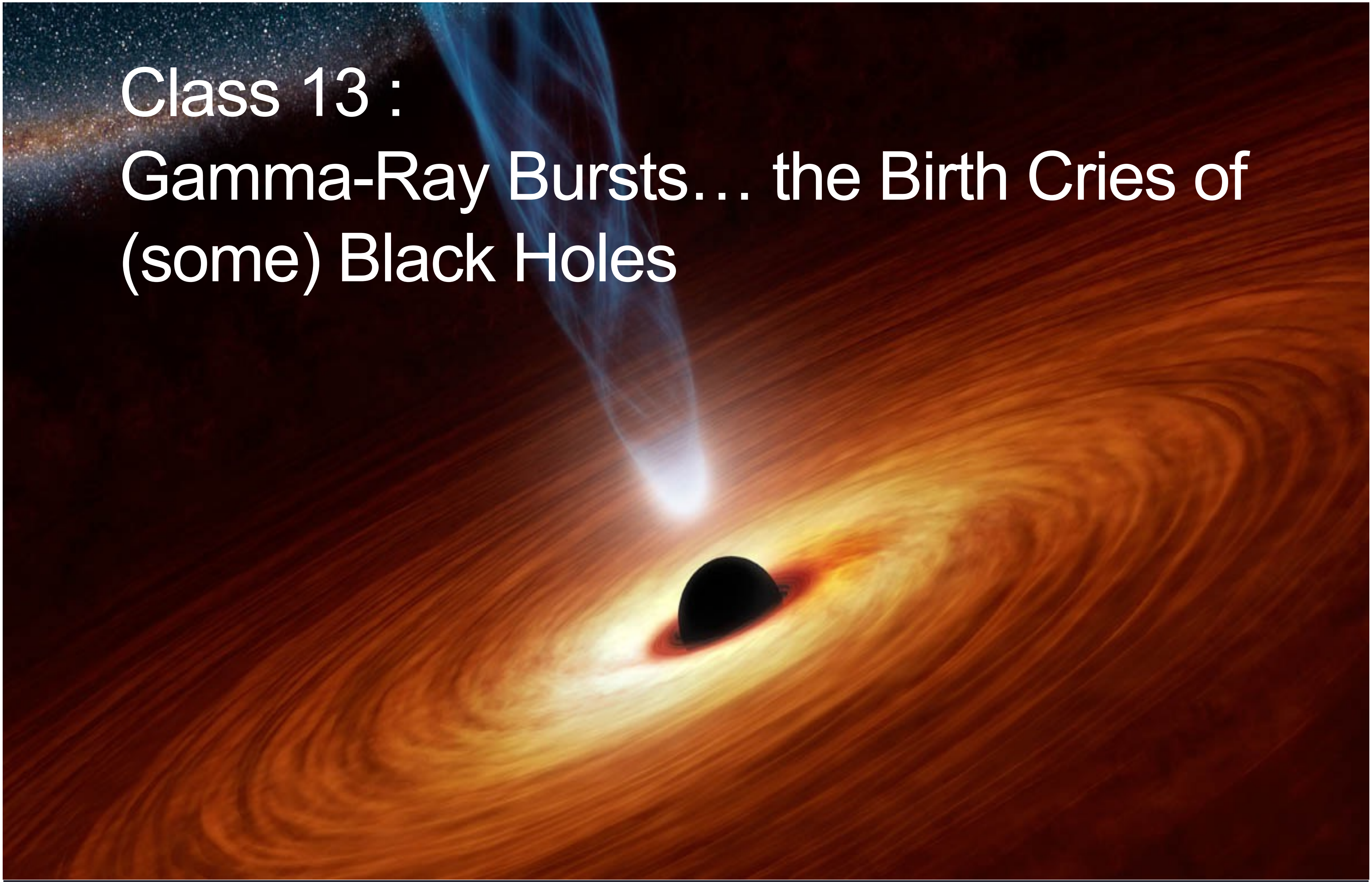
Class 13 : Gamma-Ray Bursts… the Birth Cries of (some) Black Holes



ASTR350 Black Holes (Spring 2022)

Cole Miller

RECAP

- Last time…
  - Development of X-ray astronomy
  - Discovery of Cygnus X-1 and its ID as a black hole
  - X-ray binaries and X-ray pulsars

This class

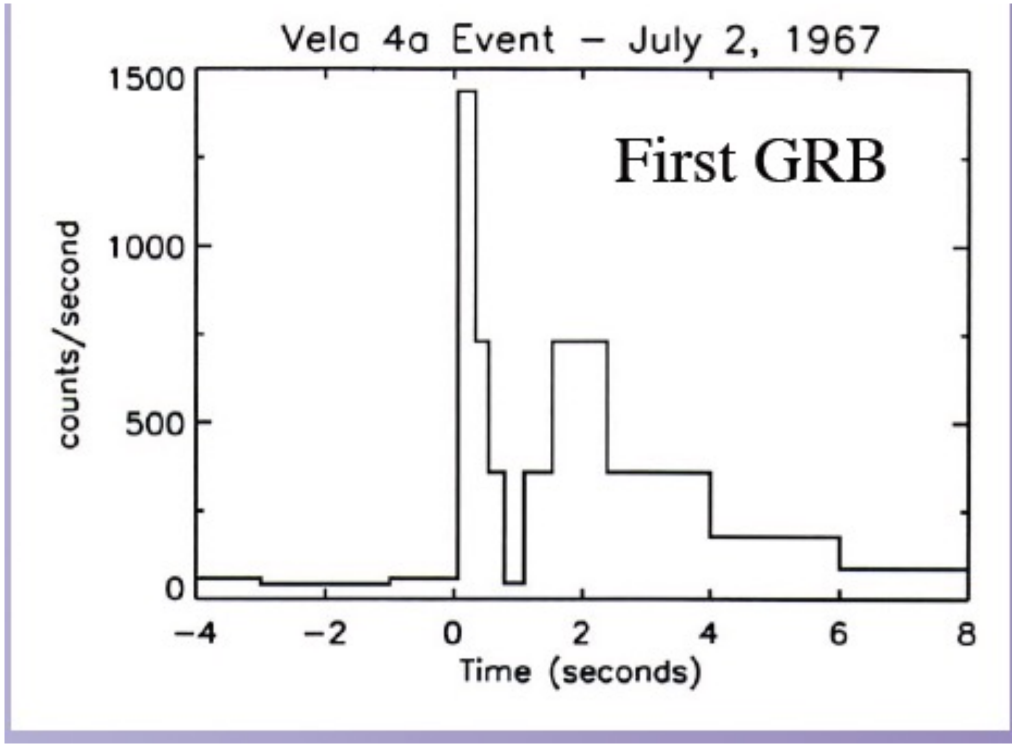
- Stellar mass black holes just are created in supernovae, right? Well, it may be a bit more interesting than that…
- Gamma-Ray Bursts!
  - Discovery by the US military
  - Long search for their basic nature
  - **Connection to the birth of black holes**
  - **two types**

I : Discovery of GRBs

- 1963: US and USSR ban above-ground nuclear tests
  - How to police the treaty?
  - Well… nuclear weapons generate gamma-rays when they detonate, so both militaries launched gamma-ray detectors into orbit
  - US has the “Vela” program
  - Started seeing flashes of gamma-rays from space! First seen in 1967, announced 1973
  - Basic nature very uncertain!
- 1991 : NASA Launched Compton Gamma-Ray Observatory (CGRO) to investigate further

Gamma-Ray Bursts

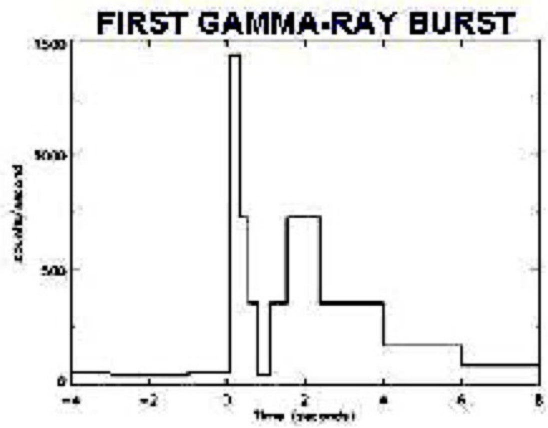
- Cosmic γ-ray bursts (GRBs) were first reported by Klebesadel et al (l973) but were first seen on July 2, 1967, based on data from US satellites designed to monitor Russian nuclear weapons tests in space
- GRBs/GRB afterglows: brightest radiation from most distant sources in the universe
- New type of object emitting most of its energy in the gamma-ray band



While they are on, they can outshine the sum of all other sources in the γ-ray sky, including the Sun

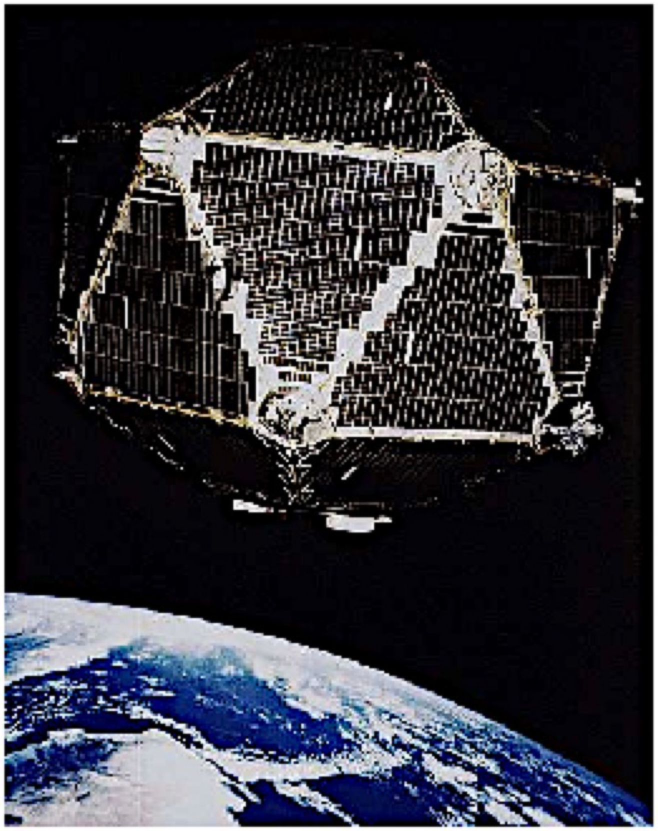
Most of their energy is emitted in the 10-1000 keV band

Discovery



1967: Vela satellites find extremely bright flares from the sky, with durations of a few seconds: Gamma-Ray Bursts (GRBs; total of 73 GRBs found between).

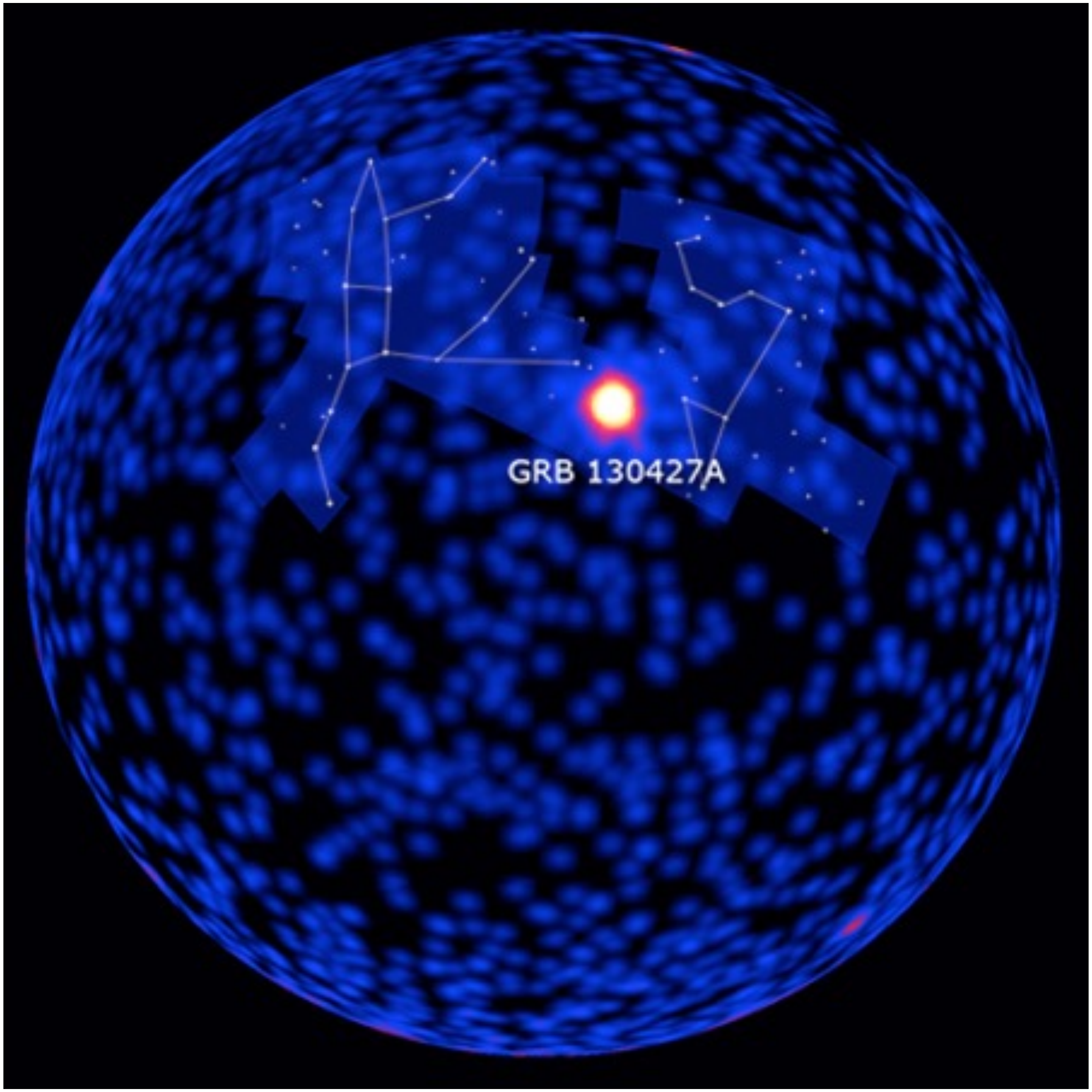
Reported in 1973 only (Klebesadel et al., 1973).



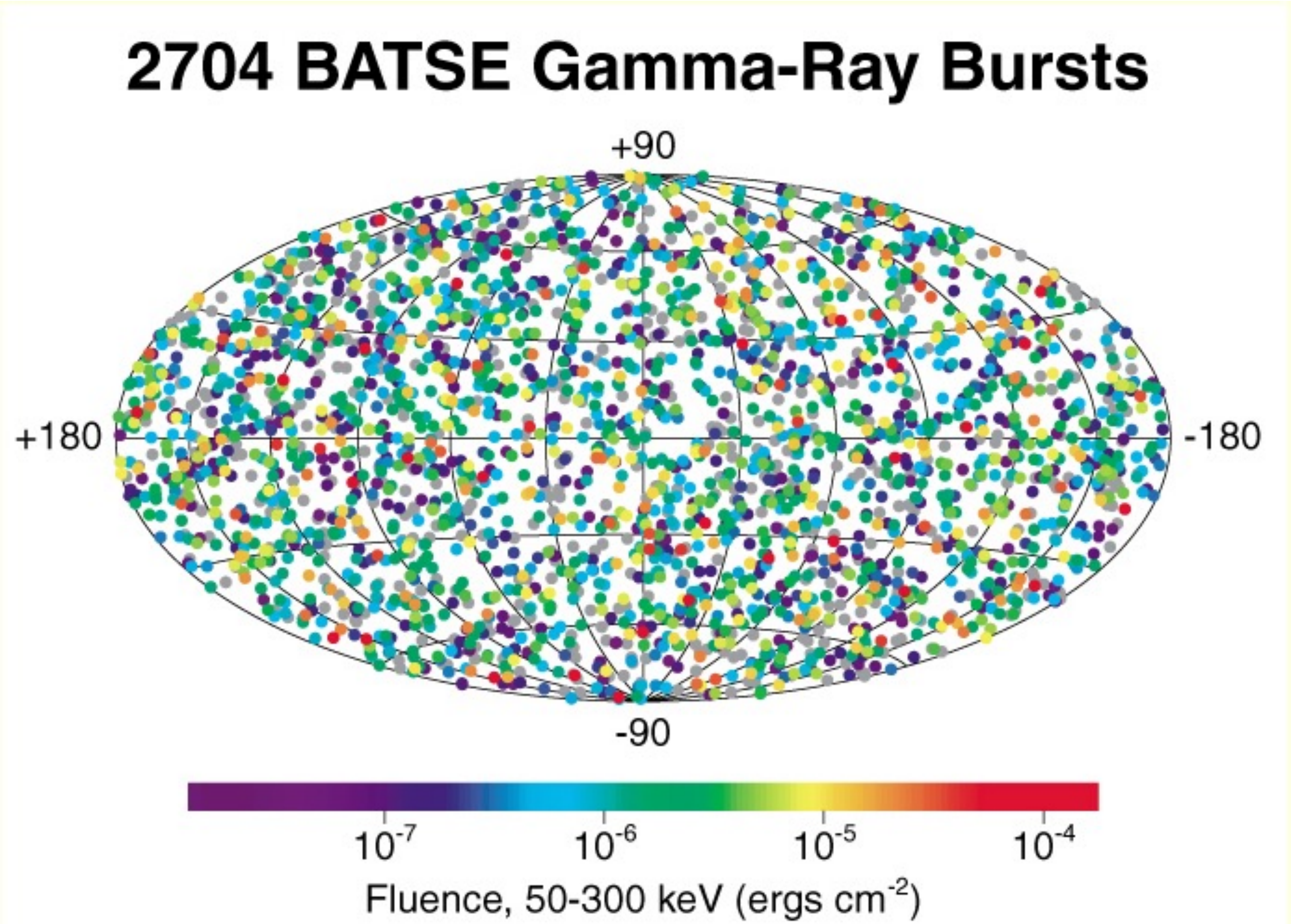
Sketch of one of the Vela satellites to search for violations of the nuclear test ban treaty.

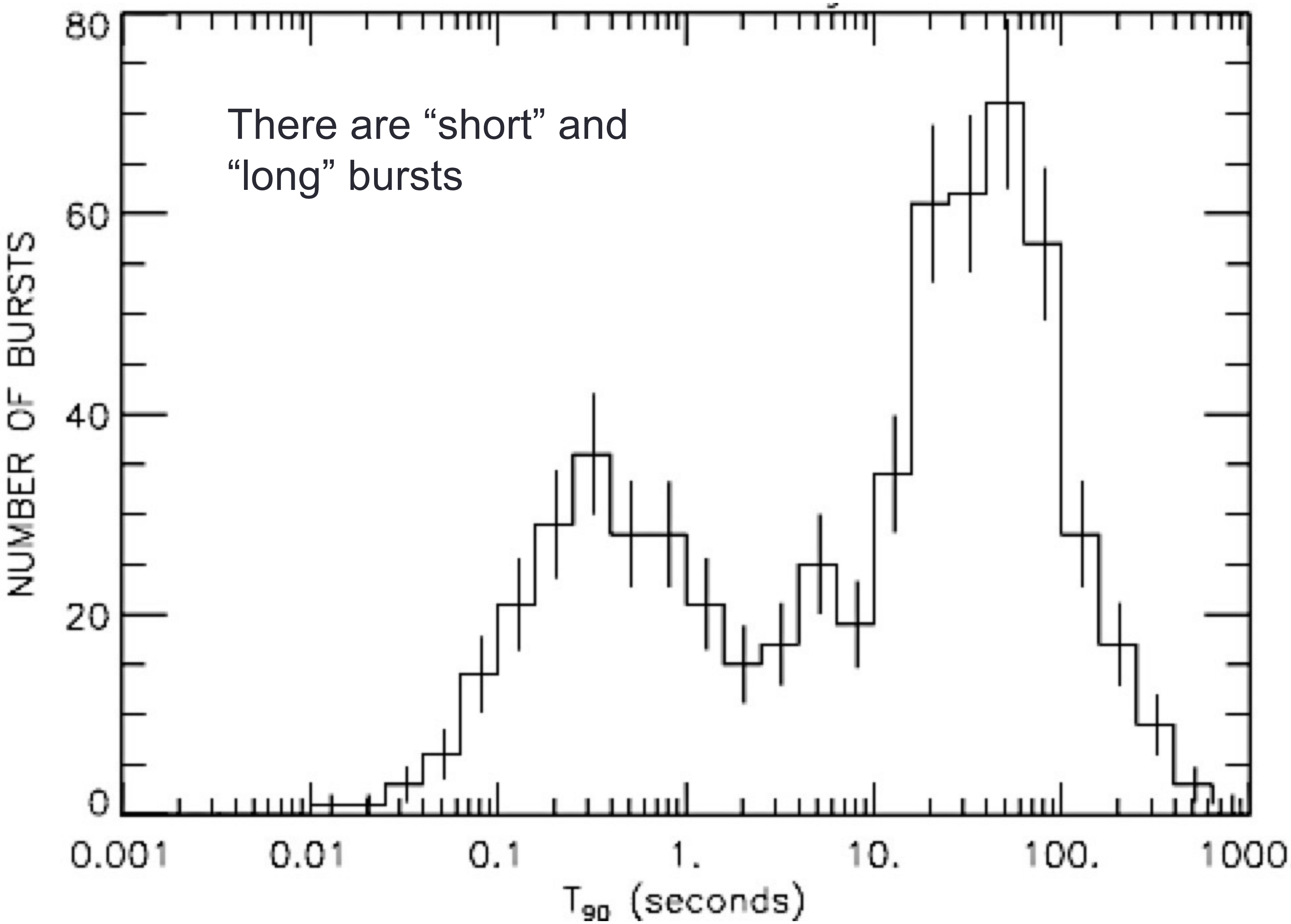
During the burst, GRBs are the *brightest* gamma-ray objects in the sky, brighter than the Sun!

Image of γ-ray Sky During Burst



Gamma-ray Observatory-GRO/**BATSE**




There are “short” and “long” bursts
NUMBER OF BURSTS
80
60
40
20
0
0.001
0.01
0.1
1.
10.
100.
1000.
T90 (seconds)

II : Getting to the bottom of GRBs

- GRBs are:
  - Common (~one a day) all sky
  - Uniform on the sky
  - Come in “short” and “long” forms
- What can we deduce from these facts?
  - isotropic distribution indicated either that they are very far away (cosmological) or very close
  - two forms suggest 2 'types'
  - lack of obvious counterparts in other wavelength bands suggests new type(s) of objects
- How do we learn more?

Need to Get a Counterpart in Other Wavelength Band

- In the 1990's there was no known class of object that emitted most of its energy in the 10-1000keV band
- To determine what GRBs 'are' need a optical/IR counterpart which would allow an estimate of their distance and nature of the host (were they in galaxies like AGN?)

Breakthrough

Breakthrough in 1997 with BeppoSax- an Italian x-ray mission

It was slewed rapidly to a localized region containing the burst

- Found x-ray afterglows- source flux decayed rapidly but if got to it soon enough a 'new' x-ray source was always found.
- The x-ray position was accurate enough to identify an optical counterpart- a 'normal' galaxy at large distances.

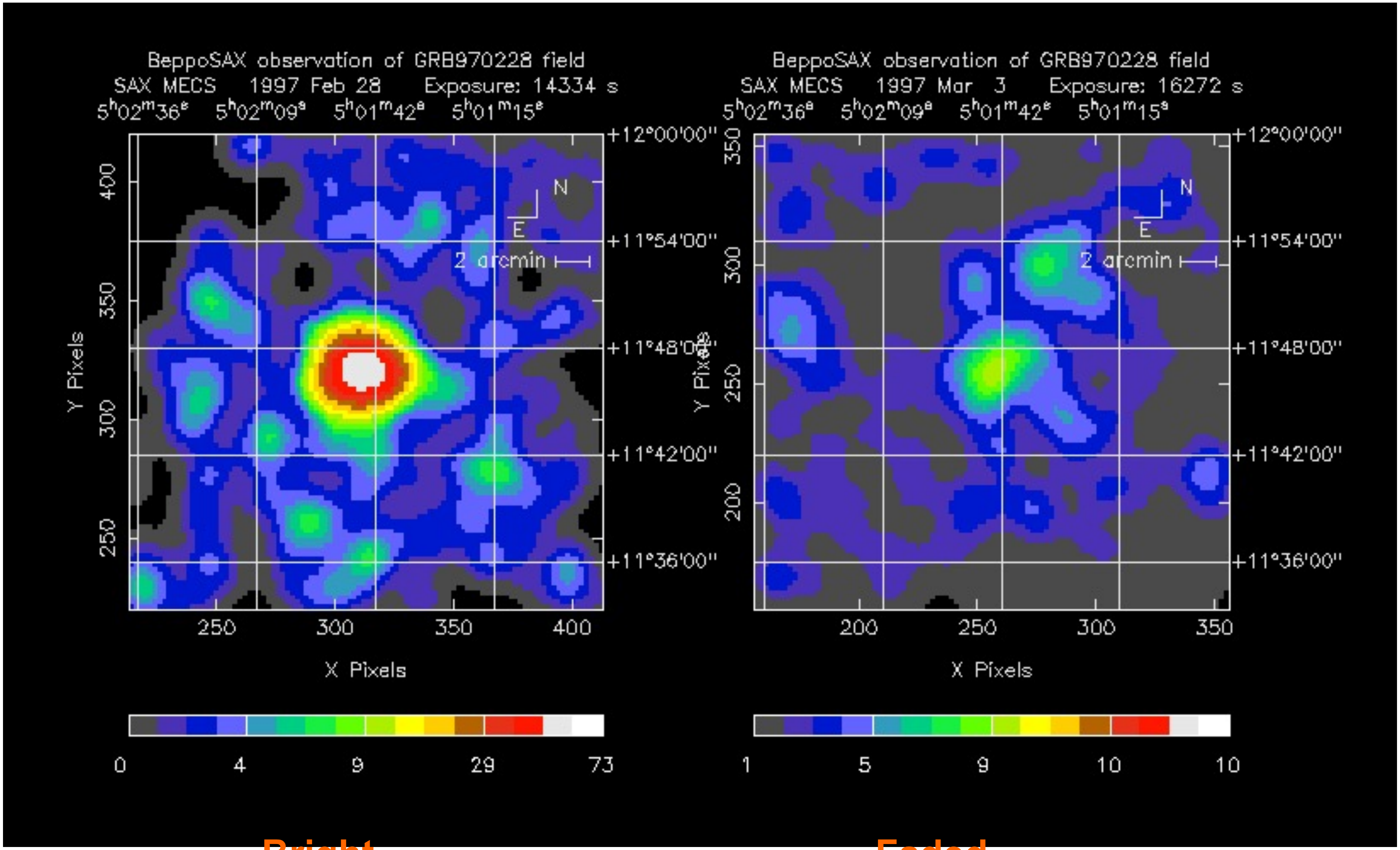
Able to localize ~10 bursts per year to accuracies of a few arcminutes.

a small enough area that optical and X-ray pointed observations could be brought to bear quickly.

People then looked for initially bright sources that faded... and found them.

High Energy Transient Explorer would have obtained results earlier... but upon its launch on 4 November 1996, bolts failed to release last stage; re-entered atmosphere

Discovery of Nature of Counterparts

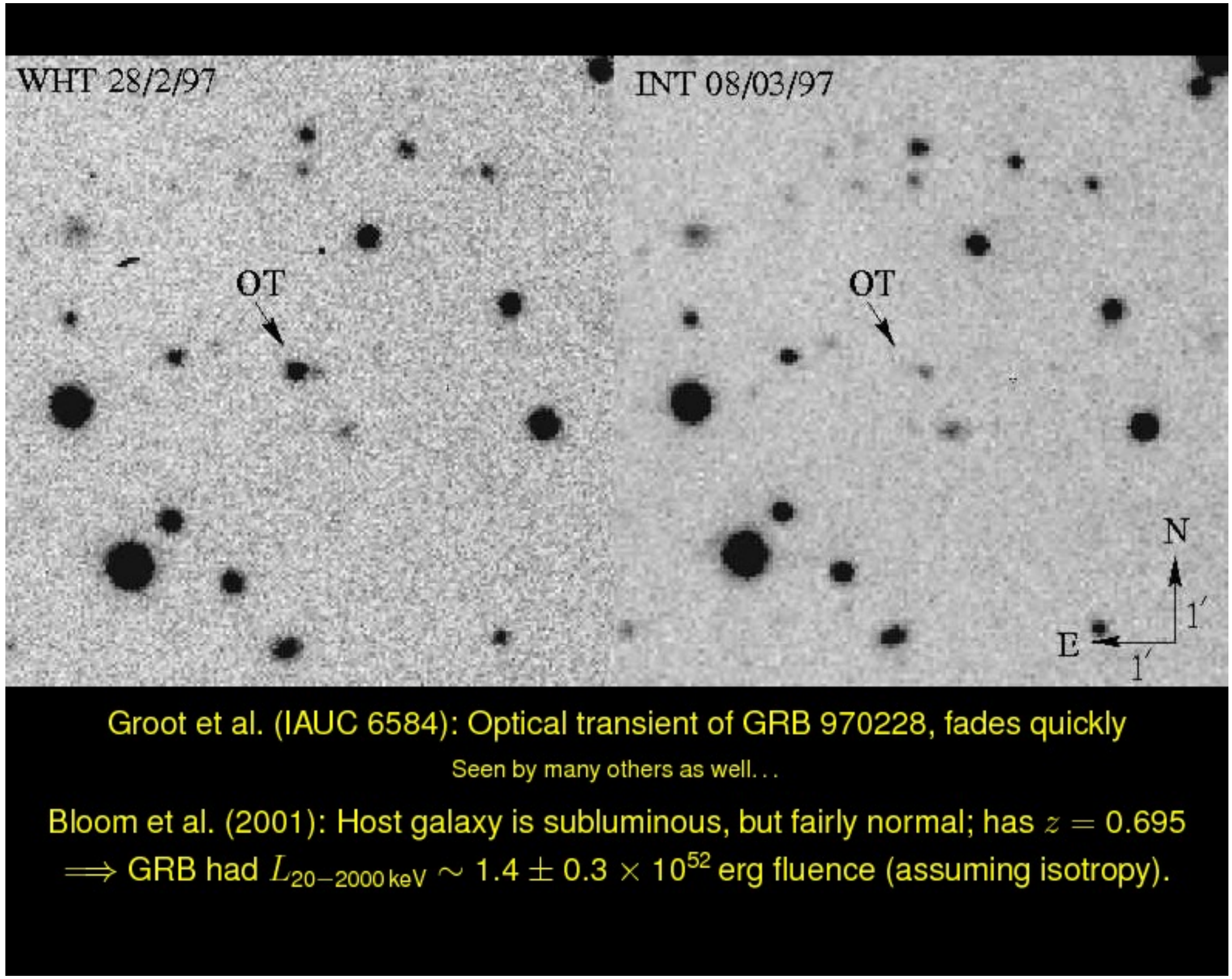


Bright

Faded

Optical Counterpart Identified

- Fades rapidly... but redshift of 0.695 (D~1490Mpc)
- GRBs are very distant! and thus extremely luminous!



Groot et al. (IAUC 6584): Optical transient of GRB 970228, fades quickly

Seen by many others as well. . .

Bloom et al. (2001): Host galaxy is subluminous, but fairly normal; has $z = 0.695$

$\Longrightarrow$ GRB had $L_{20-2000\,\mathrm{keV}} \sim 1.4 \pm 0.3 \times 10^{52}$ erg fluence (assuming isotropy).

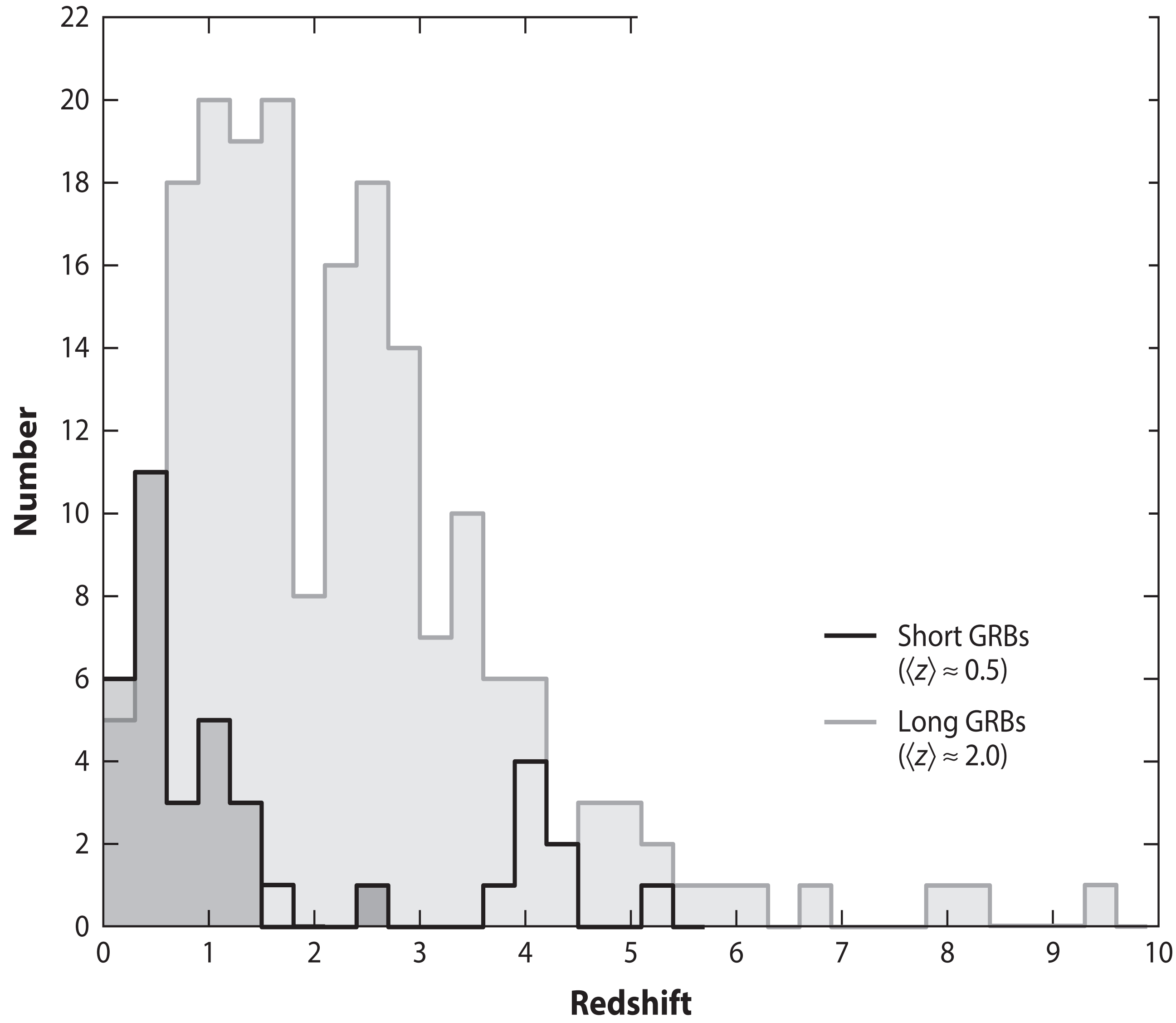
GRB had L~10^{50} ergs- equivalent to 1 trillion years of solar luminosity

Redshifts

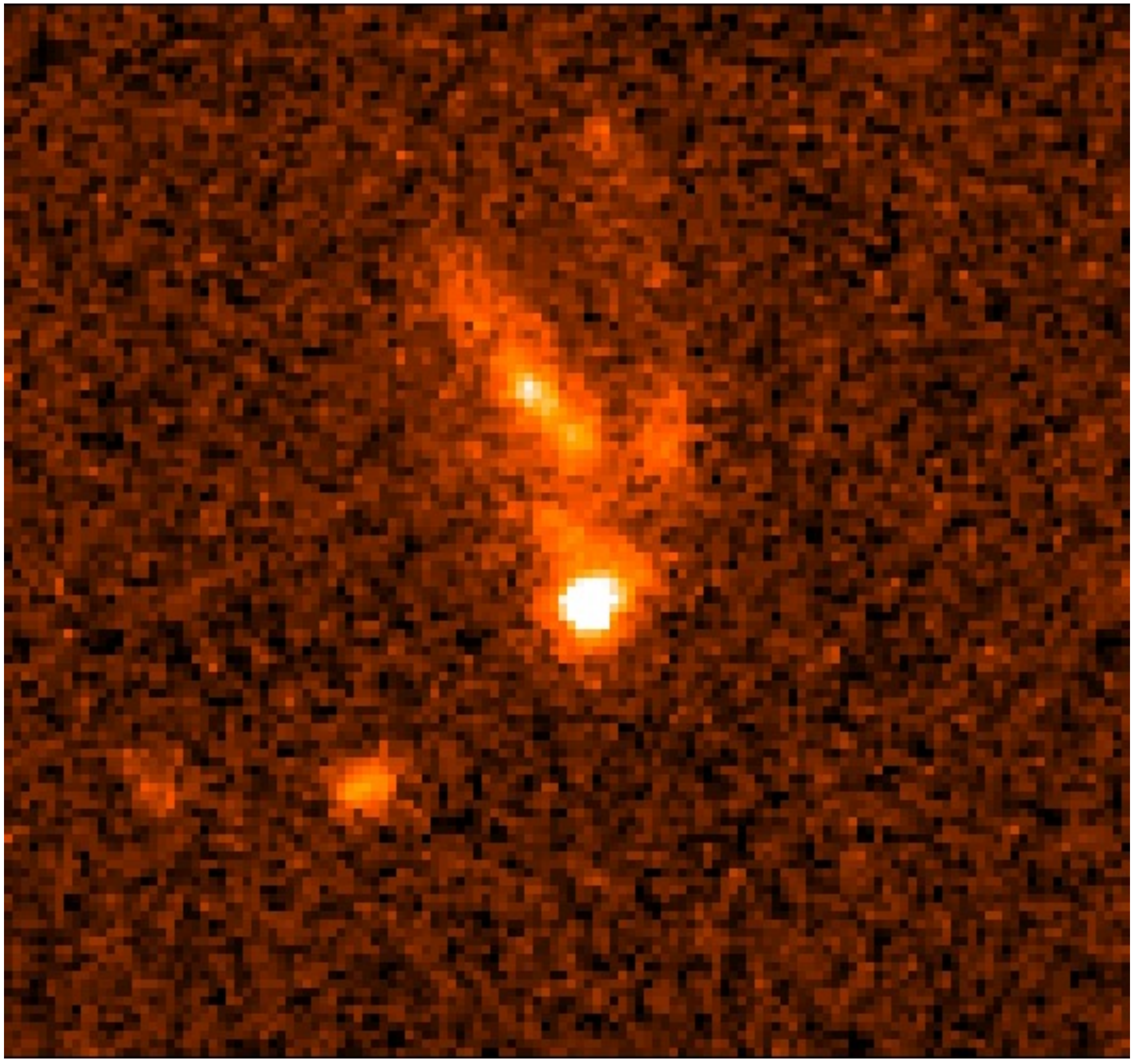
- In an expanding universe (like ours) the farther an object is away from us the faster it appears to move away from us
- Using the Doppler effect, if an object is moving away the light is redshifted
- The relationship between distance and redshift is called the Hubble relation
  - at small distances $D=cz/H_0$ where H_0 is the Hubble constant, c is the speed of light and z is the redshift

Redshift Distribution of Short and Long Bursts
(Berger 2014)

Long GRBs are among the most distant objects known (redshift=7 universe only 700Myrs old)



OK… so they are in distant galaxies. So what??

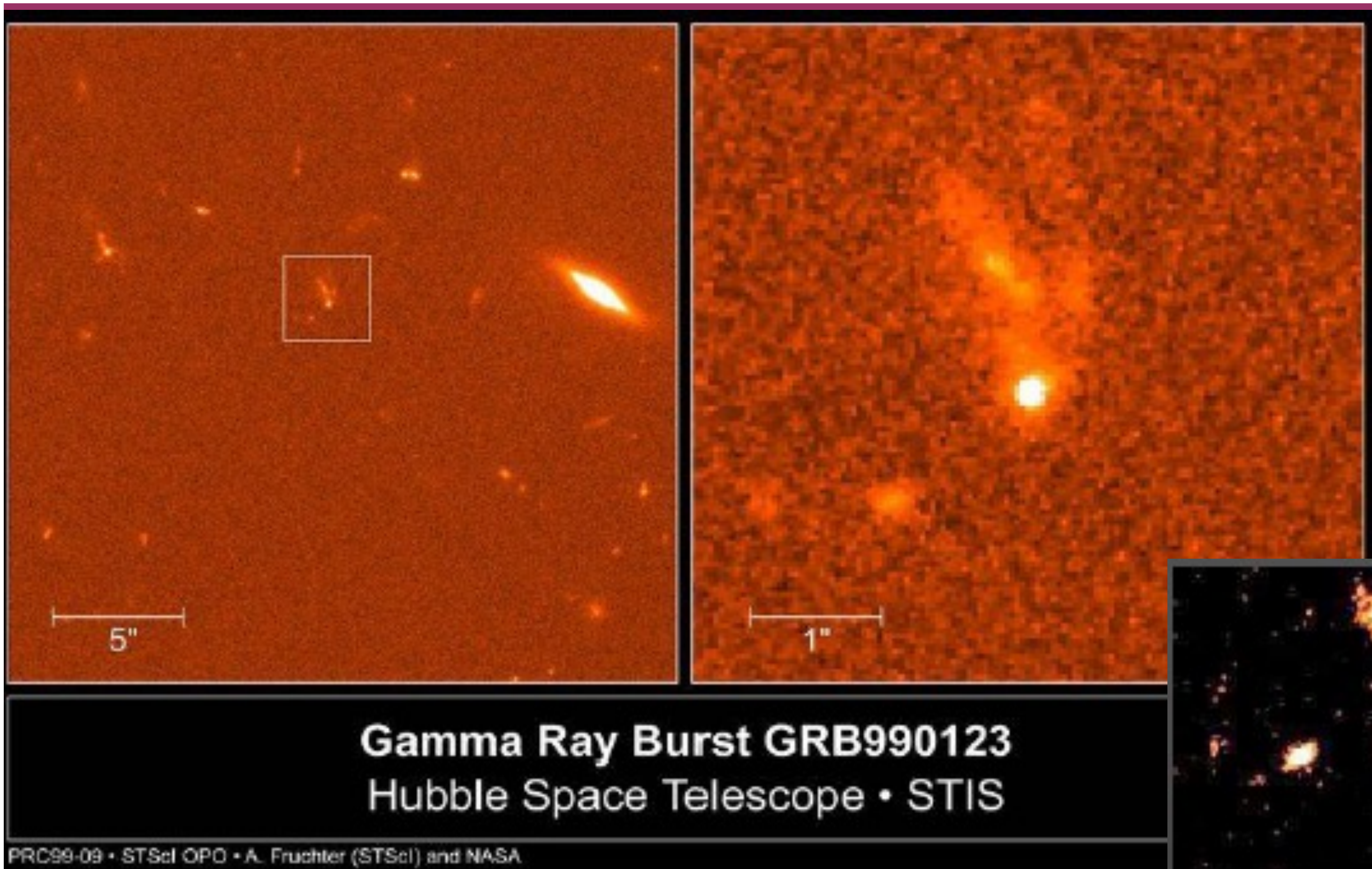


Gamma-Ray Bursts-

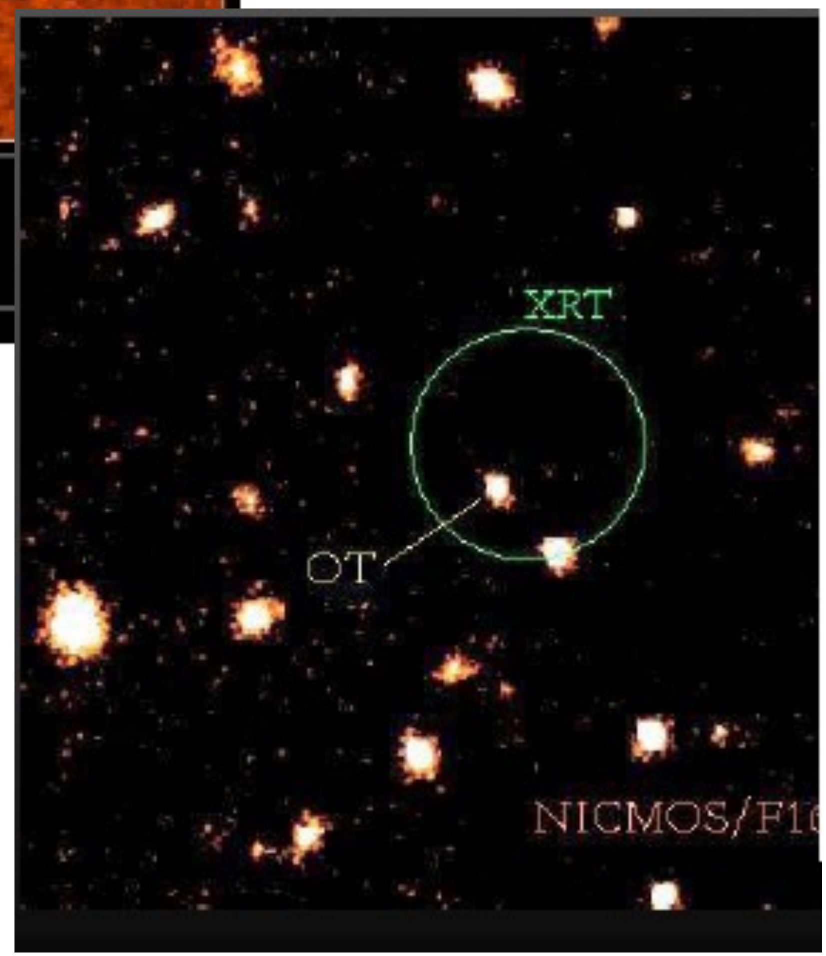
- Are bright flashes of γ-rays-for a short period of time (<100 sec)
- energy emitted primarily in the 20-500 keV band.
  - Distribution is isotropic on the sky
  - **They are at very large distances (z up to 8 (!)) with apparent energy release of ~10^{54} erg **IF** energy is isotropic**
  - Rate is ~10^{-7}/yr/galaxy
- What are they?- short timescales imply compact object ; Mc^2 implies M~10^{33} gms~ M_{sun} if total conversion of mass into energy How does all this energy end up as γ-rays ?
  - Location of long γRBs is in and near star forming regions in smallish galaxies- associated with star formation
  - a few γRBs have been associated with a *type of supernova*

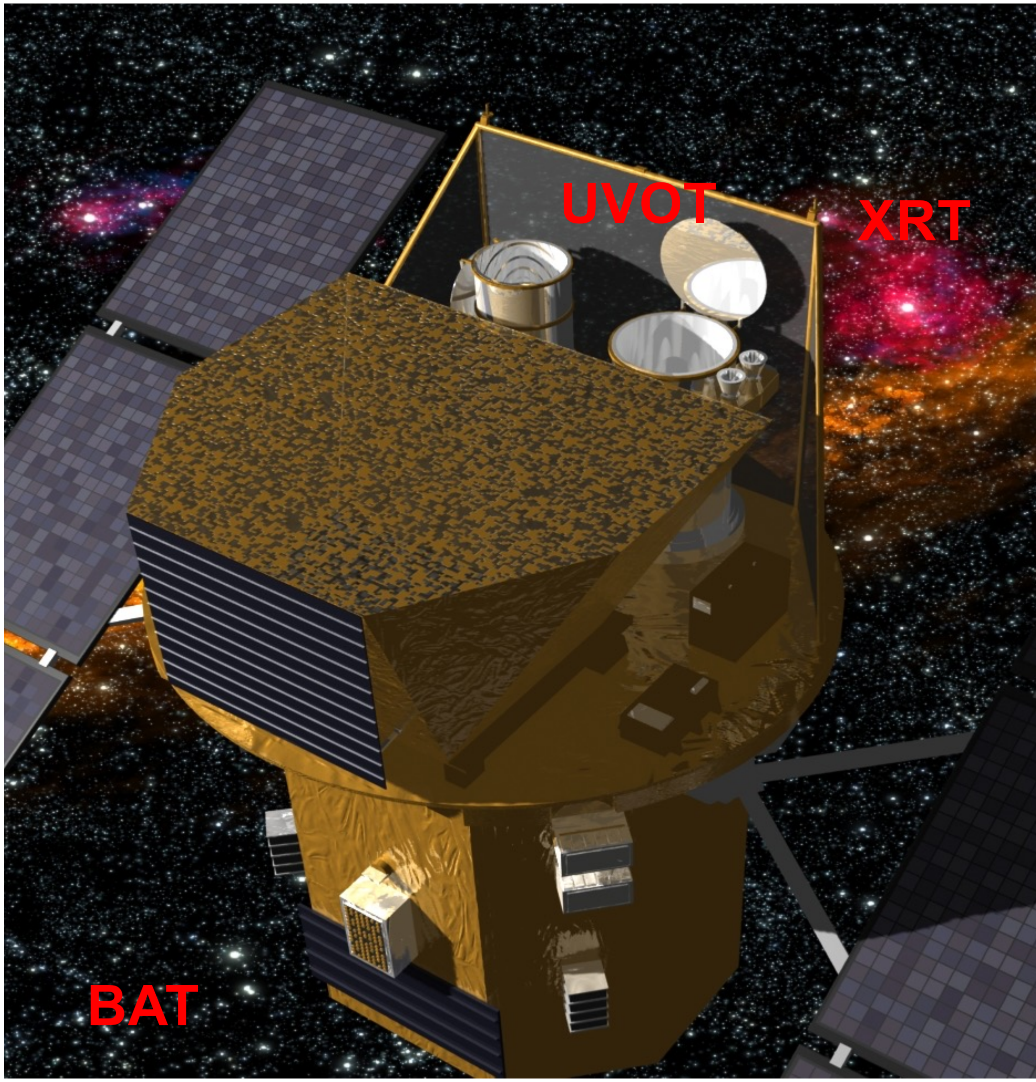
III : The Swift Era

- NASA launched “Swift” in 2004
  - Amazing automated spacecraft
  - X-ray detector (BAT)with “fuzzy” imaging but huge field of view detects GRBs
  - Then… spacecraft automatically slews, bringing a high-definition X-ray telescope and an optical/UV telescope to bear
  - Maneuver takes less than 1 minute
  - Then tells ground-based astronomers exactly where to point all of their other instruments!



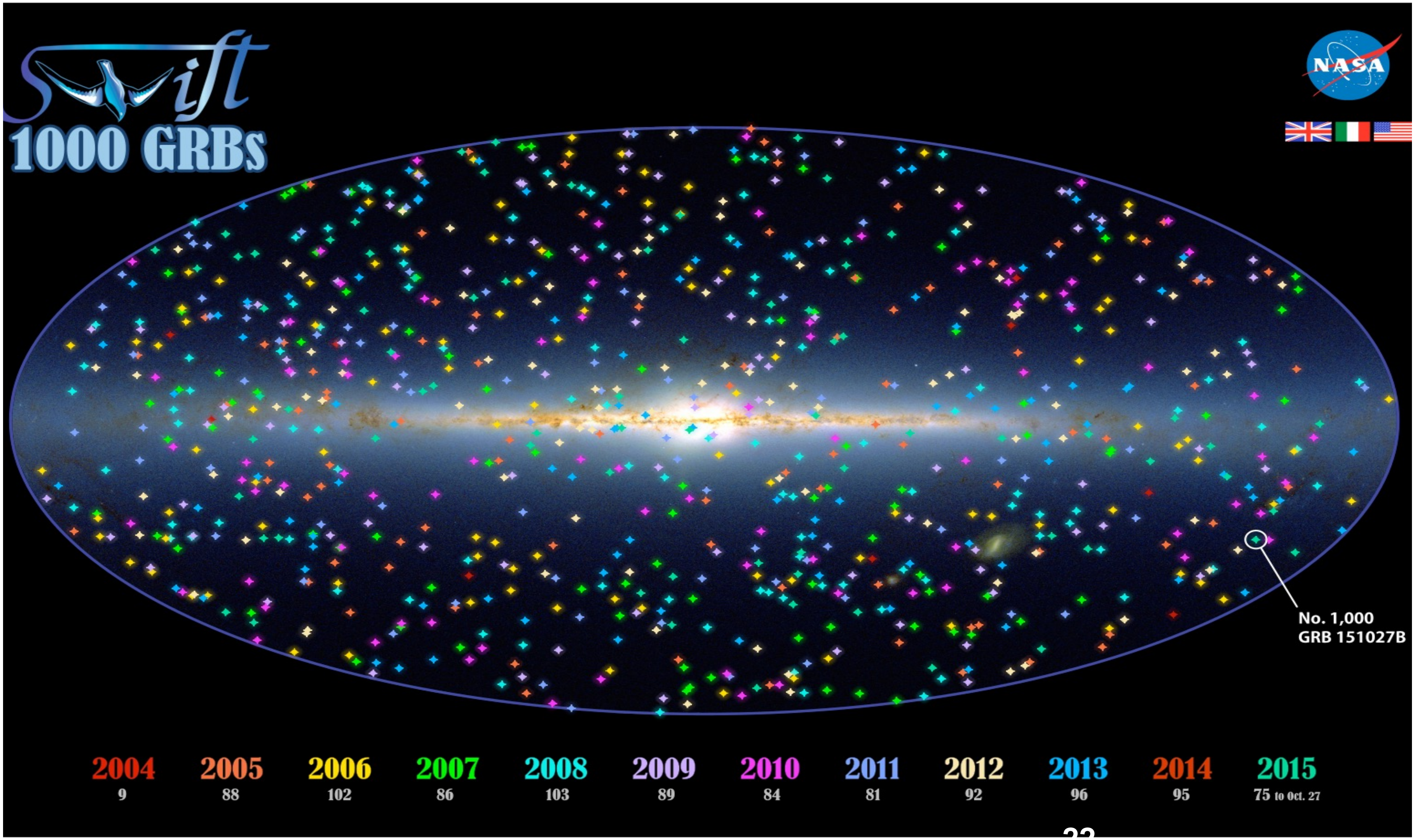
- Identification based on positional agreement with x-ray afterglow and fading of optical point source



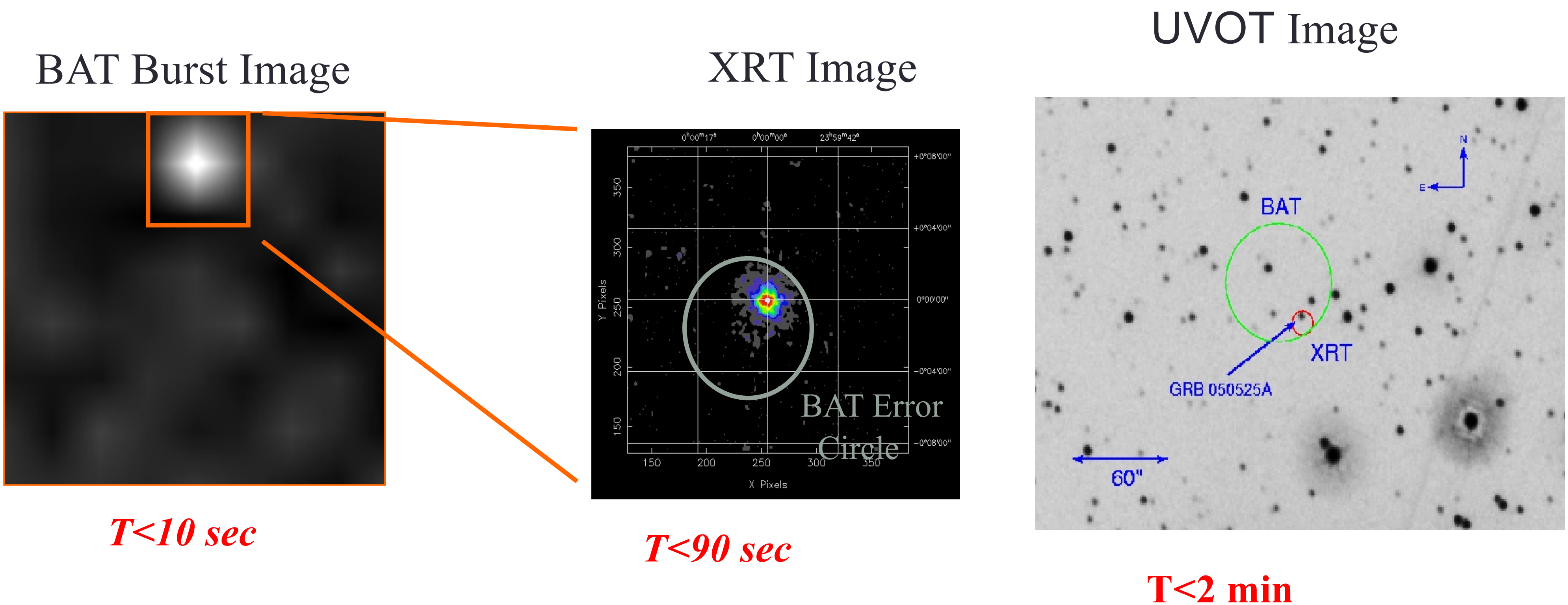


Swift γ-ray Burst Chaser over 1000 GRBs

Swift was designed to find and study GRBs
BAT- GRB finder and localizer
UVOT, XRT: UV/optical and x-ray telescopes to study afterglow and identify source


Swift
1000 GRBs
NASA
No. 1,000
GRB 151027B
2004
9
2005
88
2006
102
2007
86
2008
103
2009
89
2010
84
2011
81
2012
92
2013
96
2014
95
2015
75 to Oct. 27

Swift Data- Multi-Wavelength



GRB Imaging

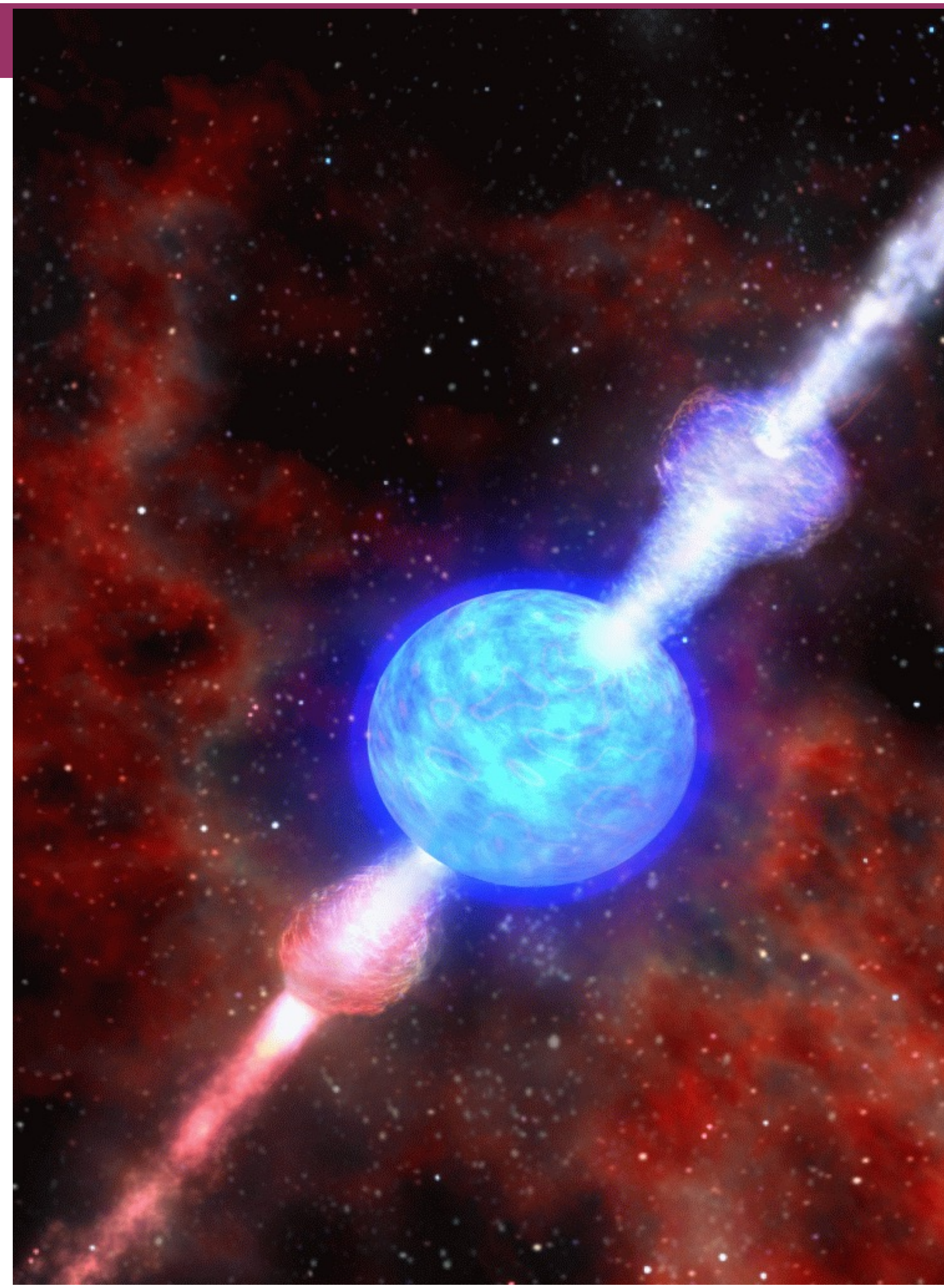
- Long Gamma-Ray Bursts
  - Sometimes/often associated with particular type of core-collapse supernova
  - **Long GRBs associated with explosion of massive star**
  - Possible picture…
    - **Black hole forms in core collapse**
    - **BH fed very rapidly… tremendous energy released**
    - Much of this energy directed into a jet
    - Jet rips through star, blowing it up
    - Get intense beam of gamma-rays directed along jet axis (consequence of Special Relativity)
  - Make sense? Yes…
    - Only find long-GRBs in galaxies with massive stars

Gamma-ray Bursts

the emission is highly collimated and due to a relativistic jet

only detect them when the beam is pointing 'at us'

Beam is highly relativistic with γ>100



Gamma-Ray and X-ray Bursters

- These are **NOT** the same sort of object
  - X-ray bursters are nuclear flashes on surface of NS –energy appears as ~1 keV x-rays
    - they repeat
    - are in the Milkyway
    - low luminosity (too dim to detect in nearby galaxies)
  - Gamma-ray bursters
    - high energy emission (gamma-rays)
    - never repeat
    - are cosmological
    - very luminous
    - birth of a BH
    - emission is highly collimated

  - However both have very short on times (seconds are less) which is why they are called 'bursters'

What About the Other Type??

- So long gamma-ray bursts are due to the collapse of a massive star into a black hole
- What about short bursts??

Short Bursts

- Short GRBs? More enigmatic
  - Can be found in old galaxies with no massive stars
  - Can even be found just outside of some galaxies!
  - *So… need a different idea.*

- Merging binary neutron stars!
  - Two neutron stars spiraling together (due to loss of energy by gravitational radiation… subject of a later class!)
  - When neutron stars smash together, BOOM!
  - **End up with black hole remnant which rapidly swallows remaining debris disk.**

Short Bursts- Progenitor

- Many short bursts are the result of the merger of 2 neutron stars (B. Paczynski 1991) –
- Observational support based on their observed properties
  - lack associated supernovae
  - occur in a mix of star-forming and elliptical galaxies
  - have a broad spatial distribution around their

    hosts, with some events offset by tens of kpc

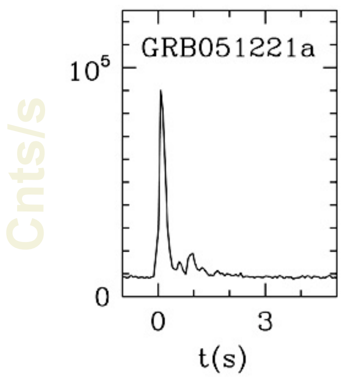
    and are located in low-density environments
    - **Confirmed with gravitational wave observation of GW170817**

–e.g runaway NS stars which merge.

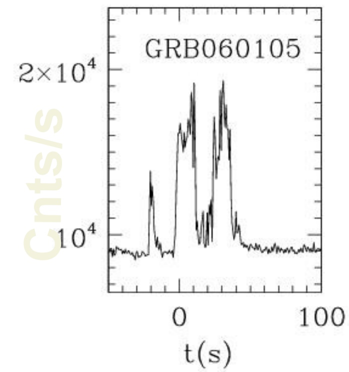
strong impact on gravitational wave searches.

Short vs Long GRBs

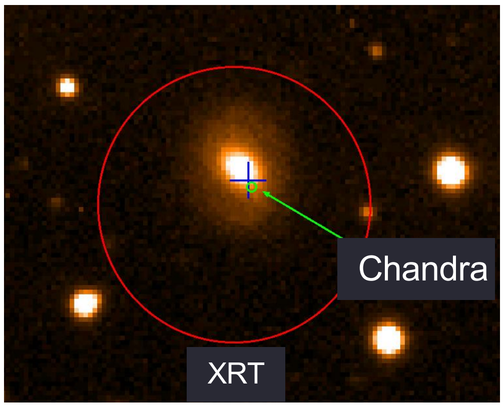
Short GRB



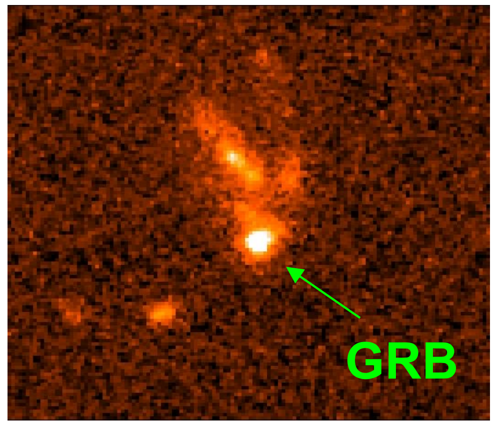
Long GRB



GRB 050724 - *Swift*
elliptical host



GRB 990123 - *SAX*
SF dwarf host

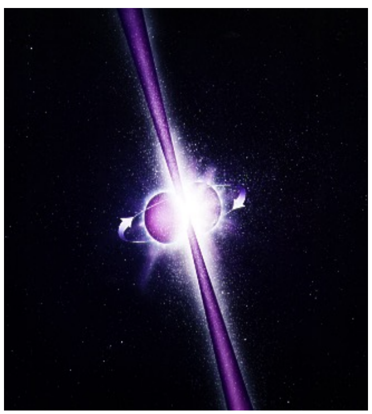


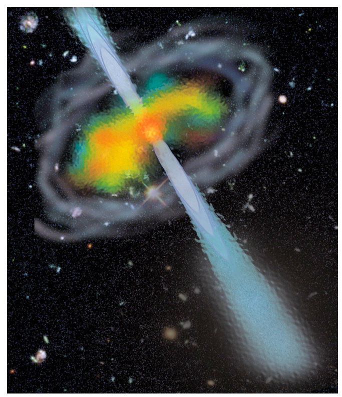
In non-SF and SF galaxies

No SNe detected

less likely to have afterglow

Possible **merger** model





BH

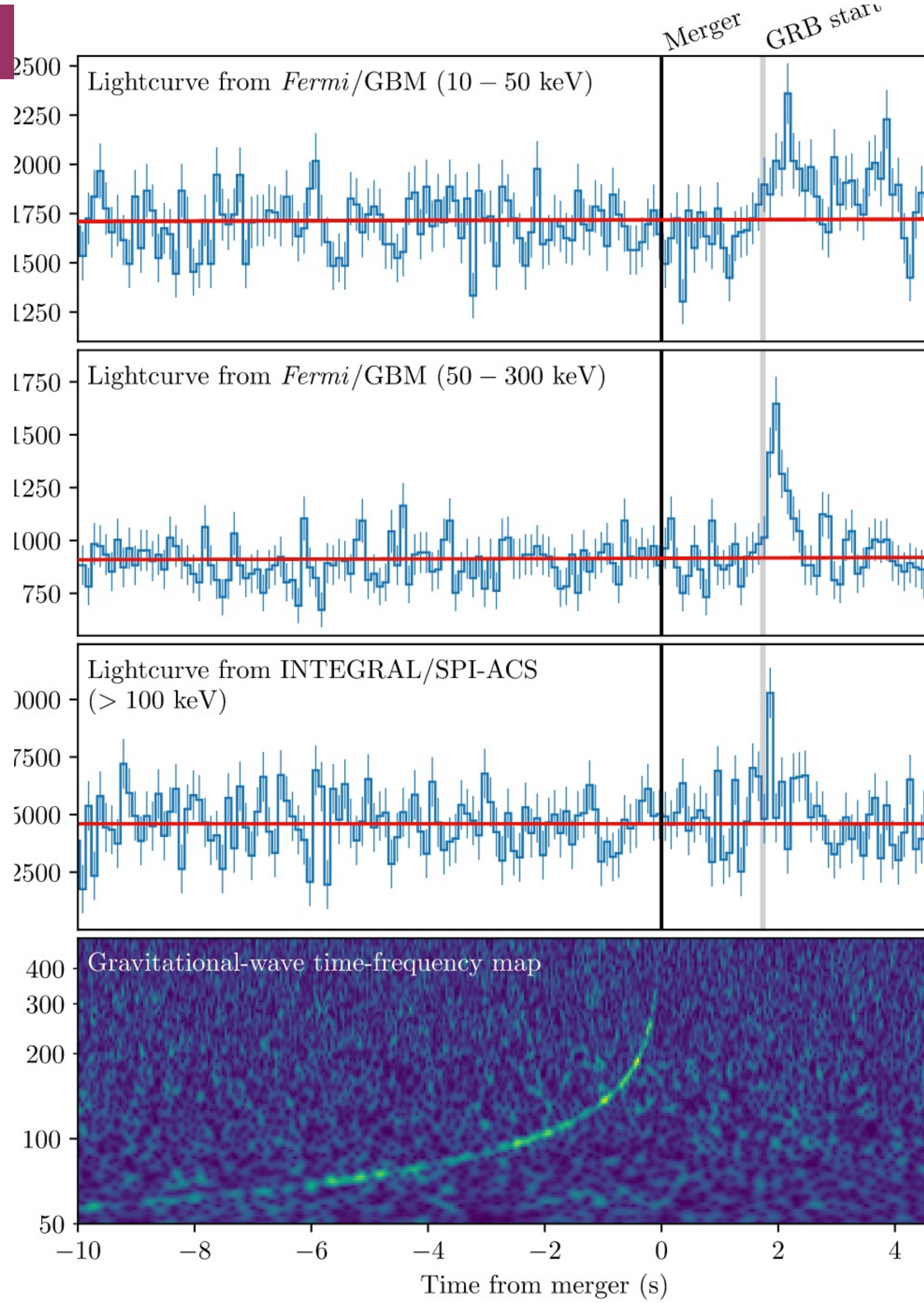
In SF galaxies

Accompanied by SNe

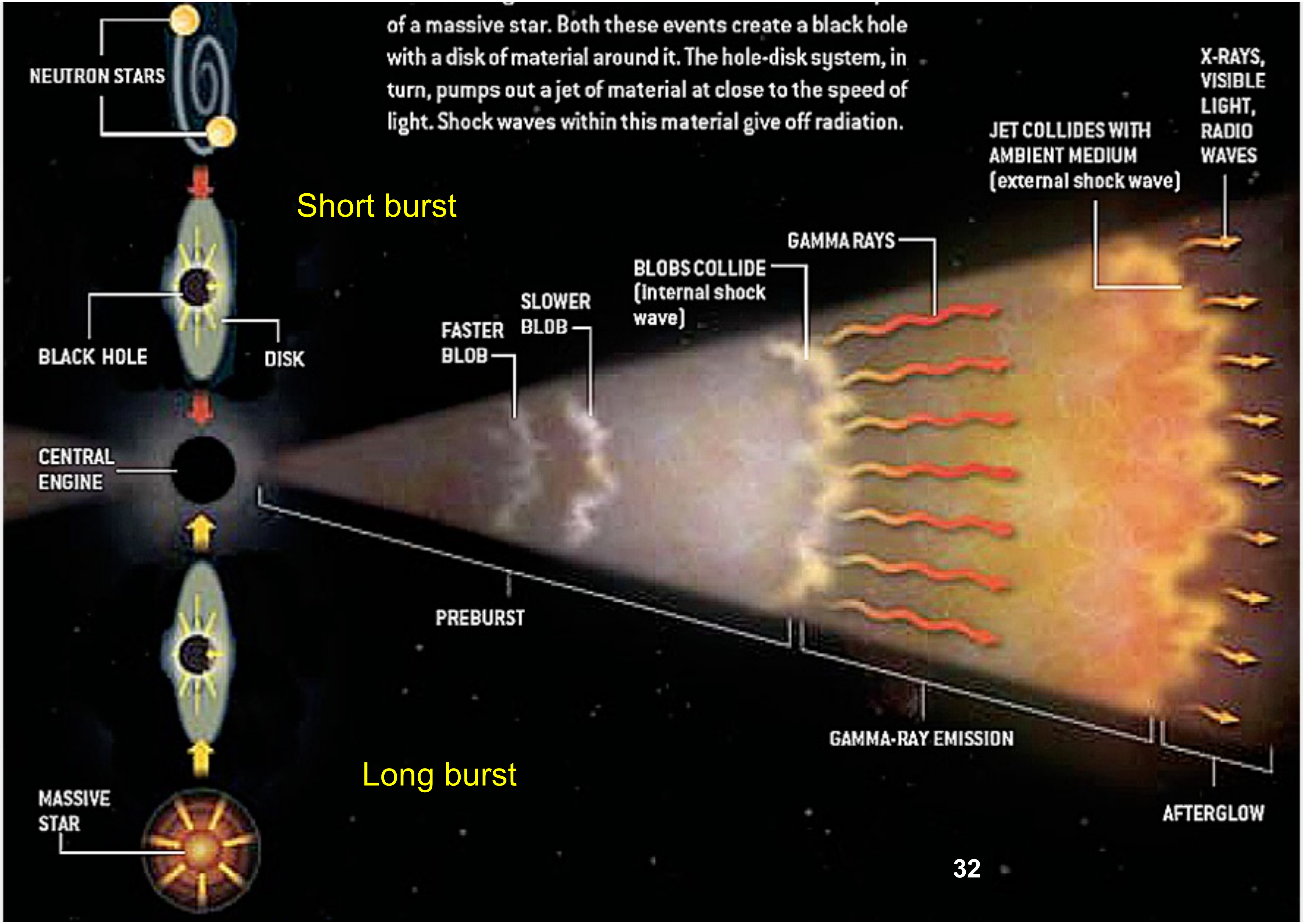
Collapsar model well supported

GW170817

- LIGO and Virgo make first detection of gravitational waves produced by colliding neutron stars
  - -Two seconds after the gravitational signal, NASA's orbiting Fermi Gamma-ray Space Telescope detected a gamma ray burst
- Discovery marks first cosmic event observed in both gravitational waves and light.



Formation of GRBs-2 Scenarios



Summary of GRBs

GRBs are powerful explosions

- visible across the universe
- most luminous sources across the electromagnetic spectrum
- afterglow lasts for days

Long GRBs

- due to core collapse to black hole of massive star
- new probe of reionization era

high redshift universe

possibility to use GRBs to trace star formation at high redshifts

Short GRBs

- associated with old stellar populations
- likely caused by NS-NS mergers
- less energetic than long bursts
- exciting sources for gravitational wave joint observations