Gamma-Ray Bursts: Review of the Current Status of the Field and Prospects for the Future

Jonathan Granot

Hebrew Univ., Tel Aviv Univ., Univ. of Hertfordshire

(Royal Society Wolfson Research Merit Award Holder)

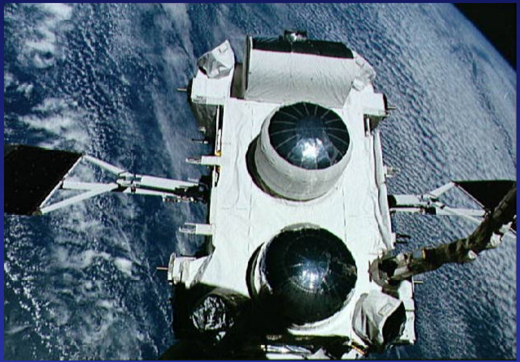
Invited talk at the International Conference on Astrophysics & Cosmology (ICAC2012), Kathmandu, Nepal, March 20, 2012

Outline of the Talk:

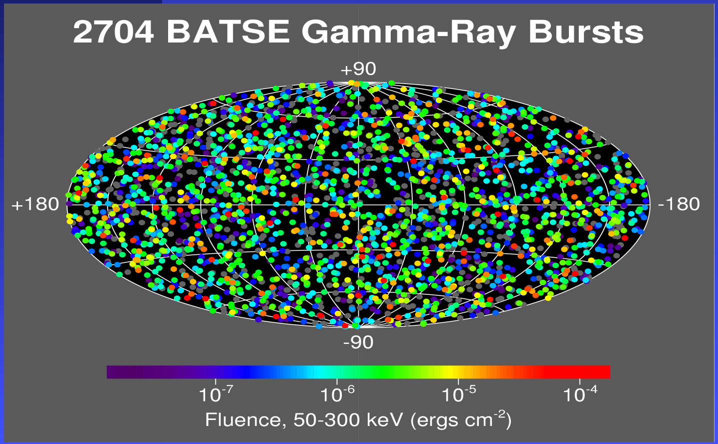
- **GRB** historical overview: observationally driven field
- Observational constraints ⇒ theoretical framework
- **Swift** Era, critical review of afterglow
- **Fermi** results, review of prompt **emission**, **dissipation**
- **Progenitors** of long and short GRBs
- The **Central Engine**: accreting BH vs. ms-magnetar
- **Outflow** acceleration and composition
- **Future prospects: theory, observations, instruments**
- **Conclusions**

GRBs: Brief Historical Overview

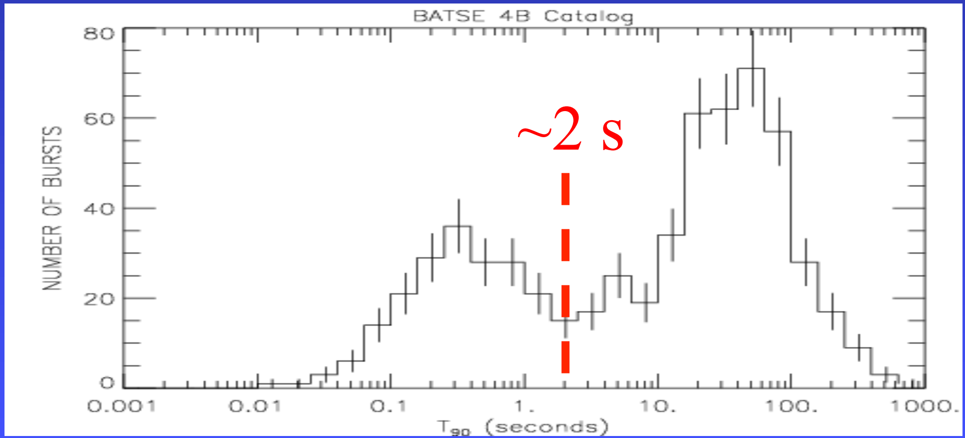
- 1967: 1st detection of a GRB (published in 1973)
- In the early years there were many theories, most of which invoked a Galactic (neutron star) origin
- 1991-99: the launch of CGRO with BATSE lead to significant progress in our understanding of GRBs



Isotropic dist. in the sky: favors cosmological origin

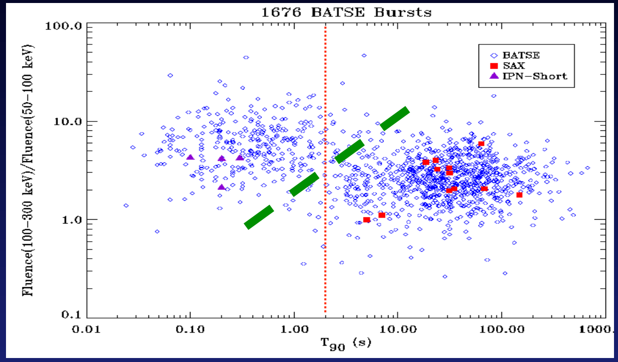


Bimodal duration distribution: **short** vs. **long** GRBs

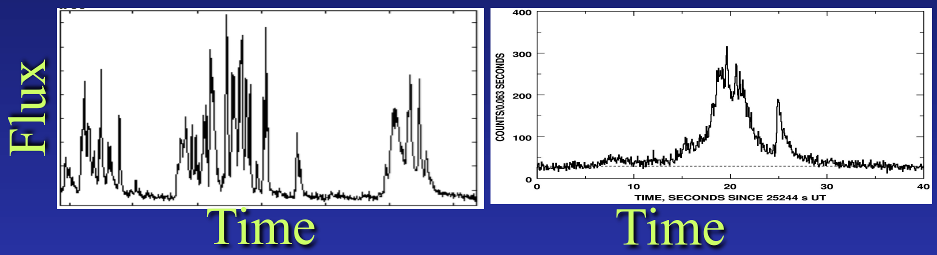


Prompt GRB Observations ($\lesssim$MeV)

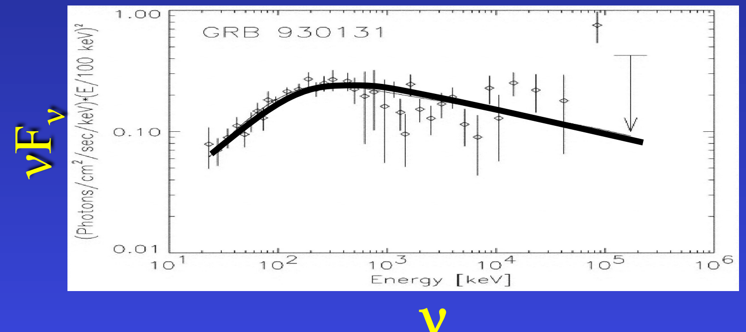
- Bimodality: short/hard bursts (SHB) & long/soft bursts (LSB)



- Variable light curve



- Spectrum: non-thermal
  νF_ν peaks at ~ 0.1-1 MeV
  (well fit by a Band function)



- Rapid variability, non thermal spectrum & z ~ 1
  ⇒ relativistic source ($\Gamma \gtrsim 100$) (compactness problem: Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;…)

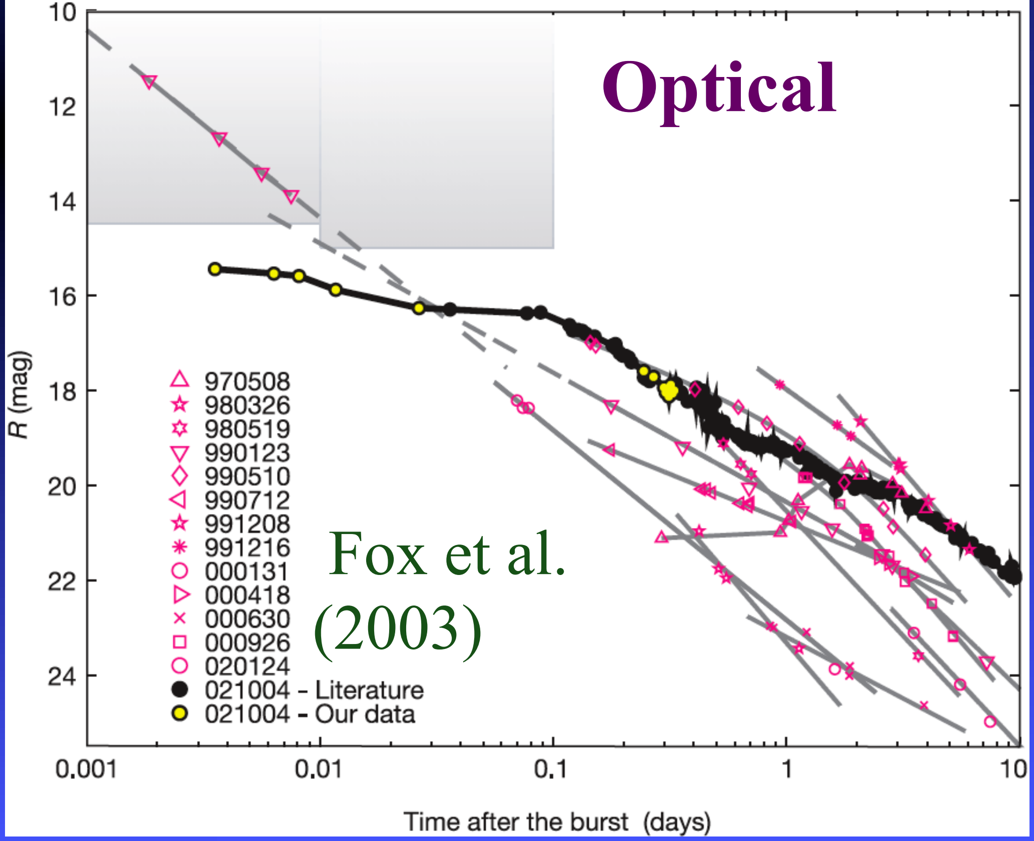
BeppoSAX (1996-2002): Discovery of Afterglow

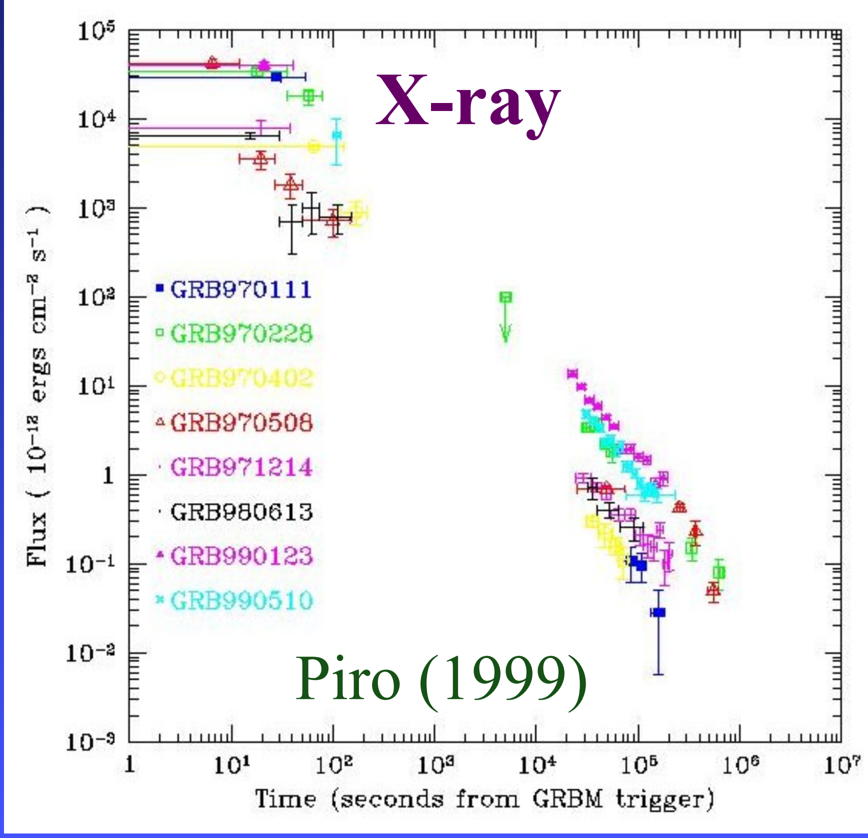
- 2 Wide Field Cameras: 40° × 40°, ~3’ res.
- Narrow Field Instruments: ~1’ resolution
- WFC → ground → point NFI → ground (hours)
- Its abilities led to **afterglow** detection (1997) in X-rays, optical, radio (for long-soft bursts - LSBs)
- This led to **redshift** measurements, and thus a clear cut determination of the distance/energy (LSBs)
  $E_{\gamma,iso} \sim 10^{52}$ -10^{54} erg, narrow jets: $E_\gamma \sim 10^{51}$ erg
- Afterglow observations provided many new constraints on beaming (narrow jets $\theta_j \sim 3° - 30°$), host galaxies (star forming), event rate (~$10^{-5.5}$ yr $^{-1}$ Galaxy $^{-1}$), external density (~10^{-3} -10^{2} cm^{-3}), Supernova connection, etc.

Afterglow Observations: pre-Swift

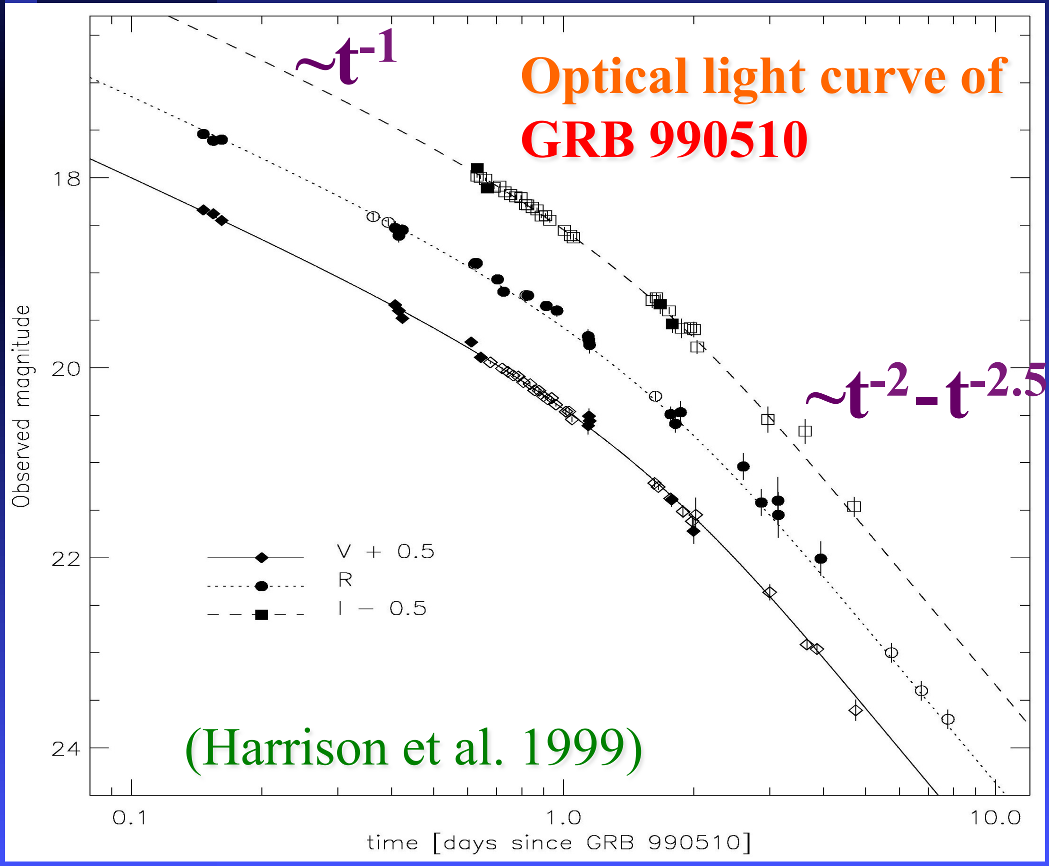
(basic features the model needs to produce)

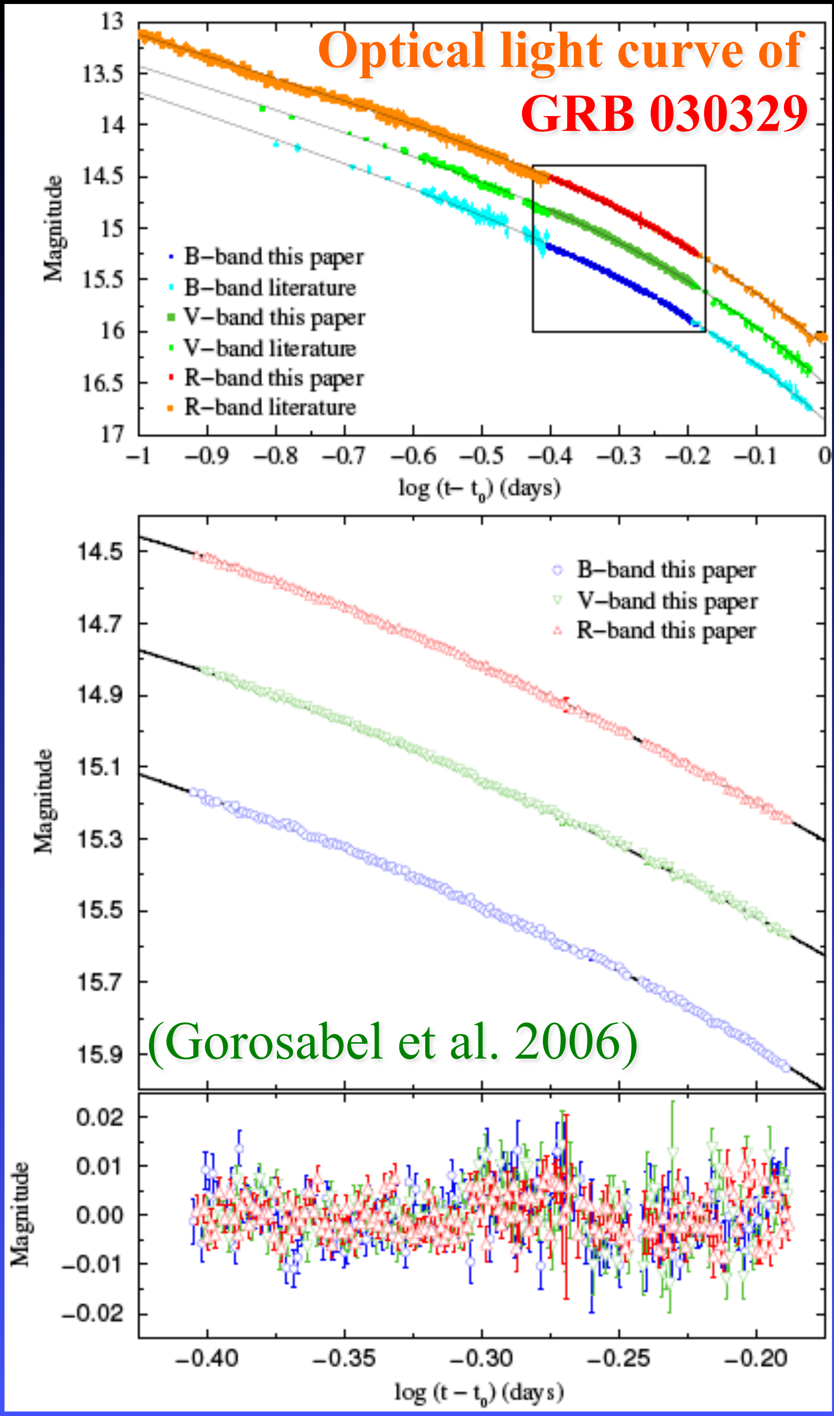
- X-ray, optical & radio emission over (pre-*Swift*) days, weeks & months, respectively, after GRB
- **Light curves**: power-law decay





Some afterglows show an Achromatic Steepening of the Light Curve ("Jet Break")

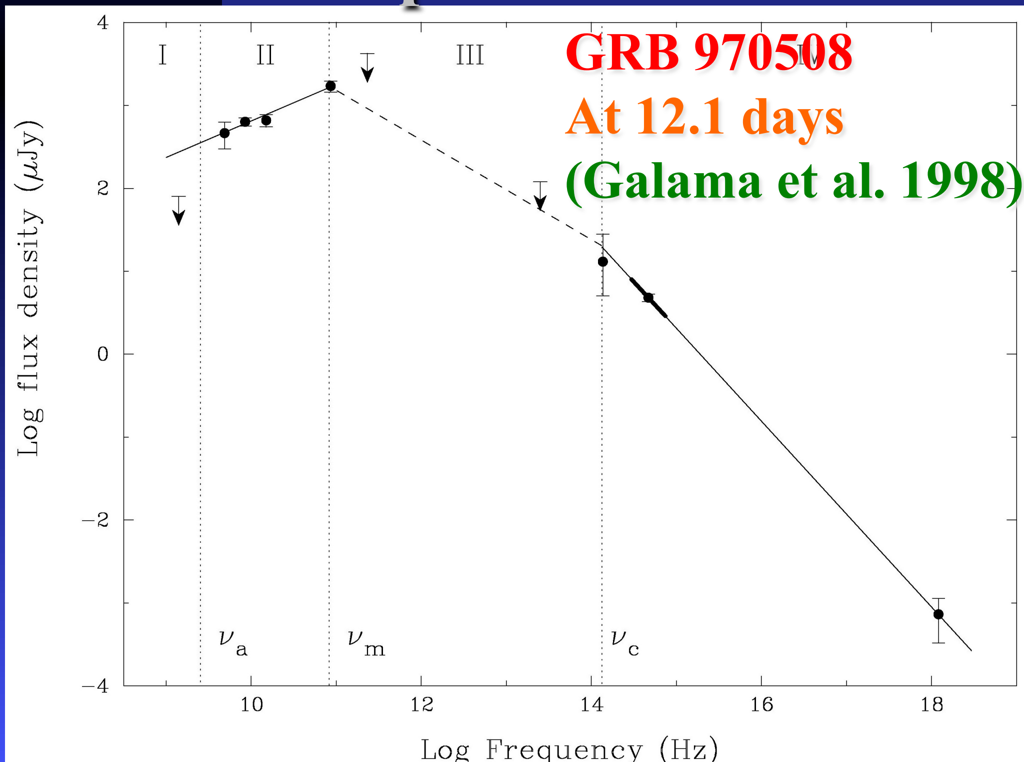




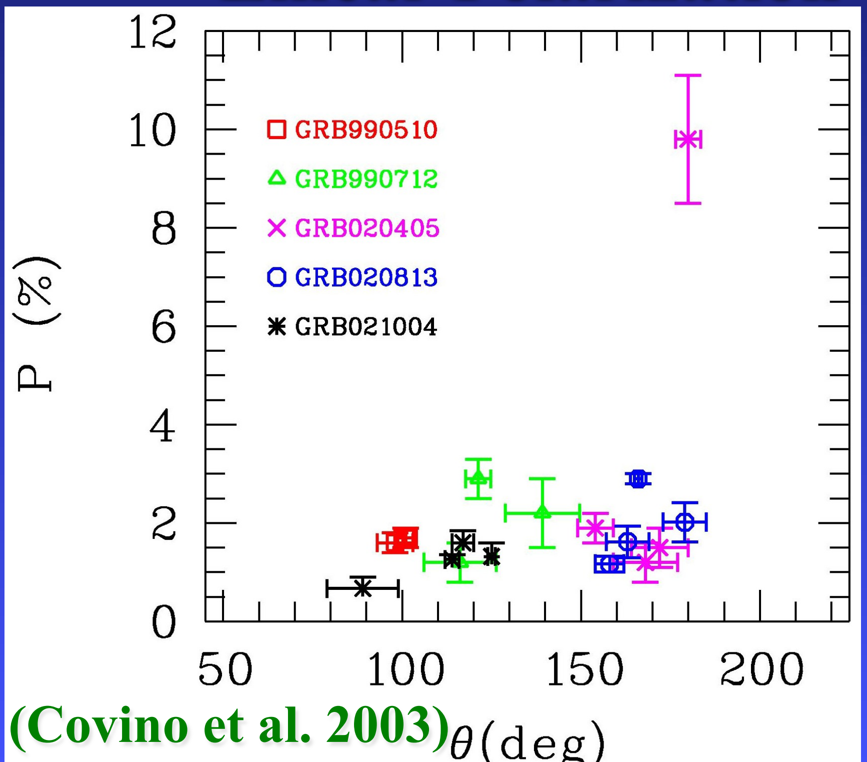
Spectrum & Linear Polarization

- **Spectrum:** consists of **several power law segments** & is well fit by synchrotron emission
- **Linear polarization of ~ 1%-3% was detected in several optical/NIR afterglows ⇒ likely synchrotron emission**

Spectrum



Linear Polarization

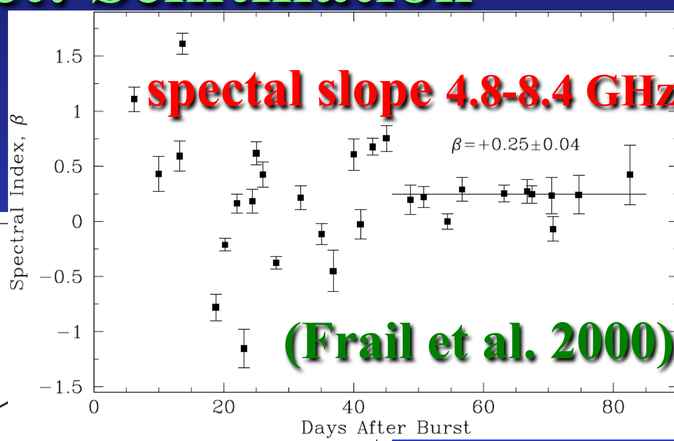


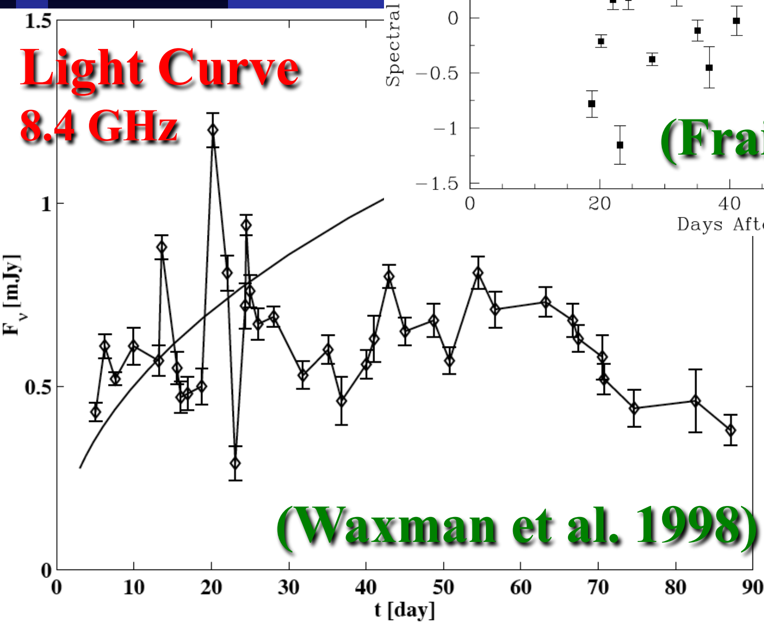
The Size of the Afterglow Image

- Quenching of diffractive scintillations after ~ 30 days in the radio afterglow of GRB 970508 ⇒ $R_\perp \sim 10^{17}$ cm
- The radio afterglow of GRB 030329 was (marginally) resolved **directly** using the VLBA (Taylor et al. 04,05)

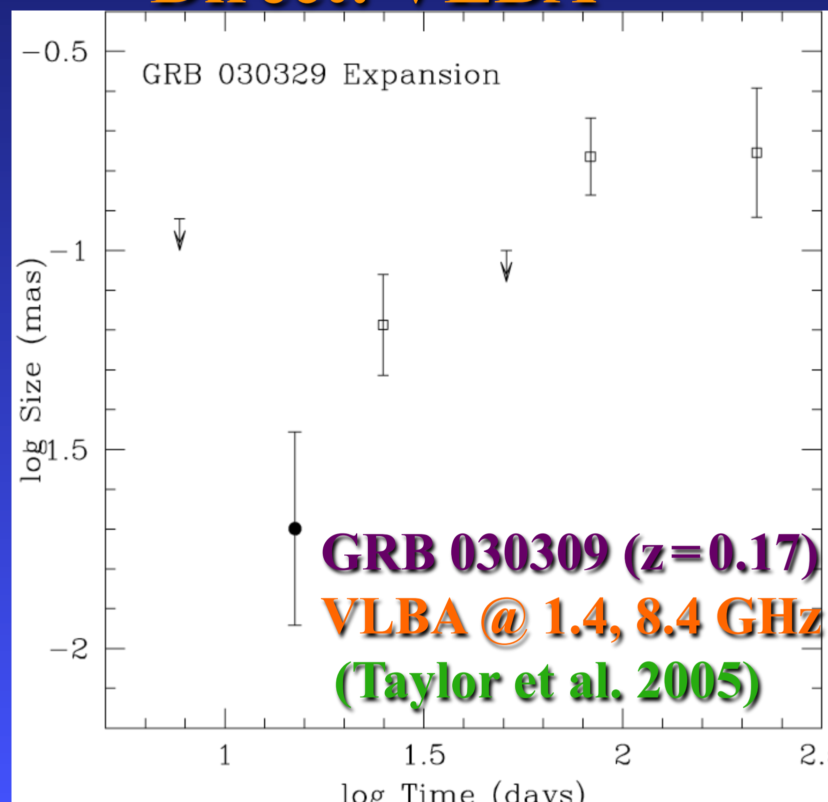
Indirect: Scintillation

GRB 970508





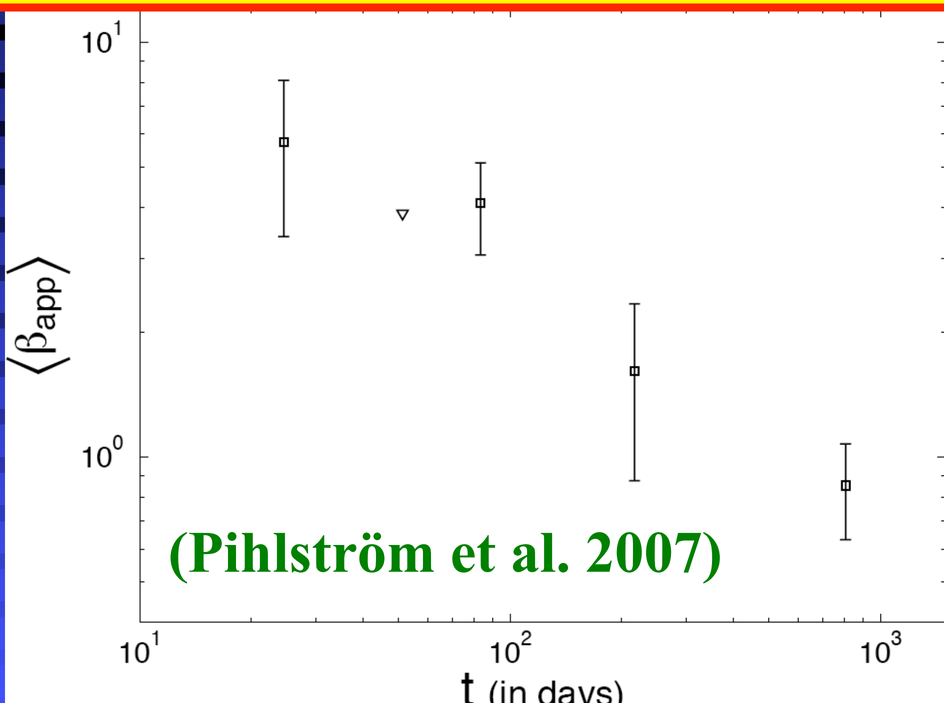
Direct: VLBA



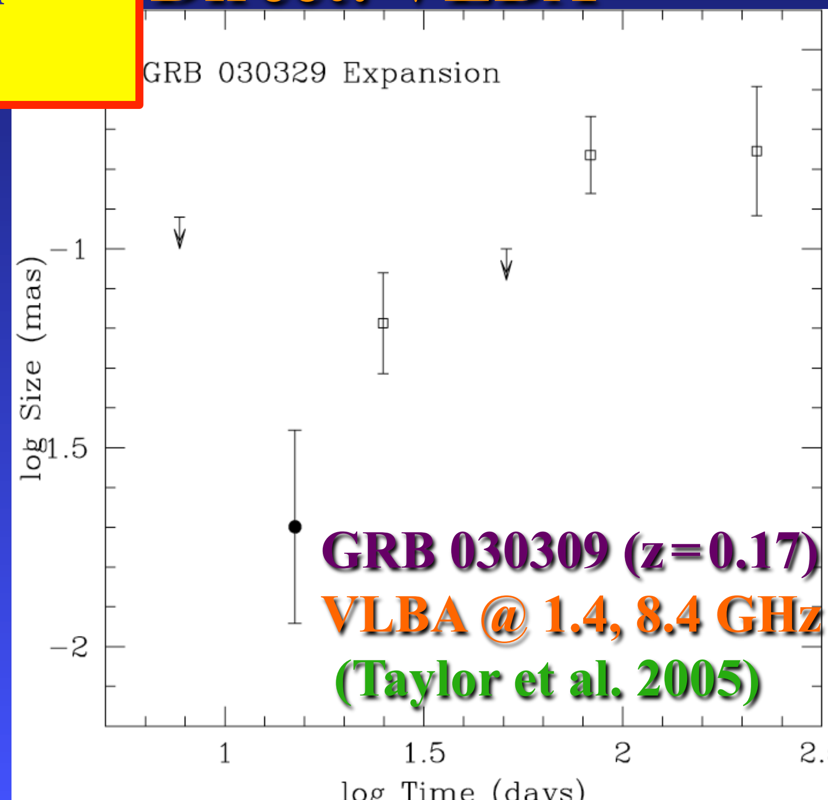
The Size of the Afterglow Image

- Quenching of diffractive scintillations after ~ 30 days in the radio afterglow of GRB 970508 ⇒ $R_\perp \sim 10^{17}$ cm
- The radio afterglow of GRB 030329 was (marginally) resolved **directly** using the VLBA (Taylor et al. 04,05)

Direct evidence for relativistic motion & deceleration during the afterglow

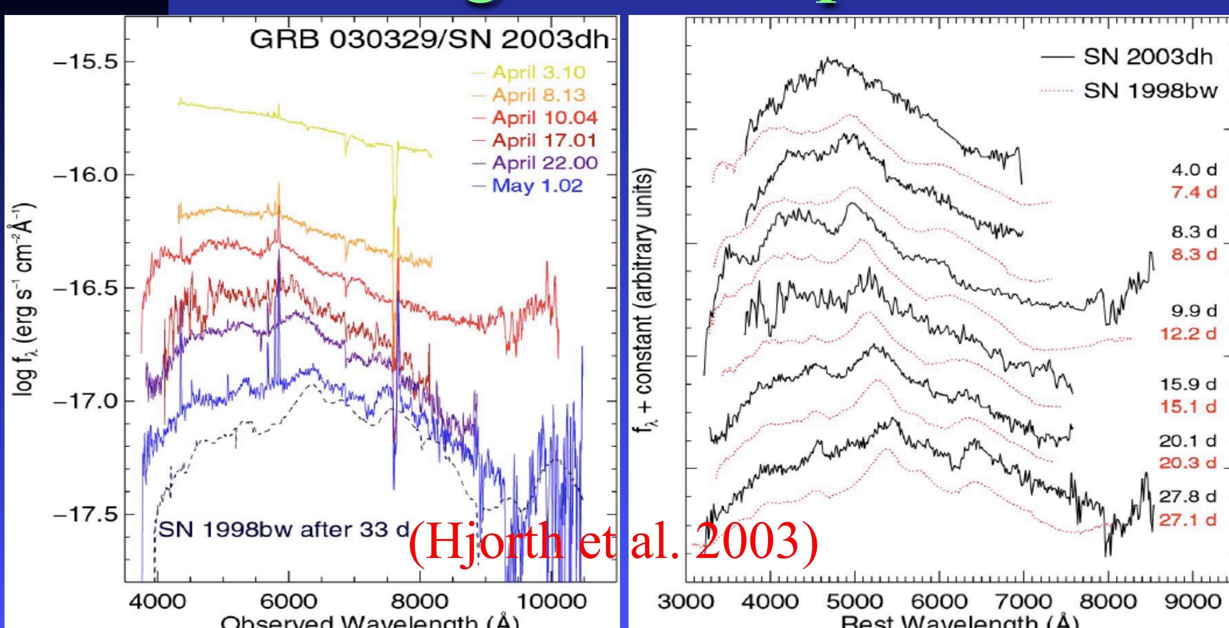


Direct: VLBA

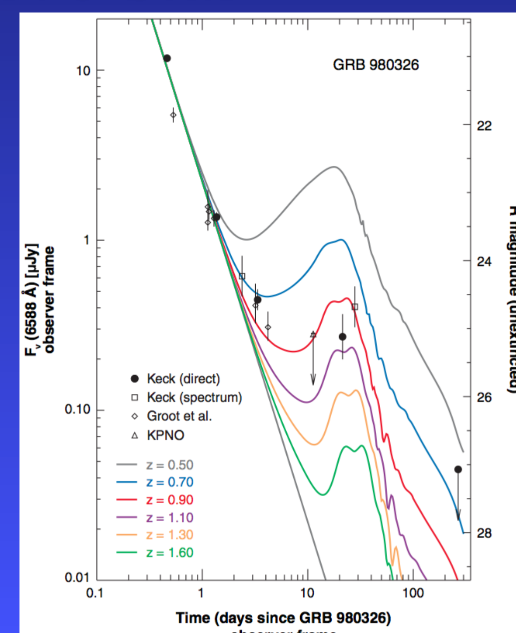


(Long-soft) GRB – SN (Type Ic) Connection

- Firmly established the connection between long GRBs and core collapse Supernovae (in 2003; earlier evidence was inconclusive – red bump in afterglow lightcurve)
- Progenitor: massive star stripped of its H & He
- Supports the “Collapsar” model, in which a BH is formed during the collapse of a massive star



(Hjorth et al. 2003)

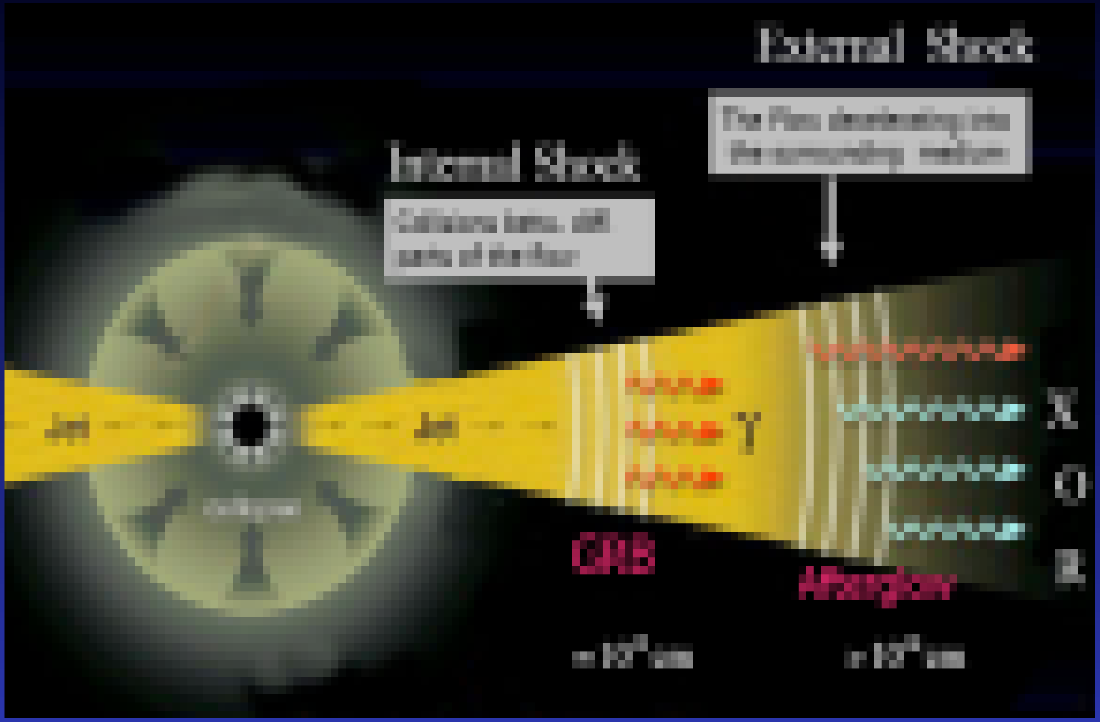


Some Basic Observational constraints

- **Energy**: $E_{\gamma,iso} \sim 10^{51}$-$10^{55}$ erg (LSB), $\sim 10^{49}$-10^{53} erg (SHB)
- Short variability time ⇒ **compact source** (likely BH or NS)
- +non-thermal spectrum with $E_{peak} \sim m_e c^2$, $L_{iso} \sim 10^{52\pm1}$ erg/s: compactness problem ⇒ **Relativistic motion $\Gamma \gtrsim 100$**
- **Narrow jet**: analogy to AGN/μQ, $E_{\gamma,iso} \gtrsim 10^{54}$ erg, jet break
- **Progenitors**: environment, event rate, LSB SN associations
- **Afterglow**: broad-band spectrum, optical/NIR polarization, radio afterglow image size (GRBs 970508, **030329**)

GRB Theoretical Framework:

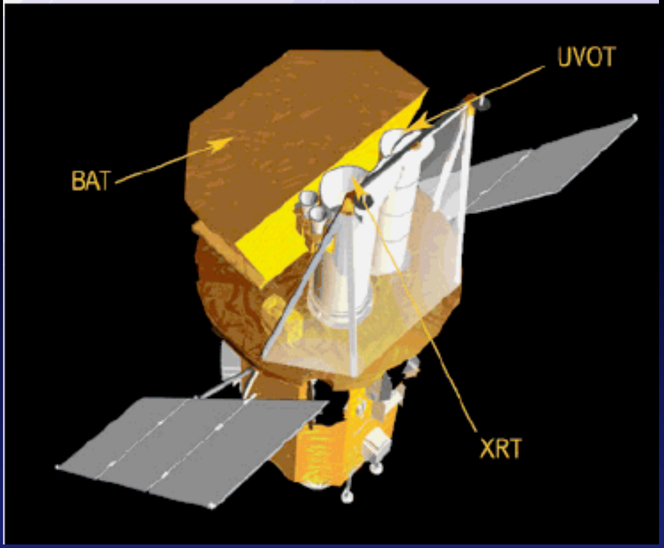
- **Progenitors**:
  - LSB: massive stars
  - SHB: binary merger?
- **Acceleration**:
  fireball or magnetic?
- **Prompt γ-rays**:
  internal shocks?
  emission mechanism?



- **Deceleration**: the outflow decelerates (by a **reverse** shock for $\sigma \lesssim 1$) as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into external medium (?); as the shock decelerates the typical frequency decreases: X-ray ➔ optical ➔ radio

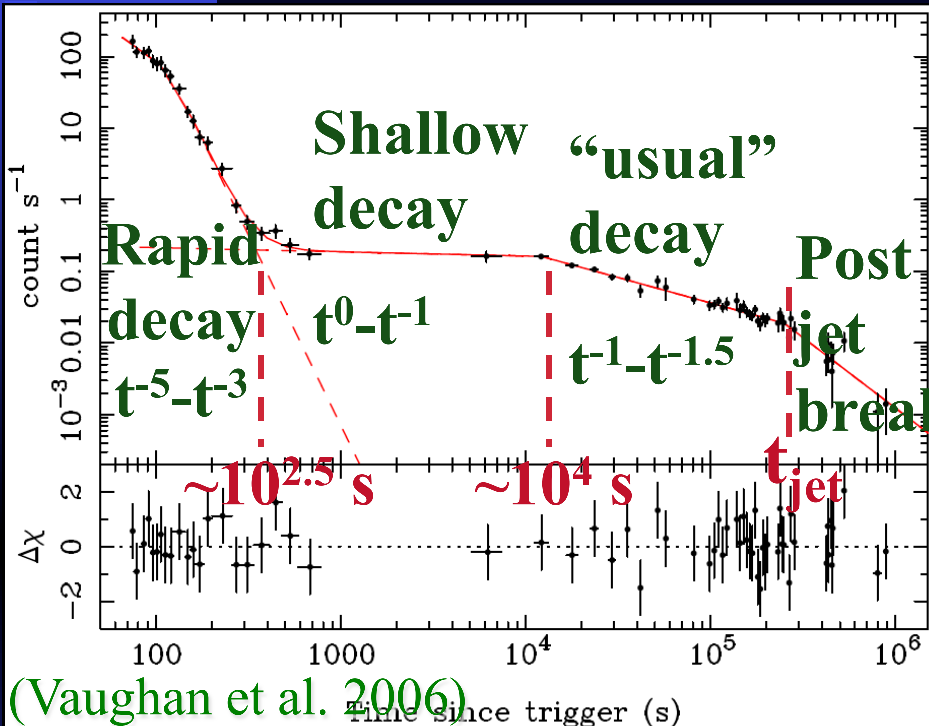
The *Swift* Era:

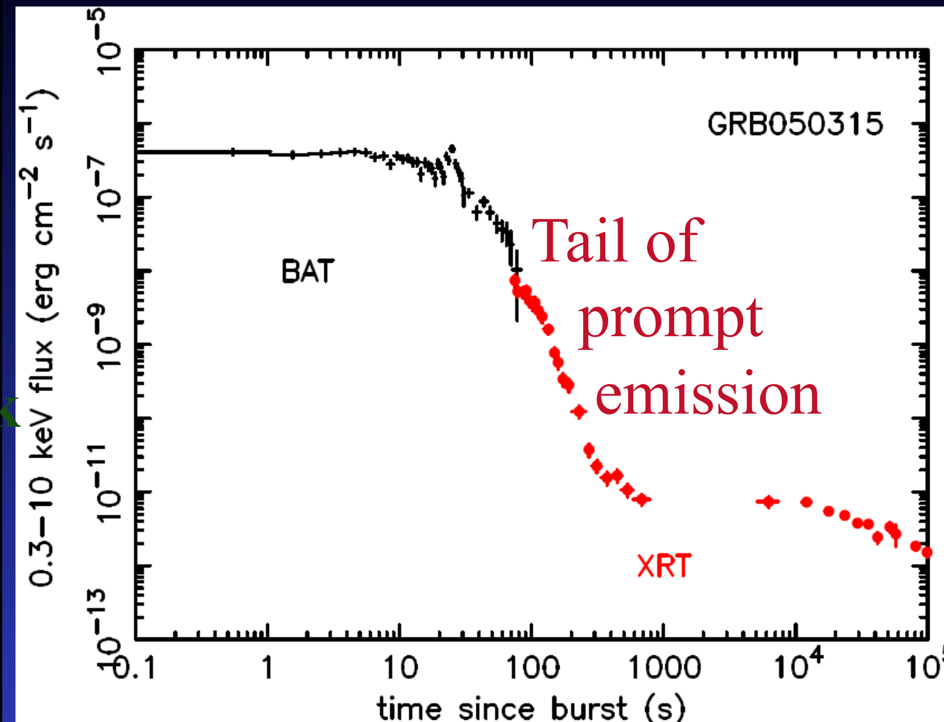
(launched 20 Nov. 2004)

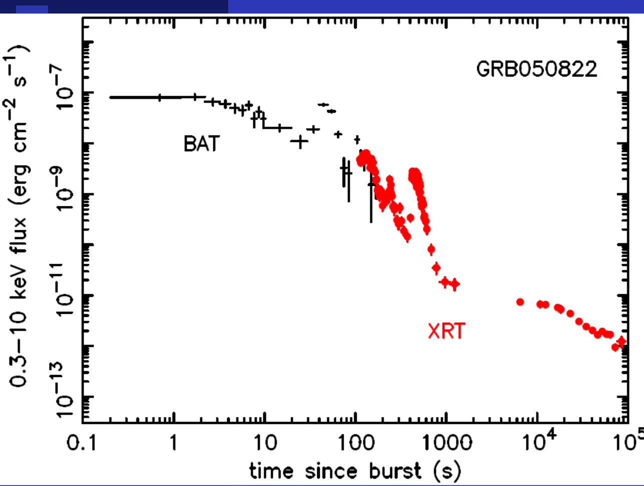


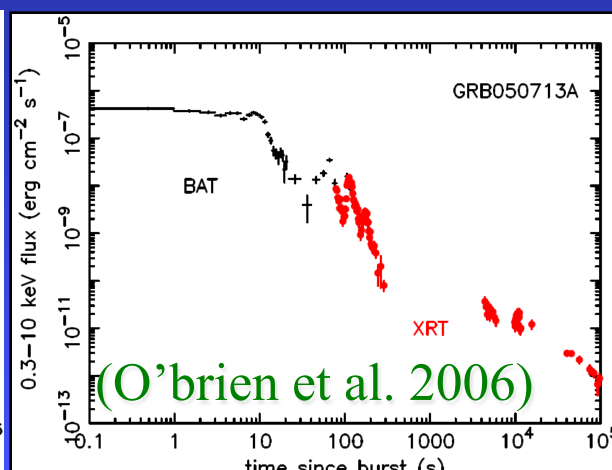
- Observes a GRB in γ-rays, then slews to its position autonomously, within 1-2 minutes & observes in X-rays, UV & optical
- Detects ~100 GRB/yr + X-ray afterglow for most
- Its early afterglow observations filled the gap between the prompt γ-ray emission and pre-Swift "late" afterglow observations, hours after the GRB
- Discovered unexpected behavior of early afterglow
- Led to the discovery of **afterglow** from **short** GRBs → host galaxies, redshifts, energy, rate, progenitors?

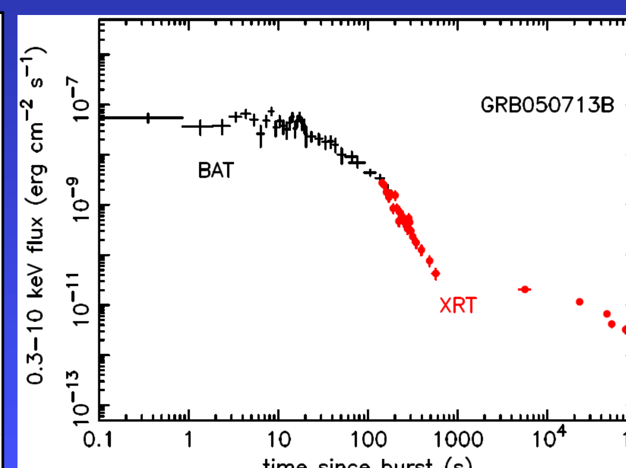
Early X-ray Afterglows from Swift:











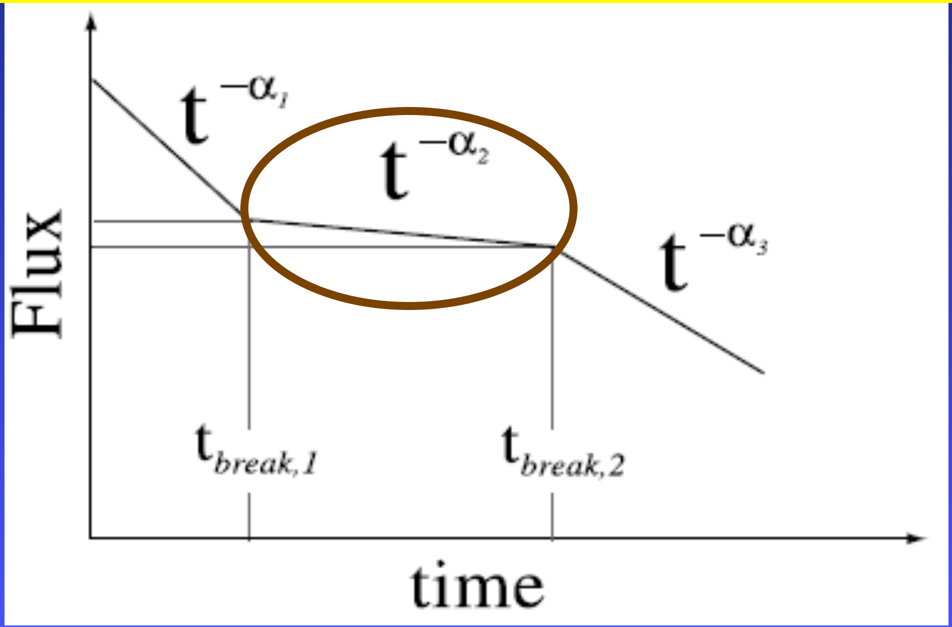
Possible Explanations for the Shallow Decay

$$\frac{\varepsilon_x(t)E_{k,iso}(t)}{tF_x(t)} \approx 4\pi d_L^2(1+z)^{\beta-\alpha-1}$$ where $\varepsilon_x(t) \equiv \frac{t\,L_x(t)}{E_{k,iso}(t)}$ is the afterglow efficiency (fraction of kinetic energy radiated in the dynamical time).

During the shallow decay phase $\varepsilon_x(t)E_{k,iso}(t) \propto tF_x(t)$ increases with time.

For $\nu_x > \max(\nu_m,\nu_c)$ and $p > 2$, under standard afterglow theory $\varepsilon_x(t)$ decreses with time, and therefore $E_{k,iso}(t)$ must increase with time.

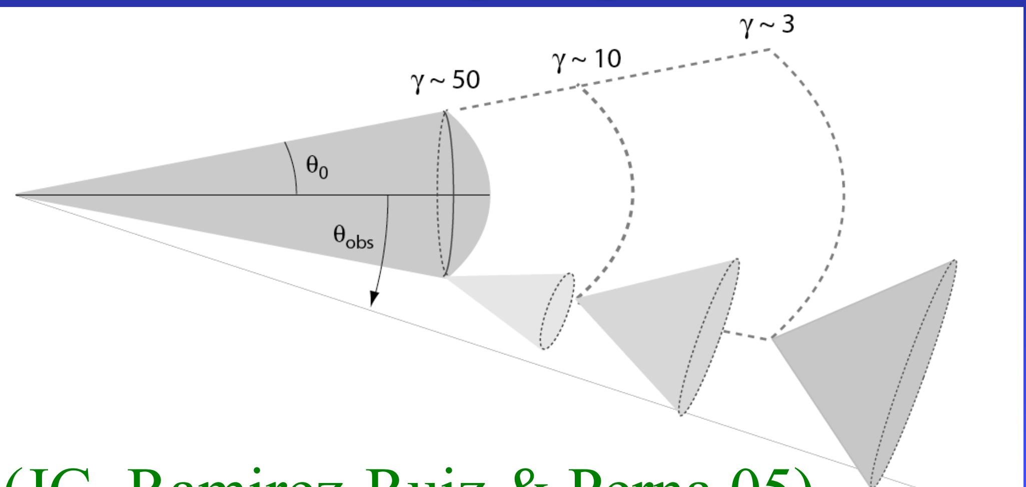
Alternatively, $\varepsilon_x(t)$ can increase in time under less standard assumptions



(JG, Königl & Piran 2006)

Possible Explanations for the Shallow Decay

- **Energy injection** into afterglow: (Nousek et al. 06)
  - I. Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - II. Slower material ejected during the prompt GRB gradually catches up the decelerating afterglow shock
- Afterglow efficiency increases with time (varying shock micro-physics parameters; JG, Königl & Piran 06)
- Observer outside emitting region (Eichler & JG 06)

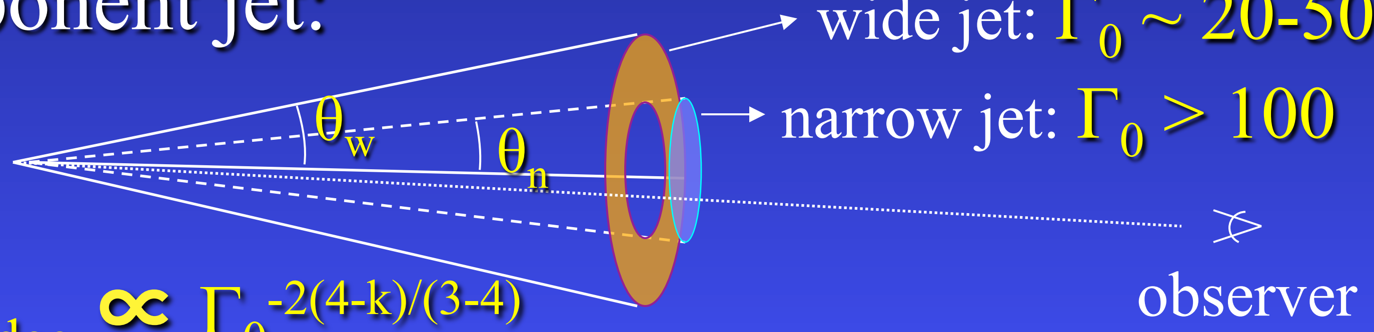


(JG, Ramirez-Ruiz & Perna 05)

Possible Explanations for the Shallow Decay

- **Energy injection** into afterglow: (Nousek et al. 06)
  - **I.** Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - **II.** Slower material ejected during the prompt GRB gradually catches up the decelerating afterglow shock
- Afterglow efficiency increases with time (varying shock micro-physics parameters; JG, Königl & Piran 06)
- Observer outside emitting region (Eichler & JG 06)
- Two component jet:

(JG, Königl & Piran 06)



$t_{dec} \propto \Gamma_0^{-2(4-k)/(3-4)}$

for $\rho_{ext} \propto r^{-k} \Rightarrow t_{dec,n} \ll t_{dec,w}$

Possible Explanations for the Shallow Decay

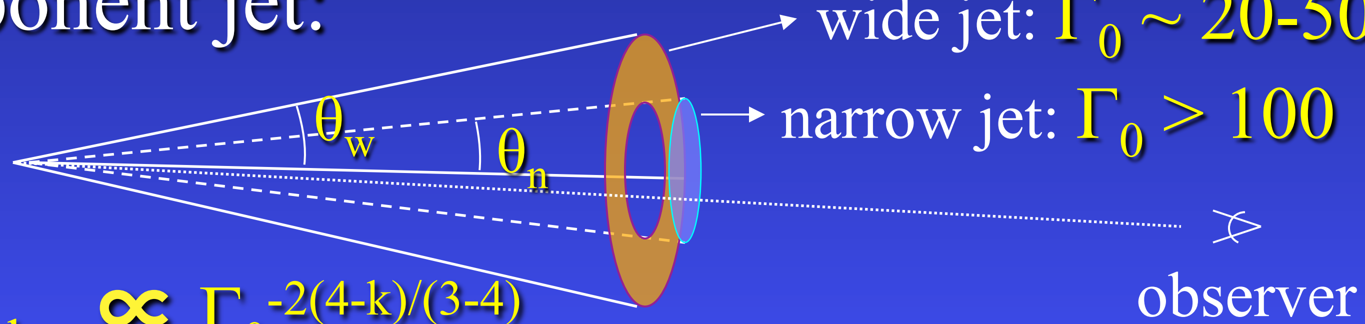
- **Energy injection** into afterglow: (Nousek et al. 06)
  - I. Continuous relativistic wind $L \propto t^{-0.5}$ (magnetar?)
  - … B

g … ck

It isn't clear which of these explanations, if any, is indeed the dominant cause for the shallow decay phase

- … shock micro-physics parameters; JG, Königl & Piran 06)
- Observer outside emitting region (Eichler & JG 06)
- Two component jet:

(JG, Königl & Piran 06)

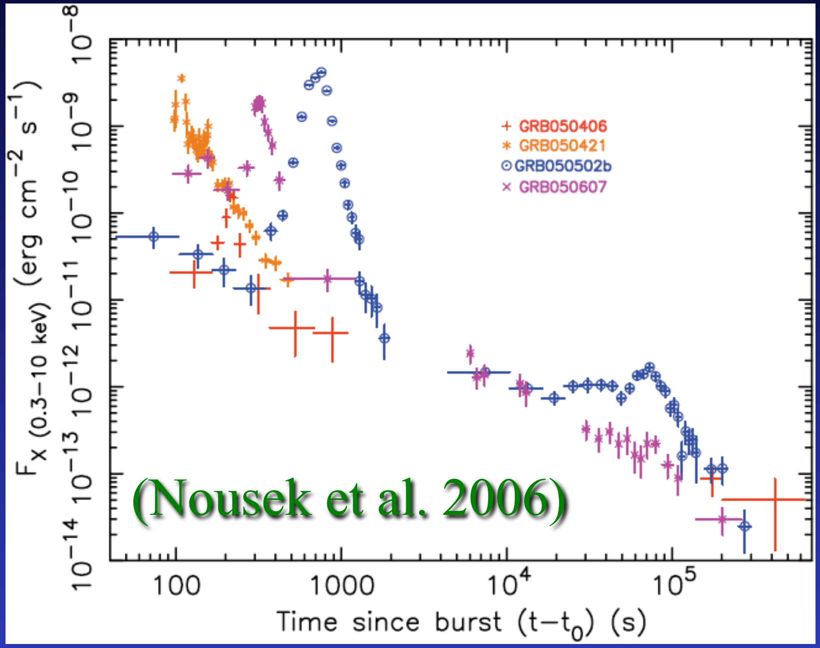


$t_{dec} \propto \Gamma_0^{-2(4-k)/(3-4)}$

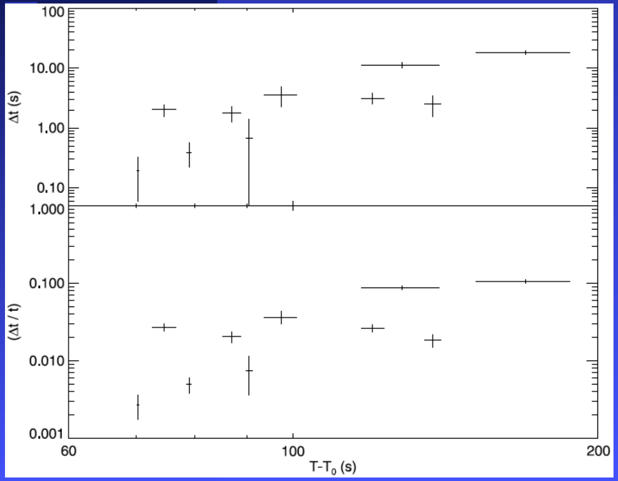
for $\rho_{ext} \propto r^{-k} \Rightarrow t_{dec,n} \ll t_{dec,w}$

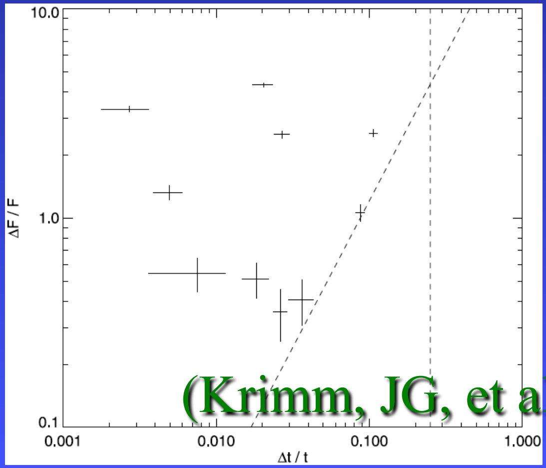
X-ray Flares: prolonged source activity?

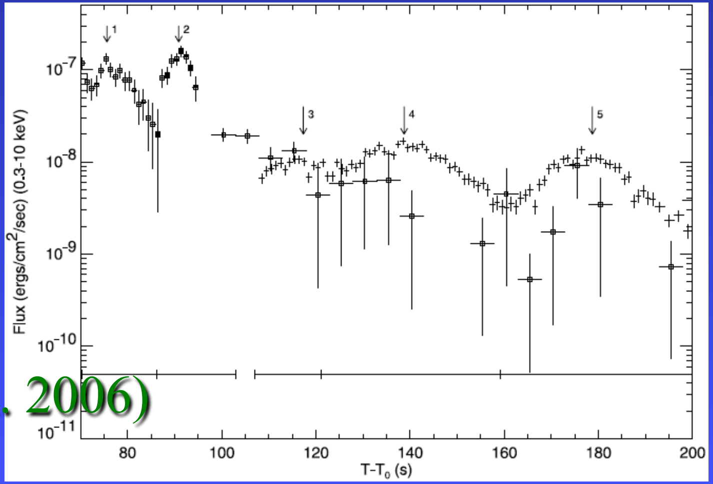
- Short time scale ($\Delta t \ll t$) Large amplitude ($\Delta F \gtrsim F$) rule out an afterglow origin
- They are most likely due to **long lived central source** activity (late time fallback?)
- Late & localized dissipation events within the outflow?



(Nousek et al. 2006)



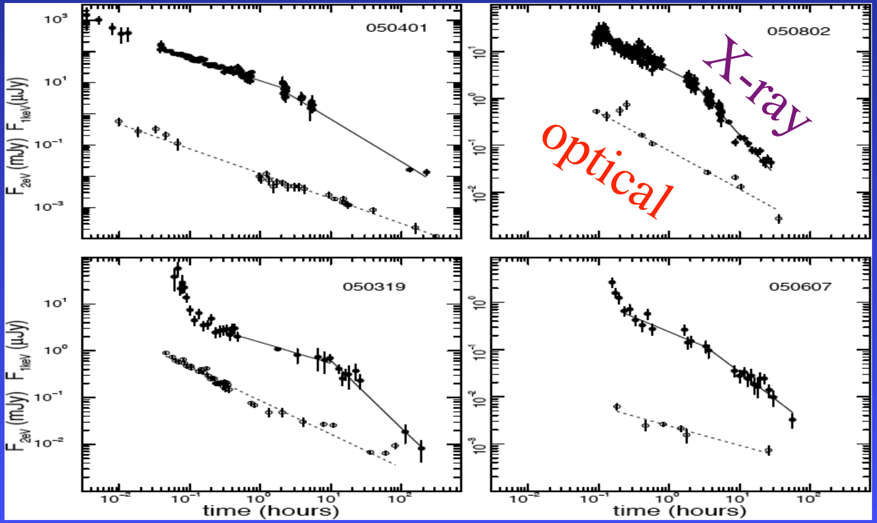




(Krimm, JG, et al. 2006)

Afterglow: what we know or don't know

- decelerated expansion GRB 030329 afterglow image
  ⇒ caused by interaction with the external medium
- Linear polarization (~few %) ⇒ mainly synchrotron
- Forward external shock: simple, hard to avoid, successful in explaining gross properties over wide frequency/time range
- Challenges: does not naturally explain some features or detailed observations, requires extensions, shock microphysics
- **Canonical afterglow:** **rapid decay, plateau, flares**
- **Chromatic breaks**:
- dim early optical,
  few jet breaks,
  α-β closure…



(Panaitescu et al. 2006)

Relevant observations

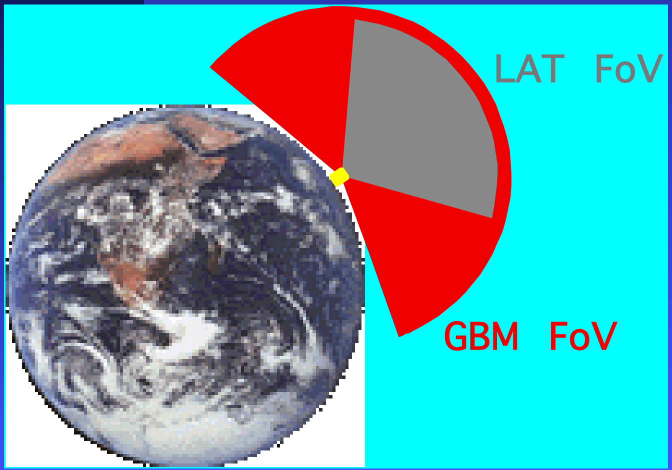
- **Rapid decay phase**: early x-ray + γ-ray & global fits
- **Plateau**: good multi-wavelengths lightcurves/spectra (add to x-ray: optical/UV, NIR/mm, radio, GeV, TeV)
- **Flares**: multi-wavelength coverage + **polarimetry**
- Chromatic breaks, etc.: multi-wavelength + theory…
- Unique events like GRB 030329 (be ready for them)

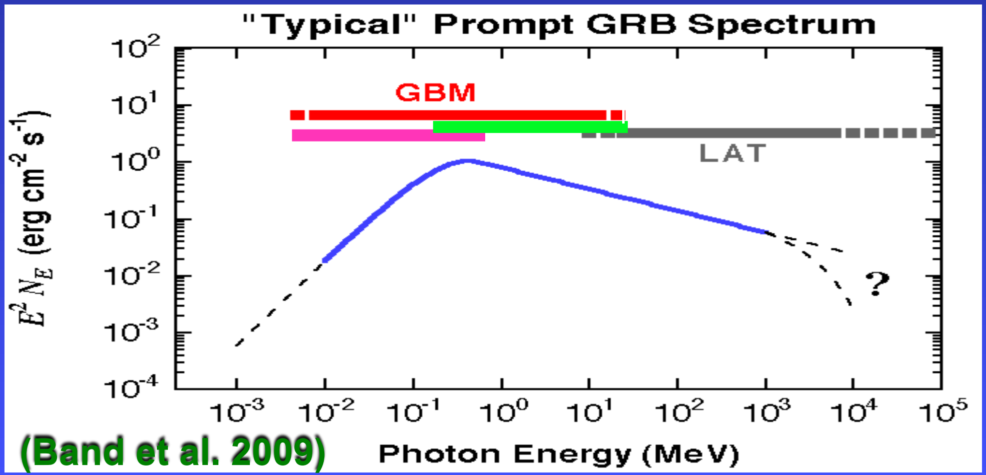
Shock Microphysics

- Afterglow model-ignorance parameters: $\epsilon_e, \epsilon_B, \xi_e, p, \ldots$
- Latest PIC simulations find: $\epsilon_e \sim 0.06\text{-}0.15$, $\epsilon_B \gtrsim 0.01$, $\xi_e \sim 0.01\text{-}0.04$, $p \sim 2.5$; dynamic range is still unrealistic
- Relevant observations: detailed optical+x-ray+**GeV**
- More theoretical work (analytic/numerical) is needed

Fermi Gamma-ray Space Telescope (Fermi Era; launched on June 11, 2008):

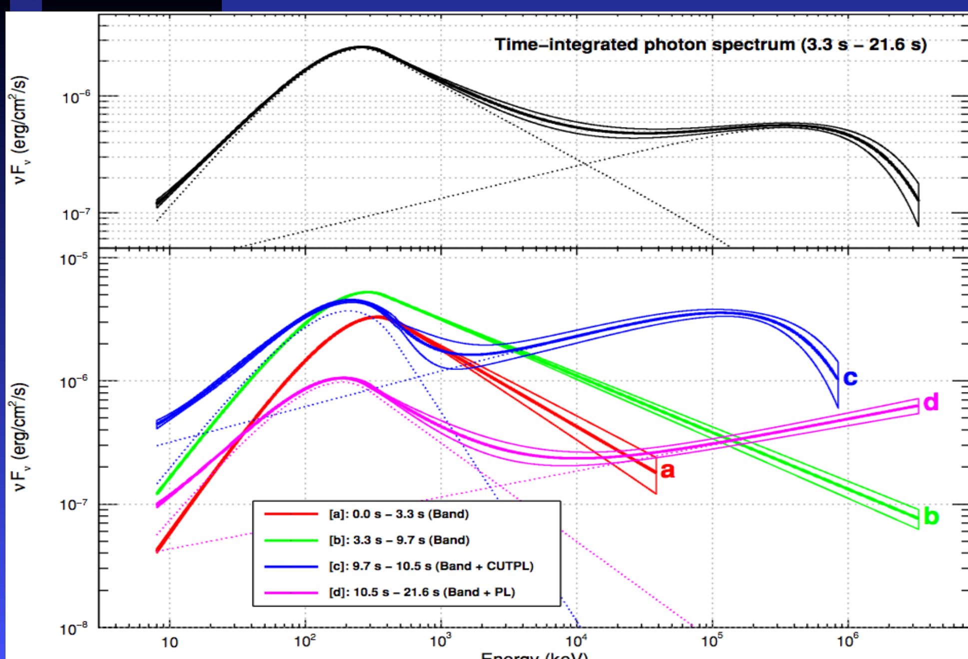
- Fermi GRB Monitor (GBM): 8 keV – 40 MeV (12×NaI 8 – 10^3 keV, 2×BGO 0.15 – 40 MeV), full sky
- Comparable sensitivity + larger energy range than its predecessor - BATSE
- Large Area Telescope (LAT): 20 MeV – >300 GeV FoV ~ 2.4 sr; up to 40× EGRET sensitivity, ≪ deadtime

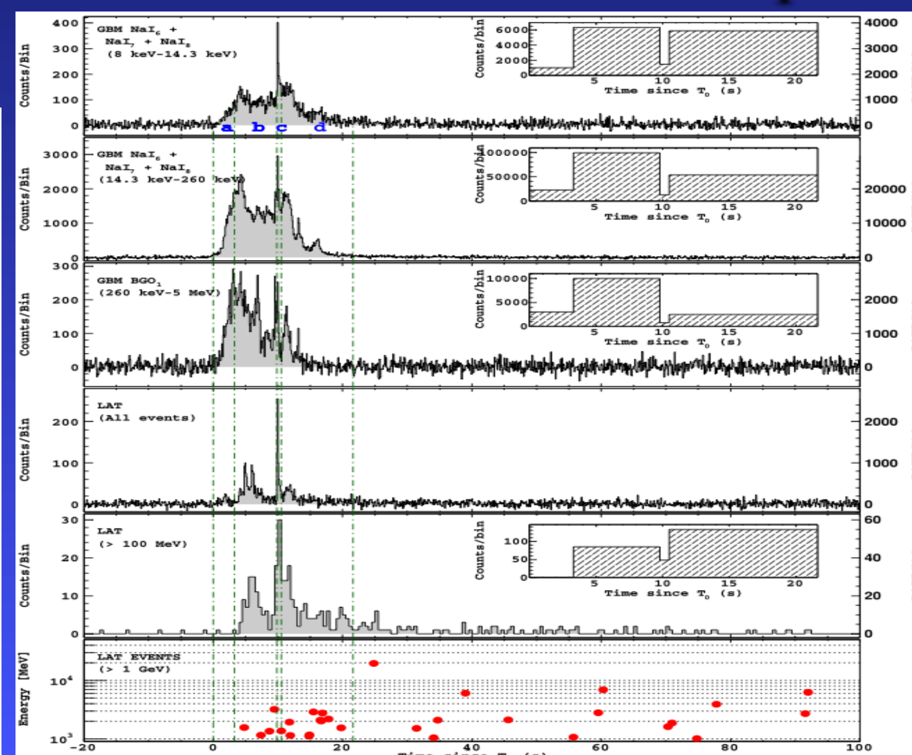




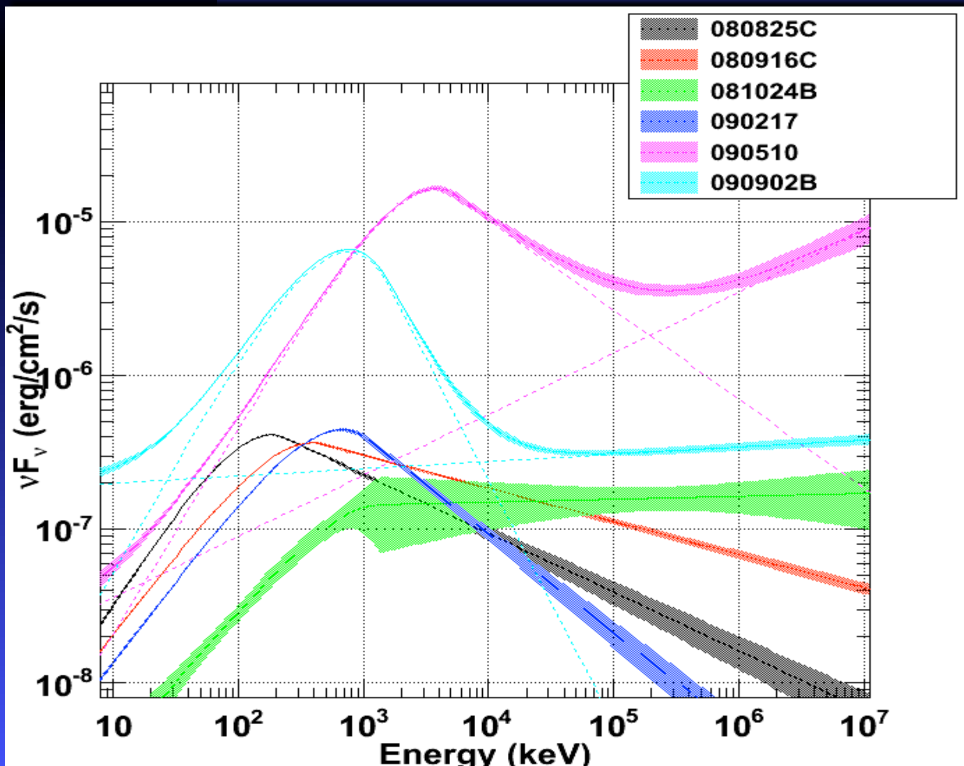
Constraints on Γ for Fermi LAT GRBs

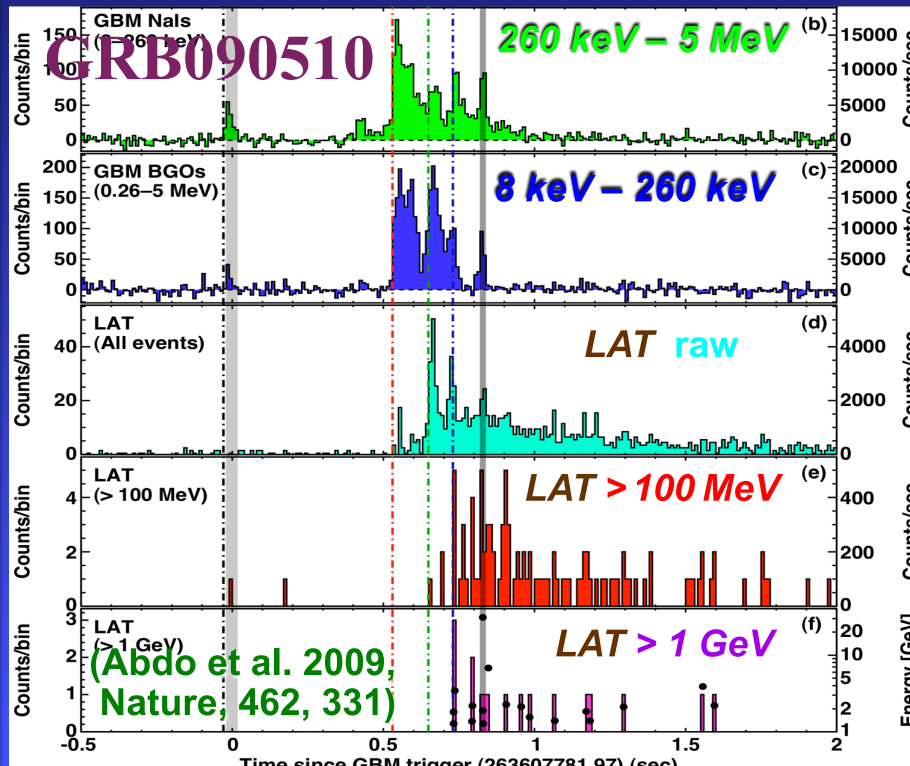
- Γ_{min}: no high-energy cutoff due to intrinsic pair production
  ⇒ lower limit on the Lorentz factor of the emitting region
- For bright LAT GRBs (long/short): $\Gamma \gtrsim 10^3$ for simple model (steady-state, uniform, isotropic) but $\Gamma \gtrsim 10^{2.5}$ for more realistic time-dependent self-consistent thin shell model (**JG et al. 2008**)
- **GRB 090926A**: high-energy cutoff – if due to intrinsic pair production then $\Gamma \sim$ **200 - 700**





- **Distinct spectral component** at high (+sometimes also low) energies in 3/4 brightest LAT GRBs ⇒ intrinsically common
- **Delayed onset** of HE emission (LSB: ~4-10 s; SHB: ~0.1-0.2 s)
- **Long lived** HE emission ($\lesssim 10^2$ - 10^4 s; HE afterglow onset?)
- The prompt emission mechanism is still unclear
- Photons >30 GeV in GRBs 090510 (SHB), 090902B (LSB) (up to 94 GeV at GRB redshift) ⇒ **great prospects for CTA**





Prompt emission mechanism, dissipation

- **Dissipation**: internal shocks
  - Well explored, account for variability + some correlations
  - Limited efficiency, don't explain some observations
- Relativistic turbulence / mag. reconnection / mini-jets
  - High efficiency may naturally be obtained
  - Not worked out yet, predicts unobserved overall evolution
- **Emission Mechanism**: **?** (leptonic: synchrotron, SSC, Compt., photospheric; hadronic: p-syn, π-decay, $e^{\pm}$ cascades)
- **Open Questions**: dominant dissipation & emission mechanisms, the distinct spectral components, Γ_0,…
- Relevant **observations**: prompt optical, x-ray, MeV, GeV, TeV; x/γ-ray polarimetry; HE ν's, UHECRs
- **Theory**: new ideas needed & testable predictions

Progenitors: Long-Soft GRBs (LSB)

- **Massive stars**: host galaxy type & SFR, location within the host (Fruchter et al. 2006), SN associations
- Handful of spectroscopic associations to **SNe Ic** (mainly GRB030329) ⇒ at least some LSBs involve (±1 day) the **core collapse** of massive stars stripped of their hydrogen & helium ⇒ **BH** or **NS** formation
- Some **Open Questions**: role of progenitor's rotation, mass, metallicity, binarity; LSBs without bright SN; local under-luminous LSBs; XRFs, shock breakout
- Relevant **observations**: GRB host studies, search for GRB-SN up to z ~0.5-1, afterglow spectroscopy, study of nearby SN Ib/c, discovery of unique events

Progenitors: Short-Hard GRBs (SHB)

- **Different progenitors than long-soft GRBs**:
  - found also in **hosts** with very **small SFR** ⇒ **long delay** from star formation; if a massive star is involved then it dies a long time before the GRB: ≥ 2 stage process
  - **no SN associations** (which are found for some LSBs)
  - location w.r.t host (**large offsets** – suggests “natal kicks”)
- **Candidates**: binary mergers (NS-NS/BH), accretion induced collapse of NS, colliding compact objects in globular clusters, nearby SGR giant flares ($\lesssim 5\%$)
- Some **Open Questions**: progenitors, extended soft tails, subclasses, collimation (true energy + event rate)
- Relevant **observations**: hosts, offsets, gravitational waves, neutrinos, “mini-SN”, late flaring, GeV/TeV

The Central Engine: Long-soft GRBs

- **Collapsar**: a massive star core collapses and a BH forms (directly/fallback) & accretes part of envelope
  - LSB durations are similar to the free-fall time of the core, but it must rotate fast enough to form an accretion disk
  - Launching a jet: magnetic (B-Z?), neutrino annihilation?
  - Collimation: by the walls of the funnel in stellar envelope
  - Can provide up to $\sim 10^{54}$ erg (enough for GRB jet + SN)
  - The disk wind can help energize the SN and make ^{56}Ni
- Millisecond-magnetar: $t_{spin\text{-}down} \sim T_{GRB} \Rightarrow B \sim 10^{15.5}$ G
  - Powered by the NS rotational energy $\Rightarrow$ **$E \lesssim 10^{52.5}$ erg** (might not be enough to power very energetic GRB + SN)
  - Jet launching: pulsar-type relativistic MHD wind
  - Collimation: magnetic hoop stress + stellar envelope
  - Might be hard to generate enough ^{56}Ni for a bright SN

The Central Engine: Short-hard GRBs

- ms-magnetar? $T_{\text{spin-down}} \sim T_{GRB} \Rightarrow B > 10^{16.5}$ G
  - Magnetars are thought to form in a SN, but no SN are obs. in SHBs & there are hosts with low SFR ⇒ requires unconventional formation: AIC of WD, NS-NS merger
- accreting **BH** (possibly from a binary merger):
  - $T_{GRB} \sim$ viscous time (variability: accretion instabilities)
  - Jet launching: magnetic (B-Z?), neutrino annihilation
  - Collimation: disk wind (?)
  - Late flares from fallback of tidal tails?
- Some **Open Questions** (LSB+SHB): BH/magnetar, jet launching & collimation, source of variability,…
- Relevant **observations**: GWs, neutrinos, afterglow energy/calorimetry, SN energy, late flares (SHB)

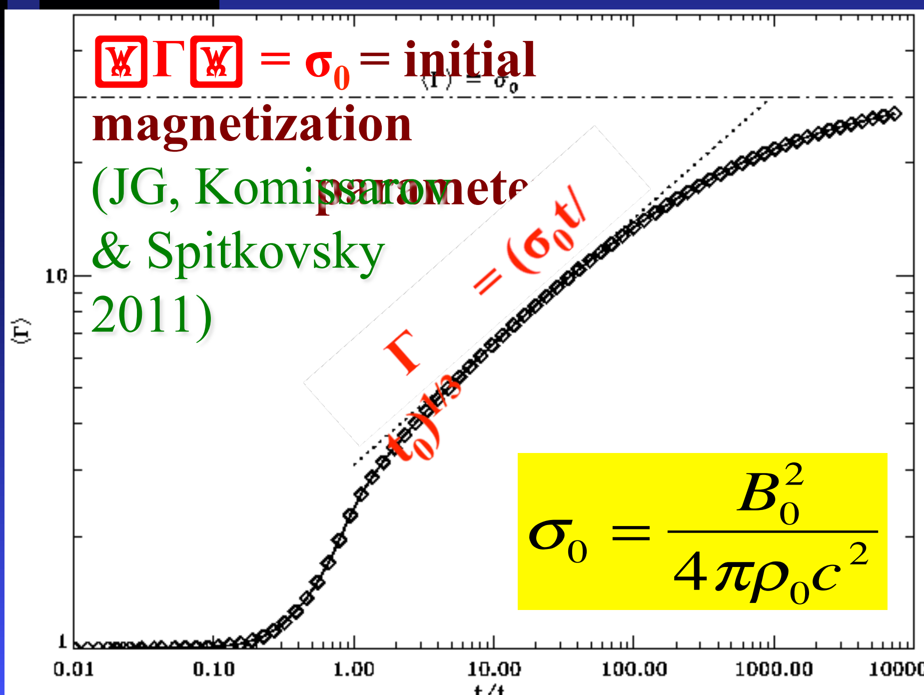
Outflow Acceleration & Composition:

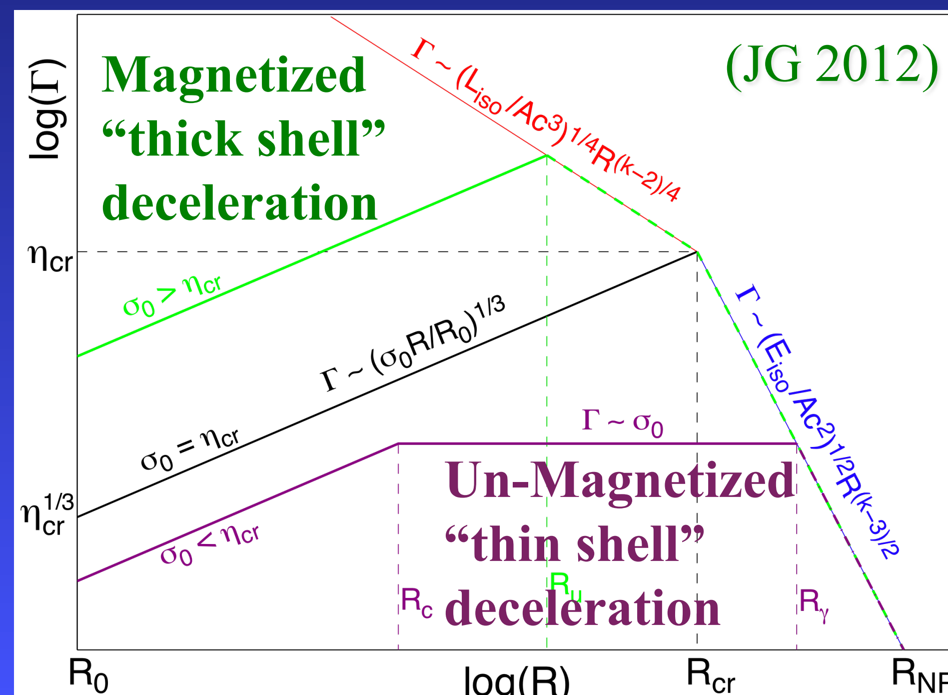
- **Fireball**: thermal (radiation pressure) acceleration
  - Fast ($\Gamma \propto R$), robust, allows efficient internal dissipation
  - Baryon kinetic energy eventually dominates
  - Requires a small baryon loading ($\sim 10^{-5}\ M_{\odot}$)
- **Magnetic** acceleration: Poynting flux dominated jets
  - Standard steady-state axisymmetric magnetic acceleration is slow & not robust or very efficient (but see next slide)
- **Composition**: baryons (neutron rich?), $e^{\pm}$ pairs, magnetic field, in different ratios; **hard to tell apart**
- **Open Questions**: thermal vs. magnetic acceleration, baryonic vs. Poynting flux dominated jets, Γ_0,…
- Relevant **observations**: afterglow onset, polarimetry (prompt, early afterglow, flares), HE ν's, thermal comp.

Recent Progress: Impulsive Acceleration of Strongly Magnetized Relativistic Flows

(JG, Komissarov & Spitkovsky 2011)

- Allows full conversion of magnetic to kinetic energy
  ⇒ can naturally produce efficient internal shocks
- Acceleration & deceleration by ext. medium: **tightly coupled**





Some Open Questions & Prospects:

- What are the progenitors of short GRBs? (more obs. - mini-SN, GW; binary mergers - detailed predictions, alternative models, explain precursors & soft tails)
- How are GRB jets launched and collimated? (analytic solutions & numerical simulations)
- What is the outflow composition (e^+e^- p-e, B-fields)? (obs. UHECRs & HE ν's: 'smoking gun' of hadrons; detailed predictions for magnetized or e^+e^--rich flow)
- What is the γ-ray emission mechanism? (Fermi/CTA obs.; new ideas called for & robust obs. predictions)

Some Open Questions & Prospects:

- The (angular) structure & dynamics of GRB jets: modeling of observations, special relativistic hydro-simulations, analytic self-similar solutions
- Physics of collisionless relativistic shocks (particle accelration, B-field amplification,…) analytic or semi-analytic studies + particle in cell simulations
- Are long GRBs powered by a BH or ms-magnetar? (robust model predictions to test against obs.)
- Do GRBs produce the highest energy cosmic rays? (model obs. of the Auger cosmic ray observatory)

Prospects for Future: Observations

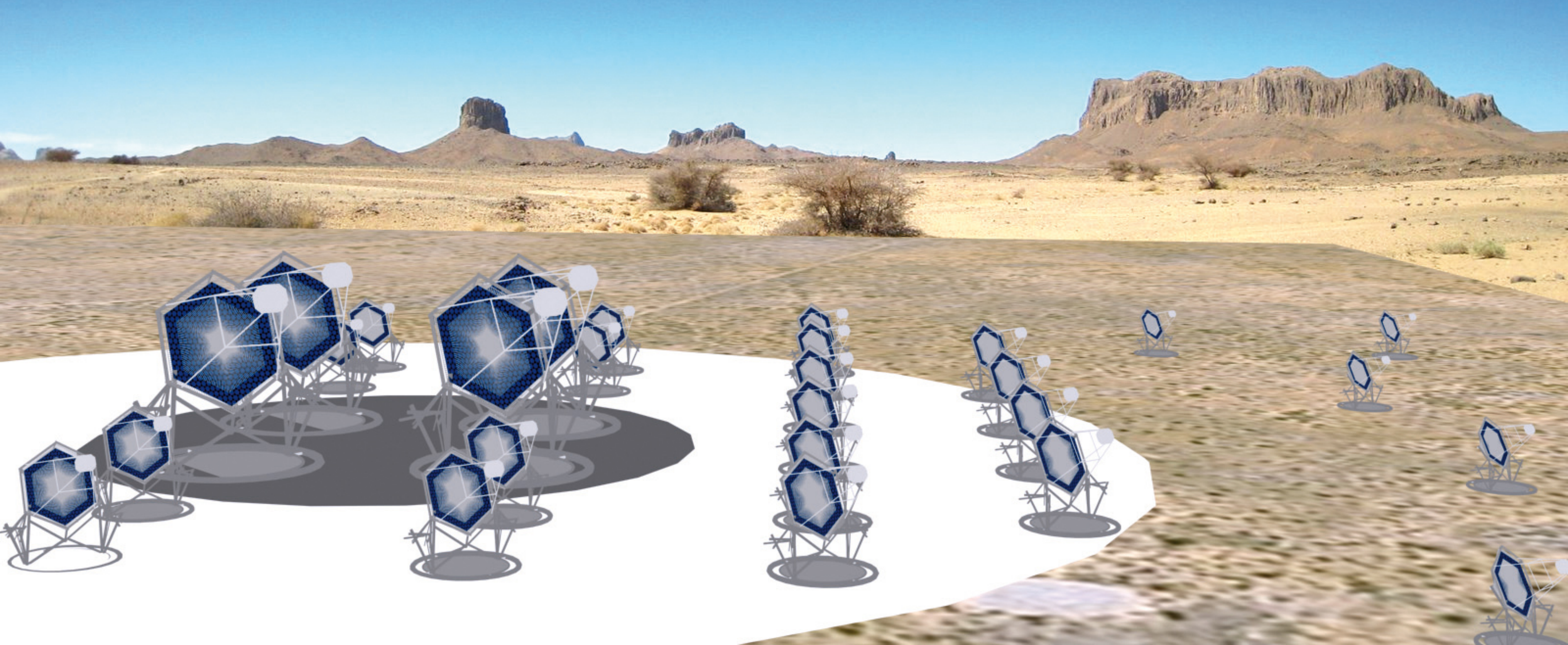
- Relevant transients: GRBs, XRFs, orphan afterglows (radio/optical/x-ray), shock breakout, nearby SN Ib/c
- Host galaxies (SFR, type, z, Z, GRB location; Progenitors)
- Polarimetry (radio, optical, x/γ-ray; outflow acceleration and composition, prompt emission mechanism, jet structure)
- Multi-wavelength: (radio, optical, x-ray, MeV, GeV, TeV composition, collimation, emission mech., afterglow, μ-phys)
- Multi-messenger: (GW, HE ν's, UHECR; progenitors, central engine, outflow composition, emission mechanism)
- Early obs.: (prompt, afterglow onset; composition/acc., Γ_0)
- Calorimetry: (radio, γ-ray, SN; central engine, beaming)
- Also: late flares, mini-SN, GRB-SN, spectroscopy

Prospects for Future: Instruments

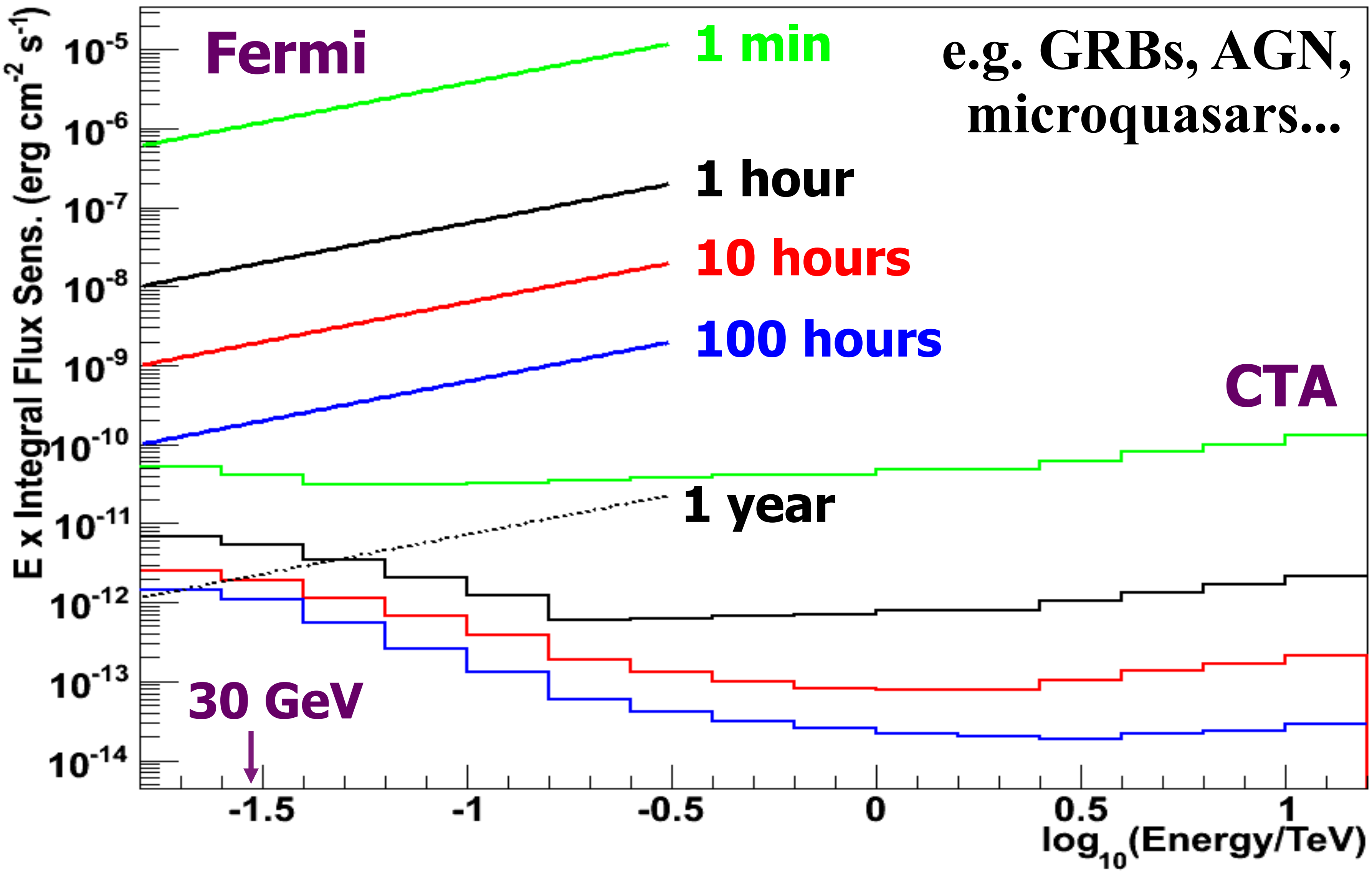
- SVOM: French-Chinese satellite, launch ~ 2014(?) γ-rays, X-ray & optical-NIR telescopes, ~ 80 GRB/yr expected
- GW: LISA pathfinder (2013), advanced LIGO (2014), LISA?
- HE neutrinos: Ice Cube (Dec. 2010), KM3NeT (?)
- Radio: EVLA, LOFAR, SKA (?)
- Infrared: ALMA (2012-13), JWST (2018?)
- Optical: TMT (30 m; ~2020?), E-ELT (39 m; ~2022?)
- X-ray: SVOM, polarimetry (POLAR, NHXM, POLARIX, HXMT, XPOL)
- MeV: Fermi/GBM, SVOM,… ?
- GeV: Fermi,… ?
- TEV: Cherenkov Telescope Array (CTA)

The Future - CTA

- **A 20 GeV to 500 TeV Observatory**
  - an order of magnitude more sensitive than current instruments around 1 TeV (£100M price tag), better angular/energy resolution
  - Preparatory Phase 2010-2013, construction 2013-2018
- **CTA consortium: ~ 700 members from 25 countries**



A bigger difference for transient sources



Conclusions:

- GRBs is an observationally driven field: progress is usually the result of important new observations
- After >40 years from the discovery of GRBs, we still don't understand many basic aspects of this phenomena
- In particular: additional GRB classes, SHB progenitors, GRB/SN explosion, acceleration, composition, angular structure, prompt emission/dis., afterglow, microphysics
- New observations can help improve our understanding: transient searches, rapid follow-up, polarimetry, calorimetry multi-wavelength, multi-messenger, hosts, new surprises…
- Theoretical work can help understand the observations & relevant physics: perhaps solve some open questions