Electromagnetic Facilities [UV, Optical, Radio]

S. R. Kulkarni

Caltech Optical Observatories

Thanks to

- Dale Frail (Radio)
- Yi Cao (Synoptic Optical)
- Mansi Kasliwal (Optical)
- Brad Cenko (Needle in the Haystack)
- Derek Fox (Brainstorming)

What might we see in the EM sky?

- Radioactive debris left behind by NS-NS coalescence
  - Optical
  - UV
- Relativistic jets launched by newly formed spinning black hole
  - Pre-coalescence coherent radio emission
  - Afterglow emission
  - Incoherent radio emission from Relic

Why pursue EM counterpart? (Positive reasons)

- Distance (independent of any GW modeling)
- Host Galaxy (needed to complete the progenitor story)
- Obtain the full story (including ejecta, nucleo-synthesis, possible relativistic outflow)

Why not pursue EM counterparts (Negative reasons)

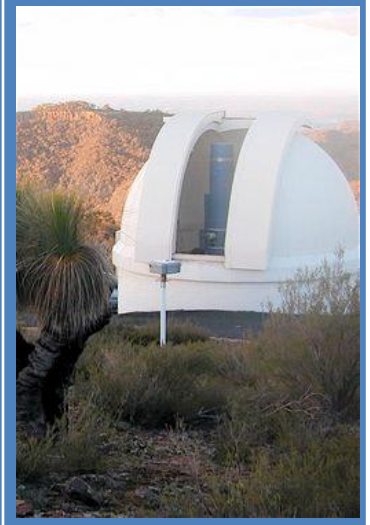
- To increase “confidence” of LIGO detection
- To dig deeper into the “noise”

Wide-field & Narrow-field

- Wide field searches: based on temporal coincidence
  - Gamma-ray bursts
  - Low Frequency Pre-event Pulse
- Narrow Field Searches: based on positional and distance coincidence
  - Radio (leisurely)
  - UV & Optical (same night or so)

WIDE FIELD OPTICAL FACILITIES

Catalina Real-Time Survey

Telescopes: **Each telescope currently uses a 4k X 4k CCD and avoid |b|<10 deg regions because of crowding**	**The Mt. Lemmon Survey 1.5m Cass** 	**Catalina Sky Survey 0.7m Schmidt** 	**Siding Springs Survey 0.5m Schmidt** 
Survey region (deg)	+/- 5 deg ecliptic	-25<Dec<70	-80<Dec<0
FoV (square deg)	1.2	8.1	4.2
V-band limiting mag	21.5	19.5	19.0

Palomar Transient Factory

- Telescope diameter: 1.2m
- FoV: 7.26 square degrees
- limiting mag: R=21, g=21.3
- Classification Telescope: 1.5 m
  - Imaging Photometer
  - Spectral Energy Distribution Machine
  - Rayleigh Scattering AO system

Pan-STARRS-1

- Telescope diameter: 1.8m
- FoV: 7 square degrees
- Limiting mag: g=21.9, r=21.8, i=21.5, z=20.7, y=19.7

La Silla Quest

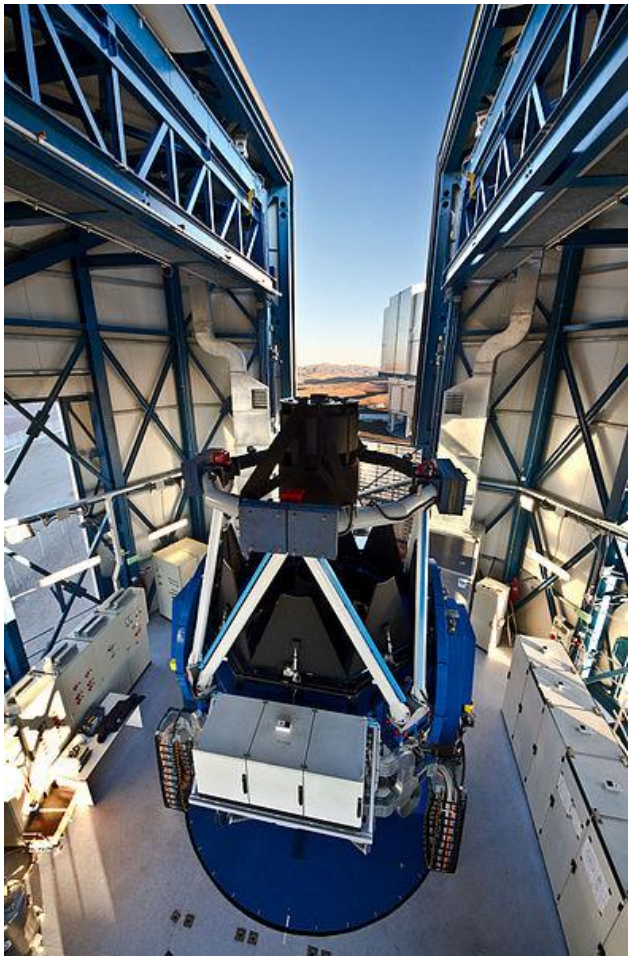
- 1-m ESO Schmidt (La Silla)
- QUEST camera (deployed earlier at Palomar)
- FOV is 9.6 sq degrees

SkyMapper

- Telescope diameter: 1.35m
- FoV: 5.7 square degrees
- Limiting magnitude: u=21.5, v=21.3, g=21.9, r=21.6, i=21.0, z=20.6

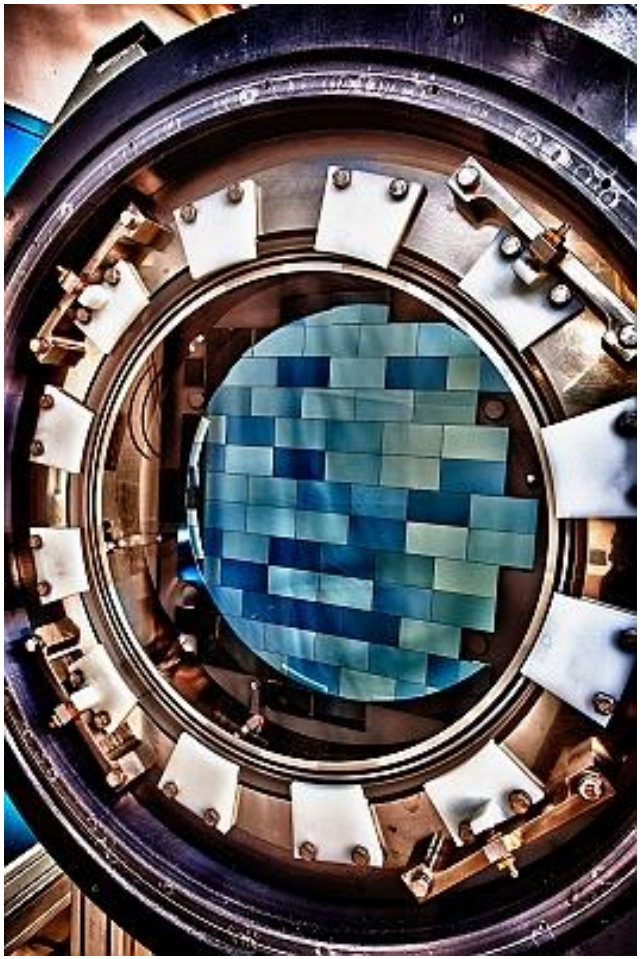
VLT Survey Telescope

- Telescope diameter: 2.65m
- FoV: 1 square degree
- Limiting magnitude: u=21.3, g=22.6, r=22.3, i=21.2, z=20.3



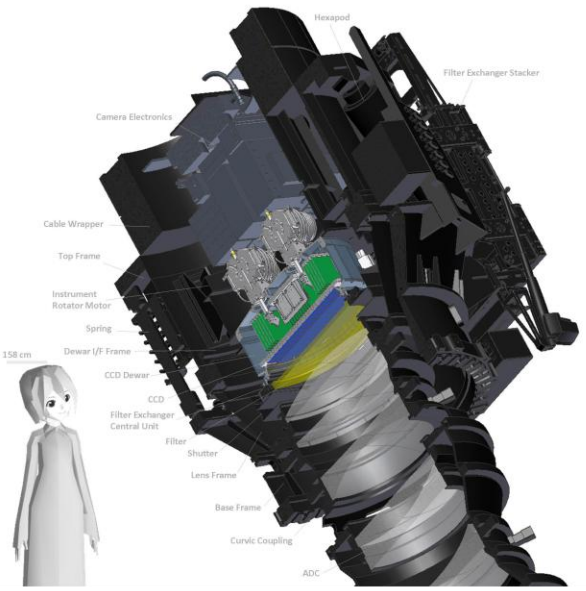
CTIO Blanco: The Dark Energy Survey

- Telescope diameter: 4m
- FoV: 3.4 square degrees
- Limiting magnitude: ~24 mag in SDSS ugriz filters



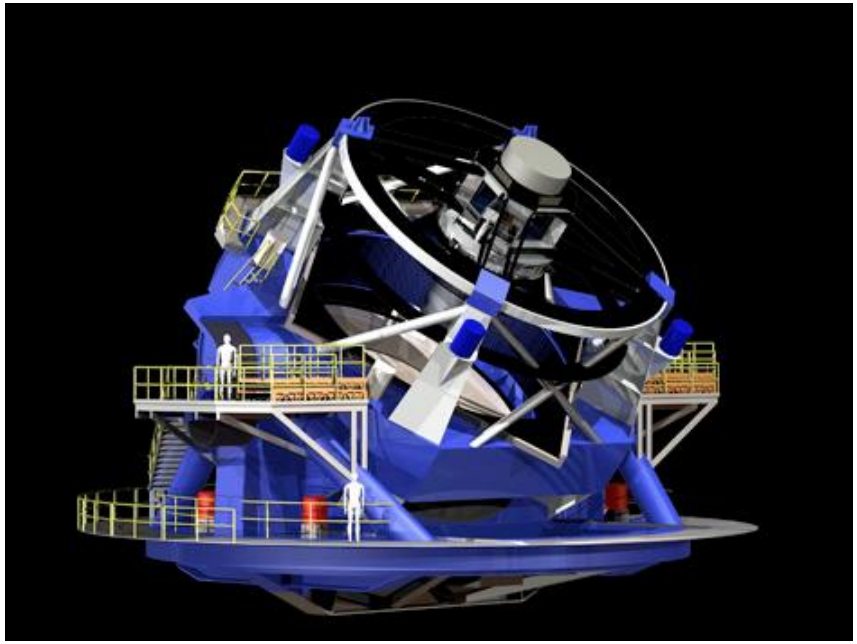
Subaru: Hyper Suprime-Cam

- Telescope diameter: 8.2m
- FoV: 1.8 square degrees
- Limiting magnitude: g~26, r~25.9, i~25.2, z~24.3, y~23.4



Large Synoptic Survey Telescope

- Telescope diameter: 8.4m
- FoV: 9.6 square degree
- Limiting magnitude: r~24.3



RADIO FACILITIES

Radio facilities for GW-EM Counterpart Searches: 2012 and Beyond

Facilities for GW-EM Counterpart Searches

Radio Facility	Observing Freq.	Field of View	1 hr rms	Beam	Start Date
ASKAP	1.4 GHz	30 deg^2	30 uJy	20”	2014?
Apertif	1.4 GHz	8 deg^2	50 uJy	15”	2013
MeerKAT	1.4 GHz	1.5 deg^2	35 uJy	15”	2013
EVLA	1.4 GHz	0.25 deg^2	7 uJy	1.3-45”	2010
EVLA	327 MHz	5 deg^2	2 mJy	5-18”	2013
LOFAR	110-240 MHz	50 deg^2	1 mJy	5”	2012
EVLA	74 MHz	100 deg^2	50 mJy	25-80”	2013
MWA	80-300 MHz	1000 deg^2	8 mJy	300”	2012+
LOFAR	15-80 MHz	500 deg^2	8 mJy	120”	2012

(Only Apertif, EVLA, LOFAR have demonstrated noise performance)

Comparison of Survey Speeds at 20-cm

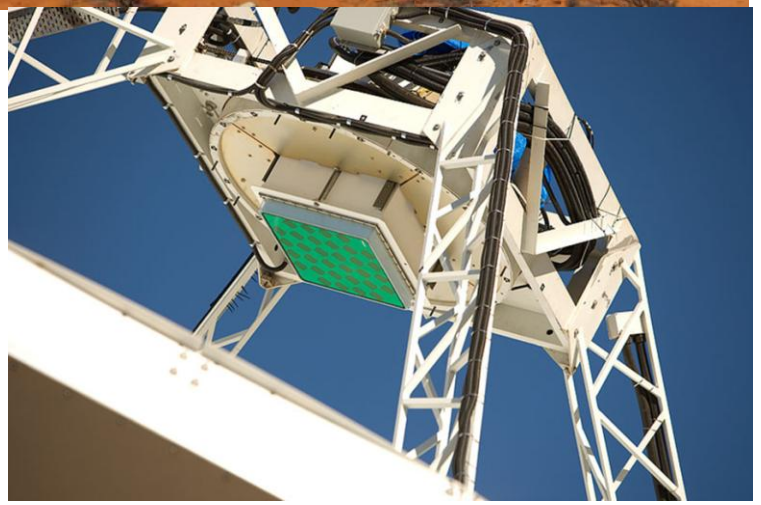
Telescope	BW (MHz)	FoV (deg^2)	D (m)	N	ε_e	T_{sys}	Survey Speed
EVLA	1024	0.25	25	27	0.5	26	1.00
MeerKAT	512	1.0	13.5	64	0.7	30	1.4
WSRT/Apertif	300	8.0	25	12	0.75	50	1.1
ASKAP	300	30	12	36	0.8	60	1.6

$$\mathrm{FoM} = \mathrm{BW}\,\Omega_{\mathrm{FOV}}(A_e / T_{sys})^2$$

The real difference is time commitment not capability.

Radio facilities for GW-EM Counterpart Searches: ASKAP

- Australian-lead effort
- 36 12-m antennas
- Operates at 1.4 GHz
- Phased-array feed technology to give 30 deg^2 FoV
- 1-hrs, rms~30 uJy (claimed)
- MkI PAF are too noisy
  - Tsys=150 K at 1.2 GHz
- MkII PAF are more expensive
  - Tsys=60 K over full band
- Need $15M to outfit the full array with MkII PAF. 2014?

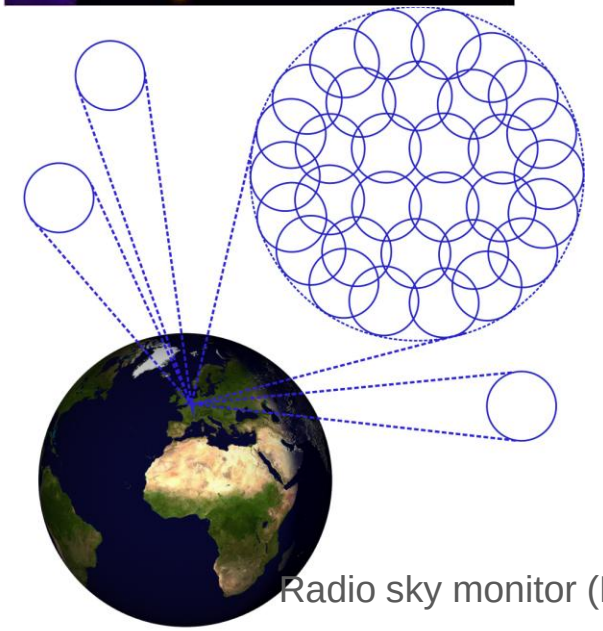


Radio facilities for GW-EM Counterpart Searches: Apertif

- Dutch effort
- Upgrade of WSRT using FPAs
- 14 25-m antennas
- Demonstrated peformance
- Operates at 1.4 GHz
- 8 deg^2 FoV
- 1-hrs, rms~50 uJy
- 75% of the time will be given to Key Science Projects (25% open)
- Install FPAs on 12 telescopes starting in mid-2013
- Delayed. Compete in 2014?

Radio facilities for GW-EM Counterpart Searches: LOFAR

- Dutch-lead European project
- 32 Dutch stations, 8 Euro stations
- 15-80 MHz & 110-240 MHz
- Key Science Projects
  - Continuum sky survey
  - Slow and fast transient searches
- Pulsar and single pulse capabilities already tested
- RSM will monitor 25% of sky
- Million source survey underway
- Real-time pipeline + alert system and external triggers all planned



Radio sky monitor (RSM)

Radio facilities for GW-EM Counterpart Searches: MeerKAT

- South African-lead effort
- 80 12-m antennas
- Operates 0.9-1.75 GHz. Expansion plans 8-14.5 GHz and 0.58-2.56 GHz
- Focal-plane array technology to give 1.5 deg^2 FoV
- 1-hrs, rms~35 uJy (claimed)
- 75% of the time given to Key Science Projects (25% open)
  - Continuum sky survey
  - Slow and fast transient searches
- 2013 delivery of 1.4 GHz

Radio facilities for GW-EM Counterpart Searches: EVLA

- The 500-lb gorilla of radio astronomy
- 27 25-m antennas
- Upgrade project almost finished. Will deliver order of magnitude increase in continuum sensitivity
- 1-50 GHz + 74 and 327 MHz
- 1-hrs, rms~7 uJy at 1.4 GHz
- Responds to external triggers
- Sub-arrays and OTF mosaicing can be used to image a large (irregular) error box

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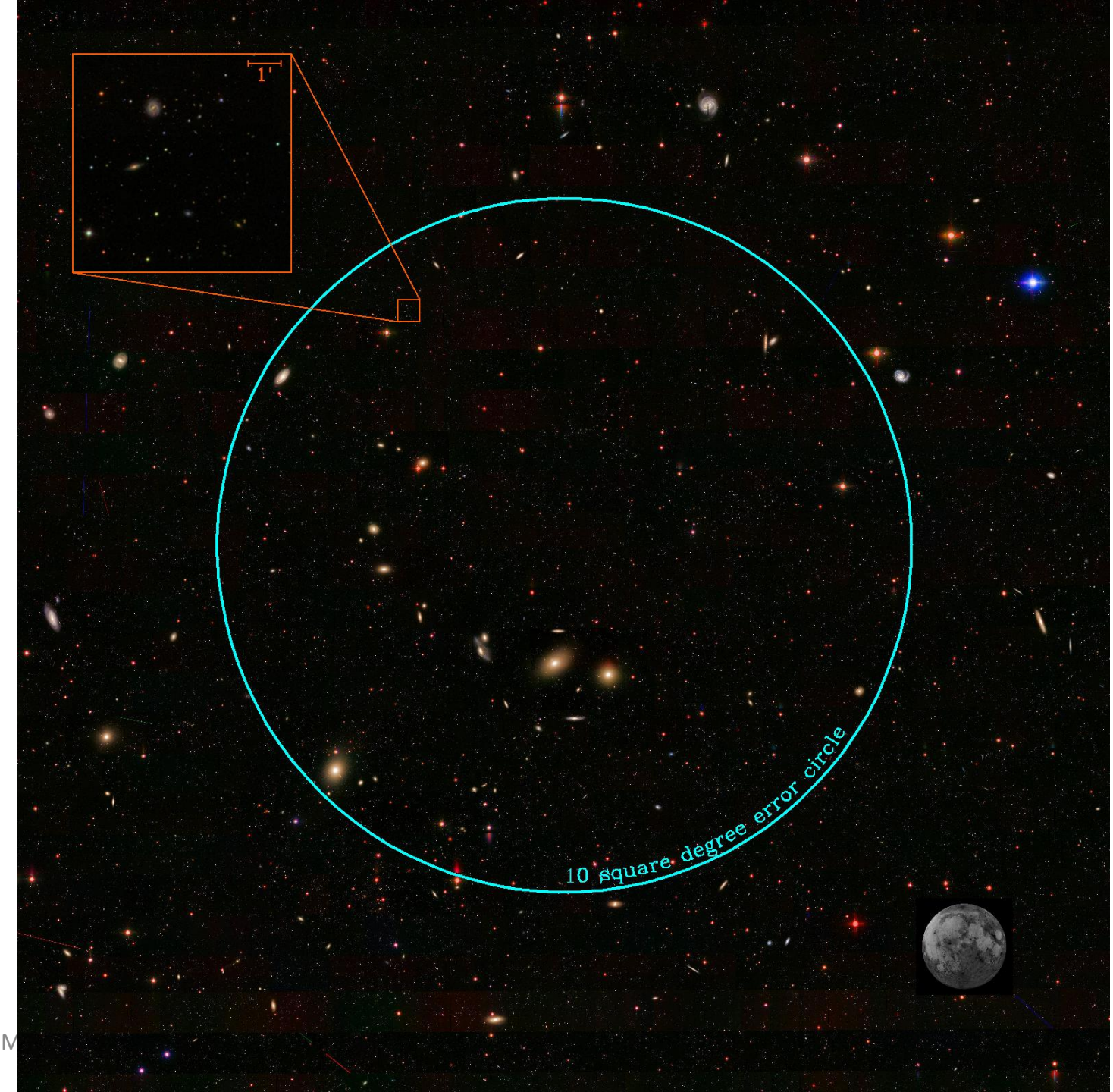
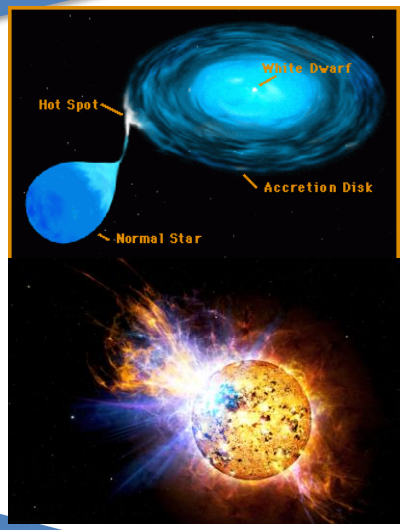
The Real Challenge


1'
10 square degree error circle

False Positives Abound: The Sky is Dynamic

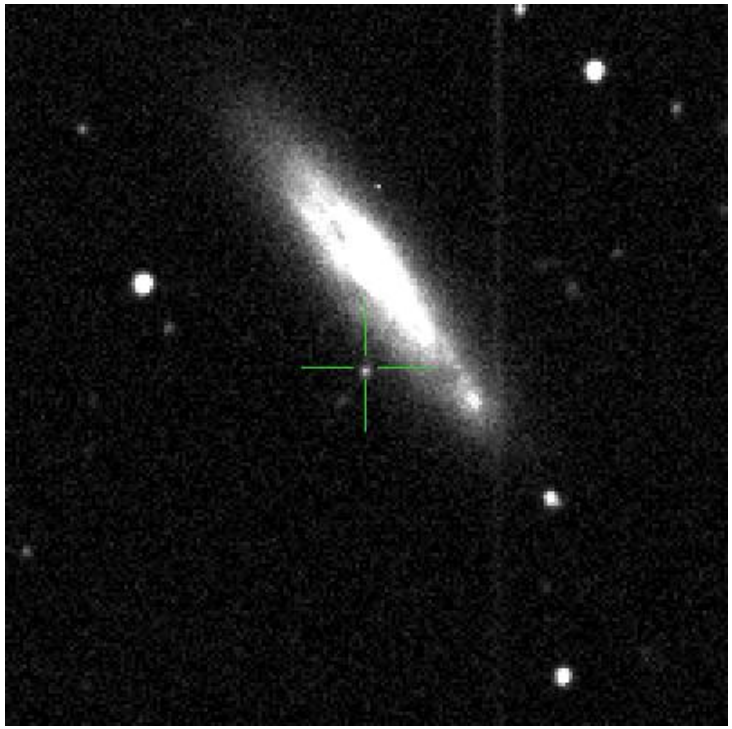
Solar System

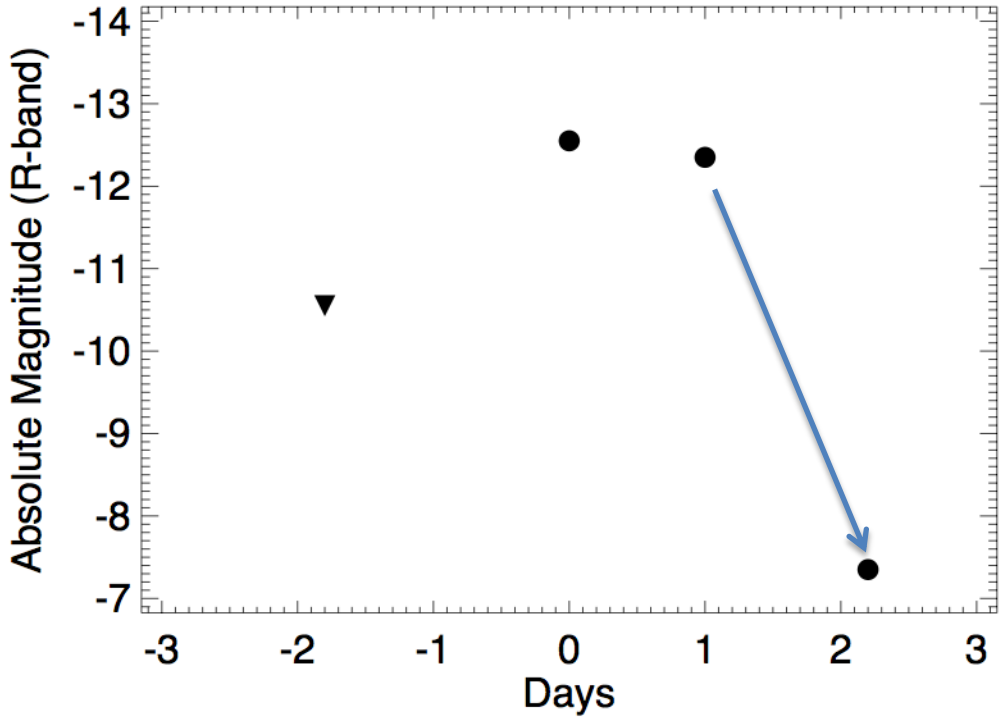


Milky Way

Far-off Galaxies

PTF discovers a kilonova!

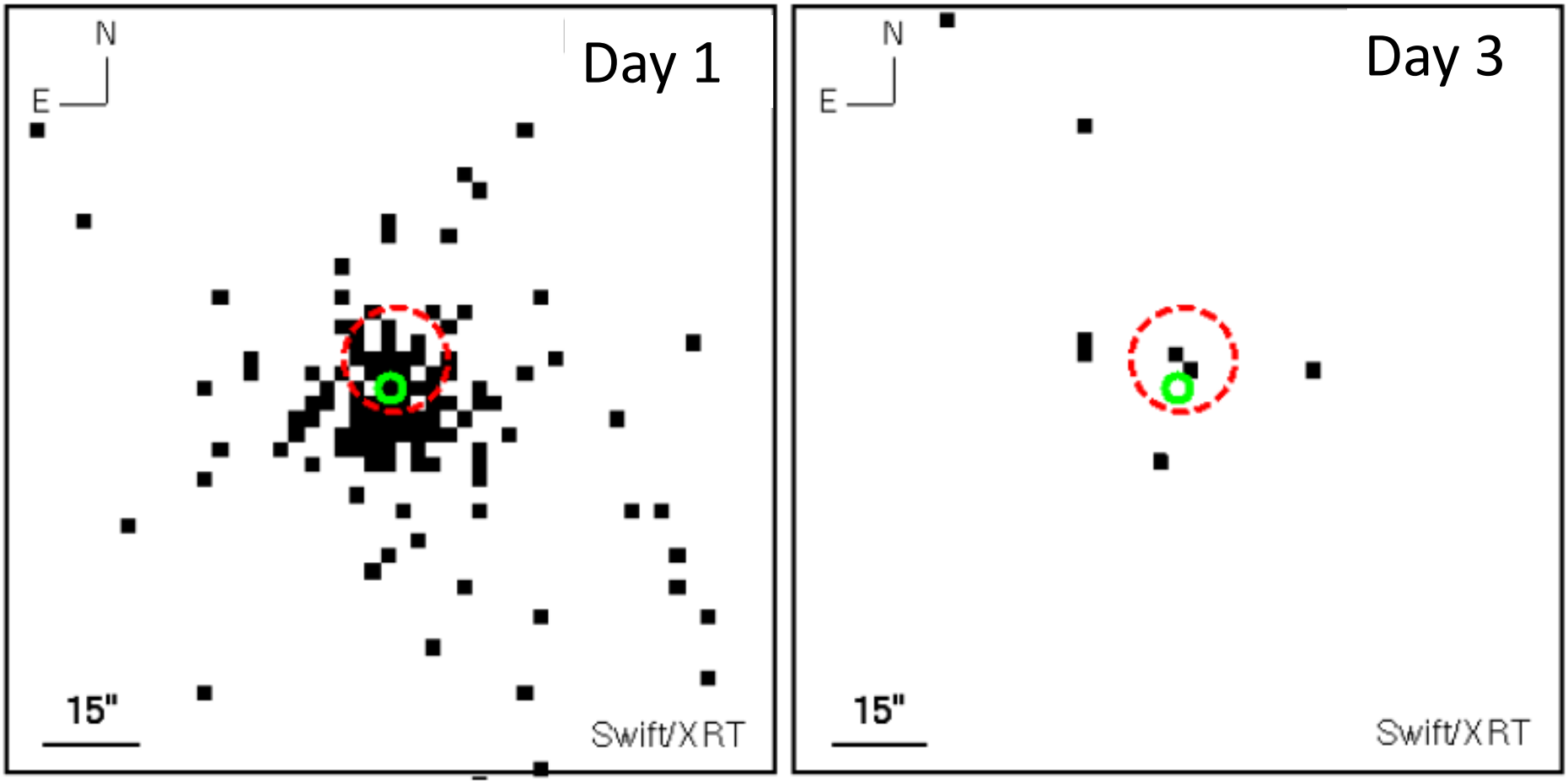




Kulkarni et al. (unpub)

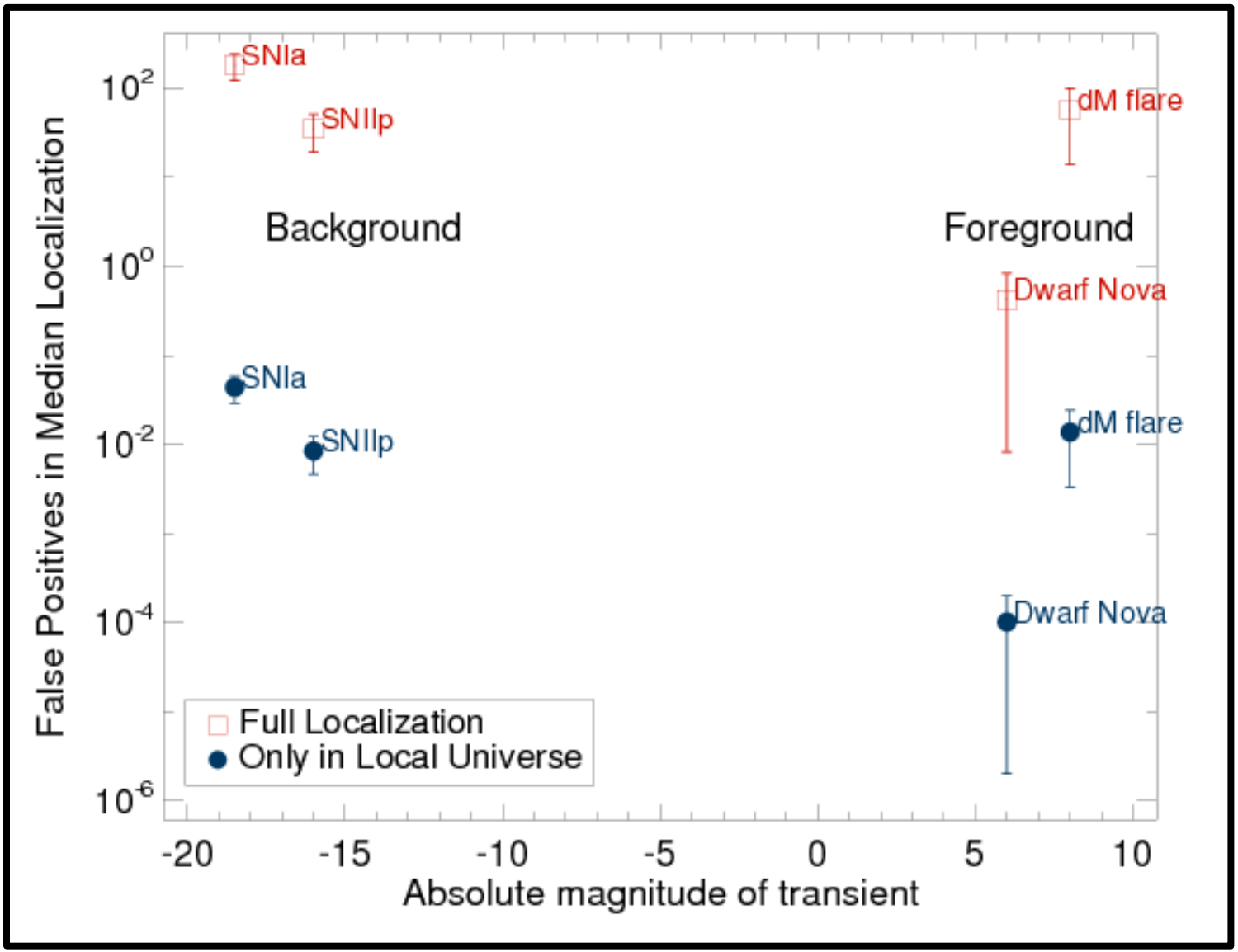
- Super-fast Decliner -- Factor of 100 in 1 day.
- Host Galaxy at 16 Mpc

Follow-up:
Keck Spectroscopy & Swift/Xray-



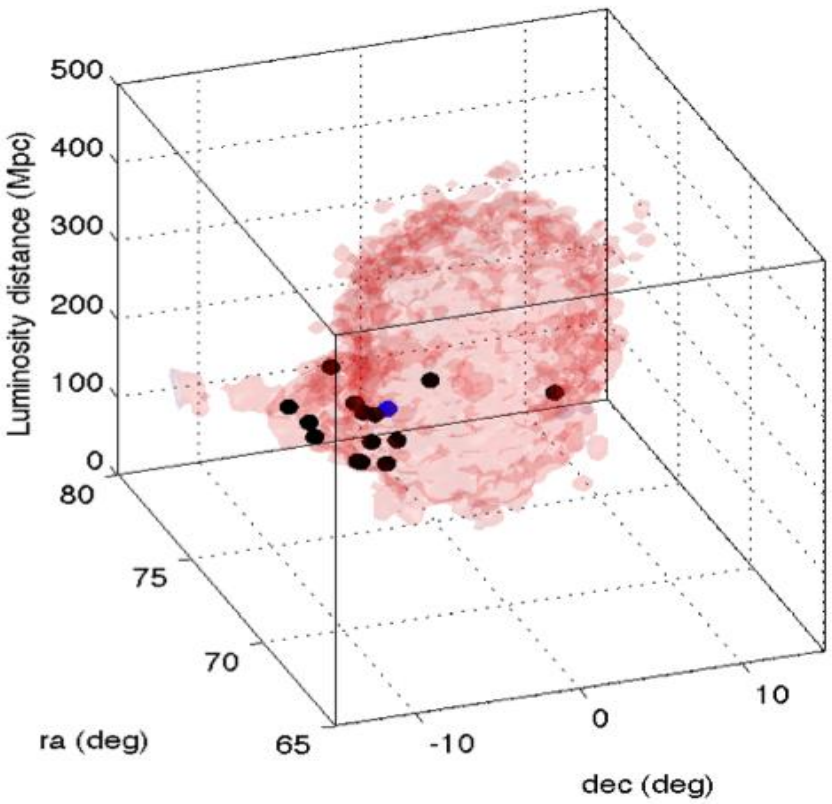
Kulkarni et al. (unpub)

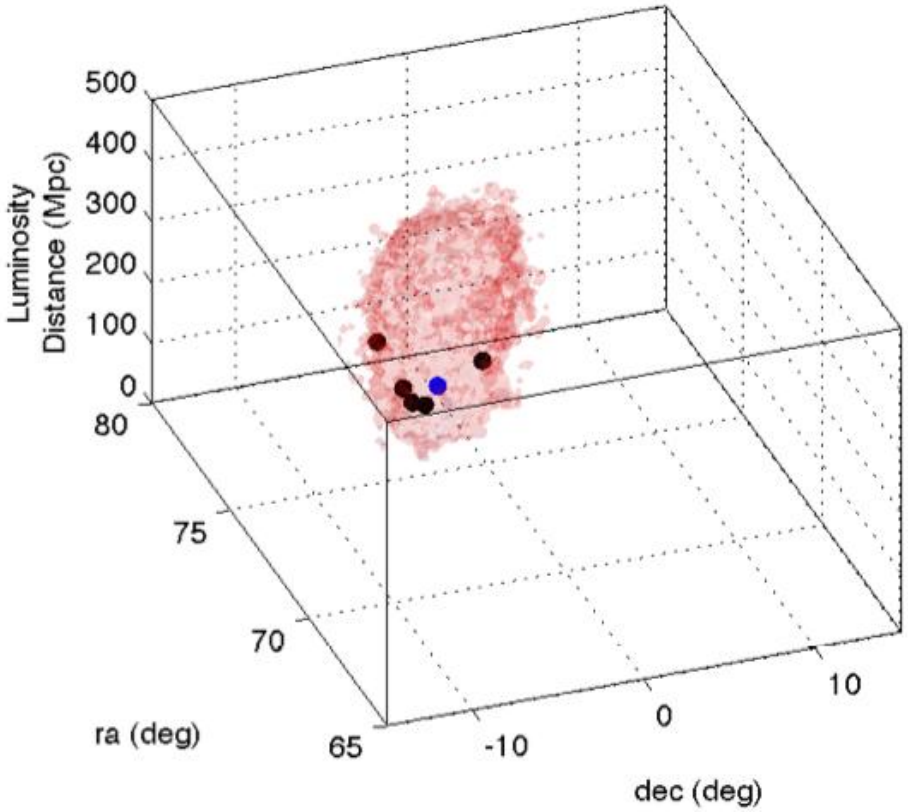
For Nearby Events: Galaxy Catalog Helps (“LUMIN”)



Kulkarni & Kasliwal 2009

Localization Volumes



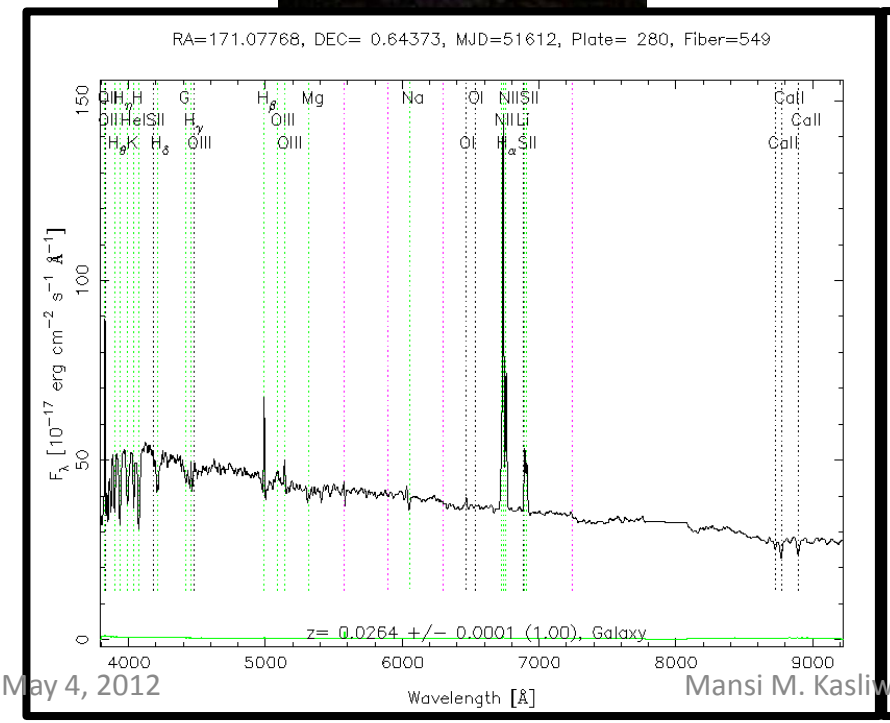


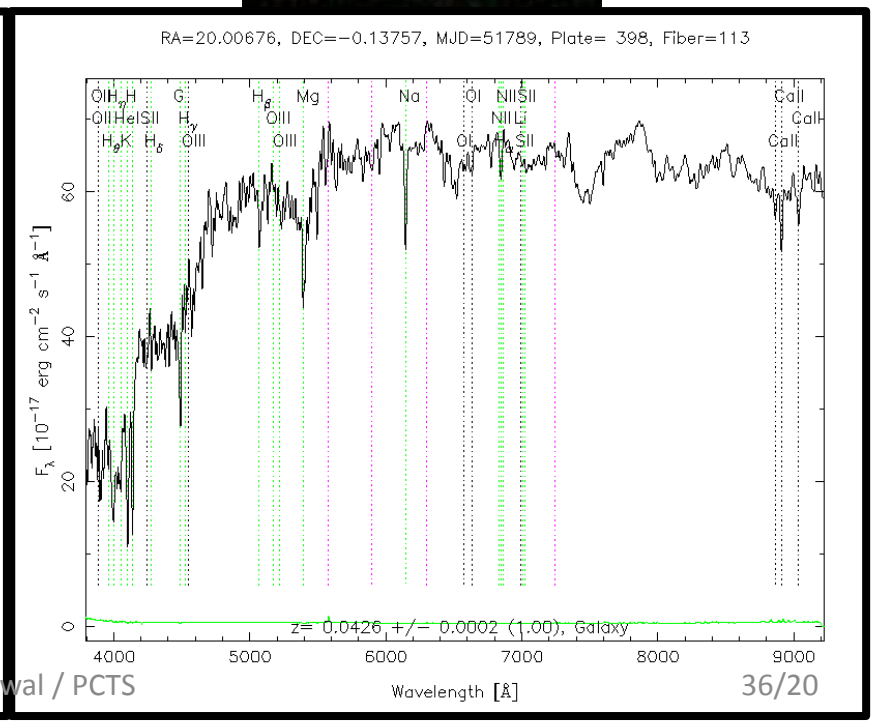
LIGO + VIRGO, 50 sq deg
233 galaxies → 14 galaxies

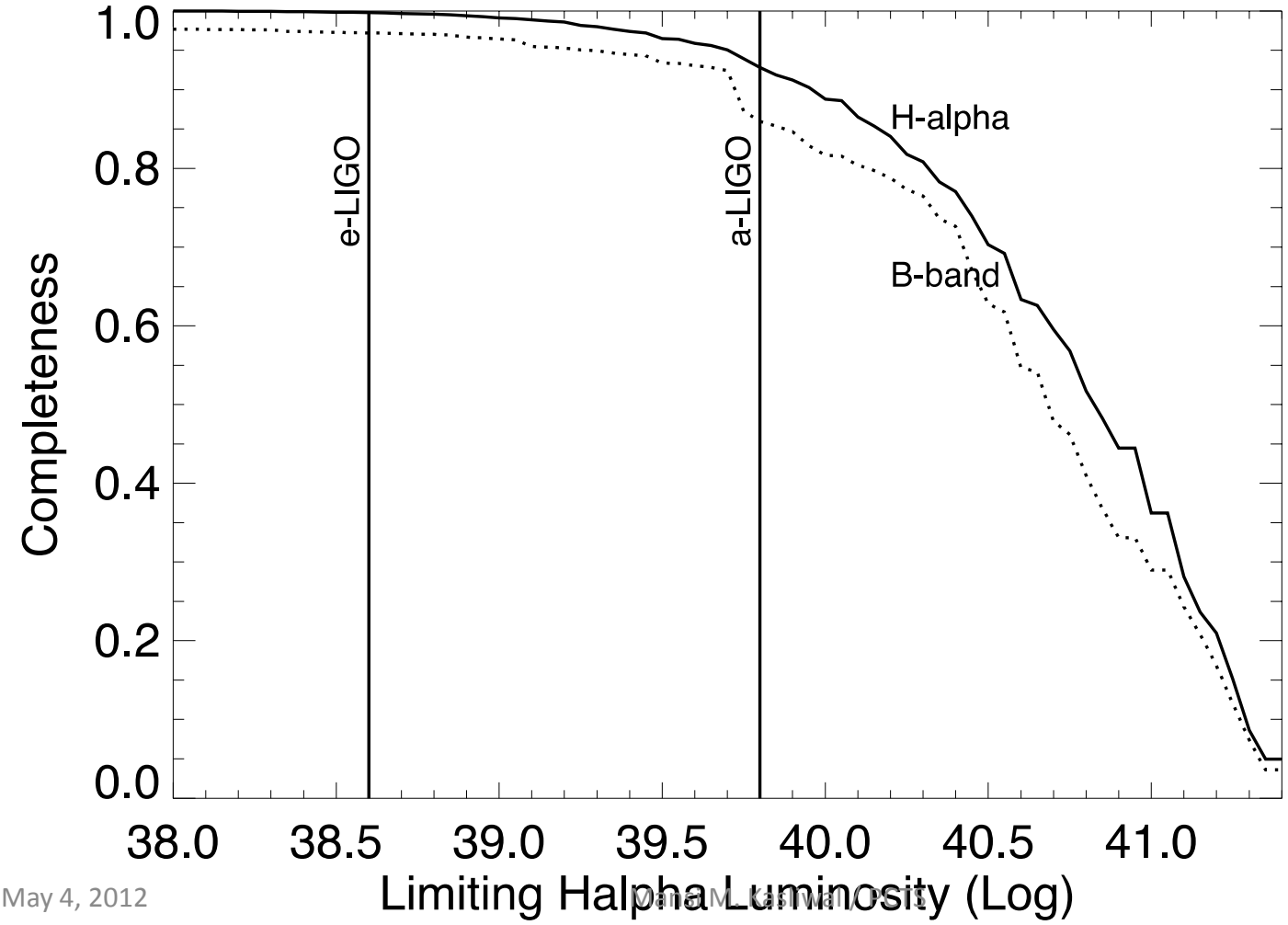
LIGO + VIRGO + KAGRA + INDIA

112 galaxies → 6 galaxies

Refresher: Galaxy Spectra







At 200 Mpc, 85% complete with a 2-min all-sky exposure

NEAR TERM

LIM

Less Is More

Transient Explorer

הצגת הפרויקט
לראש סוכנות החלל הישראלית
ולמנכ"ל משרד המדע

יום רביעי, 7 למרץ, 2012


ampelos
pinot noir
ampelos vineyards
sta.rita hills


942
Espresso
Art

The Team

Scientific

- **Weizmann Institute of Science**
  O. Aharonson, A. Breskin, A. Gal-Yam, E. Ofek, I. Sagiv, J. Topaz, E. Waxman
- **Caltech**
  S. R. Kulkarni, F. A. Harrison, E. S. Phinney
- **NASA Ames Research Center** S.
  P. Worden
- **Tel Aviv University**
  D. Maoz
- **Indian Institute of Astrophysics**
  J. Murthy
- **University of McGill**
  V. Kaspi
- **U. Toronto**
  M. H. van Kerkwijk
- **Raman Research Institute**
  B. Paul
- **Inter-Univ. Center for A&A**
  D. Bhattacharya

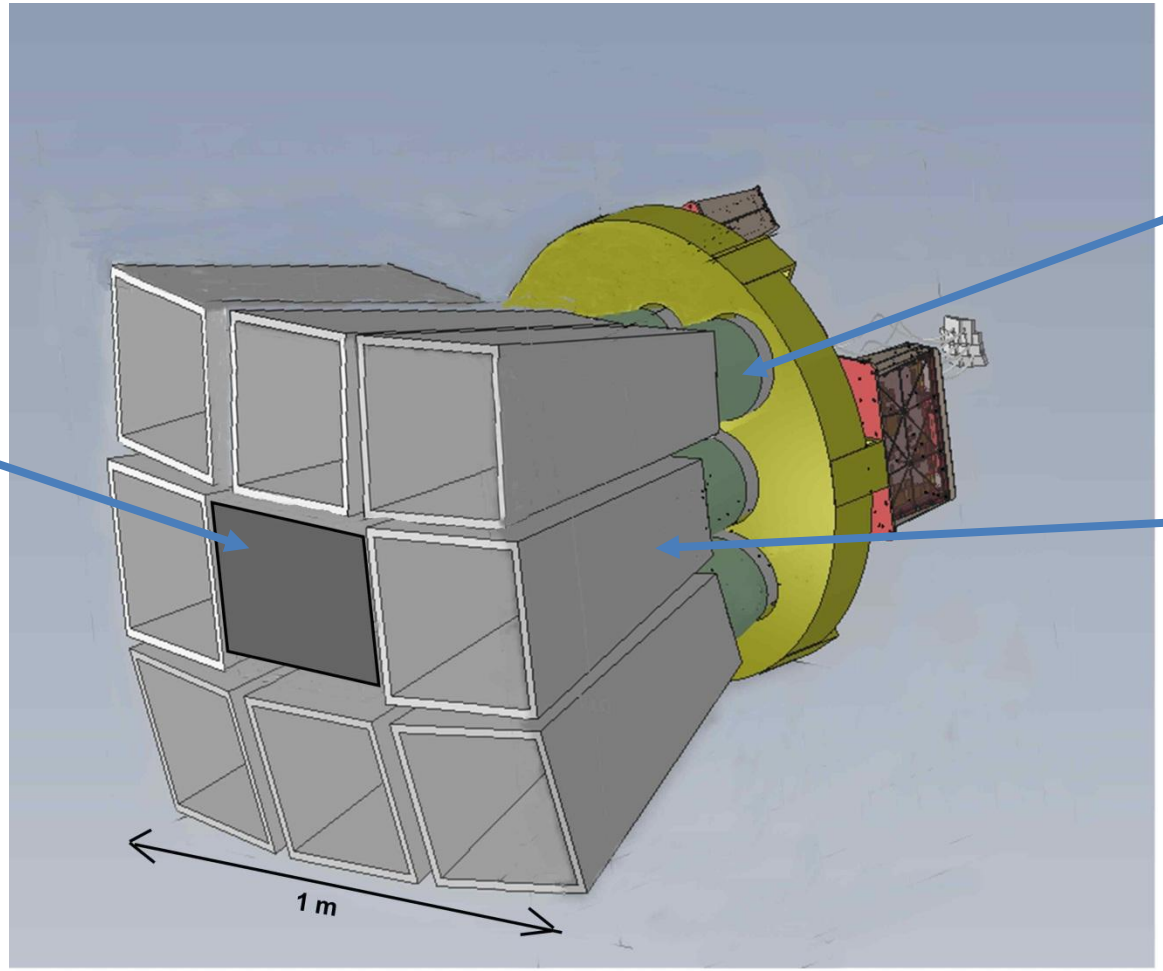
Gov.

- **ISA**
  (Z. Kaplan) A. Kafri
- **IMOD DDR&D Space Program**
  O. Lapid, N. Ganot, A. Perry, U. Segalis
- **NASA Ames Research Center**
  J. Belgacem, M. Bicay, Cohen, J. L. Dotson, S. P. Worden

Industry

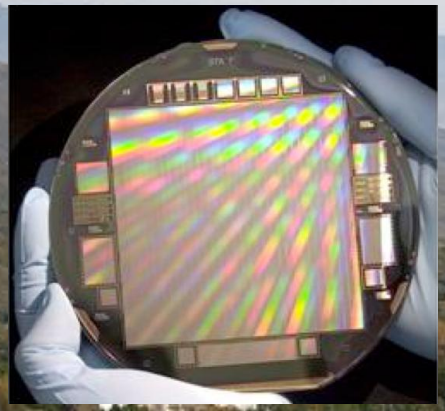
- **IAI**
  Y. Yaniv
- **Elbit Systems electro optics (El-Op)**
  O. Braun, A. Nir, I. Porat, T. Sprecher

Preliminary Mechanical Layout



Elbit Systems
Electro-optics - Elop

2015



P48
Discovery:
35 sq deg!

P200:
Spectroscopy

P60:
Follow-Up
The SED
Machine

The Zwicky Transient Facility

LETS GET REAL

TITLE: GCN CIRCULAR 13487
SUBJECT: IPN Triangulation of unusual GRB 120716A
DATE: 12/07/17 20:16:23 GMT
FROM: Dmitry Svinkin at Ioffe Institute <svinkin@mail.ioffe.ru>

The long-duration GRB 120716A has been observed by Fermi (GBM: trigger 364151106), Konus-Wind, INTEGRAL (SPI-ACS), Suzaku (WAM), and MESSENGER (GRNS), so far, at about 61504 s UT (17:05:04).

The burst light curve shows a short initial pulse followed in ~170 s
period of quiescence by two long pulses with a total duration of ~60 s.

RA(2000), deg	Dec(2000), deg
Center:	
313.089 (20h 52m 21s)	+9.558 (+9d 33' 28")
Corners:	
311.595 (20h 46m 23s)	+9.913 (+9d 54' 46")
313.791 (20h 55m 10s)	+10.049 (+10d 02' 56")
314.615 (20h 58m 28s)	+9.110 (+9d 06' 36")
312.407 (20h 49m 38s)	+9.046 (+9d 02' 45")

The error box area is 2.04 sq. deg, and its maximum dimension is 3.1 deg

TITLE: GCN CIRCULAR
NUMBER: 13488
SUBJECT: Konus-Wind observation of GRB 120716A
DATE: 12/07/18 10:21:17 GMT
FROM: Dmitry Frederiks at Ioffe Institute <fred@mail.ioffe.ru>

S. Golenetskii, R.Aptekar, D. Frederiks, E. Mazets, V. Pal'shin,
P. Oleynik, M. Ulanov, D. Svinkin, and T. Cline on behalf
of the Konus-Wind team, report:

The long-duration unusual GRB 120716A
(IPN detection and localization: Hurley at al., GCN 13487)
triggered Konus-Wind at T0=61507.357s UT (17:05:07.357)

The light curve started with a short (~0.9 s) pulse followed,
after ~170 s, by a double-peaked structure lasting for ~60 s.
The total duration of the burst is ~230 s.

This GRB is similar to GRB 041219A, GRB 050820A, and GRB 060124,
which display a rather short precursor, a ~200 s long period
of quiescence, and the main episode of emission. For this burst,
the precursor is relatively short and bright and the main part
is shorter and dimmer.

TITLE: GCN CIRCULAR 13489
SUBJECT: GRB 120716A: Candidate Optical Afterglow from PTF
DATE: 12/07/19 00:01:37 GMT
FROM: S. Bradley Cenko at Caltech <cenko@srl.caltech.edu>

S. B. Cenko (UC Berkeley), E. O. Ofek (Weizmann Institute of Science), and
P. E. Nugent (Lawrence Berkeley National Laboratory / UC Berkeley) report
on behalf of a larger collaboration:

We have imaged the location of the IPN GRB 120716A (Hurley et al., GCN 13487) with the Palomar 48 inch Oschin Schmidt telescope as part of the Palomar Transient Factory (PTF). Images were obtained in the r' filter beginning at 4:25 UT on 18 July 2012 (~ 1.5 d after the IPN trigger).

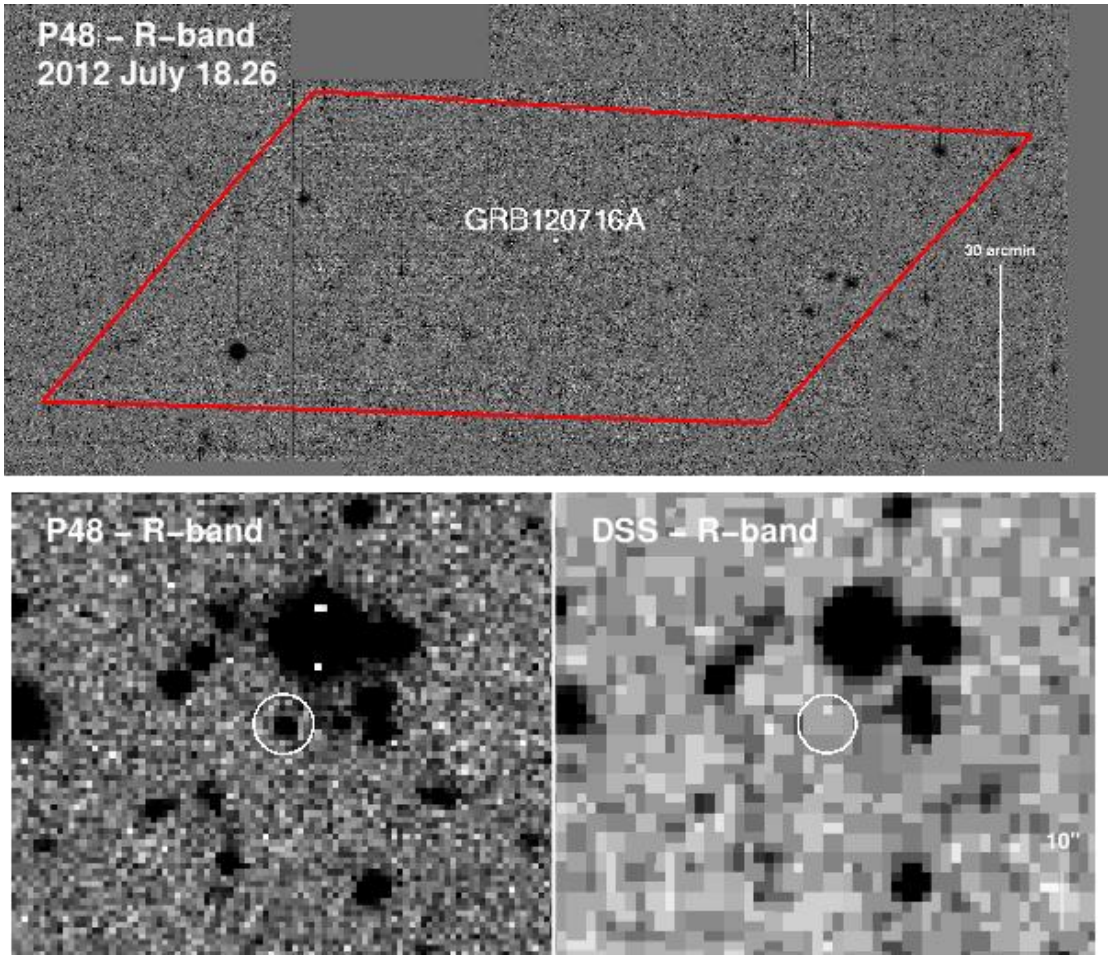
Within the IPN localization, we identify a new point source with coordinates:

RA: 20:52:12.10 Dec: +09:35:53.7 (J2000.0)

Using several nearby stars from the Sloan Digital Sky Survey for reference, we measure a magnitude of r' ~ 20.4 at this time.

Nothing is detected at this location in previous PTF imaging of this field, with images beginning in June 2011. Furthermore, no source is detected in archival SDSS imaging of this location (a faint nearby object in the SDSS database, SDSS J205212.01+093551.9, appears to be of very low significance). However, our most recent epoch of PTF imaging was obtained in March 2012, so we cannot currently rule out the chance alignment of an unassociated foreground or background transient.

GRB120716A



PTF

TITLE: GCN CIRCULAR 13490
SUBJECT: GRB 120716A: Optical decay from NOT
DATE: 12/07/19 05:52:35 GMT
FROM: Dong Xu at Weizmann Inst <dong.dark@gmail.com>

D. Xu (WIS), N. Groeneboom, K. Mikkelsen (U. Oslo) report on behalf of
a larger collaboration:

We observed the field of the candidate optical afterglow (Cenko et al., GCN 13489) of GRB 120716A (Hurley et al., GCN 13487), using the 2.5m Nordic Optical Telescope (NOT) equipped with ALFOSC. Observations started 04:03 UT on 2012-07-19 (i.e., 2.455 days after the IPN trigger) and 5x300s SDSS r'-band images were obtained in a seeing of ~0.7".

The optical source reported in GCN 13489 is well detected in each NOT image at coordinates

RA(J2000)=20:52:12.17
Dec(J2000)=+09:35:53.9

with an uncertainty of ~0.1 arcsec radius, being consistent with the PTF position.

The source had r(AB)=20.10+/-0.04, calibrated with nearby SDSS stars. The decay between the PTF and NOT epochs indicates that the source maybe the optical afterglow of GRB 120716A.

TITLE: GCN CIRCULAR 13492
SUBJECT: GRB 120716A: GROND confirmation of the optical/NIR afterglow
DATE: 12/07/19 06:26:31 GMT
FROM: Patricia Schady at MPE/Swift <pschady@mpe.mpg.de>

P. Schady (MPE Garching), M. Nardini (Universita degli studi di Milano-Bicocca) and J. Greiner (MPE Garching) report on behalf of the GROND team:

We observed the field of GRB 120716A (Hurley et al., GCN #13487) at the position of the afterglow candidate (Cenko et al., GCN #13489) simultaneously in g'r'i'z'JHK with GROND (Greiner et al. 2008, PASP 120, 405) mounted at the 2.2 m MPG/ESO telescope at La Silla Observatory (Chile).

Observations started at 05:07 UT on 2012-07-19, 2.5 days after the GRB trigger. They were performed at an average seeing of 1.4" and at an average airmass of 1.3.

We found a single point source at a position consistent the afterglow candidate reported in Cenko et al. (GCN #13489) and Xu et al. (GCN #13490). Based on the first 460s of total exposures in g'r'i'z' and 480 s in JHK, we estimate preliminary magnitudes (all in AB system) of

g' = 21.8 +- 0.1 mag, r' = 20.9 +- 0.1 mag, i' = 20.5 +- 0.1 mag, z' = 20.3 +- 0.1 mag, J = 19.9 +- 0.2 mag, H = 19.6 +- 0.2 mag and K = 18.8 +- 0.5 mag

The optical/NIR SED is well fit by a power-law with a spectral slope of ~1.3, typical for GRB afterglows, confirming this to be the afterglow of GRB120716A.

TITLE: GCN CIRCULAR
NUMBER: 13493
SUBJECT: VLT/FORS2 redshift of GRB120716A
DATE: 12/07/19 08:40:51 GMT
FROM: Arne Rau at MPE <arau@mpe.mpg.de>

Jochen Greiner, Arne Rau, Patricia Schady (all MPE), Ivo Saviane (ESO), and Brad Cenko (UC Berkeley) report on behalf of a larger collaboration.

We observed the afterglow candidate of GRB 120716A (Hurley et al., GCN 13454; Cenko et al. GCN 13489; Xu et al, GCN 13490; Schady et al. CGN 13492) with the ESO VLT equipped with the FORS2 spectrograph. Observations with the 600B grism, covering a spectral range of 350-610nm) started at ~06:54 UT on July 19th 2012 (~58.2 hr after the gamma-ray trigger) and lasted for ~ 1.5hr.

The spectrum shows a prominent, broad absorption trough centered at ~4250A, interpreted as Lyman-alpha, together with numerous metal lines (SiII, OI, SiIV, CIV) at longer wavelength. We find a common redshift of these features of z=2.48.

TITLE: GCN CIRCULAR
NUMBER: 13494
SUBJECT: GRB 120716A: Redshift confirmation from VLT/X-shooter
DATE: 12/07/19 16:56:53 GMT
FROM: Valerio D'Elia at ASDC <delia@asdc.asi.it>

V. D'Elia (ASDC/INAF-OAR), P. Goldoni (APC,CEA/Irfu),
D. Xu (WIS), T. Kruehler, J. P. U. Fynbo, D. Malesani (DARK/NBI), O.E.
Hartoog (UvA, Netherland), N. R. Tanvir (U. of Leicester)
report on behalf of the X-shooter GRB GTO collaboration:

We observed the GRB 120716A (Hurley et. al GCN 13487) optical counterpart
(Cenko et al. GCN 13489, Xu et al. GCN 13490, Schady et al. GCN 13492) with
X-shooter at the VLT (Paranal, Chile). Observations started on 19 July
at 8:40 UT
(2.6 days after the burst) and consisted of a total observing
time of 3600 s in each of the UVB, VIS and NIR arms, covering the range
between 3000 and 18000 A.

The spectrum shows a broad absorption trough at ~4250A which we interpret
as due to Lyman-alpha. At the same redshift z=2.486 we detect plenty of metal
absorption lines, such as (CII, SiII, OI, FeII, CIV, SiIV), fine
structure (CII*, SiII* FeII*) and metastable (NiII) lines.
We thus confirm the redshift reported by Greiner et al. (GCN 13493).

TITLE: GCN CIRCULAR
NUMBER: 13495
SUBJECT: GRB 120716A: Swift/XRT position consistent with that of the optical counterpart
DATE: 12/07/19 18:22:19 GMT
FROM: Dong Xu at Weizmann Inst <dong.dark@gmail.com>

D. Xu (WIS) reports on behalf of a larger collaboration:

The Swift satellite observed the field of the decaying optical transient (Cenko et al. GCN 13489; Xu et al. GCN 13490; Schady et al. GCN 13492), which is very likely the optical afterglow of GRB 120716A (Hurley et al., GCN 13487). Initial observation started at 12:47 UT and ended at 13:12 UT on 2012-07-19 (i.e., a median time of 2.83 d after the IPN trigger), and consisted of a total observing time of 1470s for Swift/XRT.

Preliminary XRT data reduction reveals a S/N~2 source at coordinates

RA(J2000) = 20:52:12.4
Dec(J2000) = +09:35:51.1

with an uncertainty of 7.7 arcsec radius, being consistent with the position of the optical source. Currently we don't know whether the X-ray source is decaying or not.

TITLE: GCN CIRCULAR
NUMBER: 13497
SUBJECT: GRB 120716A: EVLA Detection
DATE: 12/07/19 22:26:20 GMT
FROM: Ashley Zauderer at CfA <bevinashley@gmail.com>

A. Zauderer, T. Laskar, A. Soderberg and E. Berger (Harvard) report on behalf of a larger collaboration:

"We observed the position of GRB 120716A (Hurley et al.; GCN 13487) with the EVLA beginning 2012 July 19.26 (dt ~ 2.5 d). At a mean frequency of 6 and 22 GHz, we detect a radio source (10 and 6 sigma, respectively) consistent with optical candidates (e.g. Cenko et al.;

TITLE: GCN CIRCULAR 13498
SUBJECT: GRB 120716A: Fermi GBM observation
DATE: 12/07/20 11:21:05 GMT
FROM: David Gruber at MPE <dgruber@mpe.mpg.de>

David Gruber (MPE) and Adam Goldstein (UAH)
report on behalf of the Fermi GBM Team:

"At 17:05:03.91 UT on 16 July 2012, the Fermi Gamma-Ray Burst Monitor
triggered and located GRB 120716A (trigger 364151106 / 120716712).

This burst was localized by the IPN (Hurley et al., GCN 13487). The GBM on-ground calculated location is consistent with the IPN location. The angle from the Fermi LAT boresight is 63 degrees. This burst was also independently detected by INTEGRAL SPI-ACS.

The GBM light curve consists of a bright precursor, followed by a double-peaked main emission after ~ 160 s. The duration (T90) is about 234 s (50-300 keV). The time-averaged spectrum of the precursor is best fit by a power law function with an exponential high-energy cutoff. The power law index is -0.84 +/- 0.11 and the cutoff energy, parameterized as Epeak, is 173 +/- 18 keV. A Band function fits the spectrum equally well with Epeak= 115 +/- 19 keV, alpha = -0.48 +/- 0.22 and beta = -2.19 +/- 0.17. The time-averaged spectrum of the main emission is best fit by
a Band function with Epeak= 114 +/- 12 keV, alpha = -1.00 +/- 0.08 and beta= -2.08 +/- 0.07.

The event fluence (10-1000 keV) is (1.47 +/- 0.01)E-05 erg/cm^2. The 1-sec peak photon flux measured starting from T0-0.13 s in the 10-1000 keV band is 8.37 +/- 0.32 ph/s/cm^2.
Using the redshift of 2.48 (Greiner et al., GCN 13493; D'Elia et al., GCN 13494) and a standard cosmology model with H_0 = 71 km/s/Mpc, Omega_M = 0.27, Omega_Lambda = 0.73, this corresponds to an isotropic energy release of ~ 3E+53 erg.

A Lost Opportunity

Kapteyn's Selected Area (SA)