LCGT F2F August 3–5, 2011

EM Counterpart Search for GW events

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Outline

- Gamma-ray bursts: brief review
- Lessons for counterpart search
  - Example of follow-up observations
  - Localization accuracy and delay
- Short GRB properties and GW prediction
- Proposed strategy

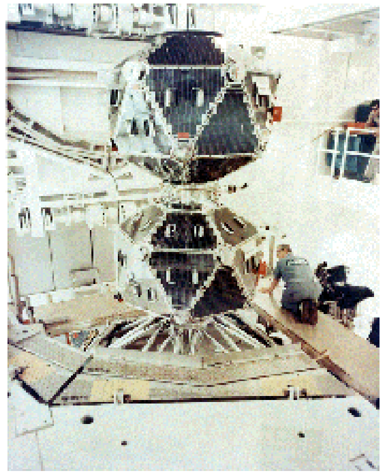
Why talk about GRB?

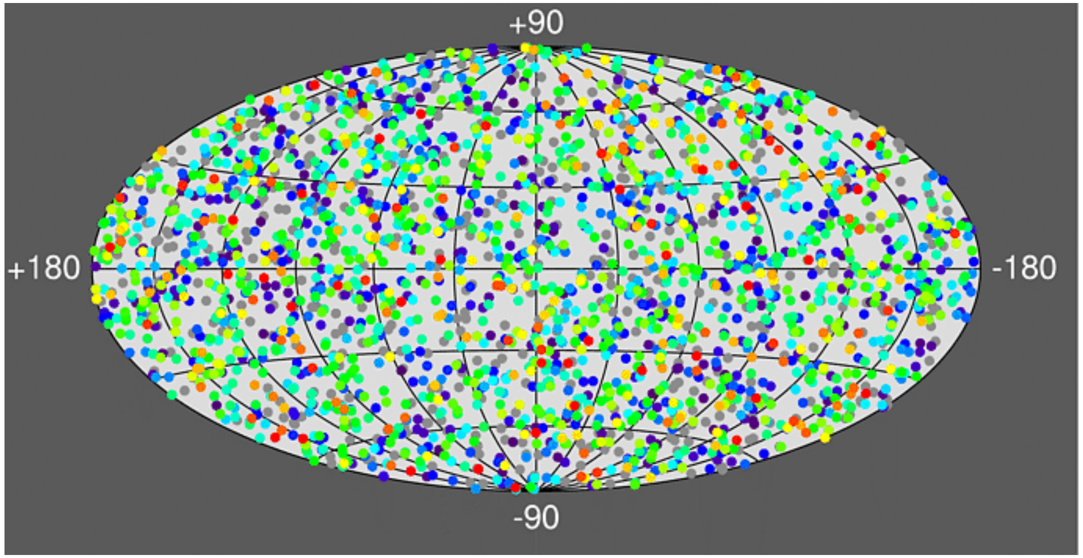
- "Short GRB" is the prime candidate for EM counterpart of promised GW source (NS merger)

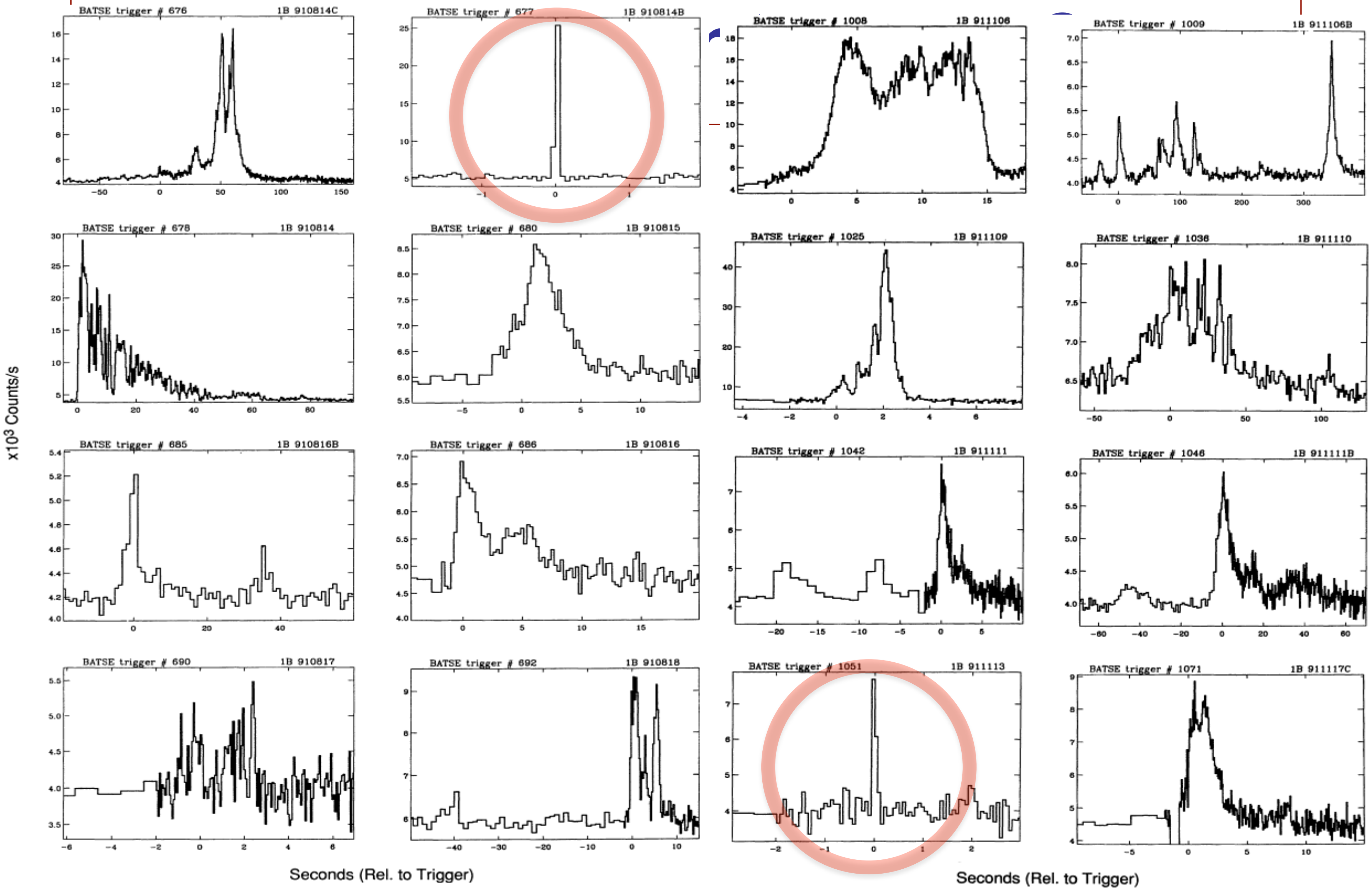
- Lessons from the history of GRB research
  - Cosmic source with poor localization
    - First detection (~1967, published in 1973)
    - First identification of counterpart (1997)

Brief review of GRBs (~1967–1997)

- Discovered in 60's, distance unknown for 30 years
- keV—GeV range (typ. hundreds of keV)
- Dominate the sky in X-ray and gamma-ray
- One GRB per day in the entire sky
- Isotropic distribution in the sky
- Not uniform in space: deficit of dim bursts
- Variety of light curves, short and long classes



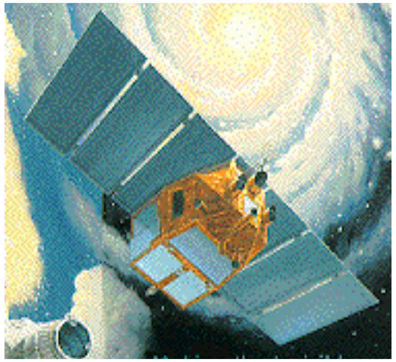


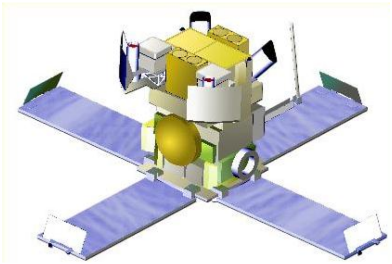


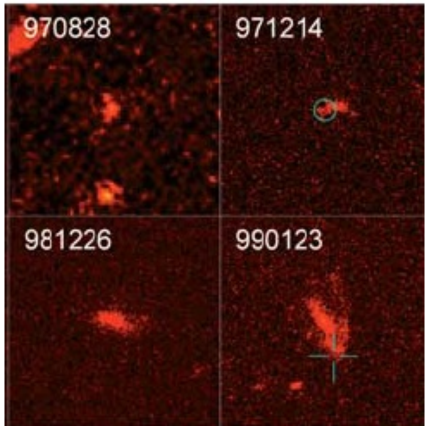
BATSE trigger # 676 1B 910814C
BATSE trigger # 677 1B 910814B
BATSE trigger # 1008 1B 911106
BATSE trigger # 1009 1B 911106B
BATSE trigger # 678 1B 910814
BATSE trigger # 680 1B 910815
BATSE trigger # 1025 1B 911109
BATSE trigger # 1036 1B 911110
BATSE trigger # 685 1B 910816B
BATSE trigger # 686 1B 910816
BATSE trigger # 1042 1B 911111
BATSE trigger # 1046 1B 911111B
BATSE trigger # 690 1B 910817
BATSE trigger # 692 1B 910818
BATSE trigger # 1051 1B 911113
BATSE trigger # 1071 1B 911117C
x10³ Counts/s
Seconds (Rel. to Trigger)
Seconds (Rel. to Trigger)

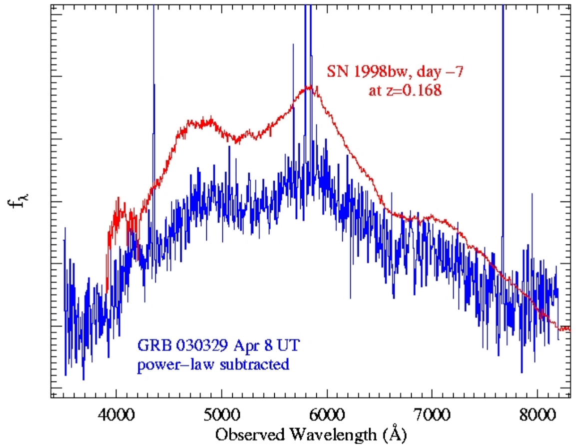
Brief review of GRBs (1997~)

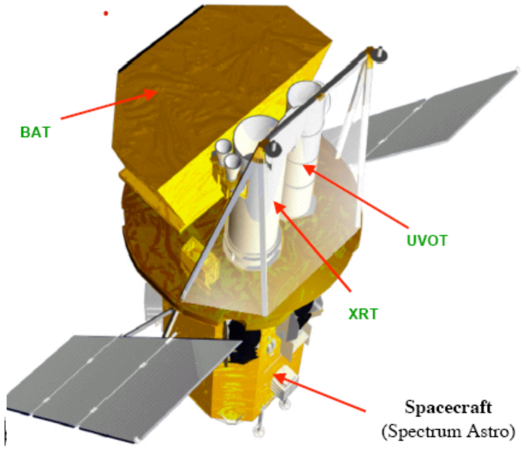
- Often associated with afterglow in X, optical, …
- Associated with distant galaxies (z~1 or larger)
- Fireball model favored
- Evidence for collimated outflow
- Long GRBs occur in star forming galaxies
- Some long GRBs associated with supernova
- Isotropic distribution in the sky
- Not uniform in space: deficit of dim bursts









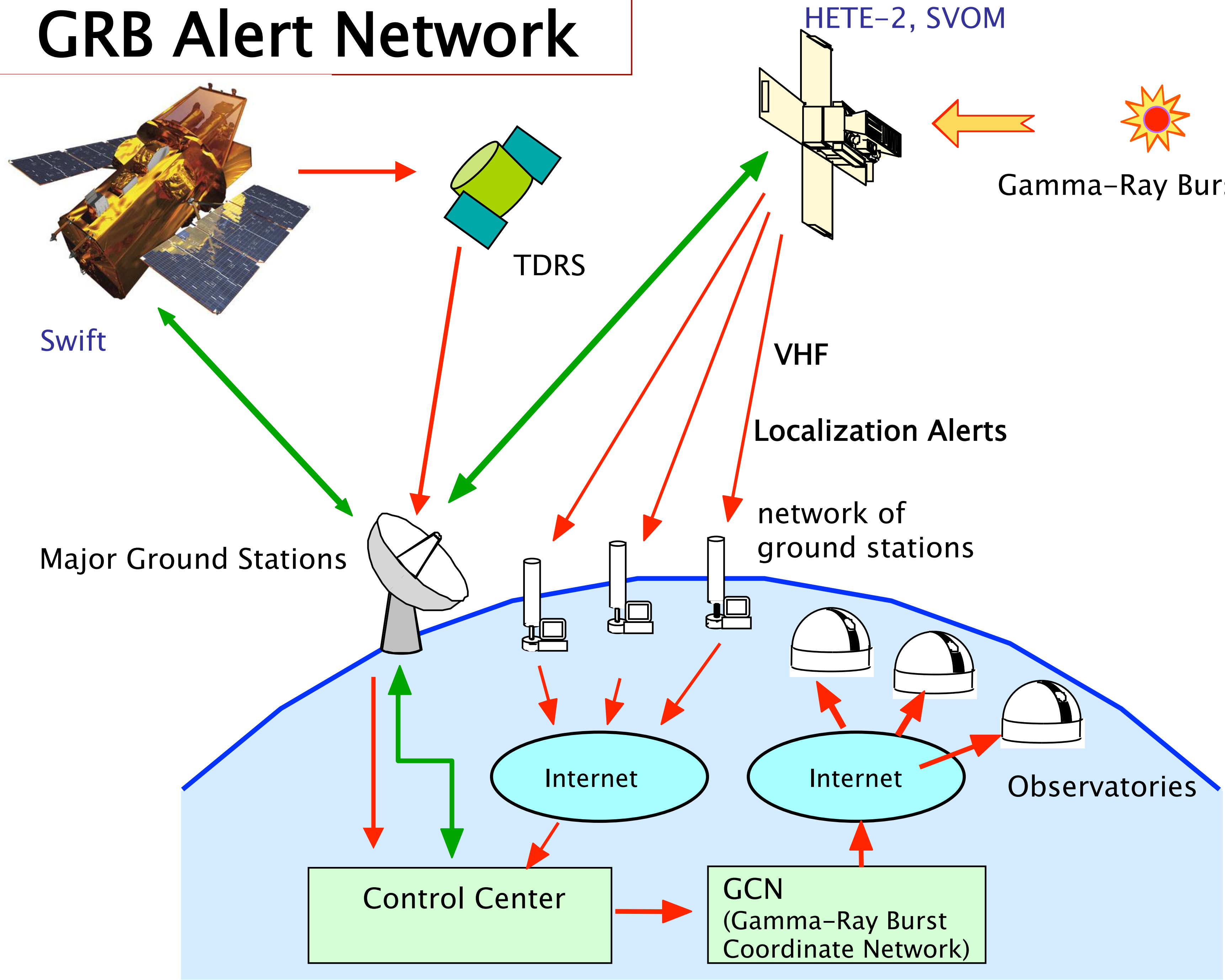


Fireball scenario of GRBs

Paczynski, Meszaros, Rees, Sari, Piran, …

Piran 2003

GRB Alert Network



GRB

- Classification: long vs. short
- Identification of GRBs
  - Early days –no success
    - Modulation collimator, aspect ratio: degree, and slow
    - Interplanetary network: arcmin, months
    - BACODINE: 5 degrees, fast (20 seconds),
  - Afterglow detection

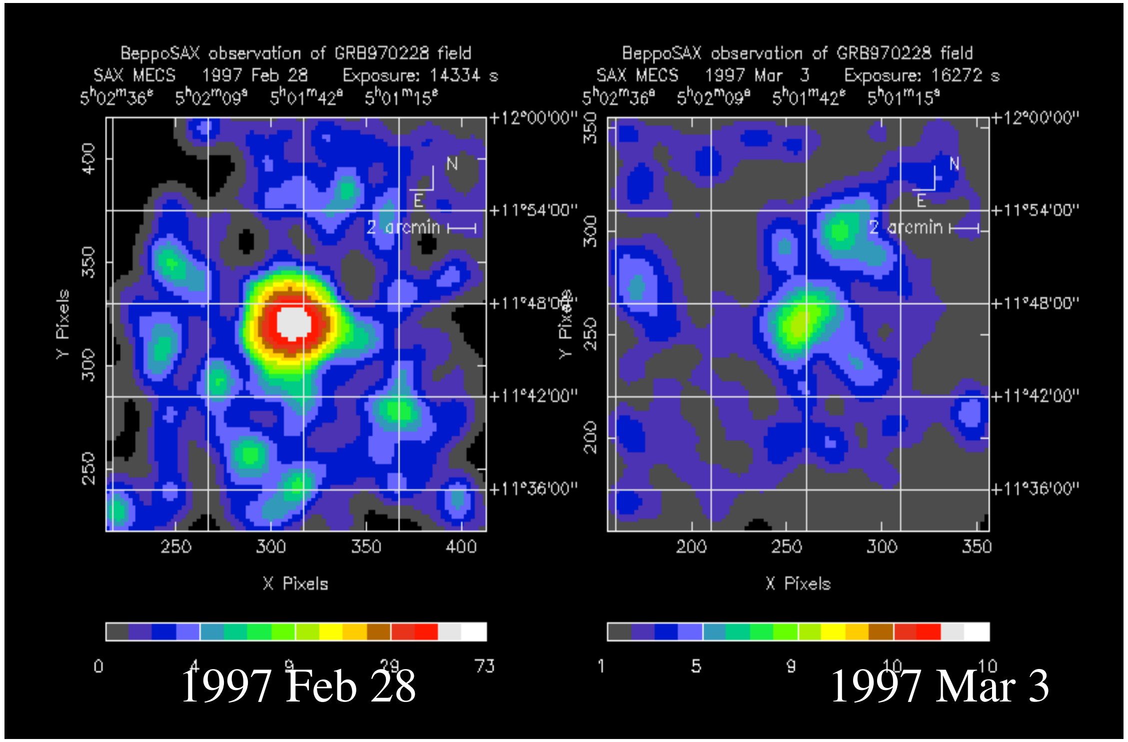
- First in X-ray
  - brightest source in the sky: easy to find
  - Imaging available: arcmin (coded mask) ~ arcsec (focusing mirror)
- Following up in optical
  - Usually faint, >20 mag at 1 day
    - » No catalog (maybe SDSS)
  - about Half obscured in optical (IR?)
  - could be bright at very early phase (<1 minof GRB)

Example of follow-up observations

- GRB 970228
  - GRBM → WFC –(human) →MECS (X-ray telescope) – fading source
  - → Optical telescope – fading source
- GRB 990123
  - BATSE –(BACODINE)- ROTSE
  - GRBM/WFC –(human) → MECS (XRT) → ROTSE inspection
- GRB 030329
  - HETE-2 → Tokyo Tech 30cm
- GRB050509B
  - Swift BAT-XRT→ Subaru etc.
- GRB050709
  - HETE-2 – Chandra – Hubble
- GRB070201
  - IPN – optical/LIGO
- GRB110721A
  - Fermi/LAT D=1.5 deg, 11 hours after the burst
  - Swift/XRT(D=0.4 deg) imcomplete tiling
  - Candidate X-ray/optical source found 2 days later
  - Turned out to be an early-type galaxy

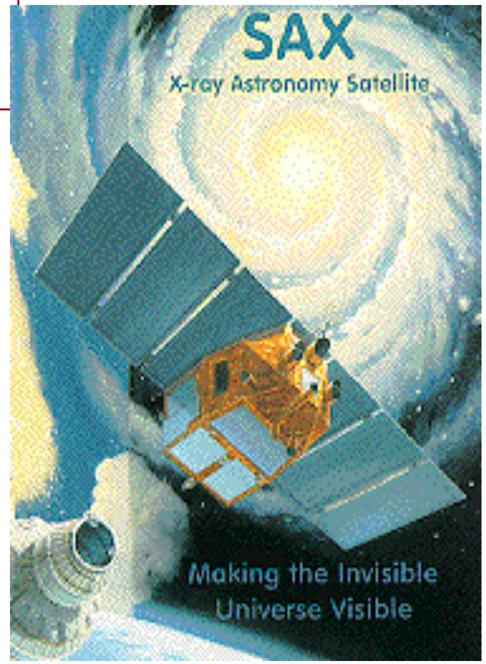
GRB970228: first afterglow

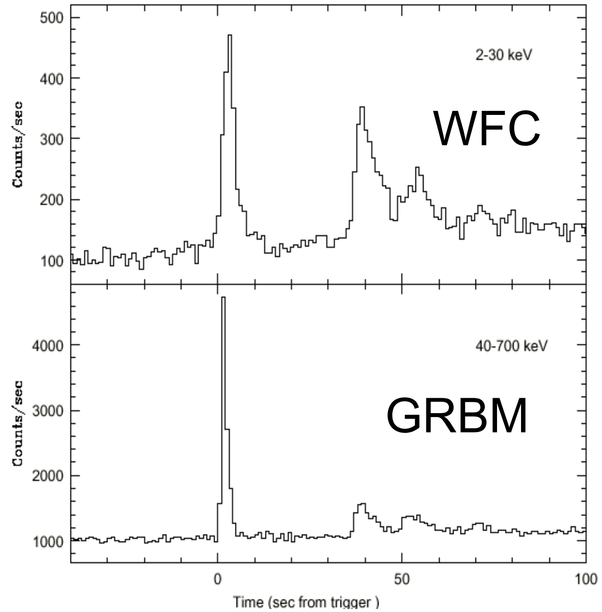
- Coincident detection in gamma and X rays
- X-ray position analyzed on ground
- Satellite repointed in 8 hours
- X-ray afterglow imaged by focusing instrument



8 hours

3 days

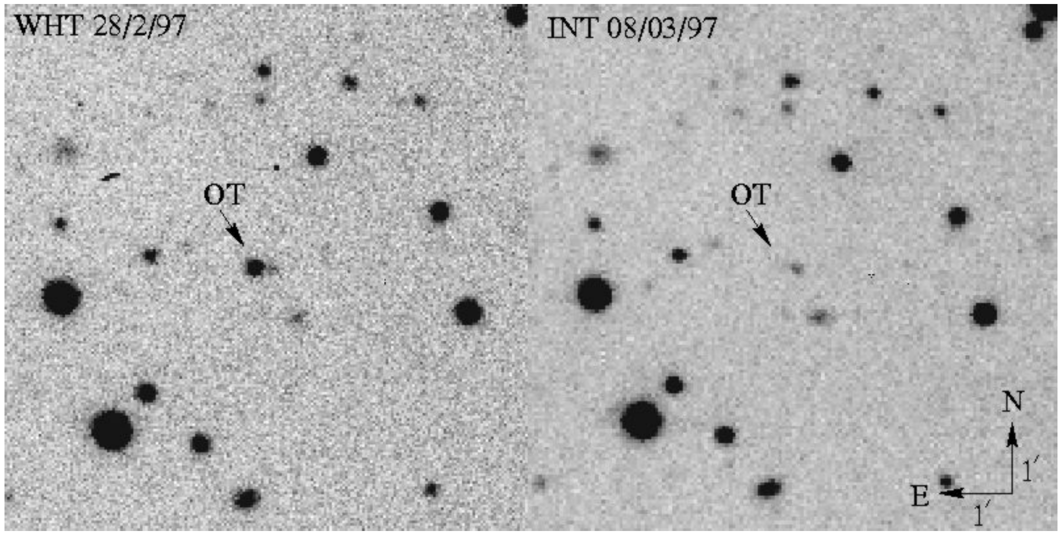




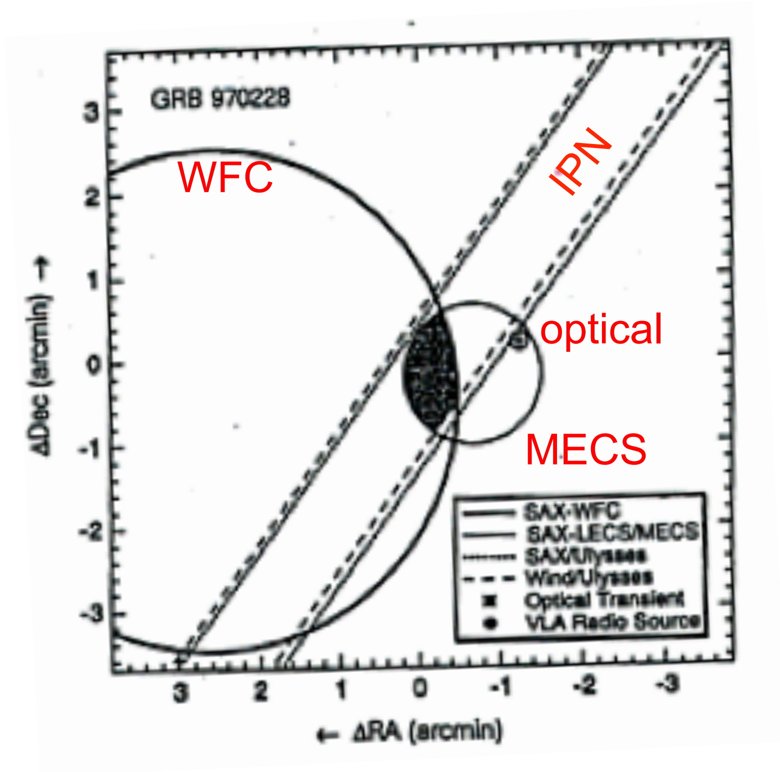
Costa et al.1997

GRB 970228: Discovery of optical transient

- Optical observation conducted based on WFC position (~ afew arcmin)
- Fading source detected
- Later Hubble observation revealed underlying extended source, probably the host of the GRB

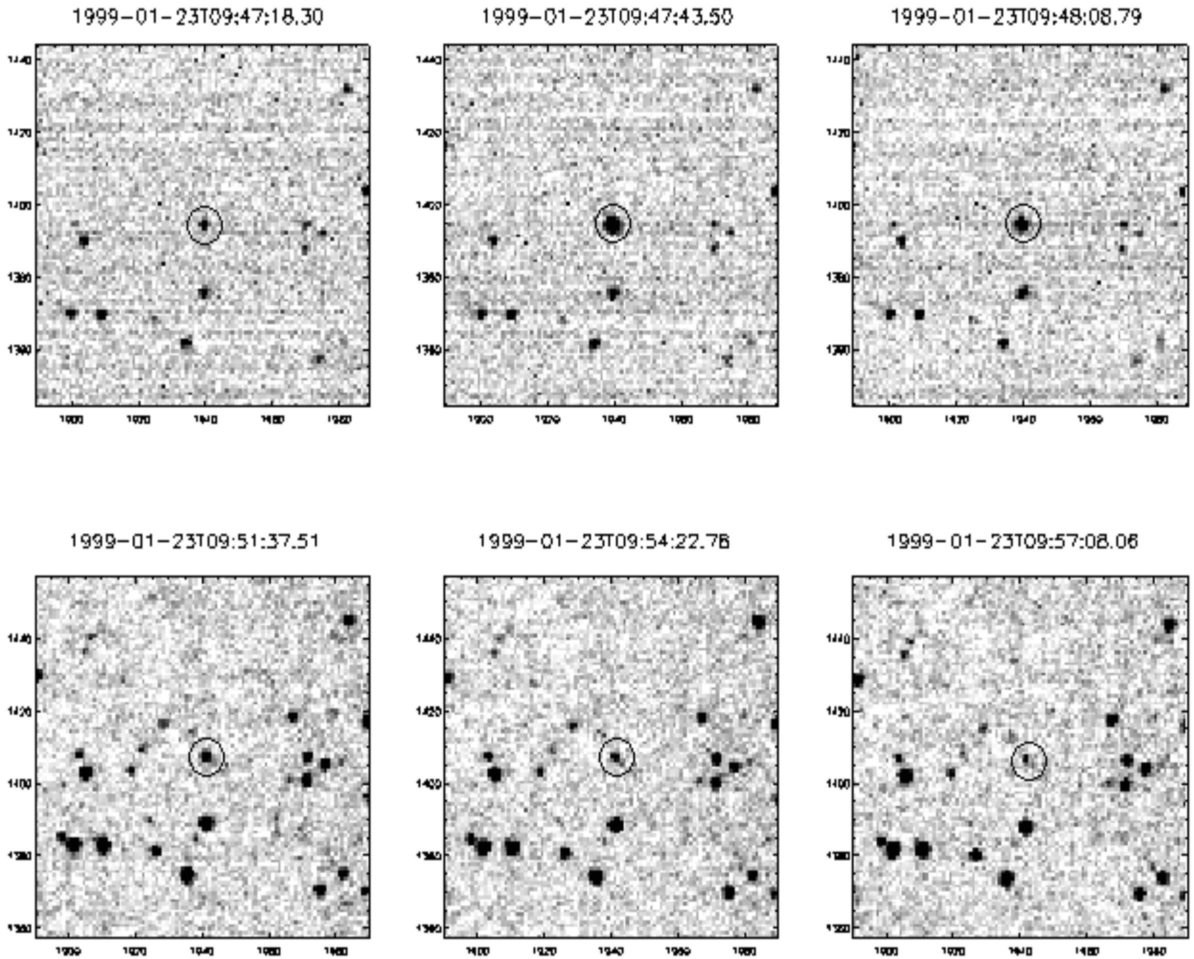


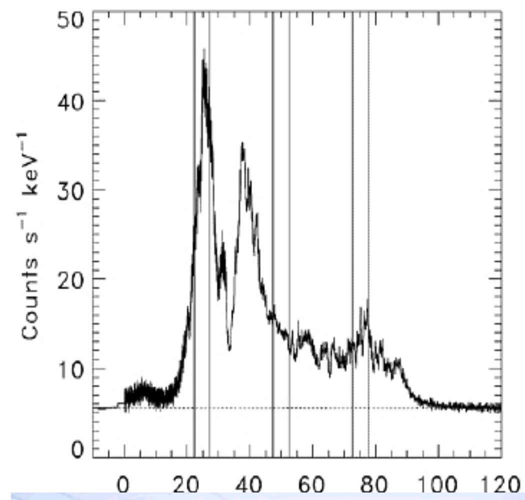
van Paradijs et al. 1997

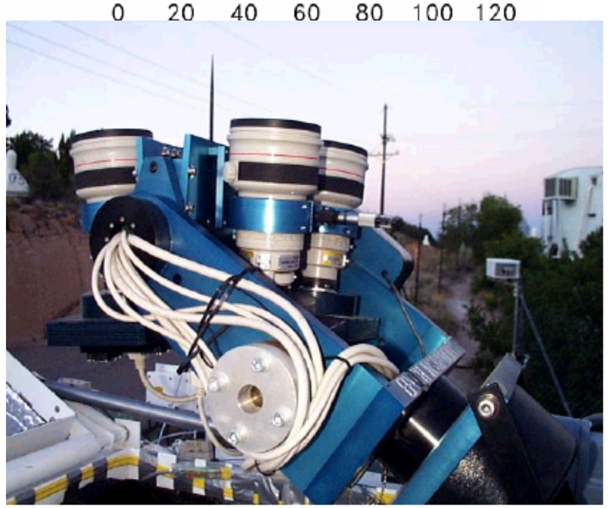


GRB 990123

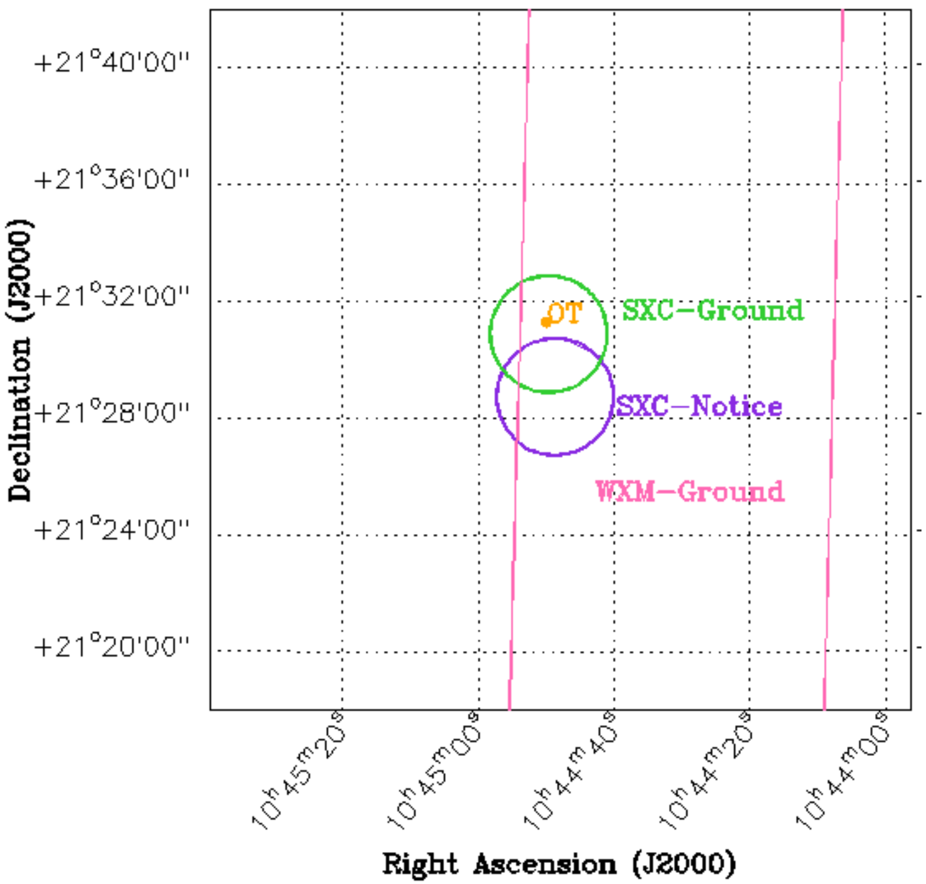
- ROTSE responded to BATSE ~5 degree localization
- 9 mag OT found in the BeppoSAX-WFC location (~ a few arcmin)

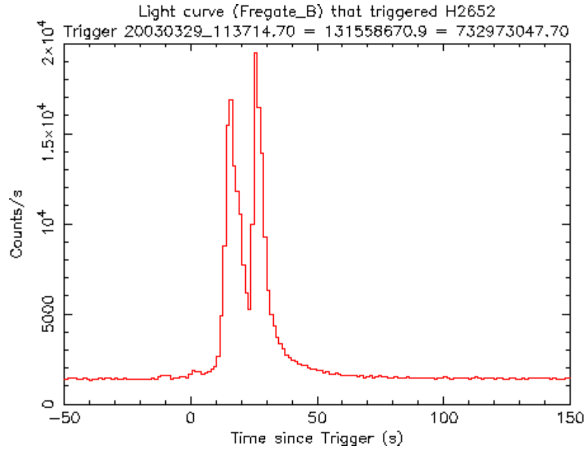






GRB 030329 – Localization by HETE-2





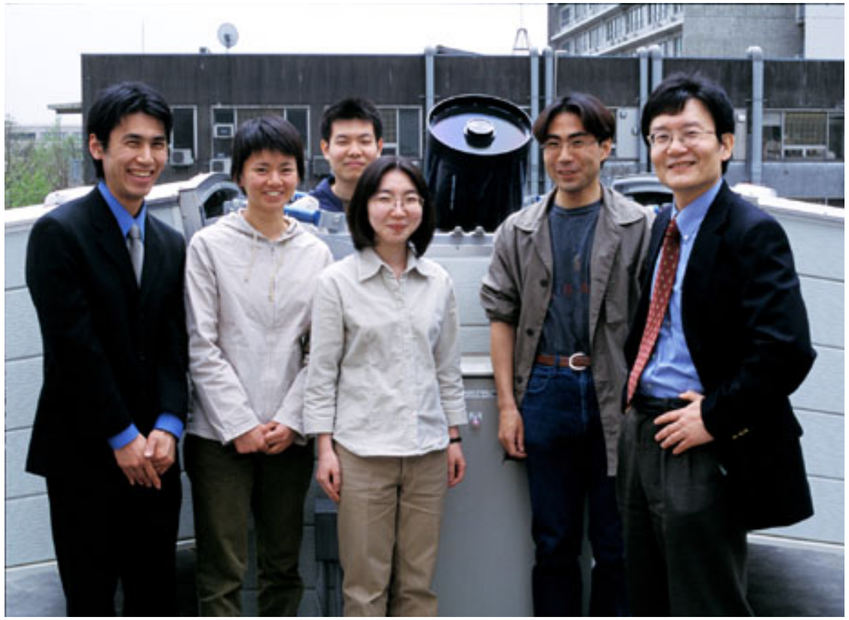
Trigger 11:37:14
Alert 11:38:41
SXC 12:50:24 (+73 min)

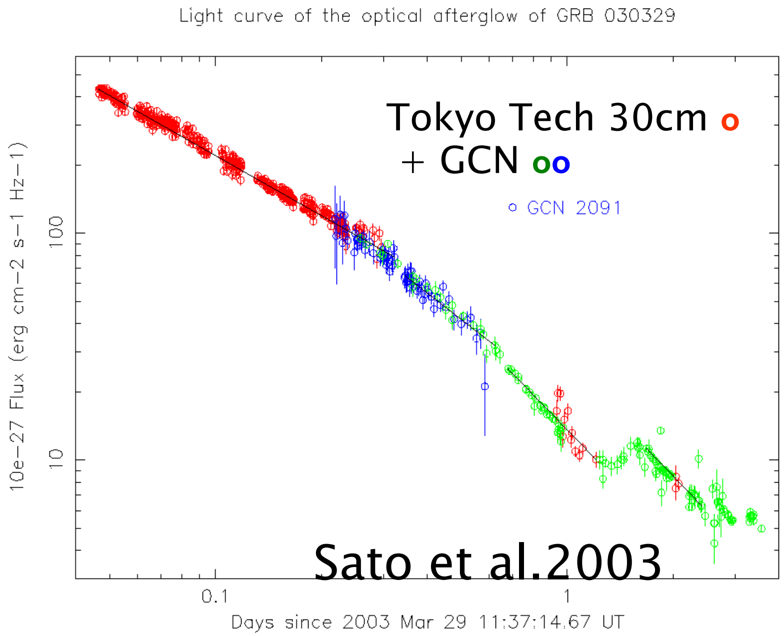
OT 12:52:09 (+75 min)

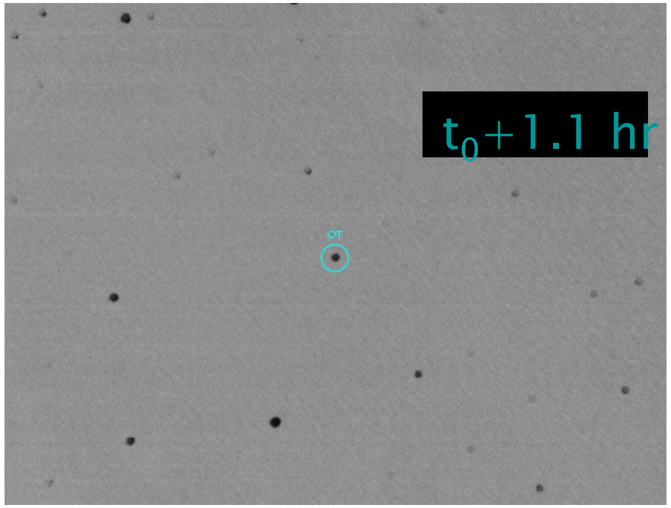
Torii GCN #1986
Peterson
GCN#1985

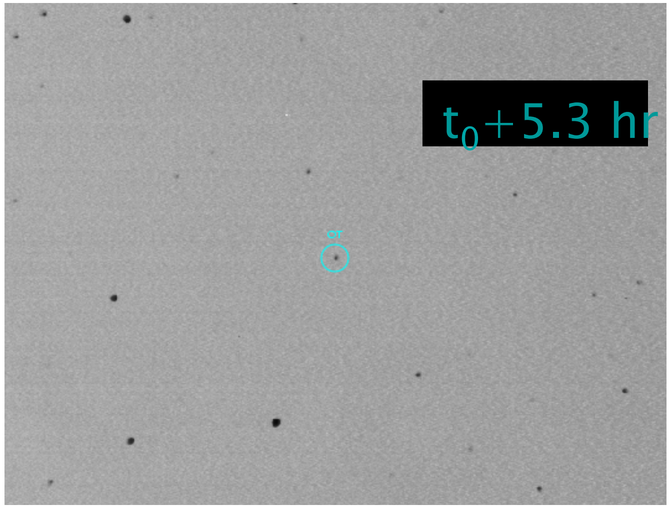
- WXM 1-D localization
- SXC 1 arcmin position in ~1hour with ground analysis
- 12-13 mag optical counterpart discovered immediately

GRB 030329
Observation with Tokyo Tech 30cm

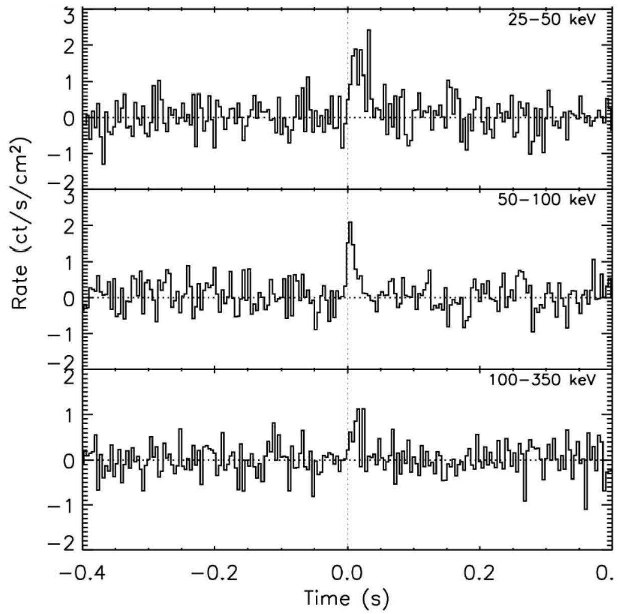


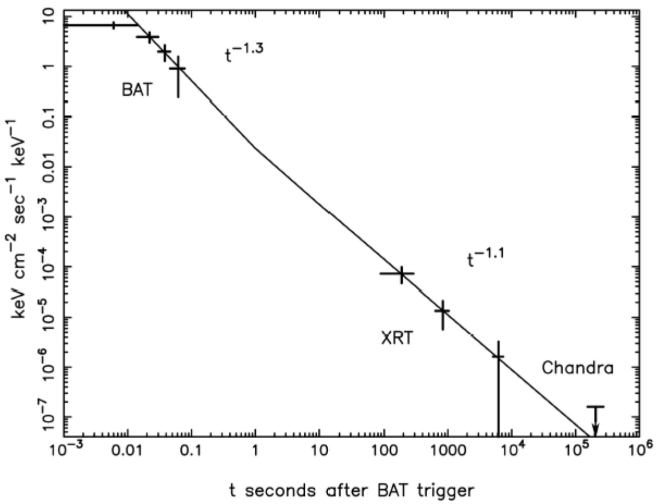






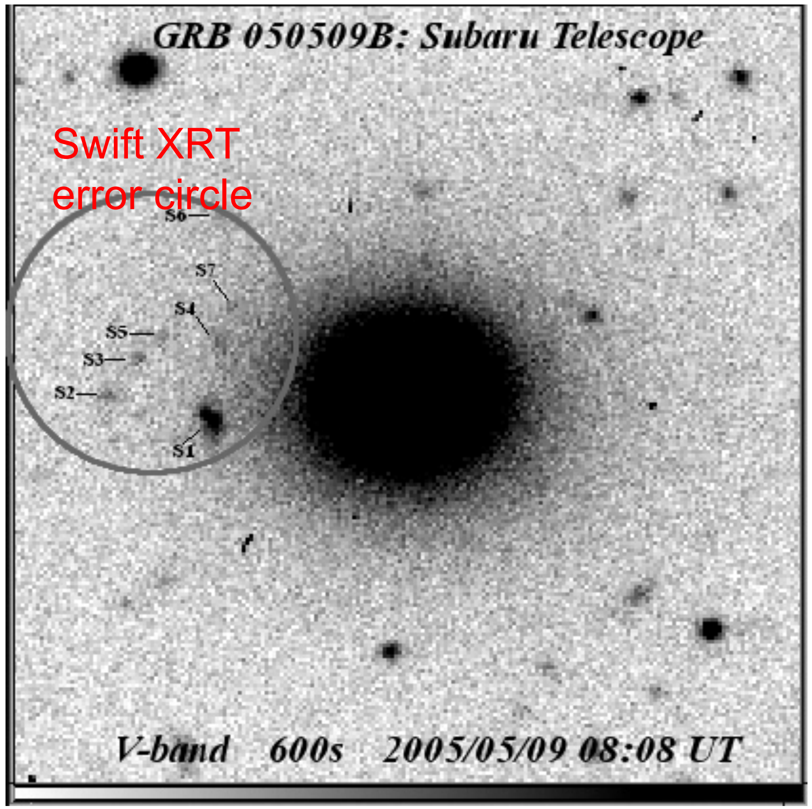
GRB 050509B – first short GRB with arcmin localization





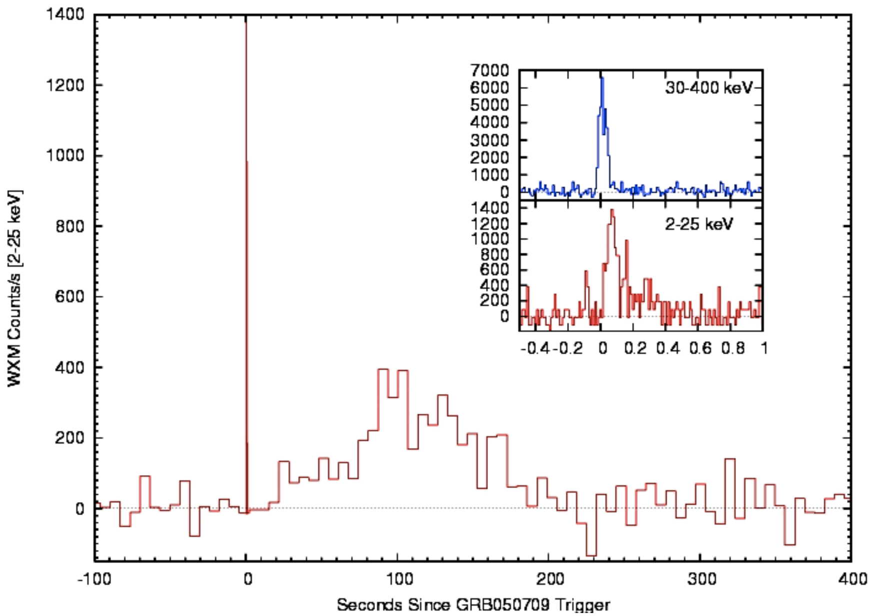
Gehrels et al. 2005

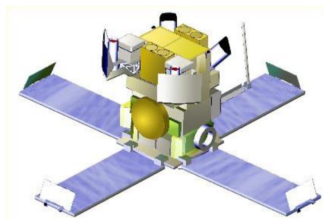
- Swift BAT → X-ray afterglow by Swift XRT
- Association with an elliptical galaxy at z=0.225: likely, but not conclusive

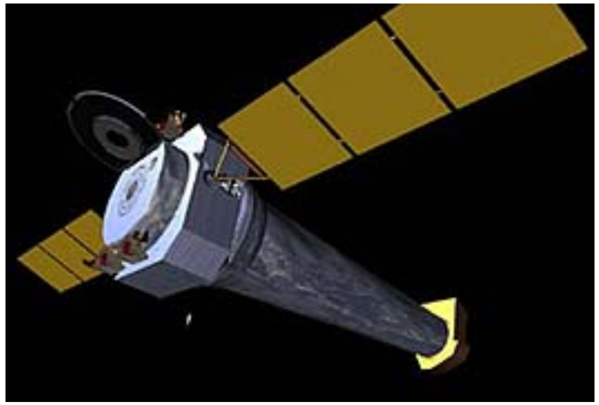


Subaru (Kosugi, et al. 2005

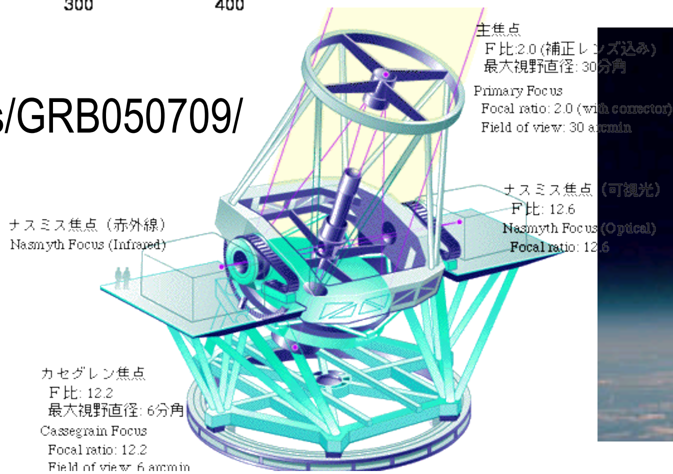
GRB050709
short GRB localized by HETE-2



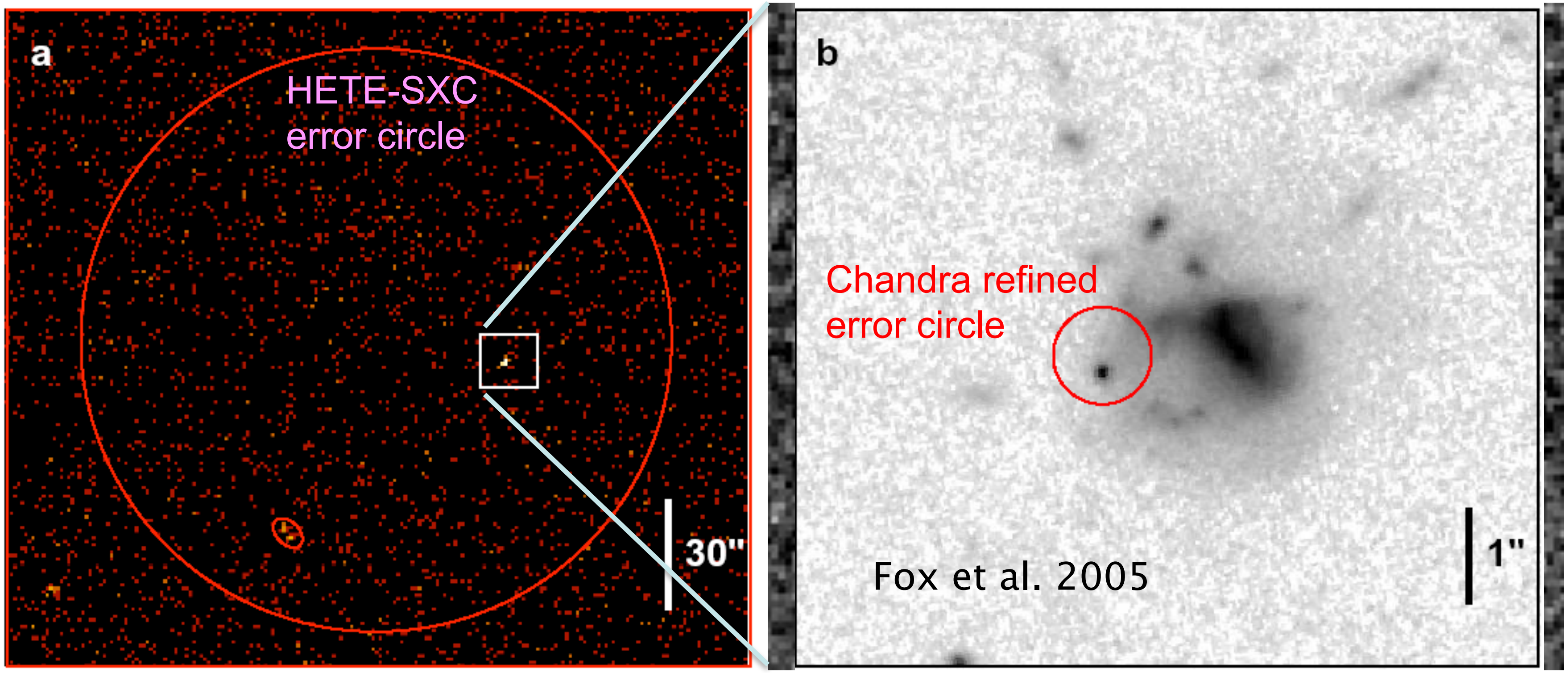




http://space.mit.edu/HETE/Bursts/GRB050709/



GRB 050709:
localization of X-ray and optical afterglow



Chandra X-ray Observatory

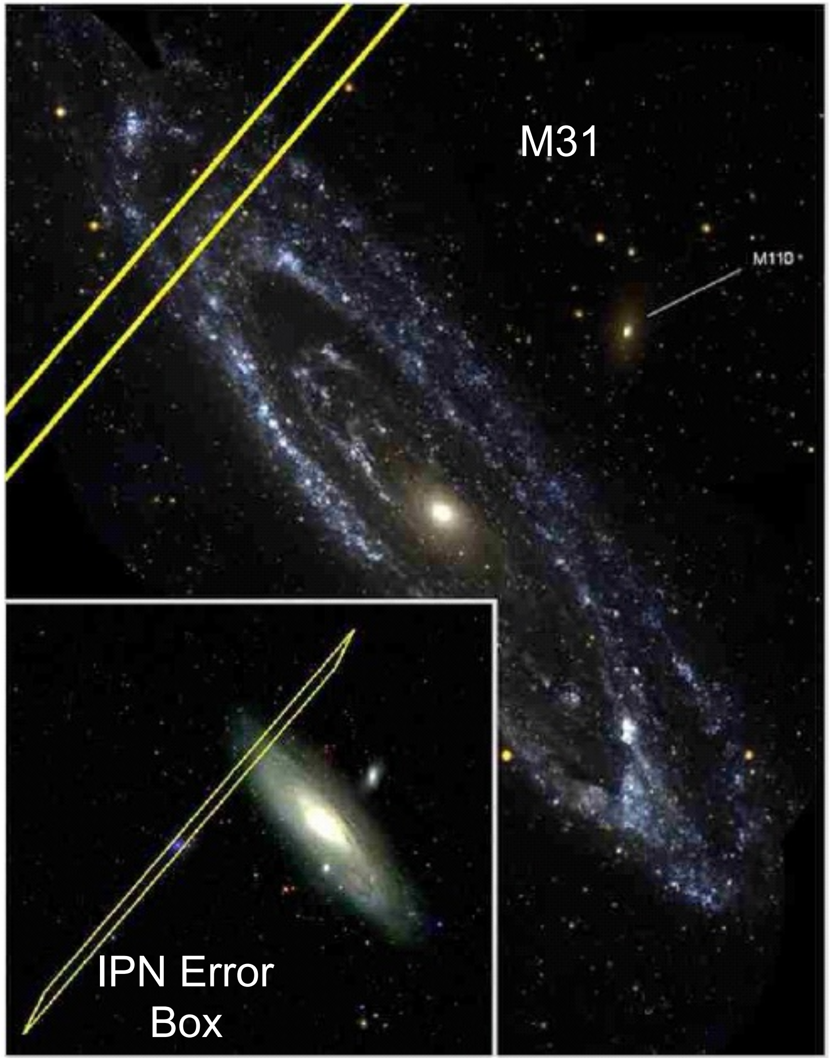
Hubble Space Telescope

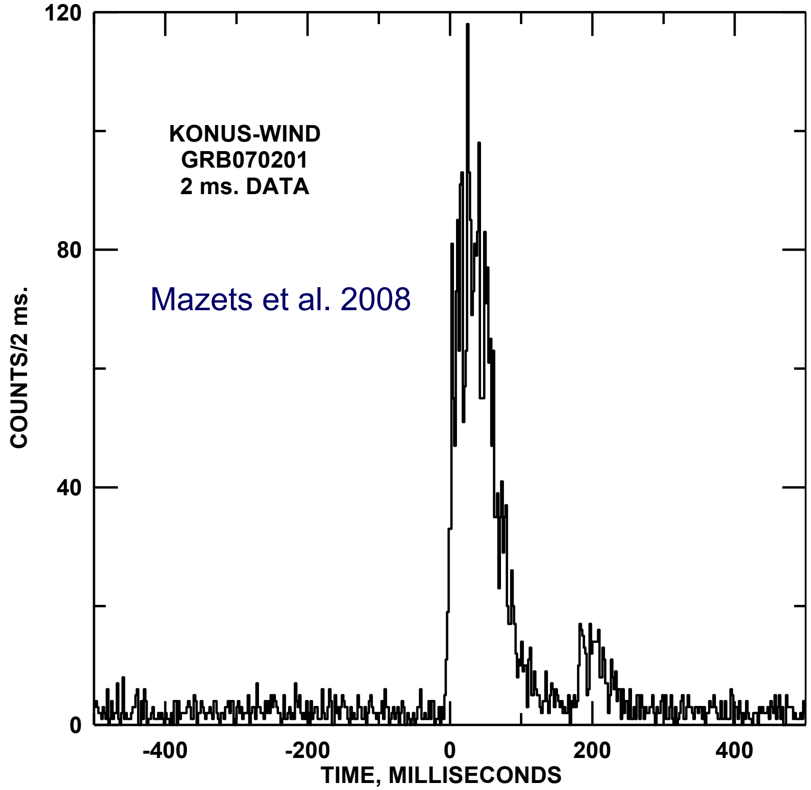
- HETE WXM+SXC ~1 arcmin
- Chandra ~0.5 arcsec
- Hubble localized it to a dwarf starforming galaxy

z=0.160
Dwarf irregular galaxy
SFR = 0.2 M_{sun}/yr

GRB070201

– short GRB from Andromeda galaxy? (780 kpc)?



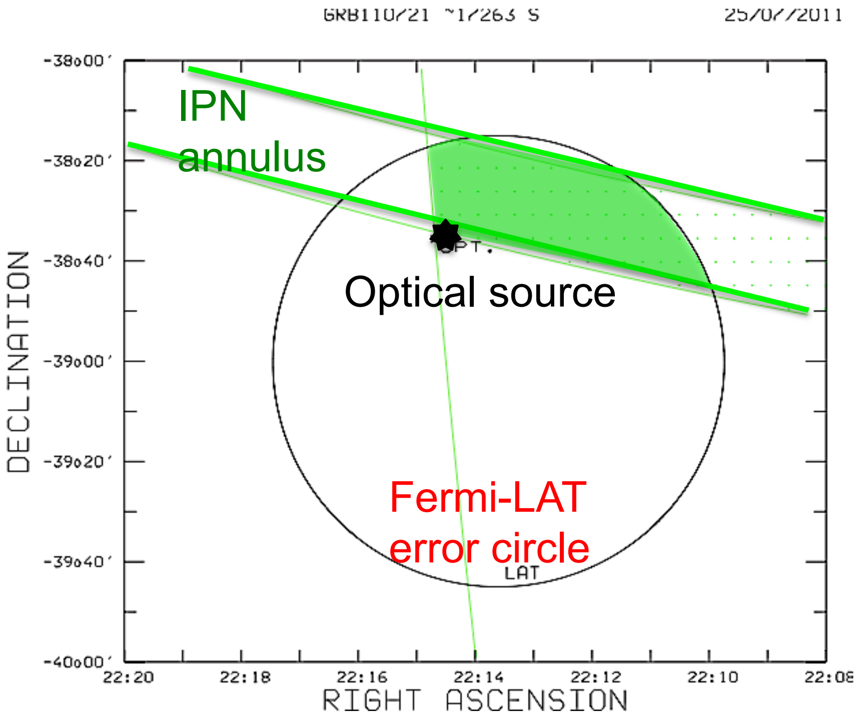


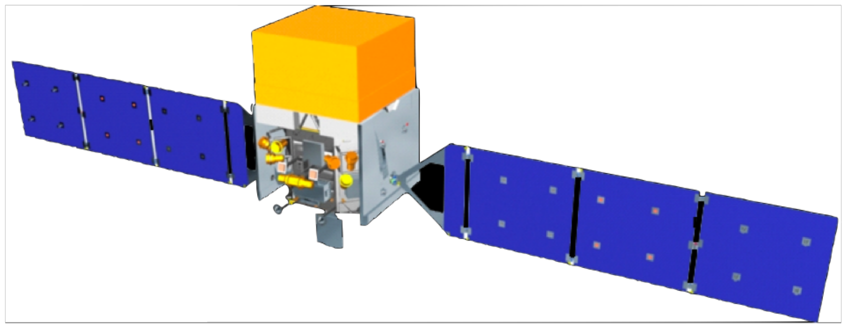
- LIGO measurements indicate that this could not have been a binary merger in M31 (Abbott et al. 2008)

$E_{\gamma}=1.5\text{x}10^{45}$ erg

GRB 110721A – GeV localization

- Fermi/LAT D=1.5 deg, 11 hours after the burst (large error and slow)
- Swift/XRT(D=0.4 deg) incomplete tiling
- IPN localization delay > 1 day
- Candidate X-ray/optical source found 2 days later
- Turned out to be an early-type galaxy





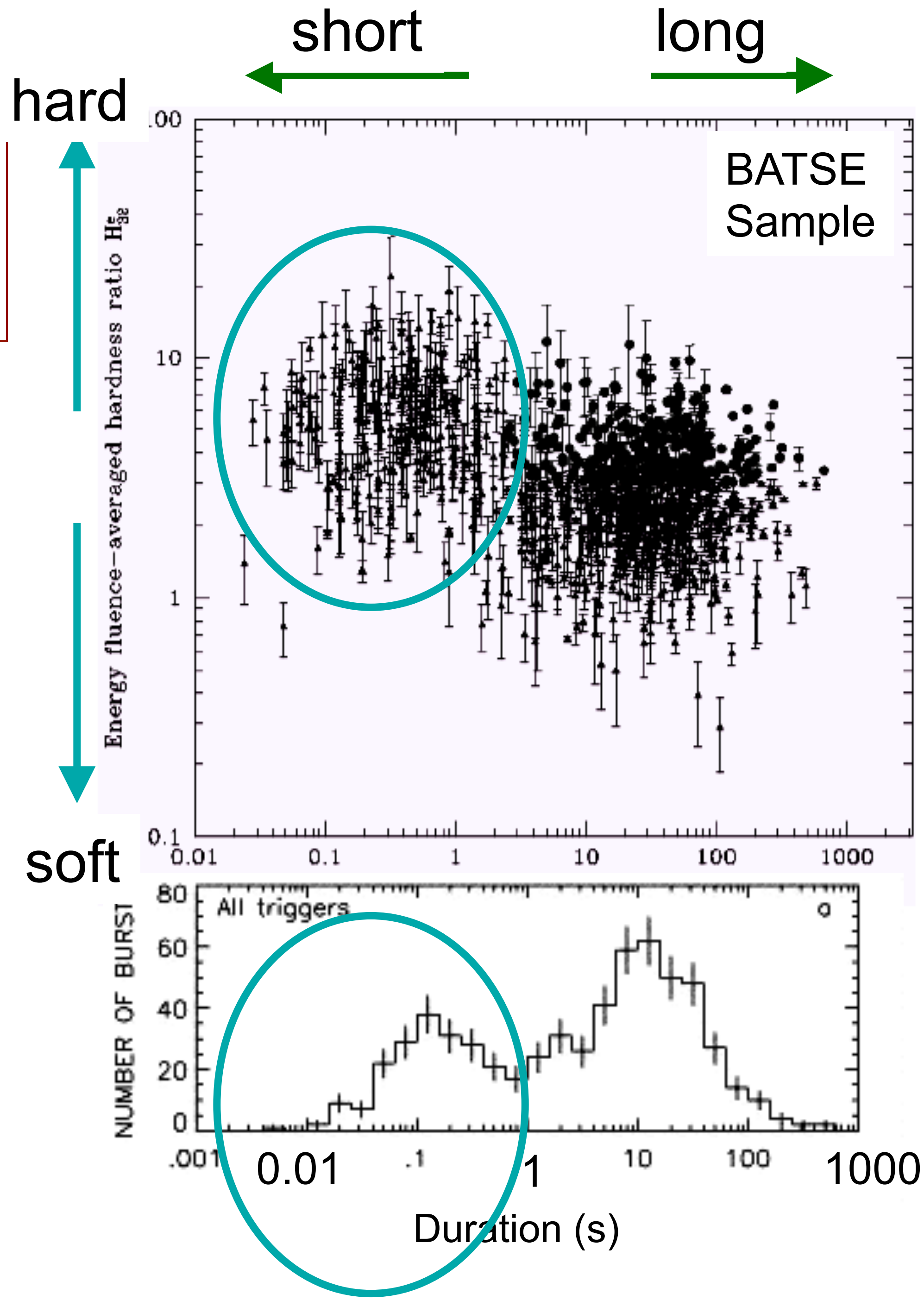
Lessons

- Pre-afterglow Era (~1997)
  - IPN: arcmin position is useless if too late
  - BATSE: prompt degrees position is useful with more constraining information
- Afterglow era (1997~)
  - Quick location is the key
  - Optical astronomers do not look at error circles larger than their field of view
  - Swift XRT: even arcmin position does not give conclusive identification
  - Optical/Near infrared imaging/spectroscopy required for unambiguous identification

Recommendations

- Localization error – the smaller the better
- Notification delay - the shorter the better

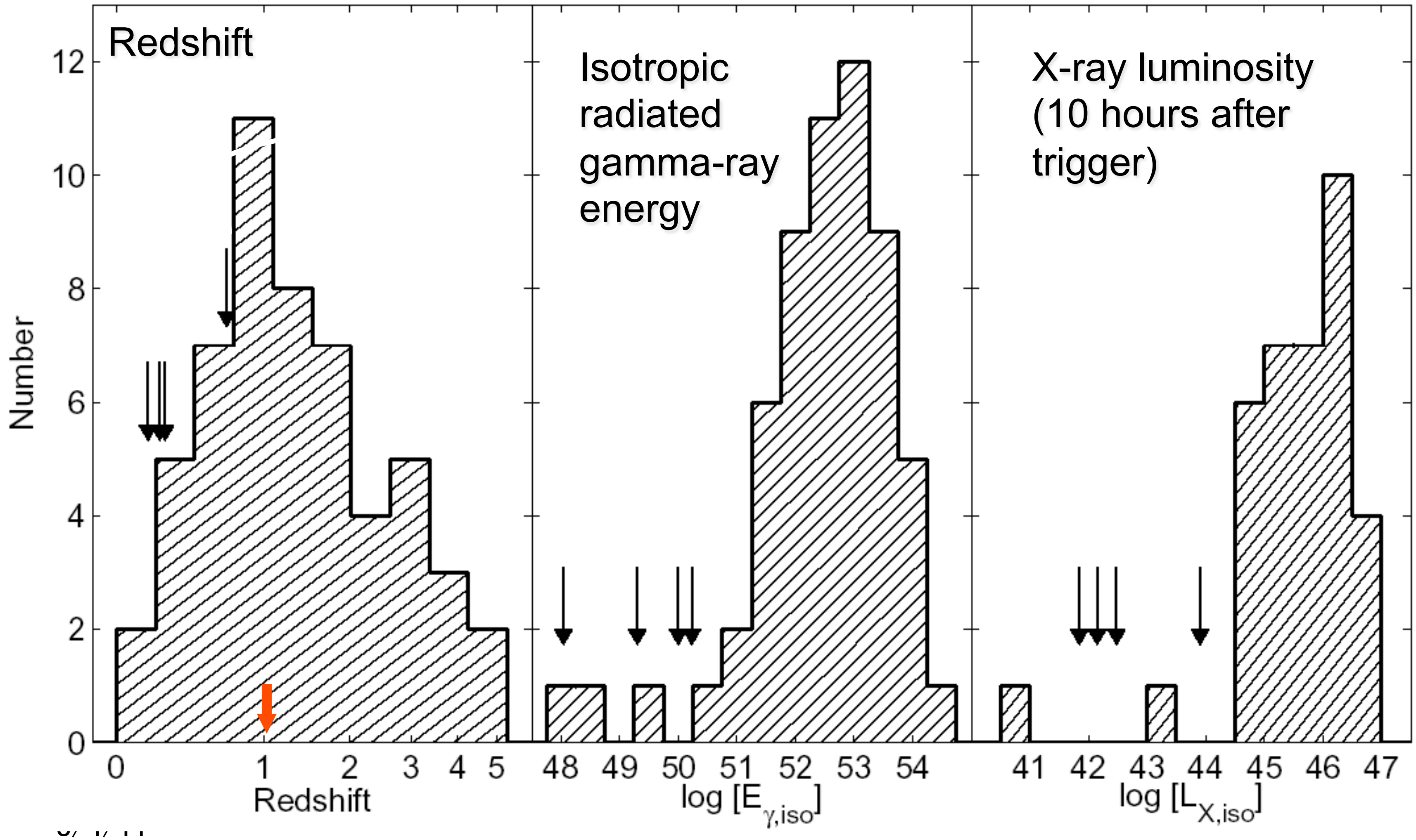
"Short hard" GRB



No afterglow detected
(until 2005)

- Different origin
  - supernovae?
  - neutron star merger?
  - magnetar flare?

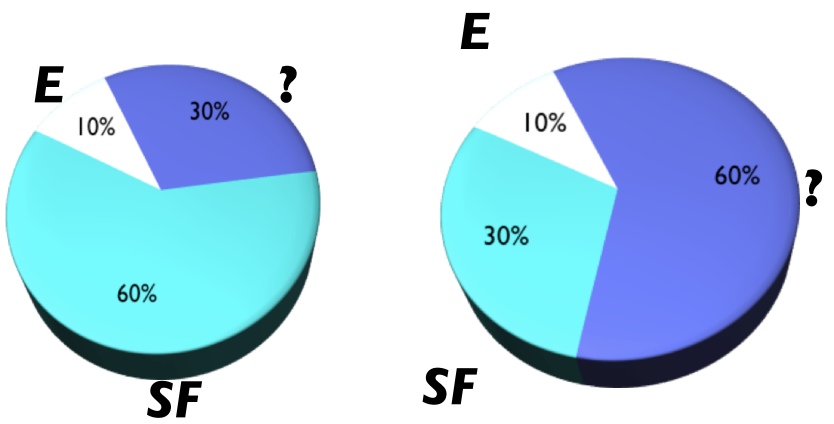
Redshift, isotropic radiated energy, and X-ray afterglow luminosity of GRBs (arrows: short GRBs)

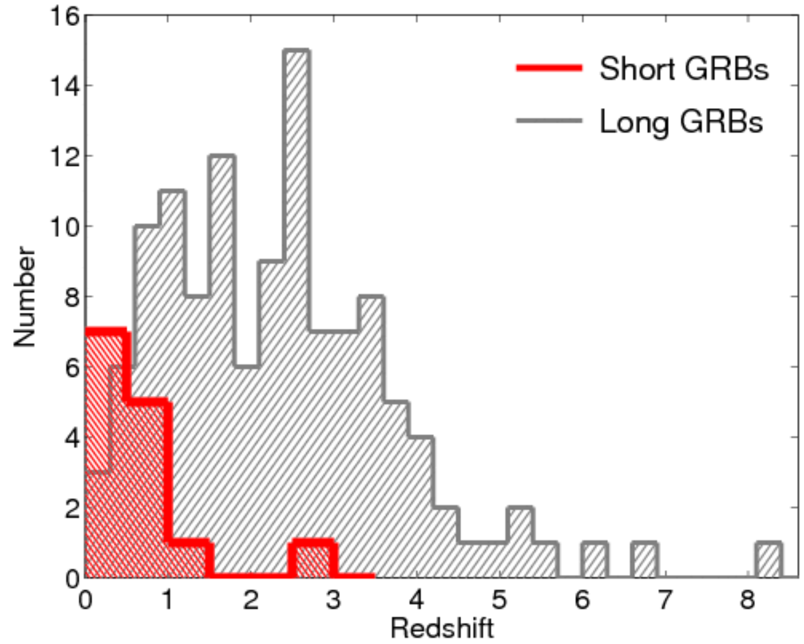


Host galaxy and redshift of short GRBs

Optical Afterglows X-ray Afterglows

Berger et al. 2007; Berger 2009





E: elliptical galaxies (old stars only)

F: Star forming galaxies

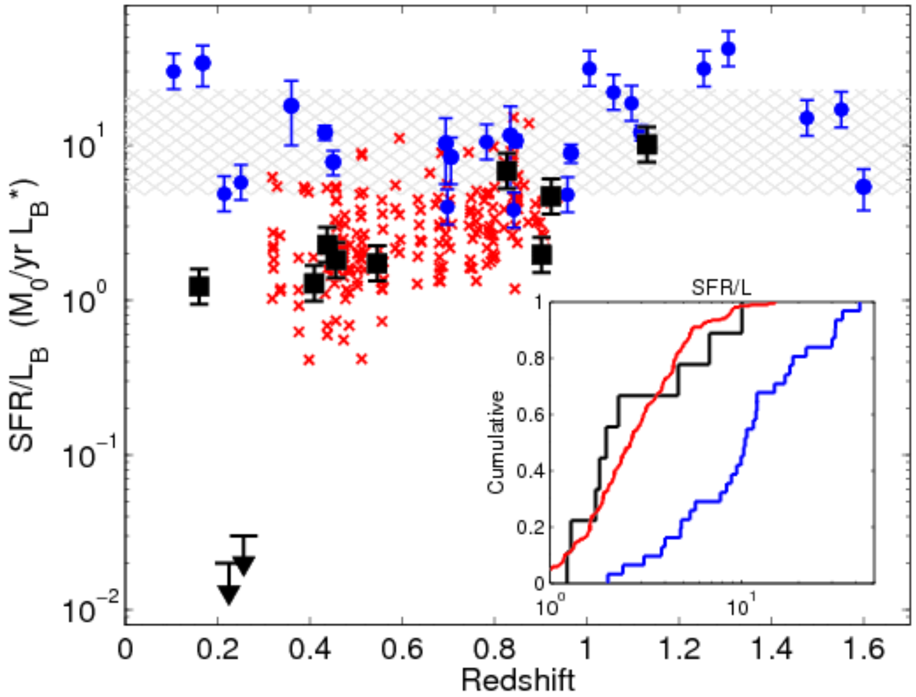
Confirmed hosts − E:SF = 2:11

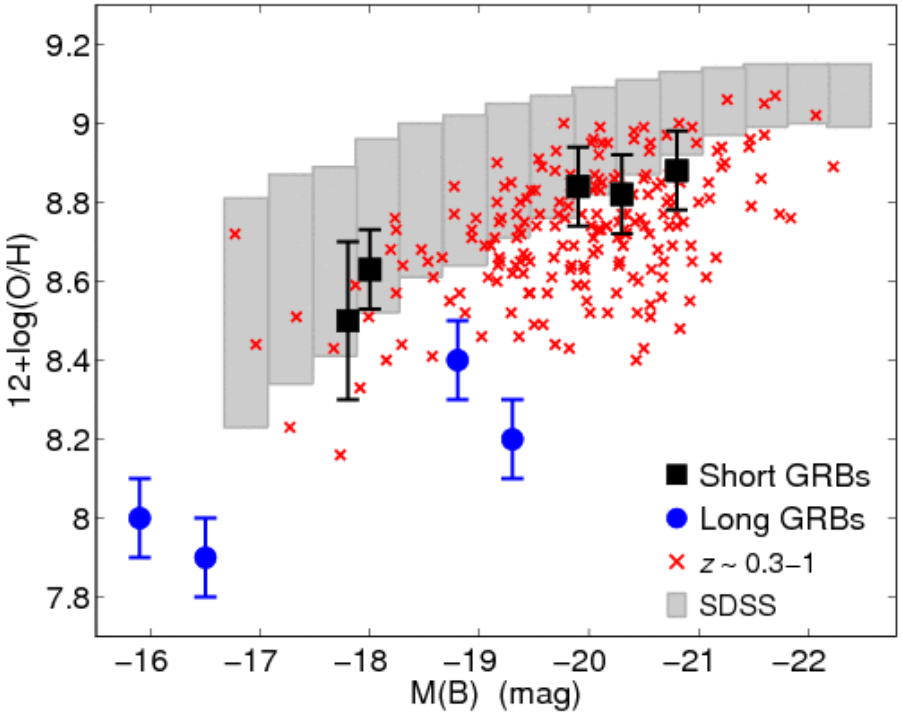
Half of short GRB at $z > 0.7$

$\Rightarrow \langle age \rangle \leq 7$ Gyr

Star formation rate and metallicity of short GRB hosts

Berger 2009



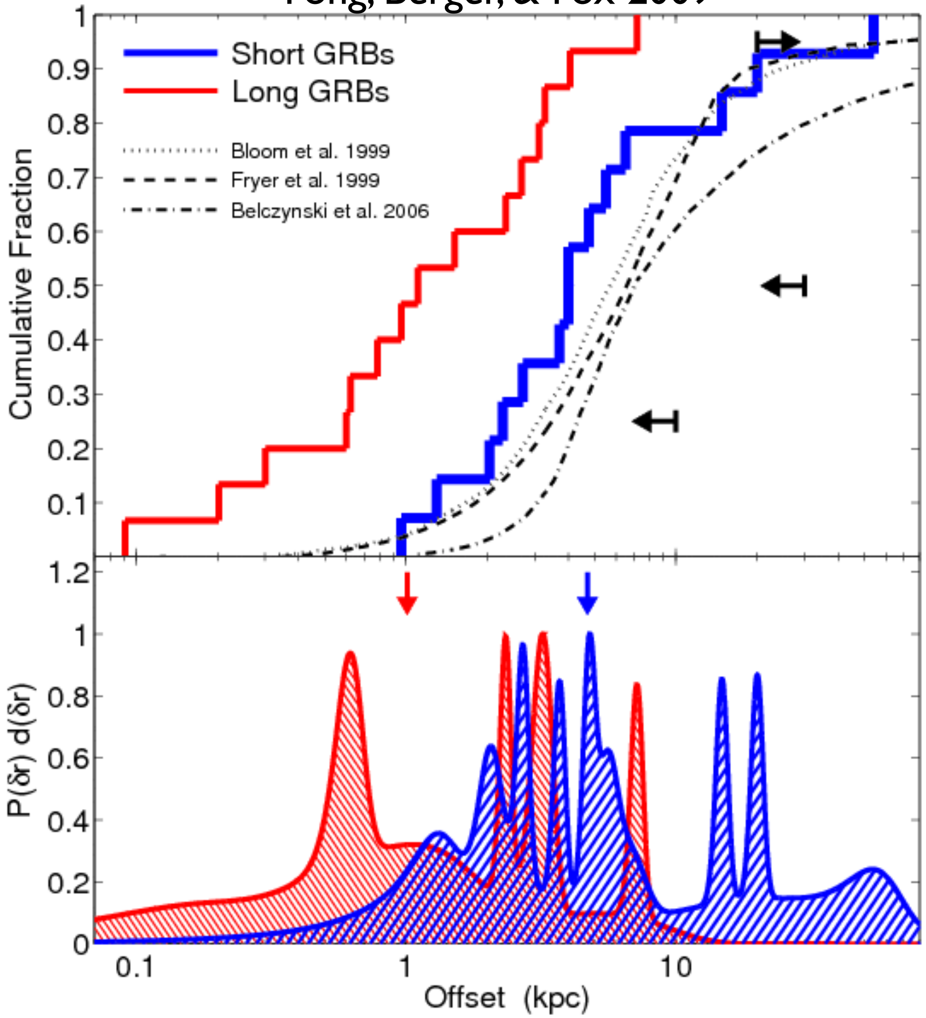


Short GRB hosts have lower specific star formation rates than long GRB hosts; they trace the general galaxy population

Short GRB hosts have higher metallicities than long GRB hosts; they trace the general galaxy population

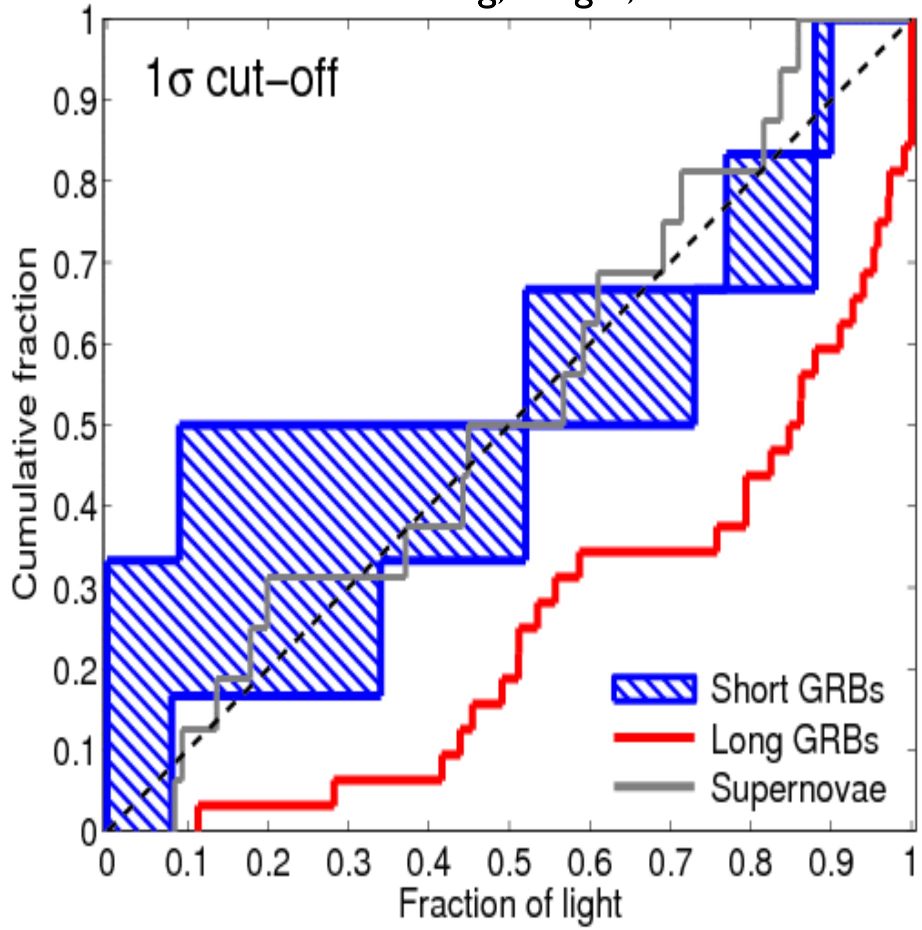
Sites of short GRBs in host galaxy

Fong, Berger, & Fox 2009



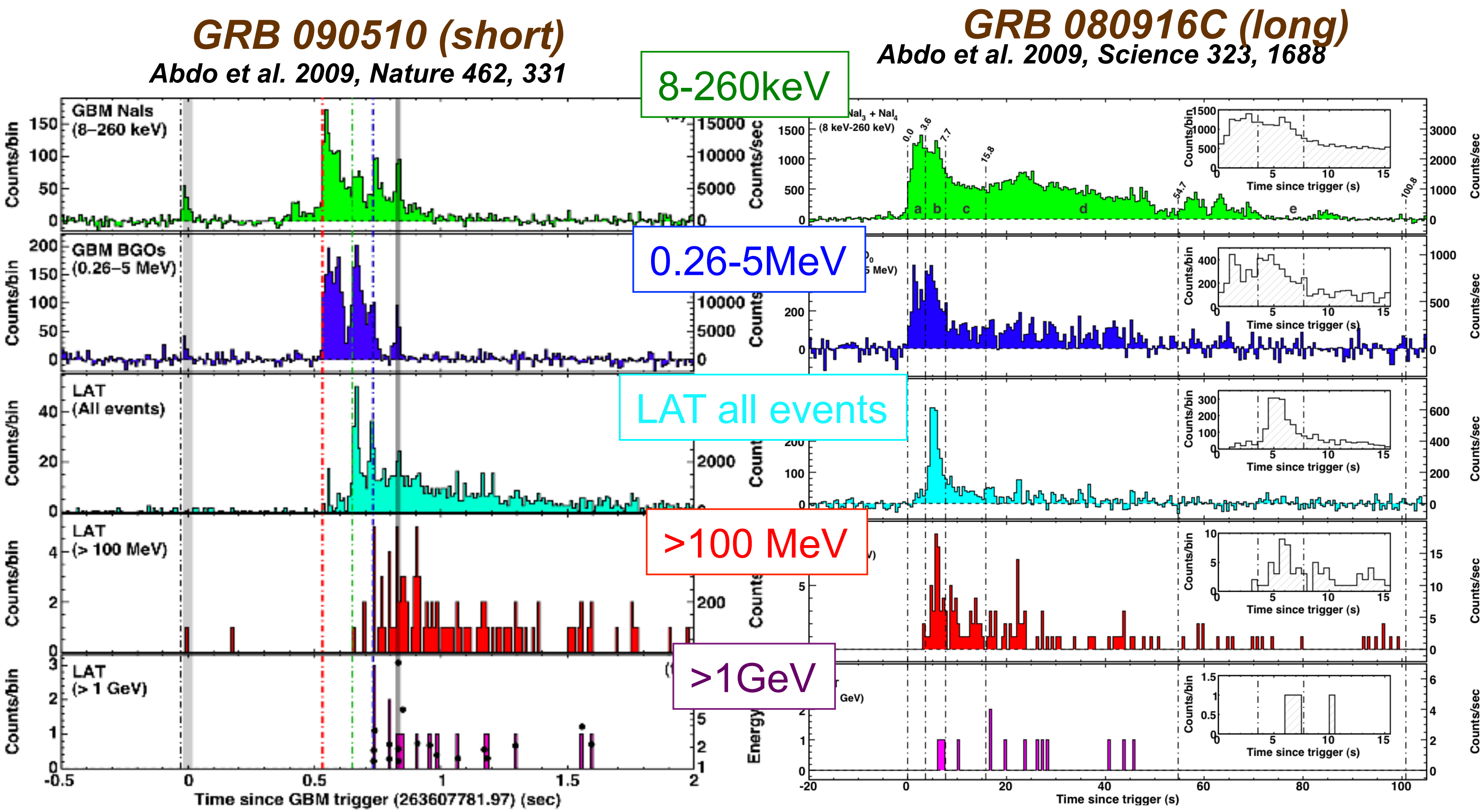
Short GRBs have larger offset from the center of their host galaxies

Fong, Berger, & Fox 2009



Short GRBs trace the light distribution of their host galaxies

Prompt emission of long and short GRBs



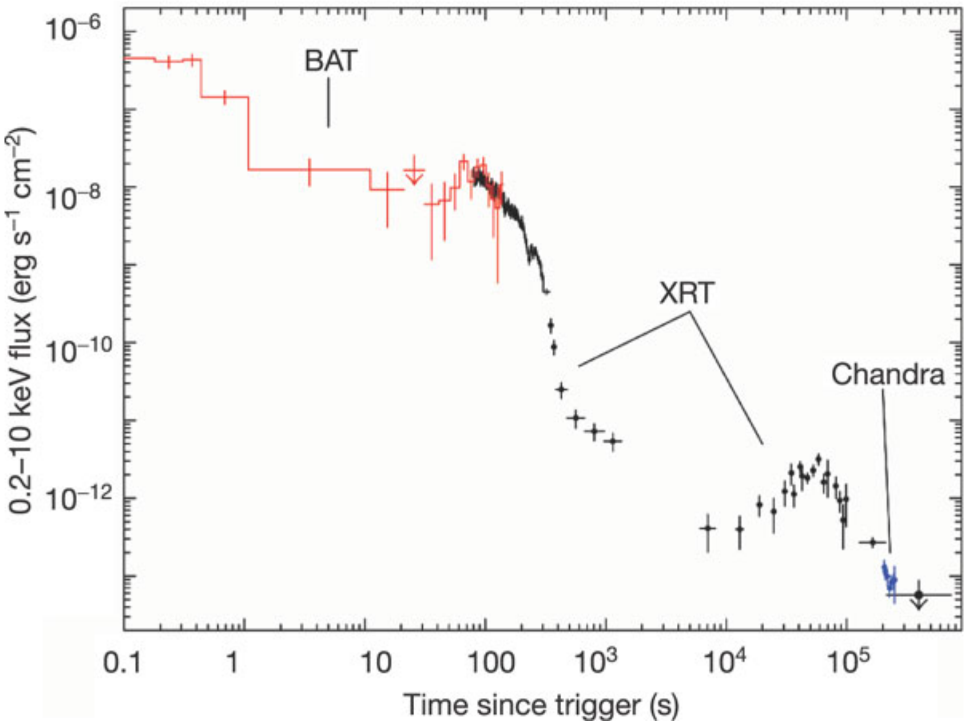
Delay in HE onset: 0.1-0.2 s

Delay in HE onset: ~4-5 s

<u>HE delayed onset can be seen from almost all LAT GRBs</u>

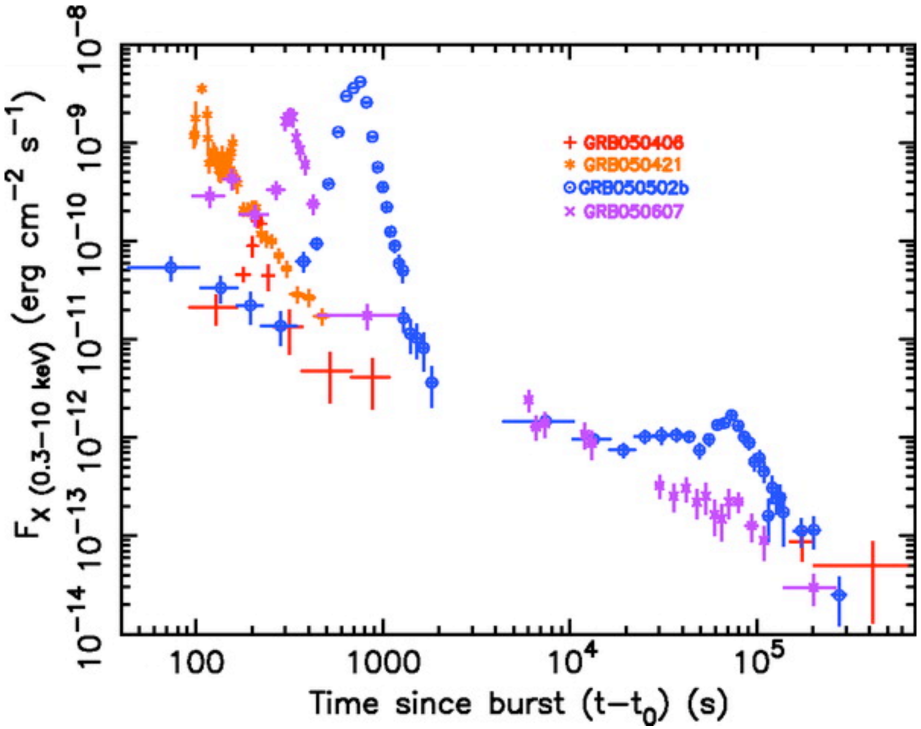
Afterglow of short and long GRBs

Short GRB050724



Barthelmy et al. 2005

Long GRBs

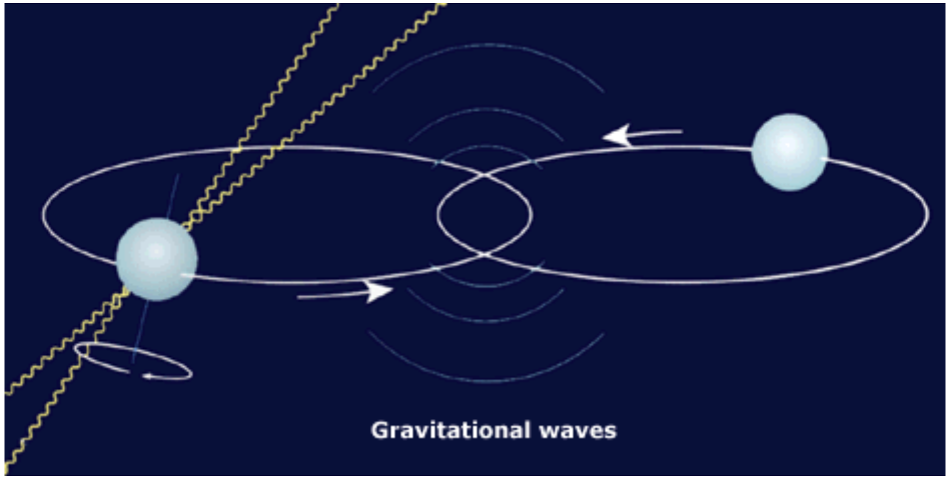


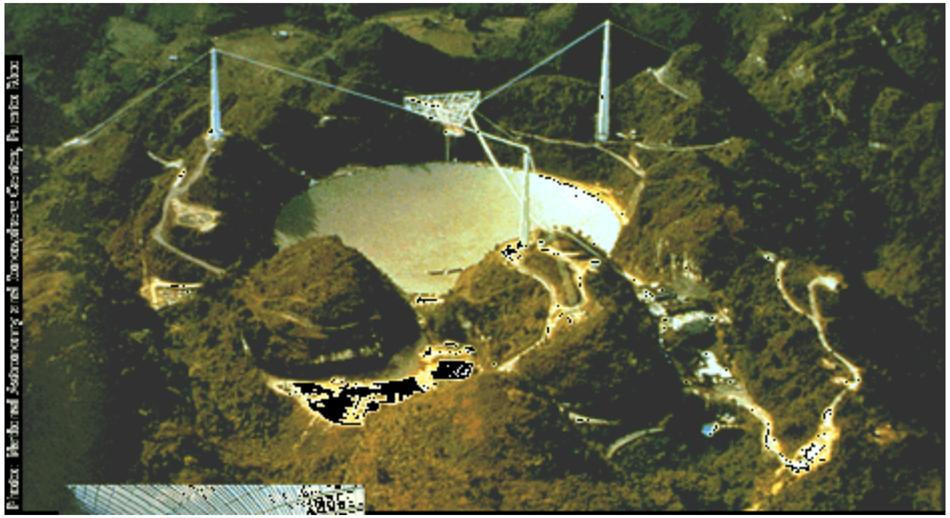
Nousek et al. 2006

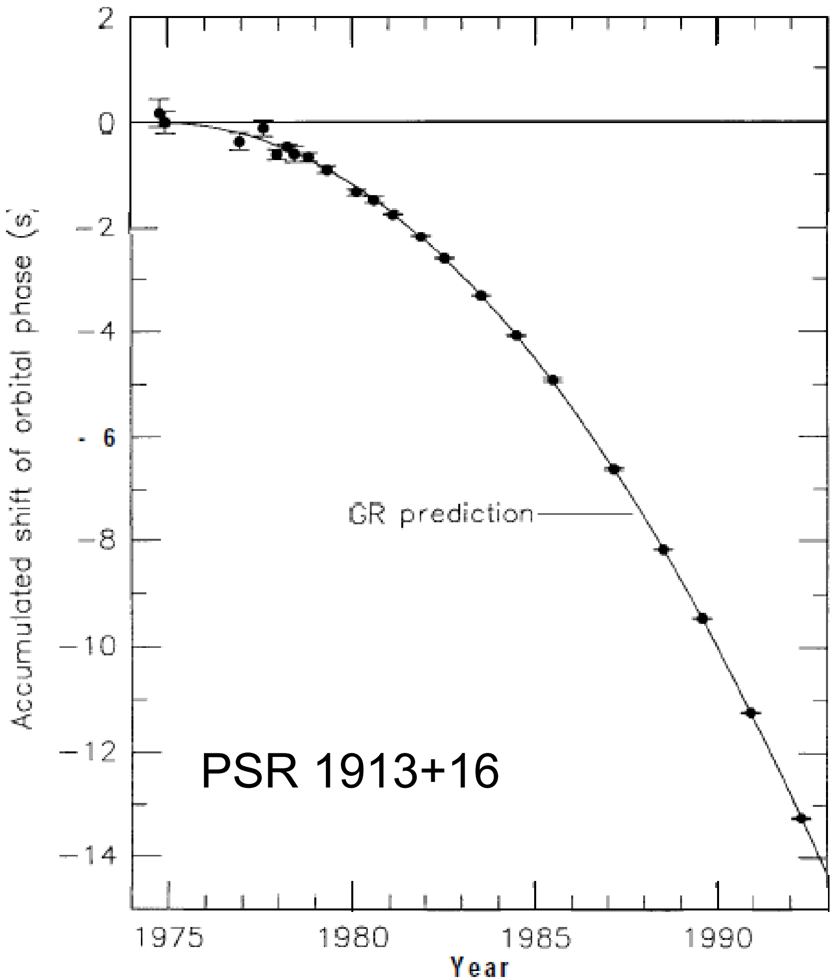
X-ray afterglows are similar to those of long GRBs

Suspect –Merging neutron star binary

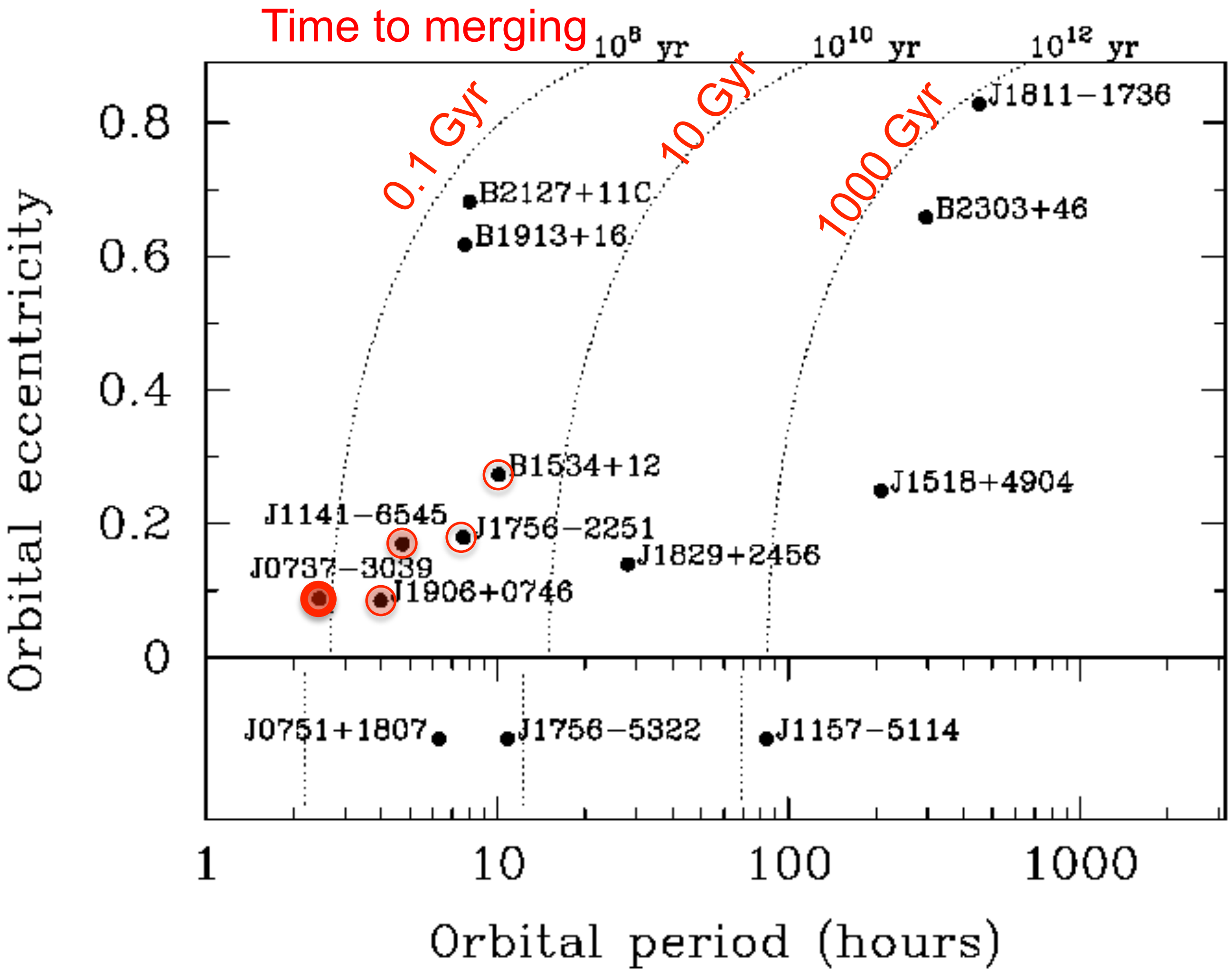
J.H. Taylor and R.H Hulse
1993 Nobel Prize in Physics





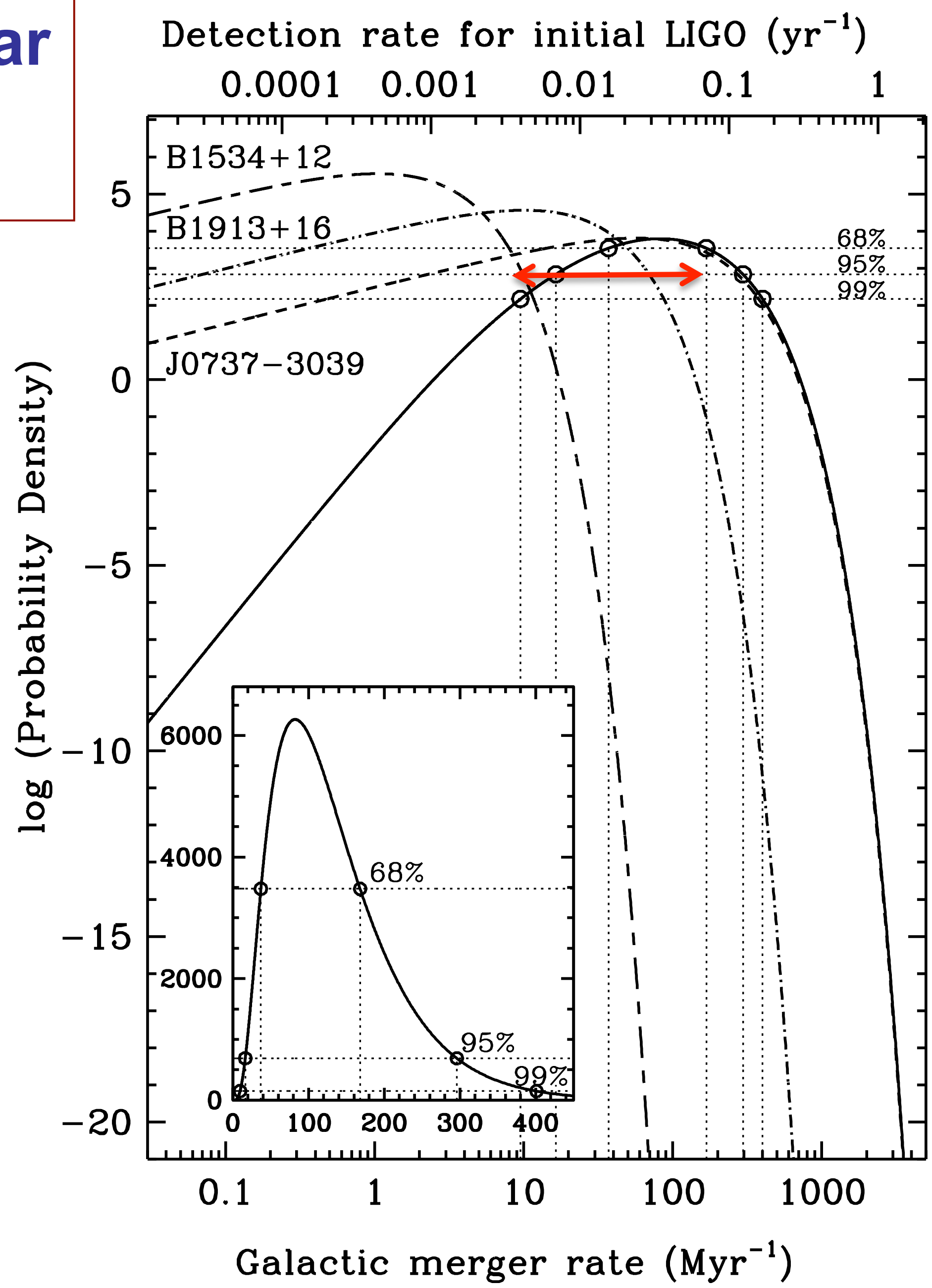


Known neutron star binaries



Detection rate of neutron star merger by GW telescope

- LIGO (range ~ 20 Mpc)
  →one per 10–630 year (95%CL)
- LCGT (range ~ 200 Mpc: z=0.015)
  →2–100 per year
- Short GRB detections <100/year
  - Most DNS mergers are not detected as short GRB

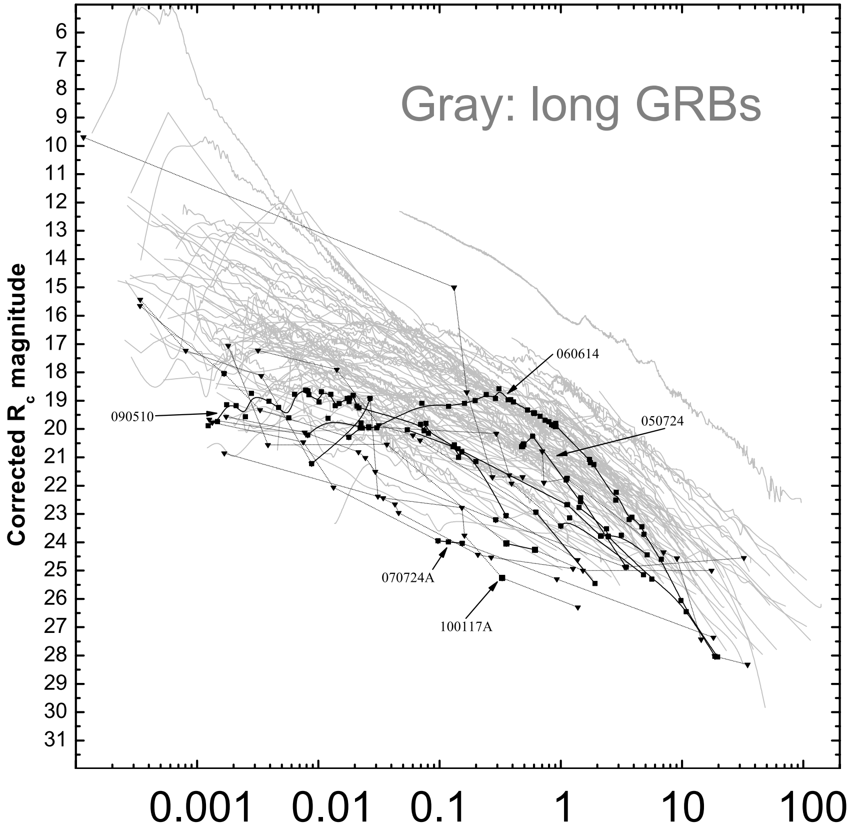


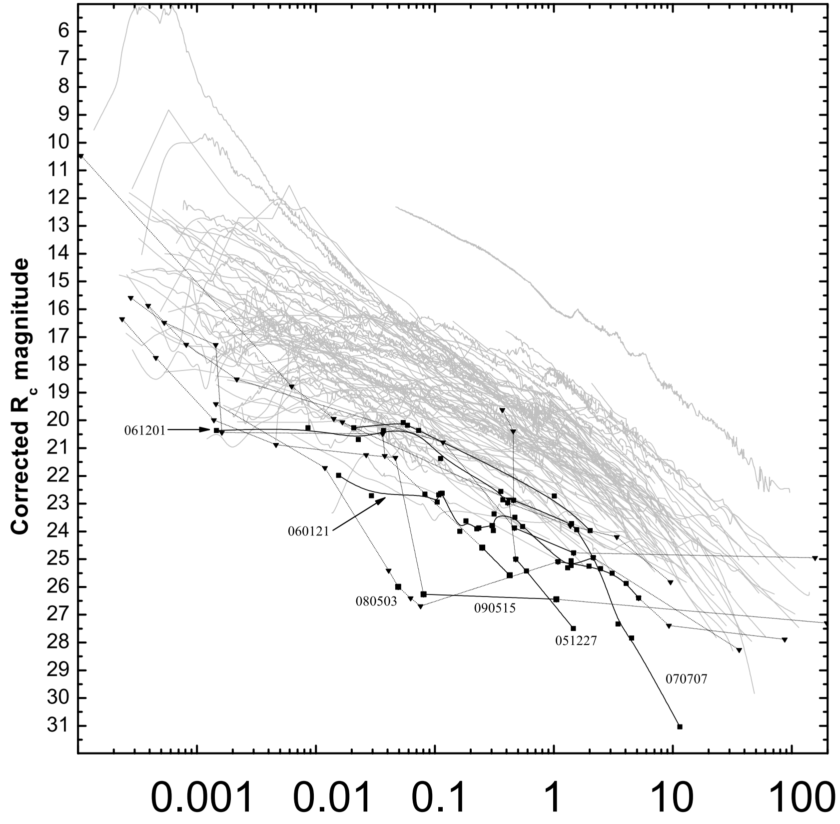
Optical afterglow of GRBs

Short GRBs with measured redshifts

Short GRBs without measured redshifts

R band magnitude at observer frame



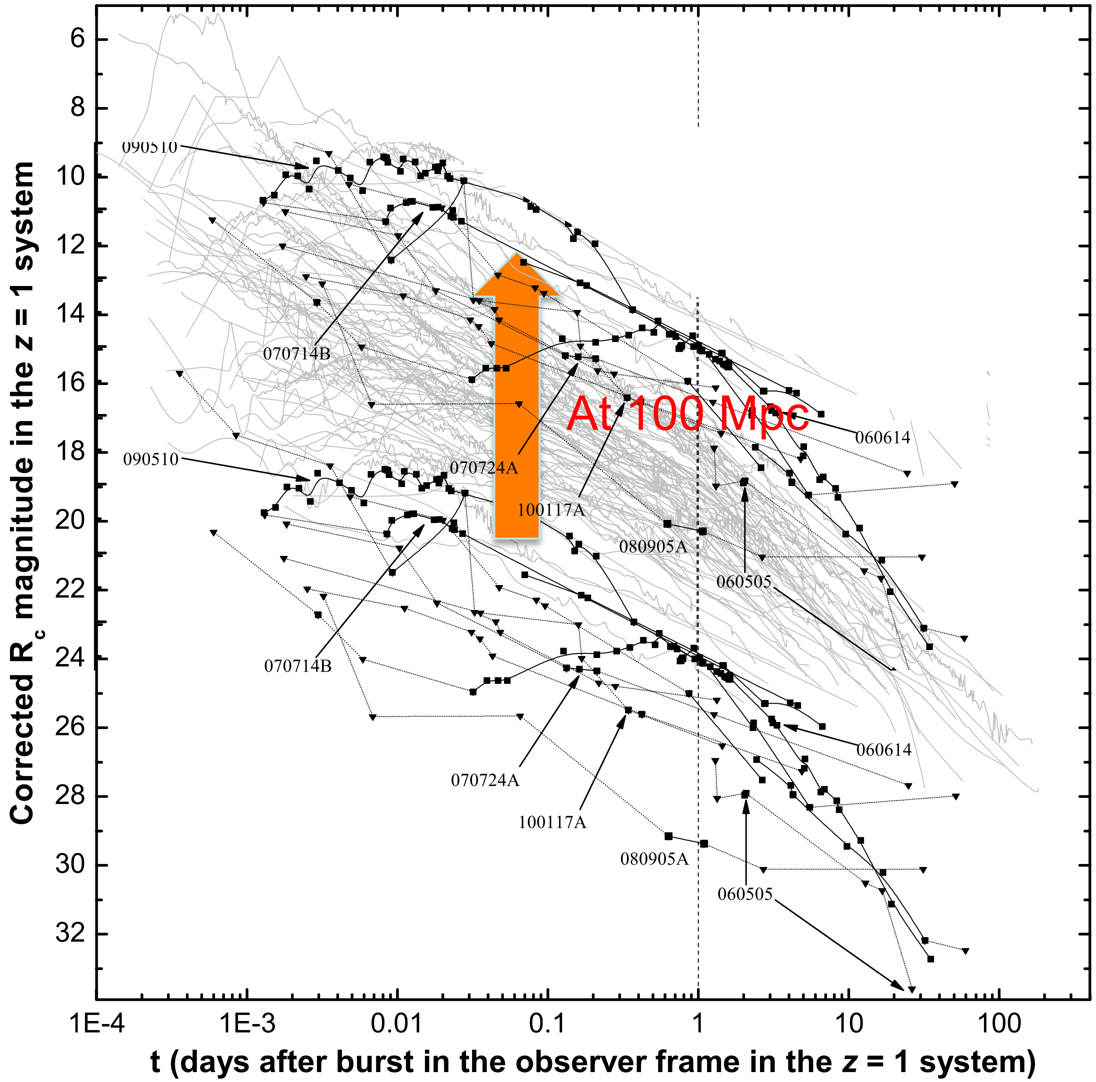


Days after burst in the observer frame

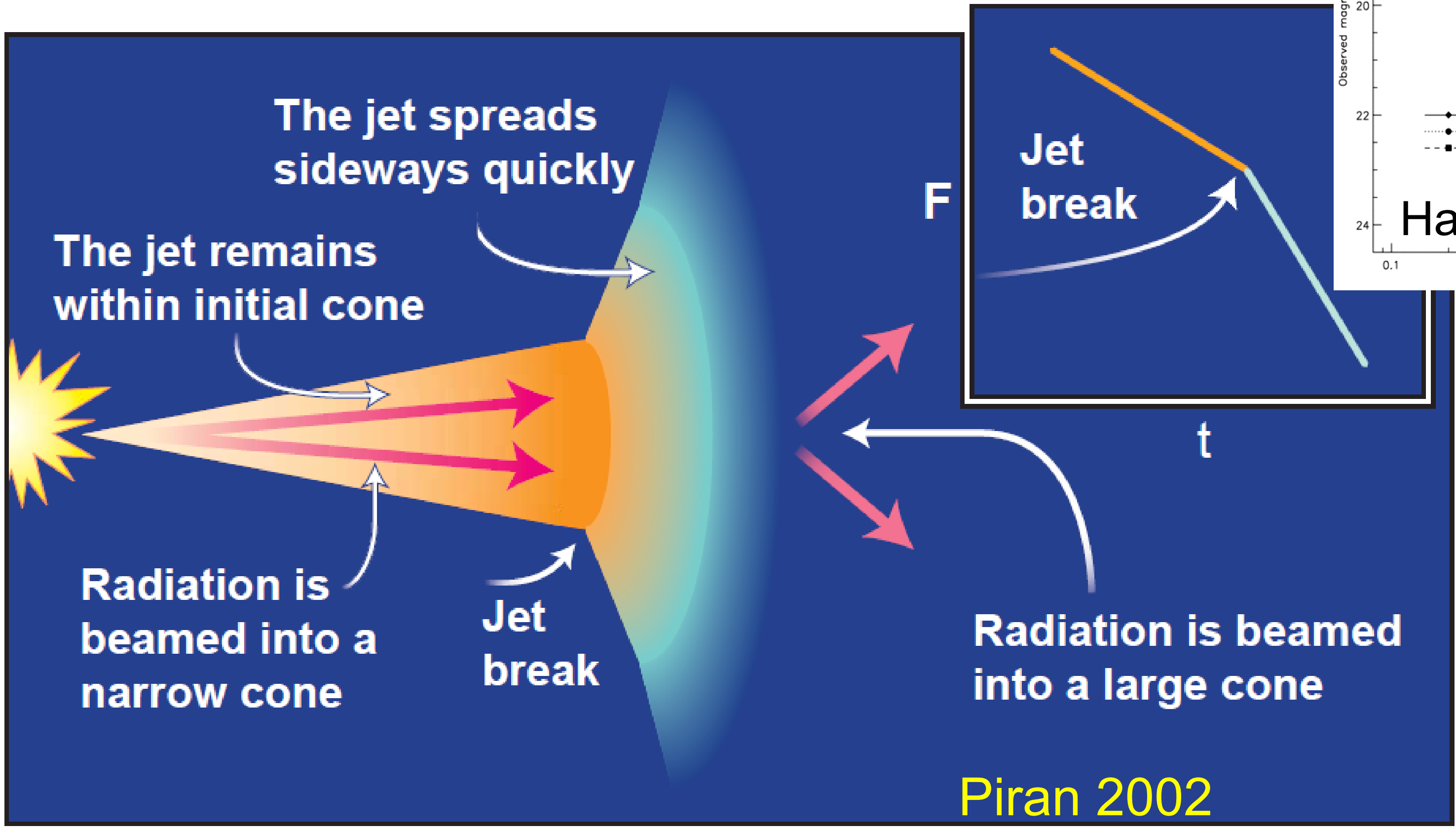
Kann et al. 2011

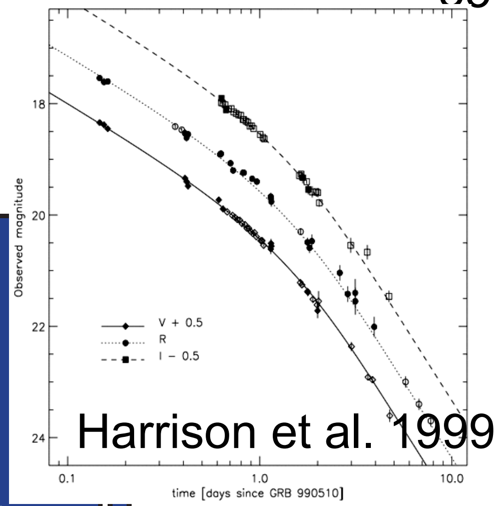
Optical afterglow of SGRB at z=1 and at 100 Mpc

Kann et al. 2011



Signature of jet break

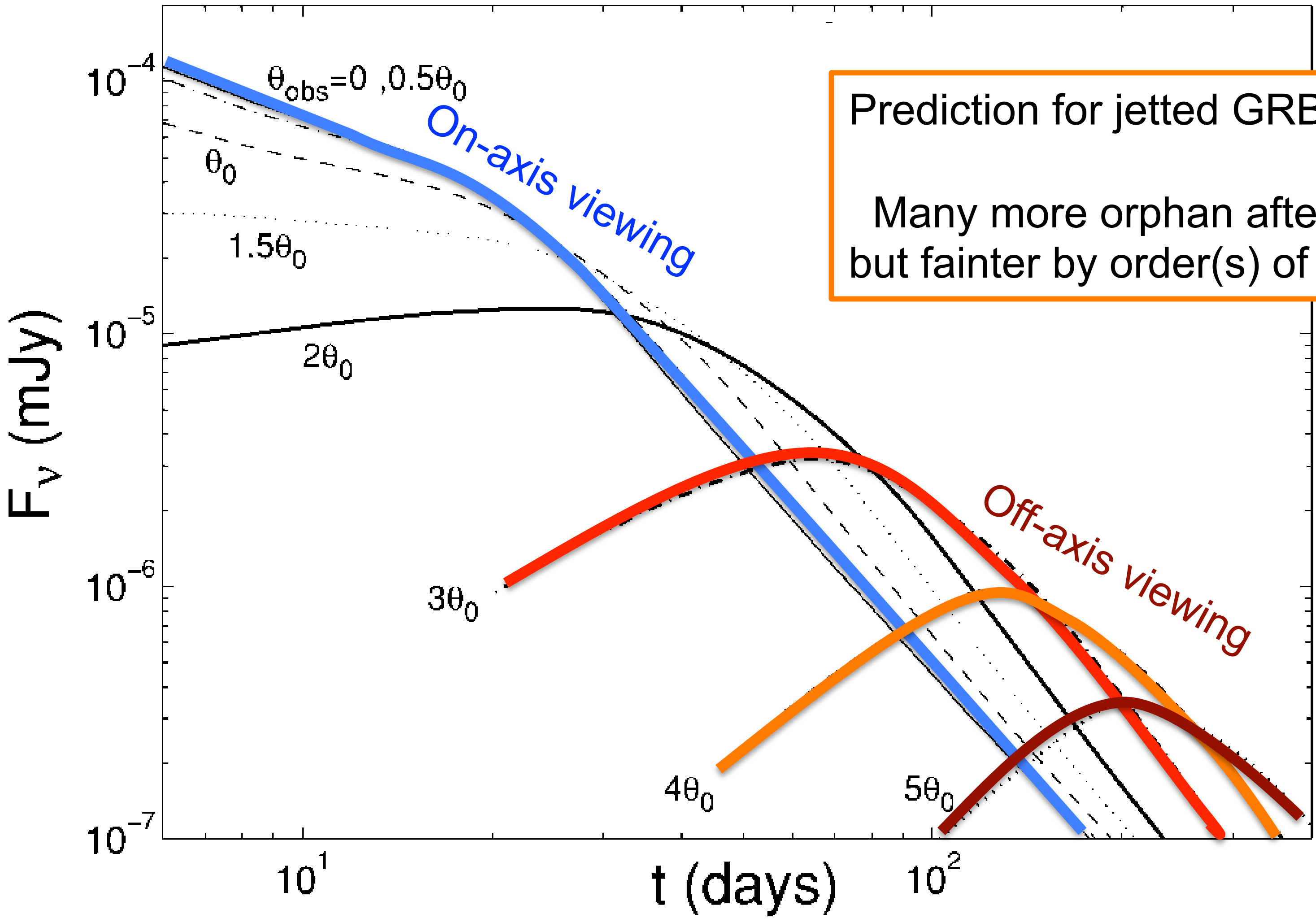




Beamed emission. A relativistic jet with a Lorentz factor γ and an opening angle θ moves forward until its Lorentz factor $\gamma = \theta^{-1}$. Then it expand sideways rapidly, resulting in a "jet break" in the light curve. A schematic light curve is depicted at the top right.

Orphan afterglow for off-axis GRBs

Granot et al. 2011



Prediction for jetted GRBs

Many more orphan afterglows, but fainter by order(s) of magnitude

Short GRB

- Occur in every type of galaxies
  - Traces star density
- Fermi LAT observation of GRB 090510:
  - high Lorentz factor – probably strong collimation
- Neutron star merger scenario favored, but not conclusive
  - Final word only given by GW detection
- If collimated (likely), there should be many off-axis events.
  - Orphan afterglow
  - GW events relatively close-by ➔ bright orphan afterglow

    ➔ follow up to GW trigger (large error box)
  - ➔ continuous monitor of large sky region for short transients

Is neutron star merger detactable as a short GRB?

- GW telescope localization ≈ 10 deg
  - Extremely difficult to find optical counterpart
    - Error circle too large for “normal” telescopes
    - however、$z<0.015$ → much closer than usual GRBs

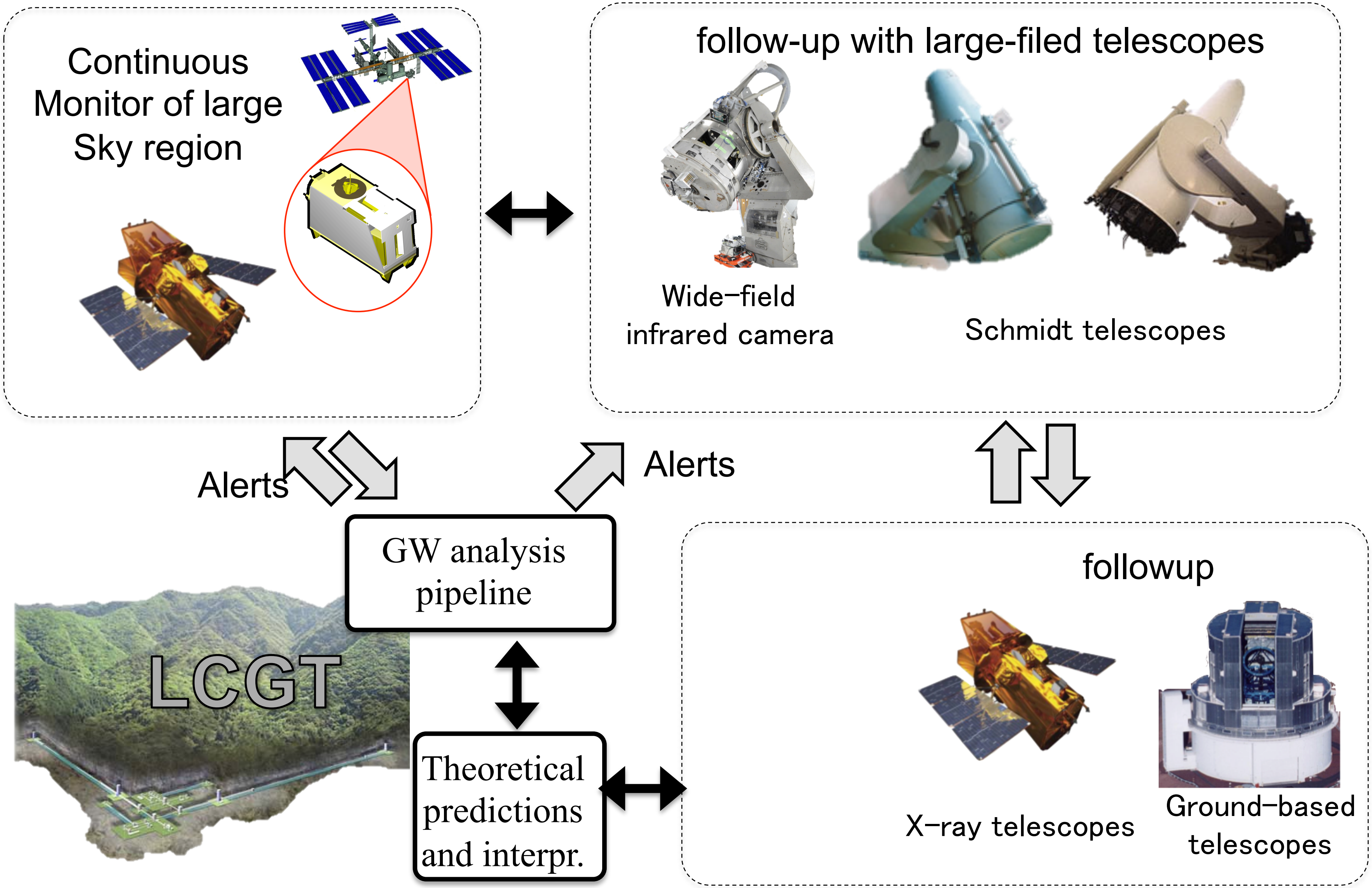
  ➔need different strategy for counterpart search

(1) Cover the large error circle (≥10 deg)

(2) Continuous monitor of large sky

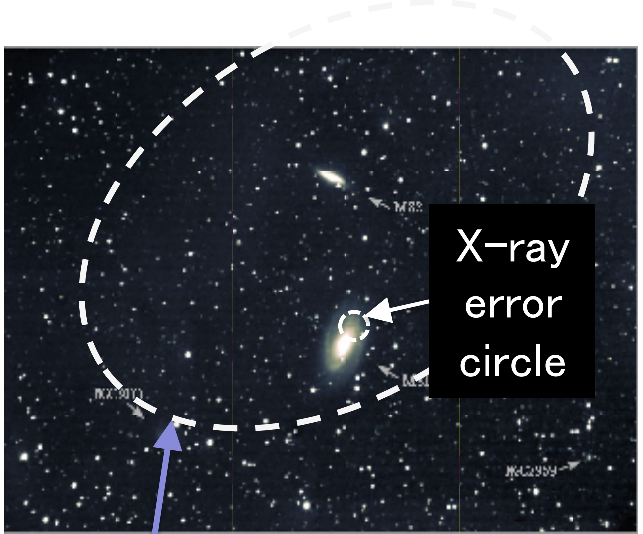
- Find temporary coincidence with GW event
- Search for orphan afterglow

Counterpart search strategy



Steps of localization and identification of GW events

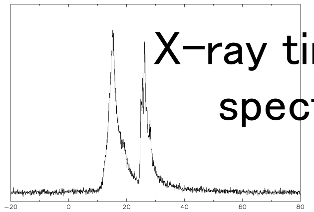
Smaller error circle by EM



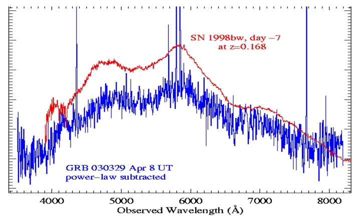
X−ray error circle

Error region for GW event

Detailed observation

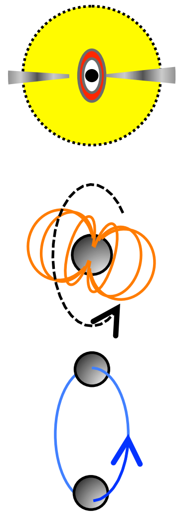


X−ray timing and spectroscopy



Optical llight curve and spectroscopy

Identification to astrophysical event



Star collapse

Pulsar glitch

NS merger

Akeno MITSuME 50 cm Telescope

50 cm autonomous robotic telescope at Akeno