Cardiff, 2015

Merging neutron stars, gravitational waves and the origin of the heavy chemical elements

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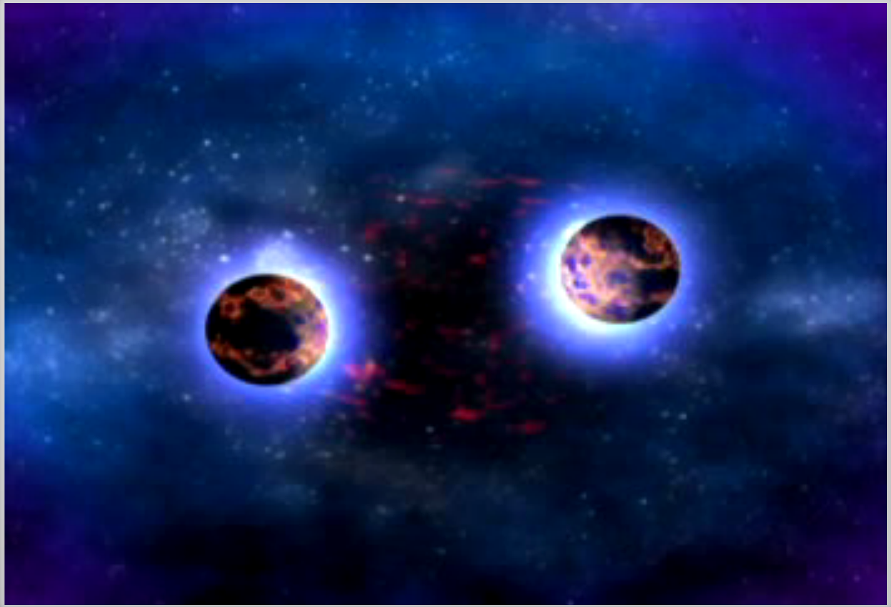
Compact binary mergers

Neutron-star/neutron-star
Neutron-star/black-hole
Black-hole/black-hole



Expected to be strong gravitational wave emitters during inspiral.

If NS component, likely sites of *r*-process nucleosynthesis (Lattimer & Schramm 1974), whose origin has long been puzzling (Burbidge, Burbidge, Fowler & Hoyle 1958).

A prime candidate for production of cosmological GRBs (plausible time-scales, energetics and rates).
(Eichler et al. 1989
Lipunov et al. 1995)

1969 ~ an unexpected flash

THE ASTROPHYSICAL JOURNAL, 182:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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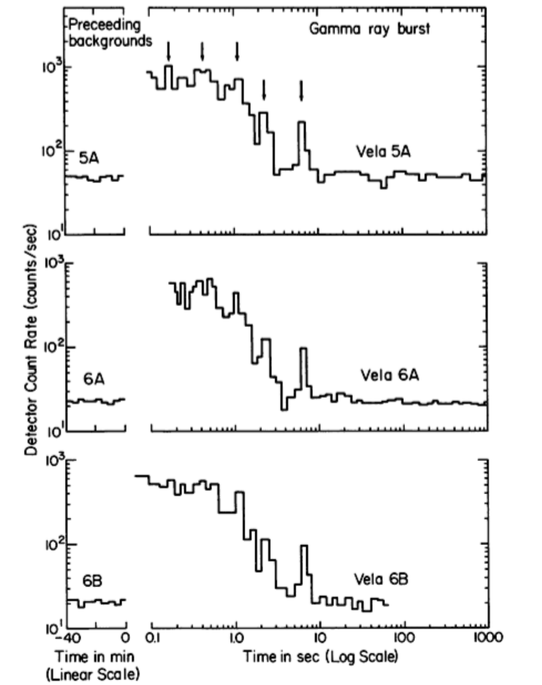
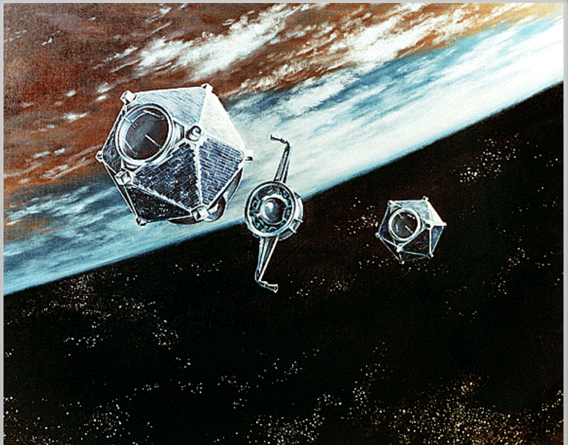
ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars

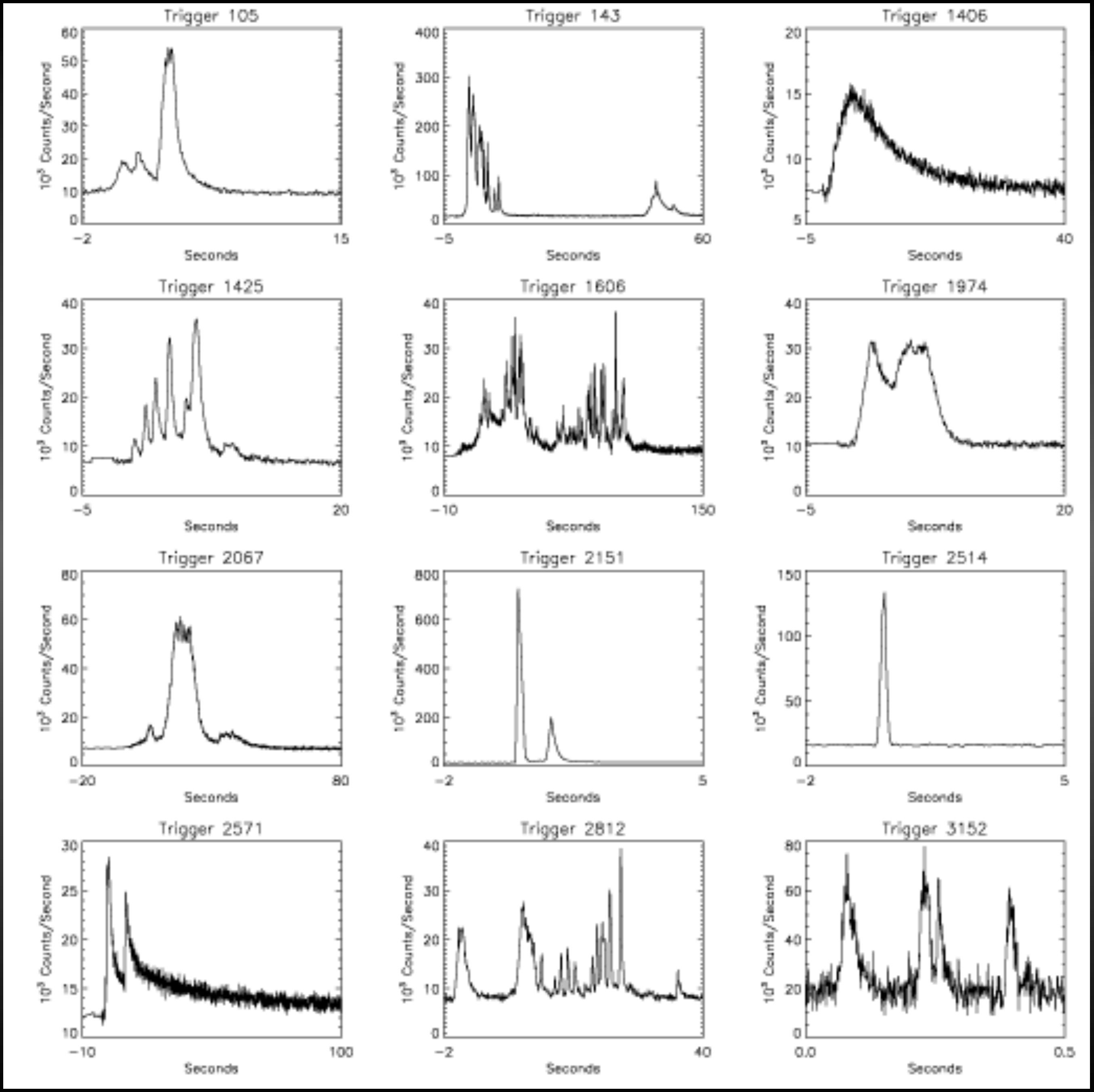




"Vela" series of 1960s US satellites intended to monitor nuclear tests in space.

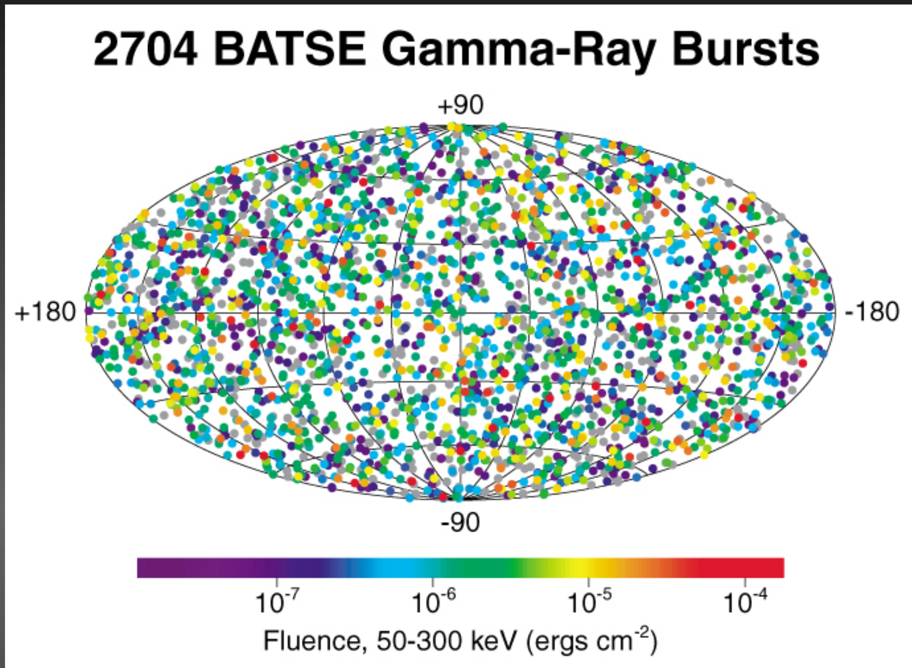
Instead find evidence for extraterrestrial bursts of gamma rays.

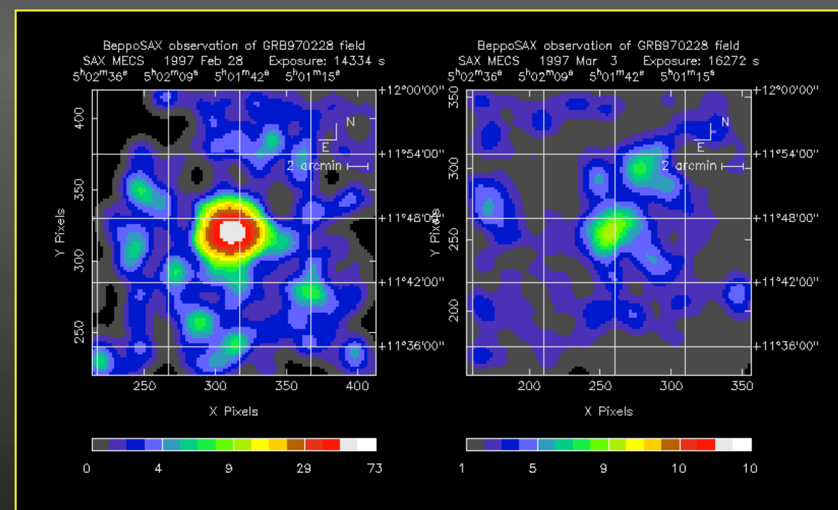
Wide range of temporal properties – variability down to few milliseconds.



Compton GRO/BATSE

Finds that the bursts are spread isotropically over the sky – thus likely cosmological.



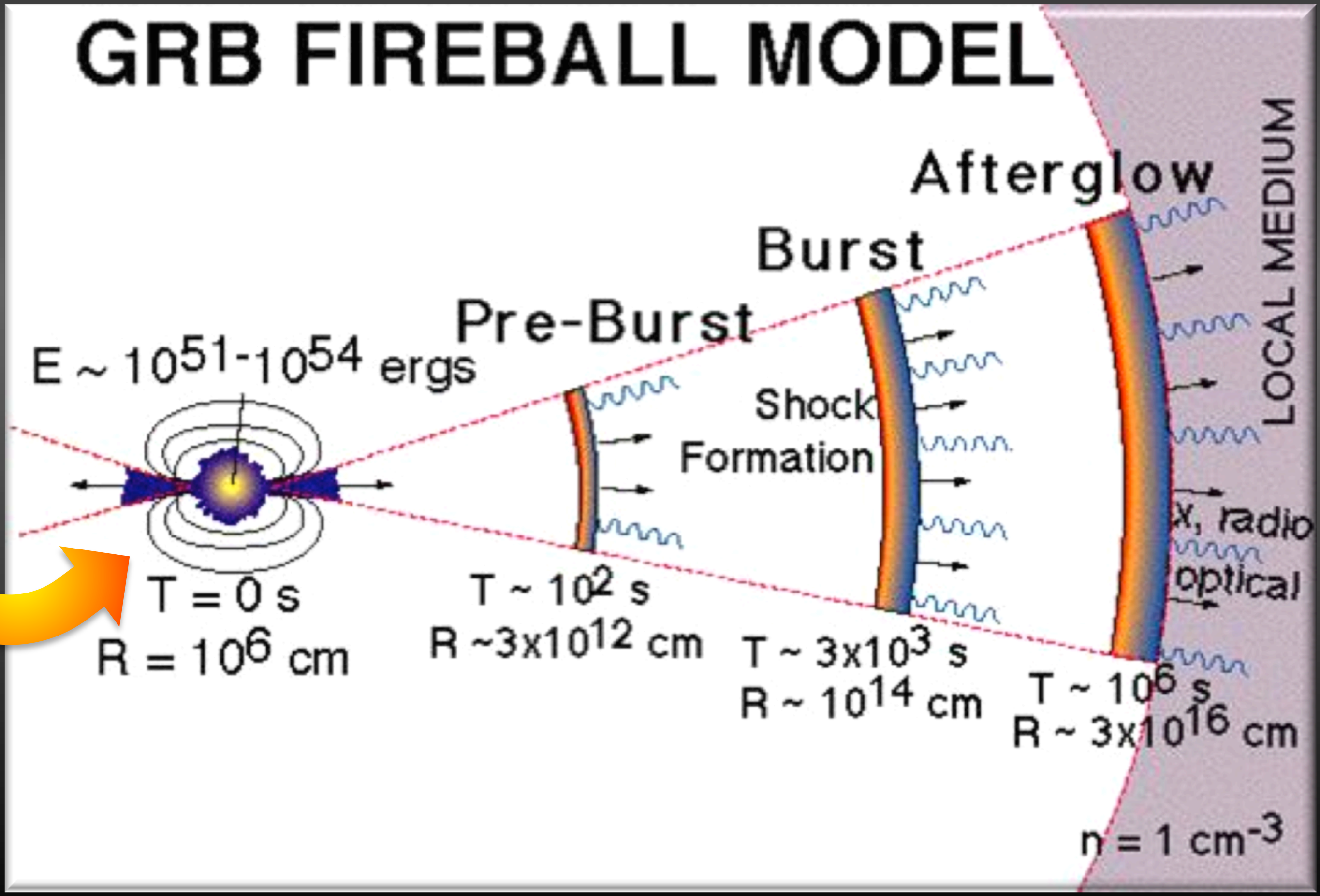


Discovers X-ray afterglows, opening route to optical afterglows and hence locations and redshifts.

Beppo-SAX

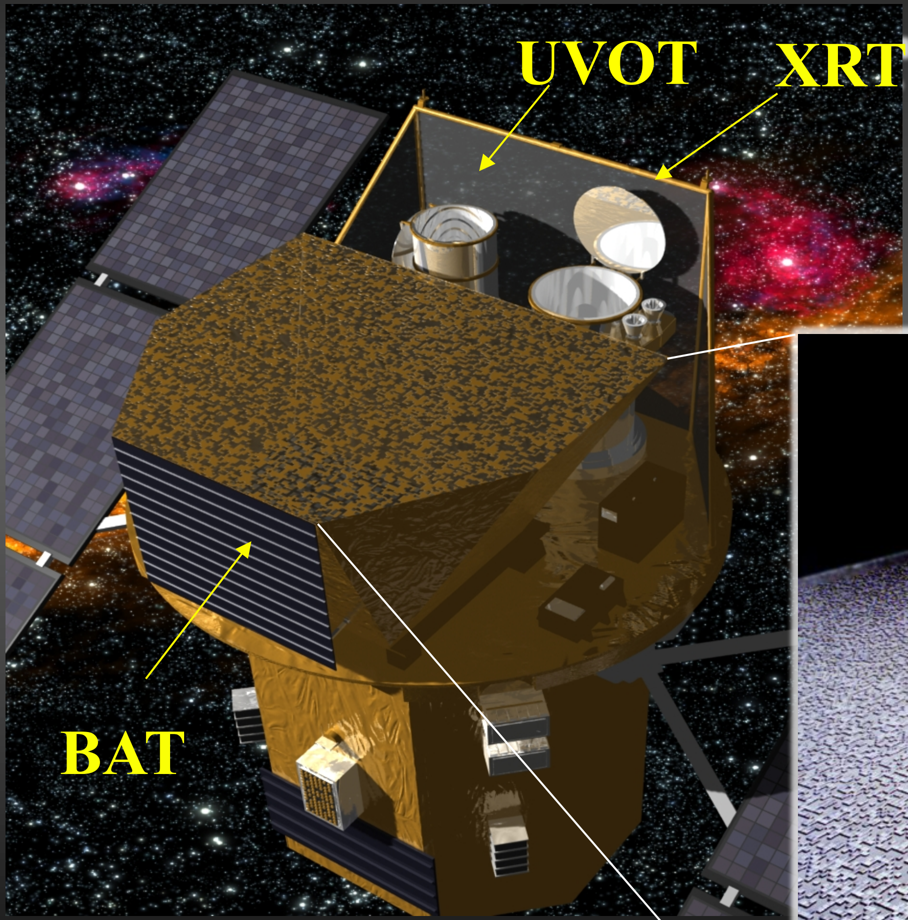
Relativistic fireball model: GRB is produced from jets with velocities very close to the speed of light (Bulk Lorentz factors of few hundred) – afterglow from shocked ambient medium.

Central engine likely a "collapsar"



SWIFT (launch Nov 2004)

Initial detection by Burst Alert Telescope.

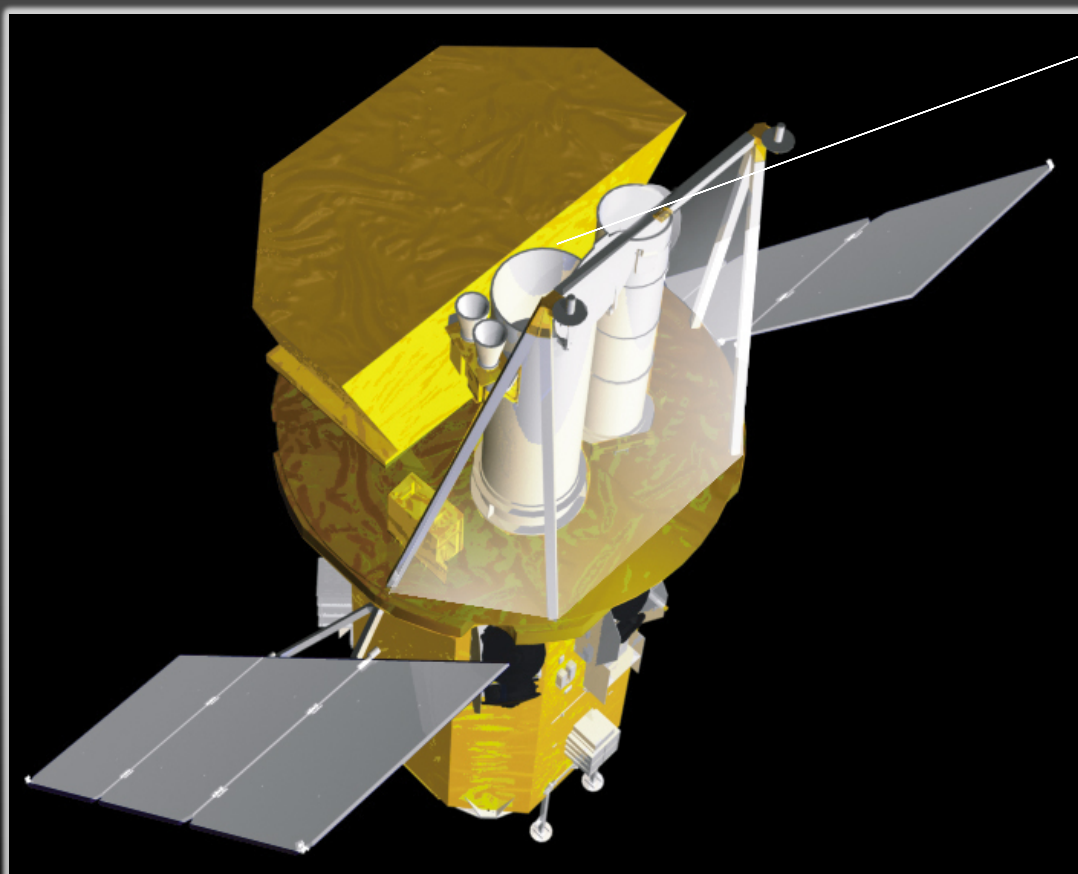


BAT coded mask:

- 54000 lead tiles.
- Project onto CZT detector plane.
- 2.5 SR field of view.

SWIFT

Nearly all bursts detected in X-rays, providing few arcsec positions and monitoring afterglow for days to weeks.

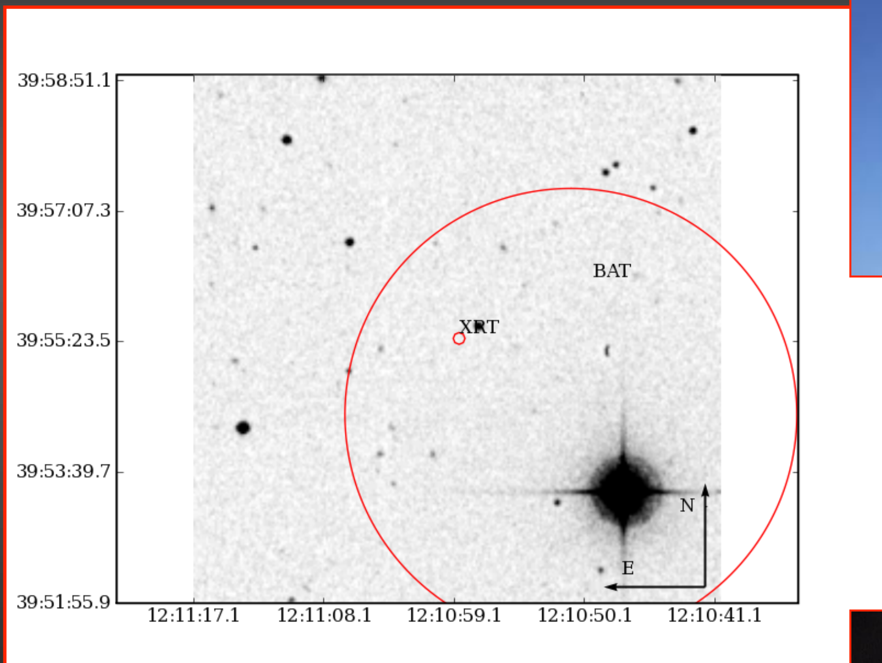


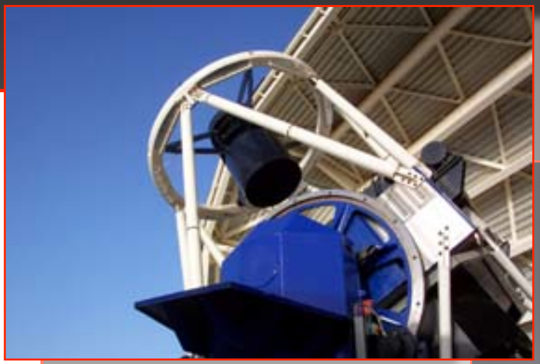
X-ray Telescope:

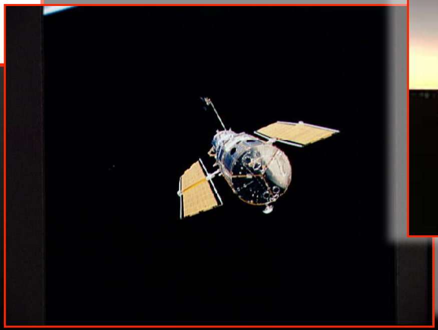
- Camera built by Leicester

Chasing …

- *Further followup from ground and space required to pinpoint afterglows, monitor their behaviour, study host galaxies and, crucially, to find redshifts.*







Short-hard GRBs~ another population

CATALOG OF COSMIC GAMMA-RAY BURSTS: I AND II

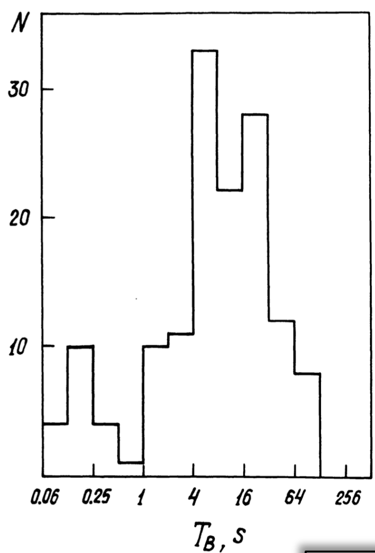


Fig. 164

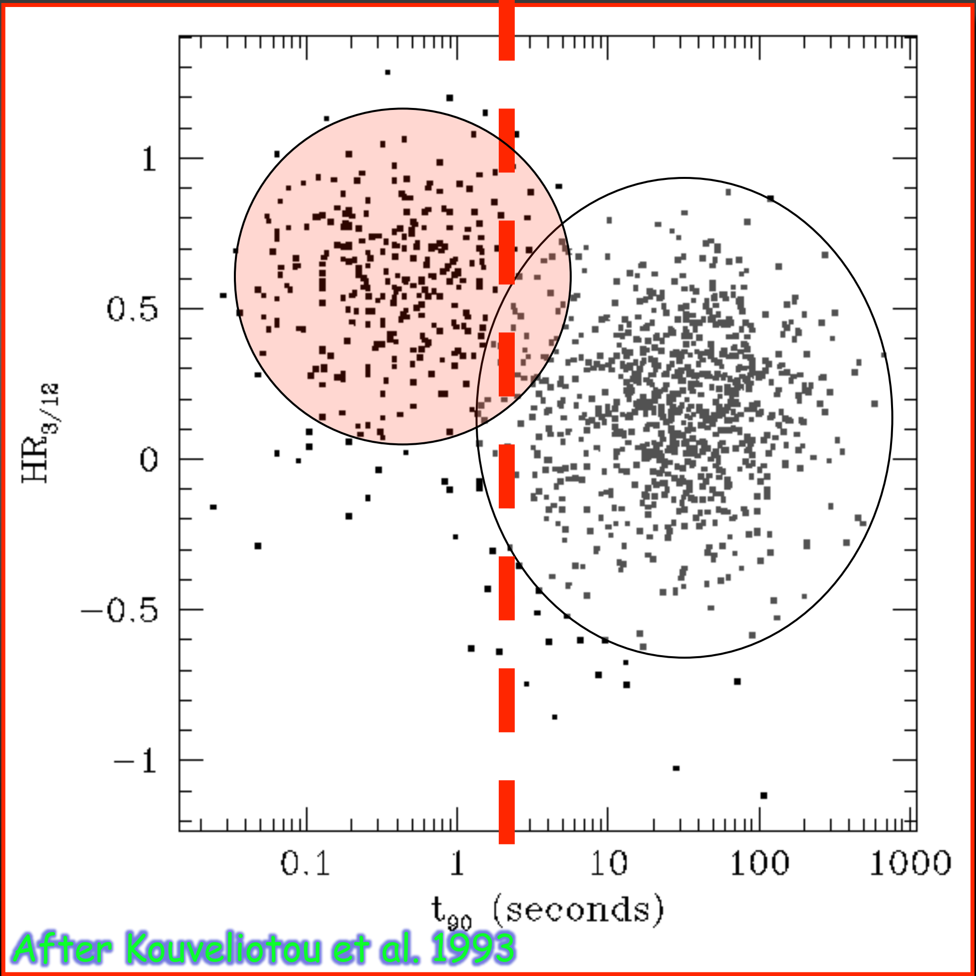
Identified as a distinct population in 1981 by Mazets et al. in a series of papers on the KONUS experiment on Venera 11 & 12.

A. THE DISTRIBUTION OF BURSTS IN DURATION

The essential differences in the gamma-burst time structure are reflected in the distribution of the observed events in duration T_b. Figure 164 shows an experimental distribution drawn for 143 events. It displays the number of bursts per equal logarithmic interval of T_b. Since some of the bursts may have long tails, the duration of the event in this case is taken to be the interval of time within which fall 80–90% of the measured burst intensity S. The distribution differs substantially from the uniform one. The main peak in the distribution is connected primarily with single and multipulse bursts. The right-hand wing is composed of double and long structureless bursts. Narrow peak in the beginning of the graph indicates the existence of a separate class of short bursts.

Short-hard GRBs- another population

T_{90}=2 s

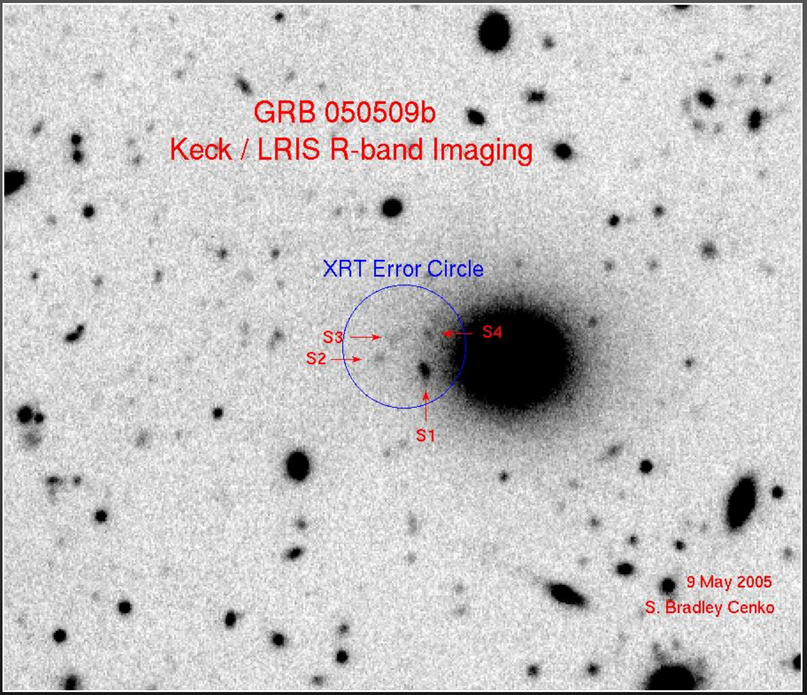


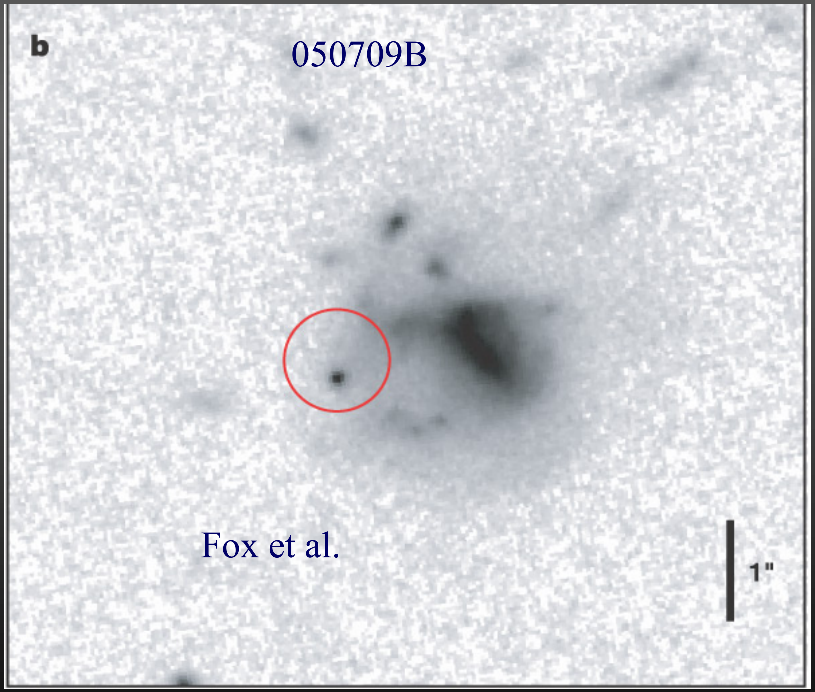
Around 25% of BATSE GRBs were "short", but:

- Populations obviously overlap
- Detector dependent (e.g. *Swift* sees fewer sGRBs, with "borderline" probably rather shorter).
- Both axes redshift dependent (in complicated ways)

Short-duration bursts

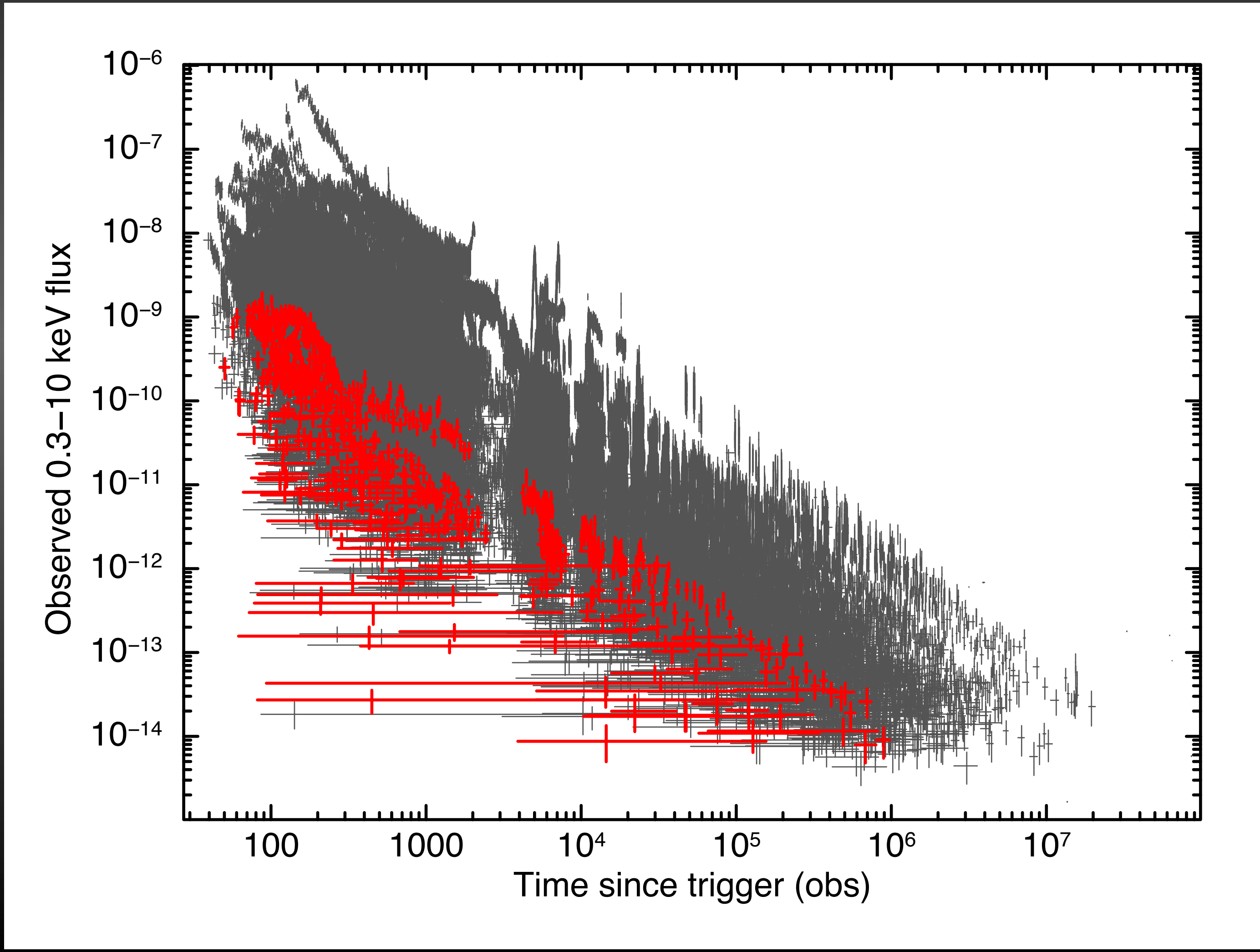
Thanks largely to Swift, several tens of short GRBs have now been rapidly localised to few arcsec accuracy, allowing identification of likely hosts, and hence redshifts in some cases.





Short-duration bursts

X-ray afterglows fainter than for LGRBs (several cases have no detection despite prompt slew).



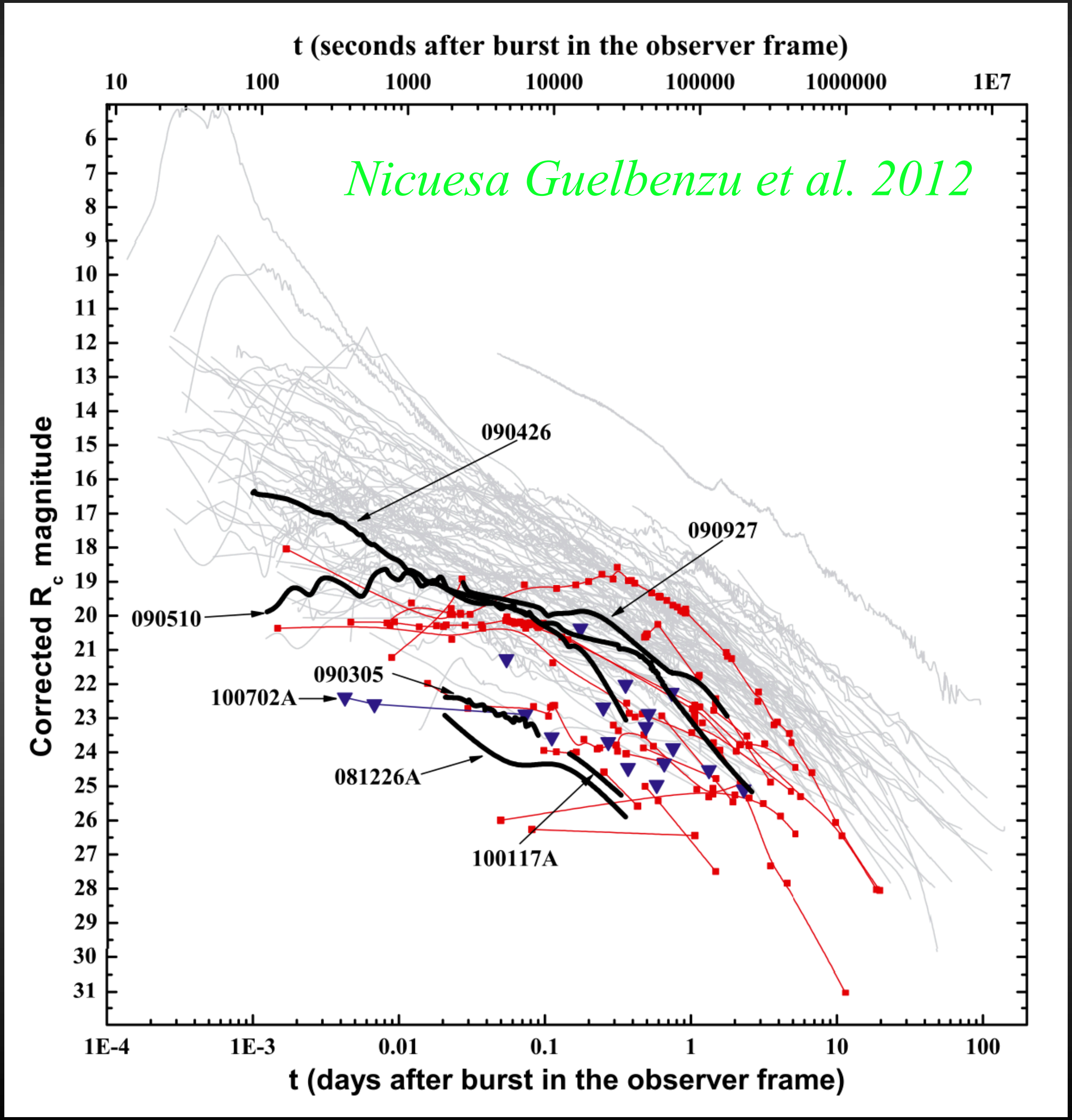
Short-duration bursts

Generally lower luminosity (hence lower <z>~0.5)

Never associated with supernovae.

May break into sub-classes e.g. a proportion have "extended soft emission".

Optical afterglows usually also very faint with weak spectral features – hard to find and hard to obtain redshifts (in practice, nearly always rely on host redshift).

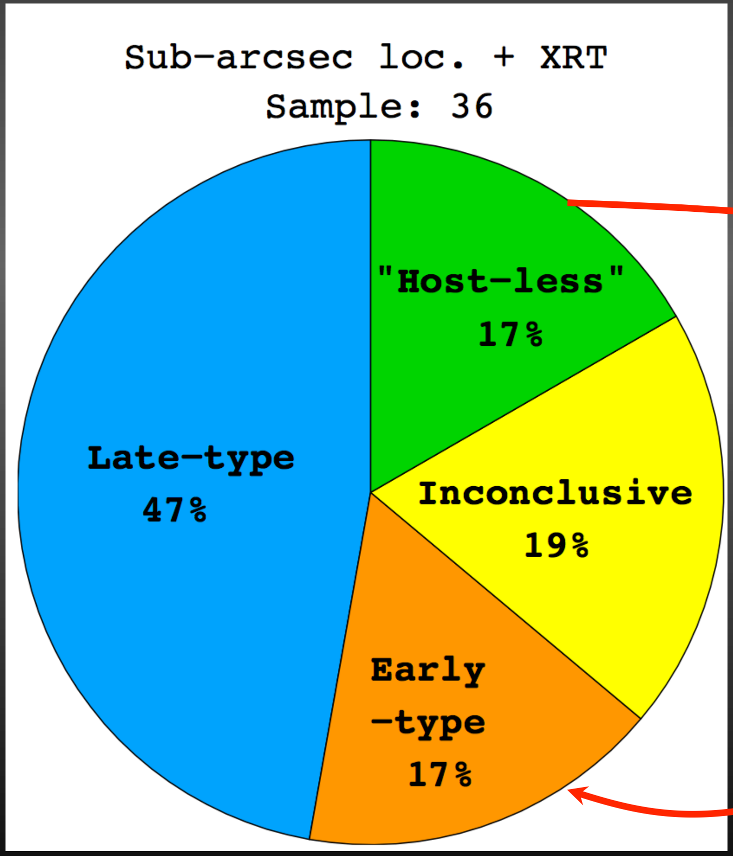


Short-hard GRBs - compact binary mergers?

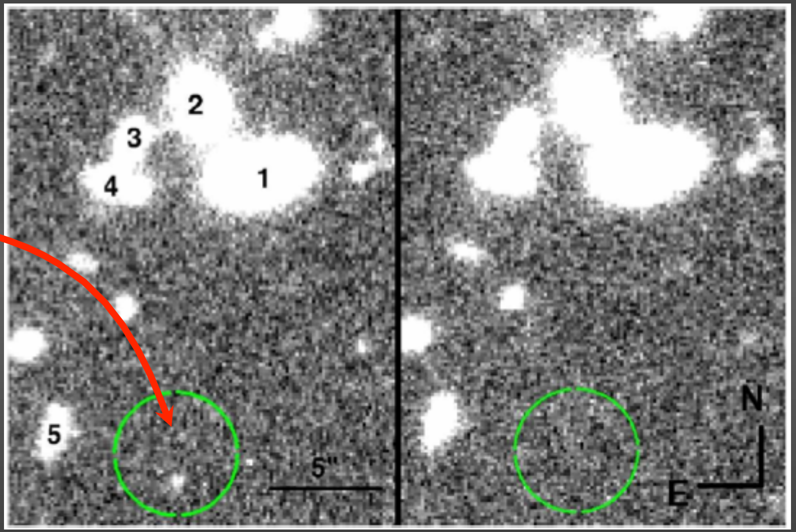
Associated with a range of host stellar populations.

Sometimes apparently far from their host.

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



Fong et al. 2013

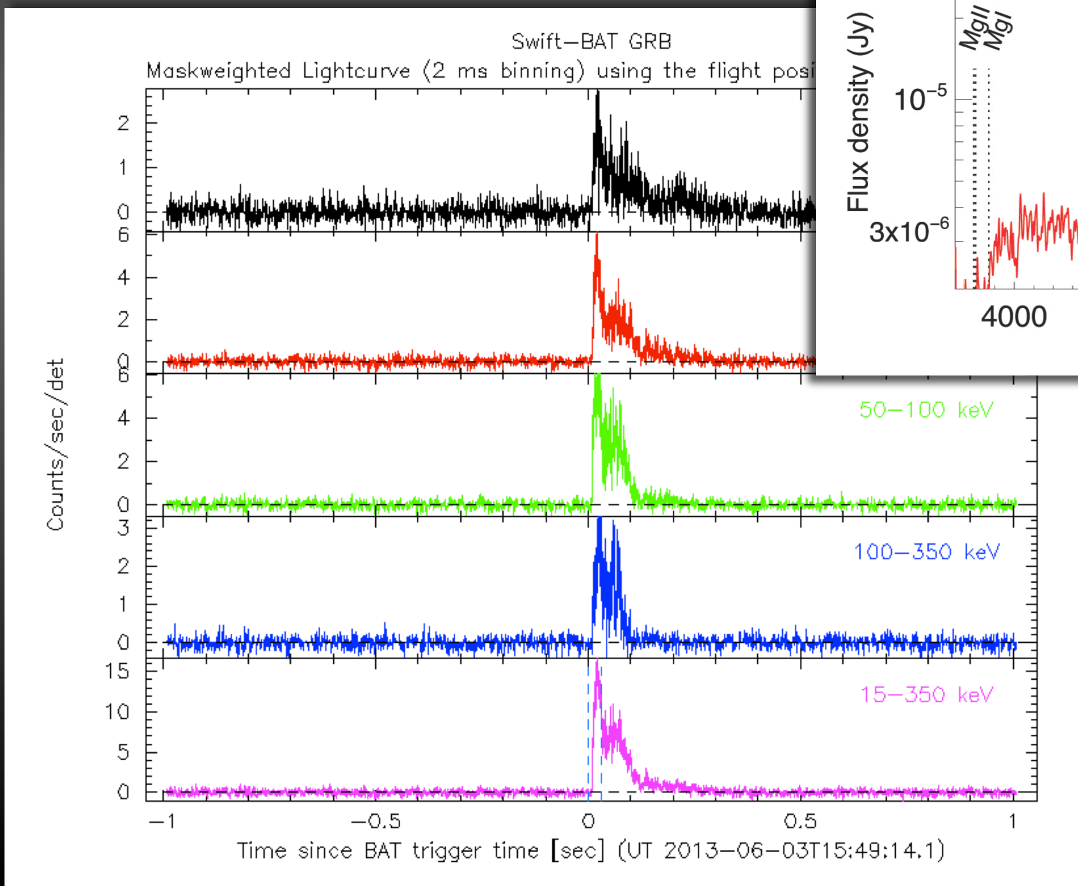


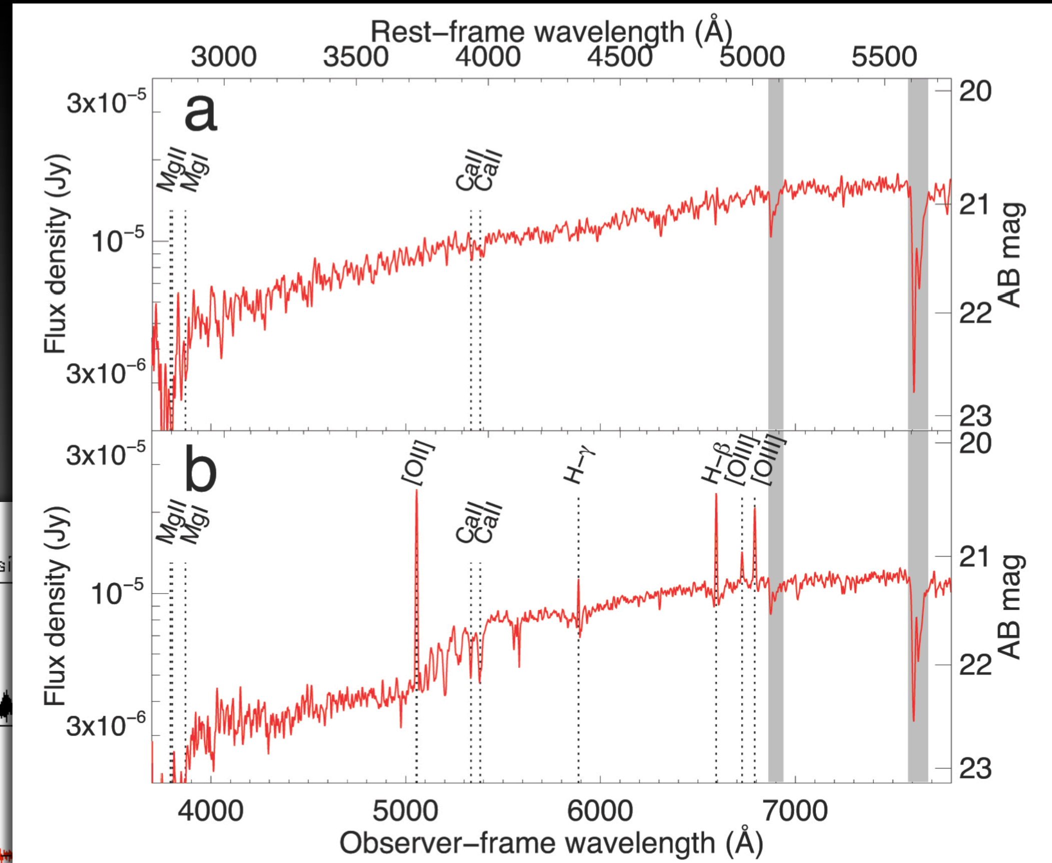
Rowlinson et al. 2010

Note, the number associated with ancient stellar populations is not high, suggesting inspiral times ~100s Myr are most common.

GRB 130603B

Relatively bright burst and unambiguously short duration.

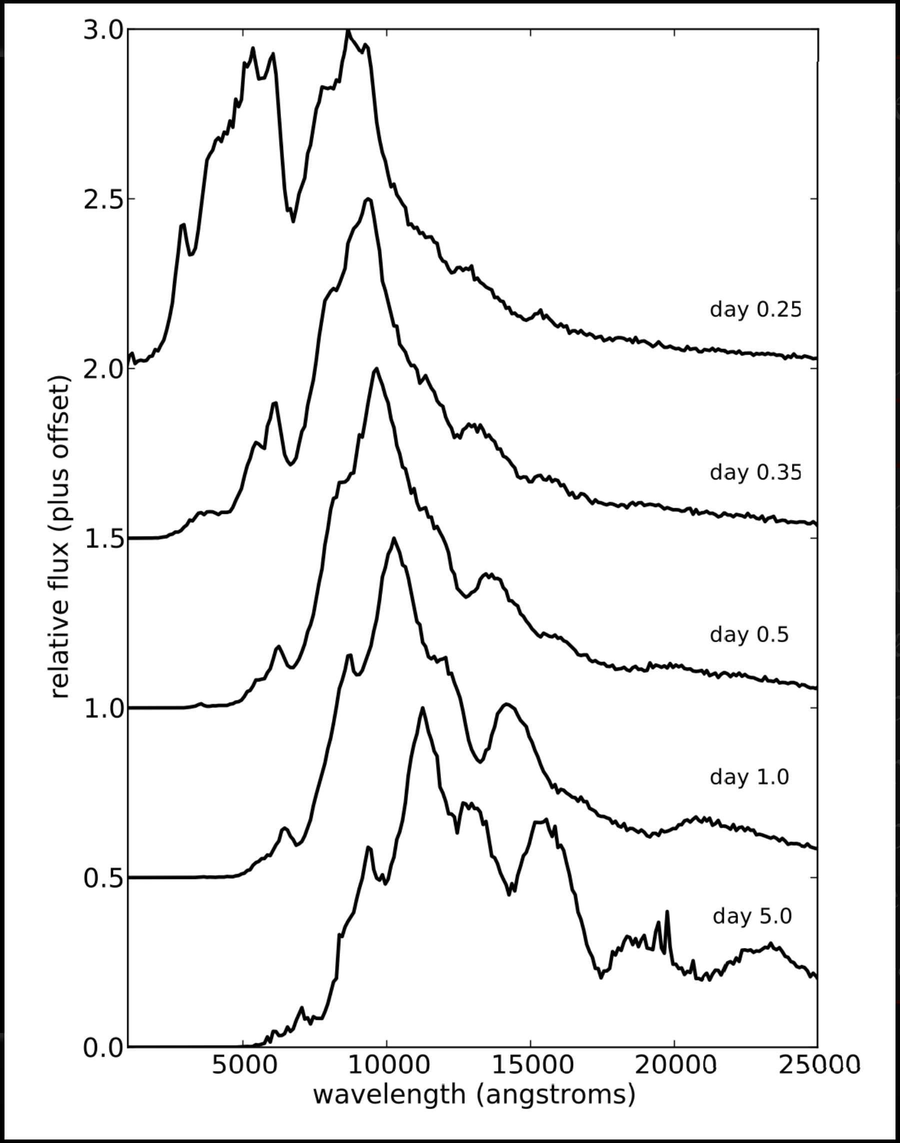




de Ugarte Postigo et al. 2013

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

r-process kilonovae



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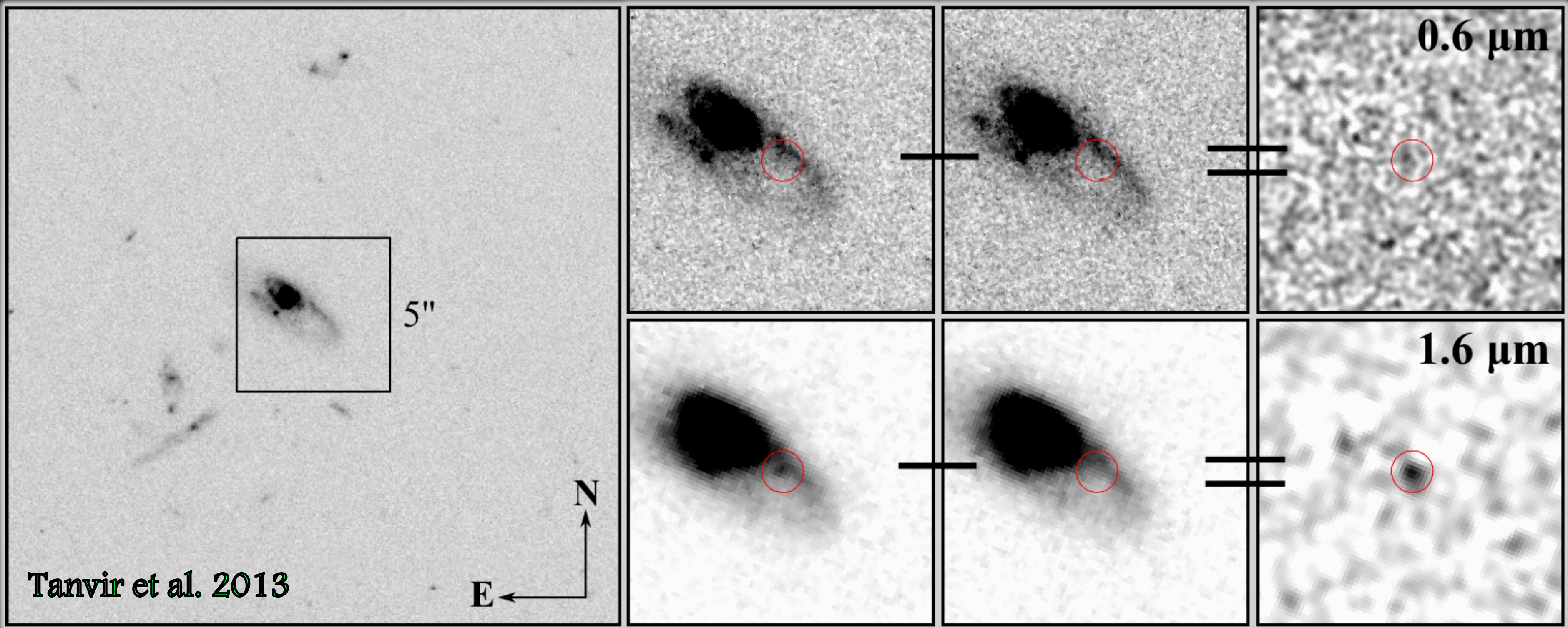
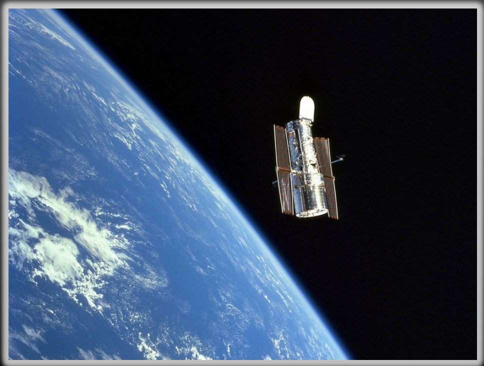
Rosswog et al. 2012

Rosswog et al. 2013
Piran et al. 2013
Kasen et al. 2013

GRB 130603B

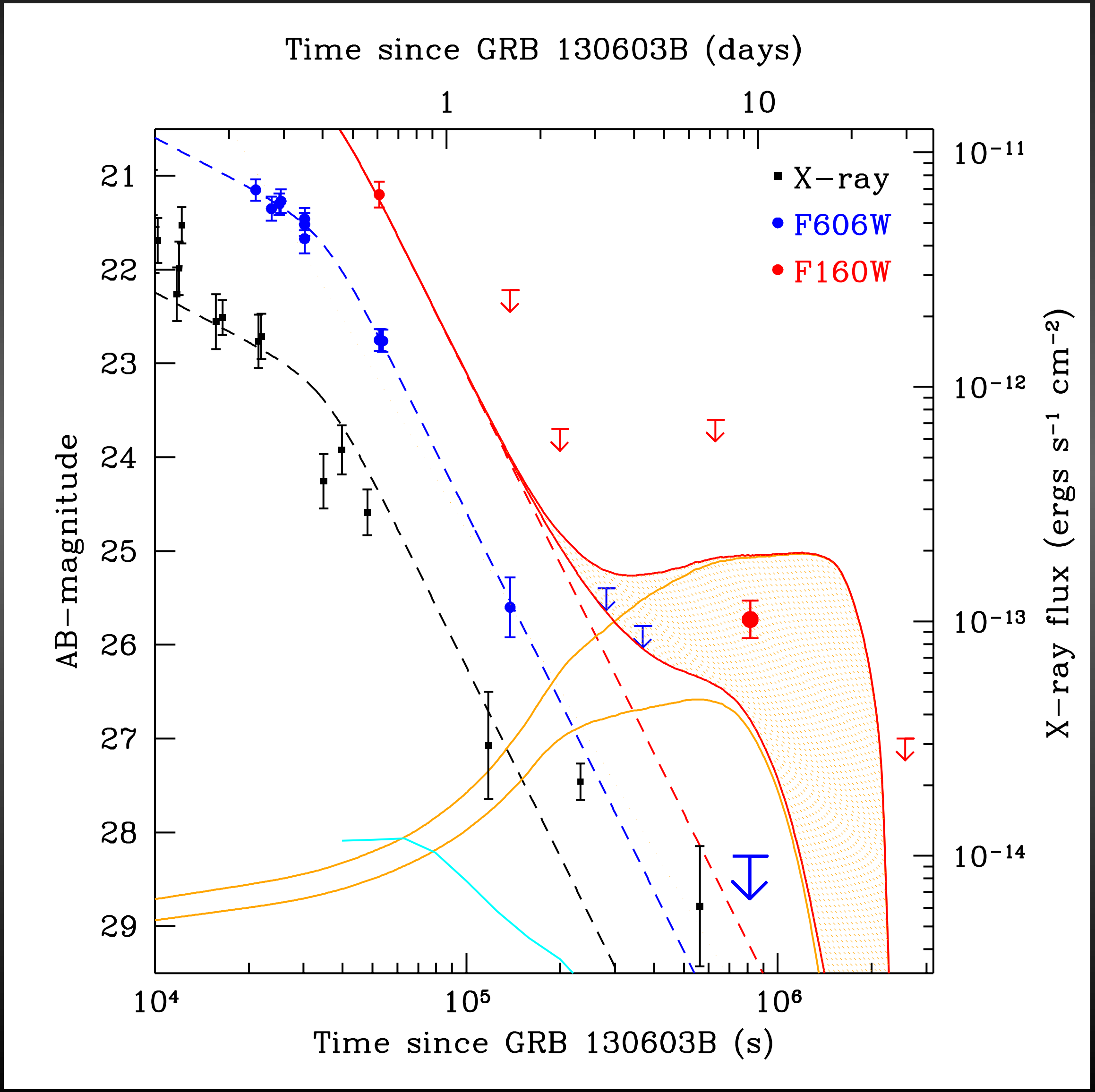


Transient emission seen in near-infrared in *HST* imaging at 9 days post-burst.



Consistent with high opacity line-blanketing of optical light.

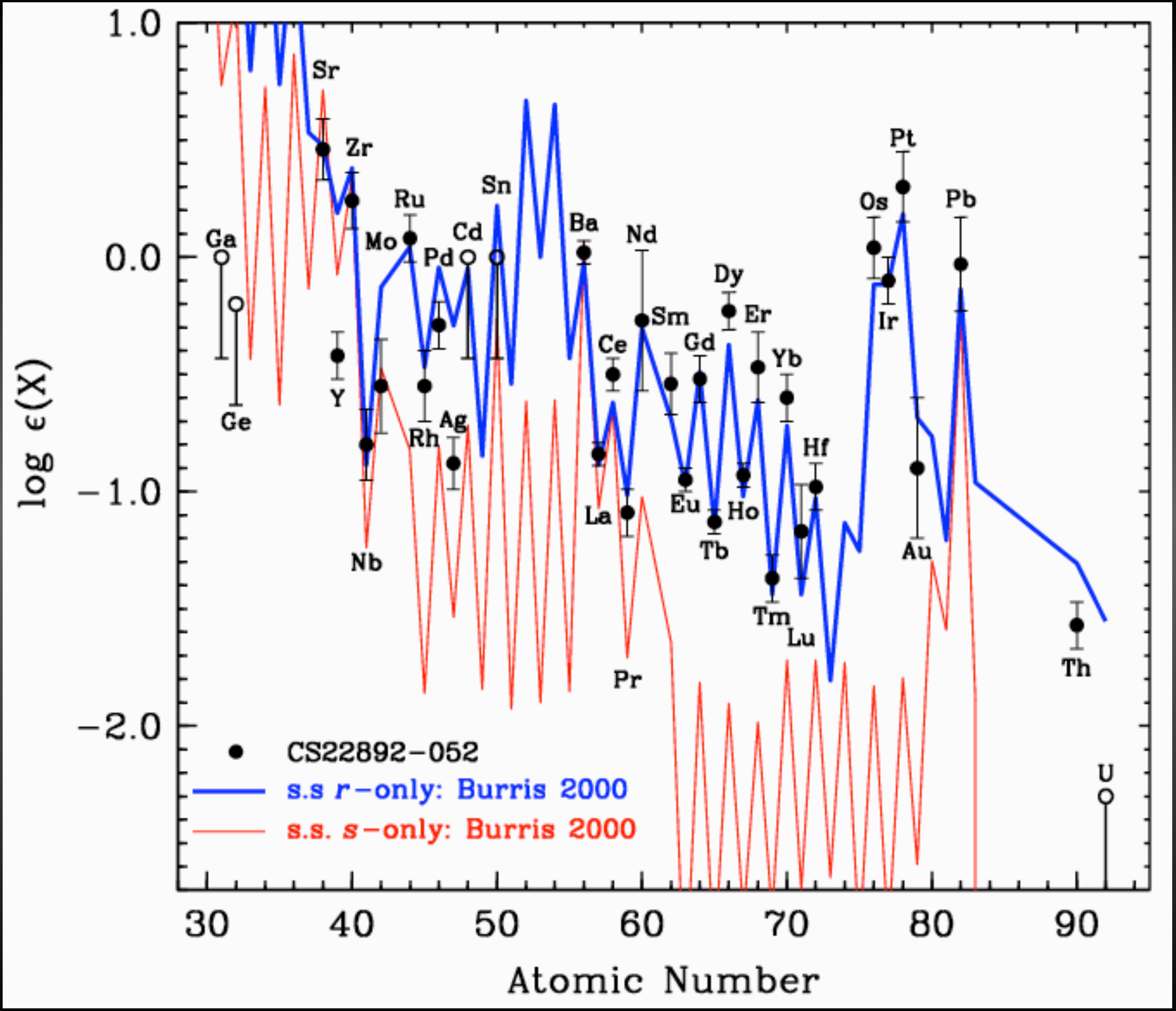
GRB 130603B



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

Rather high, compared to recent simulation predictions, but many uncertainties e.g. emission could be boosted by being seen "pole on" (e.g. Grossman et al. 2014), or system may be NS~BH.

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



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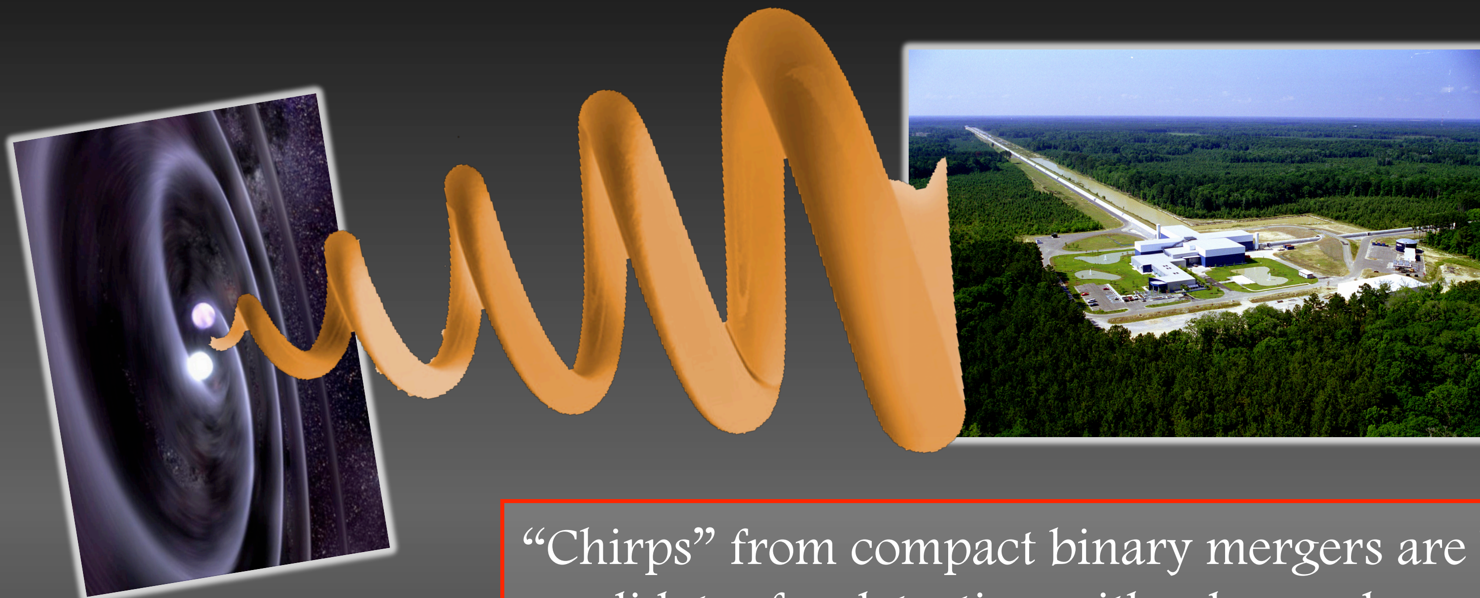
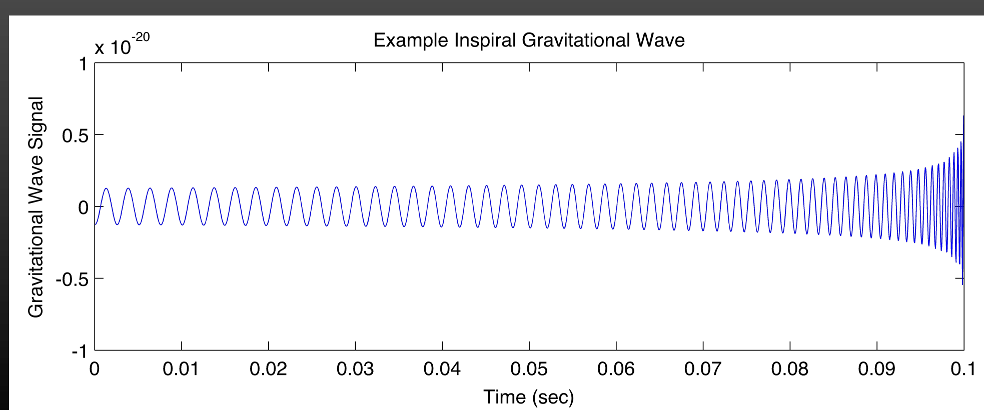
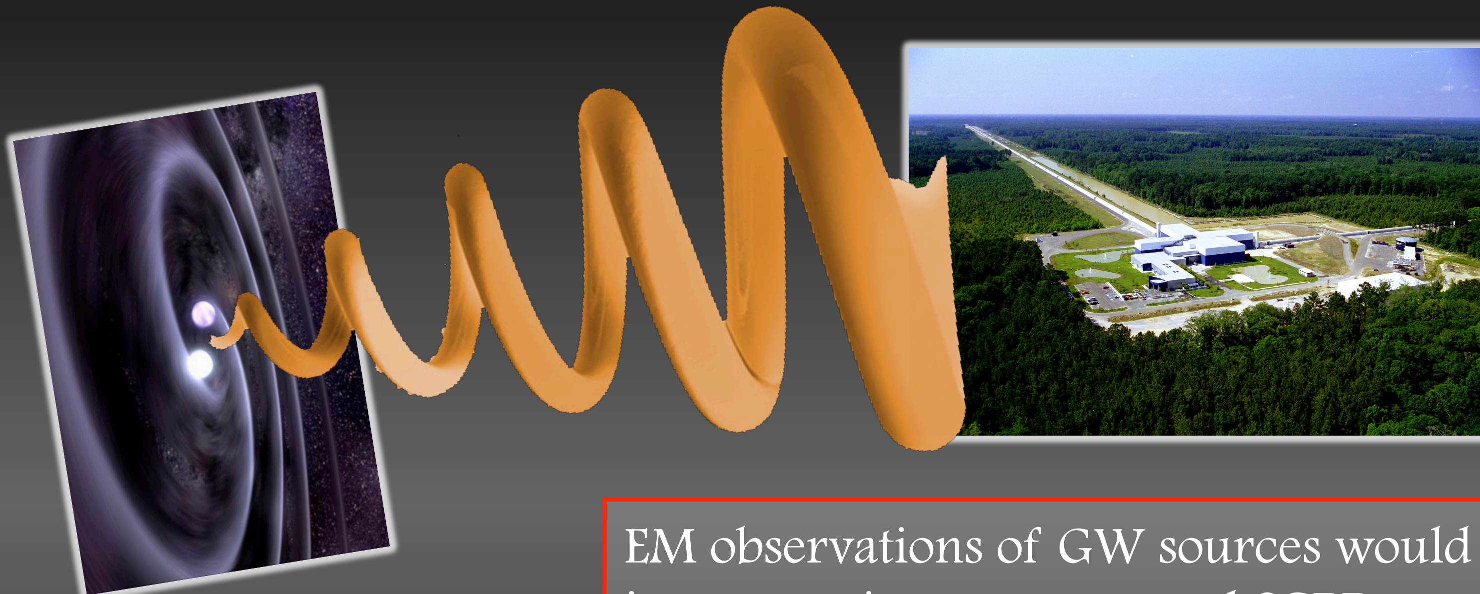
Short-hard GRBs- prospects for GW



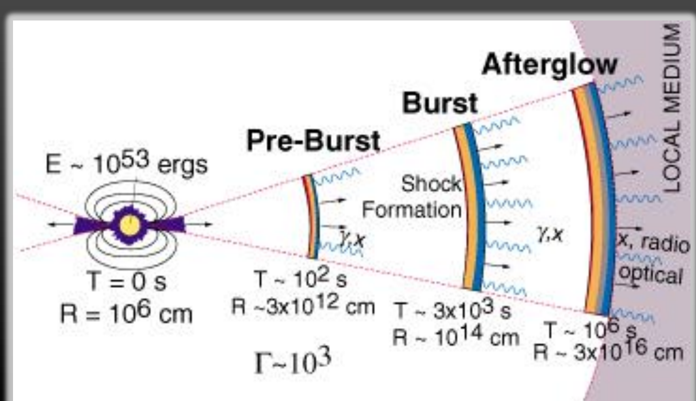
"Chirps" from compact binary mergers are best candidates for detection with advanced generation of gravitational wave detectors, from ~mid-2015.

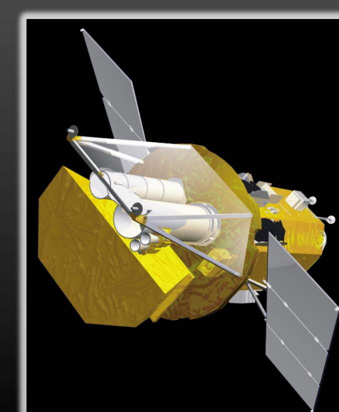


Short-hard GRBs- prospects for GW



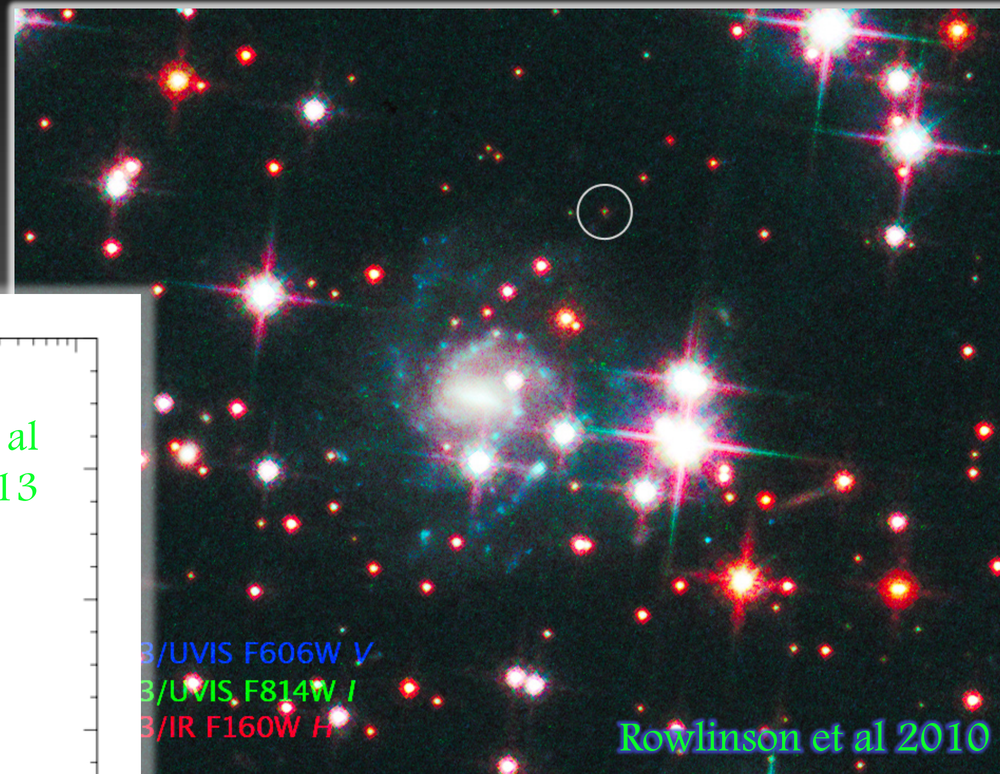
EM observations of GW sources would greatly increase science return, and SGRBs could be the signatures of compact binary mergers, but…

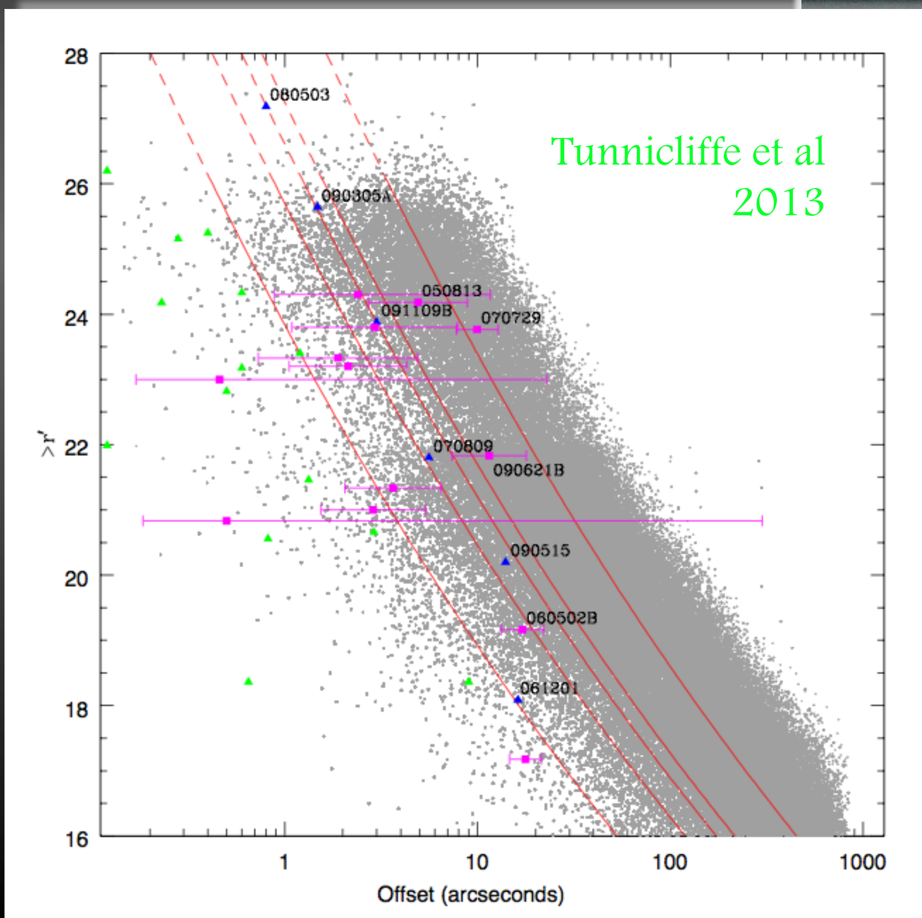




Short-hard GRBs~ rates

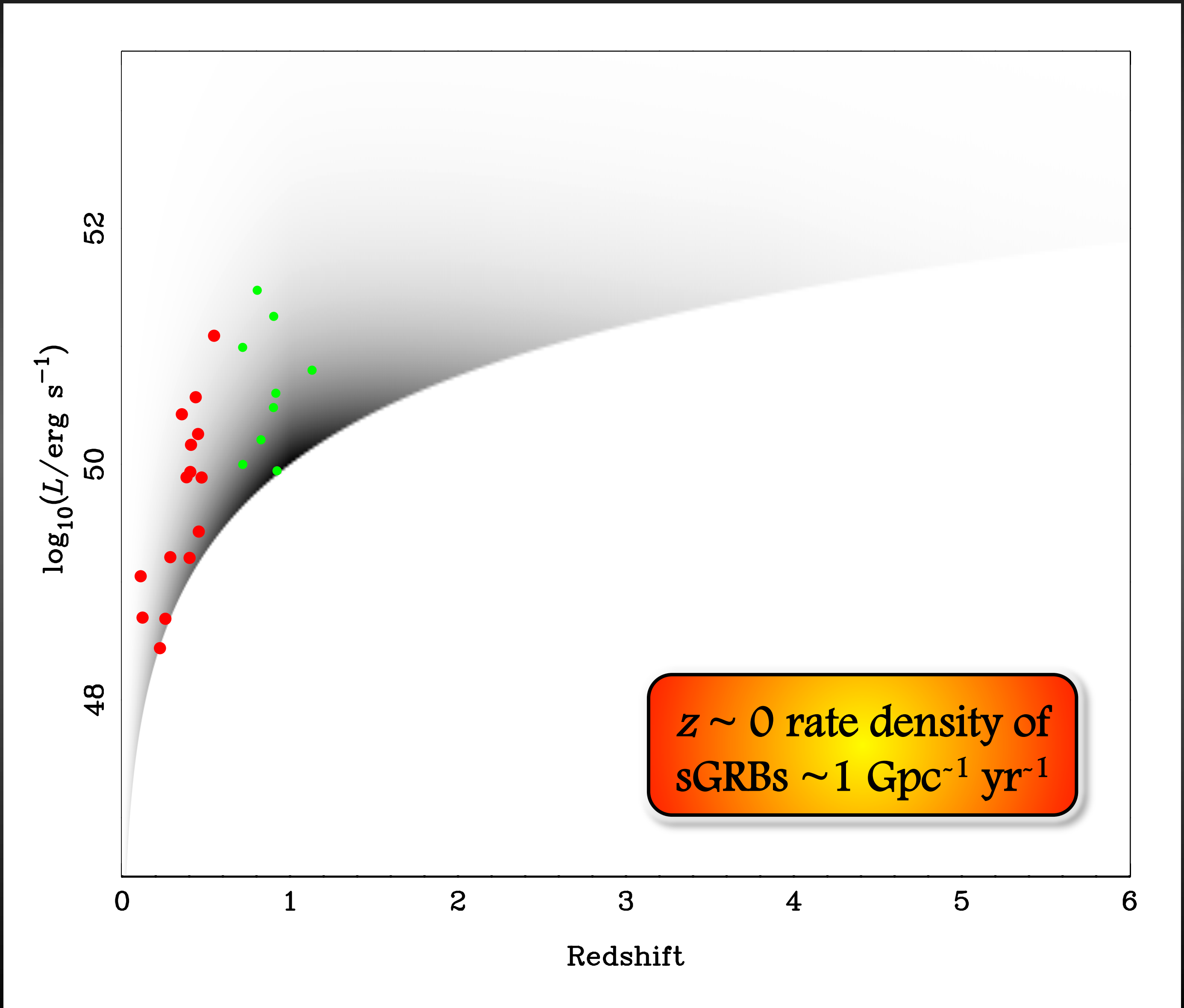
Nearest SGRB so far found by *Swift* is GRB 080905A at $z = 0.12$ (~500 Mpc)





Hostless shorts also do not appear to be at lower redshifts, since most probable hosts are typically also faint galaxies.

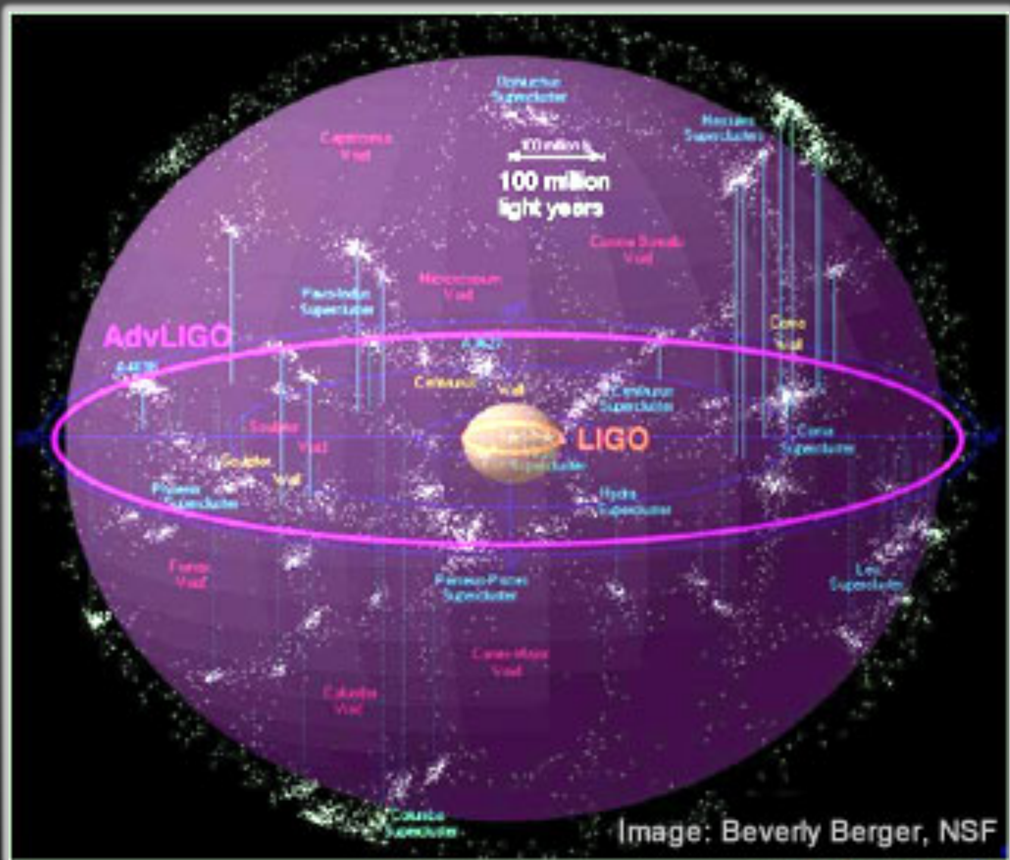
Short-hard GRBs- rates



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- horizons

For NS-NS ultimate (sky and orientation averaged) horizon of Advanced detectors is ~200 Mpc (larger for NS-BH).



Suggests prompt detections with *Swift* or other satellites will be rare (~1 per decade) – helped somewhat if timing coincidence produces sub-threshold detection (either EM or GW).

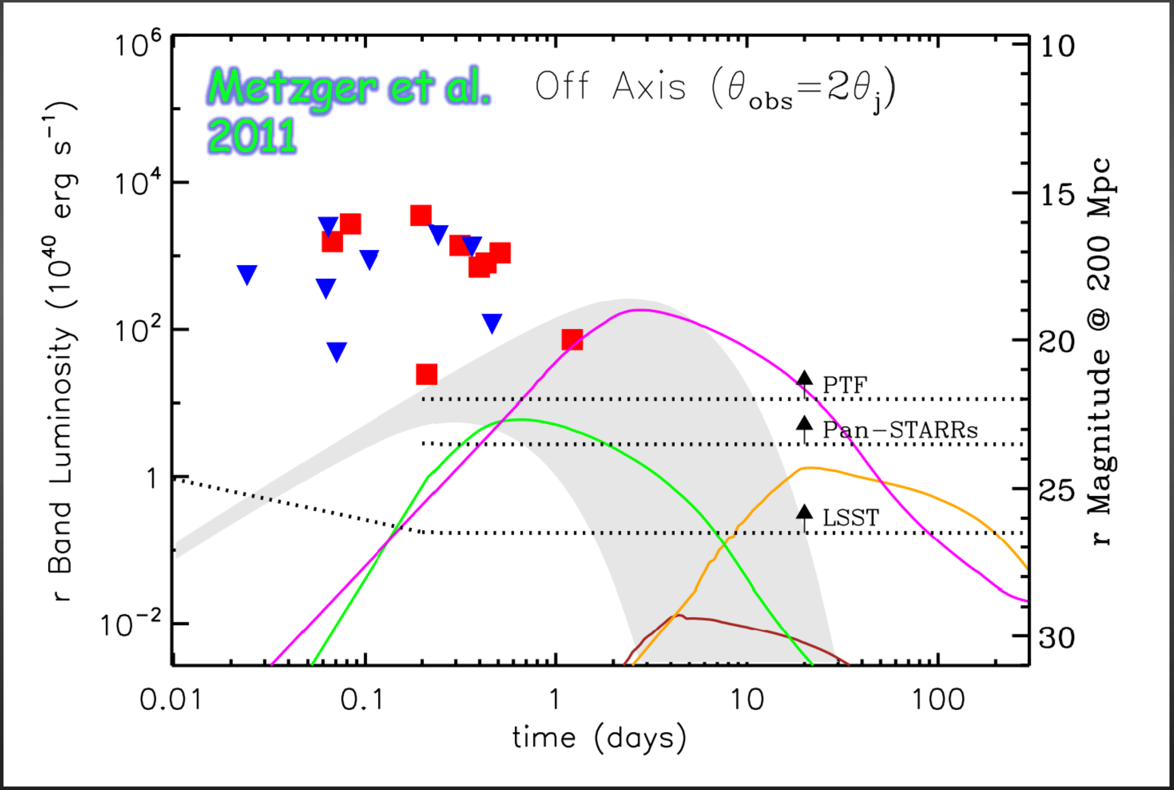
Why such low rate density? May be beaming of SGRBs - poorly constrained, but $f_b > 100$ is plausible.

Short-hard GRBs- faint afterglows

What about afterglow emission if not prompt? On-axis events similarly rare. Off-axis implies faint, late optical afterglows which may be hard to identify.

The intrinsically brightest, the least far off axis and the nearest may be visible to modest telescopes.

e.g. at 100 Mpc, GRB 130603B would have peaked M_{AB}~15.

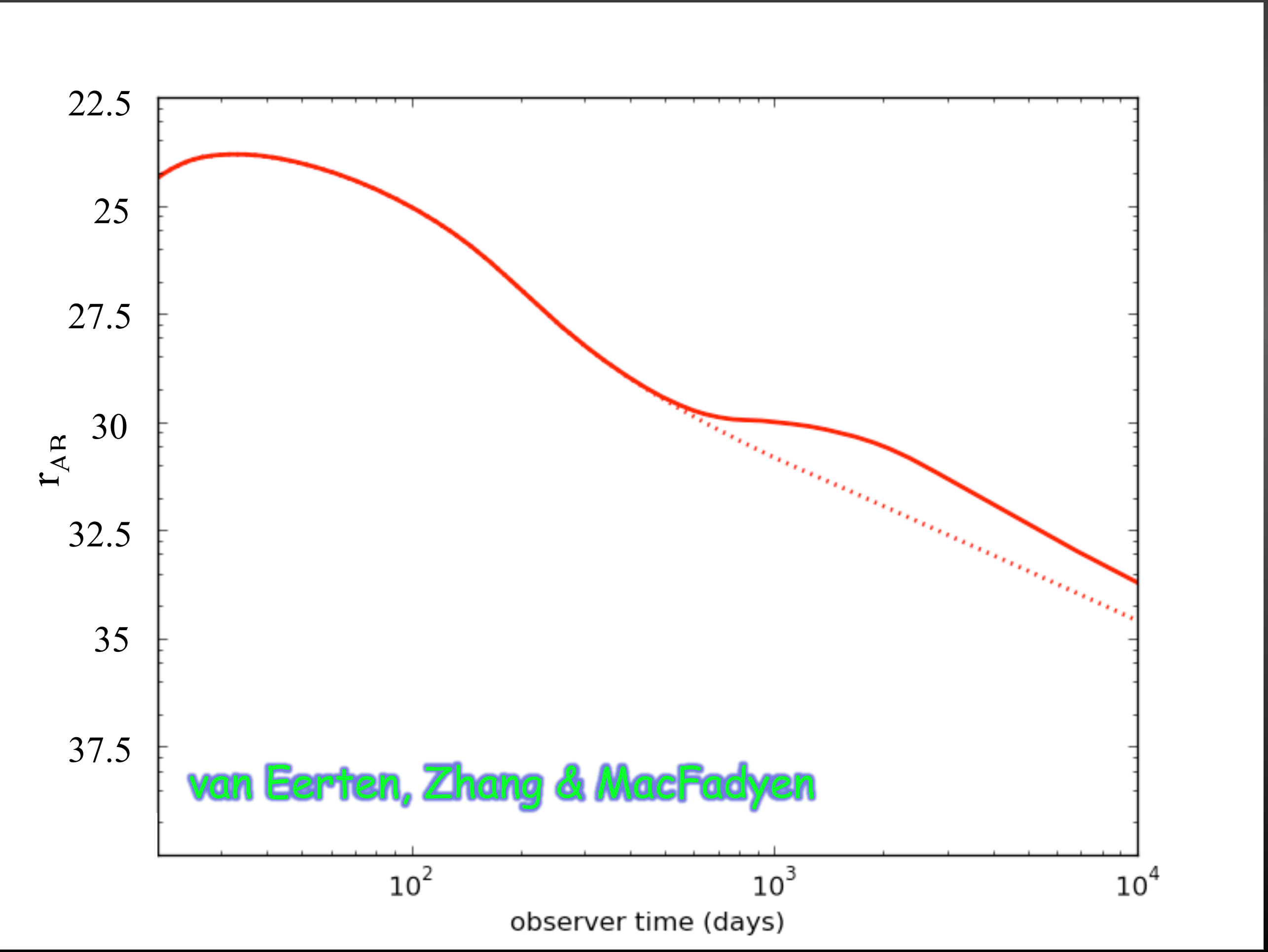


Short-hard GRBs- faint afterglows

More typically will require large aperture, large camera telescopes (e.g. LSST) to give good prospects for significantly off-axis emission.

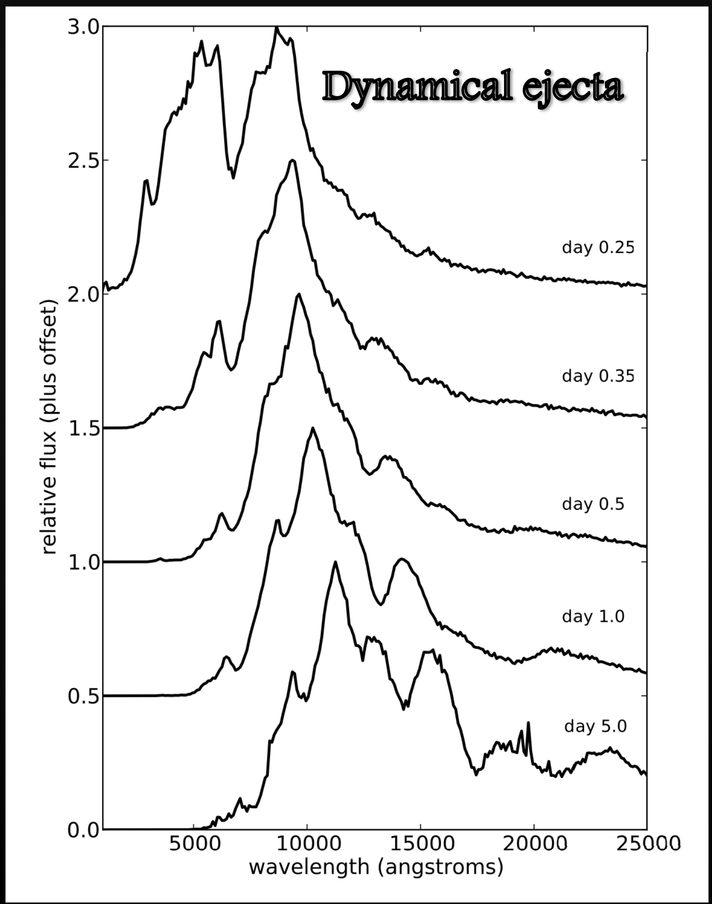
Same example, and assuming a 10° jet opening angle and observing and 35° to line of sight (n =1 cm^{-3}).

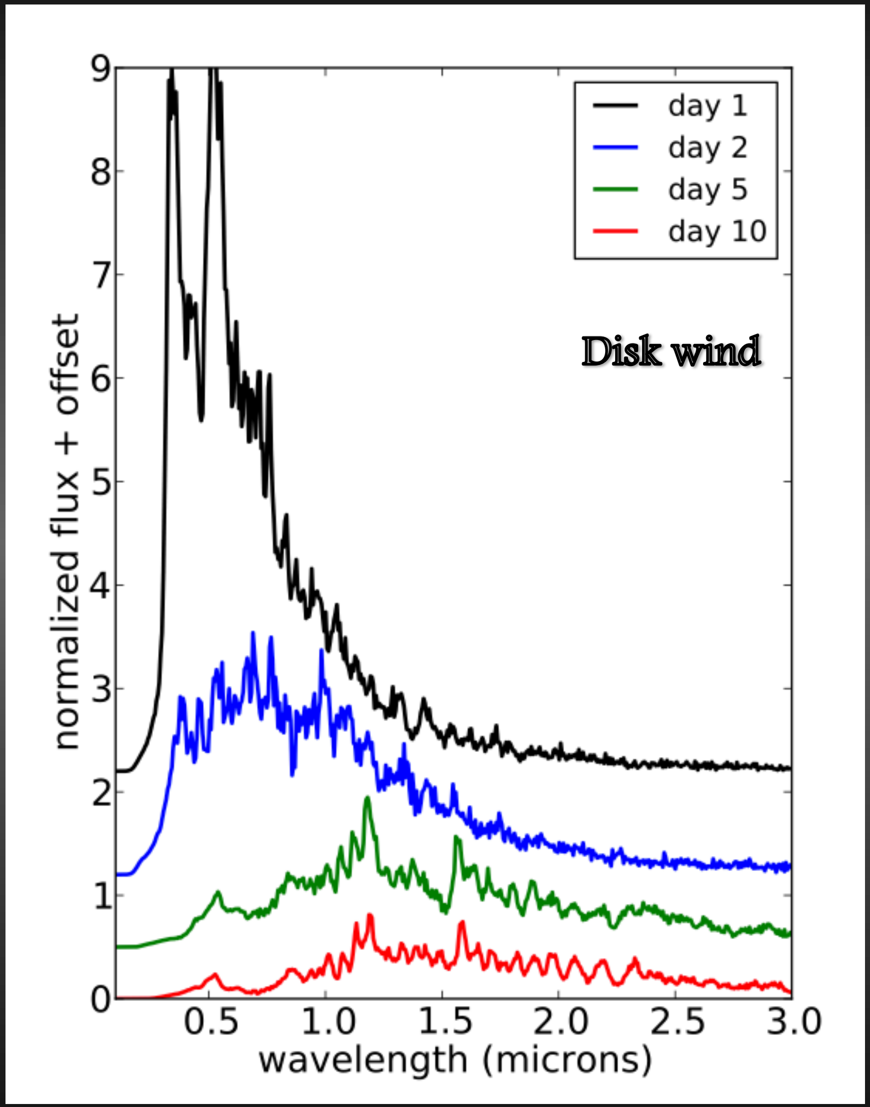
Viable, but hard even in optimistic case (and rate only increased by ~10x).



Next steps: basic characterisation

Near SGRBs would provide further opportunities to monitor light curves and spectra of KN emission.

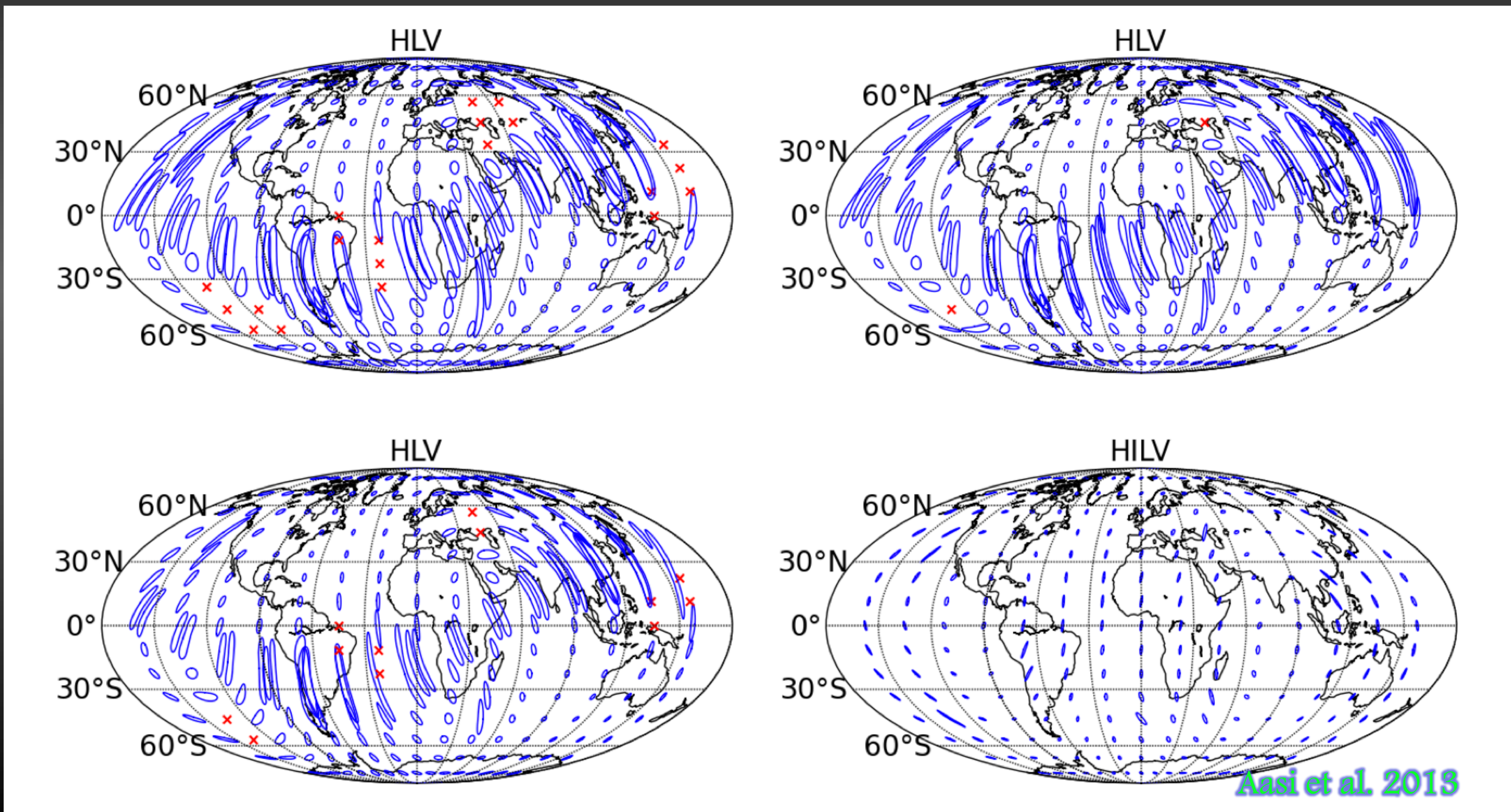




Kasen et al 2013; 2014

Next steps: monitoring of aLIGO error regions

KN emission likely to be roughly isotropic and environment independent.



Scanning for kilonova signatures

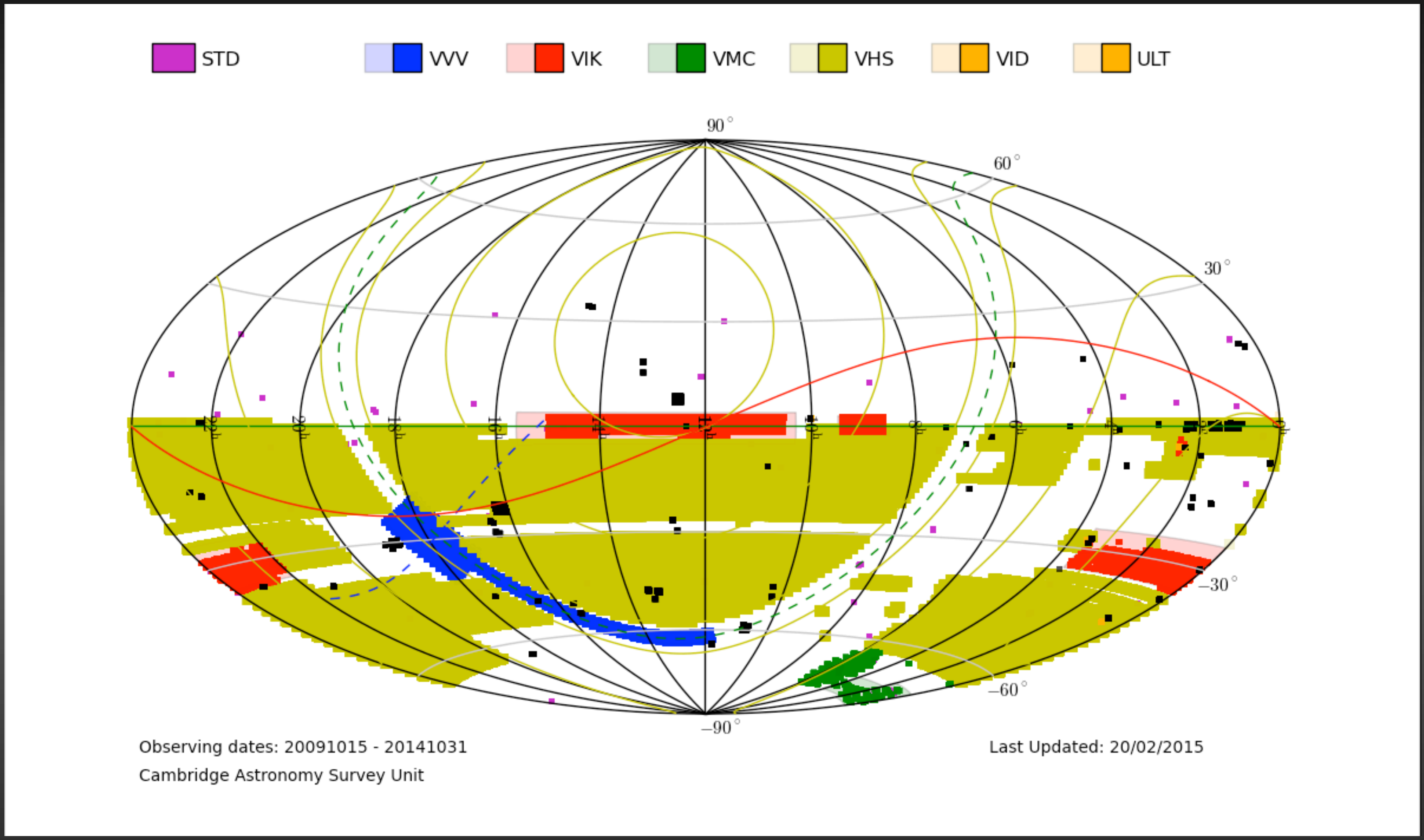
Network	BNS Horizon	Typical error region
Early aLIGO/AdV (2016)	60~100 Mpc	100 □°
Full Advanced Network (inc. India; 2022)	130~200 Mpc	20 □°

Telescope	Time to scan 100 □°	Time to scan 20 □°
VISTA	7 hr, reaching $J_{AB} = 20$	21 hr, reaching $J_{AB} = 21.5$
LSST	3 hr, reaching $z_{AB} = 24$	8 hr, reaching $z_{AB} = 25.5$

Exposure times required to reach S/N=15 σ (assuming GRB130603B is typical). Strategies likely to require multiple filters and possibly multiple visits.

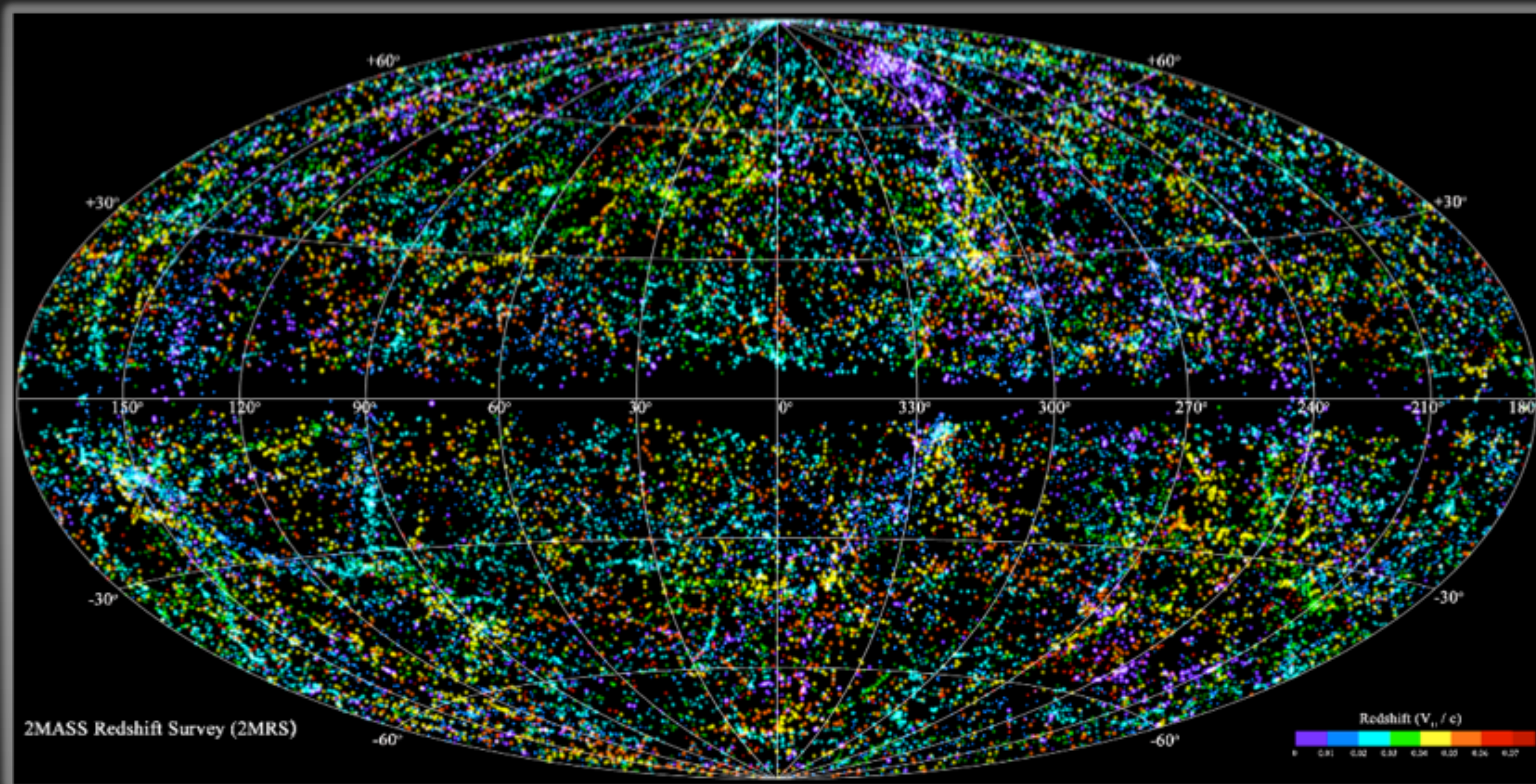
=> Viable over several nights, but demanding. Also requires further followup (spectra, light curves, host searches) to weed out false positives.

Scanning for kilonova signatures



VISTA Hemisphere Survey provides a good source of prior imaging to suitable depths. Candidates followed up with e.g. GROND to obtain SED and light curves – comparatively rapid colour evolution may be signature + plausible host.

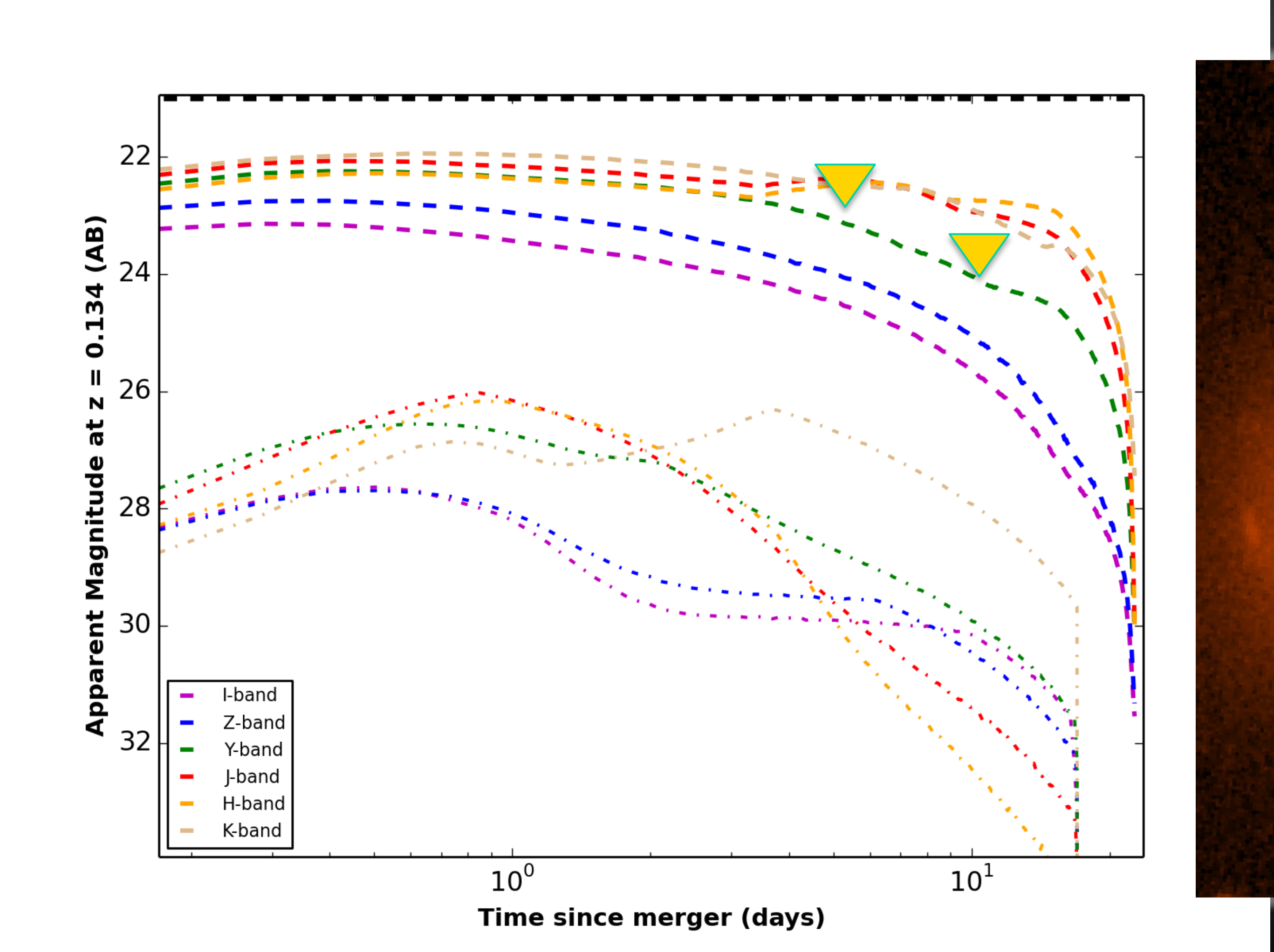
Scanning for kilonova signatures

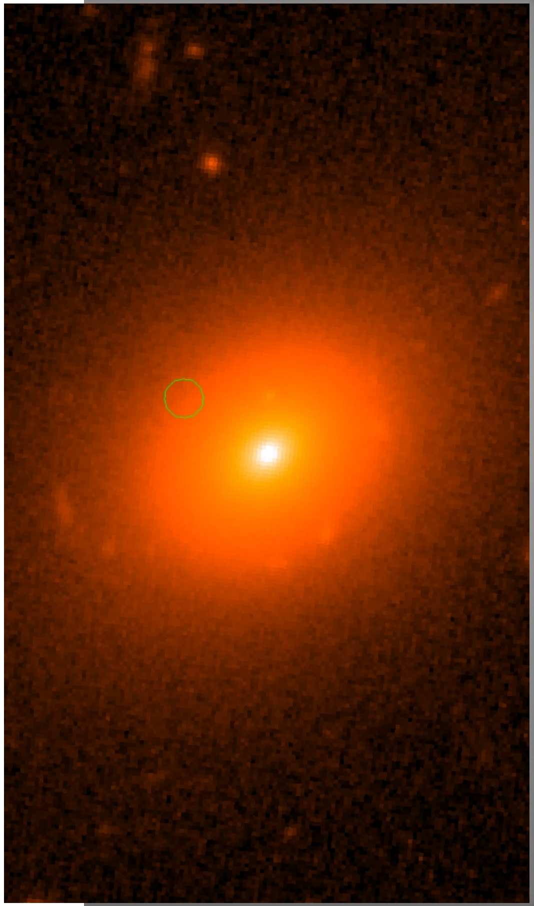


Strategy to prioritise highest likelihood and high galaxy density regions.

GRB 150101B

Unusual, very short (but soft) GRB, likely in outskirts of a z~0.13 elliptical – but status is far from clear!





Conclusions and prospects

- Compelling evidence that compact object mergers produce both sGRBs and r-process kilonovae.
- Electromagnetic signatures therefore include prompt emission, afterglow emission and radioactive emission.
- Best prospects for electromagnetic detection may be near-IR searches for accompanying kilonovae, and optical searches for faint off-axis afterglow emission.
- Further KN studies required to understand range of behaviour (early bright optical?).
- Outflows (both relativistic and not) should also produce longer-lived, late-time radio emission, which may also be detectable (e.g. Nakar and Piran 2011).
- Searches of GW error regions will require significant dedicated follow-up and effort in chasing down false positive detections.
- Blind surveys for KNe may be possible e.g. with LSST.