Multi-Messenger Astrophysics with Gamma-Ray Bursts

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Lecture I – Sept. 20th 2023

Outline of the lectures

I. The Gamma-Ray Bursts phenomenon

- Basic Observations
- Standard scenarions for progenitors and physics
- Main open issues

II. Gamma-Ray Bursts and Graviational Waves

- GRBs progenitors as sources of Graviational Waves
- Multi-messenger astrophysics, cosmology and fundamental physics with GRBs
- Multi-messenger science with next-generation GRB space missions

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GRBs basic observations

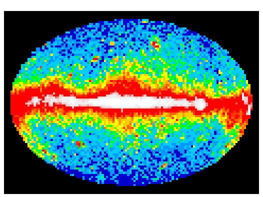
➢ 70s – 80s: GRBs = sudden and unpredictable bursts of hard X / soft gamma rays with huge flux

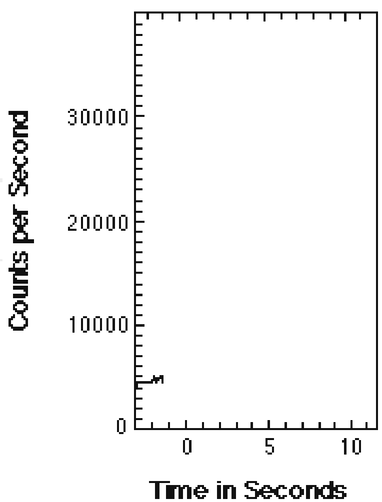
❑ most of the flux detected from 10-20 keV up to 1-2 MeV

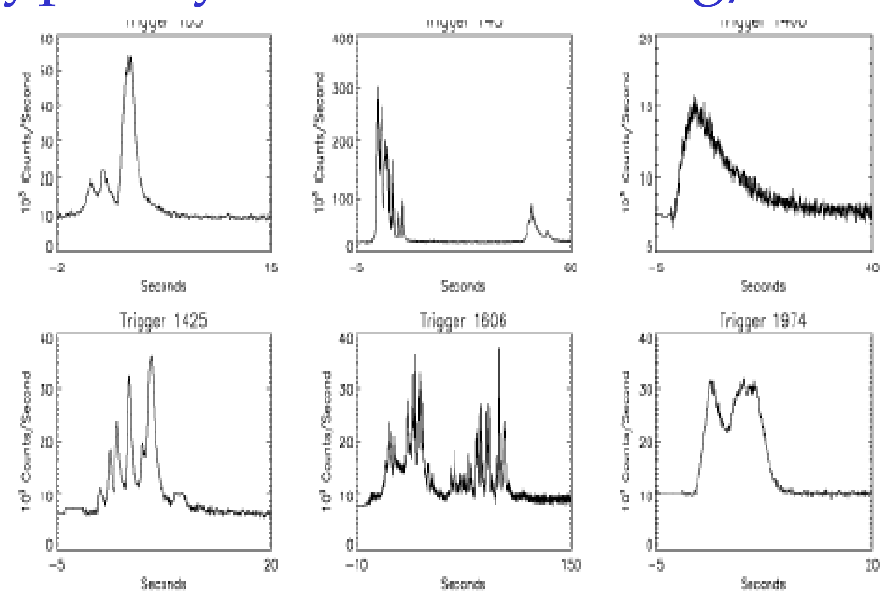
❑ measured rate (by an all-sky experiment on a LEO satellite): ~0.8 / day; estimated true rate ~2 / day

❑ complex and unclassifiable light curves

❑ fluences (= av.flux * duration) typically of $\sim 10^{-7} - 10^{-4}$ erg/cm^2







➢ Detectors in the energy range from a few keVs to a few MeVs

- proportional counters (classical): ~1.5 – 30 keV, gas (e.g., 90% argon, 10% methane), photoelectric, imaging with a few arcmin accuracy (position sensitive + coded mask), energy resolution of ~1 keV, timing a few hundreds of μs
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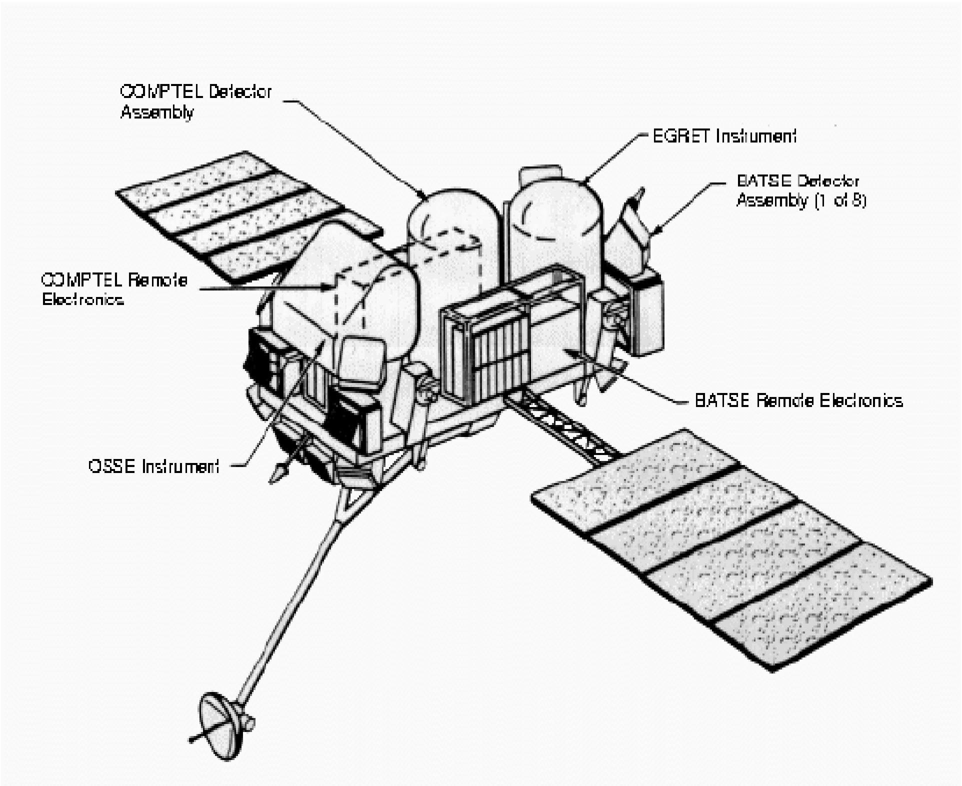
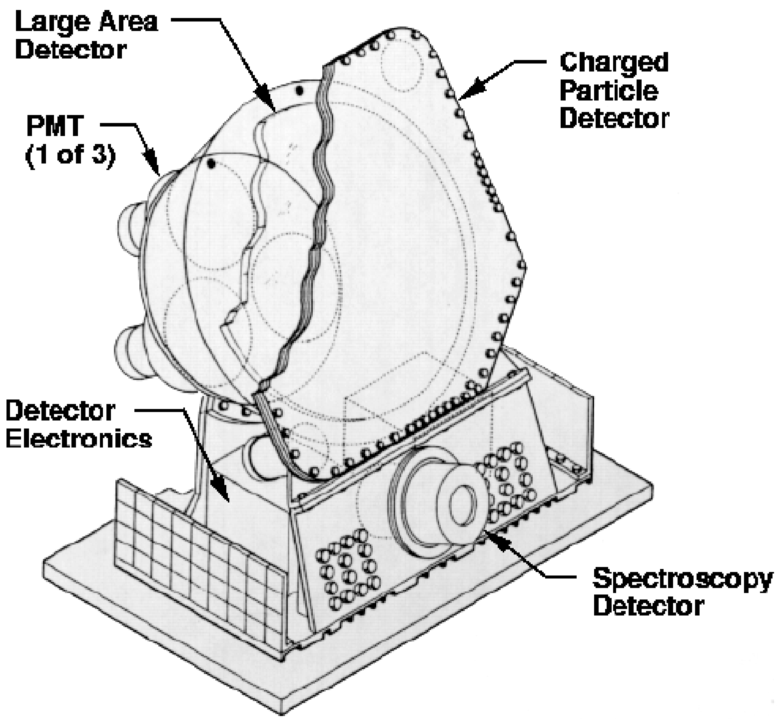
➢ '90s: The contribution by CGRO/BATSE

- ❑ major contribution came in the '90s from the NASA BATSE experiment (25-2000 keV) onboard CGRO (1991-2000)
- ❑ based on NaI scintillator detectors; 8 units covering a ~2π FOV



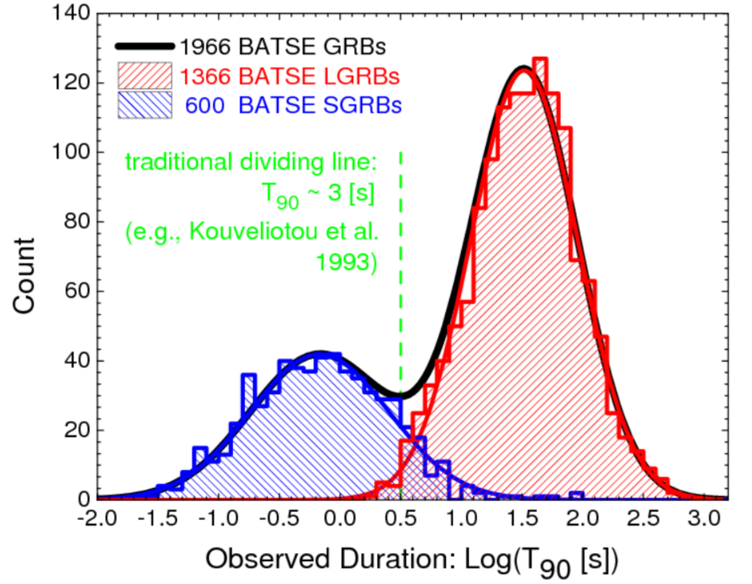


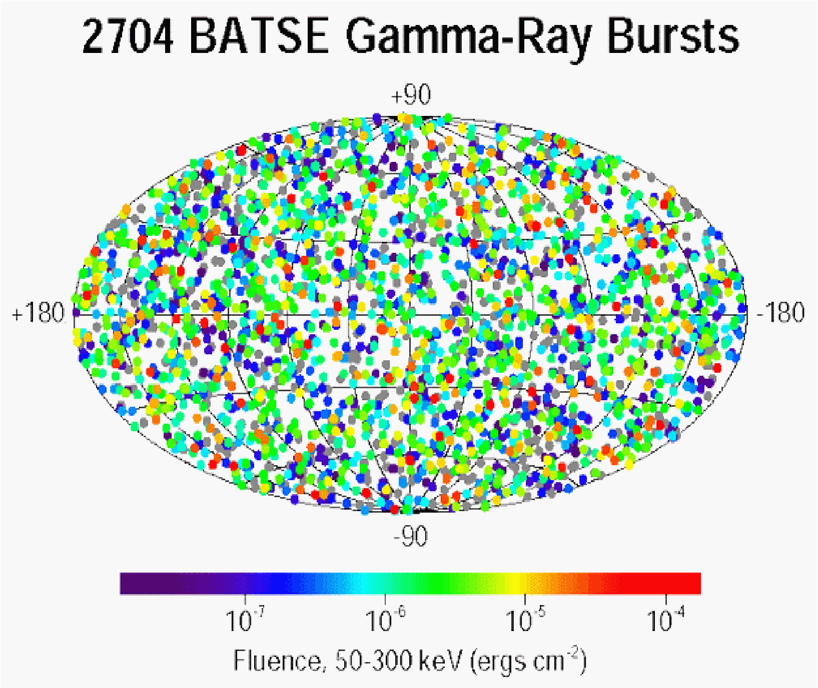
➢ '90s: the contribution by CGRO/BATSE

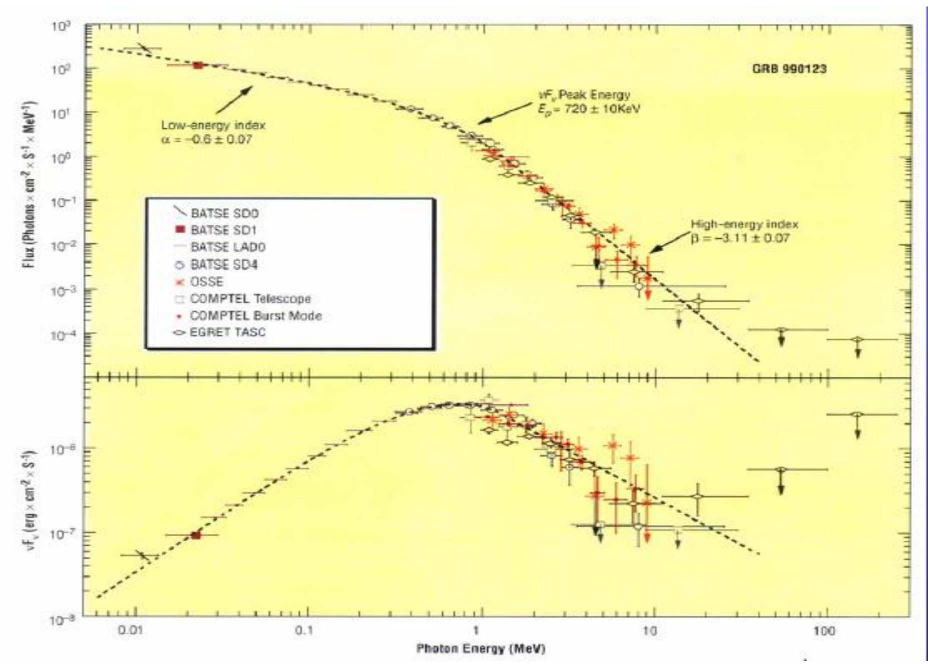
❑ bimodal distribution of durations

❑ characterization of GRB non thermal spectra

❑ isotropic distribution of directions

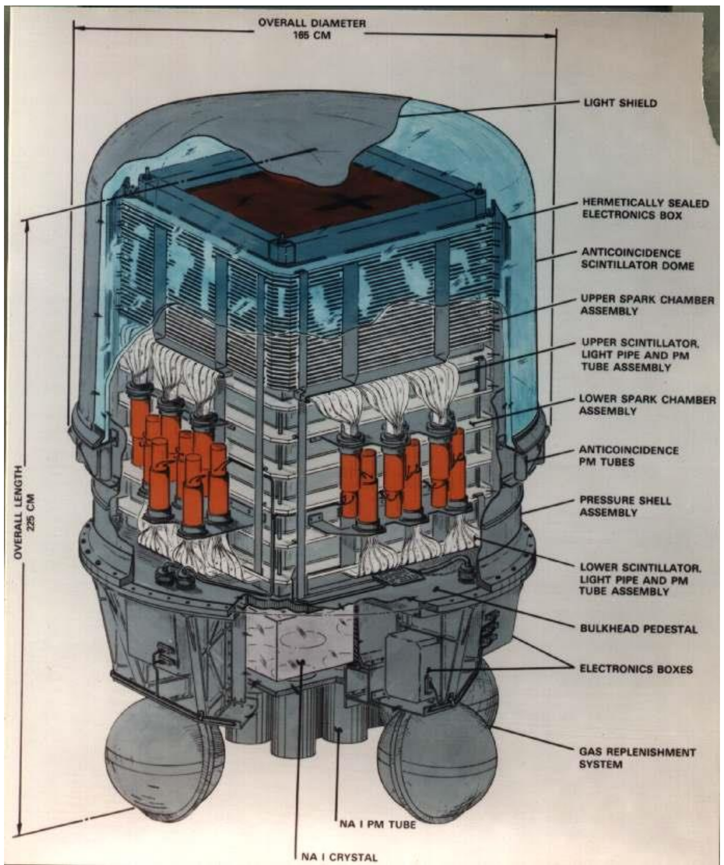


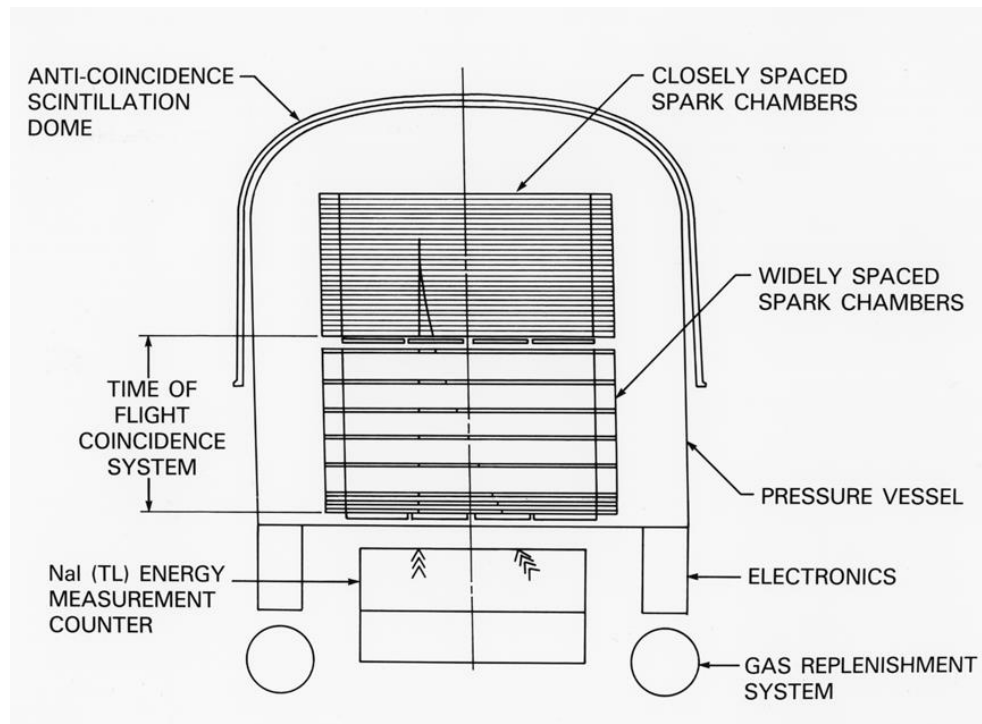




➢ ’90s: Dection of GRB VHE emission by CGRO/EGRET

❑ pair conversion gamma-ray telescope based on spark chambers sensitive in the 20 MeV – 30 GeV energy band

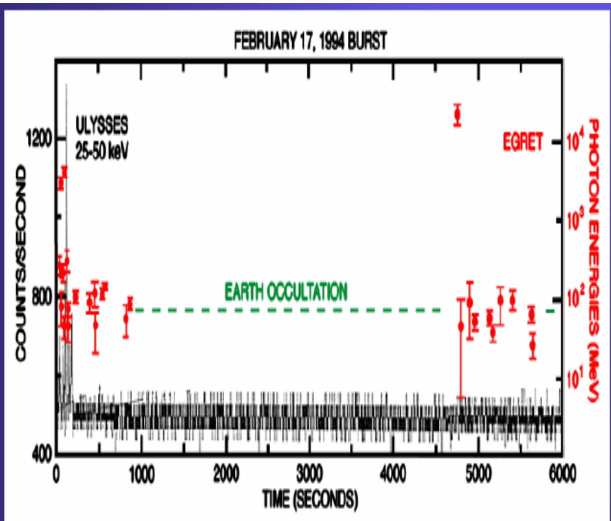


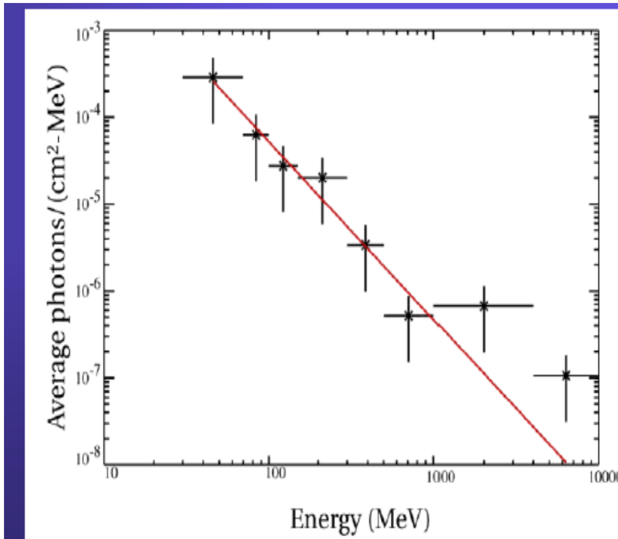


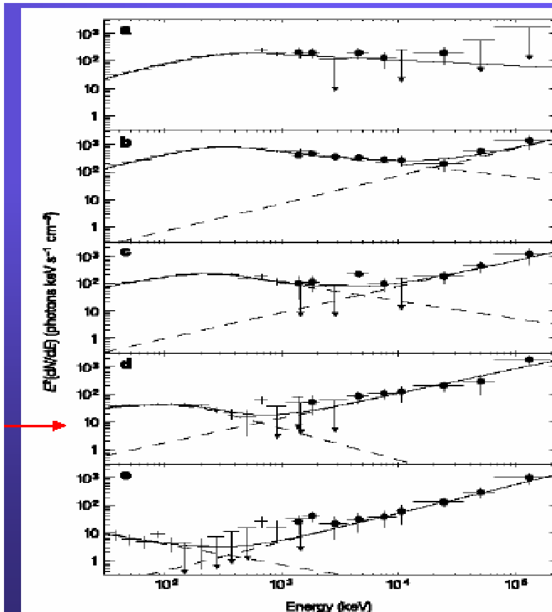
BATSE/EGRET team

➢ ’90s: dection of GRB VHE emission by CGRO/EGRET

- ❑ CGRO/EGRET detected VHE (from 30 MeV up to 18 GeV) photons for a few GRBs
- ❑ VHE emission can last up to thousends of s after GRB onset
- ❑ average spectrum of 4 events well described by a simple power-law with index ~2 , consistent with extension of low energy spectra
- ❑ GRB 941017,measured by EGRET-TASC shows a high energy component inconsistent with synchrotron shock model



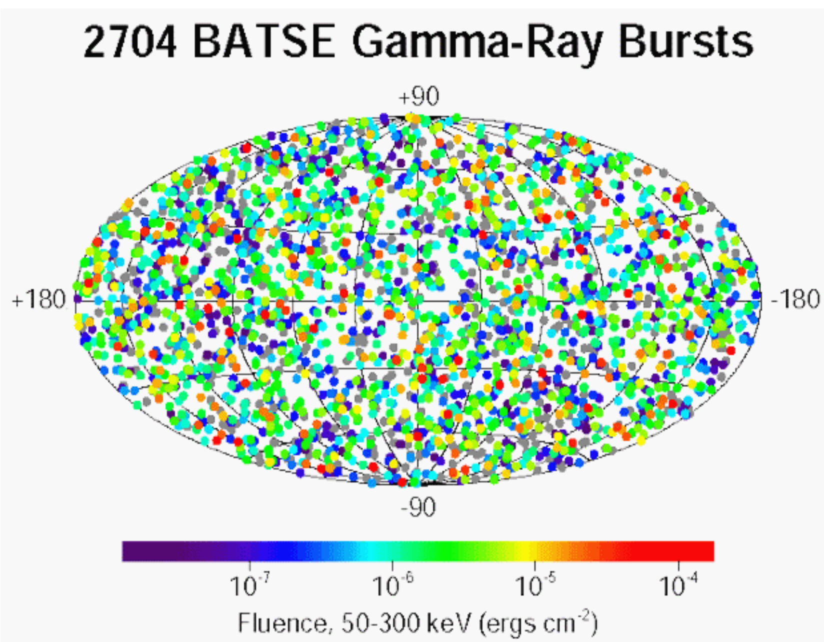


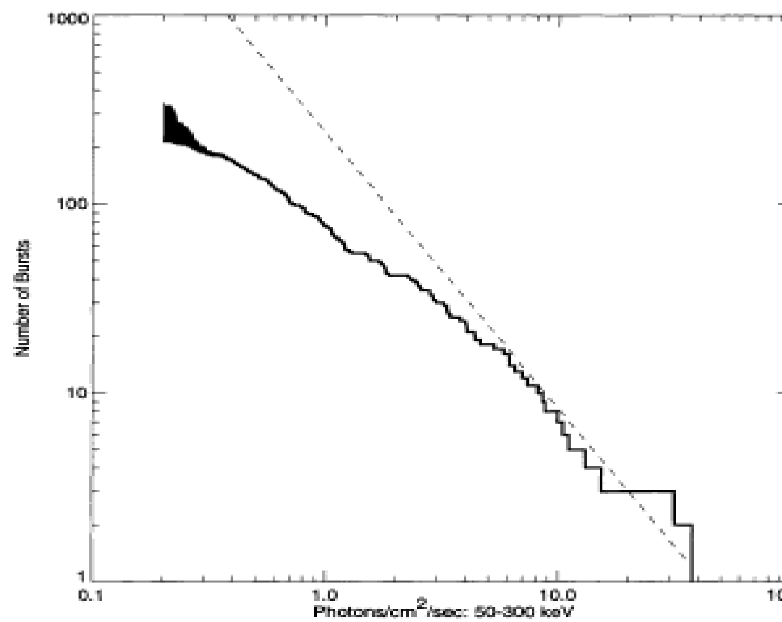


BATSE/EGRET team

➢ Early evidences for a cosmological origin of GRBs

- ❑ isotropic distribution of GRBs directions
- ❑ paucity of weak events with respect to homogeneous distribution in euclidean space
- ❑ **given the high fluences (up to more than 10^{-4} erg/cm2 in 20-1000 keV) a cosmological origin would imply huge luminosity**
- ❑ thus, a "local" origin was not excluded until 1997 !





The Distance Scale to Gamma-Ray Bursts Great Debate in 1995

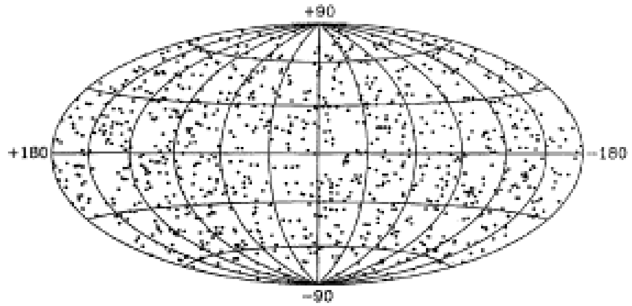


FIG. 1—Sky map of the first 1005 gamma-ray bursts observed by BATSE. Of these, 485 are from the second BATSE catalog and have positional uncertainties of about 7°. The remainder have preliminary positions or are affected by gaps in the telemetry stream, and have more uncertain positions. (From Briggs et al. 1995.)

piece of evidence. But eventually, through the process of weighing-up the evidence, scientists reach a conclusion.

Paczyński (1995) focuses on the isotropic sky distribution of gamma-ray bursts. He describes the impact that the announcement that the sky distribution of faint bursts is consistent with isotropy had on him and on some others when it was made by the BATSE team in September 1991 (Meegan et al. 1992). The isotropy of the bursts on the sky is an important piece of evidence. The cosmological hypothesis is consistent with it. But the Galactic hypothesis is also consis-

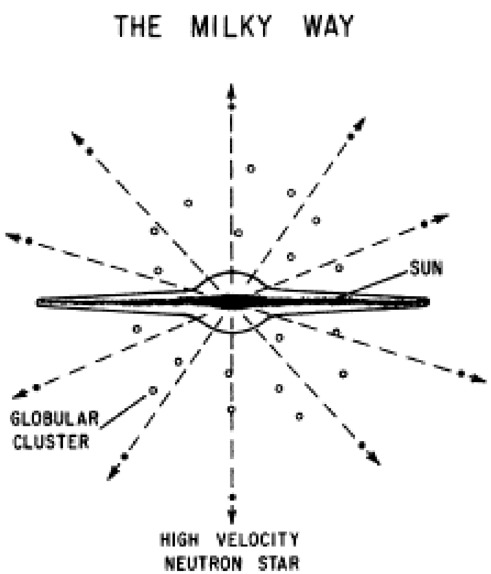


FIG. 3—Side view of the Milky Way. The Galactic bulge and disk are clearly visible; the dark lane along the plane of the Galaxy is due to dust. Also shown are the Sun, the globular clusters which surround the Galactic disk, and the trajectories of high-velocity neutron stars which are escaping from the Milky Way. These high-velocity neutron stars form a previously unknown Galactic "corona." The corona contains an ample population of neutron stars which appears isotropic when viewed from Earth. Many scientists believe that this population of distant neutron stars is the source of gamma-ray bursts.

- **Need for a substantial improvement in the location accuracy several degrees (BATSE, scintillators) to arcmin**

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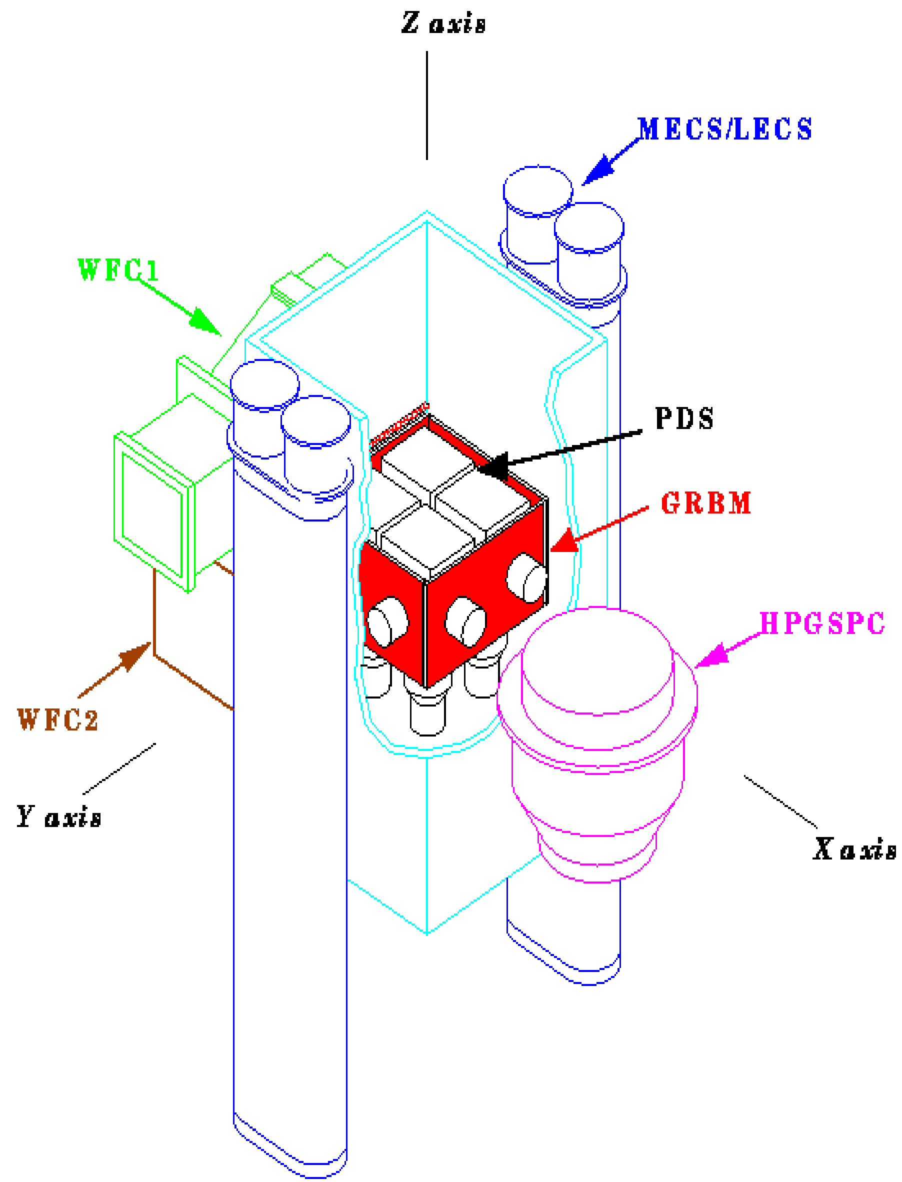
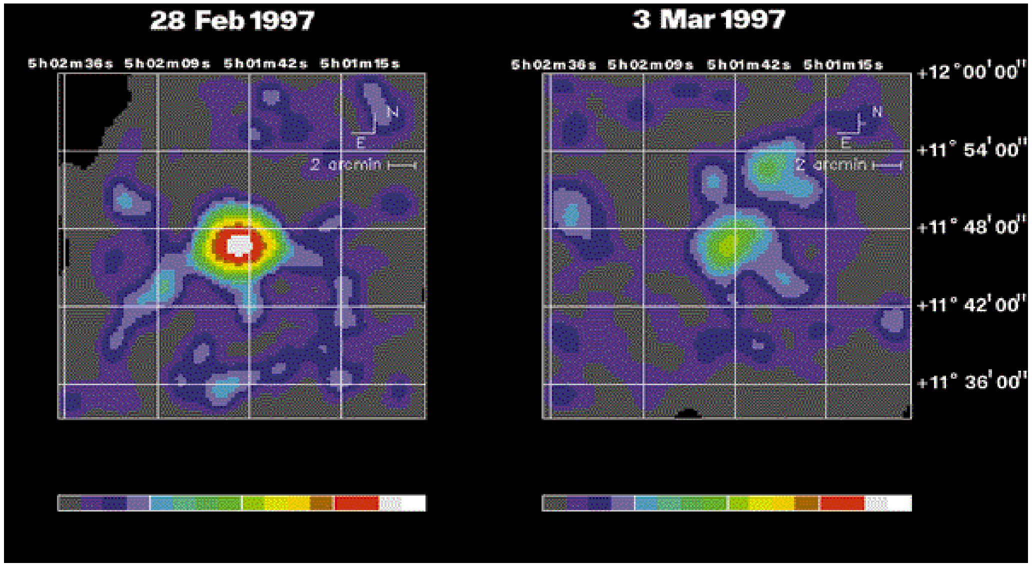
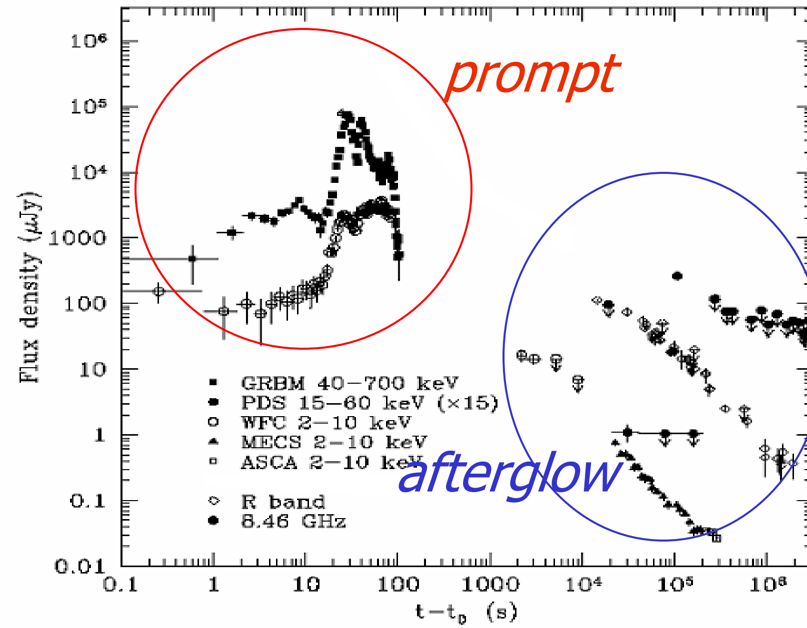
➢ The BeppoSAX revolution (1996 – 2002)

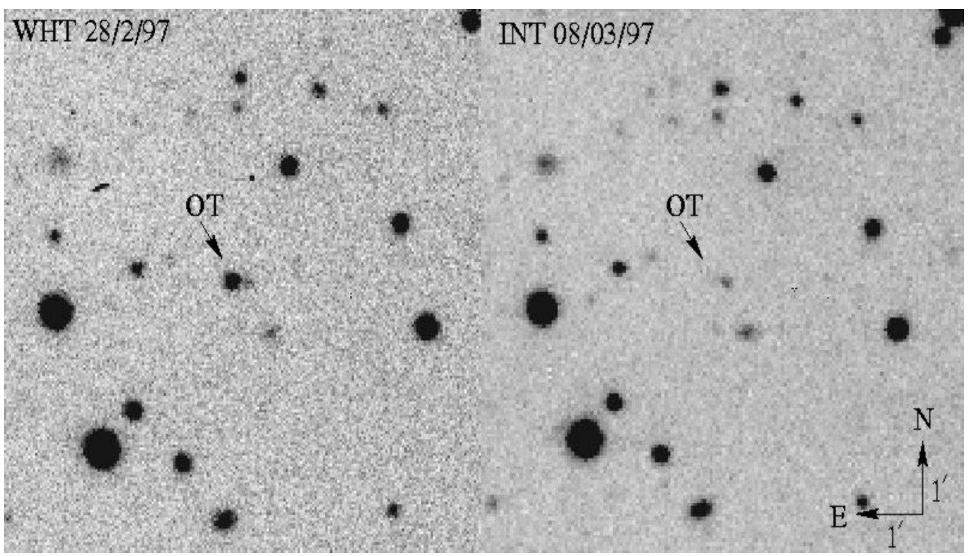
- ❑ NFI (X-ray focusing telescopes, 0.1-10 keV + PDS, 15-200 keV)
- ❑ WFC (2 units, proportional counters + coded mask, FOV 20°x20° each unit, 2-28 keV)
- ❑ GRBM (4 units, CsI scintillators, large FOV, GRB triggering, 40-700 keV)
- ❑ WFC and GRBM co-aligned

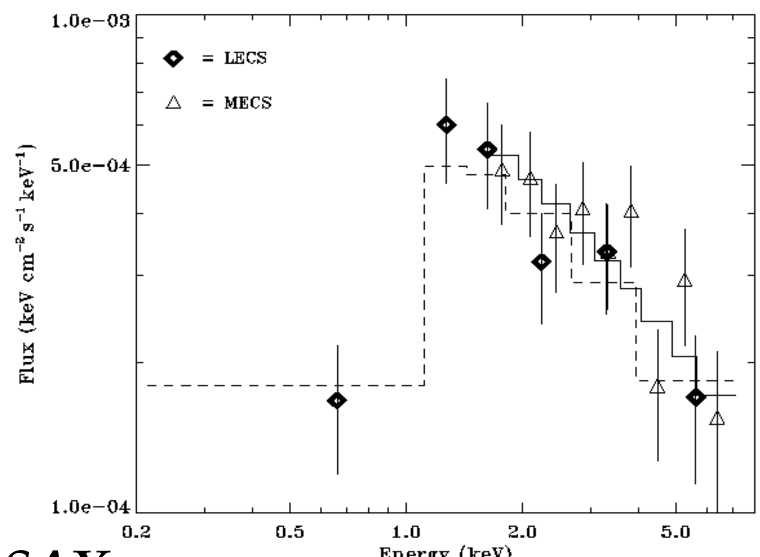


➢ BeppoSAX: afterglow emission (late ’90s): power-law decay and spectrum (with exceptions)



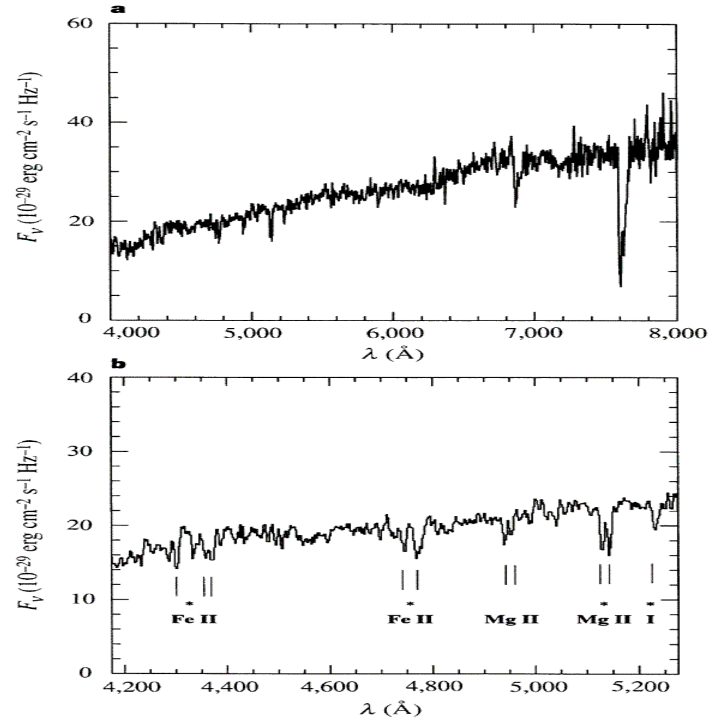






Costa et al. 1997, Van Paradijs et al. 1997, SAX

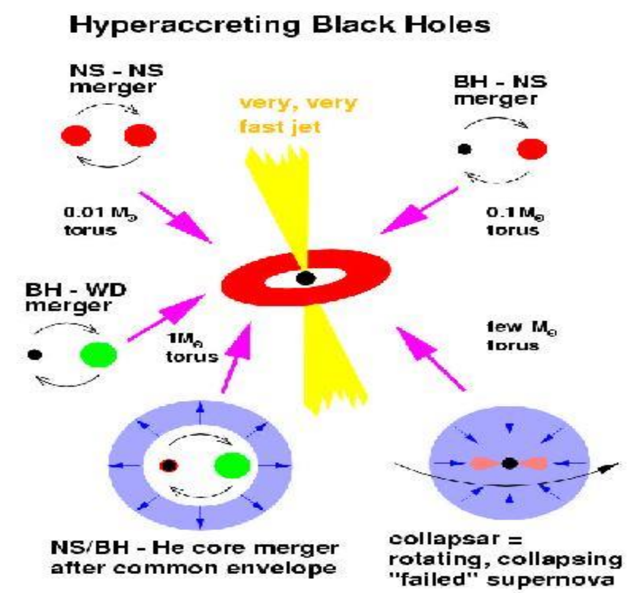
- ➢ optical spectroscopy of afterglow and/or host galaxy –> first measurements of GRB redshift

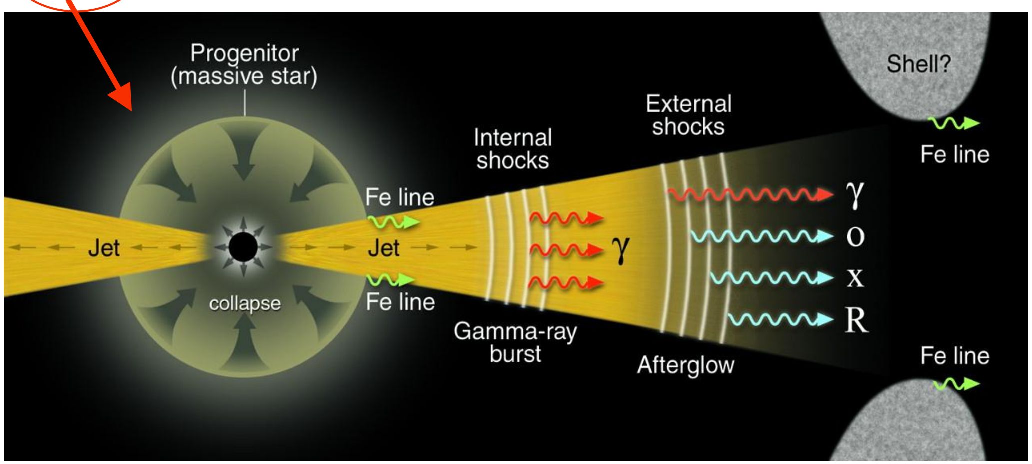


- ➢ **redshifts higher than 0.01 and up to > 9 GRB are cosmological**

- ➢ **their isotropic equivalent radiated energy is huge (up to more than 10^{54} erg in a few tens of s !)**

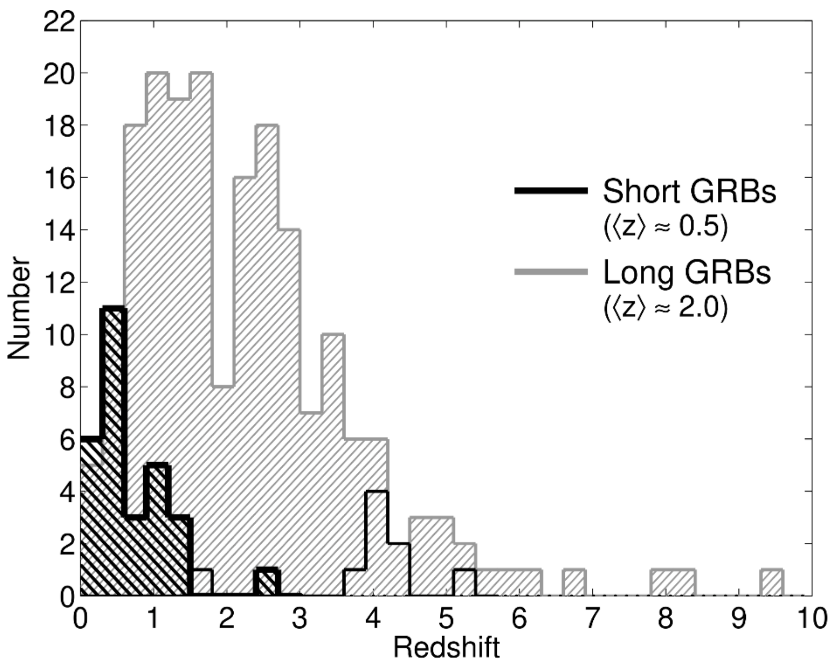
- ➢ fundamental input for origin of long / short

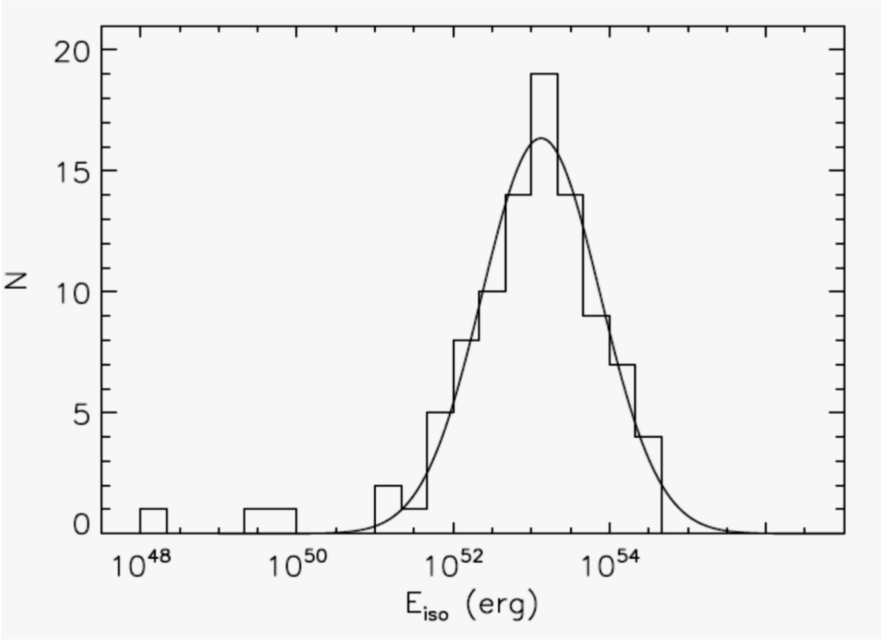




➢ Distance and luminosity (>1997)

- ❑ from optical spectroscopy (OT or HG) -> redshift estimates
- ❑ **all GRBs with measured redshift (~400) lie at cosmological distances (except for the peculiar GRB980425, z=0.0085)**
- ❑ **isotropic equivalent radiated energies can be as high as > 10^{54} erg**
- ❑ short GRB lie at lower redshifts (<~2) and are less luminous (Eiso < ~10^{52} erg)



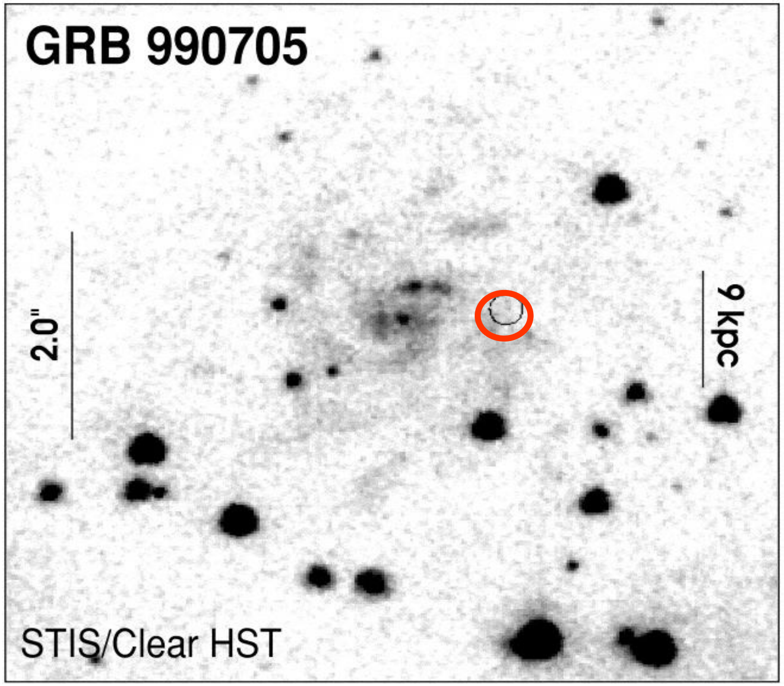


➢ Host galaxies (>1997, X-ray loc. + optical follow-up)

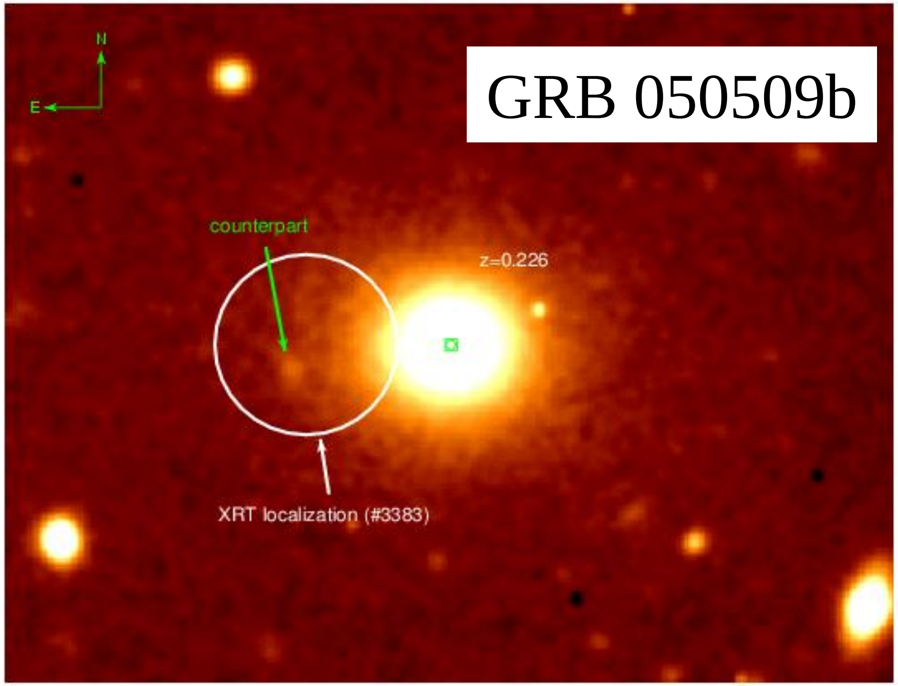
❑ host galaxies long GRBs: blue, usually regular and high star forming, GRB located in star forming regions

❑ host galaxies of short GRBs (more recent): no preferred type

Long



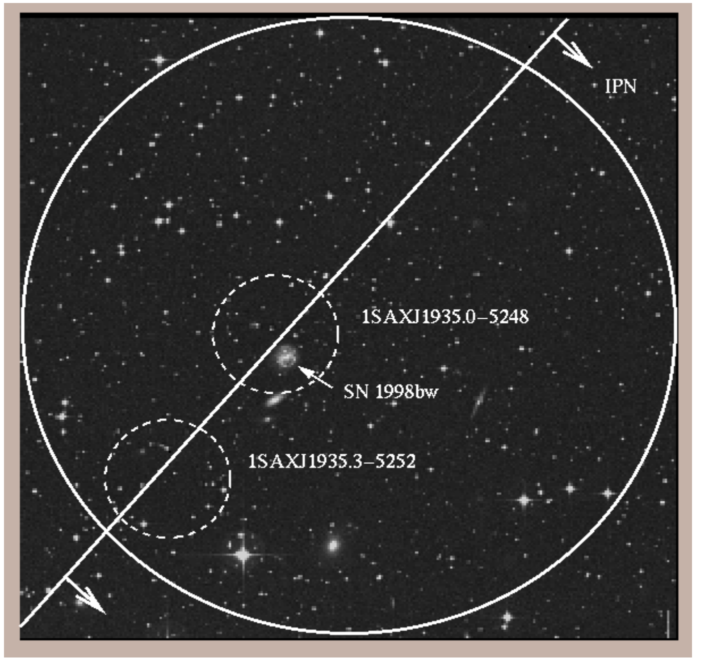
Short



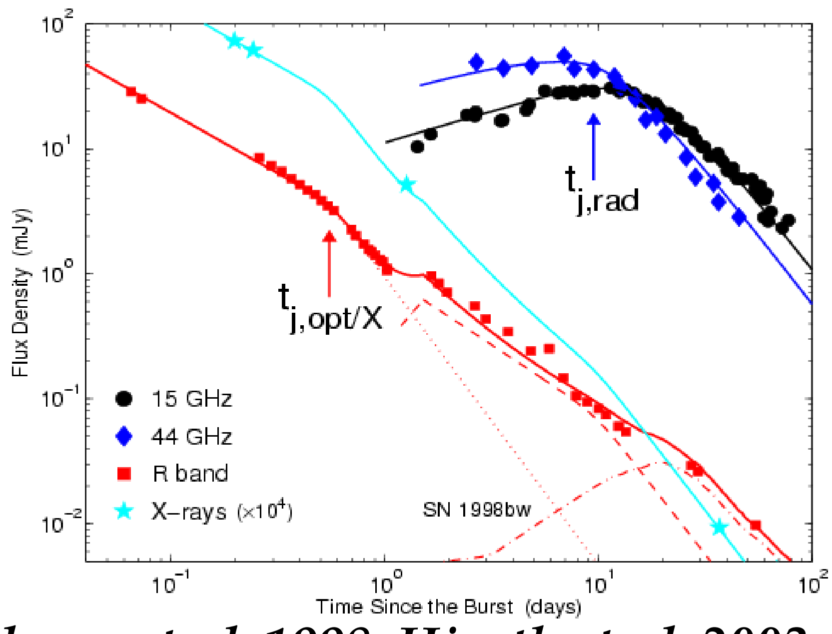
Bloom et al. 2002 , 2006

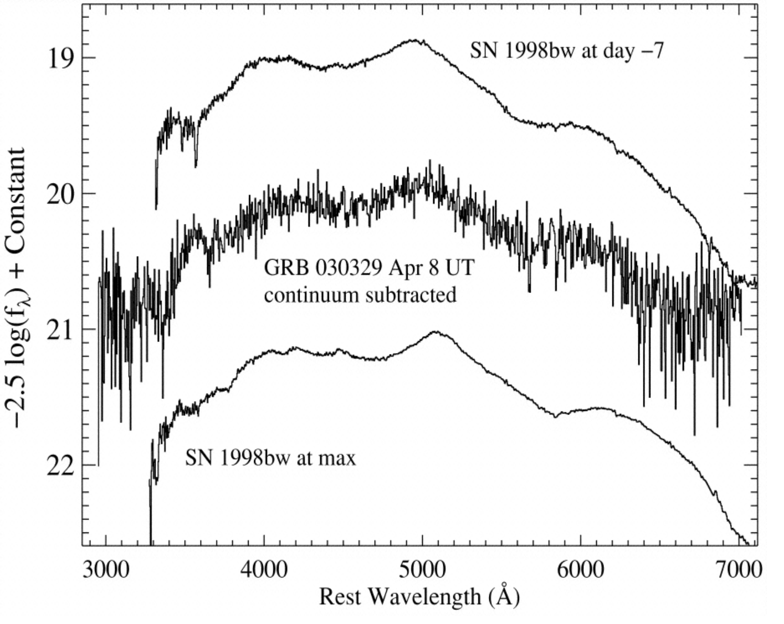
➢ GRB/SN connection (> 1998)

➢ GRB 980425, a normal GRB detected and localized by WFC and NFI, but in temporal/spatial coincidence with a type Ib/c SN at z = 0.008 (chance prob. 0.0001)



➢ Bumps in optical afterglow light curves and optical spectra resembling that of GRB980425 (e.g., GRB 030329)

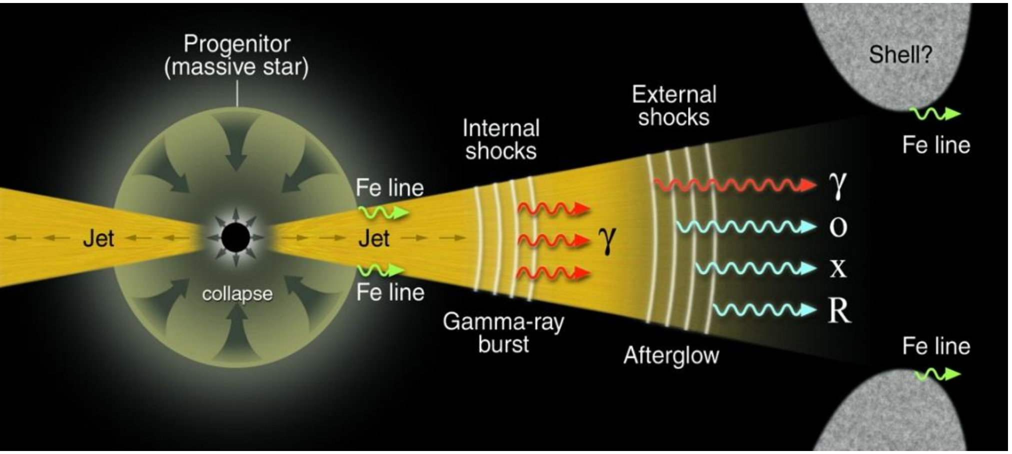




Galama et al. 1998, Hjorth et al. 2003

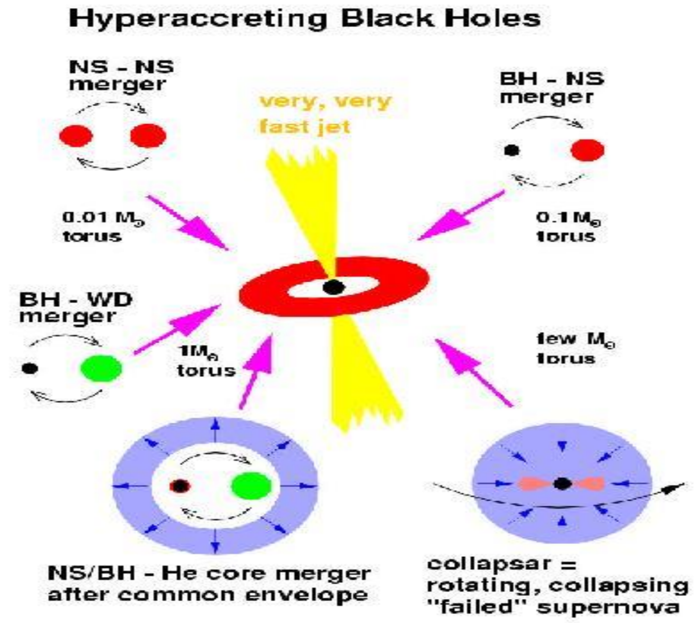
Standard scenarios for GRB progenitors

LONG



- energy budget up to >10^{54} erg
- long duration GRBs
- metal rich (Fe, Ni, Co) circum-burst environment
- GRBs occur in star forming regions
- GRBs are associated with SNe
- likely collimated emission

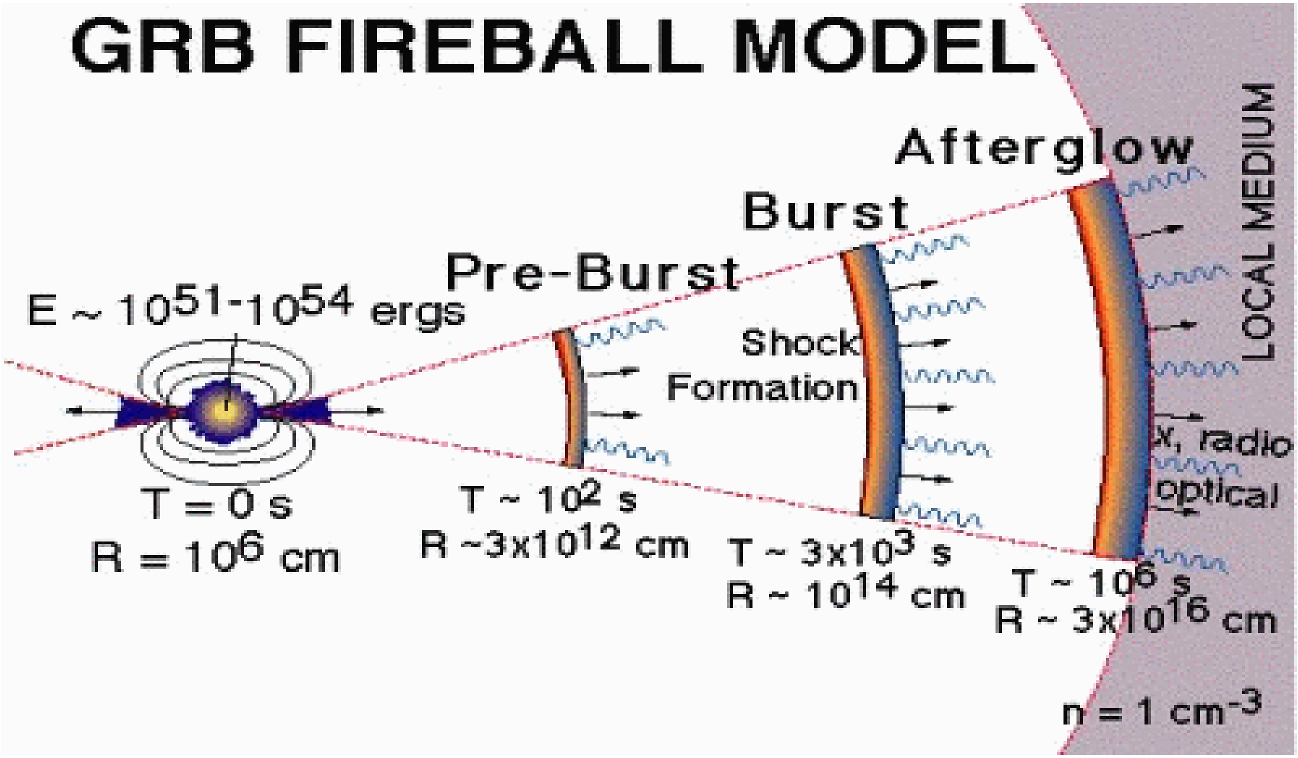
SHORT



- energy budget up to 10^{51} - 10^{52} erg
- short duration (< 5 s)
- clean circum-burst environment
- old stellar population

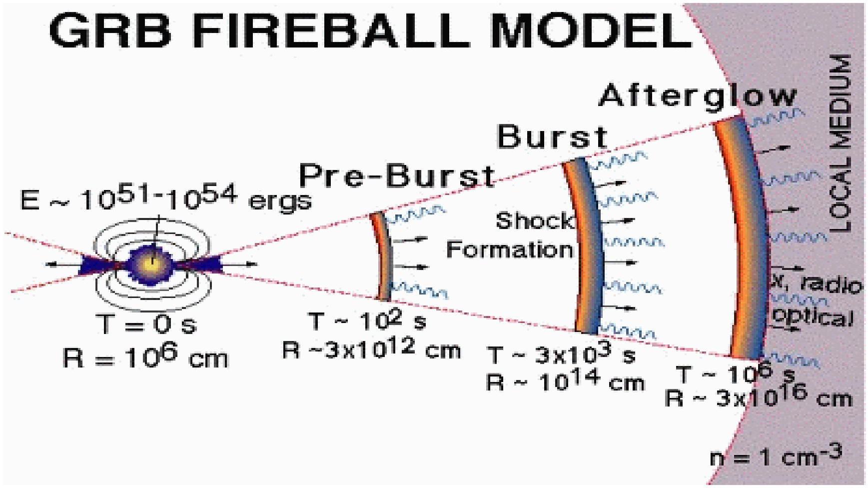
Standard scenarios for GRB phisics

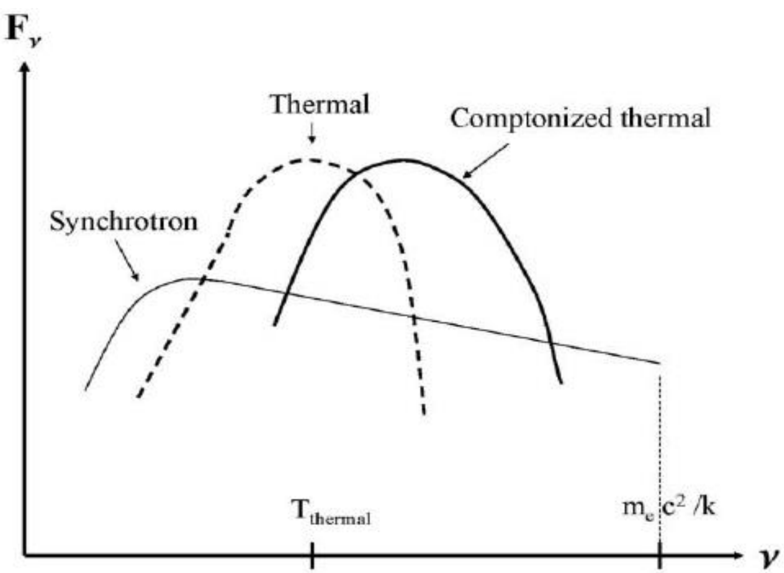
- ms time variability + huge energy + detection of GeV photons -> plasma occurring ultra-relativistic ($\Gamma > 100$) expansion (fireball or firejet)
- non thermal spectra -> shocks synchrotron emission (SSM)
- fireball internal shocks -> prompt emission
- fireball external shock with ISM -> afterglow emission



➢ GRB prompt emission physics

❑ physics of prompt emission still not settled, various scenarios: SSM internal shocks, IC-dominated internal shocks, external shocks, photospheric emission dominated models, kinetic energy dominated fireball , Poynting flux dominated fireball

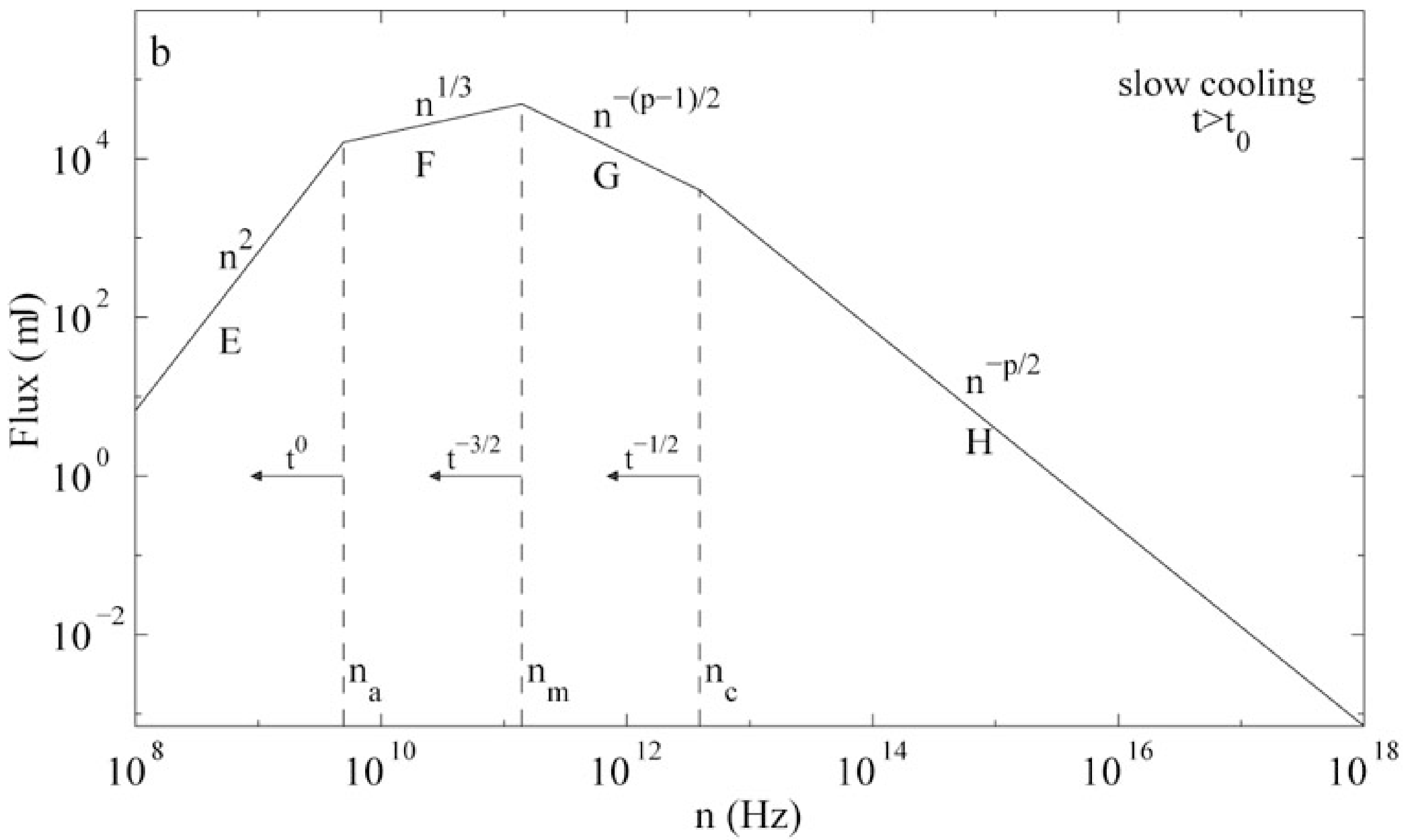




α $N(E)$	$\alpha+1$ $F(E)$	$\alpha+2$ EF_E	model/spectrum
-3/2	-1/2	1/2	Synchrotron emission with cooling
-1	0	1	Quasi–saturated Comptonization
-2/3	1/3	4/3	Instantaneous synchrotron
0	1	2	Small pitch angle/jitter inverse Compton by single e^-
1	2	3	Black Body
2	3	4	Wien

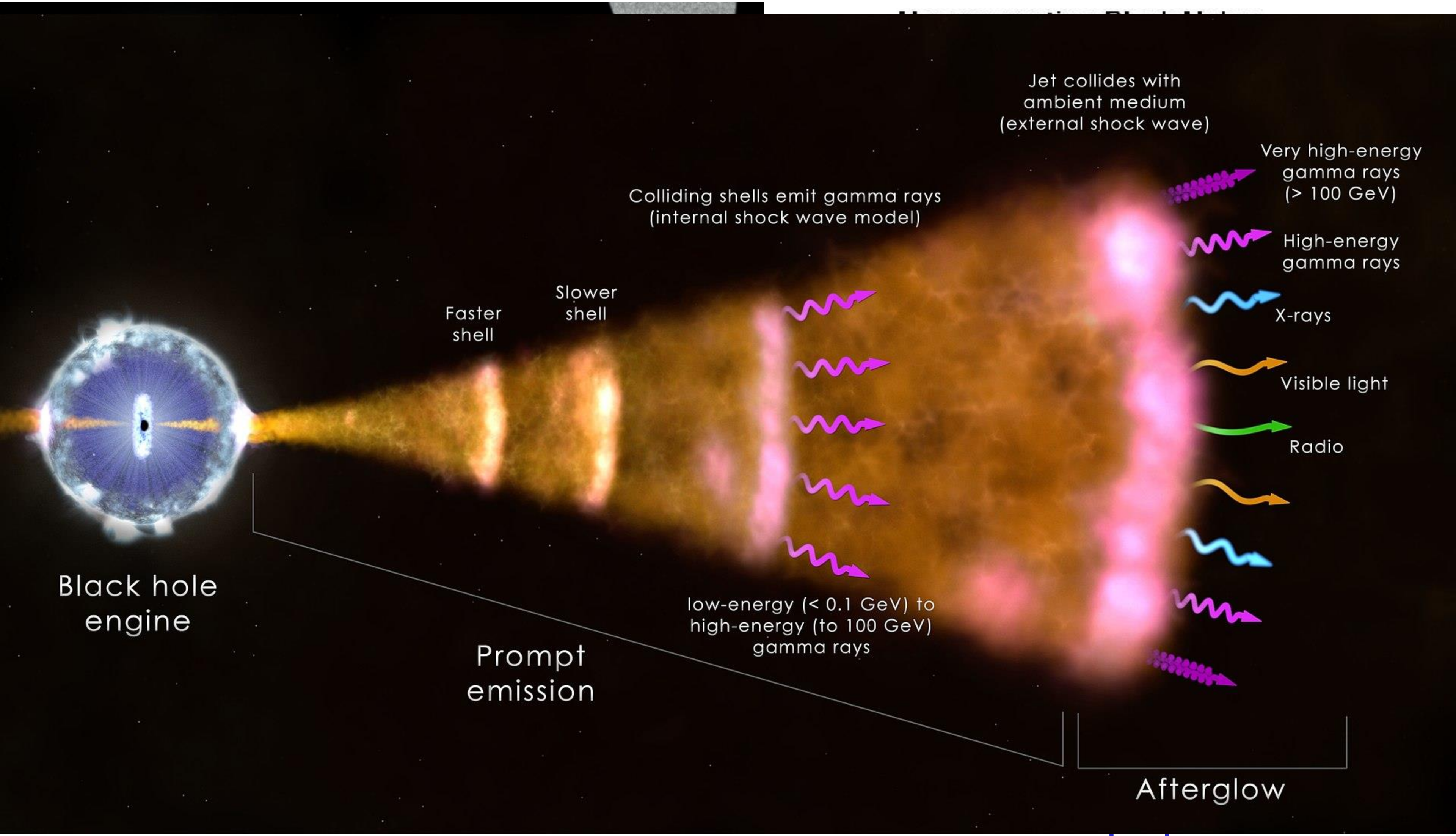
➢ GRB afterglow emission physics

- ❑ less complex and better understood w/r to prompt emission (but VHE emission is challenging): power-law decay and spectra
- ❑ Mostly explained thorugh synchrotron shock emission models



Standard scenarios for GRB progenitors

LONG *SHORT*



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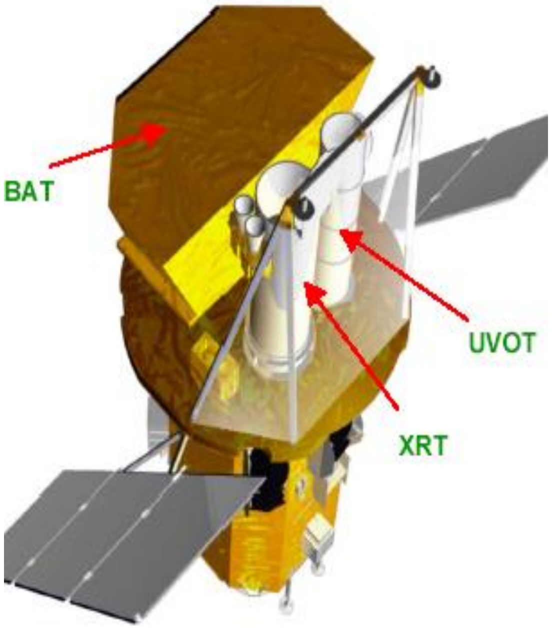
➢ Swift (> 2004): transition from prompt to afterglow



❑ **Swift**: NASA mission dedicated to GRB studies launched 20 Nov. 2004 USA / Italy / UK consortium

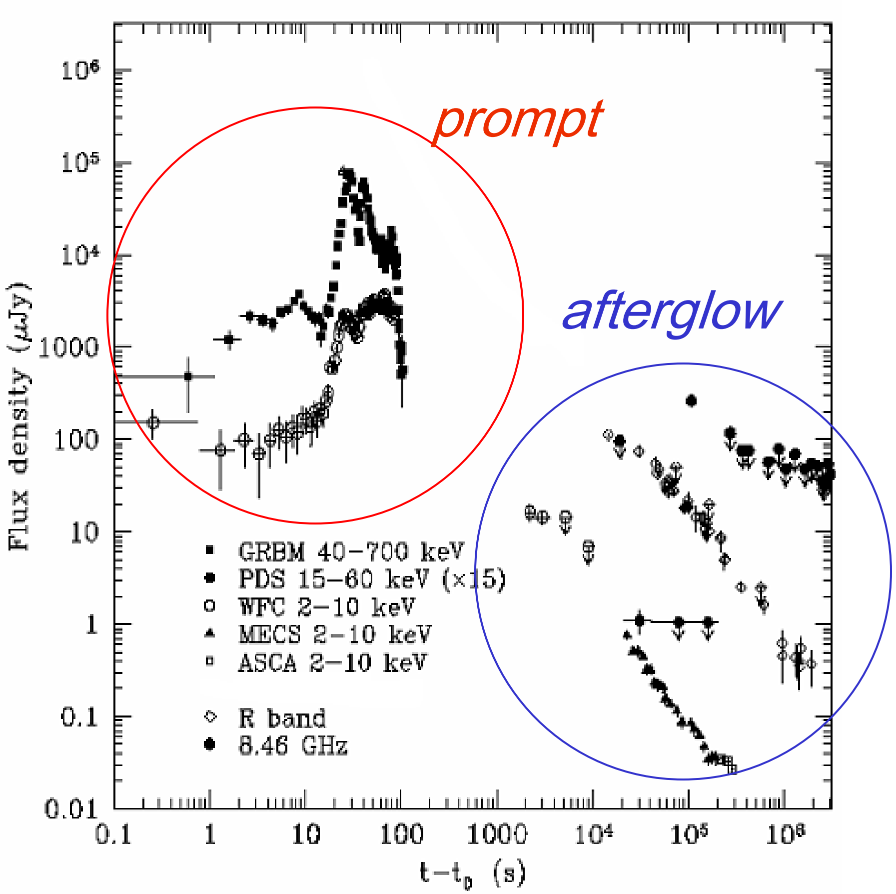
❑ main goals: afterglow onset, connection prompt-afterglow, substantially increase of conunterparts detection at all wavelengths (and thus of redshift estimates)

❑ payload: BAT (CZT+coded mask, 15-150 keV, wide FOV, arcmin ang. res.), XRT (X-ray optics, 0.3-10 keV, arcsec ang.res.), UVOT (sub-arcsec ang.res. mag 24 in 1000 s)

❑ spacecraft: automatic slew to target source in ~1 - 2 min.

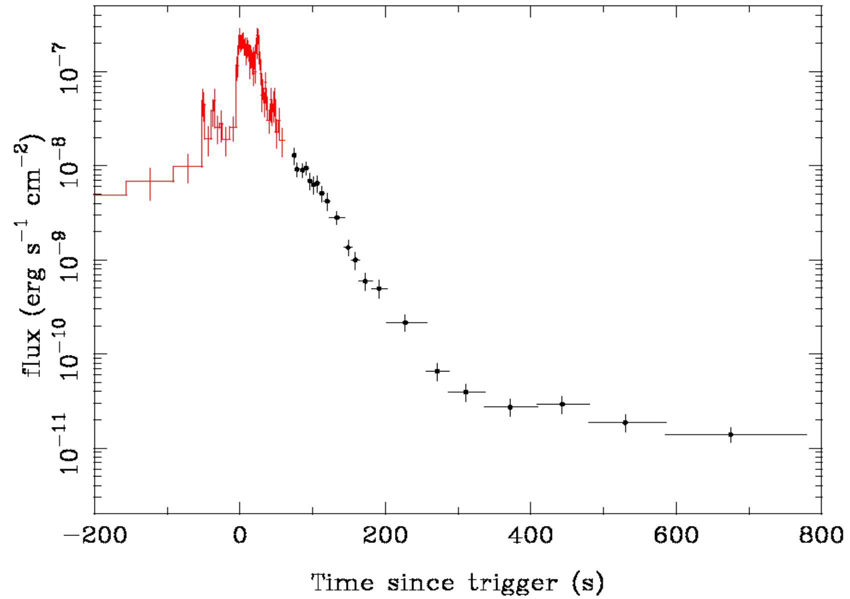
➢ Swift: transition from prompt to afterglow (>2005)

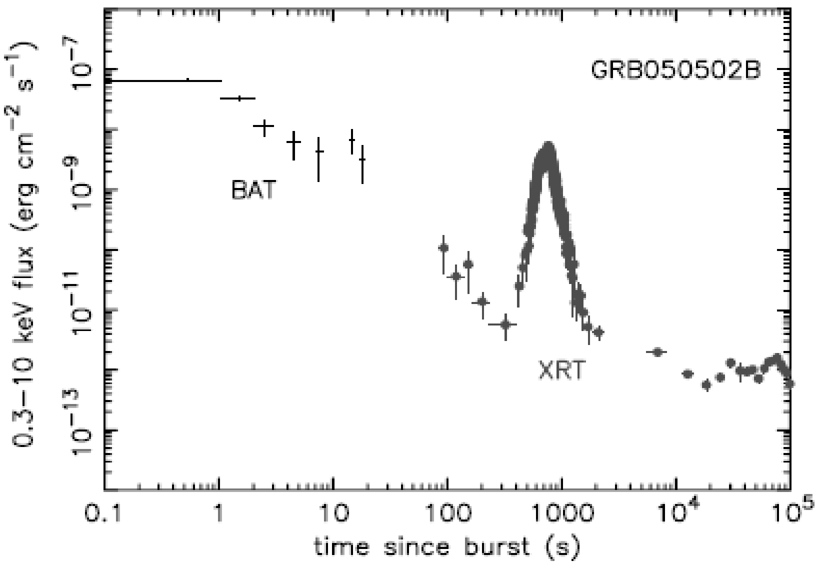
❑ BeppoSAX era



Maiorano et al., 2005 ; Swift team

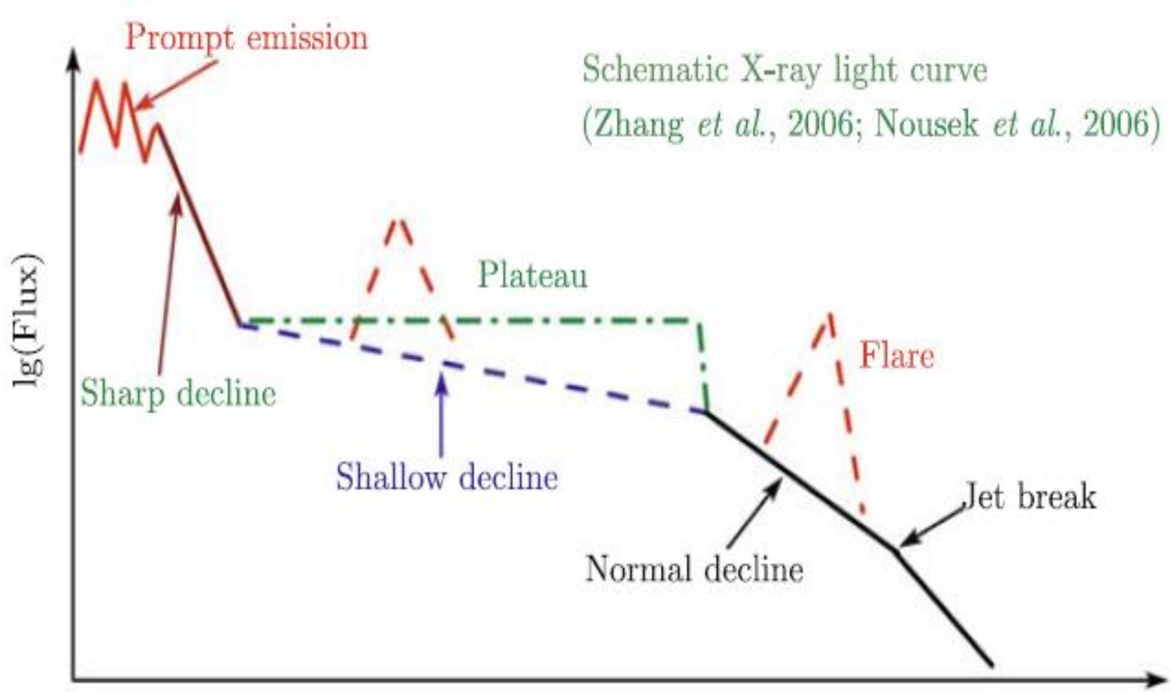
❑ Swift era





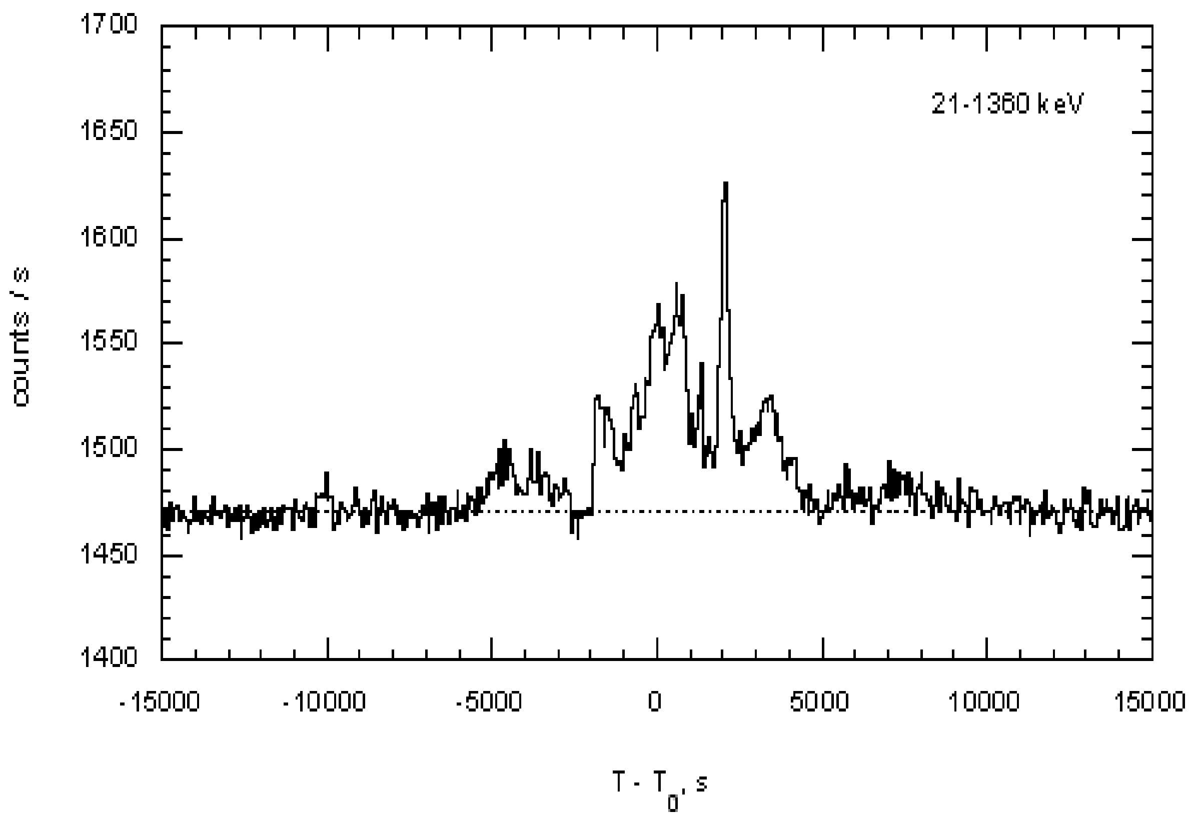
➢ Early X-ray afterglow

- new features seen by Swift in X-ray early afterglow light curves (initial very steep decay, early breaks, flares) mostly unpredicted and unexplained
- initial steep decay: continuation of prompt emission, mini break due to patchy shell, IC up-scatter of the reverse shock sinchrotron emission ?
- flat decay: probably "refreshed shocks" (due either to long duration ejection or short ejection but with wide range of Γ) ?
- flares: could be due to: refreshed shocks, IC from reverse shock, external density bumps, continued central engine activity, late internal shocks…

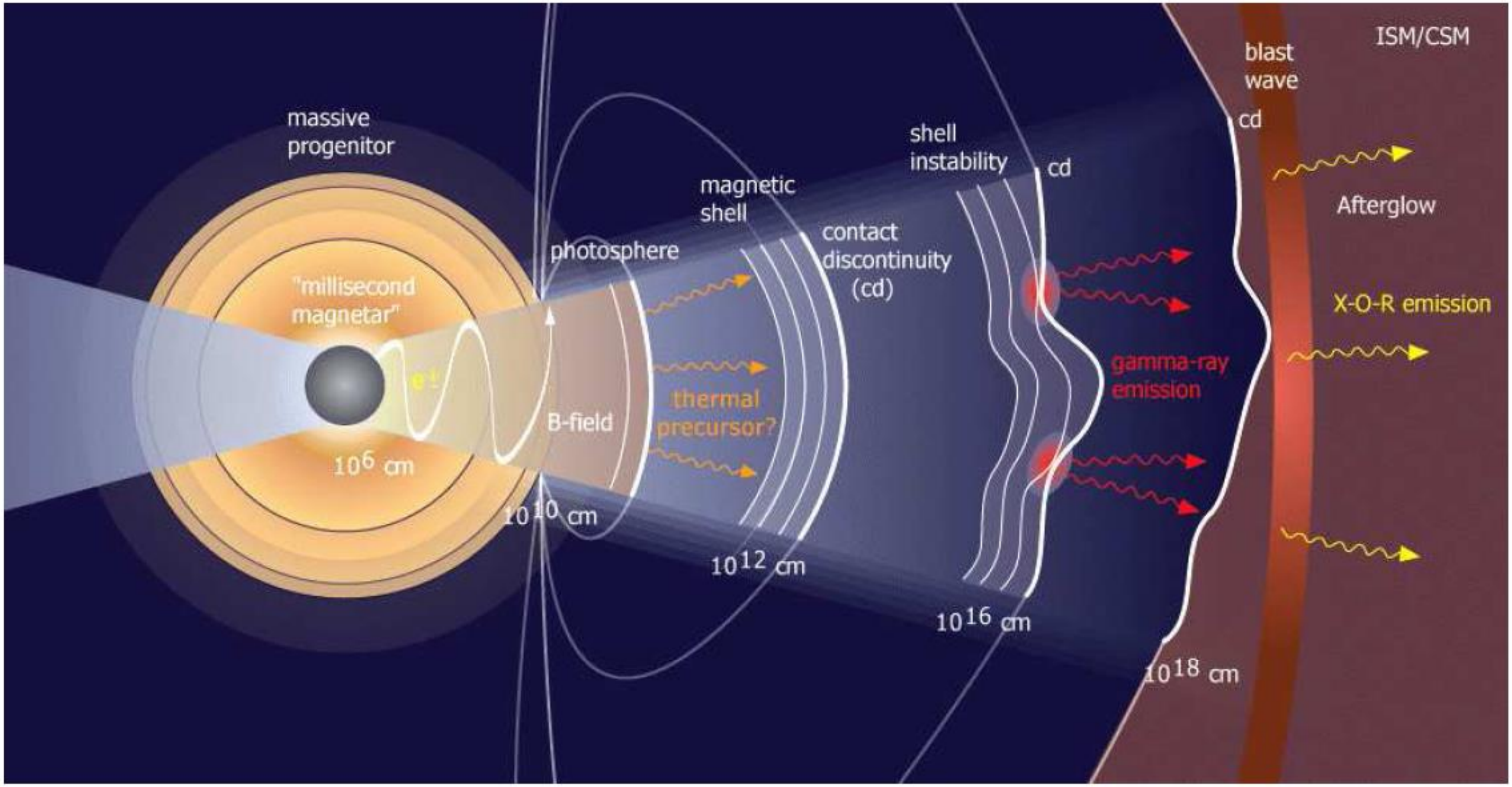


➢ Duration of the central engine: X-ray flares and ultra-long GRBs

❑ The X-ray flares, discovered by Swift, super-imposing to the early afterglow and the recently investigated class of ultra-long GRBs (i..e. lasting hours instead of minutes) are challenging evidences for models of long GRB central engine and progenitors

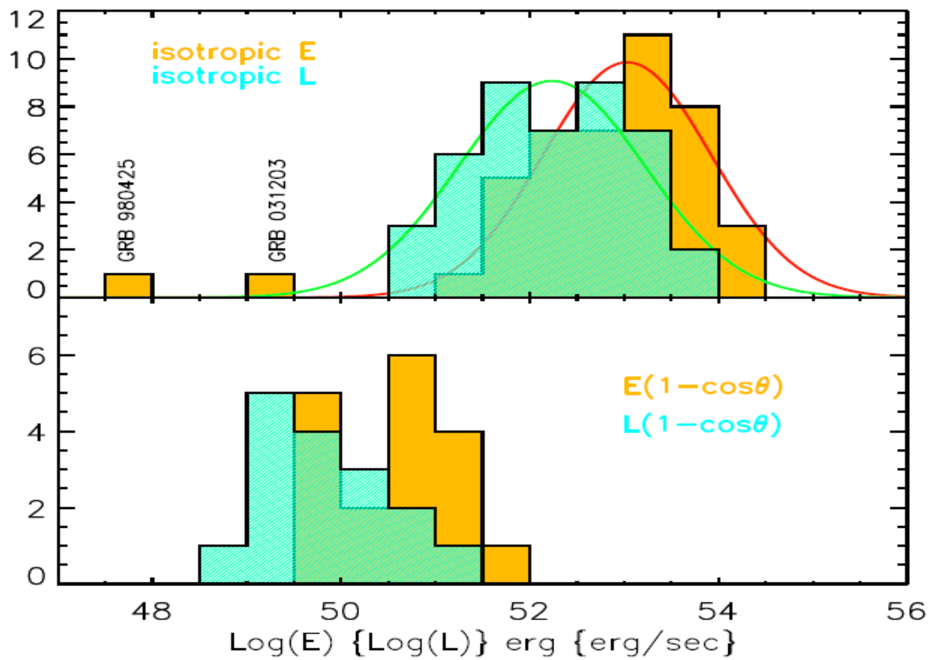


❑ Central engine: BH or NS? -> Fireball nature : baryon kinetic energy or Poynting flux dominated?



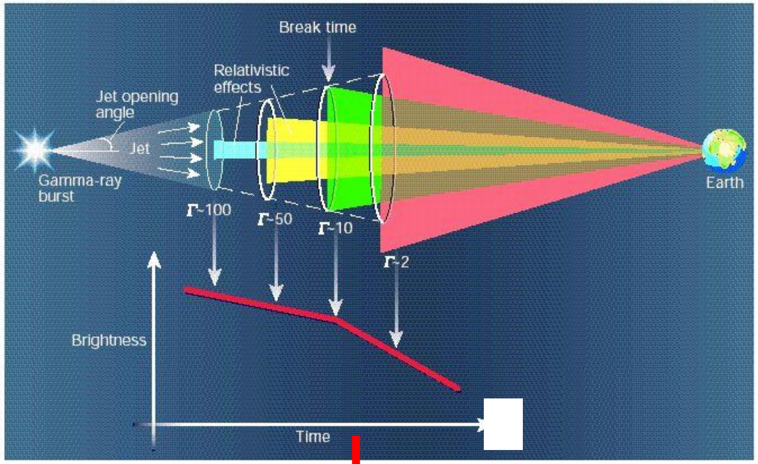
➢ Why emission collimated into a jet?

- ❑ Less "demanding" energy budget
- ❑ Numerical simulations of collapsars (long GRBs) and NS-NS / NS-BH mergers (short GRBs) produce a jet if internal engine (BH or NS) fastly spinning and with strong magnetic field associated (as expected)
- ❑ Degree of collimation depending on several parameters and assumptions, can range from 1-2 deg to tens of degrees



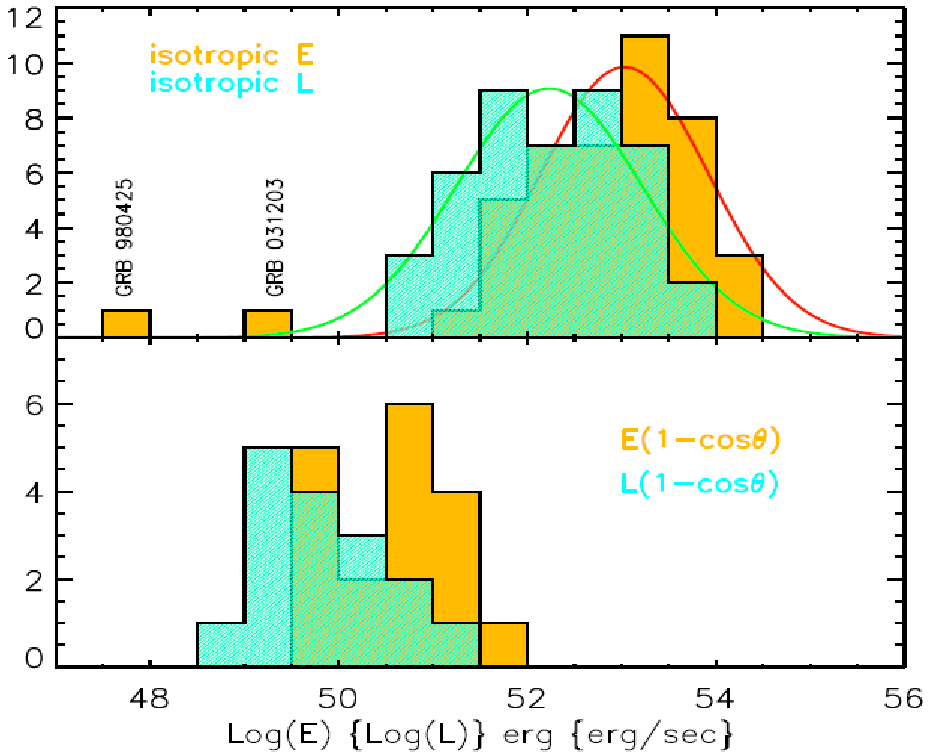
➢ Afterglow emission and jet opening angle

- ❑ jet angles, derived from break time of optical afterglow light curve by assuming standard scenario, are of the order of few degrees
- ❑ the collimation-corrected radiated energy spans the range ~5×10^{49} – 5×10^{52}



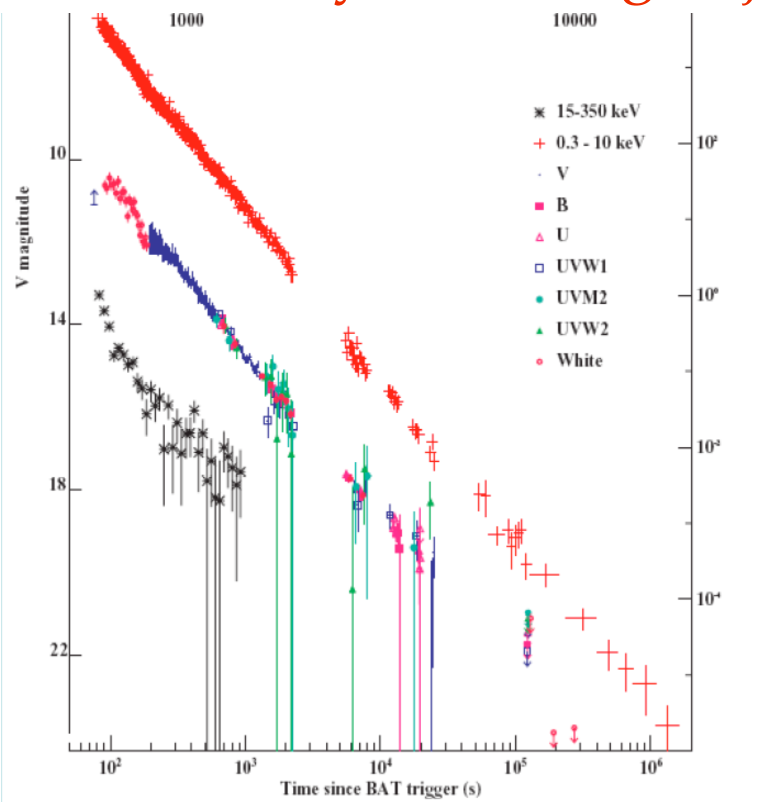
$$\theta = 0.09 \left(\frac{t_{jet,d}}{1+z}\right)^{3/8} \left(\frac{n\,\eta_\gamma}{E_{\gamma,iso,52}}\right)^{1/8}$$

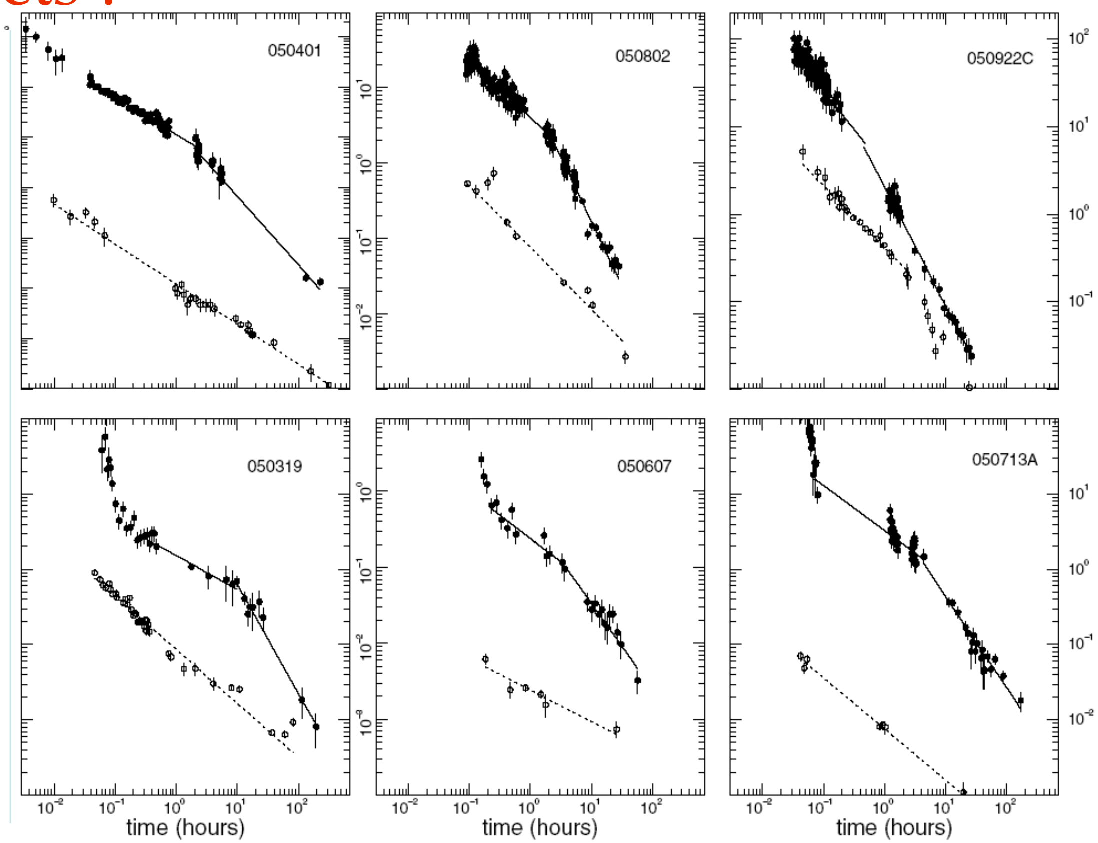
$$E_\gamma = (1 - \cos\theta) E_{\gamma,iso}.$$



Ghirlanda et al., 2006

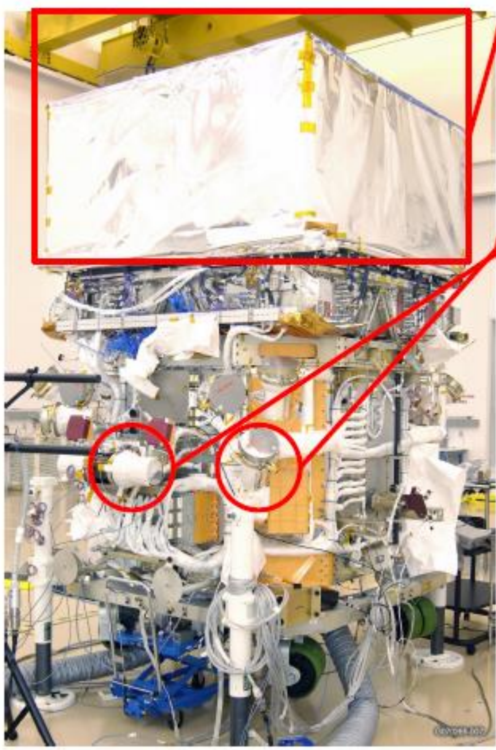
- lack of jet breaks in several Swift X-ray afterglow light curves, in some cases, evidence of achromatic break
- challenging evidences for Jet interpretation of break in afterglow light curves or due to present inadequate sampling of optical light curves w/r to X-ray ones and to lack of satisfactory modeling of jets ?



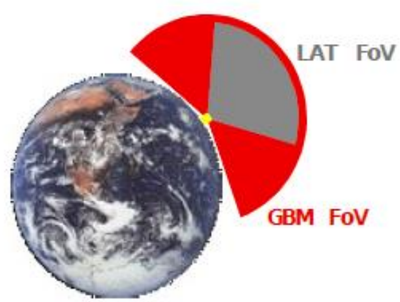


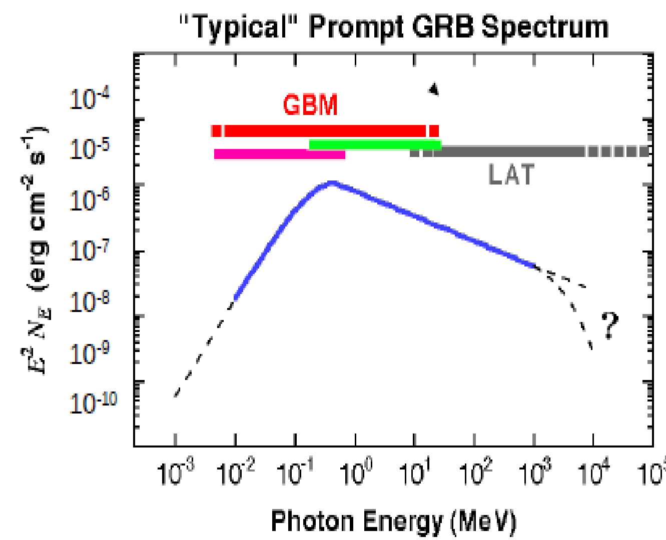
➢ Fermi (> 2008): broad band prompt emission and VHE

- ❑ Detection, arcmin localization and **study of GRBs in the GeV energy range** through the ***Fermi*/LAT instrument**, with dramatic improvement w/r CGRO/EGRET
- ❑ Detection, rough localization (a few degrees) and **accurate determination of the shape of the spectral continuum of the prompt emission of GRBs from 8 keV up to 30 MeV through the** Fermi/GBM instrument



- Large Area Telescope (LAT)
  - Pair conversion telescope.
  - Independent on-board and ground burst trigger, spectrum from 20 MeV to 300 GeV
- Gamma-ray Burst Monitor (GBM)
  - 12 NaI detectors, 2 BGO detectors.
  - Onboard localization over the entire unocculted sky, spectrum from 8 keV to 40 MeV.





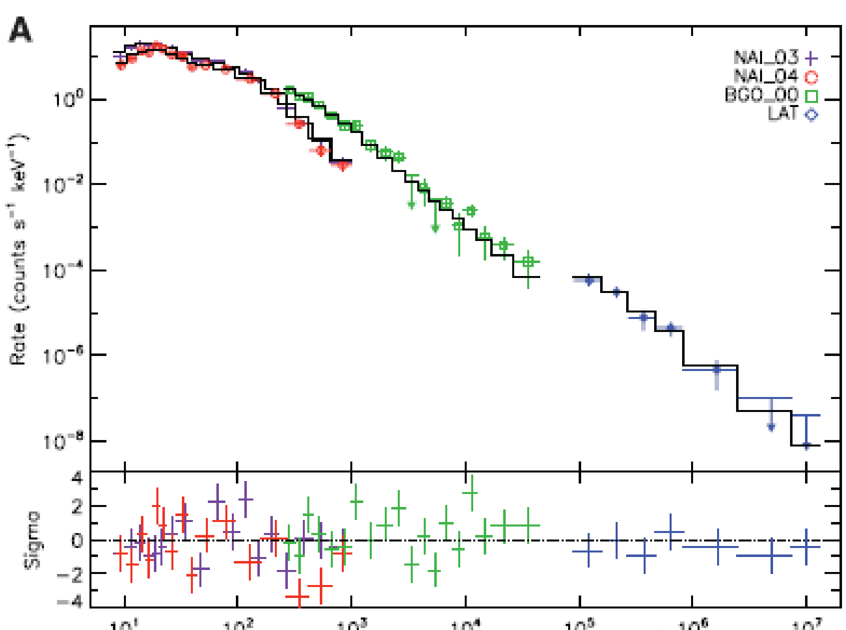
February 02, 2009

L. Baldini
Rencontres de Moriond, 2009

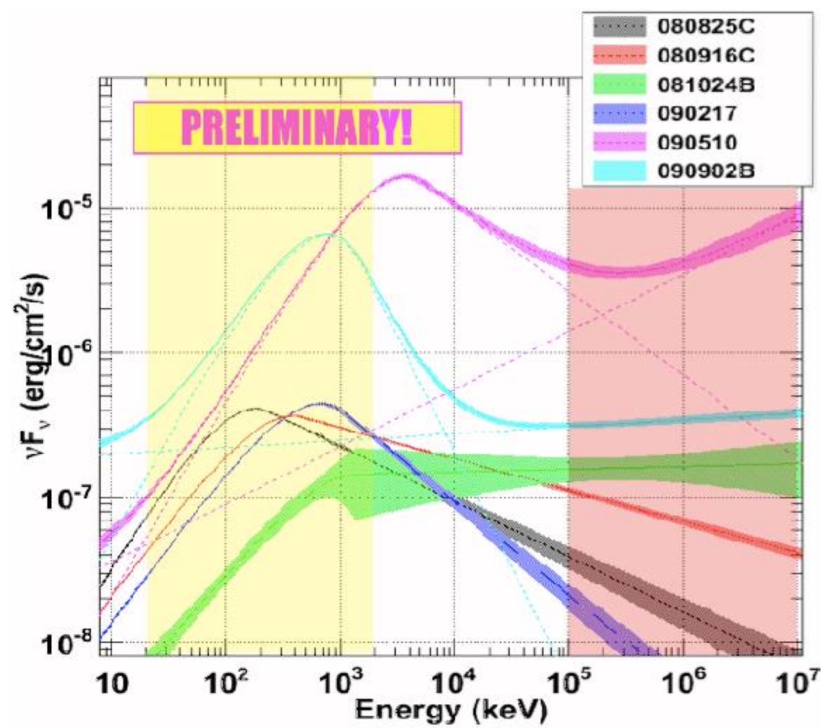
➢ VHE (> 100 MeV) properties of GRBs by Fermi

❑ the huge radiated energy, the spectrum extending up to VHE without any excess or cut-off and time-delayed GeV photons of GRB 080916C measured by Fermi are challenging evidences for GRB prompt emission models

❑ nevertheless, an excess at E > 100 MeV, modeled with an additional power-law component, is detected in some GRBs (e.g., GRB 090902B, GRB090510): SSC of lower energy sinchrotron emission, IC of photospheric emission, hadronic processes



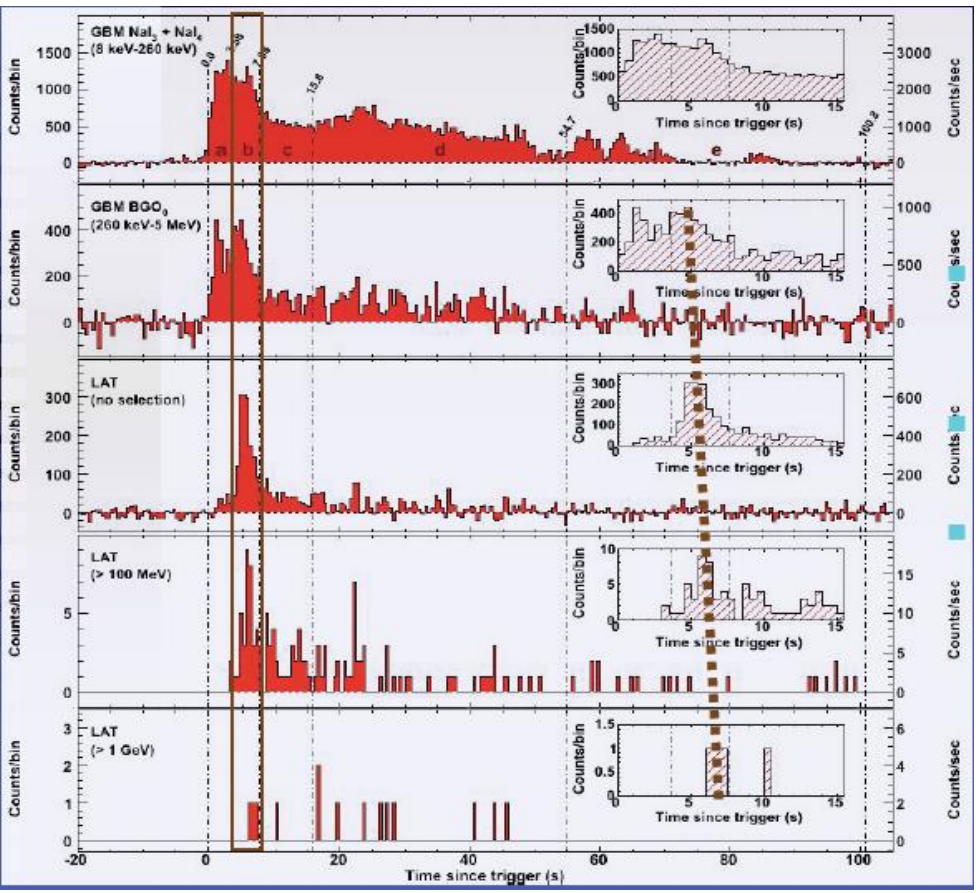
Abdo et al. 2

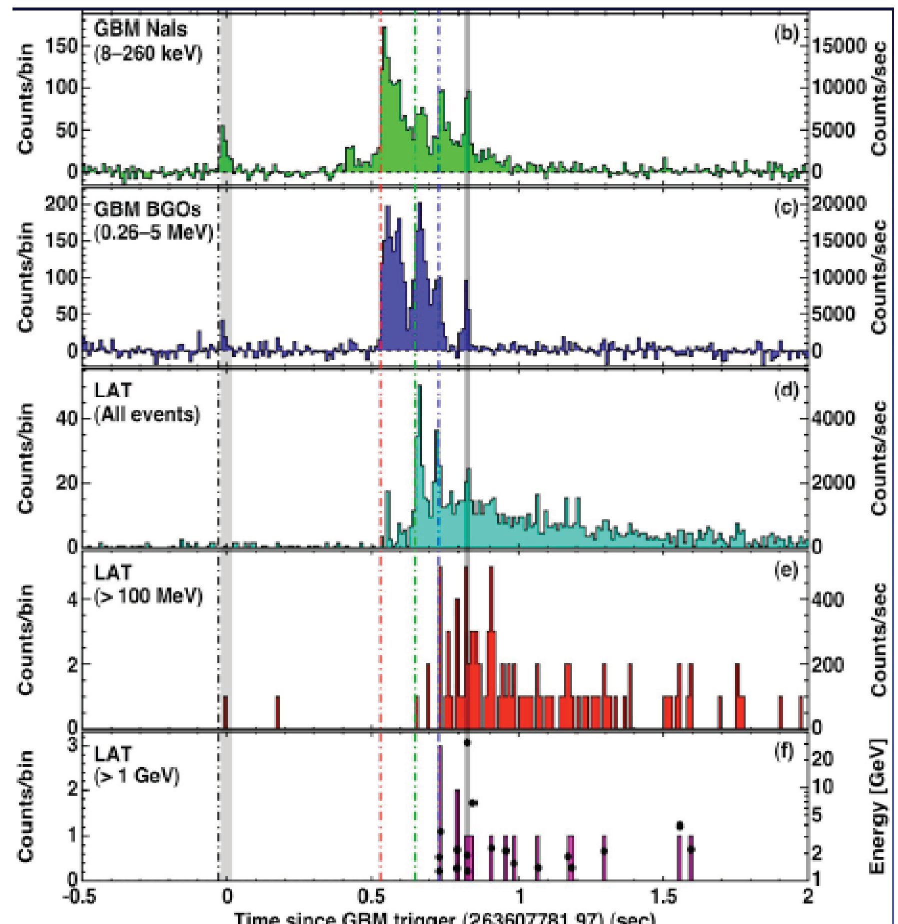


- significant evidence (at least for the brightest GRBs) of a delayed onset of VHE emission with respect to soft gamma rays;

- the time delay appears to scale with the duration of the GRB (several seconds in the long GRBs 080916C and 090902B, while 0.1 − 0.2 s in the short GRBs 090510 and 081024B)

- again, challenging for models (hadronic: e.g., proton acceleration time ?)

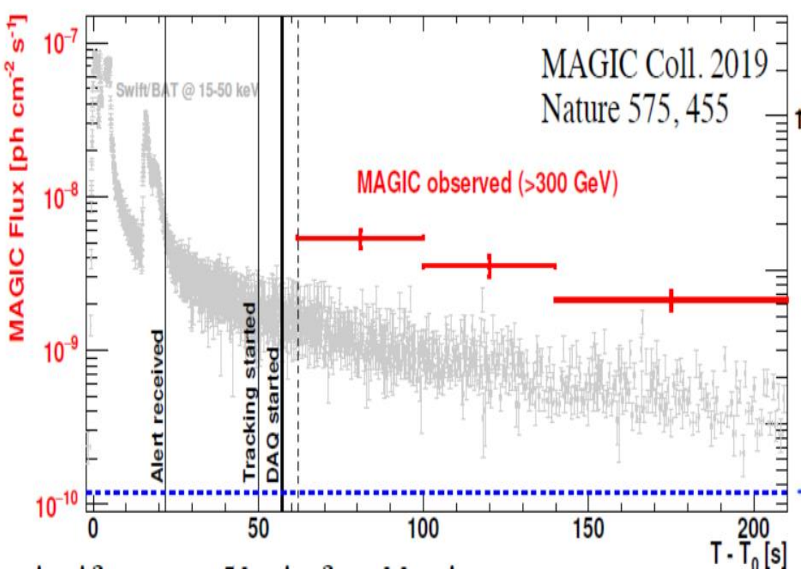




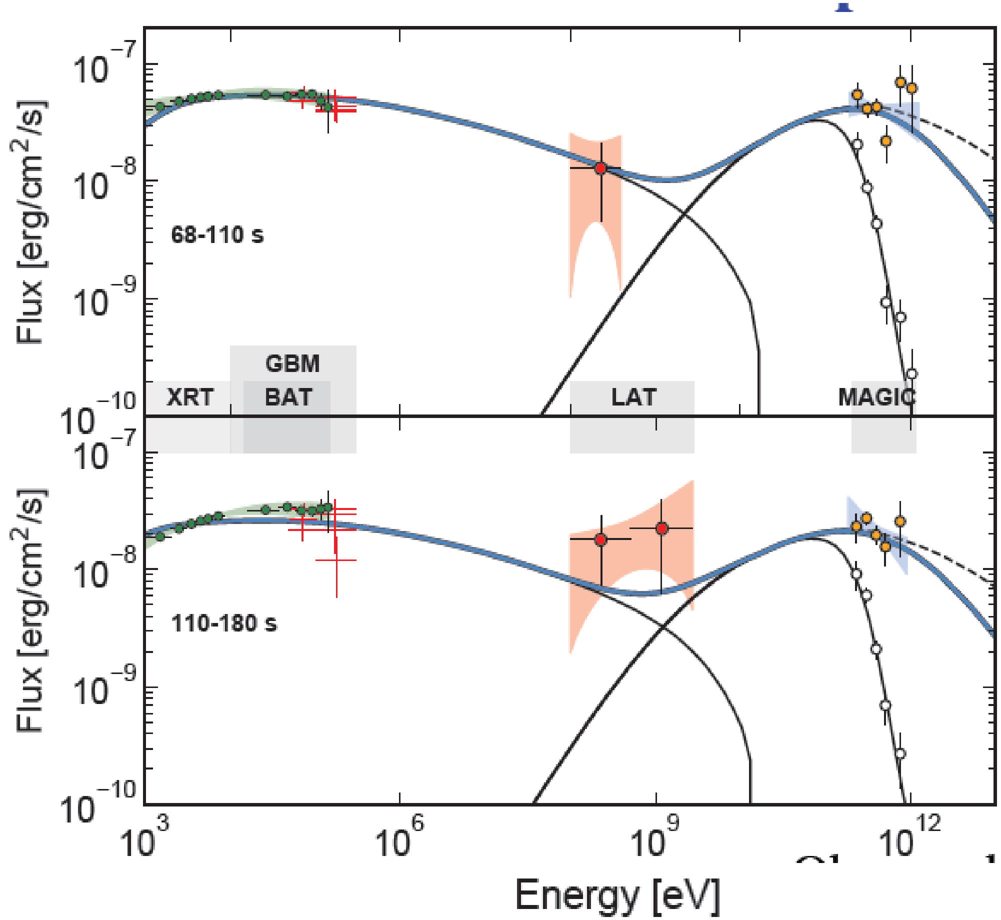
➢ Detection of TeV photons from GRBs by Cherenkov telescopes

❑ Long GRB180720B (HESS) and GRB190114C (MAGIC), plus two more events

❑ Further evidence of possible SSC or IC component in GRB afterglow emission



GRB190114C: TeV early afterglow emission



➢ Detection of TeV photons from GRBs by Cherenkov telescopes

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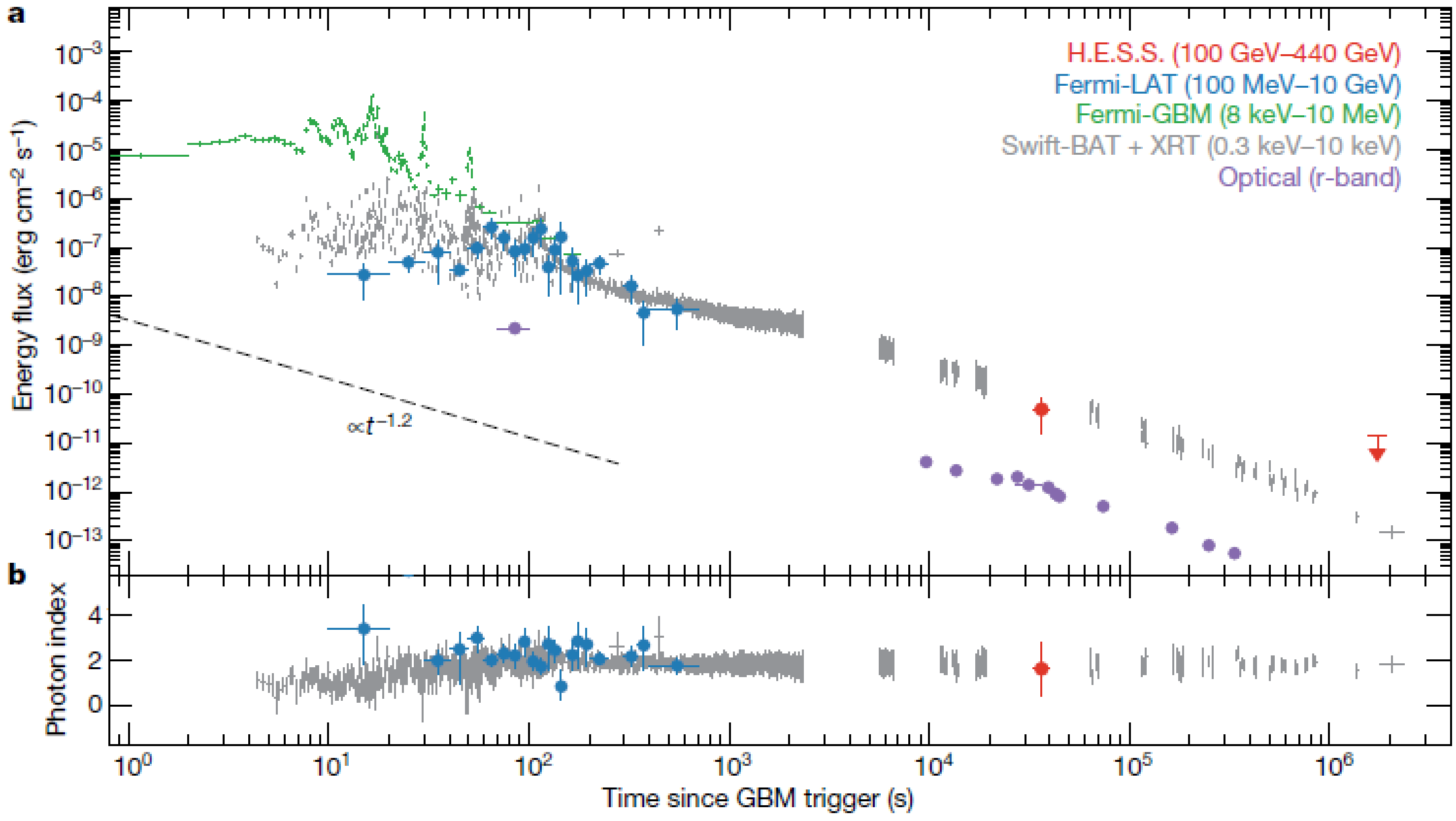
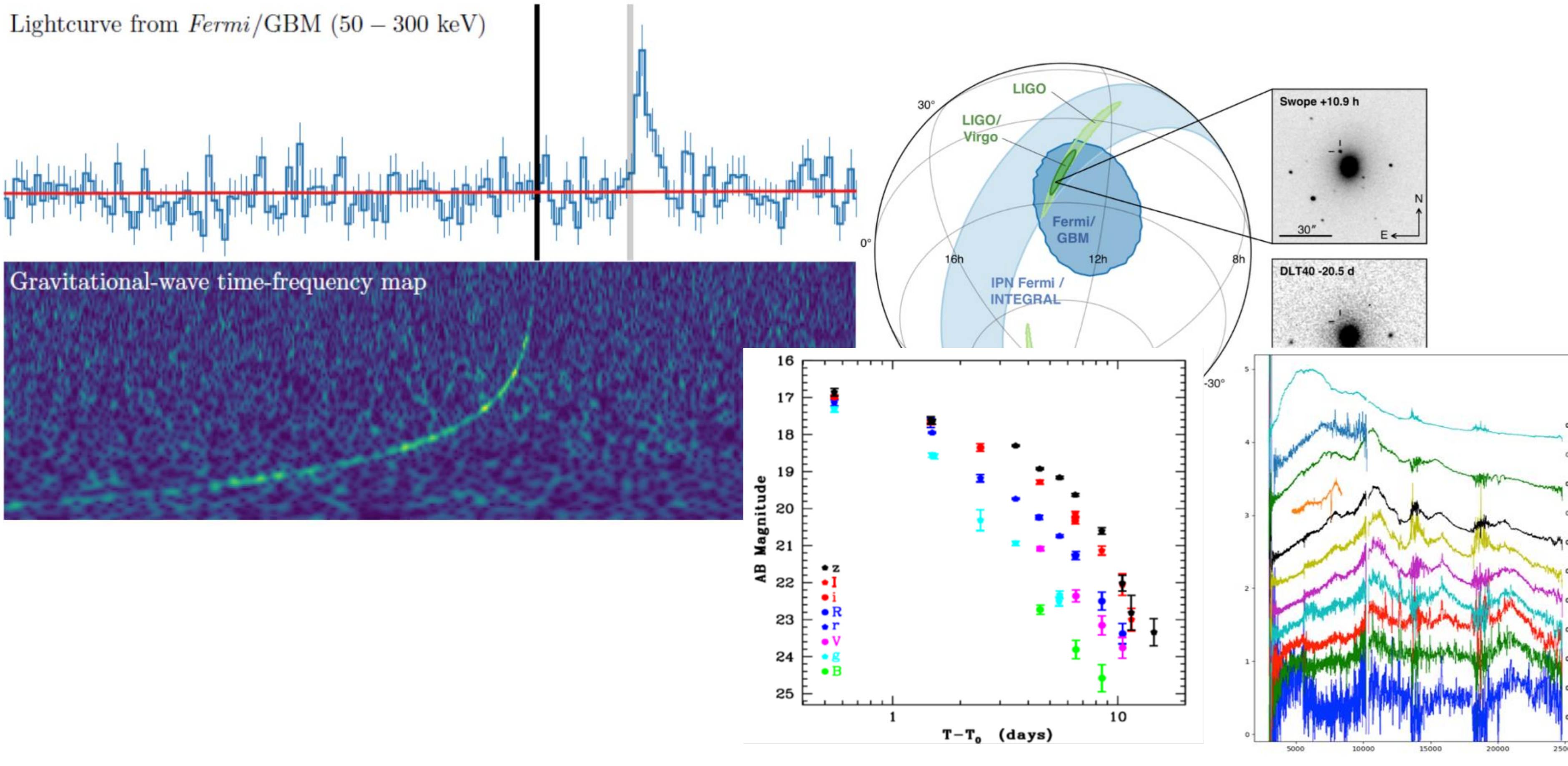
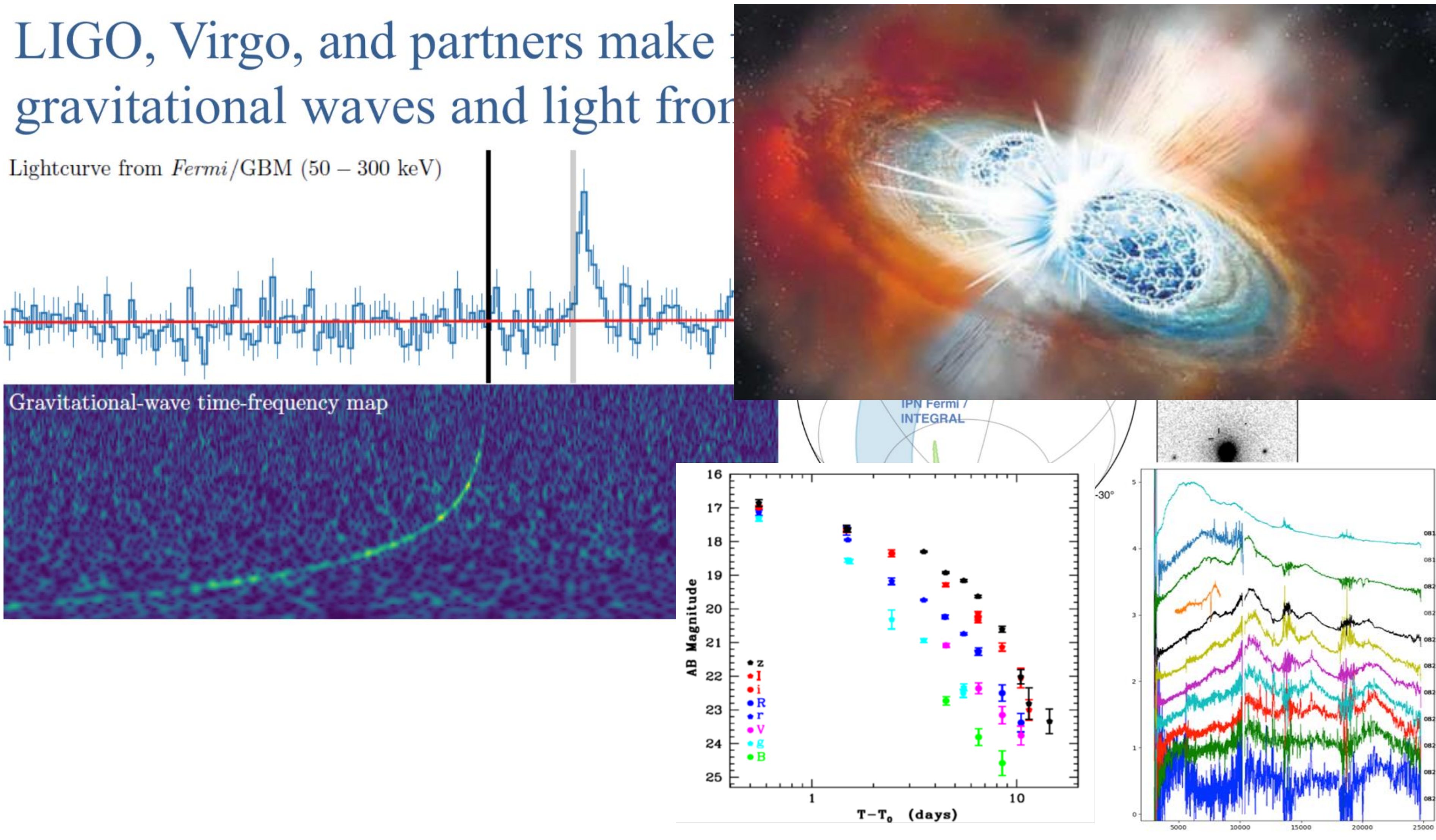


➢ 2017- The birth of multi-messenger astrophysics and confirmation of NS-NS (BH) origin for short GRBs

LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars



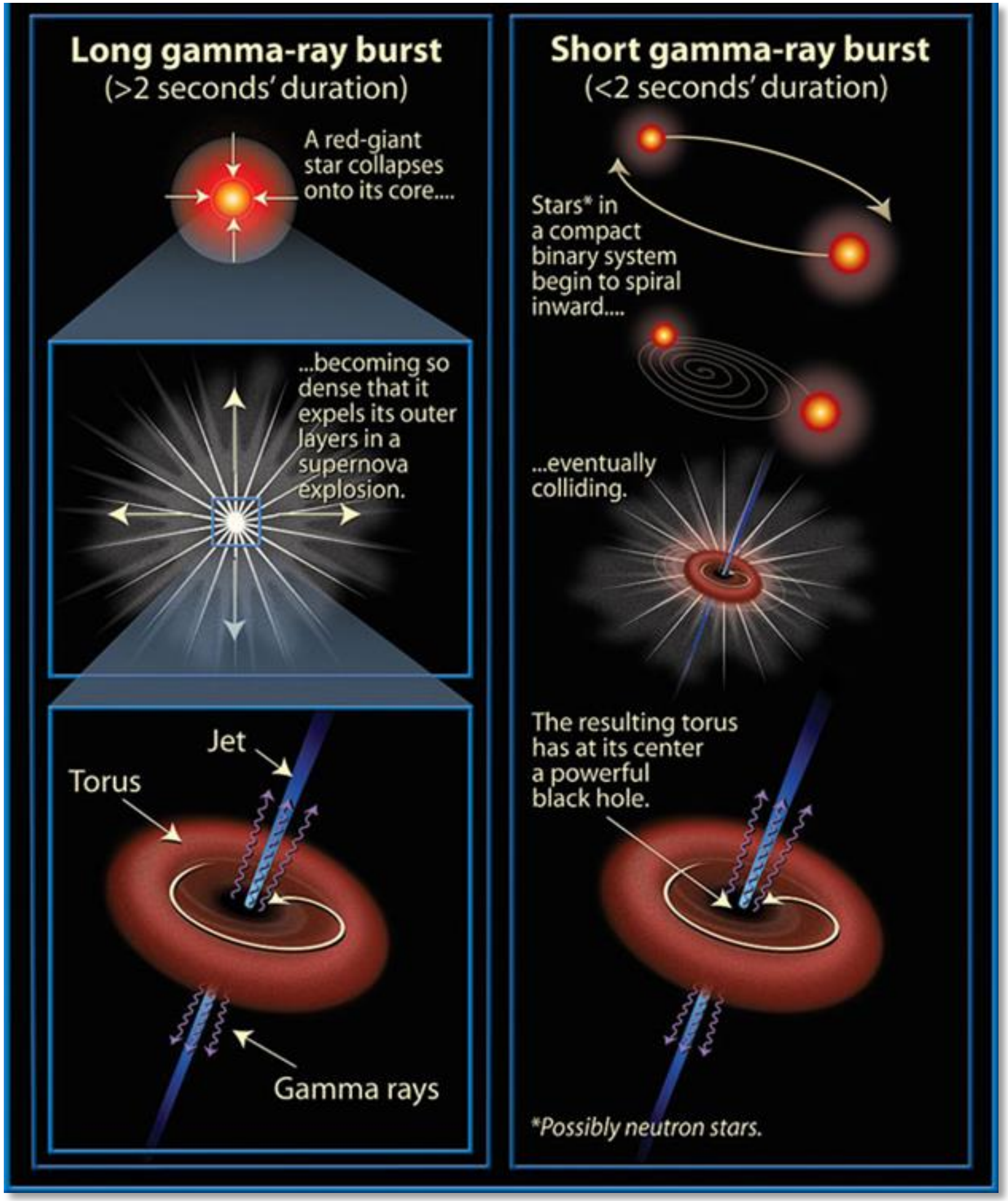
➢ 2017- The birth of multi-messenger astrophysics and confirmation of NS-NS (BH) origin for short GRBs



Standard scenarios for GRB progenitors

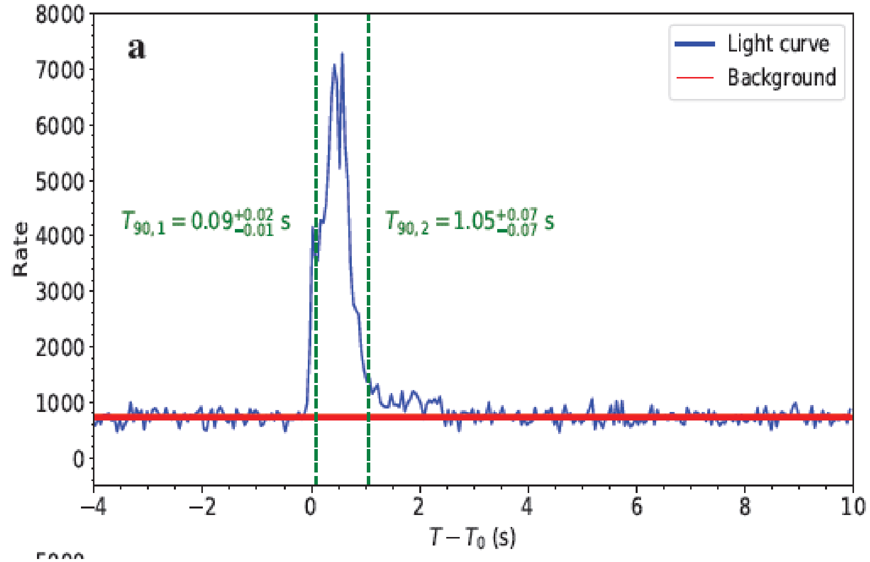
Long GRBs: core collapse of particular massive stars, association with SN, star formation rate, primordial galaxies -> COSMOLOGY

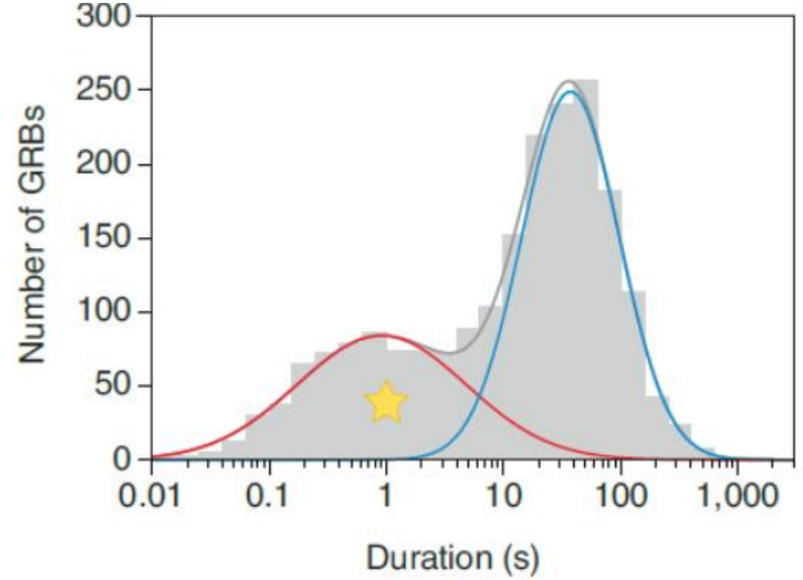
Short GRBs: NS-NS or NS-BH mergers, association with GW sources -> MULTI-MESSENGER ASTROPHYSICS

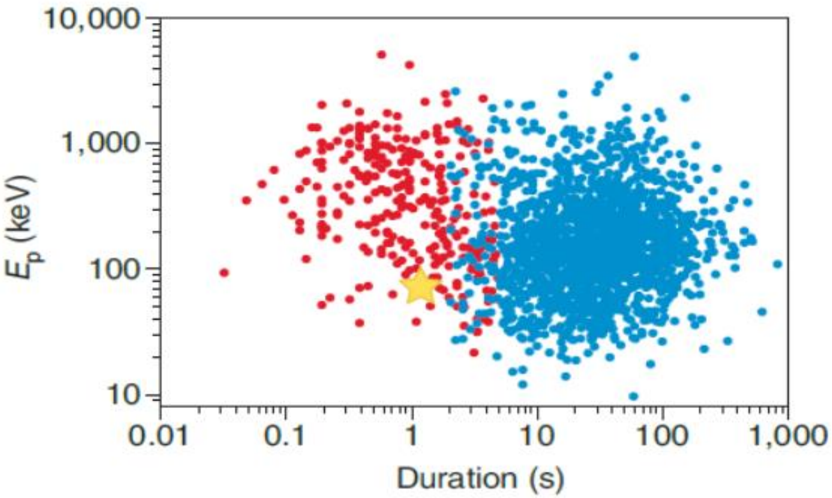


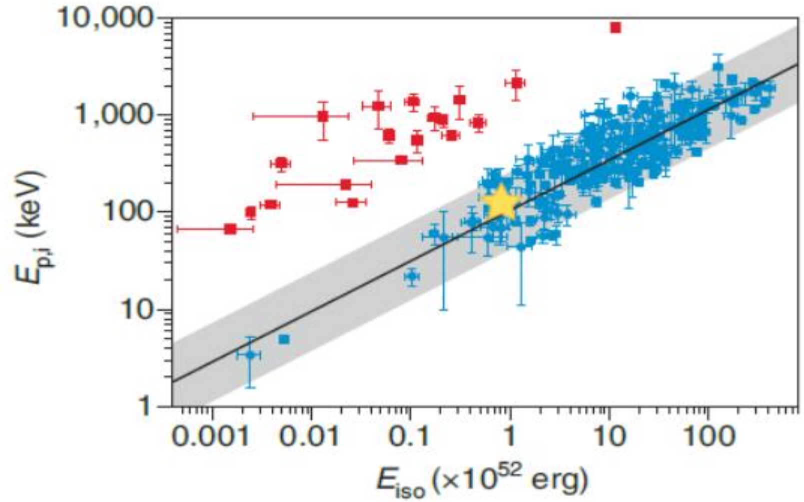
➢ Short / long classification and physics

❑ GRB 200826A: a short GRB with evidence of association with a SN





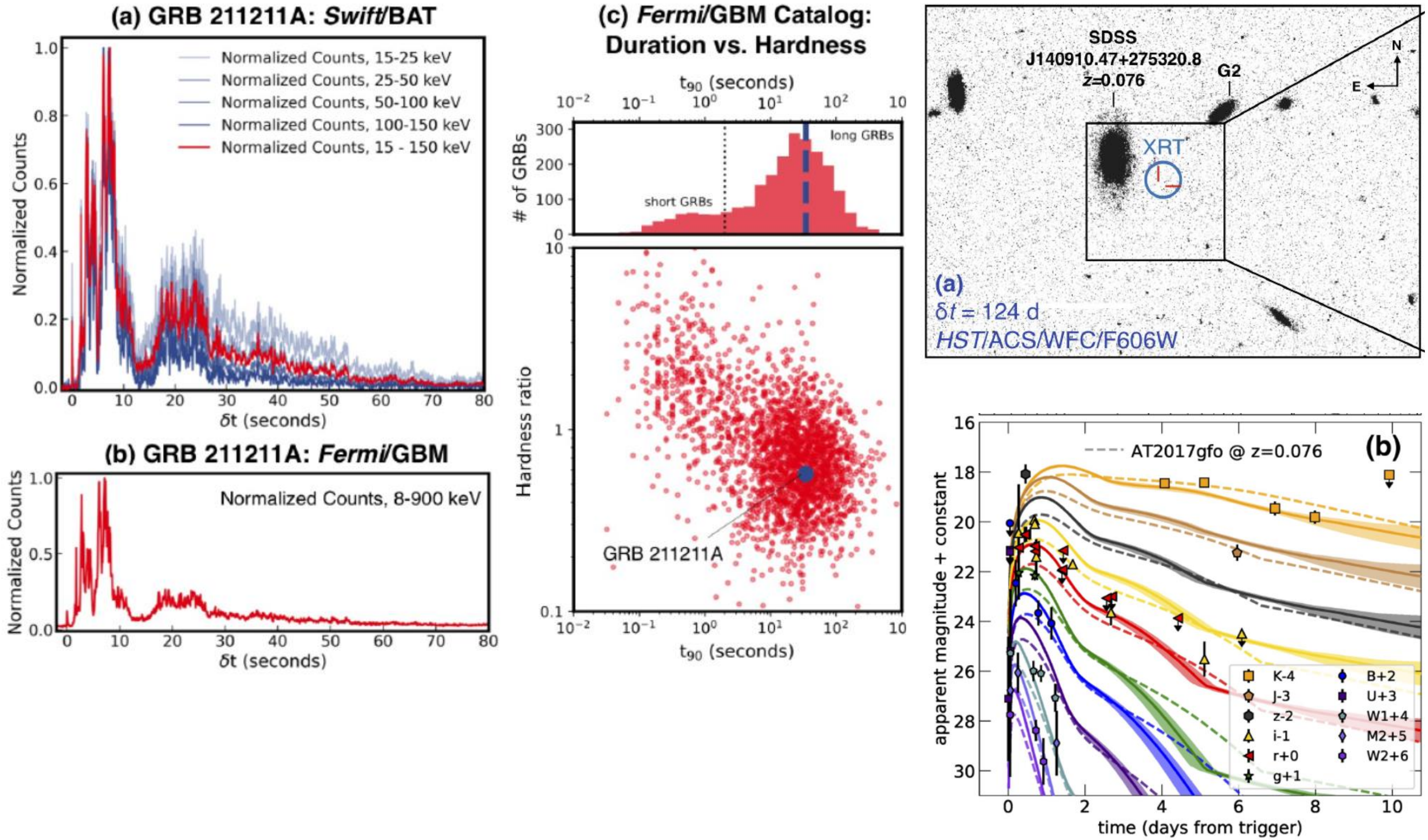




Ahumata et al., Zhang et al., Rossi et al., Amati 2021

➢ Short / long classification and physics

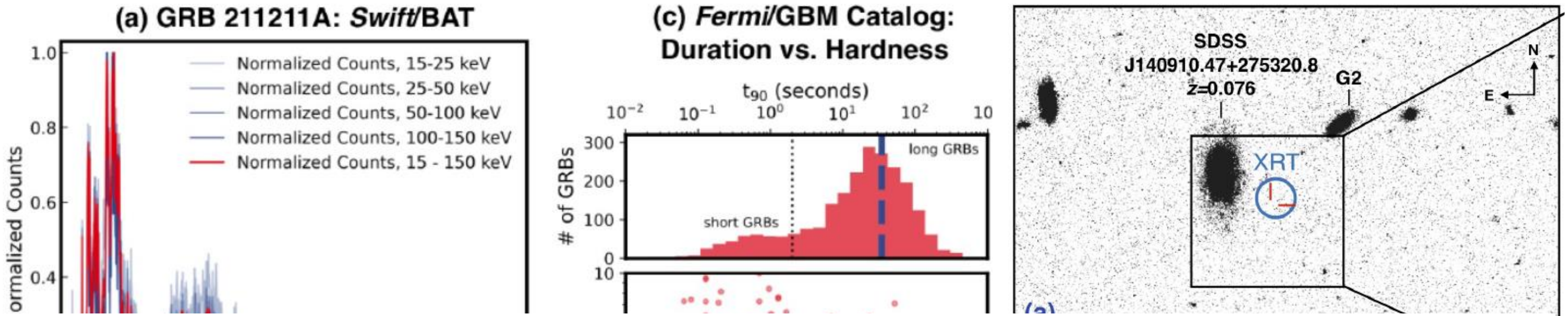
❑ GRB 211211A: a long GRB with evidence of association with a KN



Rastinejad et al. 2022

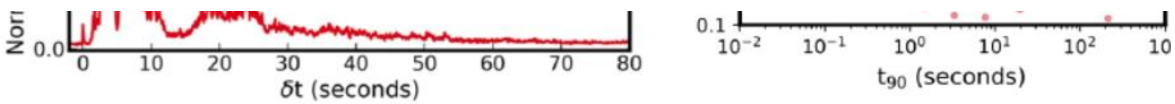
➢ Short / long classification and physics

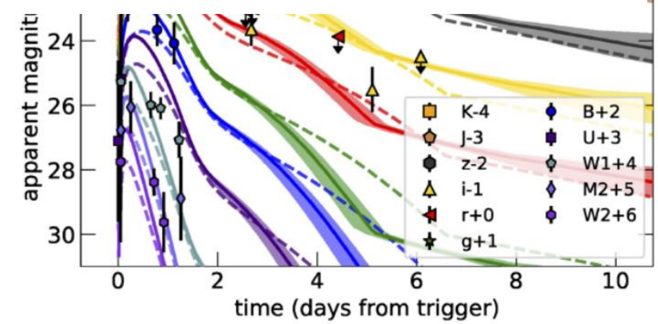
❑ GRB 211211A: a long GRB with evidence of association with a KN



- **NEED TO GO BEYOND THE CLASSIFICATION BASED ON DURATION (also theroretical considerations: T<0.5s for GRBs produced by collapsing stars)**

- **-> Type I GRBs (from NS-NS/BH mergers), Type II GRBs (from collapsing stars)**





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End of Lecture I