What we Know, Don't Know, or Would Like to Know about Gamma-Ray Bursts

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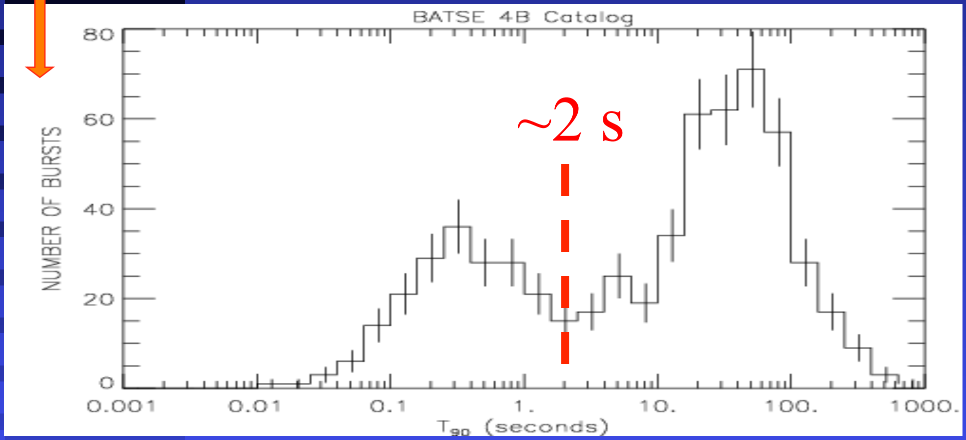
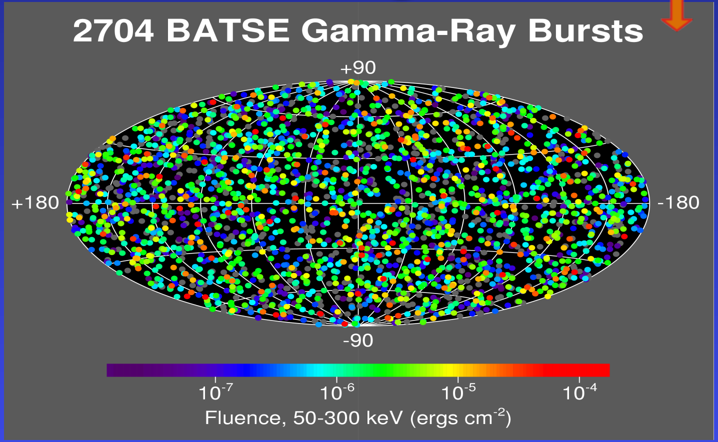
Outline of the Talk:

- **GRB**s: short historical overview (obs. driven field)
- Observational constraints ⇒ theoretical framework
- **Progenitors** of long and short GRBs
- The **Central Engine**: accreting BH vs. ms-magnetar
- **Outflow** acceleration and composition
- **Jets**, **beaming**, **energy** budget & true **event rate**
- **Prompt emission**: dissipation, emission mechanism
- **Afterglow**: model vs. observations
- **Shock microphysics**
- **How can new observations help?**
- **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: the launch of CGRO with BATSE lead to significant progress in our understanding of GRBs
  - **Isotropic dist. on sky**: favors a cosmological origin
  - **Bimodal duration** distribution: **short** vs. **long** GRBs





- **BeppoSAX** (1996–2002): led to **afterglow** discovery (1997) in X-rays, optical, radio (for long GRBs)

- This led to **redshift** measurements: clear determination of **distance/energy** scale (long GRBs) $E_{\gamma,iso} \sim 10^{52}$ - 10^{54} erg
- Afterglow observations provided information on beaming (narrow jets: $E_\gamma \sim 10^{51}$ erg), event rate, external density, supernova connection (⇒ long GRB progenitors)

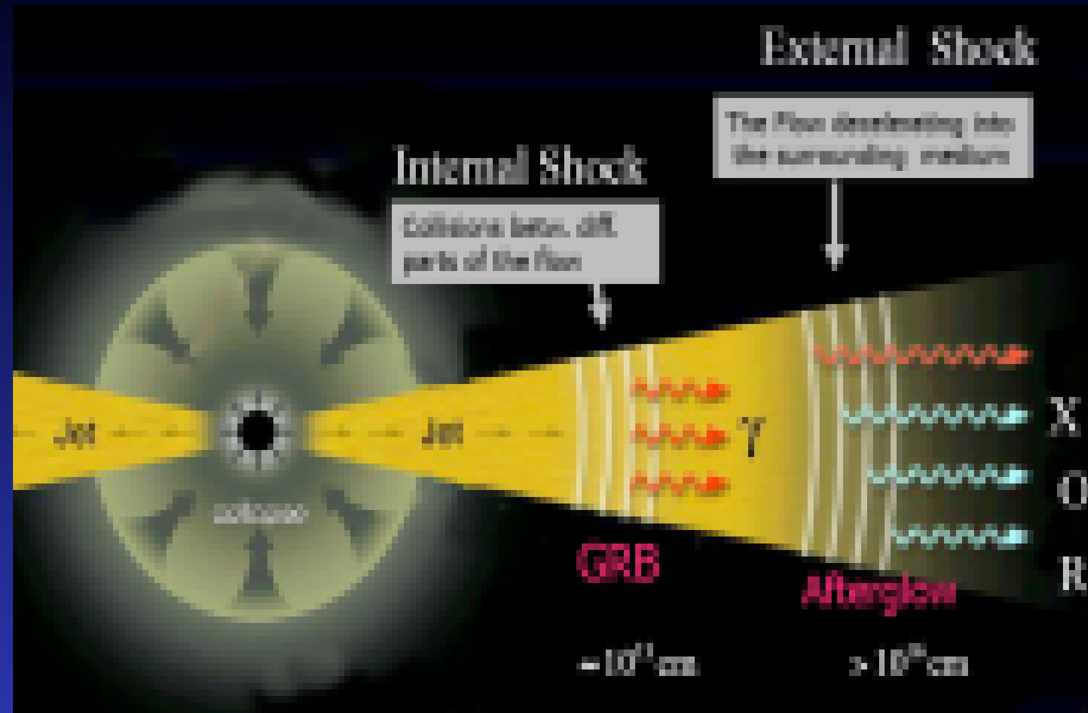
- **Swift** (2004-?): autonomously localizes GRBs, slews (in ~1-2 min) and observed in X-ray + optical/UV
  - Discovered unexpected behavior of early afterglow: rapid decay phase, plateaus, flares, chromatic breaks
  - Led to the discovery of **afterglow** from **short** GRBs → **host galaxies**, redshifts, energy, rate, clues for progenitors
- **Fermi** (2008-?): high-energy emission - delayed onset, long lived emission, distinct high-energy component, high Γ_{min}, short GRBs show a smaller delay + harder spectrum

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**
- +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, SN associations
- **Afterglow**: broad-band spectrum, optical/NIR polarization, radio afterglow image size (GRBs 970508, **030329**)

GRB Theoretical Framework:

- **Progenitors**:
  - Long: massive stars
  - Short: 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 the external medium; as the shock decelerates the typical frequency decreases: X-ray ➔ optical ➔ radio

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 progenito'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? $T_{\text{spin-down}} \sim T_{\text{GRB}} \Rightarrow B > \mathbf{10^{16.5}}$ **G**
  - Usual magnetar formation requires: suppression of SN emission, located in massive star forming regions ⇒ unconventional formation: AIC of WD, NS-NS merger
- accreting **BH** (possibly from a binary merger):
  - $T_{\text{GRB}} \sim$ 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)

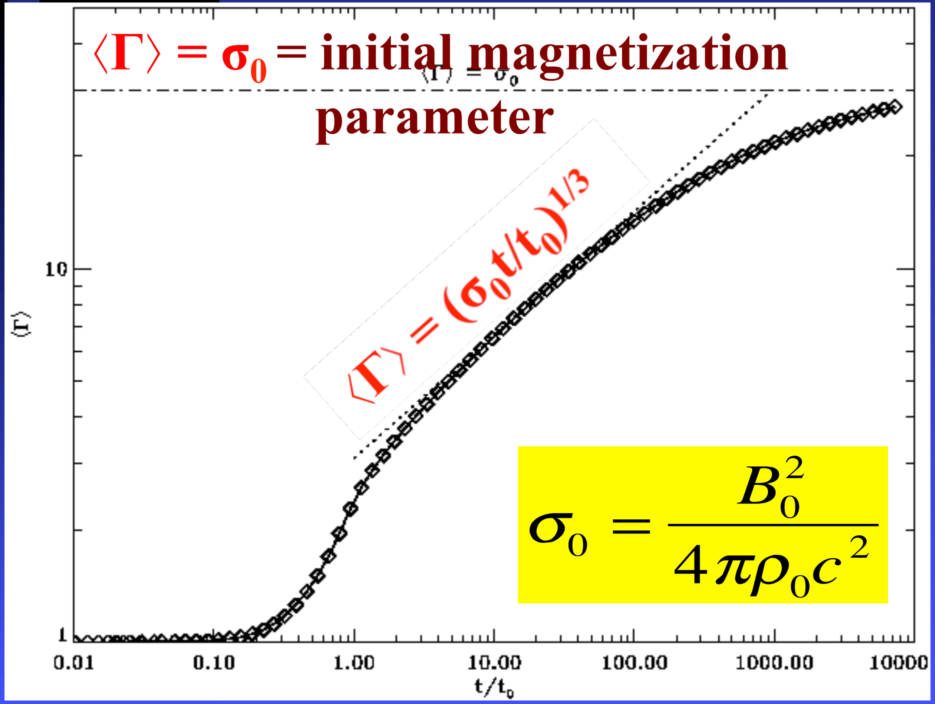
Outflow Acceleration & Composition:

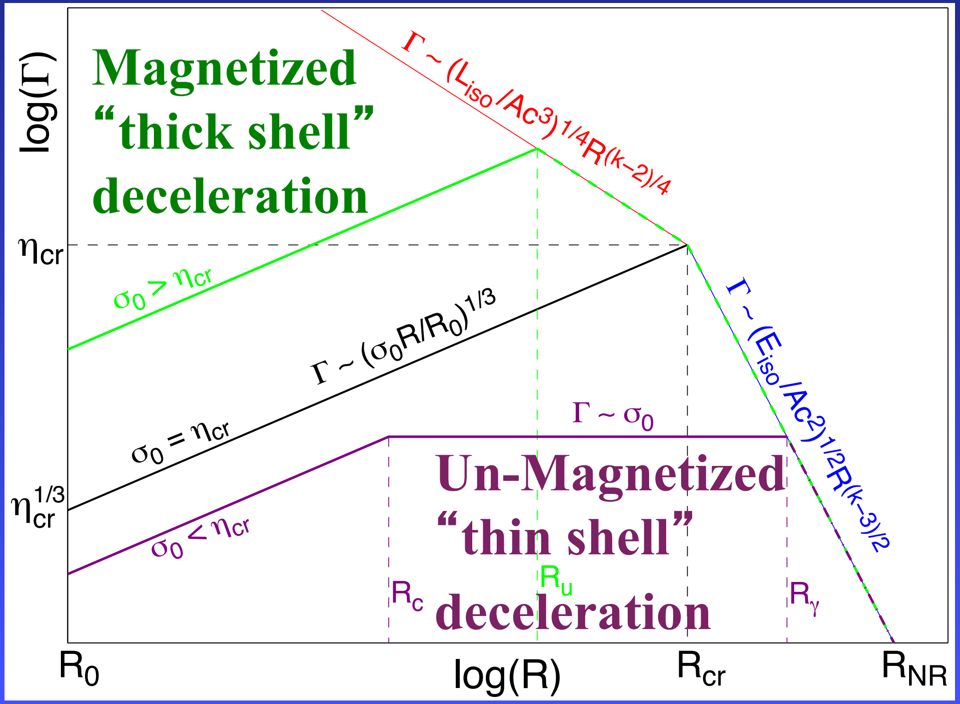
- **Fireball**: thermal (radiation pressure) acceleration
  - Fast ($\Gamma \propto R$), robust, allows efficient internal dissipation
  - Baryon kinetic energy eventually dominates
  - Requires a small baryon loading ($\sim 10^{-5}\ M_\odot$)
- **Magnetic** acceleration: Poynting flux dominated jets
  - 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 2010; arXiv:1004.0959)

- $\langle\Gamma\rangle(t_0) \approx \sigma_0^{1/3}$, $< \langle\Gamma\rangle(t_0 < t < t_c) \propto t^{1/3} \propto R^{1/3}$, $t_c \sim t_0\sigma_0^2$
- For $\sigma_0 < \eta_{cr}$: $\langle\Gamma\rangle \approx \sigma_0$, $\langle\sigma\rangle \approx t_c/t < 1$ at $t > t_c \Rightarrow$ full conversion of magnetic to kinetic energy: allows efficient internal shocks
- Acceleration & deceleration by ext. medium: **tightly coupled**





Jets, beaming, true energy & event rate

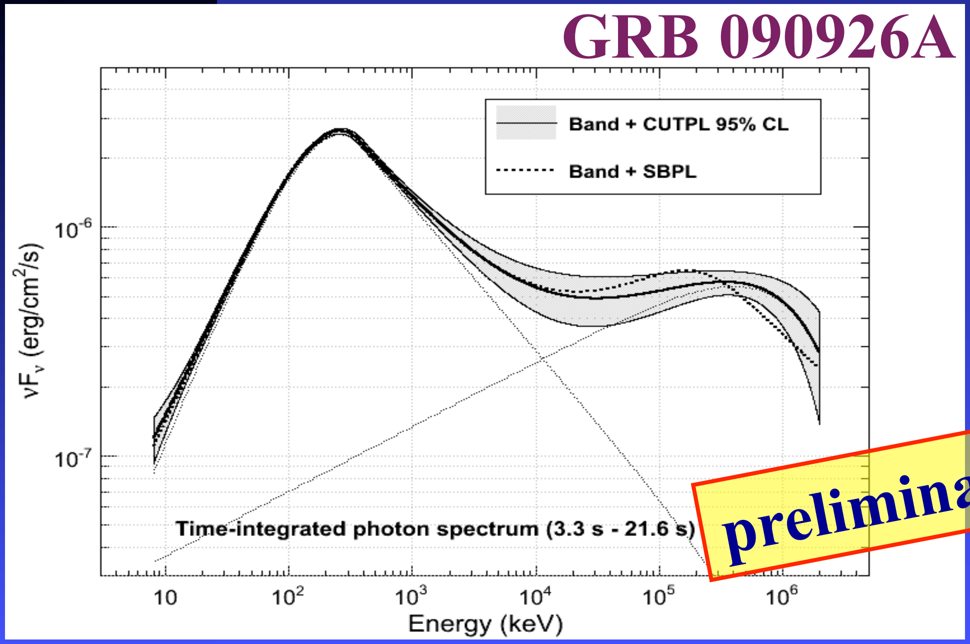
- Evidence of Jets: analogy to AGN/μQ, $E_{\gamma,iso} \gtrsim 10^{54}$ erg jet break, LSB: spherical explosion can't produce $E \gtrsim 10^{51}$ erg in ejecta with $\Gamma \gtrsim 100$ (no "smoking gun")
- Jet structure: unclear (uniform, structured, hollow cone,...)
  - Affects $E_{\gamma,iso} \rightarrow E_\gamma$ & observed GRB rate → true rate
  - Viewing-angle effects (afterglow & prompt - XRF)
  - Can also affect late time radio calorimetry
- Some **Open Questions**: the jet angular structure, role of viewing effects in the observed properties, true energy budget and GRB event rate,…
- Relevant **observations**: orphan afterglow surveys, polarization L.C., good multi-wavelength afterglow L.C., radio calorimetry, nearby GRB / radio SN Ib/c

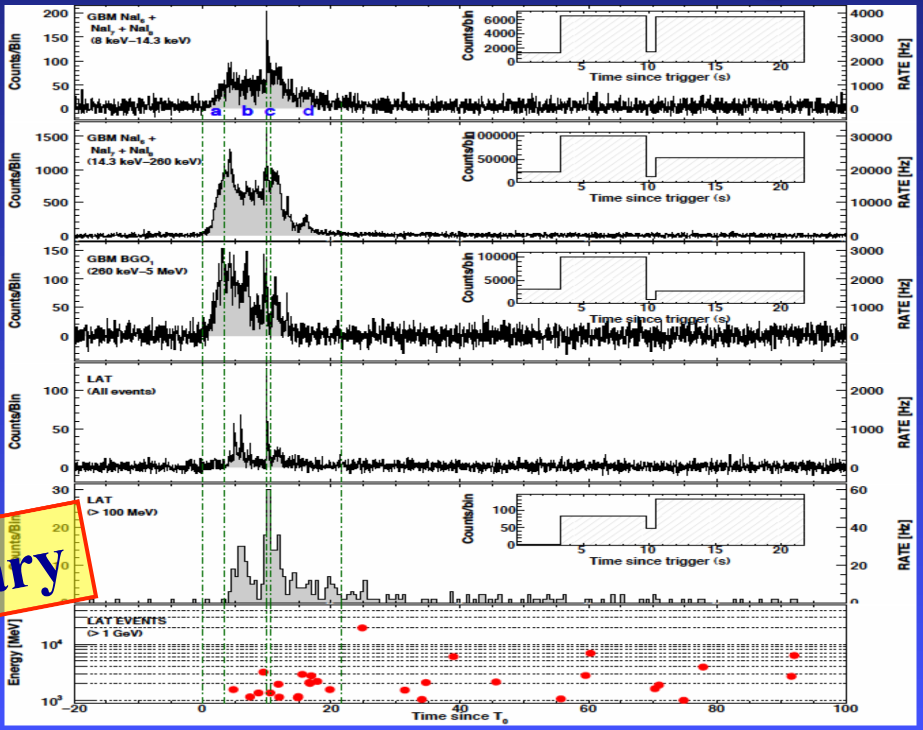
Prompt emission maechanism, dissipation

- **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)
- Some **Open Questions**: the dominant dissipation & emission mechanisms, identity of distinct spectral components at high/low energies, Γ_0, …
- Relevant **observations**: prompt optical, x-ray, MeV, GeV, TeV; x/γ-ray polarimetry; HE ν's, UHECRs

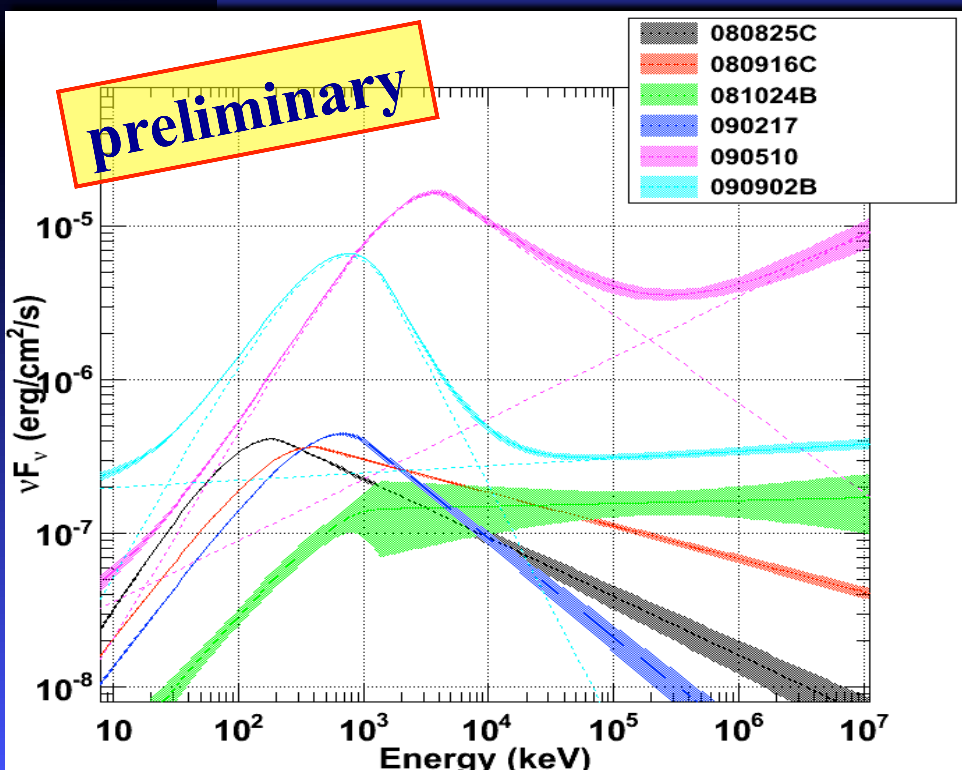
Recent Progress: Fermi Observations

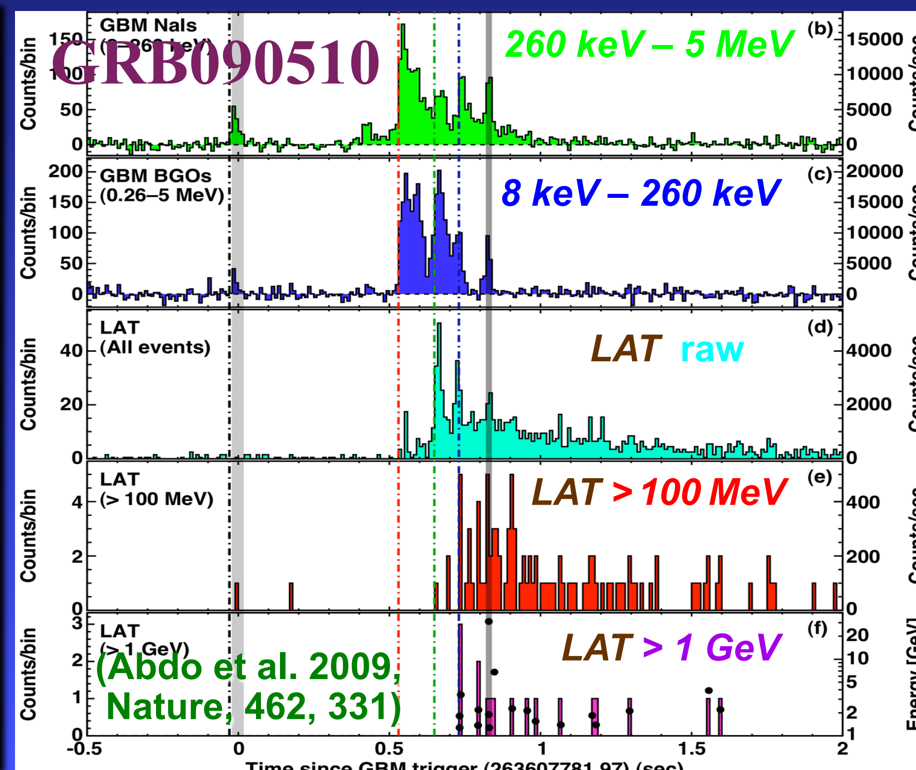
- Γ_{min}: no high-energy cutoff due to intrinsic pair production ⇒ strict lower limits on Lorentz factor of the emitting region
- For bright LAT GRBs (long/short): $\Gamma \gtrsim 10^3$ for simple model (steady-state, uniform, isotropic) but $\Gamma \gtrsim 10^{2.5}$ for more realistic time-dependent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





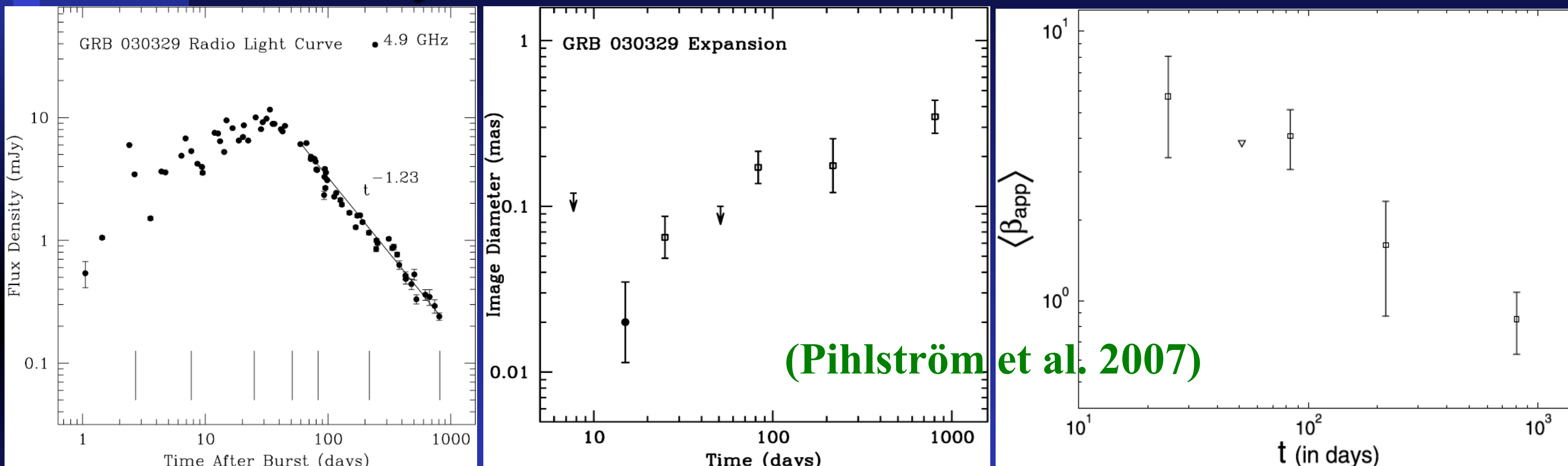
- **Distinct spectral component** at high (+sometimes also low) energies in 3/4 brightest LAT GRBs ⇒ intrinsically common
- **Delayed onset** of HE emission (LSB: ~4-10 s; SHB: ~0.1-0.2 s)
- **Long lived** HE emission ($\lesssim 10^2$-10^4 s; HE afterglow onset?)
- The prompt emission mechanism is still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





Afterglow: what we know or don't know

- decelerated expansion GRB 030329 afterglow image
  ⇒ caused by interaction with the external medium

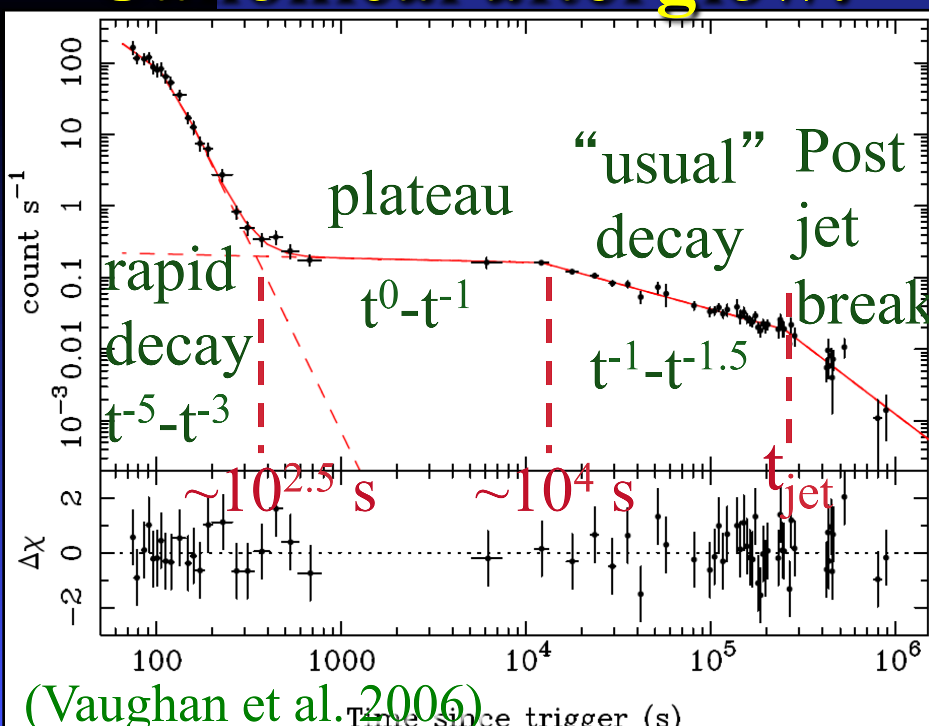


(Pihlström et al. 2007)

- 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

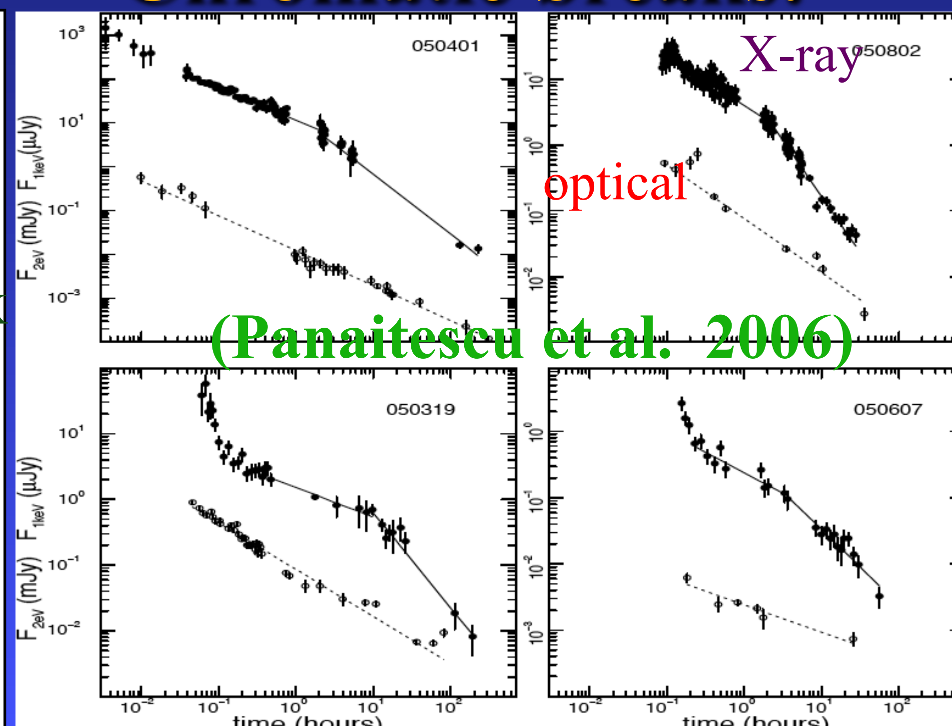
- **Rapid decay phase**: tail of prompt emission (smooth temporal/spectral transition) HLE? late residual emission?
- **Plateau**: energy injection? time varying microphysics? viewing angle effects? deceleration of slow wide 2nd jet?
- **Flares**: similar properties to prompt ⇒ likely similar origin
- Chromatic breaks +dim early optical, few jet breaks, α-β closure

Canonical afterglow:



(Vaughan et al. 2006)

Chromatic breaks:



(Panaitescu et al. 2006)

Relevant observations

- **Rapid decay phase**: early x+γ-ray obs. + 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: $\varepsilon_e, \varepsilon_B, \xi_e, p, \ldots$
- State of the art – PIC simulations: $\varepsilon_e \gtrsim 0.1, \varepsilon_B \gtrsim 0.01, \xi_e \sim 0.01, p \sim 2.4 \pm 0.1$; dynamical scale still not realistic
- Relevant observations: detailed optical+x-ray+**GeV**
- More theoretical (analytic/numerical) work is needed

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

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
- E.G.: transient searches, rapid follow-ups, polarimetry, multi-wavelength, multi-messenger, hosts, calorimetry
- New observations can always provide new surprises that help drive progress in unexpected ways