Gamma-ray Bursts in the Fermi era

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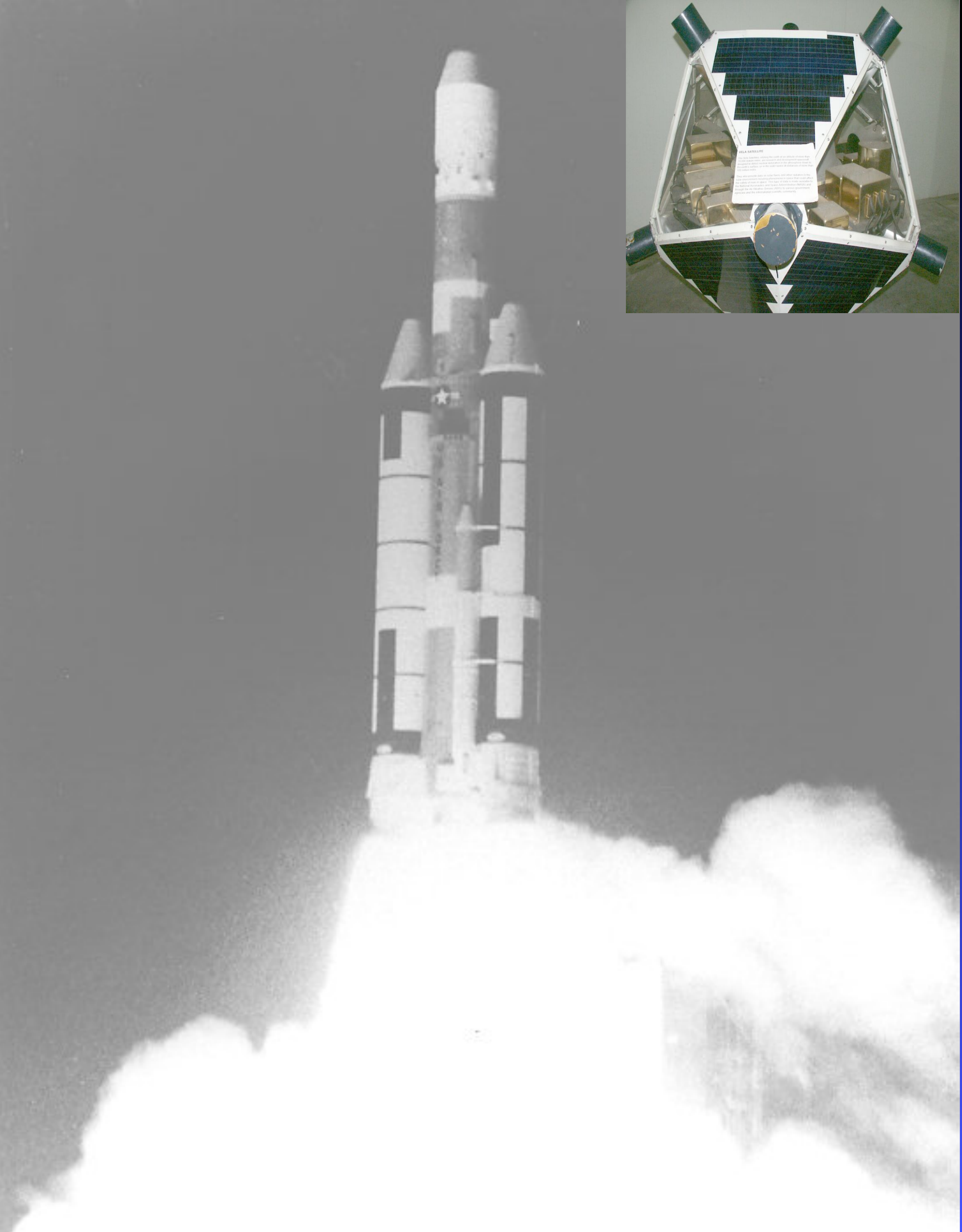
Outline†

- **Summary of main discoveries in last 12 yrs**
- **Fermi data & developments of last 7 years**
- **Problems with the current paradigm and possible solutions.**

TIFR, June 27, 2017



History

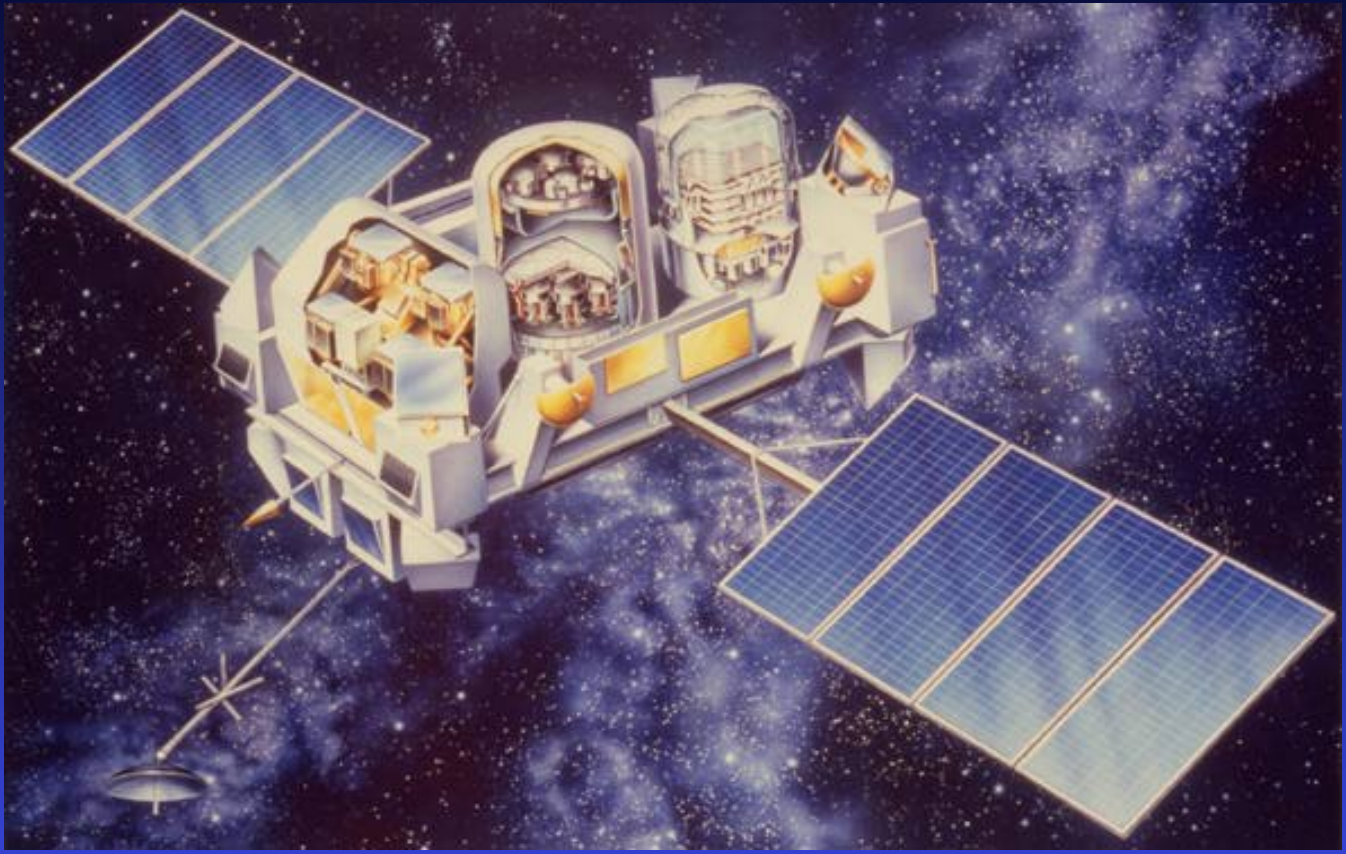
Gamma-ray Bursts (GRBs)

were discovered (accidentallyȣ) by Vela satellites in 1967.

For about 25 years the distance to GRBs was completely uncertain.

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

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 →

The next important CLUE came in 1997)

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

BeppoSax (1996-2002)

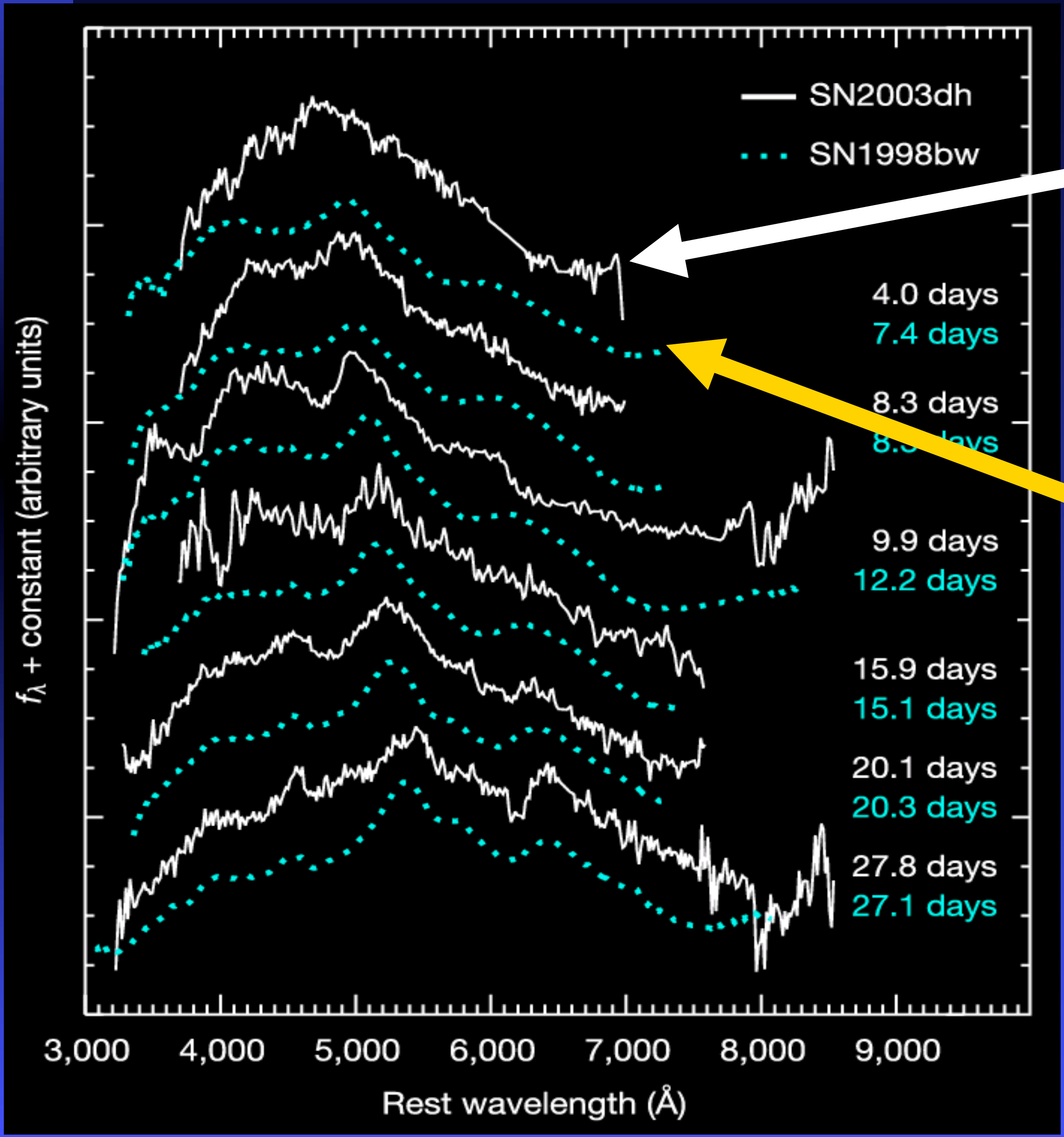
Italiensk/Hollandsk Røntgensatellit

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.

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



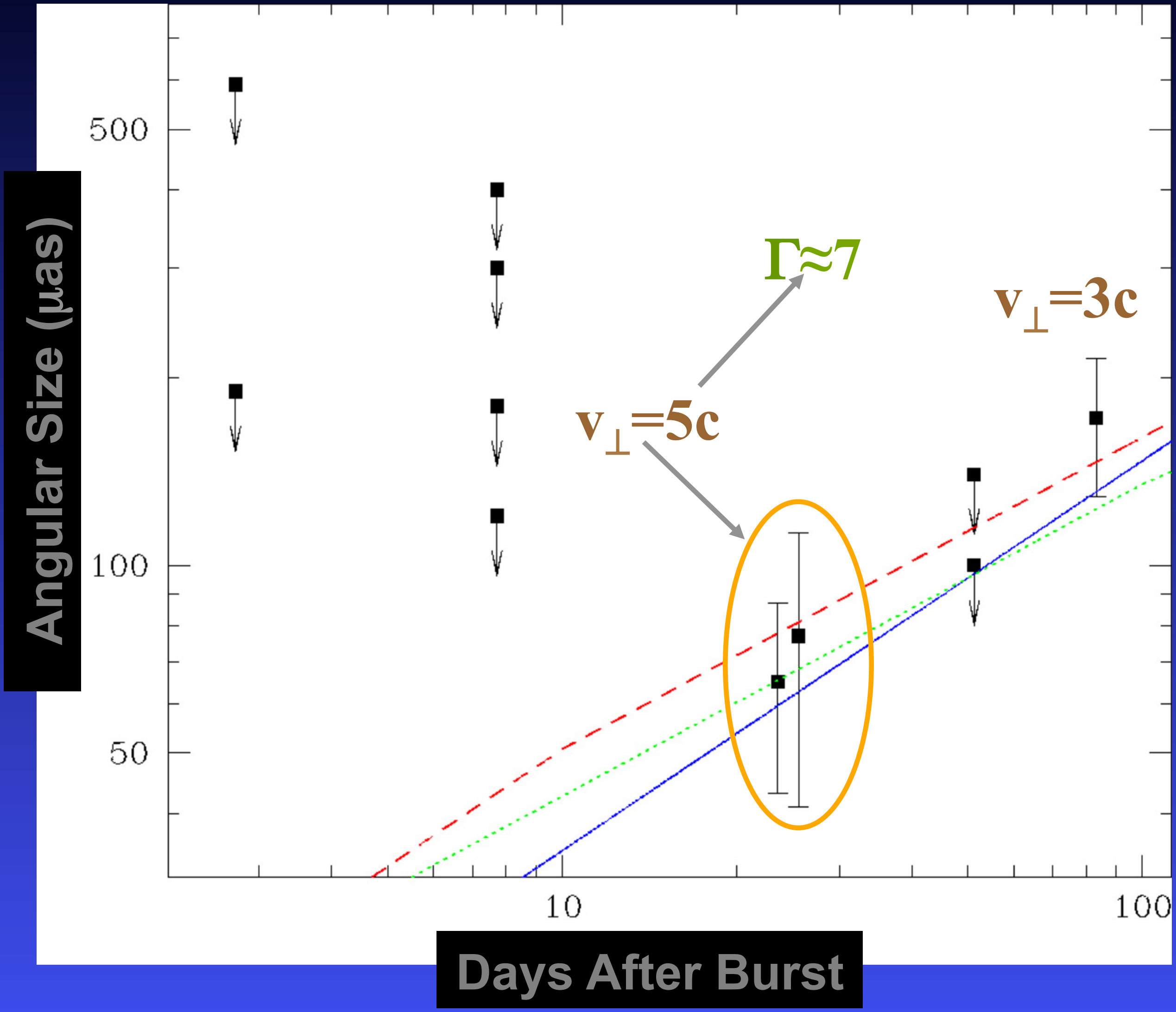
GRB 030329: z=0.17
(afterglow-subtracted)

SN 1998bw:
local, energetic, core-collapse 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)



$\Gamma \approx 7$

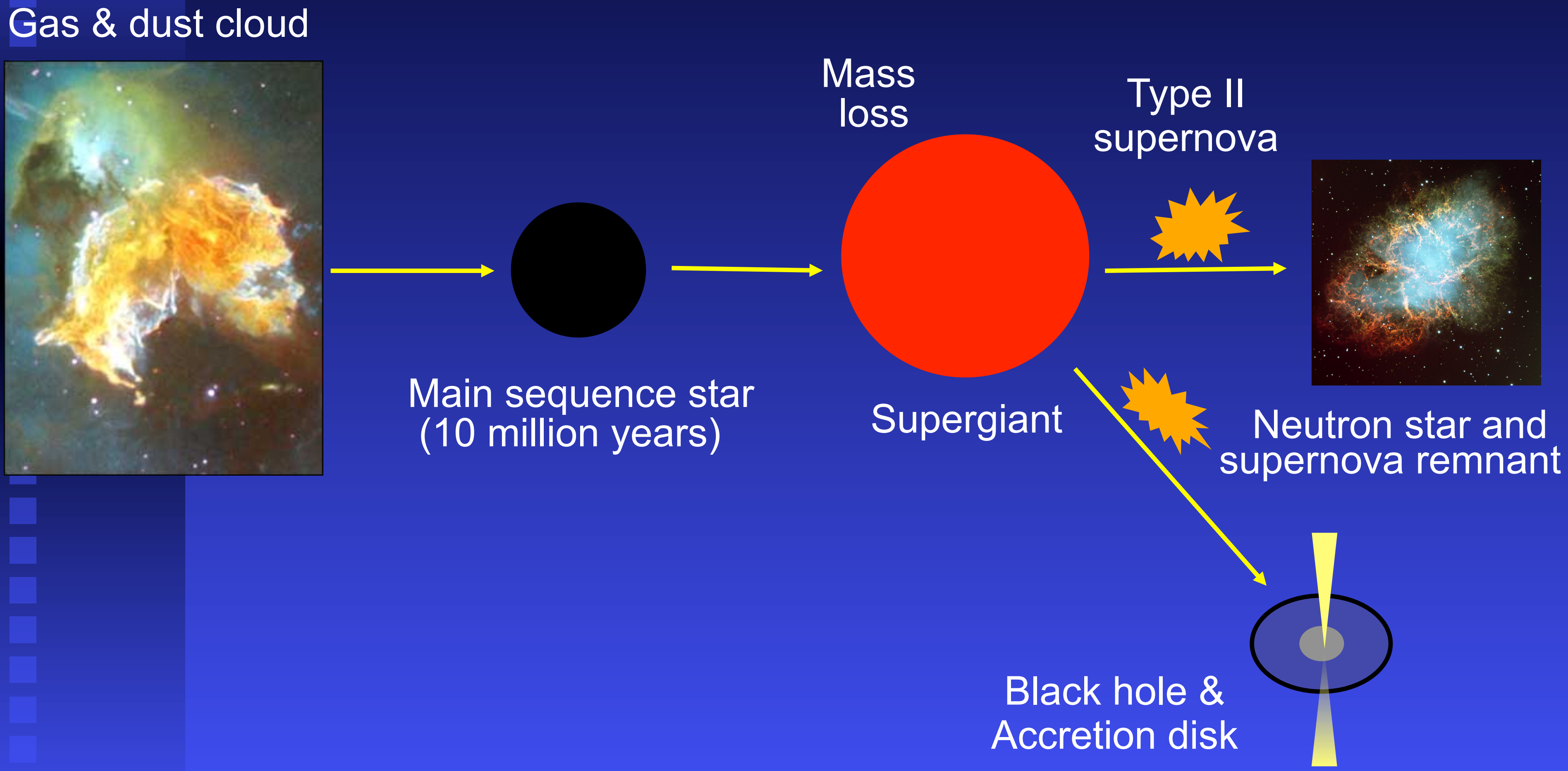
$v_\perp = 5c$

$v_\perp = 3c$

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

$\theta \approx 5^0$

Life & Death of a Massive Star



Gas & dust cloud

Main sequence star
(10 million years)

Mass
loss

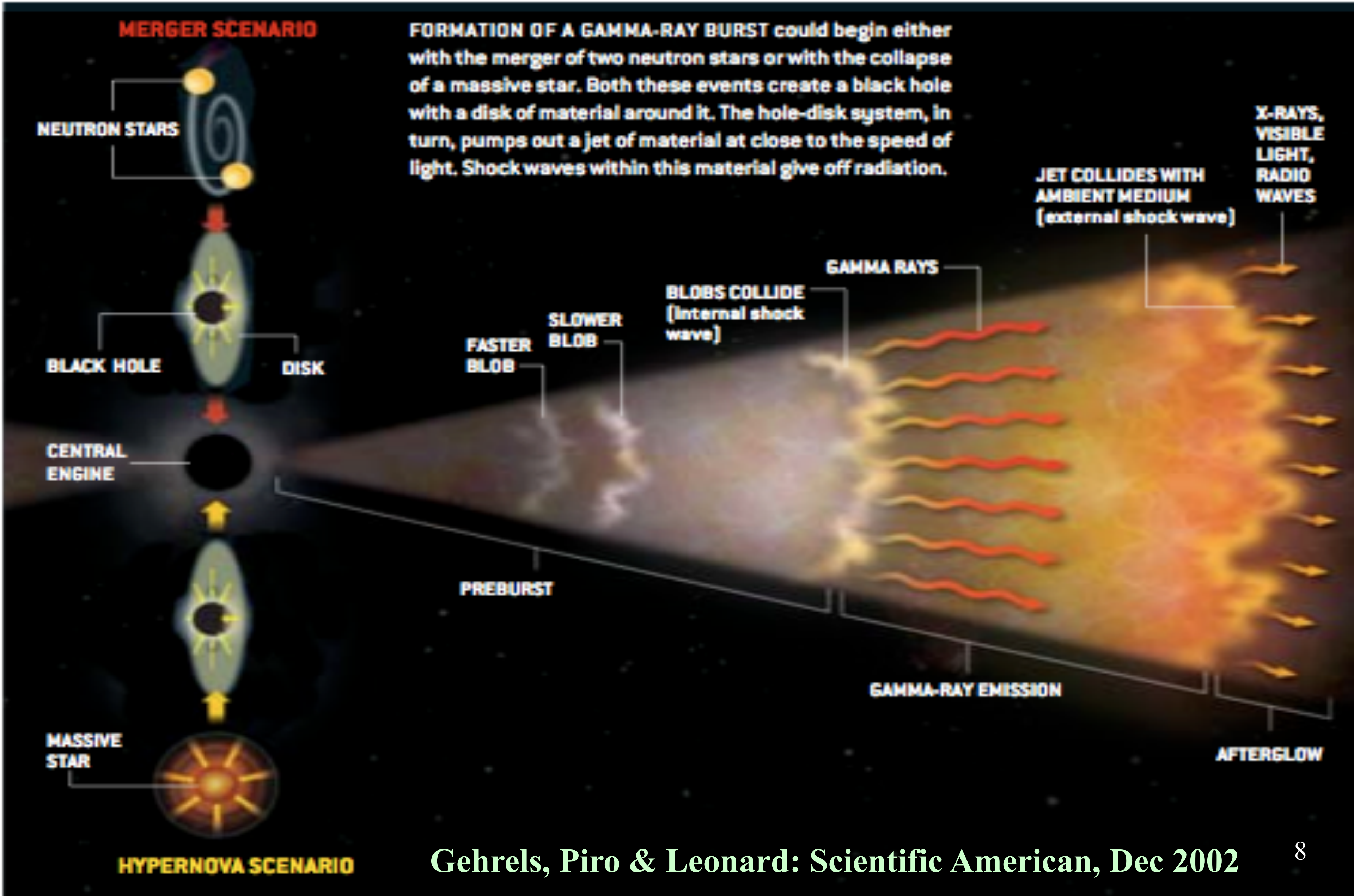
Supergiant

Type II
supernova

Neutron star and
supernova remnant

Black hole &
Accretion disk

Interaction of the jet with the surrounding medium – GRB afterglow

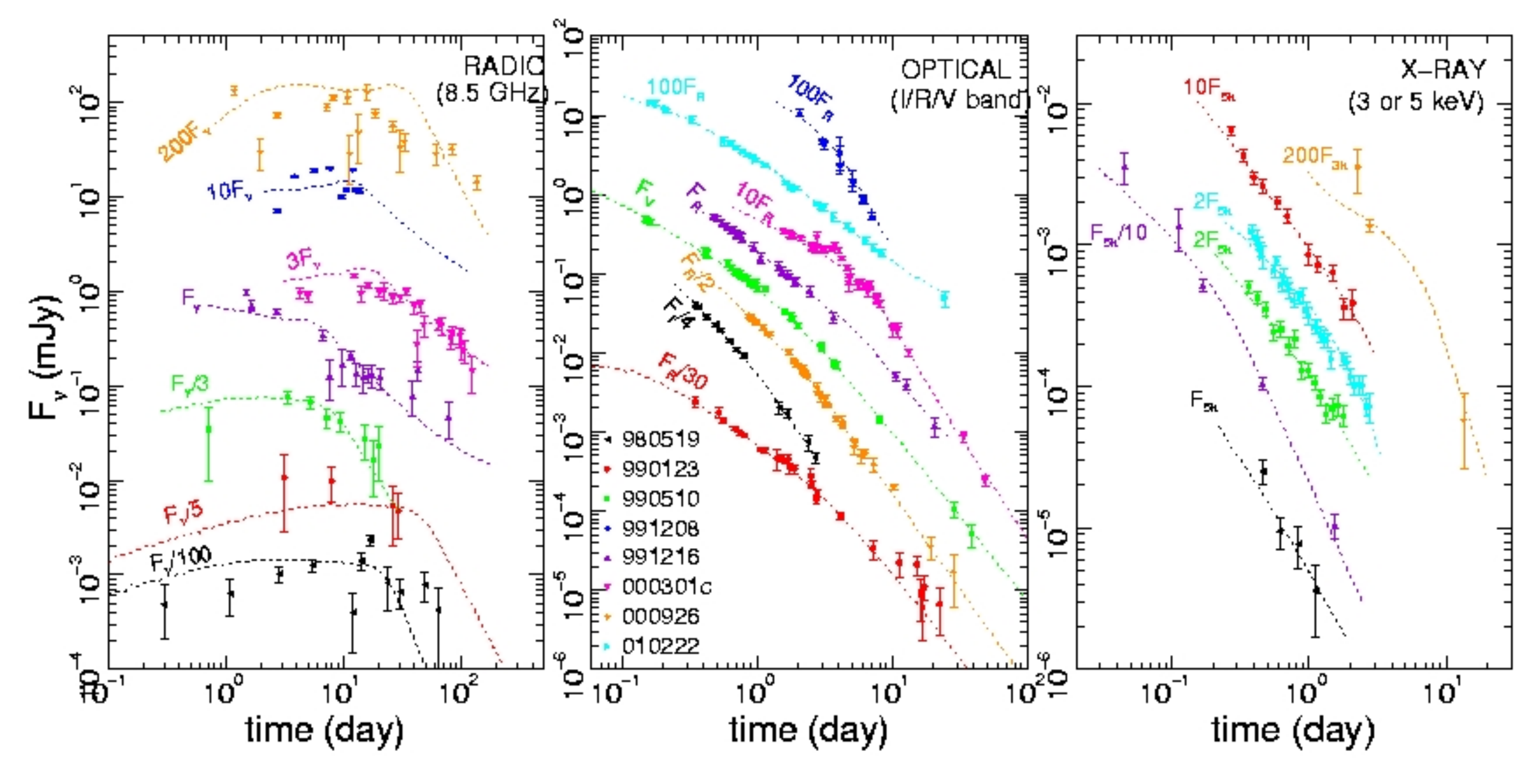


FORMATION OF A GAMMA-RAY BURST could begin either with the merger of two neutron stars or with the collapse of a massive star. Both these events create a black hole with a disk of material around it. The hole-disk system, in turn, pumps out a jet of material at close to the speed of light. Shock waves within this material give off radiation.

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.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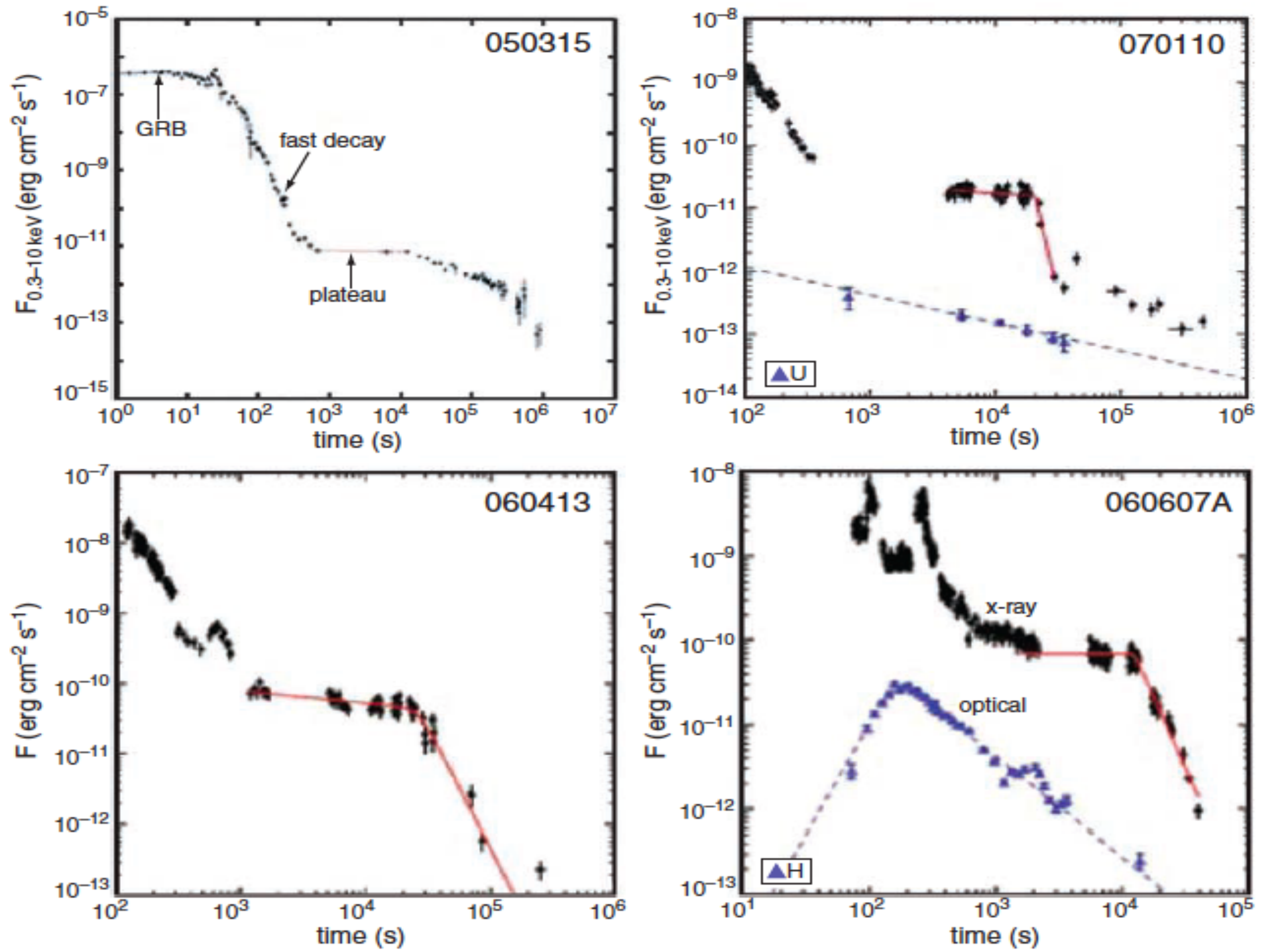
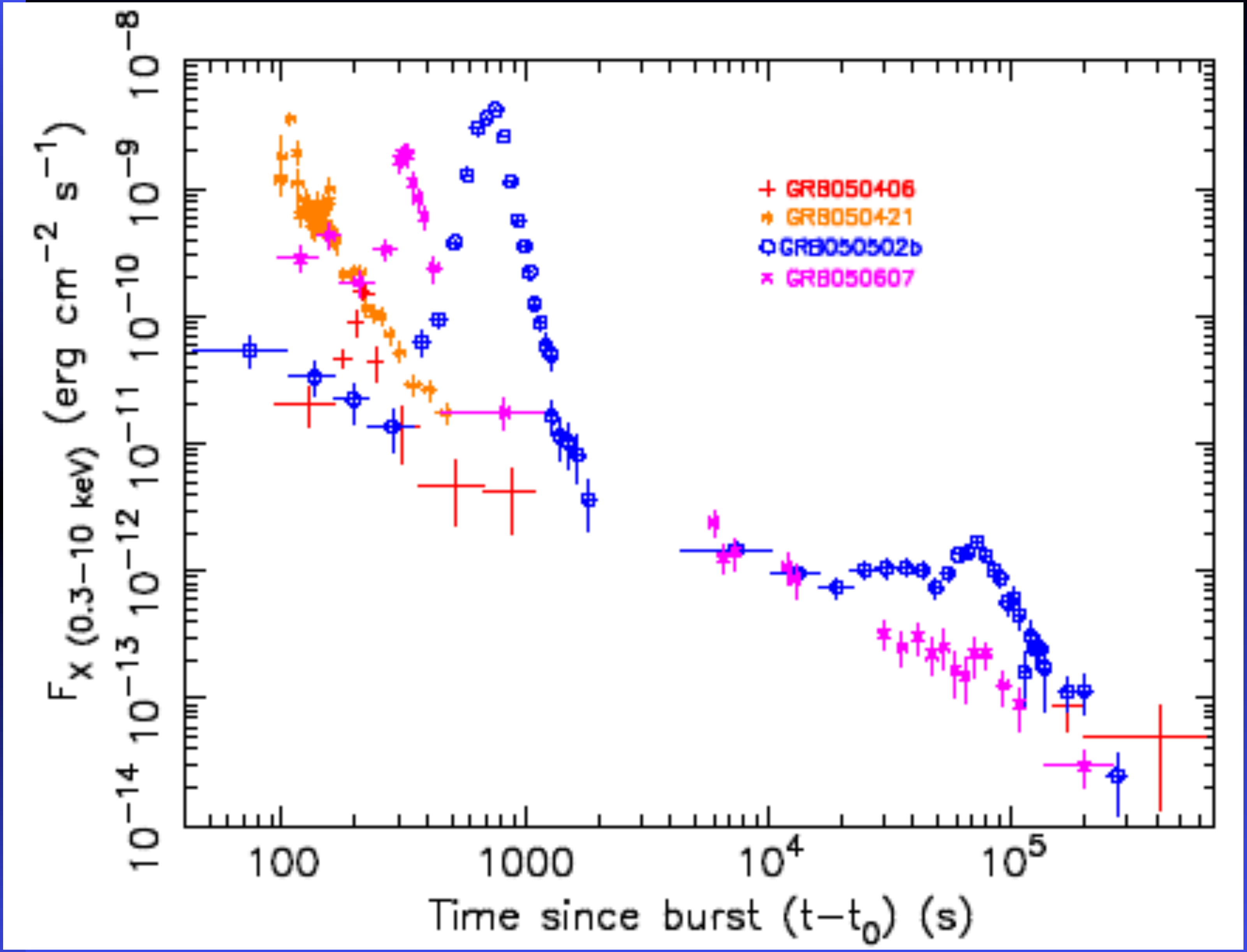
Plateau in the X-ray AG lightcurves, but no plateau in optical

Liang et al. 2007



0.3-10 kev LCs of some Swift bursts with flares

Nousek et al. 2005

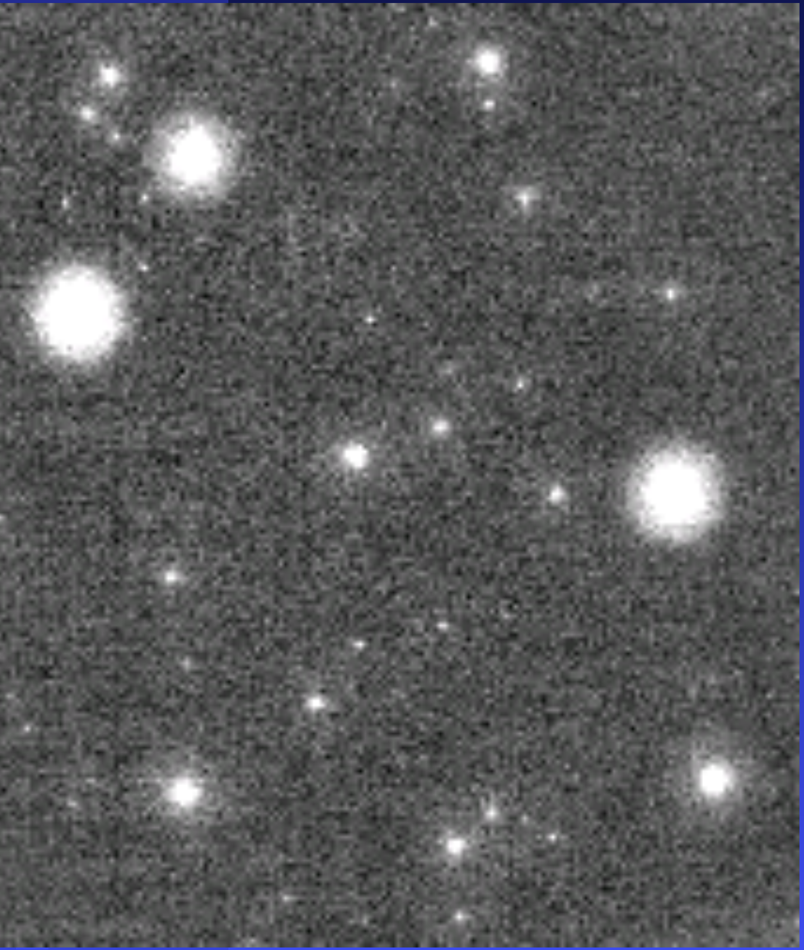


Because of smearing due to curvature dt/t ~ 1 in FS. Many of the flares have dt/t << 1 which suggests late time engine activity.

Two 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



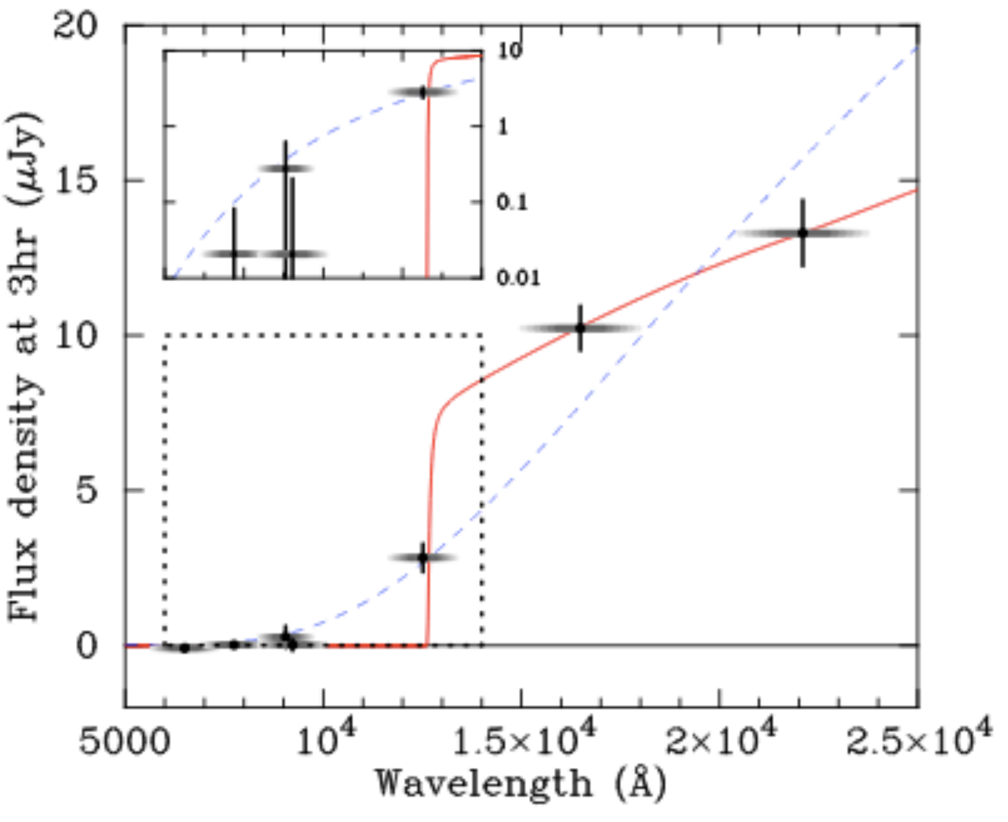
movie made by Pi of the Sky, a Polish group that monitors transient events

GRB 090429B: z=9.4, E_{iso}=3.5x10^{52}erg

T = 5.5s, fluence=3.1x10^{-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~15

How far away can we see Bursts?

Burst	z	t_γ(s)	flux (erg cm^{-2} s^{-1})	E_{iso}(erg)
050904	6.3	225	3×10^{-8}	$\sim10^{54}$
080913	6.7	8	7×10^{-8}	$\sim10^{53}$
090423	8.2	10.2	6×10^{-8}	1.2×10^{53}
090429B	9.4	5.5	5×10^{-8}	3.5×10^{52}

Swift/BAT sensitivity is 1.2×10^{-8}erg cm^{-2}s^{-1}

So Swift can detect bursts like these to z ~ 15, when the universe was 270 million years old.

- **SVOM**: a Chinese-French mission (2017?) – more sensitive than Swift for GRBs with $E_{peak} < 20$ keV (4--250 keV band); 2 IR telescopes (0.4 to 0.95 µm – located in Mexico & China) to look for z~8 bursts.

- **JANUS**: funded for phase A study, but not selected for launch; x-ray (1-20 keV) and IR telescope (0.7—1.7 µm) can determine GRB redsfit to z=12.

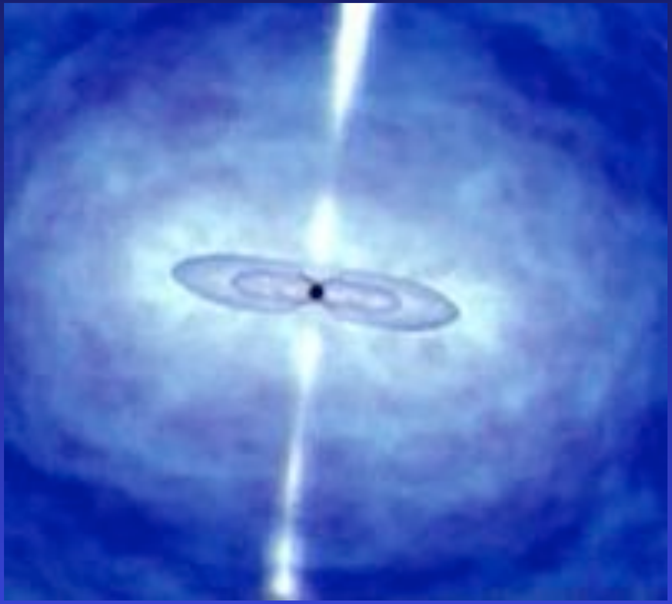
- Our understanding of GRBs has improved dramatically in last ~15 years.

- However, there are a number of fundamental questions that remain unanswered. The foremost amongst these are:

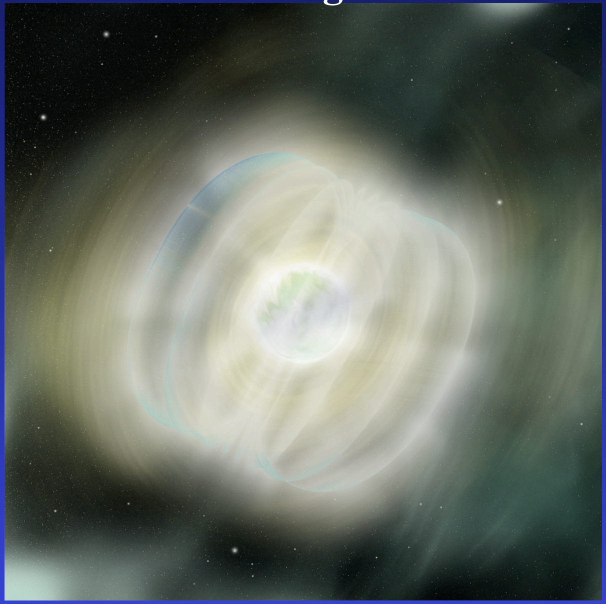
1. Whether a BH or a NS is produced in these explosions?

Woosley, 1993
Paczynski, 1998

blackhole



magnetar



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

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.

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

Two other basic unanswered questions about GRBs

2. Only a small fraction of core-collapse SNe result in GRBs (~1%)

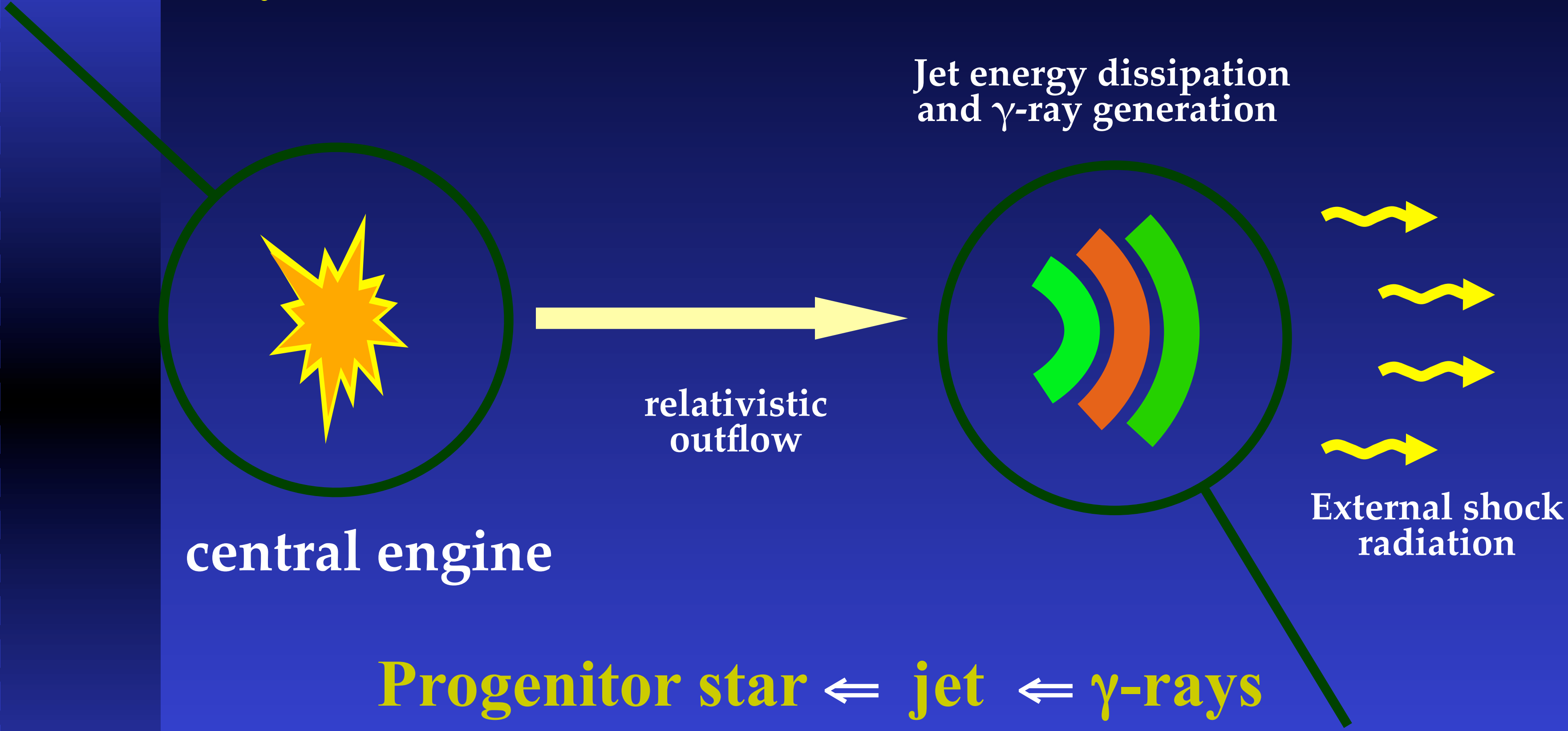
GRB rate is ~3% of SNe Ib/c, and ~10% of broad-line Ic SNe

So GRB explosion is a rare channel – however, we have little information regarding GRB progenitor star's special properties from observations.

3. We don't know whether relativistic jets in Blazars, micro-quasars, TDEs, and GRBs are magnetic outflows, baryonic, or $e^{\pm}$.

Recent work of Patrick Crumley et al. (2016) answers this question for a highly luminous TDE – which might apply to other relativistic jets as well.

Size of the star is ~10^{11}cm. However, the γ-rays are produced at a distance of ~10^{14}—10^{16} cm , i.e. far away from the star.



Jet energy dissipation
and γ-ray generation

central engine

relativistic
outflow

External shock
radiation

Progenitor star ⇐ jet ⇐ γ-rays

We have to rely on indirect means to understand progenitor star properties

Fermi

8 KeV to 300 GeV

6/11/2008

How are γ-rays generated?

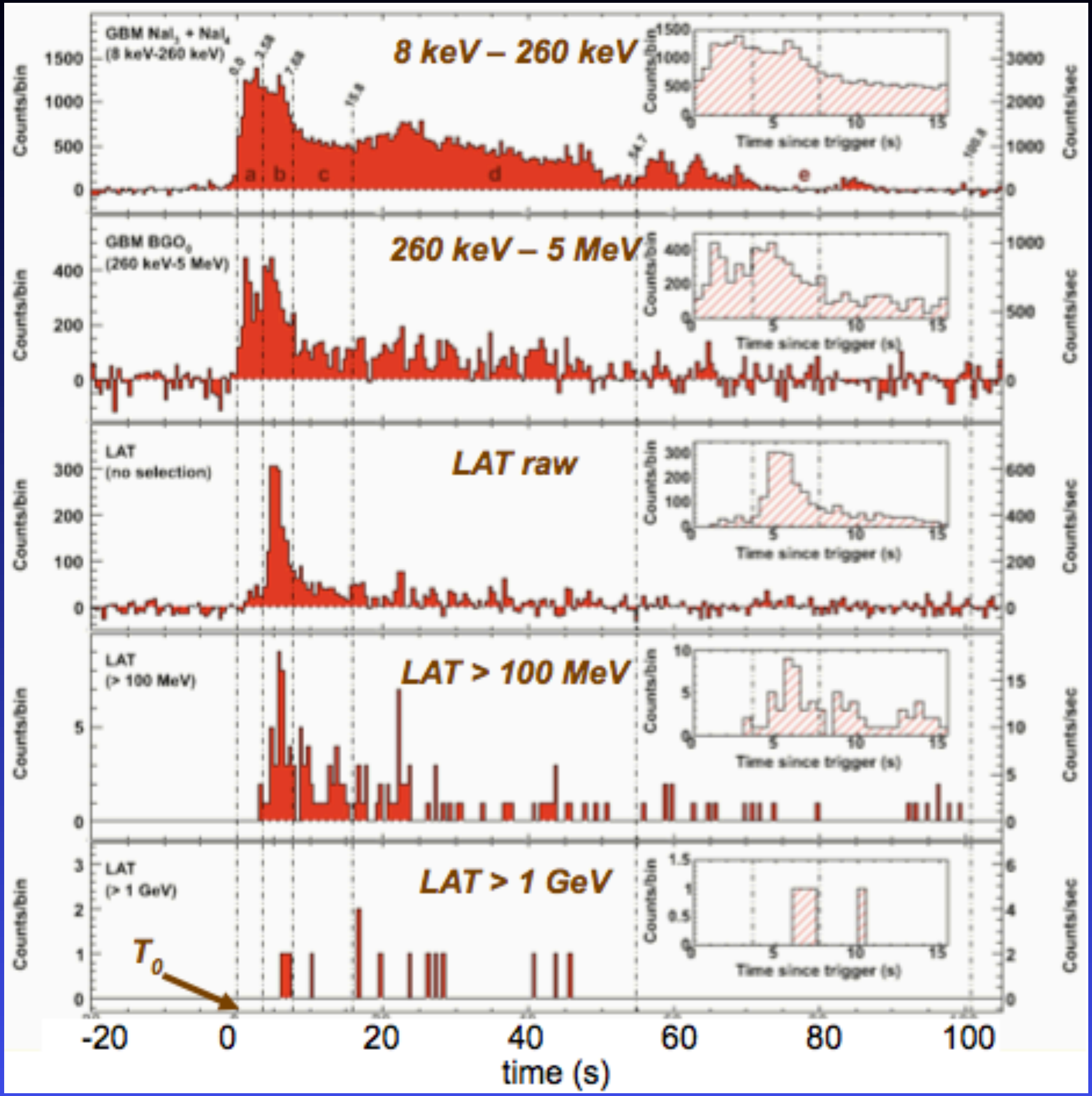
One of the goals for Fermi is to understand γ-ray burst prompt radiation mechanism by observing high energy photons from GRBs.

However, there were surprises in store for us:

Fermi discovered that →

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

Abdo et al. 2009

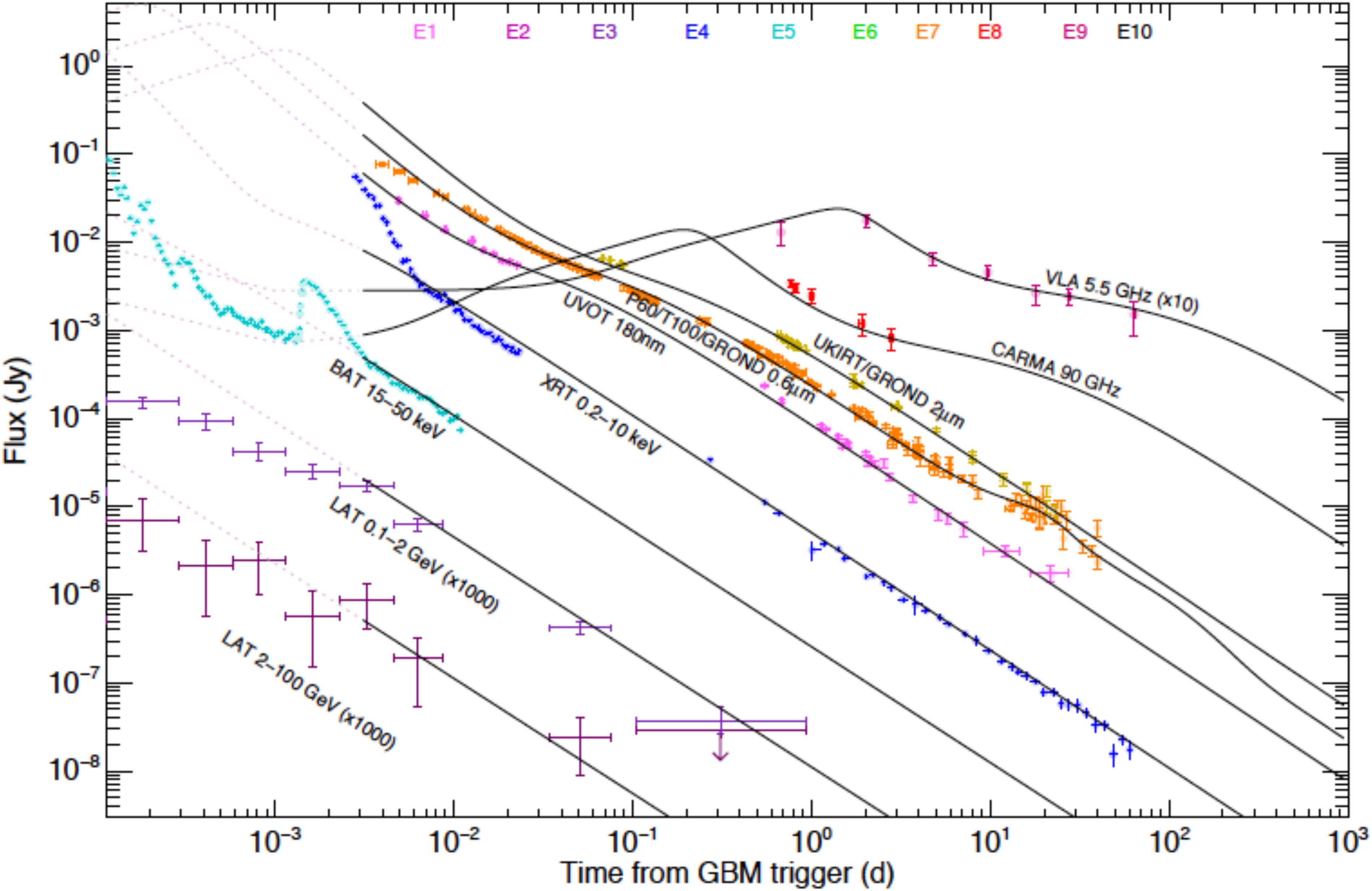


2. >100 MeV radiation lasts for ~10^3s whereas emission below 10 MeV lasts for ~30s or less!

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

MeV duration (T_{90}) = 138s, LAT duration (T_{GeV}) > 4.3×10^3s; $T_{GeV}/T_{90} > 31$

Highest energy photon (95 GeV) detected 242s after T_0; z=0.34; $E_{\gamma,iso} = 7.8 \times 10^{53}$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.

Observers need to quantify the statistical significance of this!

- **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.

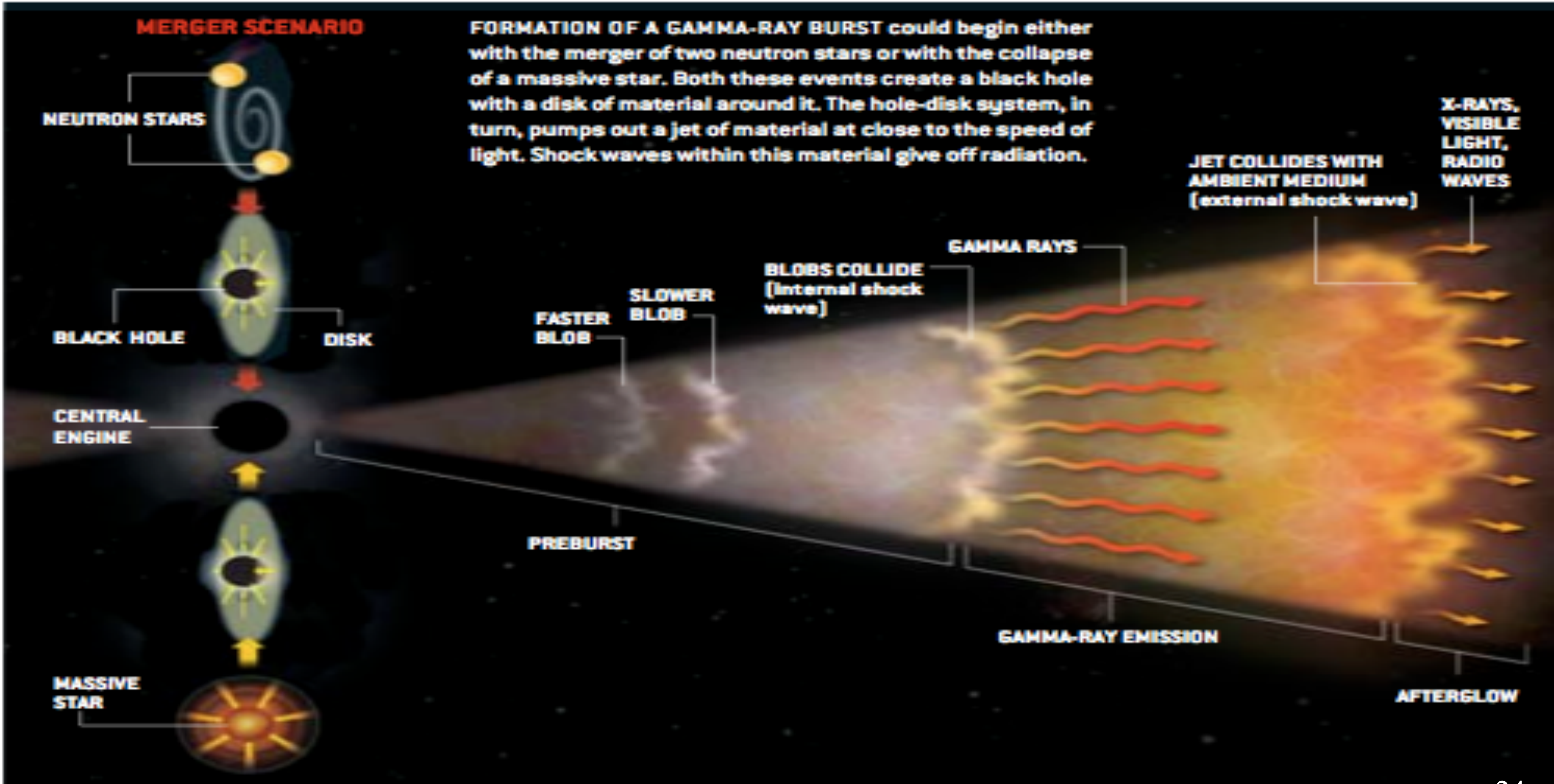
- **Internal shock and SSC**: e.g. Bosnjak et al. 2009, Daigne et al. 2011

Afterglow: external shock synchrotron, IC in forward or reverse shock of prompt radiation or afterglow photons; IC of CMB photons by $e^{\pm}$ in IGM; pair enrichment of external medium and IC…

Dermer et al., 2000; Zhang and Meszaros, 2001; Wang et al. 2001; Granot and Guetta, 2003; Gupta and Zhang, 2007b; Fan and Piran, 2008; Zou et al., 2009; Meszaros and Rees 1994; Beloborodov 2005; Fan et al., 200; Dai and Lu 2002; Dai et al. 2002; Wang et al. 2004; Murase et al. 2009; Beloborodov 2013….

Kumar & Barniol Duran (2009) and Ghisellini, Ghirlanda & Nava (2010) showed that high energy γ-ray radiation from GRBs, after the prompt phase, are produced in the external-forward shock via the synchrotron process. The reasoning for this will be described in the next several slides.

Gehrels, Piro & Leonard: Scientific American, Dec 2002



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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:

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

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

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

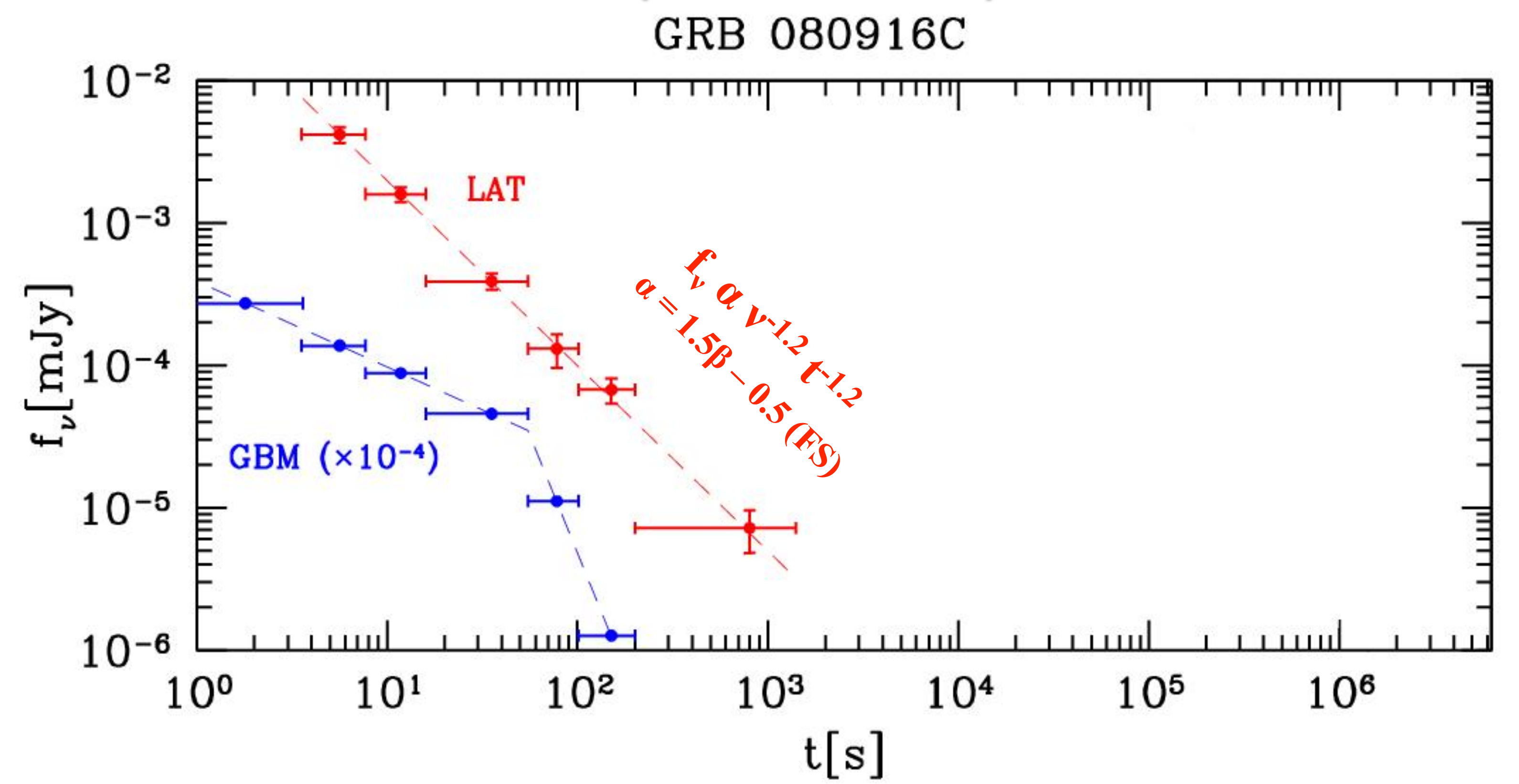
Table of expected and observed 100 MeV flux

	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 = $3E_\gamma$, $\varepsilon_e=0.2$, $p=2.4$, $\varepsilon_B=10^{-5}$

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

(GRB 080916C)



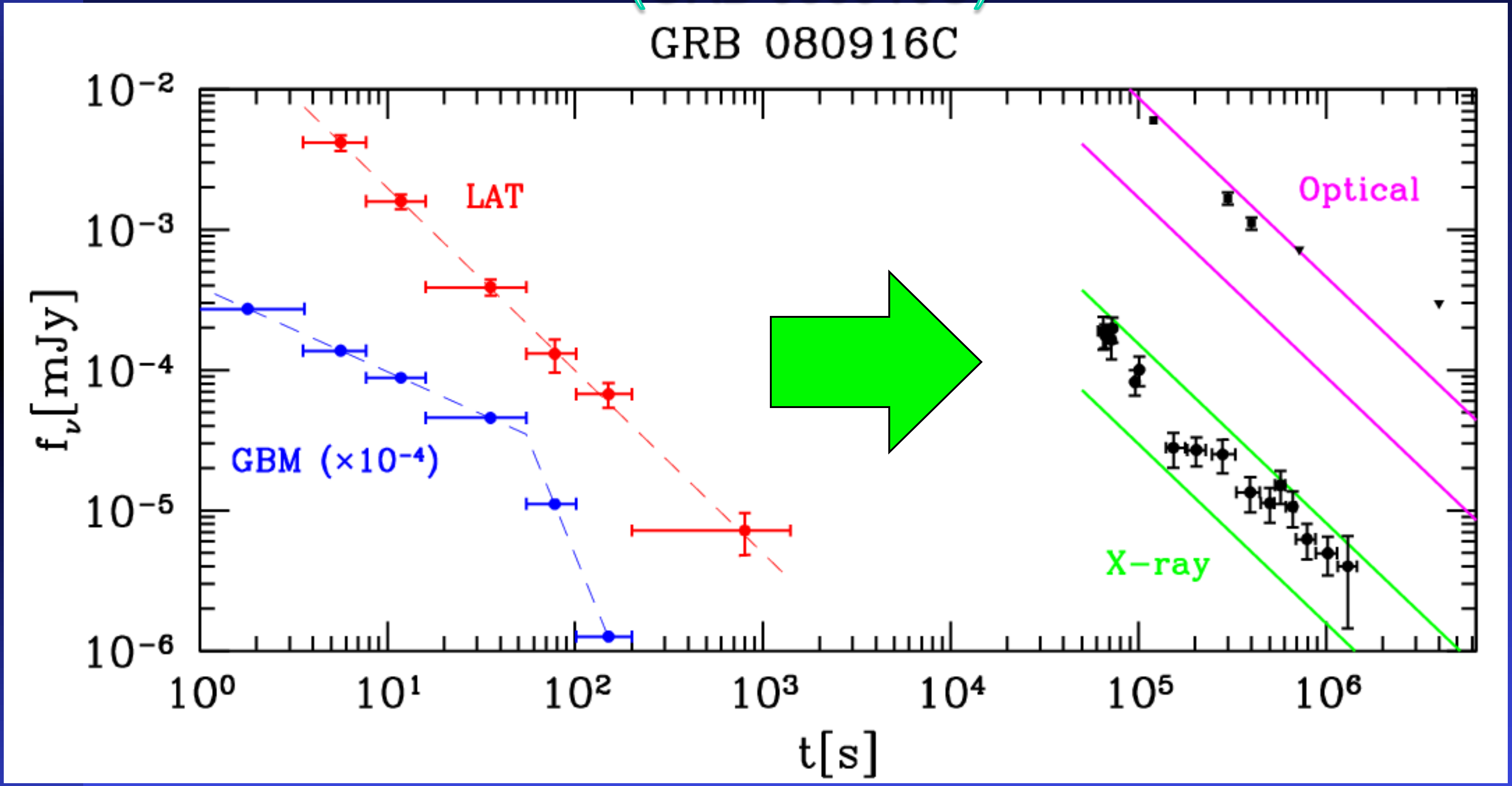
$f_\nu \,\alpha\, \nu^{-1.2} t^{-1.2}$

$\alpha = 1.5\beta - 0.5$ (FS)

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)



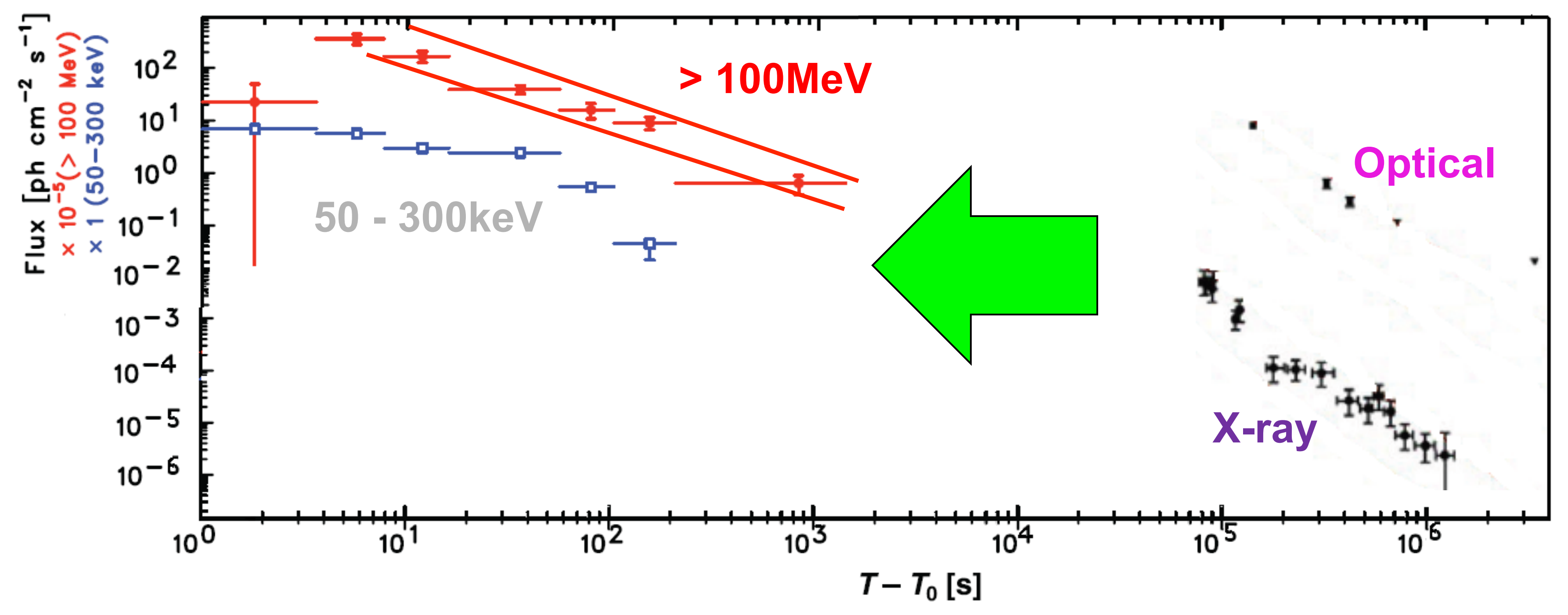
Kumar & Barniol Duran (2009)

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



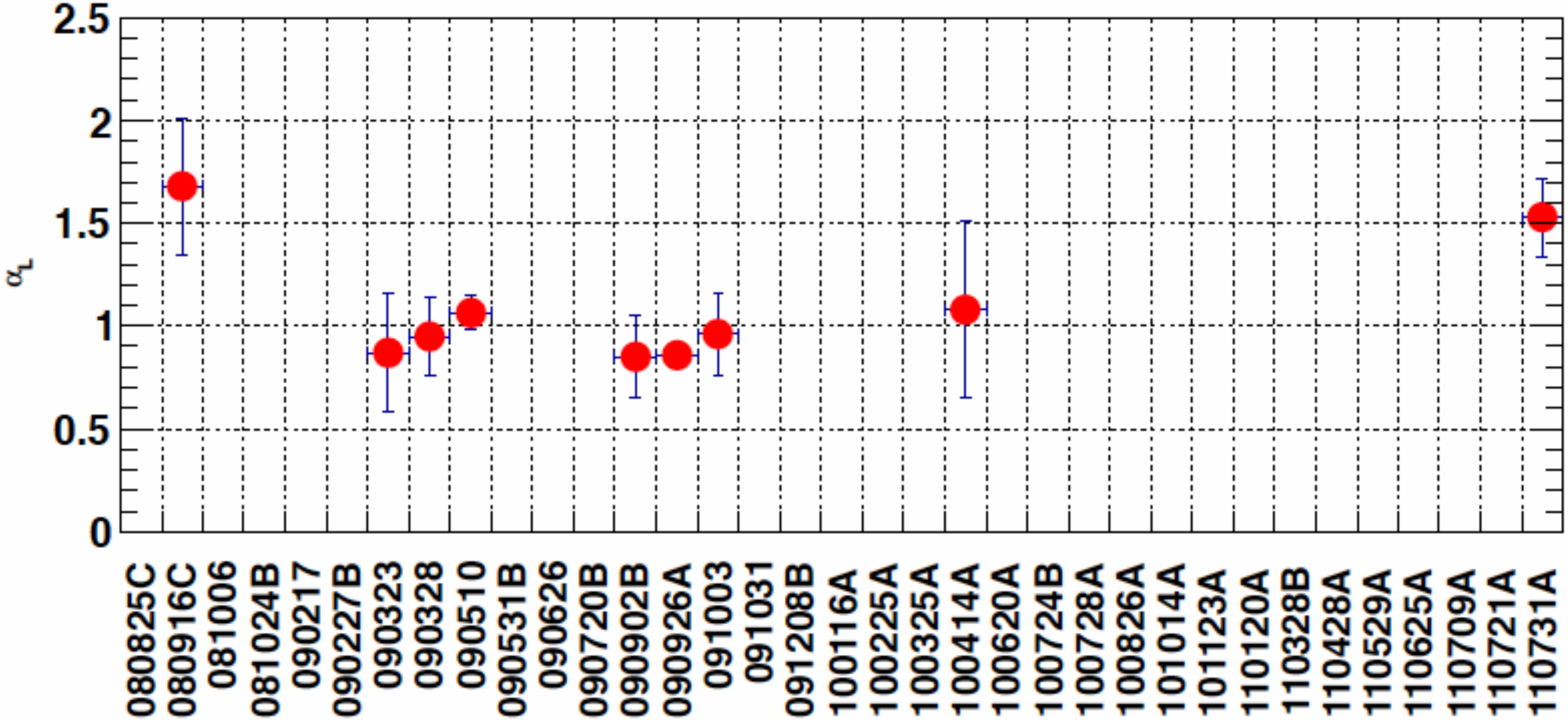
Kumar & Barniol Duran (2009)

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

And that compares well with the available Fermi data.

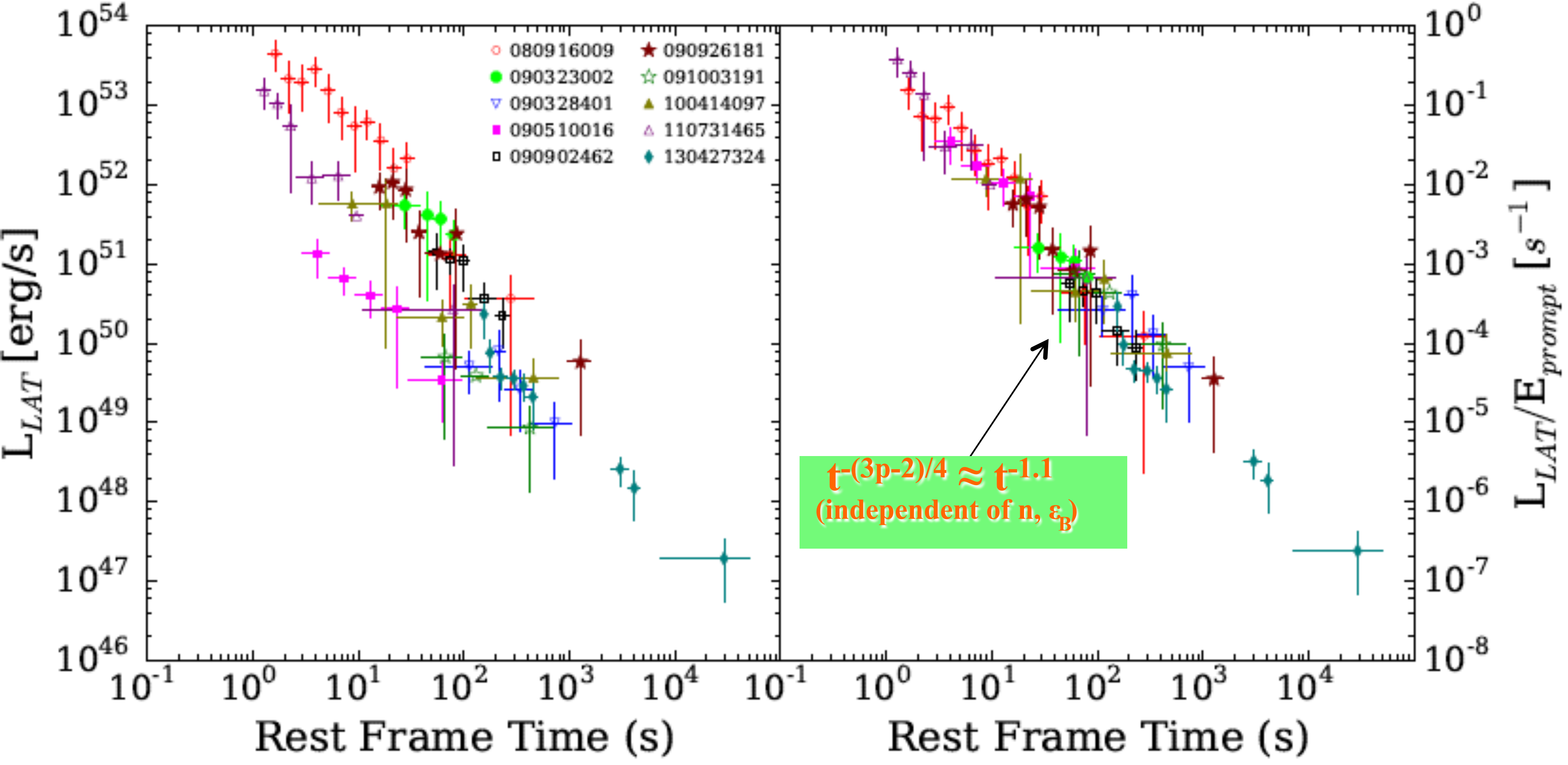
The expected decline of the >100 MeV lightcurve according to the external shock model is $t^{-(3p-2)/4}$. For p=2.2 the expected decline is $t^{-1.1}$ which is in agreement with Fermi/LAT observations.

Temporal decay index in Fermi/LAT band; Ackermann et al. 2013



According to the external shock model the LAT flux should be proportional to $E^{(p+2)/4}\,\varepsilon_e^{p-1}$ or $\sim(E\varepsilon_e)$

(E is proportional to $E_{\gamma,iso}$ and PIC simulations suggest $\varepsilon_e \sim 0.1\text{-}0.2$)



$t^{-(3p-2)/4} \approx t^{-1.1}$

(independent of n, ε_B)

Nava et al. 2014 (MNRAS 443, 3578)

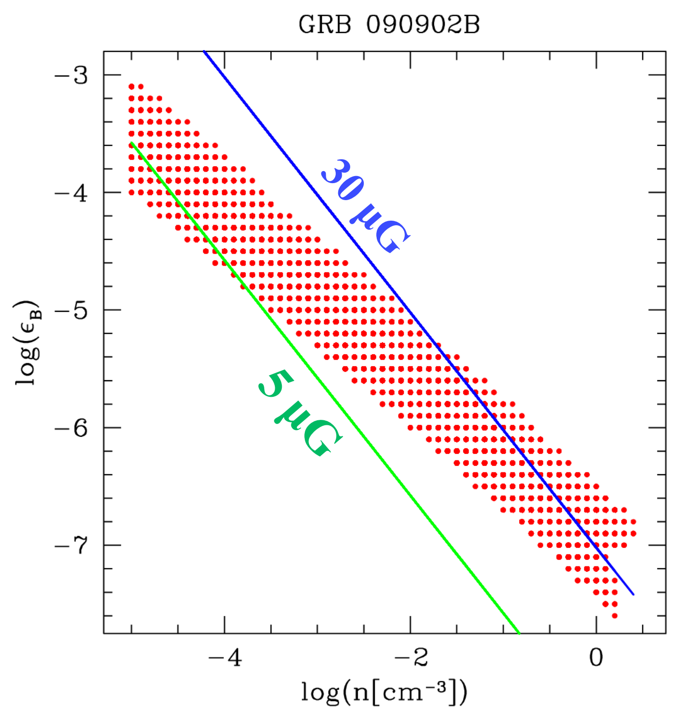
How are Magnetic fields Generated in Shocks?

(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 or at best a modest amplification by factor ~10-10^2 (Kumar & Barniol Duran 2009)

Using only >100MeV *Fermi* data

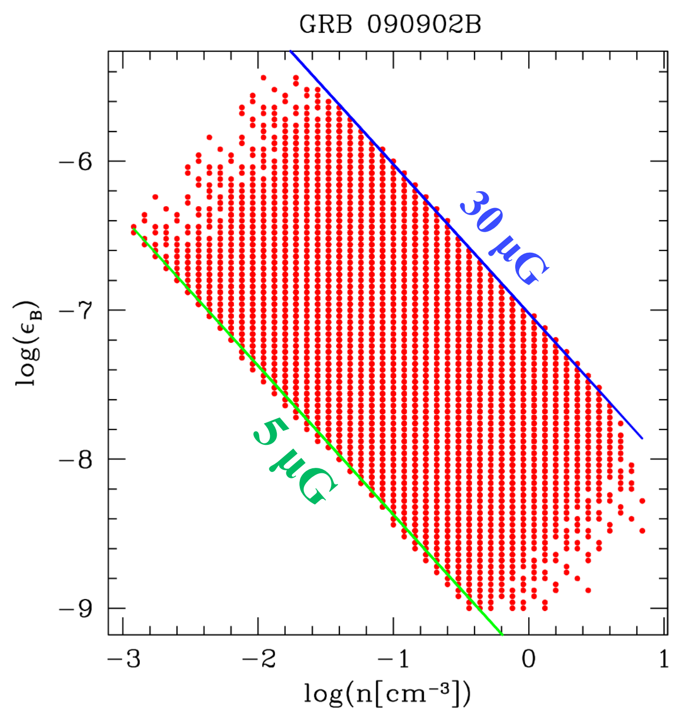
Parameter search at t = 50 sec



GRB 090902B

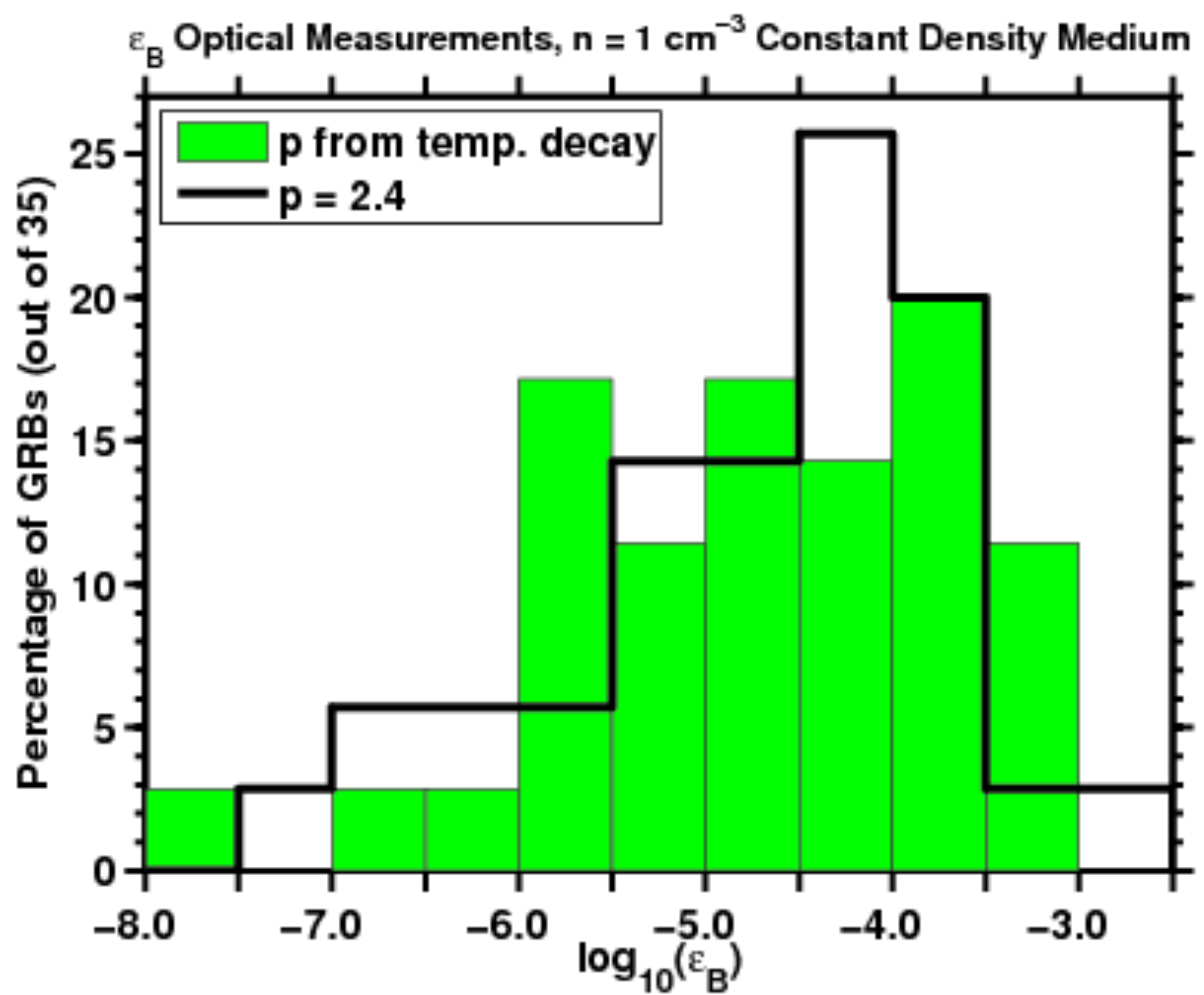
Using late time x-ray, optical & radio data

Parameter search at t = 0.5 day



GRB 090902B

Santana et al. 2014

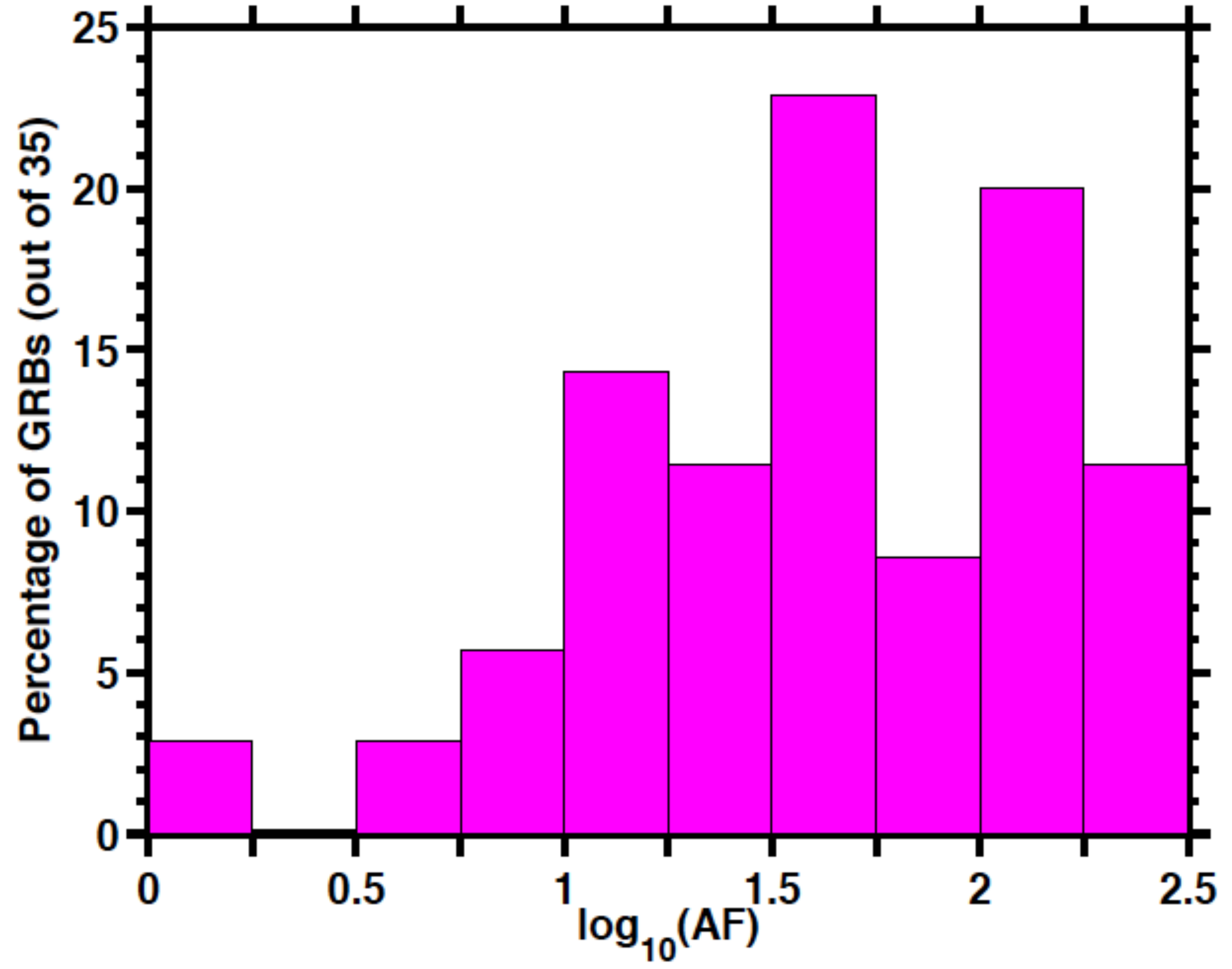


This result suggests a weak magnetic dynamo in relativistic shocks

Beniamini, Nava, Barniol Duran & Piran (2015, 16) also find small value for ϵ_B based on the analysis of GeV & X-ray data for 10 GRBs. Larger energy in blast wave (>10^{52} erg) and efficiency for MeV ~ 15%.

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

$$AF \ \alpha \ n^{0.2}/B_{ism}$$

Acceleration of Electrons

(Barniol Duran & Kumar, 2010)

- Electron Lorentz factor for 10 GeV synchrotron photon:

$$\nu = \frac{q\,\gamma_e^2\,\Gamma B}{2\pi\, m_e c} \leftarrow \boxed{4\Gamma B_{ism}} \qquad \rightarrow \qquad \Gamma\,\gamma_e = 1.5\mathrm{x}10^{11}\, B_{ism,-5}^{1/2}$$

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

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

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

- Radiative energy loss a problem?

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

$$\rightarrow \qquad h\nu_{max} < 50\ \mathrm{GeV}\ \ \Gamma_3$$

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

What about 10 GeV – 95 GeV photons detected from GRB 130427A (160509A)?

Could these be produced by the synchrotron process?

- ★ Highest energy photon (95 GeV) was detected 242s after the trigger ($z=0.34$, $E_{\gamma,iso} = 7.8\times10^{53}$erg) when $\Gamma \sim 10^2$.

- ★ Highest possible energy for synchrotron photons is when electrons lose half their energy in one Larmor time

  (Because electrons gain energy by a factor ~2 in shock acceleration in ~ a few Larmor time)

- ★ Larmor time $= \dfrac{m_e \gamma_e c}{qB}$ Synchrotron loss rate $= \dfrac{\sigma_T B^2 \gamma_e^2 c}{6\pi}$

$$\text{Larmor time x } \boxed{\begin{matrix}\textbf{Synchrotro}\\ \textbf{loss rate}\end{matrix}} < m_e \gamma_e c^2$$

$$\Rightarrow \nu_{max} = \frac{q\,\gamma_e^2\,\Gamma B}{2\pi\, m_e c} < \frac{9 m_e c^3\,\Gamma}{16\pi\, q^2} = 50\,\Gamma\text{ MeV} \lesssim 10\text{GeV}$$

>10GeV photons might be due to IC in external shock, however, perhaps the above limit could be violated by inhomogeneous B.

Generation of ~ 10 GeV to 95 GeV photons detected from GRB 130427A & GRB 160509A (29 & 52 GeV at t_0 + 77s) is unclear; it might be due to SSC process in the external shock.

And a bigger unsolved problem is the uncertain mechanism for the generation of ~MeV photons during the prompt GRB phase.

Polarization measurements (prompt phase)

	polarization	
RHESII (GRB 021206)	80 ± 20%	[disputed]
INTEGRAL (041219A)	63 ± 30%	[2.8 σ; Mcglynn et al. 2007]
IKROS-GAP (100826A)	27 ± 11%	[2.8 σ; Yonetoku et al. 2011]

[110301A (70 ± 22%) , 110721A (84 ± 28%)]

Polarization during afterglow phase (optical)

Very nice work has been done by Mundell et al. (RINGO-team). They have firm measurements of optical polarization in early afterglow of several GRBs:

- **090102** – at ~ 160s (RS) – **$\Pi = 10 \pm 1\%$** (Mundell et al. 2009)
- **091208B** – 150-700s (FS) – **$\Pi = 10.4 \pm 2.5\%$** (Uehara et al. 2009)
- **120308A** – 150-700s (RS→FS) – **Π ↓ with time** (Mundell et al. 2012)
- **121024A** – 0.15 day – **4% linear & 0.6% circular!** (Wiersema et al. 2014

India's first Multiwavelength Space Observatory

ASTROSAT

The 5 telescopes of the Astrosat

1. Large Area X-ray Proportional Counter (LAXPC)
2. Soft X-ray Telecope (SXT)
3. Cadmium-Zinc-Telluride Imager (CZTI)
4. Scanning Sky Monitor (SSM)
5. Ultra Violet Imaging Telescope (UVIT)

AstroSat might be able to answer the long unsolved question of prompt MeV radiation mechanism (via polarization measurement).

Sept 27, 2015

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 & Astrosat will continue to provide excellent data.
- ☆ SVOM – a French-Chinese mission (2021?) 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 should detect short-GRBs
- ☆ ALMA (Atacama Large Millimeter Array) – 90-950 GHz with ~10^2 times the sensitivity of VLA – will be powerful tool for afterglow observations.
- ☆ CTA, MAGIC, HESS & VERITAS (air Cerenkov telescopes) would be looking for TeV and higher energy photons.
- ☆ JANUS – proposed small explorer – will have 1-20 keV & near-IR telescopes spot high-Z GRBs.