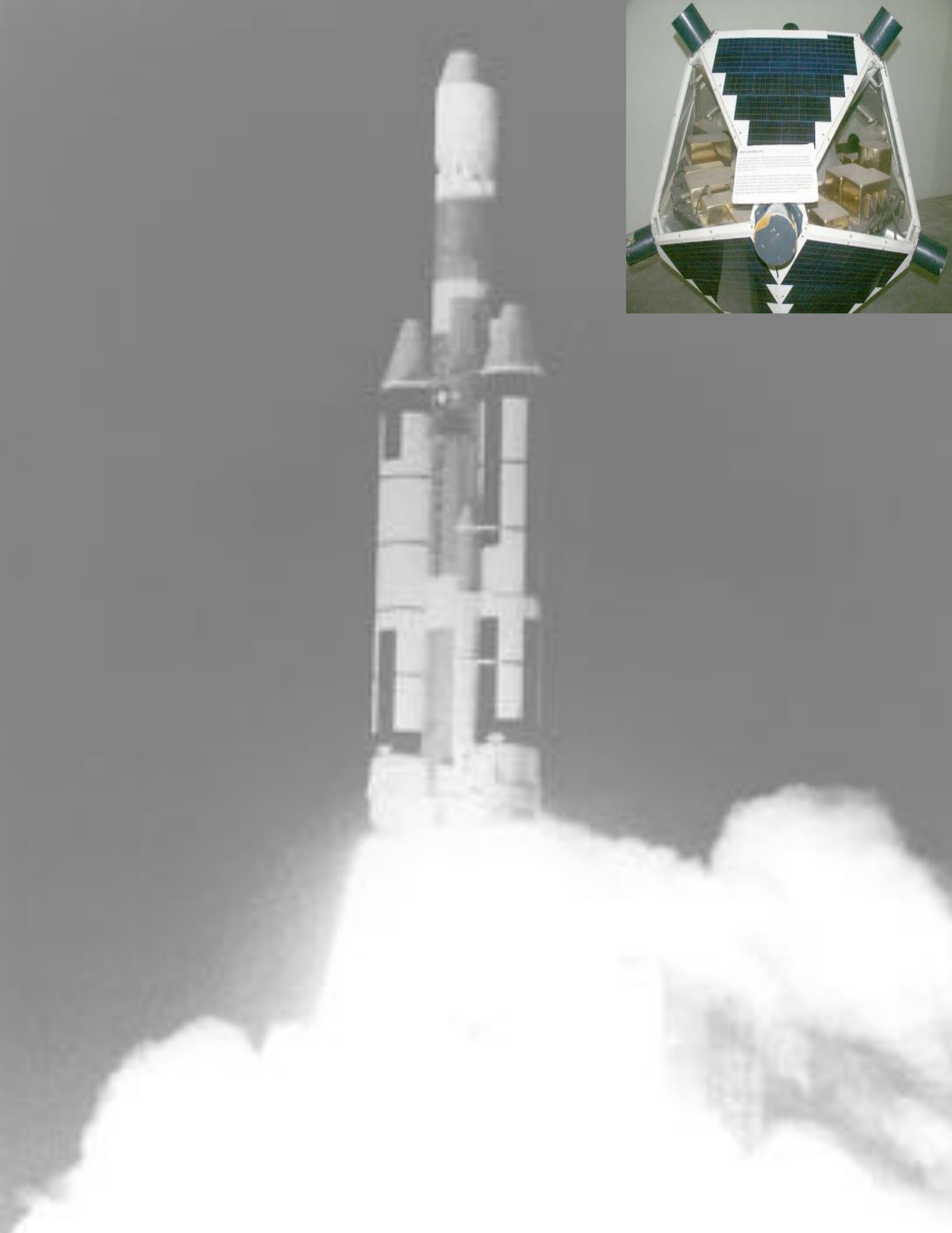
Gamma-ray Bursts in the Fermi Era

Pawan Kumar

Outline†

- **Summary of main discoveries in last 10 yrs**
- **Fermi data & developments of last 2 years**
- **Problems with the current paradigm and possible solutions.**

October 2, 2015



History

Gamma-ray Bursts
(GRBs)

were discovered (accidentally*) by Vela satellites in 1967.

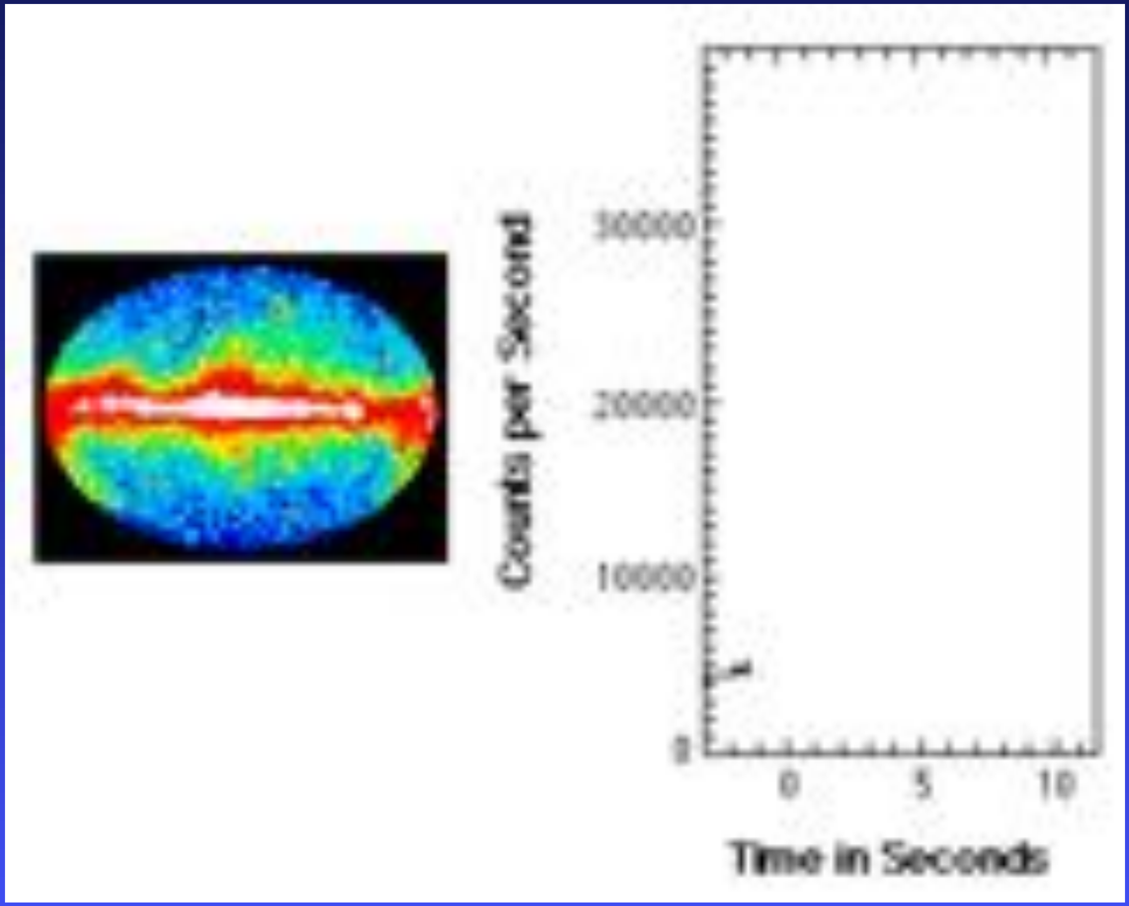
For about 20 years the distance to GRBs was completely uncertain.

*Colgate (1968) anticipated GRBs -- associated with breakout of relativistic shocks from the surfaces of SNe.

Gamma-ray Bursts

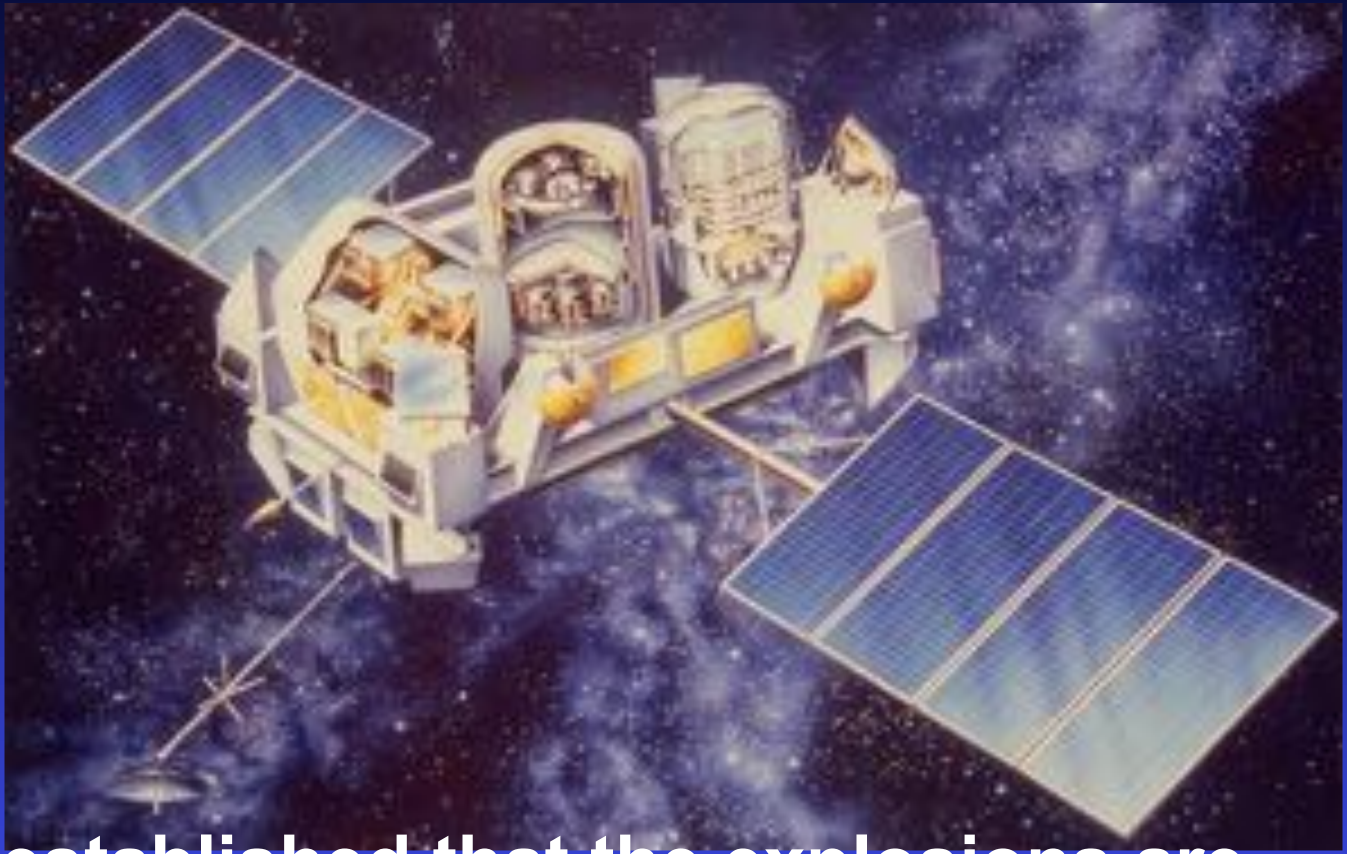
What are these?

We see bursts of energy in gamma-rays from outer space, a few times a day, lasting for a few seconds.



The energy involved is enormous!

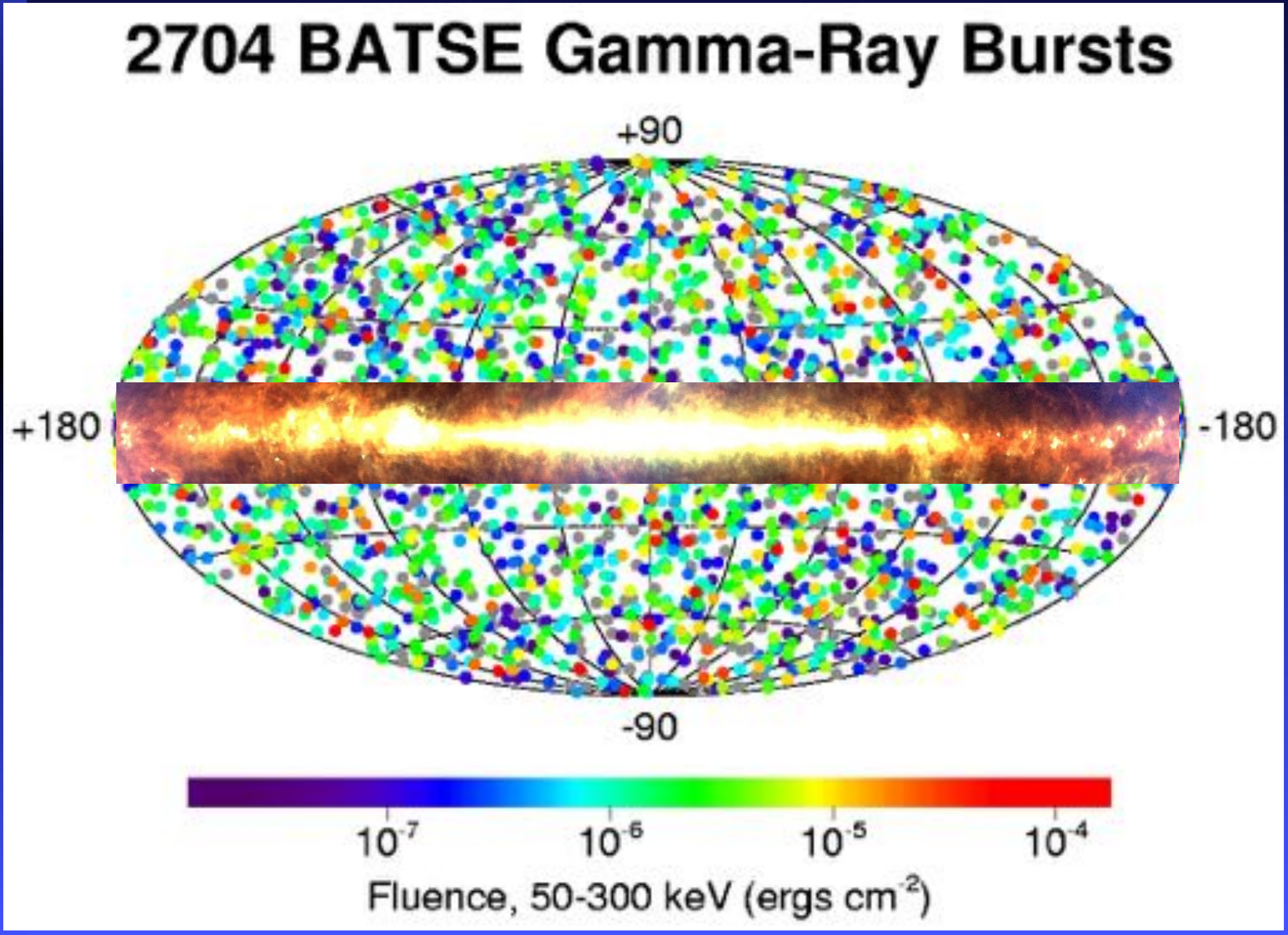
The first important clue was discovered by the Compton Gamma-ray Observatory (launched in 1991)



It established that the explosions are coming from random directions (isotropic) & have non-Euclidean space distribution.

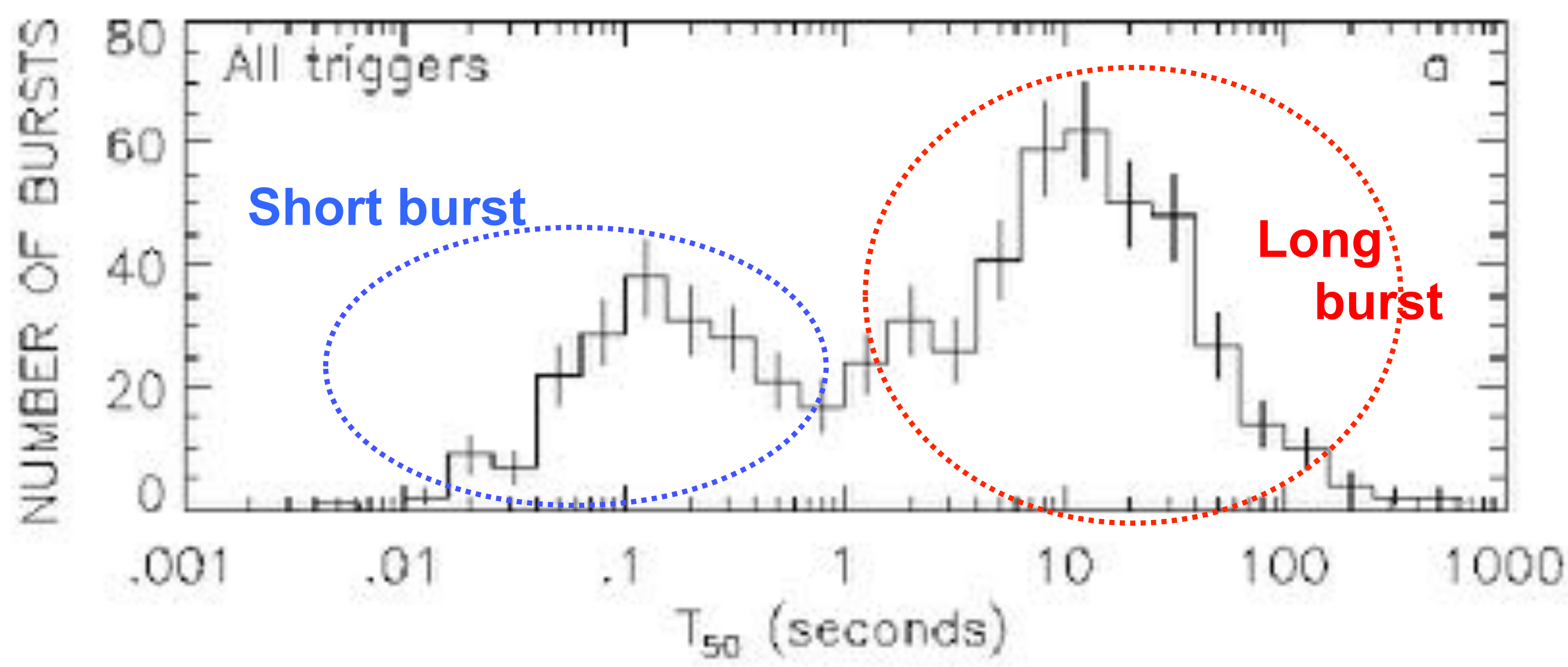
And therefore very large distances →

ISOTROPY



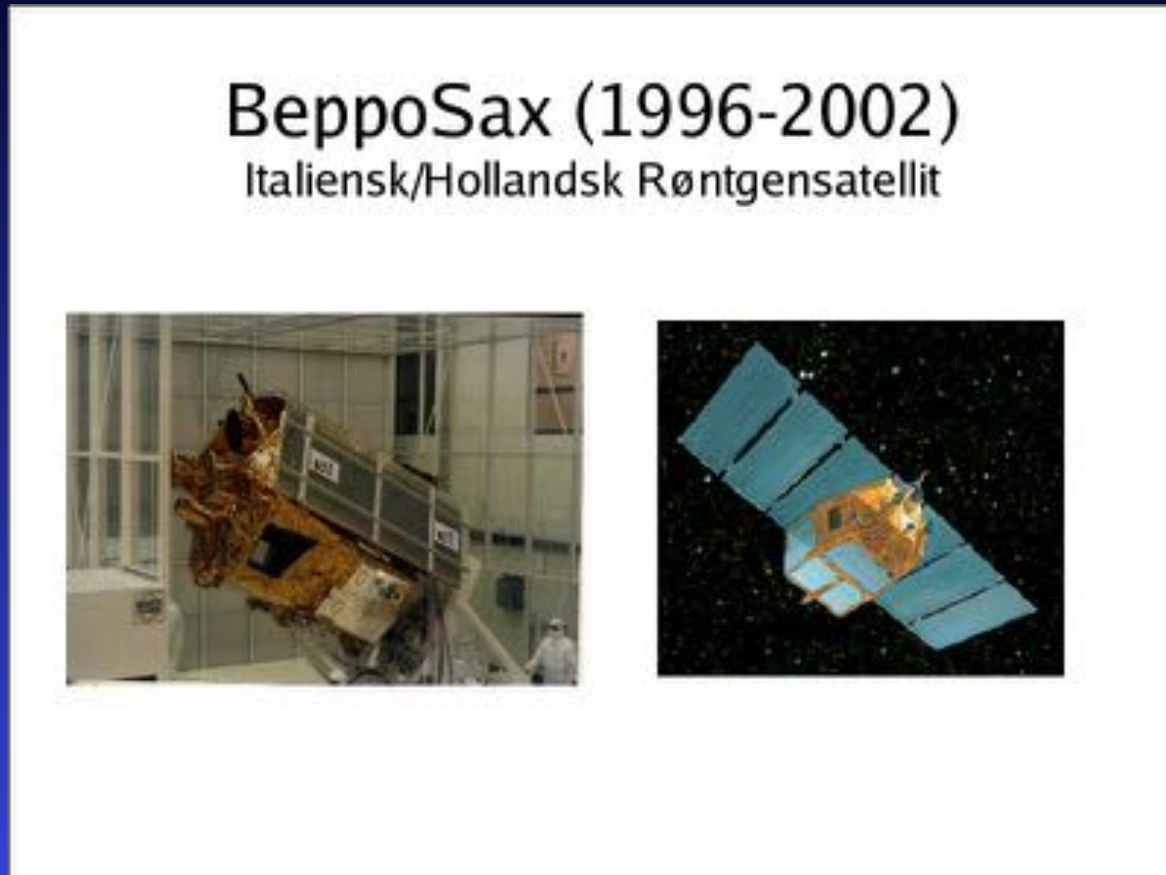
2704 BATSE Gamma-Ray Bursts
+90
+180
-180
-90
10-7
10-6
10-5
10-4
Fluence, 50-300 keV (ergs cm-2)

GRB Duration



The next important CLUE came in 1997)

(A Italian/Dutch satellite – Beppo/SAX – was launched in 96)



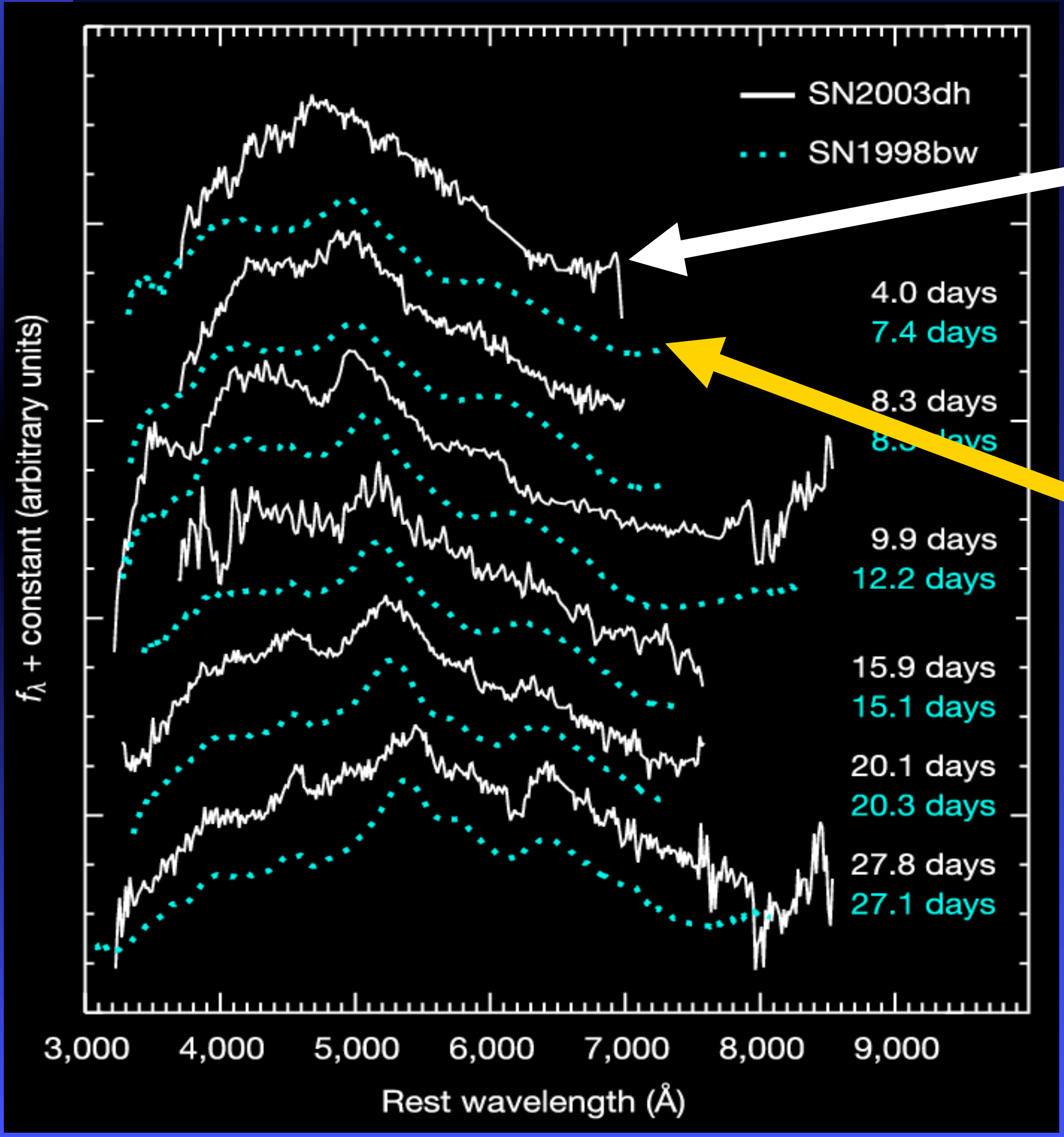
It localized long-bursts to 5-arcmin (a factor ~20 improvement)

Which led to the discovery of optical afterglow, and redshift.

Thus, it was discovered that energy (isotropic) $E_{iso} \sim 10^{53}$ erg.

In 2003 astronomer's analog of a finger print was found – facilitated by a NASA satellite HETE II (launched in Oct 2000)

Long-GRB – collapse of a massive star (Woosley and Paczynski)



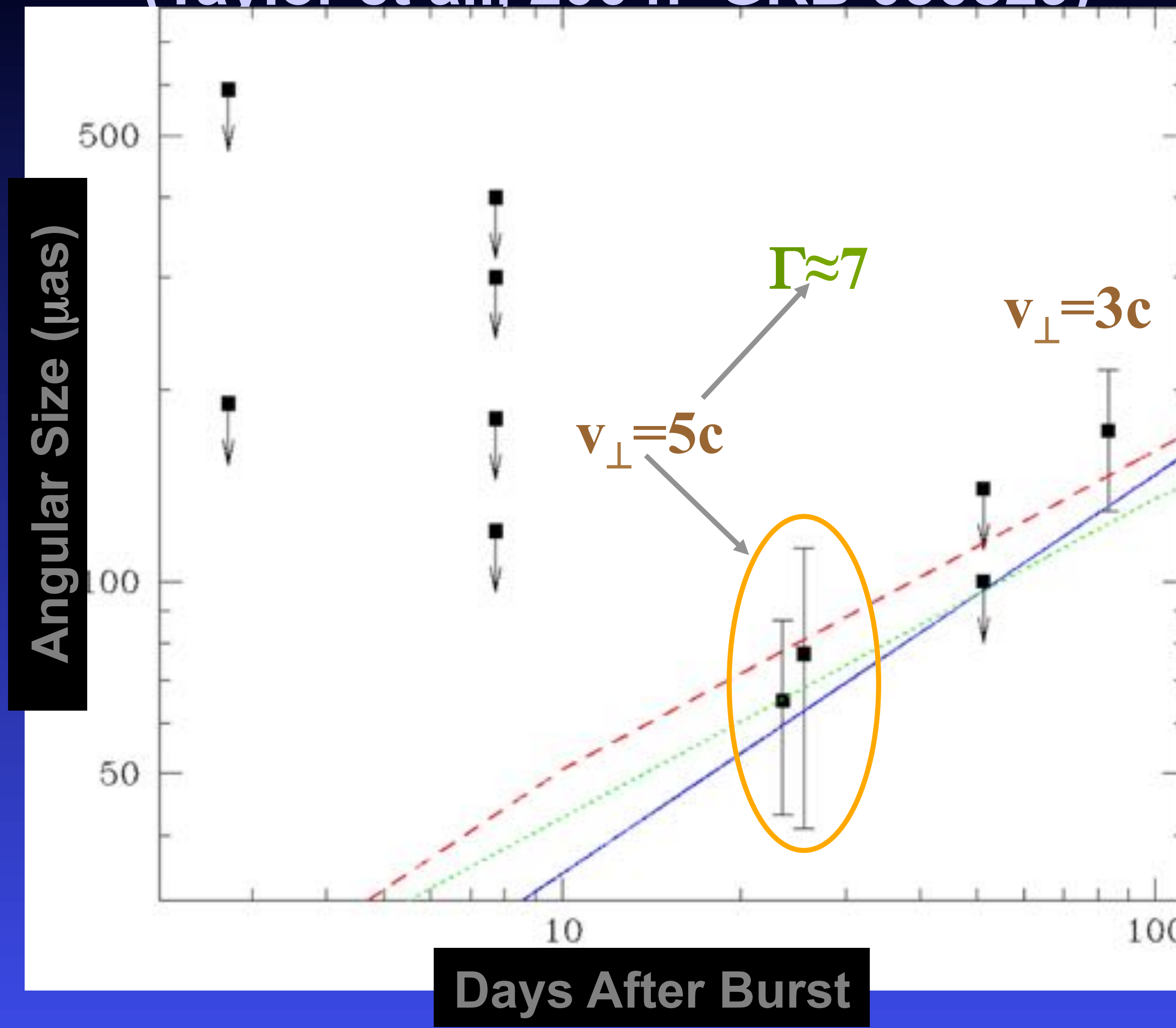
GRB 030329: z=0.17
(afterglow-subtracted)

SN 1998bw:
local, energetic, core-collapsed Type Ic

Stanek et al.,
Chornock et al.
Eracleous et al.,
Hjorth et al.,
Kawabata et al.

Explosion speed

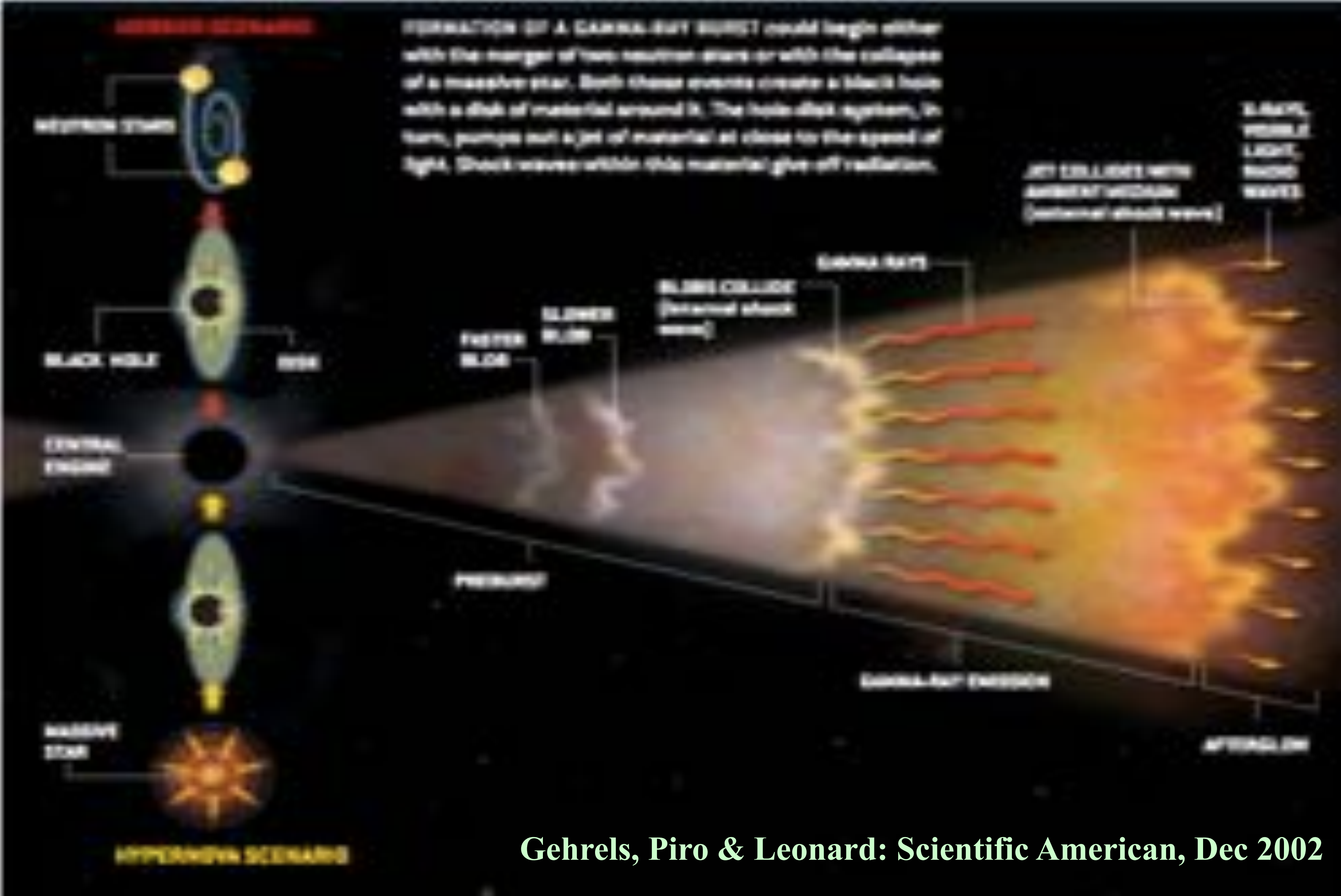
(Taylor et al., 2004: GRB 030329)



$$v_\perp = \frac{\beta \sin\theta}{1-\beta\cos\theta}$$

$\theta \approx 5^0$

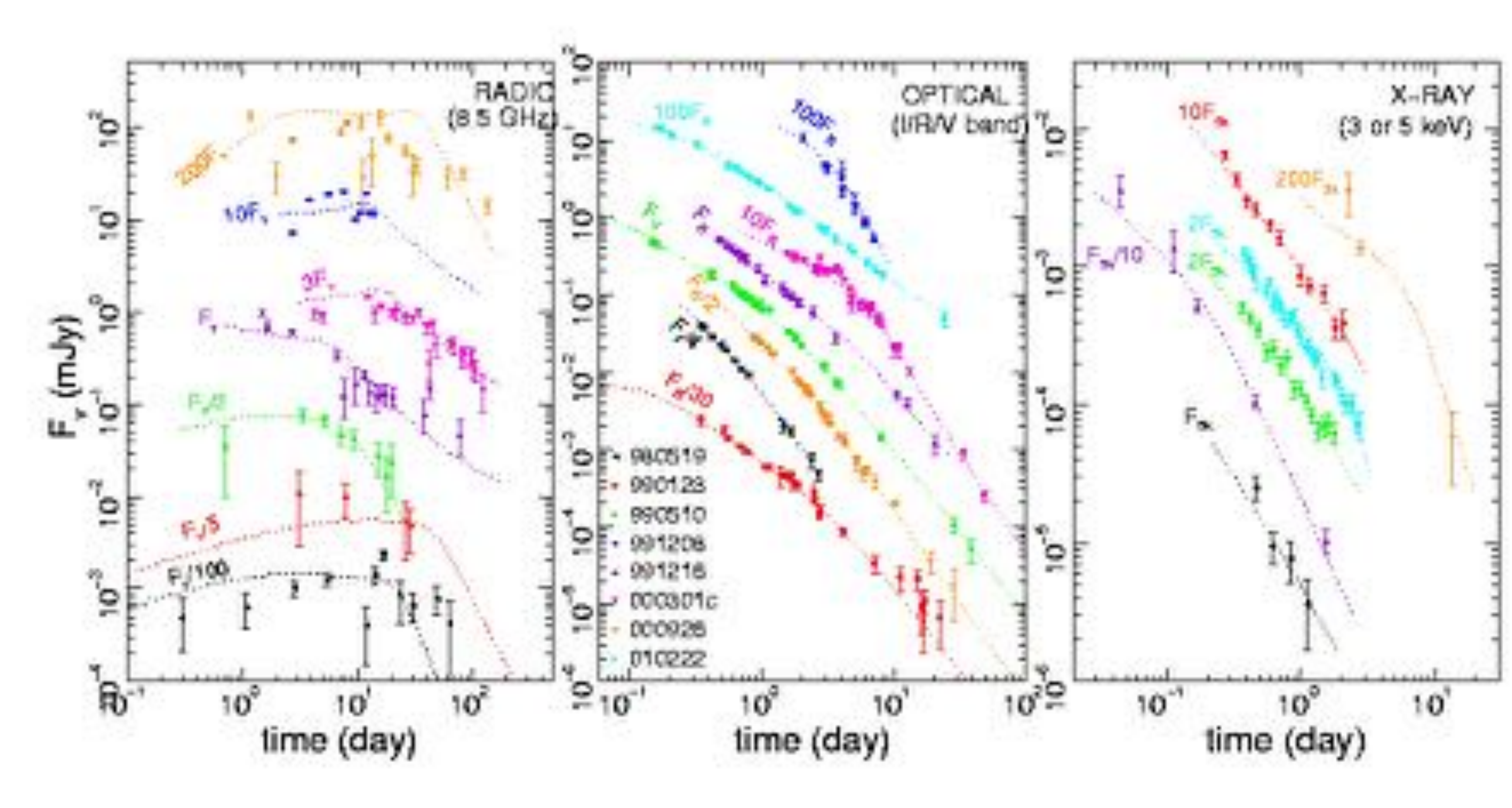
Interaction of the jet with the surrounding medium – GRB afterglow



Gehrels, Piro & Leonard: Scientific American, Dec 2002

- The “Afterglow” radition is produced by the synchrotron process in external shock
- The true amount of energy release in these explosions is determined by theoretical modeling of multiwavelength afterglow data, and is found to be ~10^{51} erg.

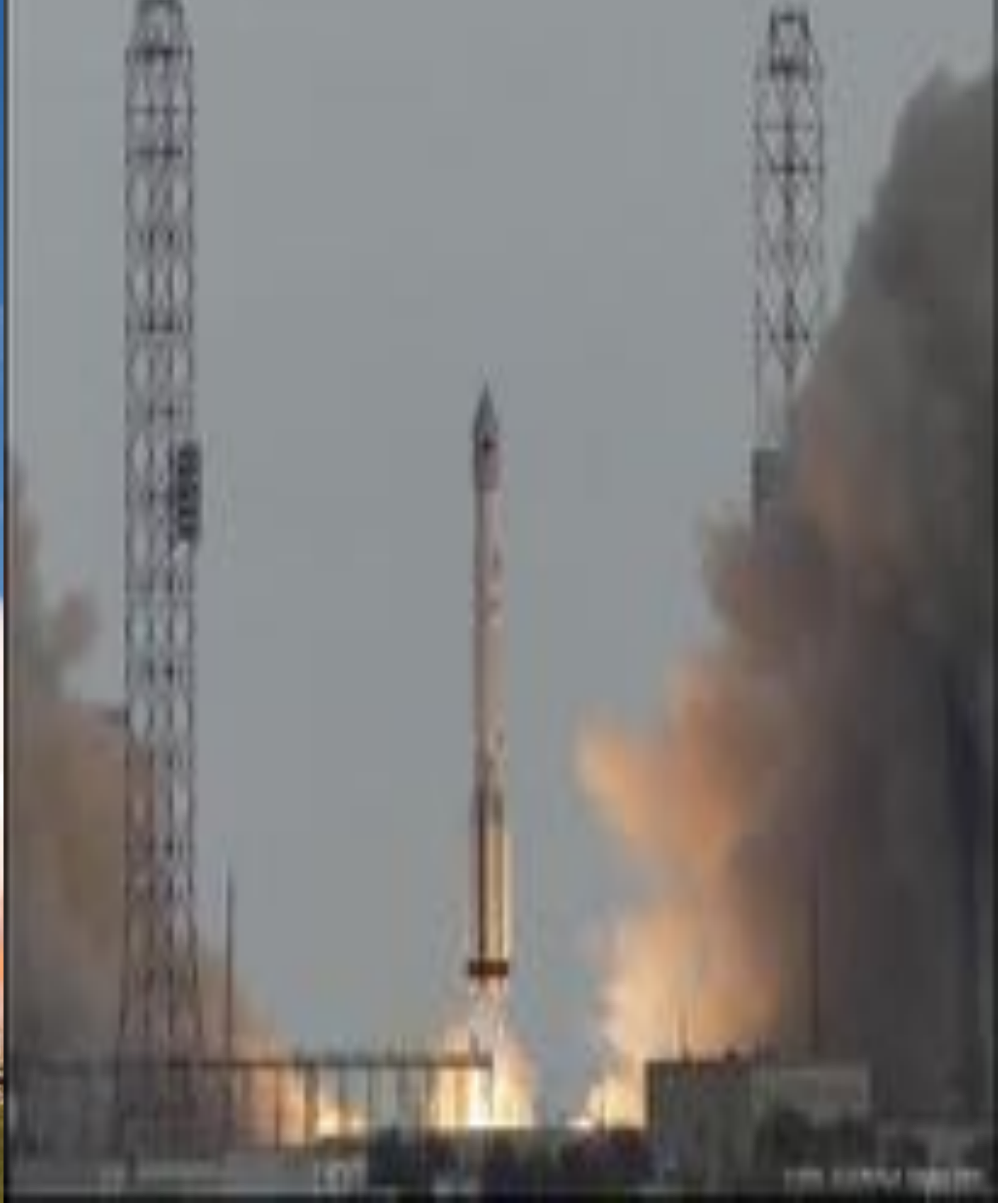
Panaitescu & Kumar (2001)



More energy comes out in these explosions in a few seconds than the Sun will produce in its 10 billion year lifetime!

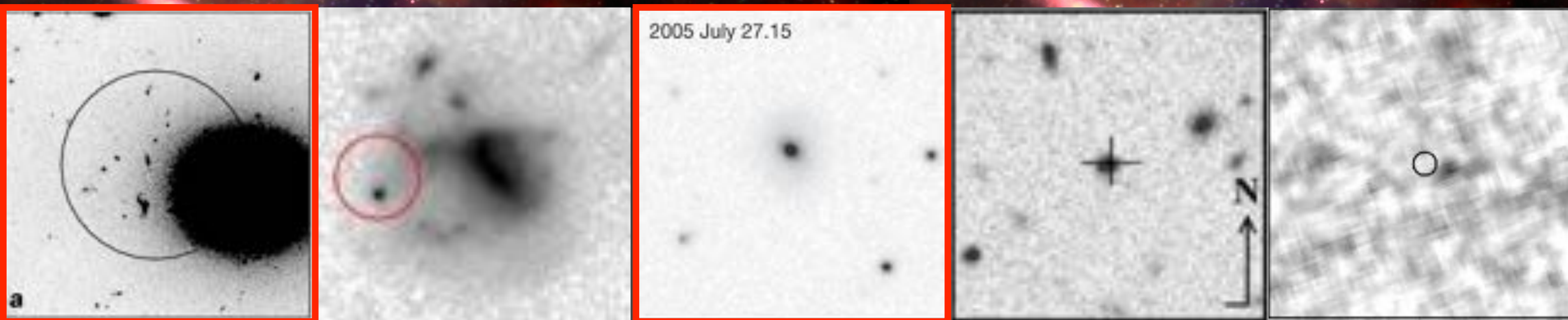
The launch of Swift satellite – 11/20/04 – was another major milestone in the study of GRBs

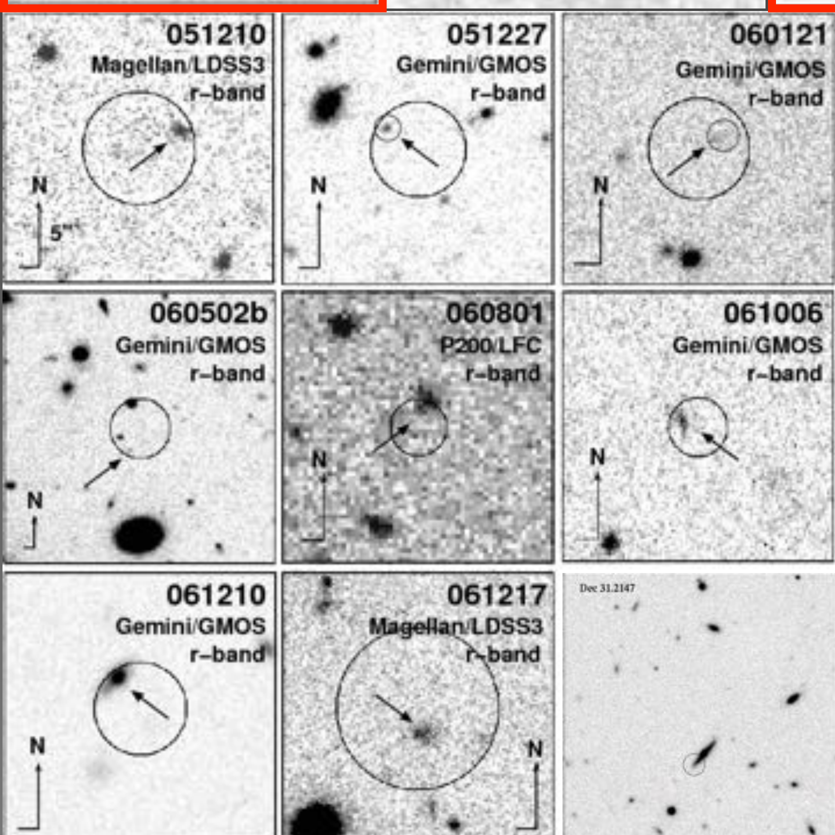
INTEGRAL satellite – Oct 17, 2002 launch – has discovered many GRBs and contributed much to our knowledge of these bursts.

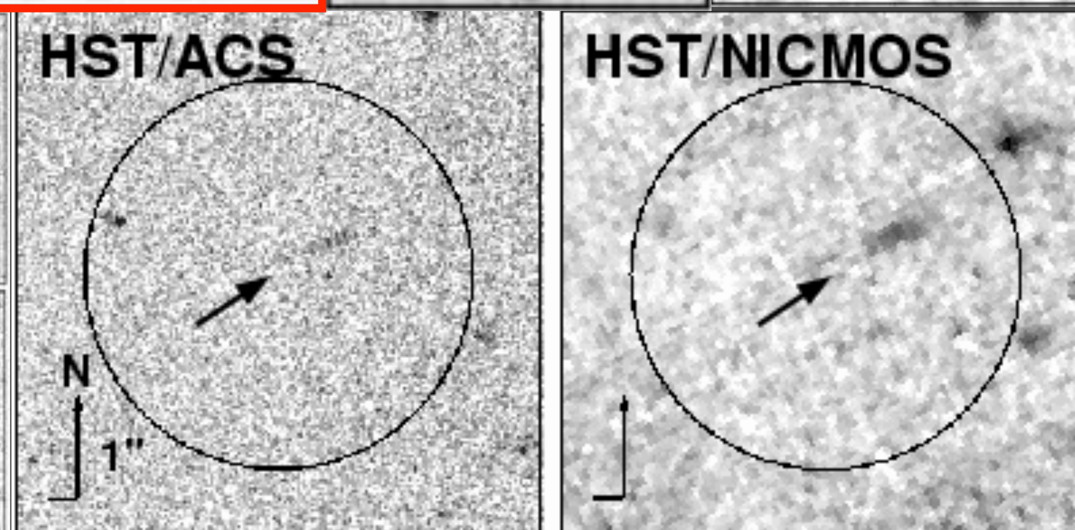


Short GRBs: Host Galaxies

Berger et al. 2007





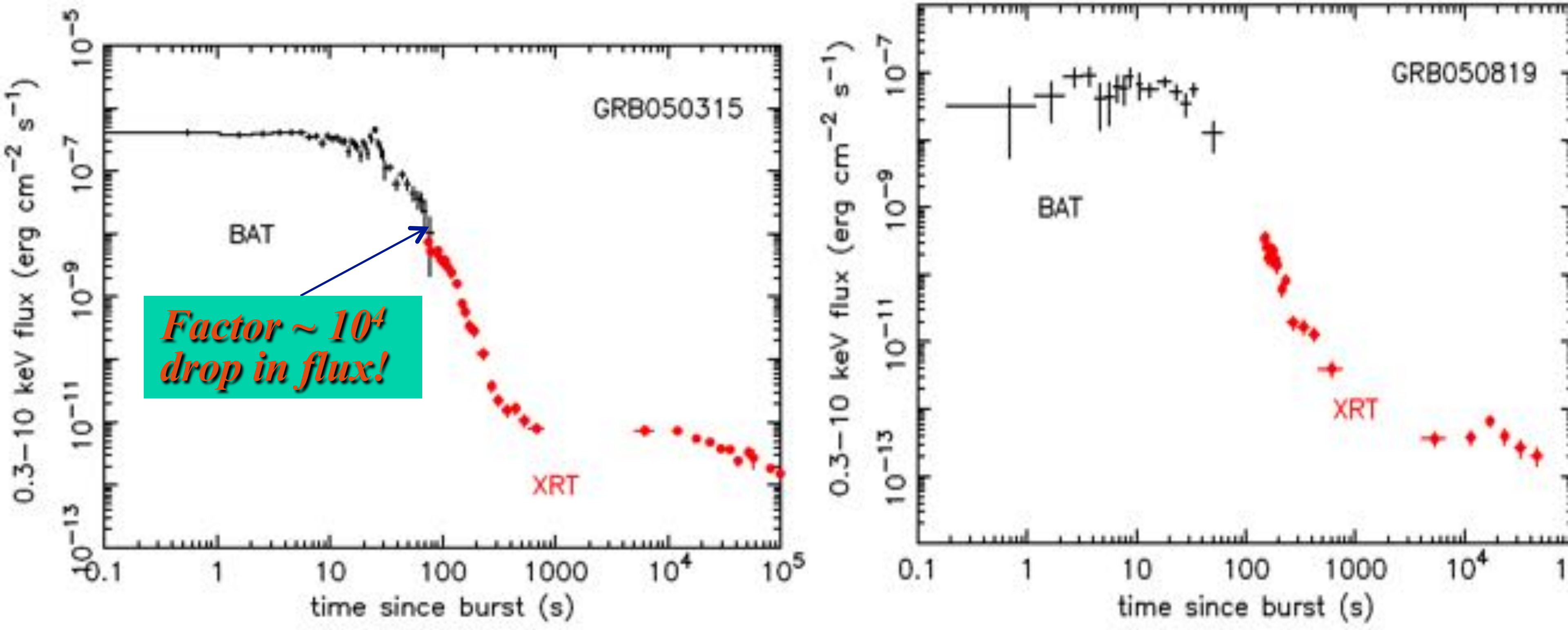


Large circle: Swift/XRT position
Small circle: optical position (if available)

Gemini & Magellan images are 20" on the side

Another major discovery of Swift was that the x-ray flux declines rapidly at the end of γ-ray burst; ***this behavior was anticipated by Kumar & Panaitescu (2000) – 5 years before the discovery*****.**

O'Brien et al., 2006

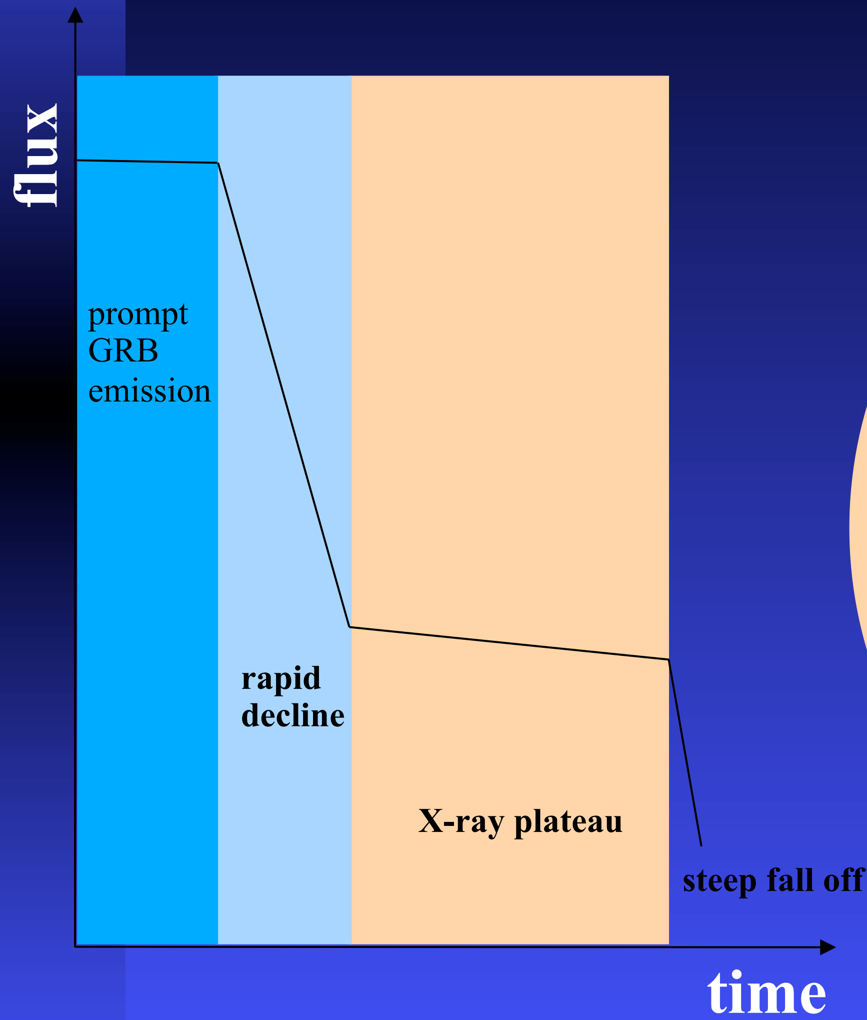


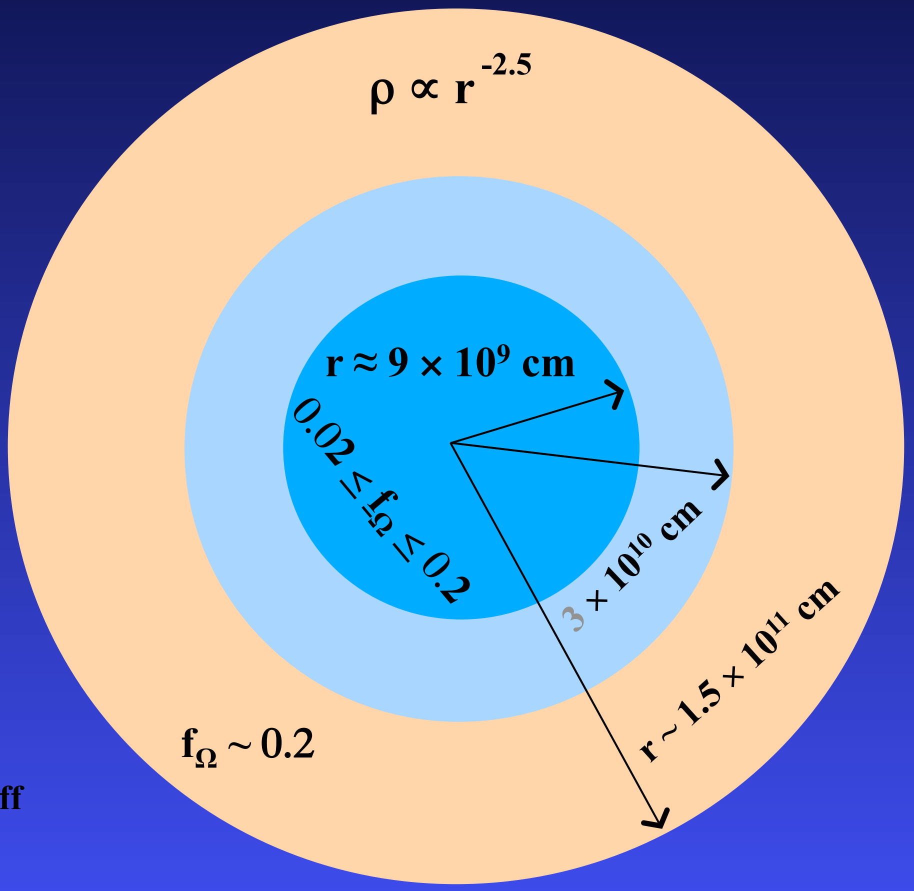
If the rapid turn-off is due to a fast decline of accretion rate onto the newly formed black-hole, then we can "invert" the observed x-ray lightcurve and determine progenitor star structure.

Progenitor Star Properties

Kumar, Narayan & Johnson (2008)

(Sophisticated simulation work of Lindner, Milosavljevic et al., 2010)



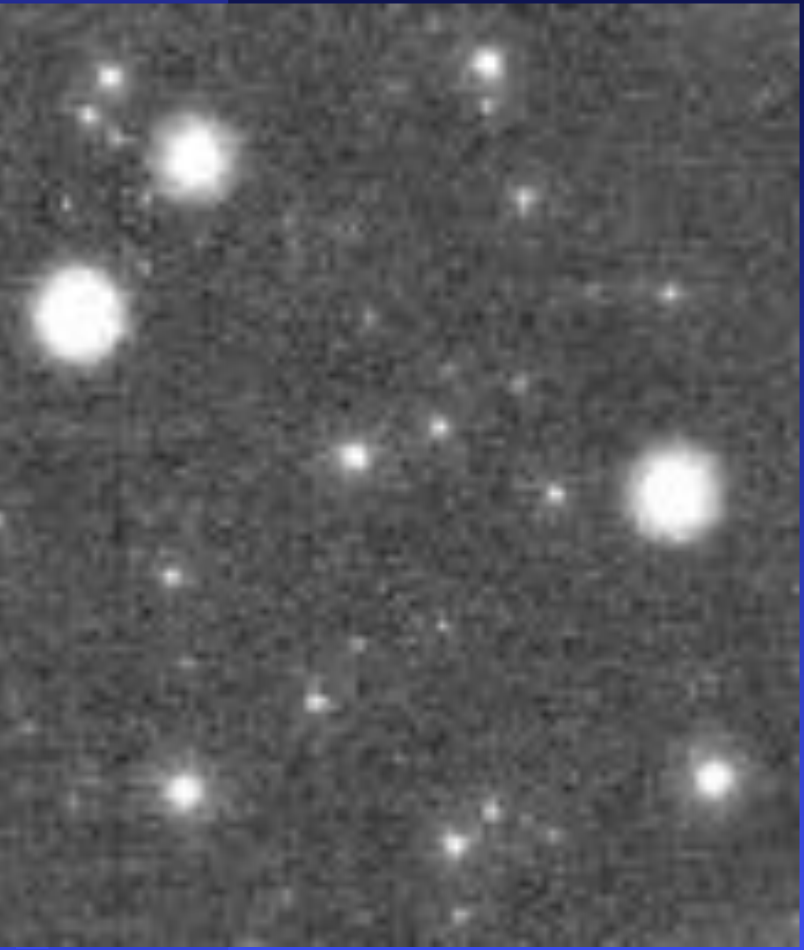


$f_\Omega \equiv \Omega/\Omega_k$

Some interesting GRBs detected by Swift

Naked Eye burst (080319B) z=0.93
7.5 Gega-ly; 5.8 mag for 30s

2.5 million times more luminous (optical) than the most luminous supernova ever recorded



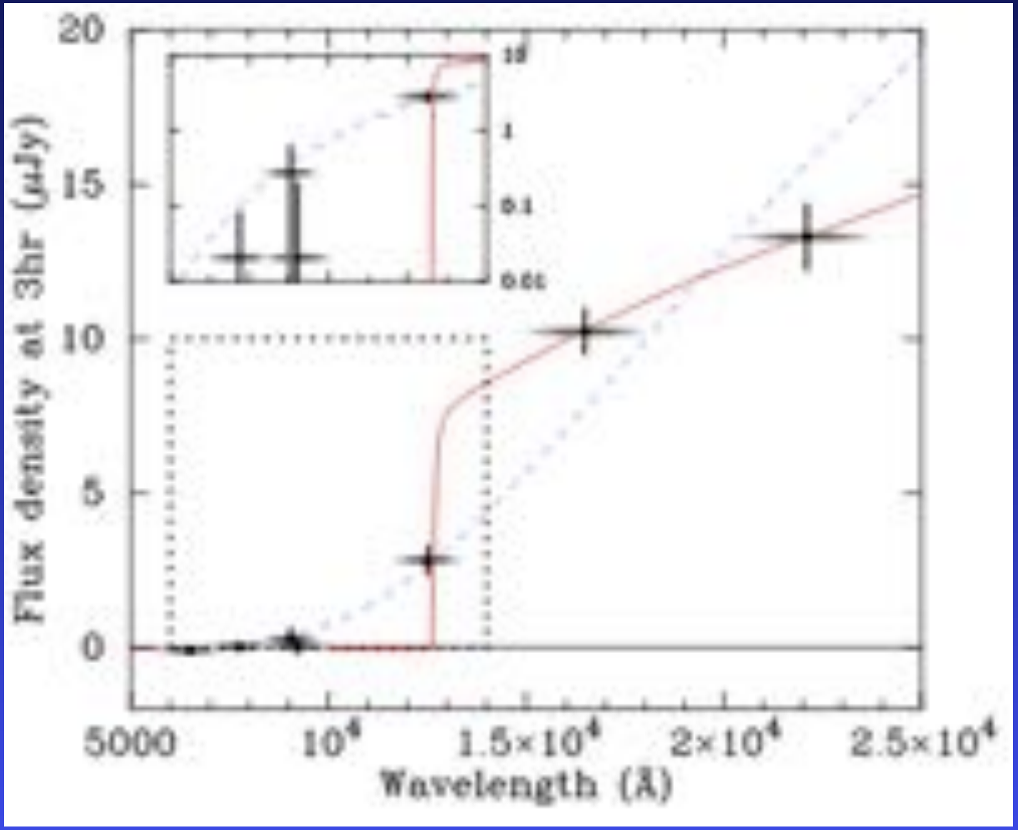
movie made by Pi of the Sky, a Polish group that monitors transient events

GRB 090429B: z=9.4, $E_{iso}=3.5\times10^{52}$erg

T = 5.5s, fluence=3.1×10^{-7} erg cm^{-2} (E_p=49 keV)

(similar to bursts at low z)

Cucchiara et al. 2011



Swift can see such GRBs even at z~20

GRBs as probe for the young Universe

- Swift has seen two bursts at z=8.2 & 9.4 these are among the most distant objects we have seen.
  - Bursts like these occurred about 13 billion years ago, when the universe was about 500 Million Years old. These bursts will help us explore the properties of the young Universe and the first stars and objects that formed.

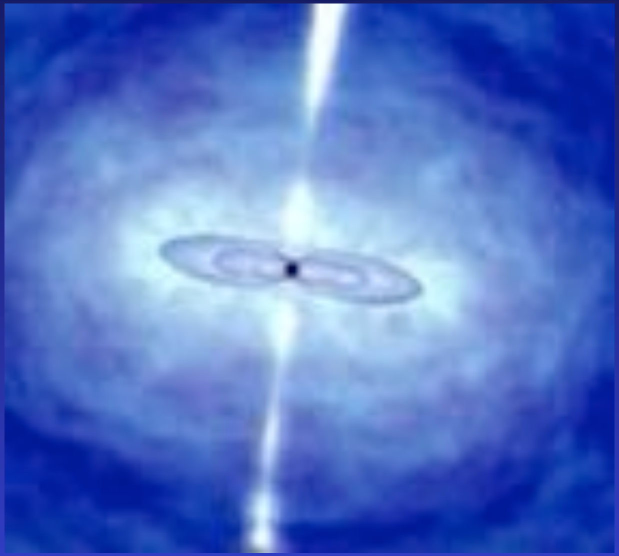
The most distant quasar is at z=6.4 & galaxy at z~10.

- Our understanding of GRBs has improved dramatically in last ~10 years.
- However, there are a number of fundamental questions that remain unanswered. The foremost amongst these are:

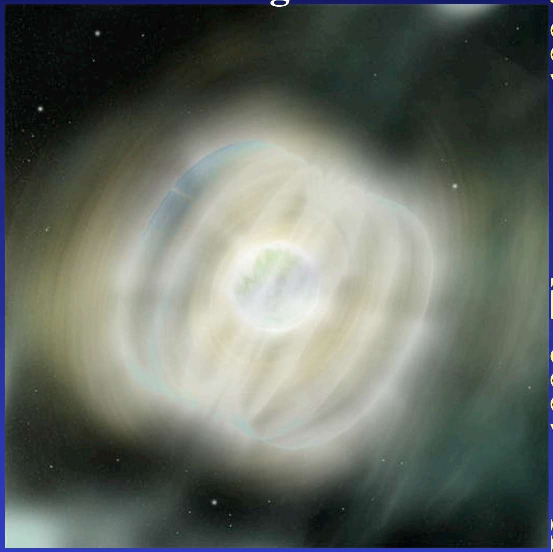
1. Whether a BH or a NS is produced in these explosions?

blackhole

Woosley, 1993
Paczynski, 1998



magnetar



Usov 1992, Thompson 1994
Wheeler et al. 2000
Thompson et al. 2004

2. Composition of relativistic jets in GRBs: Baryons? $e^{\pm}$? or B?

We can answer these questions if we could understand how γ-rays are generated in GRBs, and use that to read the signatures of different central engine models and jet composition

Fermi

8 KeV to 300 GeV

6/11/2008

<u>How are γ-rays generated</u>?

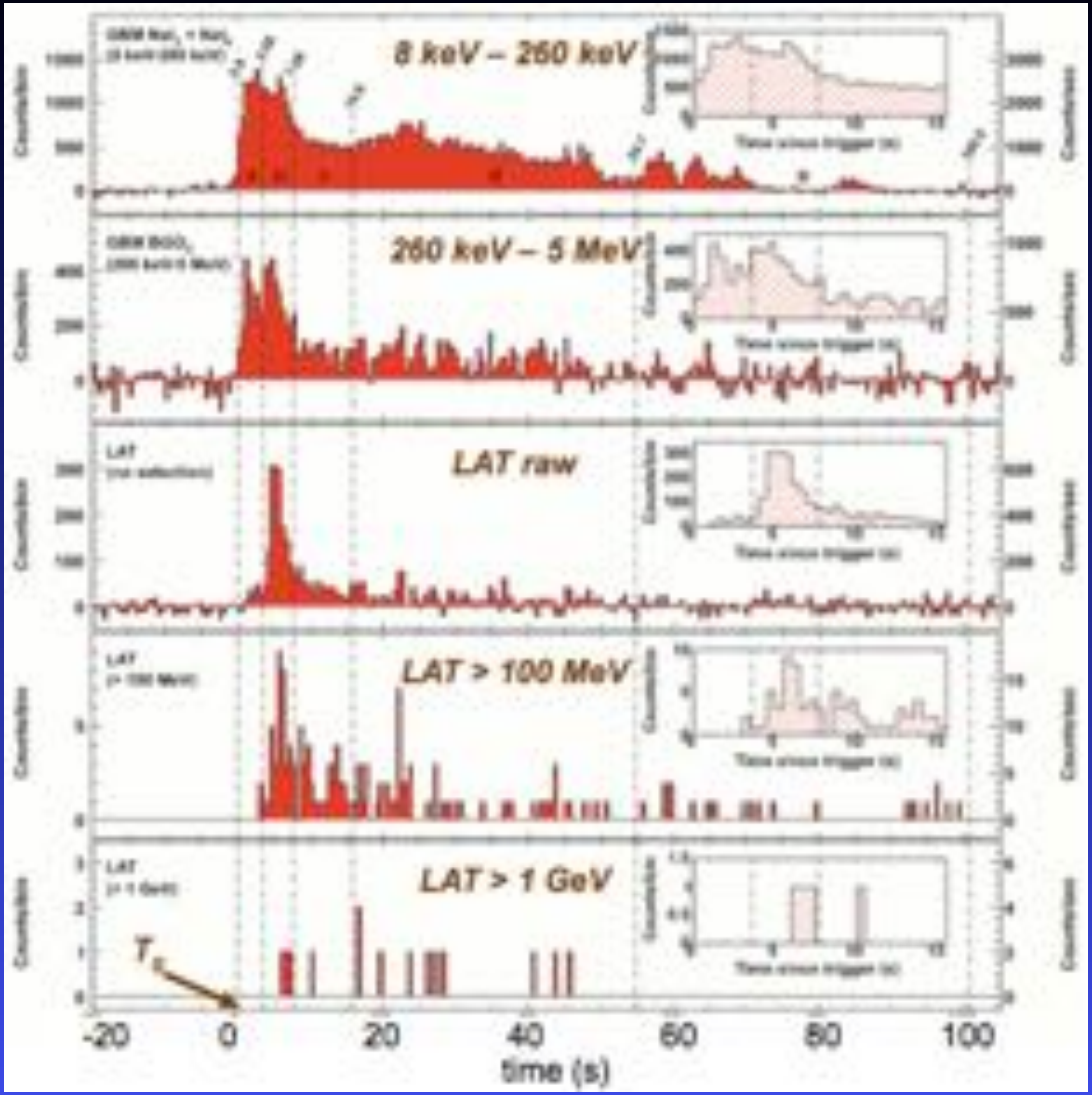
One of the goals for Fermi is to understand γ-ray burst prompt radiation mechanism by observing high energy photons from GRBs.

However, there were surprises in store for us:

Fermi discovered that →

1. >10^2MeV photons lag <10MeV photons (2-5s)

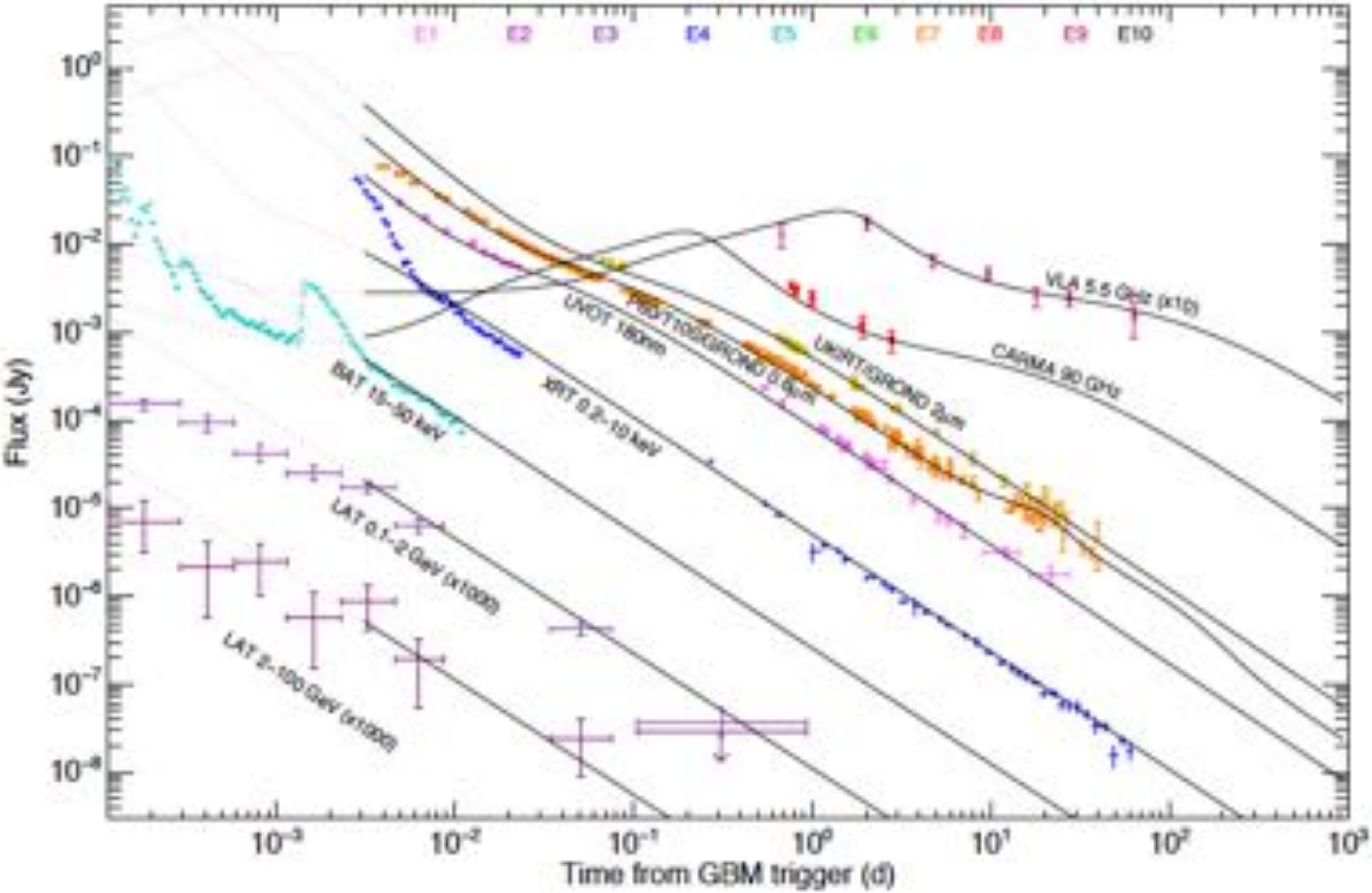
Abdo et al. 2009



2. >100 MeV radiation lasts for ~10^3s whereas emission below 10 MeV lasts for ~30s or less!

GRB 130427A (Perley et al. arXiv:1307.4401)

MeV duration (T_{90}) = 138s, LAT duration (T_{GeV}) > 4.3×10^{3}s; T_{GeV}/T_{90} > 31
Highest energy photon (95 GeV) detected 242s after T_0; z=0.34; $E_{\gamma,iso}$= 7.8×10^{53}erg



Origin of high energy photons in GRBs

Prompt phase: **high energy photons during this phase might have a separate origin than photons that come afterwards if rapid fluctuations and correlation with MeV lightcurve is established.**

- **Hadronic processes: proton synchrotron, photo-meson …**

  Bottcher and Dermer, 1998; Totani, 1998; Aharonian, 2000; Mucke et al., 2003; Reimer et al., 2004; Gupta and Zhang, 2007b; Asano et al., 2009; Fan and Piran, 2008; Razzaque et al. 2010; Asano and Meszaros, 2012; Crumley and Kumar, 2013….

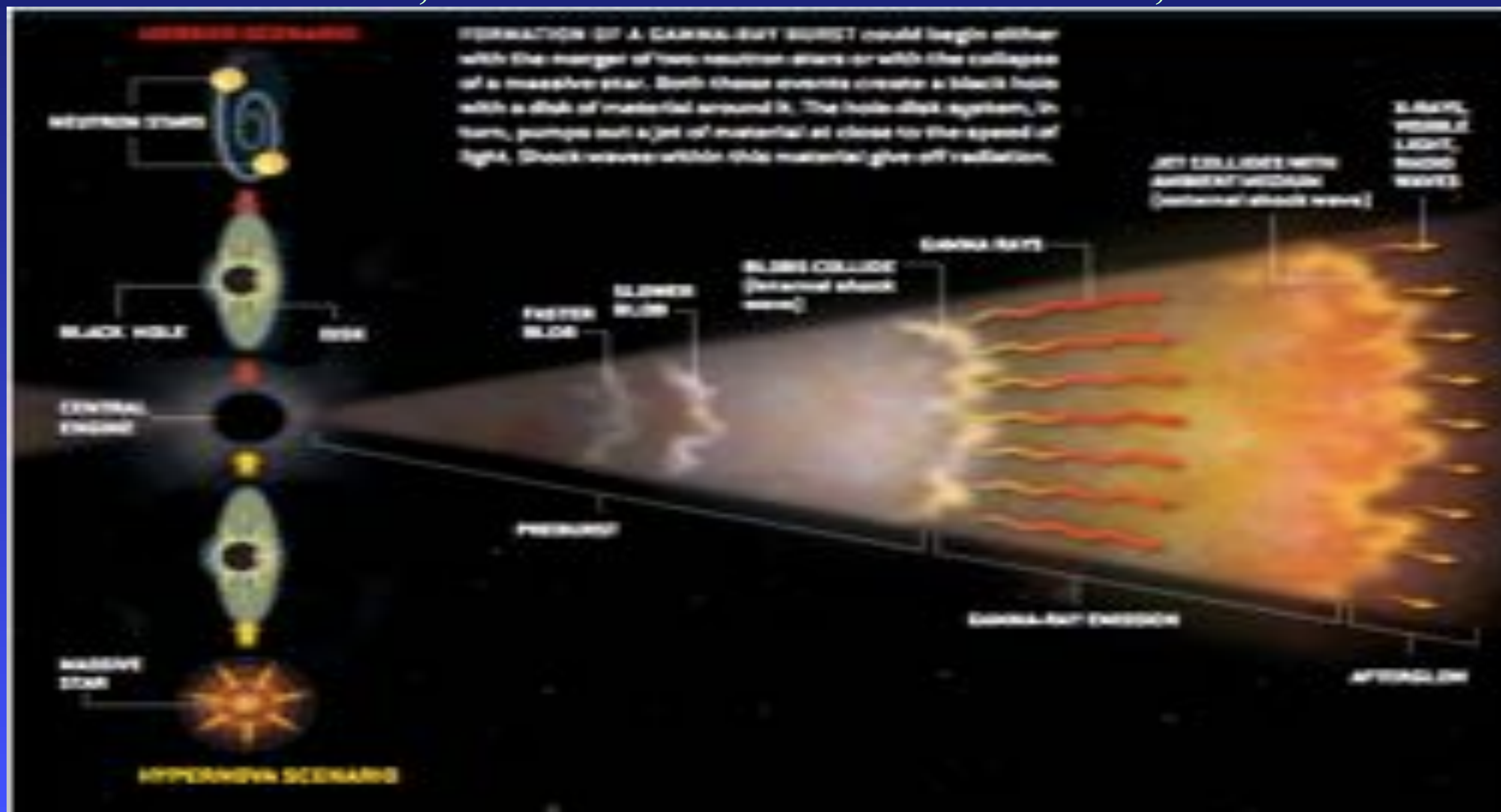
  Inefficient process – typically requires several order more energy than we see in the MeV band (unless Γ were to be small, of order a few hundred, which few people believe is the case for Fermi/LAT bursts), e.g. Razzaque et al. 2010, Crumley & Kumar 2013.

- **Internal shock and SSC: e.g. Bosnjak et al. 2009, Daigne et al. 2011**

Within a few months of these discoveries (by Fermi) Kumar & Barniol Duran (2009) proposed a model – now widely accepted – which will be discussed in the next few slides.

They suggested that high energy photons (>100 MeV) are produced in the External-shock via synchrotron

Gehrels, Piro & Leonard: Scientific American, Dec 2002



Flux above ν_c is independent of density and almost independent of ε_B

- Consider GRB circumstellar medium density profile: $\rho \propto r^{-s}$
- Blast wave dynamics follows from energy conservation: $\Gamma \propto r^{-(3-s)/2}$
- Observer frame elapsed time: $t_{obs} \approx \frac{r}{2c\Gamma^2} \propto r^{4-s}$
- Comoving magnetic field in shocked fluid: $B'^2 \propto \varepsilon_B \rho \Gamma^2$
- Synchrotron characteristic frequency: $\nu_m \propto B' \gamma_m^2 \Gamma \propto \varepsilon_B^{1/2} t_{obs}^{-3/2}$
- Observed flux at ν_m: $f_{\nu_m} \propto \varepsilon_B^{1/2} r^{-s/2}$
- Synchrotron cooling frequency: $\nu_c \propto \varepsilon_B^{-3/2} r^{(3s-4)/2}$

∴ Observed flux at ν: $$f_\nu = f_{\nu_m} \left(\frac{\nu_m}{\nu_c}\right)^{(p-1)/2} \left(\frac{\nu_c}{\nu}\right)^{p/2} \propto \varepsilon_B^{(p-2)/4} t_{obs}^{-(3p-2)/4}$$

The flux from the external shock above the cooling frequency is given by:

$$f_\nu = \frac{0.2\ \mathrm{mJy}\ E_{55}^{(p+2)/4}\ \varepsilon_e^{p-1}\ \varepsilon_B^{(p-2)/4}(1+z)^{(p+2)/4}}{d_{L28}^2 (t/10s)^{(3p-2)/4}\ \nu_8^{p/2}\ (1+Y)}$$

Y << 1 due to Klein-Nishina effect for electrons radiating 10^2MeV photons.

Note that the flux does not depend on the external medium density or stratification, and has a very weak dependence on ε_B.

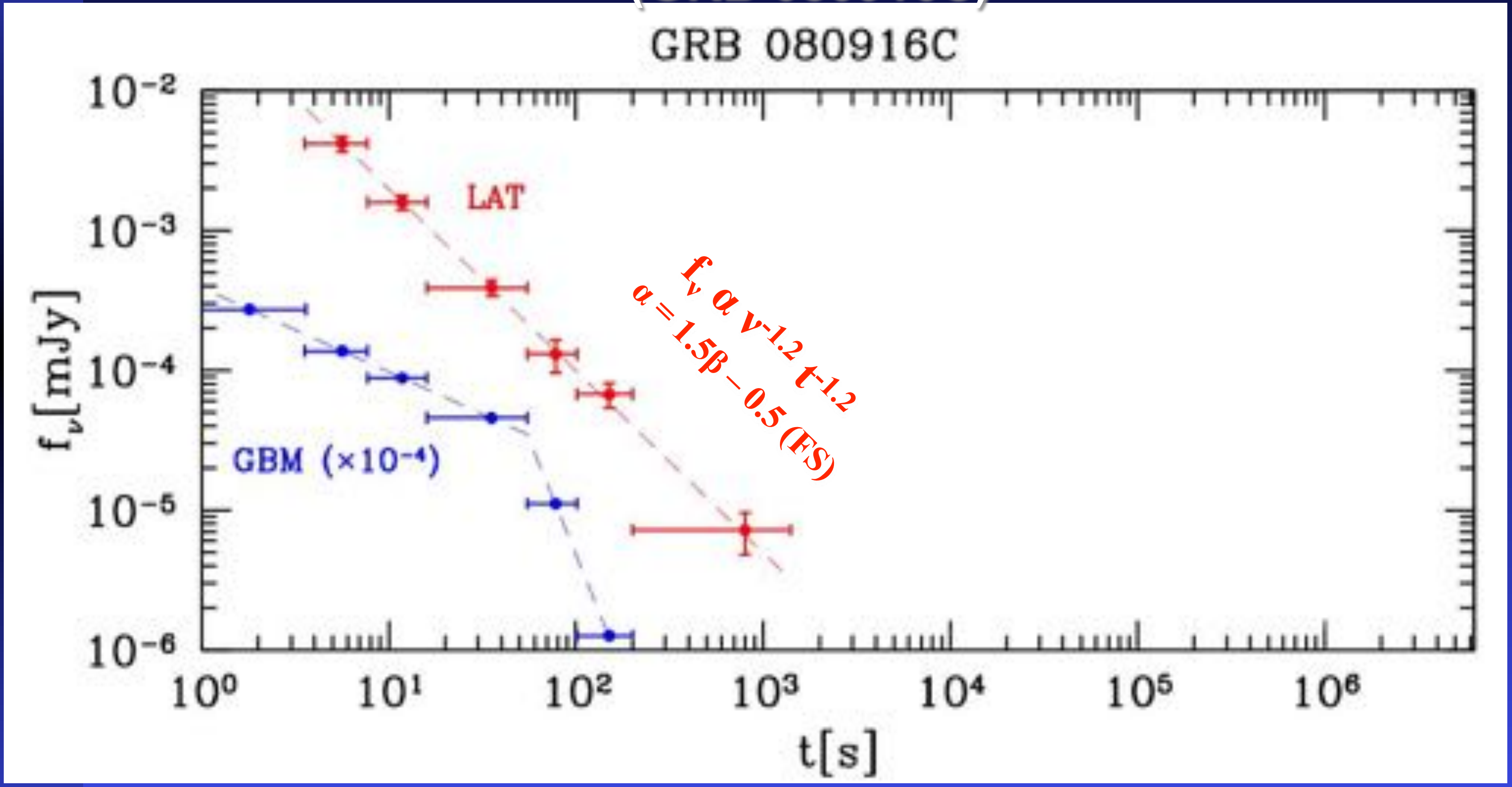
Table of expected and observed 100 MeV flux

	z	$E_{\gamma,54}$	Time (observer frame in s)	Expected flux ♪ from ES in nJy	Observed flux (nJy)
080916C	4.3	8.8	150	50	67
090510	0.9	0.11	100	9	14
090902B	1.8	3.6	50	300	220
110731A	2.83	0.6	100	8	~5
130427A	0.34	0.78	600	48	~40

♪We have taken energy in blast wave = $3E_\gamma$, $\epsilon_e=0.2$, $p=2.4$, $\epsilon_B=10^{-5}$

Long lived lightcurve for >10^2MeV (Abdo et al. 2009)

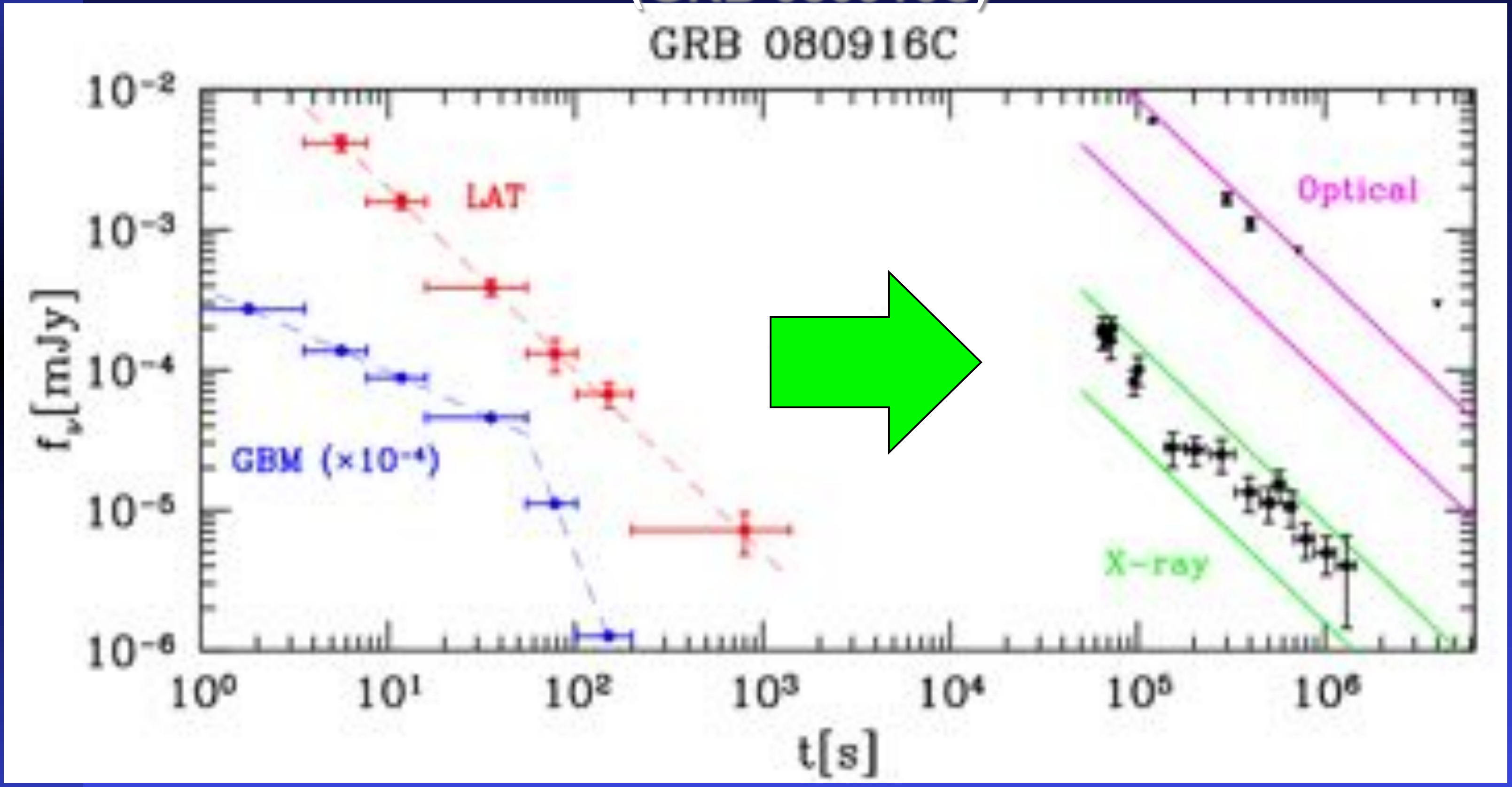
(GRB 080916C)



Abdo et al. 2009

Long lived lightcurve for >10^2MeV (Abdo et al. 2009)

>10^2MeV data ⇒ expected ES flux in the X-ray and optical band (GRB 080916C)



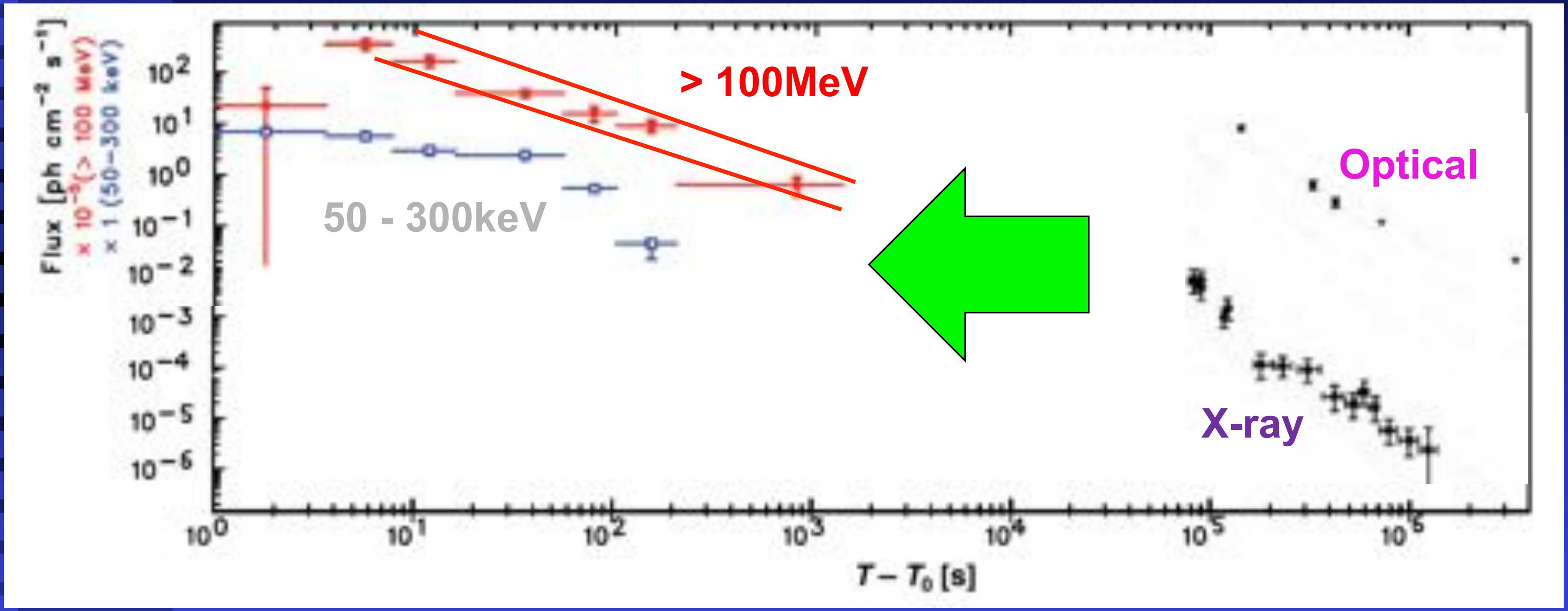
Kumar & Barniol Duran (2009)

Abdo et al. 2009, Greiner et al. 2009, Evans et al. 2009

We can then compare it with the available X-ray and optical data.

Or we can go in the reverse direction…

Assuming that the late (>1day) X-ray and optical flux are from ES, calculate the expected flux at 100 MeV at early times



Kumar & Barniol Duran (2009)

Abdo et al. 2009, Greiner et al. 2009, Evans et al. 2009

And that compares well with the available Fermi data.

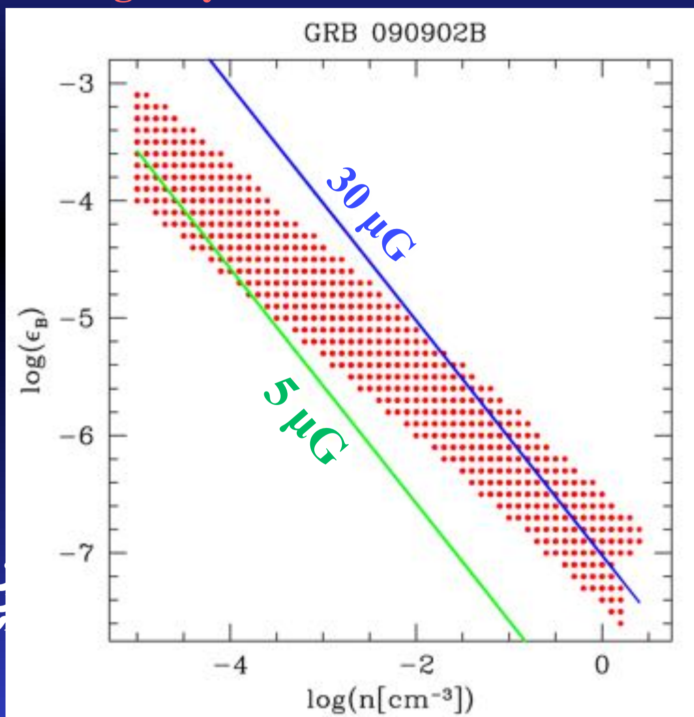
How are Magnetic fields Generated in Shocks?

(A long standing open question)

Recent work has provided a surprising answer: ϵ_B is consistent with shock compressed magnetic field of CSM of ~ 10 μG (Kumar & Barniol Duran 2009)

Using only >100MeV *Fermi* data

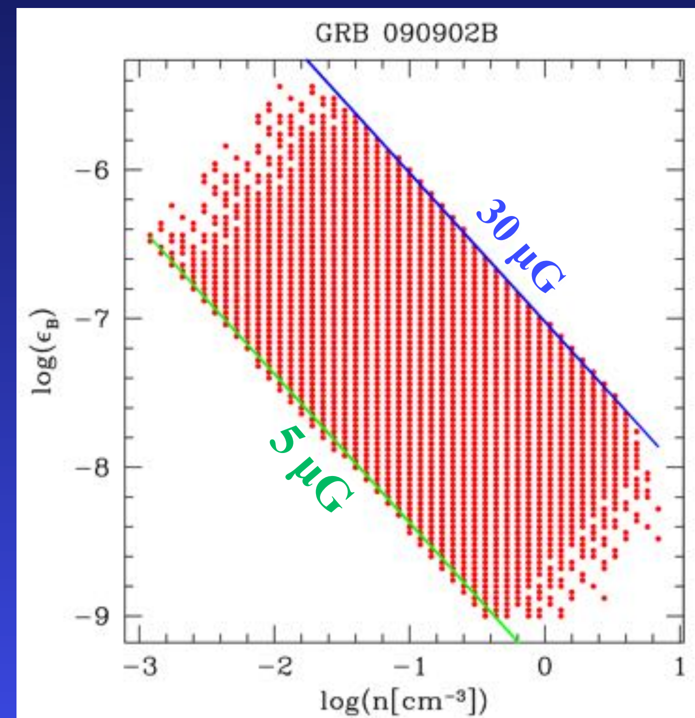
Parameter search at t = 50 sec.



GRB 090902B

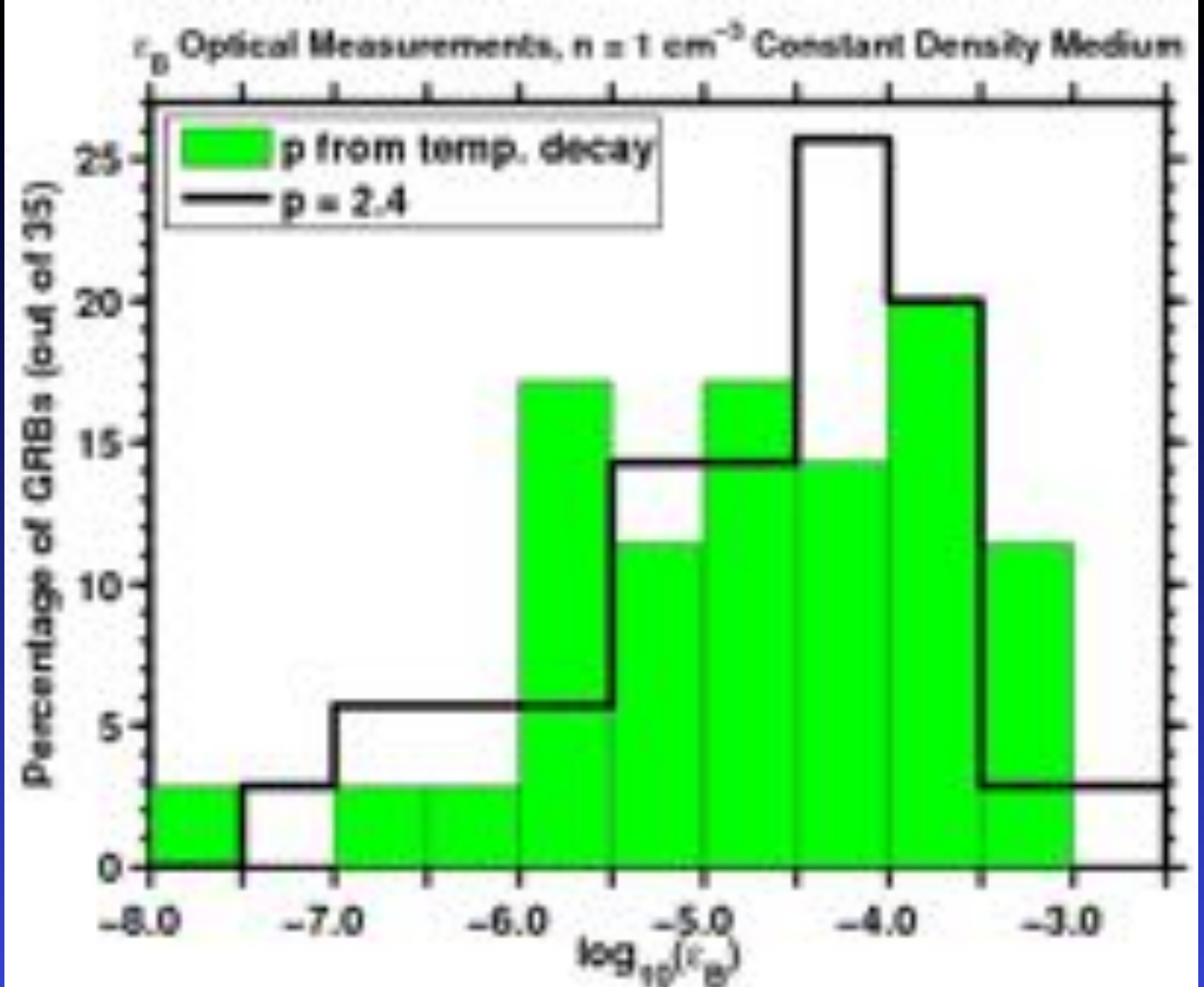
Using late time x-ray, optical & radio data

Parameter search at t = 0.5 day.



GRB 090902B

Santana et al. 2014

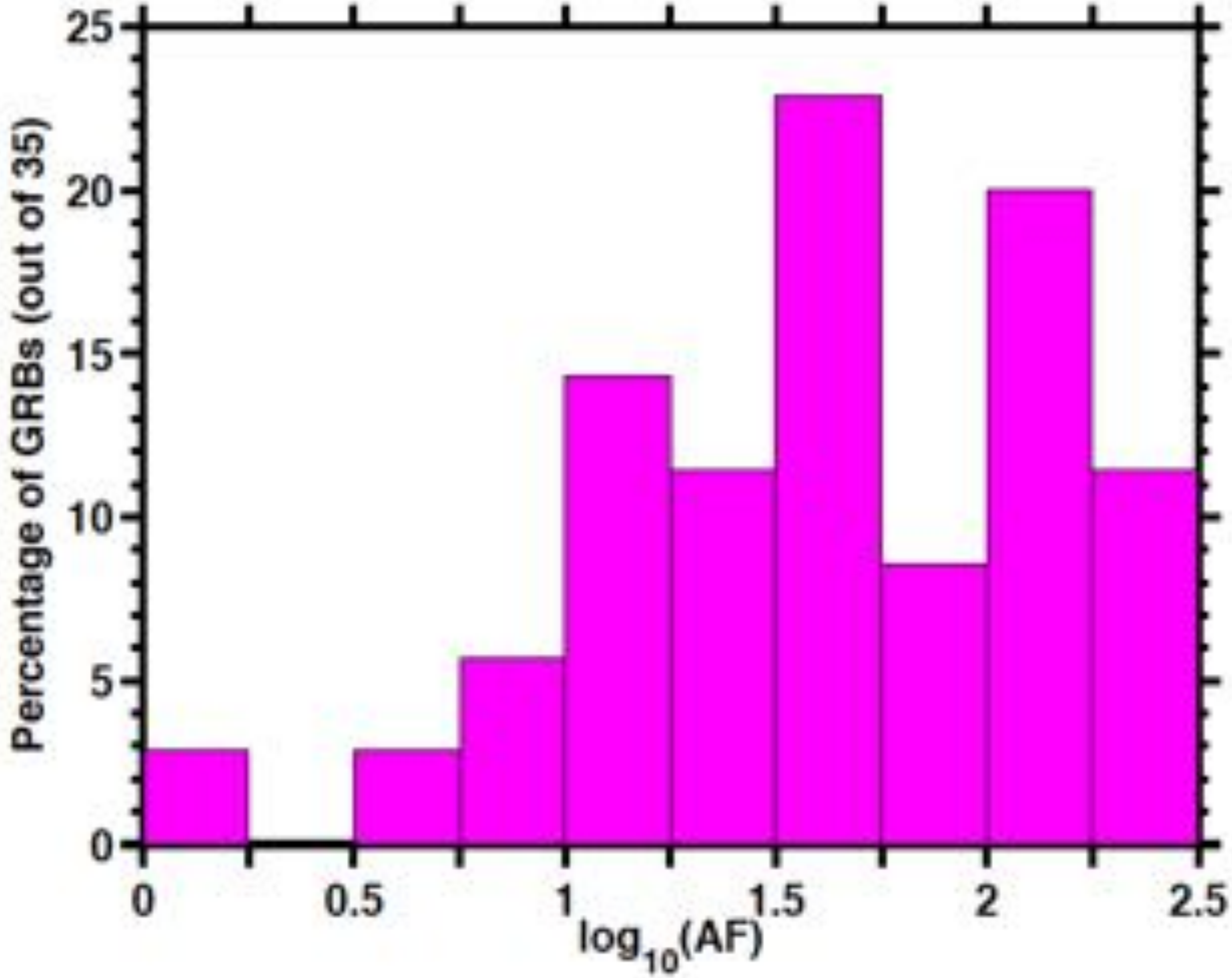


This result suggests a weak magnetic dynamo in relativistic shocks

Melandri et al. (2008), Antonelli et al. (2006), Panaitescu & Vestrand (2011), Schulze et al. (2011), Stratta et al. (2009), Covino et al. (2010), Perley et al. (2008), Perley et al. (2009), Uehara et al. (2010), Guidorzi et al. (2011), Perley et al. (2011), Greiner et al. (2009),Yuan et al. (2010), Melandri et al. (2010)

Magnetic field amplification factor (AF), for ISM density n = 1 proton cm^{-3}, and magnetic field = 10μG

Santana et al. 2014



This result suggests a weak magnetic dynamo in relativistic shocks

$AF \;\alpha\; n^{0.2} B^{-1}$

Acceleration of Electrons

(Barniol Duran & Kumar, 2010)

- **Electron Lorentz factor for 10 GeV synchrotron photon:**

$$\nu = \frac{q\,\gamma_e^2\,\Gamma B}{2\pi\, m_e c} \quad (\Gamma B = 4\Gamma B_{ism}) \quad \rightarrow \quad \Gamma\,\gamma_e = 1.5\times10^{11}\, B_{ism,-5}^{1/2}$$

- **Can electrons be accelerated to $\Gamma\,\gamma_e \sim 10^{11}$ when $B_{ism} \sim 10\mu G$?**

$$\frac{\text{Larmor radius}}{\Gamma} = \frac{m_e\,\gamma_e\,c^2}{qB} = 2\times10^{16}\text{ cm } B_{ism,-5}^{-3/2} < R \approx 10^{17}\text{cm}$$

∴ e^-s are confined by ~10μG field upstream & downstream

- **Radiative energy loss a problem?**

synchrotron energy loss rate * shock-crossing time < $m_e c^2 \gamma_e$

$$\rightarrow \quad h\nu_{max} < 50\text{ GeV } \Gamma_3$$

The maximum photon energy might be ~ a few x 100 GeV when we consider a realistic situation of inhomogeneous B.

Generation of ~ 10 GeV to 95 GeV photons detected from GRB 130427A is unclear.

Black-hole vs. Magnetar & jet composition

- **Swift found that the x-ray flux at the end of GRBs declines very rapidly — t^{-3} or faster.**

  The expected decline of luminosity for a magnetar is t^{-2}

- Some GRBs have $E > 10^{52}$ erg – more than expected of a magnetar.

  Recent work of Metzger et al. (2011) offers interesting suggestions regarding magnetars, but I see some problems...

- **One of the best ways to determine jet composition is by looking for optical/IR radiation from RS–heated jet (and ~TeV ν_e ν_μ).**

  Improved sensitivity (~10) in optical/IR is needed on a timescale of less than 10^2s from GRB trigger; ICECUBE is looking for ν.

Summary

☆ We have learned many things about GRBs in the last 10 years:

Produced in core collapse (long-GRB) & binary mergers (short-GRB)

Highly relativistic jet ($\Gamma \geq 10^2$), beamed ($\theta_j \sim 5^0$), $E_j \sim 10^{51}$ erg

They do occur at high redshifts (current record z=9.4)

High energy photons (>100 MeV) are produced in external shock

Generation of magnetic fields in relativistic shocks is clarified

☆ **But we don't yet have answers to several basic questions:**

Are blackholes produced in these explosions (or a NS)?

What is the GRB-jet made of?

How are gamma-rays of ~MeV energy produced?

Future Prospects

- ☆ Fermi, Swift & INTEGRAL will continue to provide excellent data.

- ☆ SVOM – a French-Chinese mission (2017?) will have γ-ray, x-ray, optical & IR telescopes and slew in < 60s – good for high-z GRB study.

- ☆ IceCube has been looking for high-energy neutrinos from GRBs with energy between ~ 30 TeV and 10 PeV (also ANTARES)

- ☆ Gravitational waves: advanced-LIGO could detect ~10 short-GRBs per year (to distances of ~200 Mpc).

- ☆ ALMA (Atacama Large Millimeter Array) – 90-950 GHz with ~10^2 times the sensitivity of VLA – will be powerful tool for afterglow observations.

- ☆ MAGIC, HESS & VERITAS (air Cerenkov telescopes) would continue looking for TeV photons; MAGIC can respond within a minute of trigger.

- ☆ JANUS – proposed small explorer – will have 1-20 keV & near-IR telescopes spot high-Z GRBs.