Short-Duration Gamma-Ray Bursts: A Primer

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Suggested Reading:

"Short-Duration Gamma-Ray Bursts", E. Berger, ARA&A, **52**, 43, 2014.

"The Physics of Gamma-Ray Bursts", T. Piran, RvMP, **76**, 1143, 2004.

Introduction

Gamma-ray bursts were serendipitously discovered in 1967 by the *Vela* satellites (Klebesadel et al., 1973). Designed to verify compliance with the 1963 Partial Test Ban Treaty signed with the Soviet Union, the satellites were configured to search for evidence of nuclear testing in space and (later) the upper atmosphere. While with one possible exception (the Vela Incident) no evidence for testing nuclear weapons was uncovered, the satellites did uncover short-duration flashes of high-energy radiation that were not consistent with the location of the Sun or the Earth.

These flashes, subsequently dubbed gamma-ray bursts (GRBs), are characterized by the following observational properties:

- Short duration, dt ~0.1-100 s
- Variability on time scales as short as ms
- Non-thermal spectra, with peak energy output ~ few hundred keV
- Non-repeating
- Extremely bright (fluences ~ 10^{-4} erg s^{-1}; outshining the entire gamma-ray sky)

A representative sample of light curves of GRBs is shown in Figure 1.

For several decades after their discovery, the origin of these events remained enshrouded in mystery. The largest limitation in our understanding was the uncertainty on the *distance scale*. GRB astronomers even held a "Great Debate" in 1995, in the model of the Shapley-Curtis Debate in 1920, to consider arguments either for a Galactic or extragalactic origin.

Strong circumstantial evidence in favor of an extragalactic origin came from the first large population of GRBs from the BATSE instrument on-board the Compton Gamma-Ray Observatory. While each individual GRB was poorly localized on the sky (error regions of tens to hundreds of square degrees), the entire population of thousands of events was clearly distributed *isotropically* on the sky (Figure 2). Given the lack of correlation with the stellar population of the Milky Way (i.e., the Galactic plane), an extragalactic origin for GRBs was strongly favored.

Together with the observed high-energy properties, an extragalactic origin for GRBs has profound implications for their origin, an issue known as the "compactness" problem (Ruderman, 1975). Specifically, the optical depth to electron-positron pair production in such a system should be extremely large, inconsistent

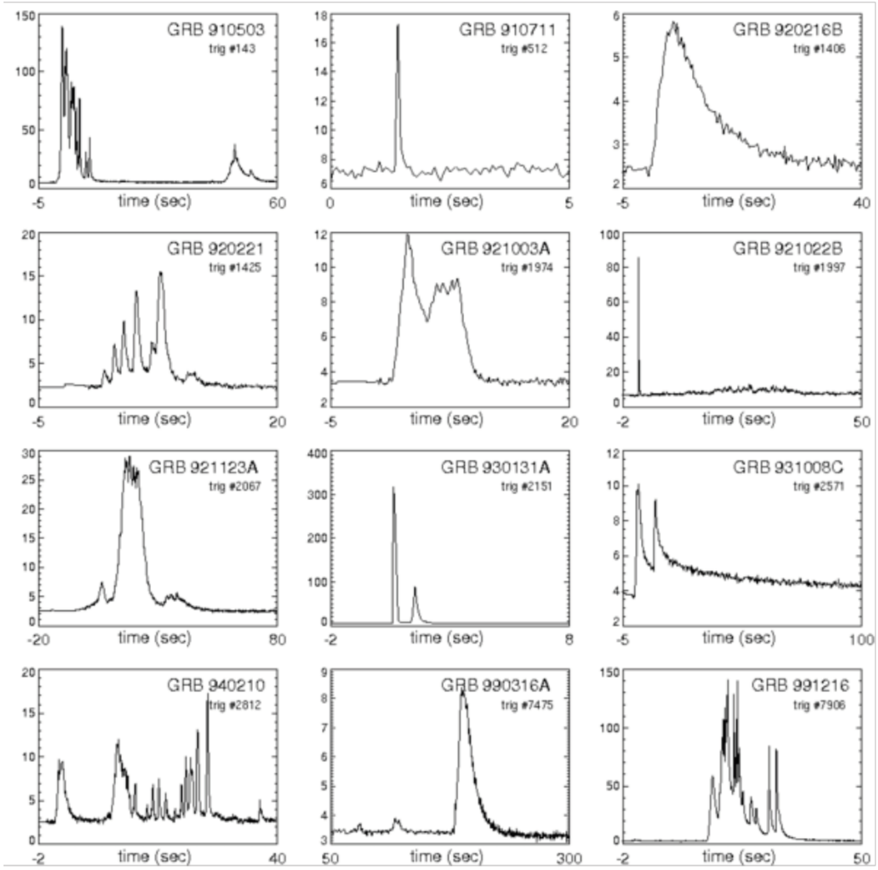

Figure 1: Representative light curves of a sample of gamma-ray bursts

with the non-thermal spectra observed out to several MeV. The solution to this problem, first identified by Bohdan Paczynski (Paczynski, 1986) was to invoke *ultra-relativistic* expansion. Specifically, Lorentz factors in excess of 100 (the most relativistic known sources in the Universe) are required in order to circumvent the compactness problem.

Excercise 1: Calculate the optical depth to electron-positron pair production for a cosmological GRB, both in the case of a static system and for relativistically expanding ejecta.

Prompt Emission Properties

Quantifying the duration of a GRB is a non-trivial process - the typical quoted value of t_{90} is a measure of the time during 5-95% of the background-subtracted photons arrive at the detector. However, t_{90} depends on the sensitivity of the instrument (more sensitive instruments will have larger t_{90} values for a given GRB, due to the "tip of the iceberg" effect), the bandpass (GRBs typically have shorter durations at higher energies), and of course the source redshift (cosmological time dilation). So it is worth taking any measure of GRB "duration" with a grain of salt.

Nonetheless, it became clear very early on (Kouveliotou et al., 1993) that the distribution of the duration of GRBs was *bimodal* (Figure 3). For reasons discussed above, the exact dividing line depends on the properties of the instrument of interest. But classically the class of **short-duration GRBs** has been defined as those having a t_{90} duration of < 2 s.

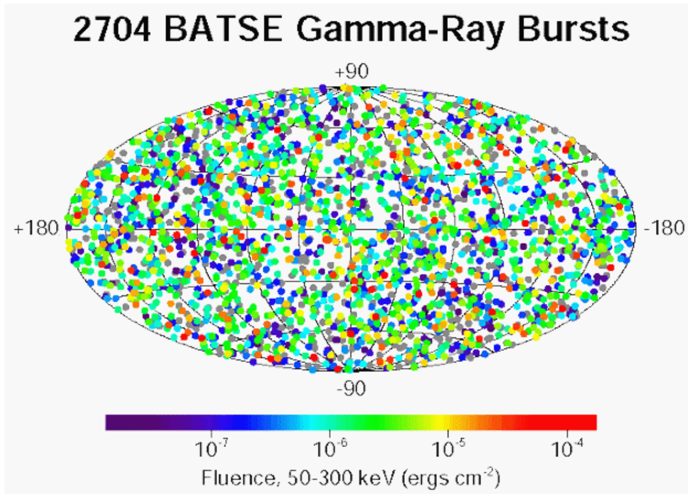

Figure 2: The spatial distribution of GRBs on the sky is isotropic (when plotted in Galactic coordinates), strongly favoring an extragalactic origin.

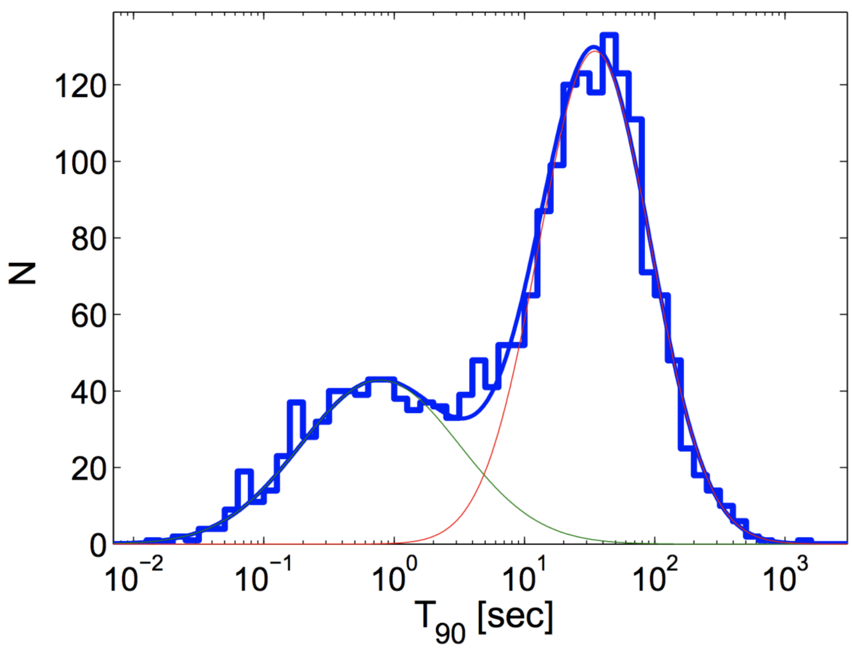

Figure 3: A histogram of the duration distribution of BATSE GRBs. A bimodal distribution is clearly evident, with the dividing line at ˜ 5 s. From (Nakar, 2007).

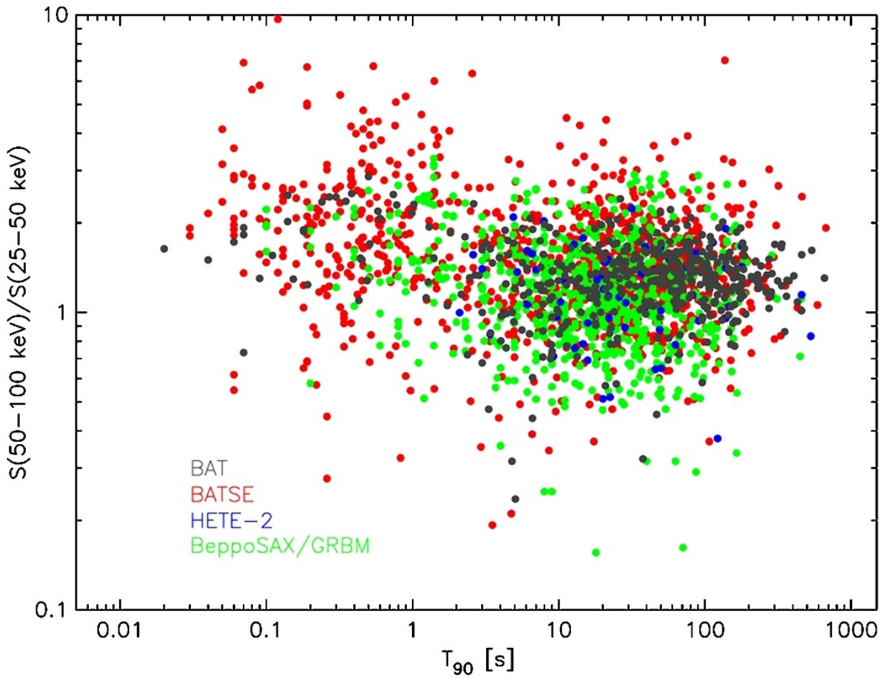

Figure 4: A duration vs. hardness ratio phase space plot for GRB prompt emission. The class of short-duration GRBs is clearly delineated from the long-soft bursts. From (Ghirlanda et al., 2011).

The time-integrated spectra of GRBs are well-described by a phenomenological model known as the Band function (Band et al., 1993):

$N_E(E) = AE^{\alpha}e^{-E/E_0}; E \leq (\alpha - \beta)E_0$
$N_E(E) = A((\alpha - \beta)E_0)^{\alpha-\beta}e^{\beta-\alpha}E^{\beta}; E > (\alpha - \beta)E_0$

The result is a shallow power-law slope with an exponential cut-off at E_0 (the peak energy output of the source), with a steeper power-law fall-off at high energies.

In addition to their smaller t_{90} values, short-duration GRBs also exhibit *harder* spectra (i.e., more high-energy photons relative to low-energy photons). This can be seen either by examining the distribution of E_0 values (which are systematically higher for short-duration GRBs, or by a more simple duration vs. hardness ratio phase space plot (Figure 4).

While a two-parameter (duration and spectral hardness) classification of GRBs has proven relatively effective at discriminating between different *progenitor* systems, it is worthwhile emphasizing that in reality the distinction can often be less clear. First, there is clearly overlap in the populations (Figure 3), and so some GRBs with $t_{90} < 2$ s will actually fall into the long-soft category. But more importantly, a number of what we consider “short” GRBs actually have a light curve with a short, hard spike, but also display longer-lived emission at higher energies as well. The most dramatic known example, shown in Figure 5, is GRB080503 (Perley et al., 2009), where the long tail actually contains a higher fluence than the short initial spike. Such events are now paradoxically referred to “short GRBs with extended emission”, a mouthful if ever there was one.

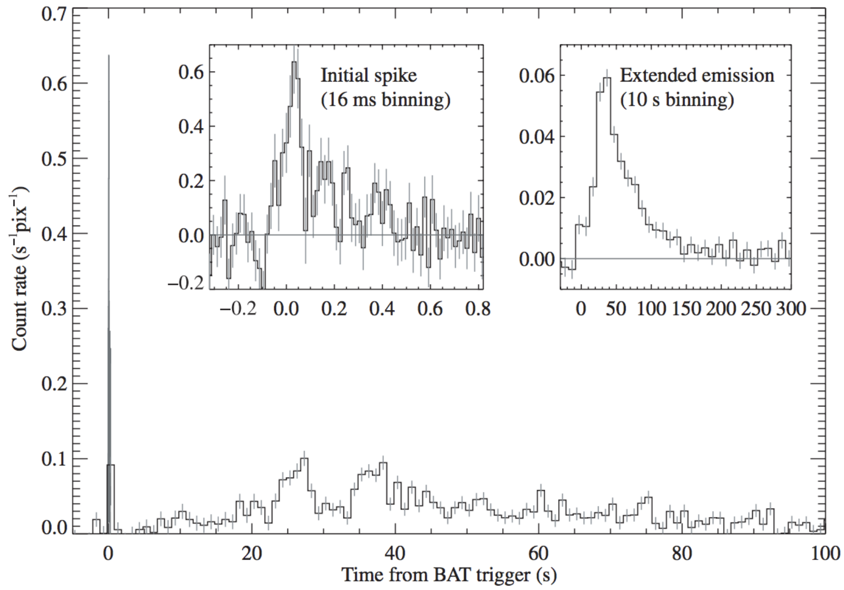

Figure 5: The gamma-ray light curve of GRB080503, a short GRB with extended emission. The total fluence in the extended emission is actually larger than that in the prompt spike. From (Perley et al., 2009).

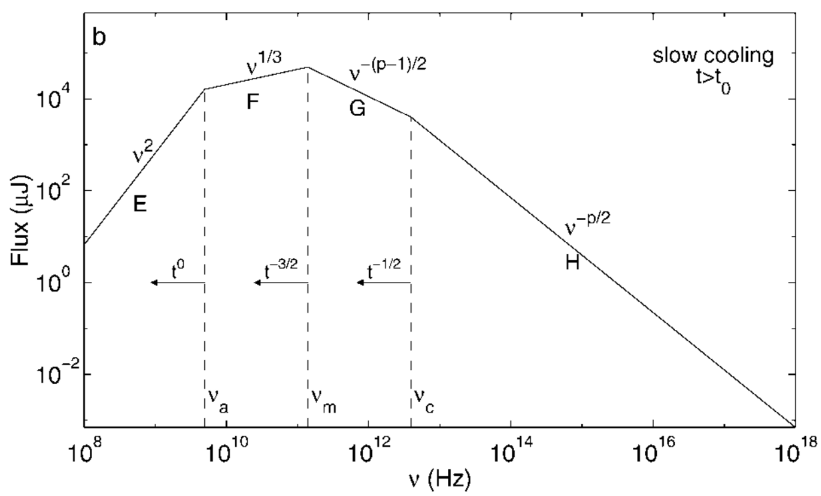

Figure 6: The broadband spectral energy distribution of the synchrotron emission powering a GRB afterglow. The characteristic frequencies are labled, and their evolution with time (for expansion into a constant density medium) is shown. From (Sari et al., 1998).

Afterglow Properties

Shortly after inference of ultra-relativistic ejecta in GRBs, it was realized that GRBs should also give rise to longer-lived, panchromatic emission that we call the "afterglow" (Meszaros and Rees, 1993). While the "prompt" gamma-ray emission arises from some process internal to the ejecta, the expanding blastwave will eventually accelerate electrons in the circumburst medium, which will then emit broadband synchrotron radiation. Confirmation of this prediction of X-ray, optical, and radio afterglows in 1997 following GRBs stands as one of the preeminent accomplishments of modern theoretical astrophysics.

The broadband spectrum resulting from this afterglow emission can be described in terms of three characteristic frequencies (Sari et al., 1998), shown for the "slow cooling" regime in Figure 6. For expansion into a constant density medium, these frequencies can be calculated as:

$$\begin{aligned}
\nu_a &\approx 2 \times 10^9 (1+z)^{-1} \epsilon_e^{-1} \epsilon_B^{1/5} n_0^{3/5} E_{52}^{1/5}\,\mathrm{Hz} \\
\nu_m &\approx 5 \times 10^{14} (1+z)^{1/2} \epsilon_e^{2} \epsilon_B^{1/2} E_{52}^{1/2} t_d^{-3/2}\,\mathrm{Hz} \\
\nu_c &\approx 8 \times 10^{12} (1+z)^{-1/2} \epsilon_B^{-3/2} n_0^{-1} E_{52}^{-1/2} t_d^{-1/2}\,\mathrm{Hz} \\
F_{\nu_a} &\approx 0.3 (1+z)^{1/2} \epsilon_e^{-1} \epsilon_B^{2/5} n_0^{7/10} E_{52}^{9/10} t_d^{1/2} d_{L,28}^{-2}\,\mathrm{mJy}
\end{aligned}$$

Here ϵ_e is the fraction of the total energy apportioned to electrons (assumed to be constant), ϵ_B is the fraction of energy apportioned to the magnetic field, n_0 is the density of the circumburst medium, E_{52} the kinetic energy of the afterglow, t_d the time since the burst (in days), and d_L the luminosity distance (in units of 10^{28} cm). Observations of both long- and short-duration GRB afterglows indicate $\epsilon_e \approx \epsilon_B \approx 0.1$. Typical values for short GRBs for the circumburst density are $n_0 = 0.1\,\mathrm{cm}^{-3}$, $E_{52} \sim E_{\gamma,\mathrm{iso},52} \sim 0.1$, and $z \approx 0.5$ (see below).

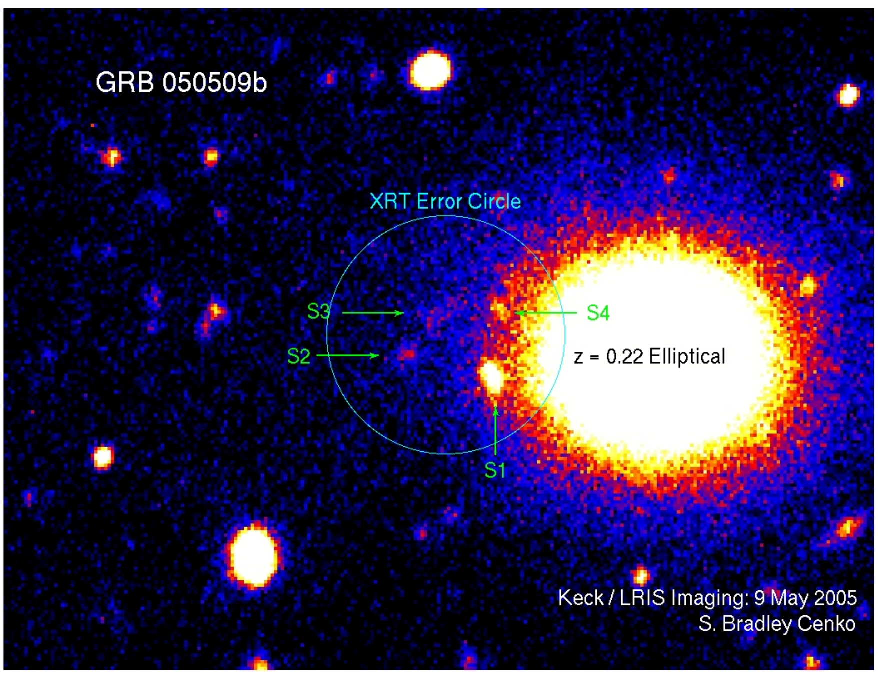

Figure 7: Optical imaging of the location of the short GRB050509B, the first short-duration GRB with an afterglow discovery. The massive, luminous elliptical galaxy at z=0.22 is the presumed host, unlike any host galaxy of a long GRB known to date.

Exercise 2: For typical short-duration GRB afterglow parameters, calculate the locations of the various break frequencies and the flux at X-ray (4e17 Hz), optical (4e14 Hz), and radio (4e9 Hz) wavelengths at a time of 12 hours after the burst. How do these sensitivities compare to various telescopes?

While the first afterglow of long-duration GRBs were discovered in 1997, it was not until nearly a decade later that the first afterglows of short GRBs were identified. Both the energy scale and density scale of the circumburst medium are significantly lower for short-duration GRBs, which make their afterglows significantly more challenging to detect. The first short-duration GRB with a long-wavelength counterpart was GRB050509B (Figure 7), where the X-ray afterglow (a mere 11 photons) was identified by the X-ray Telescope on the *Neil Gehrels Swift Observatory* (Gehrels et al., 2005). Shortly thereafter, the first optical (GRB050709) and radio (GRB050724) afterglows were discovered. Immediately the population of host galaxies was starkly different from the heavily star-forming galaxies that dominate the long-duration GRB population (see below).

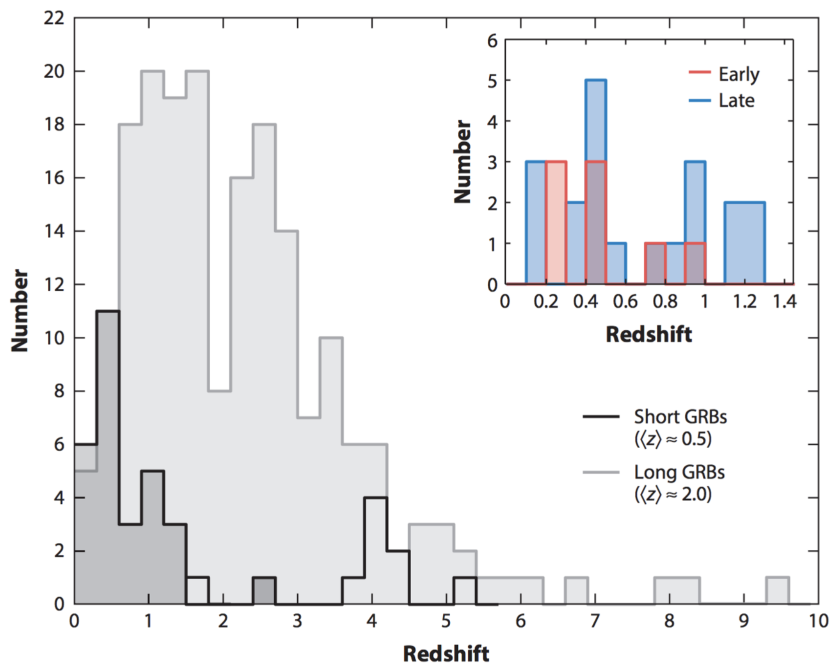

Figure 8: The redshift distribution of short GRBs (dark grey), compared to long GRB (light grey). The lower median redshift results from a combination of sensitivity effects and their longer progenitor delay time. From (Berger, 2014).

With afterglows came host galaxy identifications and thus redshifts, allowing us to establish the distance scale to these events for the first time. Unlikely long GRBs, which have massive star progenitors and thus live in dense regions of their hosts, we have only a single example of an absorption redshift for a short-duration GRB (GRB130603B). The remaining host associations are done probabilistically, an issue that we will return to in the next section.

The median redshift of short GRBs is ˜ 0.5, significantly smaller than the median redshift of long GRBs (<z> ˜ 2; Figure 8). The cause of this smaller average redshift is likely a combination of two factors: first, short GRBs are more challenging to detect than long ones (fewer photons for a fixed fluence), and so detector sensitivity almost certainly plays a role. But because of their old progenitor system, we expect an offset of

˜ 1 Gyr between the peak of cosmic star formation (z ˜ 3) and the time of merger.

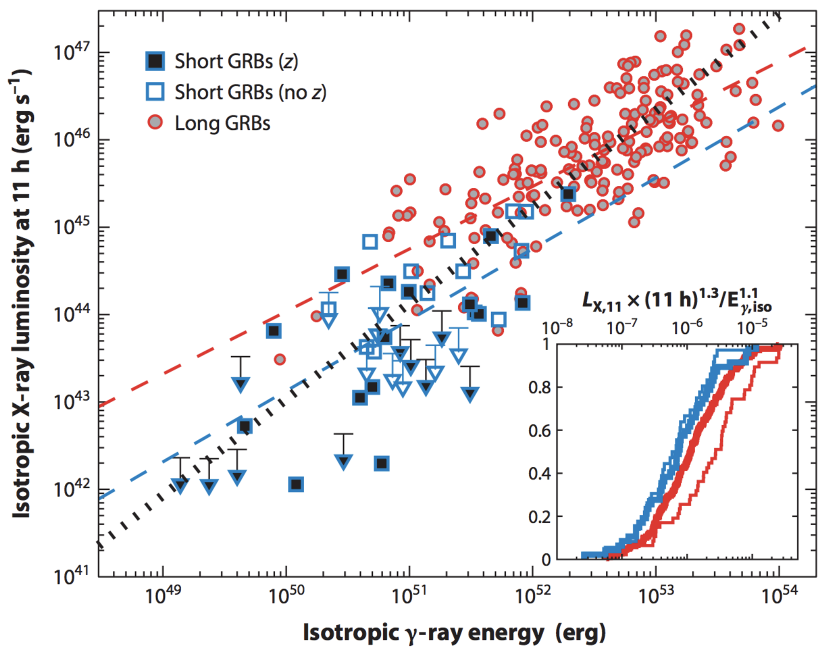

Figure 9: A comparison between the X-ray afterglow luminosity of short-duration (blue) and long-duration (red) GRBs. From (Berger, 2014).

For short-duration GRBs that are promptly (within ˜ 100 s) followed up by the X-Ray Telescope (XRT) on *Swift*, ˜ 80% have detectable X-ray emission. While this is a relatively large fraction, it is noticeably smaller than the fraction of long-duration GRBs, for which nearly every promptly followed burst is detected in X-rays. In fact the early X-ray emission from some short GRBs fades extremely rapidly, becoming undetectable by the XRT within ˜ 1000 s. It is not clear if the X-ray emission in this case is bona fide afterglow emission, or simply the high-latitude tail of the prompt gamma-rays rays.

In Figure 9 we plot the ratio of the X-ray luminosity at 11 hours after the burst (sufficiently late to be dominated by the afterglow) as a function of the isotropic gamma-ray energy release, both for long (red) and short (GRBs). It is immediately clear that X-ray afterglows of short-duration GRBs are intrinsically fainter than those of long-duration GRBs, even after correcting for the prompt energy release in gamma-rays. The dotted black line shows the expected correlation from synchrotron radiation with $\nu_X > \nu_c$: $L_X \propto E_K^{1.1}$, while the dashed red and blue lines show the best fit relation for long and short GRBs, respectively. The inset shows the distribution of the ratio of $L_X/E_K^{1.1}$ for both samples (thick lines for the full sample, thin for the region of overlap in $E_{\gamma,\rm iso}$).

A similar phenomena is observed at optical wavelengths, where the optical afterglows of short-duration GRBs are systematically fainter than those of their long-duration brethren (Figure 10). In fact the median brightness of a short-duration GRB optical afterglow at 7 hr after the trigger, r 23 mag, means that only moderate and large-aperture facilities are sufficiently sensitive to detect their optical emission at this time. Continuum spectroscopy for such a source is not feasible even with the largest optical facilities currently available (e.g., Keck, VLT). For $\nu_m < \nu_{opt} < \nu_c$, the expected relation is $L_{opt} \propto E_K^{1.4}$ (black dotted line), which matches the observed data for both long- and short-duration GRBs reasonably well.

To date, only four short-duration GRBs have detected radio counterparts (Fong et al., 2015) compared to

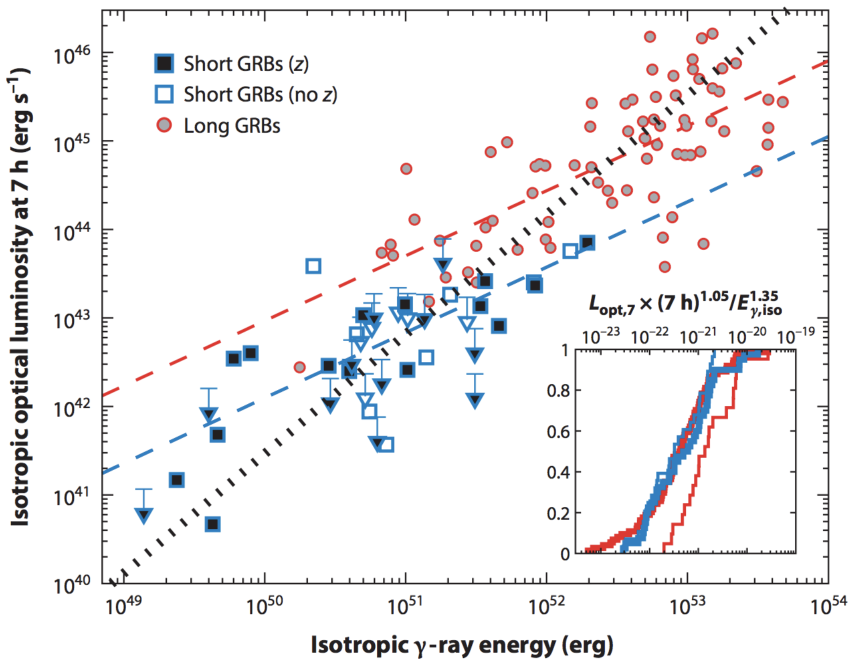

Figure 10: Same as Figure 9, but for optical luminosity (instead of X-ray). From (Berger, 2014).

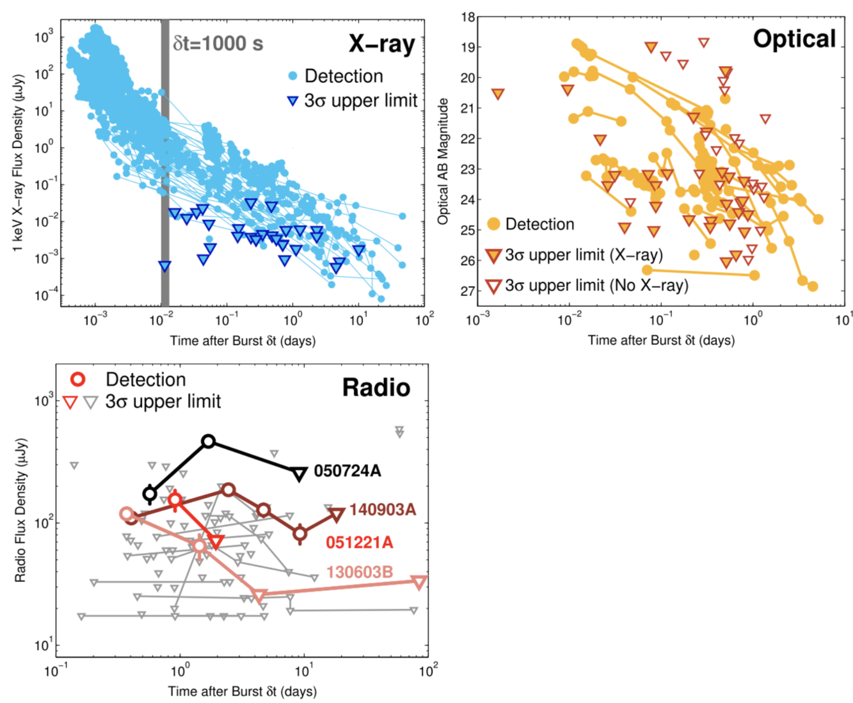

Figure 11: Compilation of X-ray, optical, and radio light curves of short-duration GRBs. From (Fong et al., 2015).

many dozen radio counterparts to long-duration GRBs (Chandra and Frail, 2012). This is almost certainly the result of the lower circumburst densities in the environments of short-duration GRBs, as the radio emission is extremely sensitive to circumburst density (Sari et al., 1998). Figure 11 displays the X-ray, optical, and radio light curves of all short GRBs in the *Swift* era, again highlighting the relative paucity of radio detections.

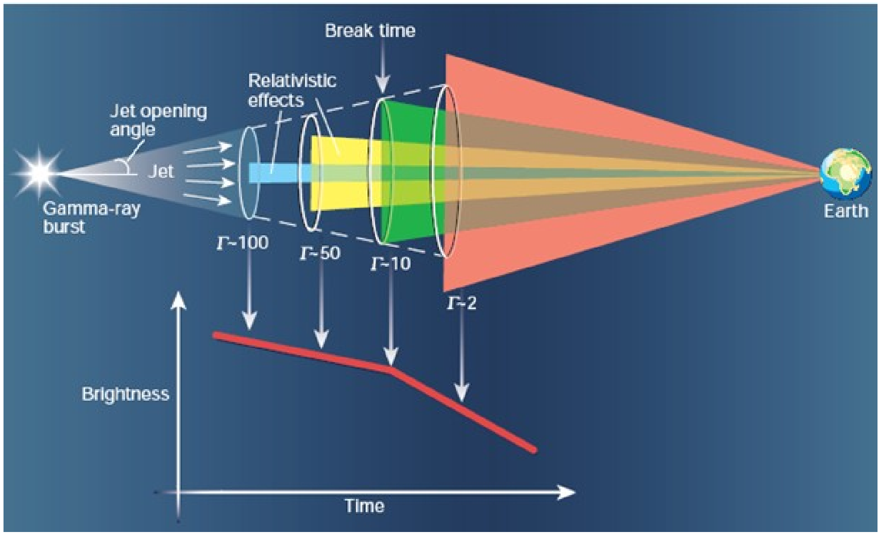

Figure 12: Beaming in GRBs. At early times, when the outflow is highly relativistic, the observer only notices emission from a small fraction of the jet. An achromatic steepening (jet break) results when the Lorentz factor decreases below the inverse of the jet opening angle.

Finally, it is widely held that long-duration GRBs are *highly collimated* explosions: bi-conical jets with opening angles ranging from several to several tens of degrees (Sari et al., 1999). At early times, when the Lorentz factor of the outflow is very high, observers will not realize that they are viewing a collimated outflow due to relativistic beaming. However, as the jet sweeps up material and slows down, observers will be able to see larger and larger fractions of the jet. Eventually, when the Lorentz factor is equal to the inverse of the jet opening angle, the jet will begin to spread laterally and observers will notice "missing" emission from wider angles. This transition is known as a *jet break*, and results in an achromatic steepening of the afterglow light curve.

While there are many fewer panchromatic examples than long GRBs, and handful of short-duration events now have opening angles inferred from jet break measurements. While still somewhat preliminary, the results to date imply a typical opening angle for short GRBs of ˜ 15 deg, which is comparable to (though perhaps a bit larger than) the population of long events (Fong et al., 2015).

Host Galaxy Properties

While the afterglows of short-duration GRBs provide valuable diagnostics, because of the ultra-relativistic nature of the outflows, the afterglow is largely decoupled from the so-called "central engine" ultimately powering these explosions. However, properties of the environment of these explosions - both the galaxies in which short-duration GRBs explode, and their location within these galaxies - can provide even more powerful (albeit circumstantial) evidence as to their origins.

Long-duration GRBs serve as a useful reference point, both for comparison and as an instructive example of the utility of such an approach (Perley et al., 2016). Compared both to the host galaxies of other stellar

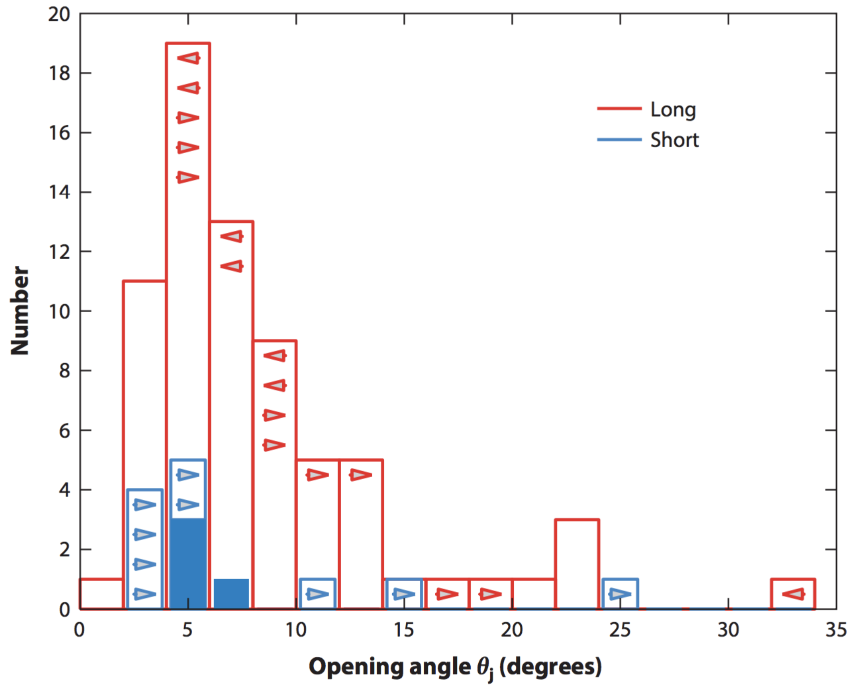

Figure 13: The distribution of opening angles in short- and long-duration GRBs. From (Berger, 2014).

explosions (e.g., core-collapse supernovae) and (to a lesser extent) the broader population of star-forming galaxies, long-duration GRB occur in galaxies that are lower in (stellar) mass, lower in metallicity, and higher in specific star-formation rate (star formation per unit mass). The morphology is often irregular. Long GRBs may also prefer compact galaxies, and dense and/or central regions of galaxies, more than other types of core-collapse explosion. They trace the UV light within their hosts more closely than other cosmic explosions. All of these properties are consistent with a young, massive, and likely low metallicity progenitor - perhaps some of the most extreme (and rapidly rotating) massive stars in the Universe explode as long-duration GRBs (Figure 14).

Even after the discovery of the first few afterglows of short-duration GRBs, it was apparent that they reside in a much broader range of galaxies than their long-duration cousins. With reasonable sample sizes now in hand, we have learned that short GRBs can explode in star-forming galaxies, elliptical galaxies, and even on some occasions far away from any potential host (making identification quite challenging). This directly indicates that their progenitors span a wide range of ages, potentially up to several Gyr. Because stellar mass is split approximately evenly between early- and late-type galaxies at $z < 1$, a population that exclusively traced stellar mass would be expected to have a roughly even split in host galaxy type. The fact that more short-duration GRBs occur in late-type galaxies (Figure 15) indicates that there is some correlation with ongoing star formation for short-duration GRBs. However, the limits on the typical progenitor ages derived from this mix indicate a broad range, much larger than observed for long-duration GRBs.

The median stellar mass of short-duration GRB host galaxies is $\approx 10^{10}\,M_{\odot}$, about an order of magnitude larger than the analogous value for long-duration GRBs (Figure 16). When compared with field galaxies, the overall distribution is skewed slightly towards lower stellar masses. A careful examination indicates this is due entirely to the events in late-type hosts – the mass distribution in early-type hosts tracks field galaxies extremely well. Again this points towards some role for ongoing star formation in determining the rate of short-duration GRBs.

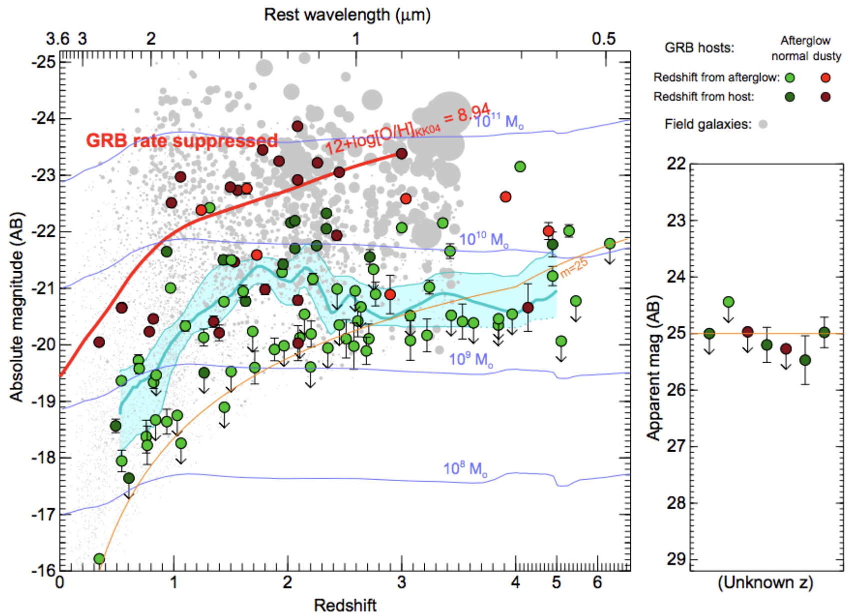

Figure 14: The near-infrared (NIR) luminosity of long-duration GRB host galaxies as a function of redshift, compared to star-forming galaxies (gray). The NIR luminosity can be used as a stellar mass proxy: the horizontal blue curves indicate equivalent stellar masses. GRBs sample galaxies of all masses and redshifts, but rarely occur in the most luminous galaxies, especially at low redshift ($z < 1.5$). This is probably because GRBs are strongly suppressed in metal-rich galaxies, leading to a soft "upper limit" on the host stellar mass that increases with z due to the evolving mass-metallicity relation: the red curve shows the luminosity of a galaxy at the metallicity threshold of 12+log[O/H]=8.94. The strong correlation between host luminosity and the degree of attenuation of the afterglow can also be seen: nearly all GRBs with dusty or "dark" afterglows are hosted within galaxies at the upper end of the mass distribution. From (Perley et al., 2016).

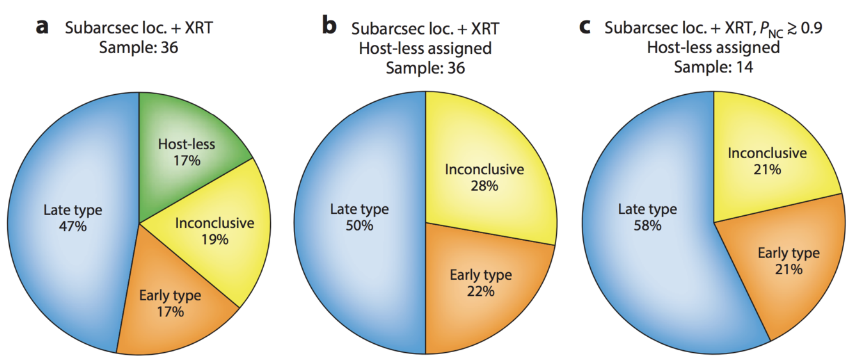

Figure 15: Demographics of the host galaxies of short-duration GRBs. Unlike long GRBs, which occur exclusively in star-forming (late-type) galaxies, short GRBs have been found in both star-forming galaxies and ellipticals. The relative ratio of late- to early- type of ˜ 2:1 indicates some correlation with ongoing star-formation and a broad range of progenitor delay times (up to at least several Gyr).

The difference between long and short GRB hosts is also apparent in the distribution of stellar populations in these galaxies. Consistent with their exclusive origin in early-type galaxies, long-duration GRBs have populations of stars with typical ages of 60 Myr. Short-duration GRBs have (on average) older stellar

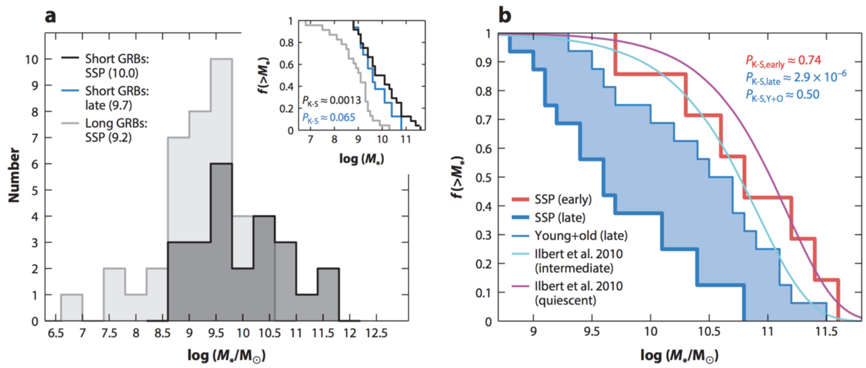

Figure 16: Left: Stellar masses in short-duration (dark gray) and long-duration (light gray) GRB host galaxies. On average, short-duration GRB hosts are approximately one order of magnitude more massive. Right: Stellar mass distribution compared with field galaxies. From (Berger, 2014).

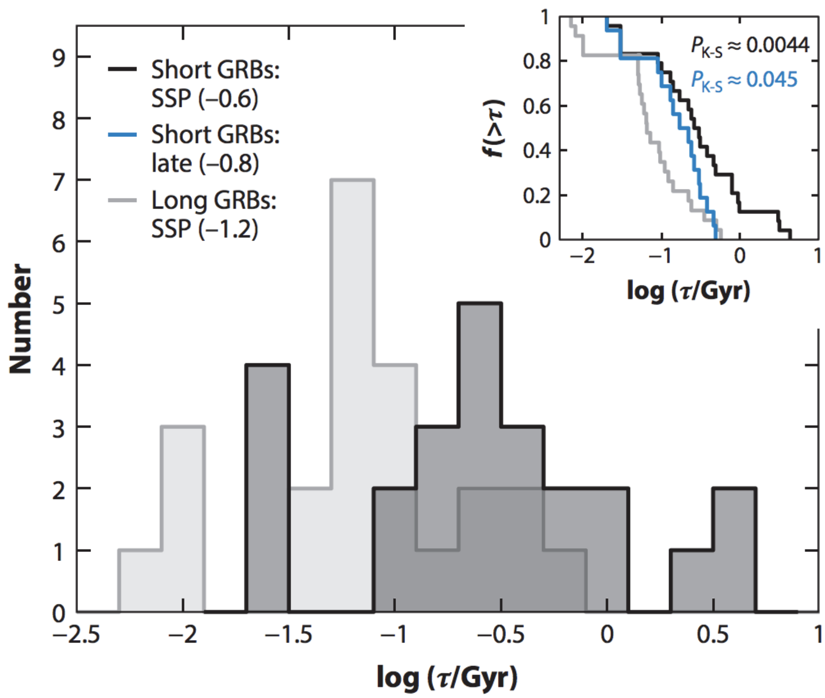

Figure 17: Stellar ages (assuming a single stellar population) for short-duration (dark gray) and long-duration (light gray) GRB host galaxies. Short GRBs arise in hosts with older stars, again pointing towards a more long-lived progenitor. From (Berger, 2014).

populations, in some cases extending out to several Gyr (Figure 17). While such modeling typically assumes a single stellar population, it nonetheless reinforces the picture of short-duration GRB hosts as arising from an older stellar population.

Long-duration GRBs stand out most when compared with the field population in terms of their specific star formation, or star formation per unit mass. Because they often explode in dwarf (i.e., low mass) galaxies, the total star formation rate is not particularly elevated. But per unit mass, their host galaxies are some of

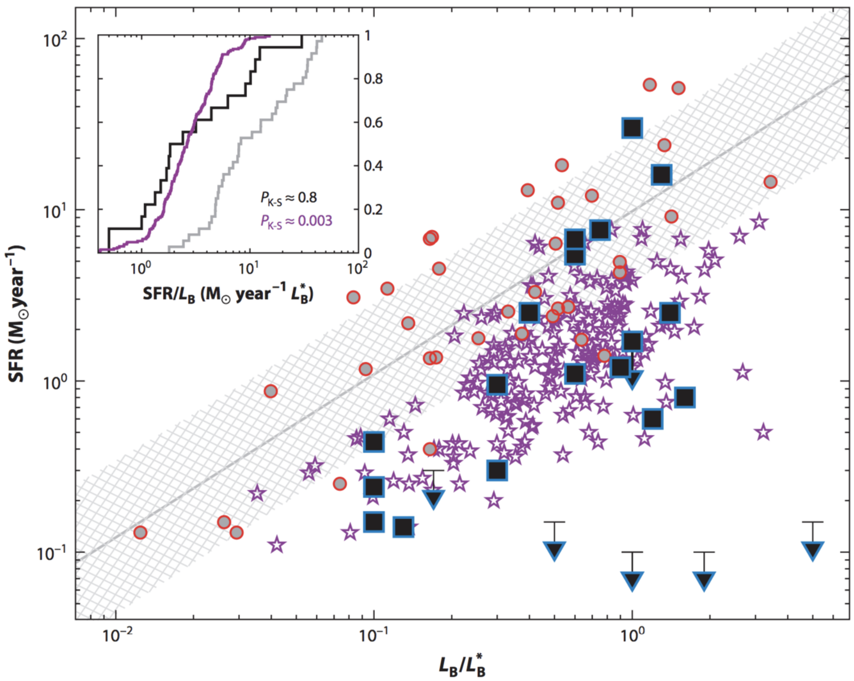

Figure 18: The star-formation rate (SFR) as a function of rest-frame B-band luminosity for long-duration GRBs (circles), short-duration GRBs (squares), and field galaxies (stars). The gray line indicates the correlation for long GRBs. Short GRBs have lower SFRs for a fixed luminosity, indicating a longer characteristic time scale associated with the star formation in these galaxies. The inset shows the distribution of specific star formation (star formation per unit mass), where short-duration GRBs are very similar to field galaxies. From (Berger, 2014).

the most extreme star-forming galaxies in the Universe. While they have comparable B-band luminosities, short-duration GRBs span a much larger range of star formation rates. As a result, the median specific star-formation rate of short-duration GRB hosts is a factor of ˜ 7 less, and is quite comparable to that in field galaxies. Because the specific star formation rate is the inverse of the characteristic time scale to build up a galaxy's stellar mass, the smaller values in short-duration GRBs indicates that the progenitors track star-formation with a delay of hundreds of millions to several billion years..

Unlike long-duration GRBs, short-duration hosts span a wide range of gas phases metallicities, from sub- to super-solar. The median value of $12 + \log(\mathrm{O/H}) = 8.8$ corresponds to approximately solar metallicity. In addition, though with limited statistics, the metallicities generally trace the relation between metallicity and luminosity known as the mass-metallicity relationship (Tremonti et al., 2004). Based on this result, it does not appear that short-duration GRB progenitors are affected by their host galaxy metallicities (Figure 19).

While the host galaxies of short-duration GRBs tell a relatively consistent story, perhaps the strongest circumstantial evidence connecting them to binary neutron star mergers comes from the distribution of offsets, i.e., the distance of the GRB from its host nucleus. Because their massive star progenitors have very short lifetimes, long-duration GRBs explode in the dense star forming regions in which they were formed. As a result, the typical physical offset for a long-duration GRB is quite small, ˜ 1 kpc. Longer-lived progenitors, particularly those with large kick velocities, would naturally be expected to have larger physical offsets (Bloom et al., 2002).

An important caveat for events with large kicks and offsets is that unique association with a host galaxy can

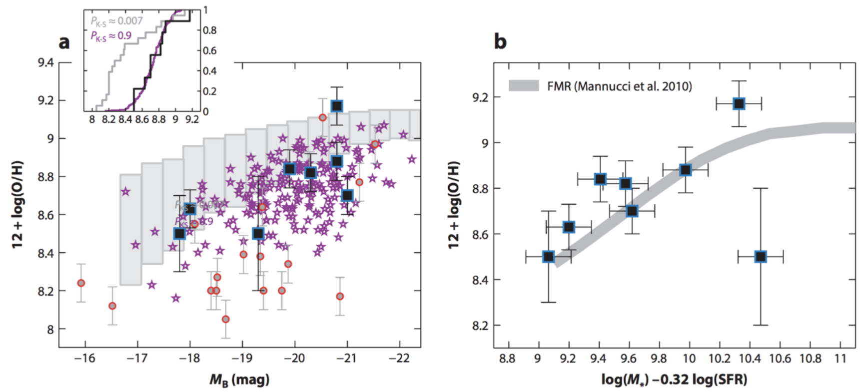

Figure 19: Left: Gas phase metallicity as a function of B-band luminosity. Long-duration GRBs show a clear preference for low metallicity environments. Short-duration GRBs, on the other hand, track field galaxies reasonably well. Right: Comparison of short-duration GRB hosts to the fundamental metallicity relation of star-forming galaxies (gray lines), which uses a combination of star-formation rate and stellar mass. From (Berger, 2014).

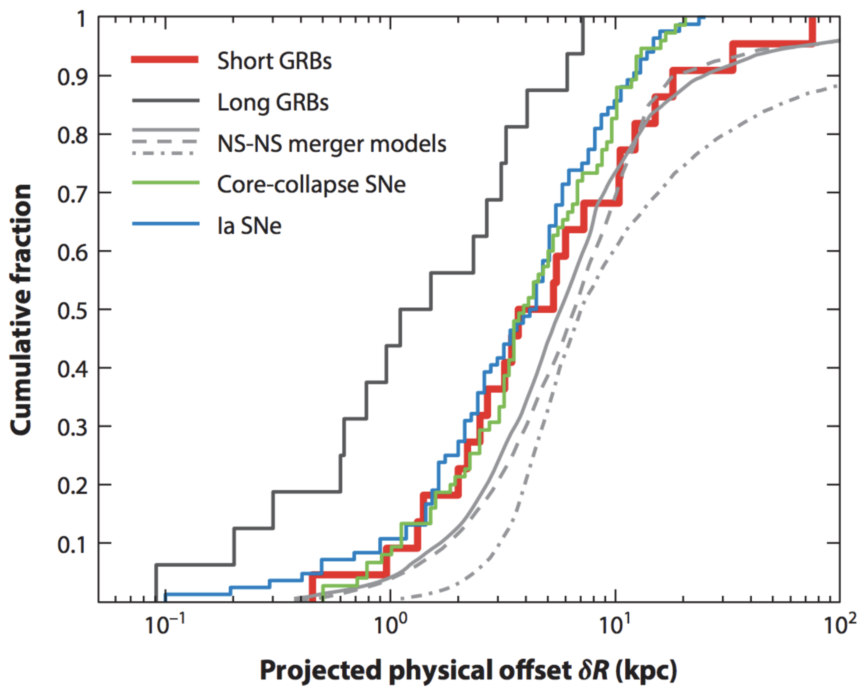

Figure 20: Projected offsets for long-duration GRBs (black), short-duration GRBs (red), core-collapse supernovae (green), and type Ia (white dwarf progenitor) supernovae (blue). Short-duration GRBs have much larger offsets than any other stellar explosion, indicating an older population and (likely) a large kick velocity imparted at birth. Remarkably, the distribution is quite similar to predictions from population synthesis models of binary neutron star mergers. From (Fong and Berger, 2013).

become challenging. It is therefore critical to evaluate the probability of chance coincidence when measuring offsets between short-duration GRBs and potential host galaxies. This value, P_c, can be calculated as:

$$P_c = 1 - e^{-\pi(\delta R)^2 \Sigma(\leq m)}$$

where δR is the projected offset (in arcseconds) and $\Sigma(\leq m)$ is the sky density of galaxies brighter than magnitude m.

Exercise 3: Calculate the projected offset at which the probability of chance coincidence reaches 10% for galaxies with magnitudes of r = 21, 23, and 25 mag. How does this compare to typical short GRB localizations?

With this caveat in mind, the projected offset distribution for short-duration GRBs is plotted in Figure 20. Observed values to date range from 0.5-75 kpc, with a median of 5 kpc (i.e., 5x larger than long-duration GRBs). *Remarkably, the short-duration GRB offset distribution matches well with predictions from population synthesis models of binary neutron star mergers.*

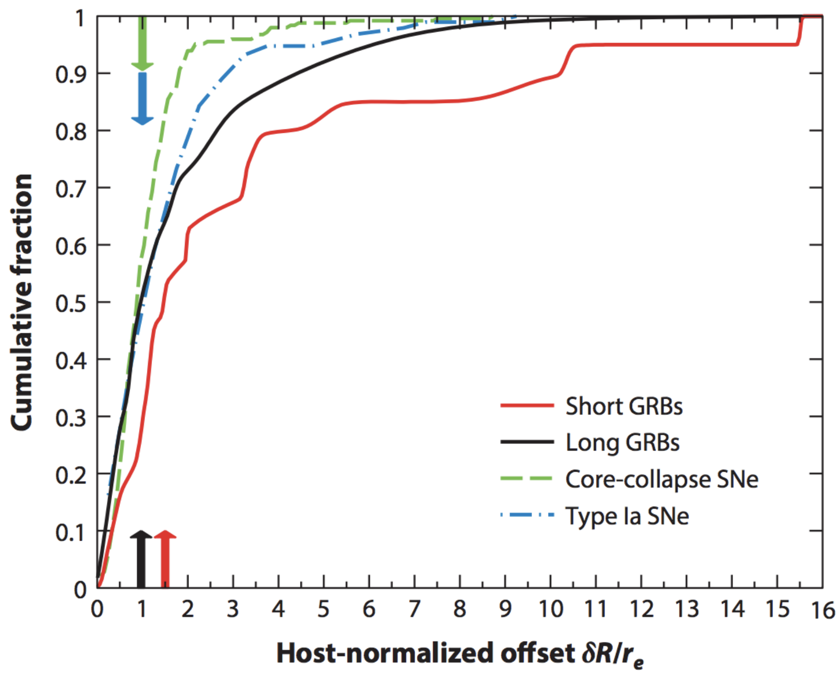

Figure 21: Host-normalized offsets of stellar explosions. Short-duration GRBs have significantly larger host offsets, even when accounting for their larger hosts. From (Fong and Berger, 2013).

As a sanity check, we also consider the effect of host galaxy size (i.e, effective radius) on the offset distribution. Short GRBs tend to be larger than long-duration GRBs, due to their larger stellar mass and luminosity. In Figure 21 we plot the host-normalized offset for the same population of stellar explosions. For long-duration GRBs and core-collapse SNe, the median normalized offset is ˜ 1, as would be expected for progenitors with short delay times (as they have no time to migrate from where they are born). Short-duration GRBs, on the other hand, have a typical host-normalized offset of ˜ 1.5, with a sizable fraction of events at very large normalized offsets.

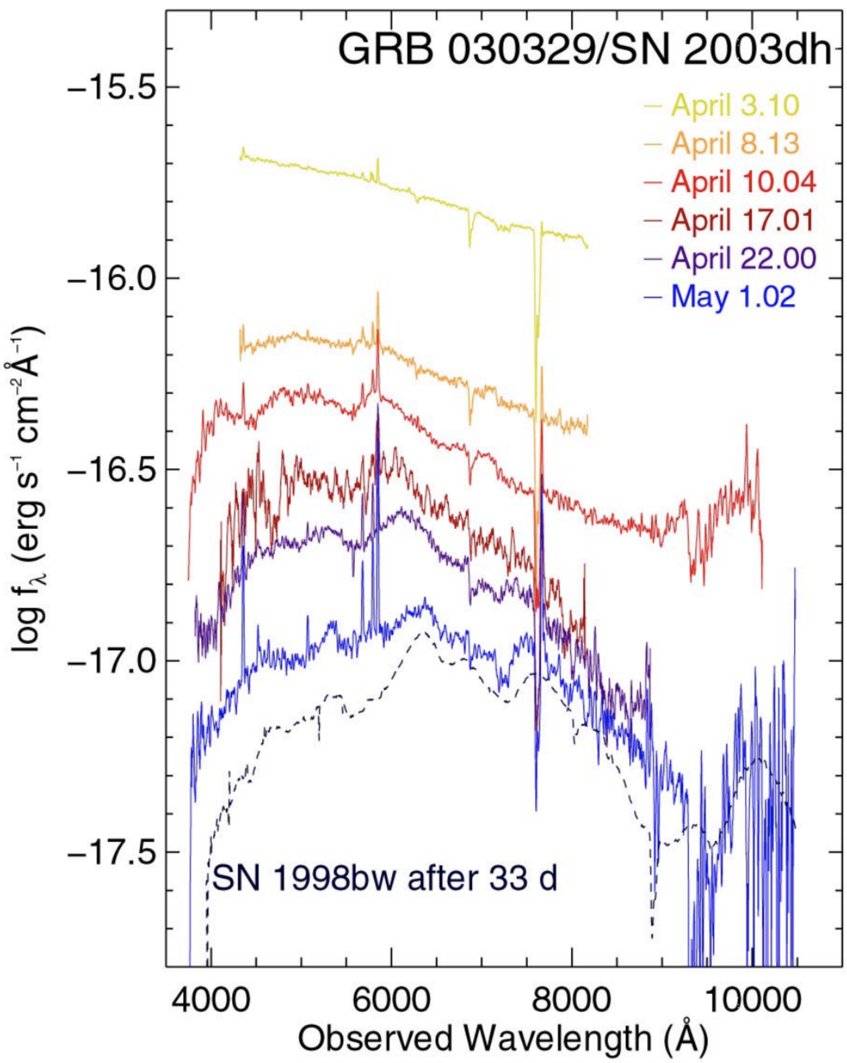

Figure 22: The emergence of broad supernova features in the nearby GRB030329. Initially the spectrum is dominated by a power-law component resulting from the synchrotron afterglow. As this fades at late times, broad features indicative of a high-velocity (but not relativistic) outflow become apparent, resembling those observed in SN1998bw. From (Hjorth et al., 2003).

Smoking Gun Evidence: Analogs of Supernovae in Long-Duration GRBs?

Both the afterglows and host galaxies of long-duration GRBs provided powerful circumstantial evidence for a massive star progenitor. However, direct confirmation of this association required a smoking gun signature, in this case the appearance of a (relatively rare) type of core-collapse supernovae in the late-time light curve of nearby long-duration GRBs (Figure 22). The discovery of a so-called broad-lined type Ic supernova in the days and weeks following nearby long-duration GRBs put to rest any doubt as to the origin of these events (Hjorth and Bloom).

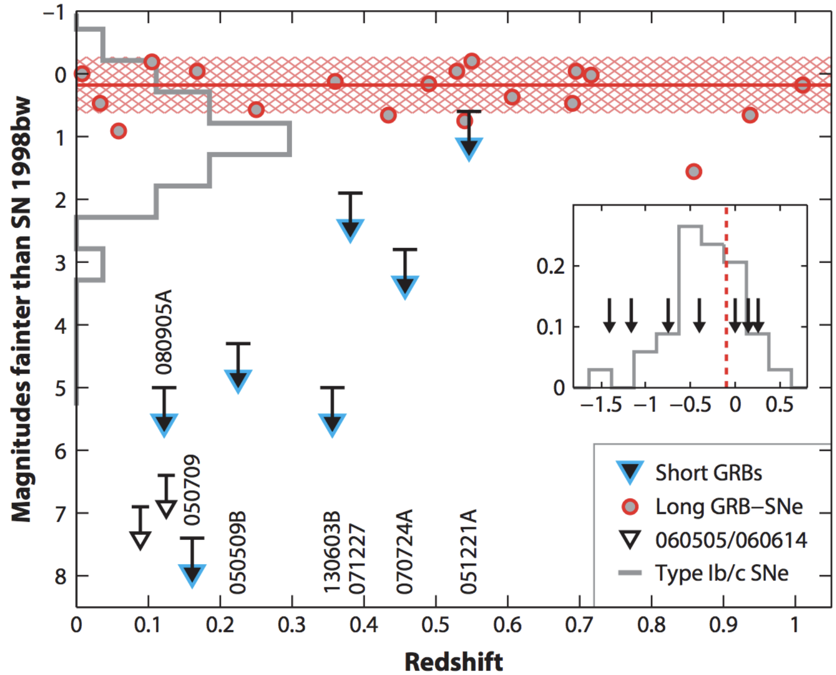

Figure 23: Limits on supernova emission from short-duration GRBs. From (Berger, 2014).

Deep searches on relevant time scales (1-2 weeks) have revealed no such supernova-like signatures from short-durations GRBs (Figure 23). In some cases, the limits are 7 magnitudes (1000x) deeper than the canonical GRB-associated supernova: SN1998bw. This definitively rules out a supernova progenitor for short-duration GRBs.

But, if supernovae are not present in the late-time light curves of short-duration GRBs, is there another smoking gun signatures that unambiguously identify their progenitors? We'll return to this question in our next lecture, when we introduce the concept of a **kilonova.**

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