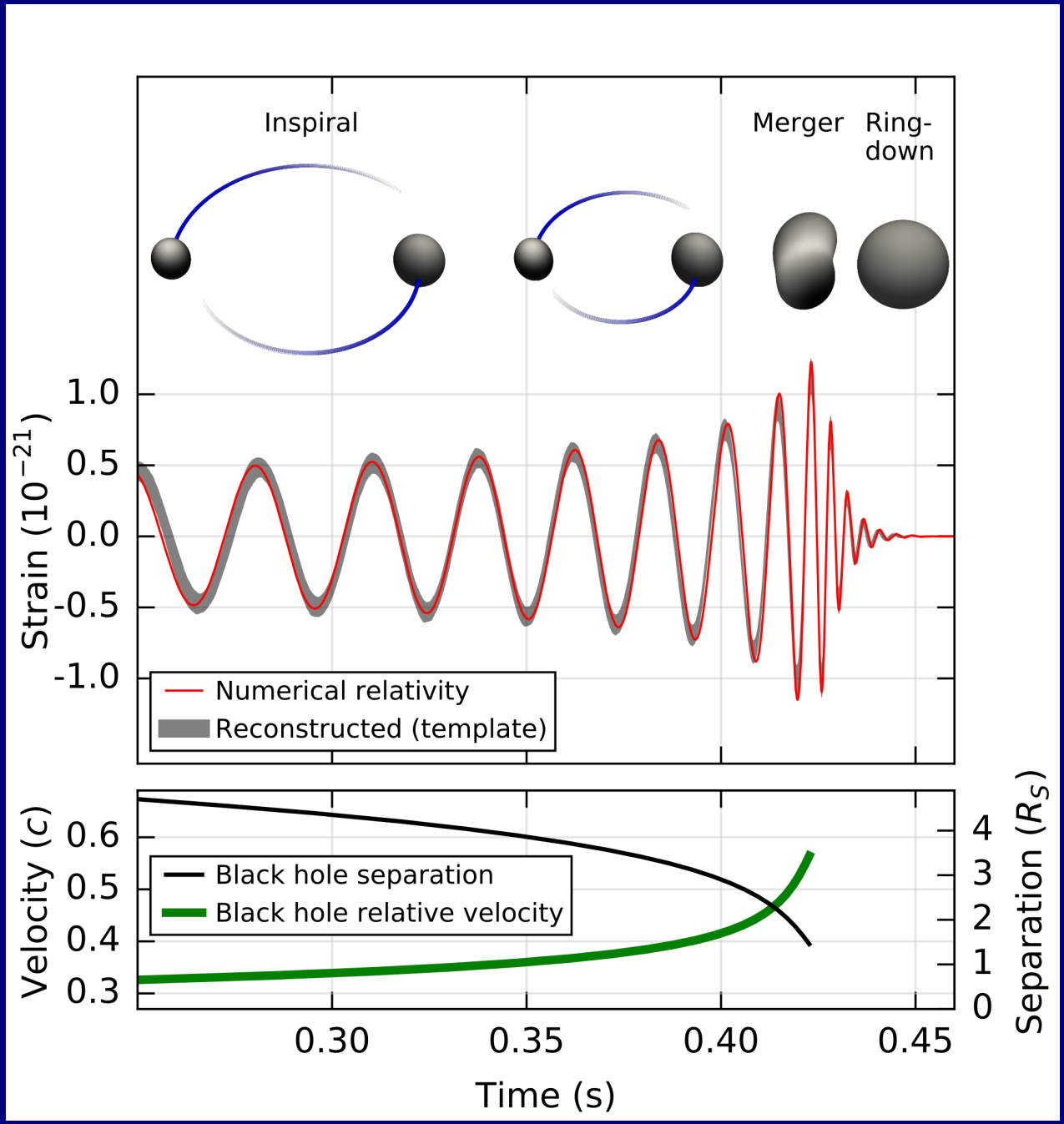
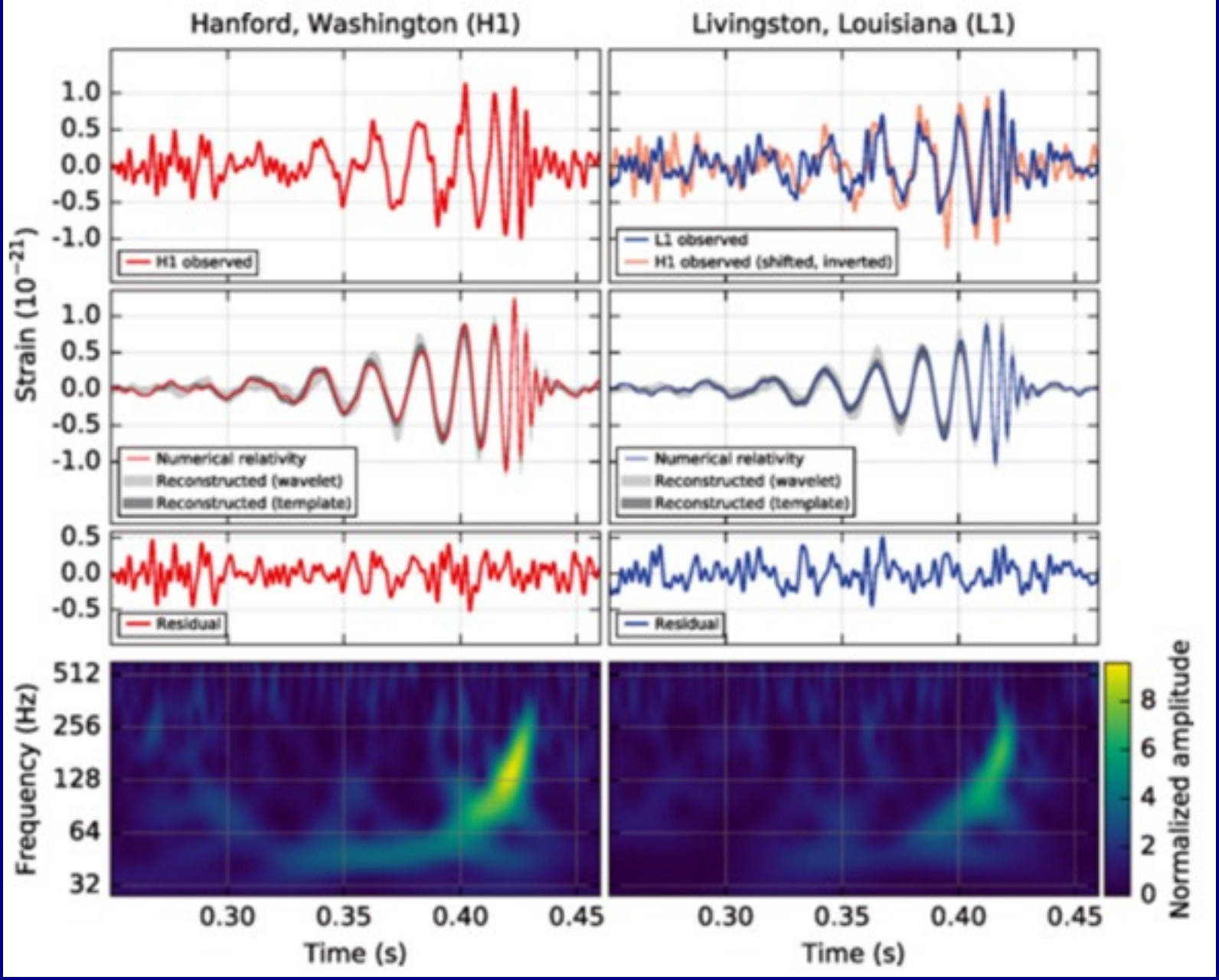
Gravitational Waves

LIGO (Laser Interferometric Gravity-Wave Observatory)

Gravitational Waves

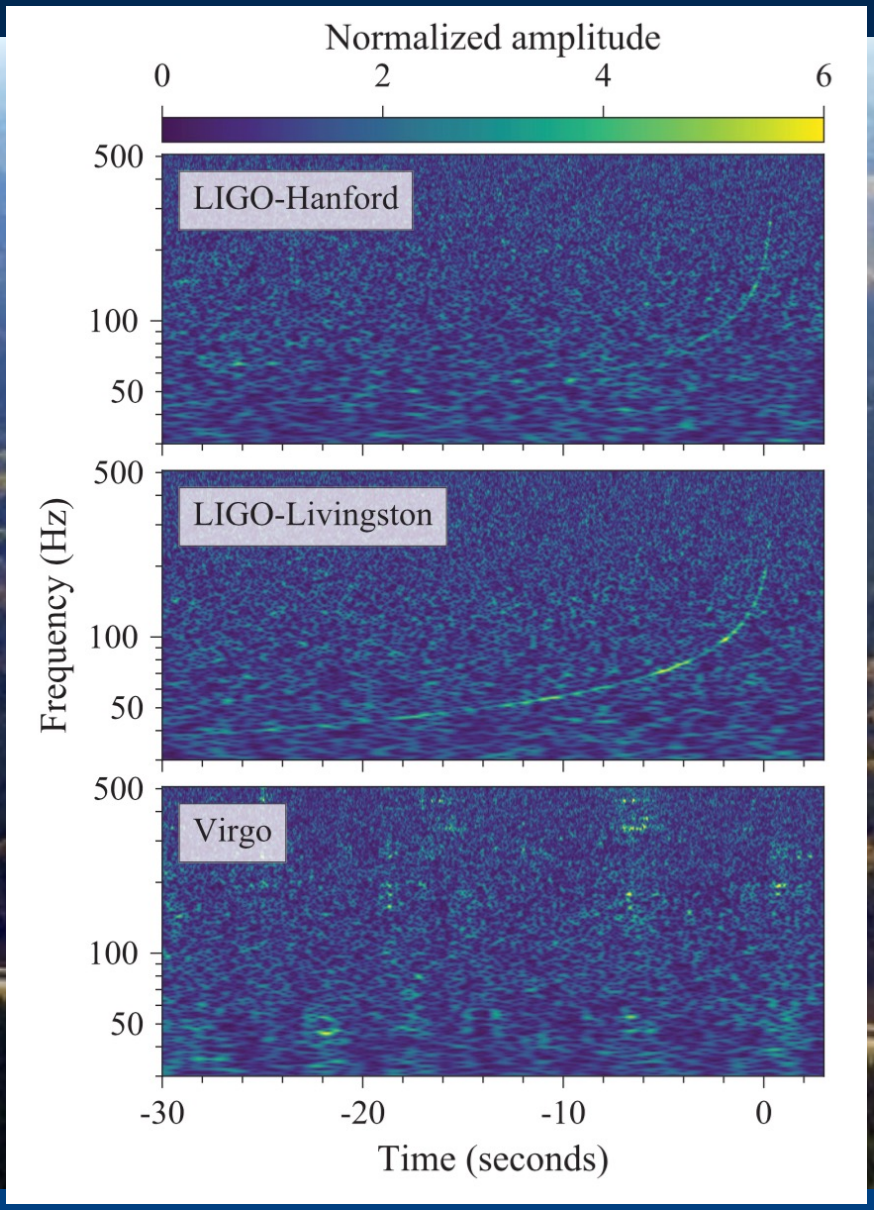


Gravitational Waves

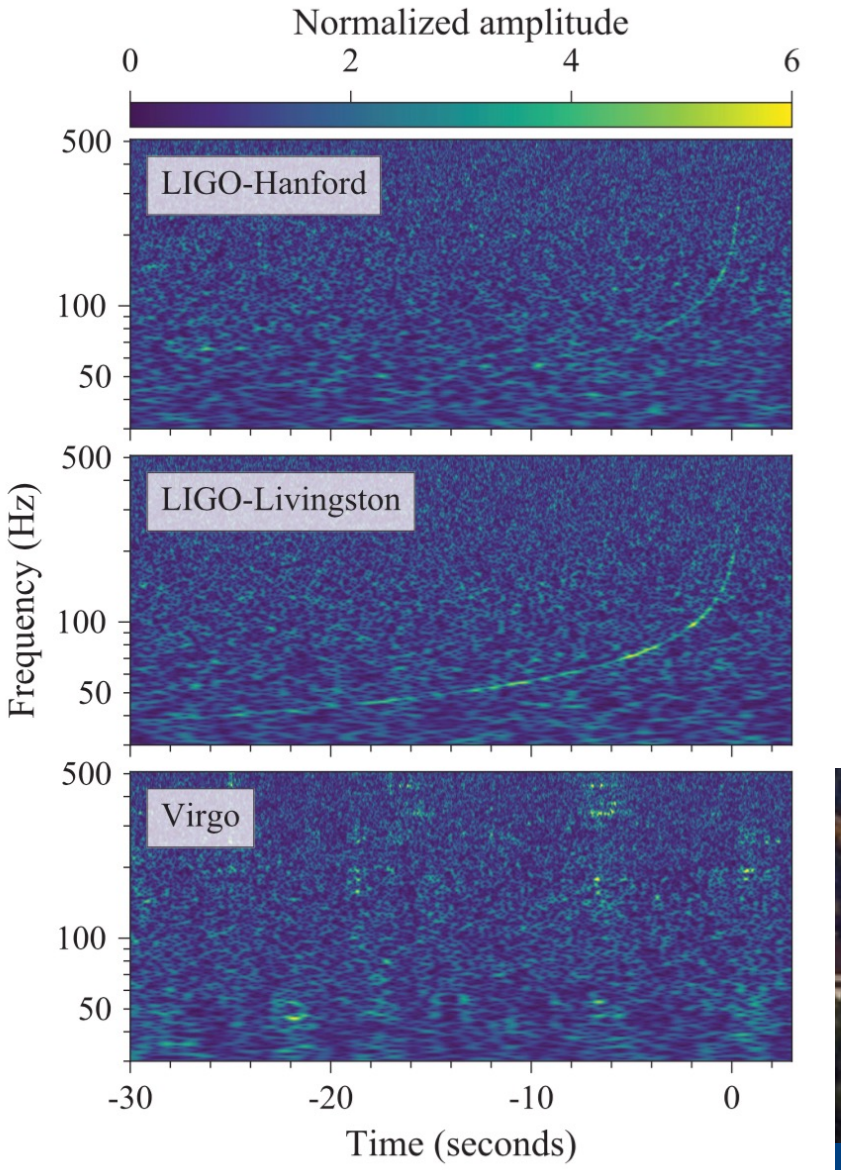


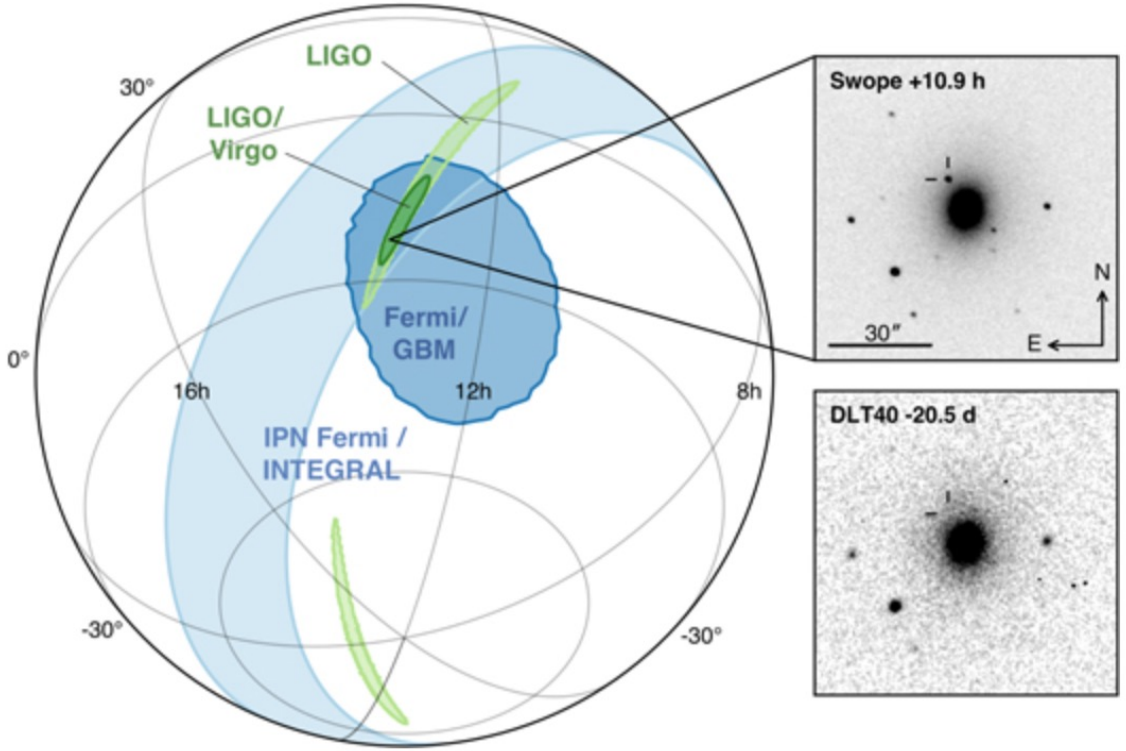

LIGO sees binary neutron star
merger on August 17, 2017

Laser Interferometer Gravitational-Wave Observatory (LIGO)

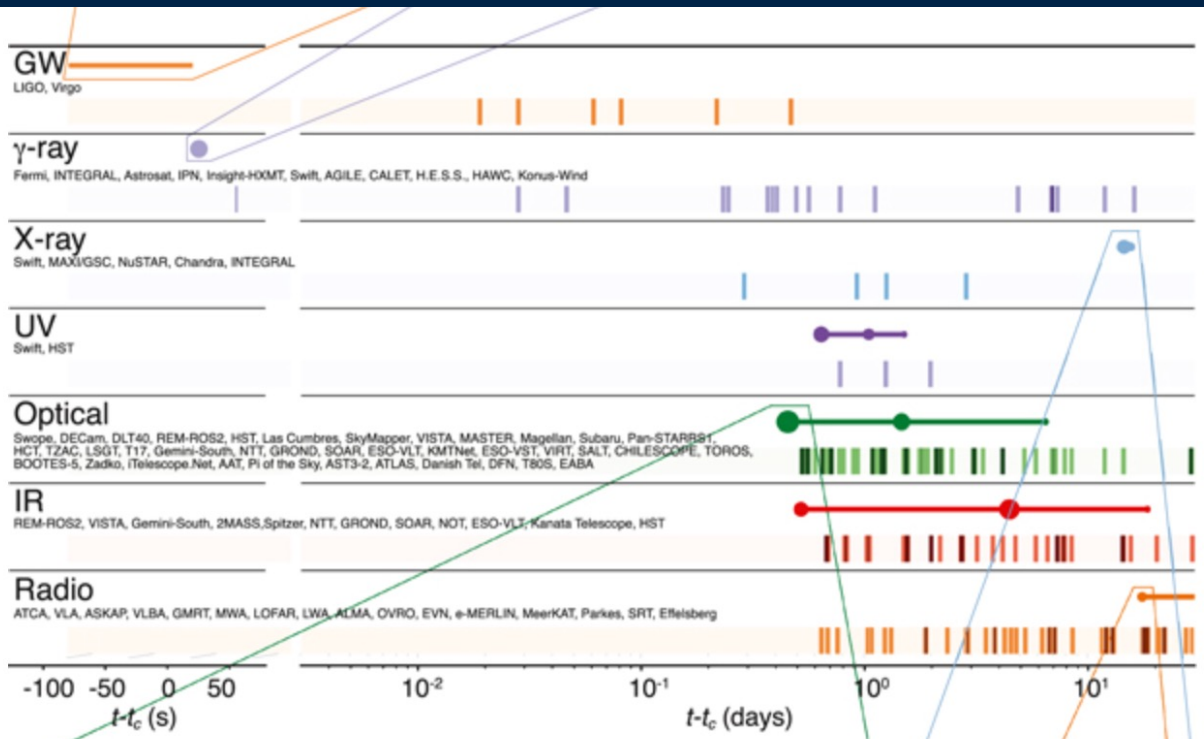


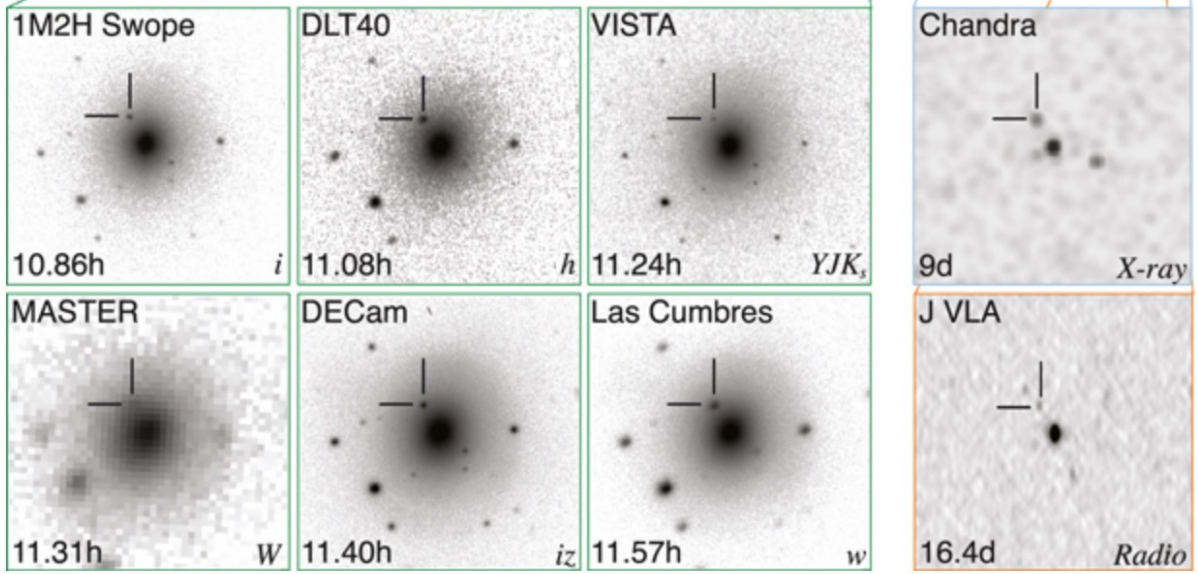
Laser Interferometer Gravitational-Wave Observatory (LIGO)

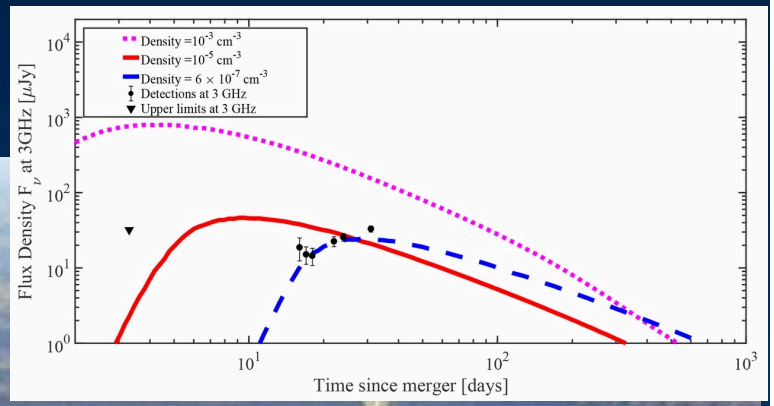


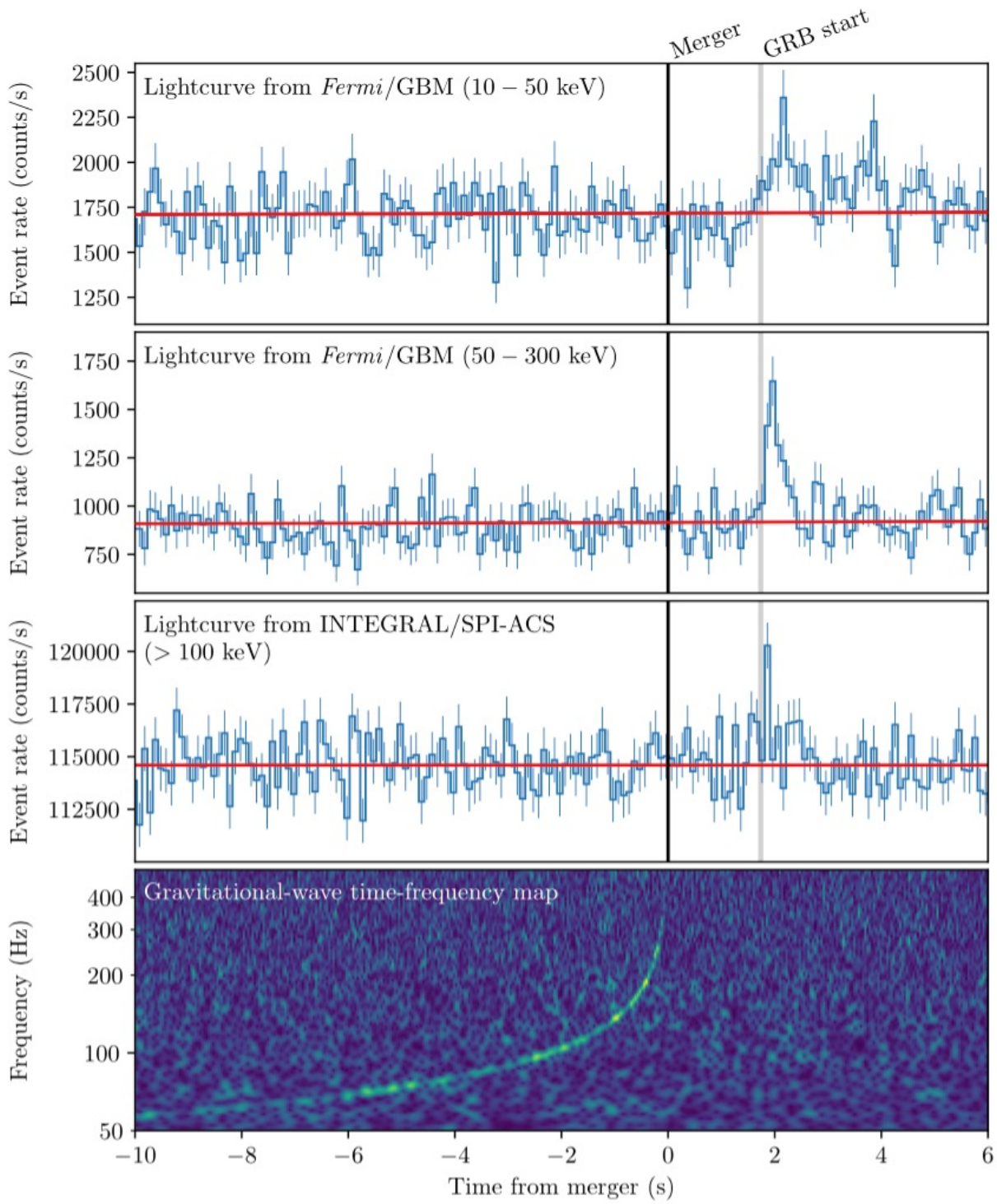


Multi-Messenger Astronomy









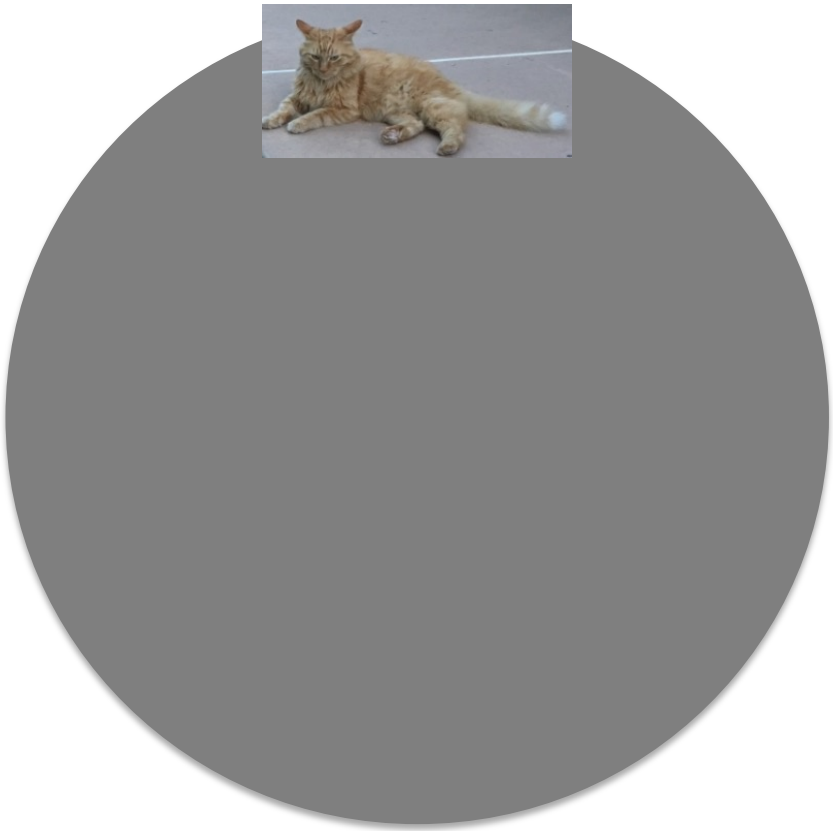
Gamma-rays look like a short GRB

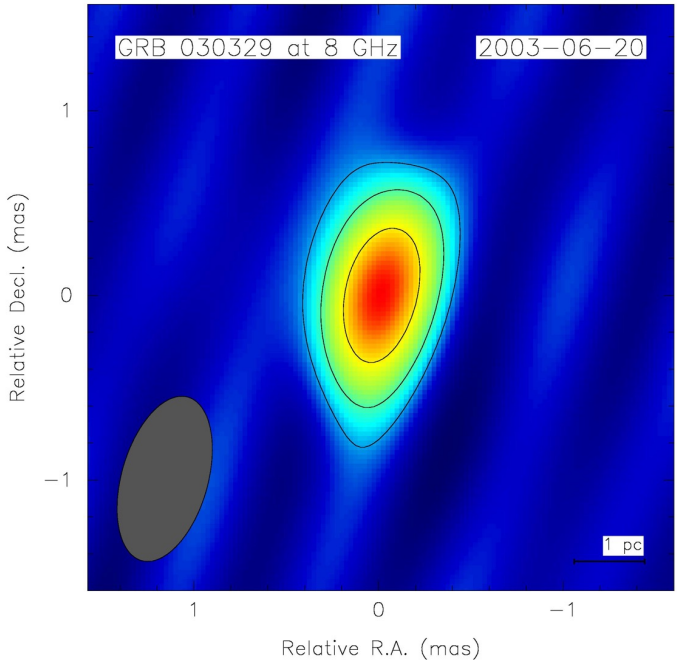
Little or no delay between arrival of photons and GWs over 100 Ml-y

Short duration GRBs are NS-NS mergers

- Peak toward high end of gamma-ray, simple gamma-ray light curves
- Often have bright afterglows
- Produce a strong gravitational wave signal
- Energy required of ~ 10^{52} ergs (isotropic)
- Associated with comparatively lower redshift galaxies, and do not have to be in a starburst galaxy
- Sometimes obscured by dust

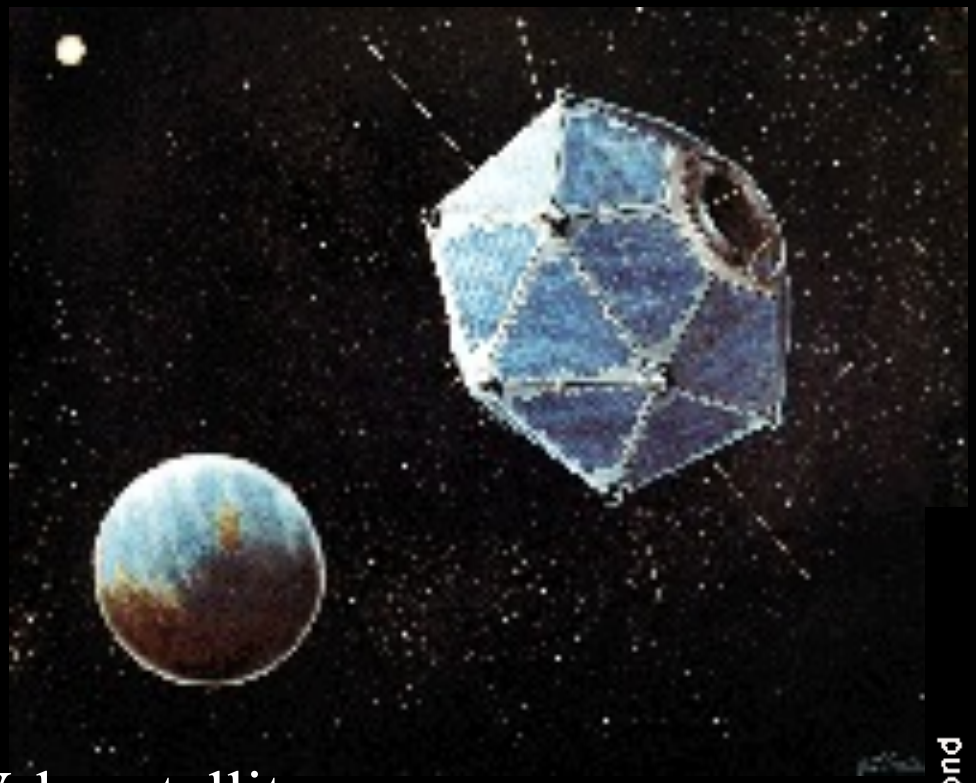
Worksheet – Standing on a Degenerate



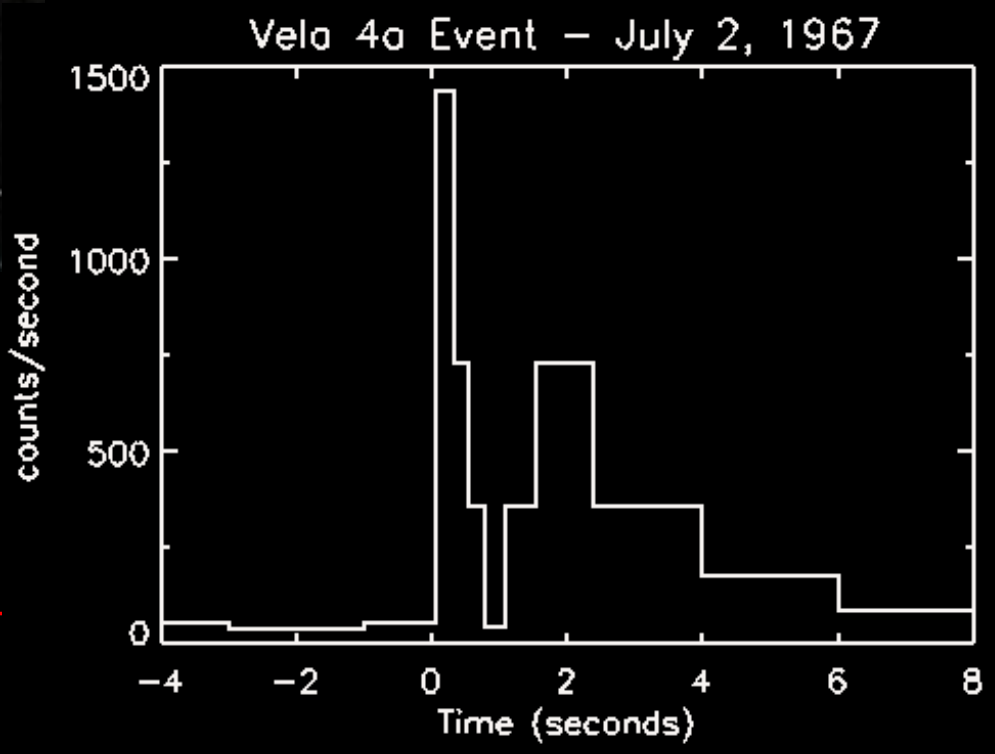


Gamma-Ray Bursts

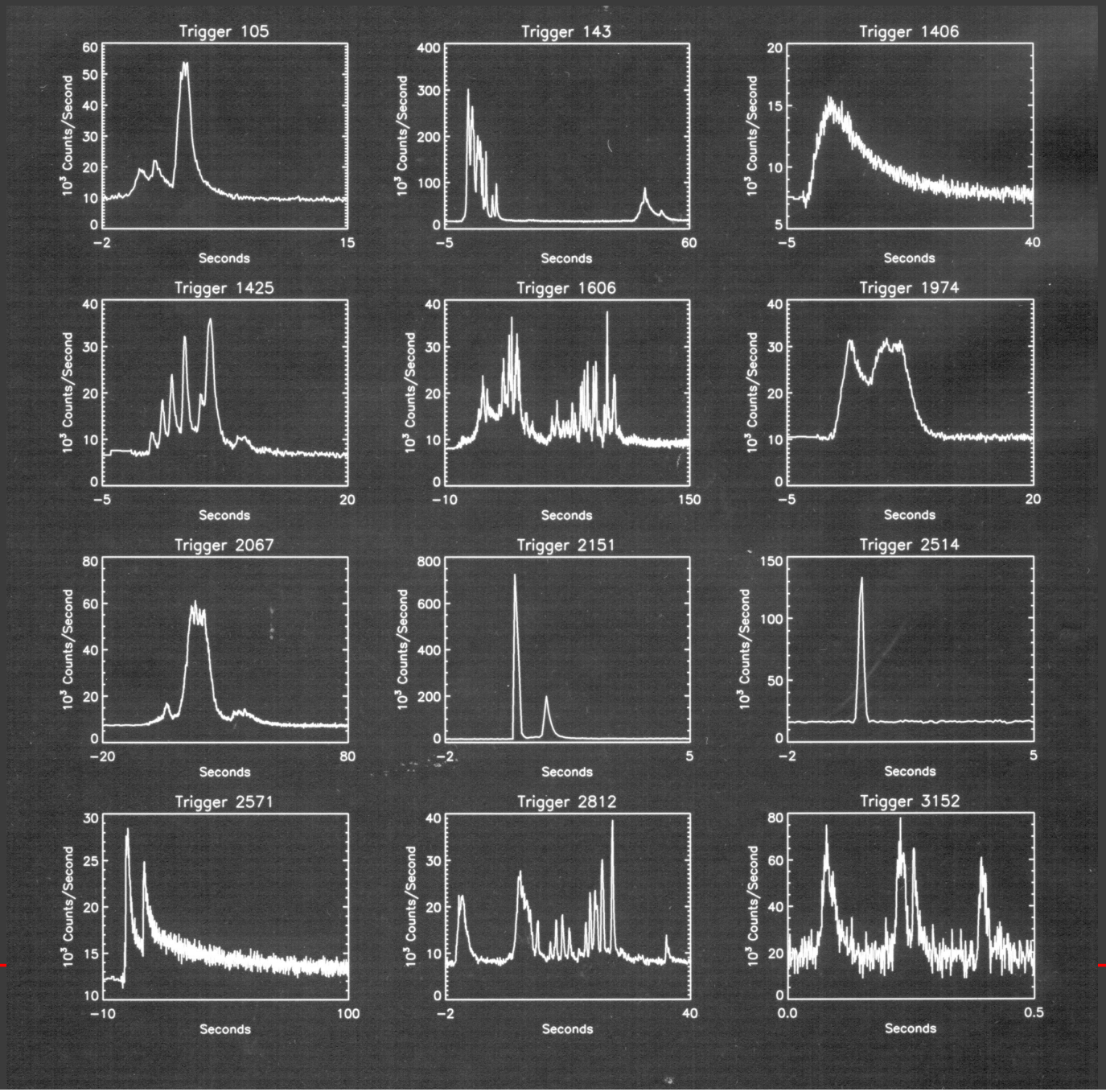
An early gamma ray-burst



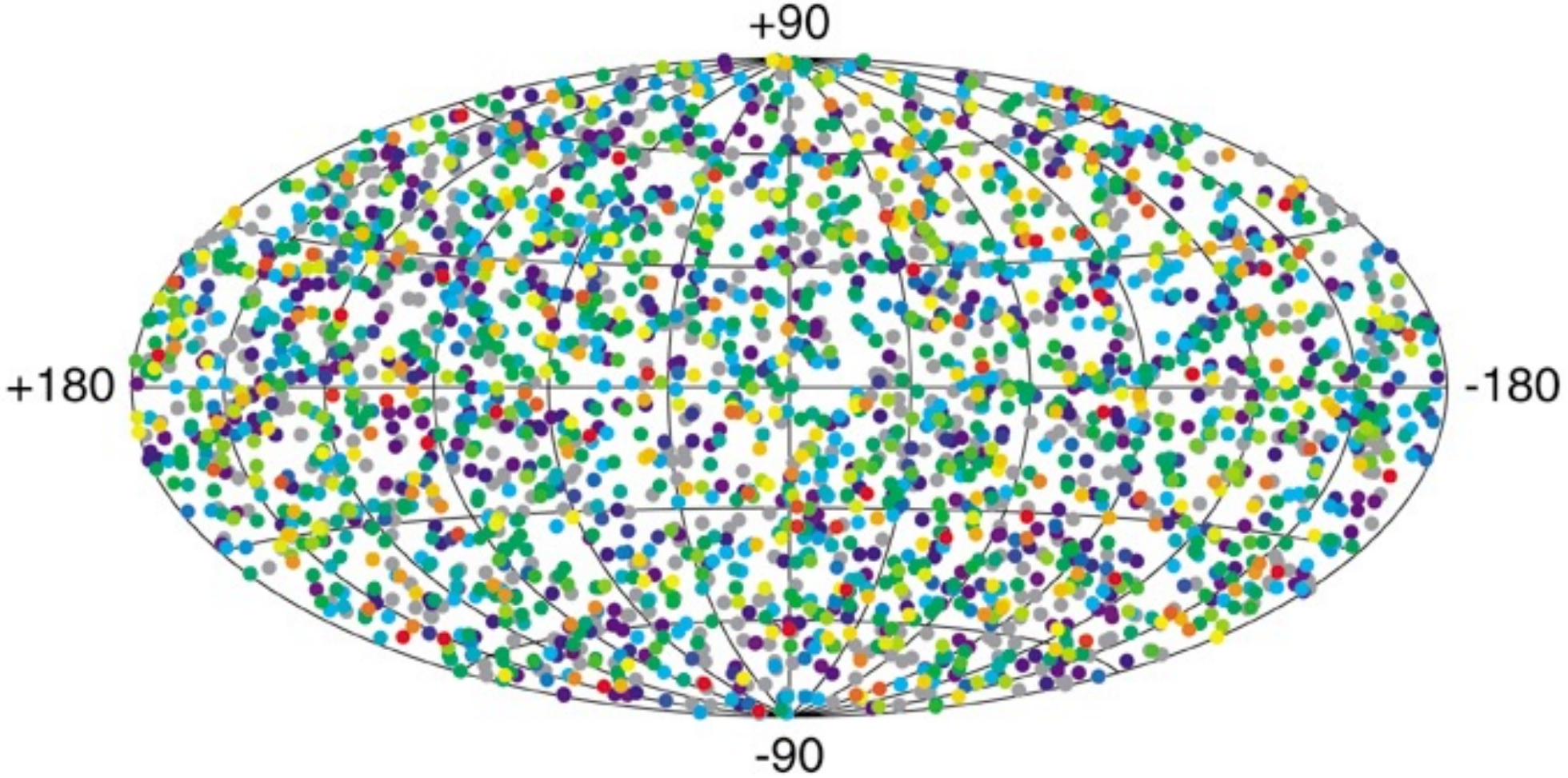
Vela satellite

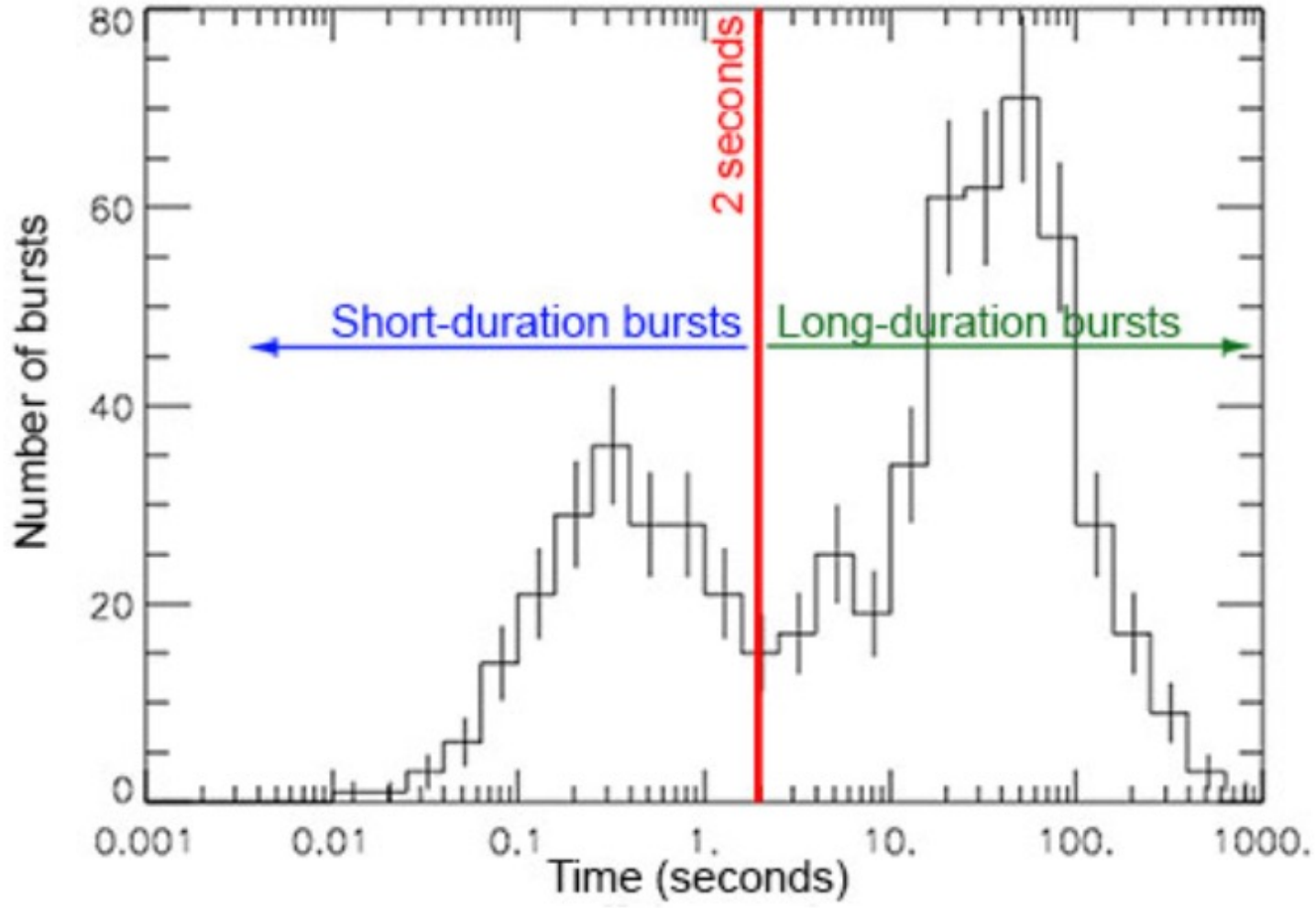


A Gamma Ray Burst Sampler



2704 BATSE Gamma-Ray Bursts





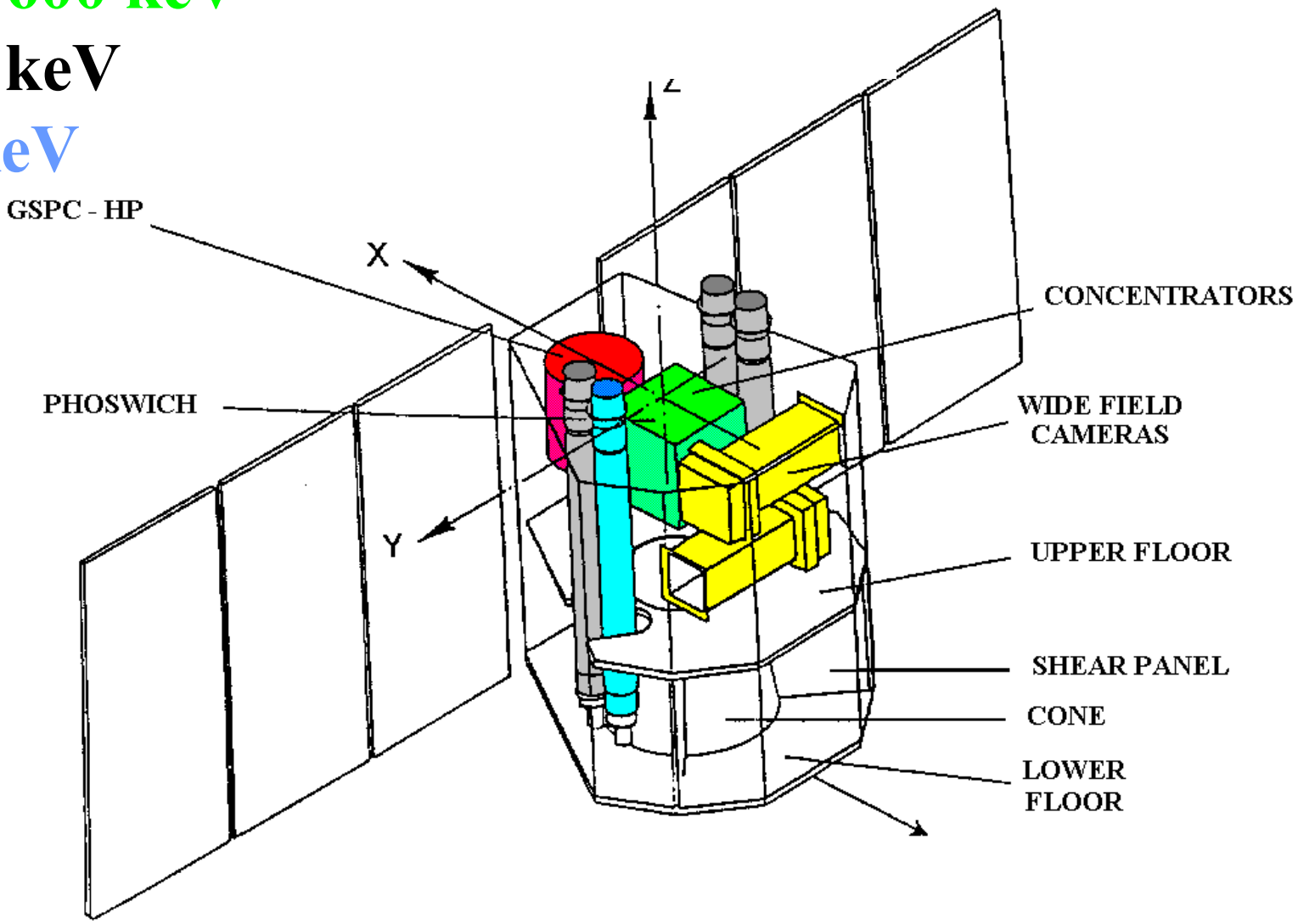
Graph of the time versus number of bursts for the gamma-ray bursts observed by the BATSE instrument on the Compton Gamma-ray Telescope.

The BeppoSAX Satellite

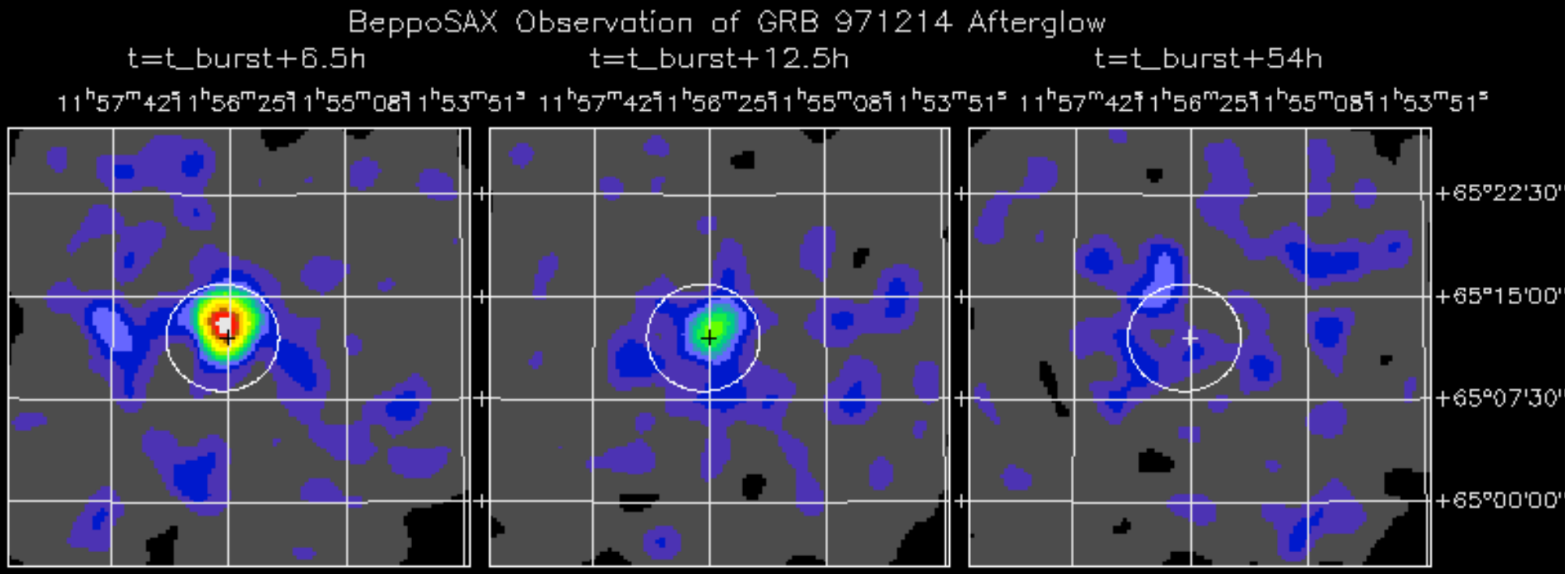
GRBM: 40-600 keV

WFC: 2-30 keV

NFI: 2-10 keV

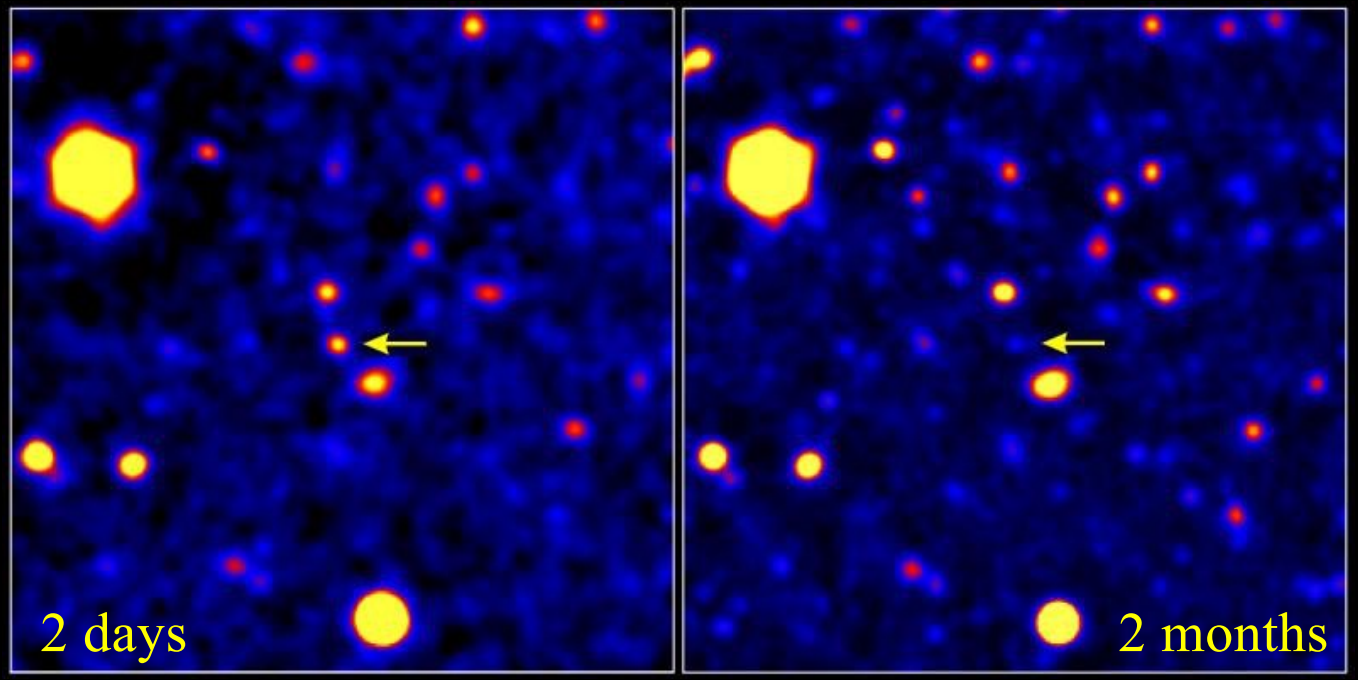


X-Ray Afterglow from GRB 971214

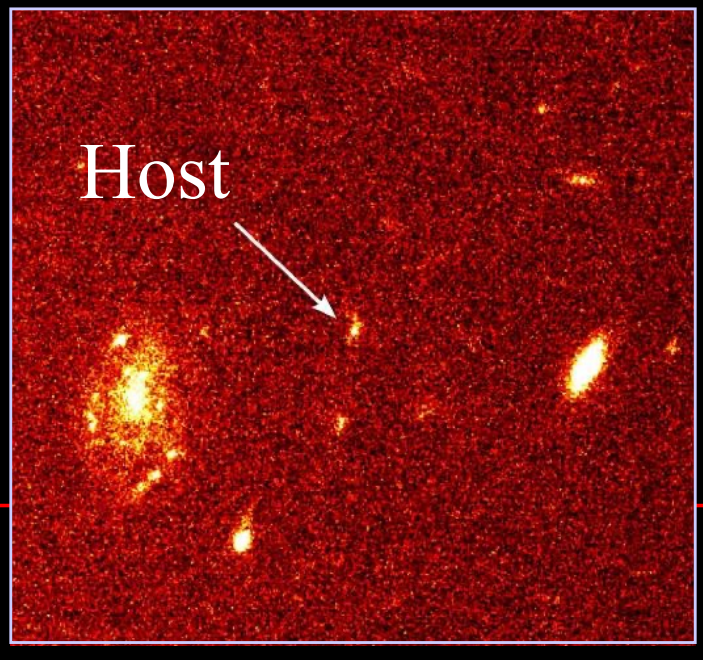


t=6.5 hrs t=12.5 hrs t=54 hrs

Optical Afterglow from GRB 971214

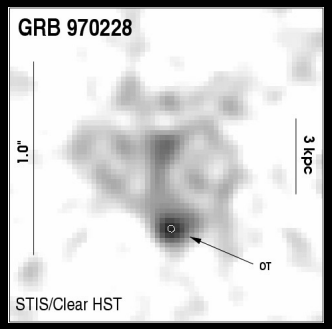


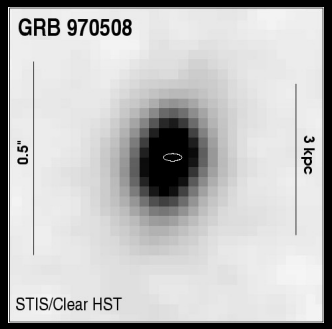
Keck Images

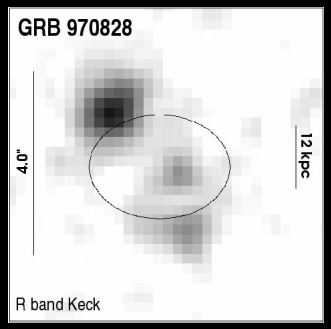


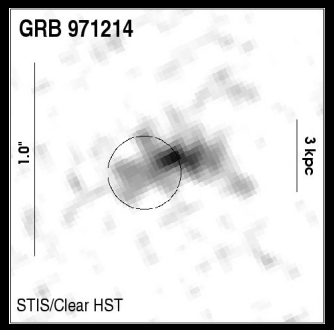
HST Image

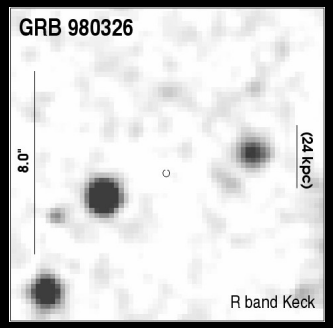
GRB Host Galaxies

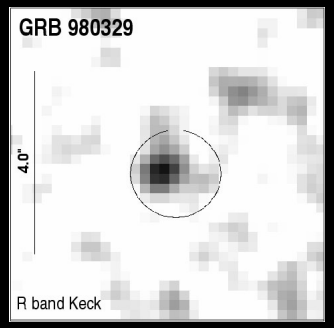


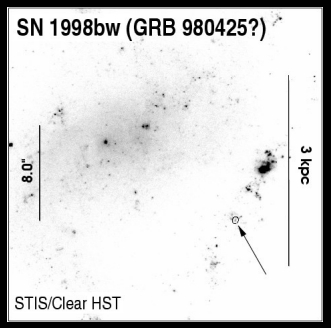


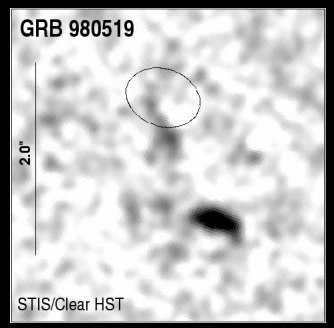


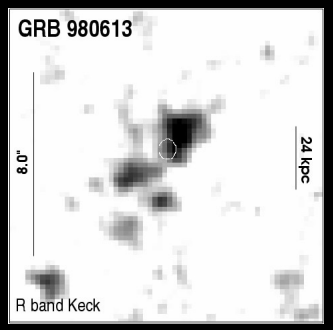


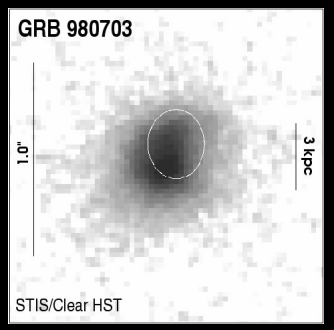


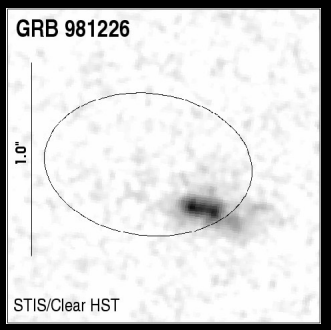


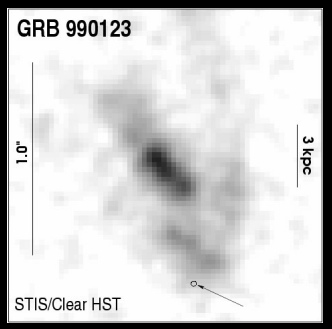


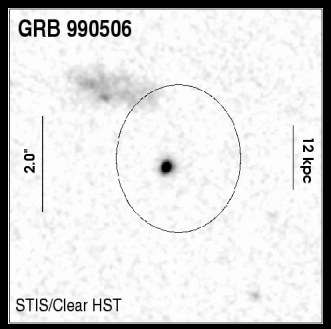


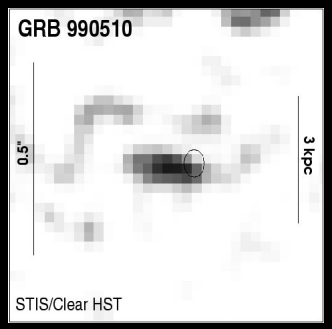


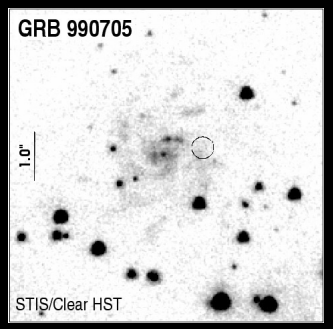


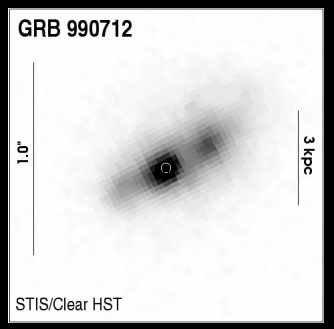


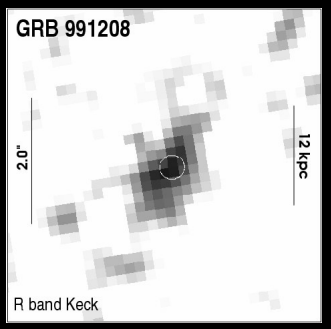


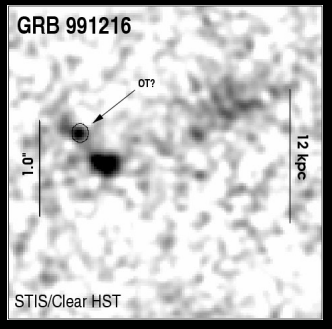


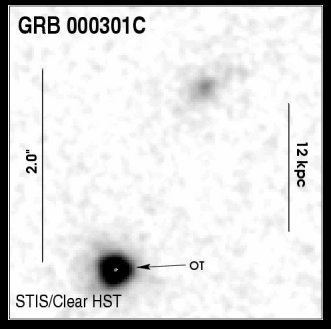


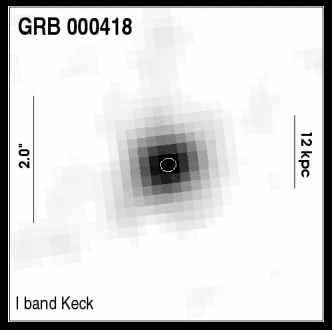


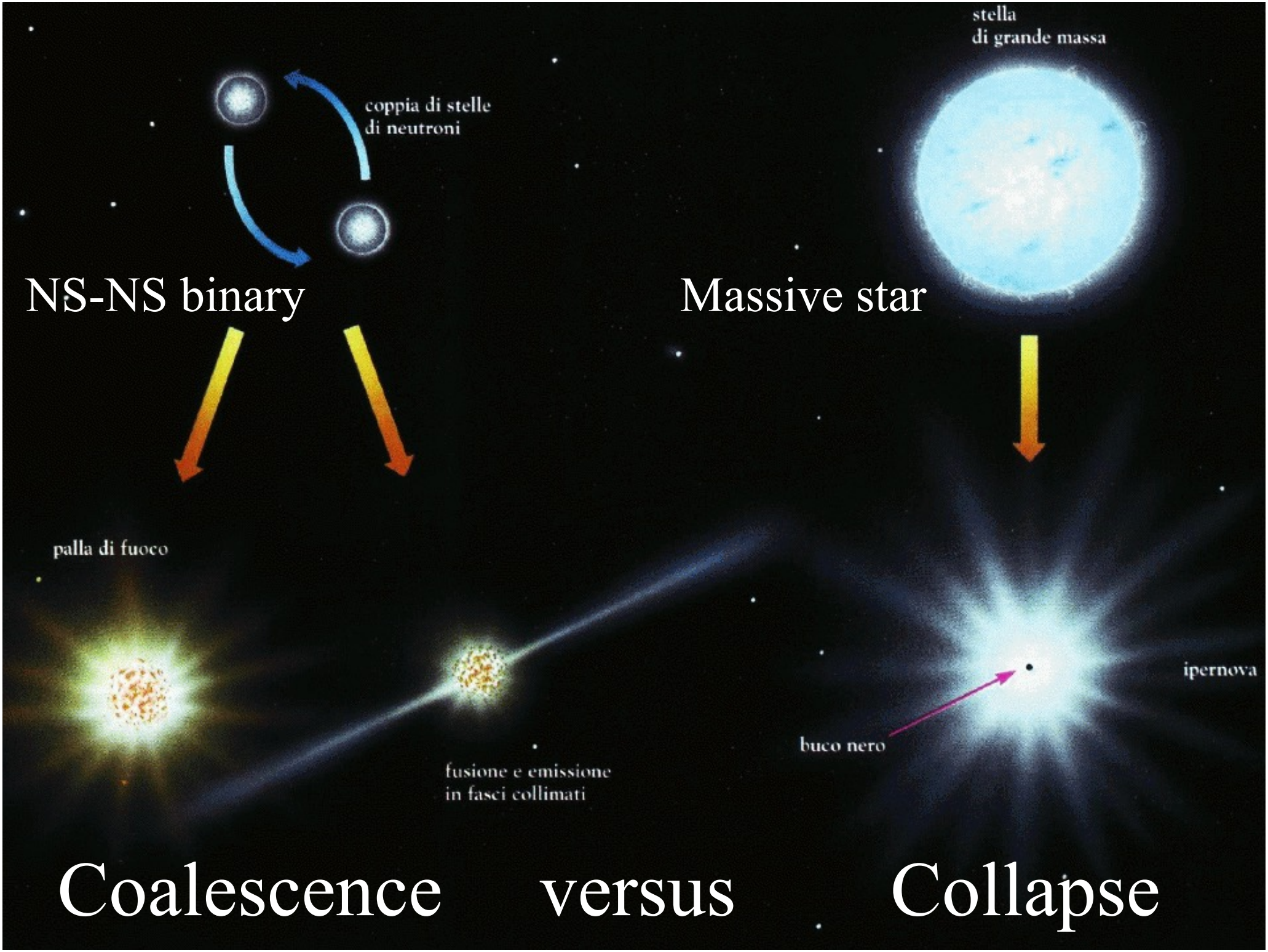


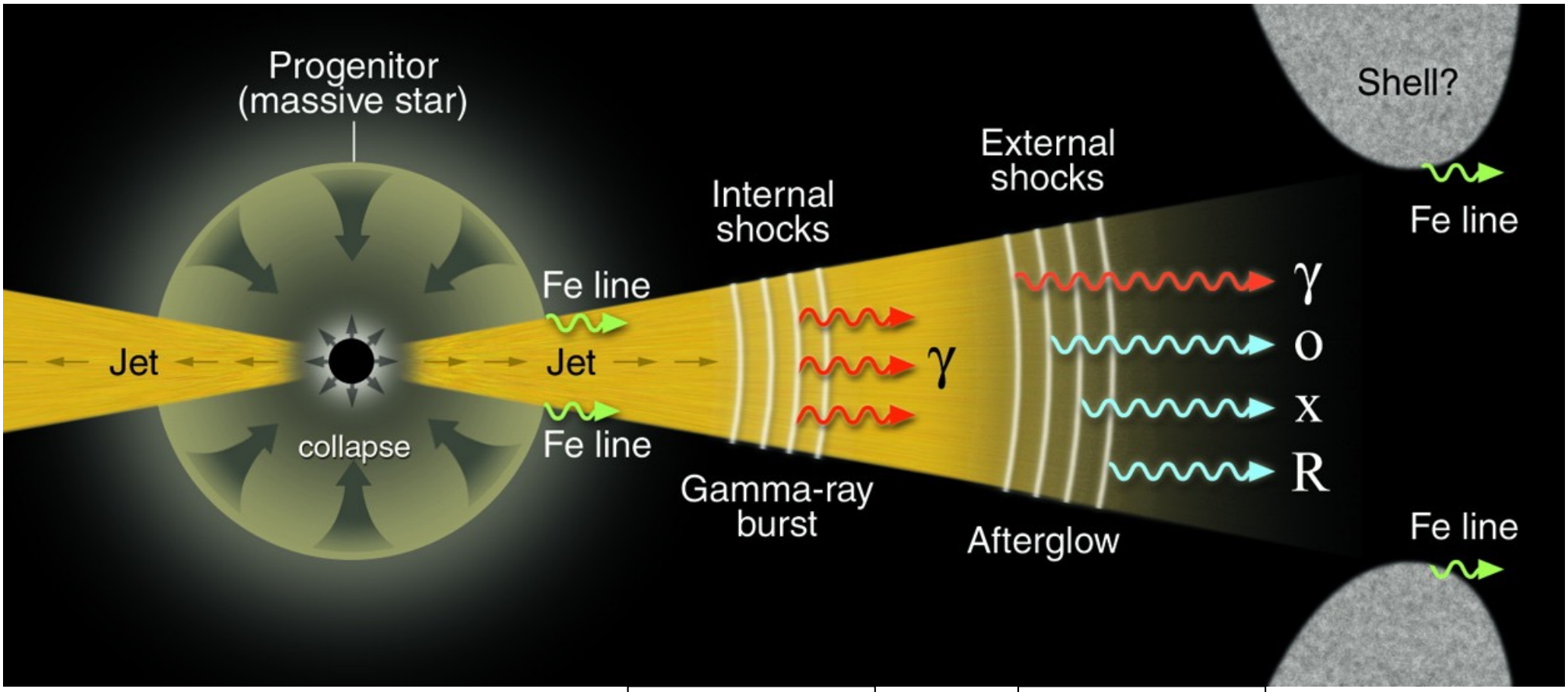








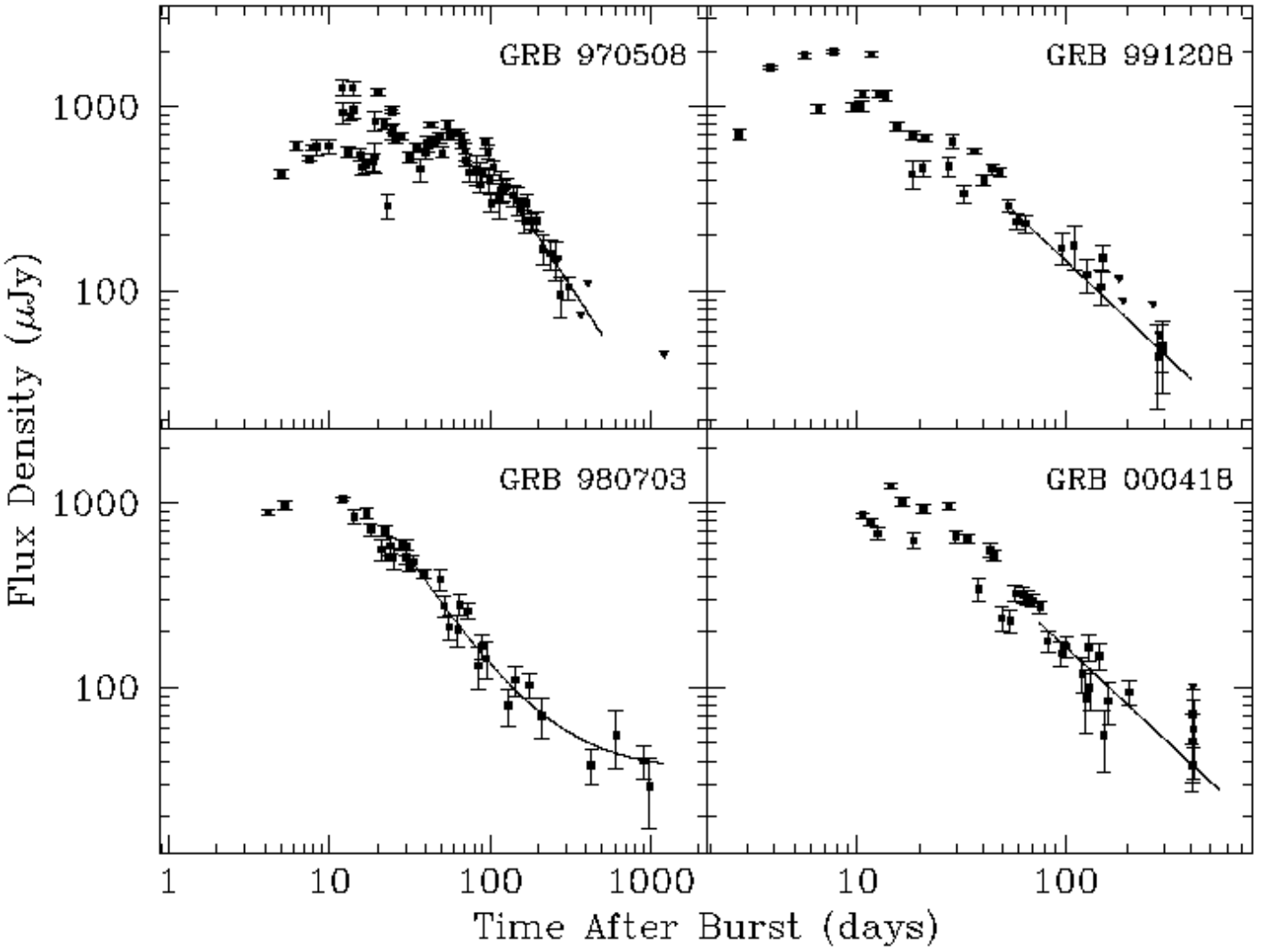

coppia di stelle
di neutroni
stella
di grande massa
NS-NS binary
Massive star
palla di fuoco
fusione e emissione
in fasci collimati
buco nero
ipernova
Coalescence versus Collapse



$\Gamma \approx 100$
$r \approx 10^{15}$ cm

$\Gamma \approx 10 \rightarrow 1$
$r \approx 10^{17}$ cm

Radio Light Curves



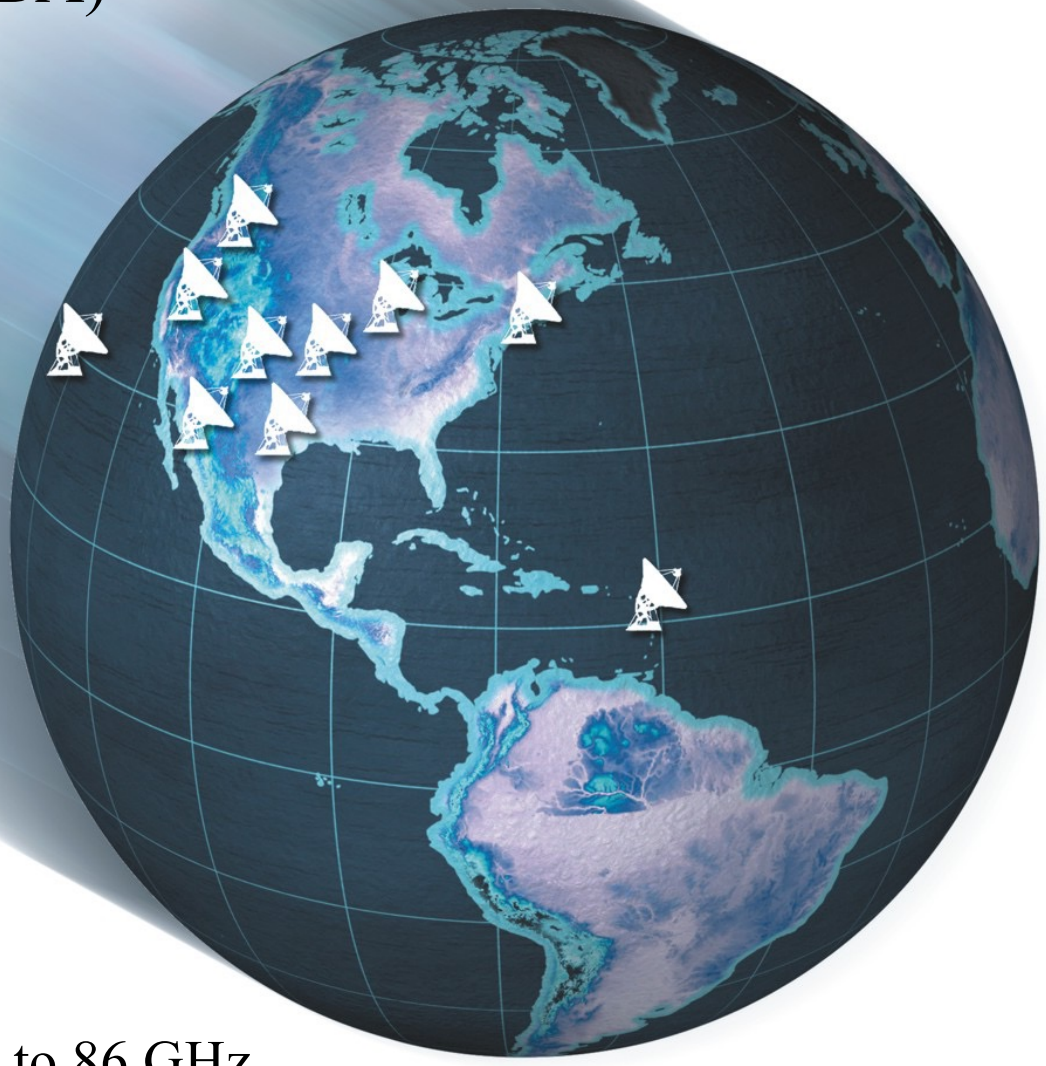
Very Long Baseline Array (VLBA)

Dedicated in 1993

10 antennas recording to tape

Correlator in Socorro, NM

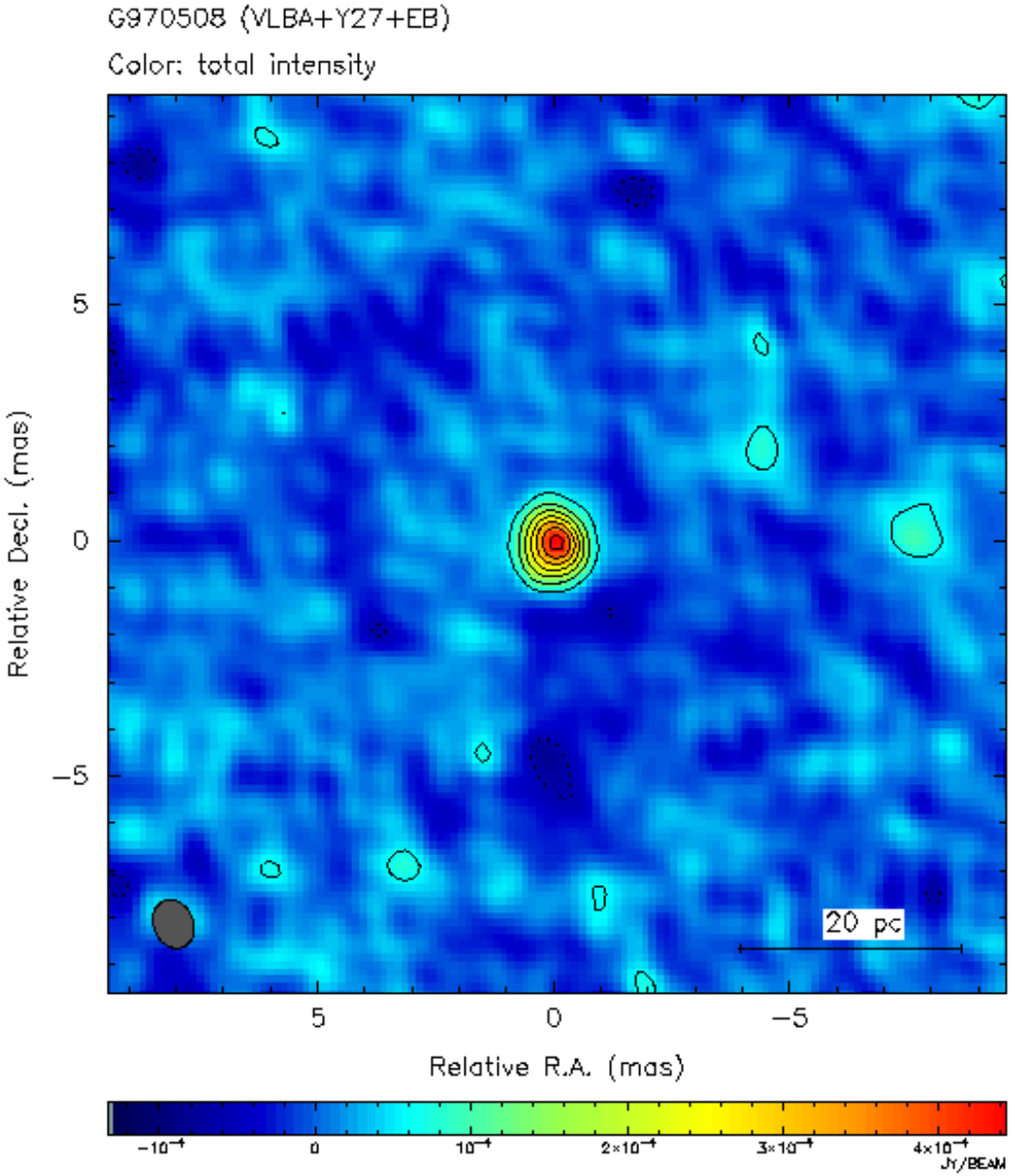
Combinable with Global Arrays



- Frequencies ranging from 330 MHz to 86 GHz
- Angular resolution to 100 microarcseconds at highest frequency

GRB 970508

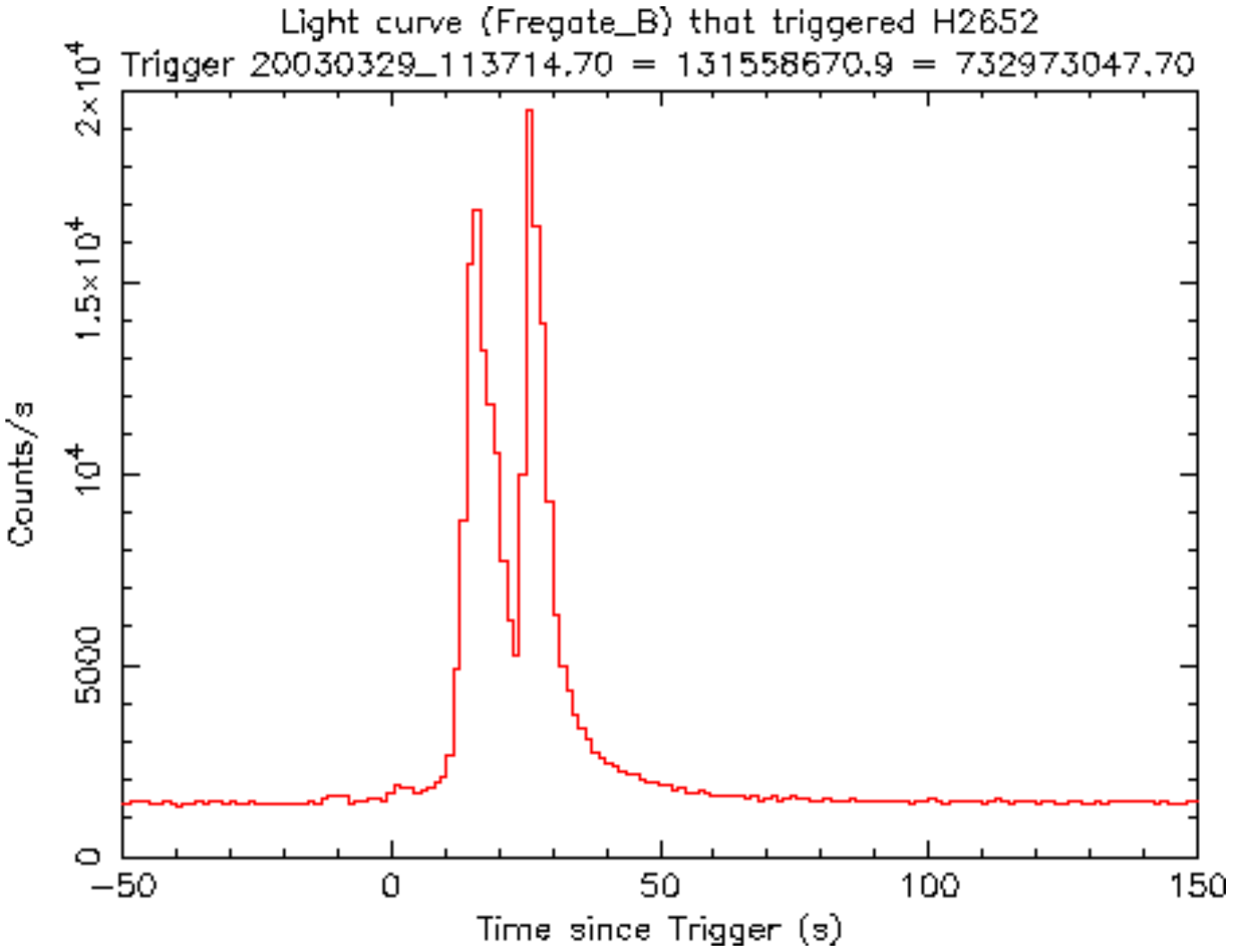
- First VLBI detection of a GRB Afterglow
- absolute position to < 1 mas
- . Size < 10^19 cm
- Distance > 3 kpc



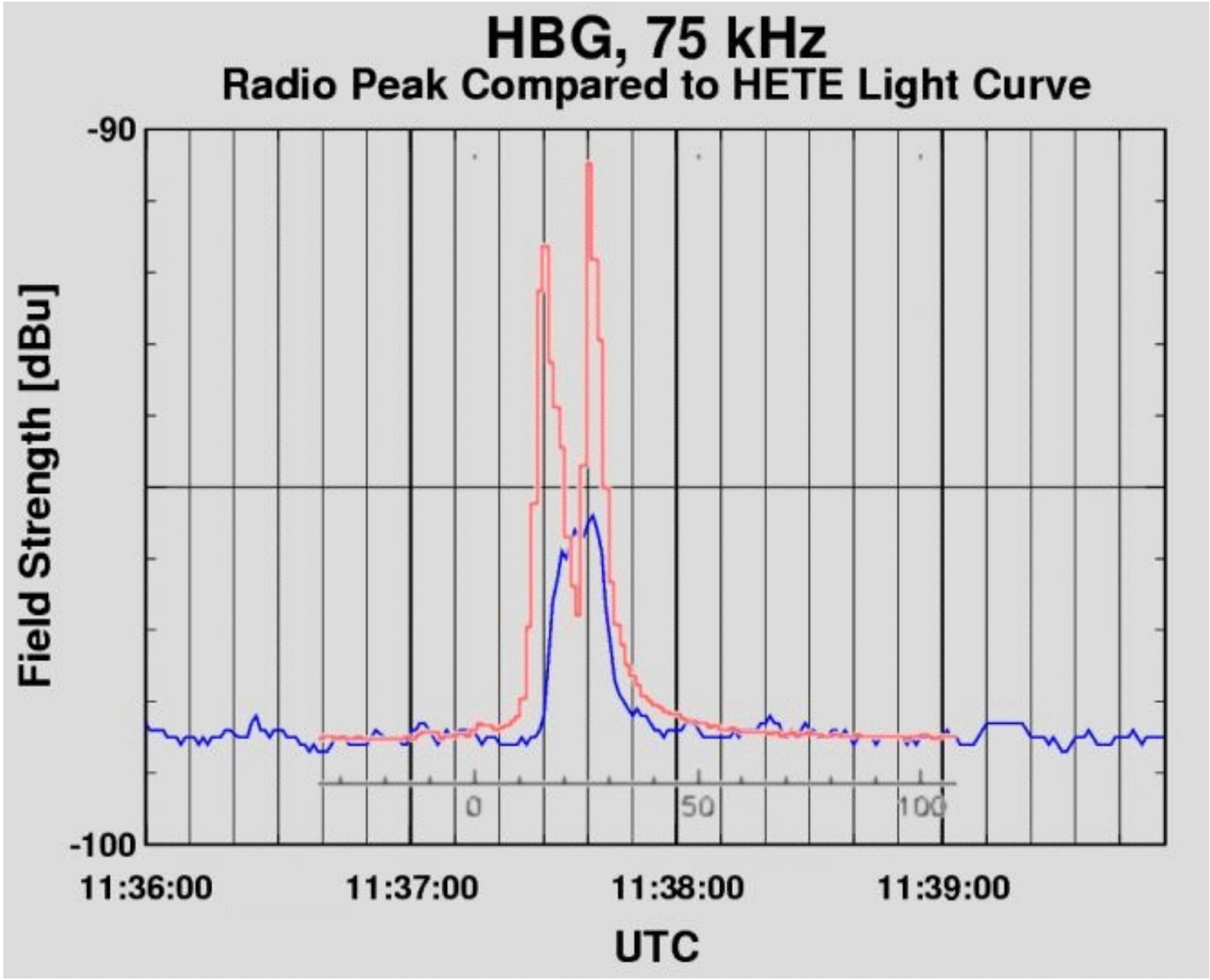
GRB 030329: The Burst of the Decade

- World-wide armada of optical telescopes (~60) observed this burst 24/7
- A very bright burst (m_v=12.5). In radio it is 50 times brighter than any previous GRB!
- Better yet at z=0.168 it is only 740 Mpc away.

The Gamma Ray Burst on March 29, 2003

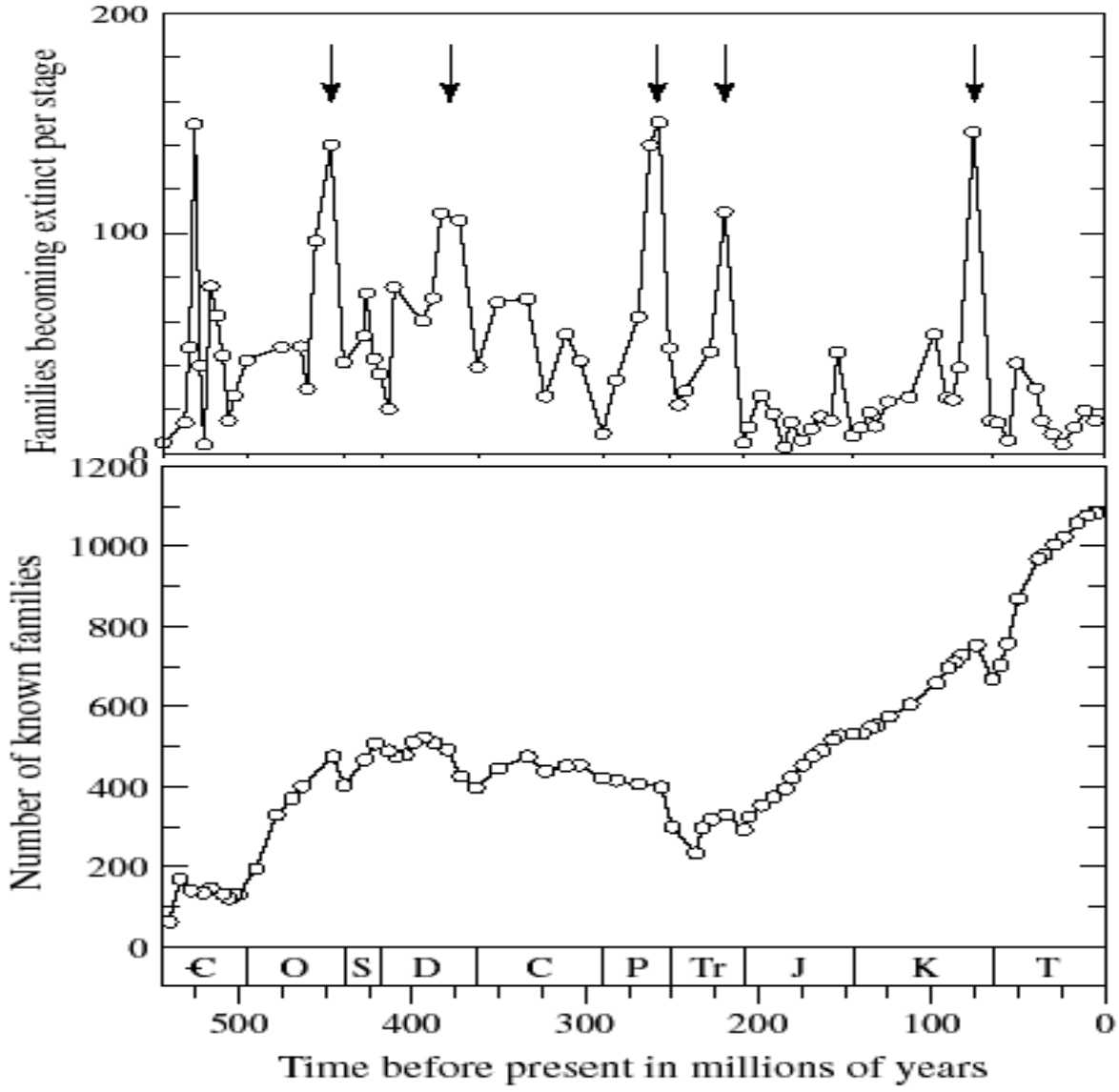


Impact of GRB 030329 on Earth's Ionosphere




Uh-oh
Credit: Dale Frail

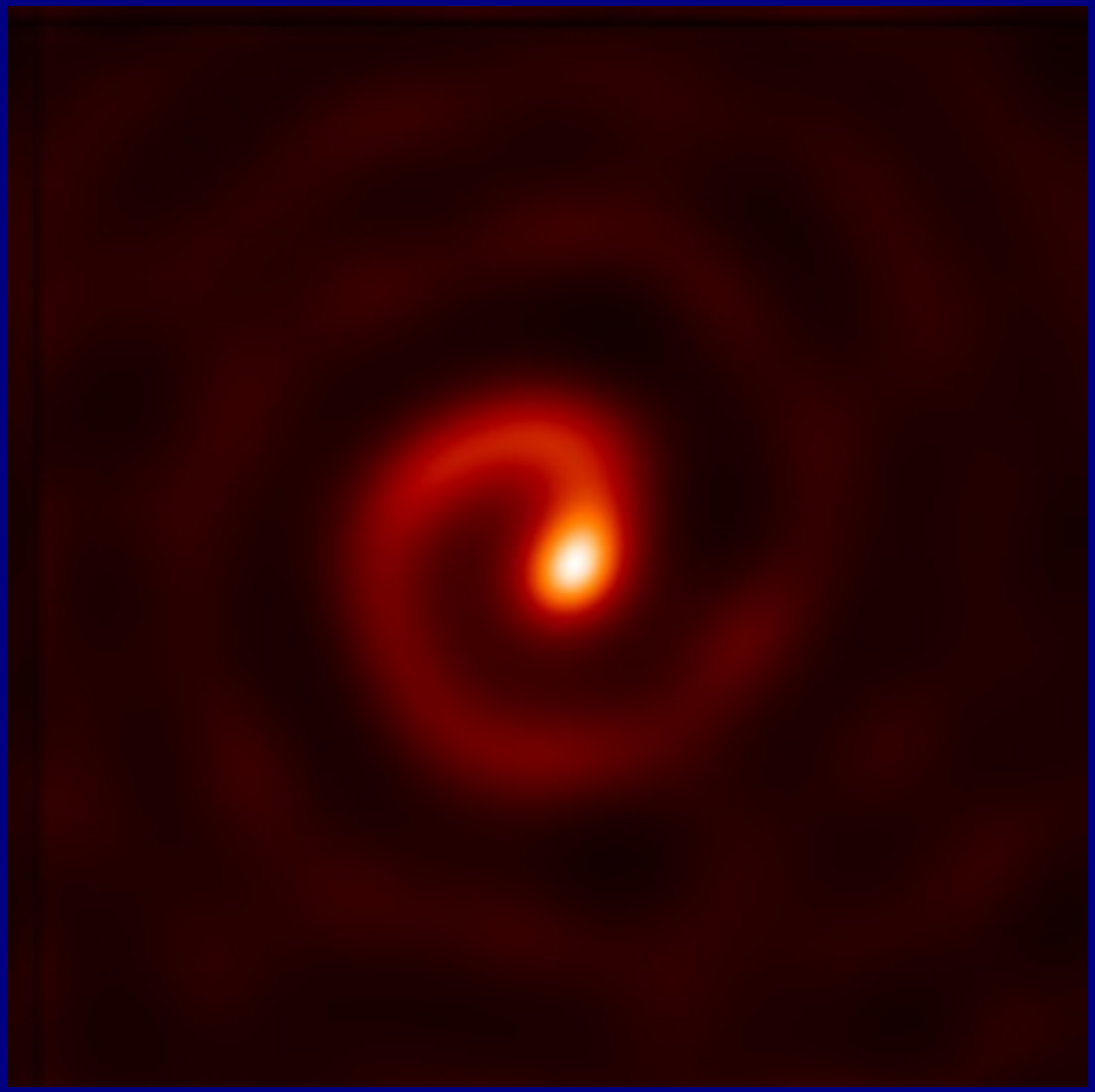
The Fossil Record is Marked by Mass Extinction Events



Extinction	Genus loss
End Ordovician	60%
End Devonian	57%
End Permian	82%
End Triassic	53%
End Cretaceous	47%

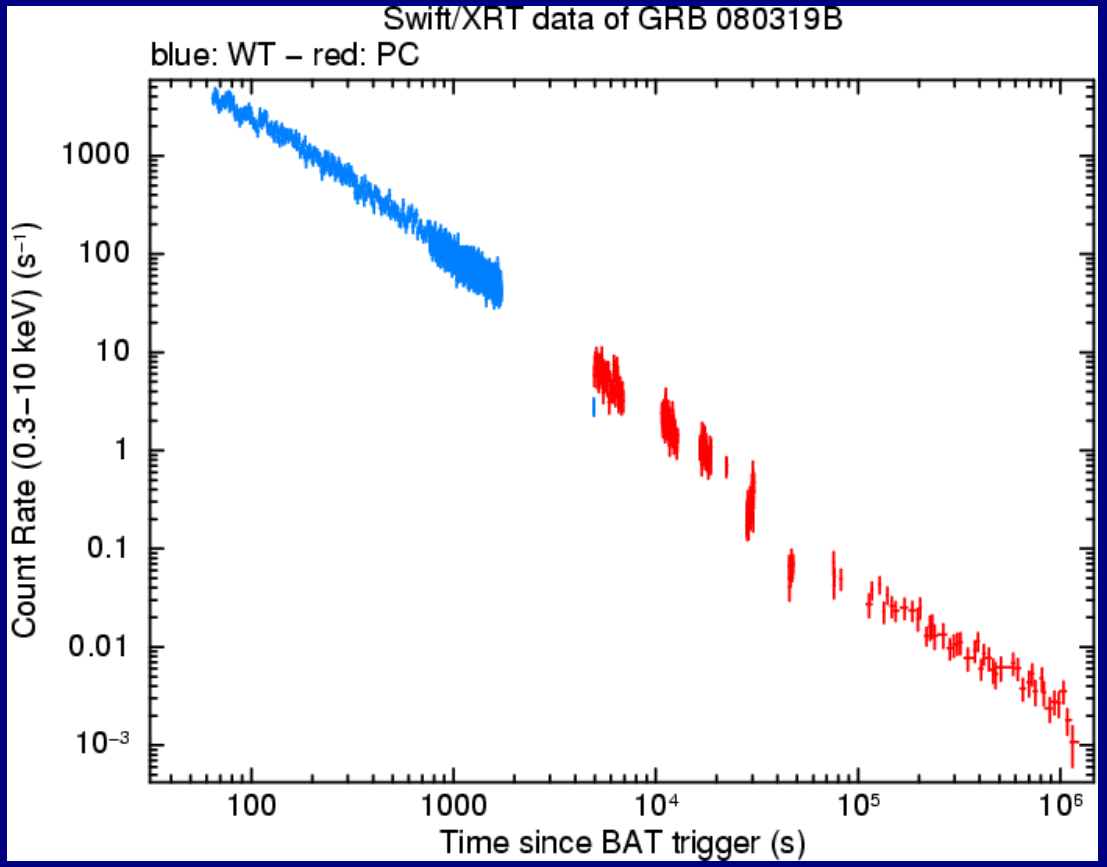
From Solé & Newman 2002

WR104 - Looking Down the Barrel of a GRB system 8000 lt-years from us



Optical Afterglow from GRB 080319b

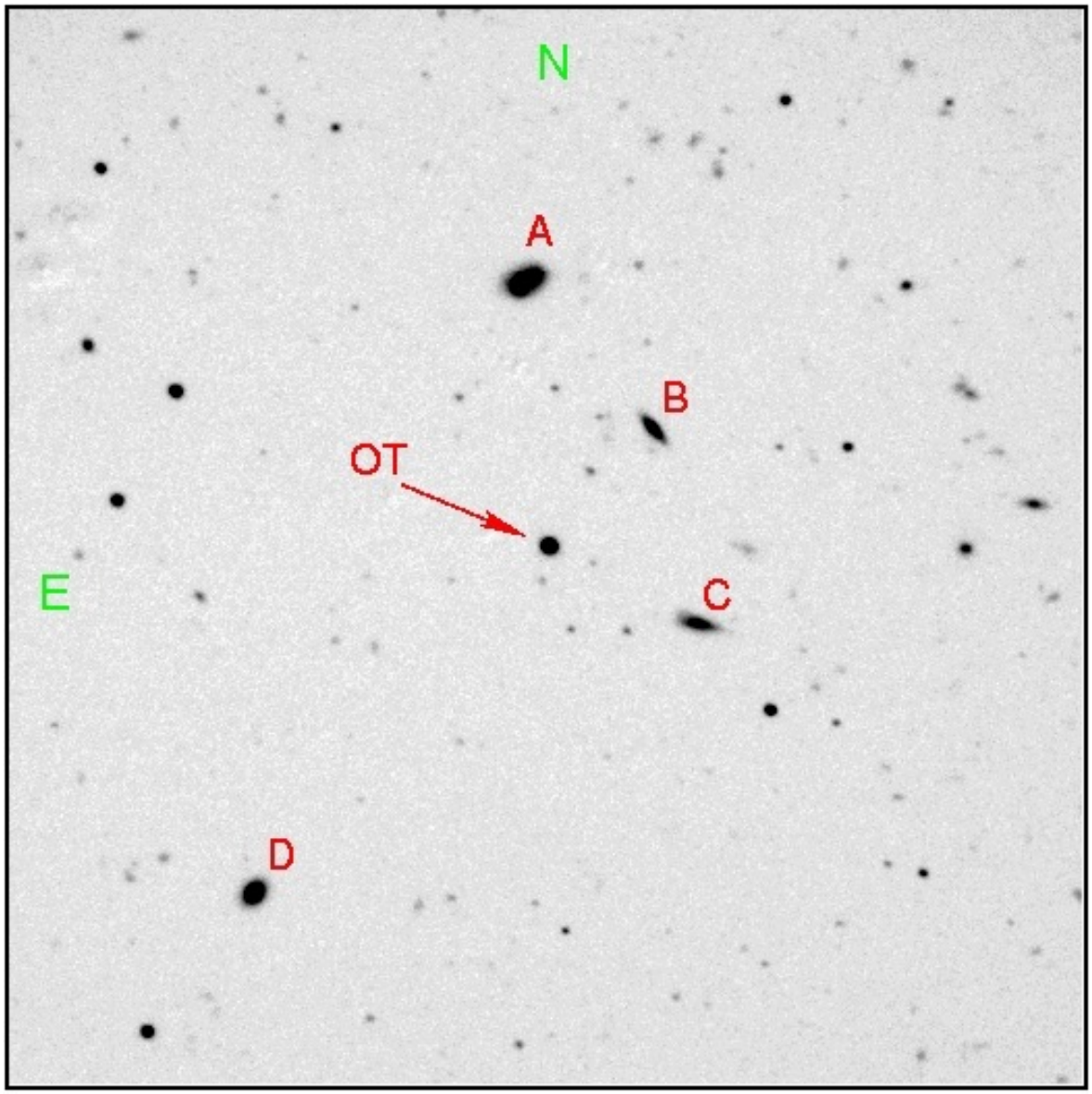
Swift Image



Light Curve

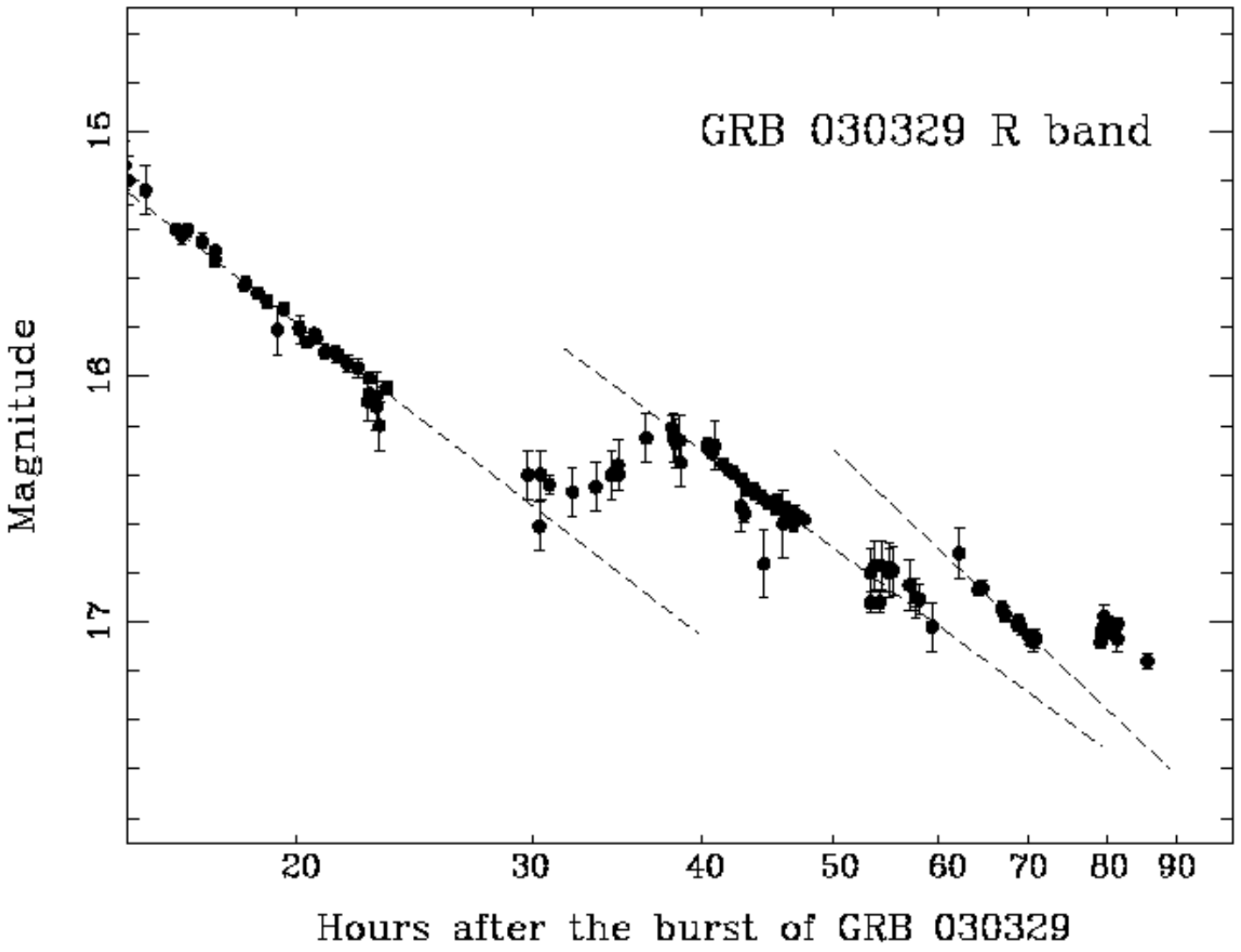
Naked-eye visible for ~30 sec. Distance = 7.5 billion ly

The Optical Transient (OT)

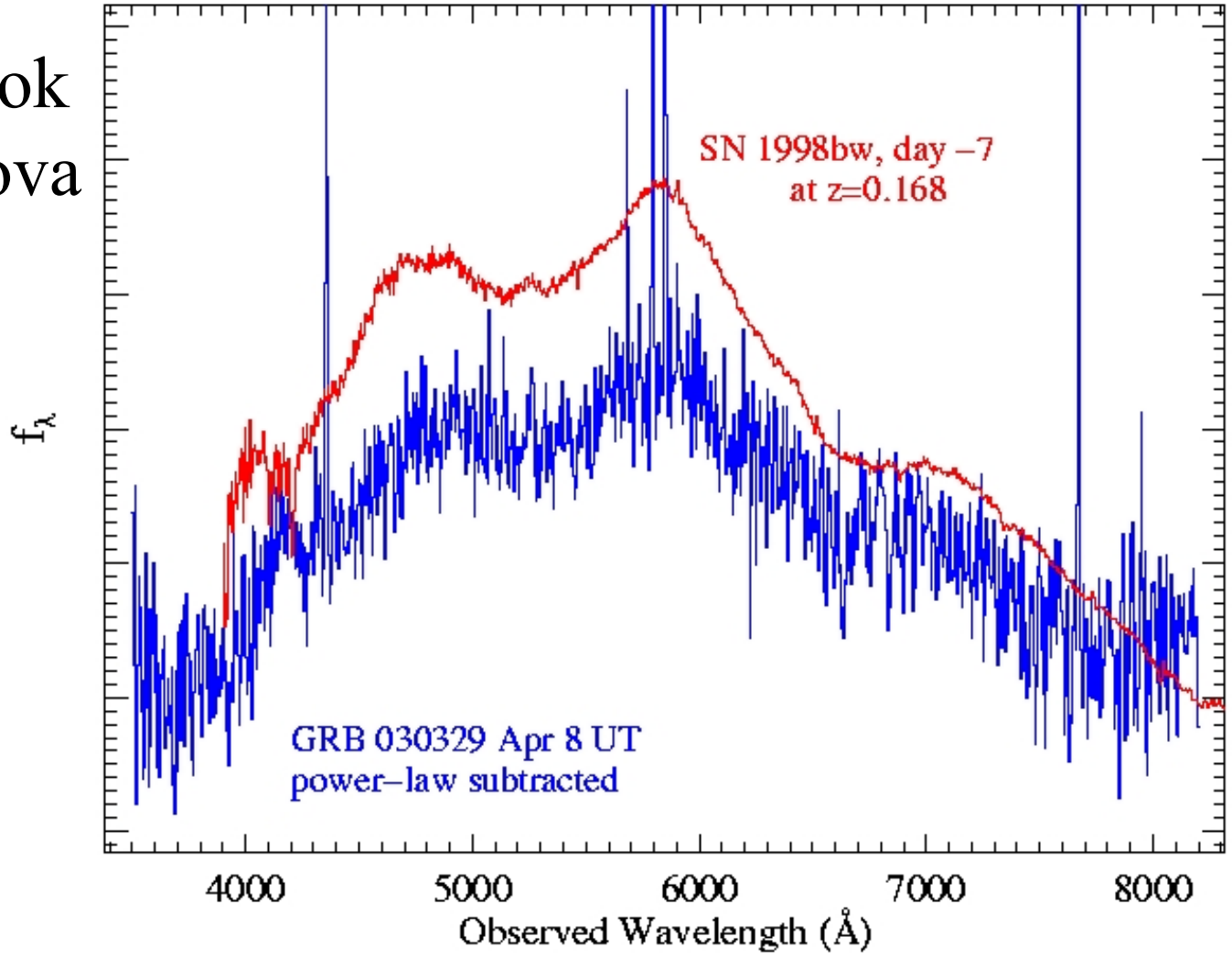


GRB 030329 3'x3' Field Magellan/LDSS2

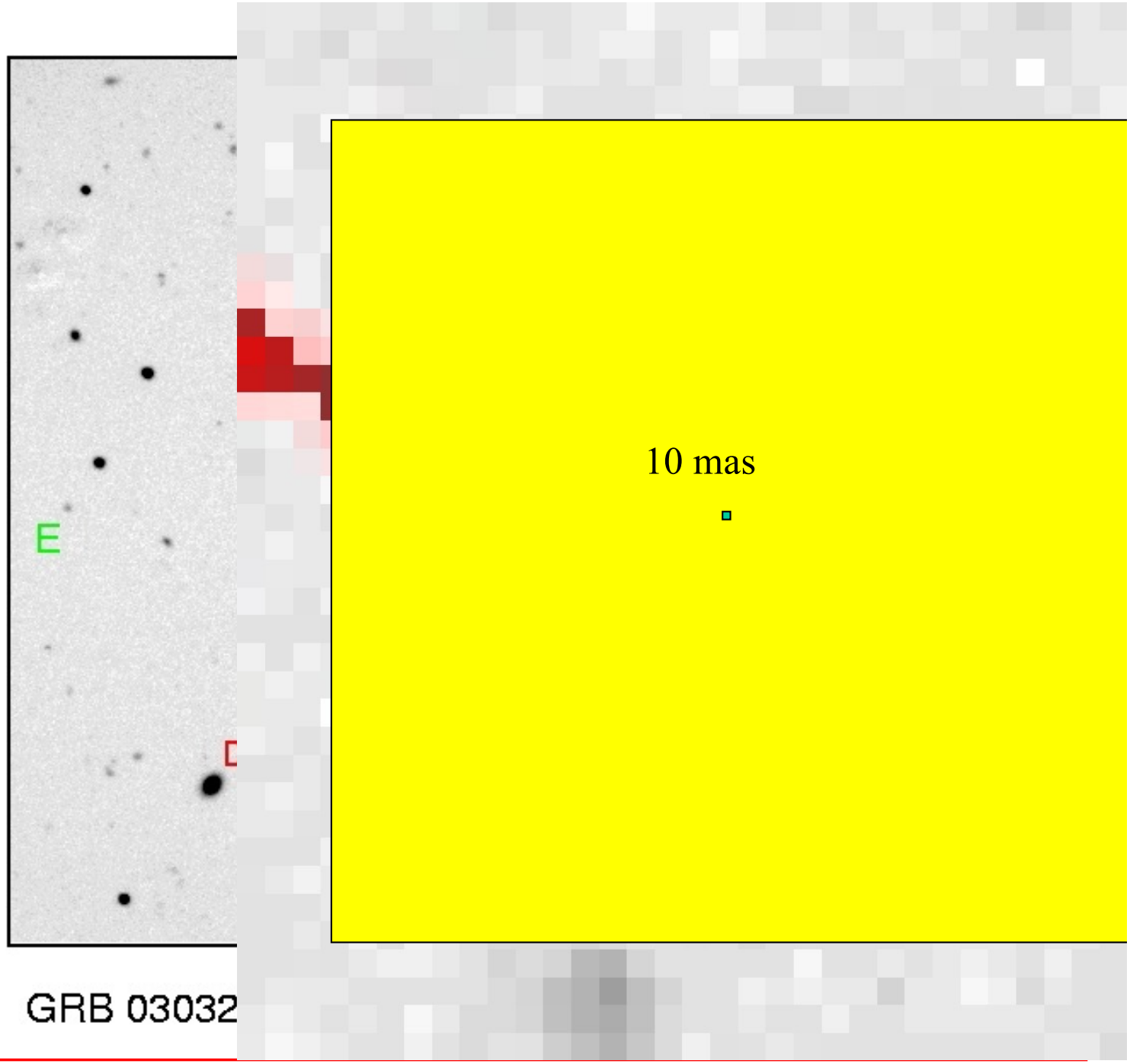
OT Fades


GRB 030329 R band
Magnitude
15
16
17
20
30
40
50
60
70
80
90
Hours after the burst of GRB 030329

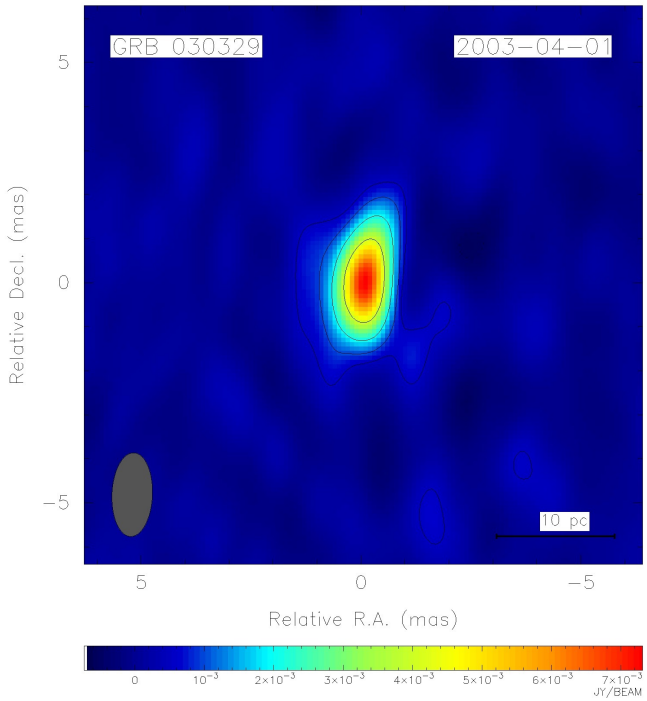
Starting to Look like a Supernova

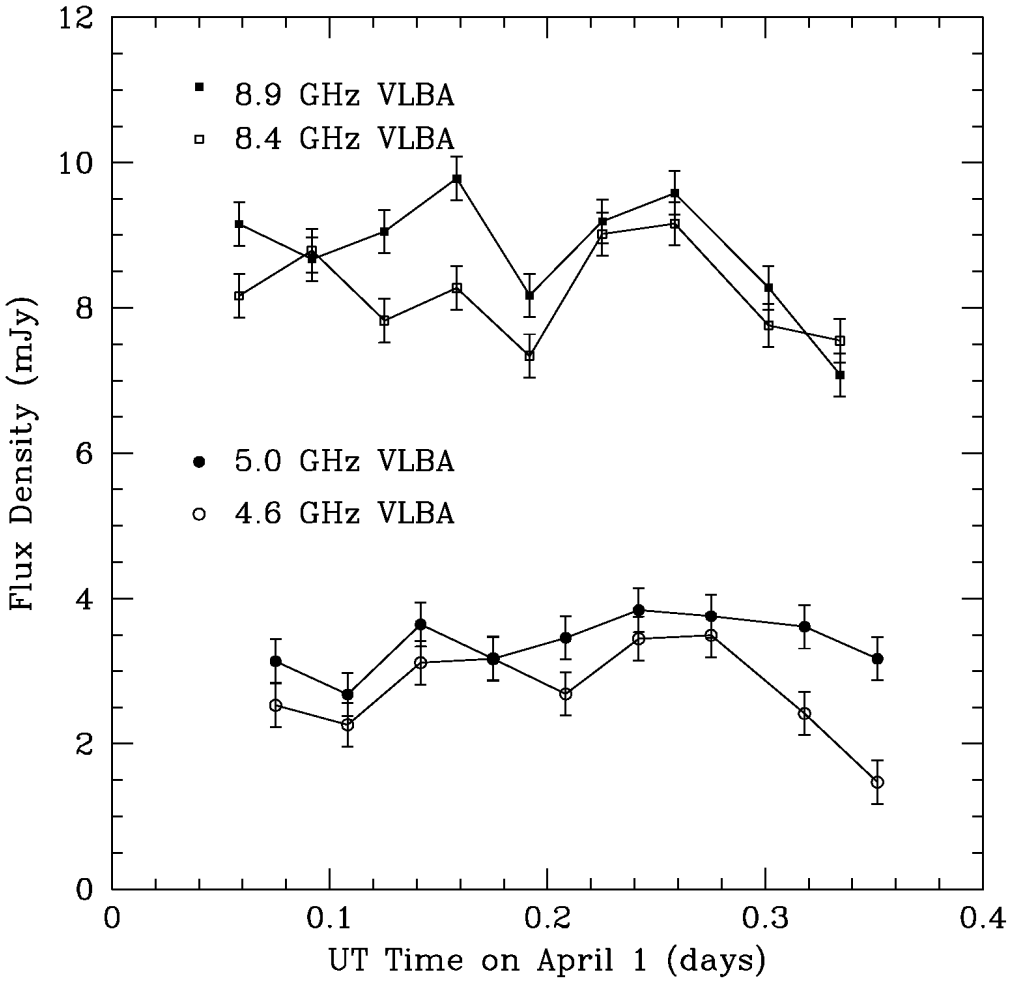


The Optical Transient (OT)



VLBA on April 1 (t+2.7 days)

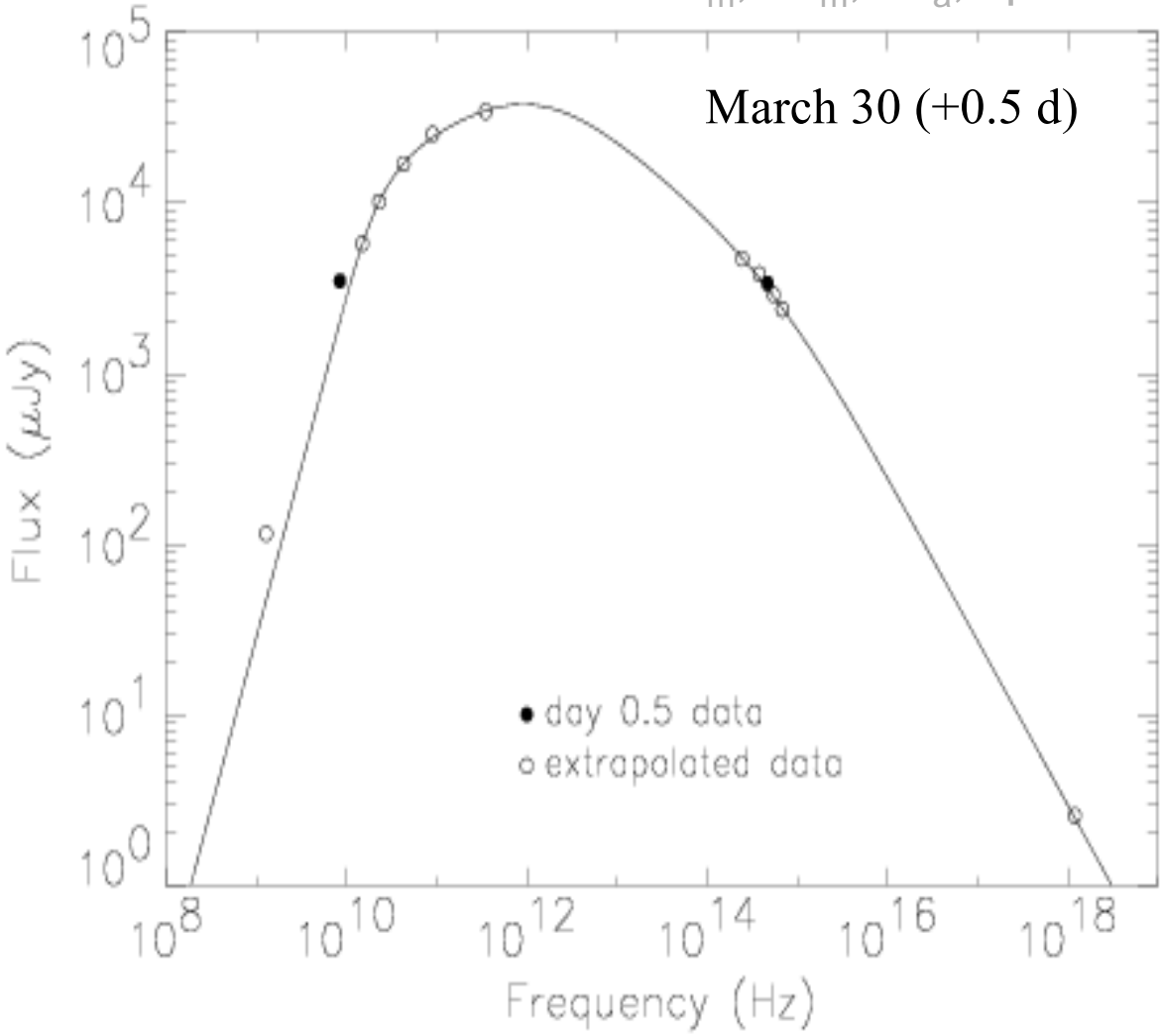




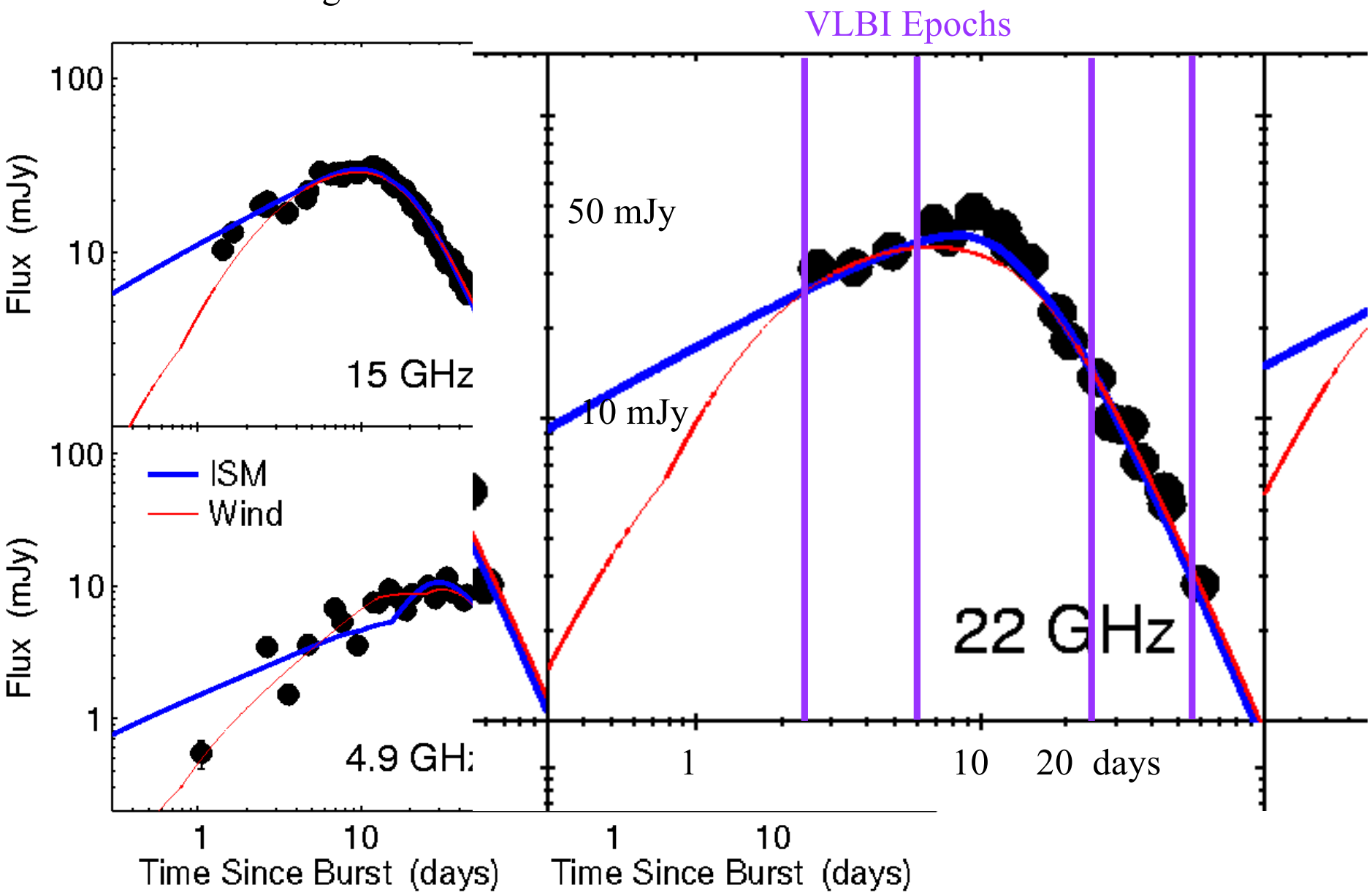
A Scintillating Result

GRB 030329 Synchrotron Spectrum

Basic Parameters: f_m, nu_m, nu_a, spectral index (p)



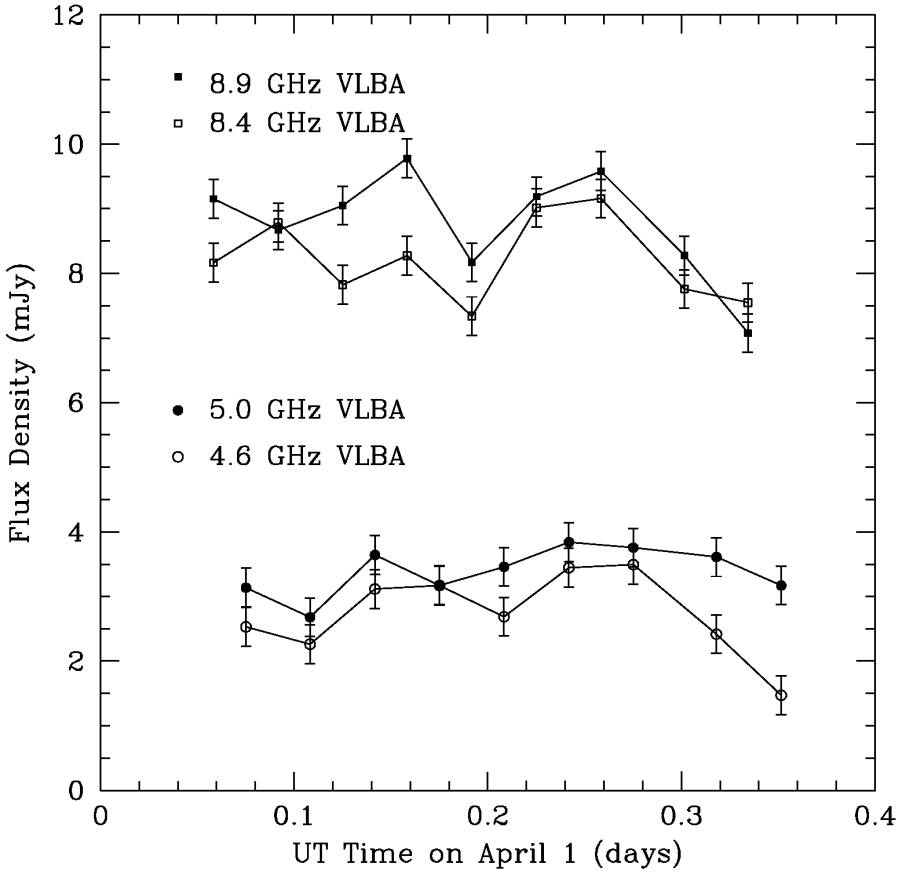
VLA Light Curves (Berger et al 2003, Nature)



The VLBI Campaign - Taylor et al (2004) and Pihlstrom et al (2007)

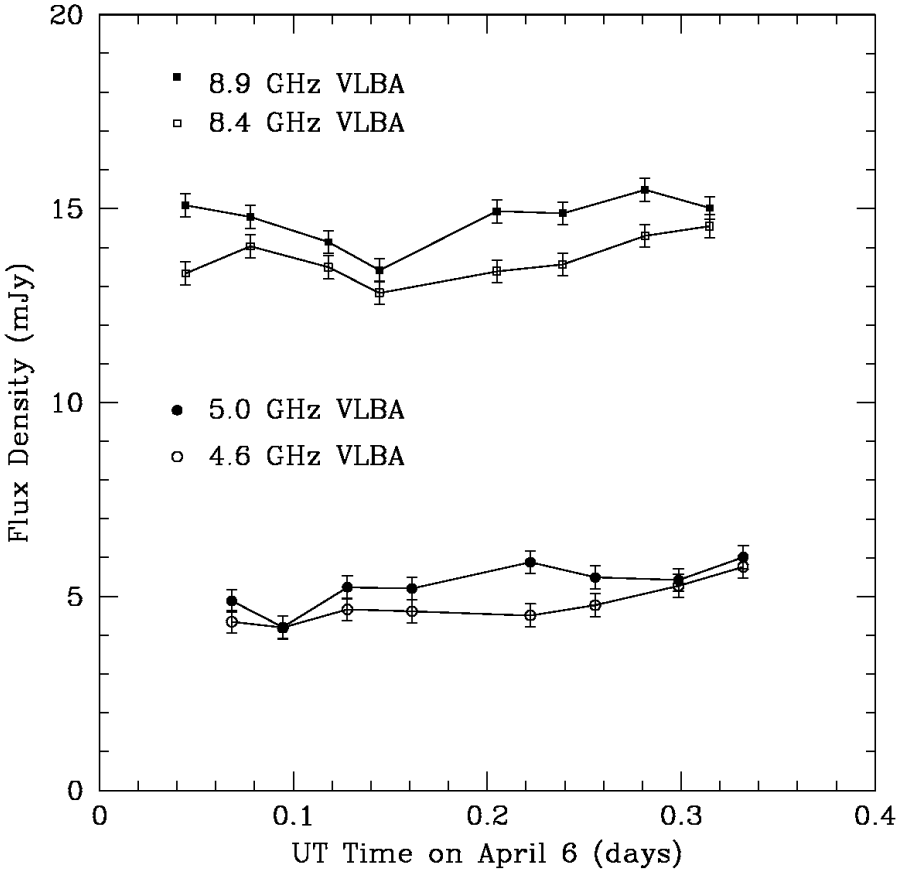
US VLBA 10 antennas	April 1, 2003 +3	5 & 8 GHz
US VLBA 10 antennas	April 6, 2003 +8	5, 8, 15 & 22 GHz
US VLBA + Bonn 100-m	April 22, 2003 +25	15 & 22 GHz
VLBA+Bonn+ GBT+VLA	May 19, 2003 +51	15 & 22 GHz
VLBA+B+WSRT+ VLA+Ar	June 20, 2003 +83	8 GHz
VLBA+B+WSRT+ VLA+Ar+Me+Nt	Nov. 1, 2003 +217	8 GHz

April 1



Modest Scintillation

April 6



Scintillation quenching
size ~ 20 microarcsec

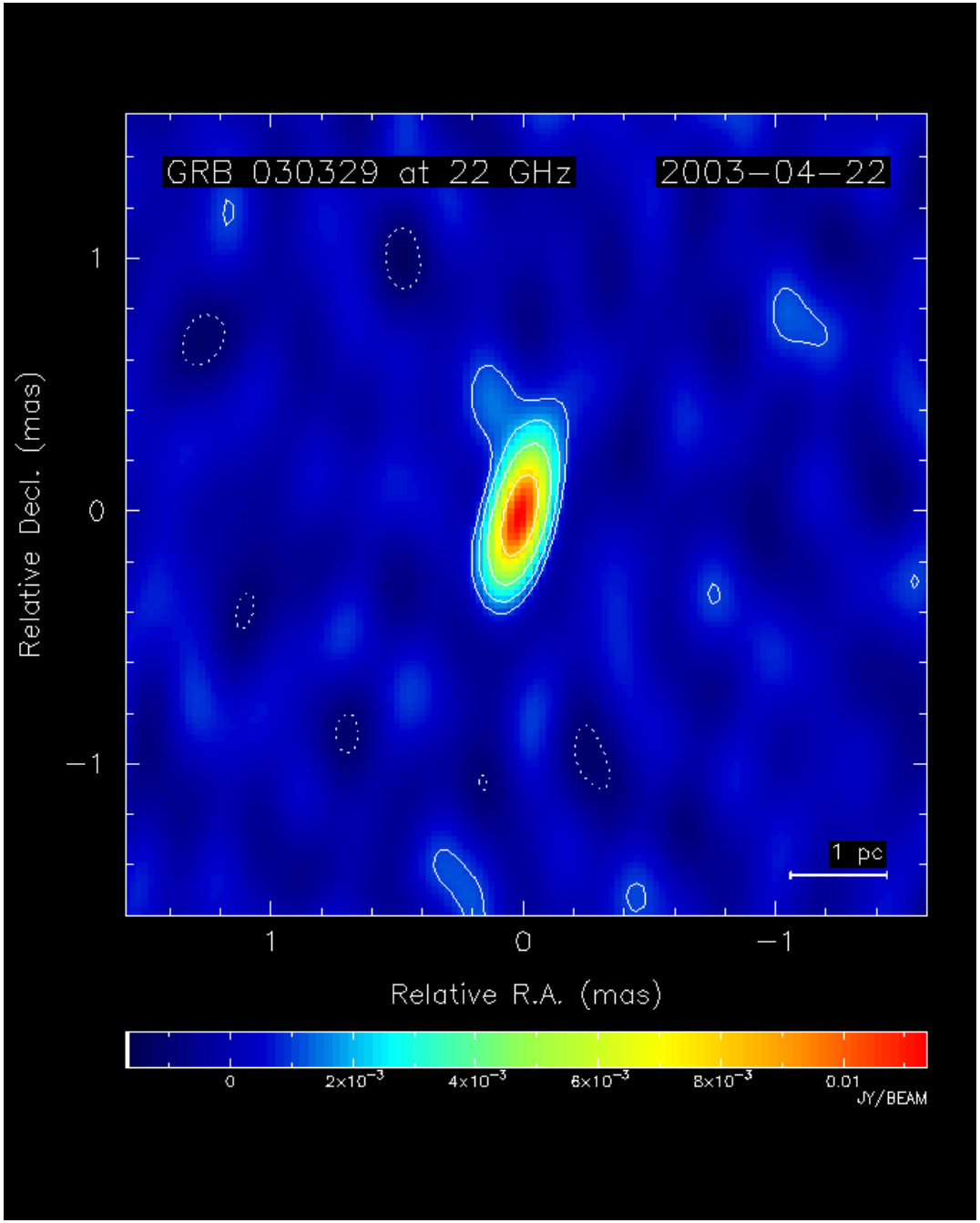
Resolving the Afterglow

3rd Epoch – April 22
VLBA + EB

Beam is 0.45 x 0.15 mas (22 GHz)

Estimated size is
22 GHz : 0.077 +/- 0.036 mas
15 GHz : 0.065 +/- 0.022 mas
(10**18 cm)
(0.2 pc)

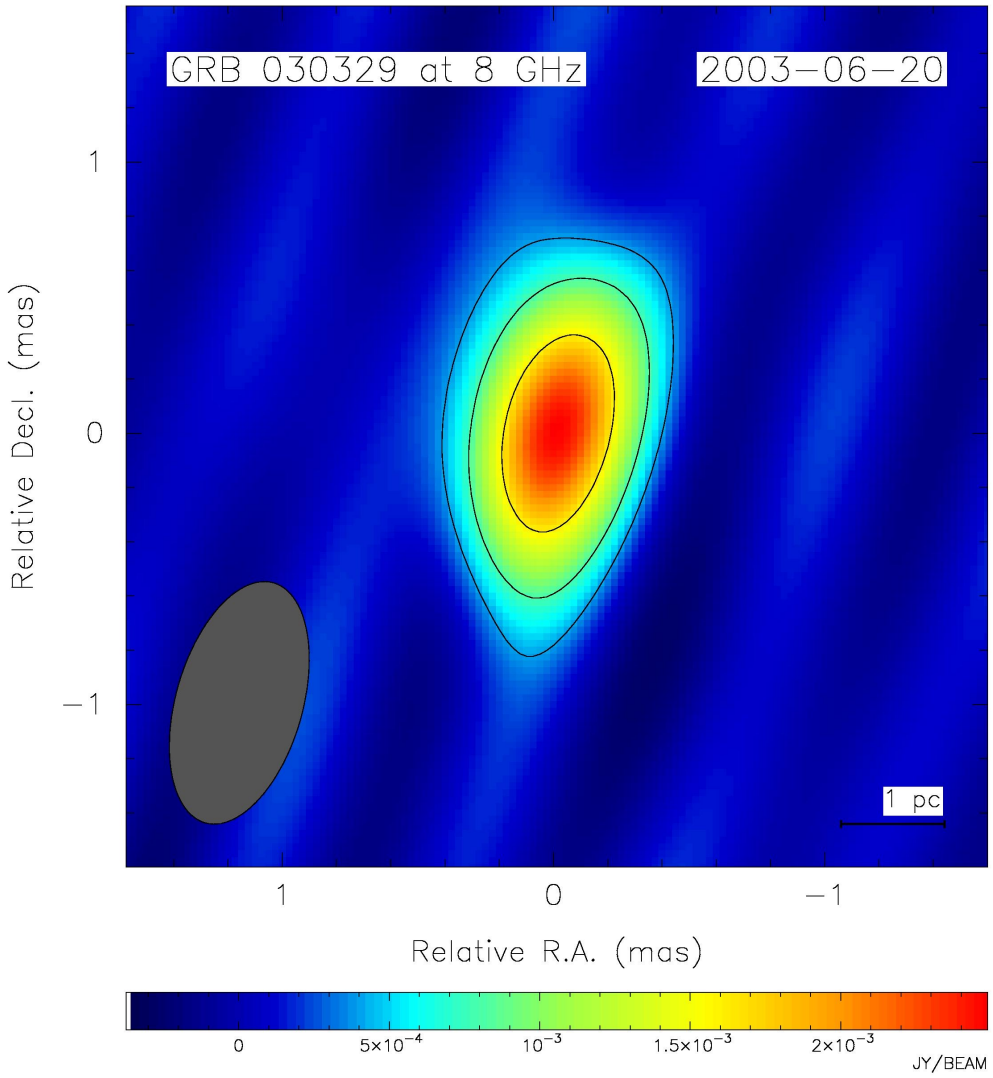
average expansion velocity of 5c



June 20, 2003

+83 days

Peak ~ 3 mJy
Size 0.172 +/- 0.043 mas
0.5 +/- 0.1 pc
average velocity = 3c

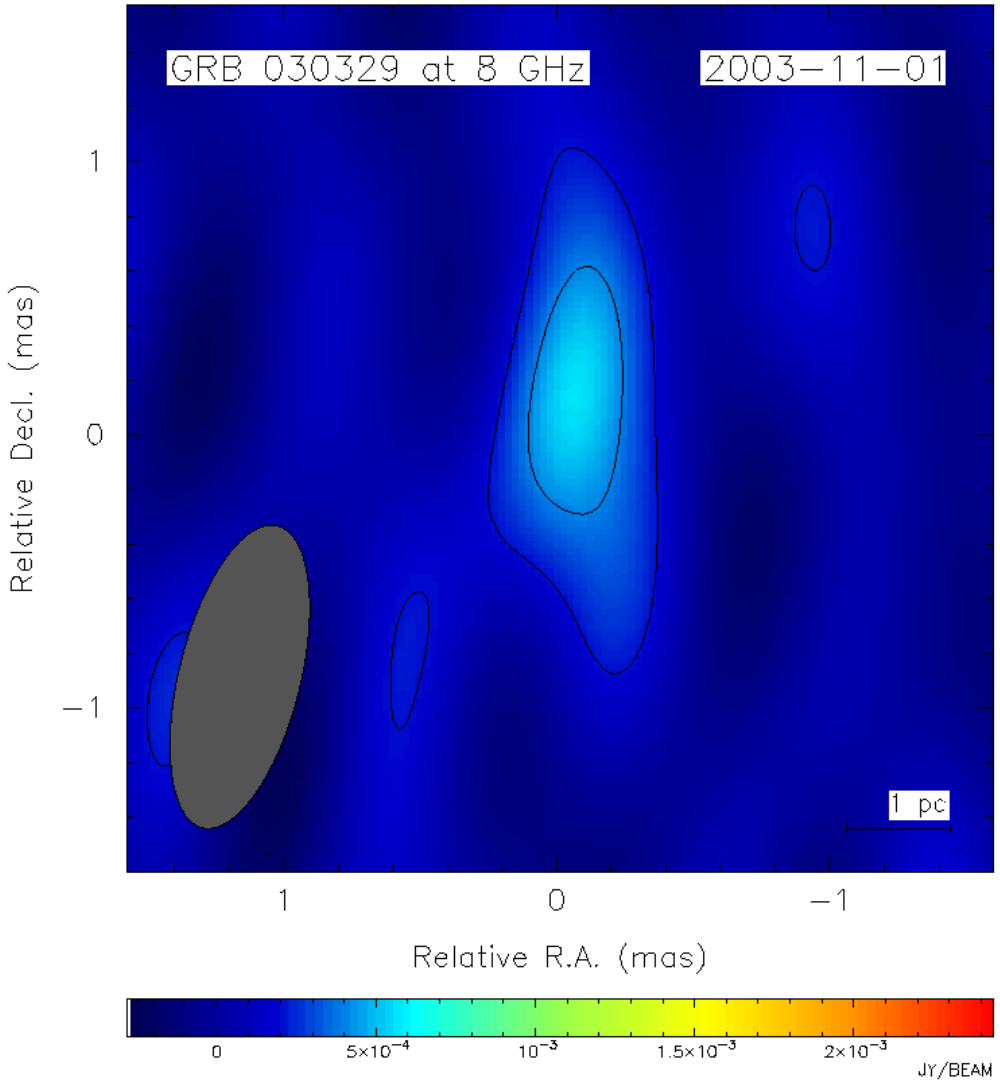


VLBA+Y27+GBT+EB+AR+WB = 0.11 km^2

Nov 1, 2003

+217 days

Peak ~ 0.5 mJy
Size 0.176 +/- 0.08 mas
0.5 +/- 0.2 pc
average velocity = 1.6c



VLBA+Y27+GBT+EB+AR+WB+NT+MC = 0.12 km^2

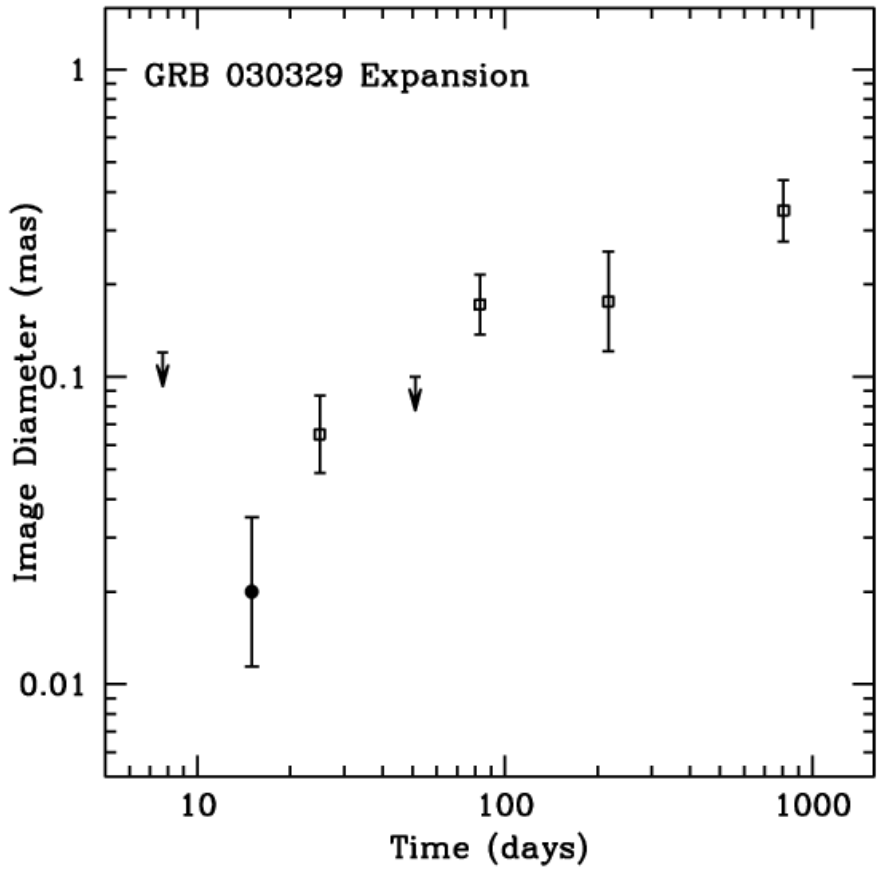
GRB Expansion

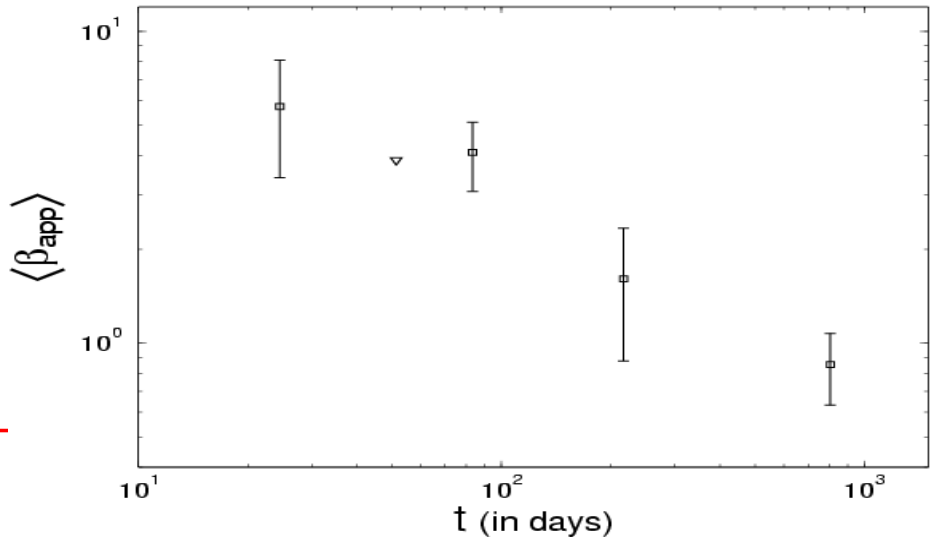
Relativistic
Expansion v ~ 0.96c

E ~ 10^53 ergs
(isotropic equivalent)

$R \sim (E/n)^{1/8}$

Taylor et al 2004
Pihlstrom et al 2007

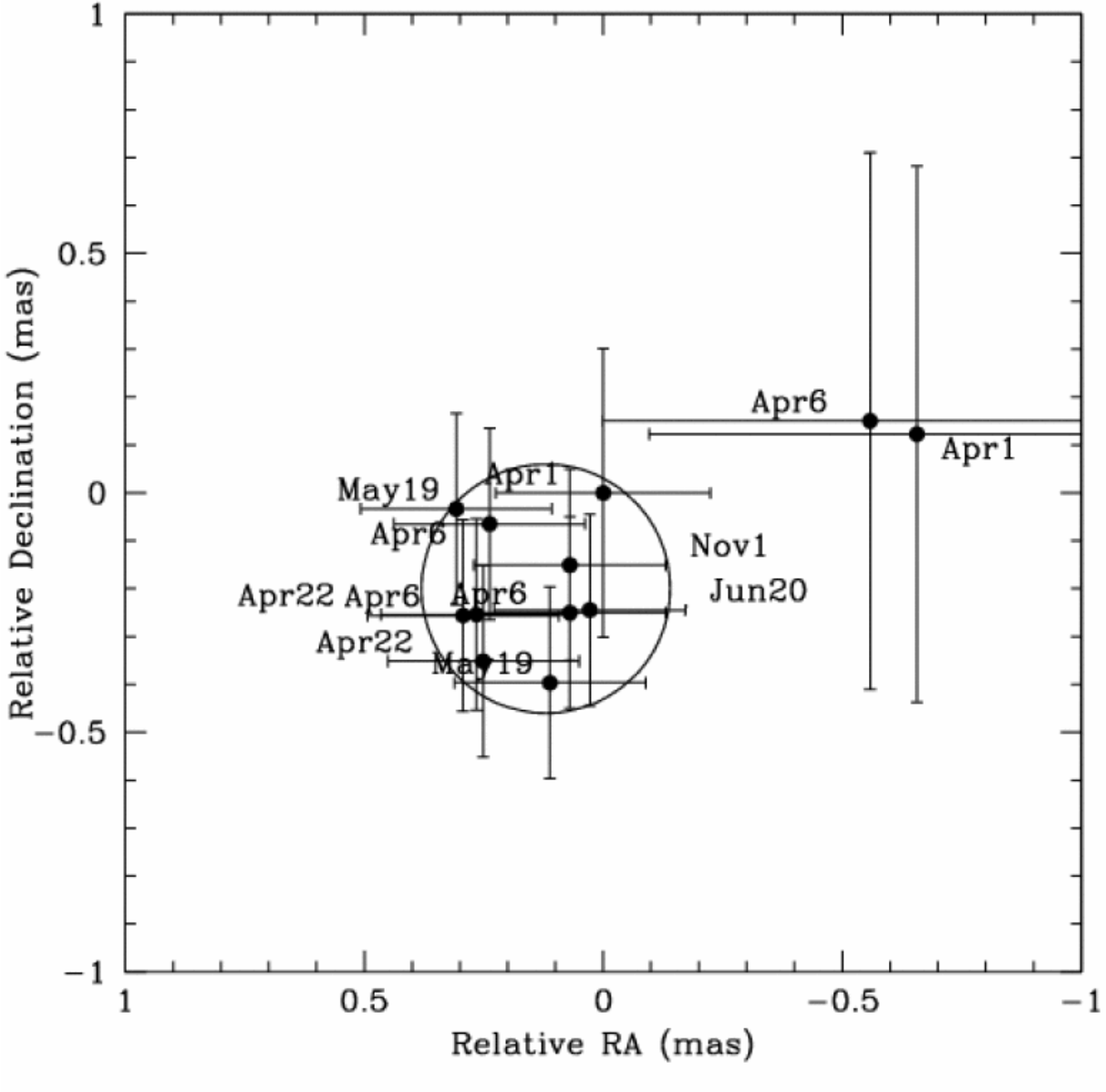




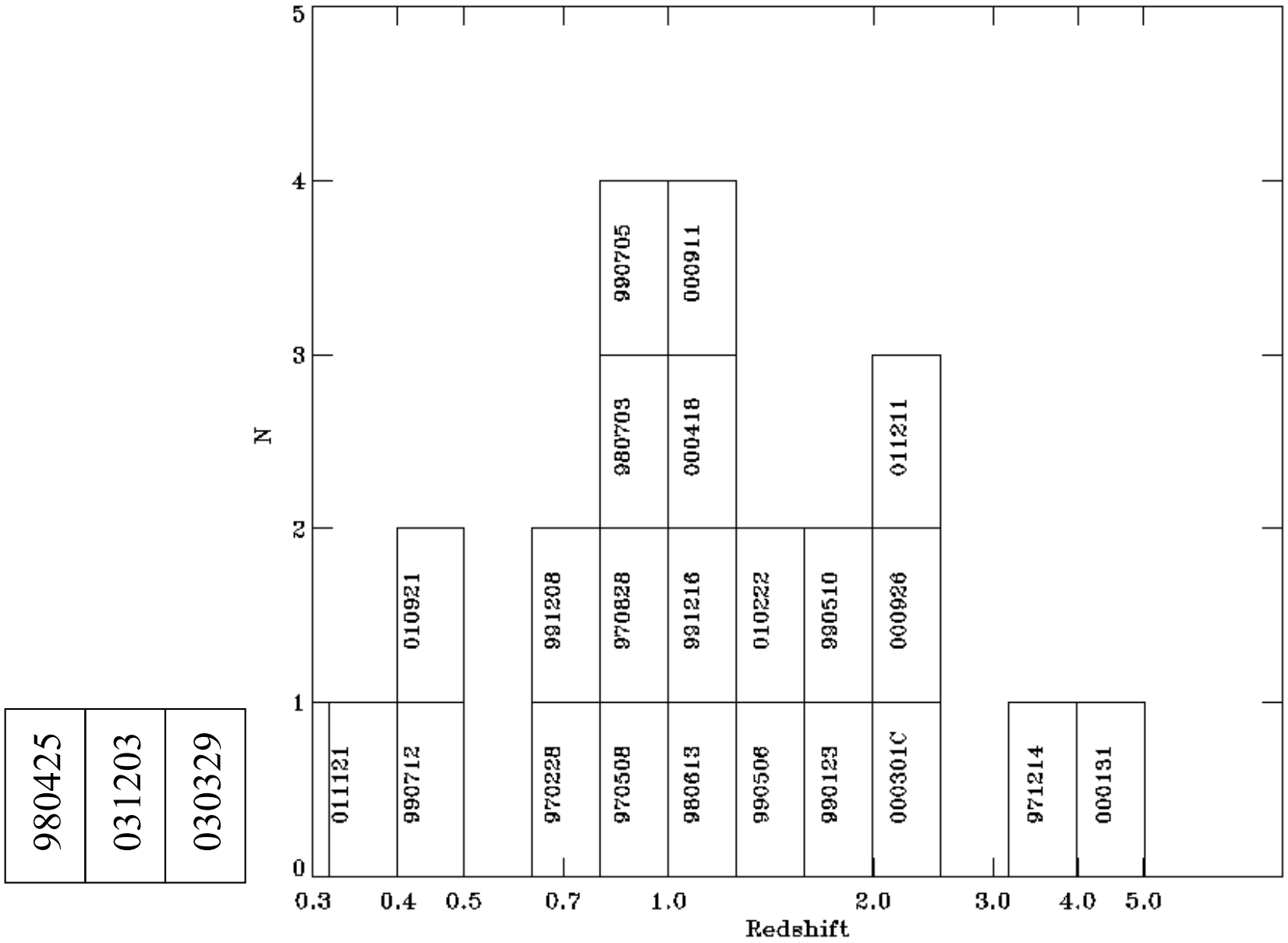
Proper motion limits

RA = -0.05 +/- 0.41 mas/yr
DEC = -0.24 +/- 0.41 mas/yr

motion < 0.28 mas in 217 days
< 0.9 pc



GRB redshift distribution -- Bloom (2002)



Long duration GRBs are a type of Supernova "Hypernova"

- Peak toward low end of gamma-ray, complex gamma-ray light curves
- Often have bright afterglows
- Evidence for a relativistic explosion
- Energy required of ~ 10^{53} ergs (isotropic)
- Associated with regions of star formation in distant galaxies (out to edge of observable universe)
- Sometimes obscured by dust

Relativistic Jets From Collapsars

S.E. Woosley's Group

Inital Model: he15

480 radial zones, 200 angular zones

Energy Deposition Rate: 10^{51} ergs/s

Half Opening Angle: 20

$f_e(E_{th}/E_{tot})$: 0.67

Lorentz Factor: 50