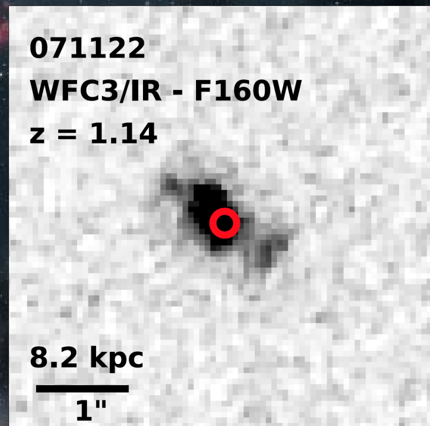
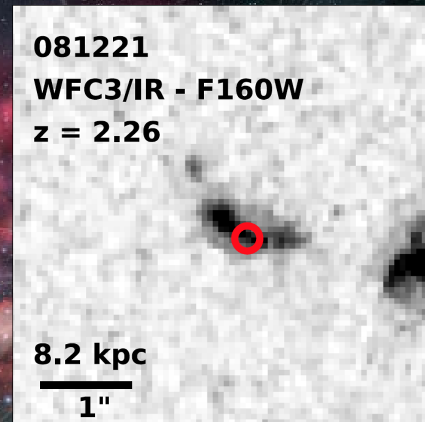
The Impact of Positional Uncertainty on Gamma-Ray Burst Environment Studies





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In collaboration with Edo Berger and Wen-fai Fong
arXiv:1509.07866

Topics in AstroStatistics
October 27, 2015

Image credit: Gemini Observatory/AURA/Lynette Cook

Outline

- Background
  - What are GRBs?
  - Host Galaxy Environment Studies
- Impact of Positional Uncertainty on:
  - Host Galaxy Identification
  - Location Measurements
- Results
  - Progenitor Implications
- Conclusions

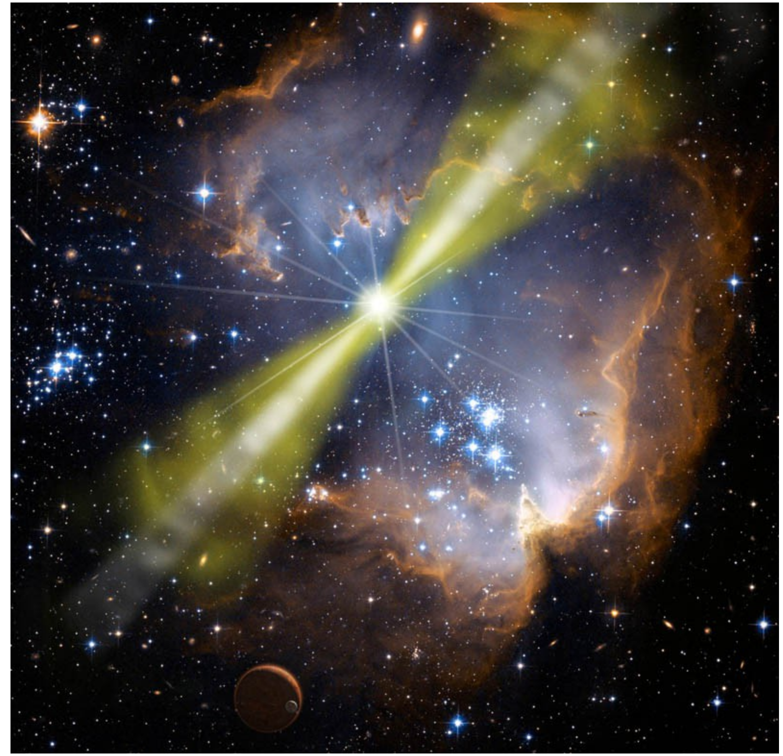
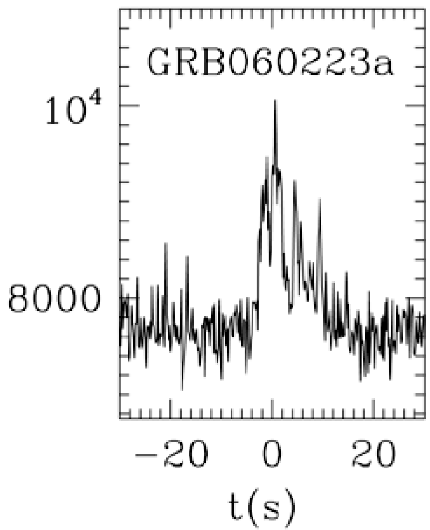
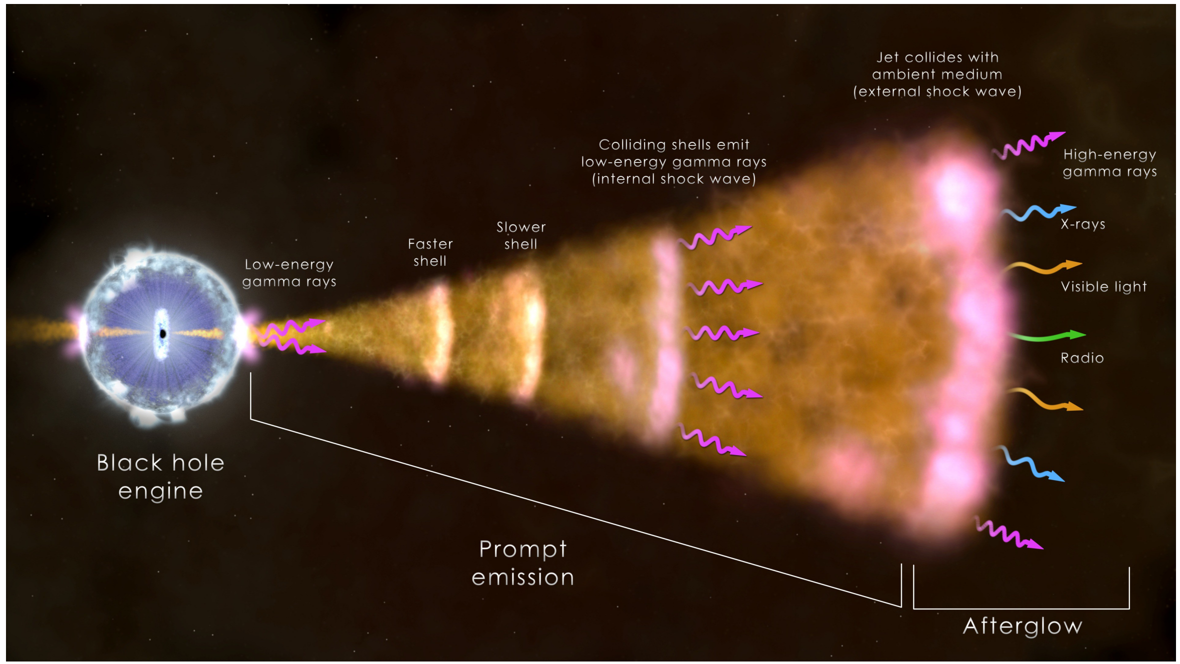


Image Credit: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

What are Gamma-Ray Bursts?

- The Universe's most energetic explosions
- Prompt emission → long vs. short duration GRBs
- Afterglow emission → spans X-ray to visible to radio wavelengths

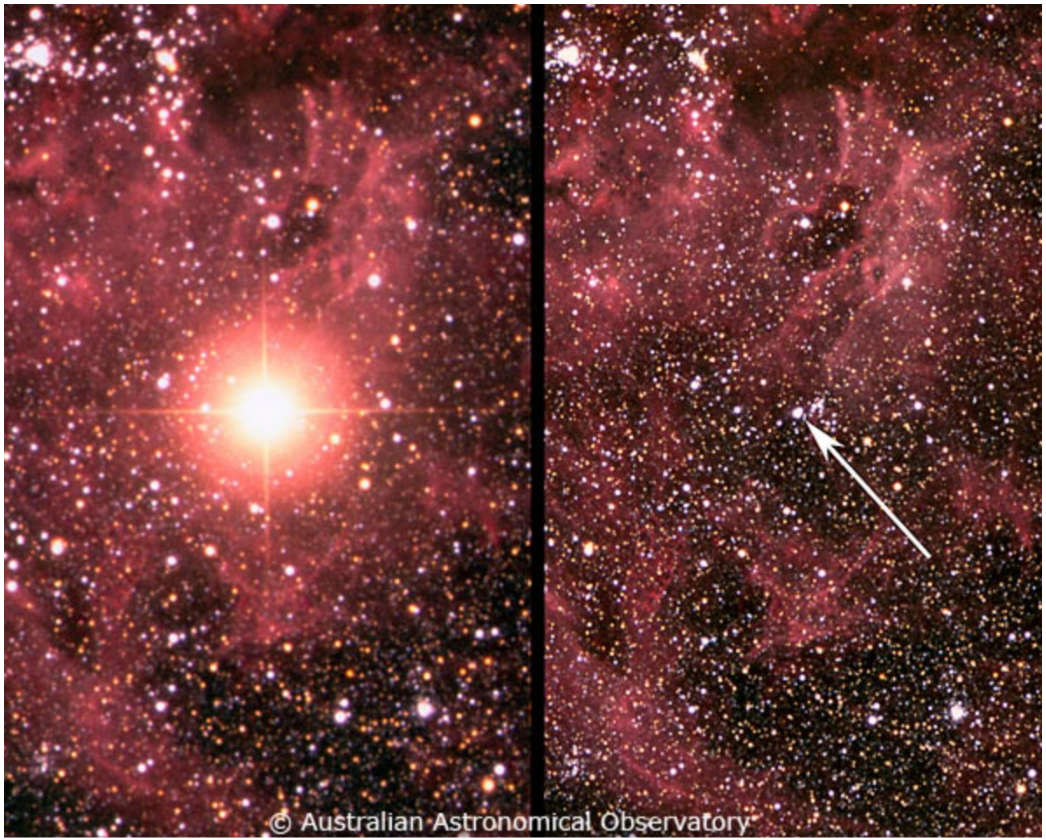


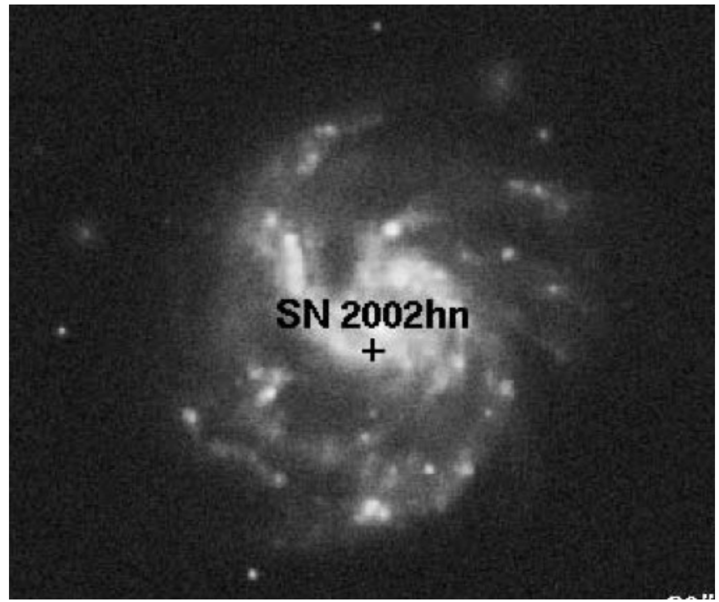


- Progenitor models
  - Collapsar model (Woosley et al. 1993) → long GRBs
  - Merging NS-NS binaries (Eichler et al. 1989) → short GRBs

Studying the Locations of Transients

- A complementary approach to studying the events themselves
  - Pre-explosion imaging to study progenitor star
  - Infer progenitor properties by studying host environments

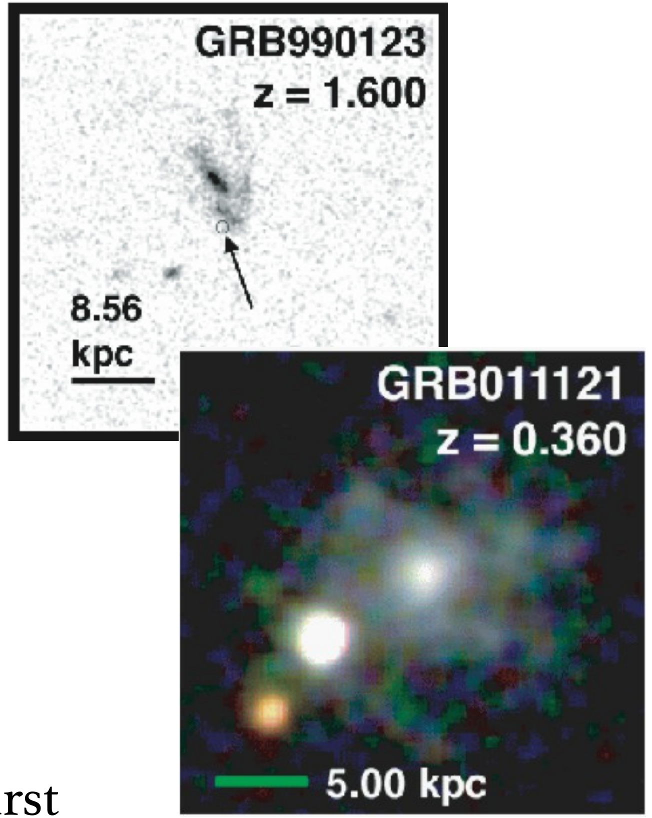




Kelly et al. 2008

Long GRB Host Galaxy Studies

- Global Host Properties
  - Irregular, faint, blue star-forming galaxies
- Sub-Galactic Environment Studies
  - Population studies
    - Offset from center of host galaxy
    - Fractional Flux
      - Statistic measuring the brightness of the burst location *relative* to the host light distribution
    - Comparisons to Supernovae

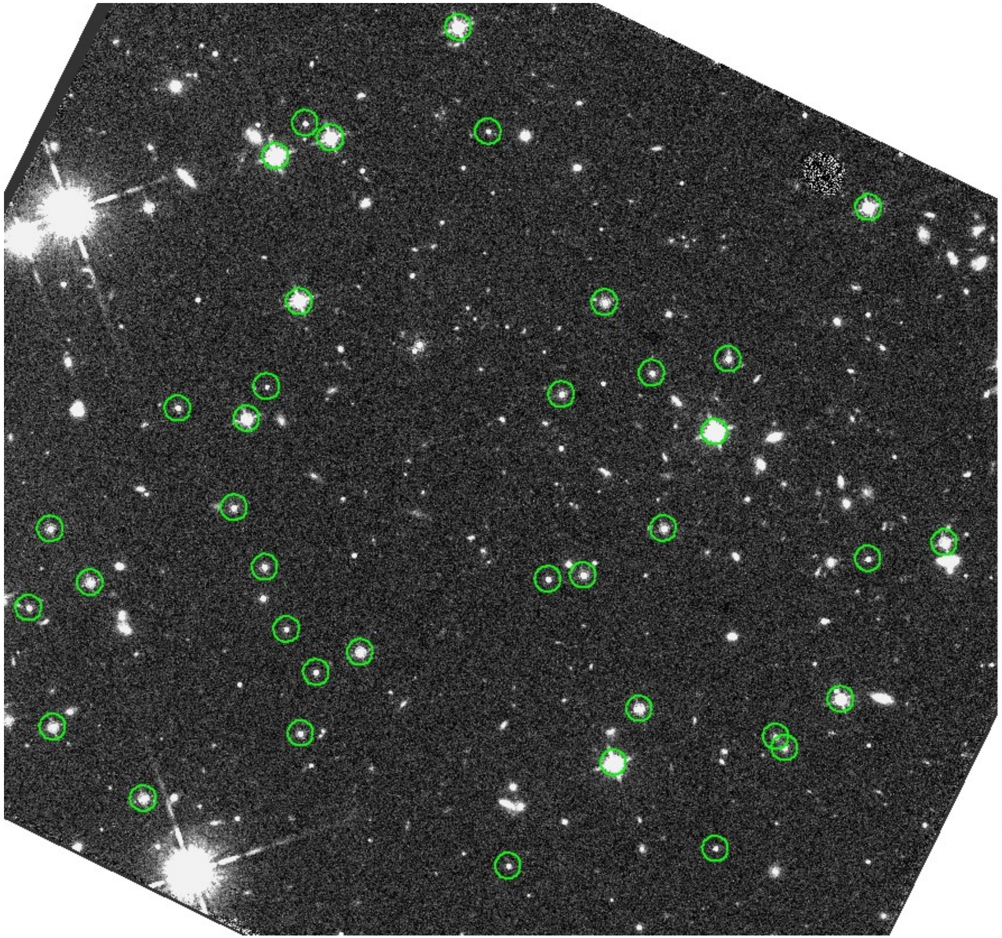


Wainwright et al. 2007

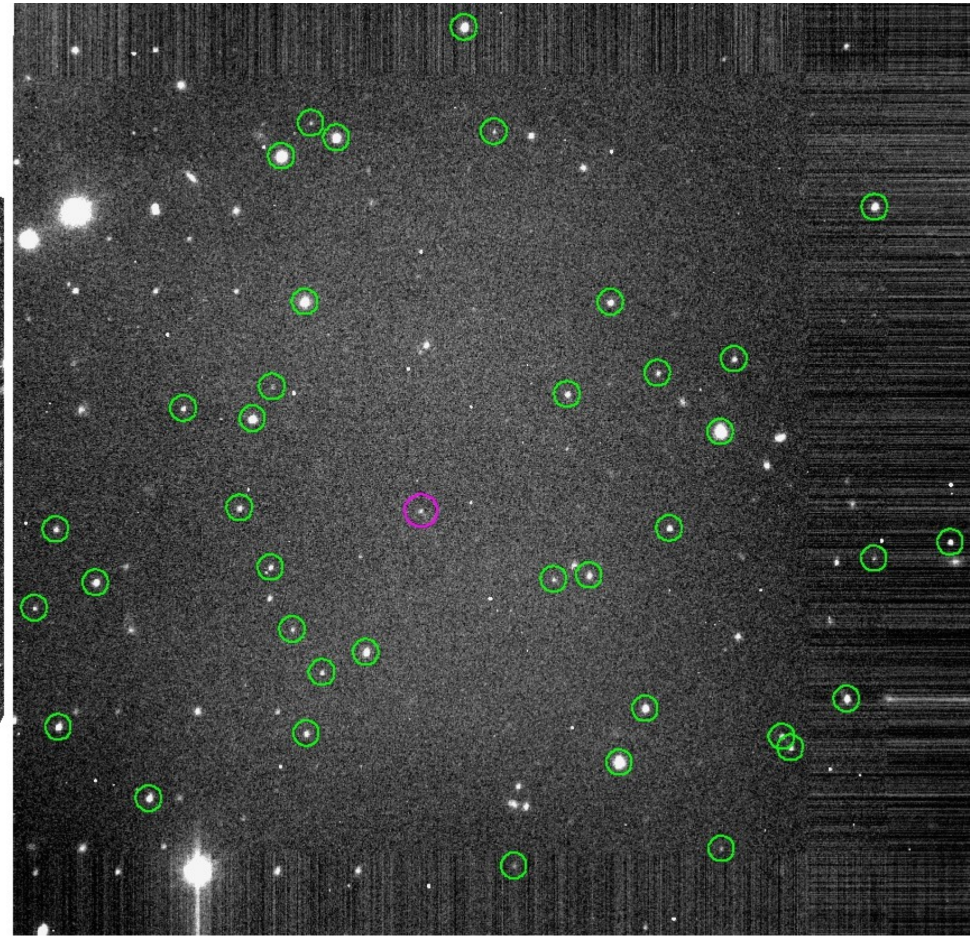
This project → analyzed the last 10 years of *HST* observations of ~100 long GRBs to investigate their preferred locations within their host galaxies

Relative Astrometry

Late-time Hubble image of host galaxy



Early-time ground-based afterglow detection

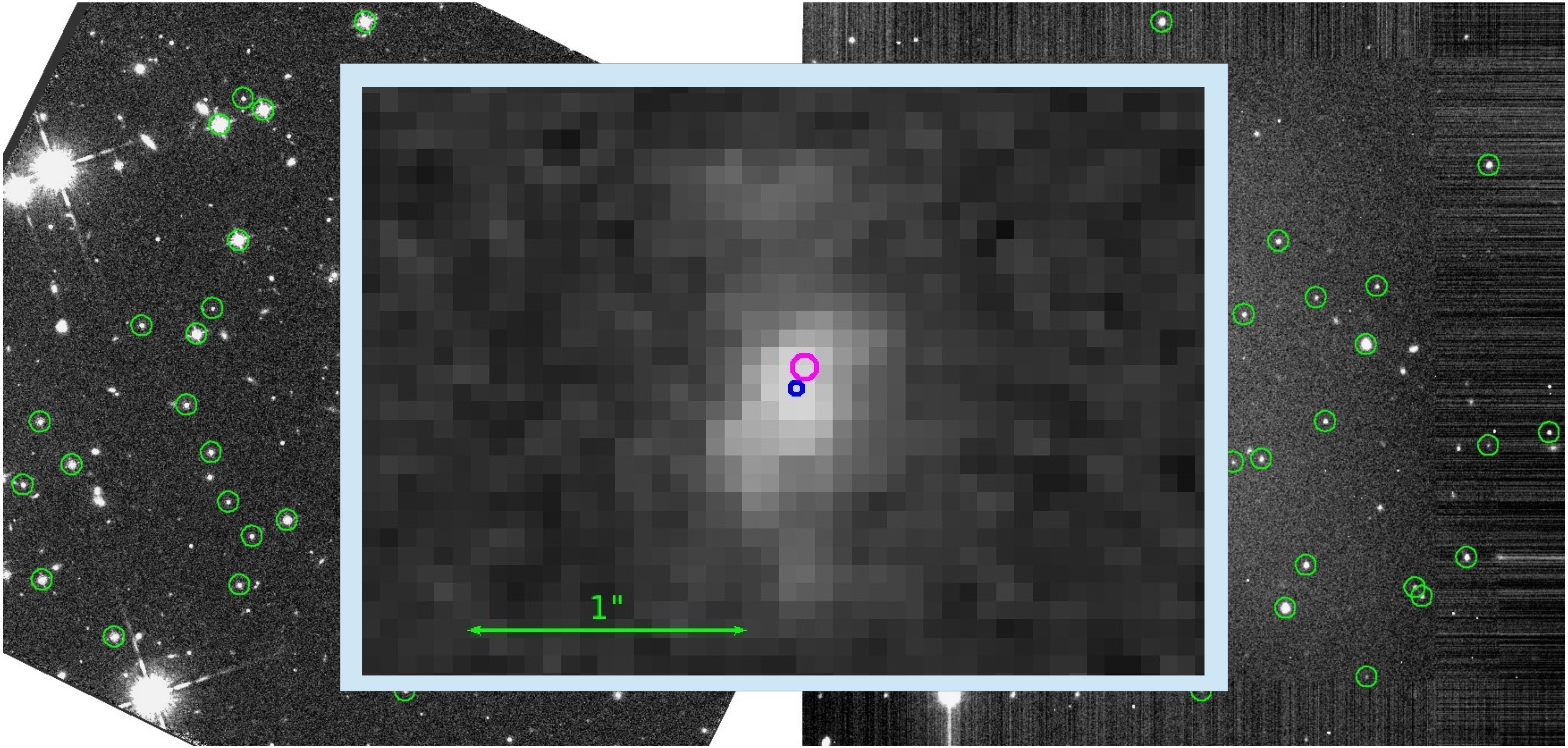


- Positional uncertainty comes from astrometric match uncertainty and uncertainty on the GRB position

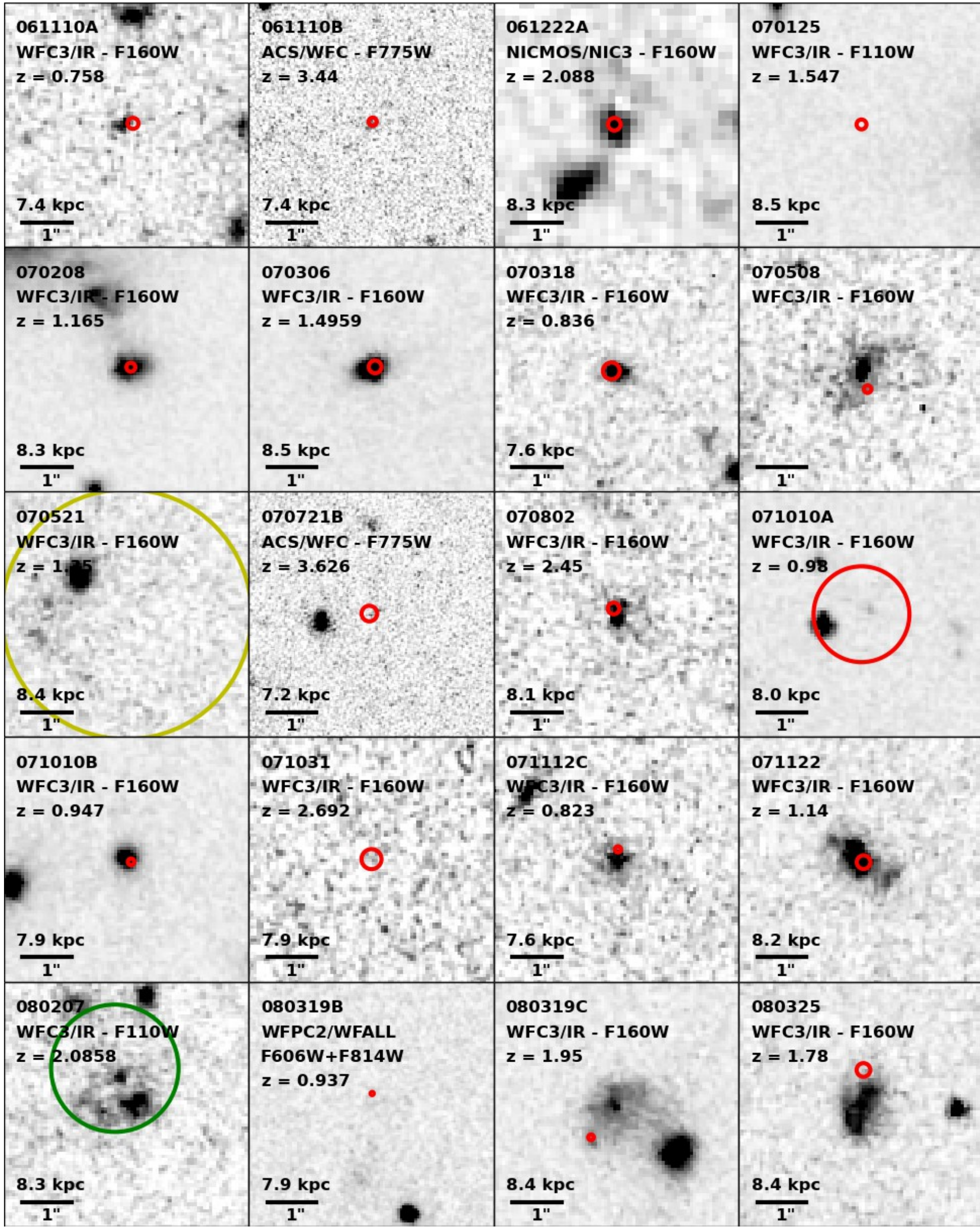
Relative Astrometry

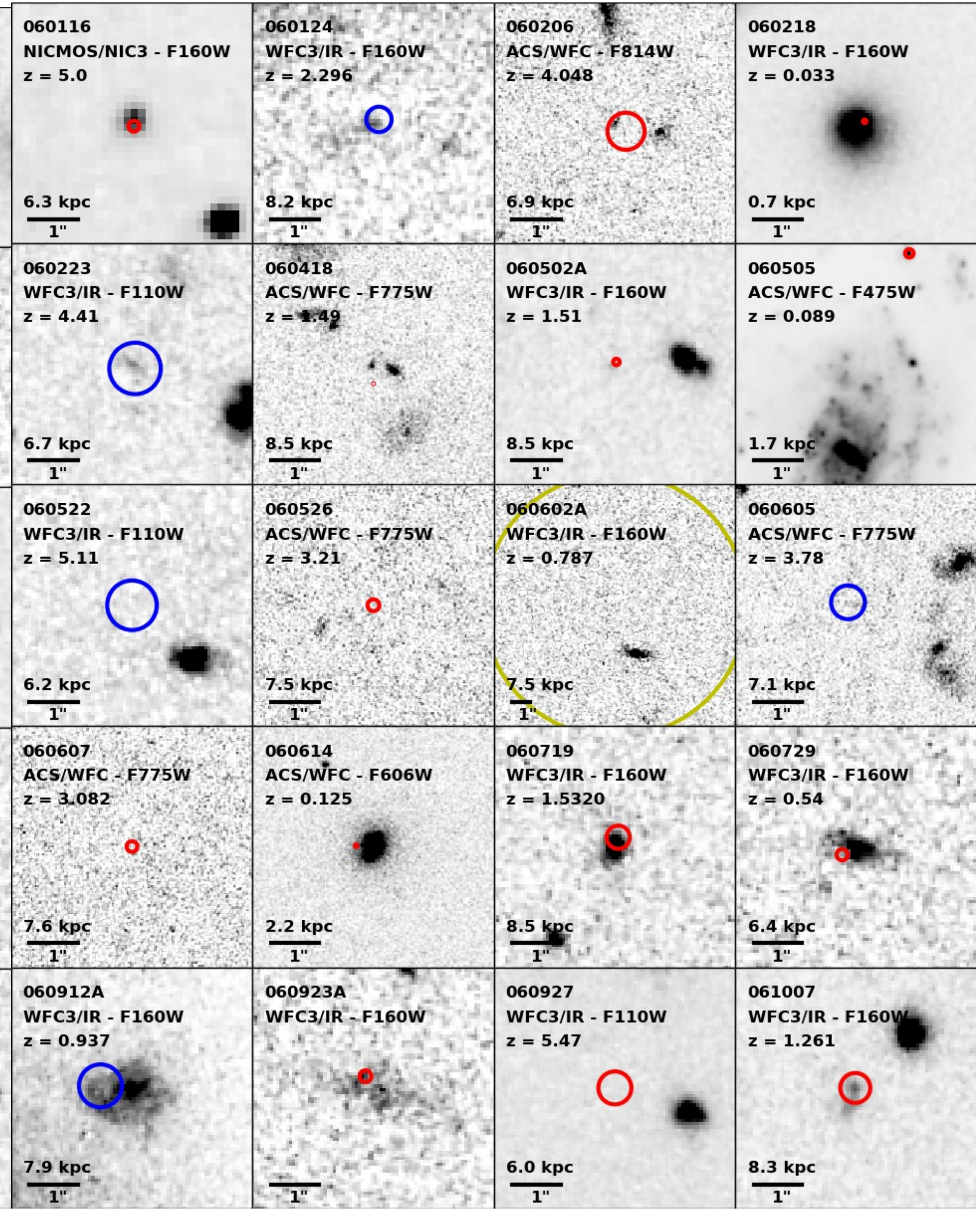
Late-time Hubble image of host galaxy

Early-time ground-based afterglow detection



- Positional uncertainty comes from astrometric match uncertainty and uncertainty on the GRB position


061110A
WFC3/IR - F160W
z = 0.758
7.4 kpc
1"
061110B
ACS/WFC - F775W
z = 3.44
7.4 kpc
1"
061222A
NICMOS/NIC3 - F160W
z = 2.088
8.3 kpc
1"
070125
WFC3/IR - F110W
z = 1.547
8.5 kpc
1"
070208
WFC3/IR - F160W
z = 1.165
8.3 kpc
1"
070306
WFC3/IR - F160W
z = 1.4959
8.5 kpc
1"
070318
WFC3/IR - F160W
z = 0.836
7.6 kpc
1"
070508
WFC3/IR - F160W
1"
070521
WFC3/IR - F160W
z = 1.35
8.4 kpc
1"
070721B
ACS/WFC - F775W
z = 3.626
7.2 kpc
1"
070802
WFC3/IR - F160W
z = 2.45
8.1 kpc
1"
071010A
WFC3/IR - F160W
z = 0.98
8.0 kpc
1"
071010B
WFC3/IR - F160W
z = 0.947
7.9 kpc
1"
071031
WFC3/IR - F160W
z = 2.692
7.9 kpc
1"
071112C
WFC3/IR - F160W
z = 0.823
7.6 kpc
1"
071122
WFC3/IR - F160W
z = 1.14
8.2 kpc
1"
080207
WFC3/IR - F110W
z = 2.0858
8.3 kpc
1"
080319B
WFPC2/WFALL
F606W+F814W
z = 0.937
7.9 kpc
1"
080319C
WFC3/IR - F160W
z = 1.95
8.4 kpc
1"
080325
WFC3/IR - F160W
z = 1.78
8.4 kpc
1"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NICMOS/NIC3 - F160W
z = 5.0
6.3 kpc
1"
060124
WFC3/IR - F160W
z = 2.296
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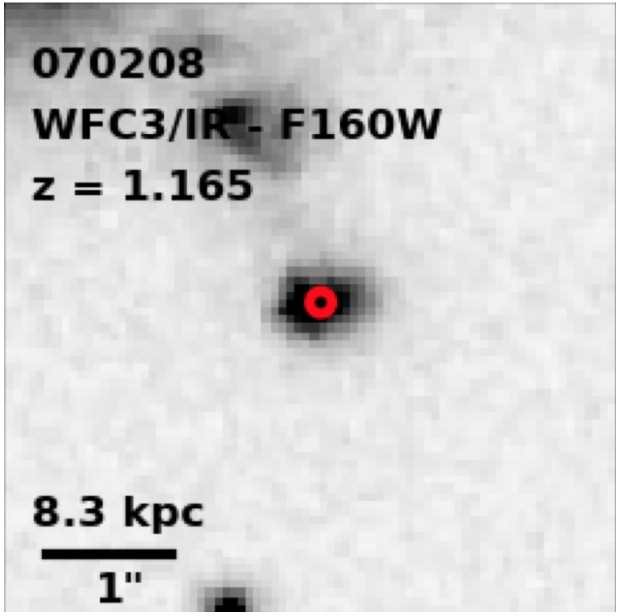
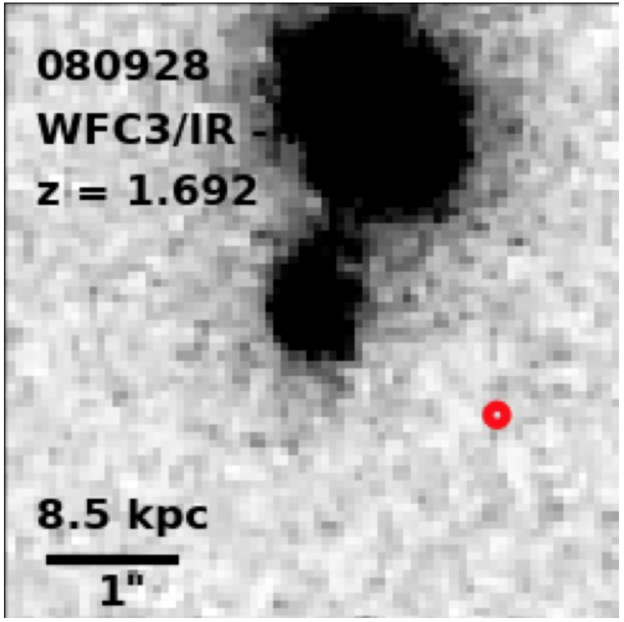
1"
060206
ACS/WFC - F814W
z = 4.048
6.9 kpc
1"
060218
WFC3/IR - F160W
z = 0.033
0.7 kpc
1"
060223
WFC3/IR - F110W
z = 4.41
6.7 kpc
1"
060418
ACS/WFC - F775W
z = 1.49
8.5 kpc
1"
060502A
WFC3/IR - F160W
z = 1.51
8.5 kpc
1"
060505
ACS/WFC - F475W
z = 0.089
1.7 kpc
1"
060522
WFC3/IR - F110W
z = 5.11
6.2 kpc
1"
060526
ACS/WFC - F775W
z = 3.21
7.5 kpc
1"
060602A
WFC3/IR - F160W
z = 0.787
7.5 kpc
1"
060605
ACS/WFC - F775W
z = 3.78
7.1 kpc
1"
060607
ACS/WFC - F775W
z = 3.082
7.6 kpc
1"
060614
ACS/WFC - F606W
z = 0.125
2.2 kpc
1"
060719
WFC3/IR - F160W
z = 1.5320
8.5 kpc
1"
060729
WFC3/IR - F160W
z = 0.54
6.4 kpc
1"
060912A
WFC3/IR - F160W
z = 0.937
7.9 kpc
1"
060923A
WFC3/IR - F160W
1"
060927
WFC3/IR - F110W
z = 5.47
6.0 kpc
1"
061007
WFC3/IR - F160W
z = 1.261
8.3 kpc
1"

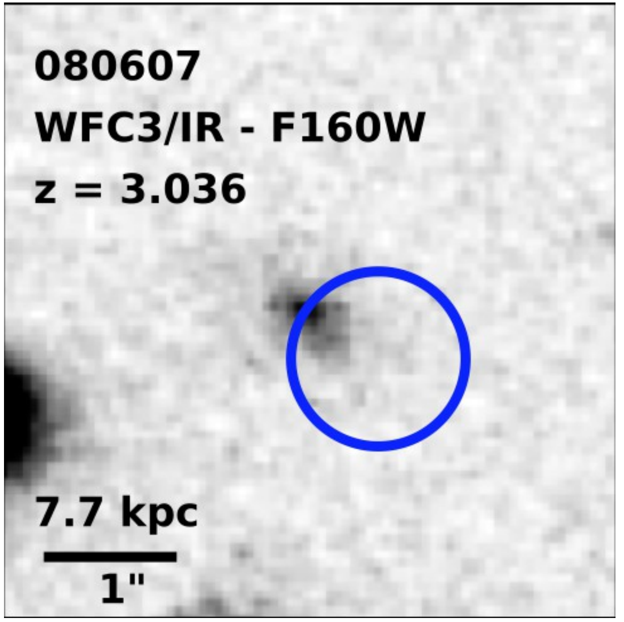
Host Galaxy Assignment

- Probability of chance coincidence (PCC)
  - Based on observed number density of field galaxies
  - PCC depends on galaxy brightness, offset, and positional uncertainty

$$P_{cc} = 1 - e^{-\pi R_e^2 \sigma(\leq m)}$$





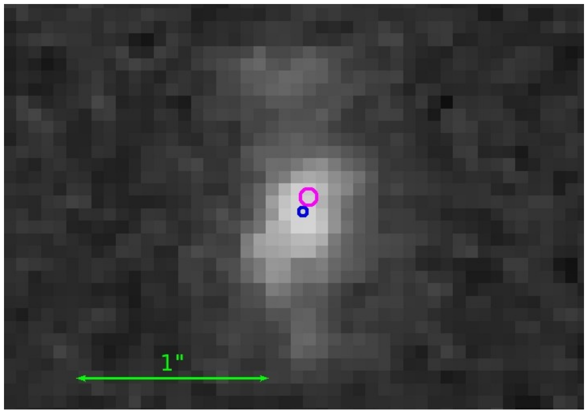


- Luminosity argument based on *a priori* host information
- Is the host candidate's luminosity consistent with the distribution observed for bursts with secure host associations?

Offset Measurements

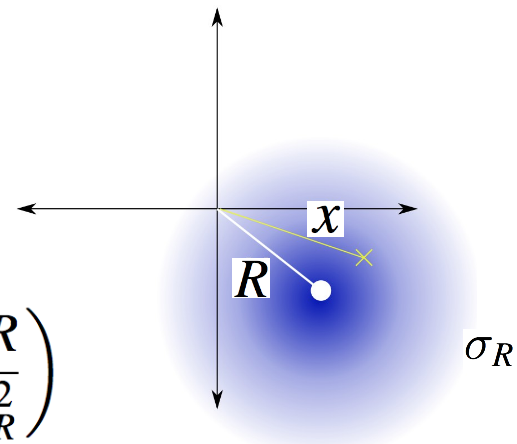
- Measure afterglow and host galaxy centroids
- Calculate the offset (*R*) of the afterglow from the host center

$$\sigma_R = \sqrt{\sigma_{\text{tie}}^2 + \sigma_{\text{OT}}^2 + \sigma_{\text{host}}^2}$$

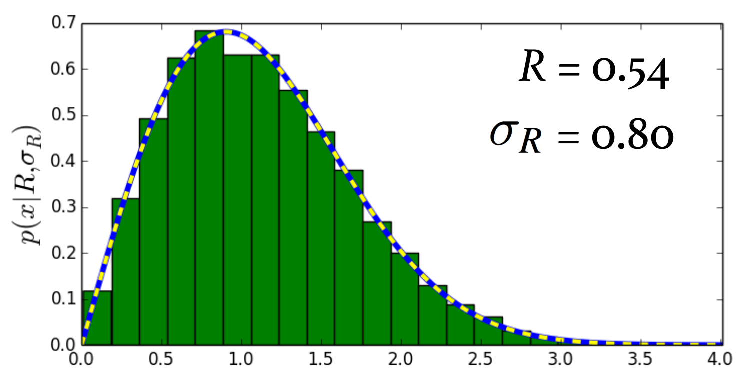


- Individual offsets described by Rice Distribution

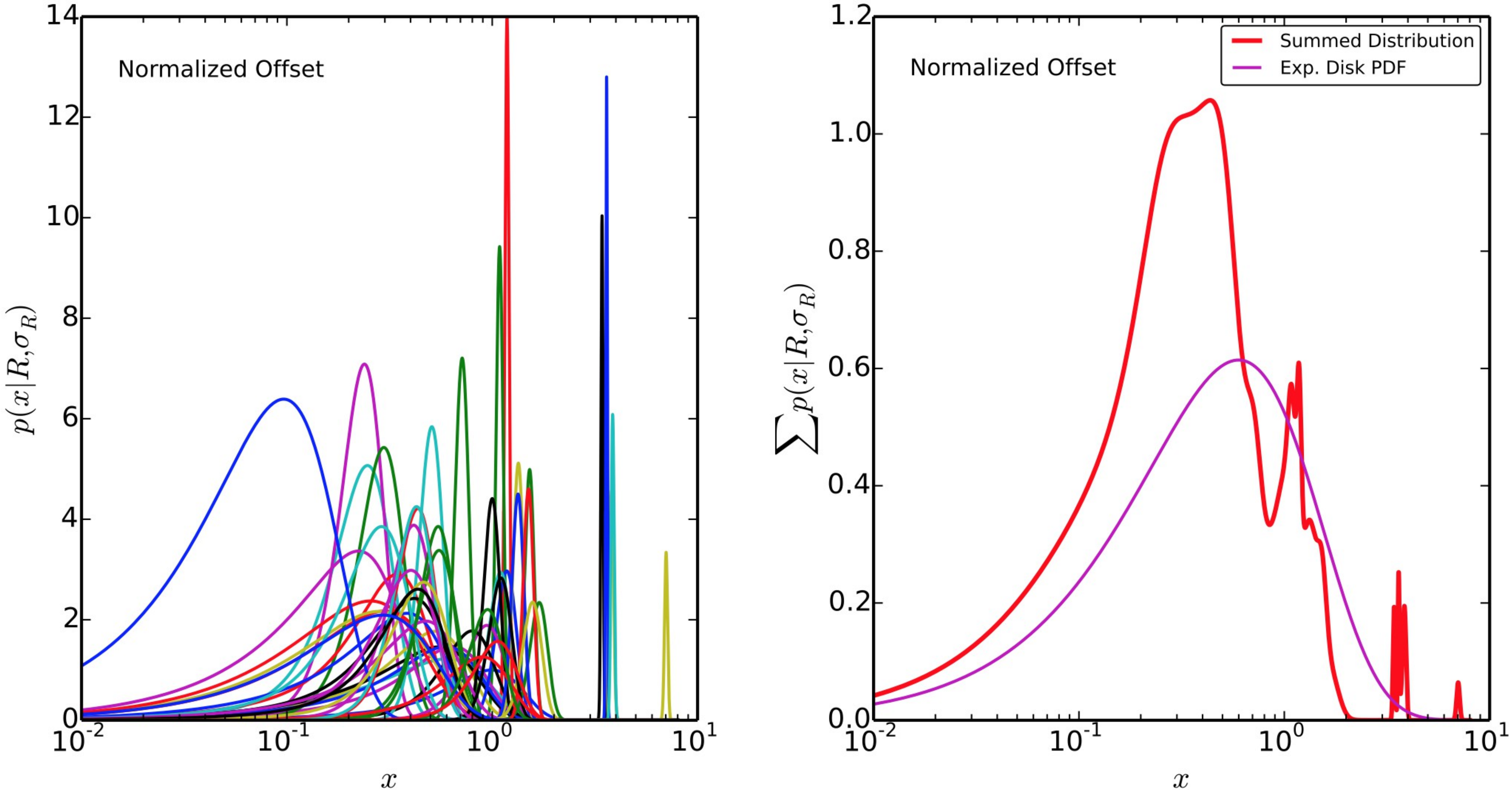
$$p(x|R,\sigma_R) = \frac{x}{\sigma_R^2} \exp\left[-\frac{(x^2+R^2)}{2\sigma_R^2}\right] I_0\left(\frac{xR}{\sigma_R^2}\right)$$



- To assess the impact of the uncertainties on the offset distribution I use a Monte Carlo simulation

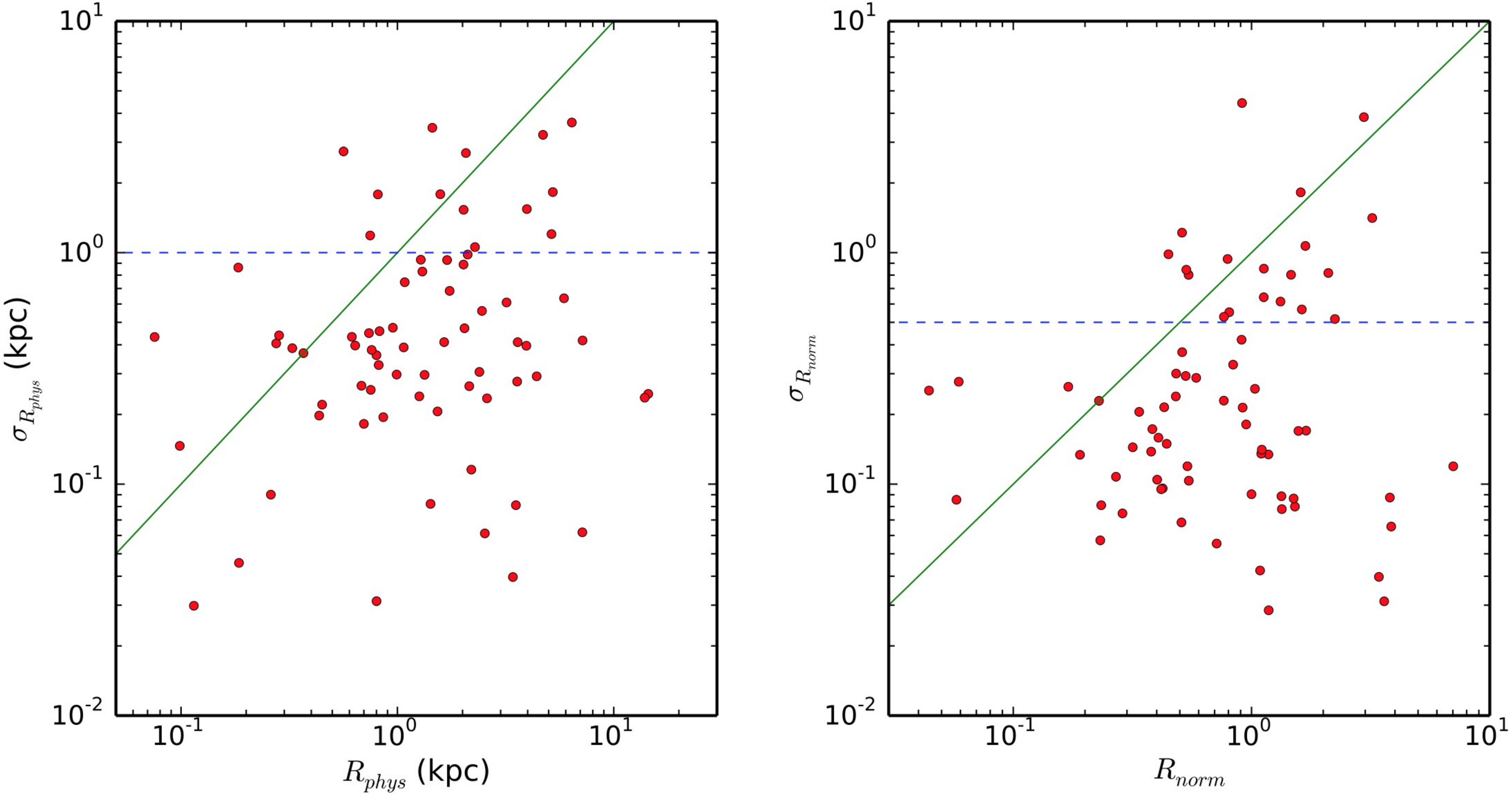


Distribution of Offsets



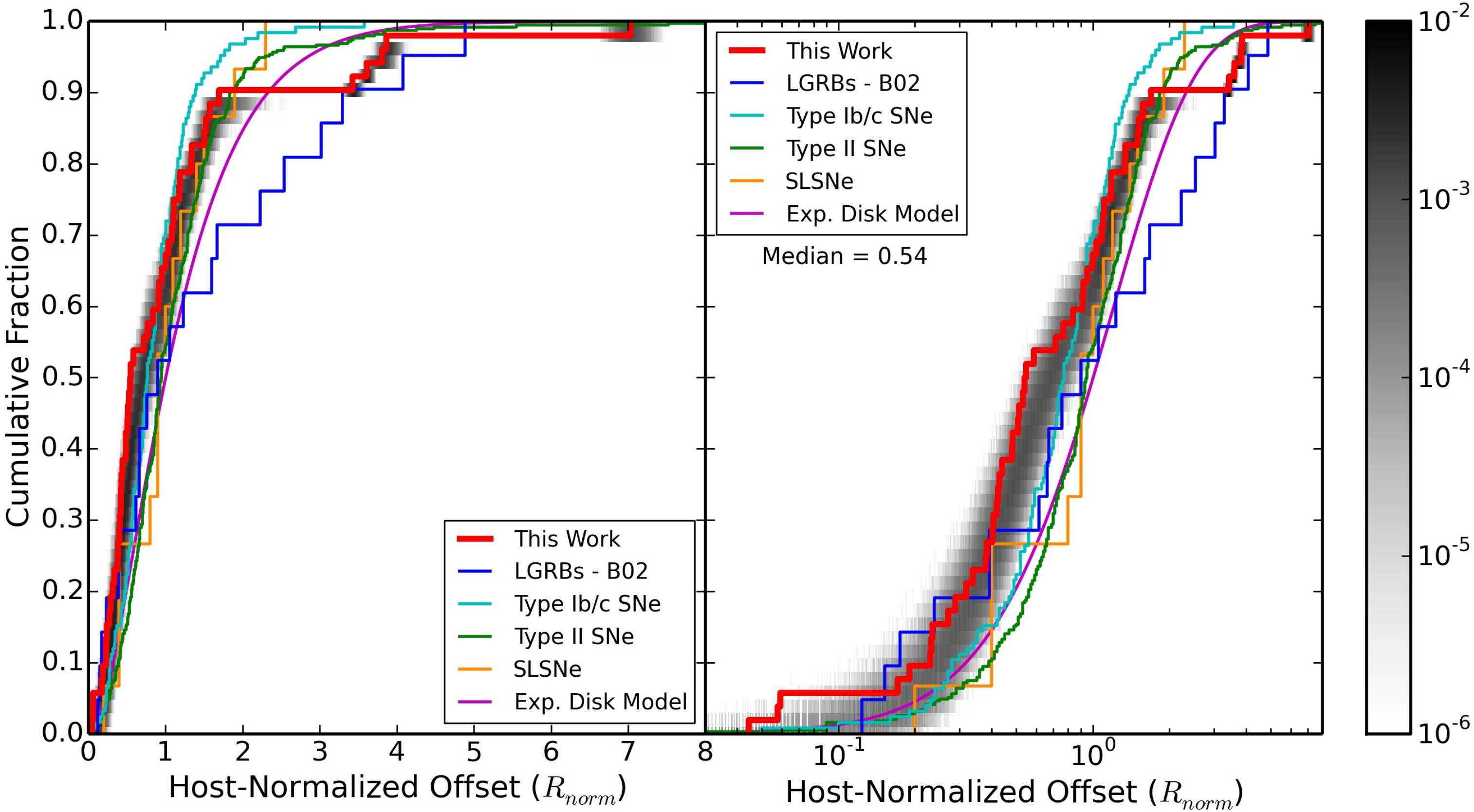
Offset Measurements

- True offset and offset uncertainty should be unrelated
- Bias to large offsets when offset uncertainty is large



Cumulative Offset Distribution

- Comparison with exp. disk profile and various types of supernovae explosions

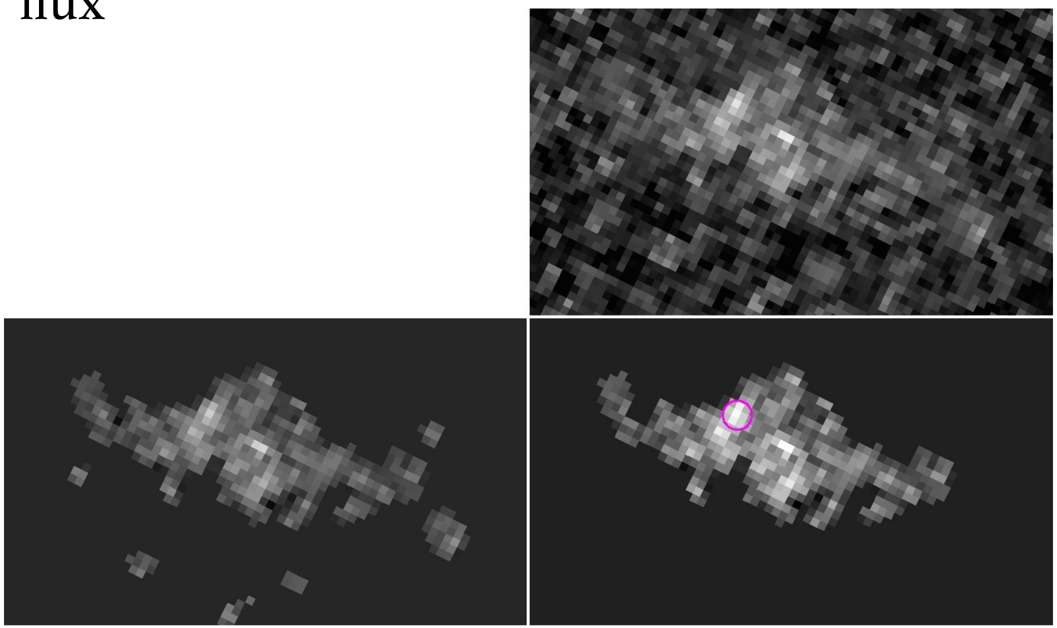


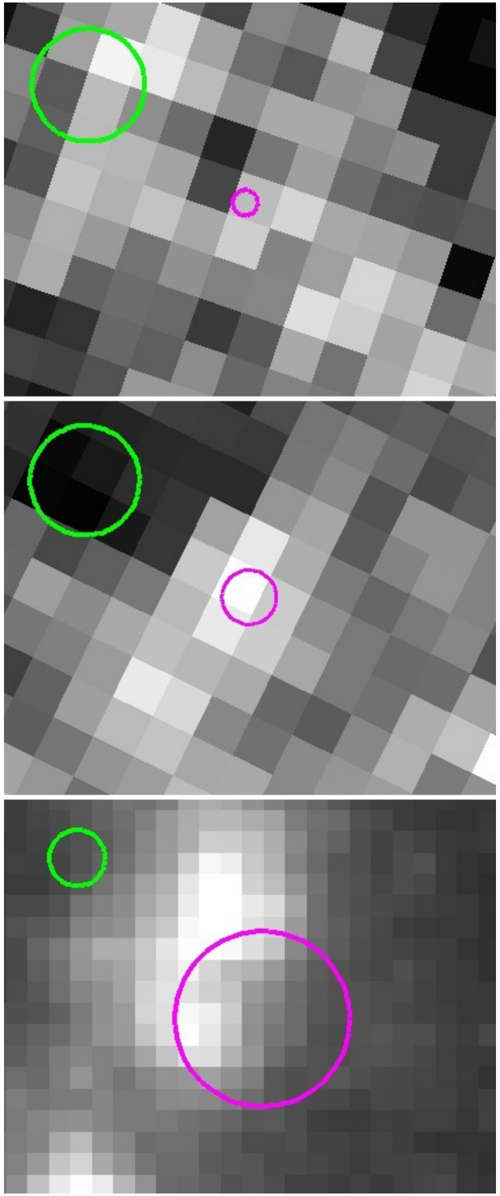
- LGRBs prefer the bright central regions of their hosts
- 50% of LGRBs occur within a region of their hosts containing 33% of the light

SNe data from Kelly and Kirshner 2012, SLSNe data from Lunnan et al. 2015

Fractional Flux Measurements

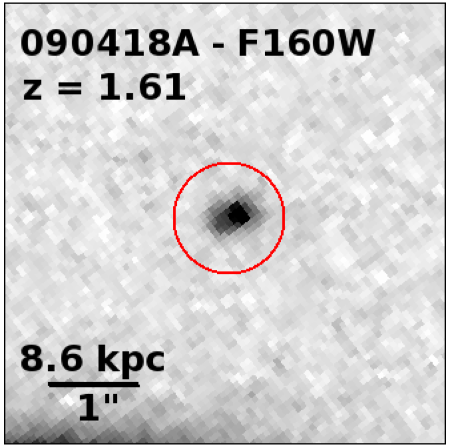
- Technique to assess spatial coincidence with bright or faint regions
- Fractional Flux = Flux from pixels fainter than burst site / Total galaxy flux
- Extract galaxy pixels and measure burst site flux

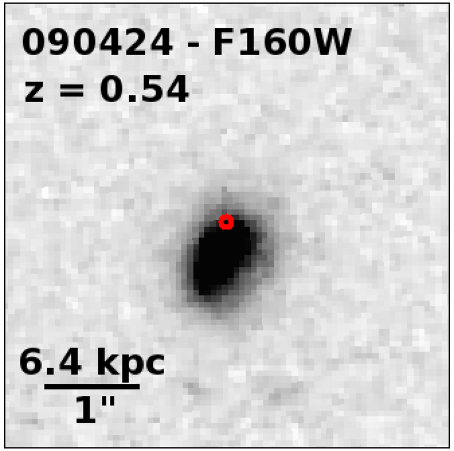


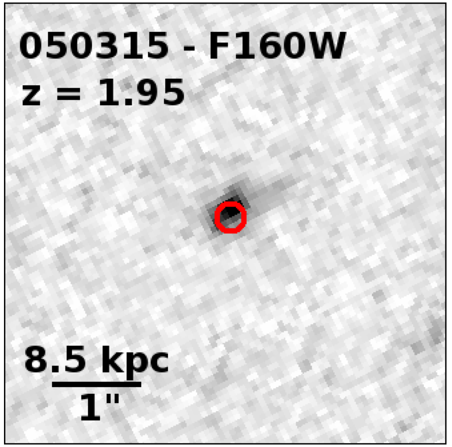


Effect of Positional Uncertainty on Fractional Flux

- Can you still constrain the FF value as your knowledge of the burst location decreases?

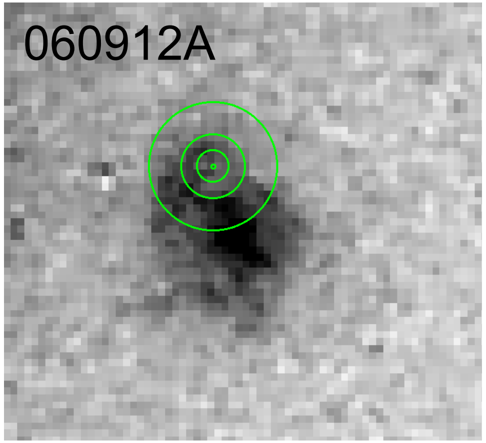


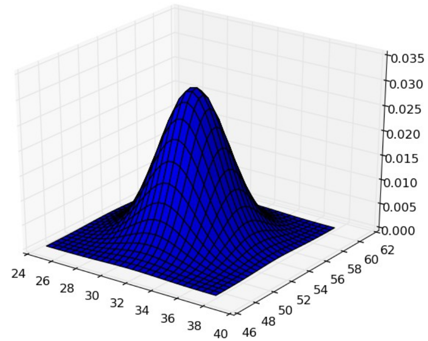




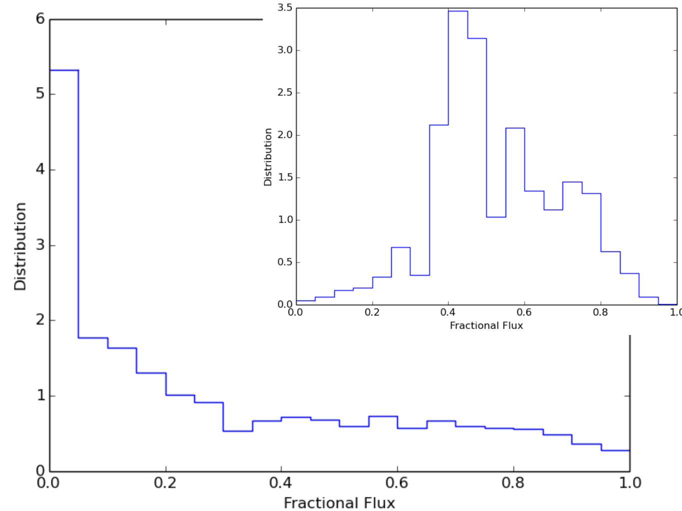
- Bayesian approach
  - Likelihood = 2D-Gaussian positional uncertainty distribution
    - Each pixel has an associated probability that the burst occurred there
  - Prior = Unif[0,1]
  - Posterior = probability distribution of FF values

Case Studies: GRBs 050820 and 060912A

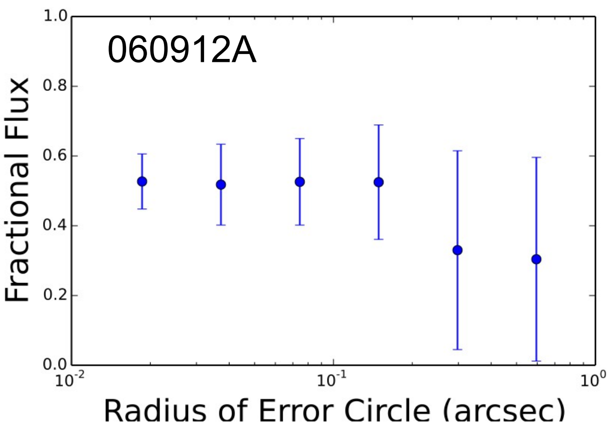


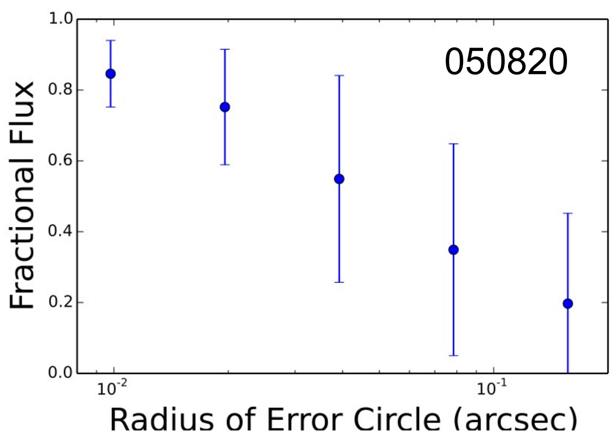


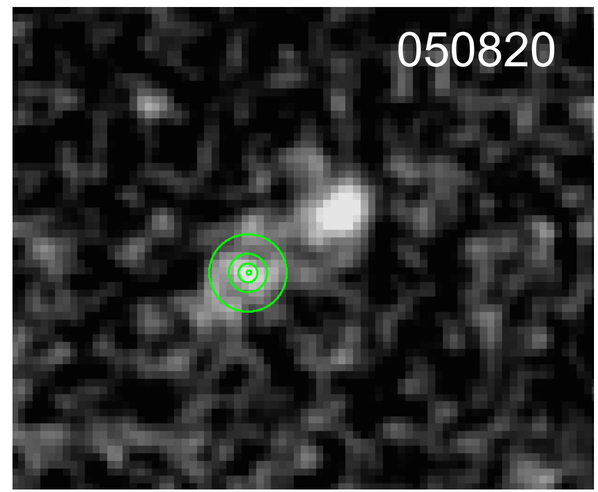
Weight by Gaussian error dist



- Vary size of error circle
  - Distribution changes significantly

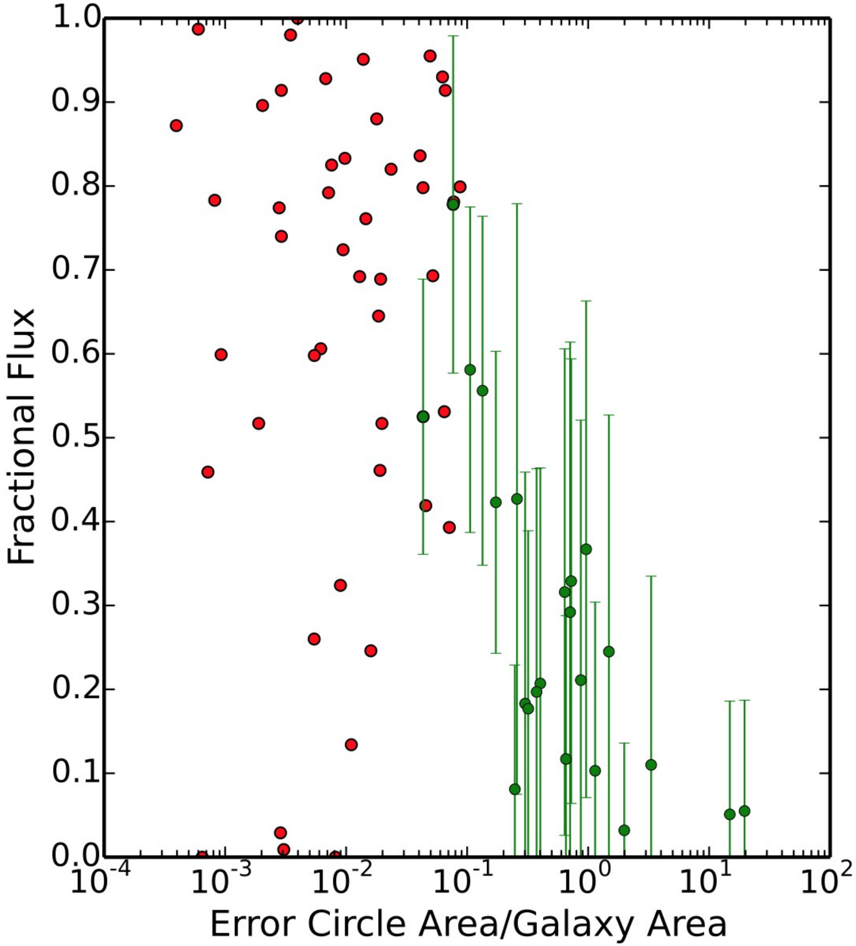


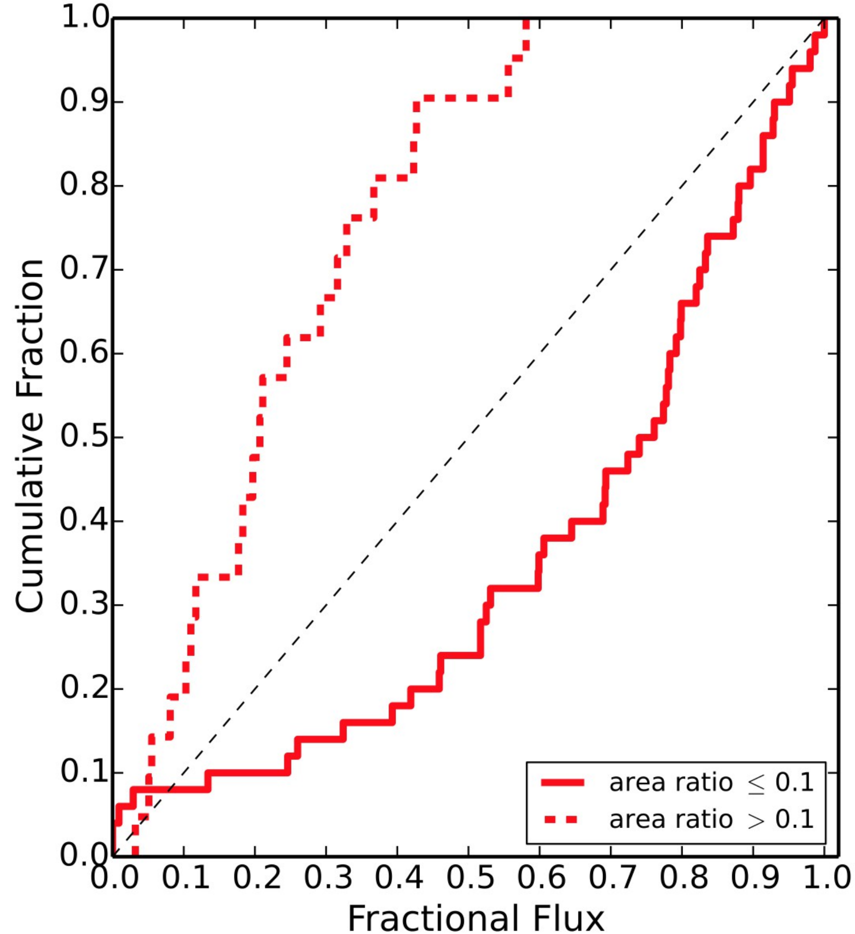




Effect on Full Sample

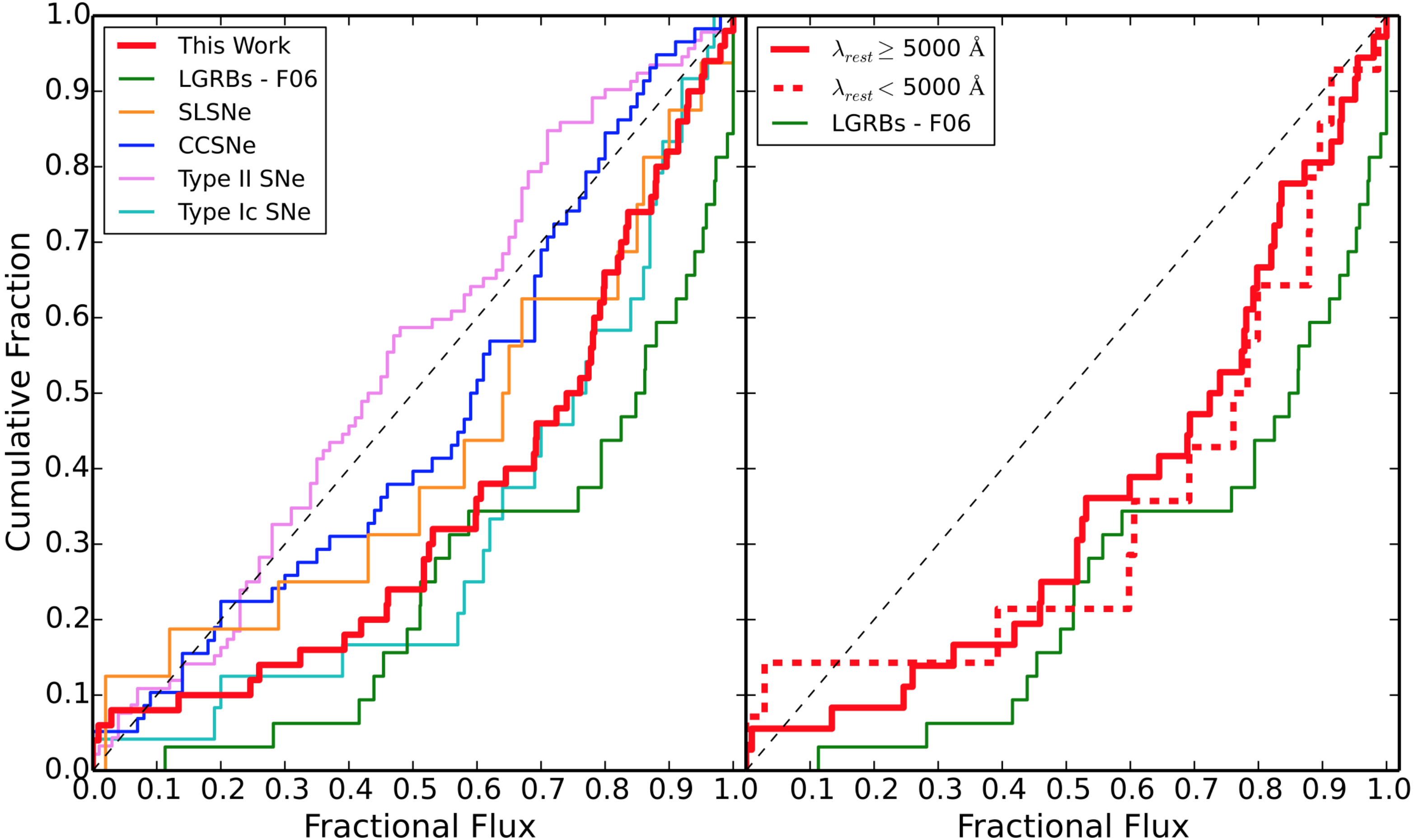
- Bias to low FF values when the error circle area > 10% galaxy area





Fractional Flux Distribution

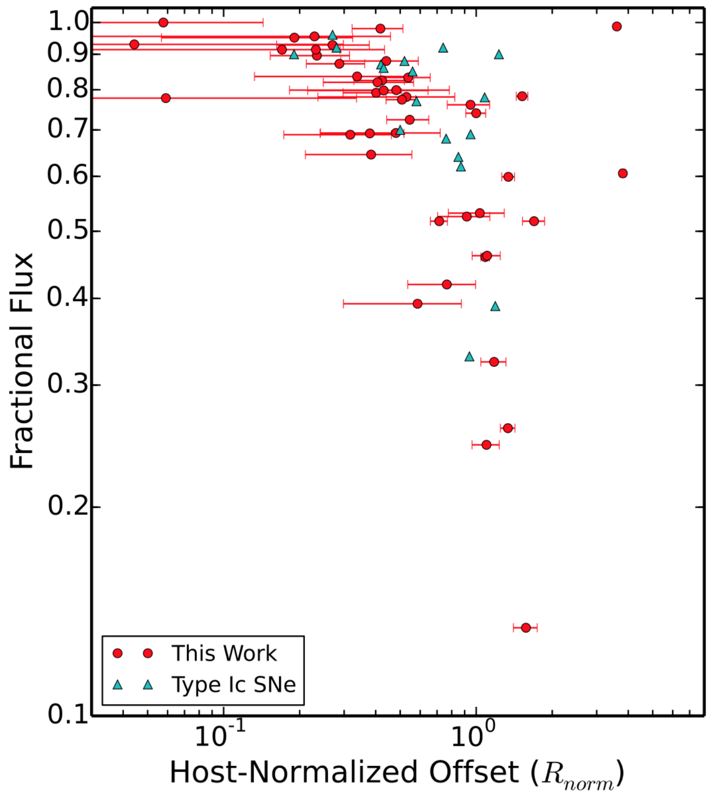
- Comparison with various types of supernova explosions

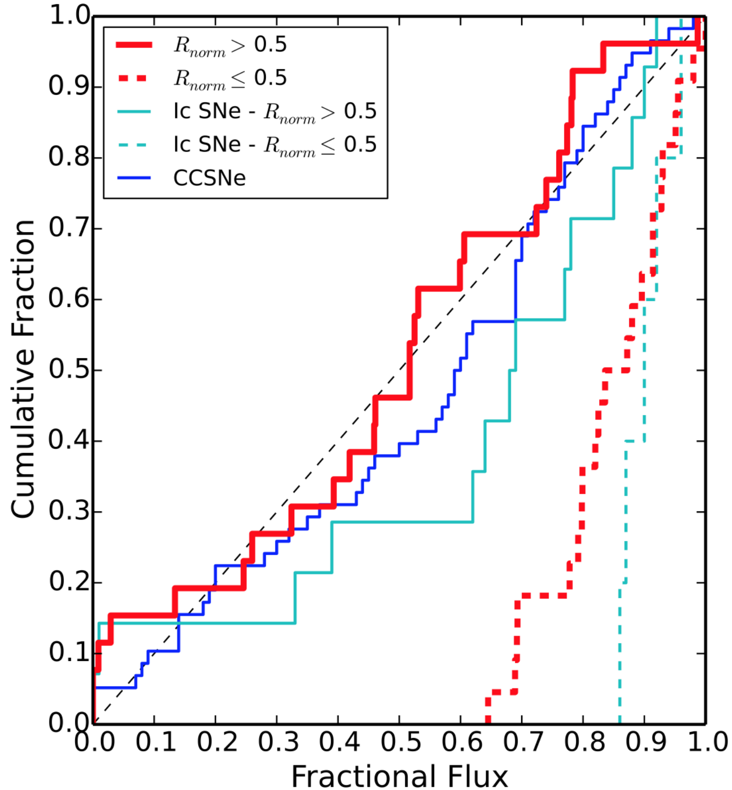


- Median = 0.75
- Agreement with Type Ic SNe
- Possible connection to SLSNe?

LGRBs – F06, CCSNe, SLSNe, and II/Ic SNe data from Fruchter et al. 2006, Svensson et al. 2010, Lunnan et al. 2015, and Kelly et al. 2008

Fractional Flux – Offset Relationship





Ic SNe and CCSNe data from Kelly et al. 2008 and Svensson et al. 2010, respectively

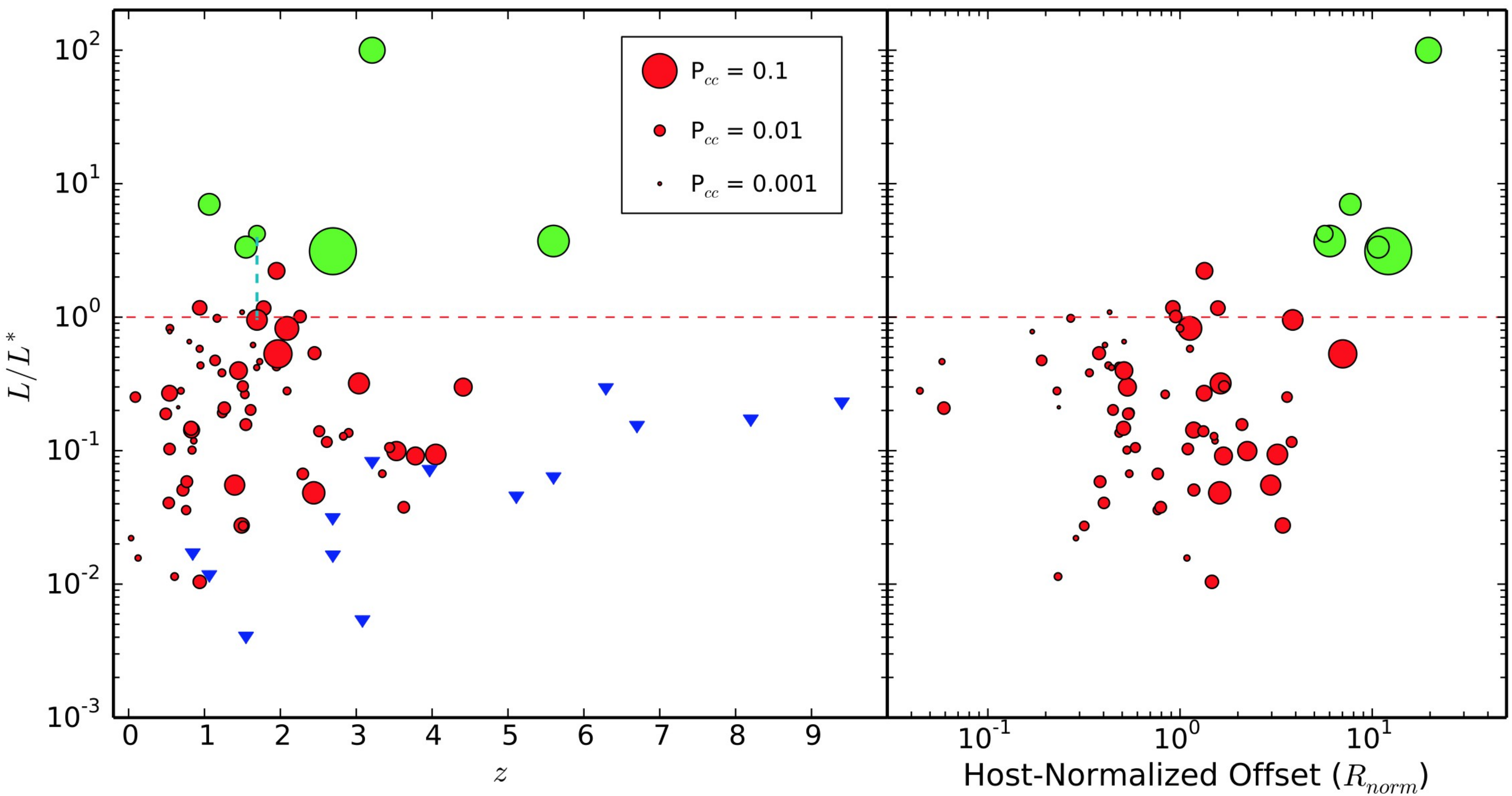
- FF-Offset correlation indicates high fractional flux preference is entirely due to bursts at small offsets
  - Bursts at large offset show no preference for unusually bright regions

Summary and Conclusions

- Analyzing the locations of GRBs within their host galaxies requires a careful consideration of positional uncertainty
  - Large uncertainties lead to:
    - the prevention of robust host associations
    - a bias to large offsets
    - a bias to low fractional flux
- Long GRBs are more centrally concentrated than the underlying light distributions of their host galaxies
  - Star formation near the central regions of their hosts is most favorable for long GRB production
- The preference for high fractional flux is due to long GRBs at small offsets
- An environmental factor such as an increased massive binary fraction may be at play in the central regions of long GRB hosts

Host Galaxy Assignment

- Luminosity argument based on *a priori* host information
- Is the host candidate's luminosity consistent with the distribution observed for bursts with secure host associations?



Rejected host candidates

Assigned host galaxies