Observations of short Gamma-Ray Bursts and future prospects

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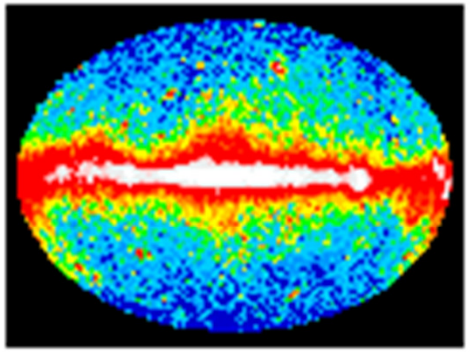
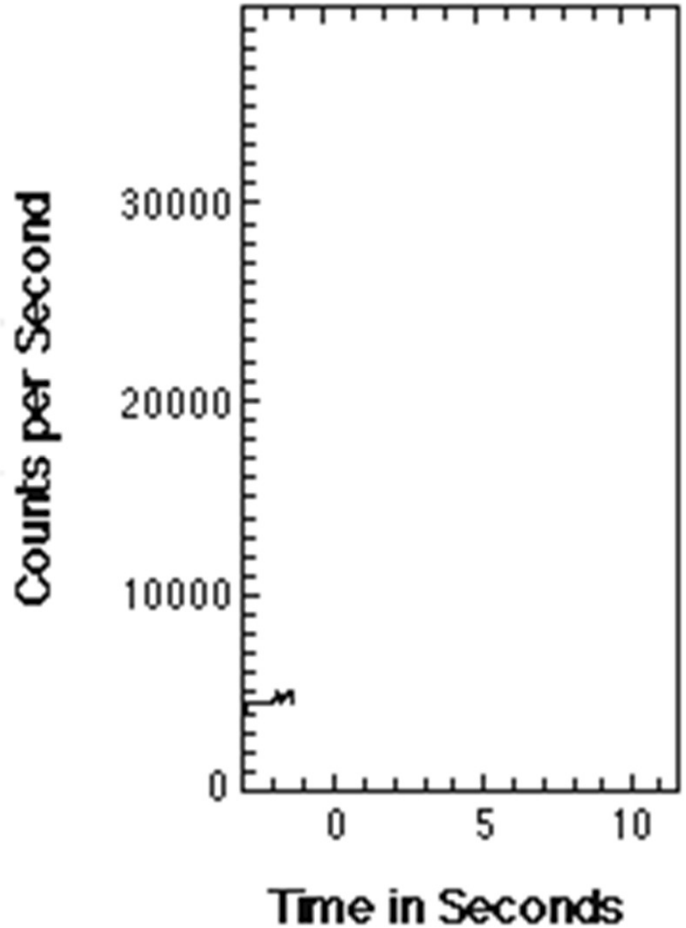
(with thanks to Antonia Rowlinson, Nicola Lyons, Ben Gompertz, Rachel Tunnicliff, Bing Zhang, Julian Osborne and Weimin Yuan)

Overview

- Gamma Ray Bursts
- Short GRBs
- Magnetars?
- Future options





1963 – partial test ban treaty

Opened for signature: 5 August 1963.

Entered into force: 10 October 1963.

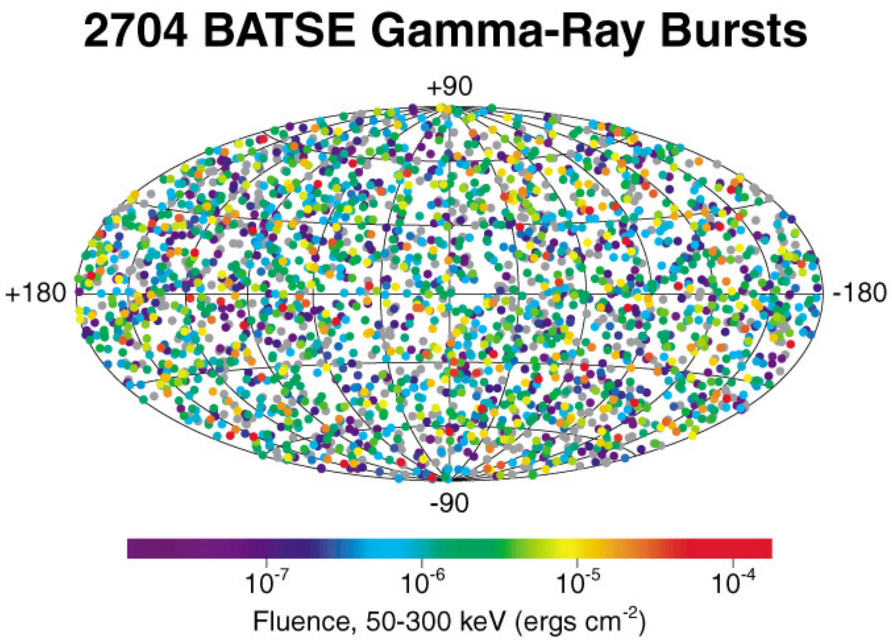
Duration: The Treaty is of unlimited duration.

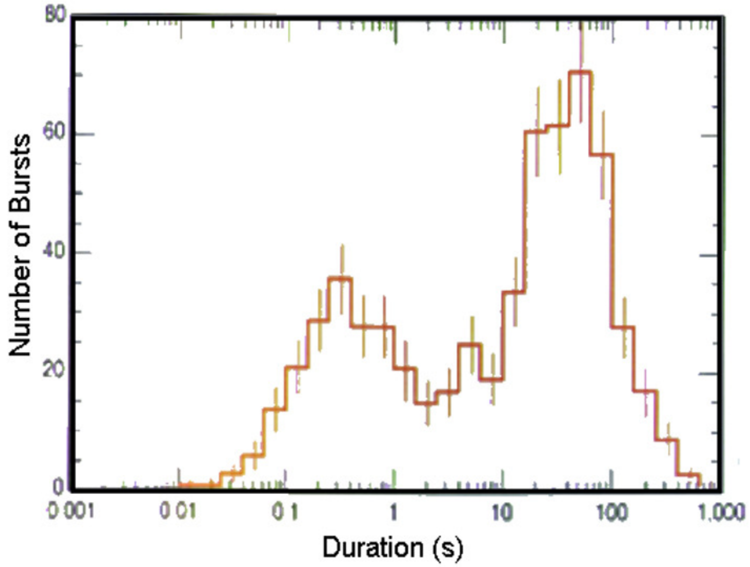
Number of Parties: 131 States.

Treaty Obligations: The Treaty requires Parties to prohibit, prevent, and abstain from carrying out nuclear weapons tests or any other nuclear explosions in the atmosphere, in outer space, under water, or in any other environment if such explosions cause radioactive debris to be present outside the territorial limits of the State that conducts an explosion; to refrain from causing, encouraging, or in any way participating in, the carrying out of any nuclear weapon test explosion, or any other nuclear explosion, anywhere which would take place in any of the above-described environments.

Led to discovery of GRBs using Vela satellites by Klebesadel et al. (1973)

CGRO/BATSE (1991-2000)



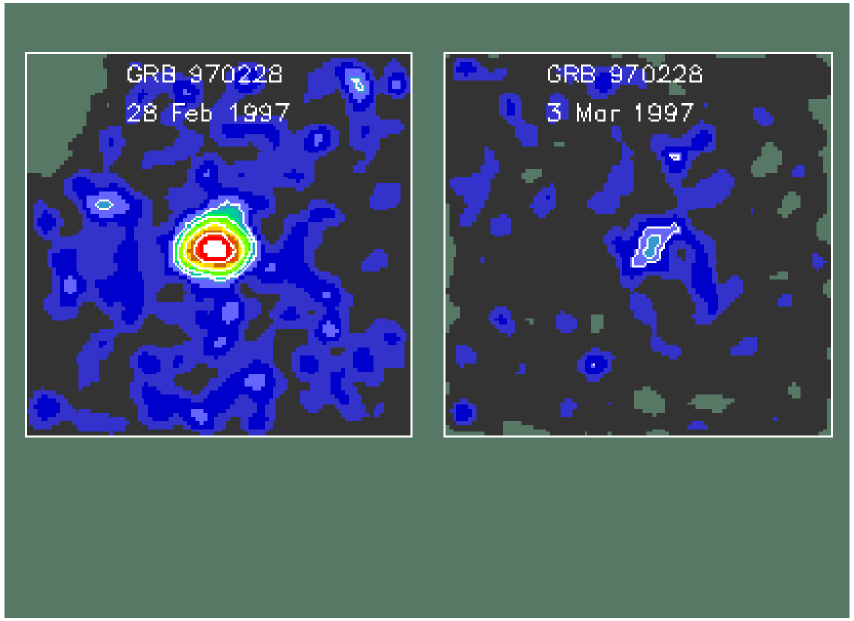


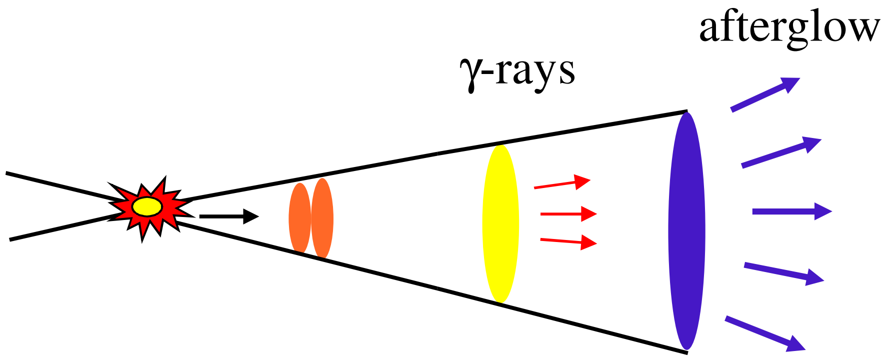
- Not along Galactic plane
- Likely cosmological origin

Double-peaked distribution of durations (split at T90 ≈ 2s)

- Short, faint, hard bursts
- Long, bright, soft bursts

GRB 970228: First X-ray afterglow detected





Fireball-shock Model

(Meszaros & Rees 1997)

Need Lorentz factors $\Gamma > 100$

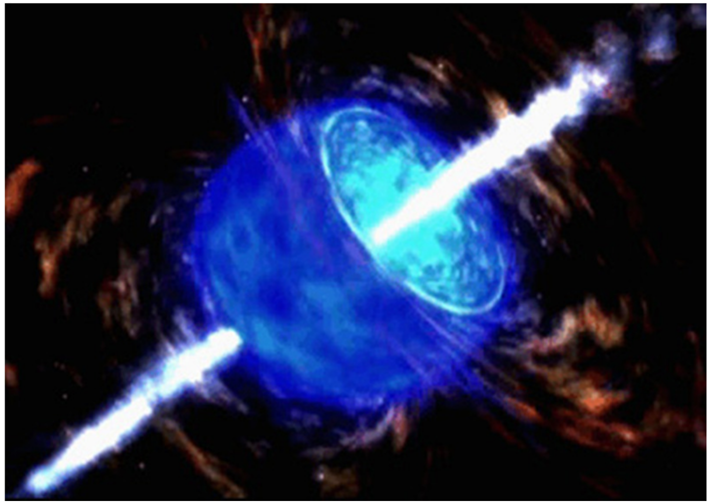
<u>All</u> bursts with known redshifts (several hundred) are cosmological

Mean observed redshift z~2.2

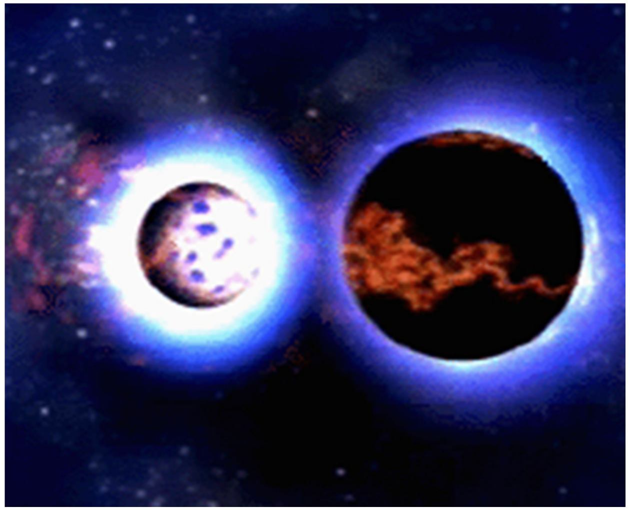
"Beaming-corrected" luminosities of 10^{51} to 10^{52} erg?

(uncertain, but if jets are very wide we are in big trouble...)

Collapsar – LGRBs



Binary Merger – SGRBs

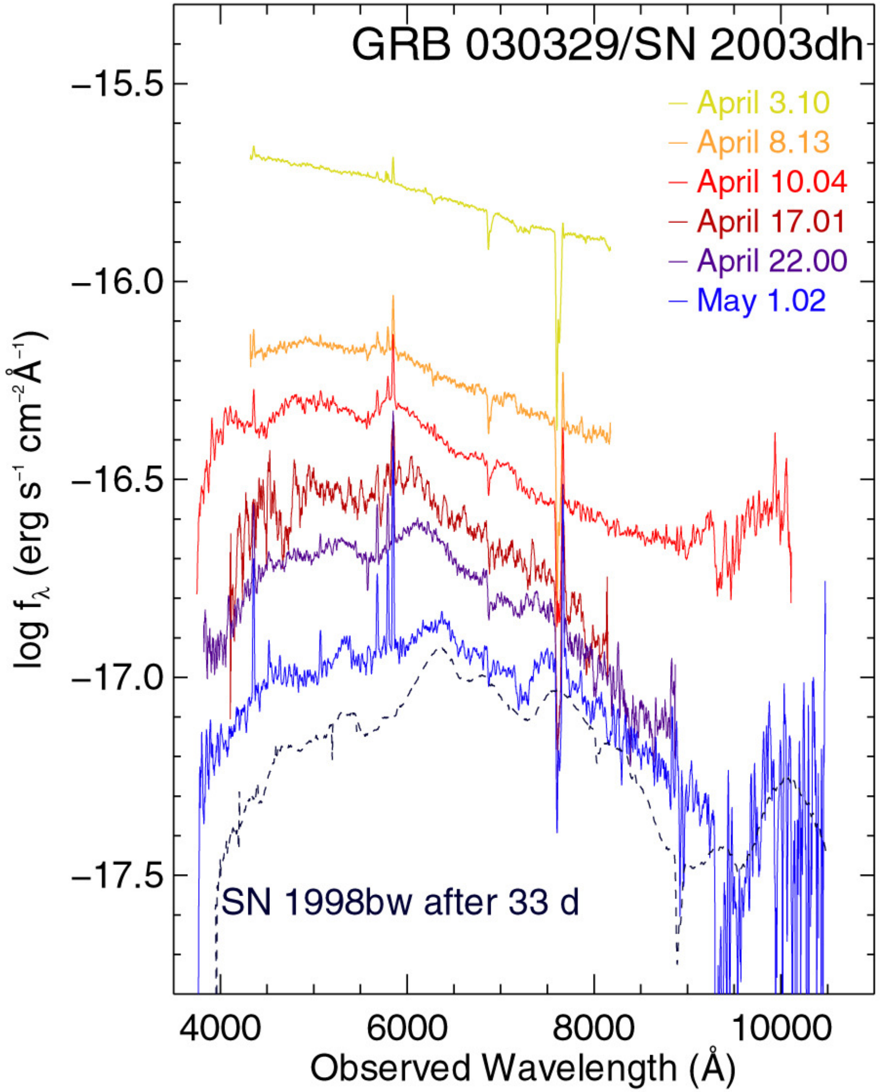


LGRB: Collapsar model – occurs in region of massive (hence recent) star formation

SGRB: Merger model (e.g. NS-NS) – can occur in any type of galaxy, and also off of a galaxy due to natal dynamic kick and long merger time

Other models are available…

GRB 980425/SN 1998bw (z=0.0085)
GRB 030329/SN 2003dh (z=0.17)



GRB associated SNe are broad line type Ic.

[ccSN that have lost their H and He envelopes prior to the supernova – helps jet escape?.]

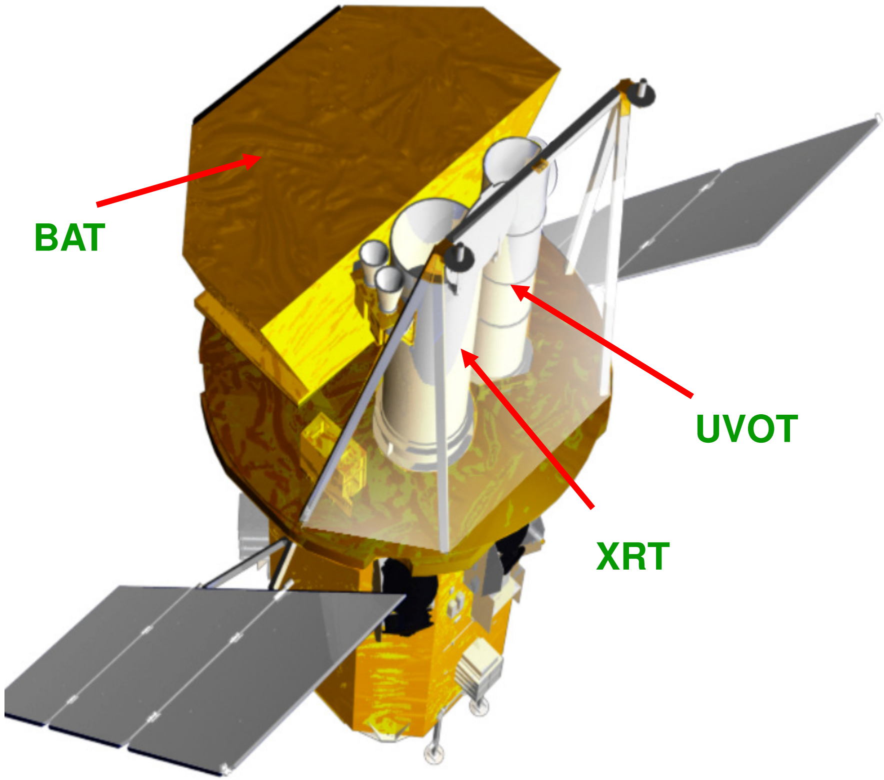
High expansion velocity (30,000 km/s), x3 larger than typical Ic SNe.

(Hjorth et al. 2003)

The Swift GRB Explorer

"Catching Gamma Ray Bursts on the Fly"

University *of* Leicester

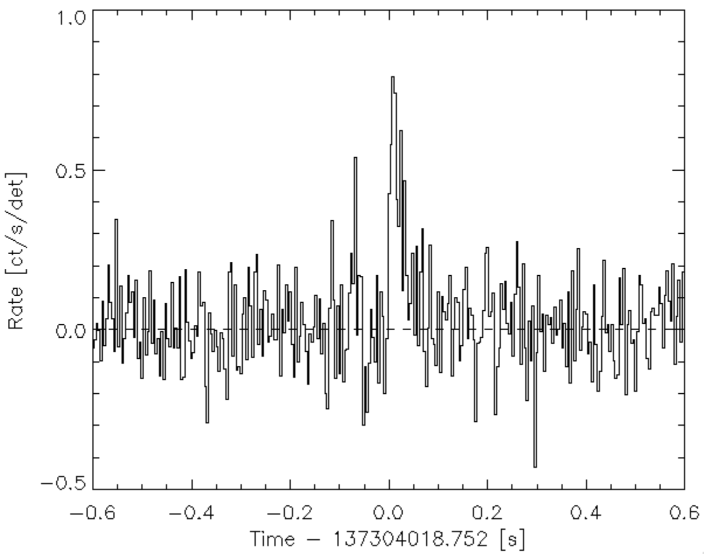


- Burst Alert Telescope (BAT)
  - CdZnTe detectors (32768)
  - Detect ~95 GRBs per year
- X-Ray Telescope (XRT)
  - Arcsecond GRB positions
  - CCD spectroscopy
- UV/Optical Telescope (UVOT)
  - Sub-arcsec imaging
  - Grism spectroscopy
- Autonomous operation with very fast slew (~1^{o} second^{-1})
- Launched 2004 November 20 Orbital lifetime to ~2025?

Swift is the only rapid, accurate GRB localisation space facility

First Swift short GRB 050509B

Gehrels et al. (2005)



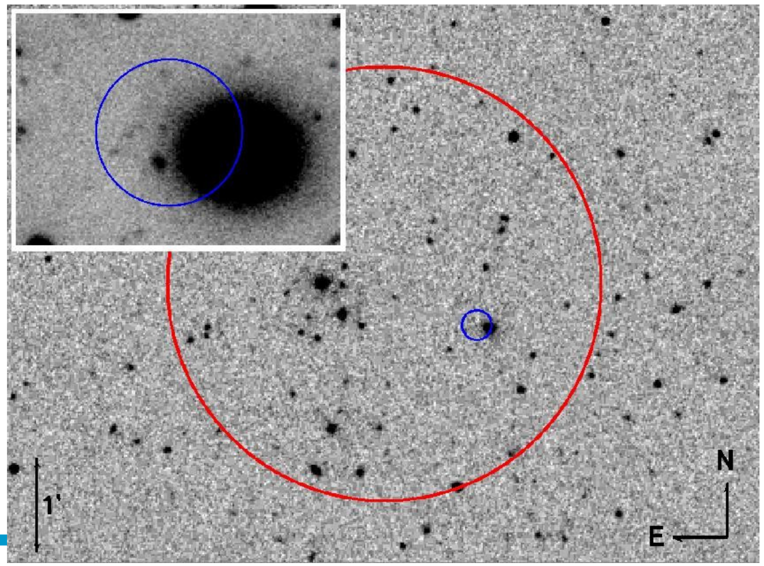
BAT
- 30 ms duration
- spectrum is medium hard
- very weak, 2×10^{-8} erg/cm^2

Spacecraft slew in 52 sec

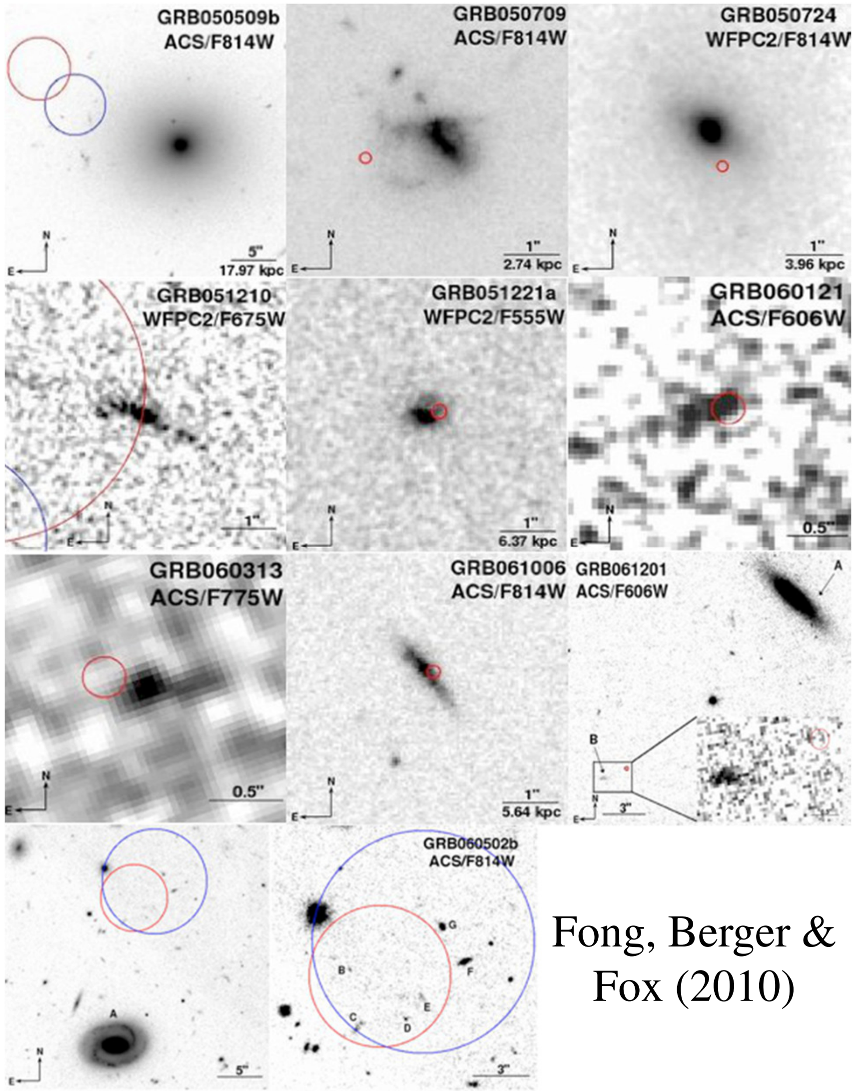
XRT
- faint source, fading
- 11 cnts = 1×10^{-12} erg/cm^2/s

Proposed host:
- cD Elliptical
- K = 14.1
- L = 3 L*
- z = 0.225
- SFR < 0.2 M_O yr^{-1}

VLT image
Hjorth et al.



Short GRB host galaxies



Fong, Berger & Fox (2010)

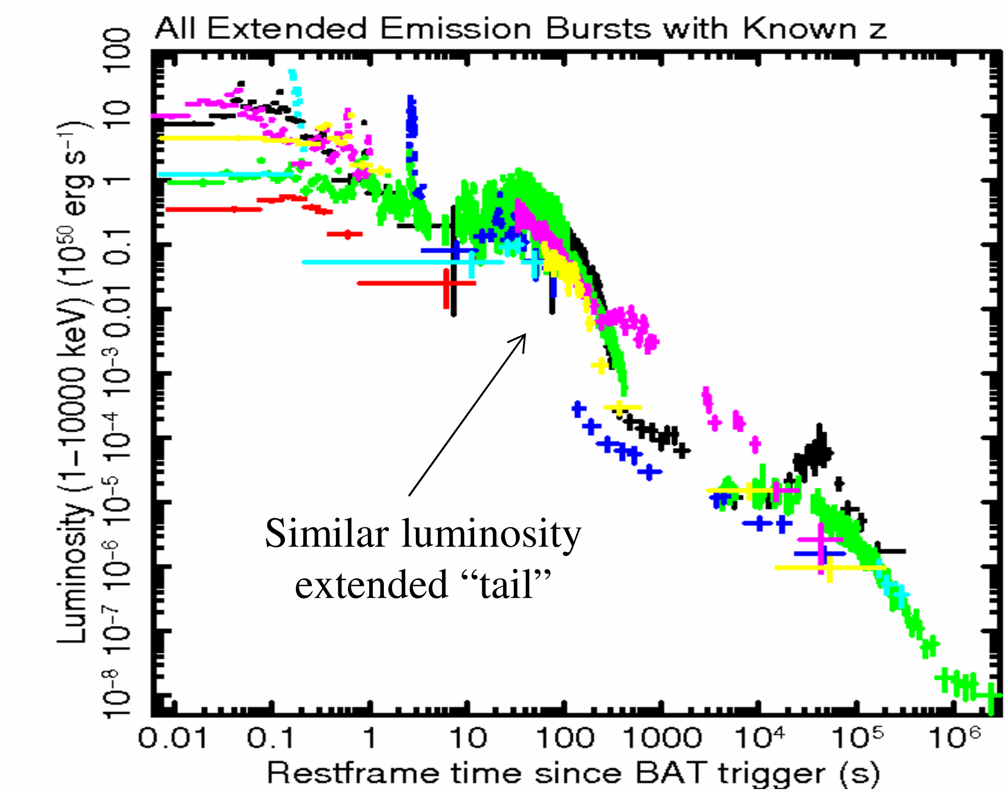
Range of stellar populations in host galaxies:

- some exclusively ancient (Berger et al. 2005, Gehrels et al. 2005, Bloom et al. 2005)
- some actively star forming (Fox et al. 2005, Levan et al. 2006)
- some have a mixture (Soderberg et al. 2006)

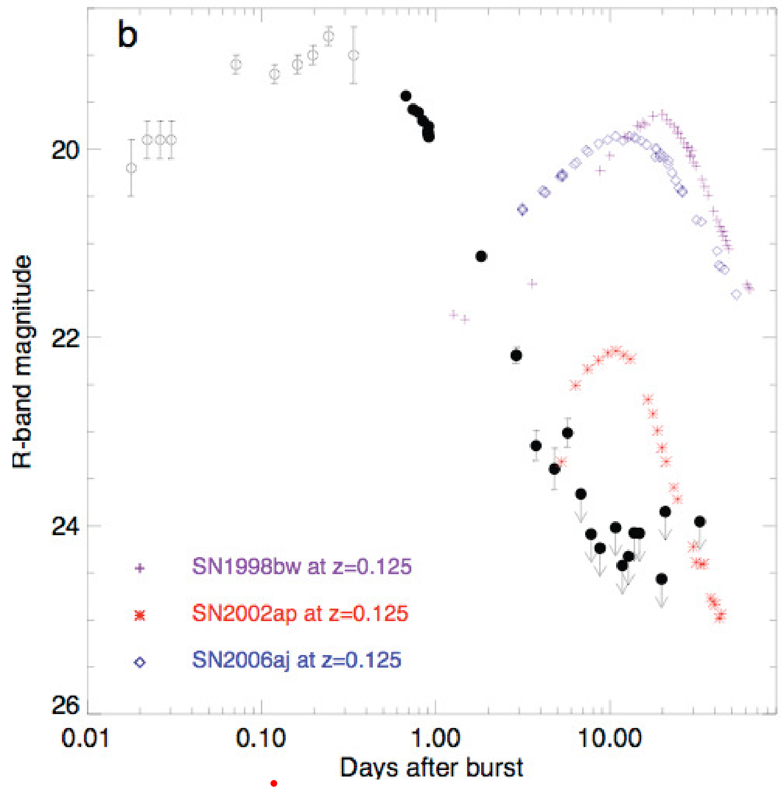
Most offset from host galaxy (Berger et al. 2005, Fox et al. 2005, Bloom et al. 2006, Troja et al. 2006, Church et al. 2011)

Caution: Some studies include T90>2s GRBs as short bursts

The long-shorts or short-longs

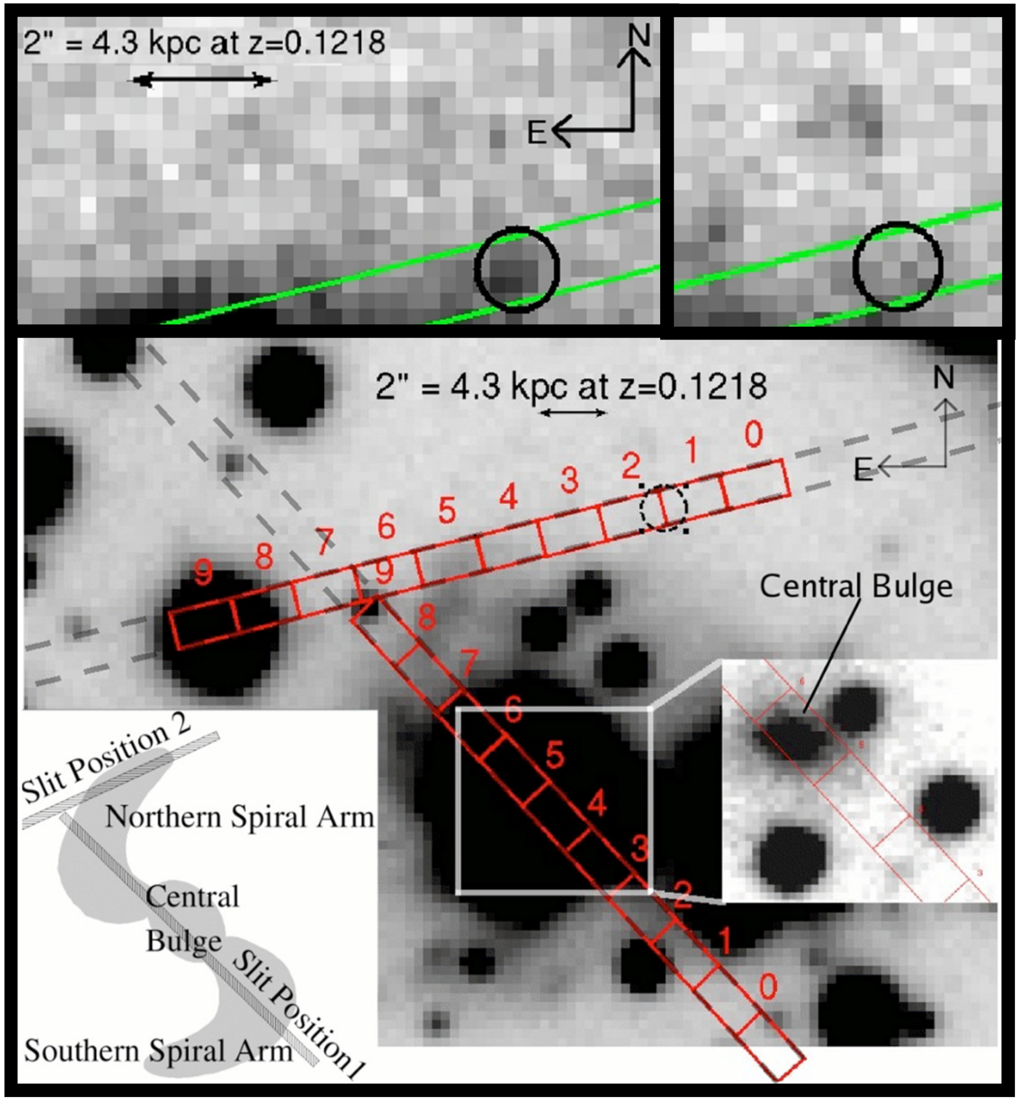


Gompertz, O'Brien et al. (2013)



GRB 060614, no SNe;
Fynbo et al. (2006)

GRB 080905A



Rowlinson et al. (2010a)

Afterglow:

R~24 at 8.5 hours

9" (18 kpc) offset from host

Chance alignment < 1%

Host:

Type S b/c

R~18

$M_{*,old}$ ~2x10^{10} $M_{\odot}$

At GRB location see:

higher metallicity

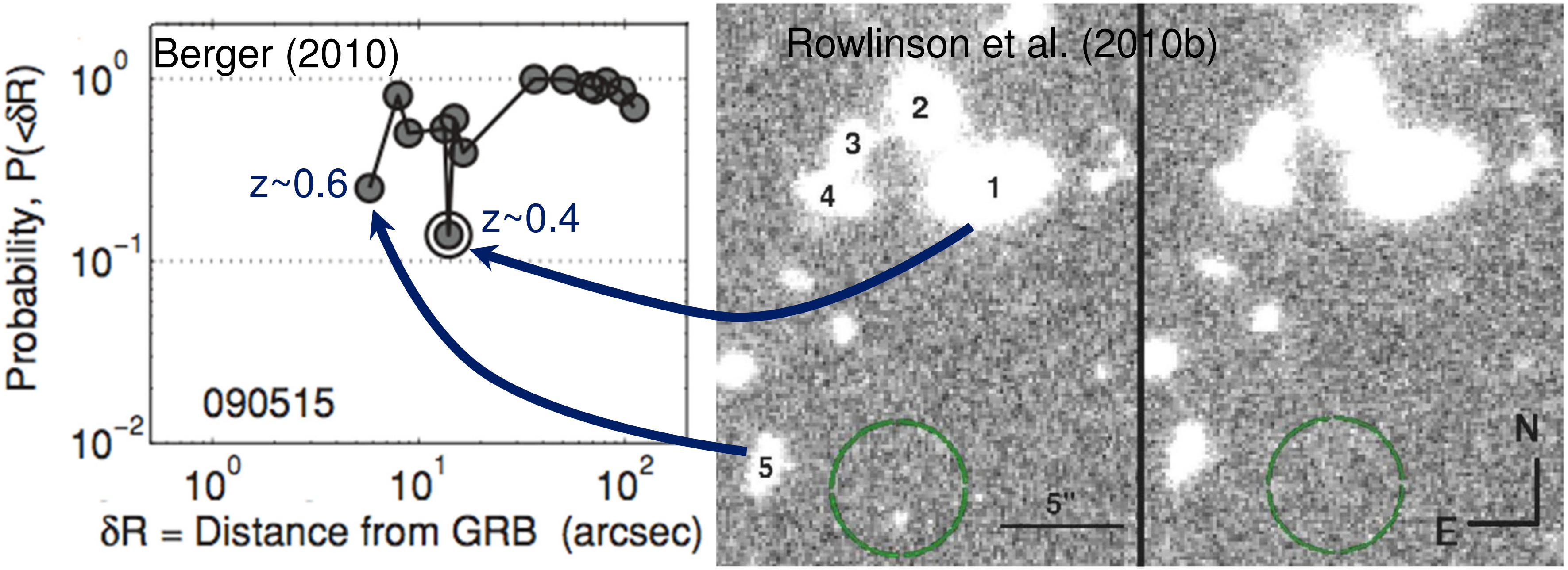
lower star formation

older population

“Hostless” short GRBs

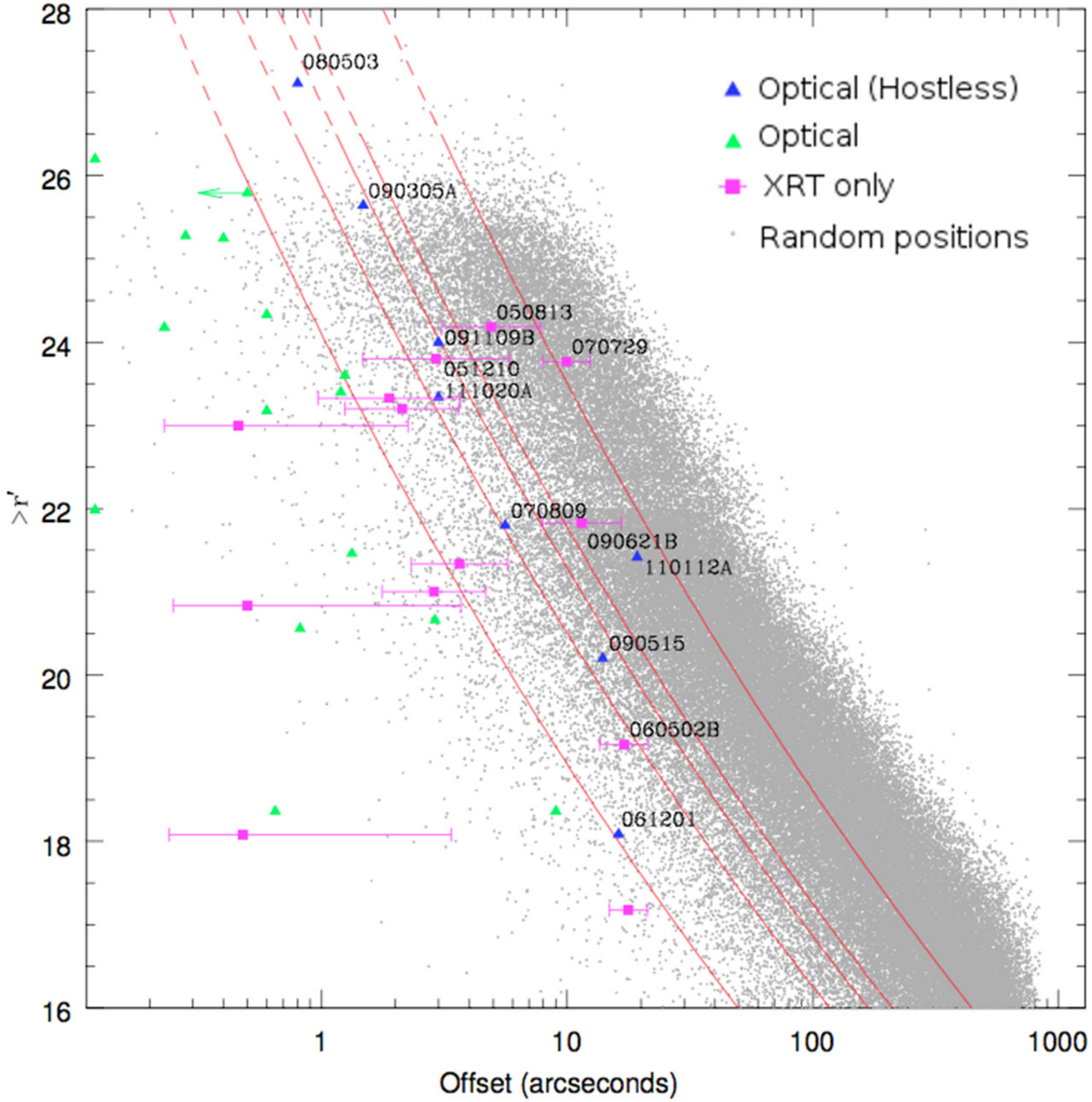
SGRB offsets make it very difficult to identify the host galaxies of some short GRBs

e.g. GRB 090515



Redshift by association

1, 5, 10,15, 50% chance probability



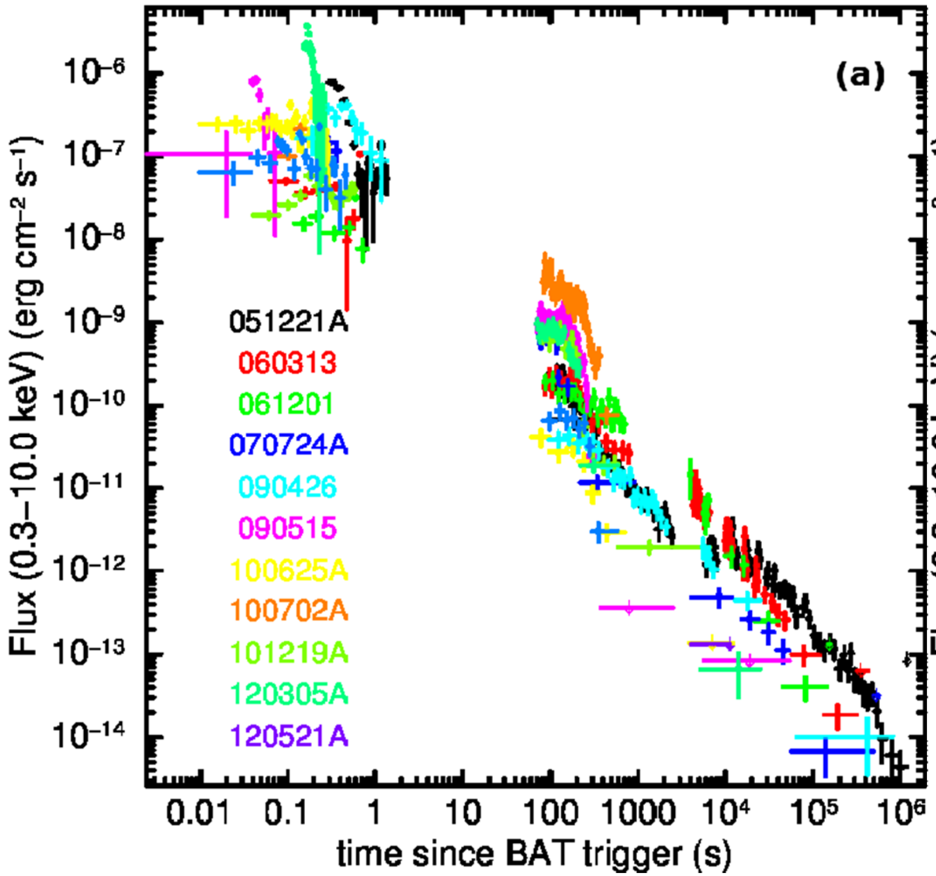
Plotted are the offsets and magnitudes of the galaxy with the lowest probability of chance alignment with the observed position

"Hostless" GRBs are consistent with being within the same redshift range as those with hosts.

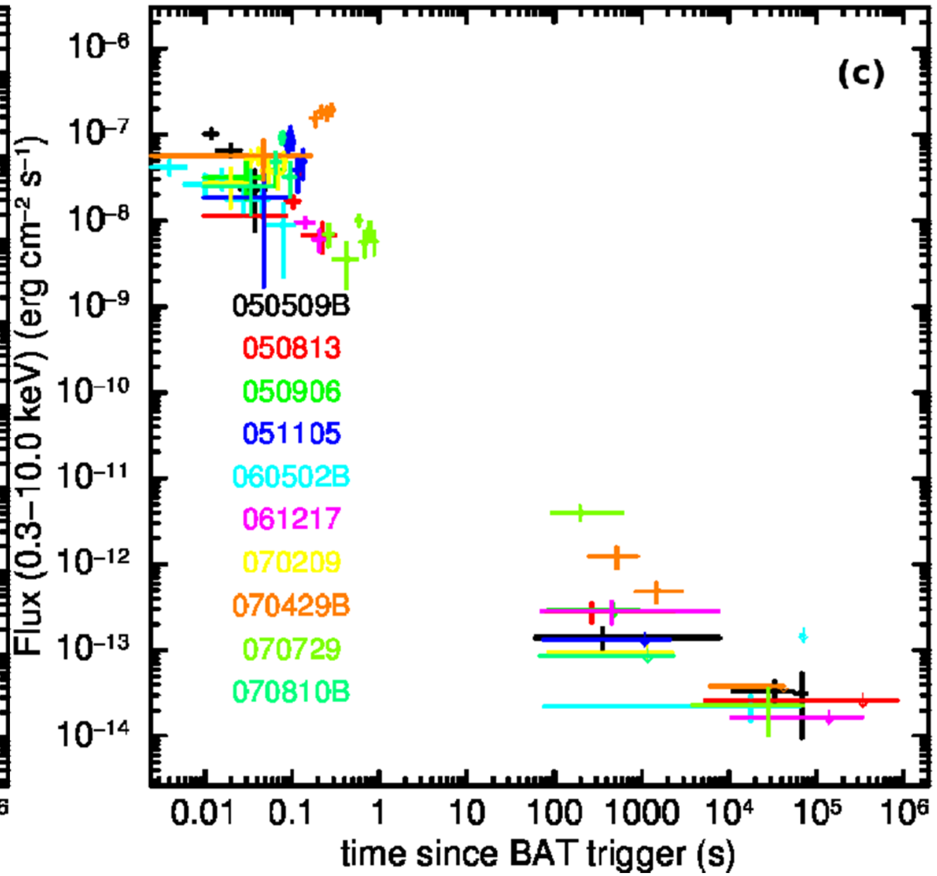
Tunnicliffe et al. (MNRAS, 2013, Submitted)

SGRB X-ray Afterglow Properties

Some have flares and plateaus...



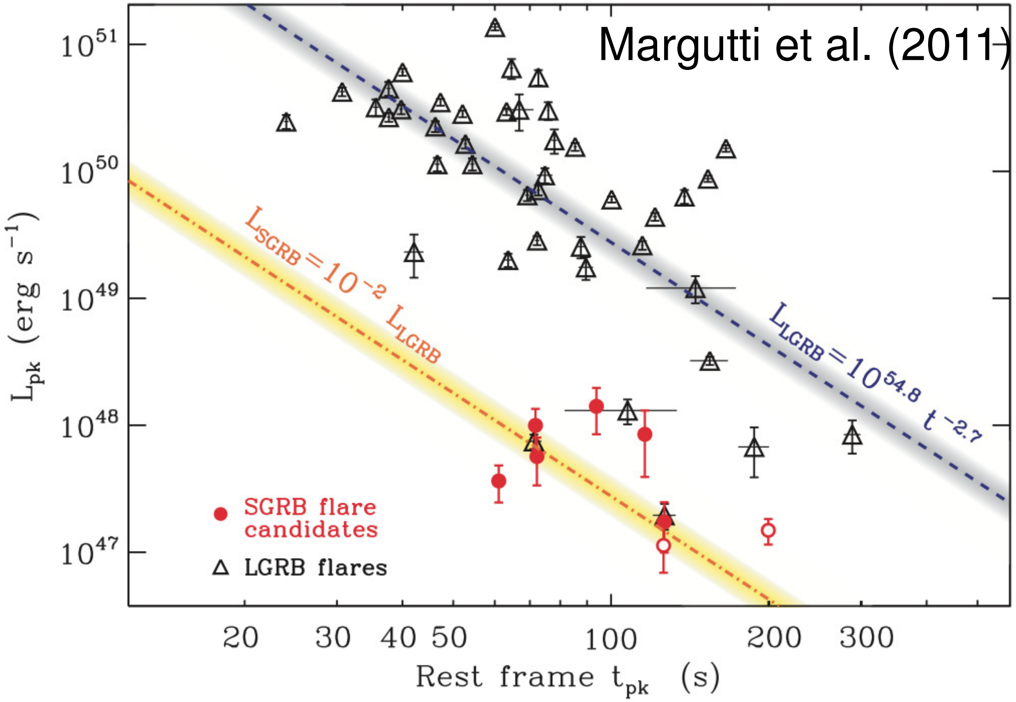
Others are faint and fade fast

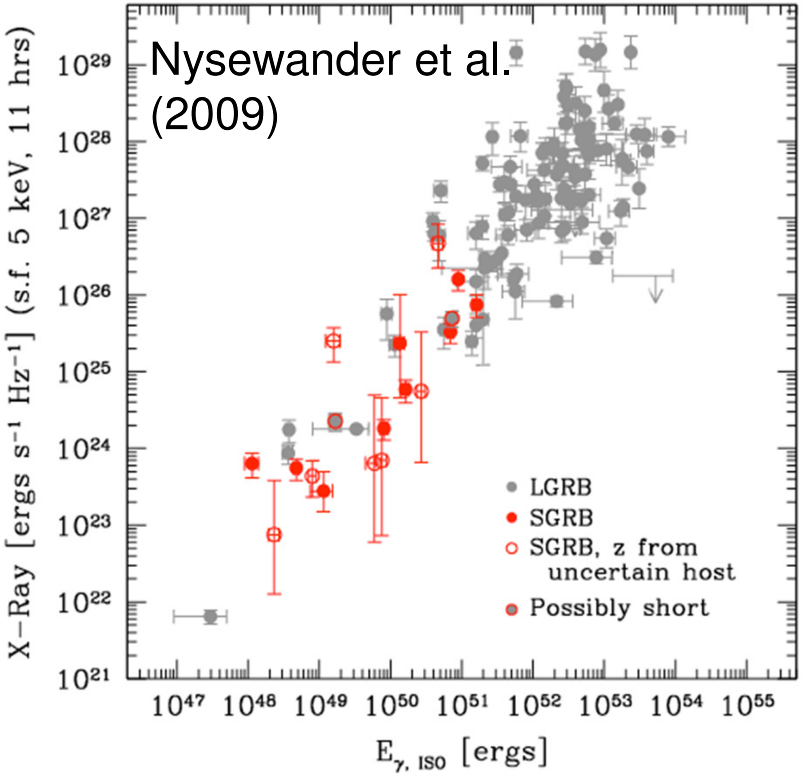


Rowlinson et al. (2013)

SGRB X-ray Afterglows

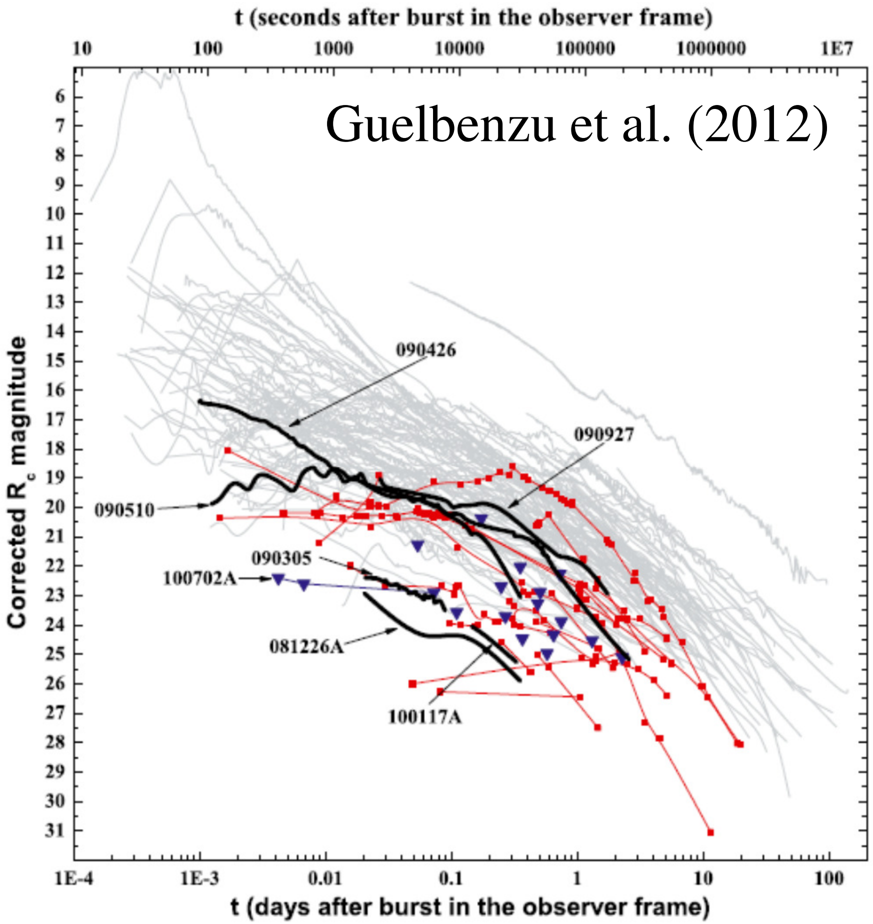
Short GRBs exhibit similar X-ray flares to long GRBs, but with significantly lower luminosities

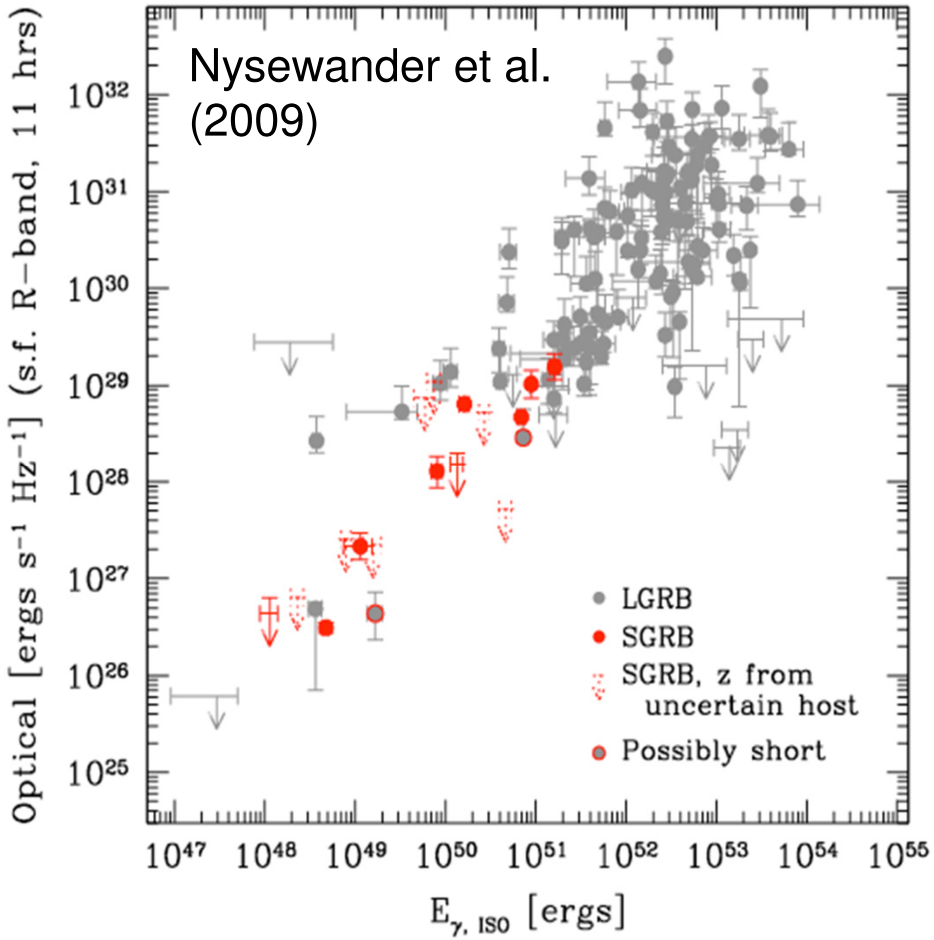




X-ray afterglows are fainter than those of long GRBs.

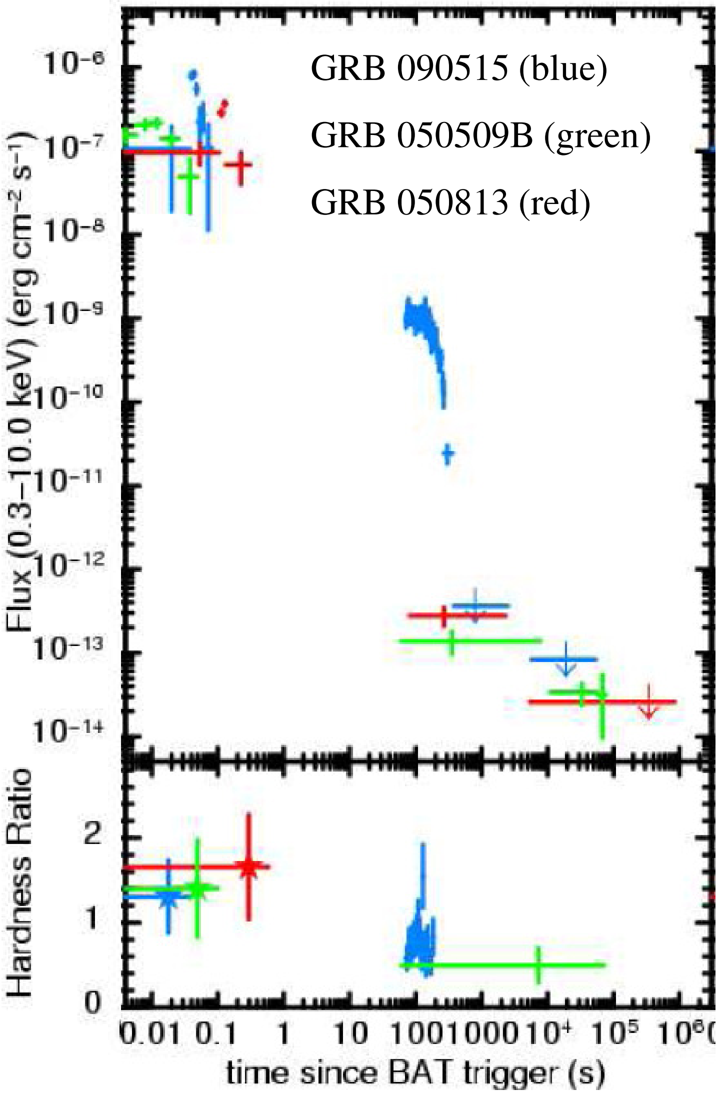
SGRB Optical Afterglows





Optical afterglows are fainter than those of long GRBs.

GRB 090515
(Rowlinson, O'Brien et al. 2010)

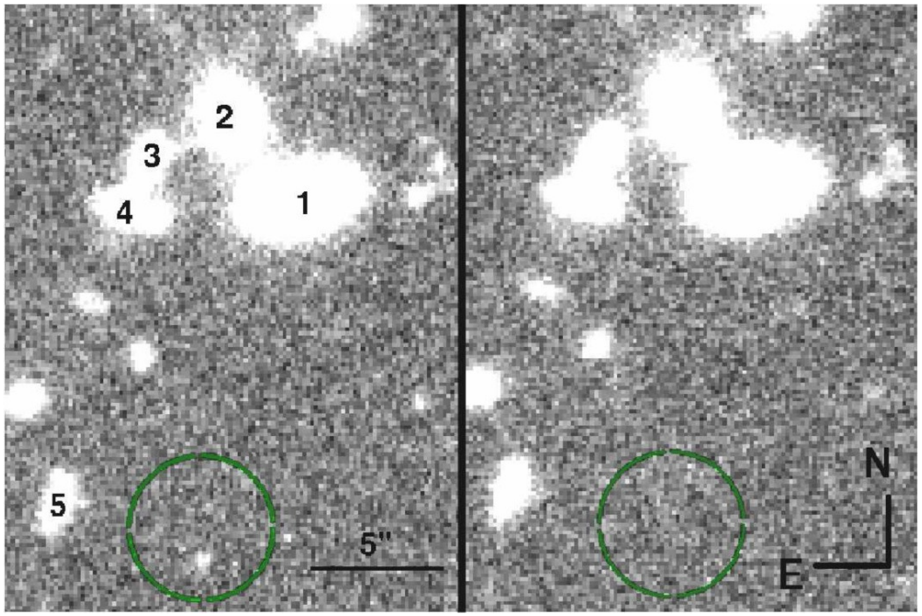


T90 = 0.036s

Fluence = $2x10^{-8}$ erg s^{-1} (15-150 keV)

Highest short GRB X-ray flux at100s

Very unusual given low γ-ray fluence

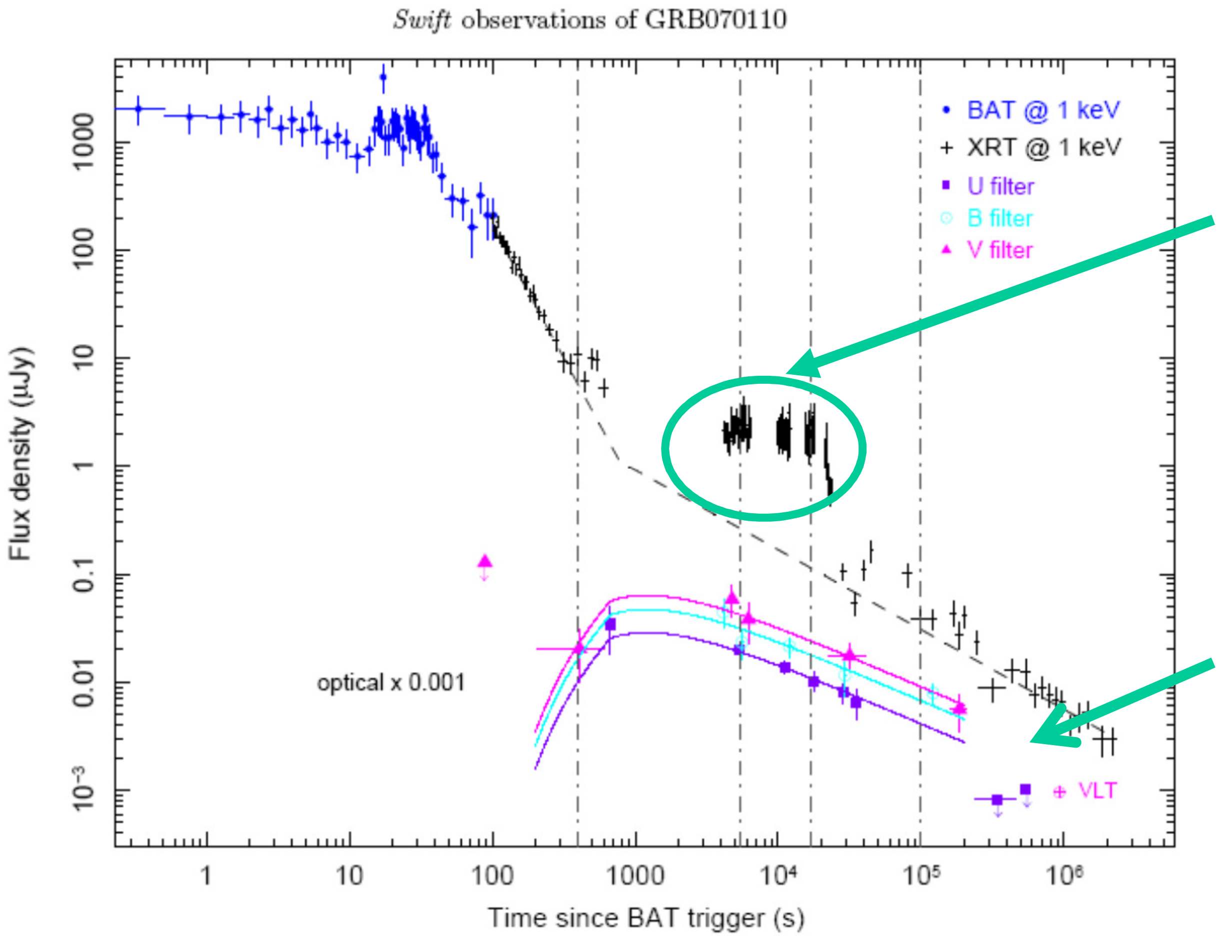


Gemini-N, r-band at 6300s

See a (fading) r=26.4 source

The LGRB "oddball sample"

1st case: GRB 070110 (Troja et al. 2007)



After the prompt decays saw a late excess or "internal plateau" followed by a very steep decay.

Not seen in the optical which appears to show a fairly "standard" afterglow.

Could this indicate a different progenitor?

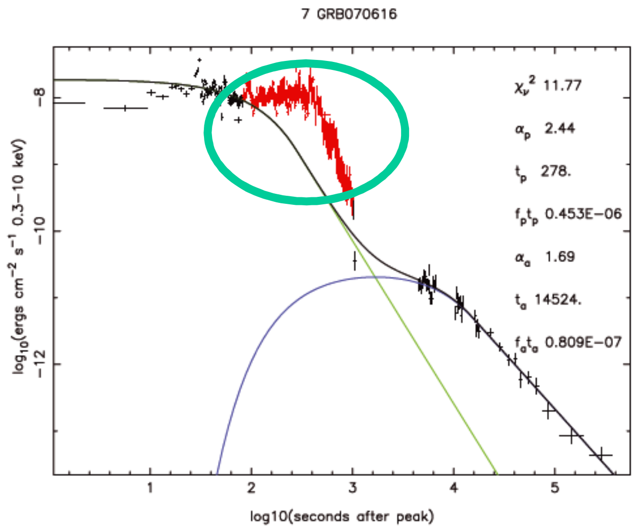
A larger LGRB sample
(Lyons, O'Brien et al. 2010)

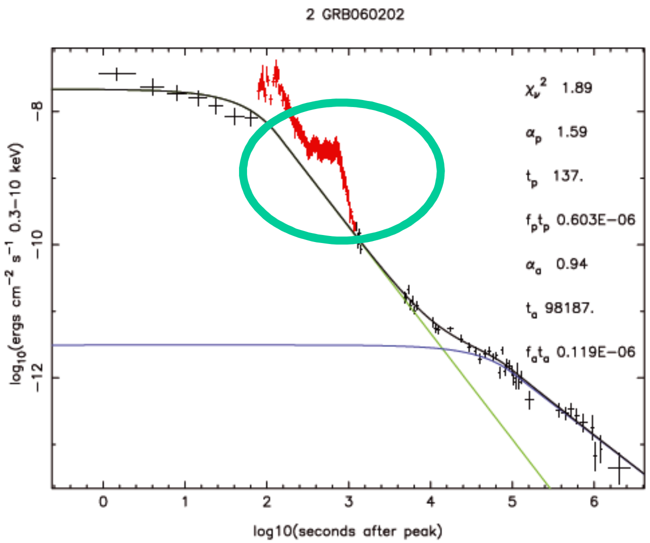
University *of* Leicester

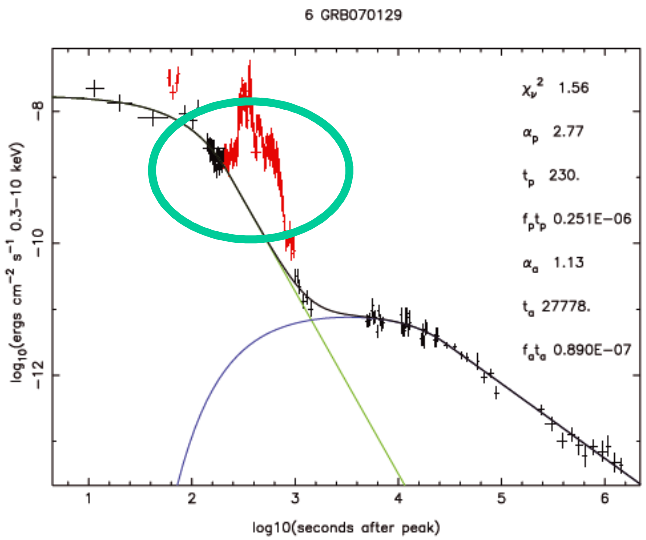
Analysed all Swift GRBs up to the end of 2008.

Find 10 candidates.

The plateau followed by rapid declines are only seen in X-rays.





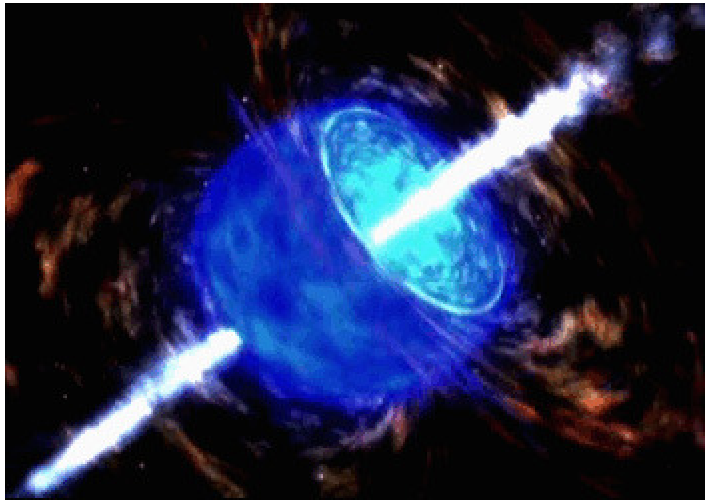


GRB progenitor models

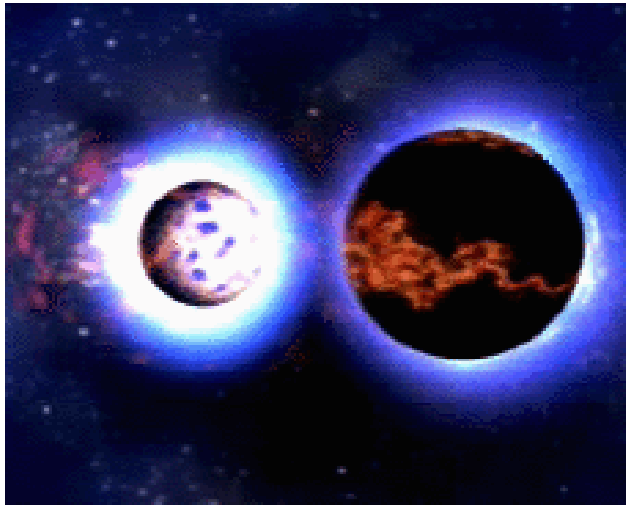
Some GRBs may be powered by an unstable, millisecond pulsar (a magnetar) (e.g., Usov 1992; Duncan & Thompson 1992; Metzger 2009; Dai et al. 2006)

Fast rotation plus very strong magnetic field may power a jet (and hypernova)

Extraction rotational energy ⇒ inject energy into the light curve ⇒ rapid decline when the magnetar collapses to a BH (Zhang & Mézsáros 2001)

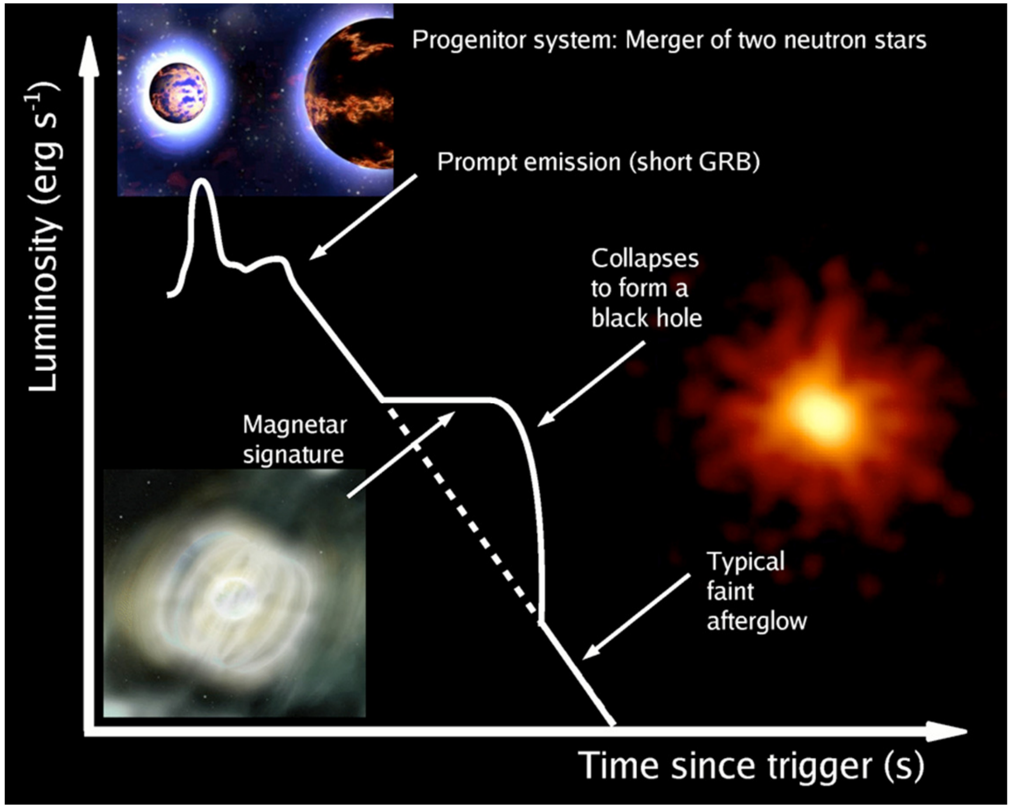


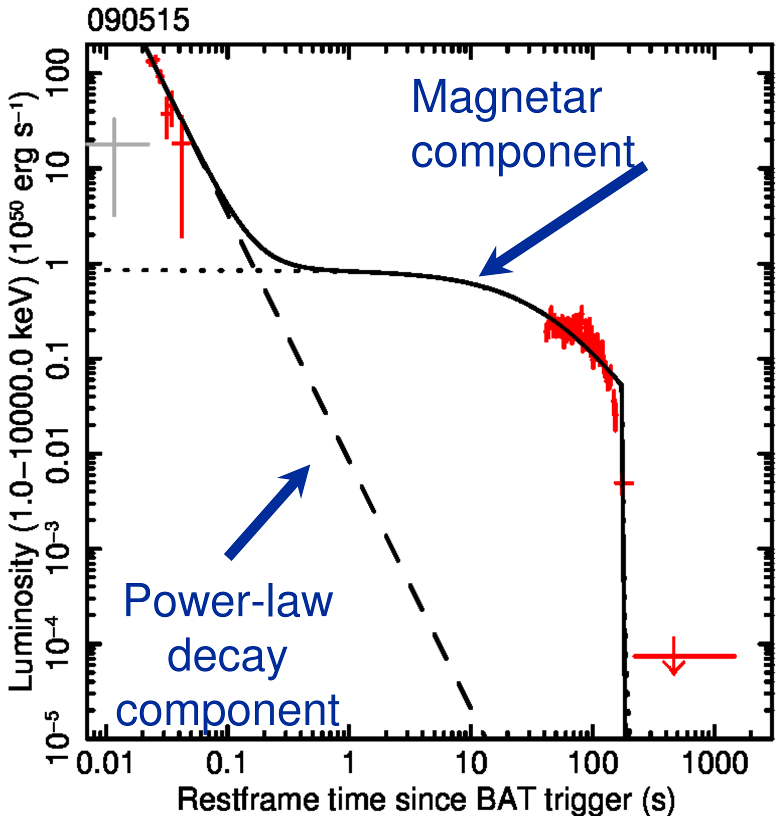
Collapsar – LGRBs



Binary Merger – SGRBs

SGRB magnetar concept

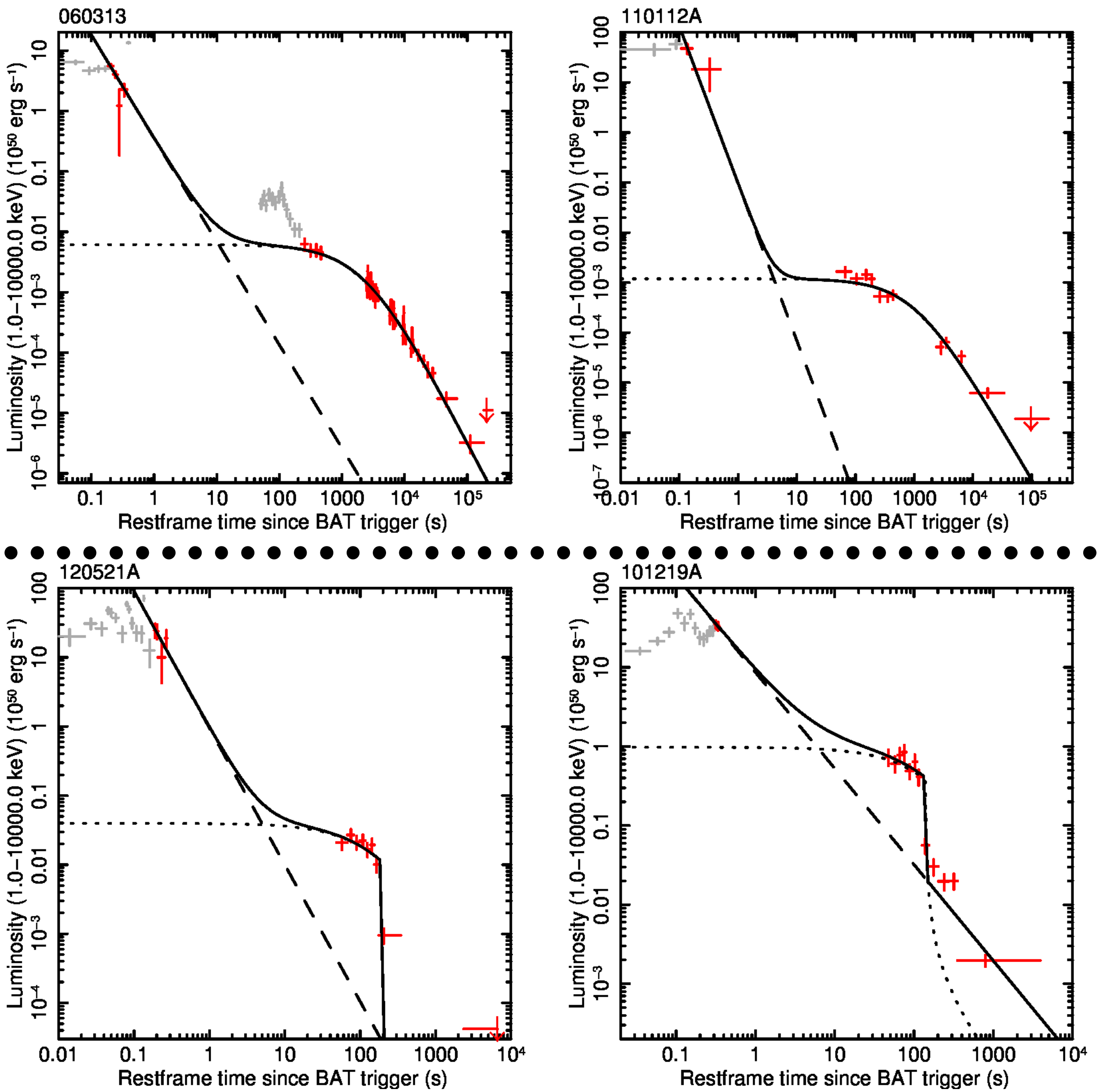




Expect a relation between the pulsar initial spin period (P_0), dipole field strength (B_p), luminosity (L) and the characteristic timescale (T_{em}) for spin-down:

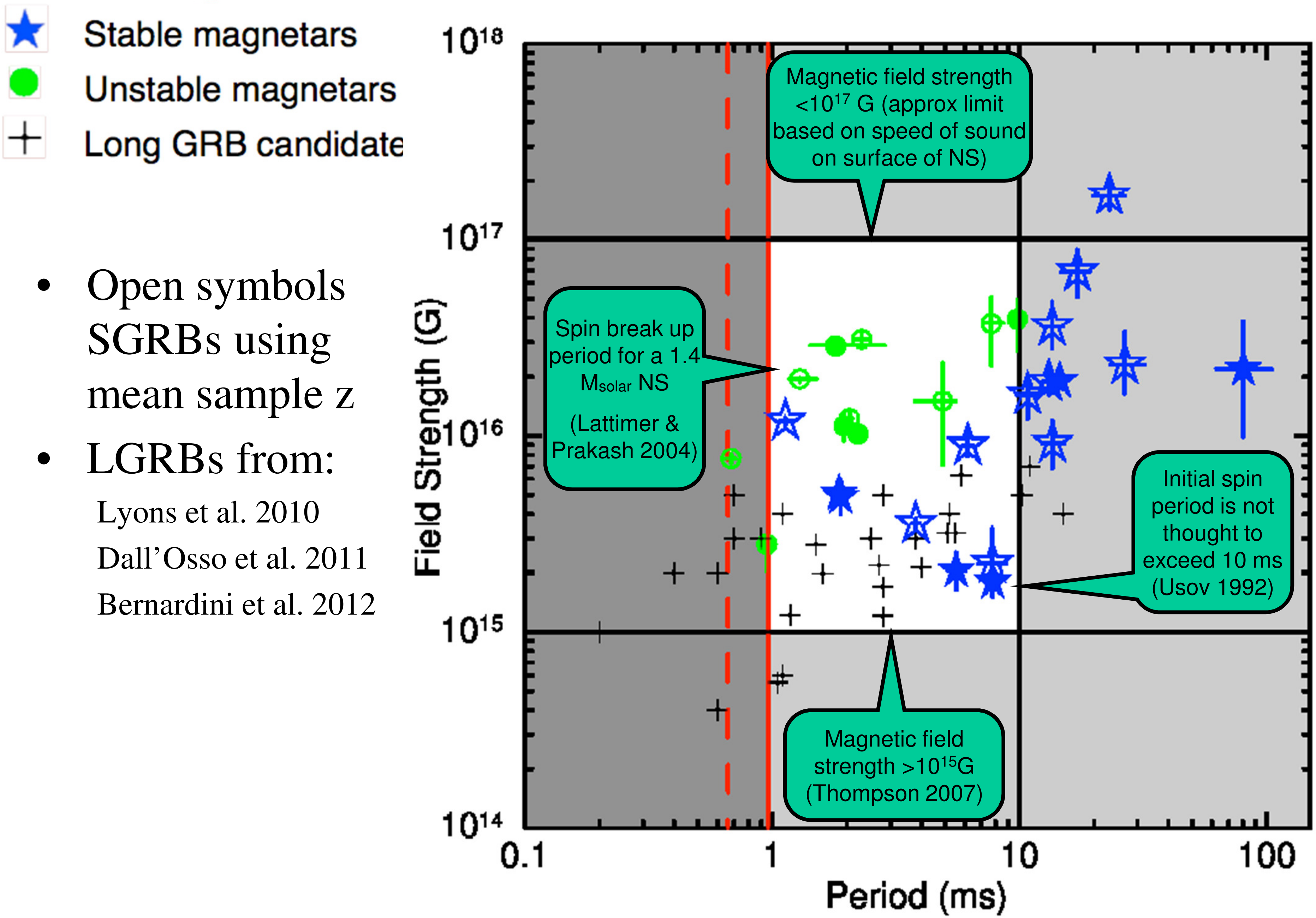
$$L \propto B_p^2 / P_0^4 \quad \text{and } T_{em} \propto P_0^2 / B_p^2$$

Example SGRB magnetar fits



Stable

Unstable



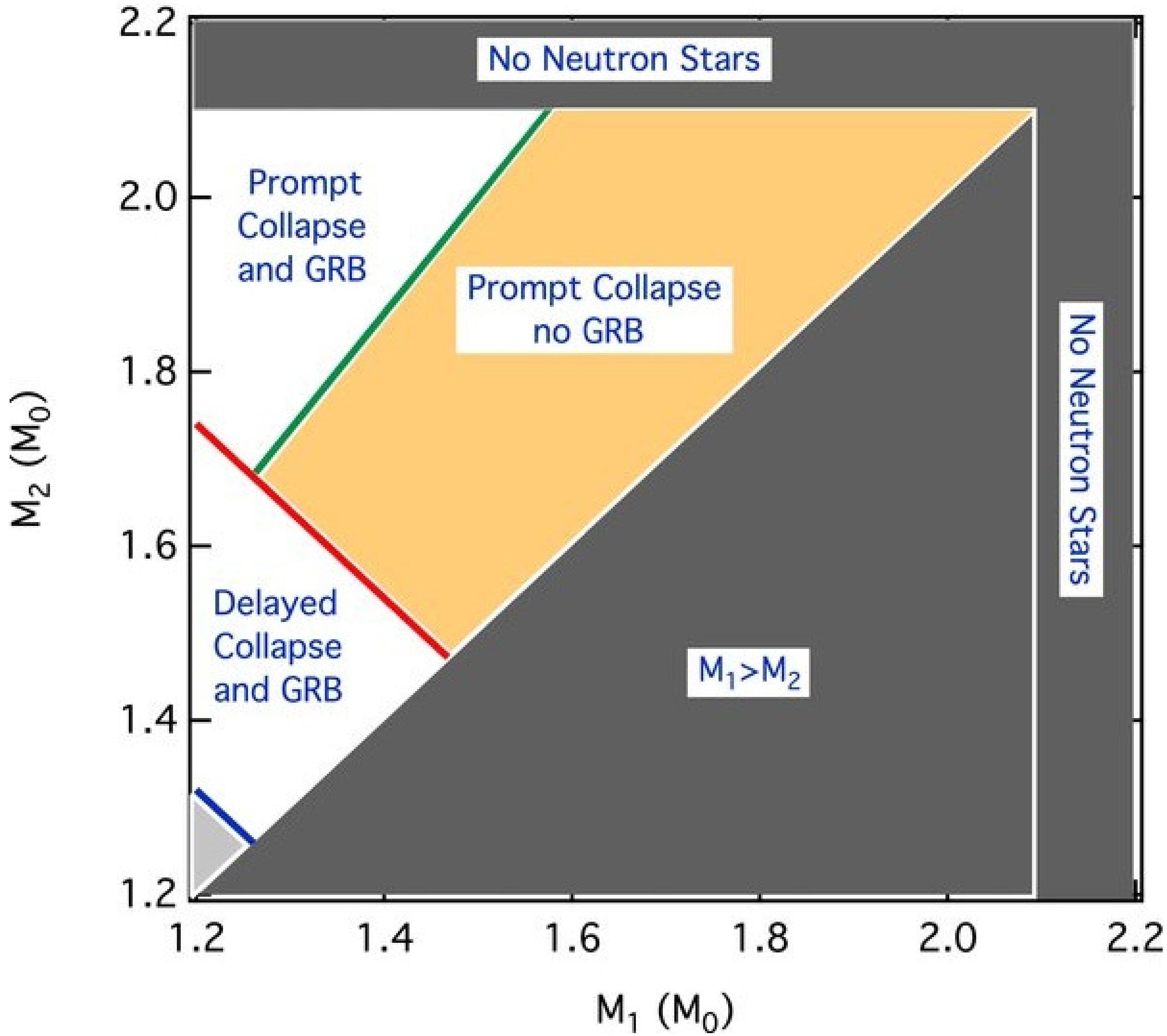
- Open symbols SGRBs using mean sample z
- LGRBs from:

  Lyons et al. 2010

  Dall'Osso et al. 2011

  Bernardini et al. 2012

Take two neutron stars…



The outcome of a binary merger of 2 Neutron Stars, assuming the maximum intial stable Neutron Star mass is ~2.1 $M_\odot$

We now have two examples of known "massive" neutron stars, with masses ~2 $M_\odot$

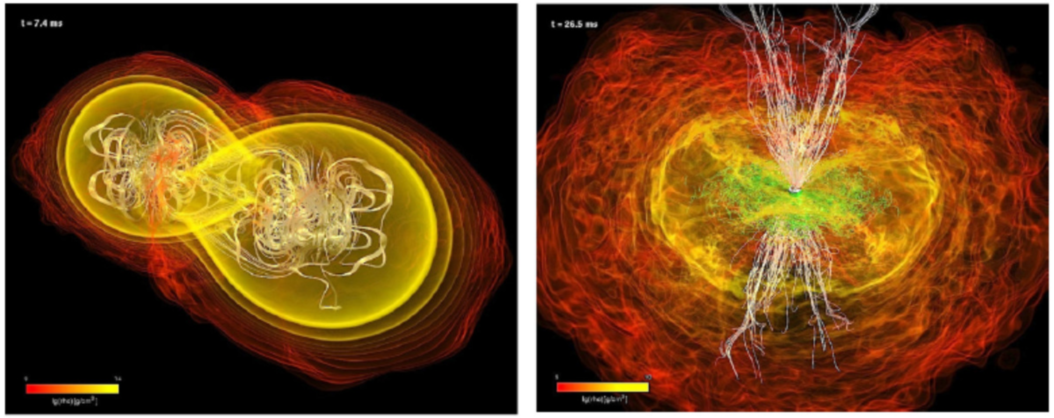
Demorest et al. (2010)

Ozel et al. (2010)

Antoniadis et al. (2013)

HMNS and magnetic fields

Model	Γ_{th}	Remnant	M_{esc} ($10^{-3} M_{\odot}$)	T_{esc} (10^{50} ergs)
APR4-130160	1.8	BH	2.0	1.5
APR4-140150	1.8	BH	0.6	0.9
APR4-145145	1.8	BH	0.1	<0.1
APR4-130150	1.8	HMNS → BH	12	8.5
APR4-140140	1.8	HMNS → BH	14	10
APR4-120150	1.6	HMNS	9	5
APR4-120150	1.8	HMNS	8	5.5
APR4-120150	2.0	HMNS	7.5	5.5
APR4-125145	1.8	HMNS	7	4.5
APR4-130140	1.8	HMNS	8	5
APR4-135135	1.6	HMNS	11	6
APR4-135135	1.8	HMNS	7	4
APR4-135135	2.0	HMNS	5	3
APR4-120140	1.8	HMNS	3	2
APR4-125135	1.8	HMNS	5	3
APR4-130130	1.8	HMNS	2	1
ALF2-140140	1.8	HMNS → BH	2.5	1.5
ALF2-120150	1.8	HMNS	5.5	3
ALF2-125145	1.8	HMNS	3	1.5
ALF2-130140	1.8	HMNS → BH	1.5	0.8
ALF2-135135	1.8	HMNS → BH	2.5	1.5
ALF2-130130	1.8	HMNS	2	1.0
H4-130150	1.8	HMNS → BH	3	2
H4-140140	1.8	HMNS → BH	0.3	0.2
H4-120150	1.6	HMNS	4.5	2
H4-120150	1.8	HMNS	3.5	2
H4-120150	2.0	HMNS	4	2
H4-125145	1.8	HMNS	2	1.5
H4-130140	1.8	HMNS	0.7	0.4
H4-135135	1.6	HMNS → BH	0.7	0.4
H4-135135	1.8	HMNS → BH	0.5	0.2
H4-135135	2.0	HMNS	0.4	0.2
H4-120140	1.8	HMNS	2.5	1
H4-125135	1.8	HMNS	0.6	0.3
H4-130130	1.8	HMNS	0.3	0.1
MS1-140140	1.8	MNS	0.6	0.2
MS1-120150	1.8	MNS	3.5	1.5
MS1-125145	1.8	MNS	1.5	0.8
MS1-130140	1.8	MNS	0.6	0.2
MS1-135135	1.8	MNS	1.5	0.6
MS1-130130	1.8	MNS	1.5	0.5



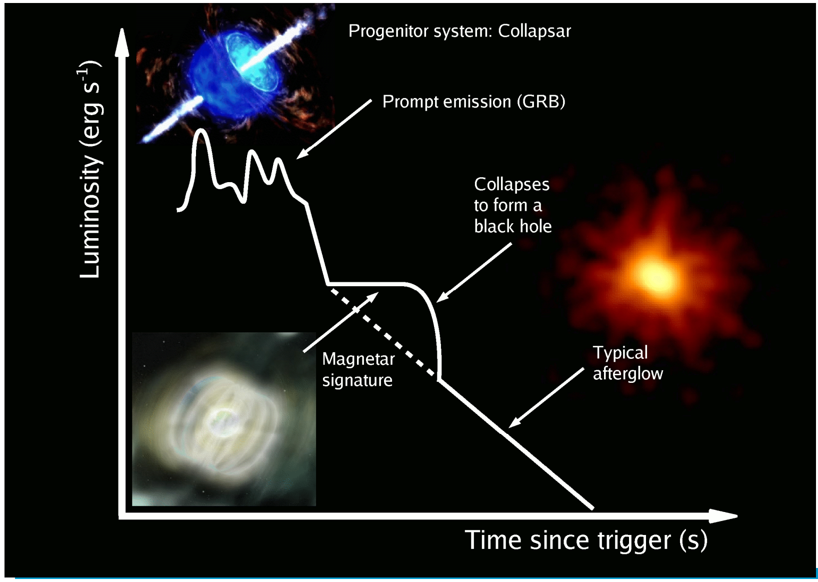
Hard to get an ordered field (jet) without a BH and MRI helps to drive rapid HMNS collapse (Rezzolla et al. (2012); Siegel et al. (2013)

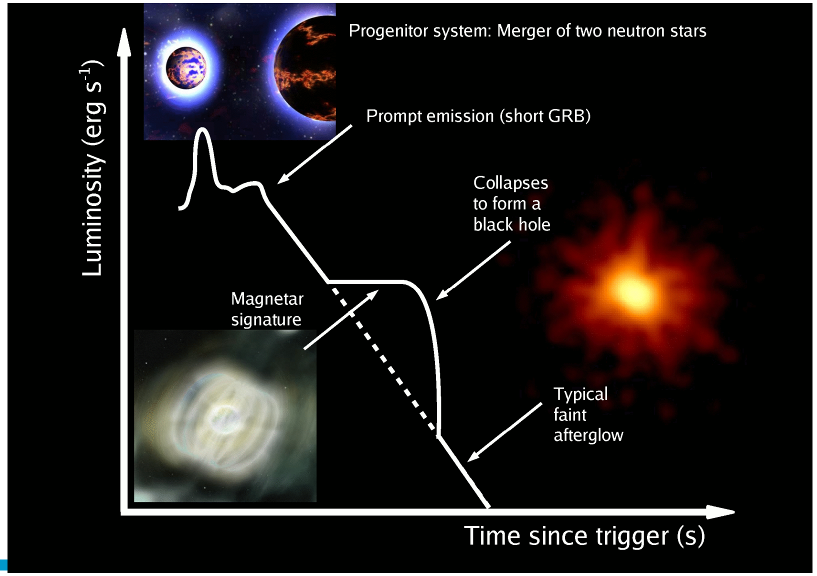
Dessart et al. (2012) also note for collapsars that "black hole formation is non-trivial…proto-magnetars seem much more easily produced".

Can often make a HMNS in mergers (Hotokezaka et al. (2013)

Test model using gravity waves?

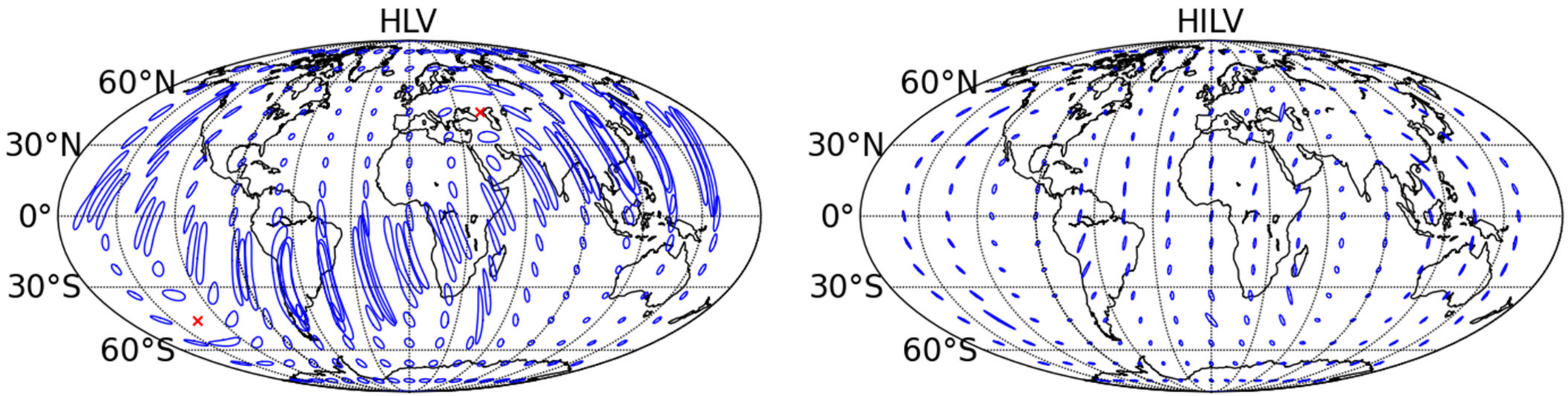
Phase	Amplitude (h)	A-LIGO limit (Mpc)	ET limit (Mpc)
NS-NS Inspiral	4×10^{-24} (Abadie et al 2010)	445	5900
Magnetar spin down	$<1.7 \times 10^{-23}$ (Corsi & Mezsaros 2009)	<85	<570
Collapse to BH	4×10^{-23} (Novak 1998)	100	1300





What do we do in the advanced Gravitational Wave era?

Advanced LIGO/Virgo GW transient location



Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within $5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

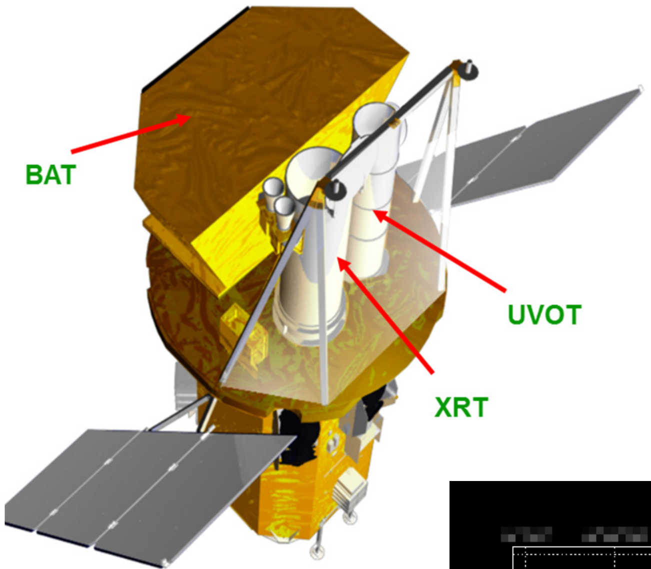
LIGO Collaboration
arXiv:1304.0670

Swift can operate for another 10+ years (funding/failure permitting) as can Fermi

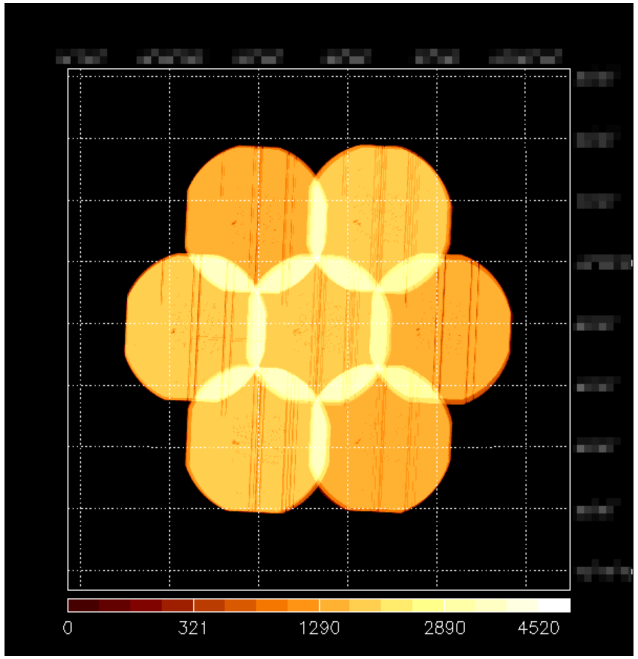
New Swift tiling approach does all tiles each orbit

Automated XRT analysis software with improved source detection (more sensitive)

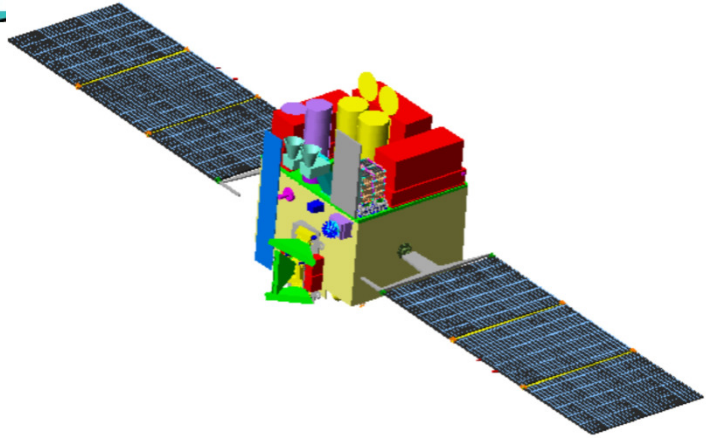
Notifies the follow-up team automatically of interesting sources



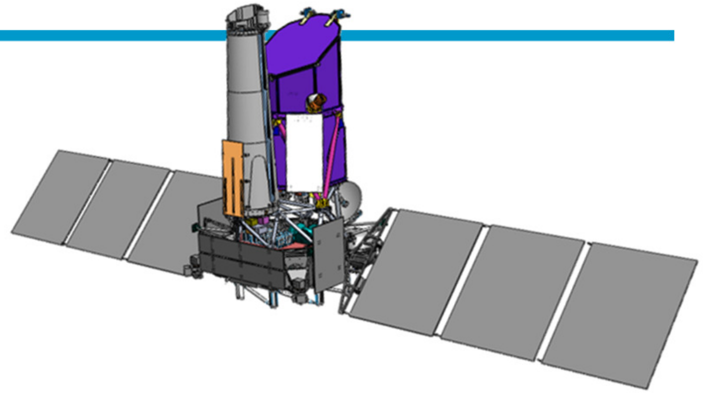
Example for IceCube



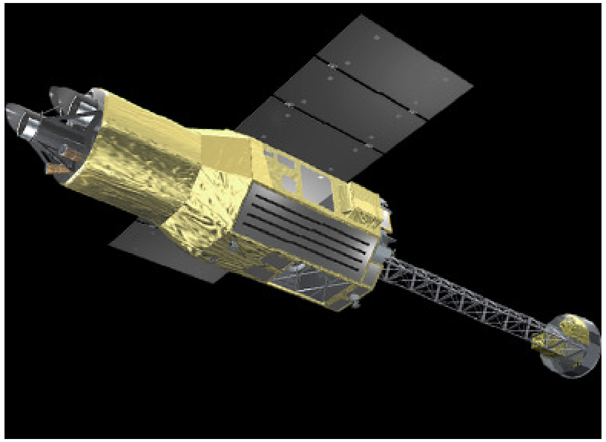
The near future



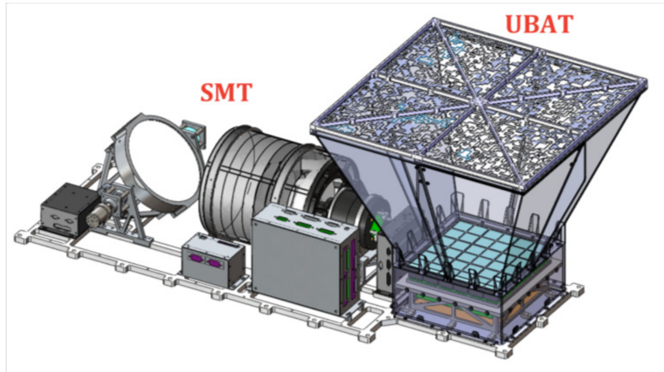
Astrosat, India, Canada, Leicester, launch 2014, 0.3-150 keV and UV



SRG, Russia, Germany, launch 2014, 0.5-10 keV (eRosita) + 3-120 keV (ART) in L2 orbit – all-sky survey



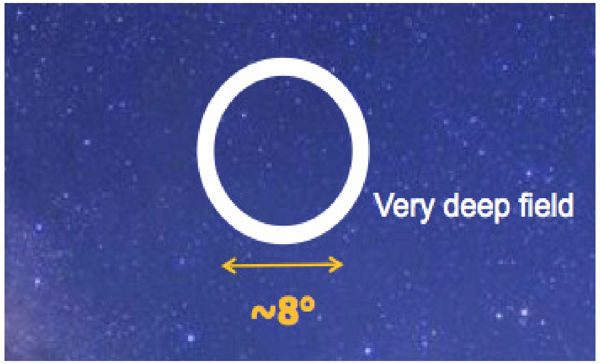
Astro-H, JAXA launch 2014, 0.5-600 keV with soft X-ray calorimeter (7eV)

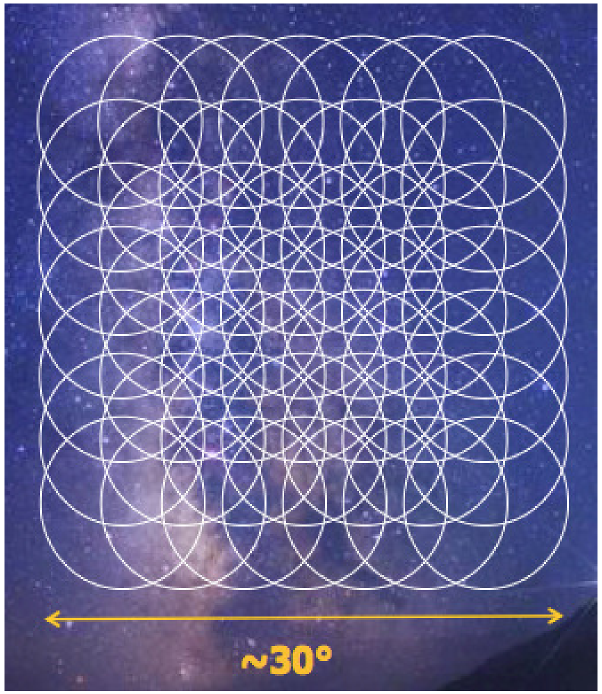


UFFO Pathfinder, launch 2014, 10cm optical (200-600nm) and UBAT GRB finder (5-200keV) ~40 GRBs/yr.

Find transients with CTA?

- Slewing mode
  - Keep Swift in operation
  - Keep Fermi/GBM in operation + work on location accuracy
  - New missions (e.g. SVOM) plus multi-messenger e.g. LOFAR, aLIGO, LSST …
  - Need follow-up + redshift measurements for CTA detected bursts (need dedicated telescope?)
- Survey mode
  - Best chance for prompt serendipitous transient detection (e.g. short GRBs) in "survey mode"
  - ~HESS sensitivity over a ~30°x 30° patch of sky
  - Find in real-time search and then repoint

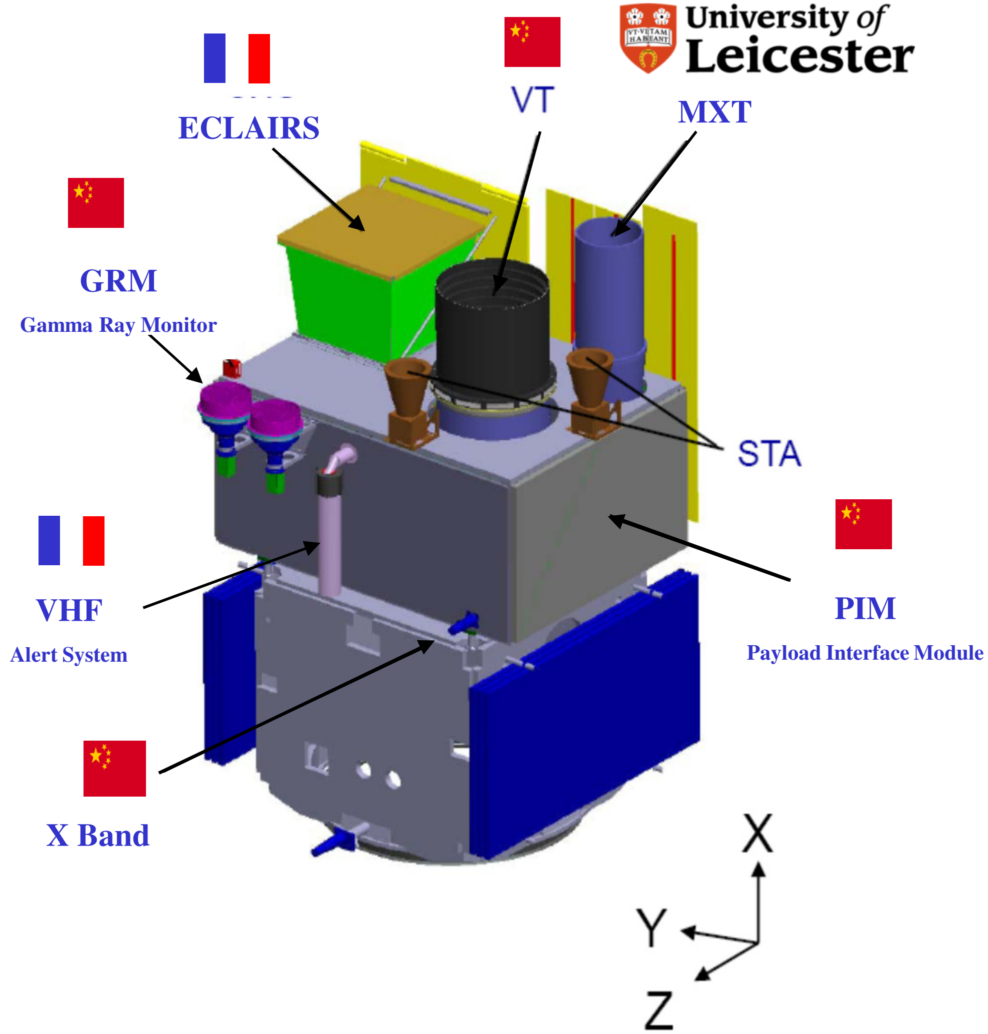


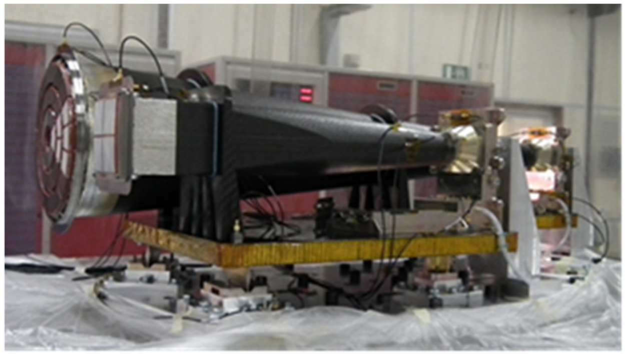


SVOM Satellite (France, China, …Leicester)

Complement Swift:

- ➢ better energy coverage, pointing strategy (anti-Sun) and lower trigger energy range (4-300keV)
- ➢ Find nearby X-ray bright, low L GRBs (SN and GW connection) and high-z GRBs
- ➢ Launch 2017-18





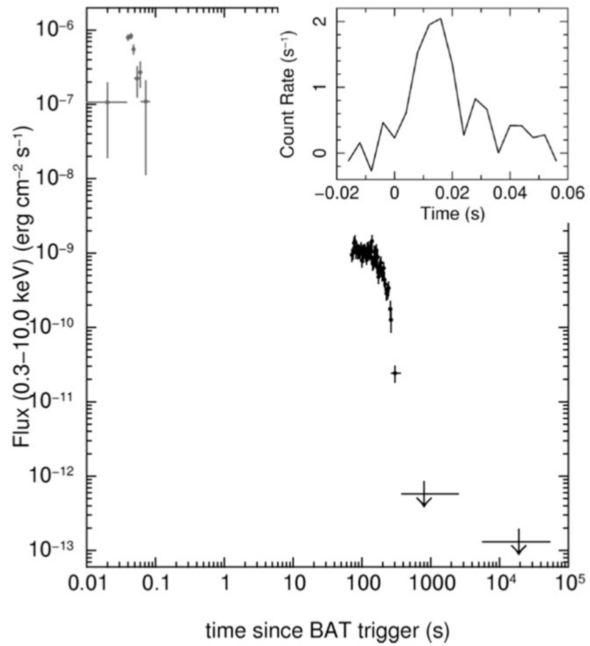
ESA BepiColumbo MIXS-T/S telescopes

Can we build a better mission?

- On board trigger and “good” localisation (<1 arcmin, preferably few-tens of arcsec) – but for GW need large sky coverage. Hard to do both.

- Prefer no data gaps due to slews

- Observe continuously in the same energy range)



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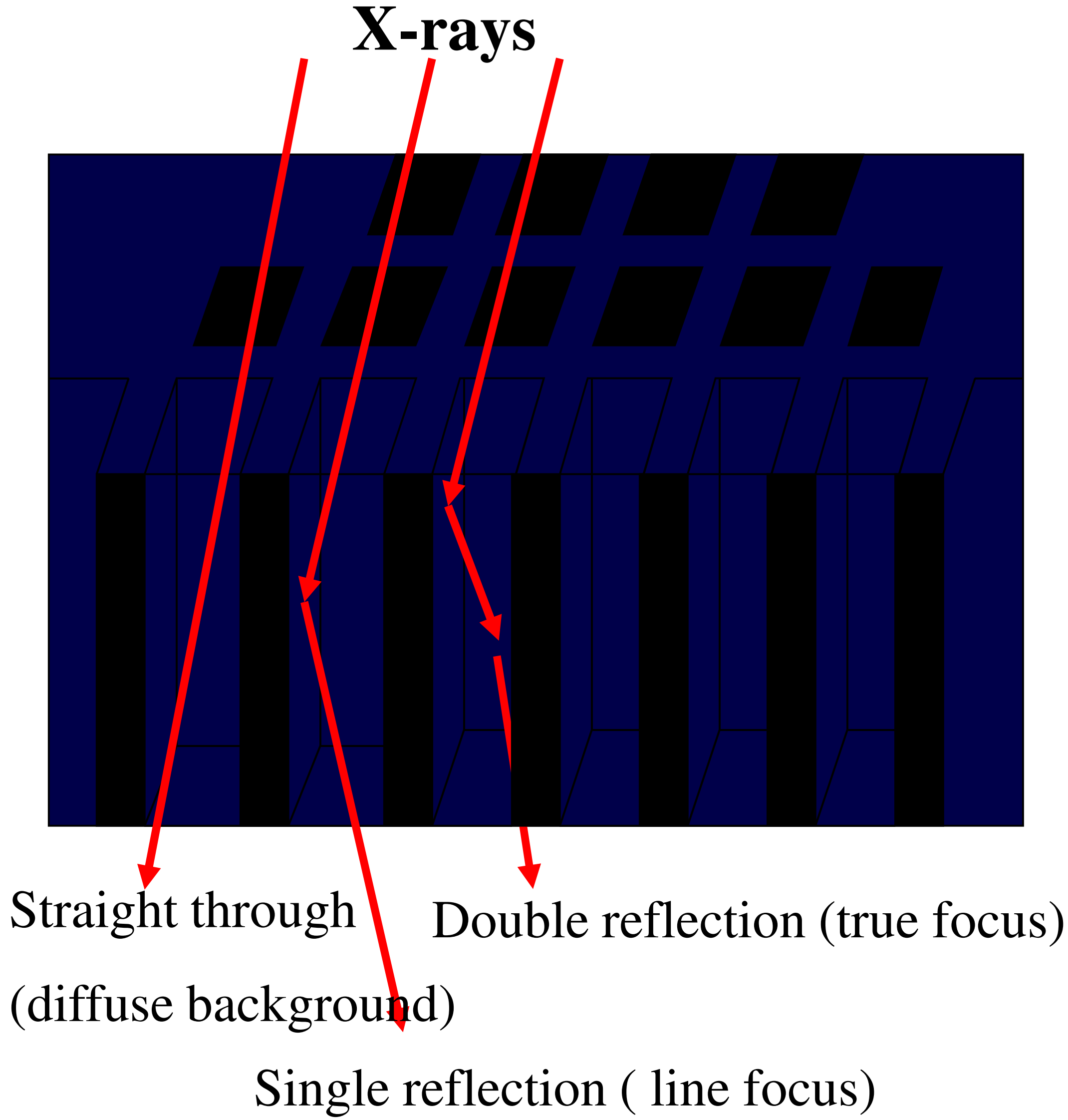
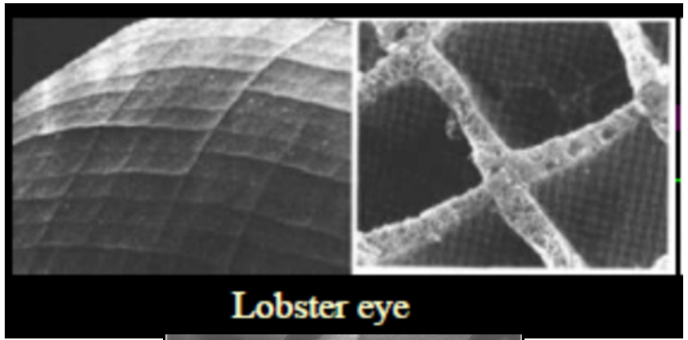
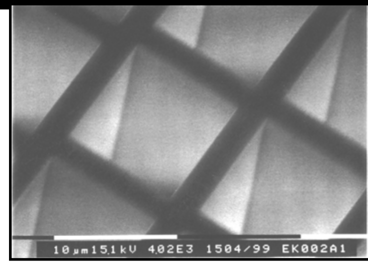
- Bias pointing towards the night sky for rapid ground-based follow-up.

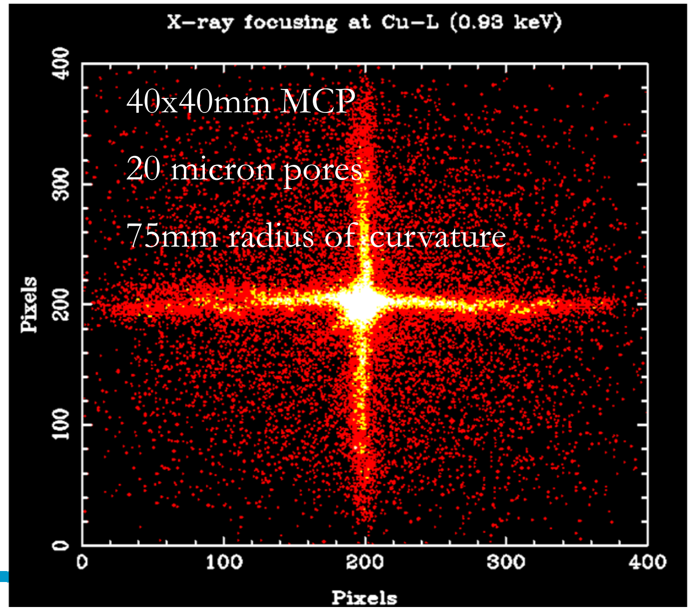
- Would like on-board redshift determination – at least to distinguish low-z red bursts from high-z ones. Requires an IR telescope

The future? Lobster-Eye Optics

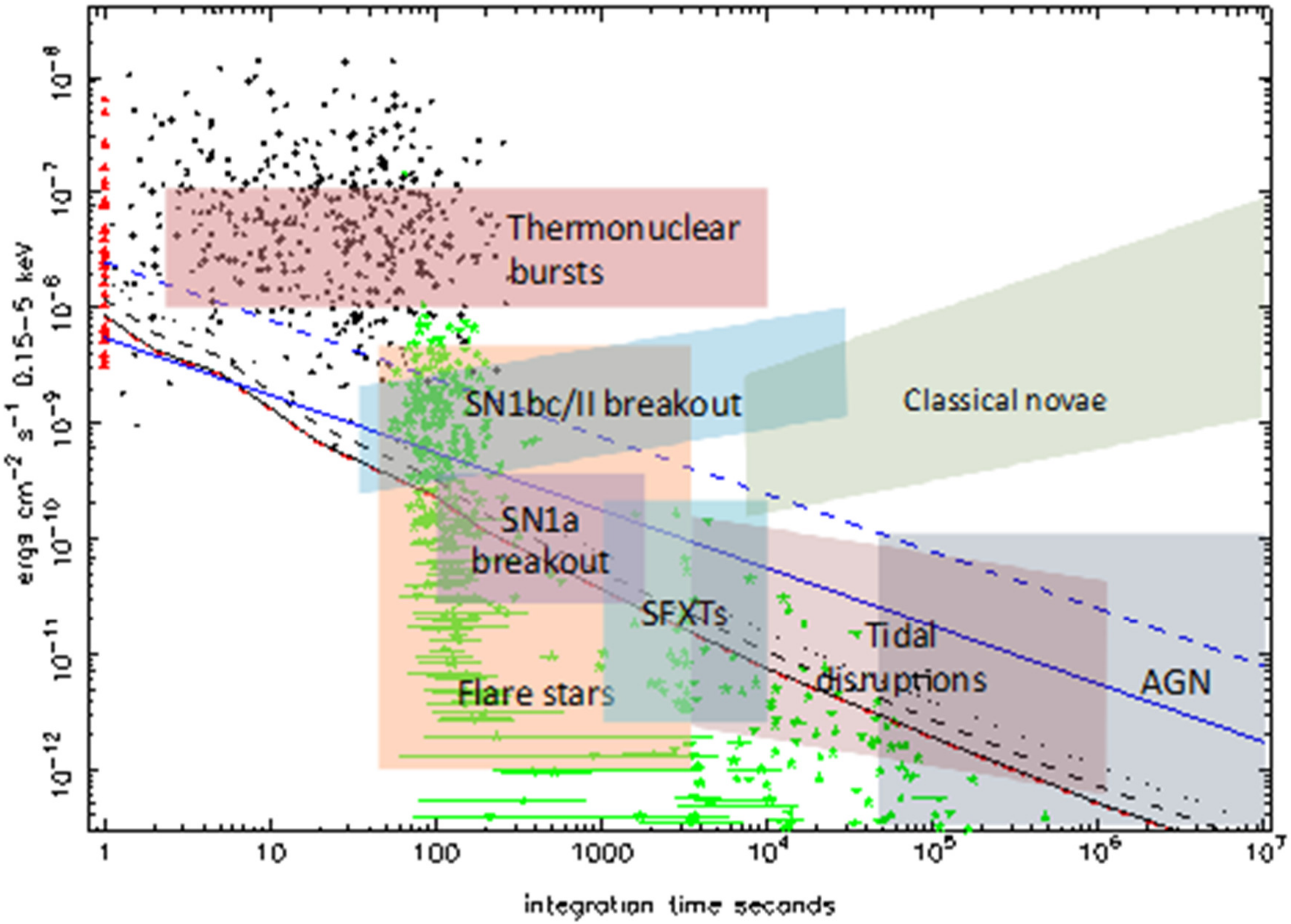








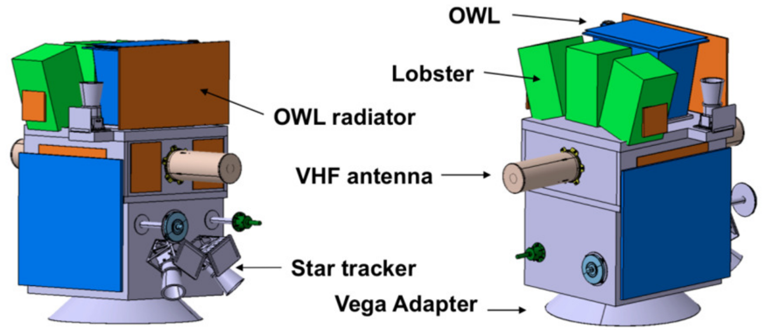
X-ray transients



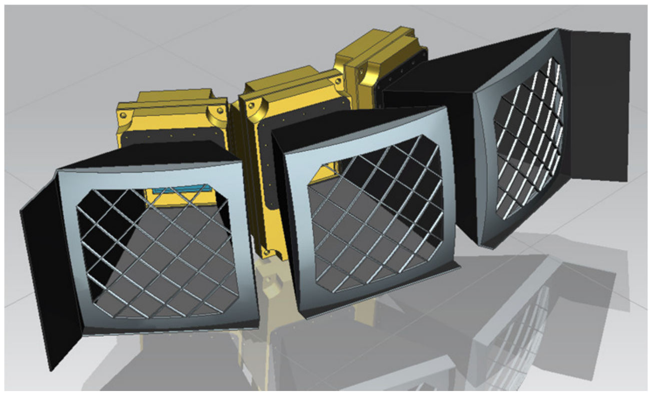
Coded mask limit in ~100s

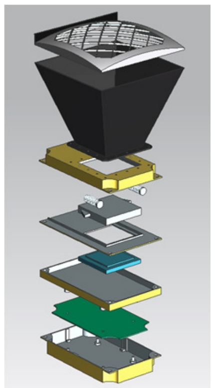
A-STAR limit for various spectra

A-STAR concept (ESA S-class)

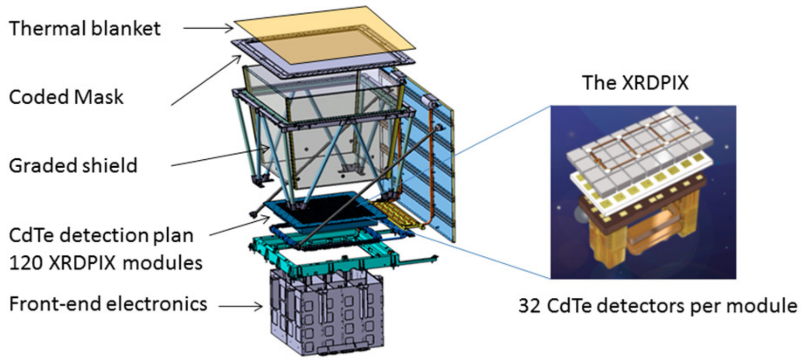


Rapid-slewing Myriade Evolutions, 30° low-earth orbit. Prompt alert downlink. All sky survey pointings of 20 mins each, 2 observations of every field per day. 50Meuro total budget!



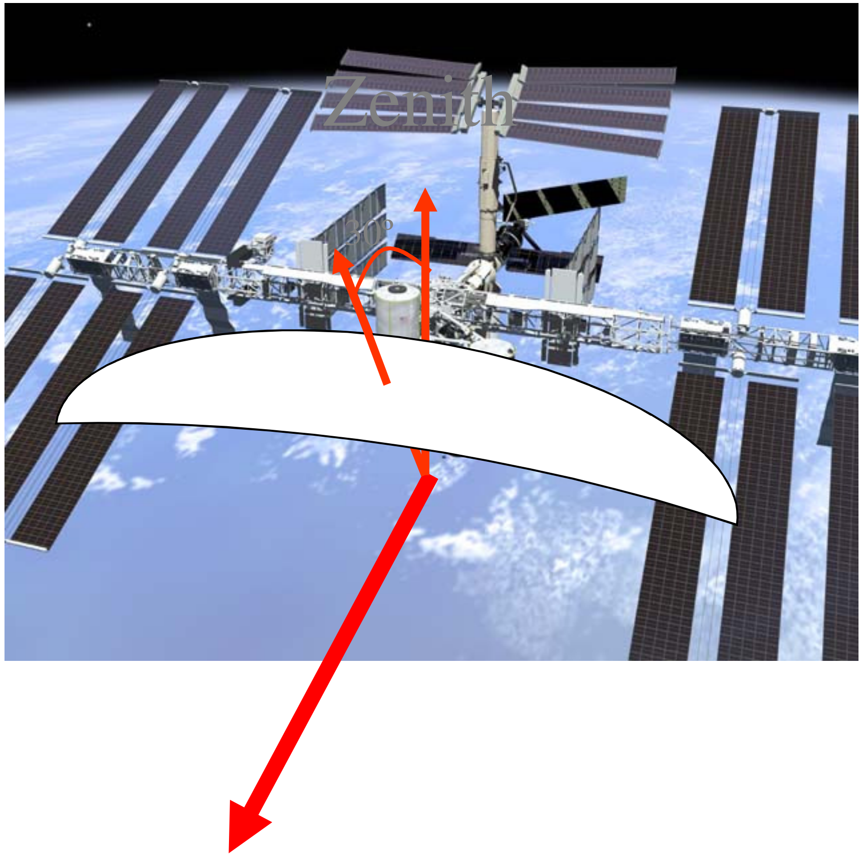


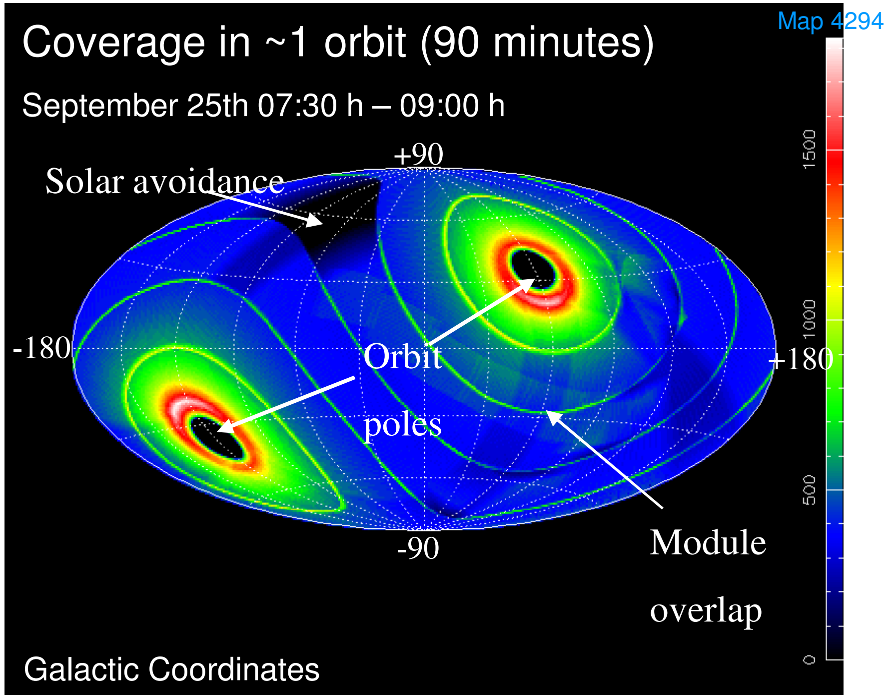
FOV	17x52°
Energy band	0.15-5.0 keV
Positions	50% <30”
Sensitivity	4×10^{-11} erg.cm^{-2}.s in 10^3 s



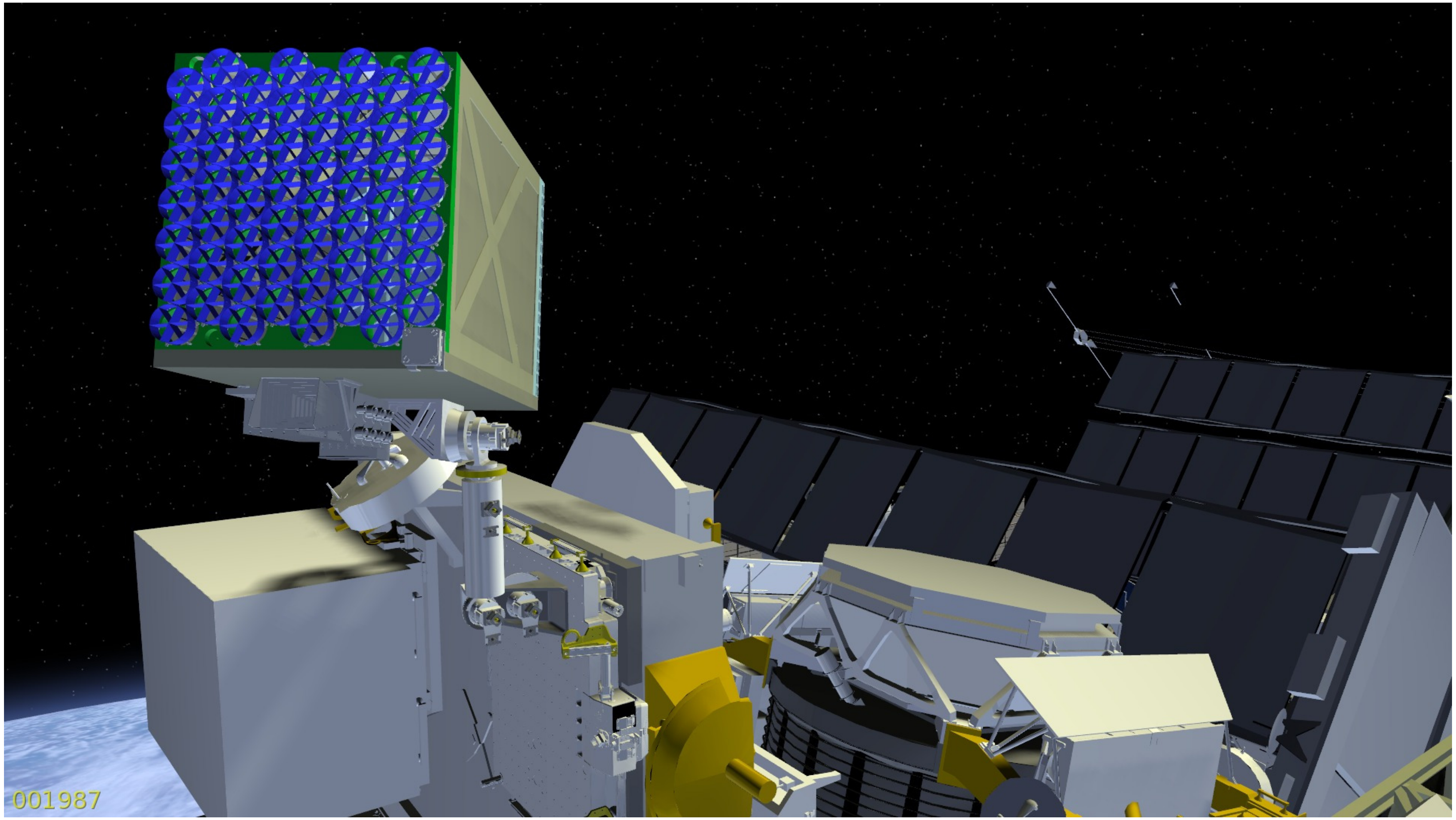
FOV	60x88°
Energy band	4-150 keV
Positions	2-10’
Sensitivity	2×10^{-10} erg.cm^{-2}.s in 10^3 s

ISS as an ASM platform





NICER (cf. Lobster-ISS option)



Mount module on pivot arm – trigger and track transient

Summary

• Short GRBs display a range of properties, lie in a variety of host galaxies and can be hard to reliably associate with any galaxy

• In some GRBs (long and short) see emission consistent with energy injection possibly by a magnetar (tapping rotational energy). It may collapse to a black hole.

• Possible progenitor tests in future using detection of gravity-waves (GW):

  - A merger or a collapsar GW signal (e.g. Abadie et al. 2010)
  - Spin-down GW signal (e.g Corsi & Meszaros 2010)
  - Magnetar collapse to a black hole GW signal (e.g. Novak 1998)

• Nearby cases (few 100Mpc) would provide a test-case where a simultaneous EM and GW light-curves show correlated multiple signals

• **We need a GRB space mission with good localisation when advanced-LIGO/VIRGO, JWST, CTA, ELT etc. are working**