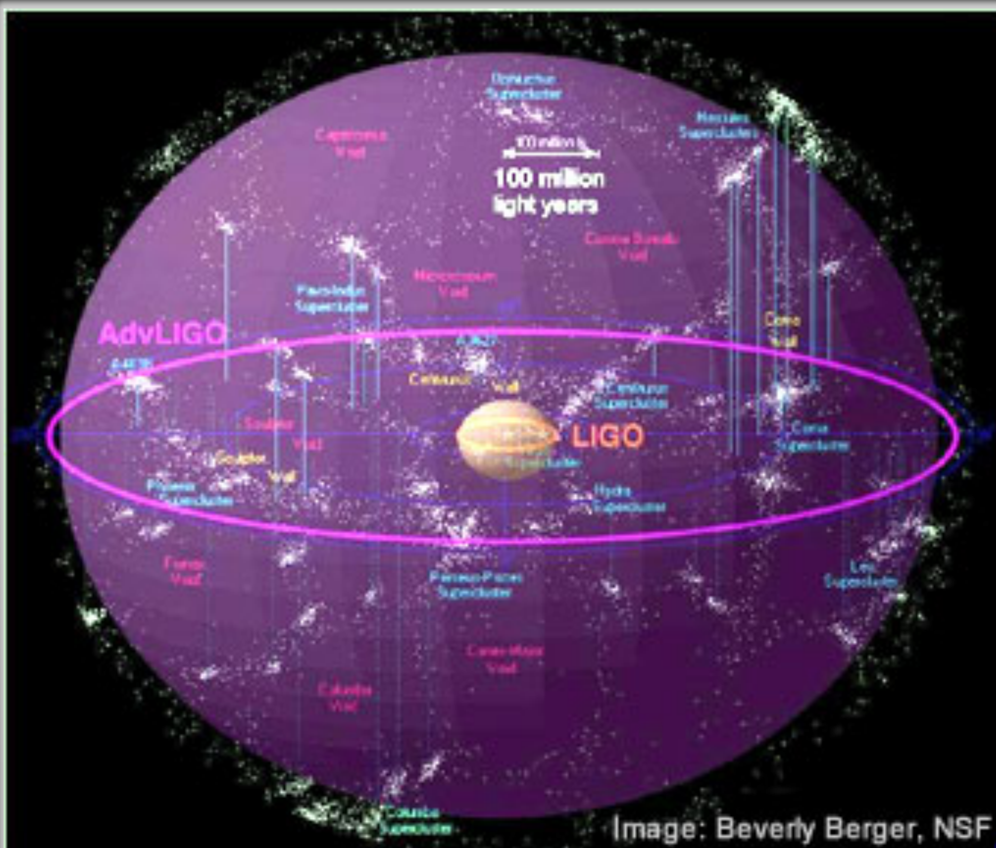


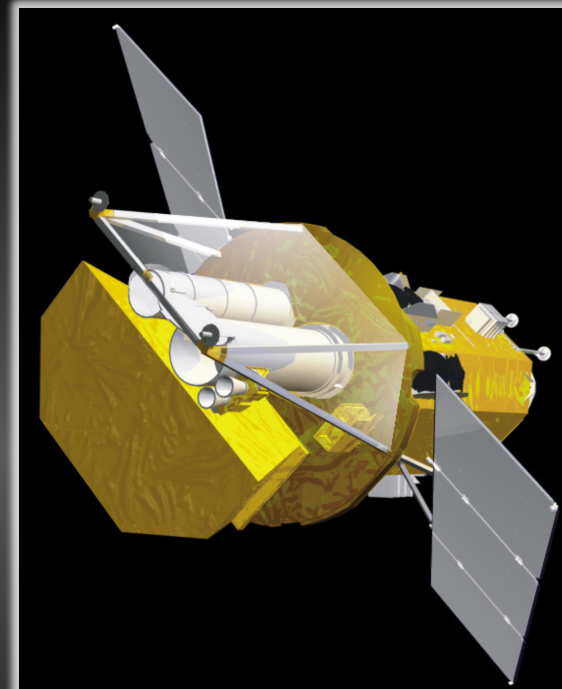


Consistent with some neutron stars being given large kicks during asymmetric supernvovae (over Gyr can move far from host).

Short-hard GRBs -potential GW counterparts?

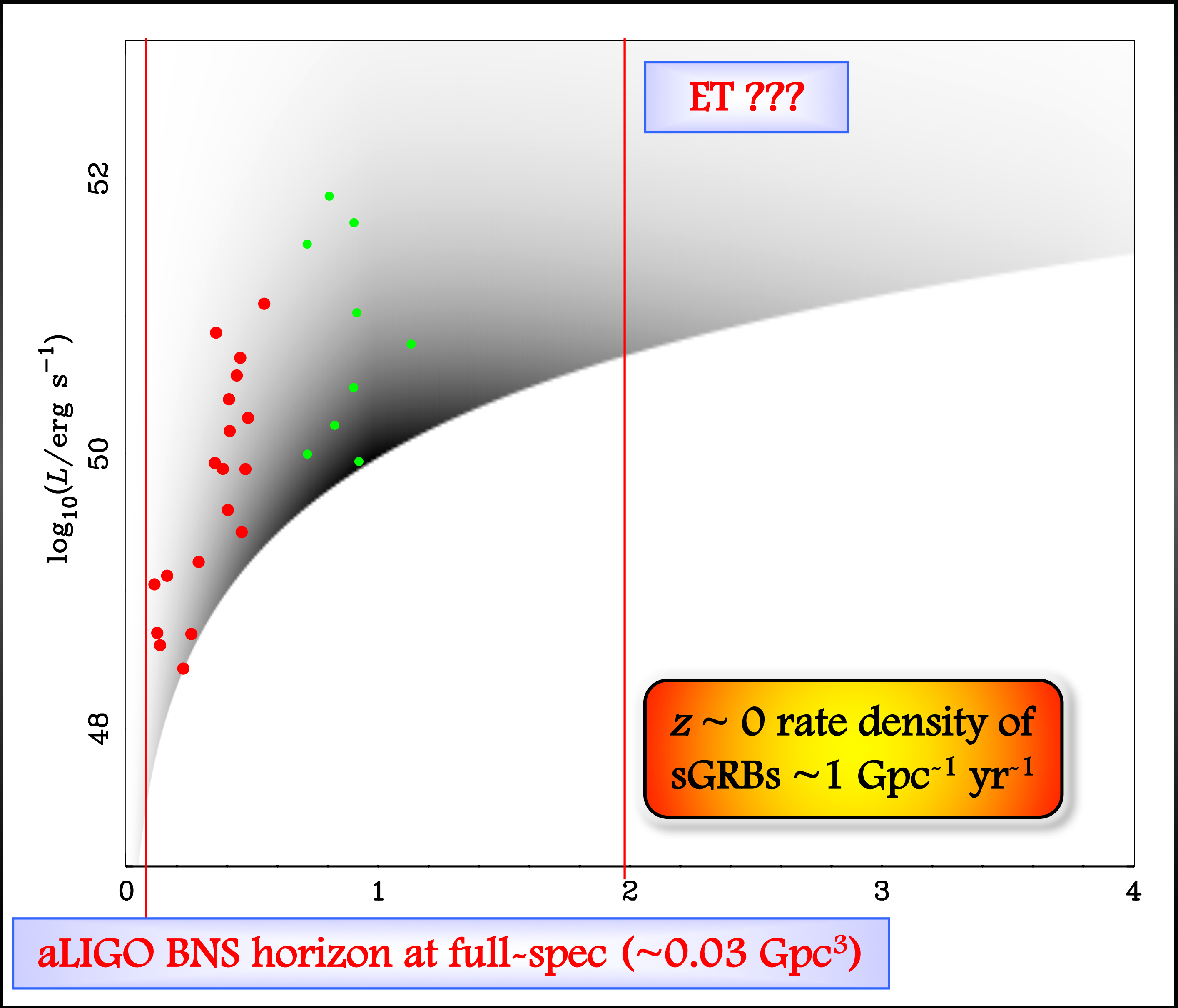
Known SGRBs would be very bright (unmissable) if they occurred within LIGO horizon.





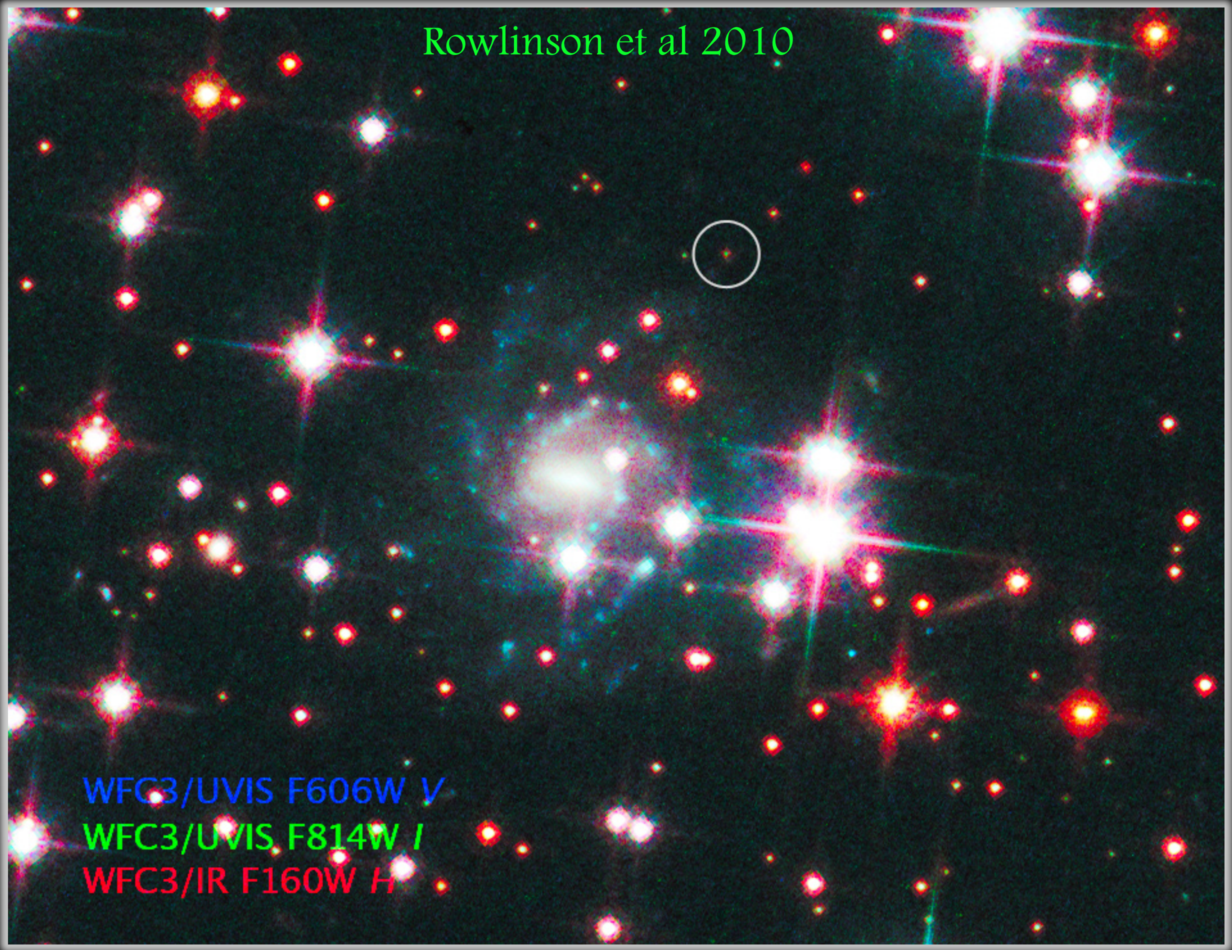
Gamma-ray satellites generally have very wide fields (and poor spatial resolution)

Short-hard GRBs - rates



Many sGRBs without redshifts are probably 0.7<z<2 with a tail to higher redshifts. Some "hostless" cases due to large kicks from lower-z galaxies, but unlikely to be within aLIGO range.

Short-hard GRBs - rates



Nearest SGRB so far found by *Swift* is GRB 080905A at *d*~500 Mpc

Prospects for gamma-rays

For NS-NS full-spec (sky and orientation averaged) range of Advanced detectors is ~200 Mpc (for NS-NS).

Reasons to be pessimistic: prompt trigger with *Swift* will be rare (<~1 per century at this rate, even with 100% GW duty cycle).

Reasons to be (more) optimistic:

(a) All/half sky instruments see more.

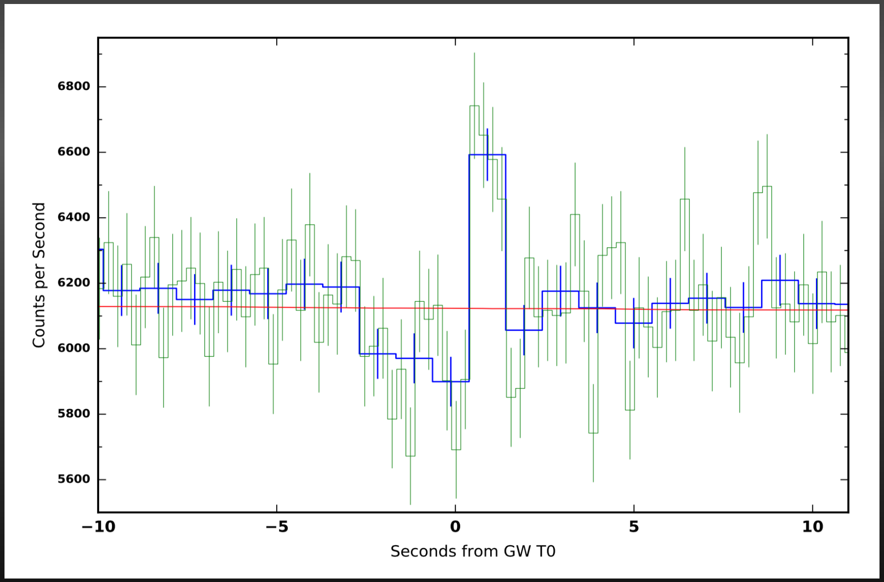
(b) Helped if timing (and spatial) coincidence produces sub-threshold detection (either EM or GW);

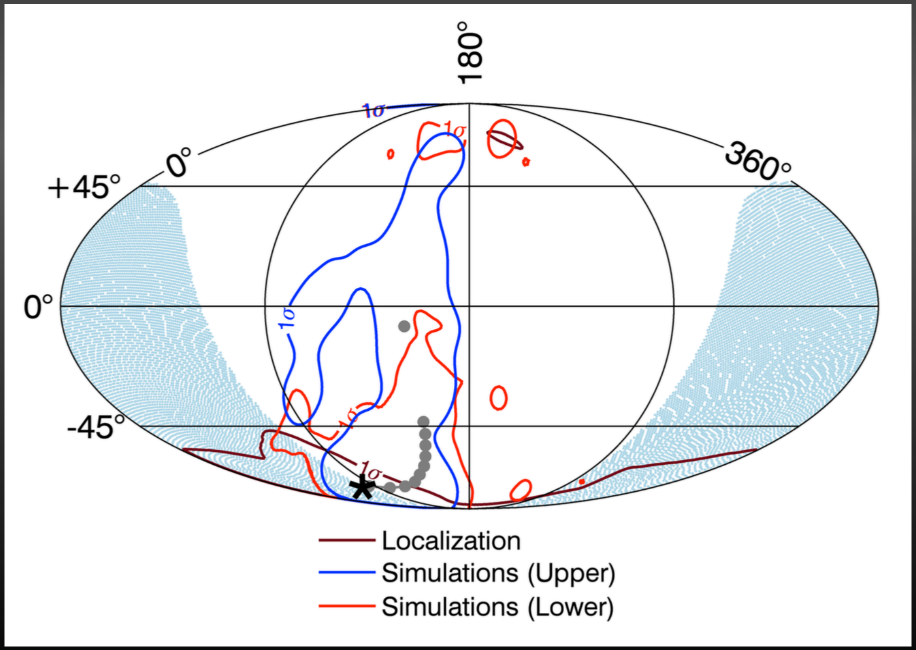
(c) Orientation roughly pole-on.

(d) Better for NS-BH.

Did *Fermi*/GBM already see GW 150914?

Claimed tentative detection of a coincident SGRB by Fermi/GBM. Statistical fluke (e.g. Greiner et al. arXiv:1606.00314)? Baryon rich environment (e.g. Loeb arXiv:1602.04735; Perna et al. arXiv:1602.05140)?

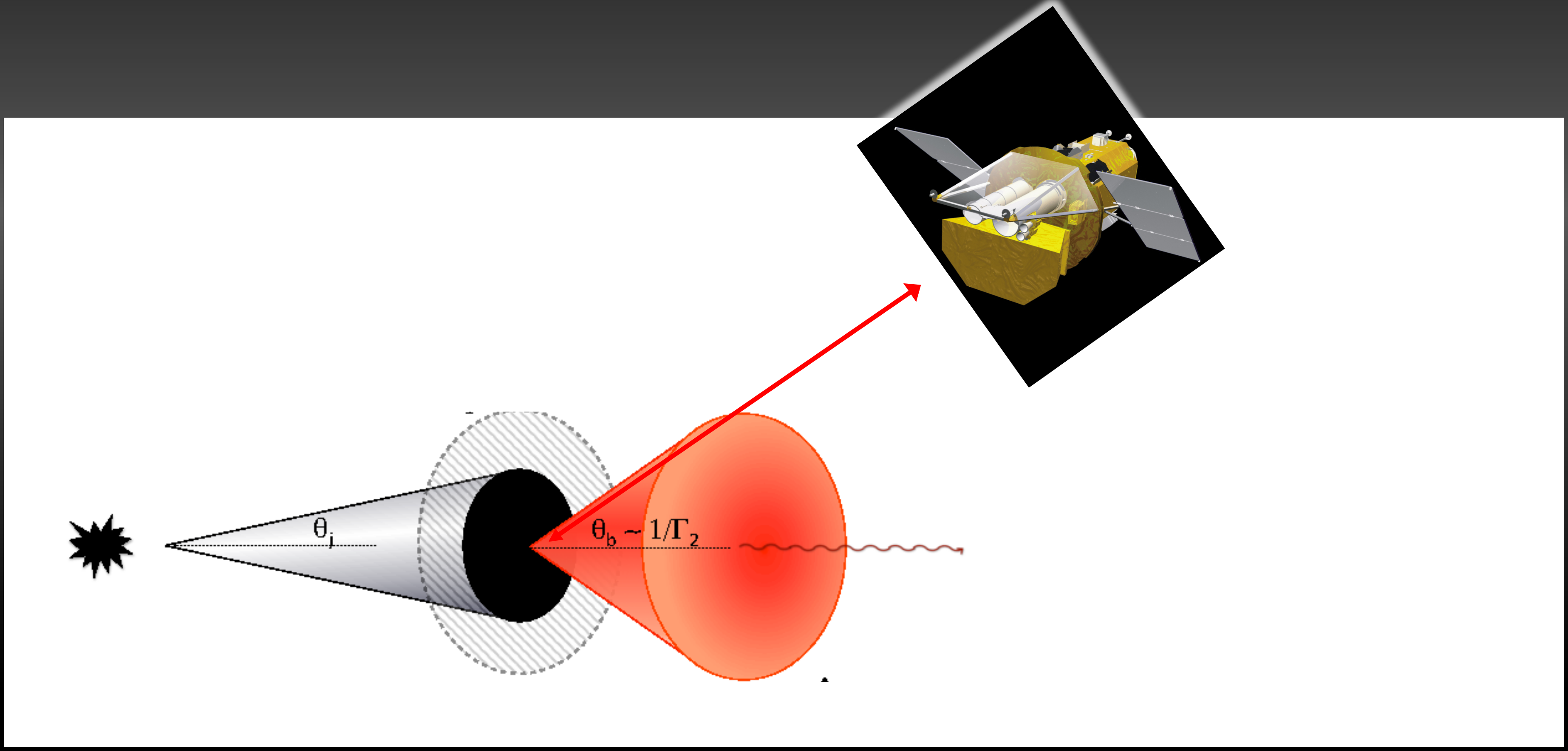




Connaughton *et al.* 2016

Prospects for X-rays

1. Detect X-ray (or optical afterglows), even when gamma-rays missed due to satellites not being in position…
2. … or, more common (though fainter, and still rather rare) if seen off-axis.



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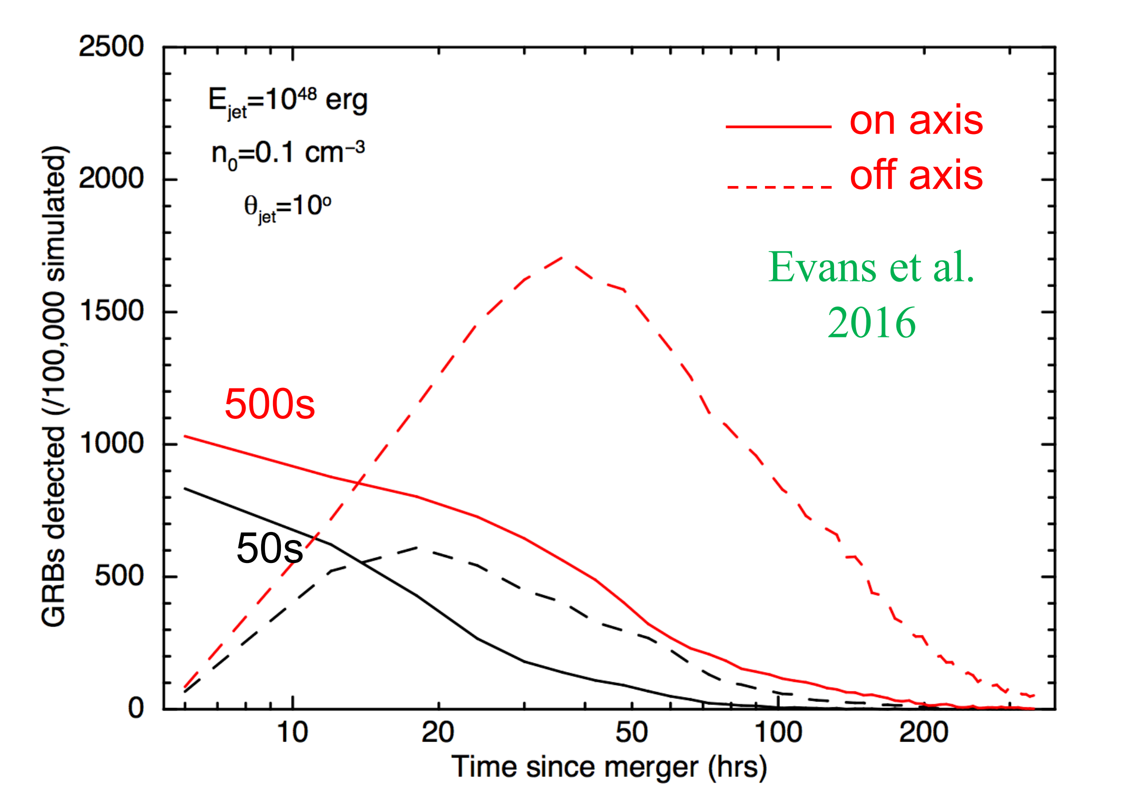
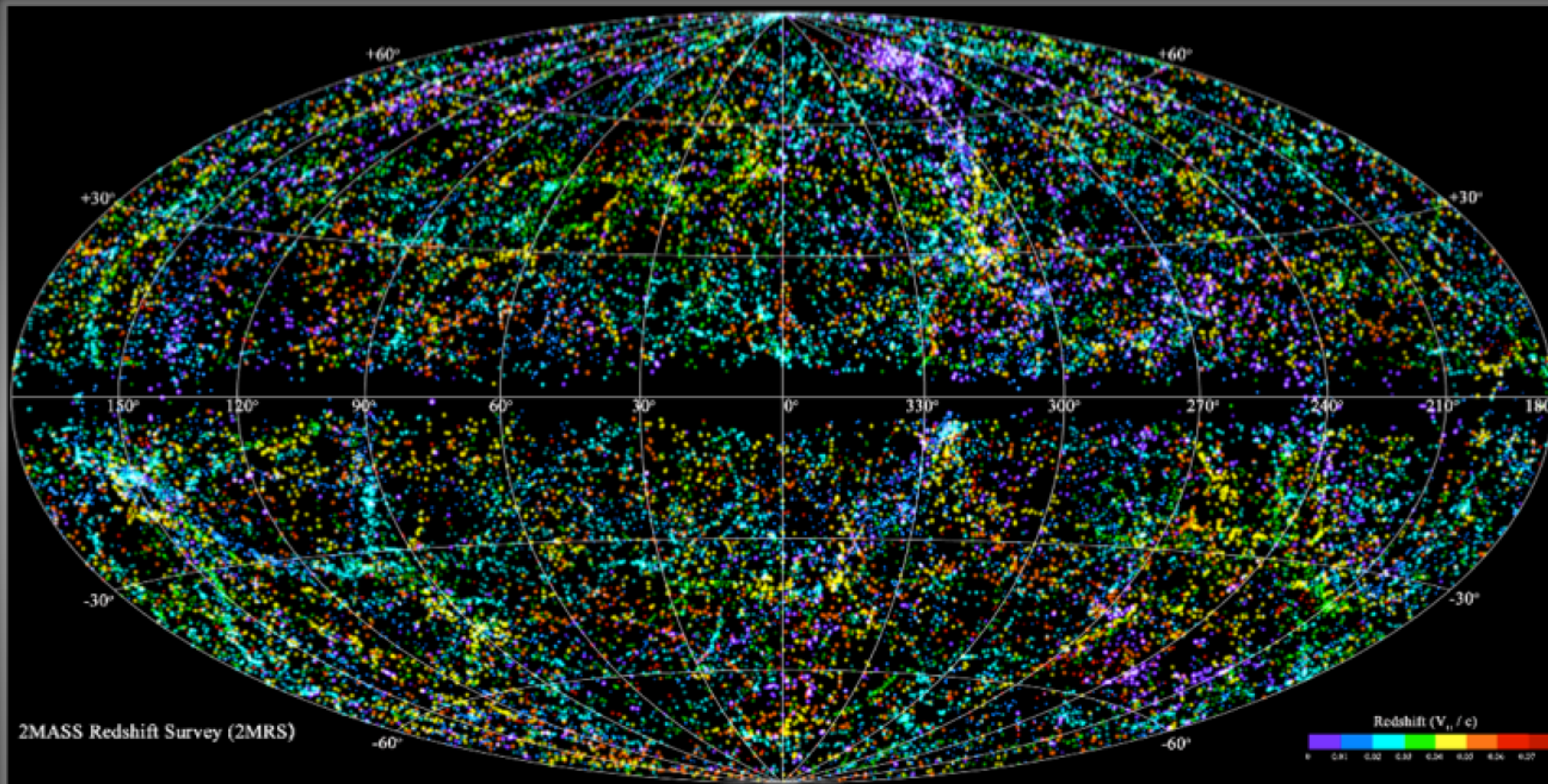


Swift

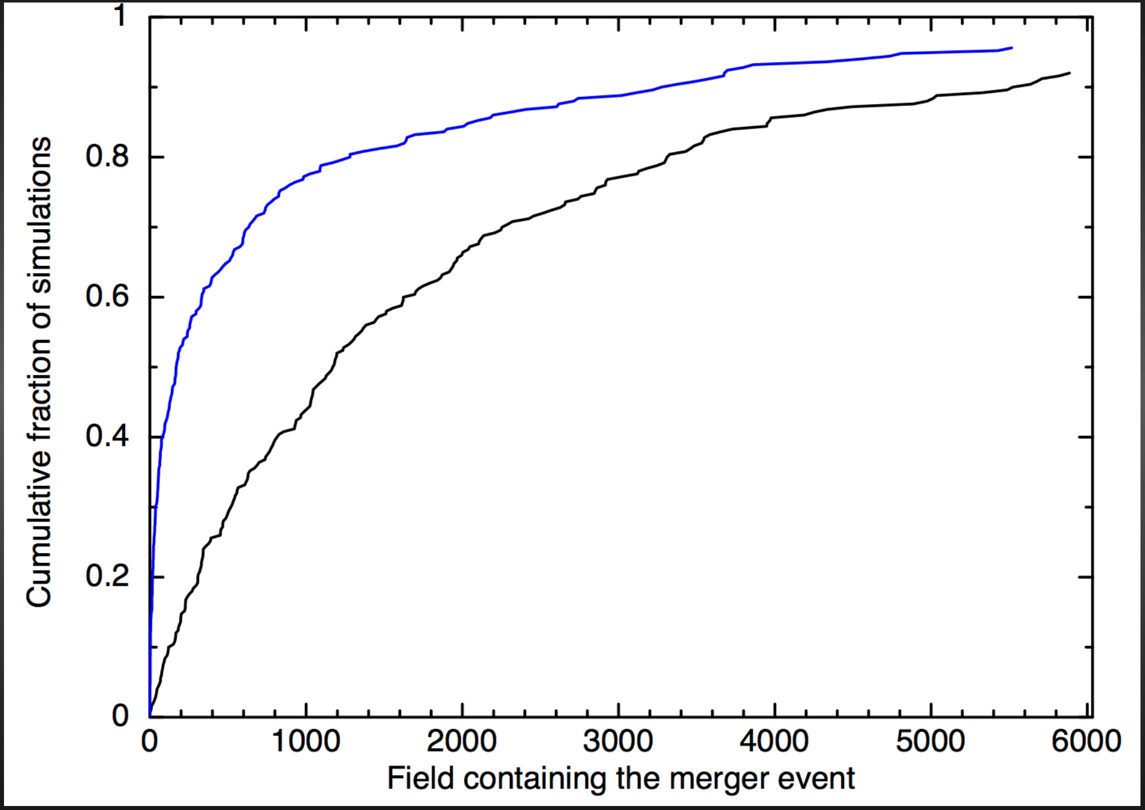
In practice, with *Swift* one runs out of time to survey large GW error regions.

Strategies for improving chances



Make use of known locations of low-z galaxies to prioritise more likely fields (although run into limits of current galaxy catalogues)

Benefits of galaxy targeting

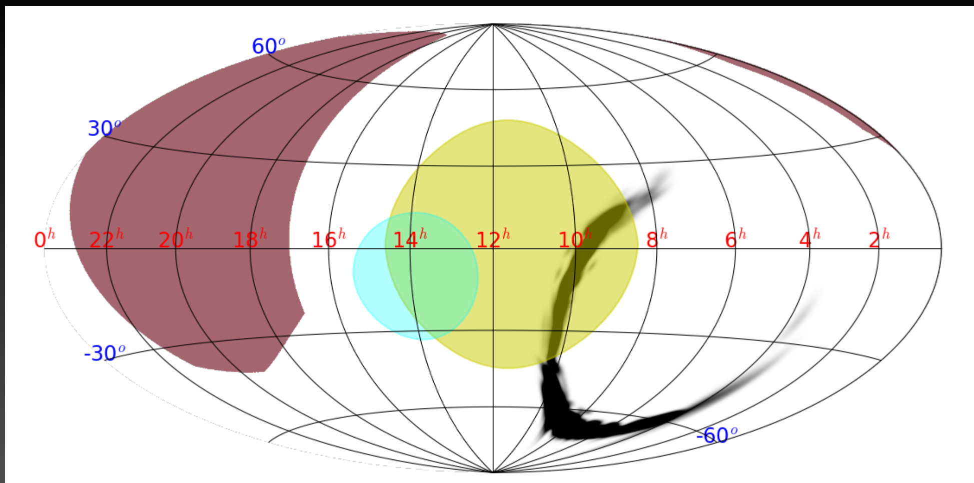


Without galaxy targeting, in the 'median' case we would have to observe nearly 1,200 fields with XRT before we get to the correct location.

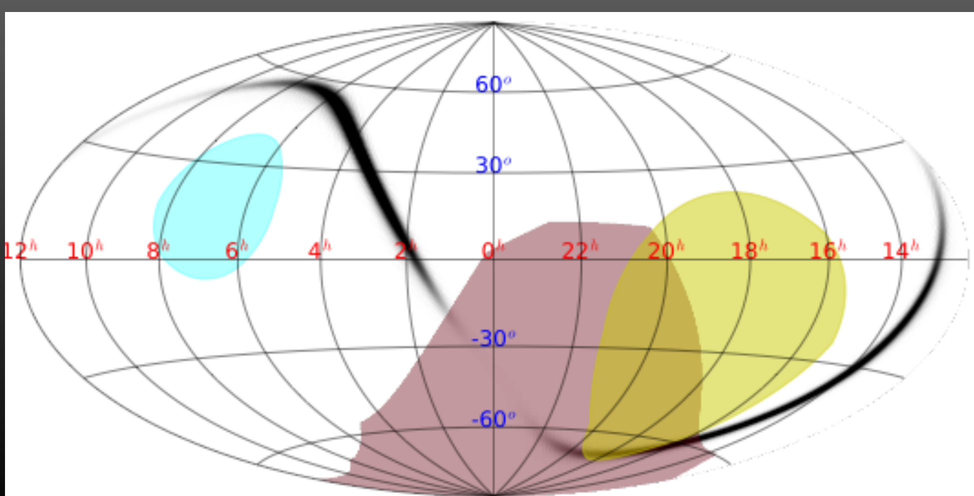
With galaxy targeting, in the 'median' case we would have to observe about 170 fields with XRT before we get to the correct location.

Evans et al. 2016, based on GW simulations by Singer et al. (2016, ApJ, 829, L15).

Swift in O1

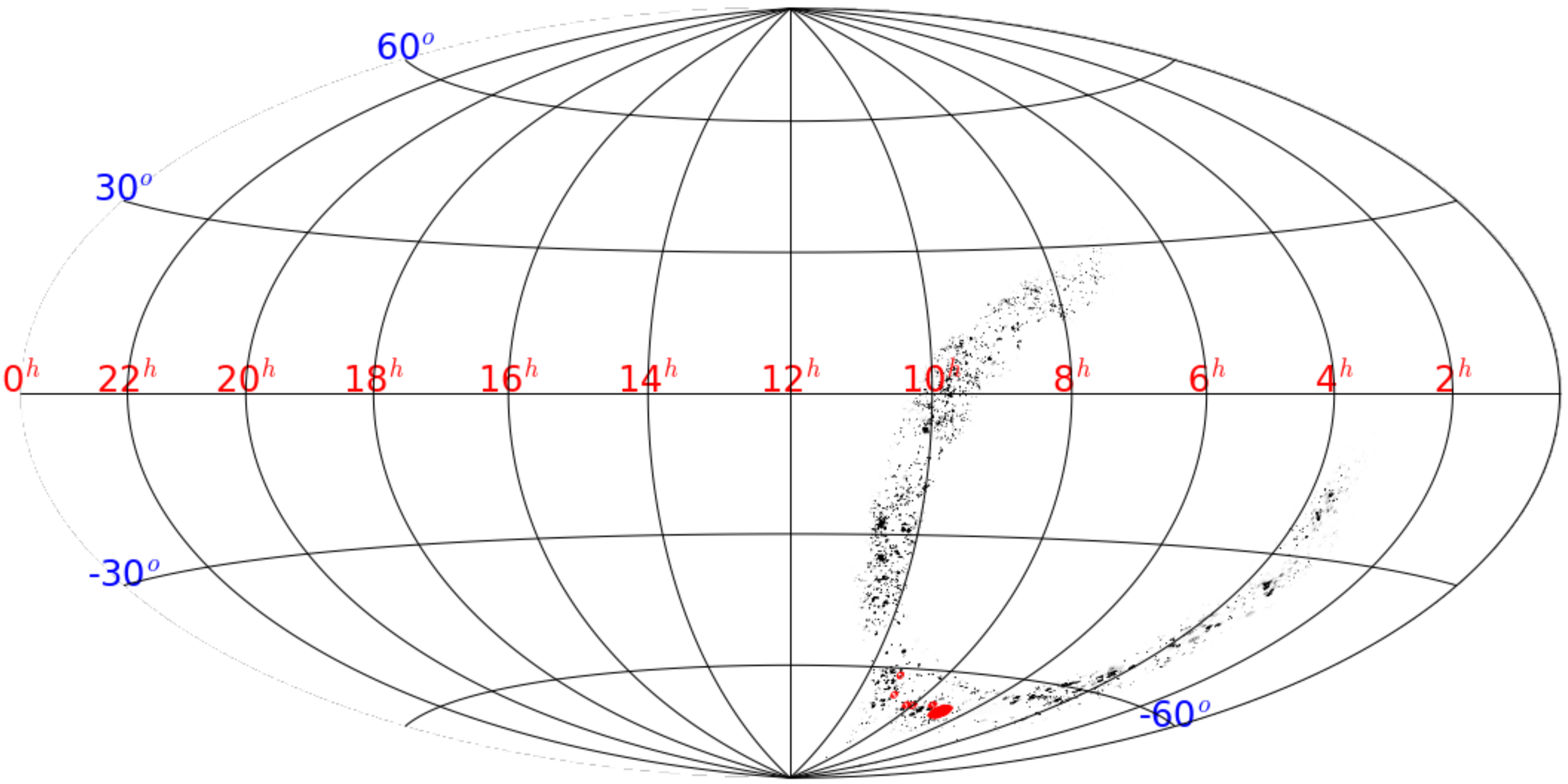


GW150914

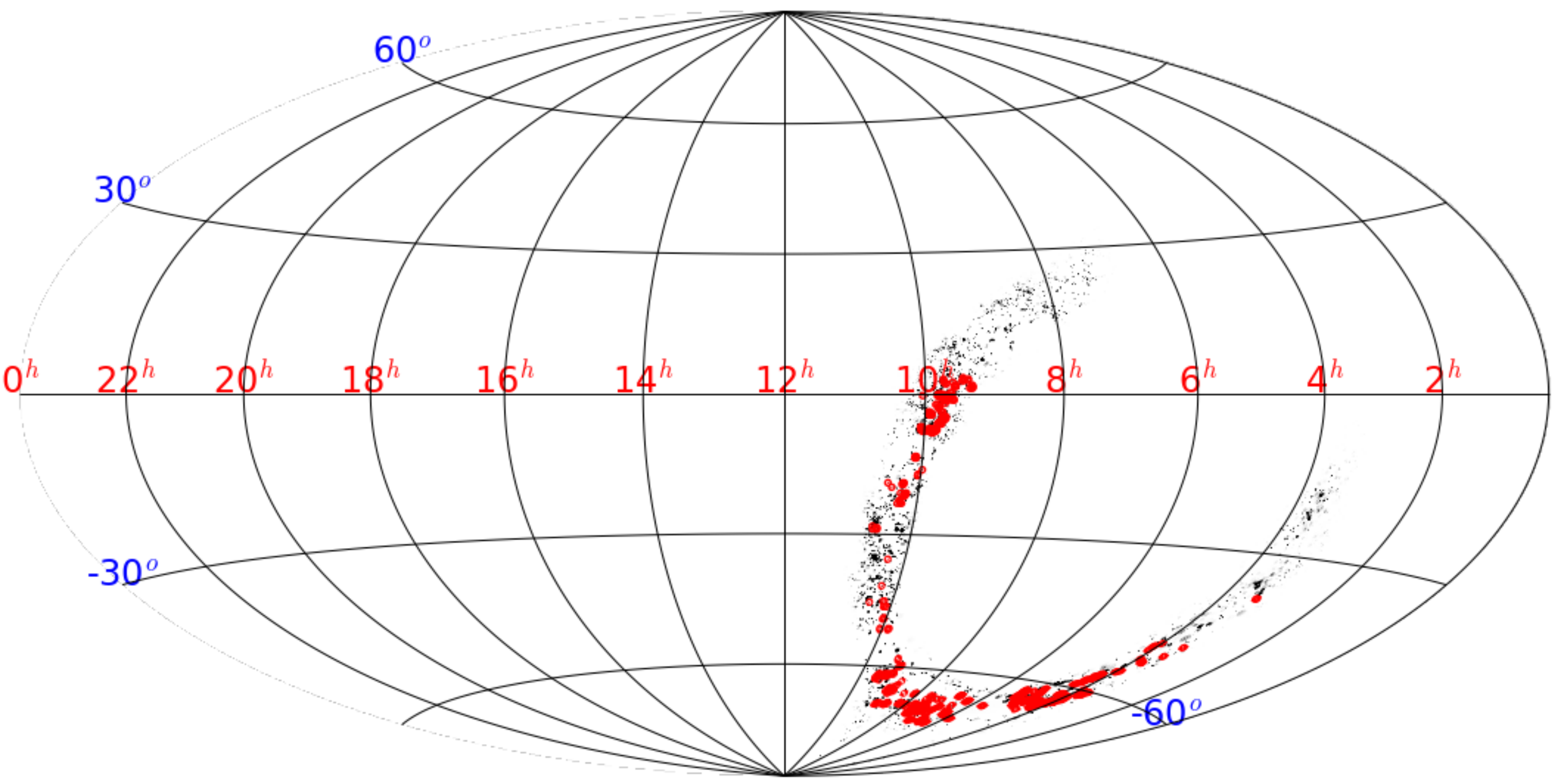


GW151226

Evans et al. 2016



Swift/XRT observations of GW150914

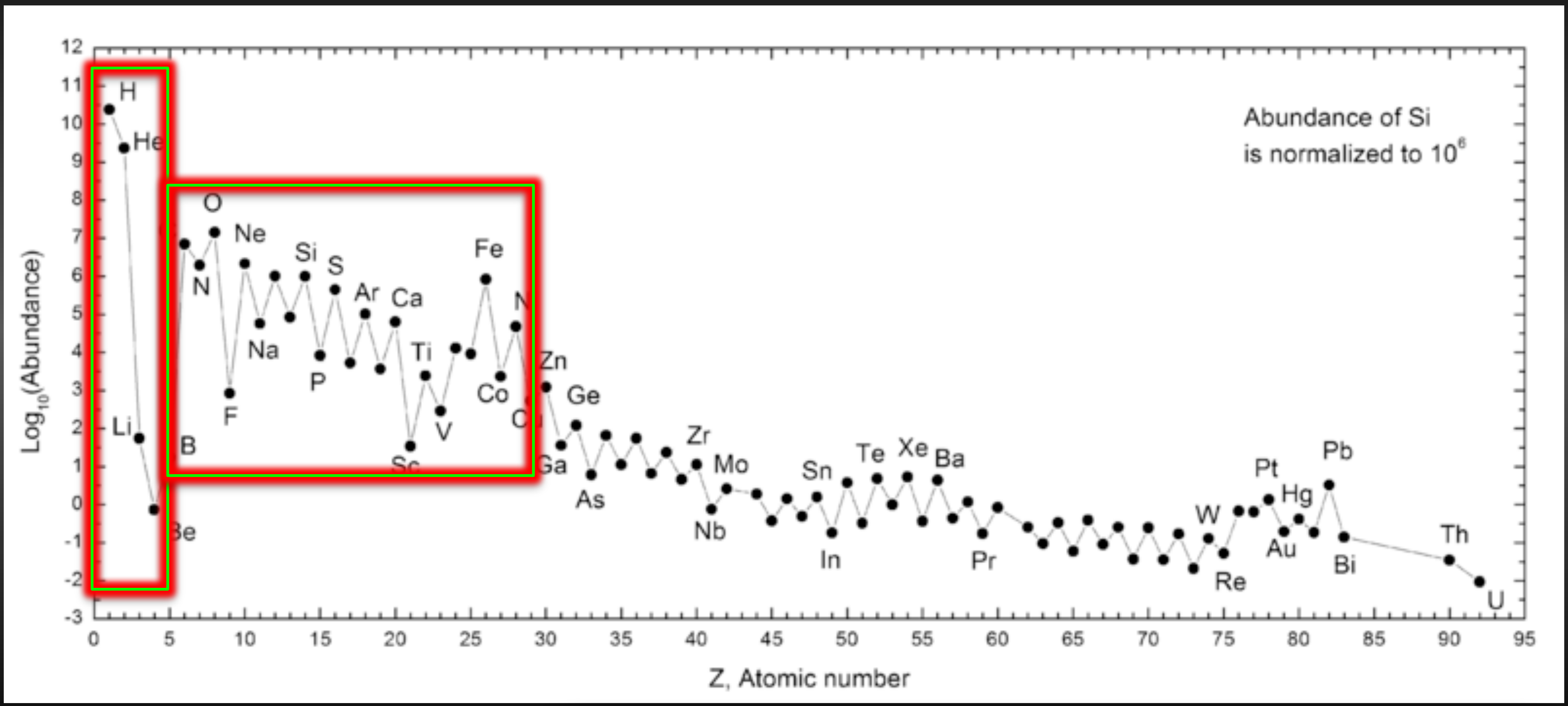


In subsequent test, *Swift* observed 426 fields from the GW 150914 error region in 24 hours.
This covered 9% of the skymap used (90% after galaxy weighting).

Conclusions for part 1

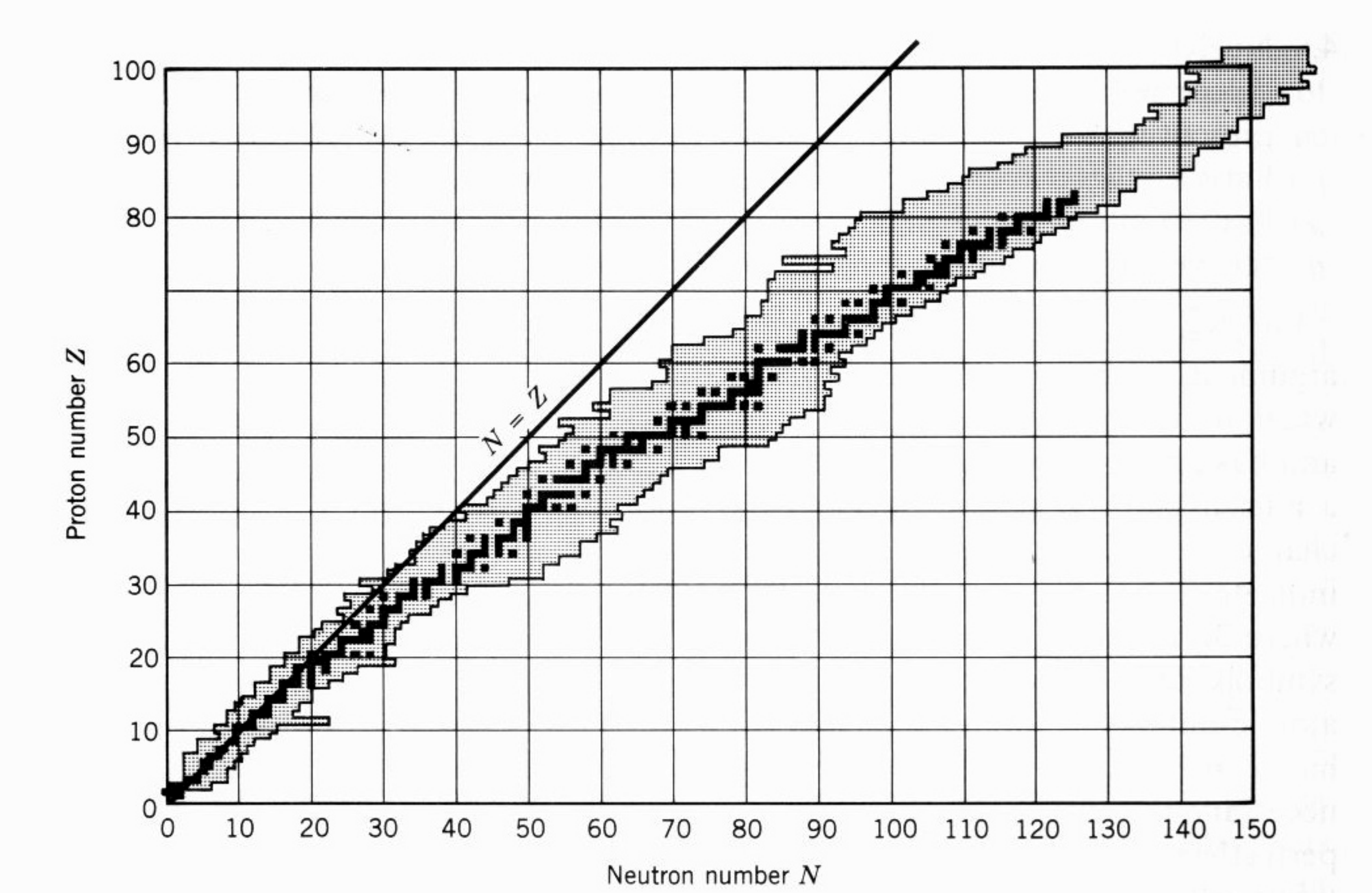
- Good indications (more to come) that SGRBs are product of compact binary mergers.
- A short-GRB within the aLIGO horizon would be an unmissable signature, and even more distant SGRBs allow sub-threshold searches.
- Alternatively, can search for X-ray afterglows even for off-axis SGRBs – challenging, but much effort made with *Swift* to give it capability of making such scans, targeting potential host galaxies.

The relative abundances of the elements

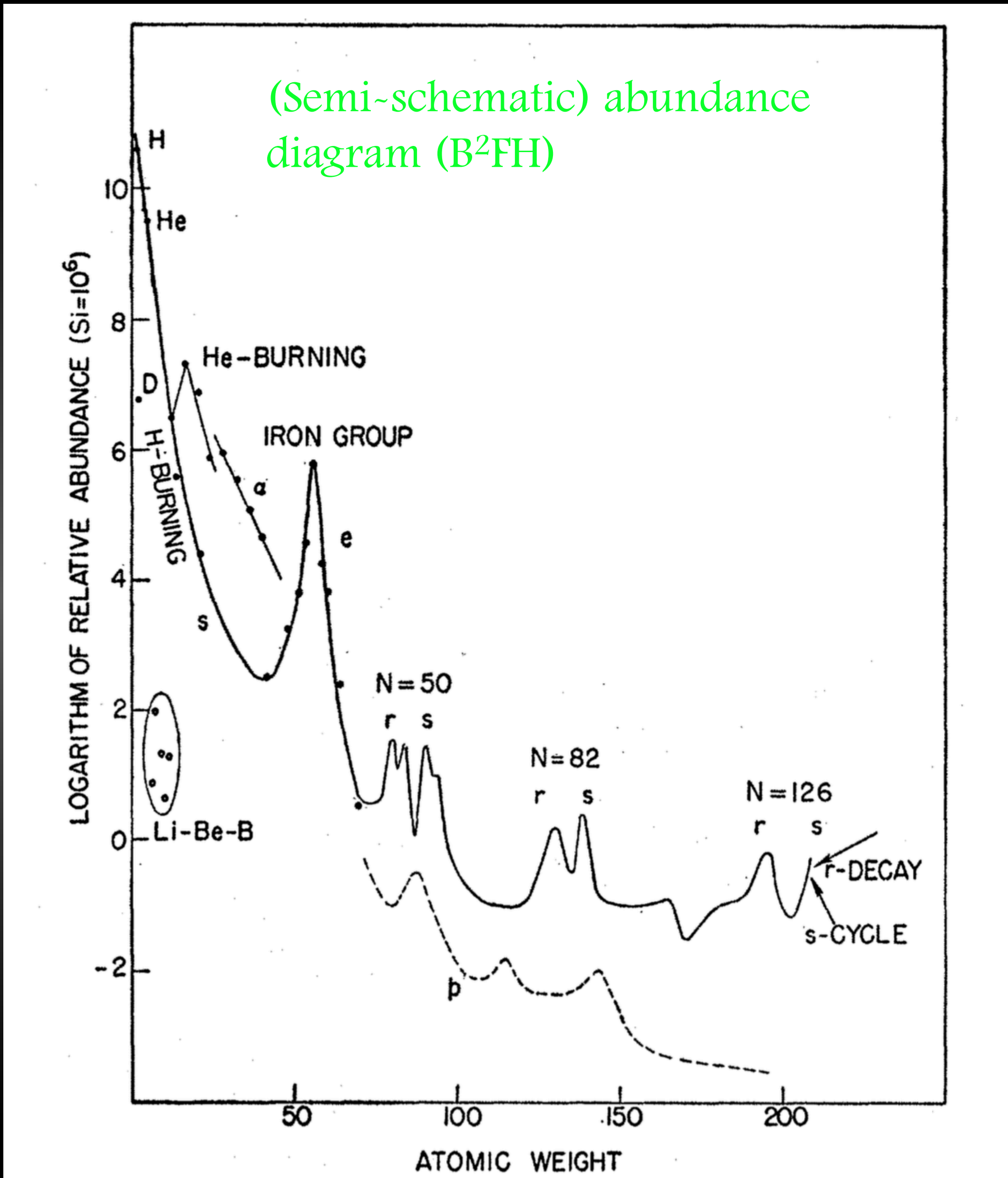


In addition to favouring of paired (i.e. even N, Z) nucleons, other peaks seen.

Easiest way to make heavier nuclei via neutron capture.



Expect peaks at nucleon "magic numbers" (closed shells occuring at 2, 8, 20, 28, 50, 82, 126…)



Find peaks as expected (s), but also offset (r) peaks.

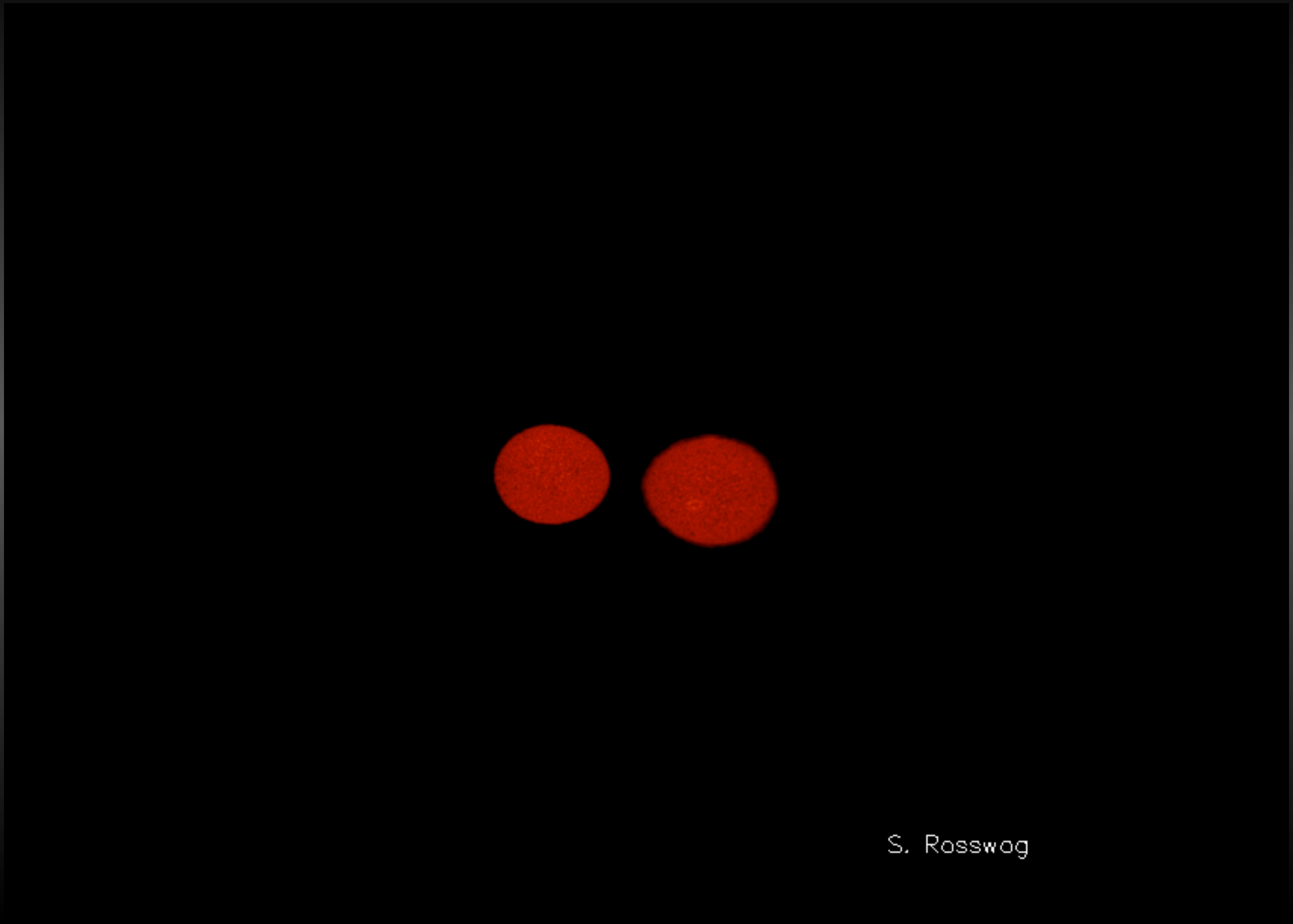
How to explain the "r" elements?

Answer: very *rapid* neutron capture to build up highly unstable species.

Requires extreme neutron rich (low "electron fraction) environment!

Long speculated may occur in core-collapse supernova explosions (but actually, the necessary conditions probably don't occur.)

Neutron stars in compact binary merger ~ some material is ejected (tidally, through collisional debris and disk winds).



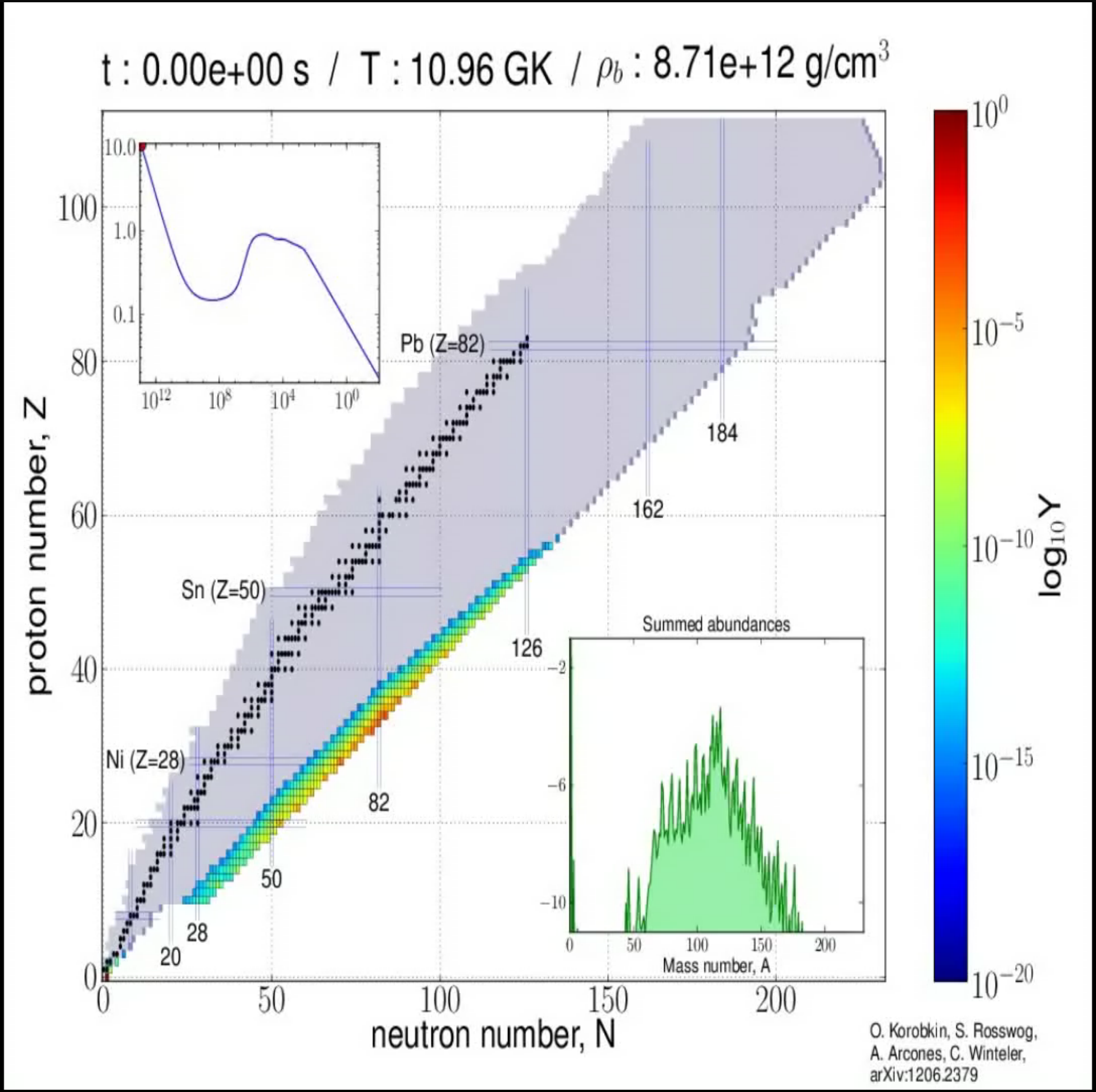
R-process nucleosynthesis

Korobkin et al. 2012

Ejecta decompresses producing exotic radioactive elements through *rapid* neutron capture.

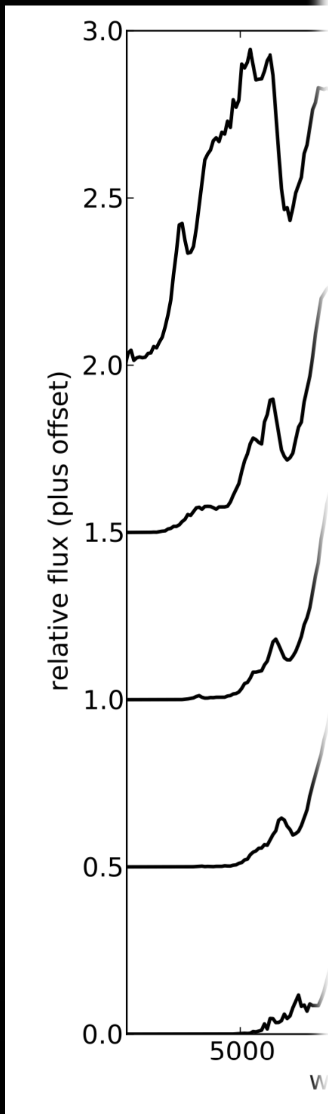
Decay may produce the stable r-process elements (Lattimer & Schramm 1974)

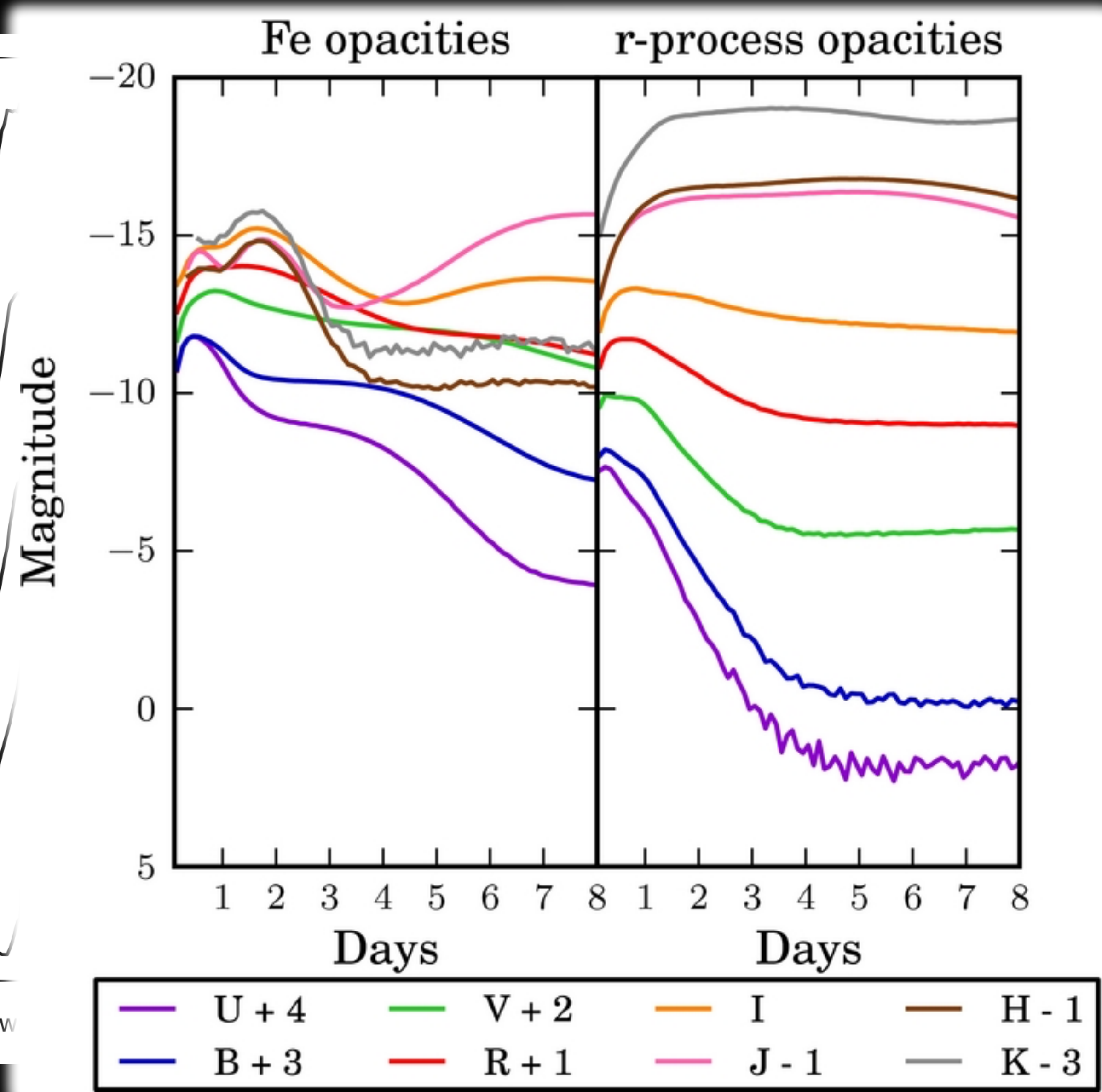
Radioactive heating powers *kilonova* (aka. *Macronova*; Li & Paczynski 1998). Energetics depend on expelled mass and velocity.



r-process kilonovae

Barnes & Kasen et al. 2013





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vog et al. 2013
et al. 2013
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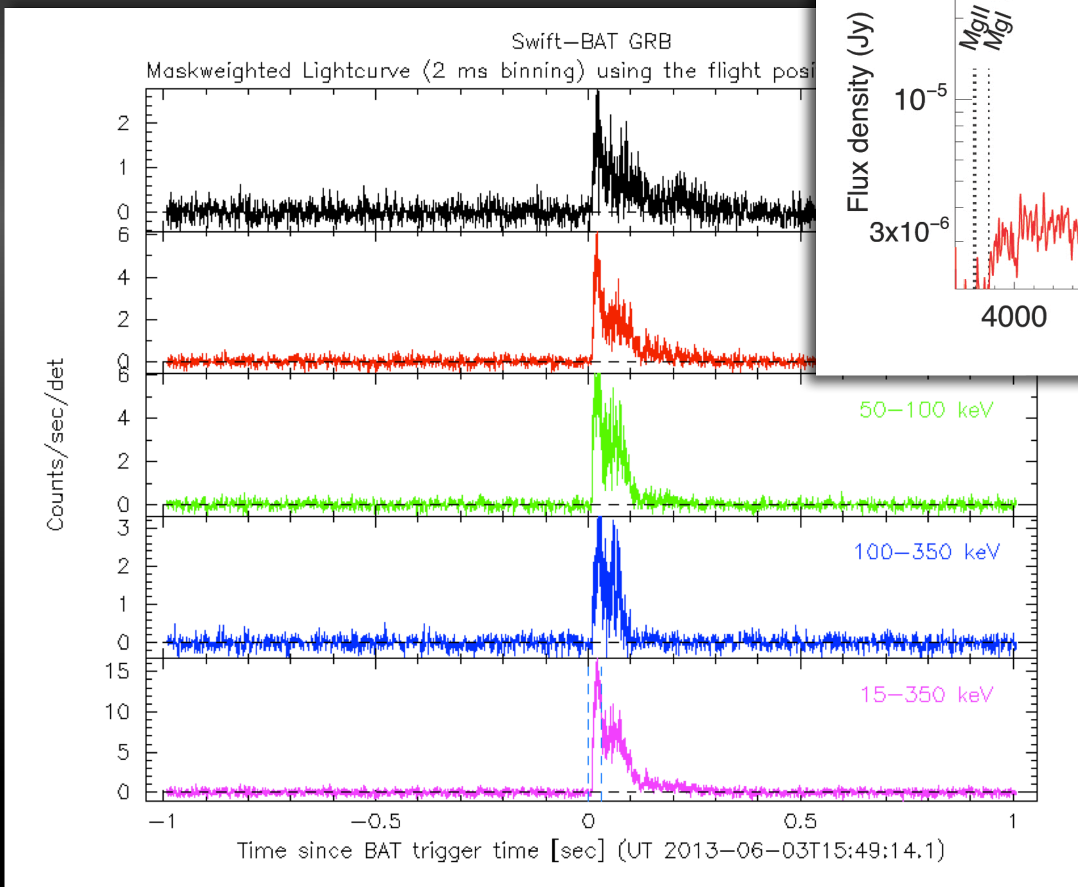
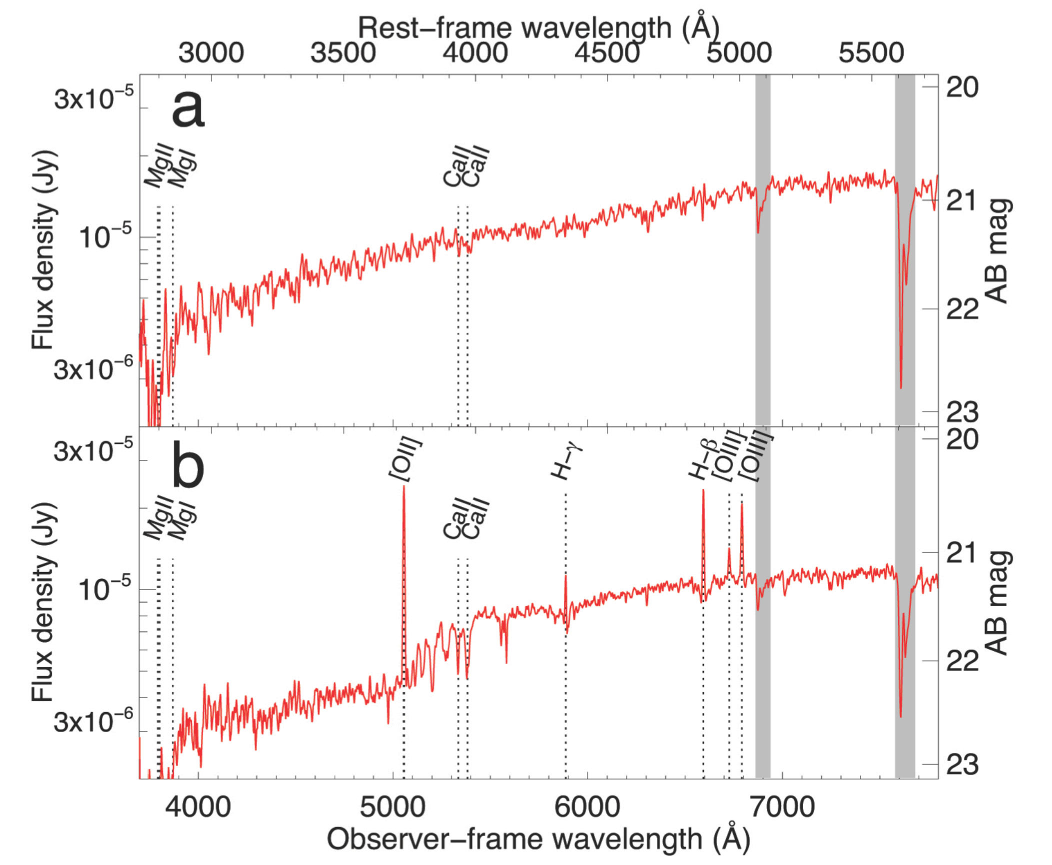
SGRB 130603B

Relatively bright burst and unambiguously short duration.

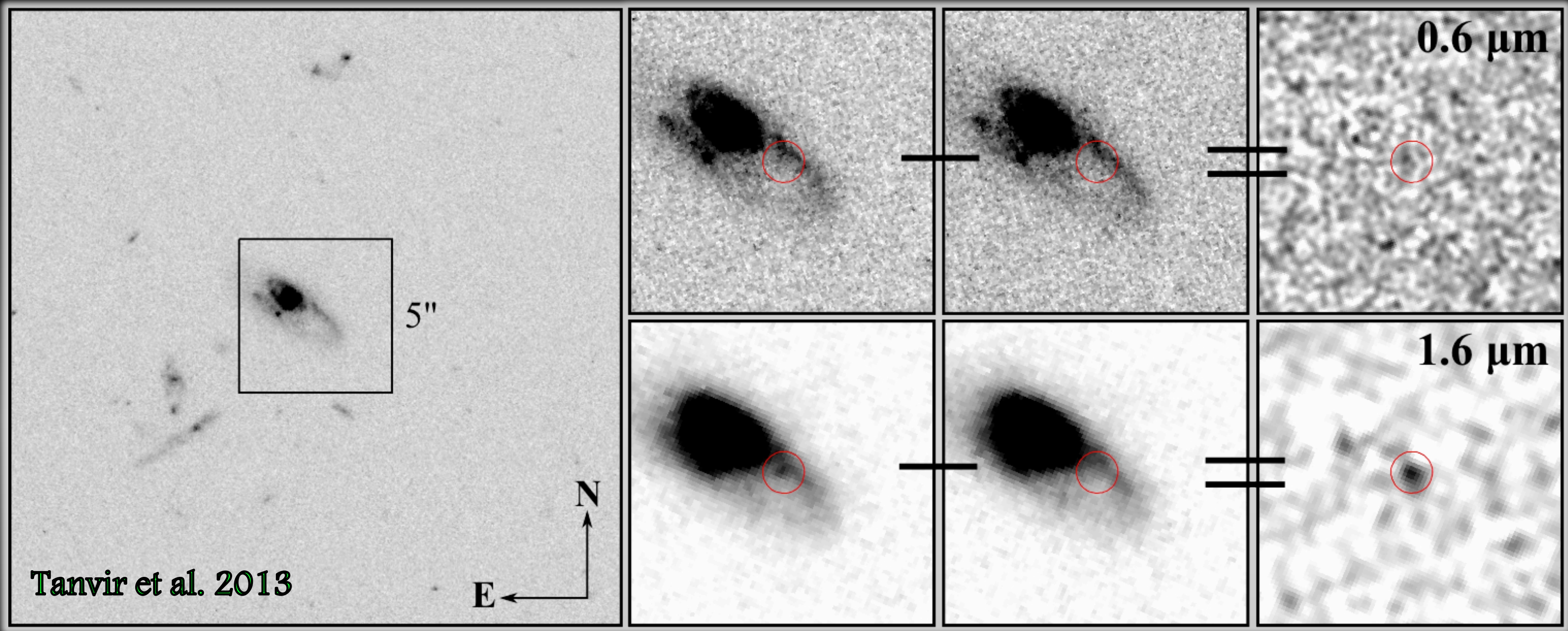




de Ugarte Postigo et al. 2013

Afterglow provided afterglow redshift with GTC, $z \sim 0.36$

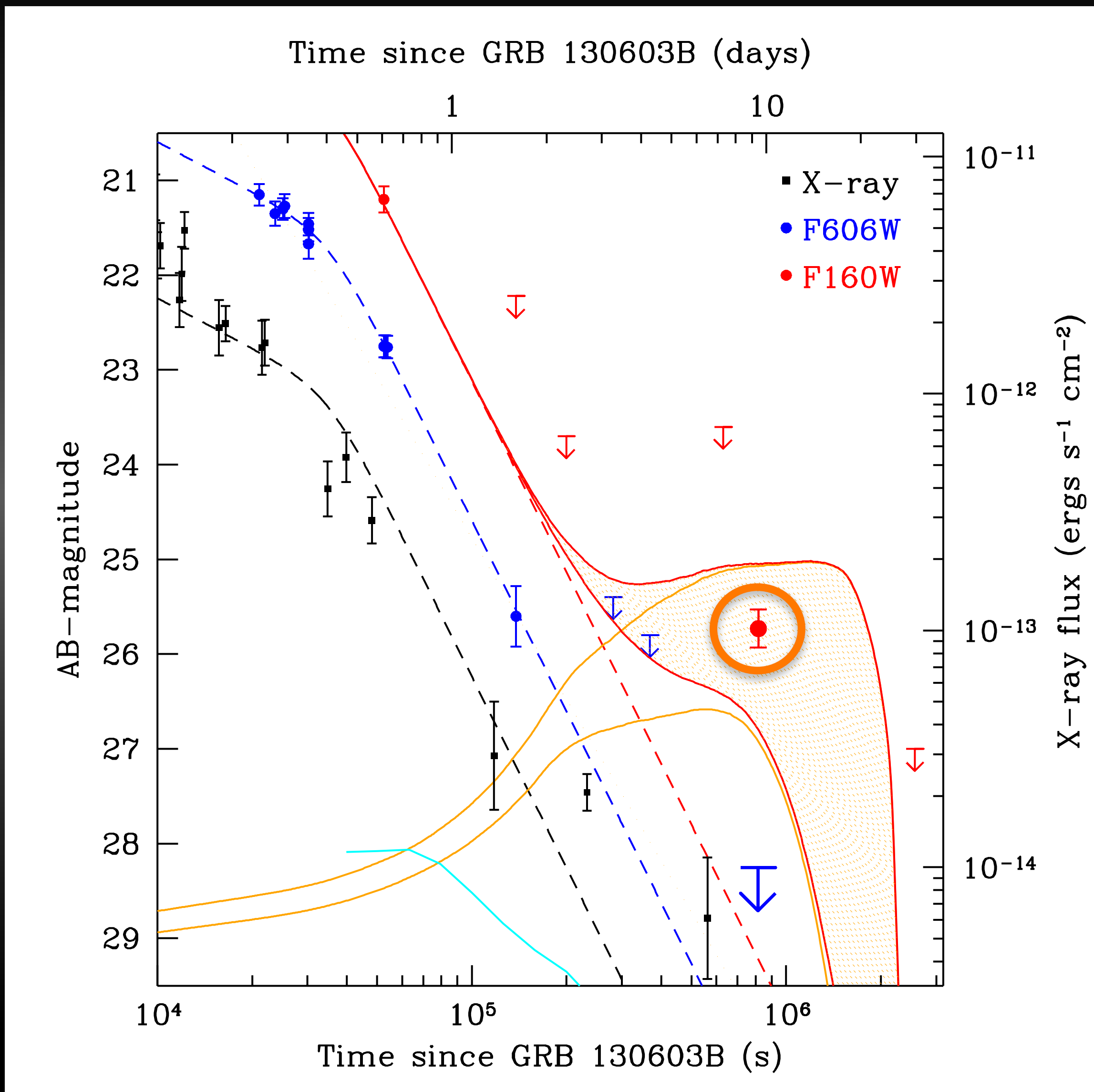
GRB 130603B



9 day

30 day

GRB 130603B ...or, much ado about a data-point

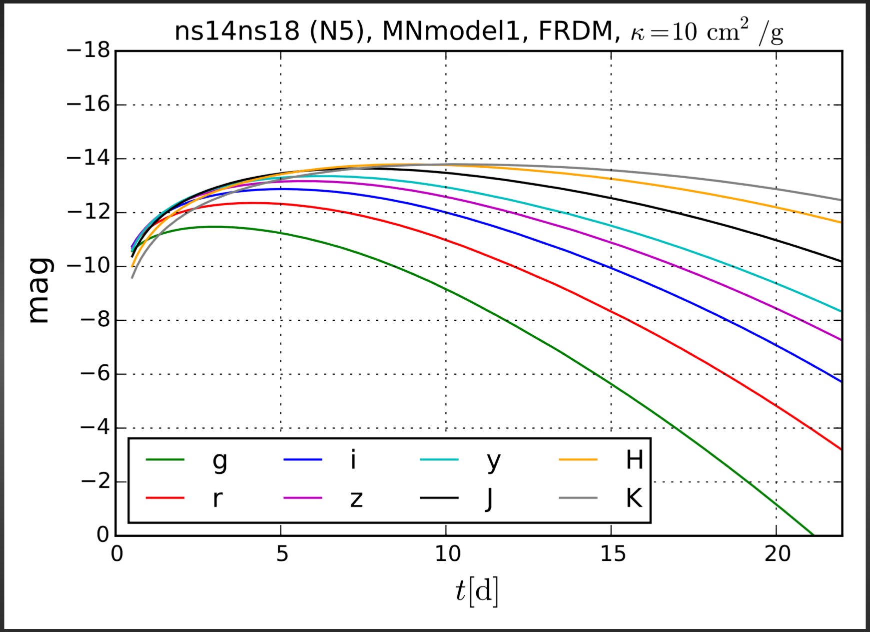


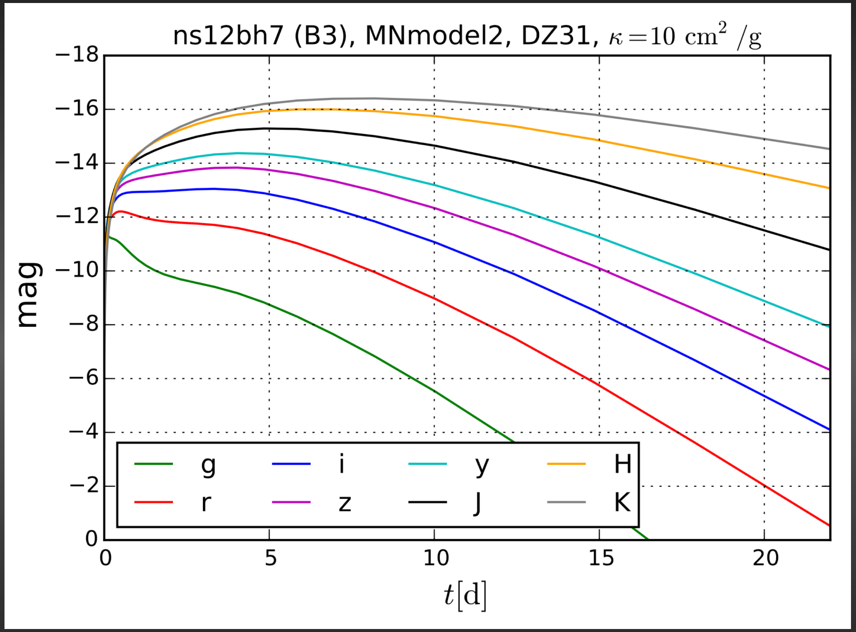
Comparison to Barnes & Kasen (2013) models suggests ejected mass ~0.05 $M_\odot$

Tanvir, Levan et al. 2013
Berger et al. 2013
Fong et al. 2014

What is expected?

Typical ejecta masses <~1% $M_\odot$, but considerable diversity depending on merger parameters – e.g. mass ratio.





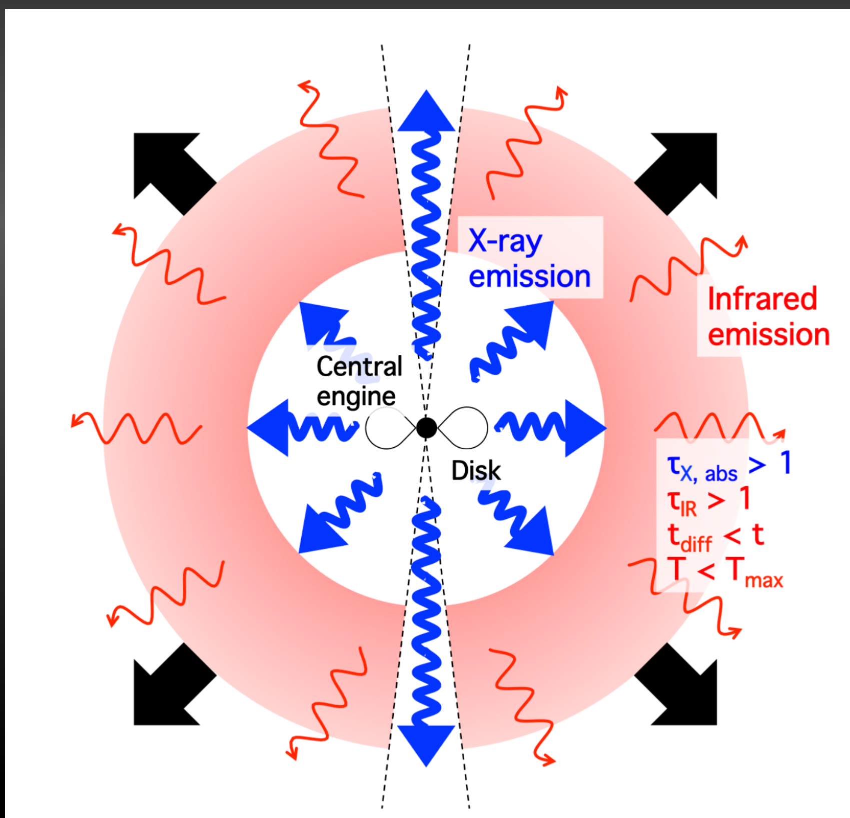
Rosswog et al 2017

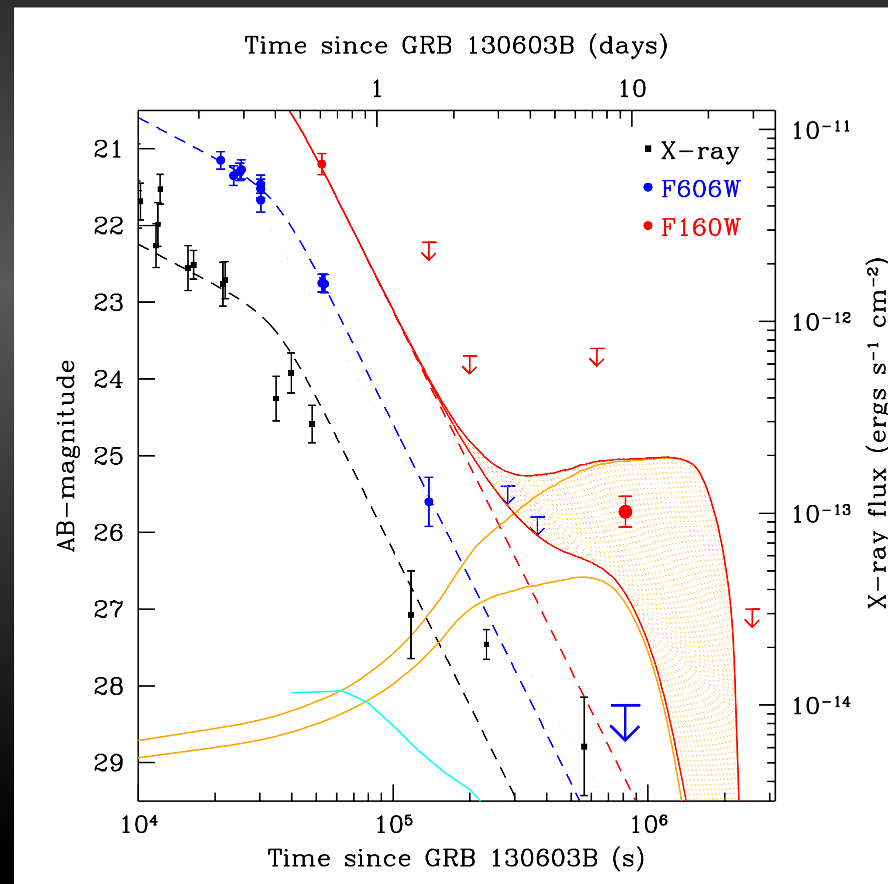
Also sensitive to (poorly understood) details of merger physics, nuclear physics and atomic physics…(e.g. Fontes et al. 2017 suggest line smearing increases opacity further, leading to peak in the mid-IR.)

X-ray signal?

The ‘kilonova’ GRB 130603B, had an X-ray excess in addition to IR bump (Fong et al., 2014).

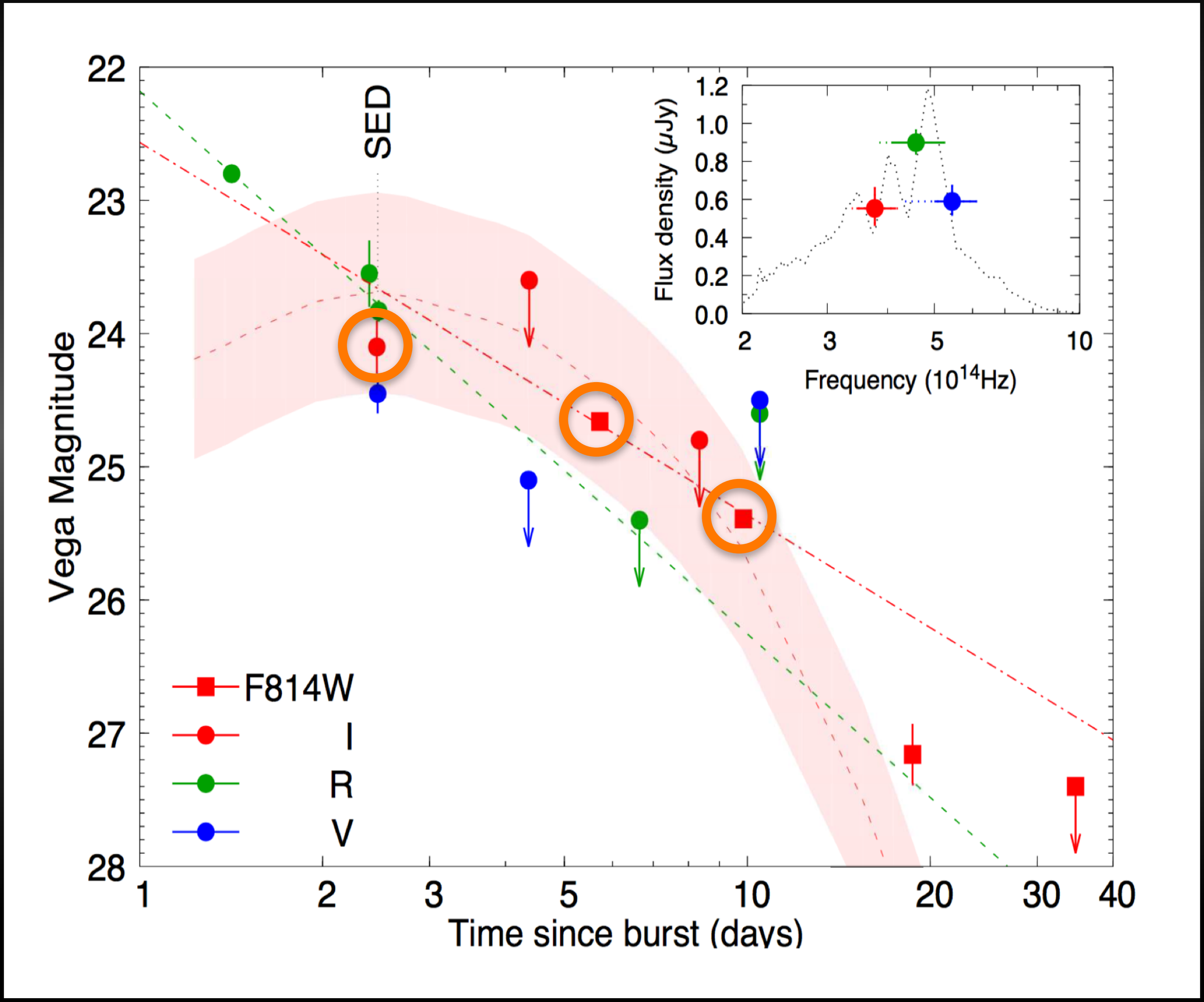
Kisaka, Ioka & Nakar (2016) suggested that the KN could be substantially powered by central engine activity via isotropic X-ray emission.





GRB 050709

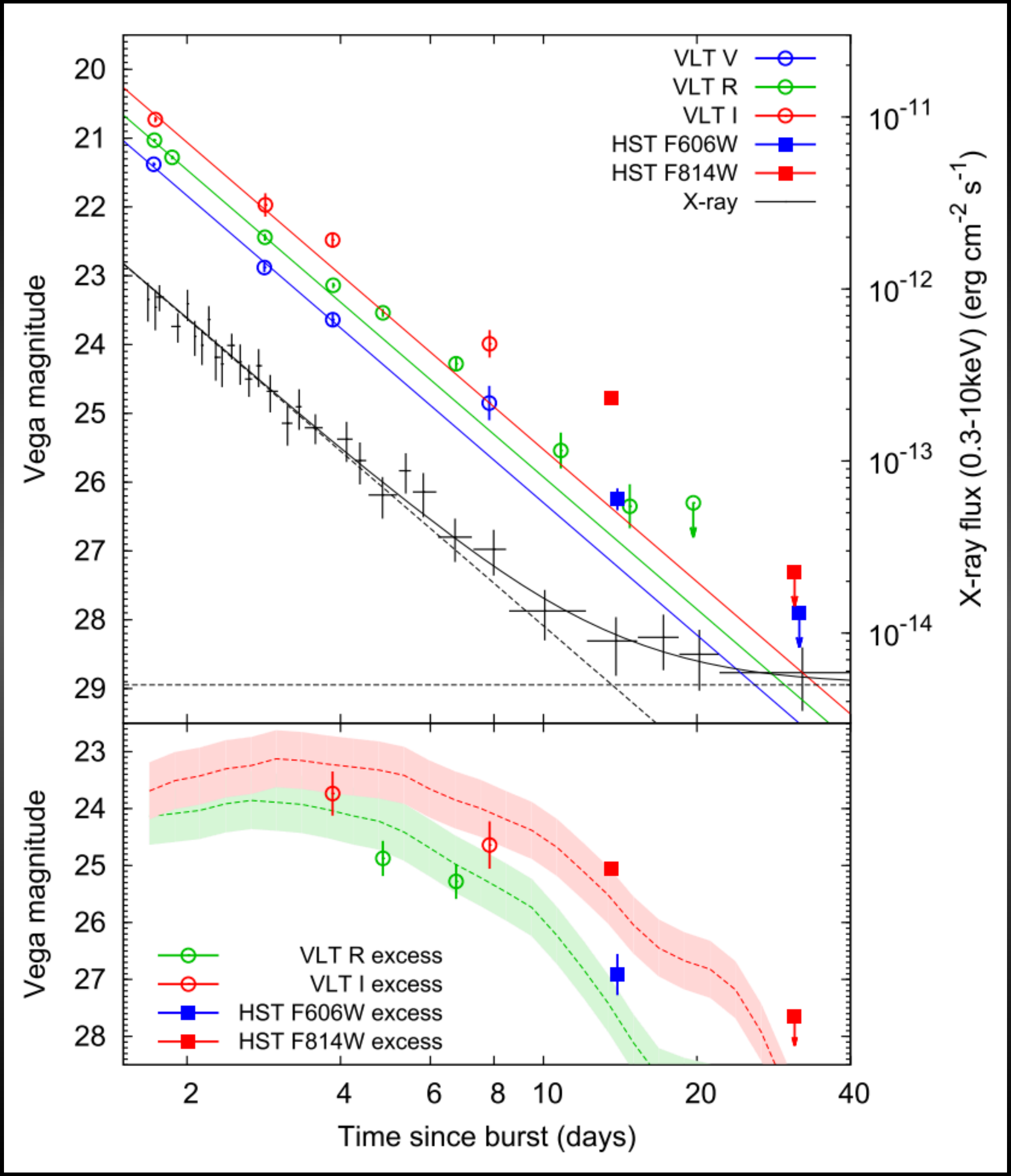
SED deviates from PL at 2.5 day, and becomes redder.
Possibly consistent with low-opacity KN in I-band.



Jin et al. 2016

GRB 060614

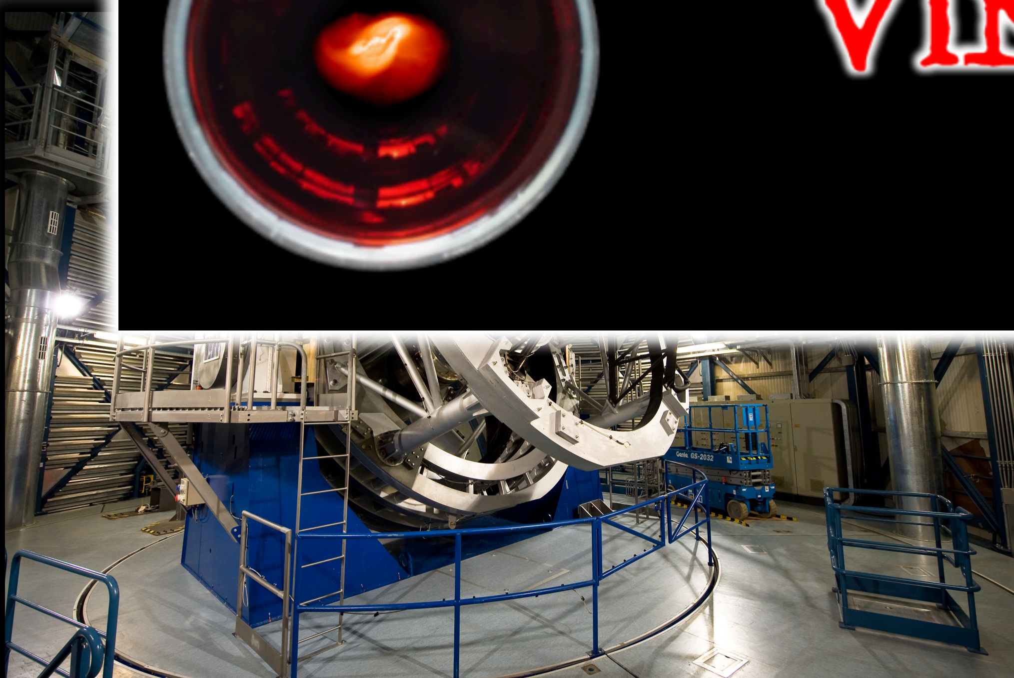
Similar excess seen in I-band even later, although controversial burst.



Jin et al. 2015 ApJ 811 22

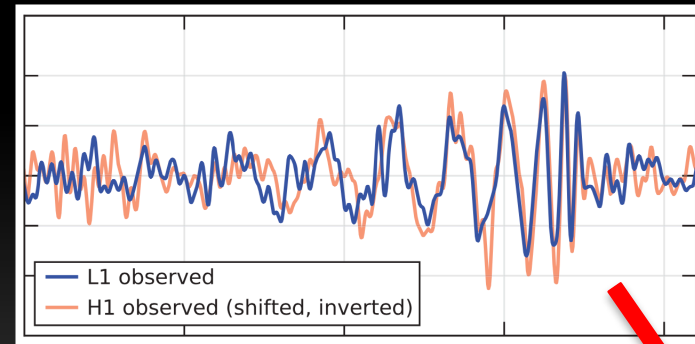
ESO/VISTA programme

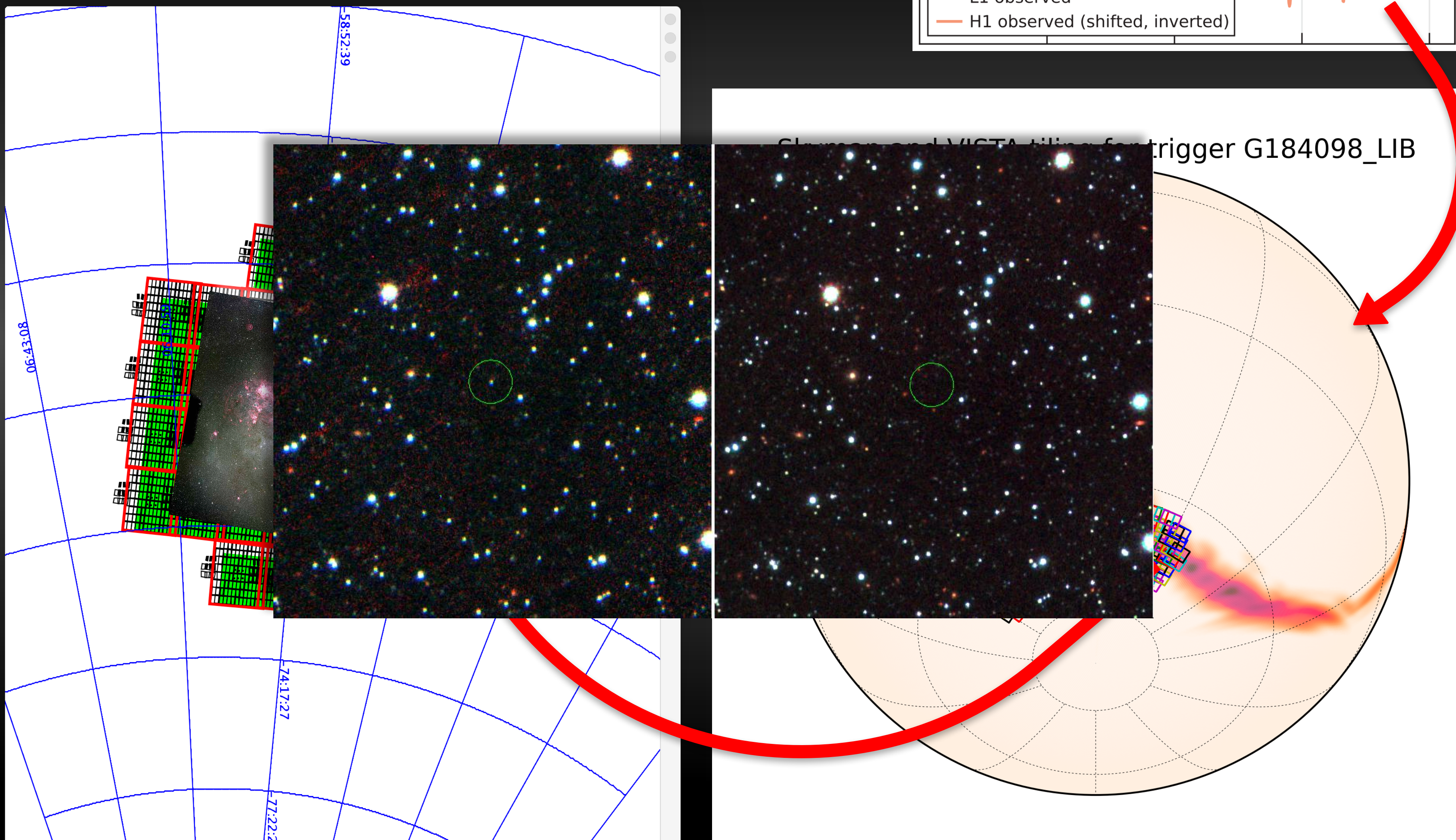
Near-IR optimised
4.1 m wide field



ESO/VISTA programme

GW150914

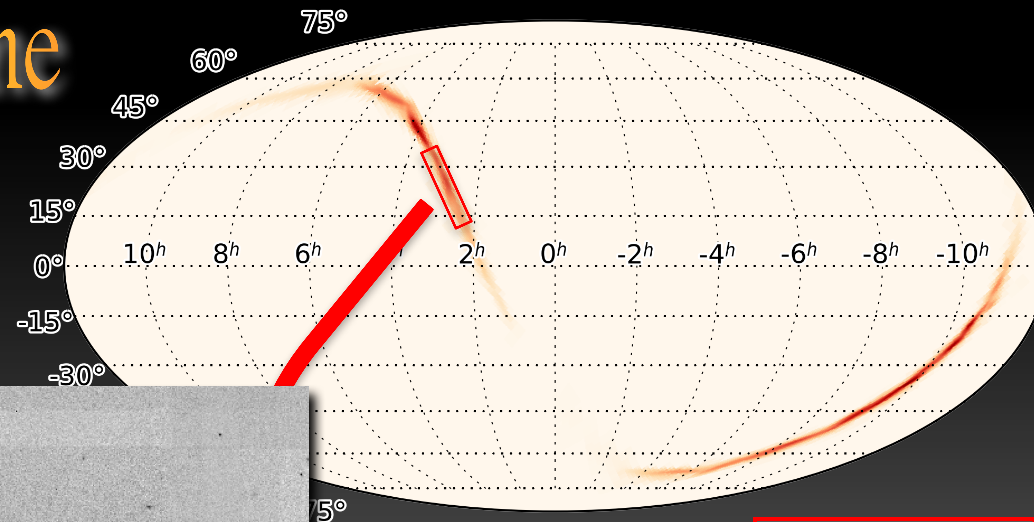


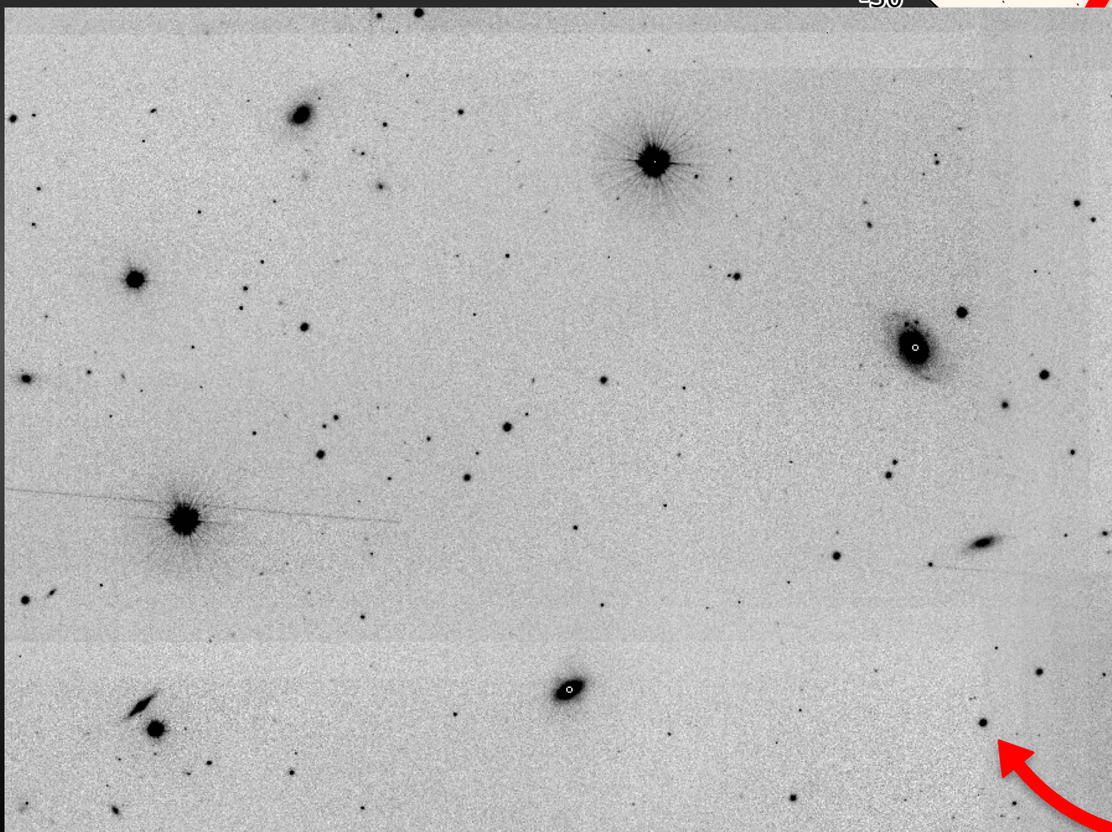


ESO/VISTA programme

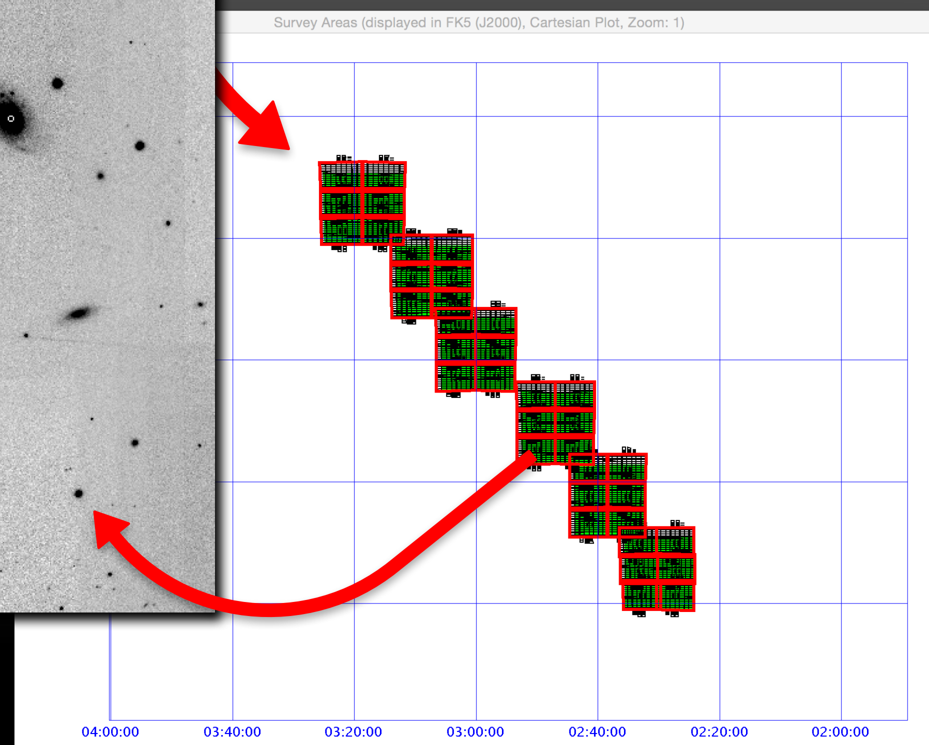
GW151226

Rosetti et al. in prep.





YJK filters



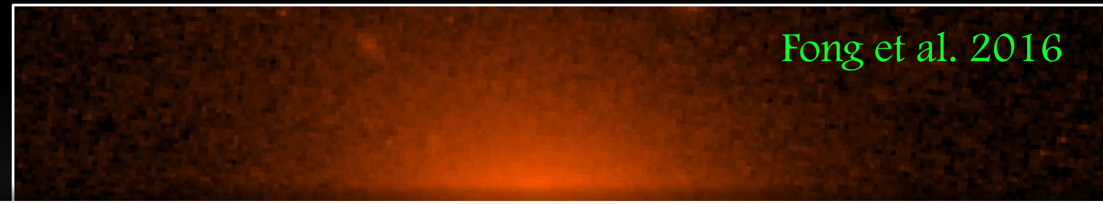
J~21 (need to trade depth and area)

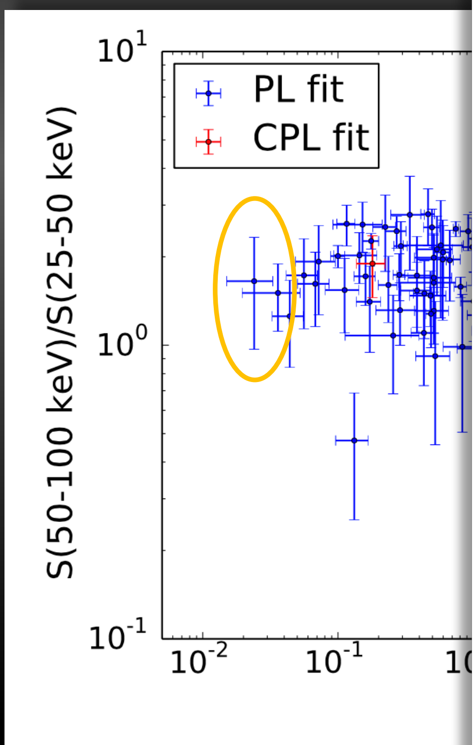
ESO VISTA programme

- ~470 hr over ~3.5 yr
- Coordinate closely with VST follow-up programme.
- Consortium includes/overlaps various small-field follow-up capabilities e.g. HST, VLT, GROND, LT, WHT, NOT
- Will prioritise triggers with high probability of NS (especially NS-BH), preferably short distance, well-placed for follow-up.
- Tiling take advantage of refined sky map and known local galaxy density.
- Exact strategy dependent on circumstances. Baseline plan – initial 3 filter (YJK) epoch at ~3-8 days and revisit in J at ~12-20 days.
- Depth dependent on expected distance and error region size: typically J(AB)~20.5, covering ~50 sq-deg per trigger in O2.
- Benefit from existing VISTA imaging of most of southern sky.
- (Prioritise candidates found in or near plausible hosts)
- Report candidates to LV-EM consortium.

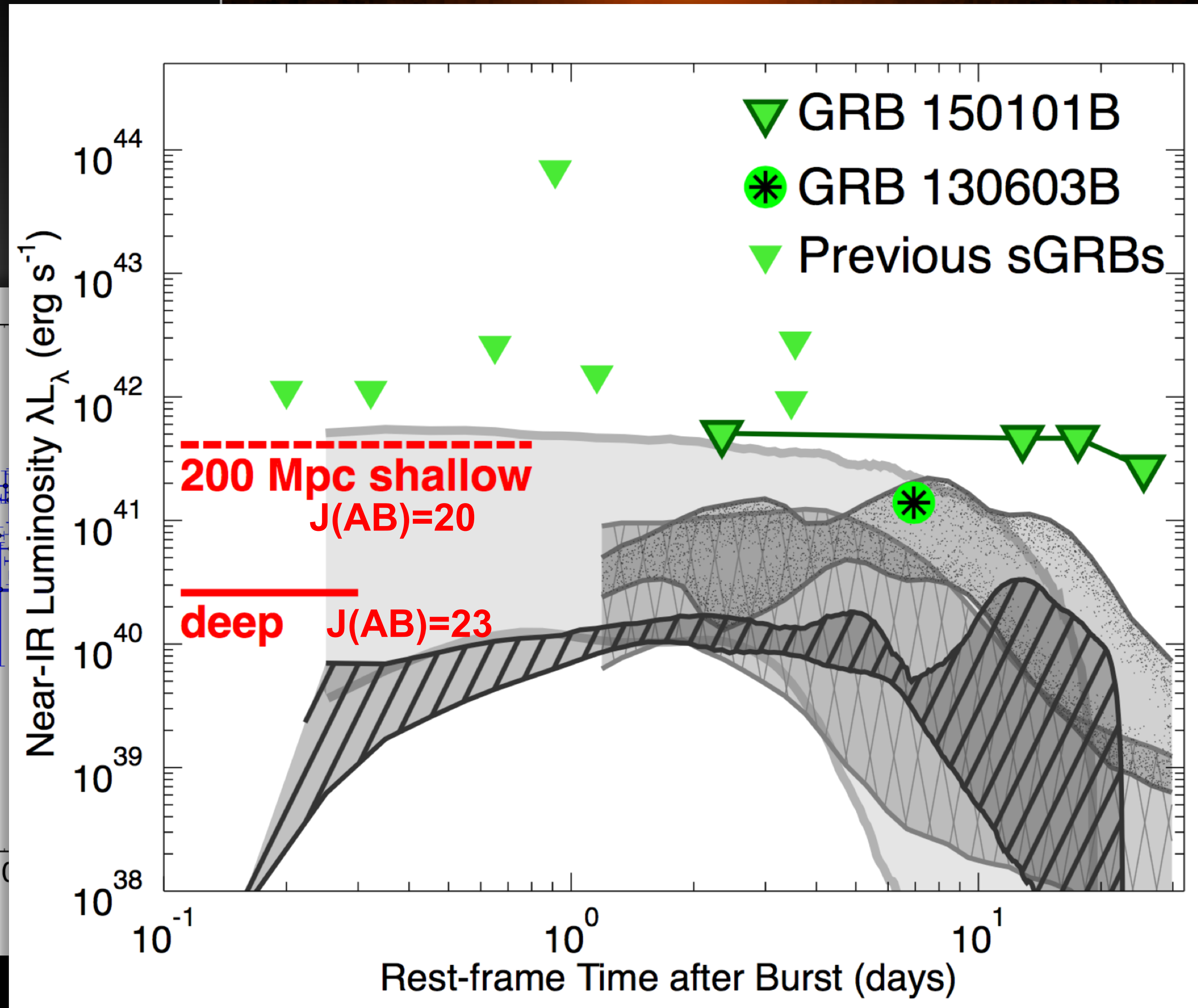
GRB 150101B

z=0.14, but unusually short and unusual (AGN) host

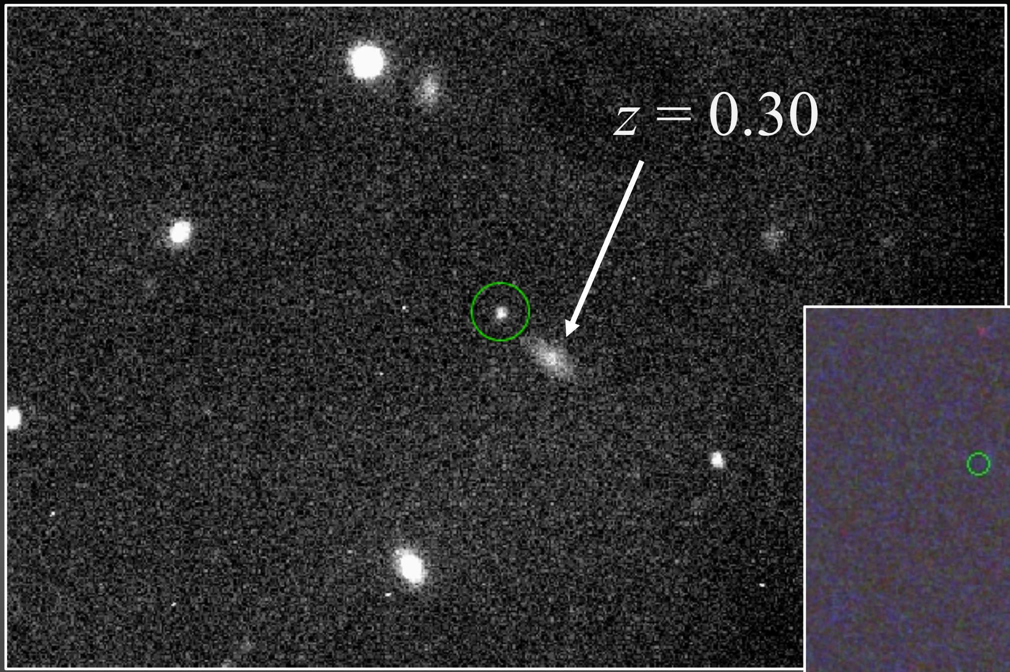


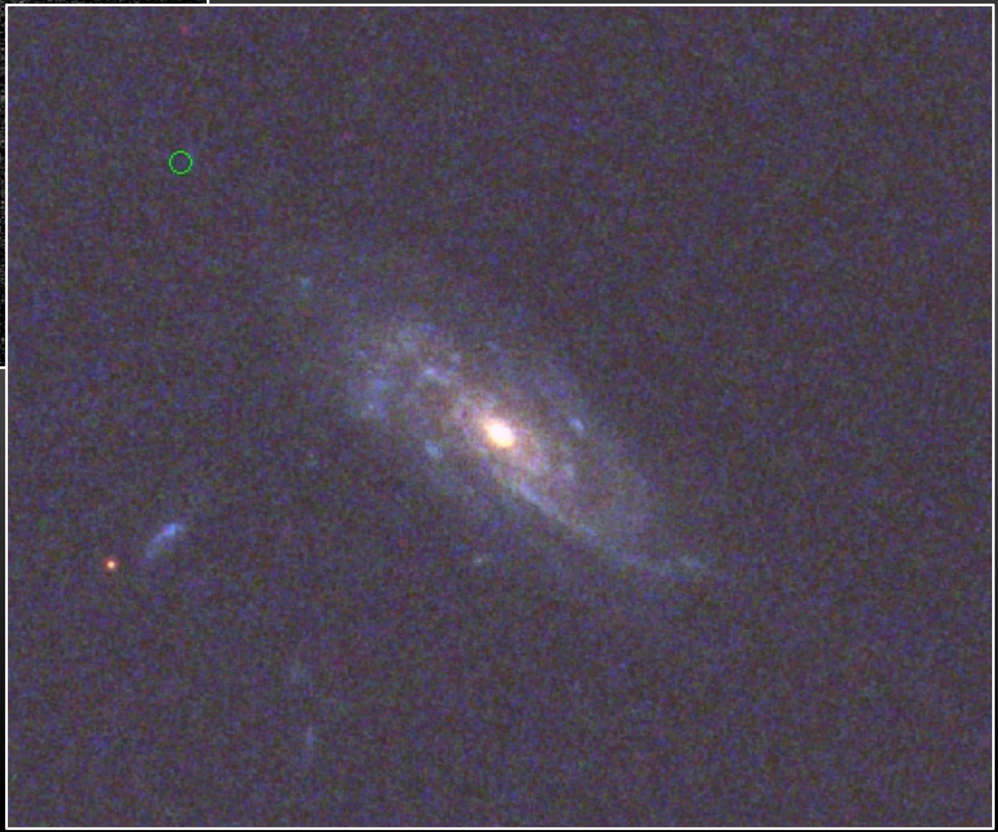


Lien et al. 2016



GRB 150424A

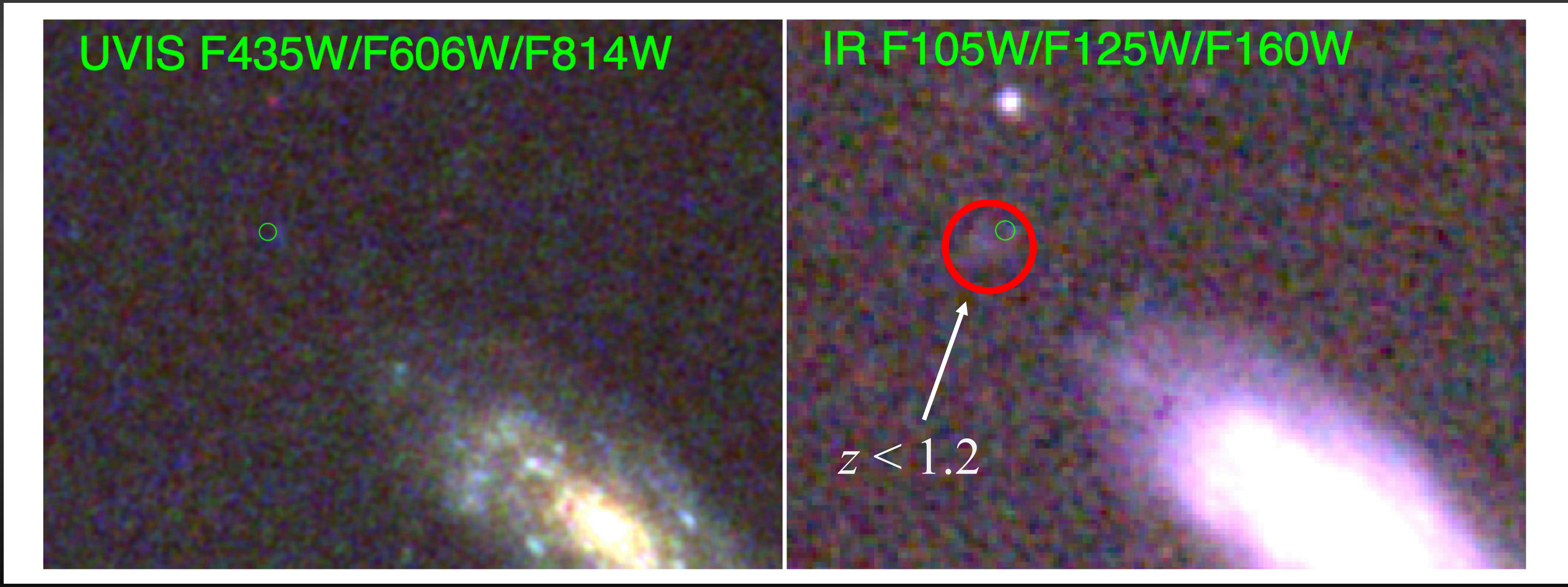




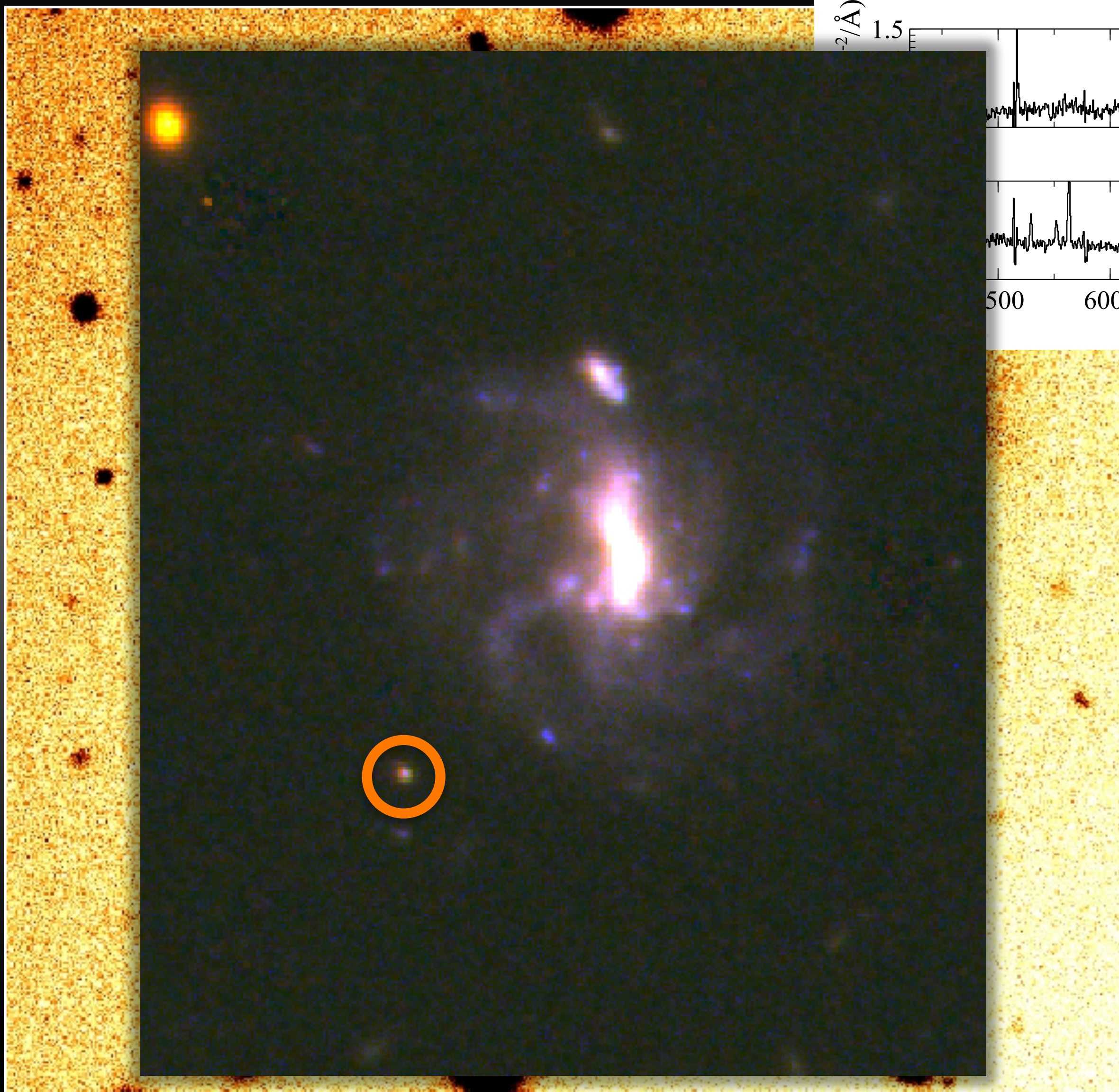
NT et al. in prep.

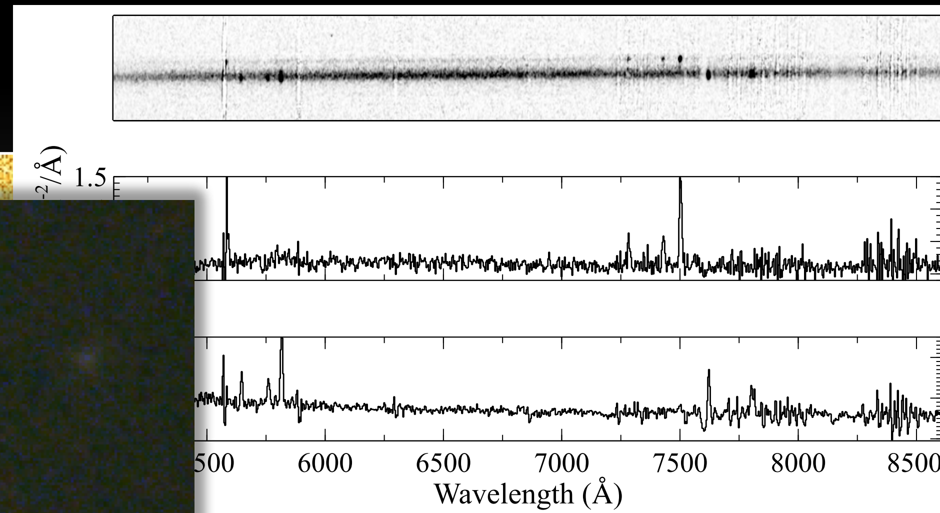
GRB 150424A

Appears to be in faint background galaxy.



GRB 160821B

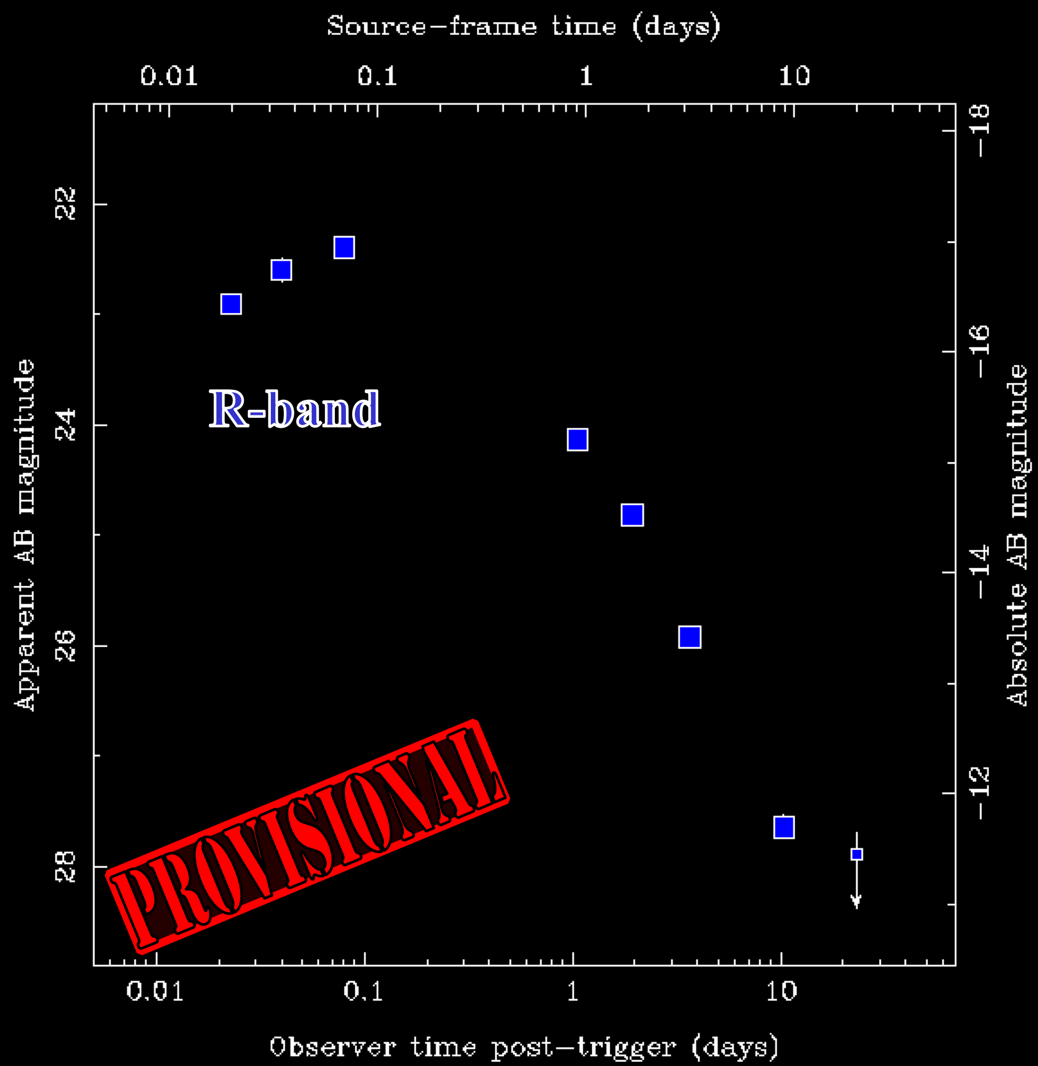




Host ~ disturbed spiral

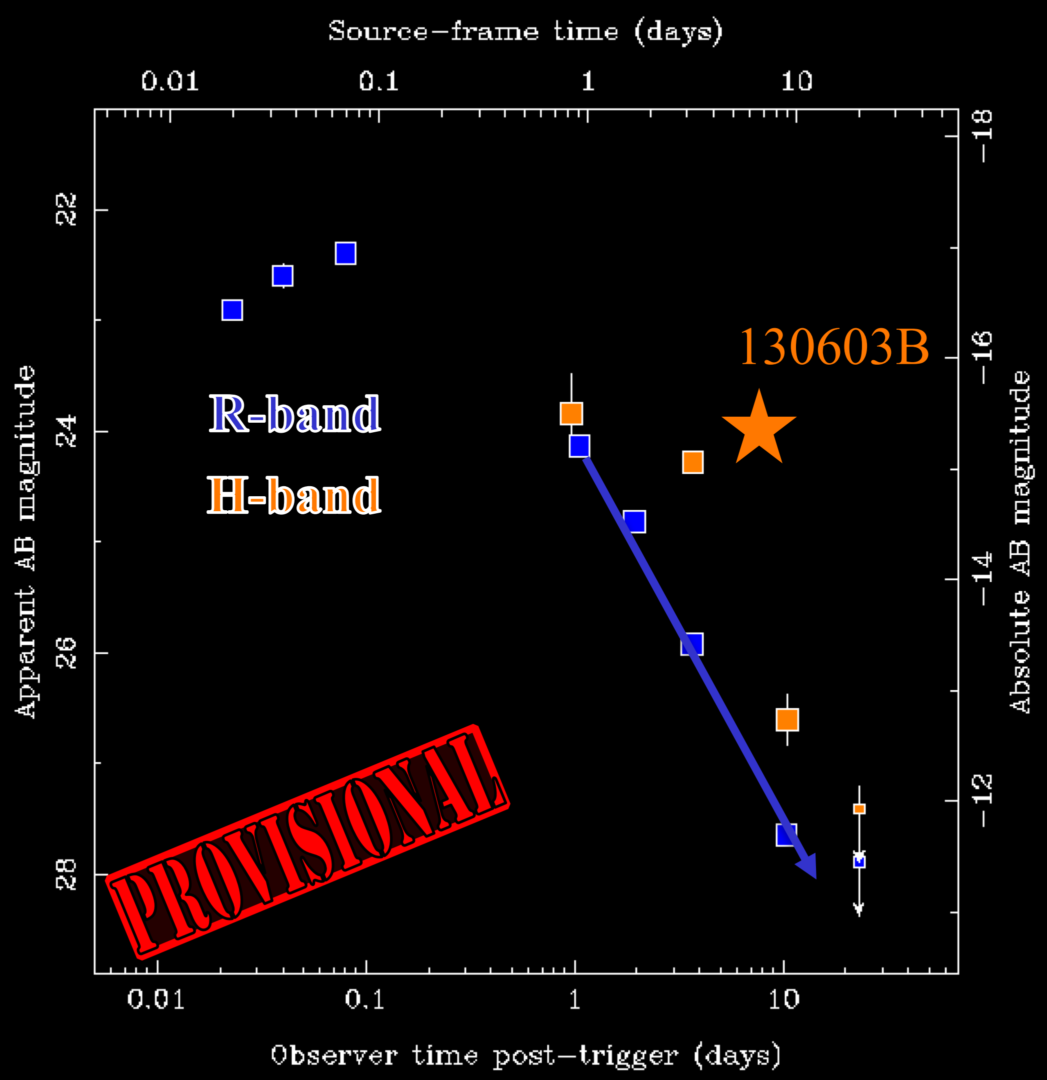
NT et al. in prep.

GRB 160821B



Source−frame time (days)
0.01
0.1
1
10
−18
−16
−14
−12
Absolute AB magnitude
22
24
26
28
Apparent AB magnitude
R-band
PROVISIONAL
0.01
0.1
1
10
Observer time post−trigger (days)

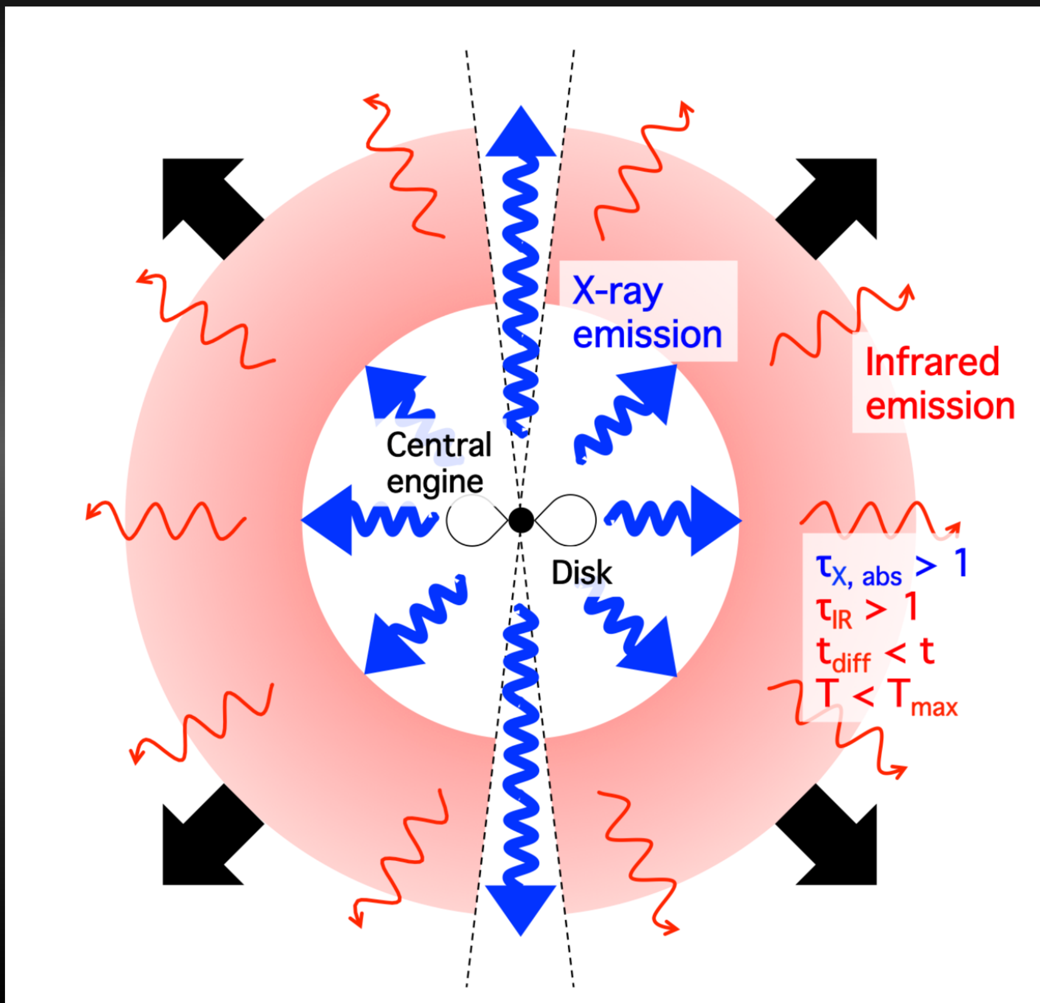
GRB 160821B

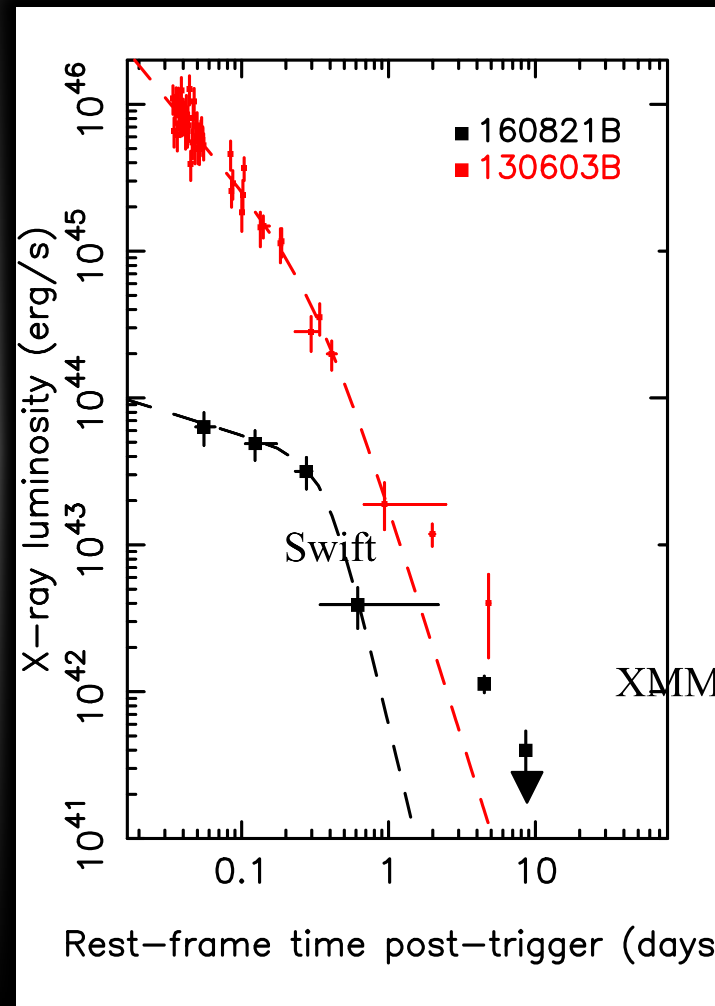


Any KN is clearly much fainter (>~5x) than 130603B.

Also X-ray excess?

Similar X-ray excess to 130603B.





Conclusions for part 2

- Compact binary mergers also potentially an important (perhaps dominant) source of r-process heavy elements.
- High opacity suggests EM signature predominantly in near-IR.
- Evidence in at least one SGRB (130603B) of a late time nIR excess consistent with such emission. More tentative suggestions in some other cases.
- Searches for this emission accompanying GW detections are challenging but feasible, especially with the VISTA telescope.