Evidence that galaxy interactions are factories for massive star formation at high redshift

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The concept

LGRBs and SLSNe are expected to have massive progenitors

The rates of SLSNe (and LGRBs?) at high-z are higher than cosmic SFR expectations *(what else changes with redshift similarly?)*

Very massive stars are more likely to form in low-metallicity gas

LGRBs and SLSN hosts appear to have an unusually high interaction fraction and the events seem to occur offset/outside of their hosts

* First-pass or fly-bys will induce star formation in the CGM/halos of galaxies which typically have lower metallicity

- *Massive stars can form and will result in LGRBs and SLSNe*
- *Cloud collapse and SNe should occur while the hosts still show interaction*

Is the LGRB and SLSN interaction and/or close pair fraction truly enhanced compared to ‘normal’ galaxies?

If so, is this an important mechanism for the formation of their progenitors?

Can the observations constrain induced cloud collapse timescales?

Previous related work *(non-exhaustive)*

LGRB locations connected to host UV light and star formation (20 LGRBs)
Bloom, Kulkarni, & Djorgovski (2002)

Hosts show tidally interacting galaxy or merger structures (3 LGRBs)
Jaunsen et al. (2003)

Host Lya emitters, LAEs nearby, interacting LBG−like (15 hosts+1000s LBGs)
e.g., Jakobsson et al. (2005), Cooke et al. (2010)

Hosts at $z > 1$ show a disproportionate amount of star formation, 68% are in disk−like or peculiar, merging galaxies (37 LGRBs) *Conselice et al. (2005)*

~30% of the hosts show direct signs of interaction, ~30% show indirect signs, and LGRBs much less likely in stable disk galaxies (42 LGRBs)
Wainwright, Berger, & Penprase (2007)

High−z LGRBs and SLSNe usually prefer lower mass, lower metallicity hosts and located in the brightest star forming regions *(or between galaxies)*
e.g., Svensson et al. (2010), Schulze et al. (2015), Perley et al. (2016)

Interactions include:

First, second, ... nth passes, major and minor mergers, fly-bys

Literature definitions:

Close pairs < 30–50 kpc separations
Imminent mergers < 15–30 kpc

Most interaction-induced SF occurs within 20 kpc, *~66% within 30 kpc*

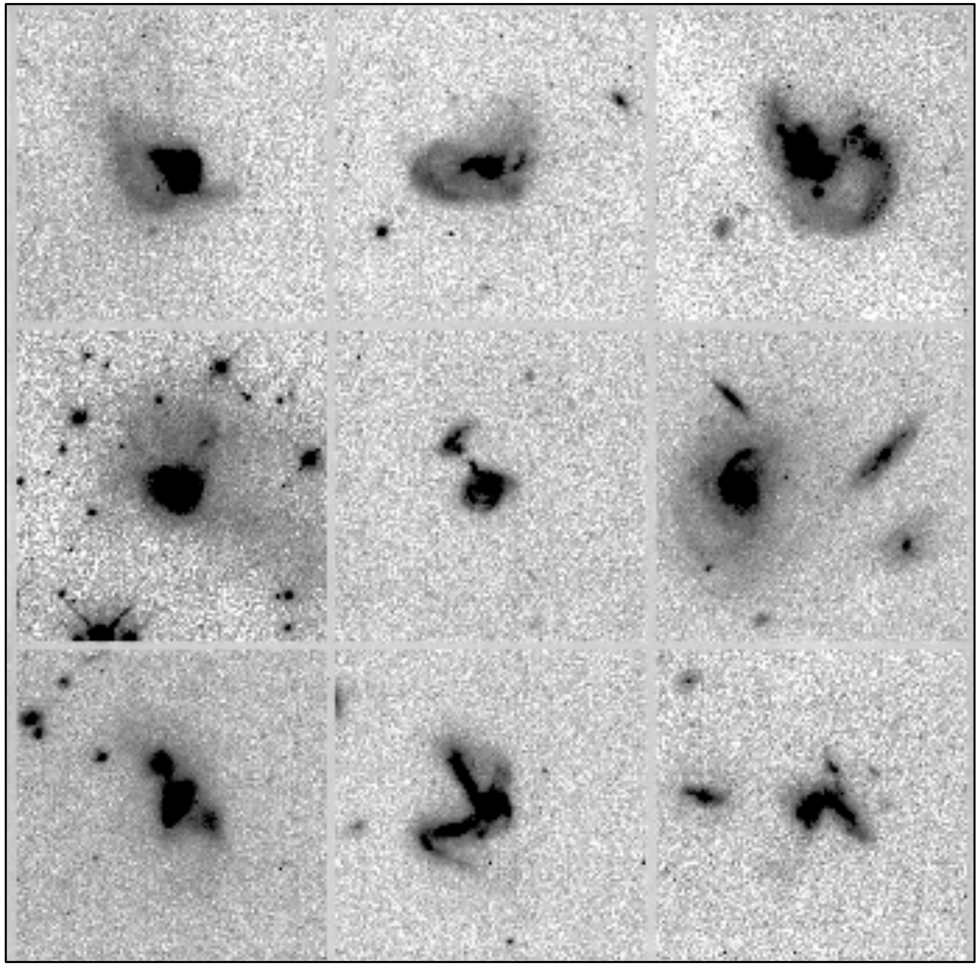
Patton et al. (2013)

Suspected interactions:

Galaxies with disturbed morphology and/or tidal features, and/or have close companions with similar colors/phot-zs

Need

- Deep, high-resolution imaging
- Colors
- Deep spectroscopy



Low-z interactions/mergers *Borne et al. (2000)*

Time scales

Induced cloud collapse + lifetime of the SN progenitor

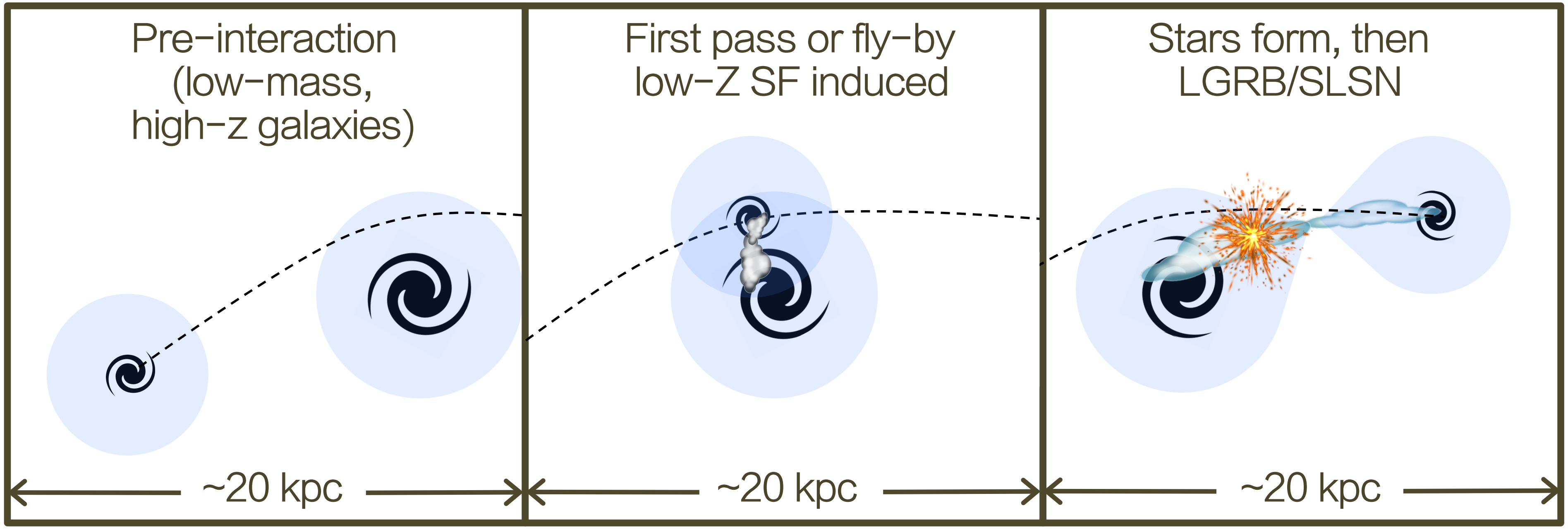
Galaxy differential velocities are ~200−600 km/s *(up to 1000 km/s?)*

Ellison et al. (2010), Patton et al. (2016)

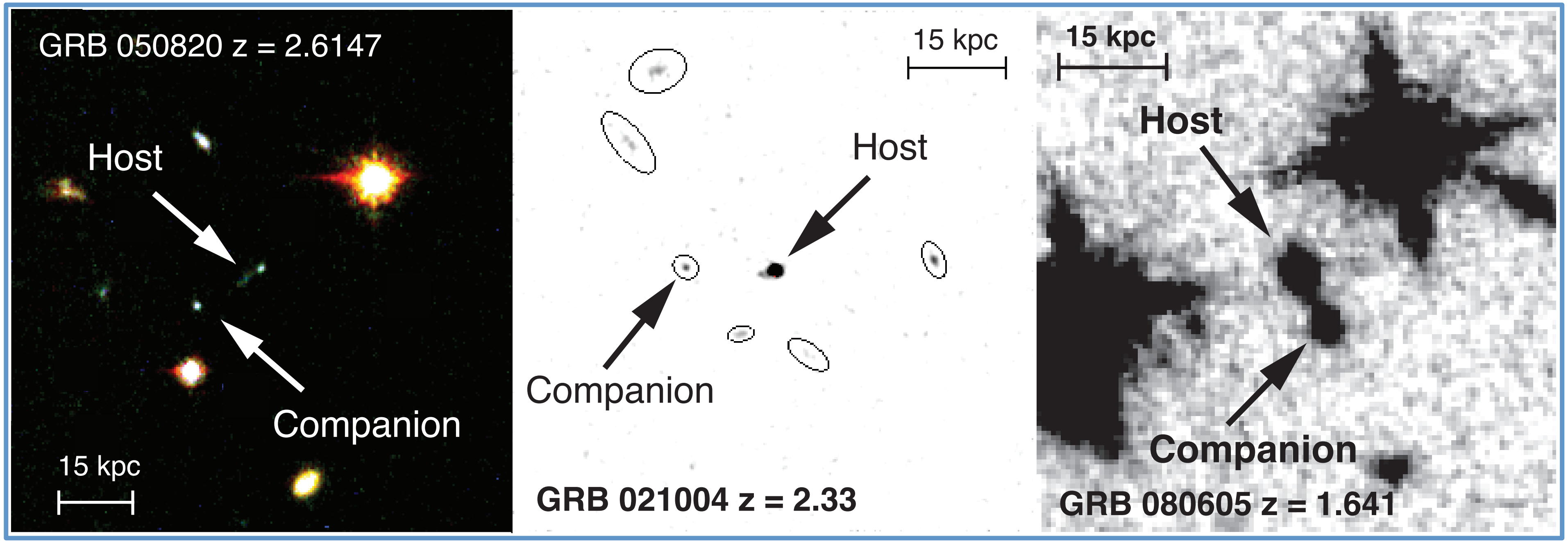
Thus, galaxies travel ~2−30 kpc from inducing SF to the LGRB/SLSN events

typical results would be 400 km/s for 10−50 Myr evolution and ~4−20 kpc

If shown to be the case, this is an independent DIRECT measurement of cloud collapse time and a strong constraint on progenitor lifetime → mass!



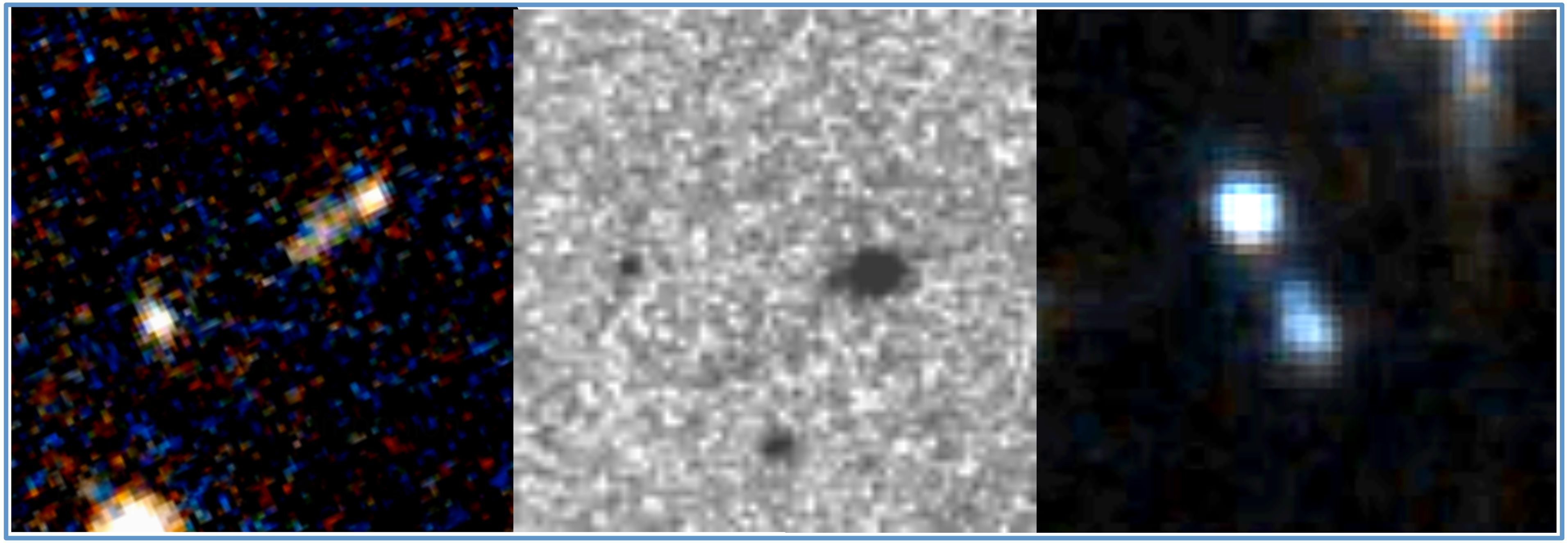
z ~ 2–4 LGRB hosts



Chen et al. (2009) *Fynbo et al. (2005)* *Kruehler et al. (2012)*

Many published LGRB hosts show disturbed morphologies and companions

z ~ 2–4 LGRB hosts



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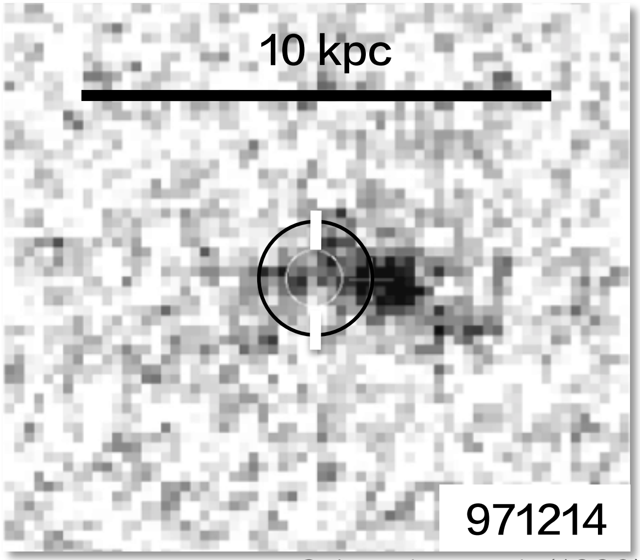
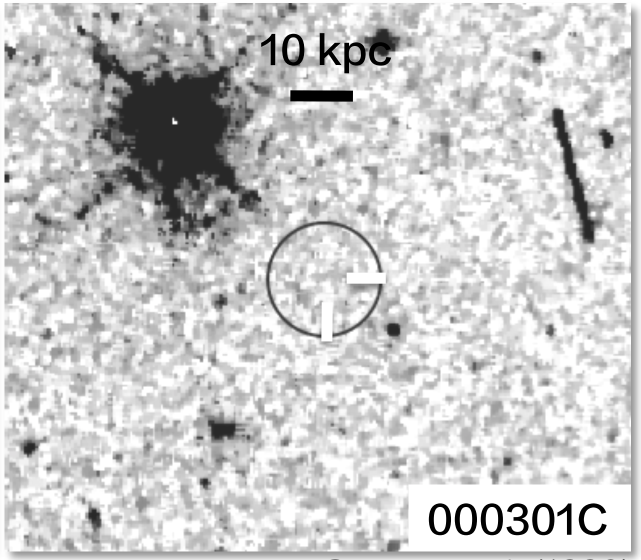
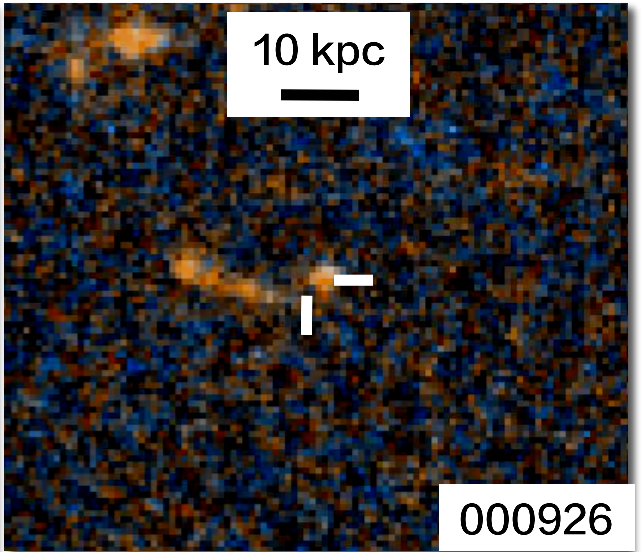


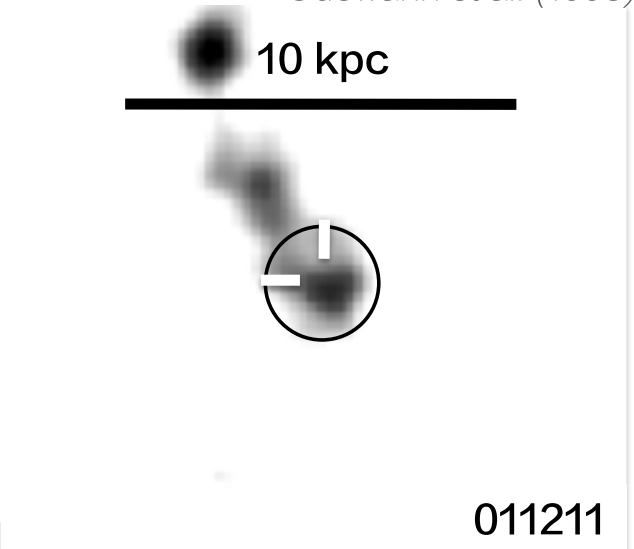
Odewahn et al. (1998)



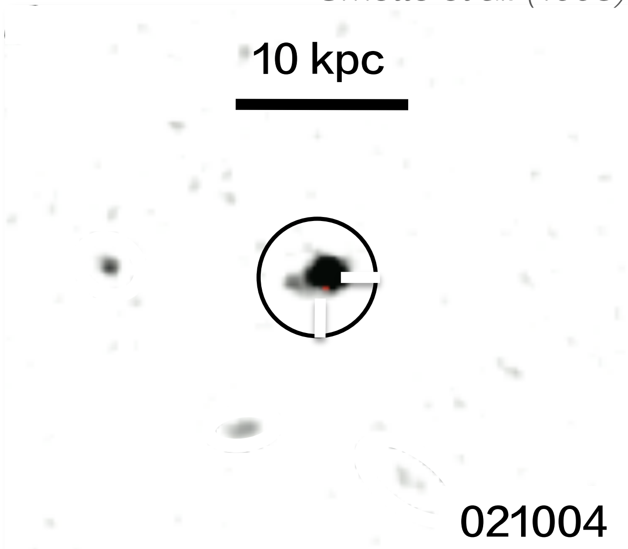
Smette et al. (1998)



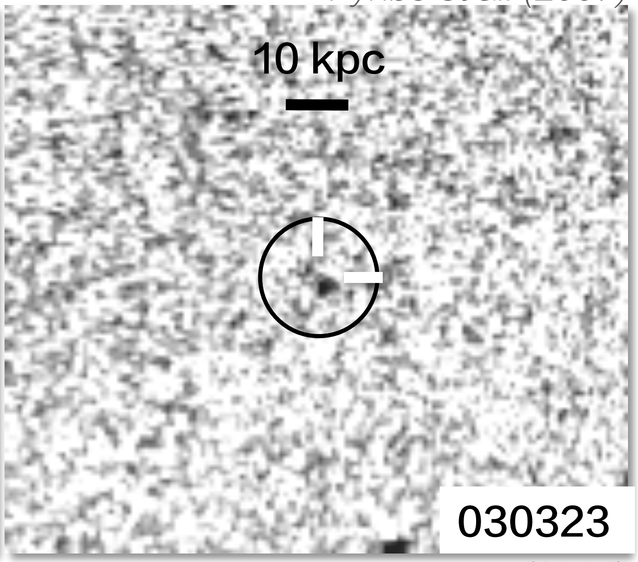
Fynbo et al. (2007)



Jakobsson et al. (2003)

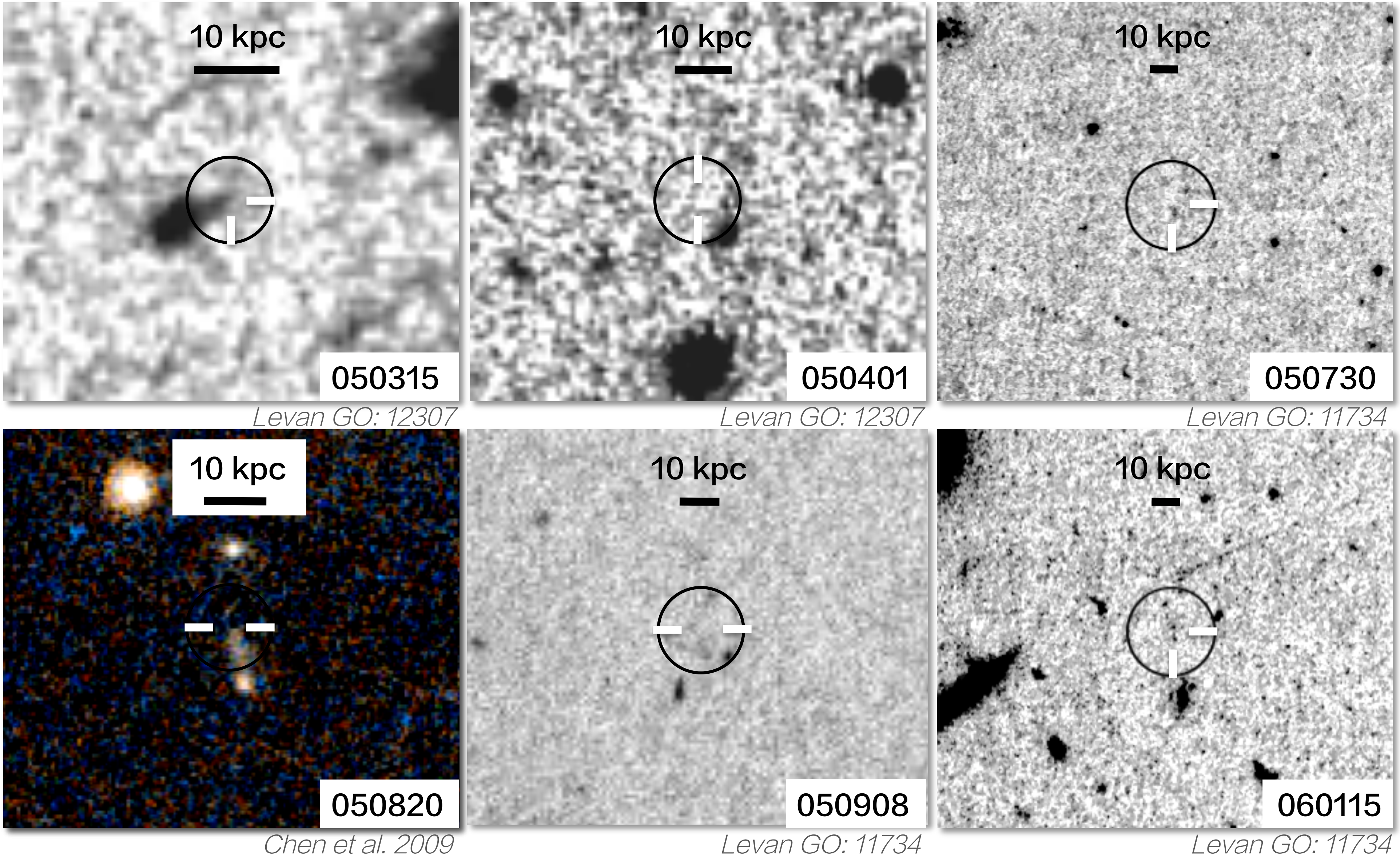


Fynbo et al. (2005)

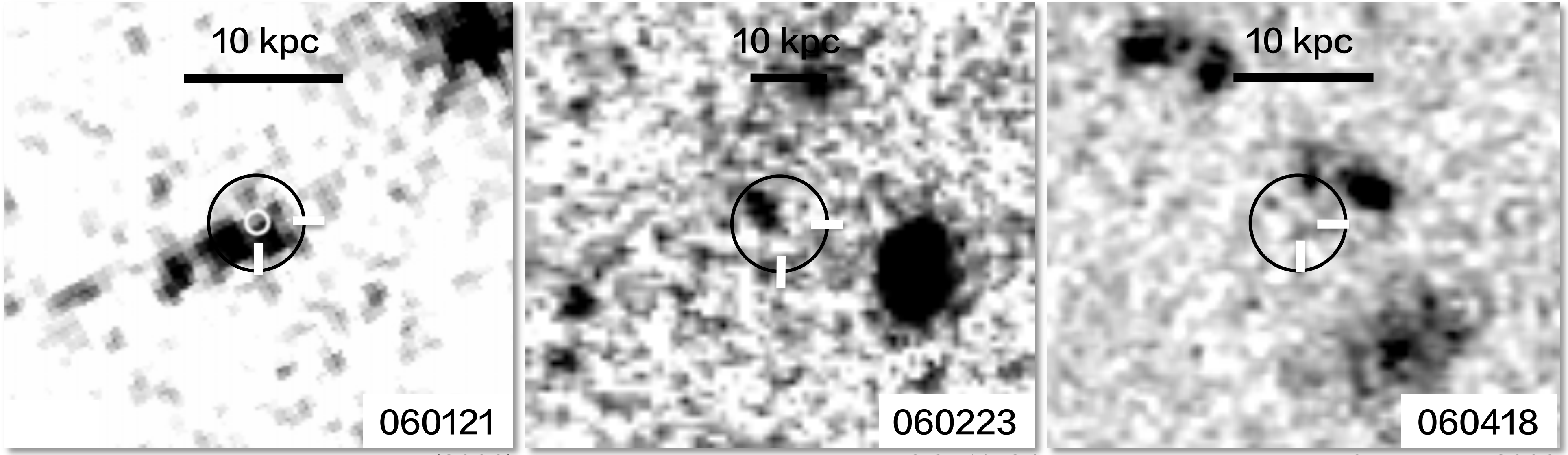


Vreeswijk et al. (2004)

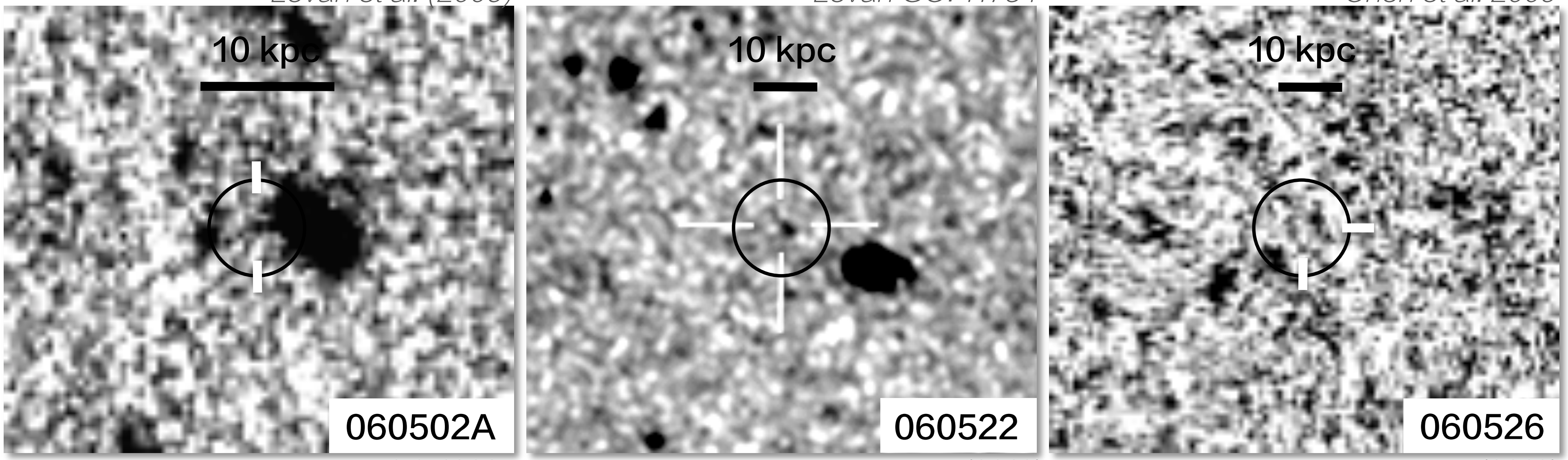
z ~ 2–4 LGRB hosts



z ~ 2–4 LGRB hosts

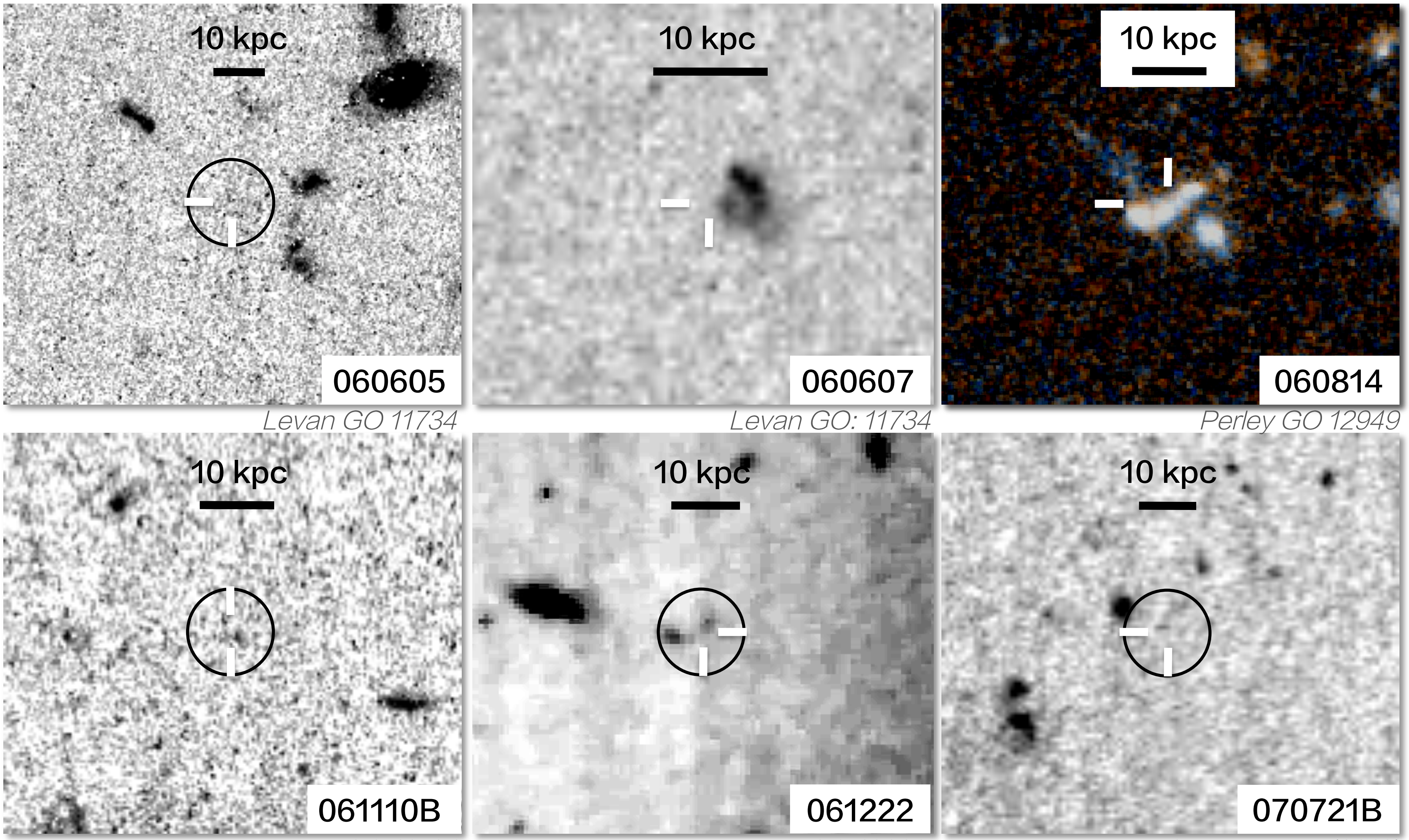


Levan et al. (2006) *Levan GO: 11734* *Chen et al. 2009*



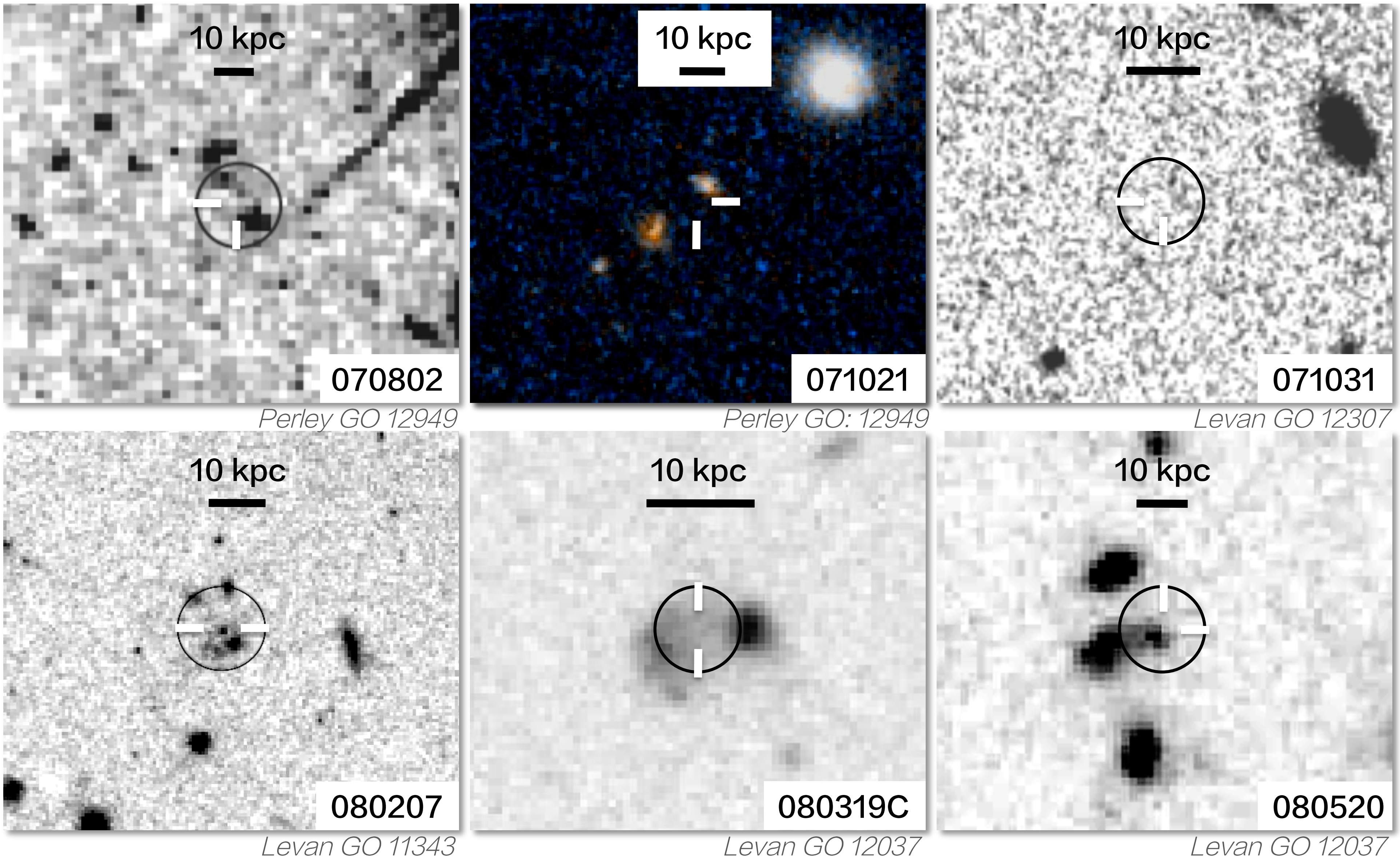
Levan GO 12037 *Tanvir et al. (2012)* *Thöne et al. (2010)*

z ~ 2–4 LGRB hosts

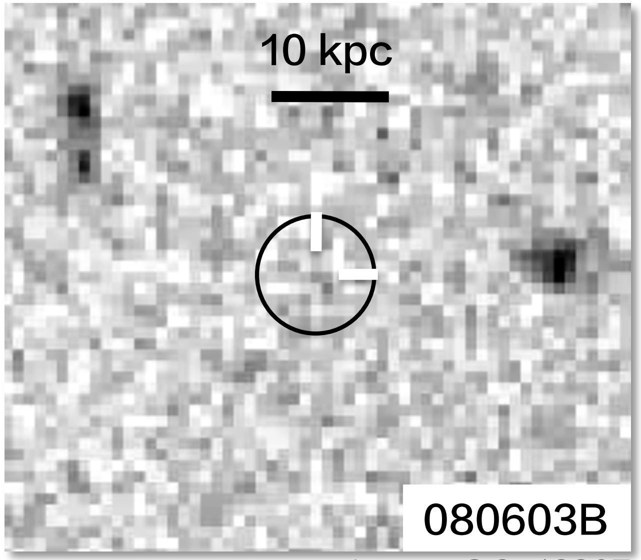


Levan GO 11734 · Berger GO 10908 · Schulze et al. (2012)

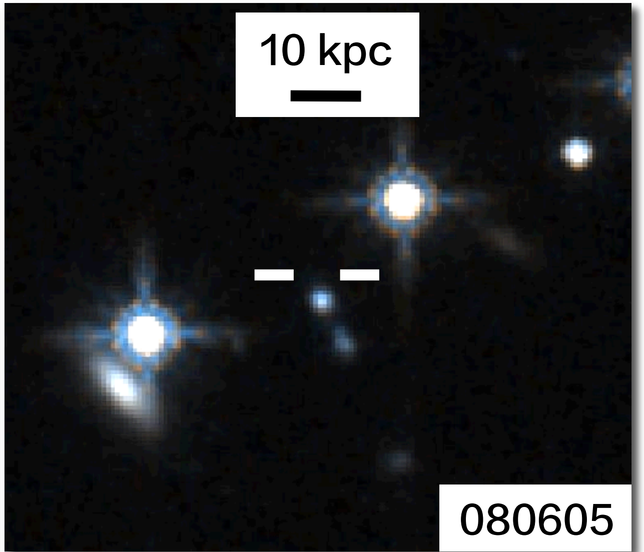
z ~ 2–4 LGRB hosts



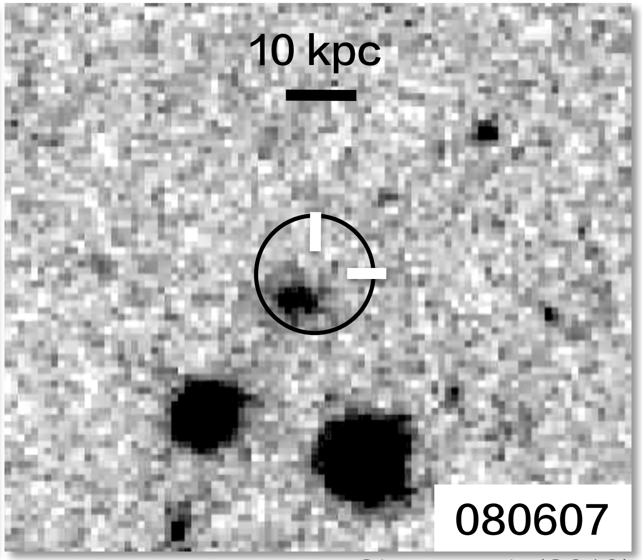
z ~ 2–4 LGRB hosts



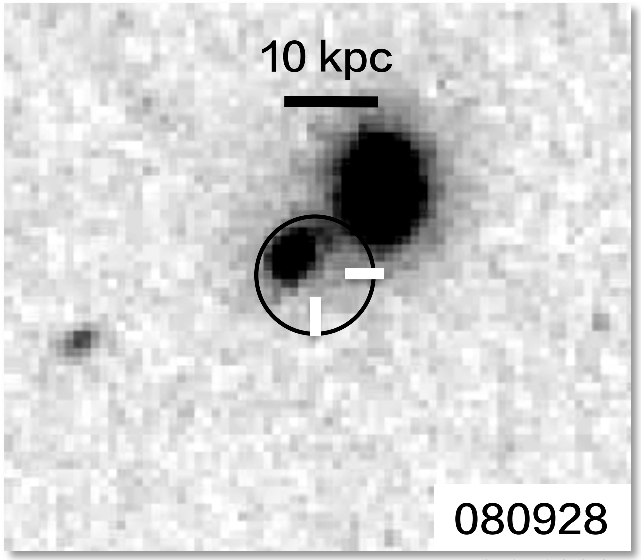
Levan GO: 12307



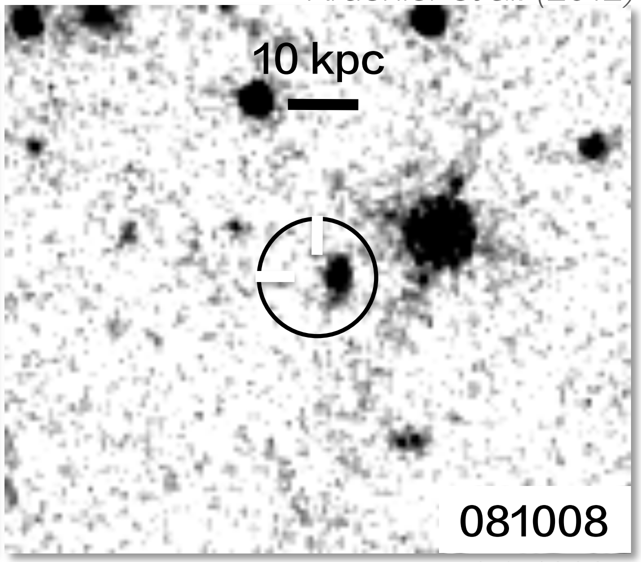
Kruehler et al. (2012)



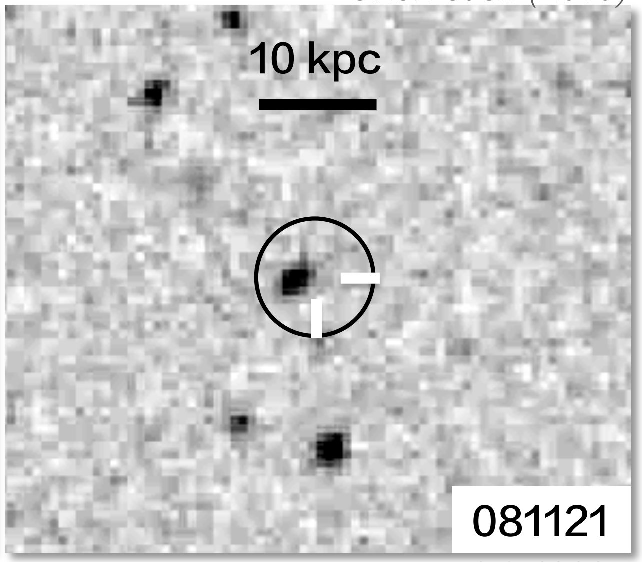
Chen et al. (2010)



Levan GO 12307

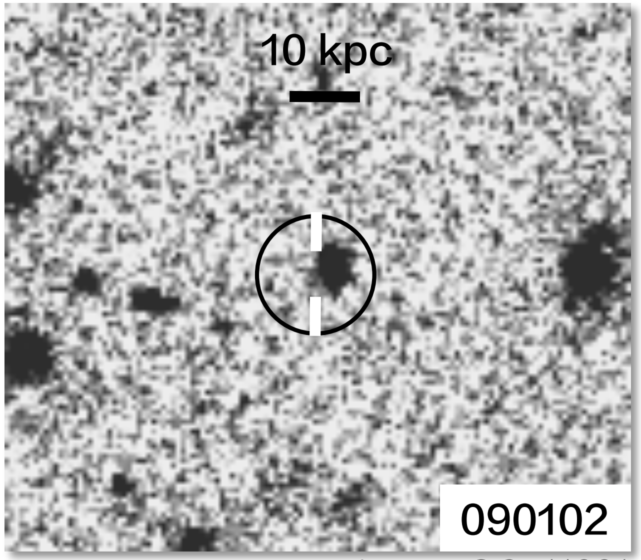


Levan GO 12037

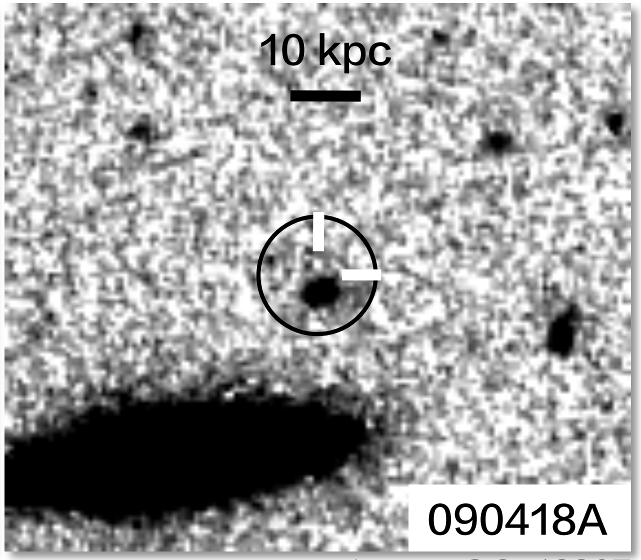


Levan GO 12037

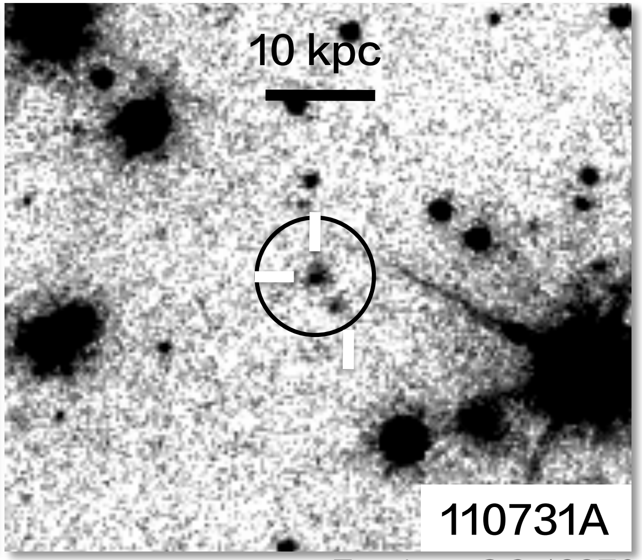
z ~ 2–4 LGRB hosts



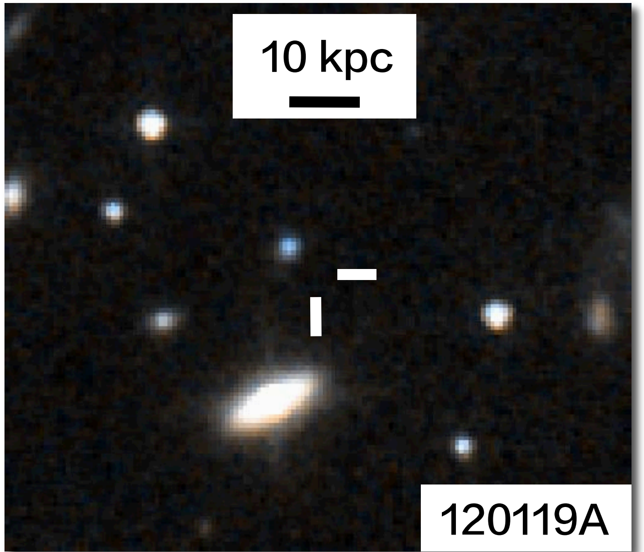
Levan GO: 11991



Levan GO: 12307



Fruchter GO 12370



Perley GO 12949

z ~ 2–4 LGRB hosts

HST LGRB hosts

45% show clear or detectable interaction features
i.e., close pairs with disturbed morphology / tidal tails or mergers

28% faint close pairs / potential interactions

73% show interaction features or are arguable close pairs and/or interactions down to the mag limit of the images

13% no host detected

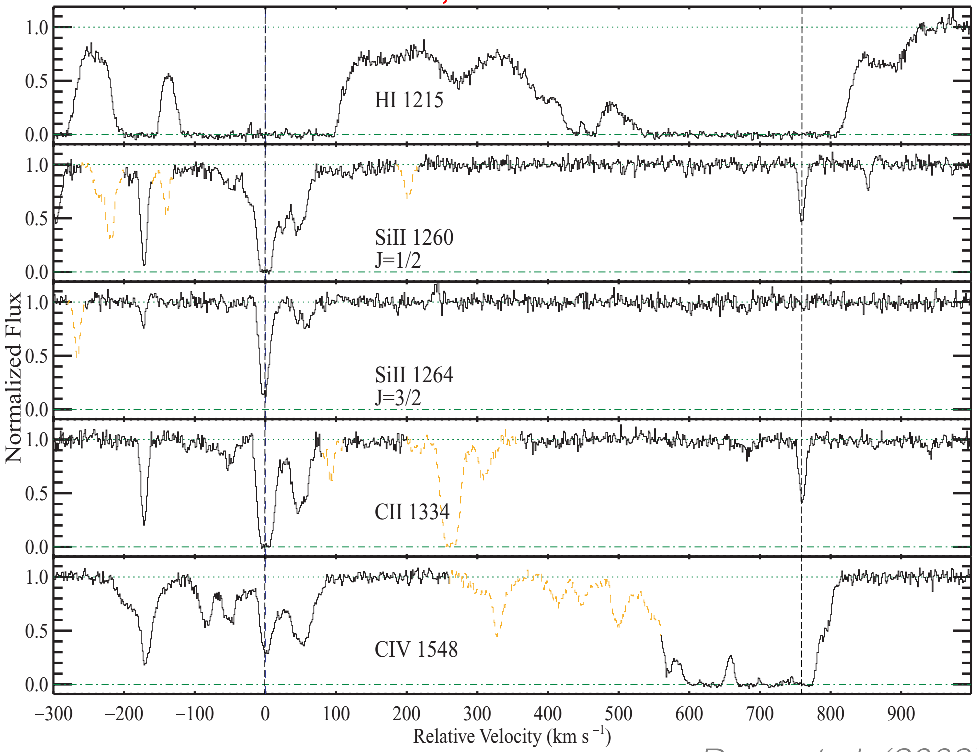
Conservatively, ~50% interaction/close pairs ... more ??

******* *Very few, if any, are clearly single isolated galaxies, undisturbed galaxies, single compact sources, or clean edge–on systems*

Pair absorbers

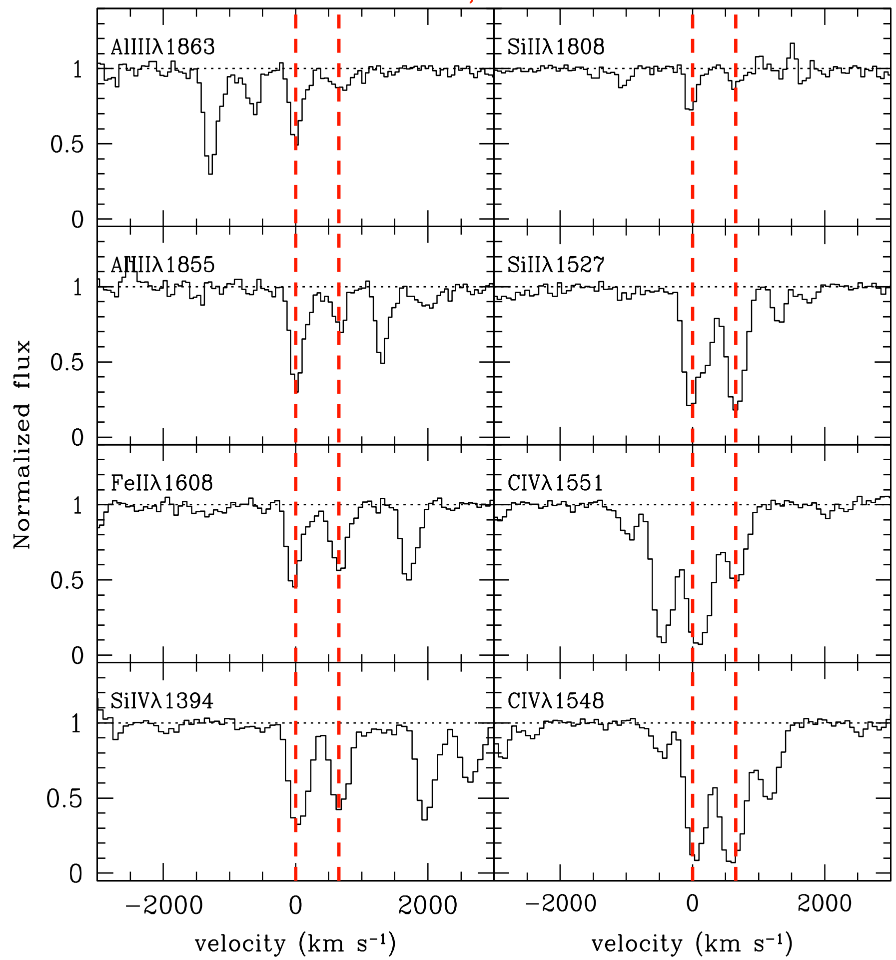
Defined *(arbitrarily)* as two sets of absorption features with > 400 km/s separation in LGRB afterglow spectra

GRB 080810 z = 3.35, 3.36



Page et al. (2009)

GRB 090323 z = 3.567, 3.577



Savaglio et al. (2012)

pair absorbers

Velocity offset (Δv > 400 km/s) is larger than expected for the host galaxy,
equates to > 5 Mpc if attributed to Hubble flow (but, low alignment probability)

Pair absorber line strengths are indicative of sightlines through galaxies,
i.e., damped Lya systems (DLAs)

By the numbers:

13%	fraction of LGRB afterglow spectra show pair absorption
26%	because the absorption originates foreground to the LGRB host
>26%	due to the limited spectral resolution and S/N of the various spectra
>26 – >52%	Δv offset definition correction – pairs will have *Δv < 400 km/s*

more are expected with l.o.s. Δv < 400 km/s than Δv > 400 km/s
from galaxy clustering and orientation

up to 100%	using observations and geometric arguments
3.6%	fraction of pair DLA absorbers in 500 QSO sightlines

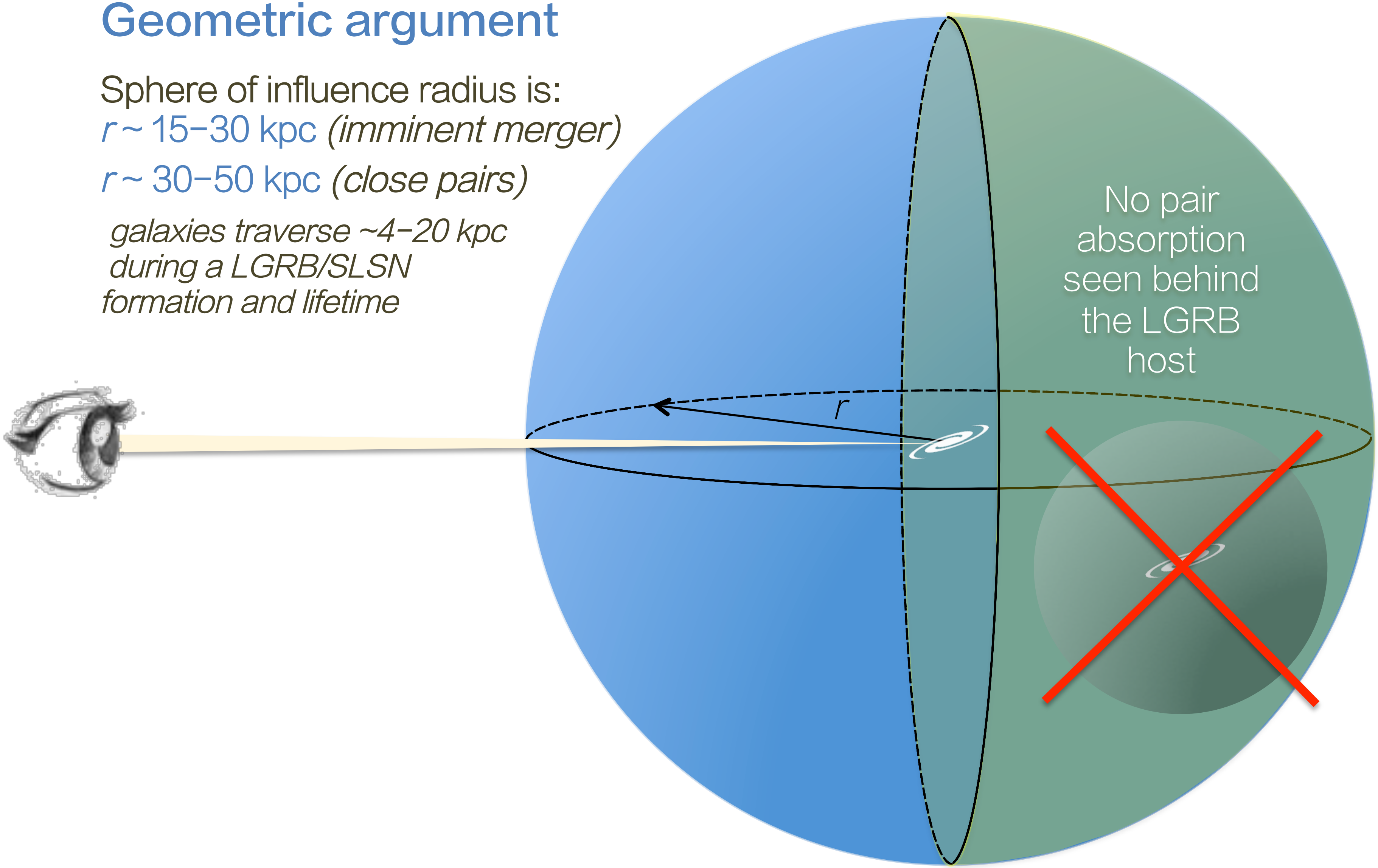
- *DLAs probe 'normal' (typical) galaxies of all mass*
- *LGRB hosts and DLAs sample the same population*

e.g., Fynbo et al. (2005), Arabsalmani et al. (2017)

Geometric argument

Sphere of influence radius is:
$r \sim$ 15−30 kpc *(imminent merger)*
$r \sim$ 30−50 kpc *(close pairs)*

galaxies traverse ~4−20 kpc during a LGRB/SLSN formation and lifetime



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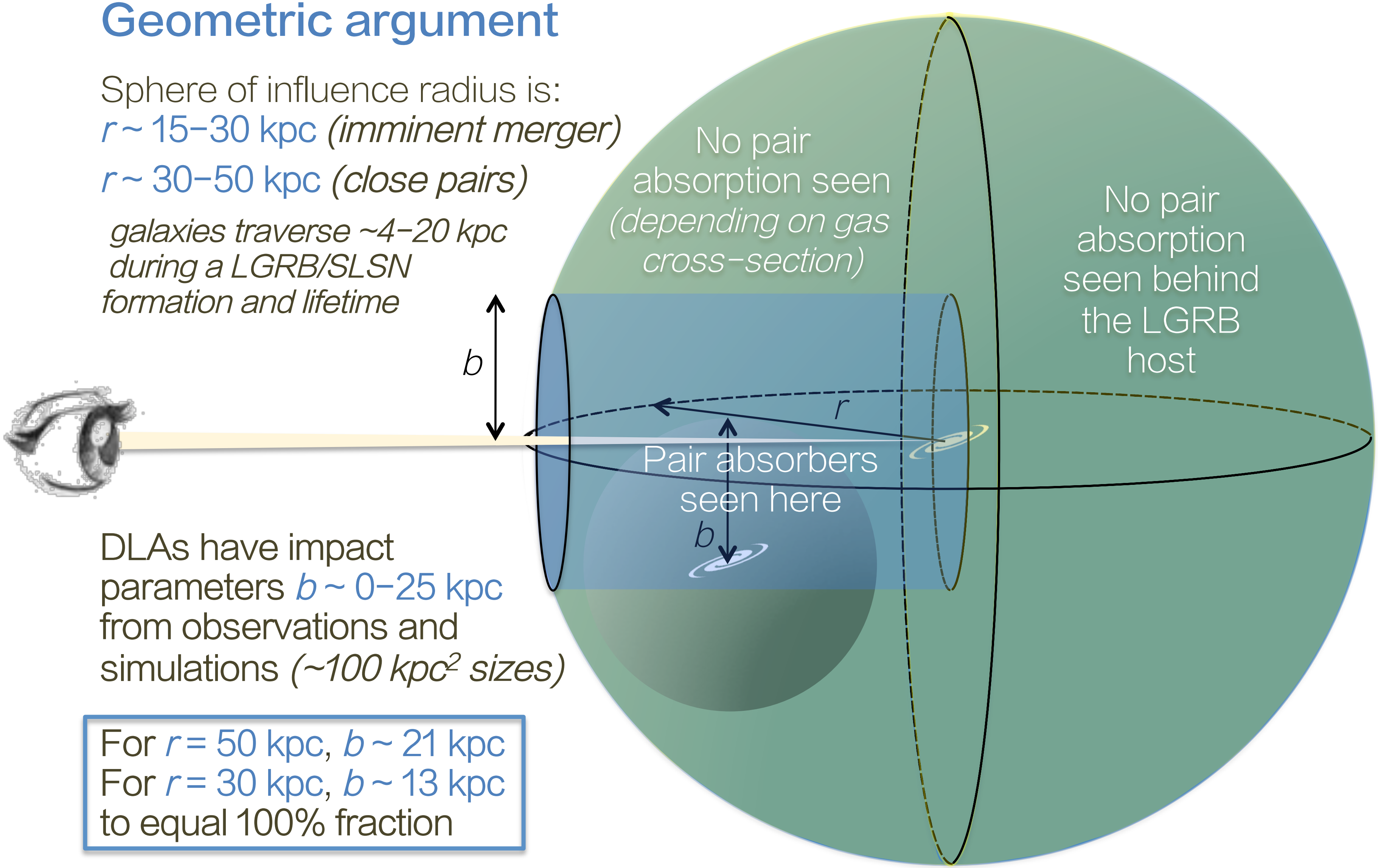
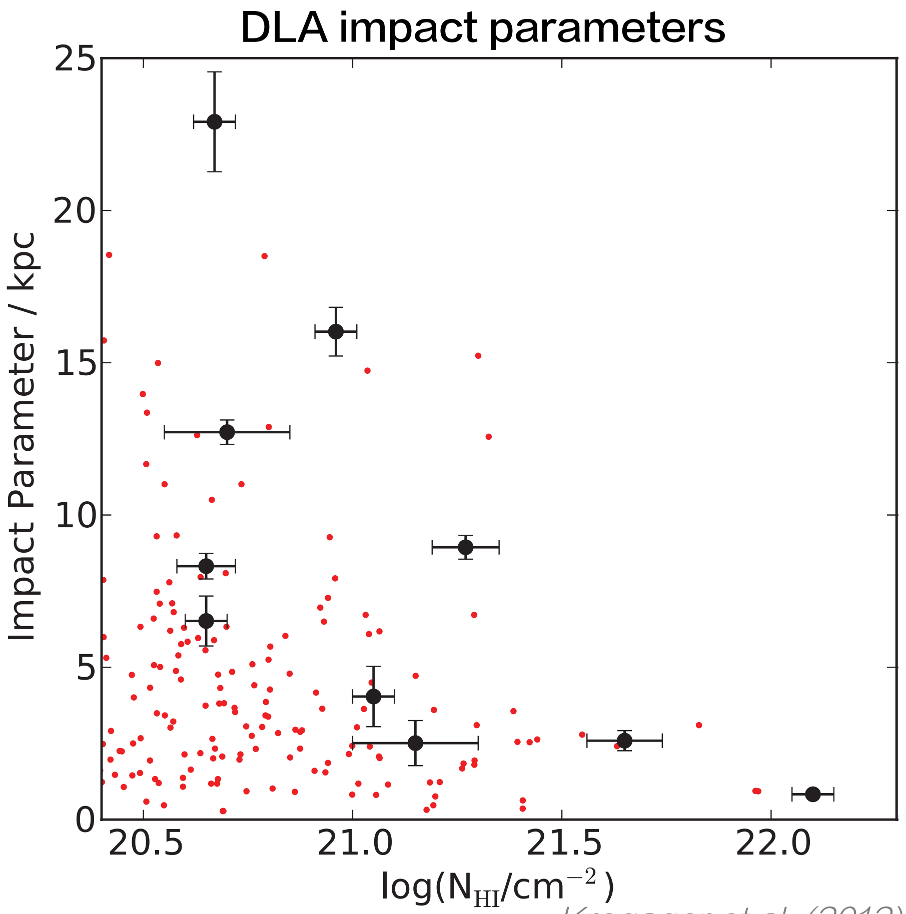


DLAs have impact parameters $b \sim$ 0–25 kpc from observations and simulations *(~100 kpc² sizes)*

For r = 50 kpc, $b \sim$ 21 kpc
For r = 30 kpc, $b \sim$ 13 kpc
to equal 100% fraction

pair absorbers



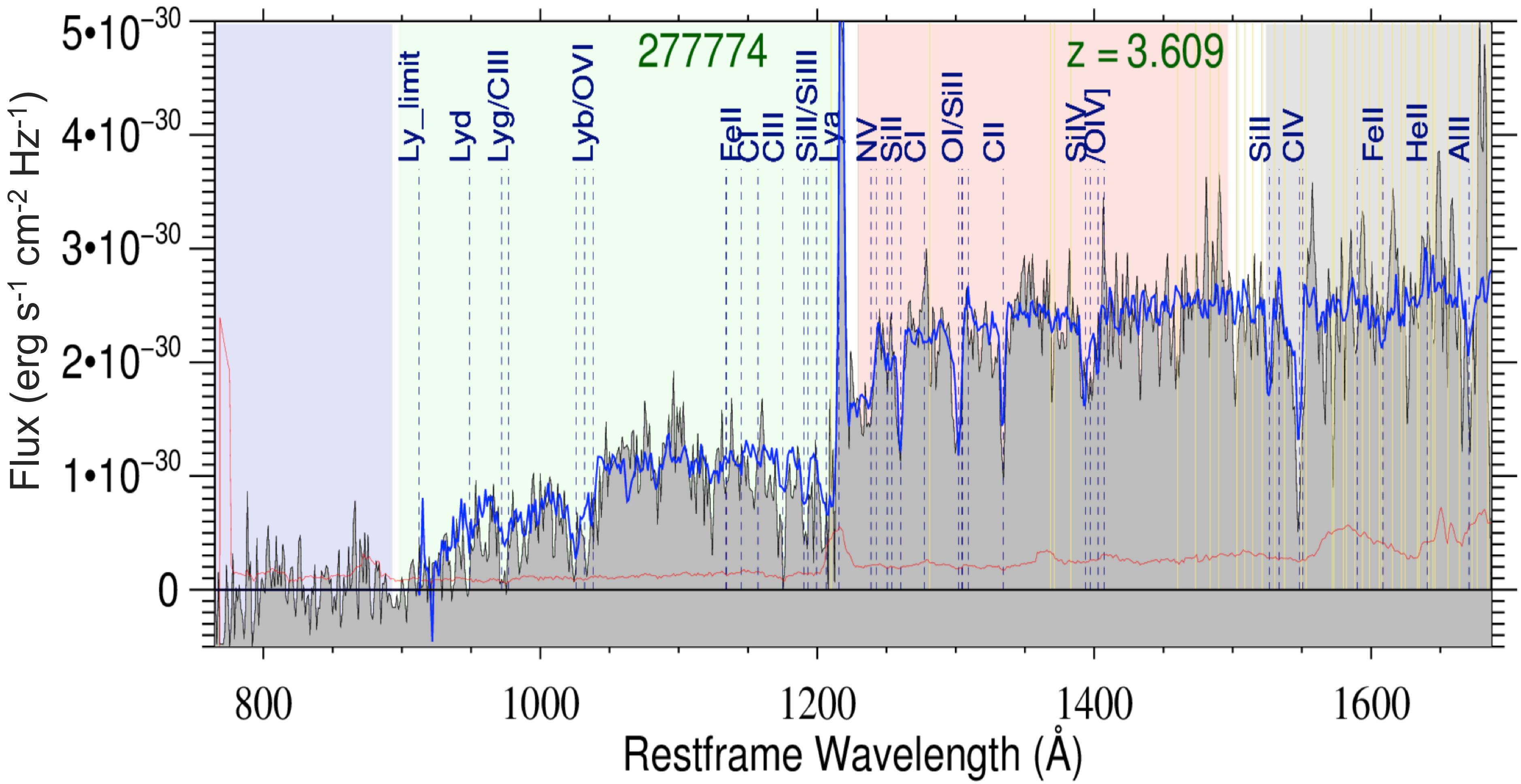
Krogager et al. (2012)

QSO name (1)	z_{DLA} (2)	log N(H I) (cm^{-2}) (3)	b (kpc) (4)	$[Zn/H]_{abs}$ (5)
Q0235+164 ID2	0.5243	21.70	13.2	−0.60 ± 0.41
Q0302−223	1.009	20.36 ± 0.11	25.0	−0.51 ± 0.12
Q0439−433[a]	0.101	19.85 ± 0.10	7.2	−0.20 ± 0.30
Q0738+313	0.2212	20.90 ± 0.07	20.3	−0.70 ± 0.16
Q0827+243	0.5247	20.30 ± 0.04	38.4	−0.49 ± 0.30
Q1009−0026	0.887	19.48 ± 0.05	39.0	0.25 ± 0.06
Q1127−145	0.3127	21.71 ± 0.07	17.5	−0.90 ± 0.11
Q0528−250	2.811	21.35	9.2 ± 0.2	−0.91 ± 0.07
Q0918+1636	2.5832	20.96 ± 0.05	16.2 ± 0.2	−0.12 ± 0.05
Q2206−1958 (total)	1.921	20.65	12.7 ± 0.6	−0.54 ± 0.05
Q2222−0946	2.354	20.65 ± 0.05	6.3 ± 0.8	−0.46 ± 0.07
Q2233+131	3.1501	20.00	17.9	−0.80 ± 0.24

Christensen et al. (2014)

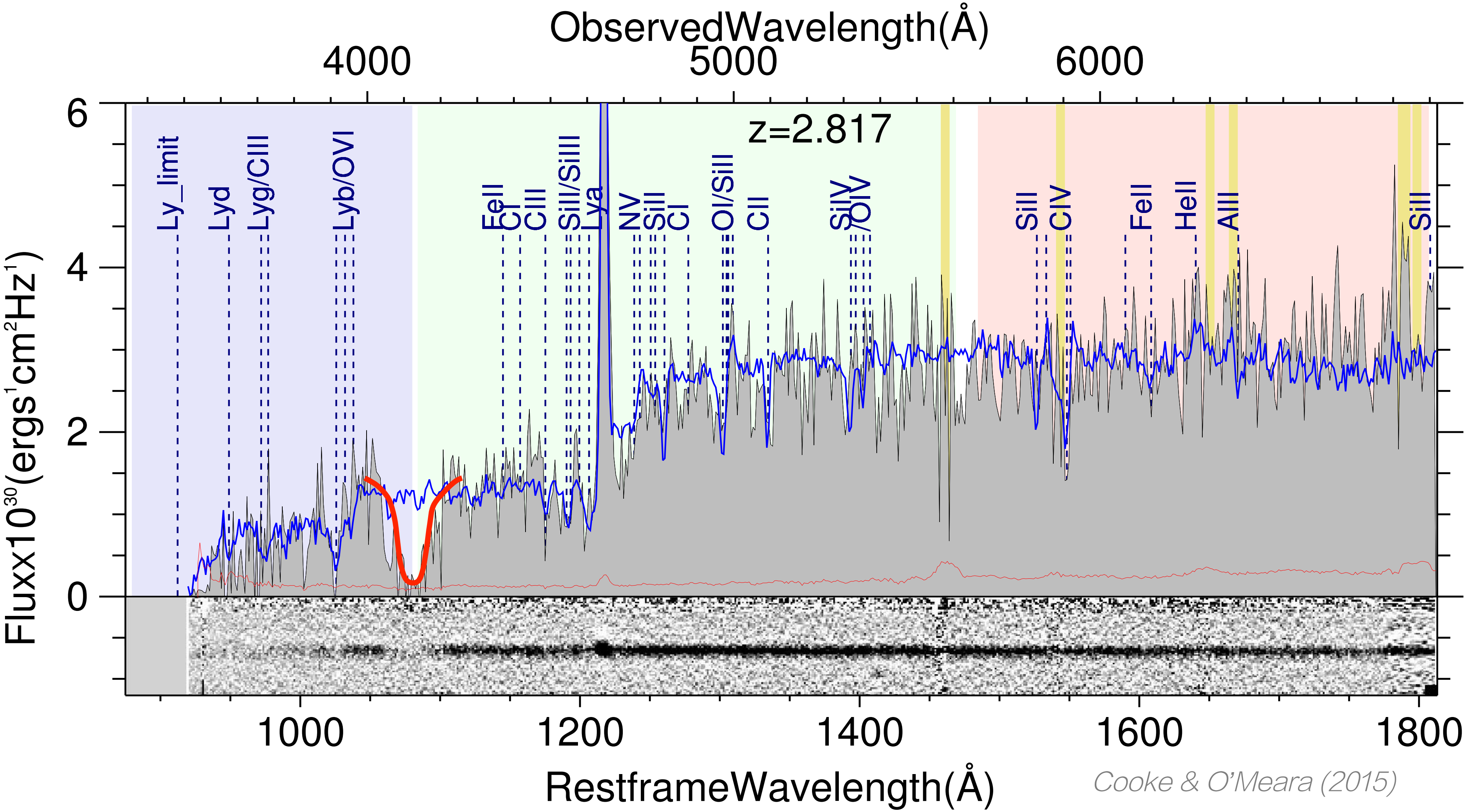
Our work and others *(e.g., Fumagalli et al. 2010, 2014, 2015)* show that DLAs are associated with faint galaxies

Typical high redshift galaxy spectrum
(Lyman break galaxy)



DLAs in galaxy sightlines

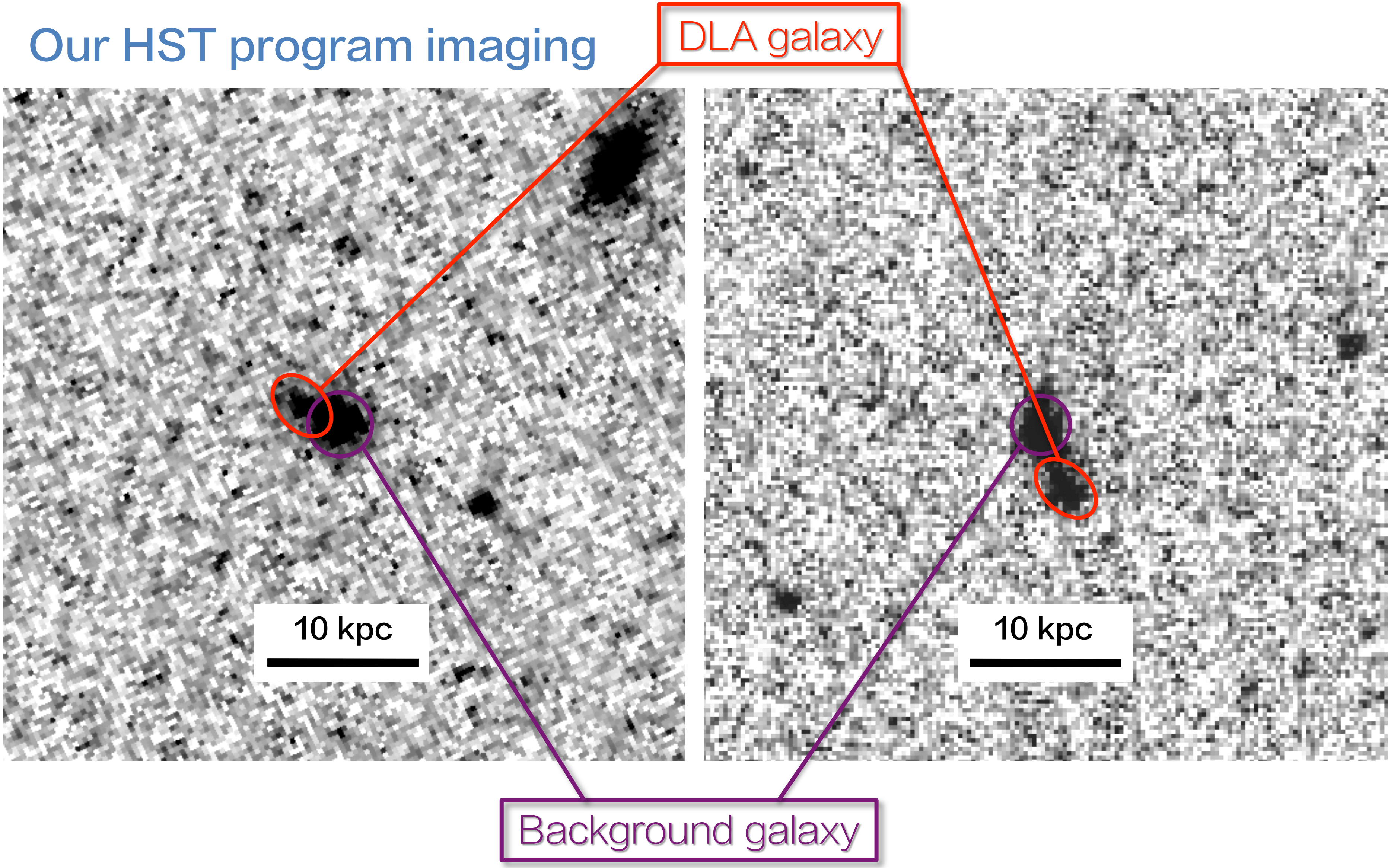
VVDS high redshift galaxy spectrum



Cooke & O'Meara (2015)

DLAs in galaxy sightlines

Our HST program imaging



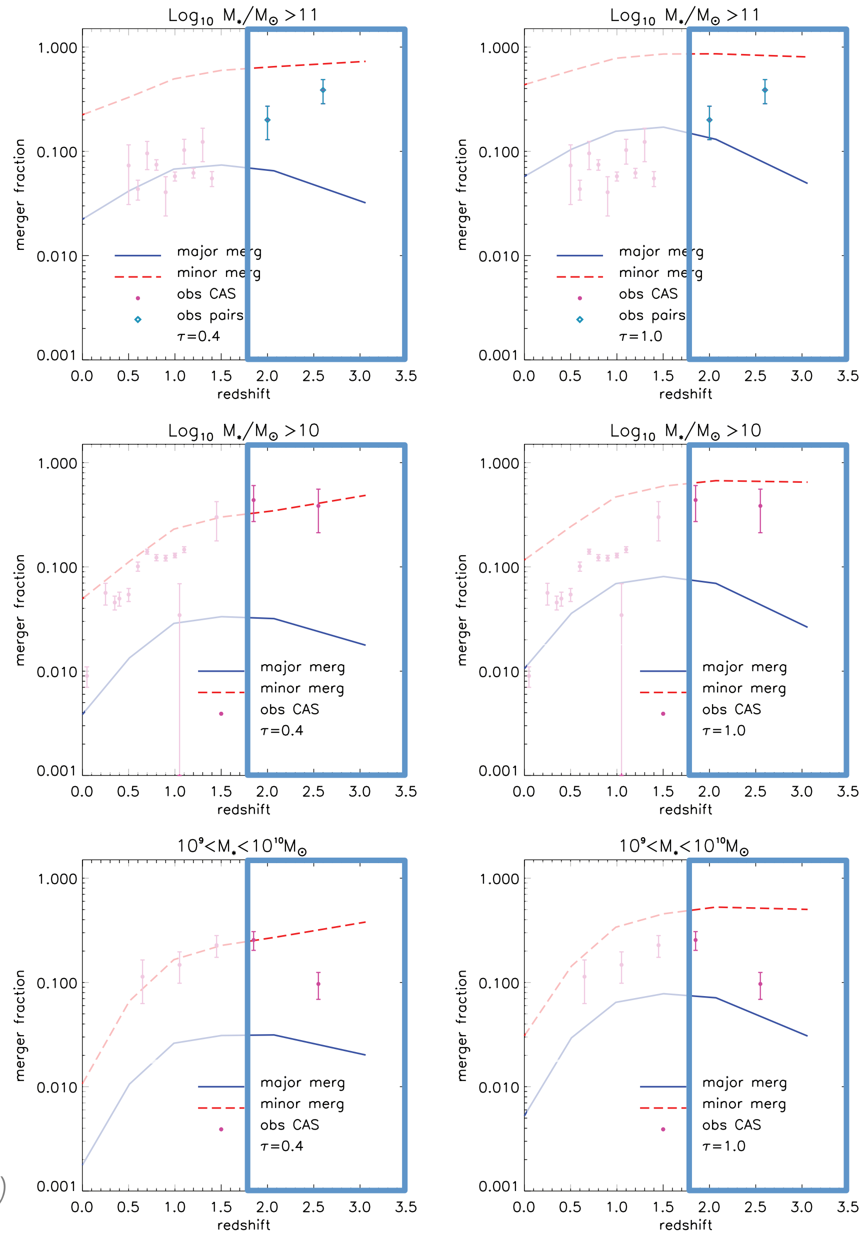
z ~ 2–4 ‘normal’ galaxies

Not a slam dunk yet!

What are the percentages for ‘normal’ galaxies at these redshifts?

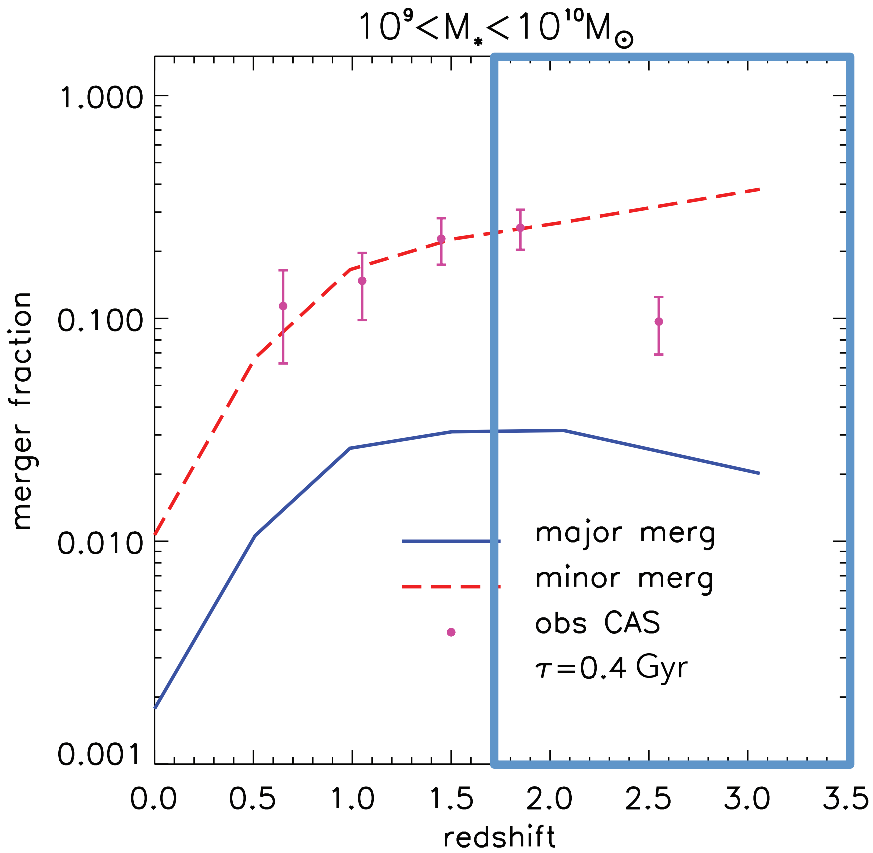
Massive z ~ 2–4 galaxy merger and close pair fractions range from ~20–40%

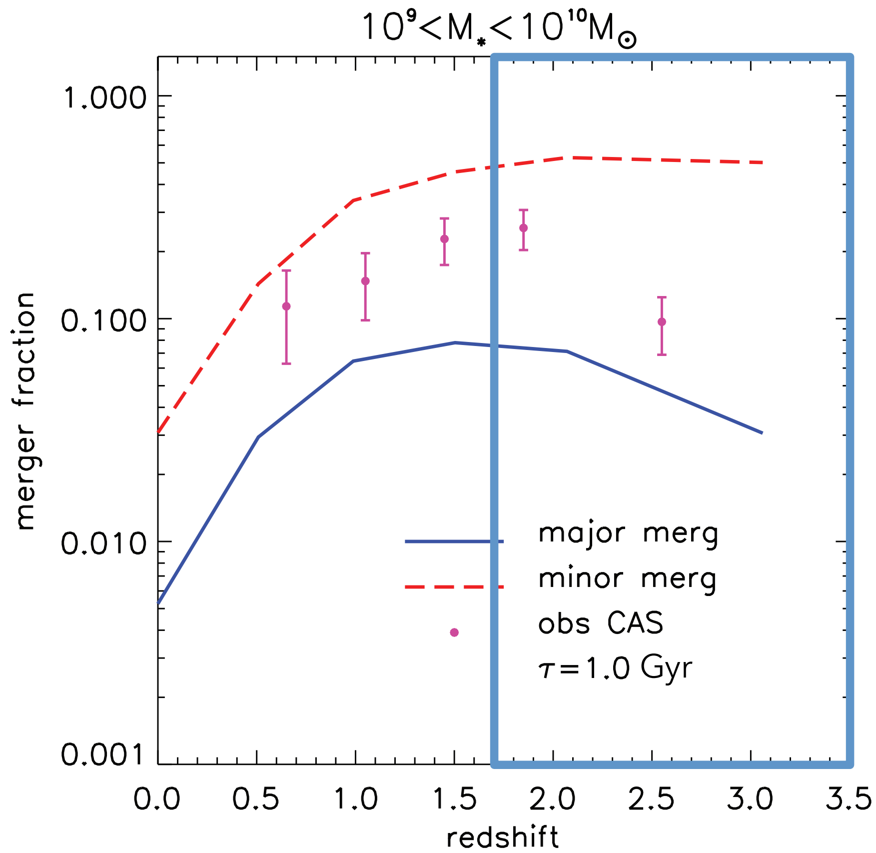
However, SLSN and LGRB host galaxies have typical stellar masses in this range or lower *(~20% down to < 10 %)* →



Bertone & Conselice (2009)

z ~ 2–4 'normal' galaxies





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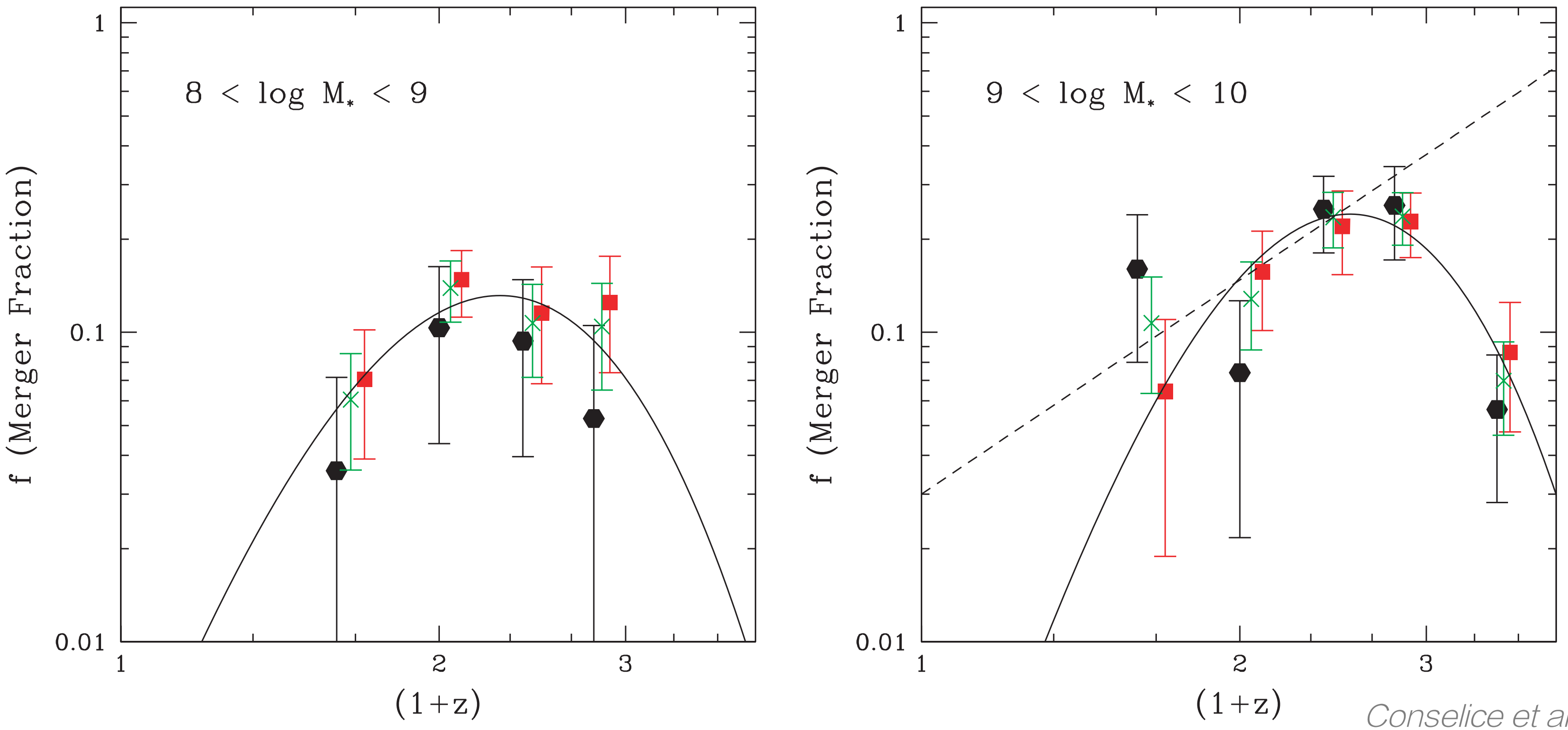


Conselice et al. (2008)

Similar mass normal z ~ 2–4 host merger fraction: ~ 10–25%

Close pair analyses agree with this value (~15–20%) *e.g., Berrier & Cooke (2012)*

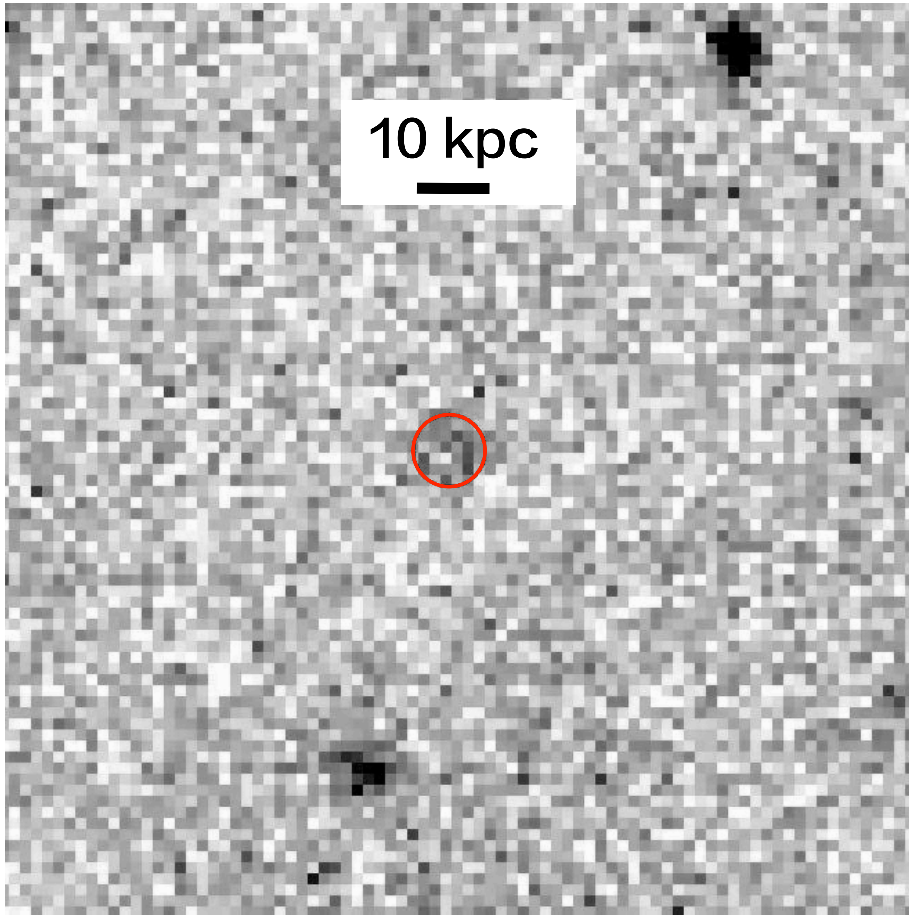
The LGRB host fraction appears to be > 50%

Finally, how about SLSN hosts?

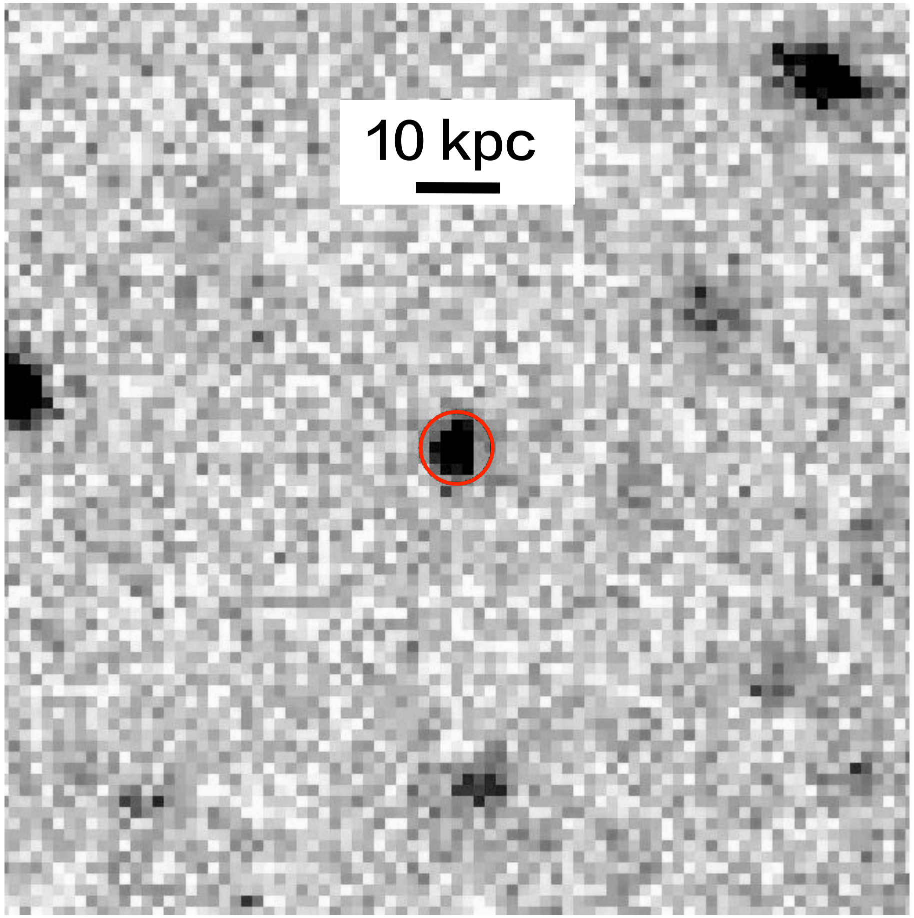
z ~ 2–4 SLSN hosts

No clear evidence of interactions or disturbed morphology
in the ground-based images

SN 235017 (z = 2.478)

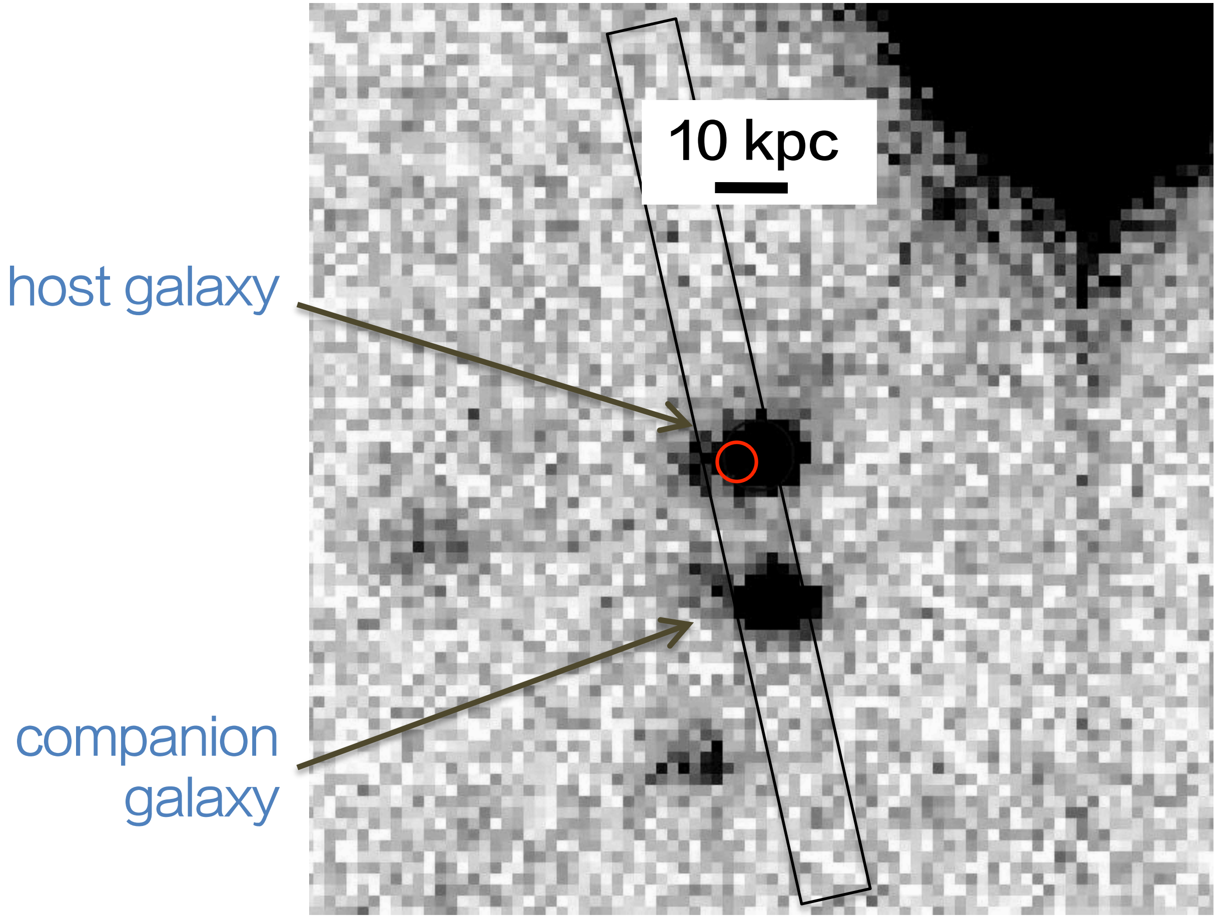


SN 1000+0216 (z = 3.899)



Spectroscopic close galaxy pair
→ Evidence of tidal tails and interaction

SN 2213−1745 (z = 2.046)



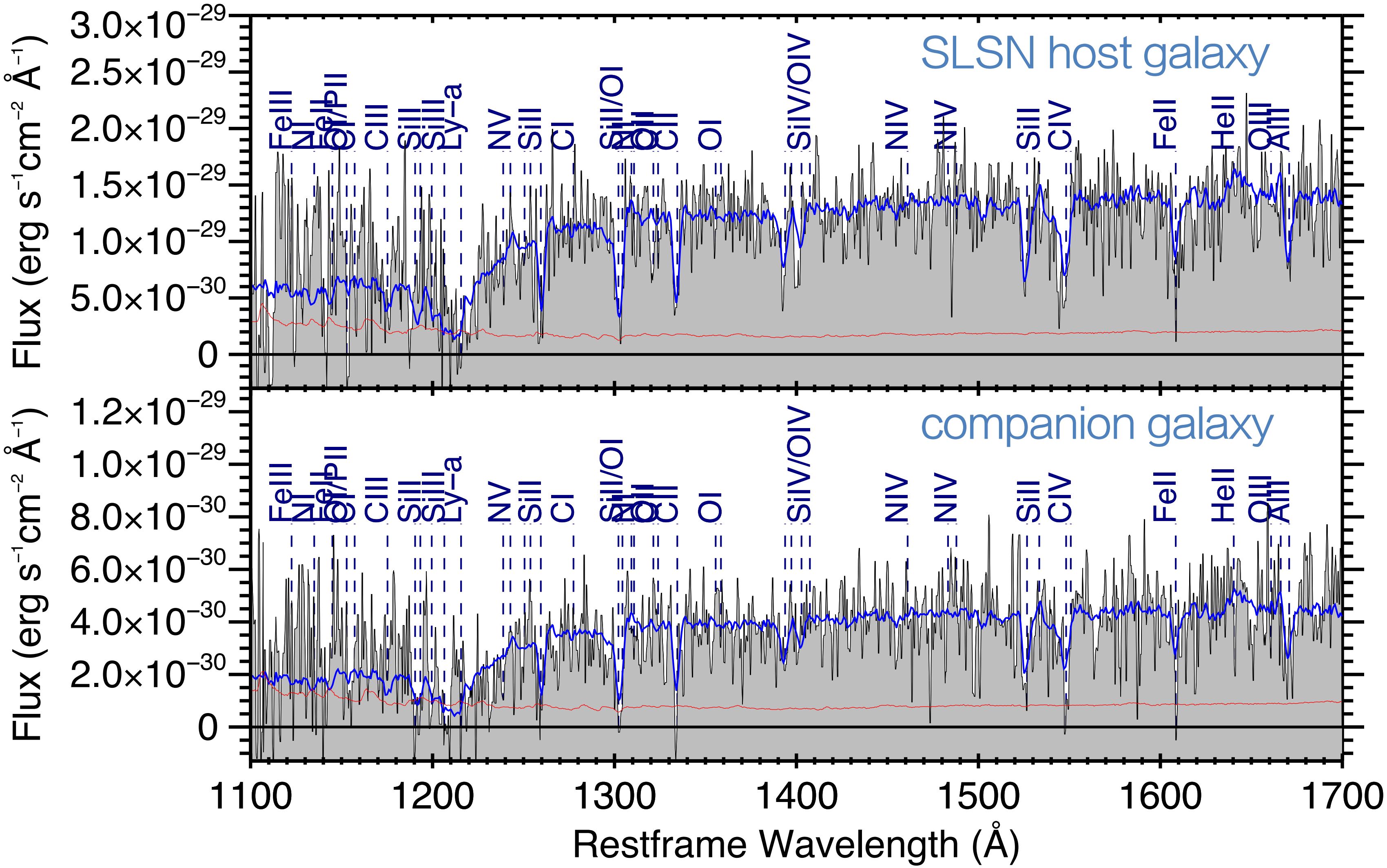
Slit has a width of 10 kpc

Both galaxies have the same redshift
$\Delta v = 150 \pm 80$ km/s

21 kpc centroid separation

z ~ 2−4 SLSN hosts

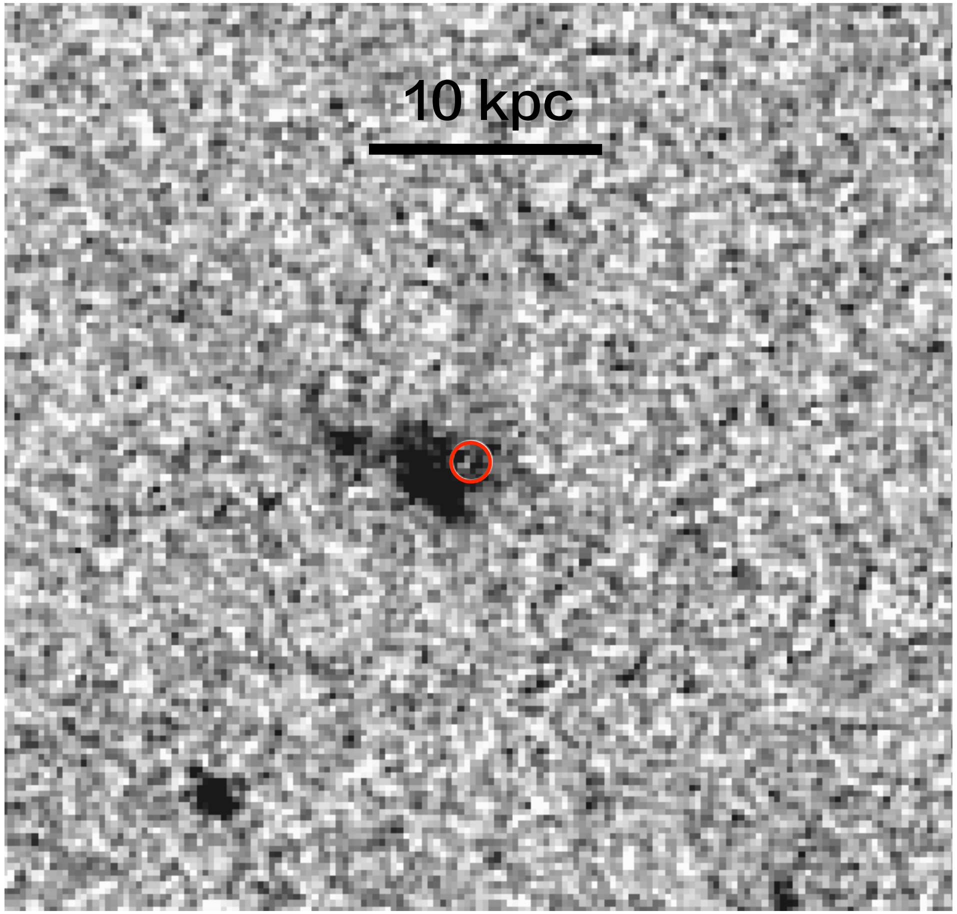
Keck LRIS spectroscopy



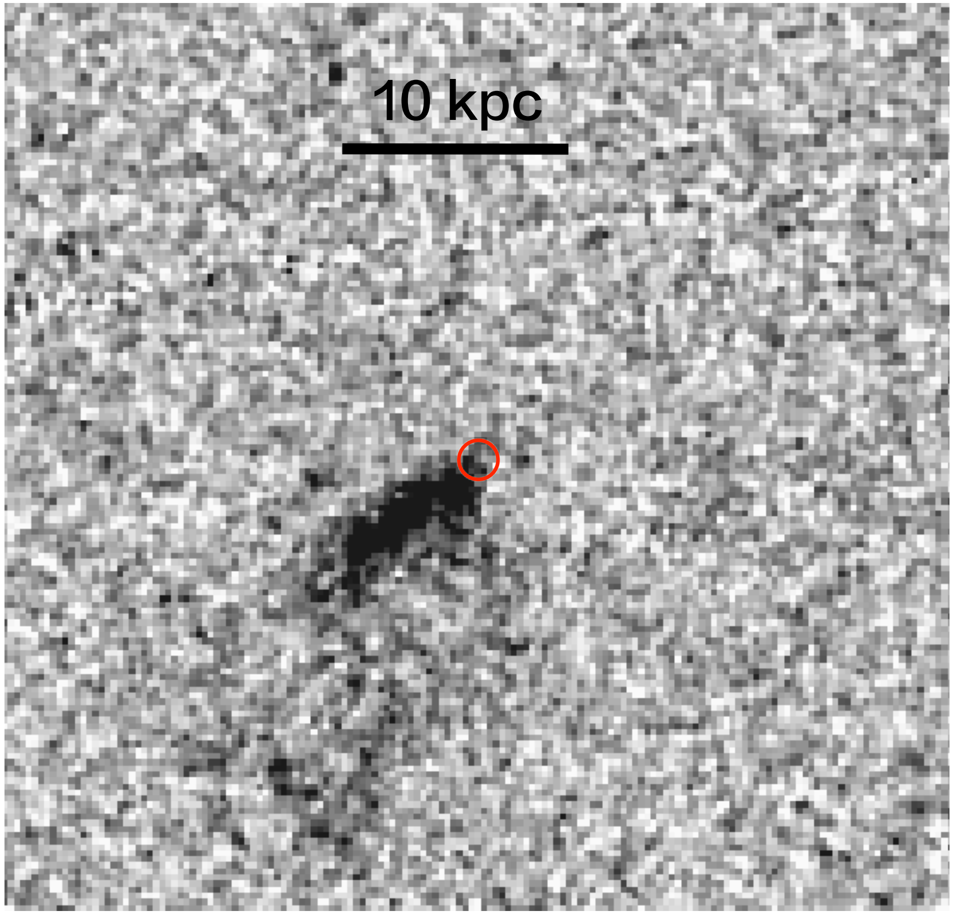
HSC-SSP z ~ 2–4 SLSN hosts

Evidence of interactions or disturbed morphology
in the space-based images

HSC16adga z_{spec} = 2.399



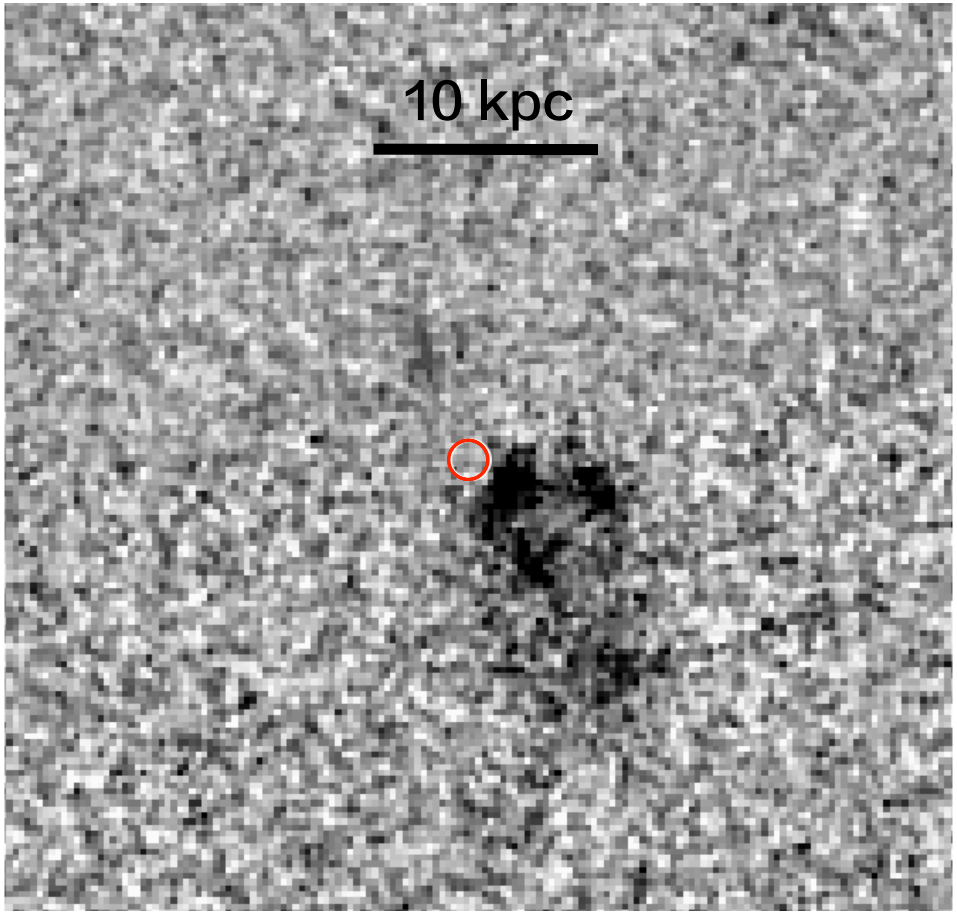
HSC17auzg z_{spec} = 1.965



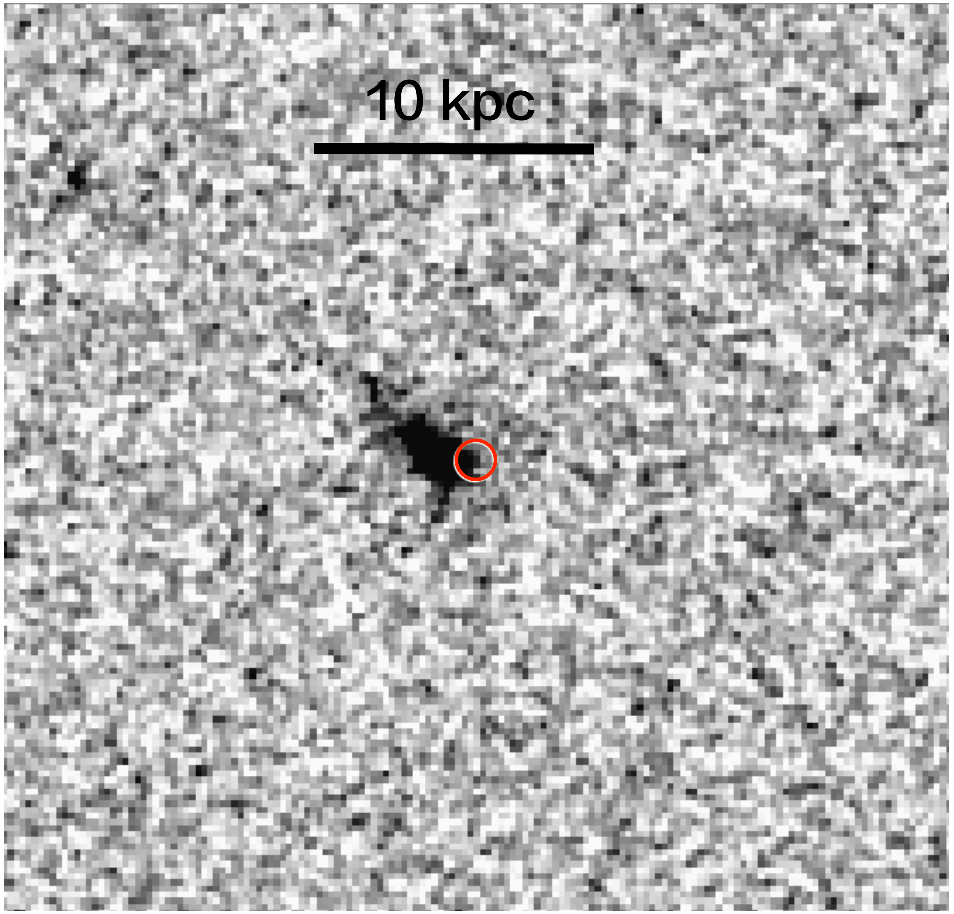
HSC-SSP z ~ 2–4 SLSN hosts

Evidence of interactions or disturbed morphology
in the space-based images

HSC17dbpf $z_{spec} = 1.851$



HSC17dsid $z_{spec} = 4.276$



Do high redshift galaxy interactions produce massive stars?

The answer currently appears to be *"yes"*

- ~45% of LGRB hosts have signs of disturbed morphology and interaction
  weak evidence, as ~10–40% is the estimate for similar z ~ 2–4 galaxies
  *although **~10%** is the fraction for similar mass galaxies*
- ~80% *(all?)* are plausible interactions or close pairs *(and to the mag limit)*
  good evidence when combined with the above
  until further tested with deeper imaging / colors / spectra
- Up to 100% of the hosts may be close pairs/interactions based on pair absorber results, impact parameters, and associated geometry
  strong evidence, when combined with above – further investigation needed
  - Note: only 3.6% of QSO sightlines show DLA pair absorption
- **All** SLSN hosts *(w/HST imaging)* appear to have disturbed morphology and one is a spectroscopically–confirmed interaction
- And then there are the event locations... *arguments for 1st pass or 'fly–bys'?*