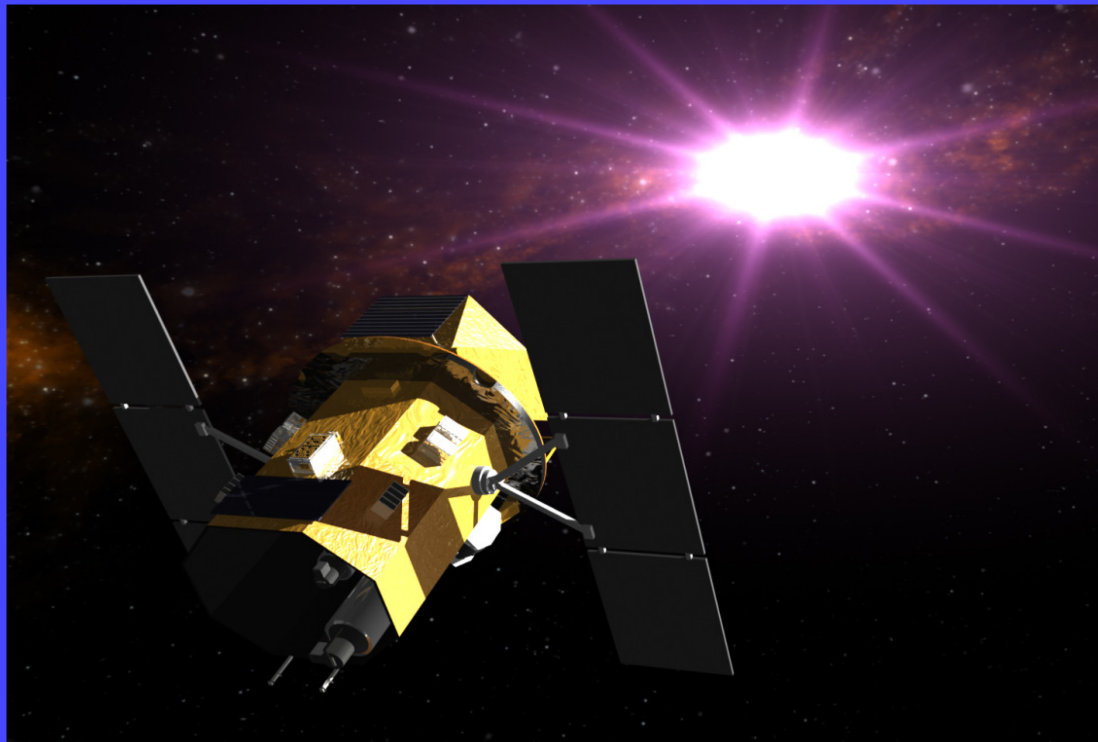
The Gamma Ray Universe: the example of GRBs

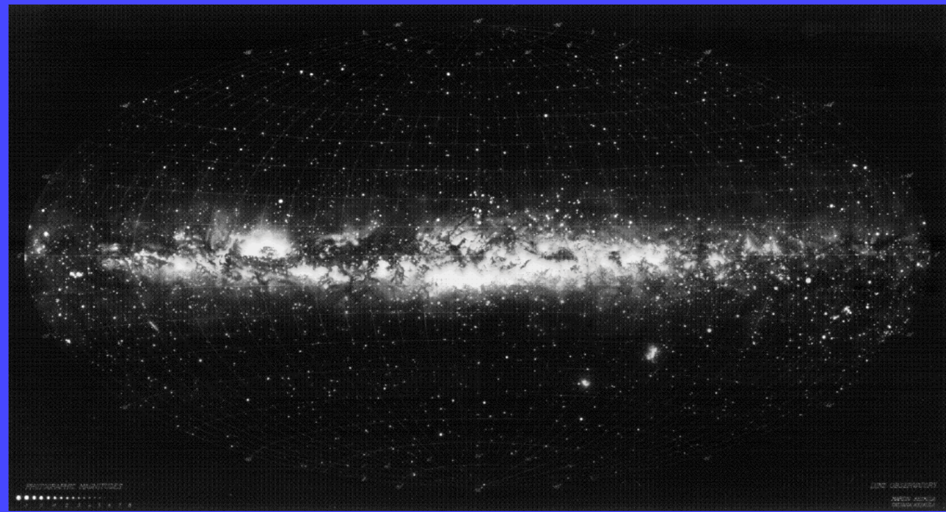


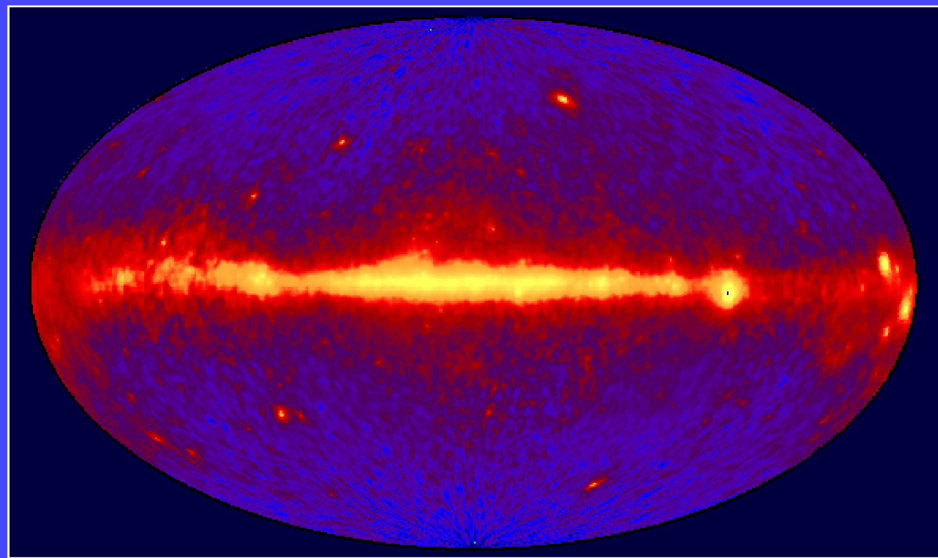
Paul O'Brien
University of Leicester

The Sky

- The optical sky is dominated by stars and galaxies
- The γ-ray sky shows us the most exotic and extreme creatures in the cosmic zoo
- In X-ray band, need to get above the atmosphere – “took off” in space era

Optical all sky map



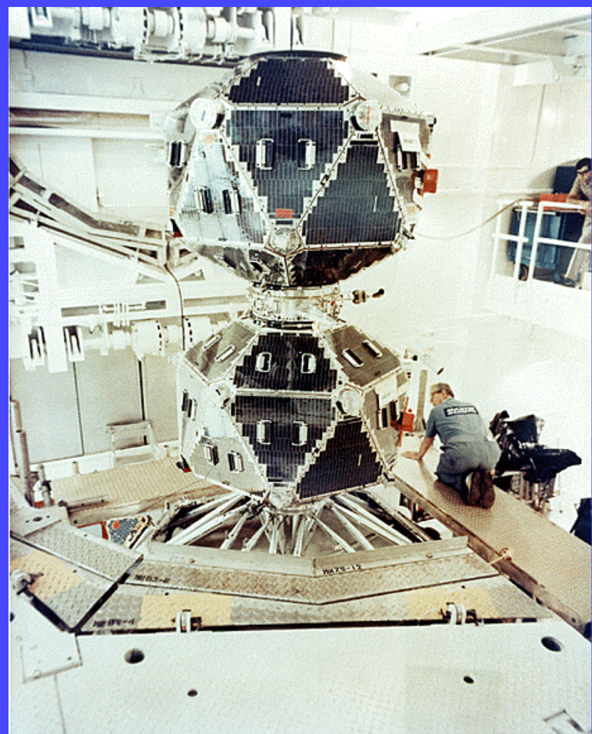


Fermi γ-ray all sky map

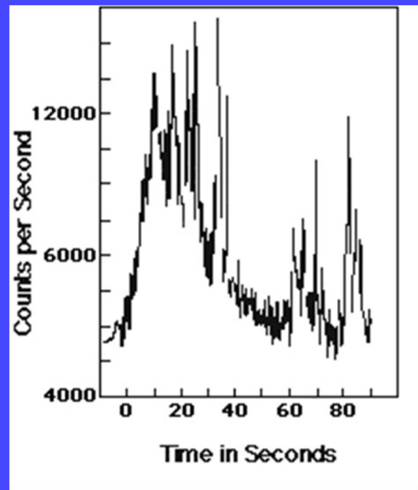
Gamma Ray Burst discovery

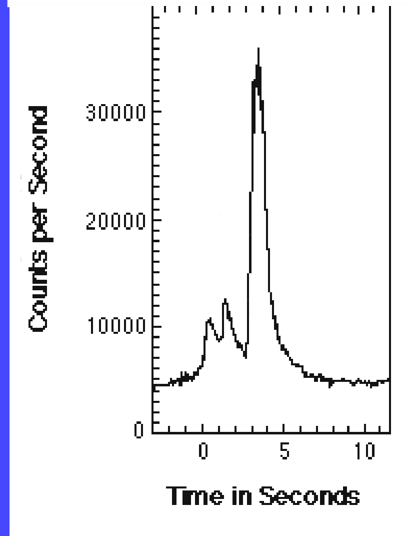
- Cold war: USA/Soviets think the other may be testing bombs in space

- USA 'Vela' satellite programme designed to detect nuclear detonations



- 1972 - data published of "interesting signals" that do not originate from the Earth, Sun or Moon



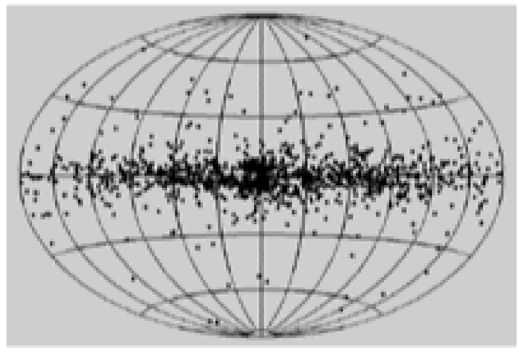


The Big Questions: What and Where?

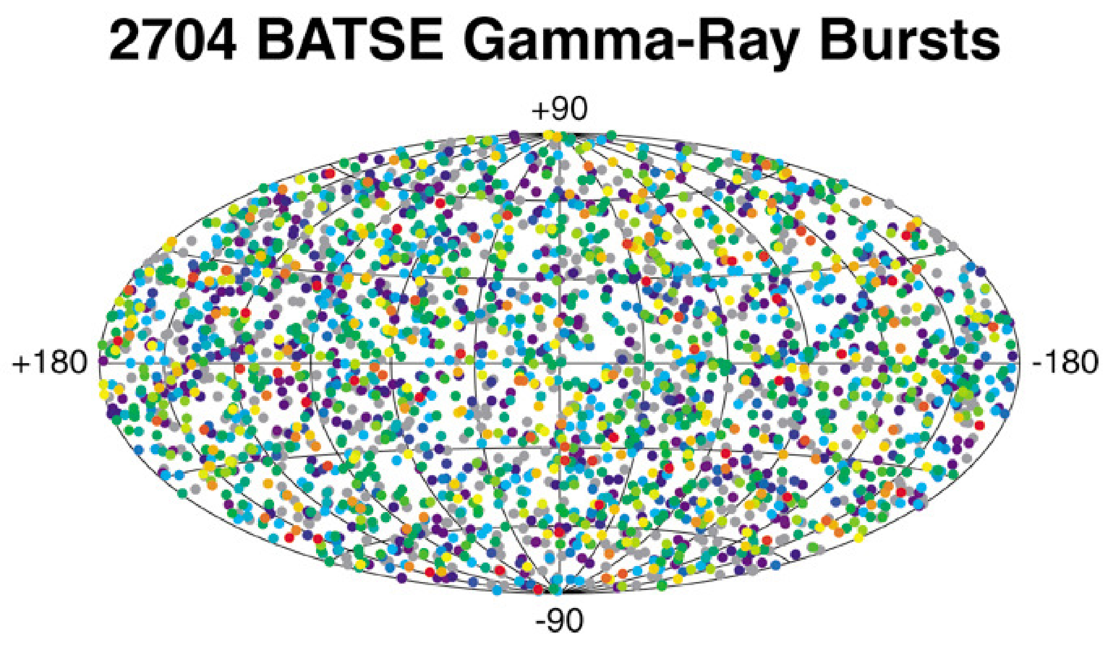
Few data but lots of theories

Clearly, dealing with high energy events

CGRO/BATSE provided a clue

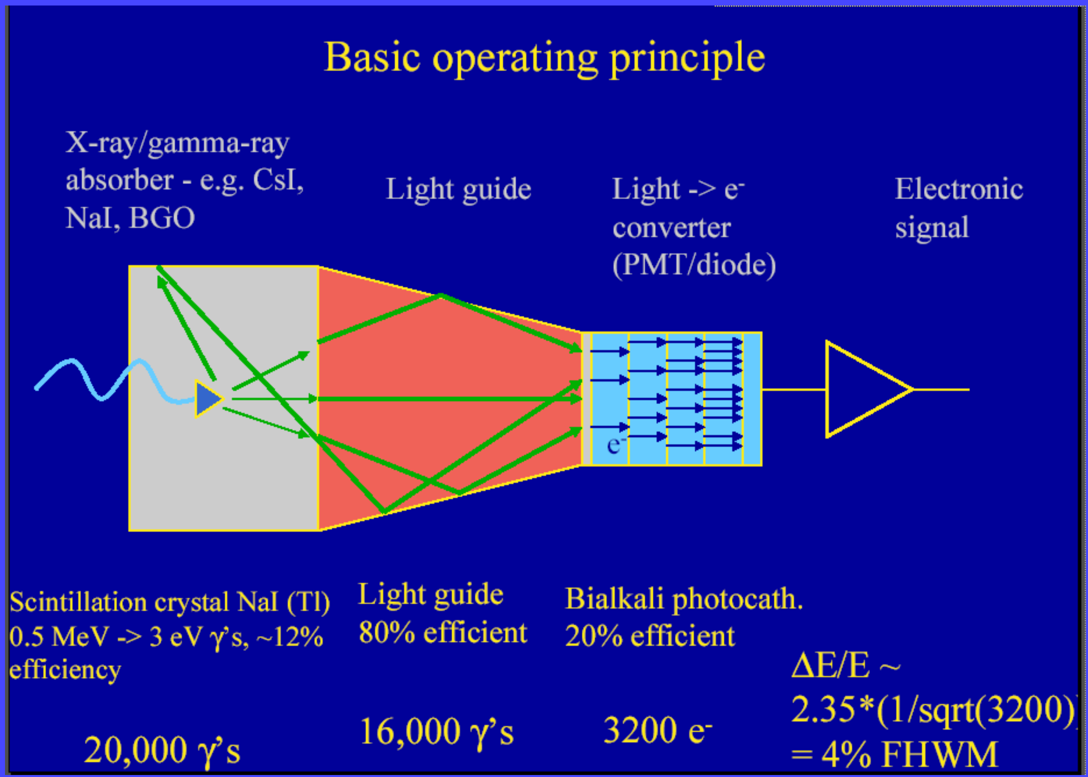


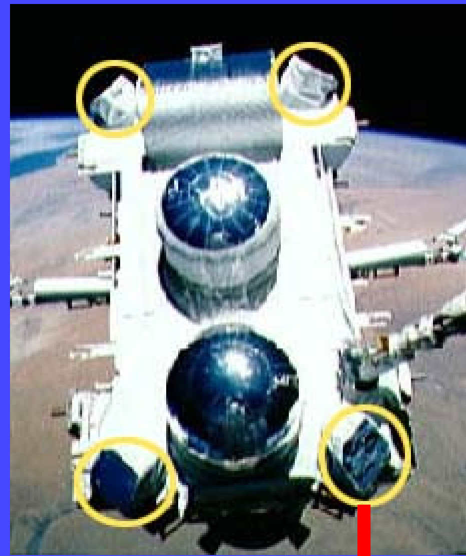
Expected

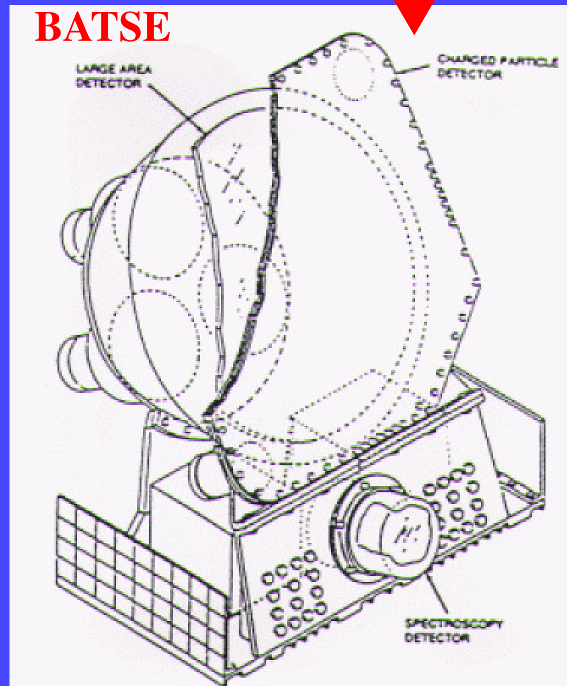


GRBs are evenly spread across the whole sky

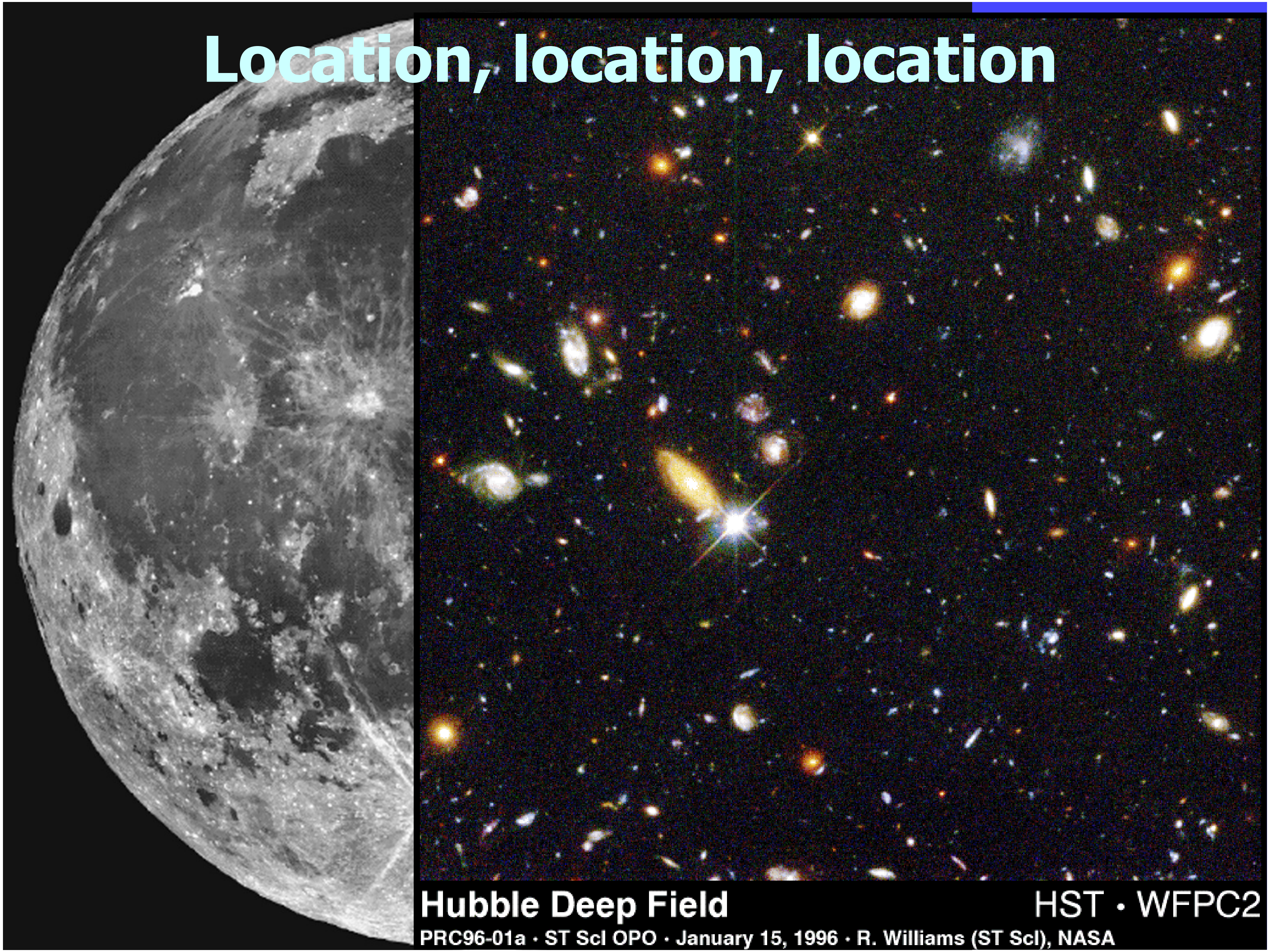
Scintillation instrument





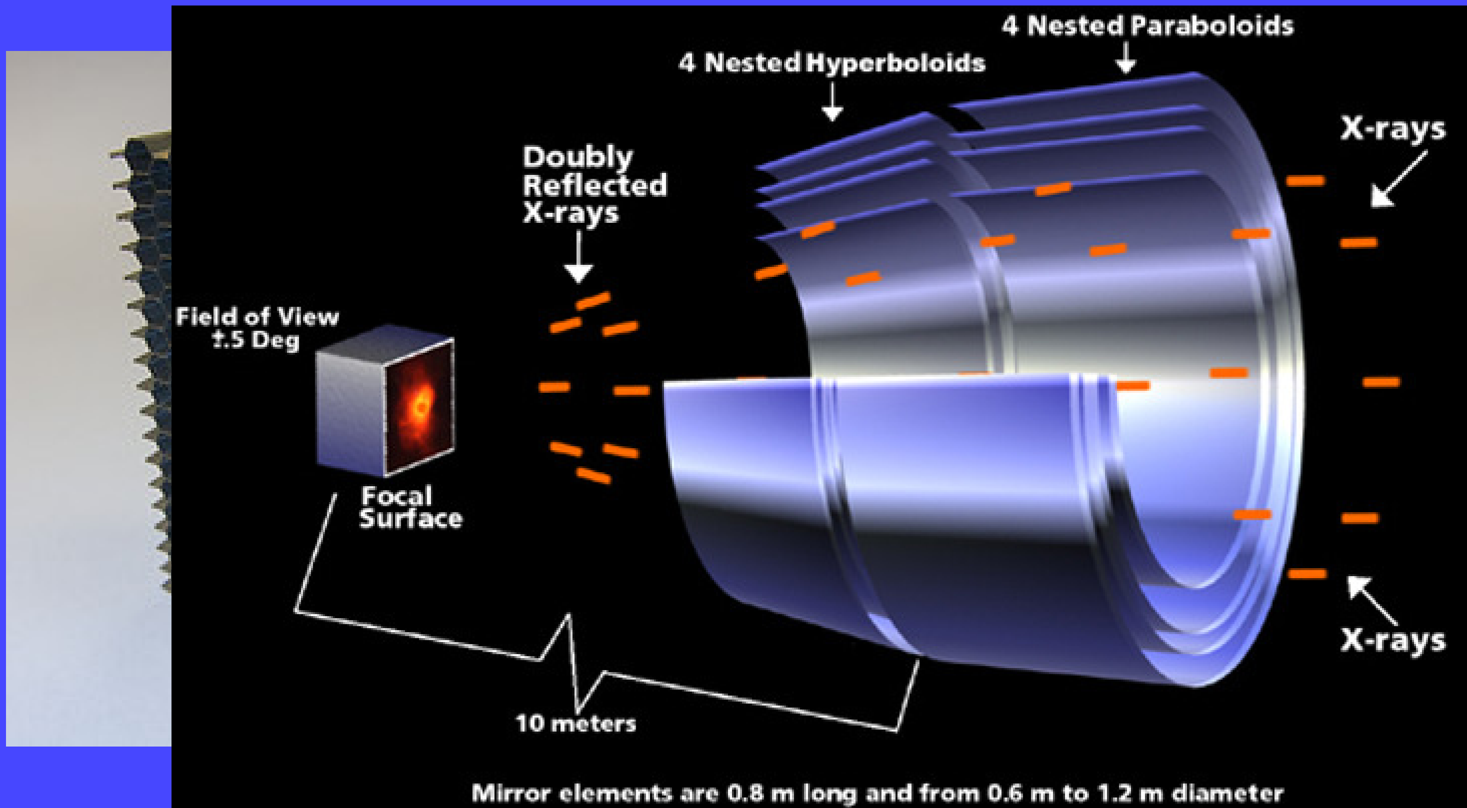


Location, location, location



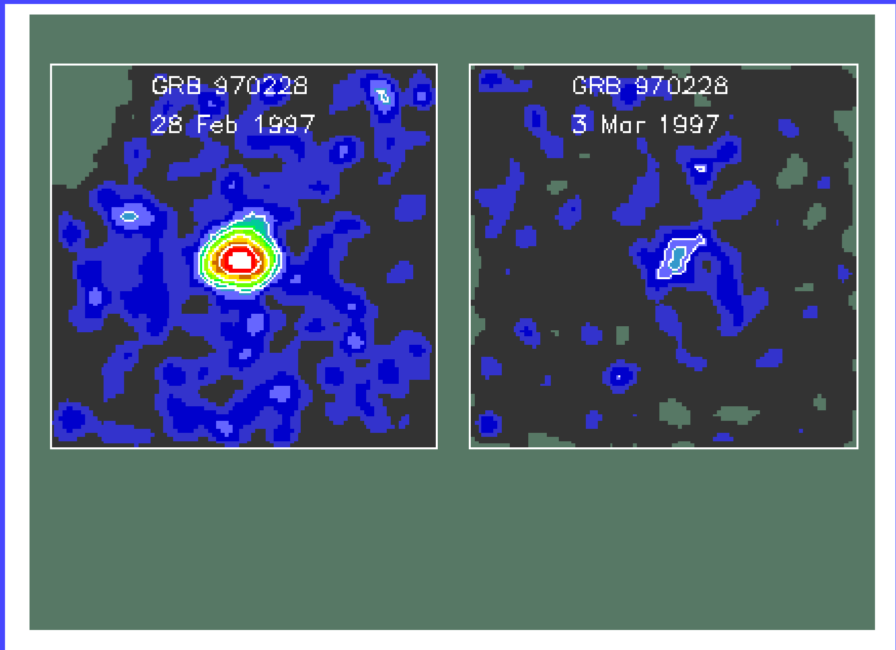
X-ray Imaging

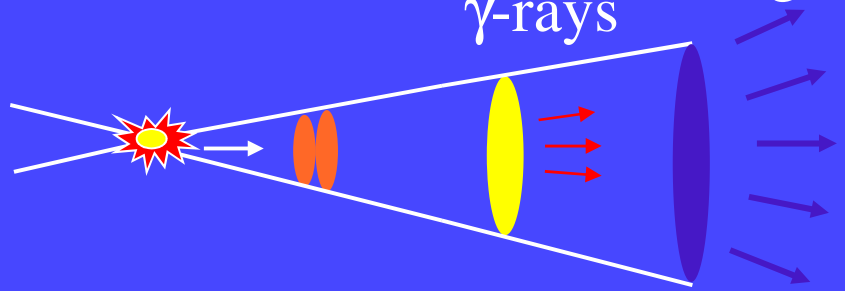
- X-rays do not reflect at normal incidence
- Mechanical collimator: cheap, large collecting area, wide field [e.g. RXTE PCA]
- Coded mask: fairly cheap, difficult to image complex sources [e.g. Swift BAT]
- Grazing incidence mirrors: good resolution, very expensive, modest collecting area, go to few tens of keV or more with multilayers [e.g. Chandra, Swift…]
- None of these are diffraction limited (not even close …)



BeppoSAX (1996-2002)

GRB 970228: First X-ray afterglow detected





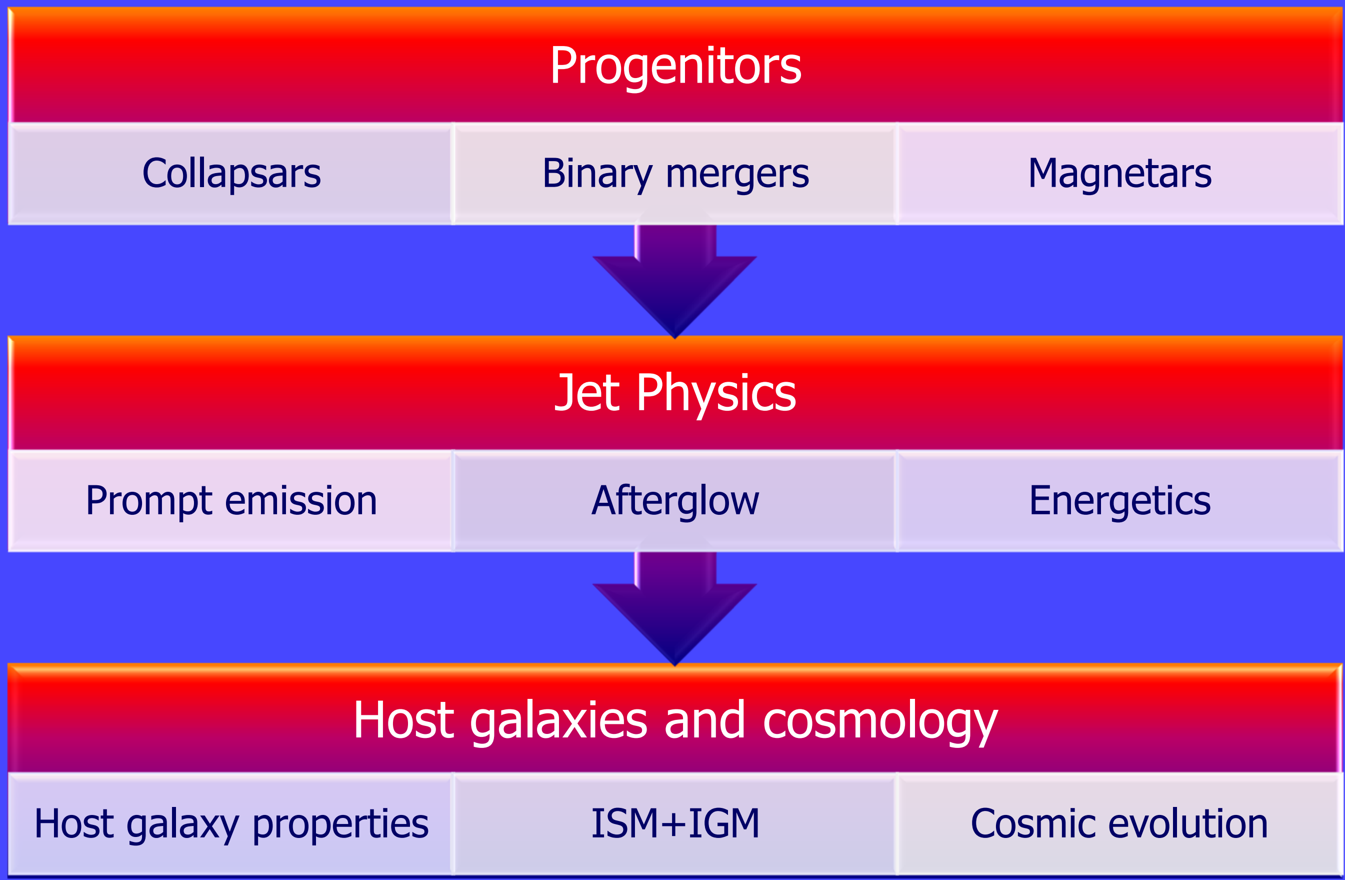
Fireball-shock Model
(Meszaros & Rees 1997)

<u>All</u> bursts with known redshifts are cosmological

“Beaming-corrected” luminosities of 10^{51} to 10^{52} erg!!!

(about Sun’s output over its entire 10 billion year lifetime or the equivalent of a million big galaxies for 10s)

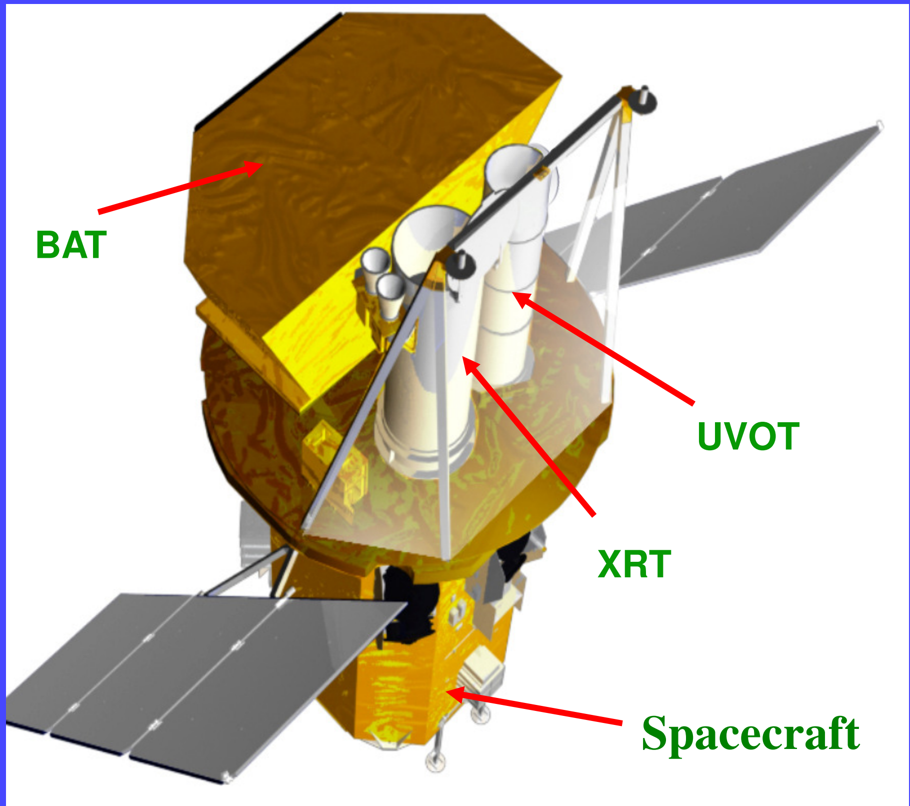
Top-level GRB science areas



GRBs emit at all wavelengths and produce non-photonic emission (i.e., we use all telescopes we can get time on!)

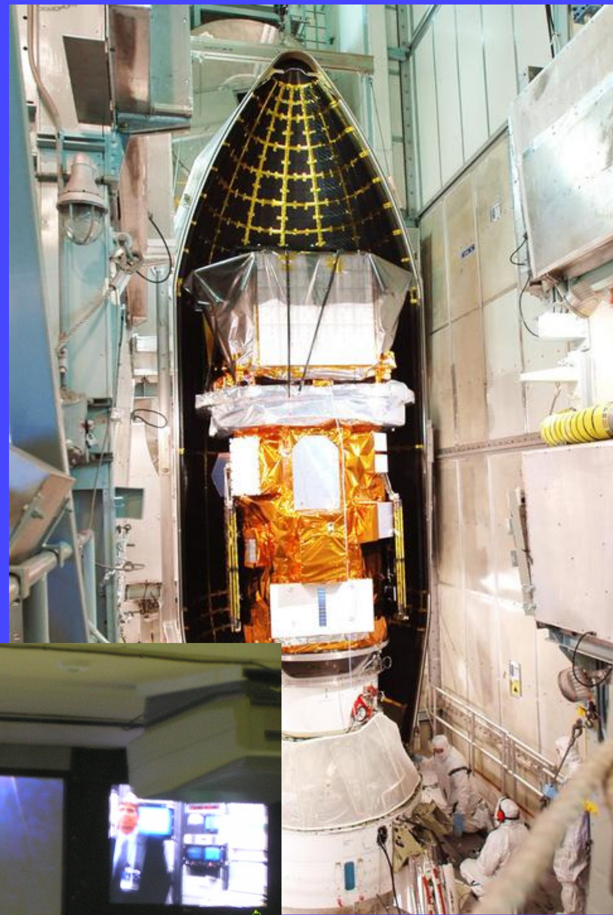
The Swift Gamma Ray Burst satellite

"Catching Gamma Ray Bursts on the Fly" (NASA/UK/Italy)

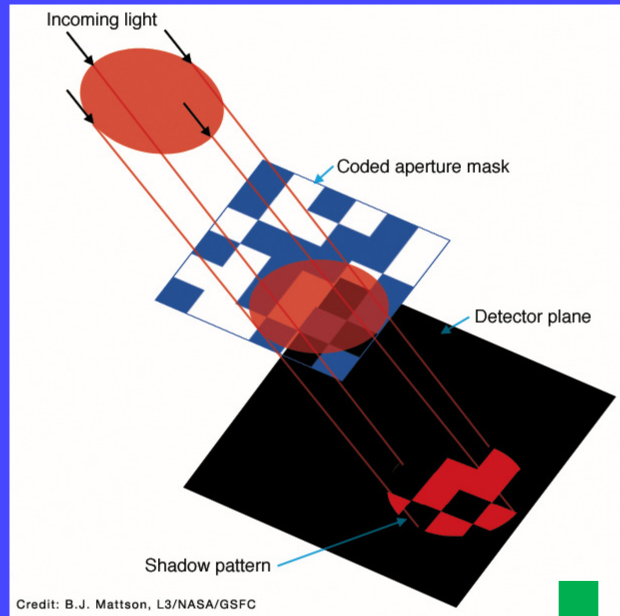


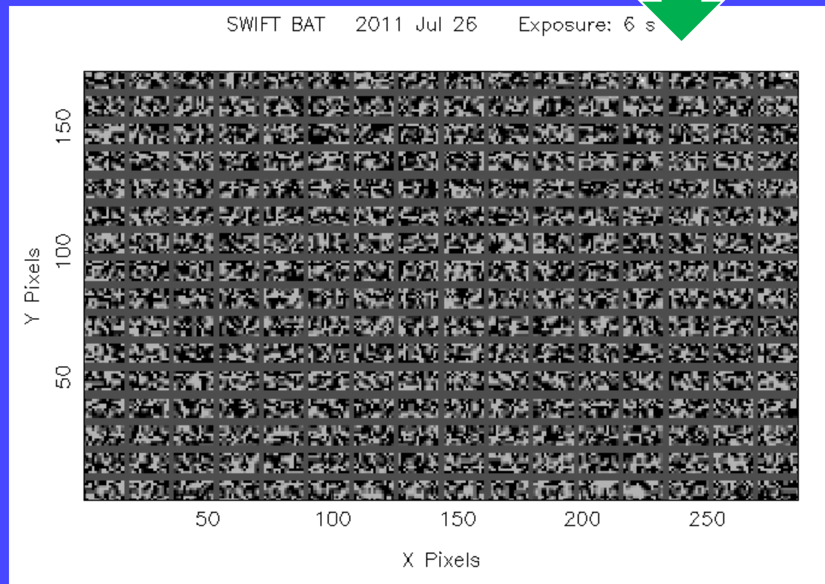
- Burst Alert Telescope (BAT)
  - **Detect 100 GRBs per year**
- X-Ray Telescope (XRT)
  - **Arc-second positions**
- UV/Optical Telescope (UVOT)
  - **Sub-arcsec imaging**
- Autonomous operation with fast slew (~1^o s^{-1})
- All data are public

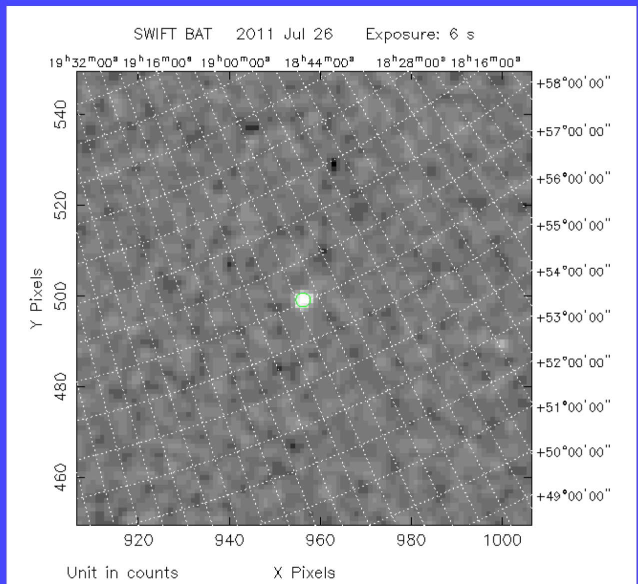
Swift launch Nov. 20 2004



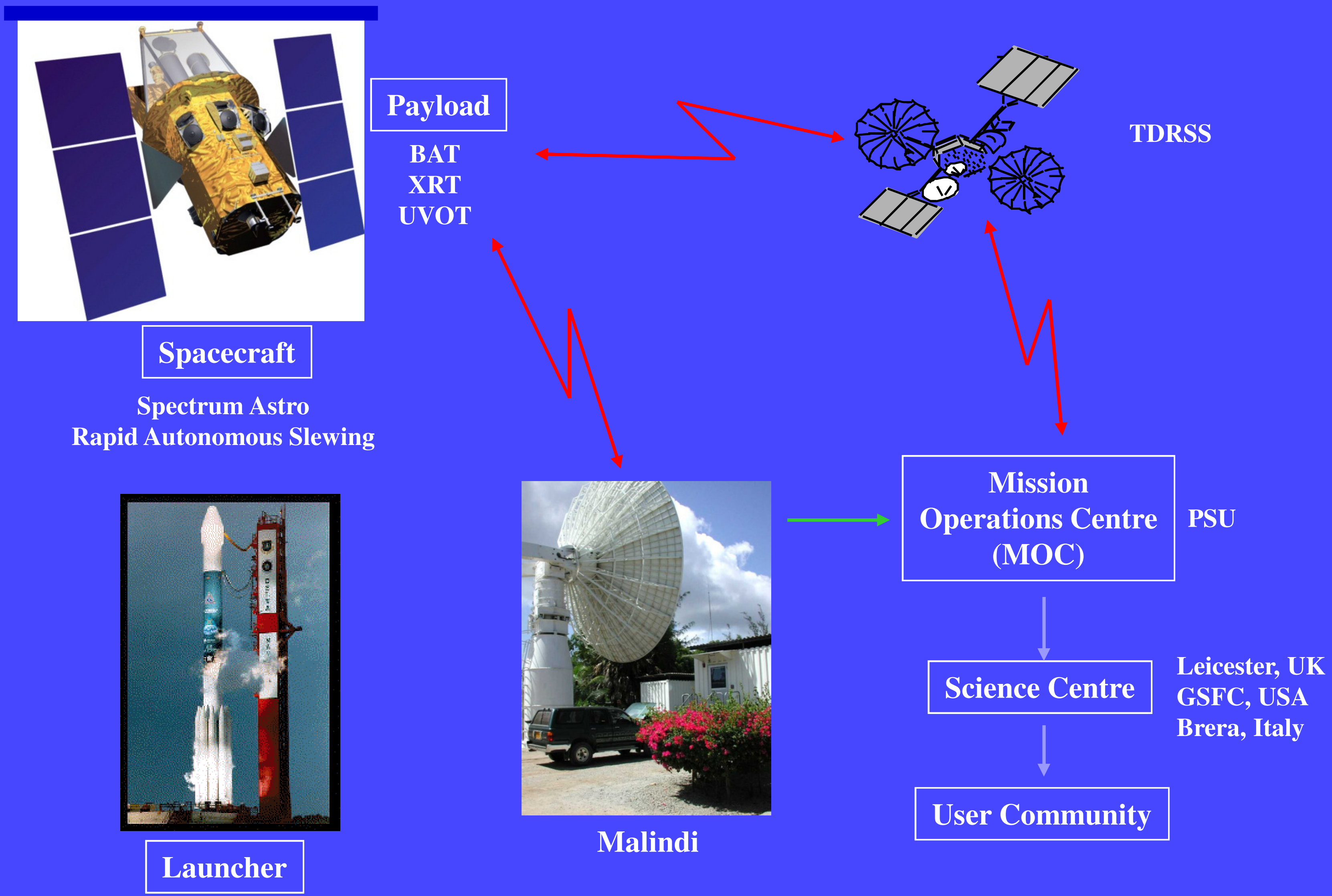
BAT γ-ray coded-mask imaging



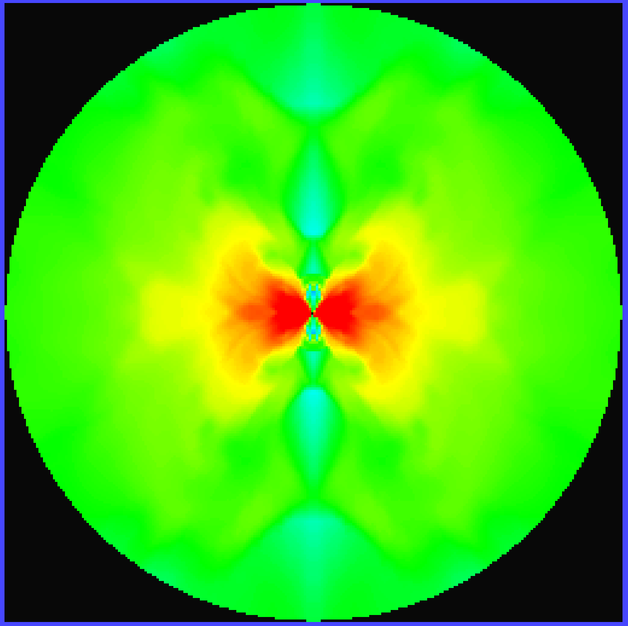




Swift Mission Operations

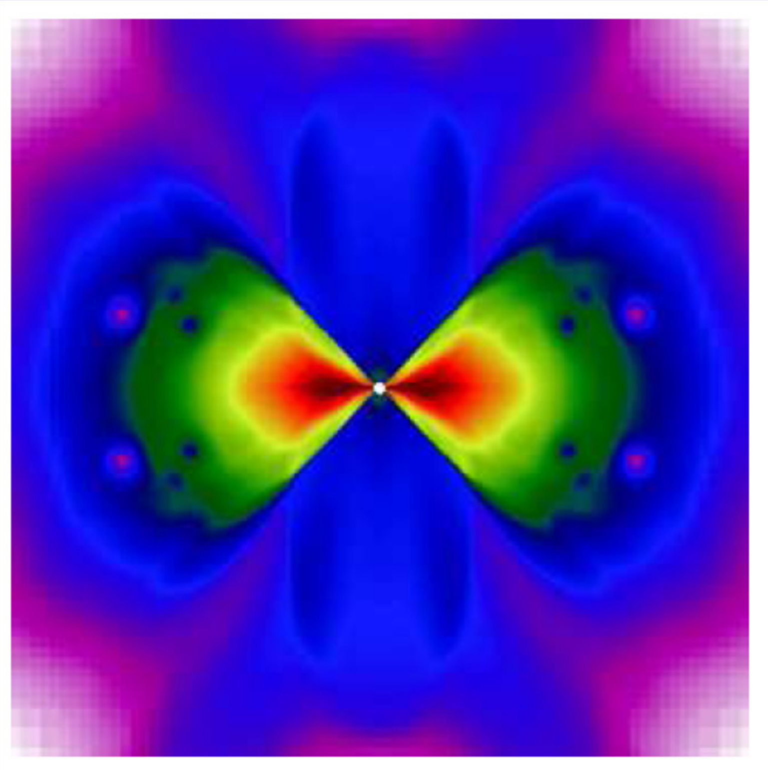


Model A: Collapsar GRB/SN

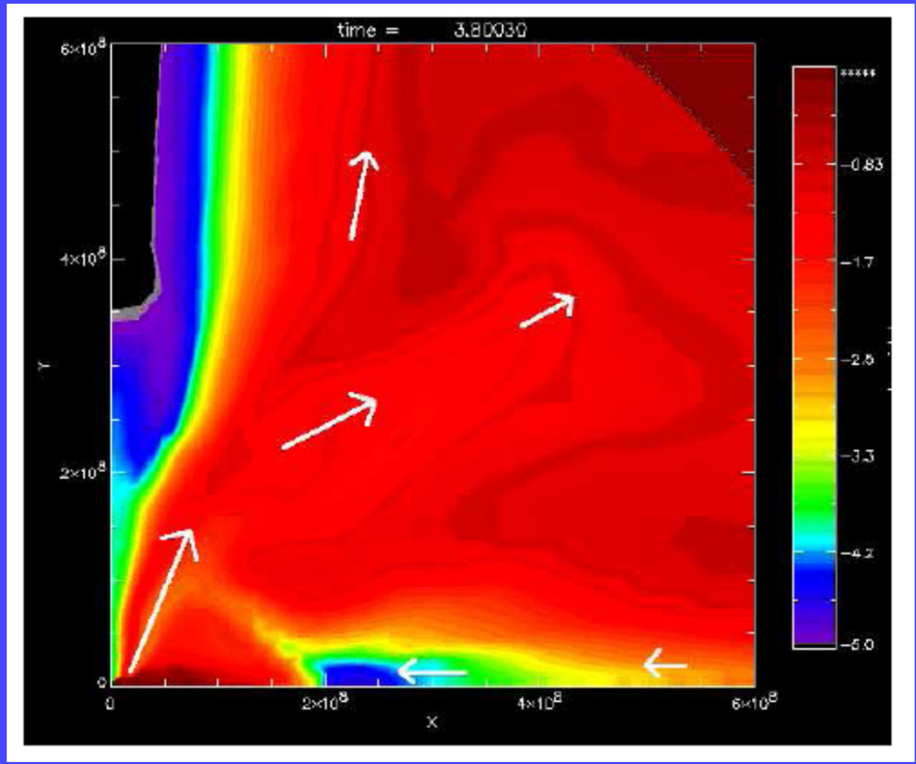


- Massive star (>30 Msun) dies – get a SN and a feeding Black Hole
- If very fast jets (>0.9999c) emitted $\Rightarrow$ GRB (jet escapes star)
- The GRB outshines the supernova by about a factor of a billion
- Standard model for long duration GRBs

Star ⇒ BH ⇒ total mess

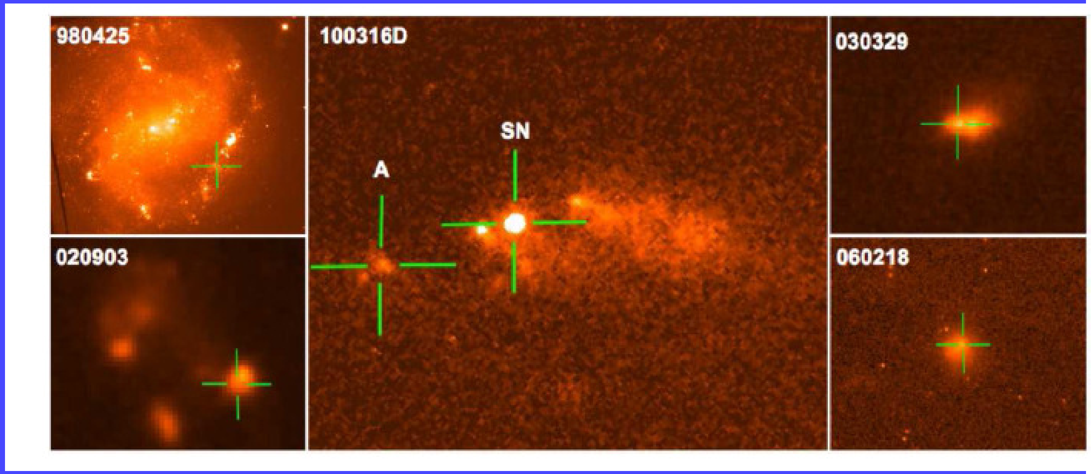


14 $M_\odot$ WR star collapse ⇒ 4.4 $M_\odot$ BH accreting 0.1 $M_\odot$ s^{-1} for ~15 s (Zhang, Woosley, MacFadyen 2006)

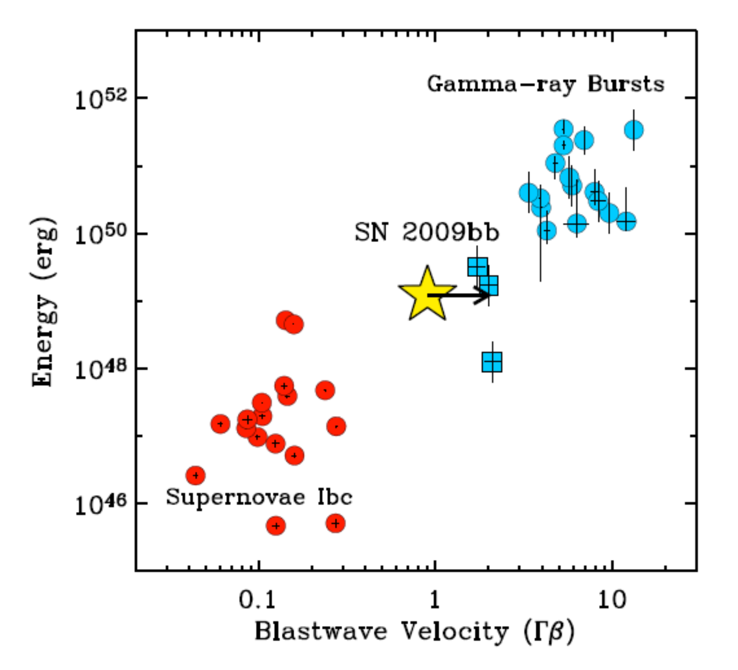


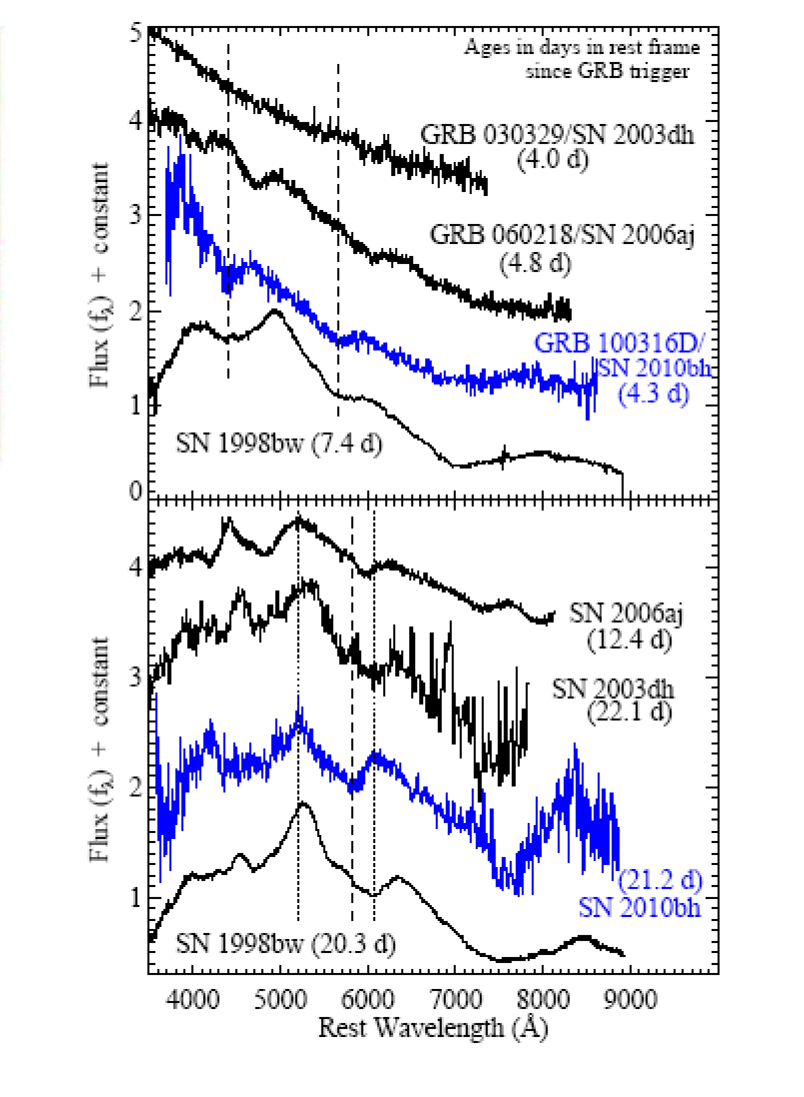
Hot nucleon-rich disk wind, flows out, cools, recombines to give ^{56}Ni ⇒SNe – what happens next?

GRBs and supernovae



GRB/SN host galaxies (7 kpc scale boxes)

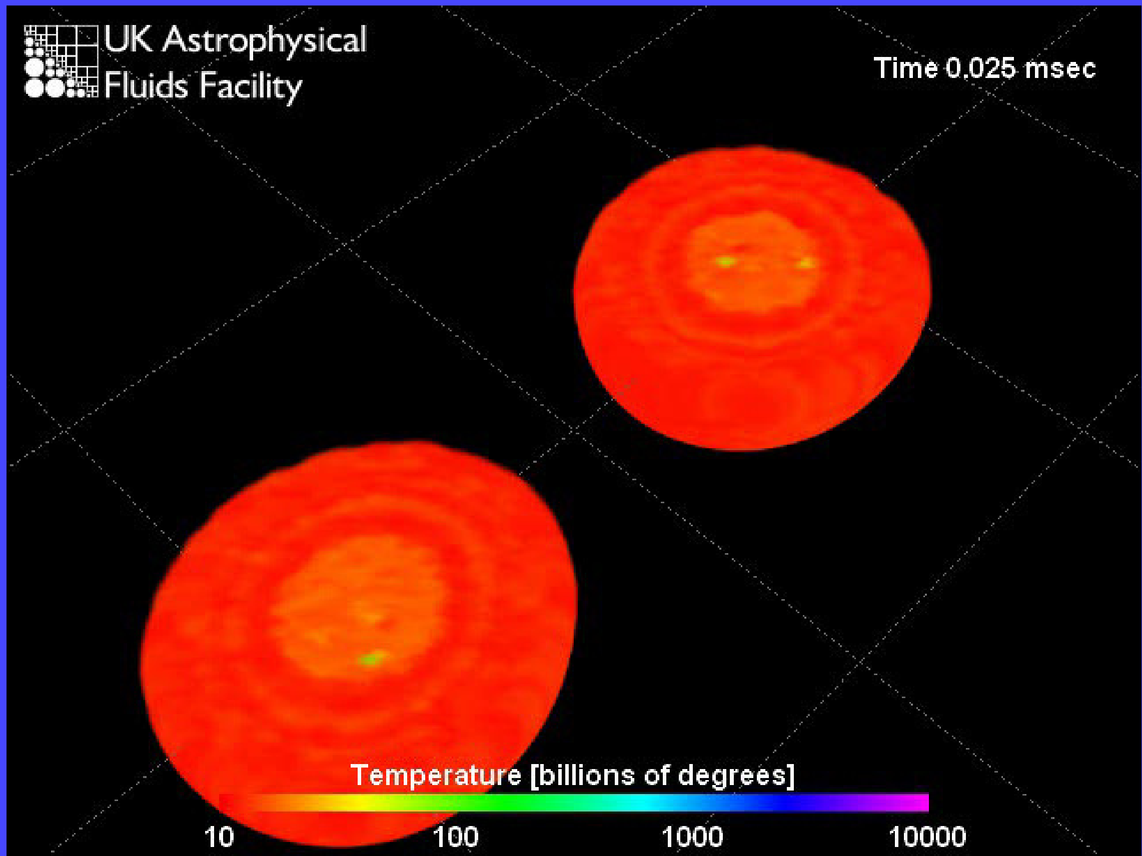




Model B: binary merger

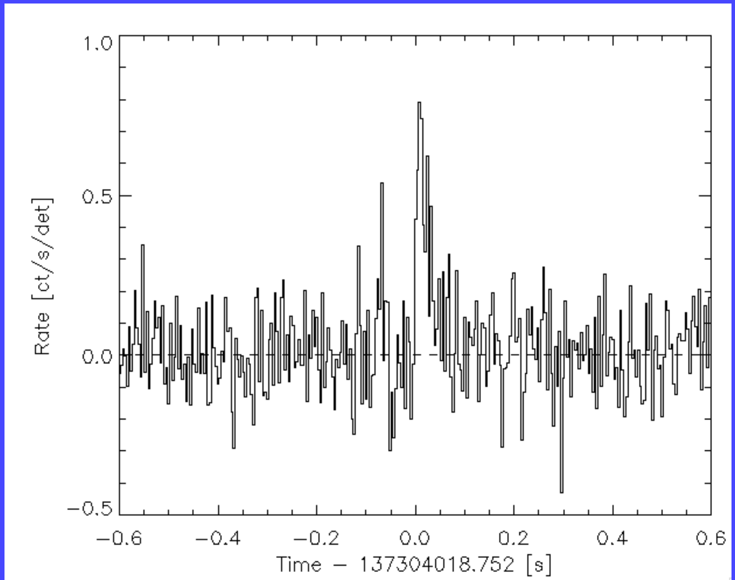
Some GRBs have no supernova - so what is it then?

Take two neutron stars, (or NS+BH) and stand well back…



1st localised short GRB 050509B

(Gehrels, Sarazin, O'Brien et al. 2005)



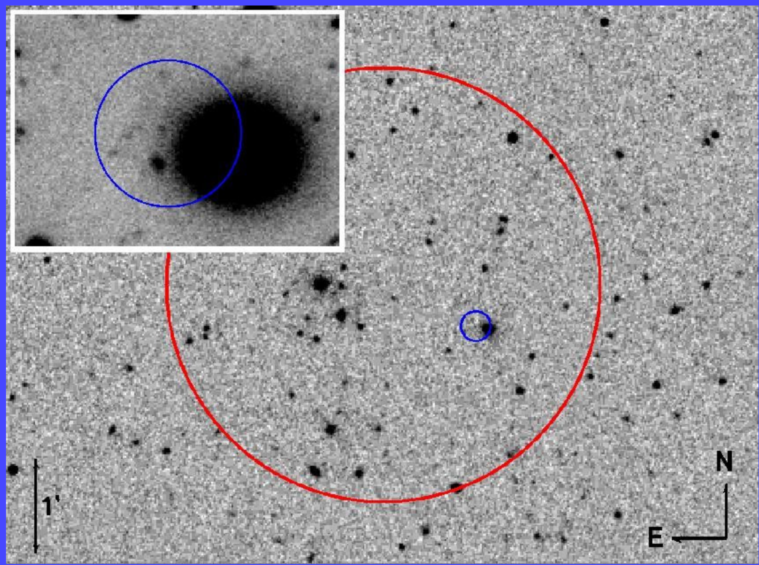
BAT
- 30 ms duration
- spectrum is medium hard
- very weak, 2×10^{-8} erg/cm^2

Spacecraft slew in 52 sec

XRT
- faint source, fading
- 11 cnts = 1×10^{-12} erg/cm^2/s

Host galaxy:
- cD Elliptical
- K = 14.1
- L = 3 L*
- z = 0.225
- SFR < 0.2 M_O yr^{-1}

VLT image
Hjorth et al.

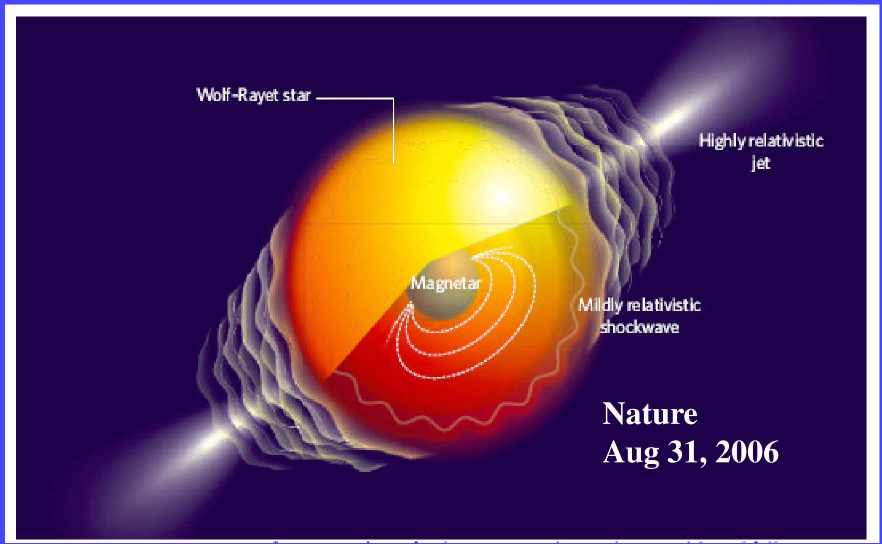


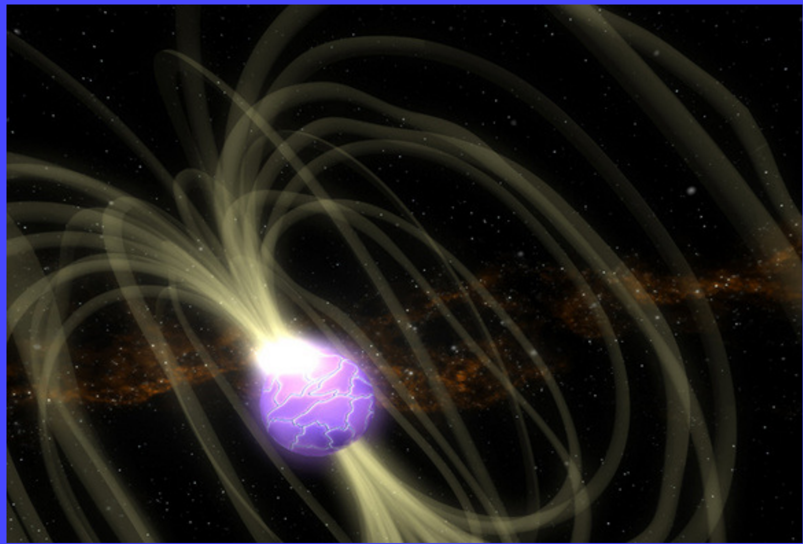
Model C: Model A or B + magnetar

Some GRBs may be powered by an unstable, millisecond pulsar (a magnetar)

Fast rotation (ms) plus very strong magnetic field (~10^{16} G)

Extraction rotational energy ⇒ inject energy into the light curve ⇒ rapid decline when the magnetar collapses to a BH (Zhang & Mézsáros 2001)

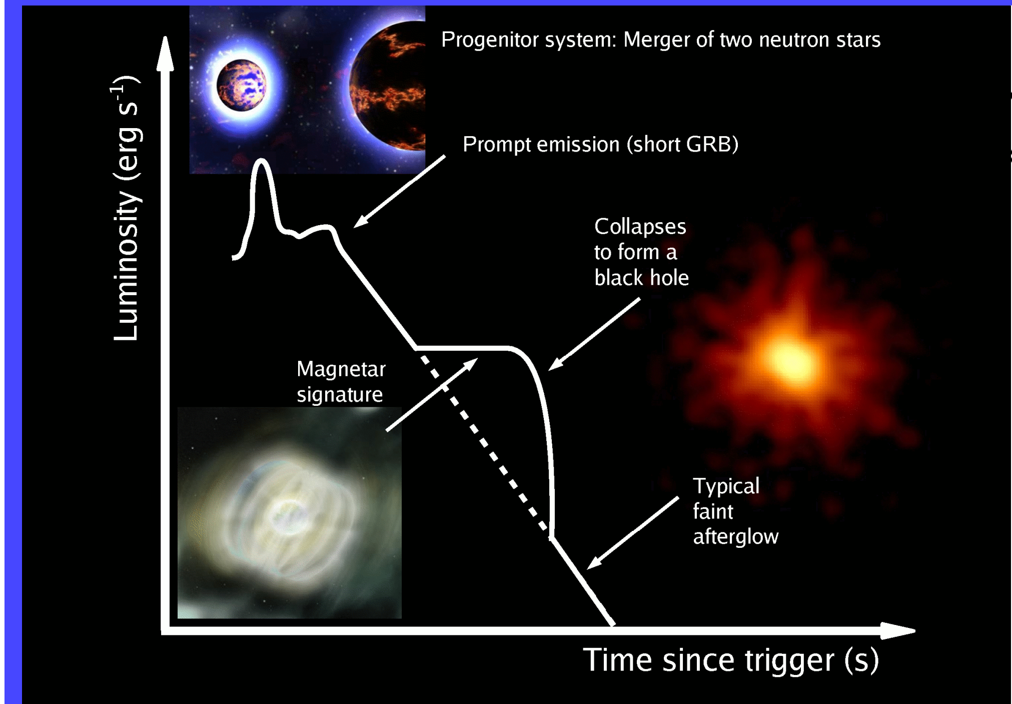


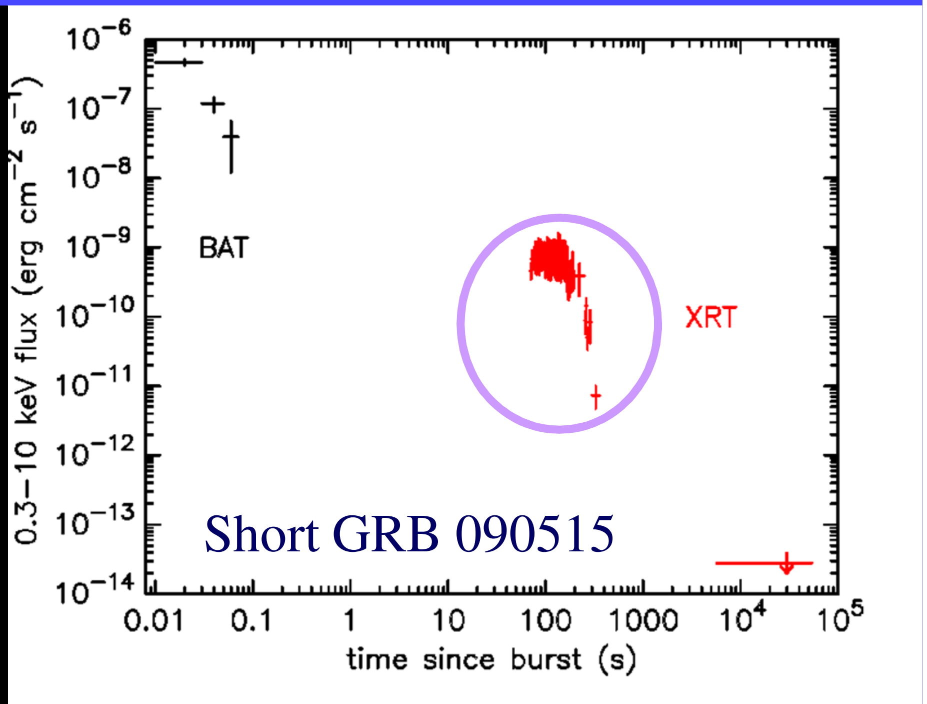


Magnetars and gravity waves

(Lyons, O'Brien et al. (2010), Rowlinson, O'Brien et al., (2010, 2011))

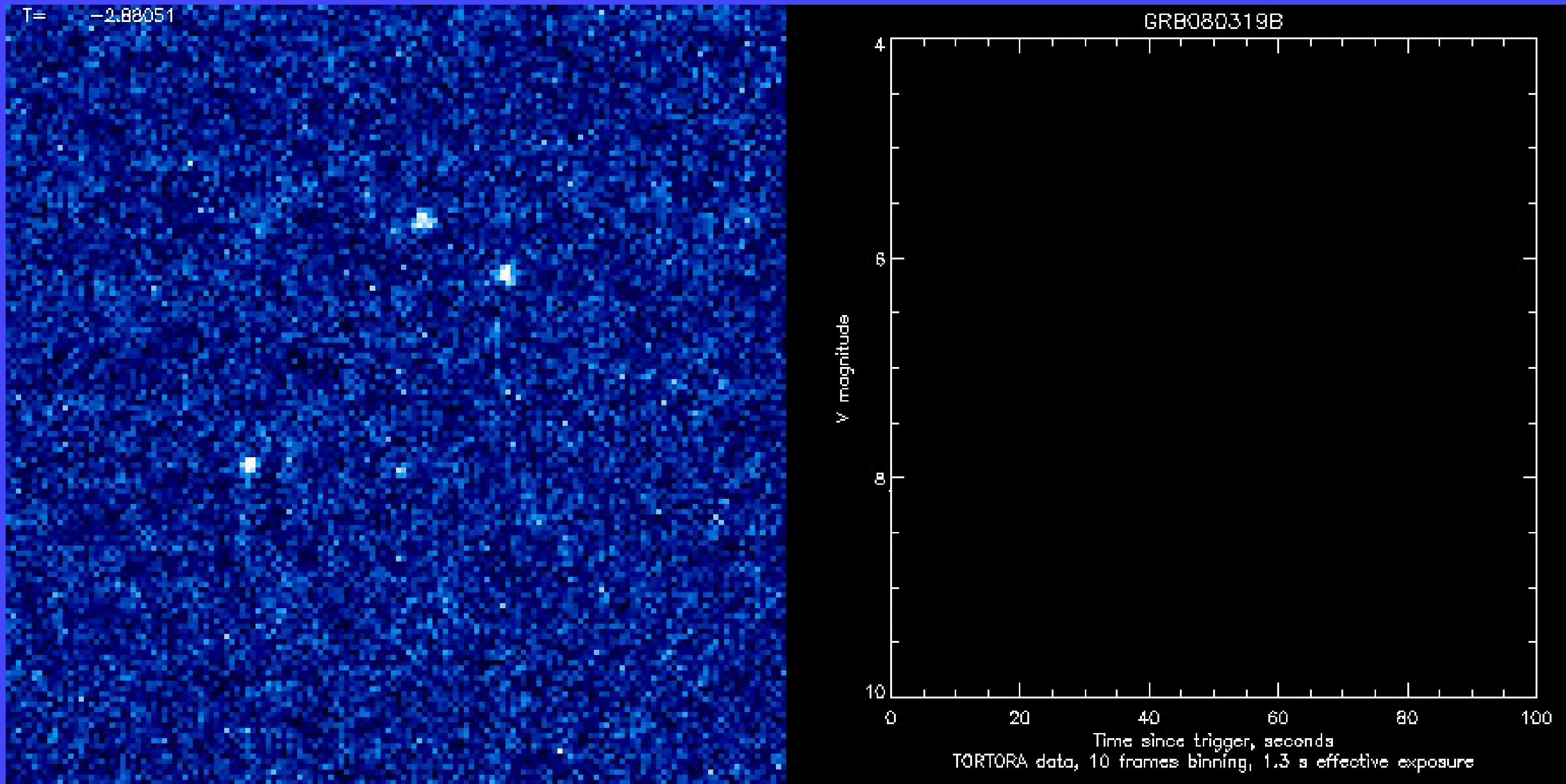
- Observe 1ong and short GRBs with a distinctive emission feature
- This feature can be explained by a spinning-down magnetar which then collapses
- This multi-stage progenitor would cause a multi-stage gravity-wave signal
- Test in future by next-generation GW facilities (Advanced-LIGO or ET)





GRB 080319B, z=0.94, 7.5Gyr

The most distant “naked-eye object” (reached V=5.6)

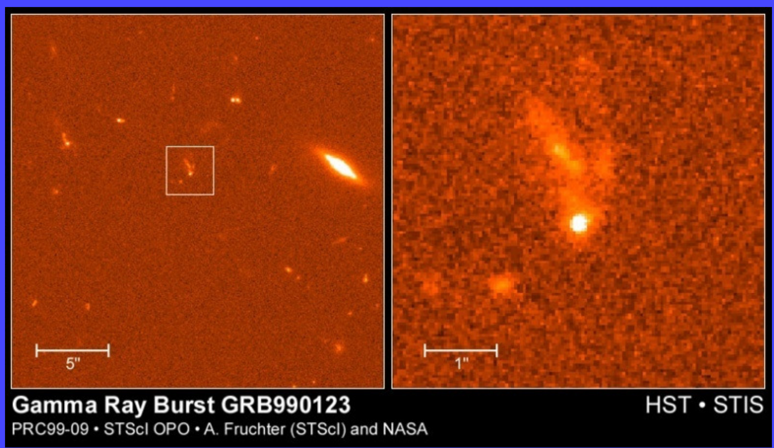


At peak this GRB was 2.5 million x a SN !! Could easily have been detected when the earliest objects formed in the Universe (Racusin et al. 2008)

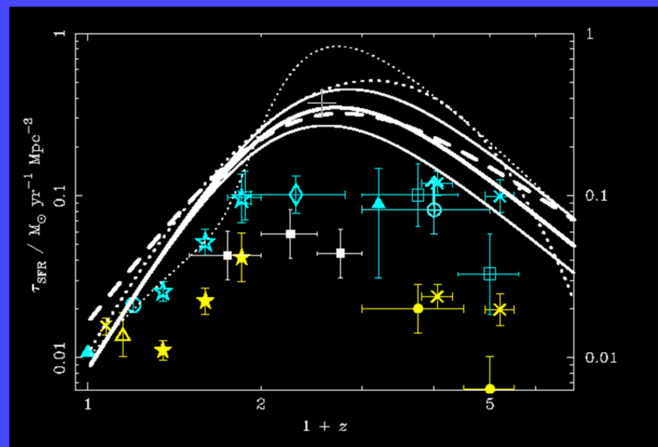
Cosmic Beacons

➔ Connection with massive stars implies GRBs trace star formation

- γ-rays can traverse large columns of gas and dust
- No requirement to detect host galaxies directly
- Bright! So visible to reionization epoch at z~11

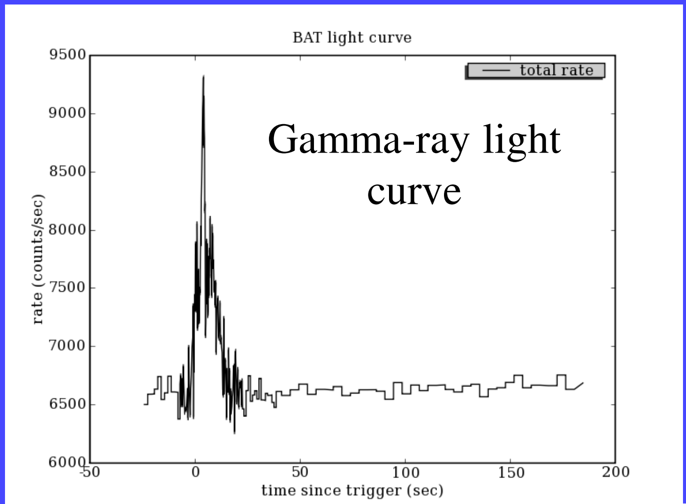


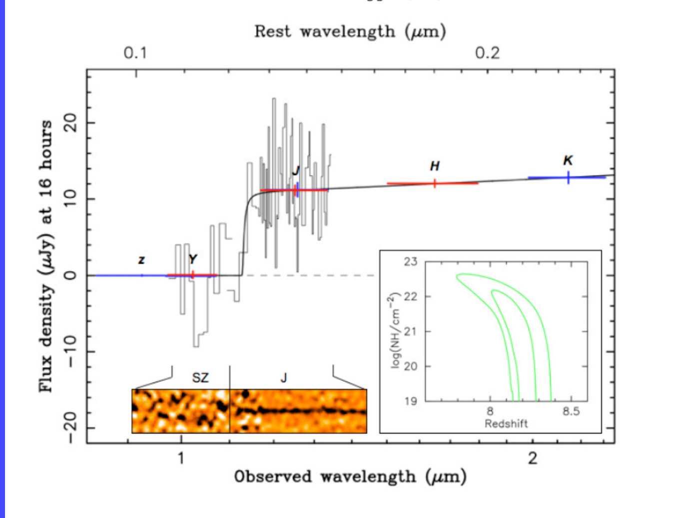
?



GRB090423

z=8.2 (spectroscopic)

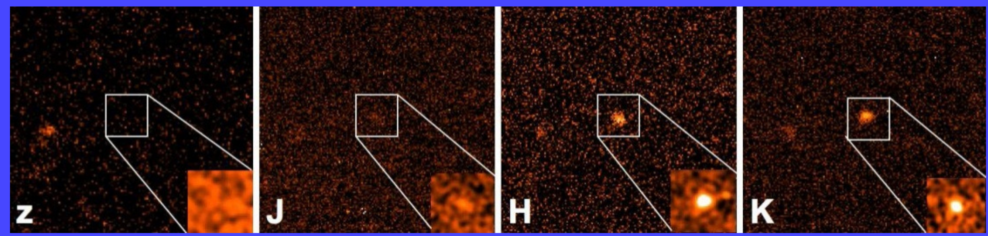




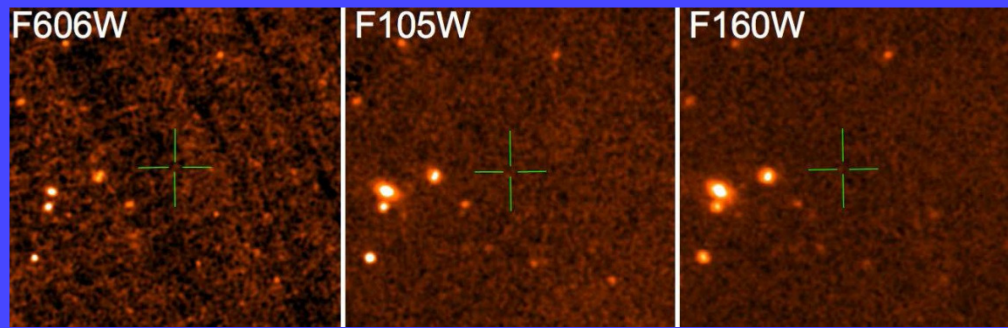
Tanvir et al. (2009);
Salvateraa et al. (2009)

GRB090429B

z≅9.4 (photometric)

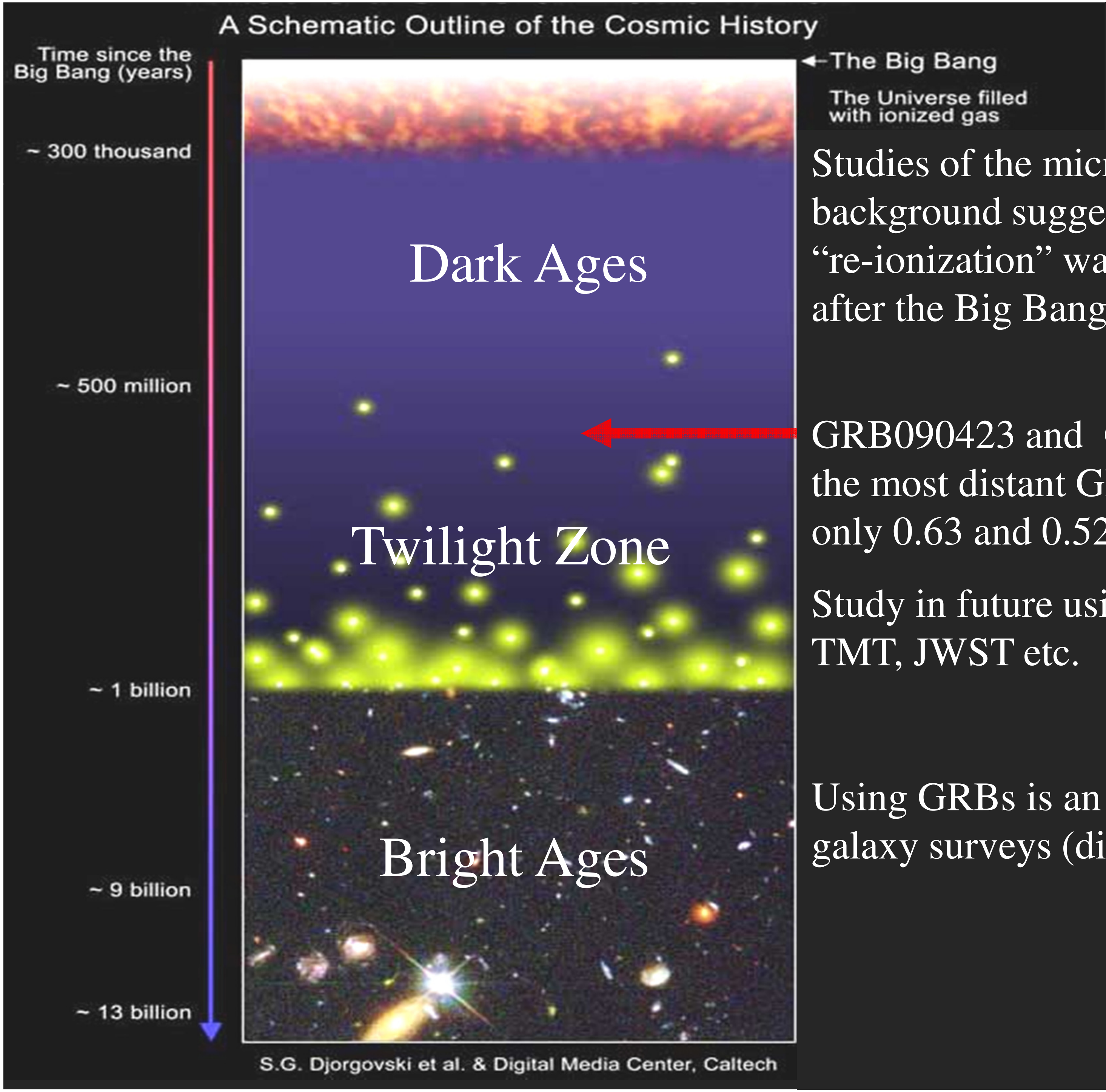


Detected only in IR



No host galaxy detected by HST helps rule out low-z dusty solution

Cucchiria et al. (2011)



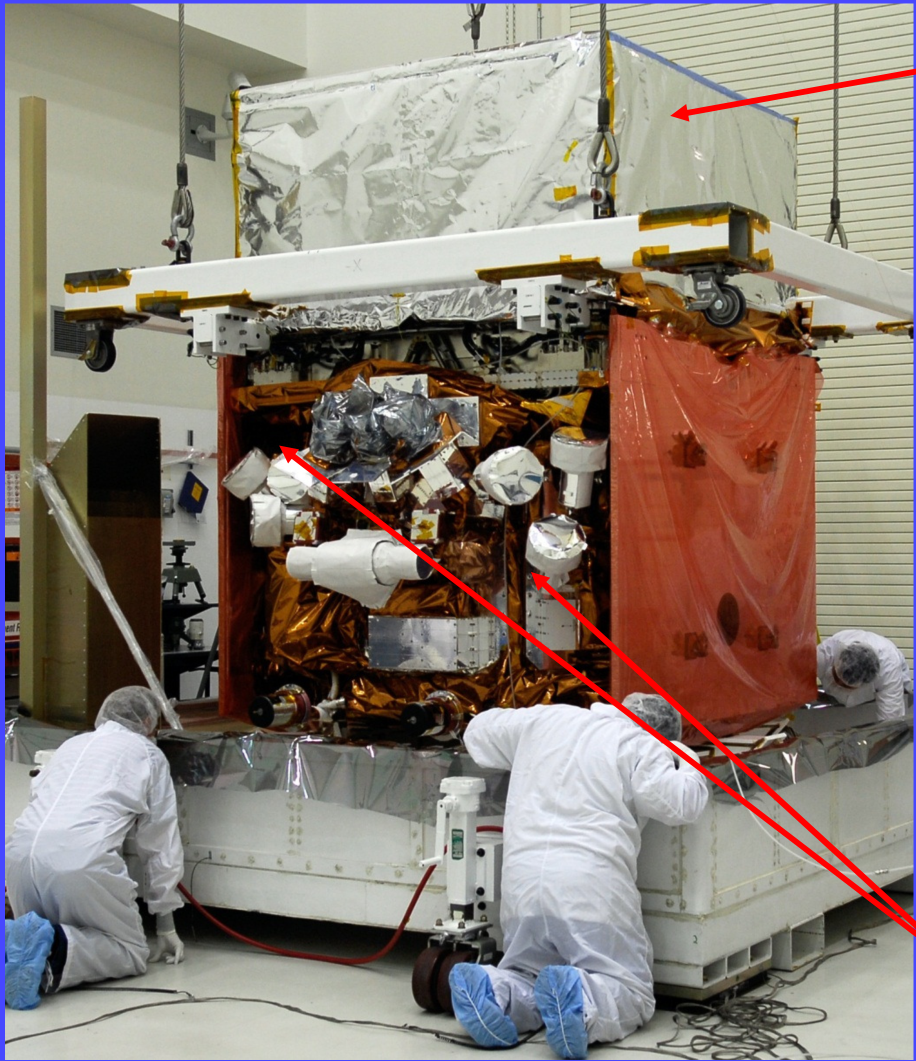
Studies of the microwave background suggest the epoch of "re-ionization" was about 400Myr after the Big Bang

GRB090423 and GRB090429B – the most distant GRBs. Universe only 0.63 and 0.52 Gyr old.

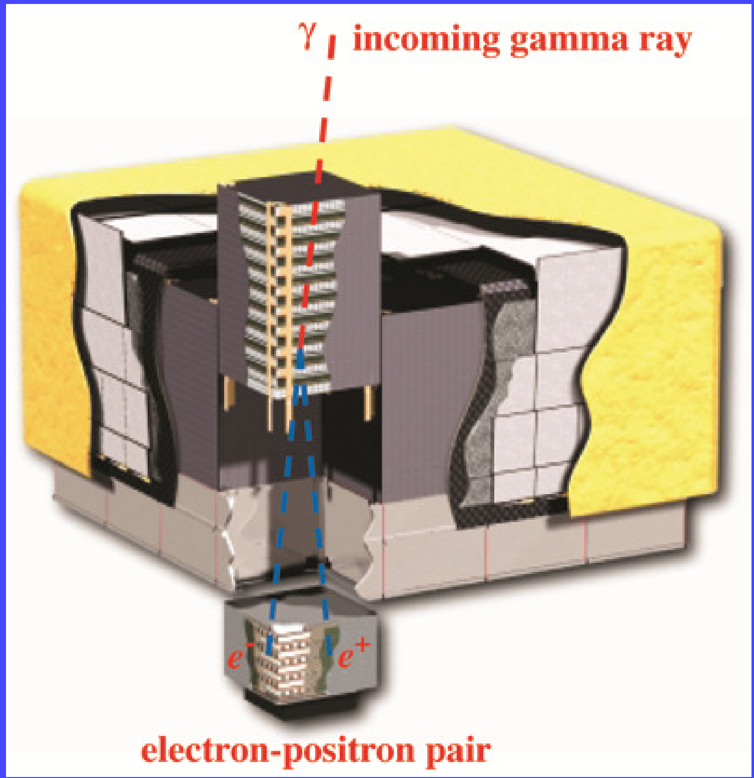
Study in future using E-ELT, TMT, JWST etc.

Using GRBs is an alternative to galaxy surveys (different bias)

Fermi Gamma-ray Space Telescope



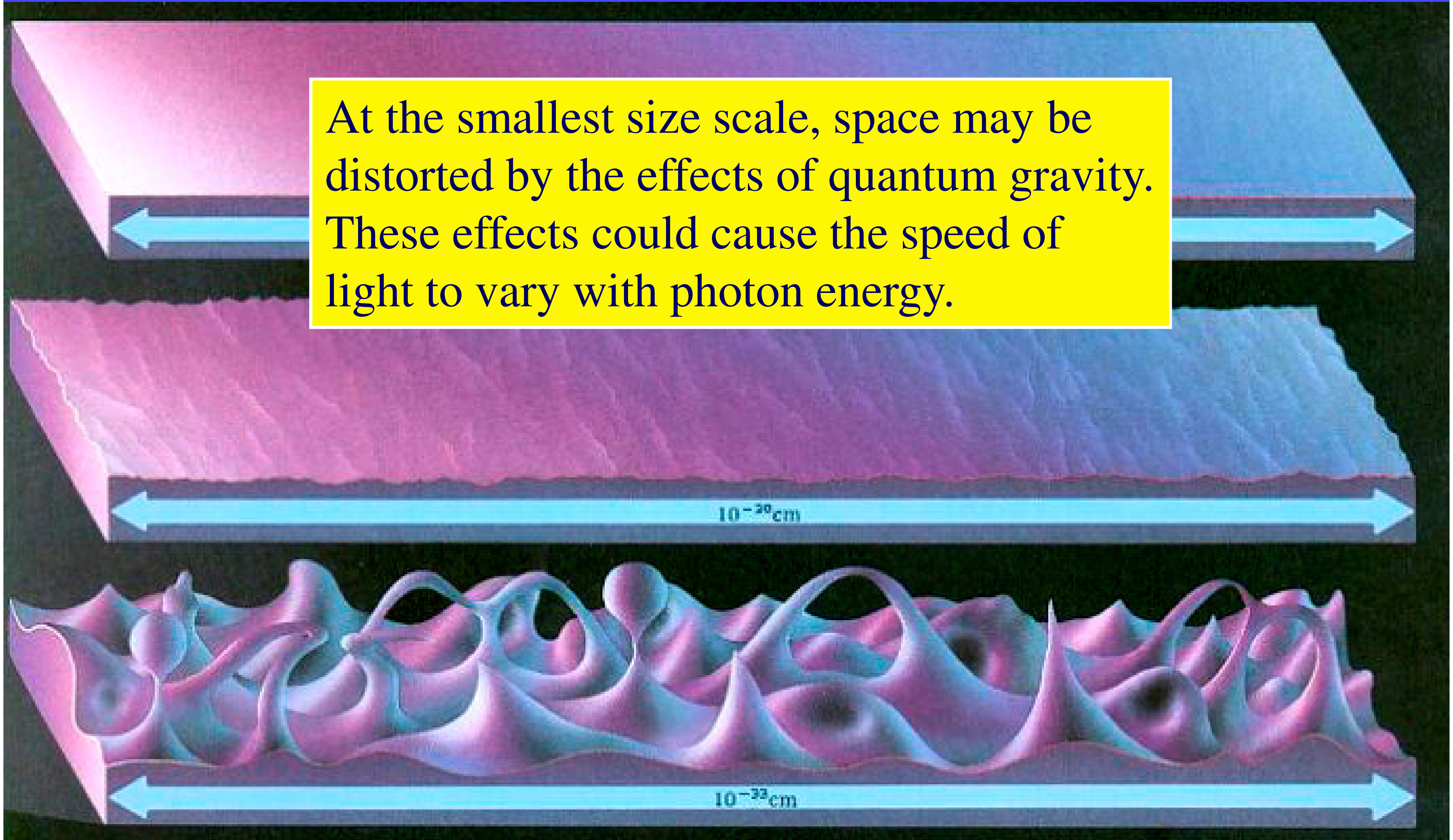
Large Area Telescope, LAT



GLAST Burst Monitor, GBM

Together, cover 10^7 in energy

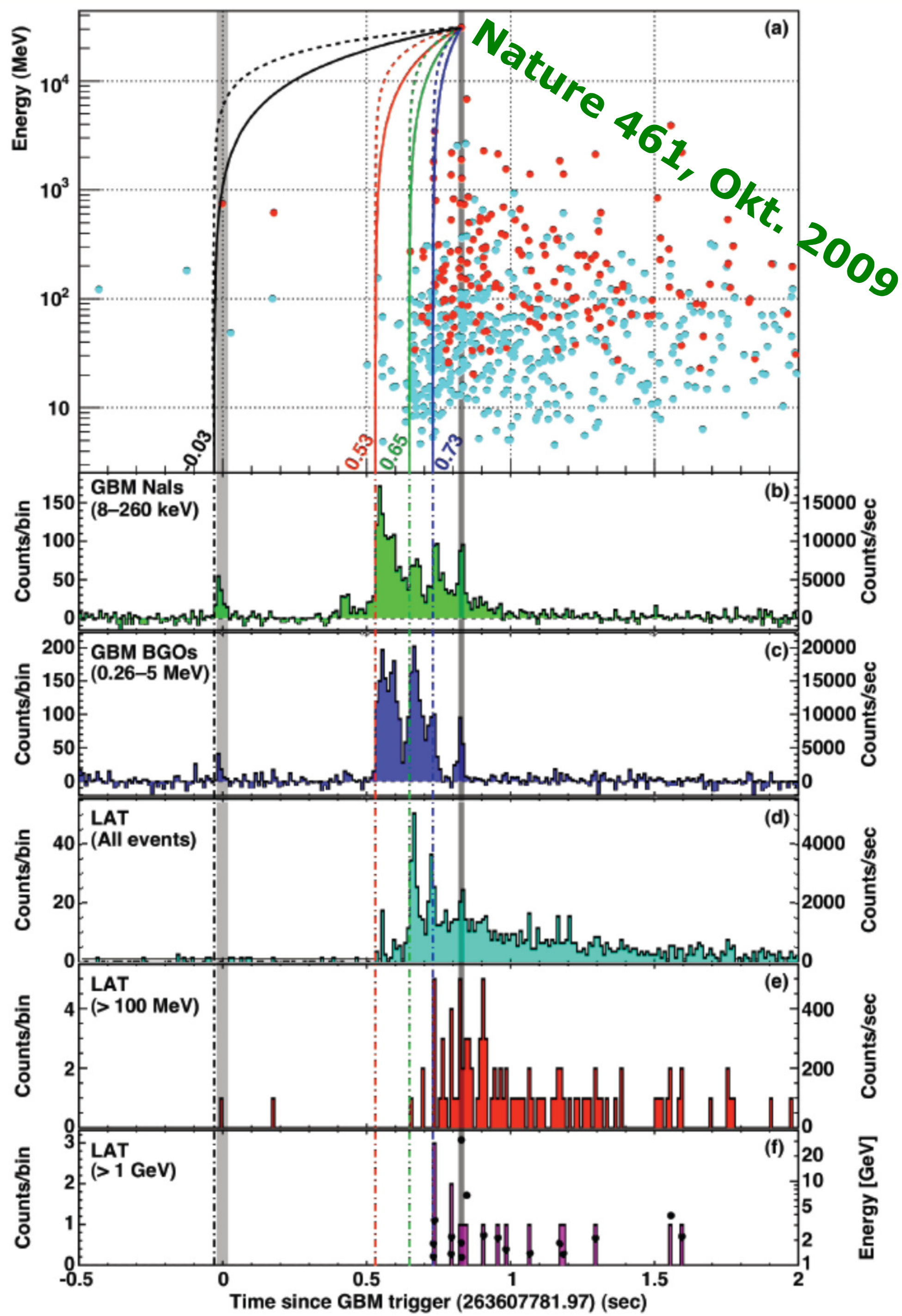
Testing special relativity: Lorentz invariance



At the smallest size scale, space may be distorted by the effects of quantum gravity. These effects could cause the speed of light to vary with photon energy.

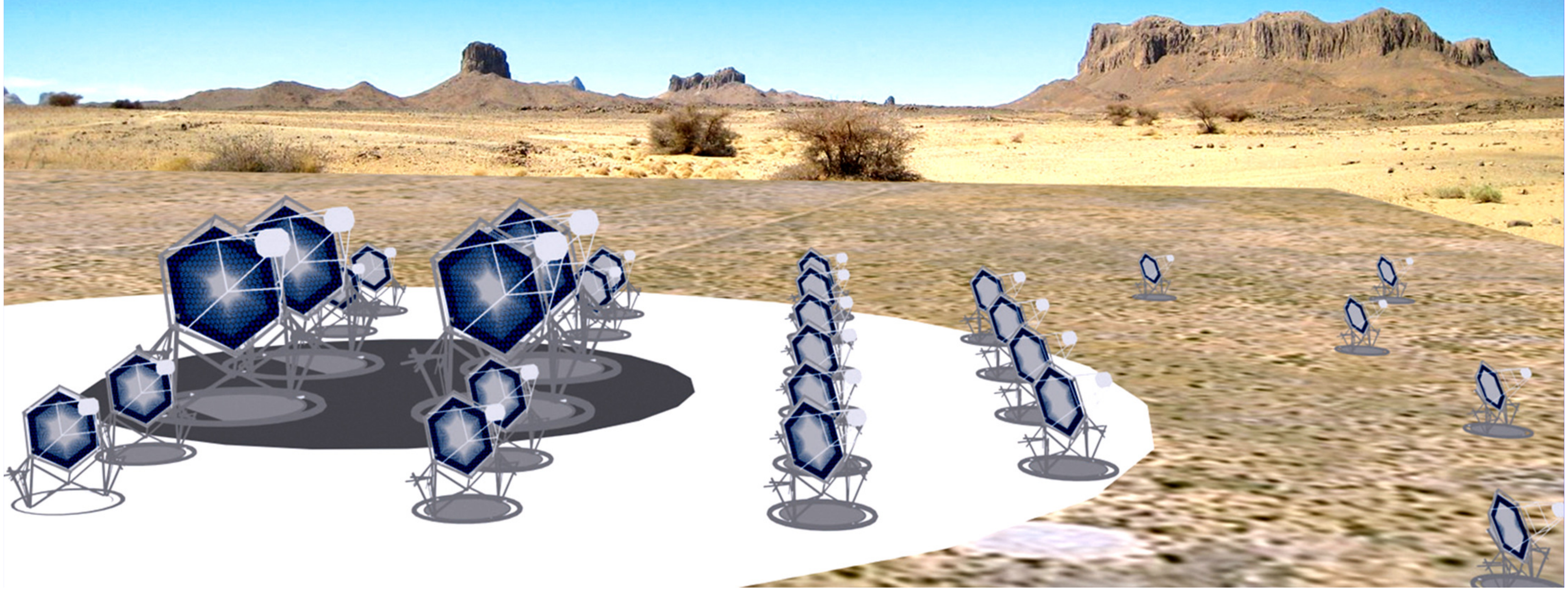
GRB 090510
(Abdo et al. 2009)

- Short GRB at z= 0.903
- Multiple peaks, clear delay for start of LAT detection and high energy emission lasts longer (also seen in other GRBs)
- 31 GeV photon is observed 0.8 s after the trigger
  - Use to constrain Lorentz invariance
  - Strongly rules out a linear speed vs. energy model
- To do better need even higher energies (CTA) or non-photonic signals (e.g. neutrinos)



The Cherenkov Telescope Array

- >10 more sensitive than current instruments (>10^4 Fermi)
  - Plus - much wider energy coverage, substantially better angular and energy resolution & wider field of view
- A ~£130M European led project (with Japan, USA...)
  - >100 institutes in 22 countries have signed MoU
  - Design 2008-2011, Prototyping 2011-13, Construction 2013-18
  - Baseline: 50-100 Cherenkov telescopes



Conclusions

- Gamma-ray astronomy/high-energy astrophysics is now routine and invaluable

- Great science advances often need large technical advances

- GRBs are a classic case of science following the technology

- They can be seen at all distances and trace stellar evolution – due to stars, albeit dead ones

- They test physics to destruction!