The host galaxies of short GRBs

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Swift & Short GRBs

Since launch, *Swift* detected ~130 short GRBs (~10/yr)

- ~15% with an extended emission

- ~75% with a X-ray afterglow detected

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

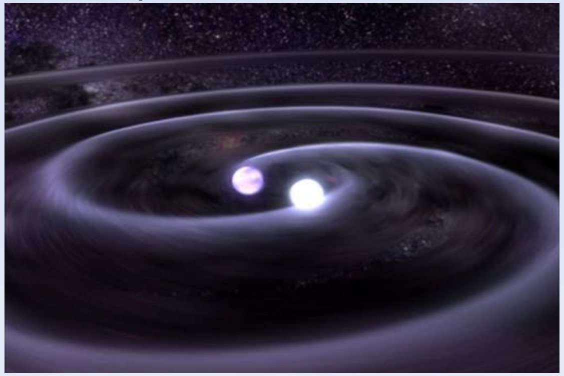
- ~35% with an optical afterglow detected

- ~5% with a radio afterglow detected

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

A lot of science cases related to short GRBs

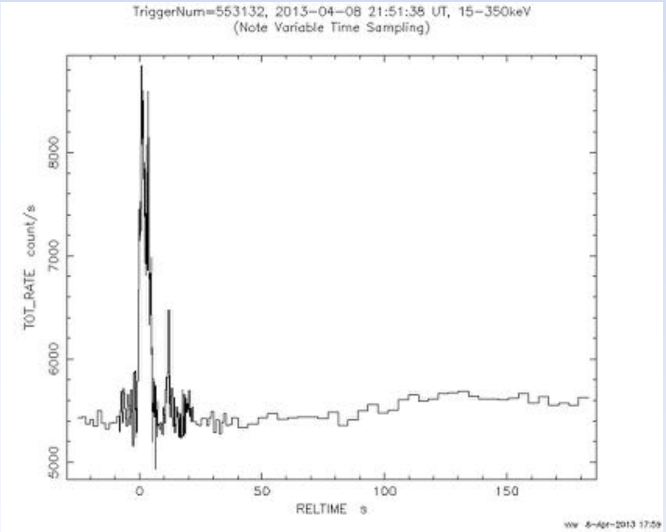
Main issue: the quest for progenitors

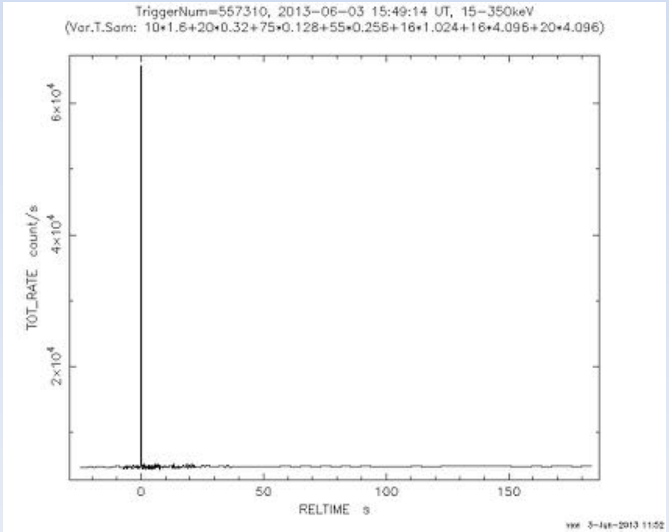


GRB progenitors

Long/soft GRBs
collapsar progenitor model

Short/hard GRBs
merger progenitor model





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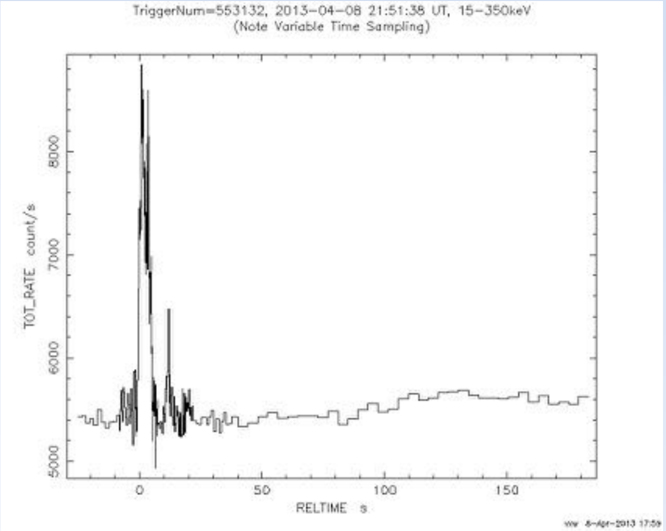
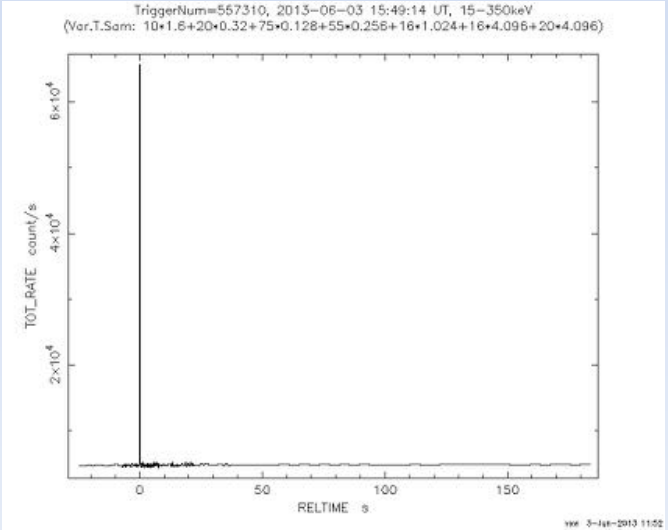
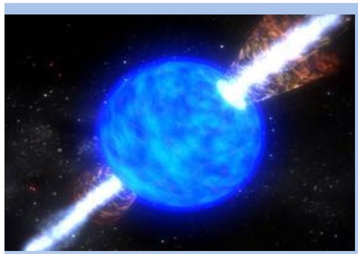
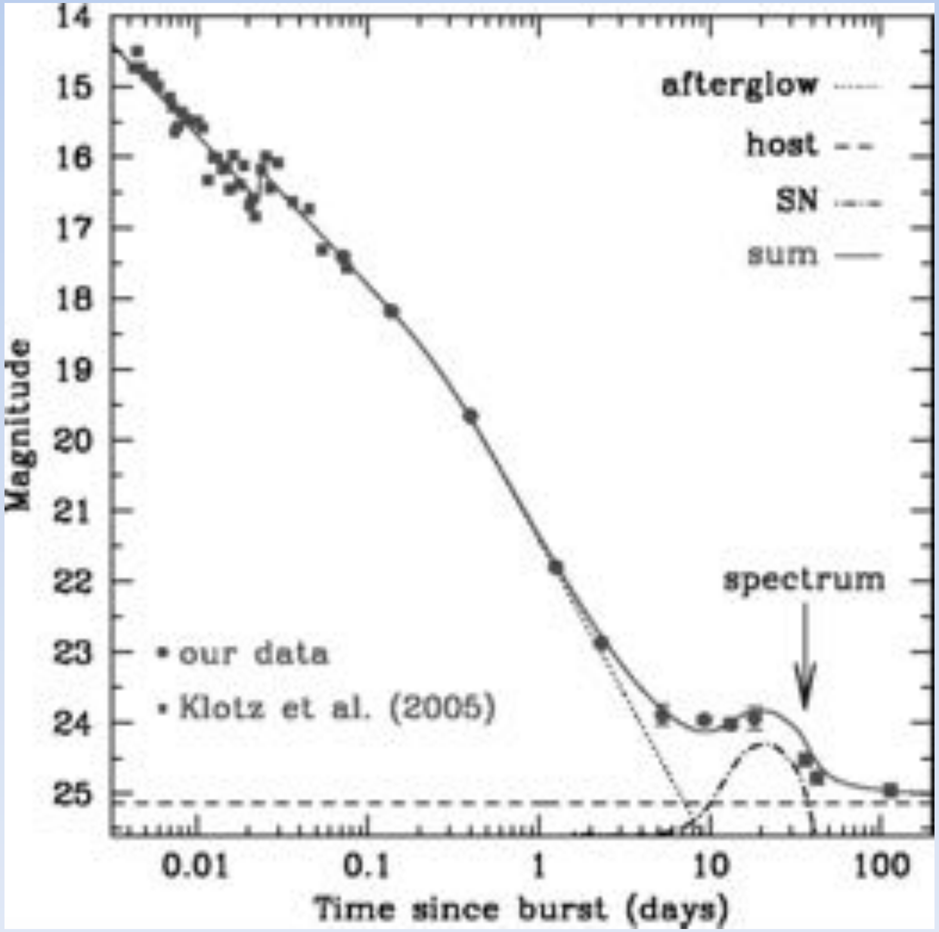


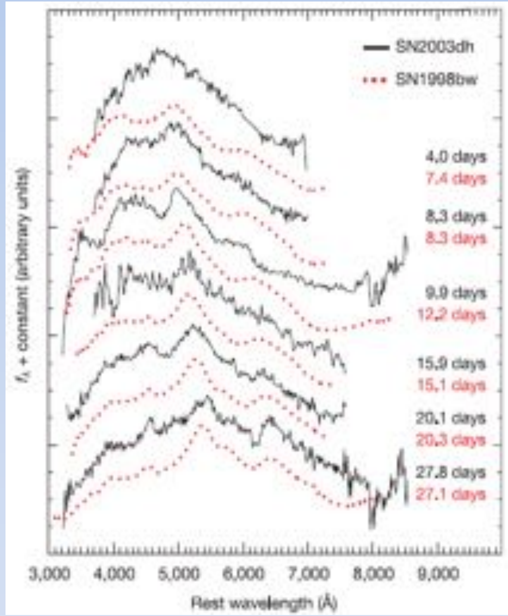
Short/hard GRBs
merger progenitor model

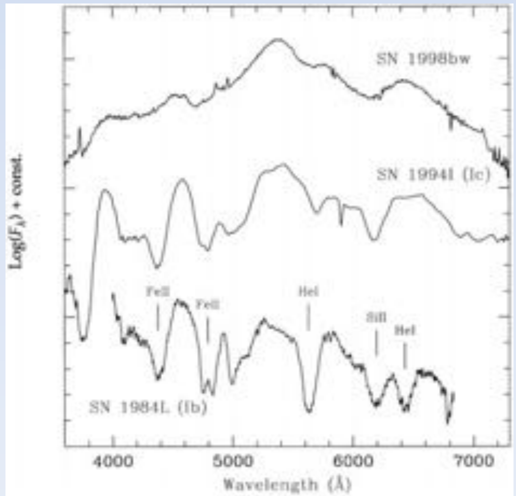




Long GRB & Supernovae



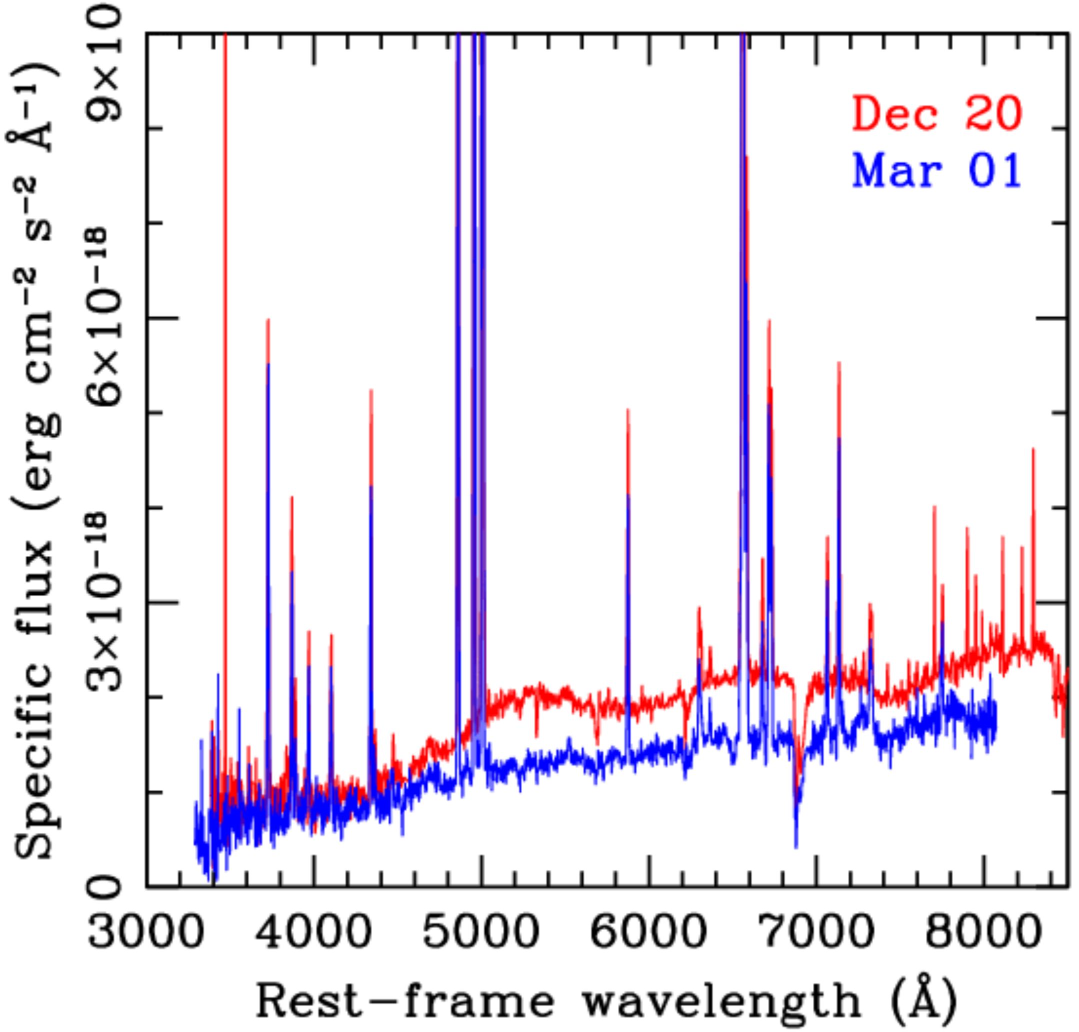


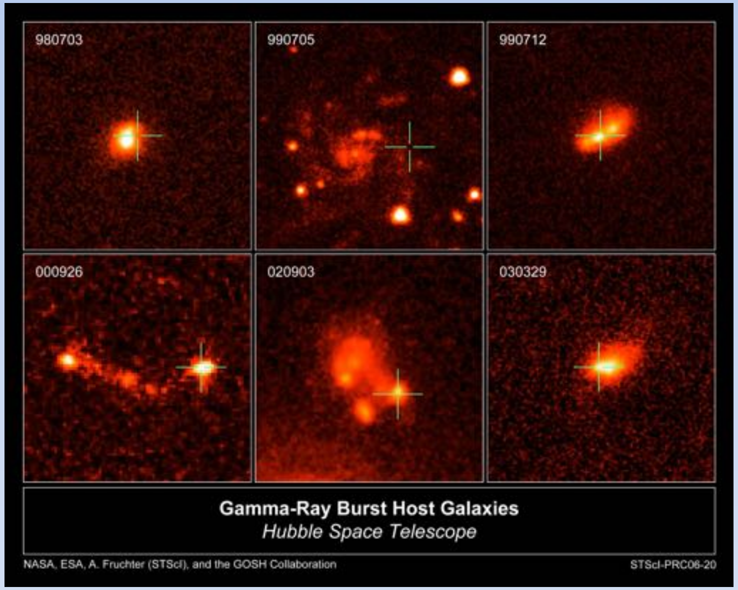


Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003; Della Valle et al. 2003; Malesani et al. 2004; Soderberg et al. 2005; Pian et al. 2006; Campana et al. 2006; Della Valle et al. 2006, Bufano et al. 2012, Melandri et al. 2012, Schulze et al. 2014, Melandri et al. 2014 and many others…

Long GRB hosts

Emission line spectra





Nebular emission lines excited by hot, young stars

Blue

⇔

Hot

⇔

Young stars

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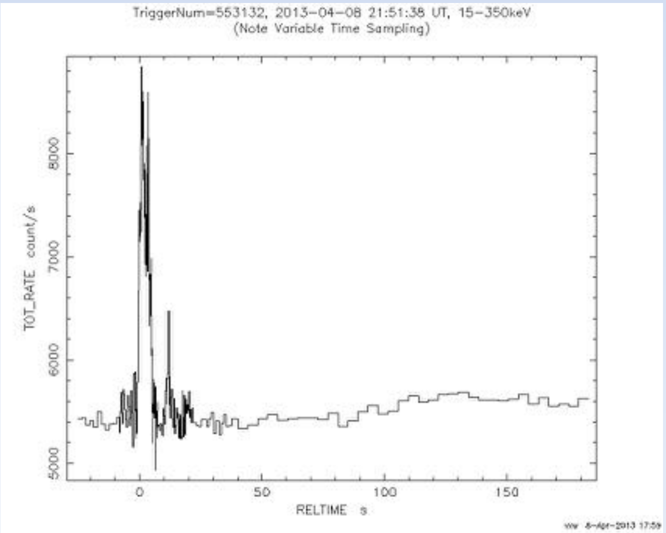
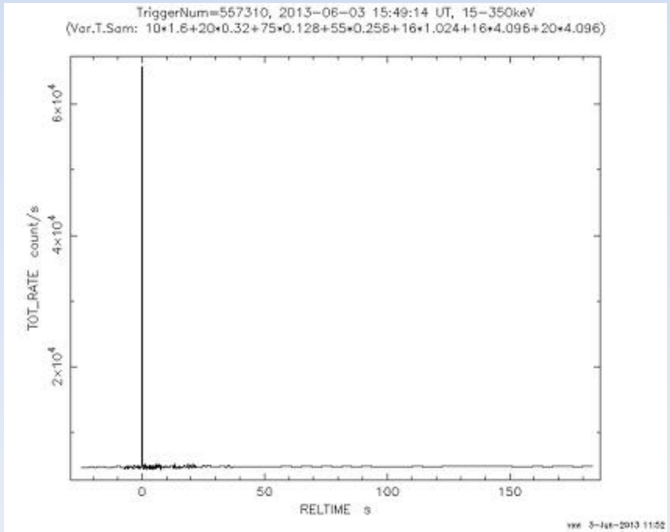
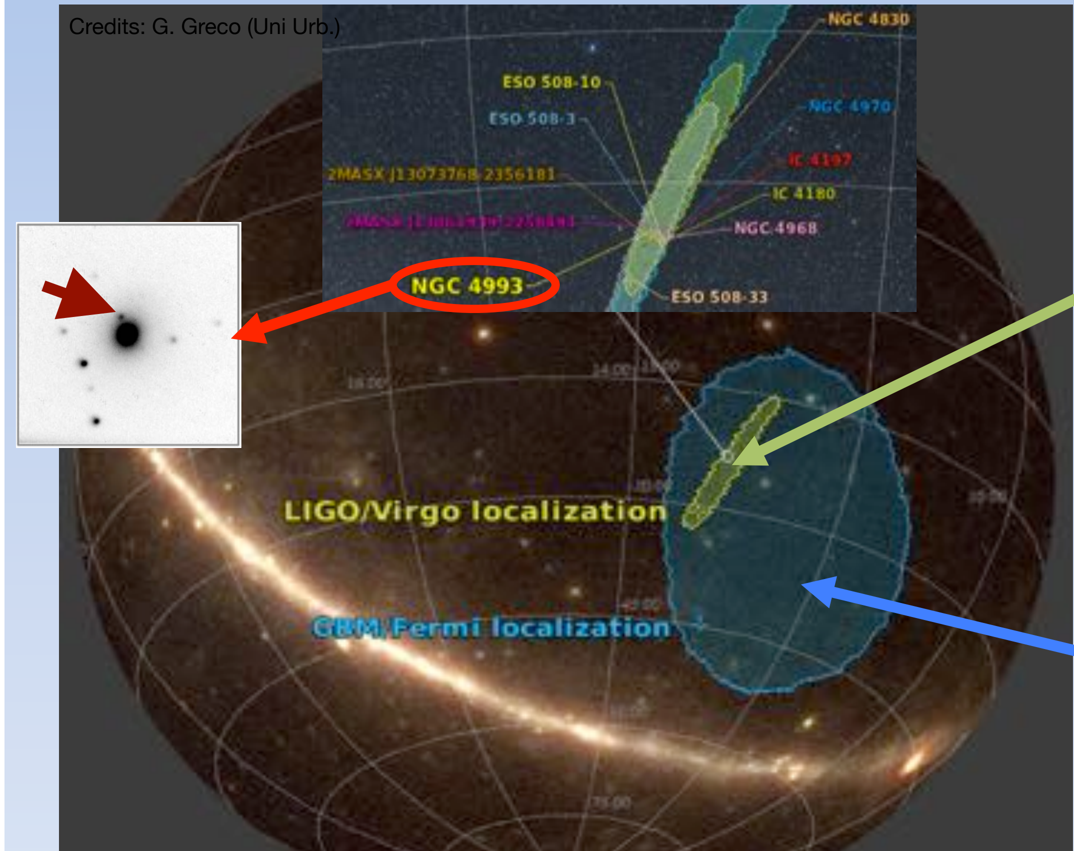
Short/hard GRBs

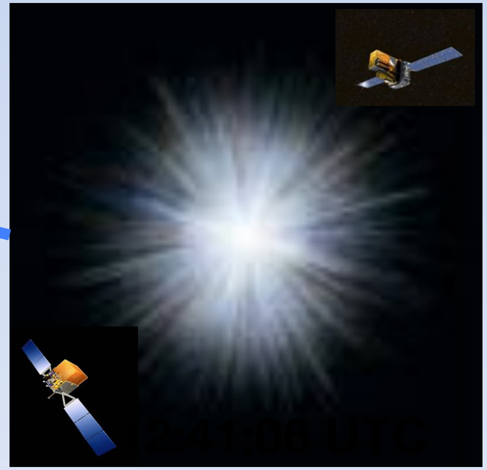
merger progenitor model





GW 170817 & GRB 170817A





PRL 119, 161101 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc

Compact object mergers: what we do expect

Diverse delay times:
- A mix of early and late type host galaxies

Kicks/migration from birth site:
- Offsets
- No correlation with UV/optical HG light
- Diversity in the environment (ev. channel)

No associated supernova

Remnant (magnetar/BH?)

Emission geometry (jet?)

Kilonova/macronova association

Gravitational waves

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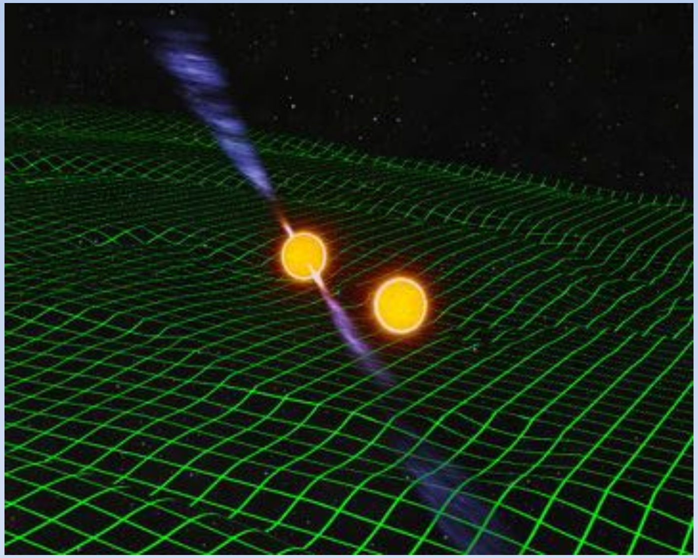
Gravitational waves

The progenitors of short GRBs

Most popular model:

Coalescence (merging) of a compact object binary system (NS-NS ; NS-BH)



While orbiting, the two objects emit gravitational waves losing energy: MERGING

NS-NS systems are observed in our Galaxy:

The progenitors of short GRBs

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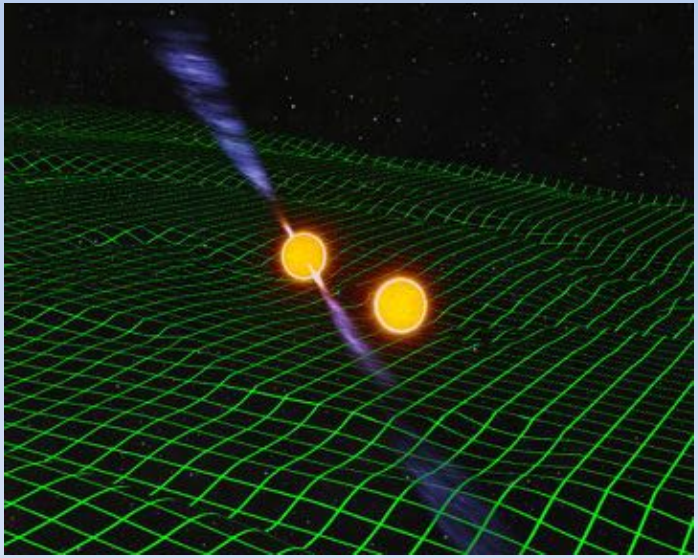

- critical parameter: **merging time t_m**

Time between the formation of the system and its coalescence

$t_m \propto a^4$ (a: system separation) **->** **~10 Myr < t_m < ~10 Gyr**

- merging can occur in old and young stellar populations

"primordial binaries"

- **kick velocities**:

Compact objects are the remnants of core-collapse SNe, that can give a "kick"

The system can escape from the HG-> OFFSET! (**1÷100 kpc**)/low density CBM

(Belczynski & Kalogera 2001; Perna & Belczynski 2002; Belczynski et al. 2006)

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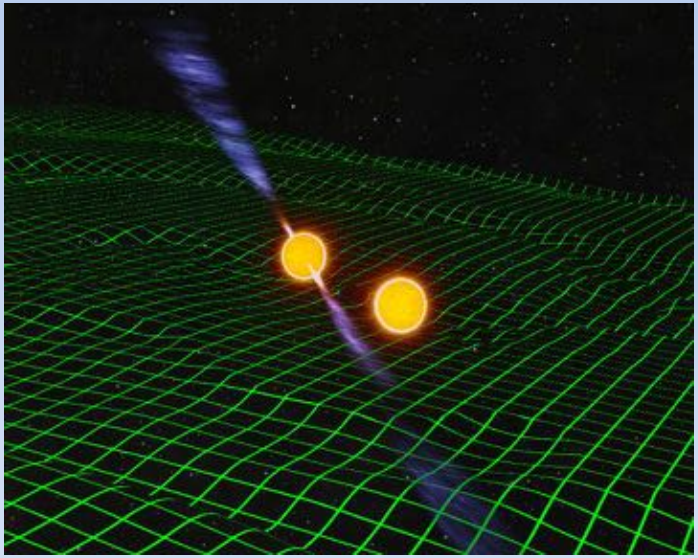
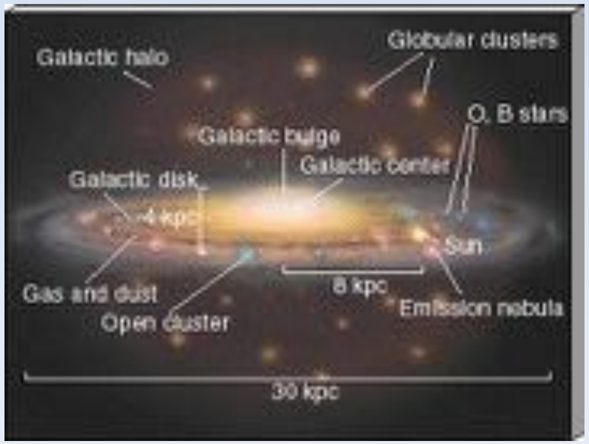


Another possibility: dynamical formation of a double compact object system (e.g. in globular clusters)

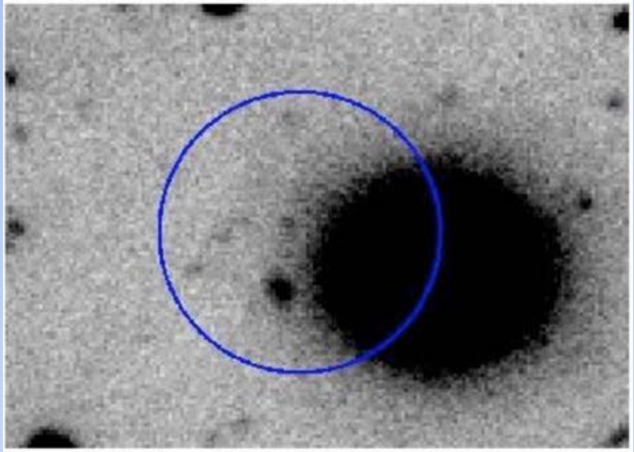
(Grindlay et al. 2006; Salvaterra et al. 2008)

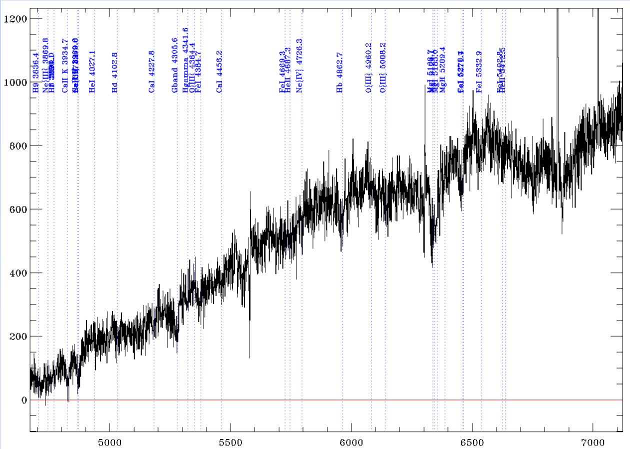
"dynamically formed binaries"



OFFSET/low density CBM

The first short GRB host galaxies





GRB 050509B (z = 0.22)

Gehrels et al. 2005; Hjorth et al. 2005; Castro-Tirado et al. 2005; Bloom et al. 2006

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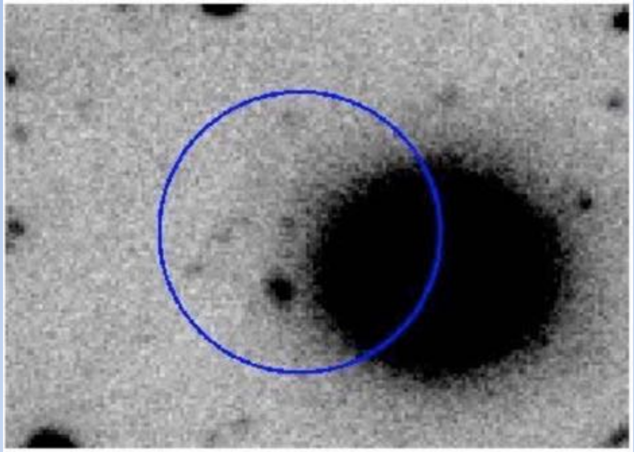

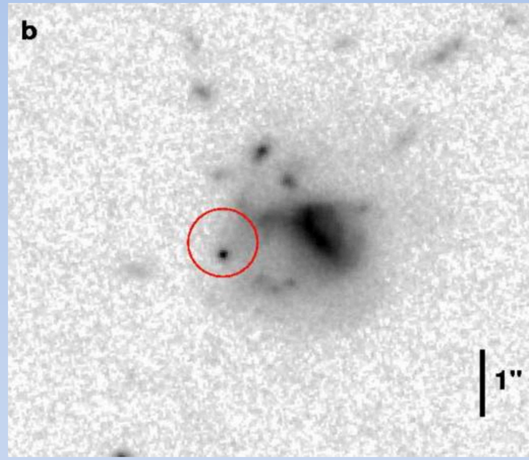

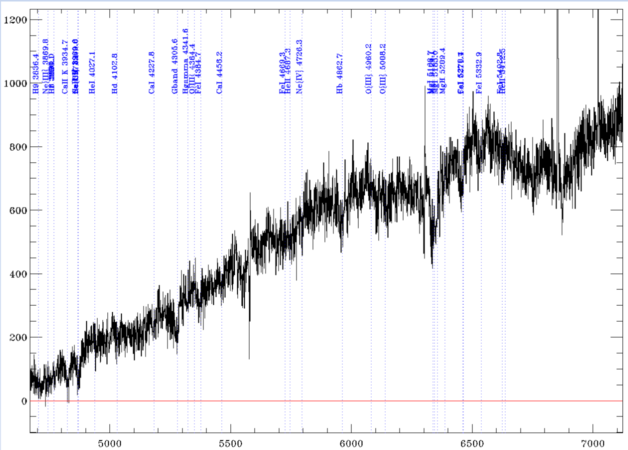

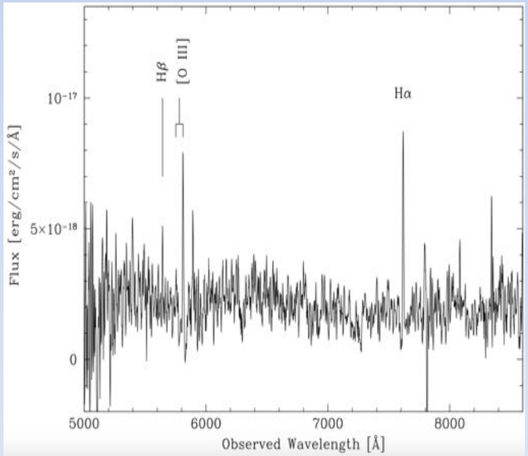

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Fox et al. 2005; Hjorth et al. 2005; Covino et al. 2006

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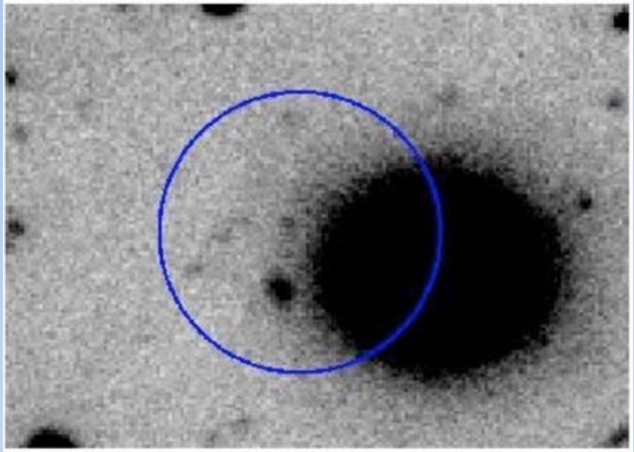

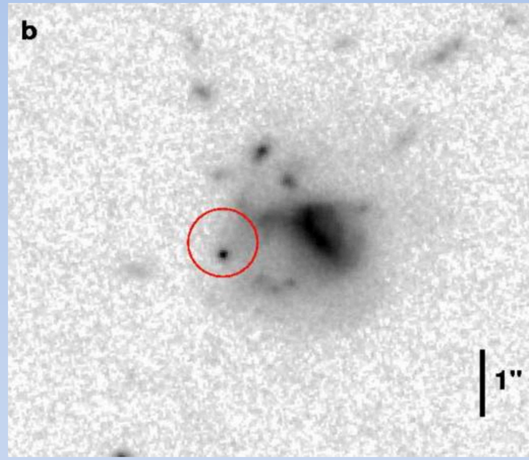

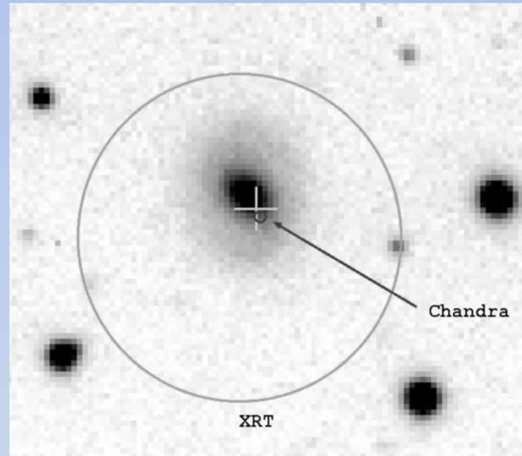

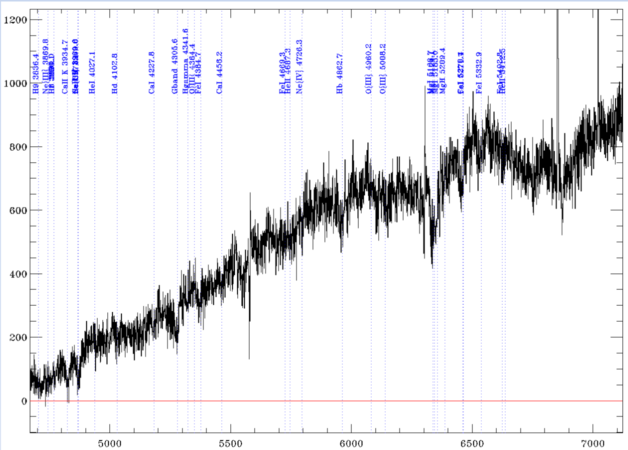

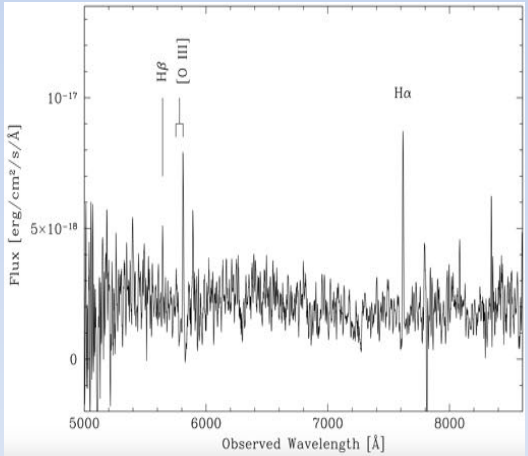

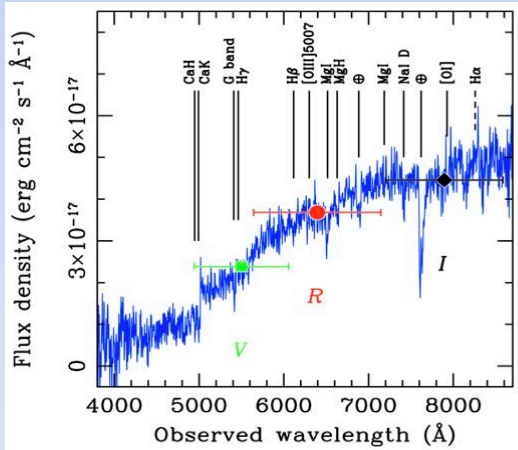

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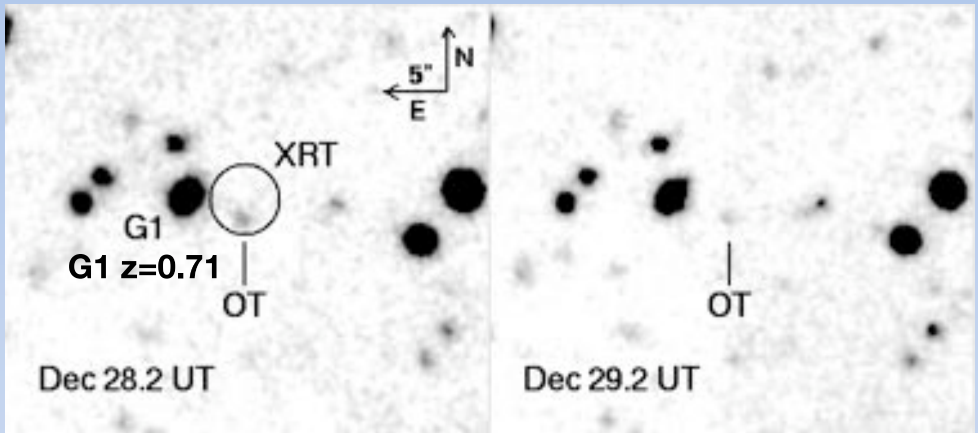
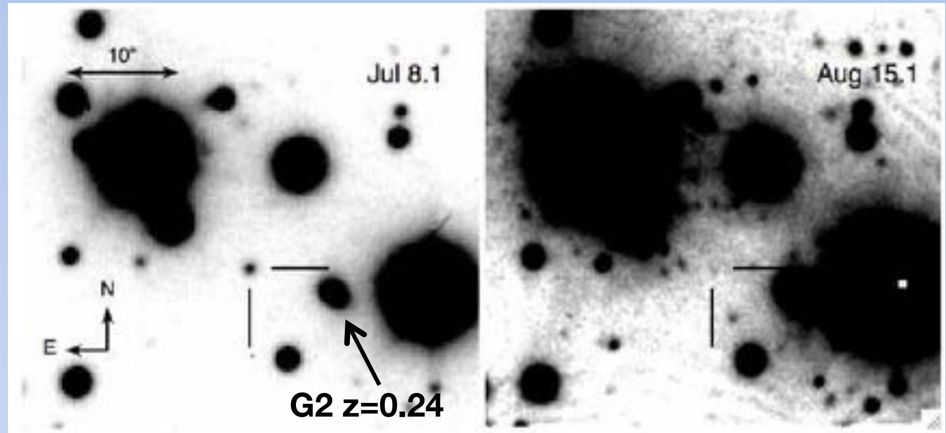
GRB 050724 (z = 0.26)

Barthelmy et al. 2005; Berger et al. 2005; Malesani et al. 2007

Short GRB - host galaxy association





GRB 051227

- G1: bright, HG candidate, large offset w.r.t. opt afterglow
- but G1 may NOT be the HG
- HG (no offset) R = 25.6 mag

GRB 070707

- G2: bright, near HG candidate, large offset w.r.t. opt afterglow
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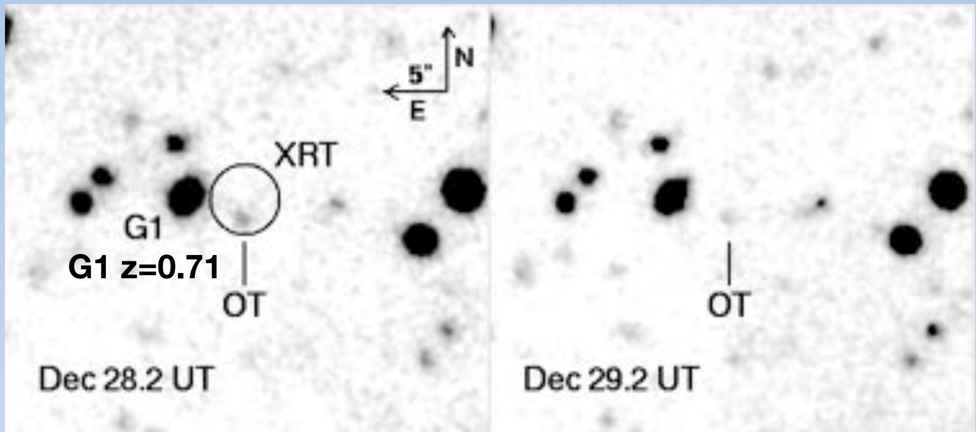
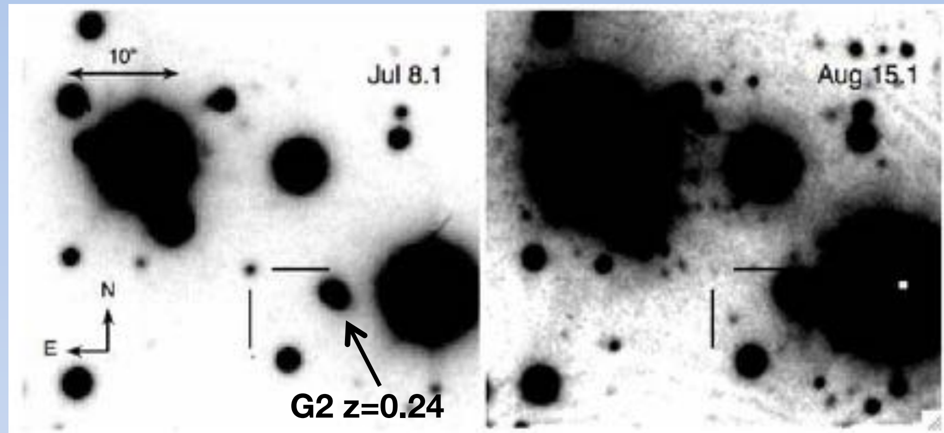
- HG (no offset) R = 27.3 mag

Short GRB - host galaxy association





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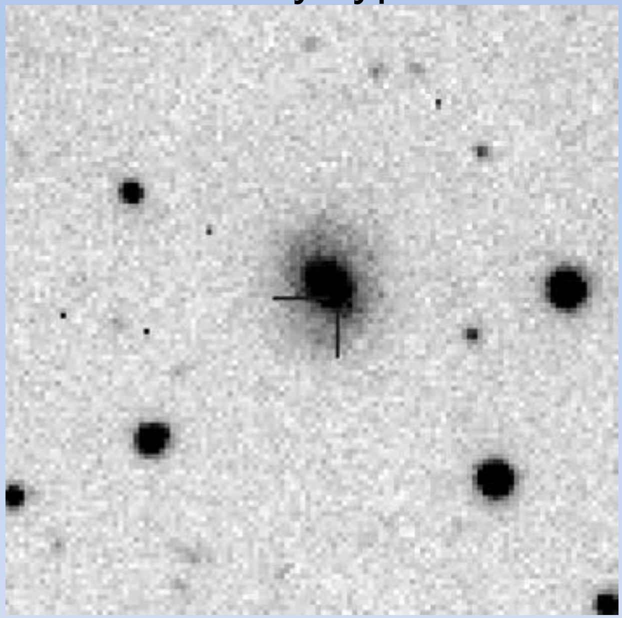
GRB 070707

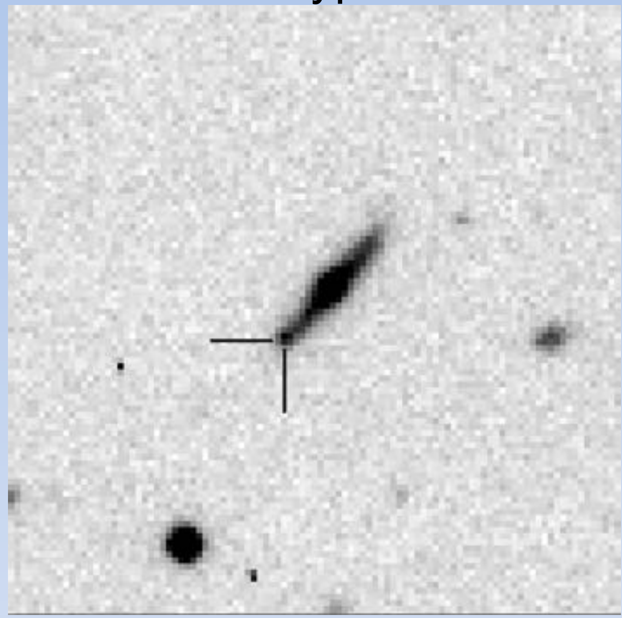
- G2: bright, near HG candidate, large offset w.r.t. opt afterglow
- but G2 may NOT be the HG
- HG (no offset) R = 27.3 mag

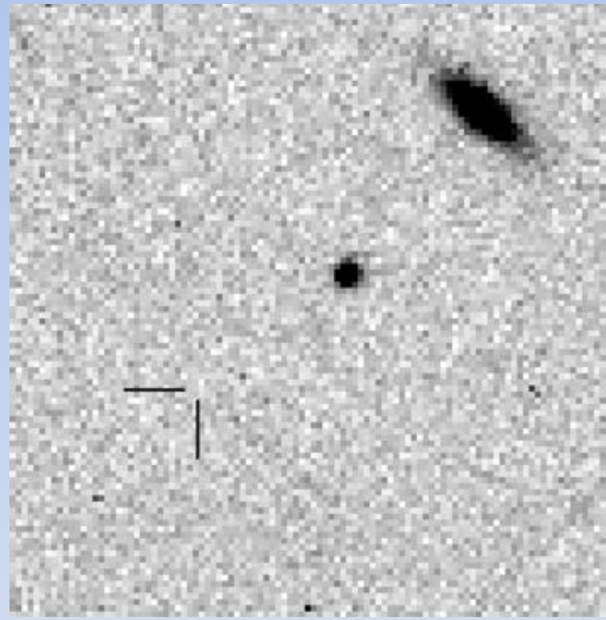
A possible proposal: we consider "secure" association when the afterglow with precise (sub-arcsec) position lies within the light of the host galaxy (PDA+14)

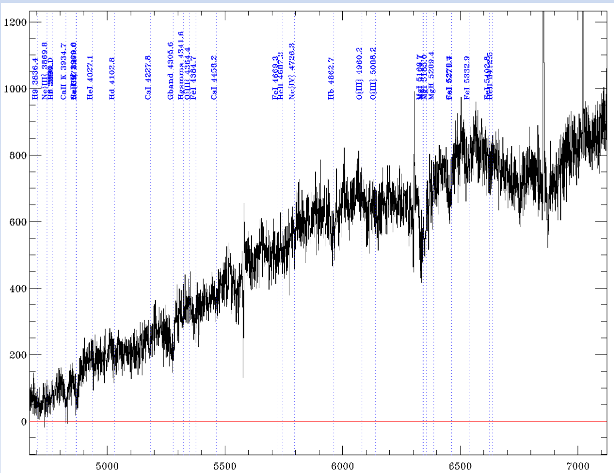
Short GRB hosts: overview

Early-type	Late-type	Host-less









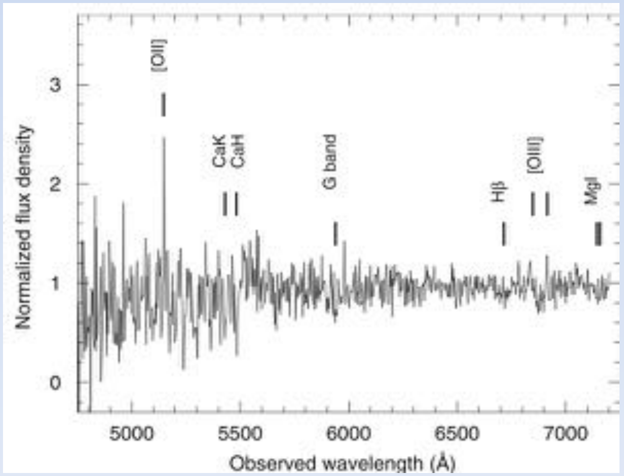


TABLE 2
OBSERVATIONS OF SHORT GRBS WITH OPTICAL AFTERGLOWS AND NO COINCIDENT HOST GALAXIES
(*Sample 2*)

GRB	Instrument	Filter	t_{exp} (s)	m_{lim} [a] (AB mag)
061201	HST/ACS	F814W	2224	26.0
070809	Magellan/LDSS3	r	1500	25.4
080503	HST/WFPC2	F606W	4000	25.7
090305	Magellan/LDSS3	r	2400	25.6
090515	Gemini-N/GMOS	r	1800	26.5

NOTE. — [a] Limits are 3σ.

Berger 2010

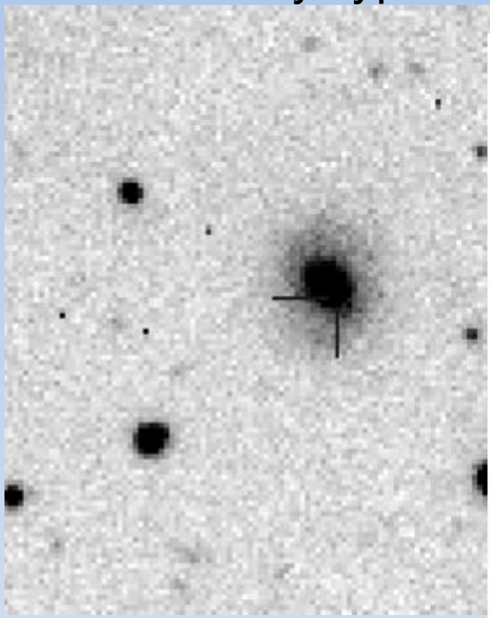
GRB 050724 (z = 0.26)
Barthelmy et al. 2005;
Malesani et al. 2007

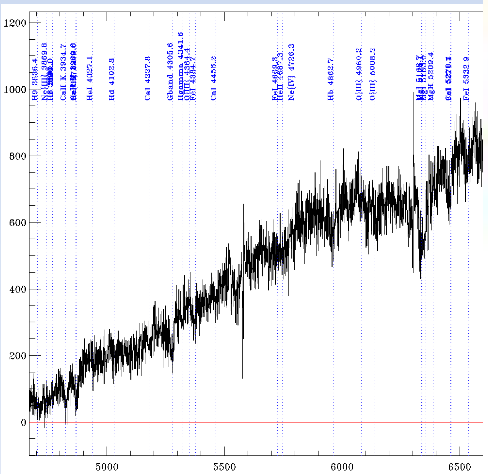
GRB 071227 (z = 0.38)
PDA et al. 2009

GRB 061201
Stratta et al. 2007

Short GRB hosts: overview

Early-type





GRB 050724 (z = 0.26)
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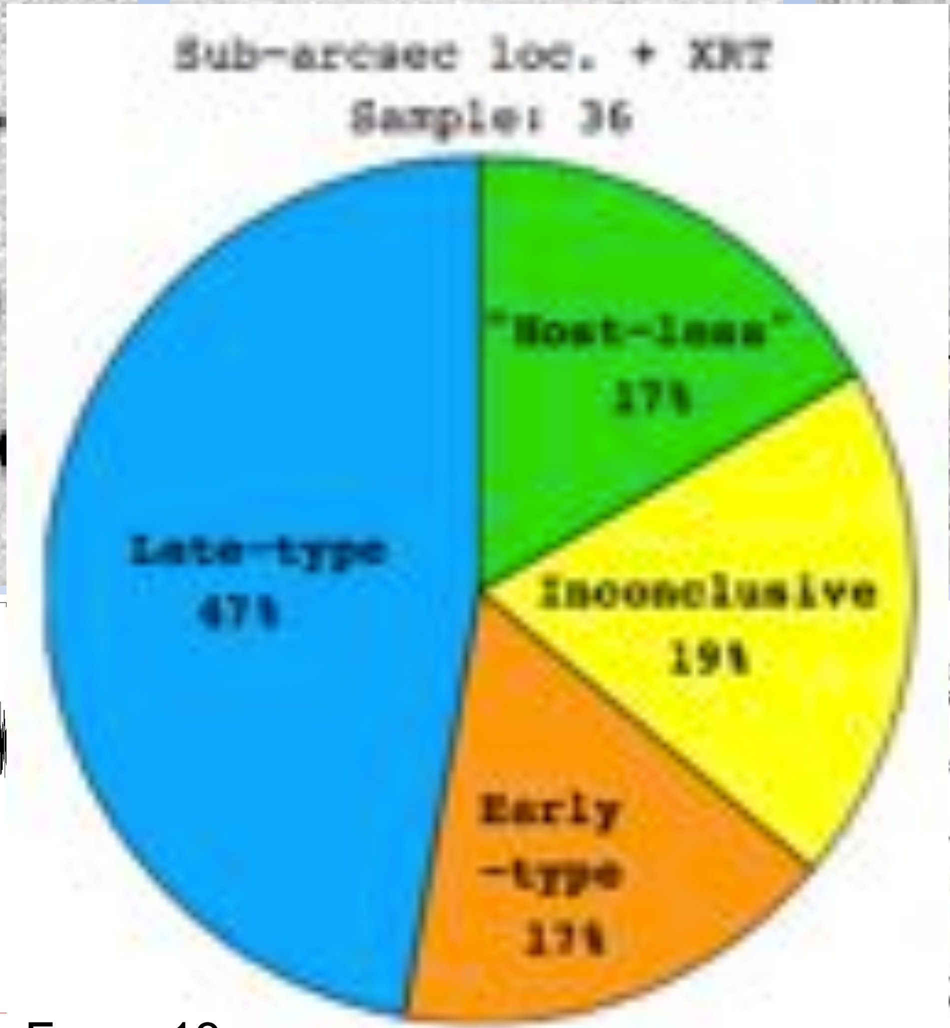
Late-type



Fong+13

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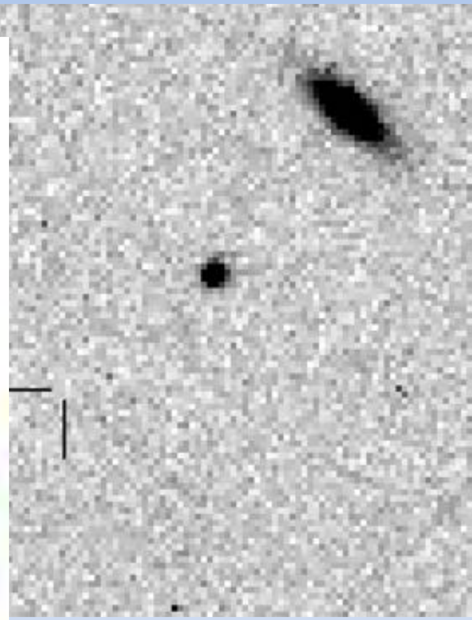
PDA et al. 2009

Host-less



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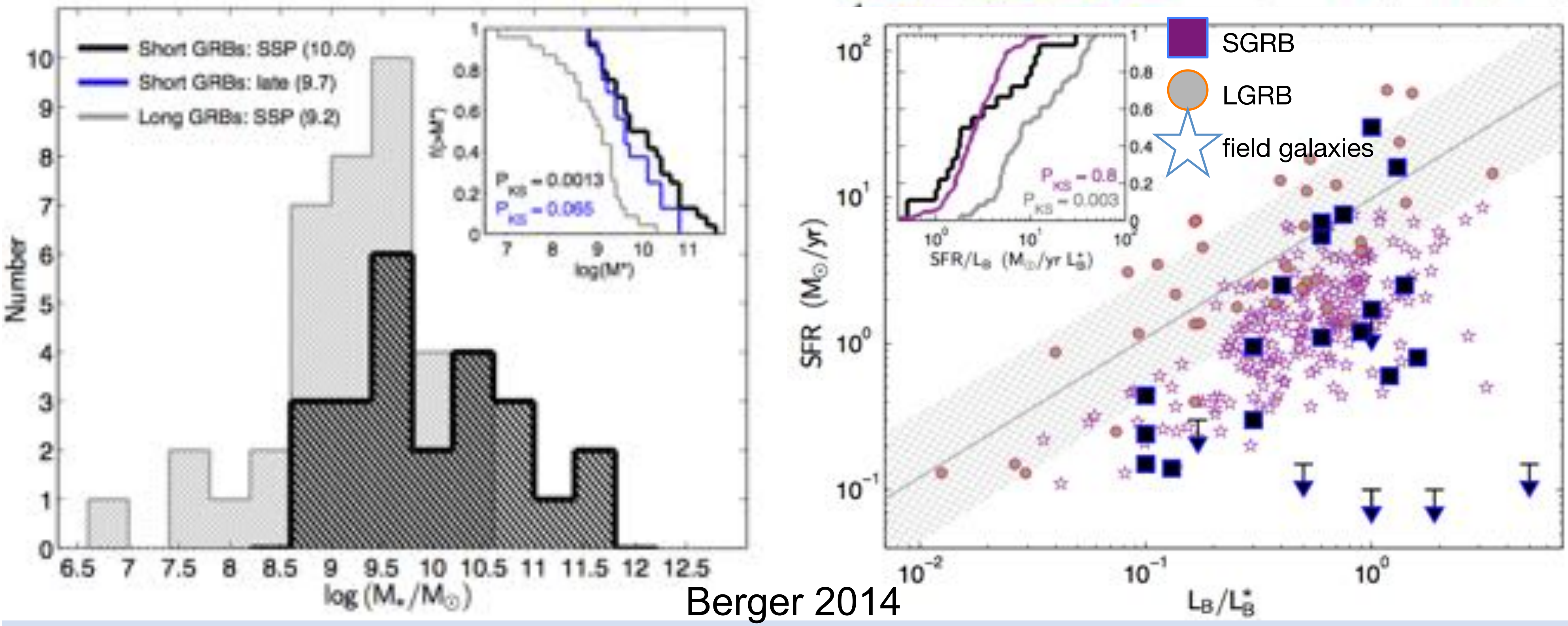
Berger 2010

GRB 061201
Stratta et al. 2007

Mass & Star Formation



Berger 2014

- SGRB HGs have larger masses with respect to LGRB HGs

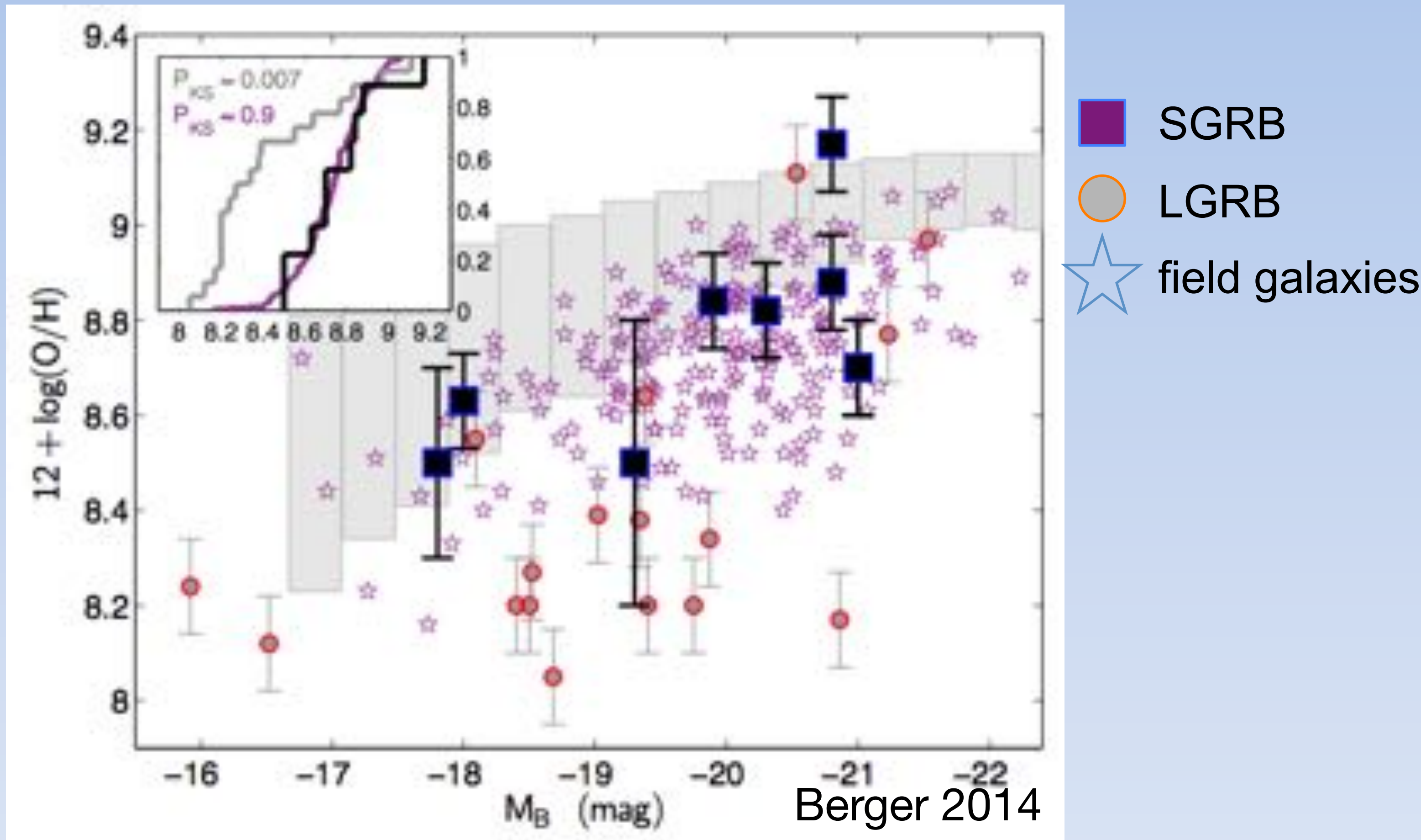
- When compared to **field** galaxies, SGRB **early-type** HGs have comparable masses while **late-type** SGRB HGs are less massive

→ The SGRB rate is determined by both stellar mass and star formation

SGRB HGs have lower SFR as a function of luminosity than LGRBs hosts (lower SSFR) and comparable to **field** galaxies. Even if the majority of SGRB HGs are star-forming, their star formation is moderate

→ LGRBs track recent star formation (tens of Myr), while SGRBs track star formation with delay of hundreds of Myr to Gyrs.

Metallicity



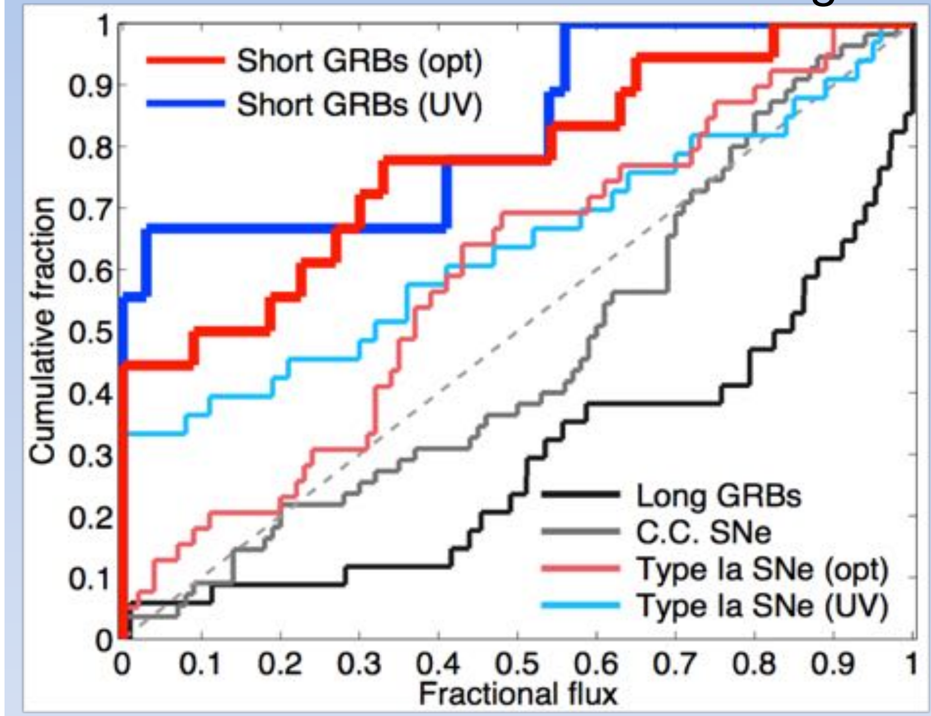
- The metallicities of SGRB hosts are significantly higher than those of LGRB hosts

- SGRB hosts track the metallicity distribution of field star-forming galaxies at similar redshifts and with similar luminosities

→ SGRB progenitors are likely not affected by metallicity.

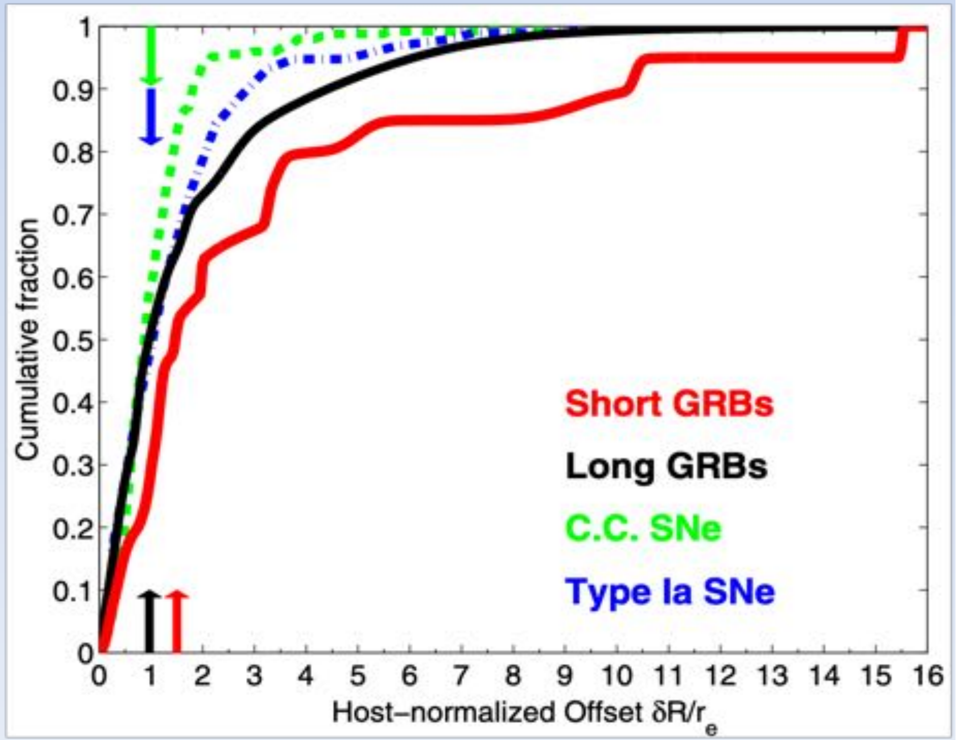
Short GRBs exploding sites

Berger14



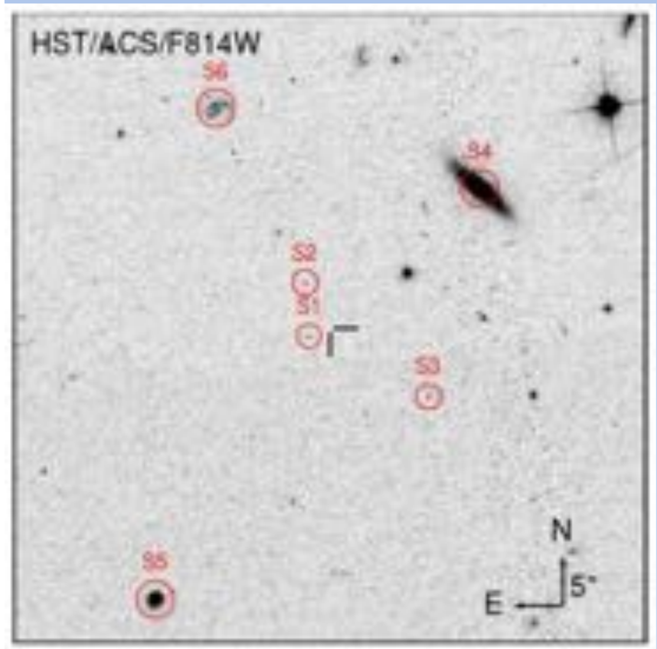
- at least half of SGRBs located in regions where the HG is faint in Opt and UV
- significant offset of the SGRB site w.r.t. their HG (even normalised to the HG size)

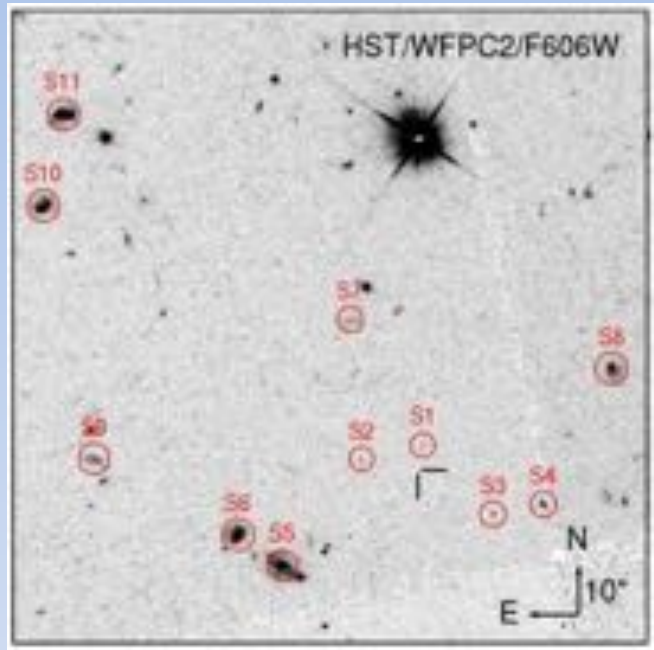
Fong+13

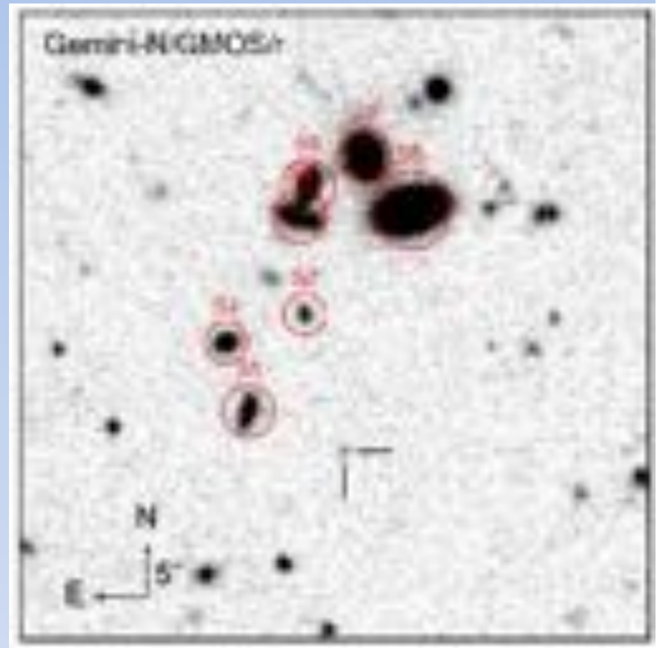


-> explosion site may not be representative of the progenitor birth site

Host-less Short GRBs







GRB 061221
See also Stratta et al. 2007

GRB 080503
See also Perley et al.2009

GRB 090515
cluster @ z=0.403

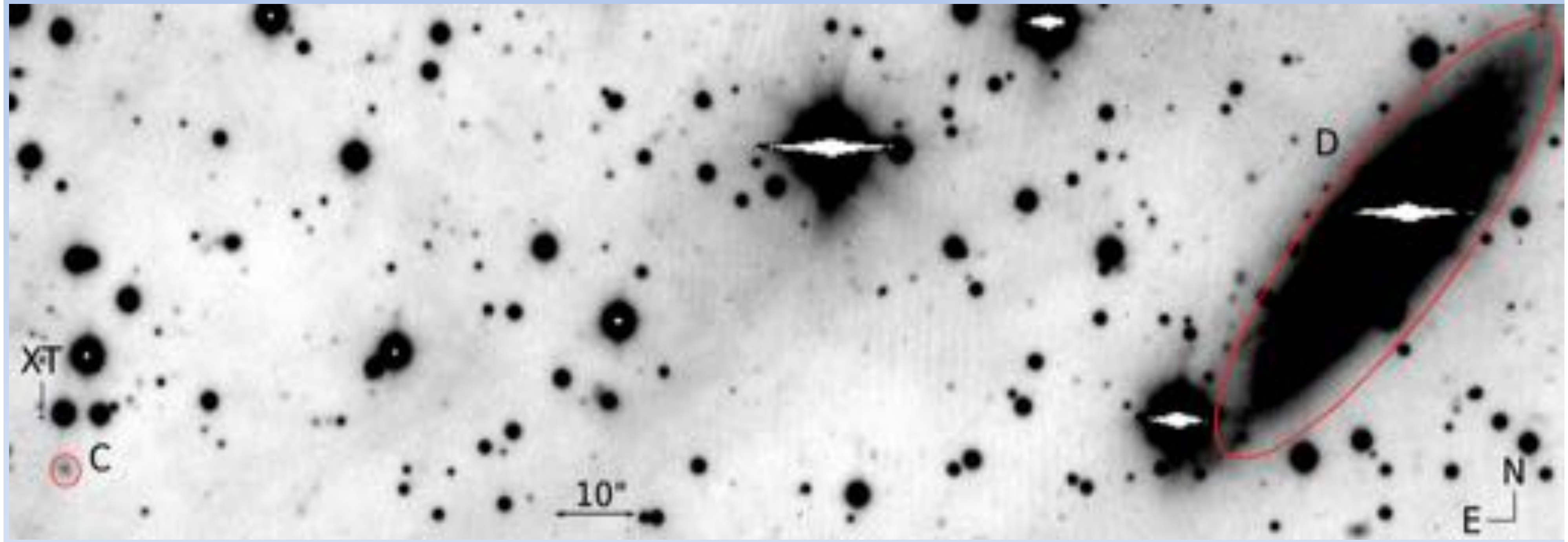
TABLE 2
OBSERVATIONS OF SHORT GRBS WITH OPTICAL AFTERGLOWS AND NO COINCIDENT HOST GALAXIES
(Sample 2)

GRB	Instrument	Filter	t_{exp} (s)	m_{lim} [a] (AB mag)
061201	HST/ACS	F814W	2224	26.0
070809	Magellan/LDSS3	*r*	1500	25.4
080503	HST/WFPC2	F606W	4000	25.7
090305	Magellan/LDSS3	*r*	2400	25.6
090515	Gemini-N/GMOS	*r*	1800	26.5

Berger 2010

- High-z?
- (very-)low lum HG?
- kicked progenitor?

Host-less Short GRBs

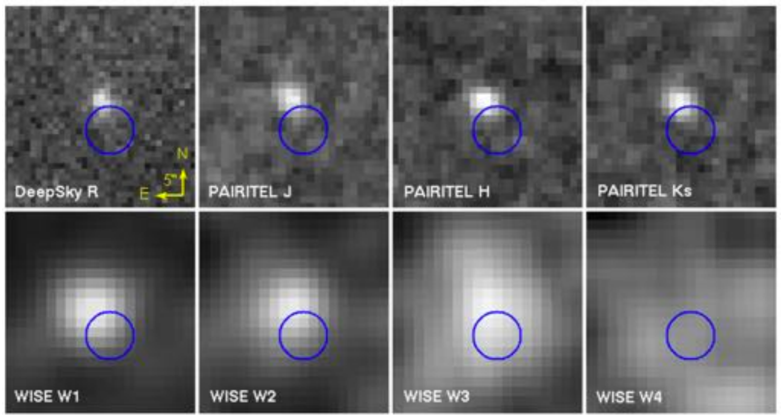


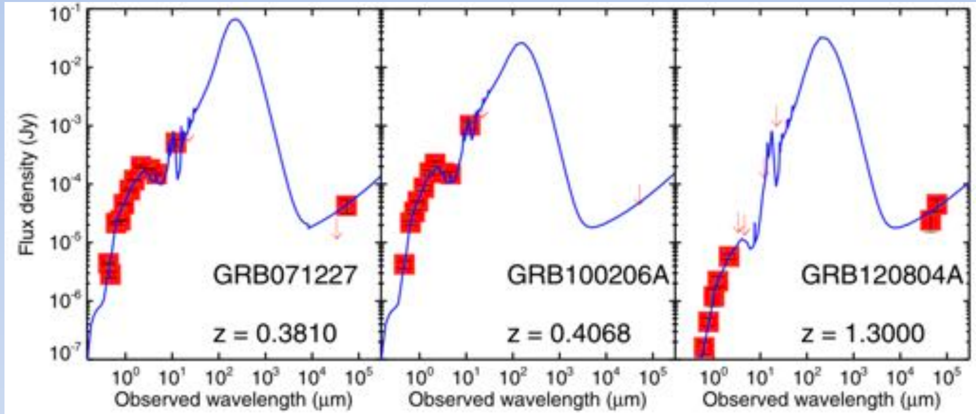
Tunnicliffe+14 estimated the fraction of host-less SGRBs to be ~ 30%. For this SGRBs, they noticed a proximity of nearby bright galaxies higher than average, which suggests kicked progenitors or dynamical channel (e.g. mergers in globular clusters).

See also poster #26 (Mandhai et al.)

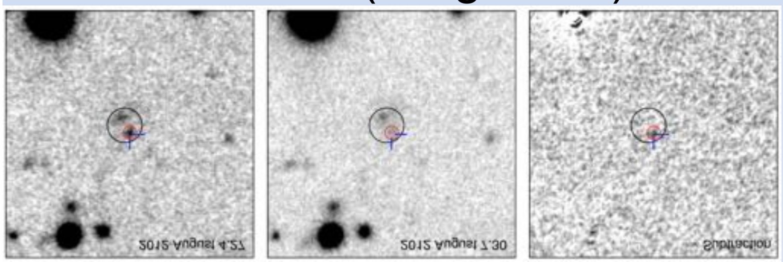
(U)LIRG SGRBs host galaxies

GRB 100206A (Perley+12)

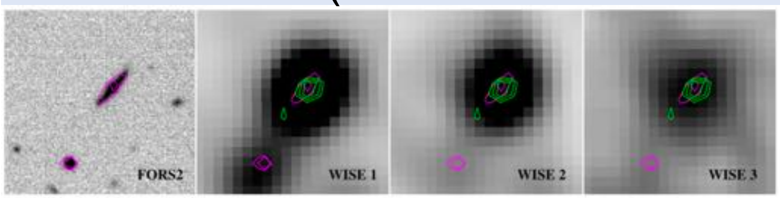




GRB 120804A (Berger+13)



GRB 071227 (Nicuesa Guelbenzu+14)

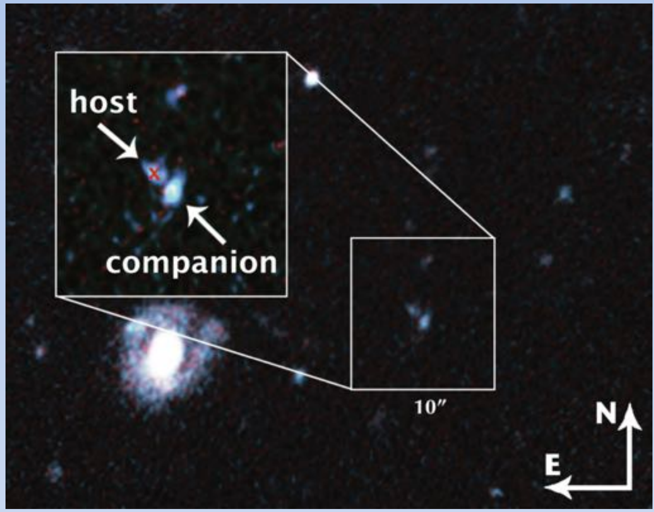


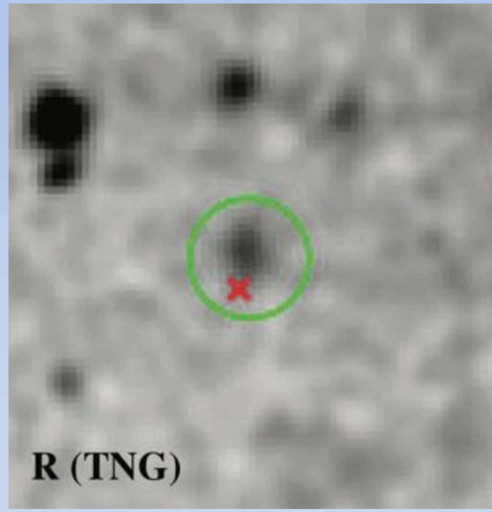
(ultra-)luminous infrared galaxies

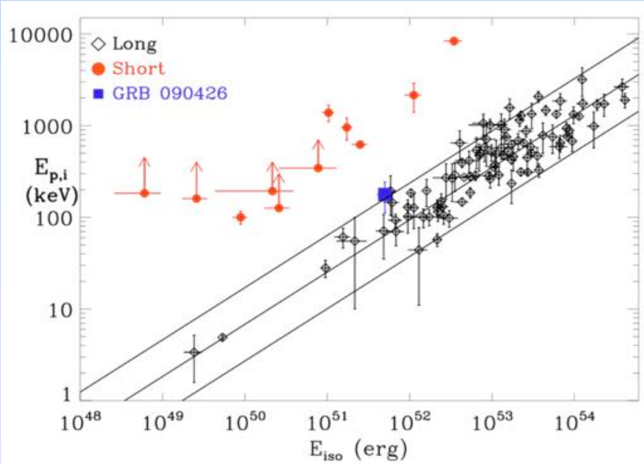
- very red color
- massive, luminous galaxies
- high SFR (~ 30-40 M_{SUN} yr^{-1})
- high extinction (A_V ~ 2 mag)

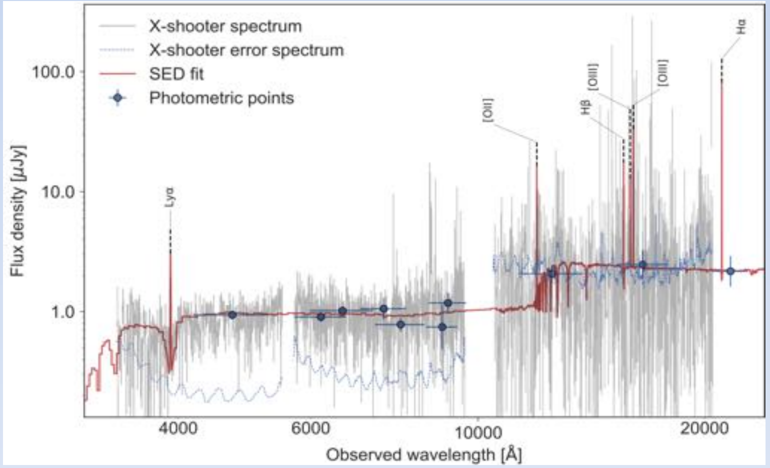
About 5%-10% of SGRB HGs sample, maybe hinting for a mix of young (fast channel) and old (slow/dynamical channel)progenitors.

High-z SGRBs host galaxies









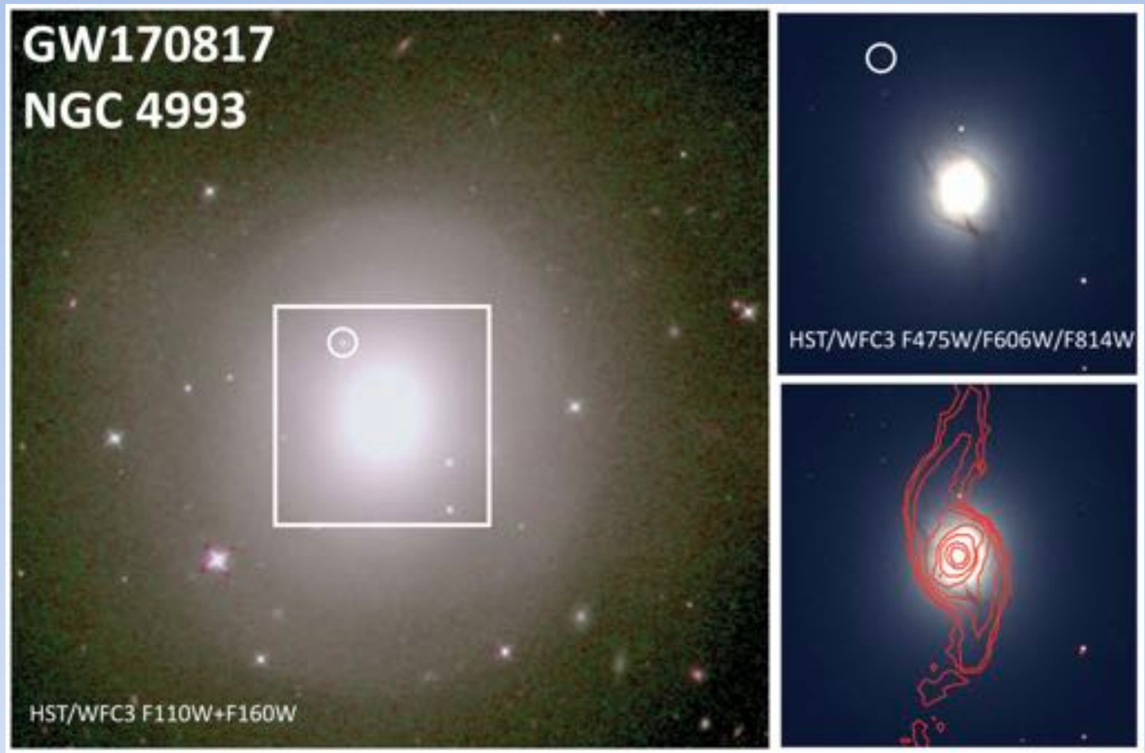
GRB 090426 (z=2.609), T_{90} = 1.25 s
- Short duration
- Prompt spectral emission consistent with LGRBs
- HG properties consistent with LGRBs

Levesque+09, Antonelli+09, Thoene+11

GRB 111117A (z=2.211), T_{90} = 0.46 s
- Short duration
- Prompt emission & HG consistent with SGRBs
- Possible fast-merging merger channel

Margutti+12, Sakamoto+13, Selsing+18

The host galaxy of GW 170817/GRB 170817A



- Early-type (S0) galaxy
- Little star formation activity, old stellar population
- Properties broadly consistent with elliptical SGRBs host galaxies
- Evidence that the galaxy experienced a relatively recent merger (as, e.g. GRB 130603B, de Ugarte Postigo+13)
- Offset of the optical afterglow well within the galaxy effective radius (no kick)
- Low extinction (the progenitor binary system may lie in front of the galaxy)
- No evidence for globular cluster in HST imaging, however hints for possible dynamical origin of the progenitor of GW 170817 / GRB 170817A

Levan+17, Palmese+19

Short GRB HGs: some conclusions

- HGs are our best tool to unveil SGRBs redshifts (and, consequently, luminosity, energetics, rest-frame properties)

- SGRB – host galaxy association not always straightforward

Clues for compact binary merger progenitors:

- Different host galaxy types (consistent with multiple channels and different timescales for binary mergers)

- host galaxy properties (M, SFR, Z, offset) significantly different w.r.t. LGRB hosts (more similar to field galaxies)

- hostless SGRBs (large offset? Dynamical channel?)

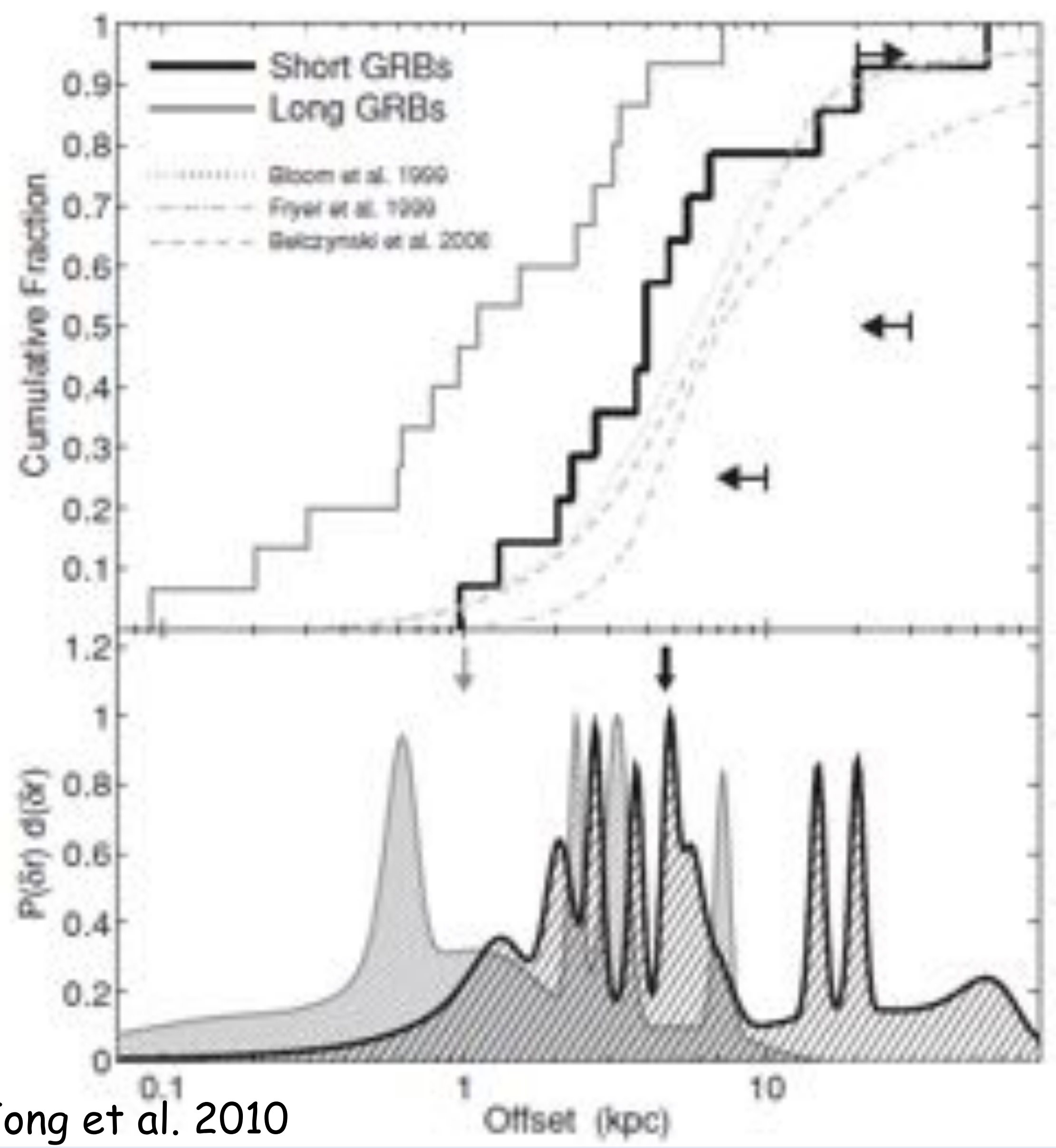
- search for close (< 200 Mpc) SGRBs in archival (and new) SGRB data using local, catalogued galaxies as tool (see, e.g., poster #57 Dichiara et al.)

- Waiting for (more) GWs

Observational reviews: Berger 2014, ARA&A, 52, 43; PDA, 2015, JHEAp, 7, 73

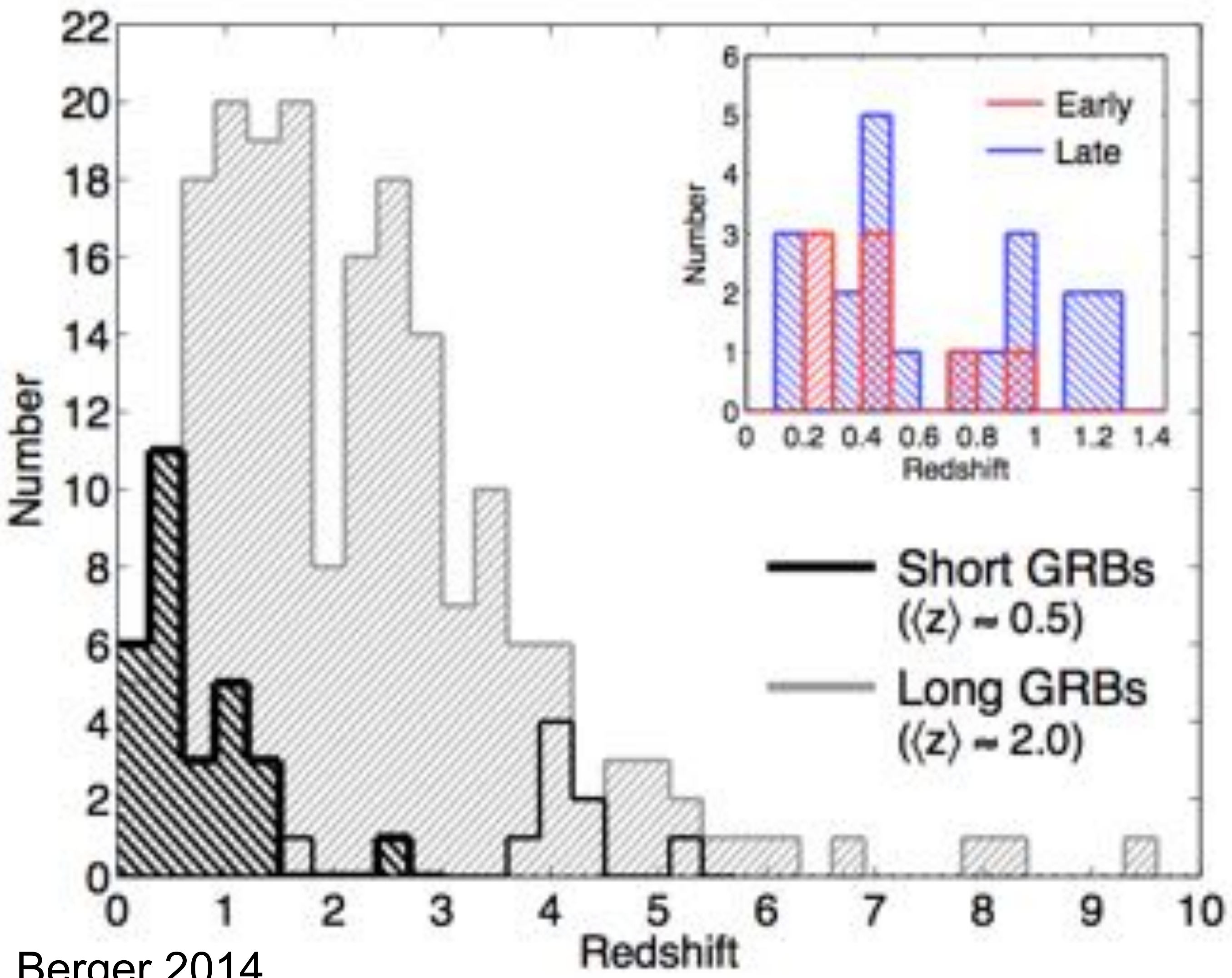
Short GRBs: Offsets

Offset from HG centre



Fong et al. 2010

Short GRB redshift distribution



Berger 2014

However:
<z> ~ 0.72

If considering *Swift* SGRBs (only) with T_{90} < 2 s

Rowlinson et al. 2013

and:
<z> ~ 0.85

for a complete (flux-limited) sample of bright SGRBs (D'Avanzo et al. 2014)

Hinting for a "primordial binary" progenitor, expected to have a z distribution peaking at z ≥ 0.8.
(Salvaterra et al. 2008).

Redshift distribution

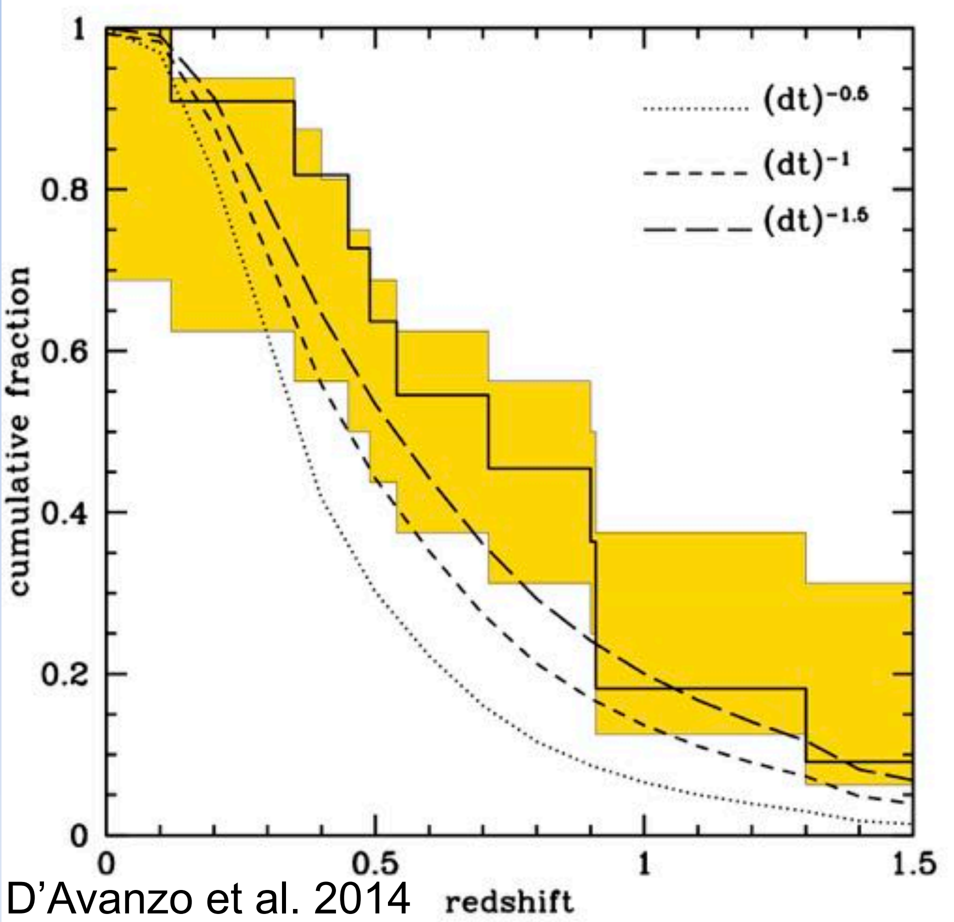
Rate of bursts with peak flux $P_1 < P < P_2$

$$\frac{dN}{dt}(P_1 < P < P_2) = \int_0^\infty dz \frac{dV(z)}{dz} \frac{\Delta\Omega_s}{4\pi} \frac{k_{\rm SGRB}\Psi_{\rm SGRB}(z)}{1+z} \times \int_{L(P_1,z)}^{L(P_2,z)} dL' \phi(L'), \quad (5)$$

Formation rate (# of bursts per unit time and unit comoving volume at redshift z) proportional to massive star binary formation rate and the delay time (interval between binary formation and merging) distribution function:

$$f_{\rm F}(t) \propto t^n$$

We compute the observed distribution of SGRBs for n = -1.5, -1, -0.5, delay times ranging from 20 Myr to ~10 Gyr (Behroozi, Ramirez-Ruiz & Fryer 2014)



D'Avanzo et al. 2014

Model with n=-1.5 favored in accounting for the observed z distribution of the SGRBs of our sample. Consistent with fast merging primordial binaries progenitors

HG properties: some numbers

Stellar population ages for SGRBs span the range 0.1-5 Gyr (peak ~ 0.3 Gyr)
SGRB(SF)~0.3 Gyr
SGRB(Ell)~ 3 Gyr

SGRB Mass $10^{8.5-11}$ M_Sun <M> ~ 10^{10} M_Sun (LGRB <M> ~ $10^{9.2}$ M_Sun)

SGRB luminosity L(B) ~ 0.1-5 L(B)*
SGRB SFR ~ < 0.1 – 5 M_Sun/yr, <SSFR> ~ 2 M_Sun/yr/L(B)

SGRB metallicity span a range 12 + log (O/H) ~ 8.5-9.2, median 8.8 (Solar)