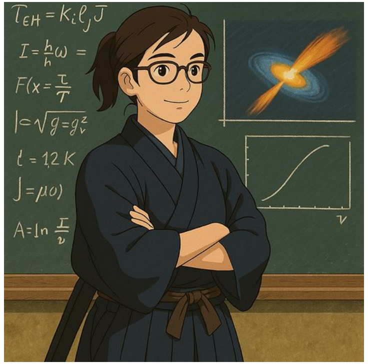
Εκλάμψεις Ακτίνων γ
Gamma-Ray Bursts

11 Ιουλίου 2026
Πάρκο Εθνικής Συμφιλίωσης

Μαρία Πετροπούλου

HELLENIC REPUBLIC
National and Kapodistrian University of Athens

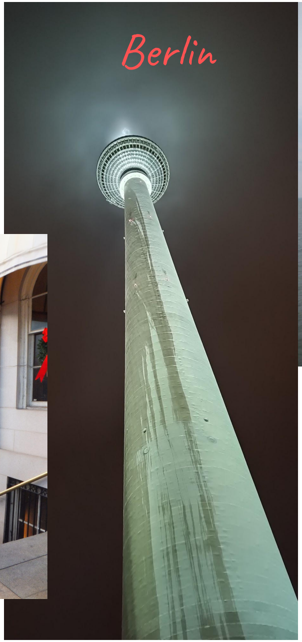
A few words about me



Main research interests

- Non-thermal radiative transfer
- Particle acceleration processes (magnetic reconnection)
- Astroparticle physics (high-energy neutrinos, cosmic rays)
- Modeling of high-energy astrophysical sources
  - Steady sources: Relativistic jets, cores of active galaxies
  - Transient sources: GRBs

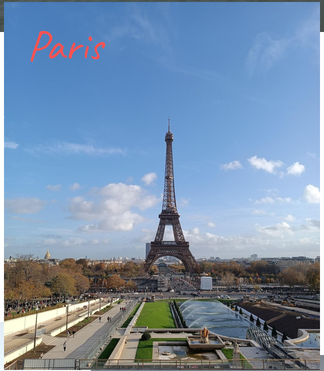

Indiana


Berlin


Atlantic City


Hawai'i


Boston


Paris


Indiana
Maze
Entrance

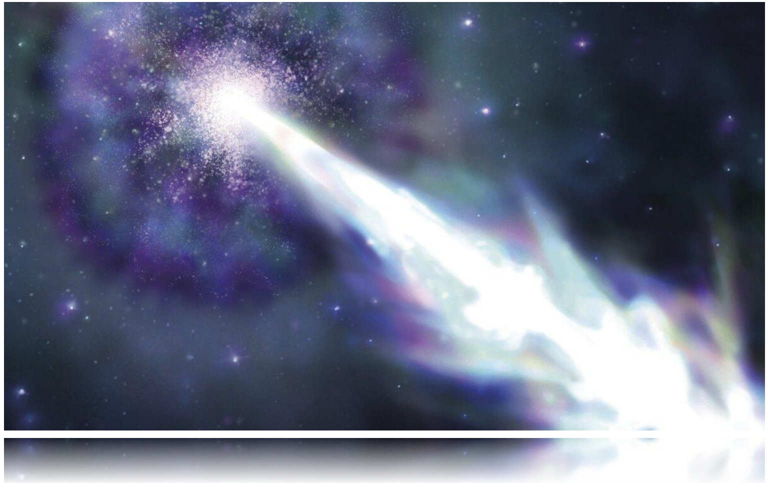

Washington D.C. -
"Reflecting Pool"


Strasbourg


Geneva

Lecture plan

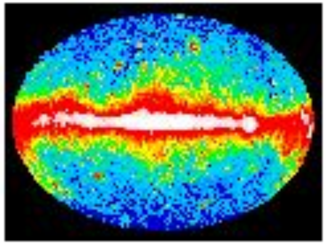
- Part 1: Introduction to Gamma-Ray Bursts (GRBs)
- Part 2: Introduction to GRB afterglows
- Part 3: Theory of GRB afterglows
- Part 4: Demonstration of *AfterglowPy*



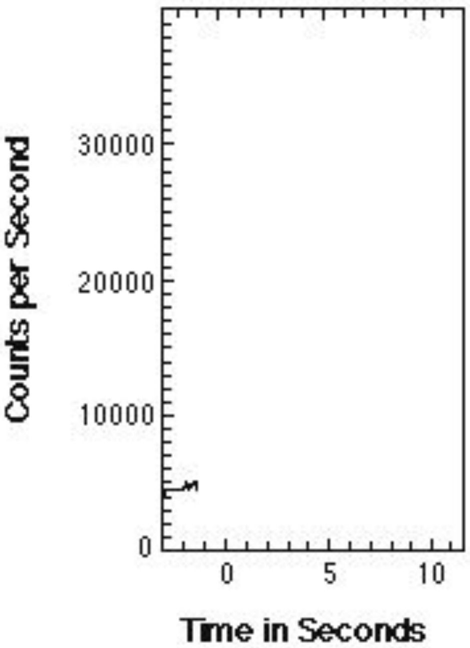
Part 1

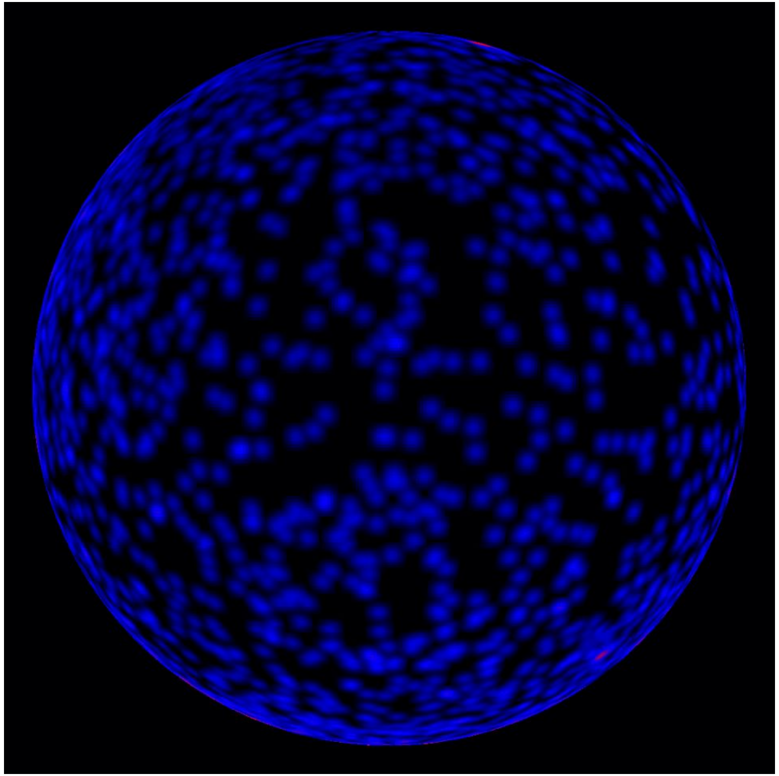
Introduction to GRBs

What are Gamma-Ray Bursts?



Credit: BATSE/CGRO



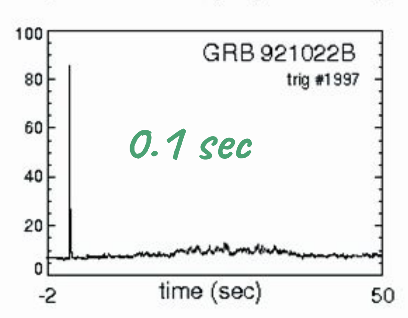


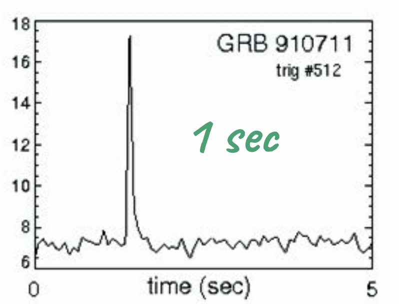
Credit: NASA/DOE/Fermi LAT Collaboration

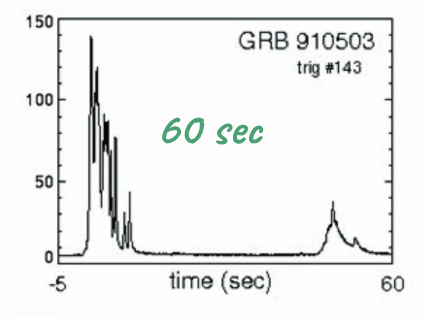
What are Gamma-Ray Bursts?

- Intense flashes of γ-ray radiation
- Short durations: ~0.1 s to 100 s
- Variability timescales:
  Δt_{var} ~ ms to 1s
- Causality argument*:
  $R < c\,\Delta t_{var} \sim (3 \times 10^7 - 10^{10})$ cm

  *ignoring relativistic effects







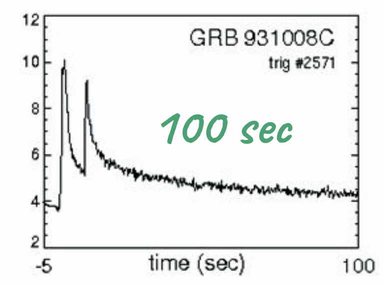
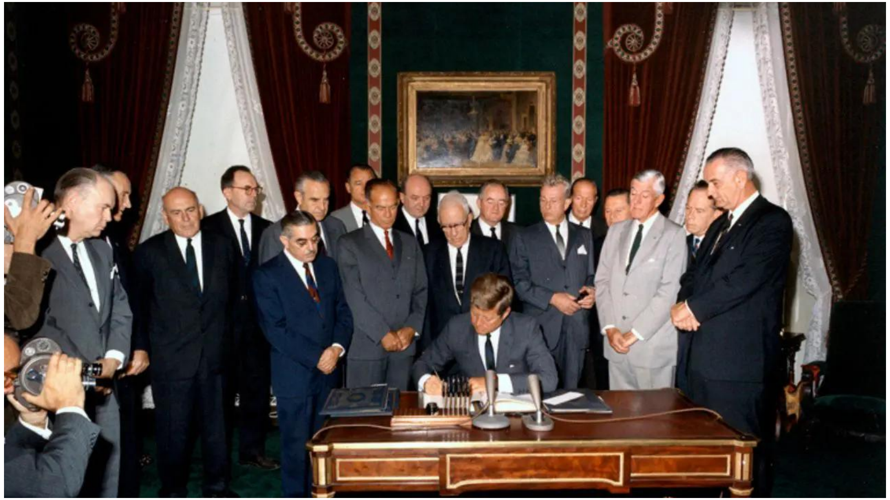


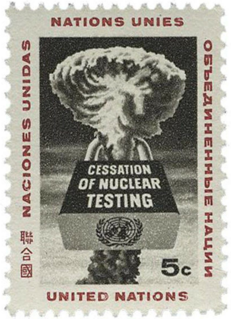
Image Credit: NASA/Marshall Space Flight Center/Space Sciences Laboratory

A random discovery

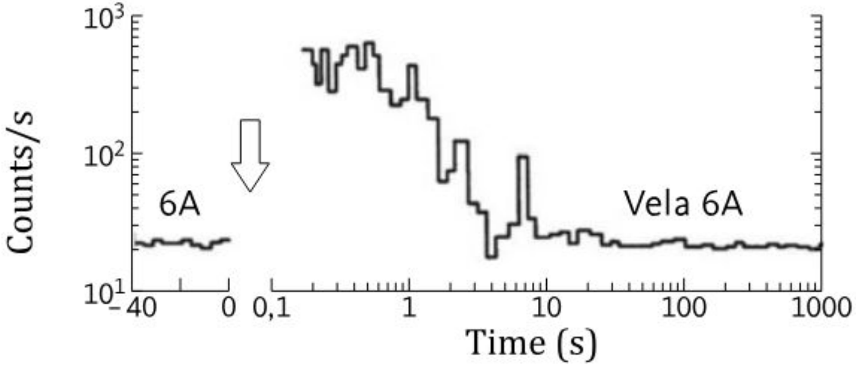


Partial Nuclear Test Ban Treaty, 1963

(Image Credit: The John F. Kennedy Presidential Library and Museum, Boston)

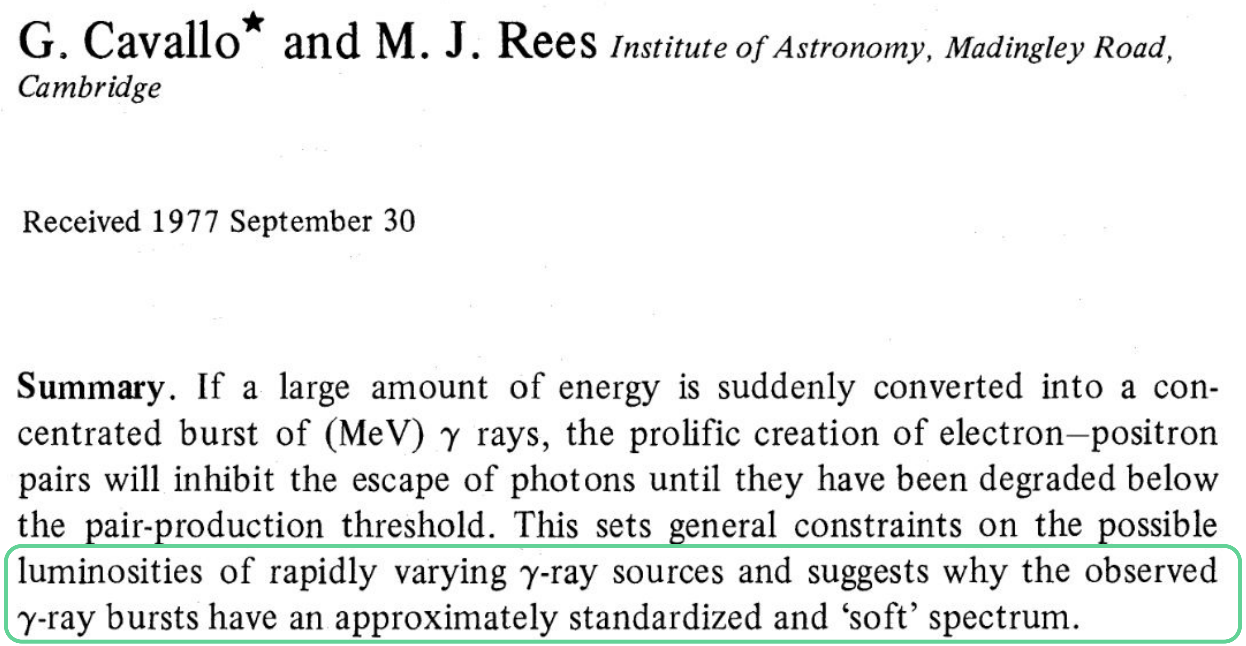


The first γ-ray flash (1967)



Klebesadel, Strong, Olson, 1973, *ApJ*

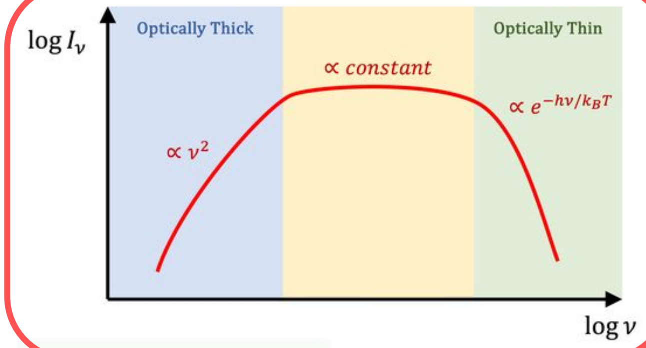
Cosmic Fireballs

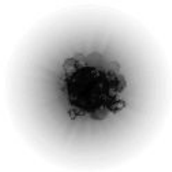

G. Cavallo* and M. J. Rees *Institute of Astronomy, Madingley Road, Cambridge*

Received 1977 September 30

Summary. If a large amount of energy is suddenly converted into a concentrated burst of (MeV) γ rays, the prolific creation of electron–positron pairs will inhibit the escape of photons until they have been degraded below the pair-production threshold. This sets general constraints on the possible luminosities of rapidly varying γ-ray sources and suggests why the observed γ-ray bursts have an approximately standardized and 'soft' spectrum.

Cosmic Fireballs





The γ-ray fireball: e^-e^+p plasma and photons

Key physical processes:

1. Creation of e^+e^- pairs:
   $\gamma + \gamma \rightarrow e^+ + e^-$, $p + \gamma \rightarrow p + e^+ + e^-$

   a. Energy threshold: $\varepsilon_1\varepsilon_2(1-\cos\theta) \geq 2\left(m_e c^2\right)^2 \rightarrow \varepsilon \sim 1\left(m_e c^2\right)$

   b. Cross section: $\sigma_{\gamma\gamma} \sim \sigma_T/\varepsilon^2$

   c. Degradation of γ -ray photon energy

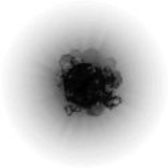
2. Creation of γ-ray photons:
   Bremsstrahlung, $e^+ + e^- \rightarrow \gamma + \gamma$

3. Compton scattering:
   $e + \gamma \rightarrow e + \gamma$

   a. Cross section: $\sigma_T = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2$

   b. Diffusion of photons when $\tau_T >> 1$

Cosmic Fireballs



Fireball Mass: $M_i \sim n_i m_p R^3 \; (n_p = n_e = n_i)$

Fireball Energy: $E_f = 10^{38}\, erg \left(\frac{D}{100\, pc}\right)^2 \left(\frac{\Phi_\gamma}{10^{-4}\, erg\, cm^2}\right) = \eta M_i c^2$

It can be smaller or larger than 1

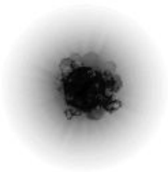
Fireball Luminosity: $L \sim \frac{E_f}{t_{\gamma,\, diff}} \sim \frac{c}{R} \frac{E_f}{\tau_T}$

Fireball adiabatic expansion: $t_{exp} \sim \frac{R}{u} << t_{\gamma, diff}, \quad if \quad \tau_T >> \frac{c}{u}$

$\varepsilon \sim R^{-1} \rightarrow E_f \sim R^{-1} \rightarrow u \nearrow$

$E_{tot} = const = E_{f,\, i} = E_{k,\, \infty} \Rightarrow u_\infty \sim \eta^{1/2} c$

Cosmic Fireballs



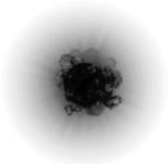
Optical depth to Thomson scatterings: $\tau_T = n_e \sigma_T R = \frac{M_i}{V\, m_p}\, \sigma_T R = \frac{1}{\eta}\, \frac{E_f\, \sigma_T}{m_p\, c^2 R^2} = \frac{\theta^*}{\eta}$

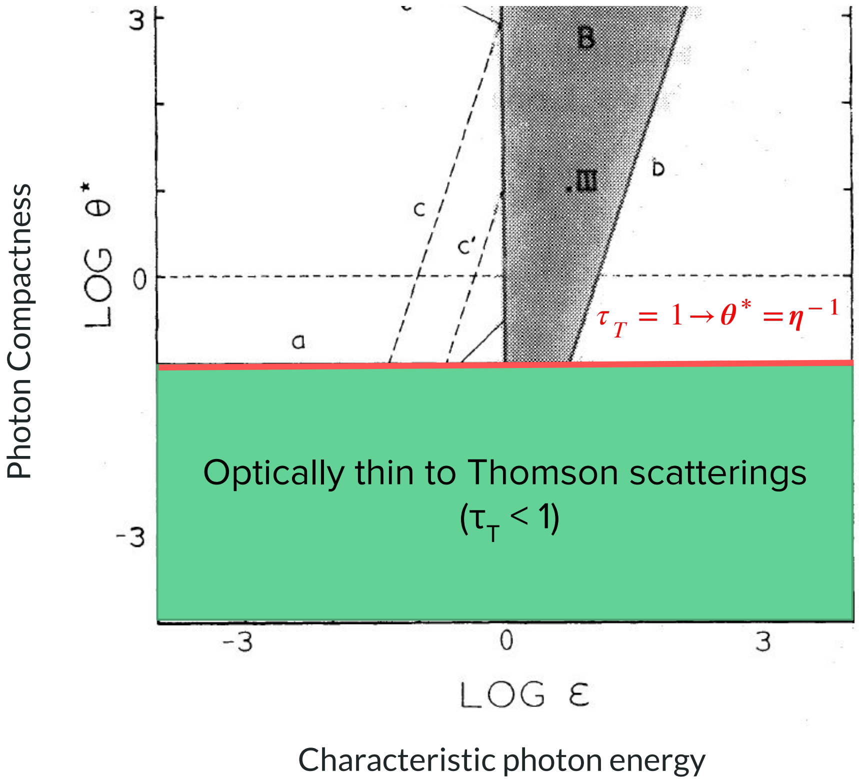
Optical depth to γγ interactions: $\tau_{\gamma\gamma} = n_\gamma\, \sigma_{\gamma\gamma} R = \frac{E_f}{V\, \varepsilon_i\, m_e c^2}\, \frac{\sigma_T}{\varepsilon_i^{\,2}} R = \frac{m_p}{m_e}\, \frac{\theta^*}{\varepsilon_i^{\,3}} \sim 184\, \frac{\theta_2^{\,*}}{(\varepsilon_{i,\,1})^3}$

Photon compactness: $\theta^* \equiv \frac{\sigma_T L}{m_p c^3 R} = \frac{E_f\, \sigma_T}{m_p\, c^2 R^2} \sim \mathbf{440}\, \frac{E_{f,38}}{R_7^{\,2}}$

Dimensionless measure of radiation energy density !

Cosmic Fireballs

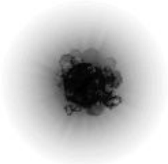


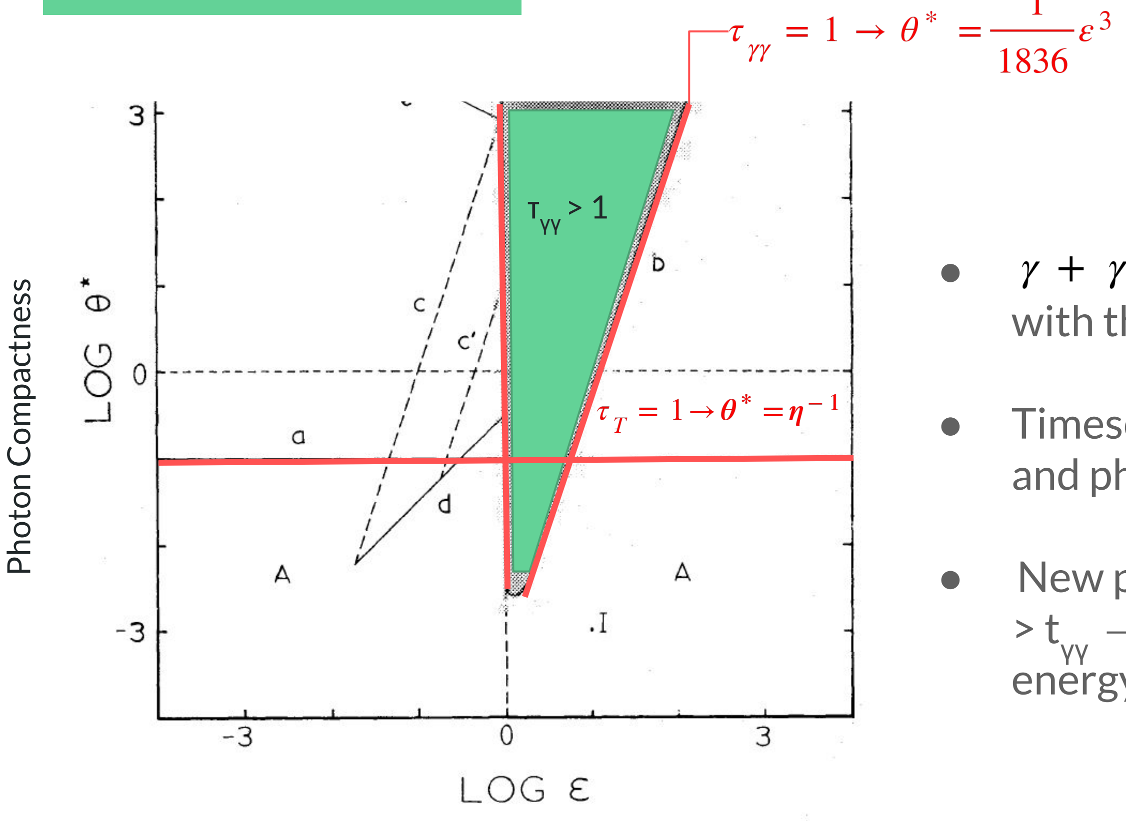


Region A

- Radiation escapes on a timescale R/c
- Photon spectrum reflects the photon production processes
- No spectral modifications due to scatterings

Cosmic Fireballs



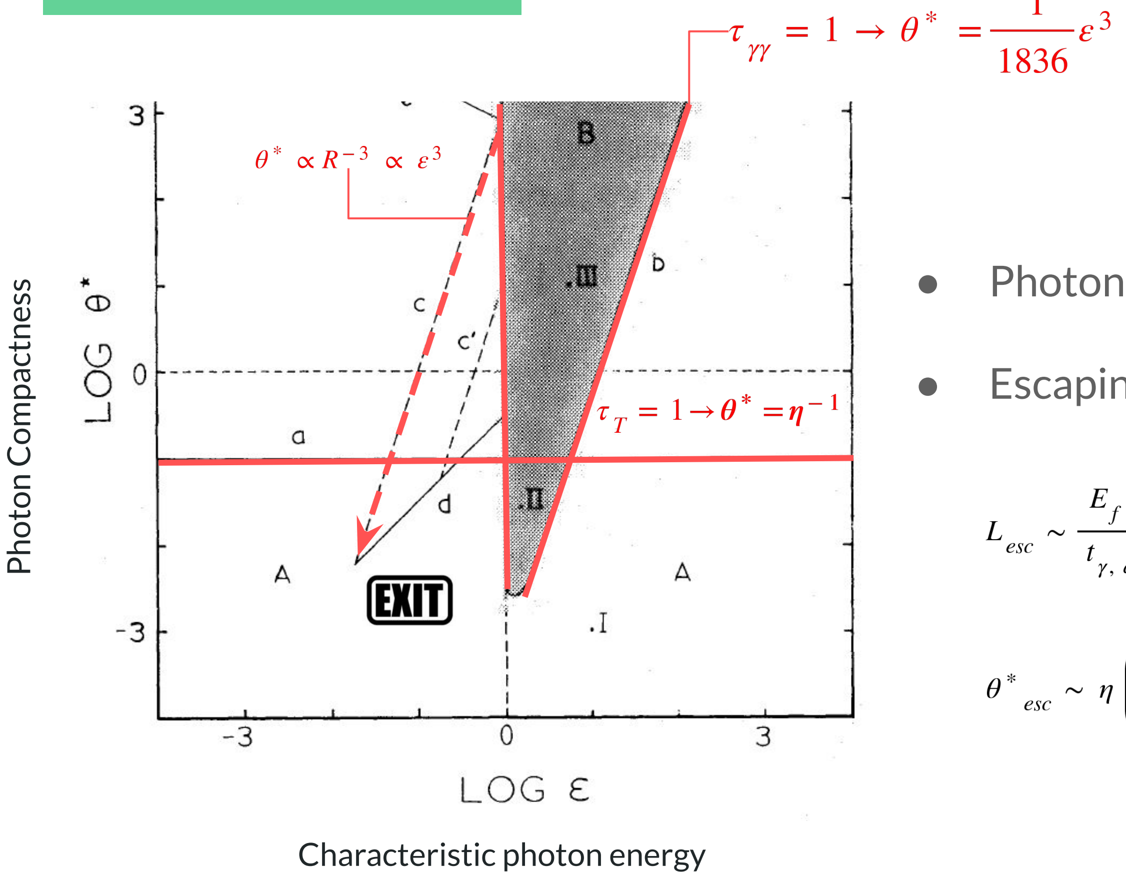


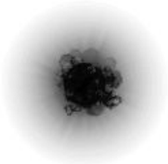
Characteristic photon energy

Region B

- $\gamma + \gamma \leftrightarrow e^- + e^+$ → lepton-photon gas with the same temperature
- Timescale $t_{\gamma\gamma}$ << timescale for photon escape and photon creation
- New photons from bremsstrahlung on t_{brem} > $t_{\gamma\gamma}$ → more particles share the same total energy → individual photon energy drops !

Cosmic Fireballs





Region B

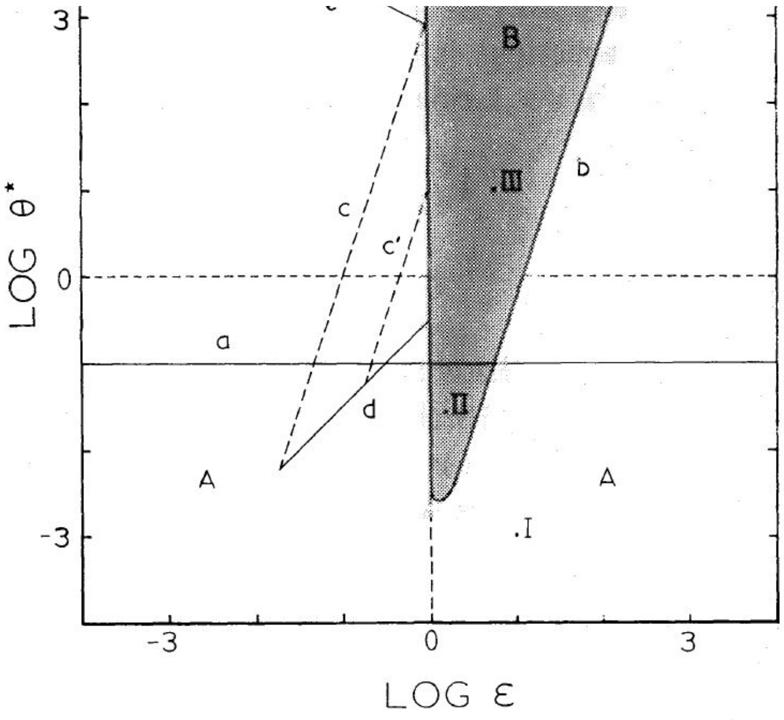
- Photons escape : $t_{\gamma,diff} \sim t_{exp} \longrightarrow R_{esc} \sim R_i(\tau_{T,i})^{\frac{1}{2}}\eta^{\frac{1}{4}}$
- Escaping photon luminosity:

$$L_{esc} \sim \frac{E_{f,esc}}{t_{\gamma,\,diff}} \sim E_{f,i}\left(\frac{R_i}{R_{esc}}\right)\frac{c}{R_{esc}\,\tau_{T,esc}} \sim \eta\,\frac{R_i}{\sigma_T}m_p c^3$$

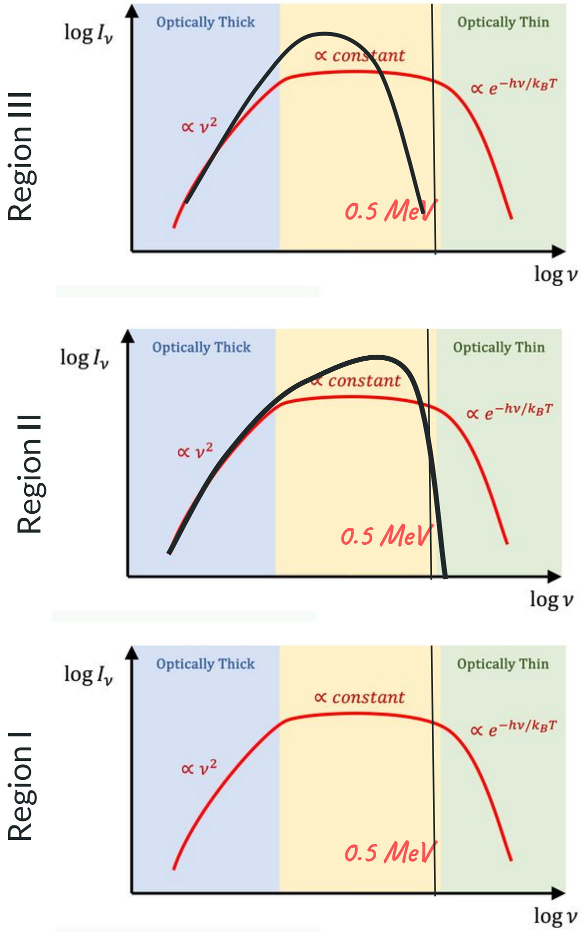
$$\theta^*_{esc} \sim \eta\left(\frac{R_i}{R_{esc}}\right) = \eta^{\frac{3}{4}}(\tau_{T,i})^{-\frac{1}{2}} << 1$$

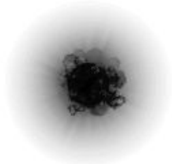
Cosmic Fireballs

Photon Compactness



Characteristic photon energy





Disclaimer! These are not realistic spectra.

The “Great Debate” of 1995

… which lasted about two decades (1973 - 1997*)

Schedule

1:00 pm
Introductory Lectures

Opening: Robert Nemiroff (2 minutes)
Lecture: The 1920 Shapley - Curtis Discussion: Background, Issues, and Outcome; Virginia Trimble (40 minutes)
Lecture: Gamma-Ray Bursts: A Brief Introduction; Gerald Fishman (40 minutes)

Intermission

2:30 pm
Debate

Moderator: Sir Martin Rees

Opening Argument: Bohdan Paczynski (Cosmological viewpoint, 20 minutes)
Opening Argument: Donald Lamb (Galactic viewpoint, 20 minutes)

Rebuttal: Bohdan Paczy ski (15 minutes)
Rebuttal: Donald Lamb (15 minutes)

Martin Rees Question to Donald Lamb (5 minutes)
Martin Rees Question to Bohdan Paczynski (5 minutes)

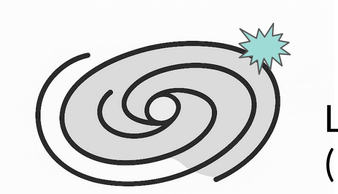
Closing Statement: Donald Lamb (10 minutes)
Closing Statement: Bohdan Paczynski (10 minutes)
Questions and Comments from the Open Floor (time remaining)

4:10 pm
Closing: Martin Rees
Announcements: Robert Nemiroff

Paczynski, Rees, and Lamb

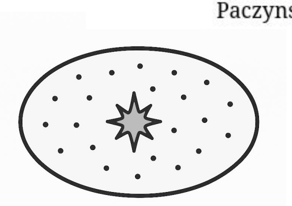
The “Great Debate” of 1995

Paczynski, Rees, and Lamb



Lamb’s school
(University of Chicago)

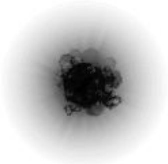
- Galactic sources
- Moderate required energetics: $\approx 10^{37}$ - 10^{40} erg
- Starquakes/magnetospheric flares from pulsars/magnetars
- Anisotropic distribution (e.g. disk)



Paczyński’s school
(Princeton University)

- Extragalactic sources
- Extreme required energetics: $\approx 10^{51}$ - 10^{54} erg >> Solar EM power released in 10 Gyrs !!
- Collapse of AGN cores ??
- Isotropic distribution

The "compactness" problem



If GRBs were found at cosmological distances → opacity to γγ pair production would be huge ! (see also Ruderman 1975, AAS) → Emergent photon spectra would be "soft" thermal → Inconsistent with observed non-thermal spectra

Photon compactness: $\theta^* \sim 4.4 \cdot 10^{16} \frac{E_{f,52}}{R_7^{\,2}}$

Opacity to γγ: $\tau_{\gamma\gamma} \sim 1.8 \cdot 10^{16} \frac{\theta_{16}^{\;*}}{(\varepsilon_{i,1})^3}$

Relativistic fireballs!
(e.g. Goodman 1986, ApJ; Paczynski 1986, ApJ)

$R \sim 2\,\Gamma^2 \Delta t_{obs}$

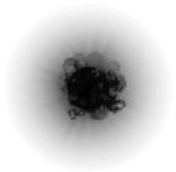
$\varepsilon' = \frac{\varepsilon}{\Gamma}$

$\tau_{\gamma\gamma} \propto \Gamma^{-2\alpha-4} \frac{E_f}{\Delta t_{obs}^{\;2}} \rightarrow \tau_{\gamma\gamma} < 1 \Rightarrow \Gamma > 100$

Relativistic Fireballs

Key assumptions:

- Relativistic lepton-photon plasma (kT >> m_e c^2)
- Spherical symmetry
- Stationary flows



Equation of State equation

$$e = \frac{1}{\hat{\gamma}-1}\frac{P}{\rho_0} \xrightarrow{\hat{\gamma}=\frac{4}{3}} e = 3\frac{P}{\rho_0} \quad (1)$$

Mass continuity equation

$$\frac{\partial}{\partial t}(\gamma\rho_0) + \vec{\nabla}\cdot(\gamma\rho_0\vec{u}) = 0 \Rightarrow r^2\gamma\rho_0 c = const \quad (2)$$

Momentum equation

$$\gamma\rho_0\left(\frac{\partial}{\partial t} + \vec{u}\cdot\vec{\nabla}\right)(\xi\gamma\vec{u}) = -\frac{dP}{dr} \Rightarrow \gamma\rho_0 c^2\frac{d}{dr}(\xi\gamma) = -\frac{dP}{dr} \quad (3)$$

1st Law of Thermodynamics

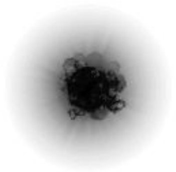
$$\left(\frac{\partial}{\partial t} + \vec{u}\cdot\vec{\nabla}\right)\left(\frac{P}{\rho_0^{\hat{\gamma}}}\right) = 0 \Rightarrow P = K(\rho_0)^{\frac{4}{3}} \quad (4)$$

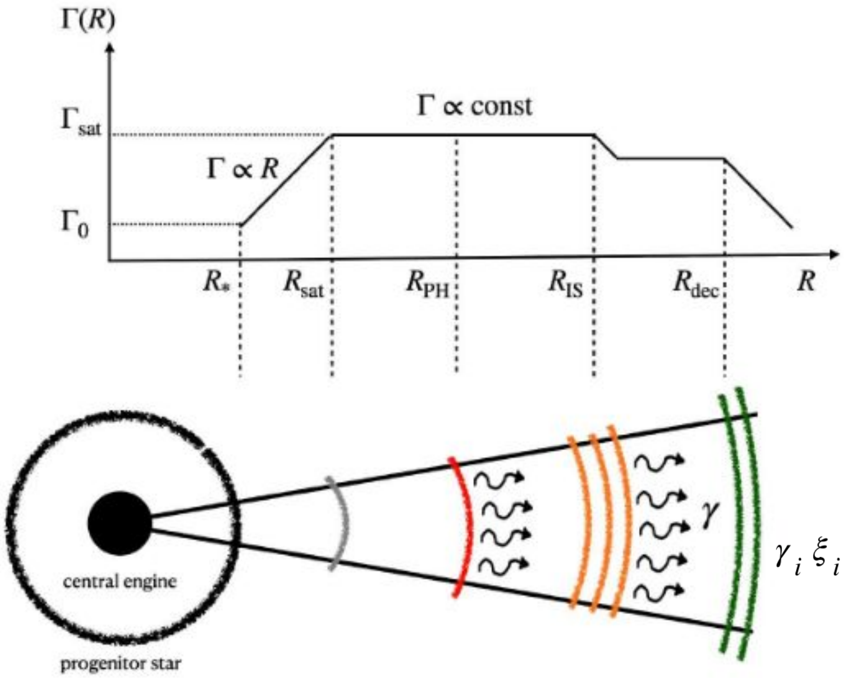
Enthalpy density (normalized)

$$\xi = 1 + \left(\frac{e}{c^2} + \frac{P}{\rho_0 c^2}\right) \xrightarrow[P >> \rho_0 c^2]{Eq.(1)} \xi = 4\frac{P}{\rho_0 c^2}$$

e.g. Paczynski 1986, ApJ

Relativistic Fireballs





Radial dependences:

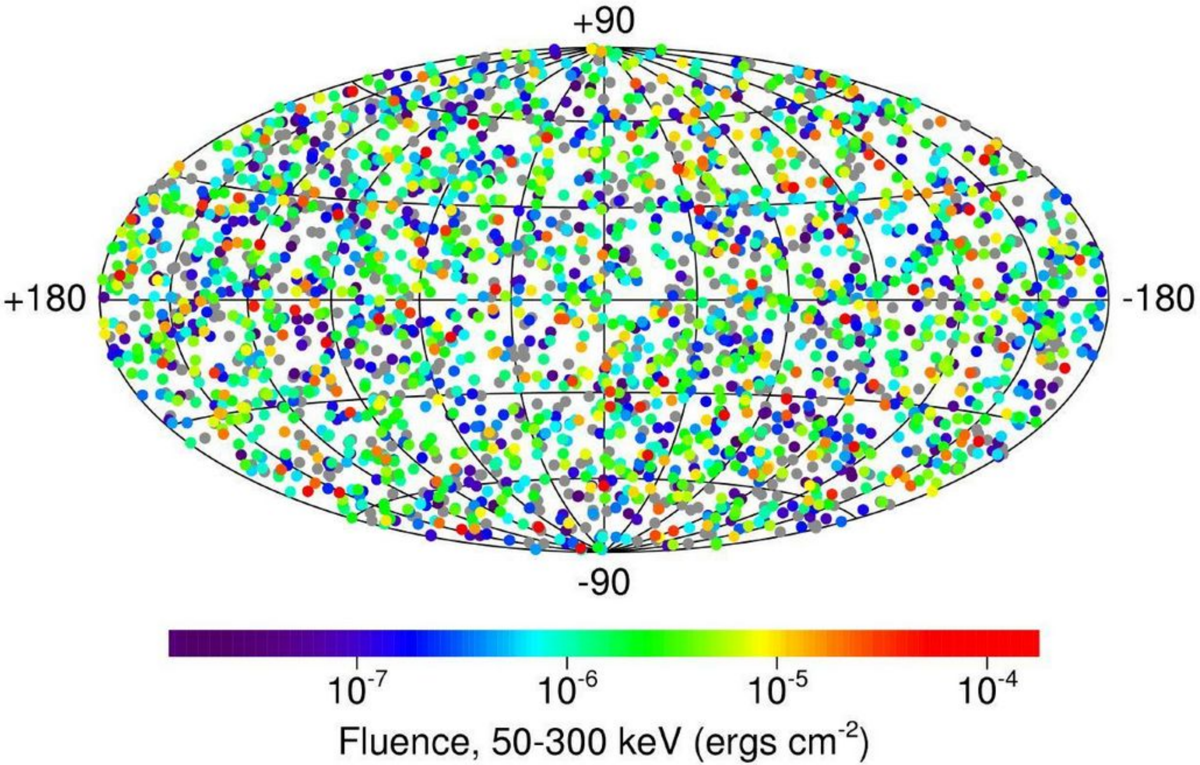
$$\gamma \sim r\,, \quad \xi \sim \frac{1}{r}, \quad \rho_0 \sim \frac{1}{r^3}, \quad P \sim \frac{1}{r^4}, \quad T \sim \frac{1}{r}$$

Asymptotic Lorentz factor:

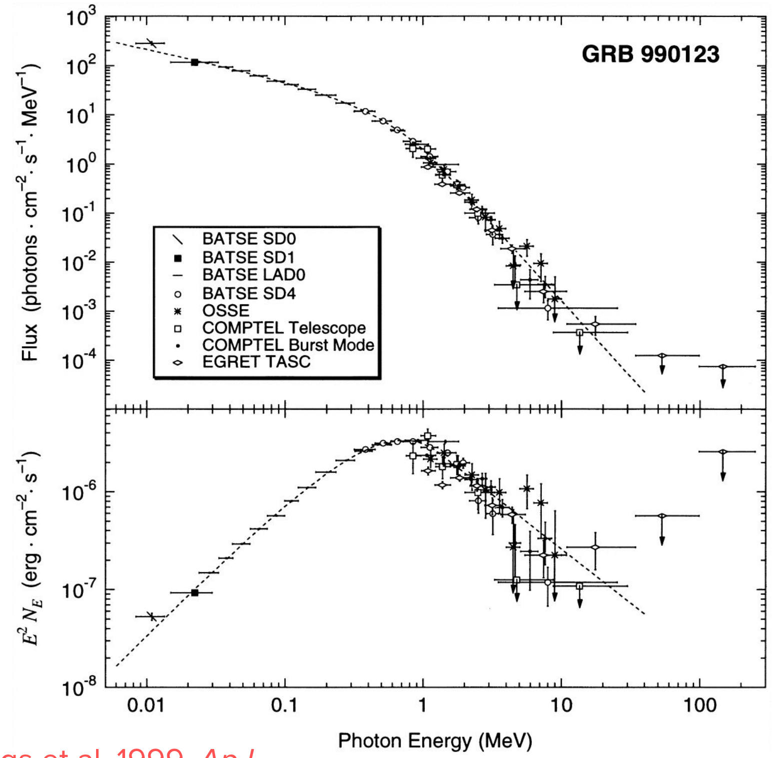
$$\gamma_i \xi_i = \gamma_\infty \xi_\infty \xrightarrow[\xi_\infty \sim 1]{\gamma_i \sim 1} \gamma_\infty = \xi_i = 4\frac{P_i}{\rho_i c^2} = \frac{4}{3}(1+\eta) \sim \eta >> 1$$

The BATSE era (1991 - 2000)

2704 bursts



The BATSE era (1991 - 2000): GRB spectra



Briggs et al. 1999, *ApJ*

$$F_{\text{Band}}(E) = \begin{cases} A\left(\frac{E}{100\ \text{keV}}\right)^{\alpha} \exp\left(-\frac{E(2+\alpha)}{E_{\text{peak}}}\right) & E < E_c \\ A\left[\frac{(\alpha-\beta)E_{\text{peak}}}{100\ \text{keV}(2+\alpha)}\right]^{\alpha-\beta} \exp(\beta-\alpha)\left(\frac{E}{100\ \text{keV}}\right)^{\beta} & E \geq E_c \end{cases},$$

$$E_c = (\alpha-\beta)\frac{E_{\text{peak}}}{2+\alpha} \equiv (\alpha-\beta)\,E_0$$

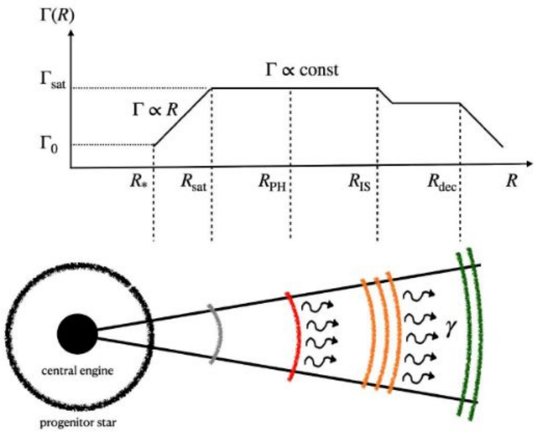
Band et al. 1993, *ApJ*

Non-thermal photon spectra → optically thin plasmas → relativistic motions

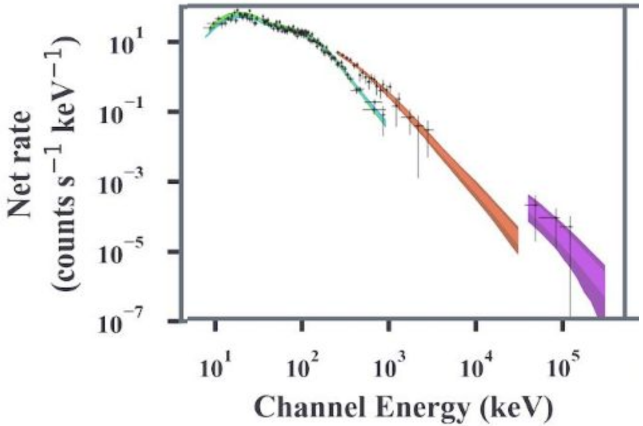
[Burgess et al. 2020, Nature Astronomy]

Synchrotron GRB models

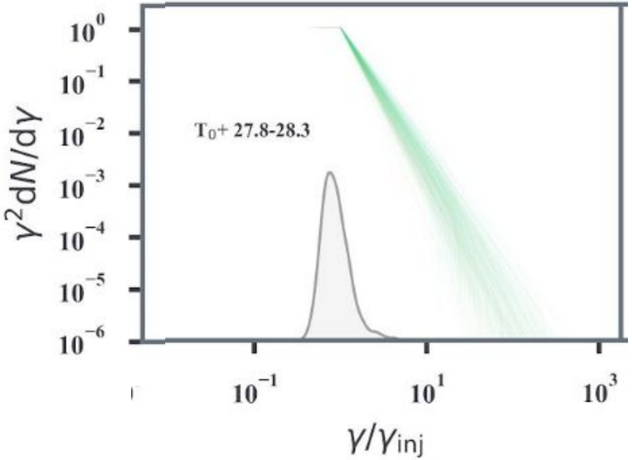
- Synchrotron radiation from relativistic electrons
- Emission from R > R_{ph}
- Jet coasting with Γ = const.



Detector photon spectra



Electron distribution in GRB jet

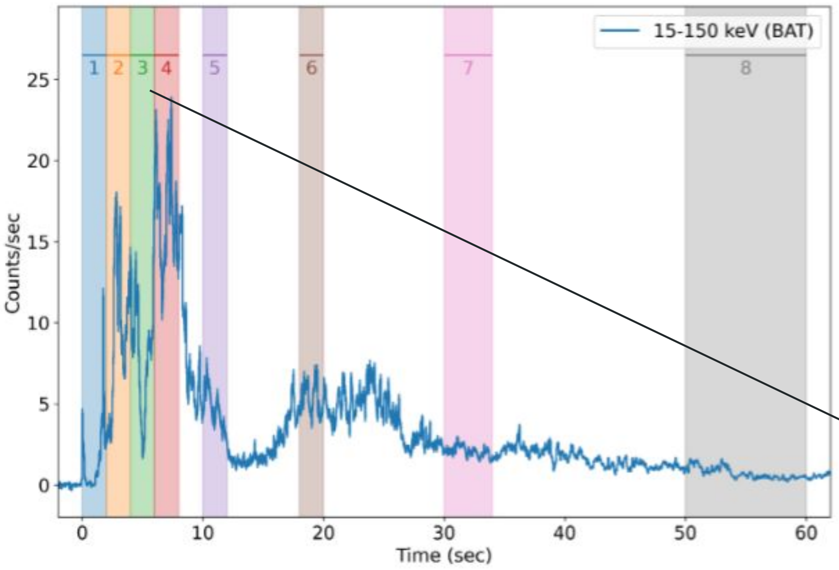


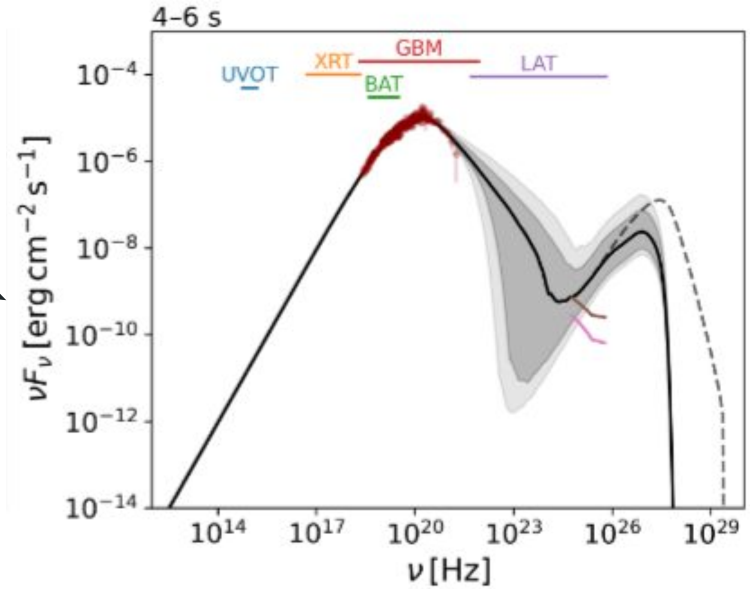
An example: GRB 211211A

[Stathopoulos et al. 2024, A&A](#)

https://github.com/mariapetro/LeHaMoC/

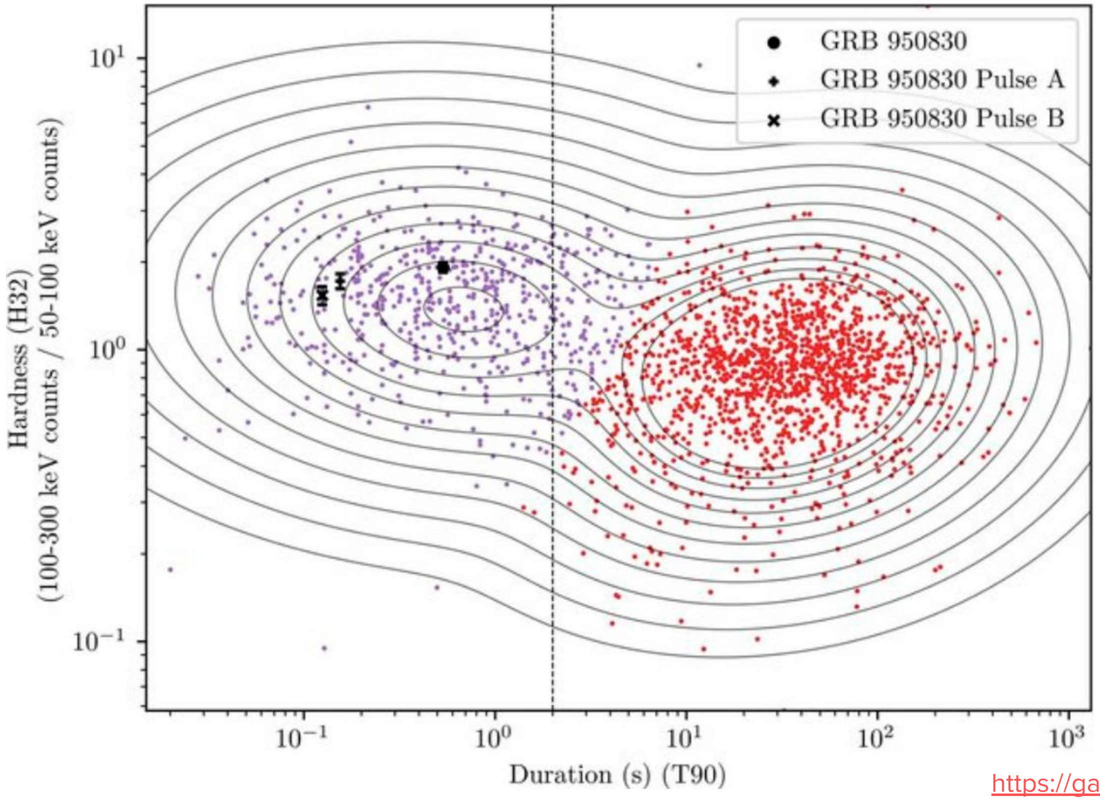
- Numerical SSC models
- MCMC fits





Petropoulou, Gkoni, Xyloportas et al. , in prep.

The BATSE era (1991 - 2000): GRB durations



- Bimodal distribution in durations
- Short GRBs (< 2 sec) have harder photon spectra
- Long GRBs (> 2 sec) have softer photon spectra
- Bimodality → different progenitors

See also [Kouveliotou et al. 1993, *ApJL*]

[https://gammaray.nsstc.nasa.gov/batse/grb/catalog/4b/index.html]

GRB progenitors

Stellar collapsars

McFadyen & Woosley 1999, ApJ; Woosley & Bloom 2006, ARA&A

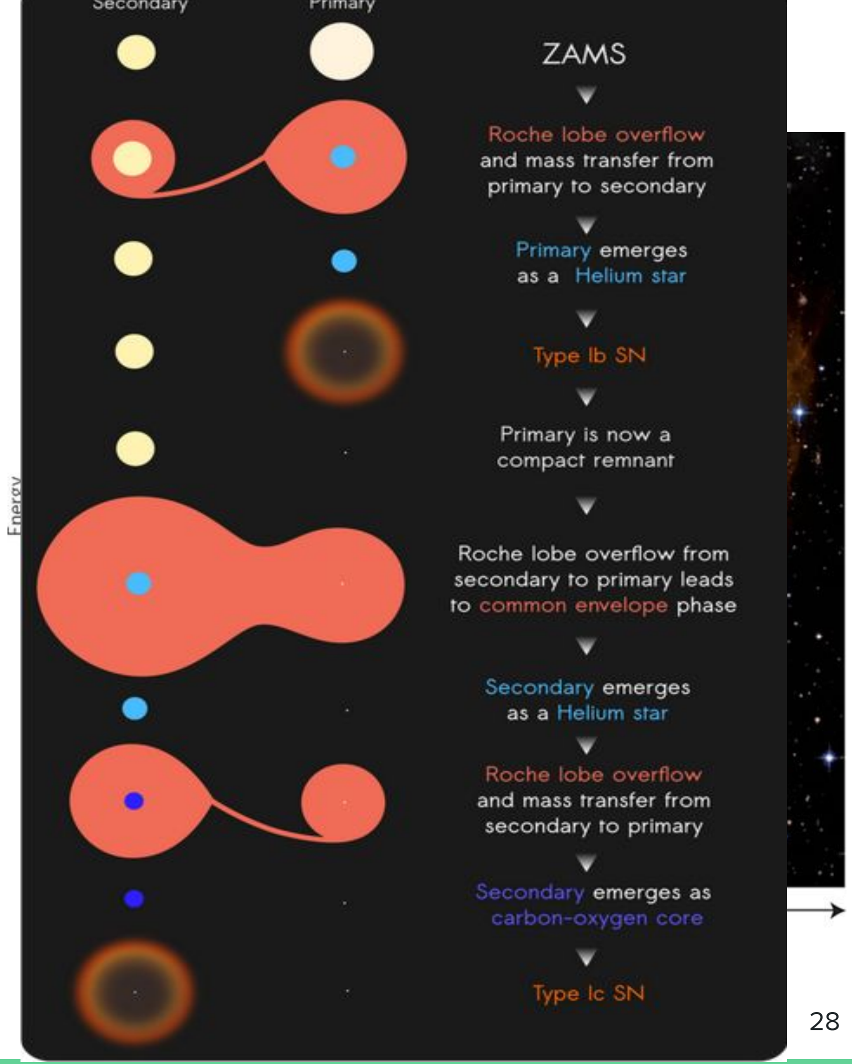
NS-NS or NS-BH mergers

Eichler et al. 1989, Nature ; Narayan et al. 1992, ApJL

Credit: NASA's Goddard Space Flight Center

Collapsars

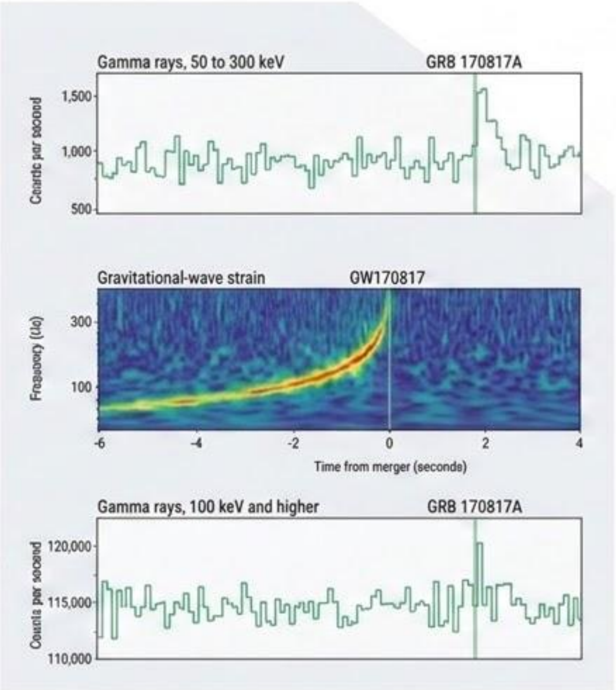
- **Key discovery: SN 1998bw with GRB 980425**
  (Bloom et al. 1999, Nature)
- GRBs associated with SNe Type Ib/c (no H, no He lines) → stripped stars
- GBR-selected SNe have broad lines → associated with fast (~0.1 c) outflows
- All GRB-selected SNe are Type Ib/c-BL

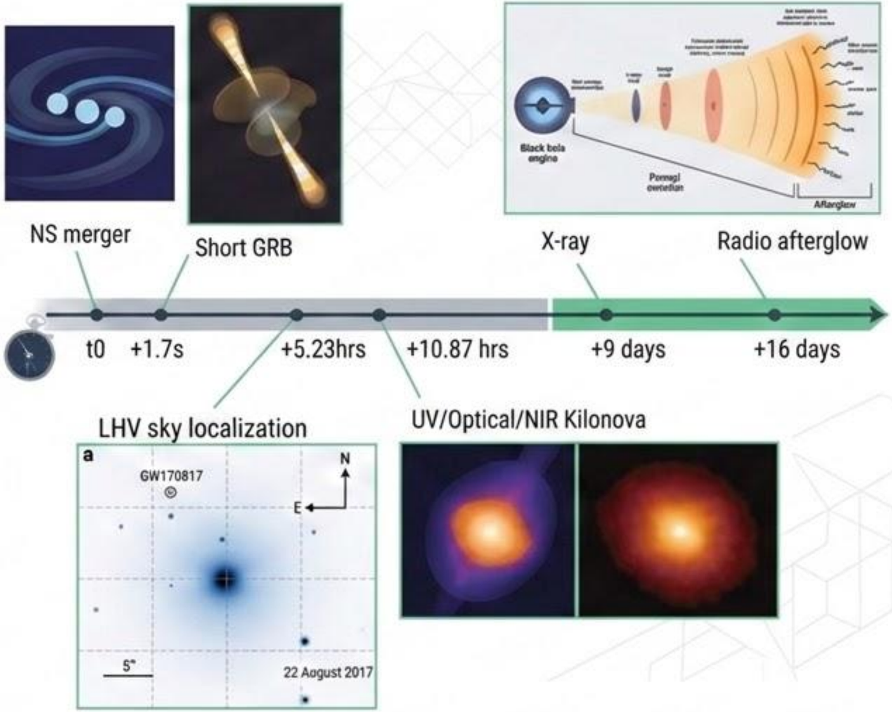


Mergers

Key discovery: GW 170817 with GRB 170817A

(Abbott et al. 2017, ApJ, Troja et al 2017,Nature)





Part 2

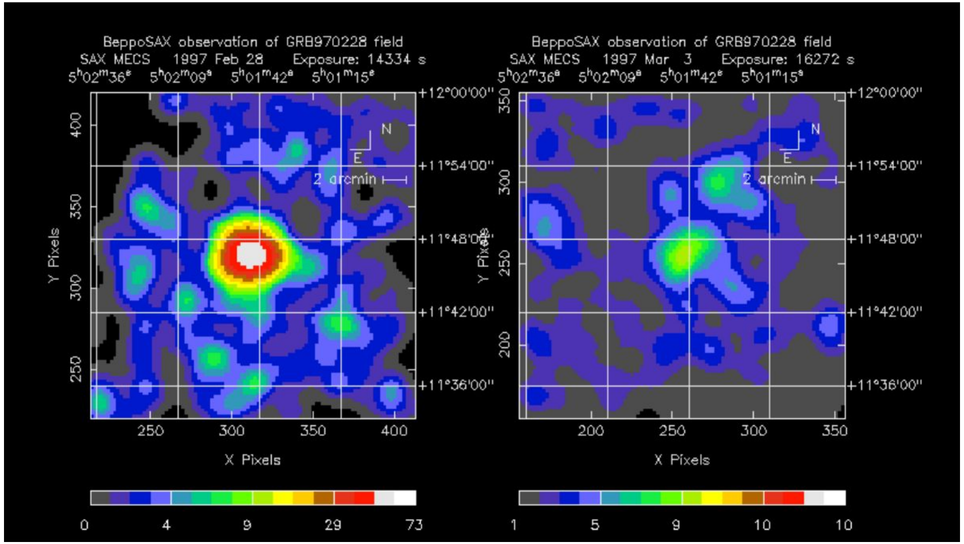
Introduction to GRBs afterglows

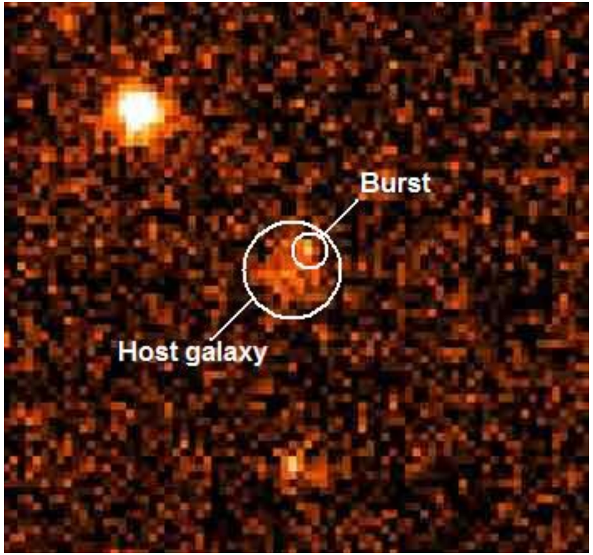
The discovery of the GRB afterglow (1997)

GRB 970228

BeppoSax (X-rays)

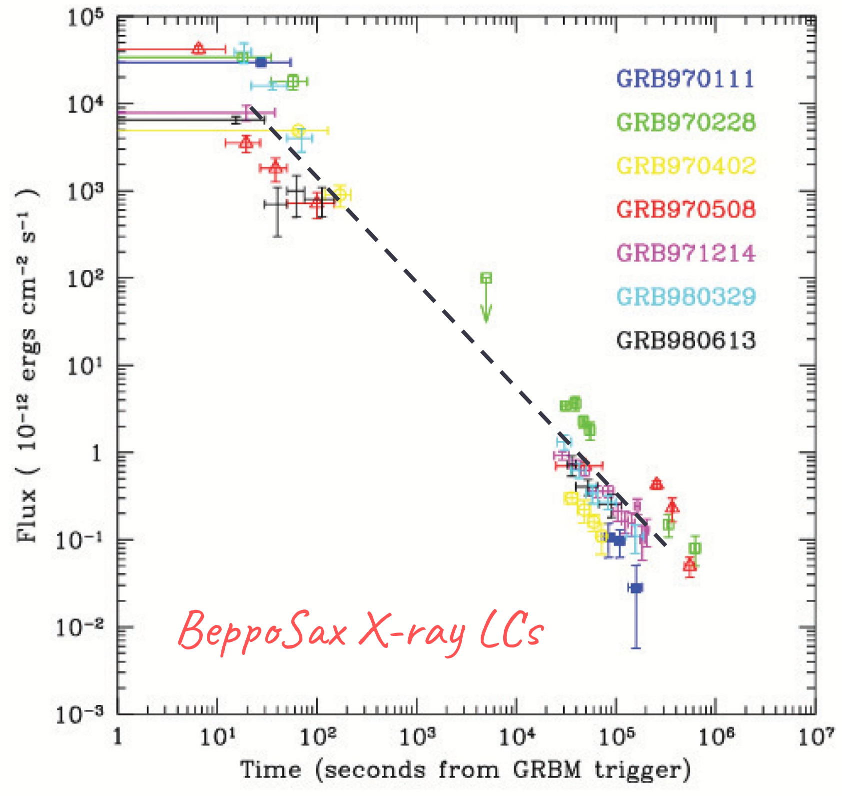
HST (optical)





- First determination of the GRB host galaxy at z = 0.695 ! → Direct evidence for extragalactic origin
- First observation of a GRB counterpart in X-ray and optical wavelengths after the γ-ray emission !

What are GRB afterglows?



- Long-lasting (hours to months) electromagnetic emission at lower energies (X-rays, optical, radio) following the brief γ-ray flash

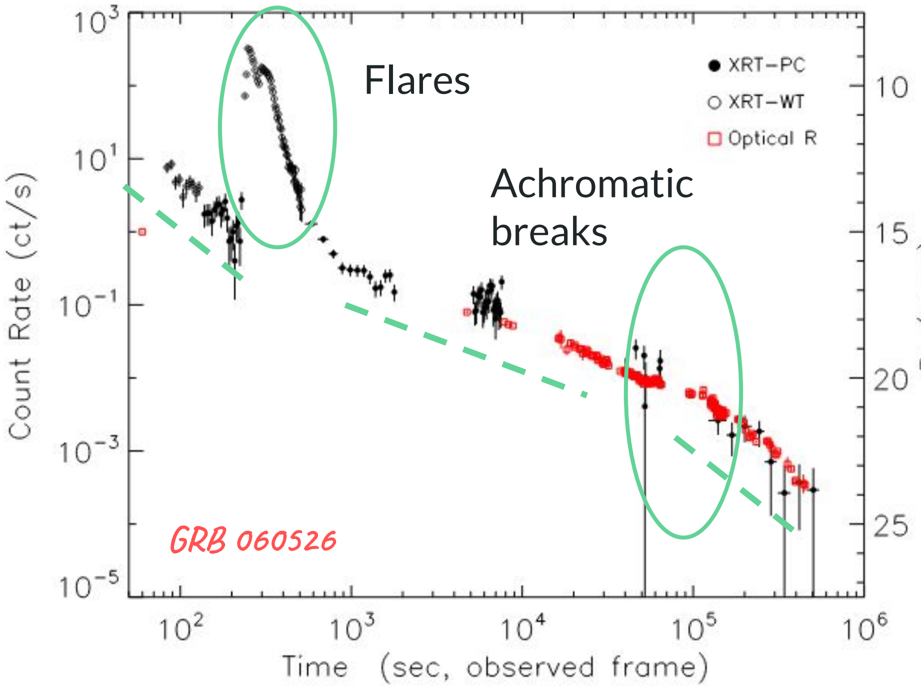
- Flux decays as a power law

- Key observables: peak time, peak flux, power-law index

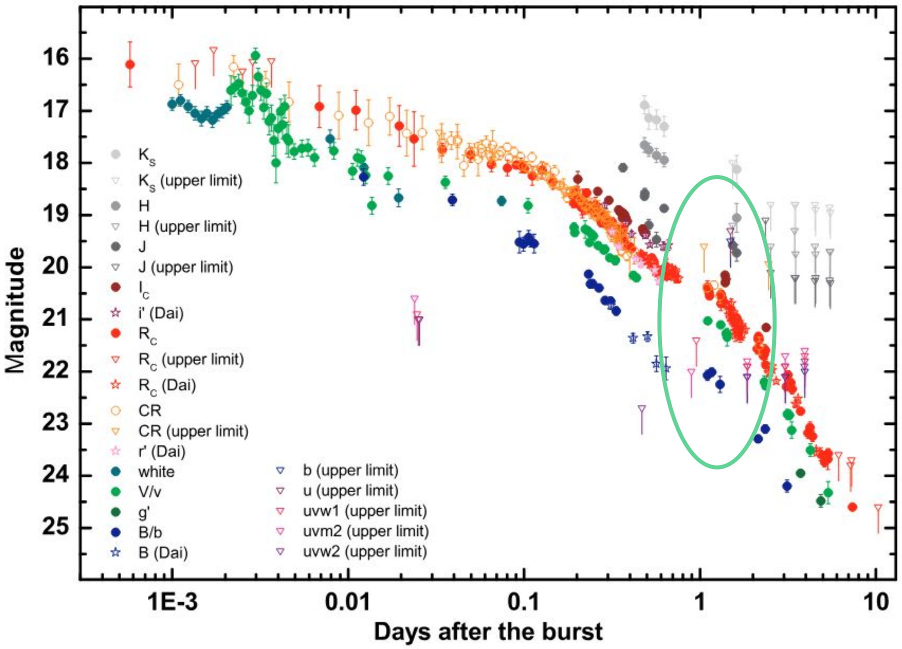
Costa et al. 1999, A&A Supplement Series

GRB afterglows in the Swift era (2004 - today)

A more complex picture emerges!



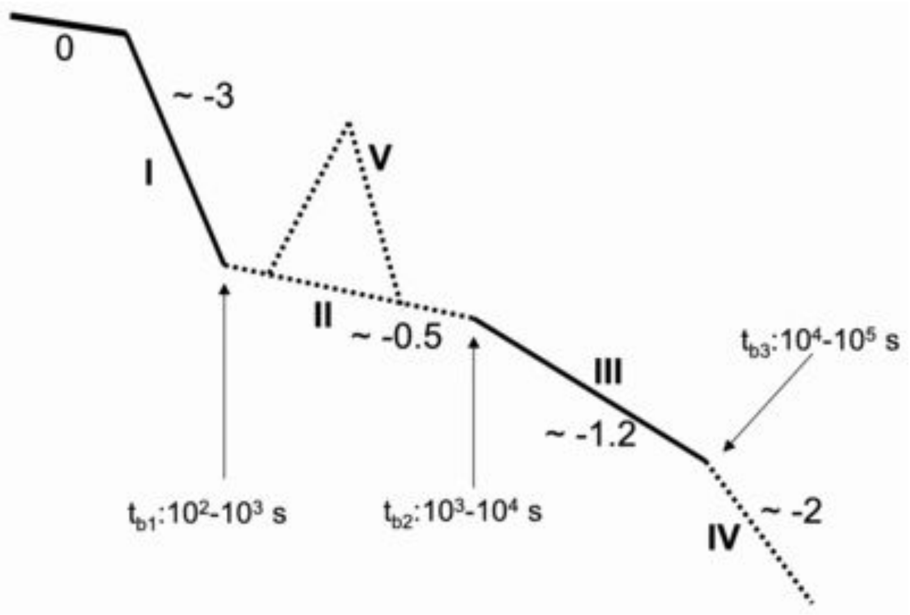
Dai et al. 2007, ApJ



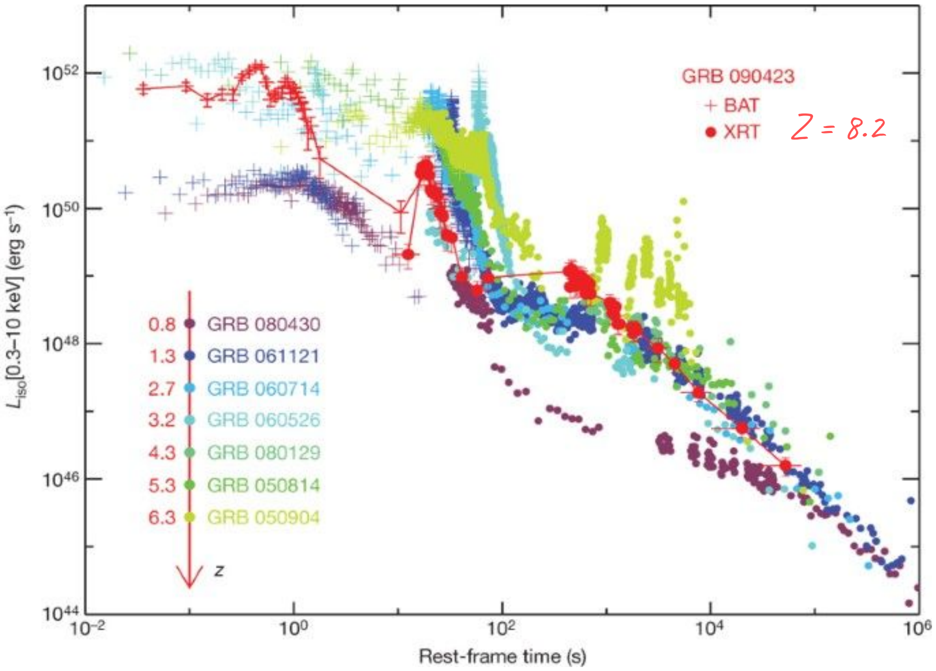
Th¨one et al. 2010, A&A

GRB afterglows in the Swift era (2004 - today)

The "canonical" X-ray afterglow



[Zhang et al. 2006, ApJ]



[Salvattera et al. 2009, Nature]

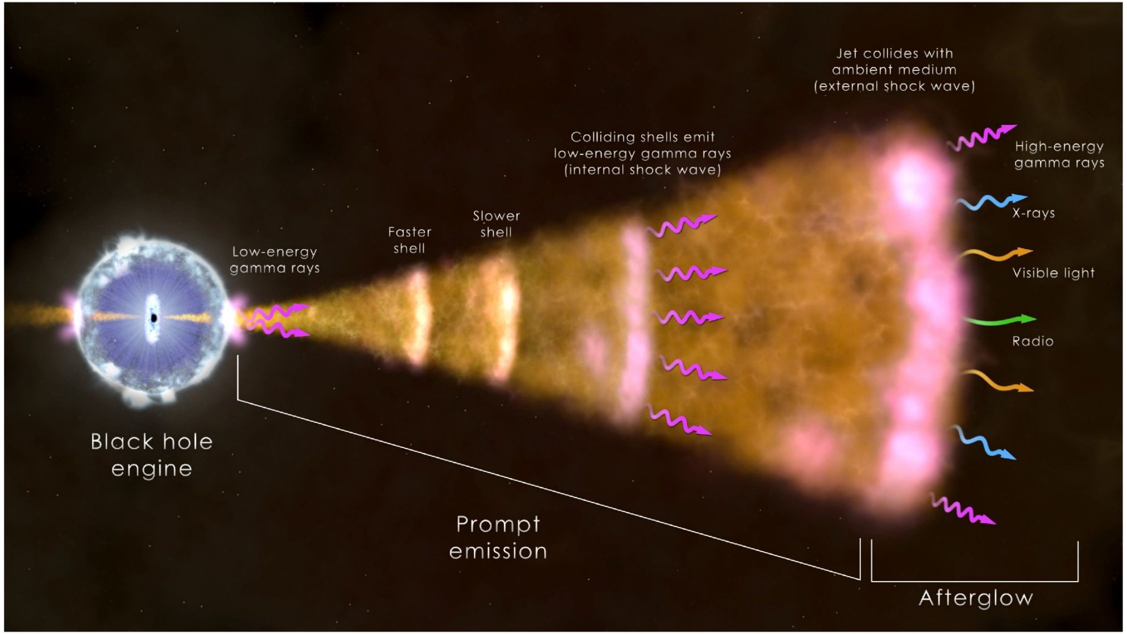
Part 3

Theory of GRBs afterglows

The GRB afterglow paradigm

Key ingredients:

- Relativistic blast wave dynamics
- Relativistic beaming of radiation
- Non-thermal radiative processes
- Particle acceleration at relativistic shocks



Relativistic blast waves

Energy conservation:

$$M\Gamma c^2 + dmc^2 = (M + dM)(\Gamma + d\Gamma)c^2 \quad (1)$$

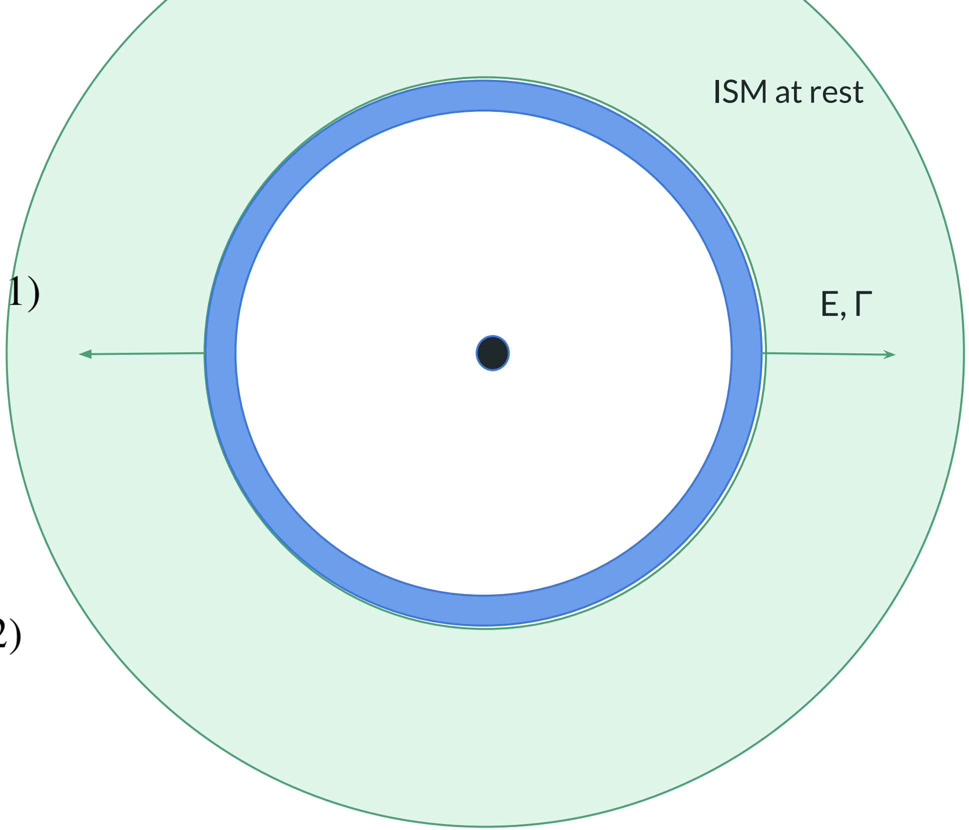
$$dm = 4\pi r^2 \rho(r)\, dr$$

Momentum conservation:

$$M\Gamma\beta c = (M + dM)(\Gamma + d\Gamma)(\beta + d\beta)c \quad (2)$$

$$(1),\ (2) \rightarrow \boxed{\frac{d\Gamma}{dm} = -\frac{\Gamma^2 - 1}{M}}$$

$$M(r) = M_0 + 4\pi \int_{r_0}^{r} dr'\, r'^2\, \Gamma(r')\, \rho(r') \Rightarrow \boxed{dM = \Gamma(r)\, dm}$$



Blandford & McKee 1976, Phys. Fluids;
Chiang & Dermer 1999, ApJ

Non-radiative relativistic blast waves

Blast wave (shocked fluid) inertial mass:

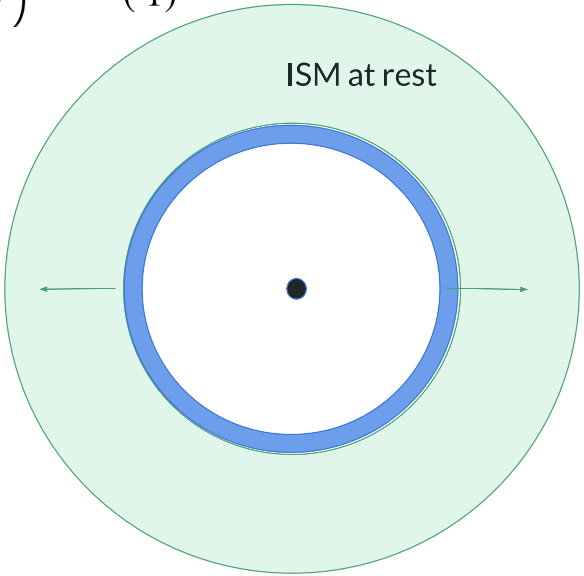
$$M(r) = \left(M_0^{\,2} + 2\Gamma_0 M_0 M_{sw}(r) + M^2_{sw}(r) \right)^{\frac{1}{2}} \quad (1)$$

Blast wave (shocked fluid) Lorentz factor:

$$\Gamma(r) = \frac{M_{sw}(r) + \Gamma_0 M_0}{M(r)} \quad (2)$$

Swept-up mass:

$$M_{sw}(r) = 4\pi \int_{r_0}^{r} dr\, r^2 \rho(r) \quad (3)$$



Non-radiative relativistic blast waves

$$M(r) = \left(M_0^2 + 2\Gamma_0 M_0 M_{sw}(r) + M^2_{sw}(r)\right)^{\frac{1}{2}} \quad (1)$$

$$\Gamma(r) = \frac{M_{sw}(r) + \Gamma_0 M_0}{M(r)} \quad (2)$$

Regime 1: Coasting Phase

$$M_0 >> \Gamma_0 M_{sw}$$

$$M(r) \approx M_0$$

$$\Gamma(r) \approx \Gamma_0$$

Regime 2: Deceleration Phase

$$\frac{M_{sw}}{\Gamma_0} < M_0 < 2\Gamma_0 M_{sw}$$

$$M(r) \approx \sqrt{2\Gamma_0 M_0 M_{sw}(r)} \propto r^{\frac{3}{2}}$$

$$\Gamma(r) \approx \Gamma_0\left(\sqrt{\frac{M_0}{2\Gamma_0 M_{sw}(r)}} + \dots\right) \propto r^{-\frac{3}{2}}$$

Regime 3: Newtonian Phase

$$M_{sw} > 2\Gamma_0 M_0$$

$$M(r) \approx M_{sw}(r) \propto r^{\frac{3}{2}}$$

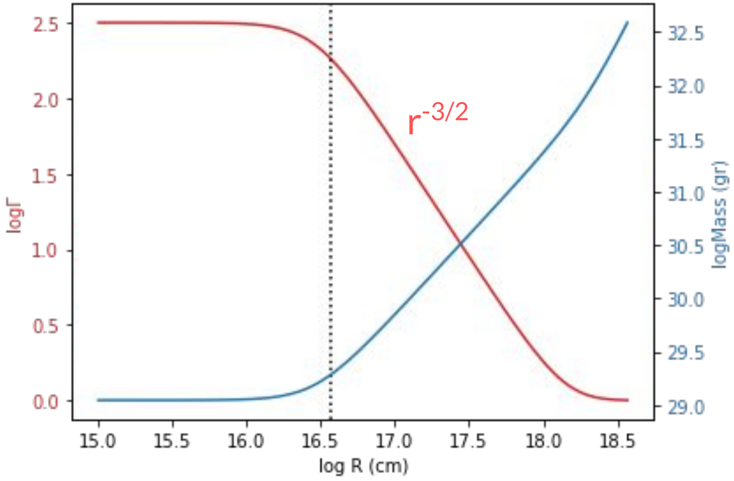
$$\Gamma(r) \approx 1 + \Gamma_0 \frac{M_0}{M_{sw}(r)}$$

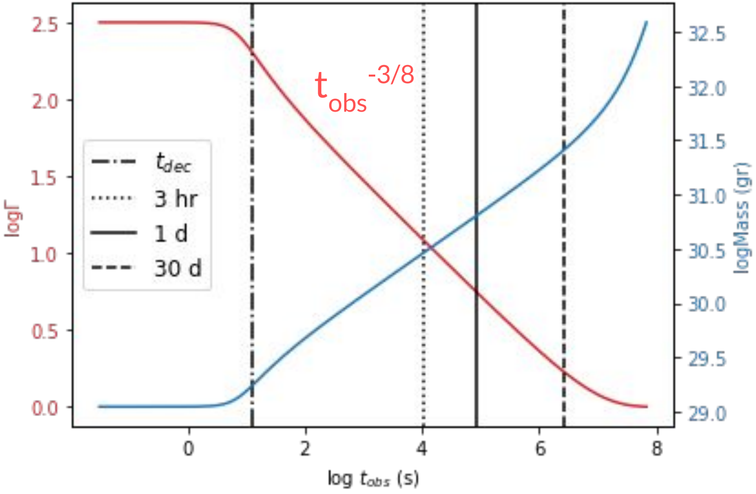
Disclaimer: constant density medium

Non-radiative relativistic blast waves

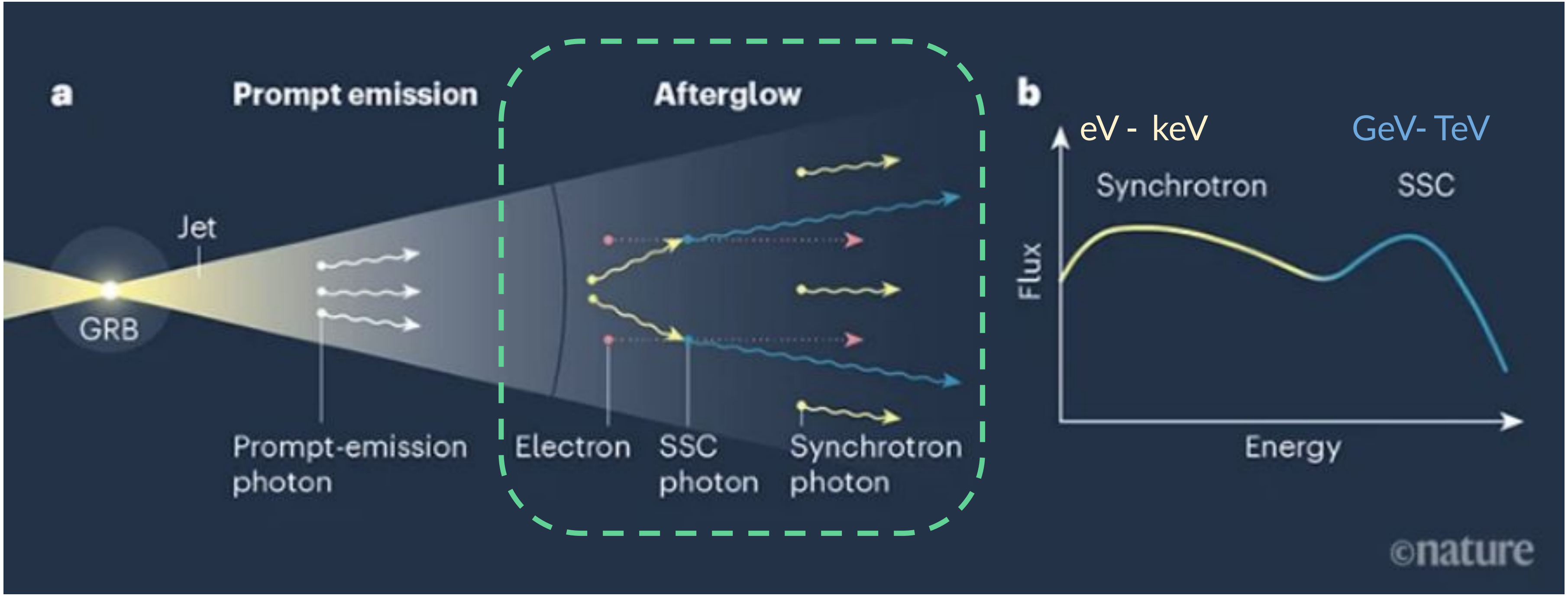
Deceleration radius: $\Gamma_0 M_{sw}(r_{dec}) \sim M_0 \Rightarrow r_{dec} = \left(\frac{3E_0}{4\pi\, n\, m_p \Gamma_0^2 c^2}\right)^{\frac{1}{3}} \approx 10^{16.5}\, cm \left(\frac{E_{0,52.5}}{n_0 \Gamma_{0,\,2.5}}\right)^{\frac{1}{3}}$

Deceleration time: $t_{dec} \sim \frac{r_{dec}}{c\,\Gamma_0^2} \propto E_0^{\frac{1}{3}}\, n_0^{-\frac{1}{3}}\, \Gamma_0^{-\frac{8}{3}}$

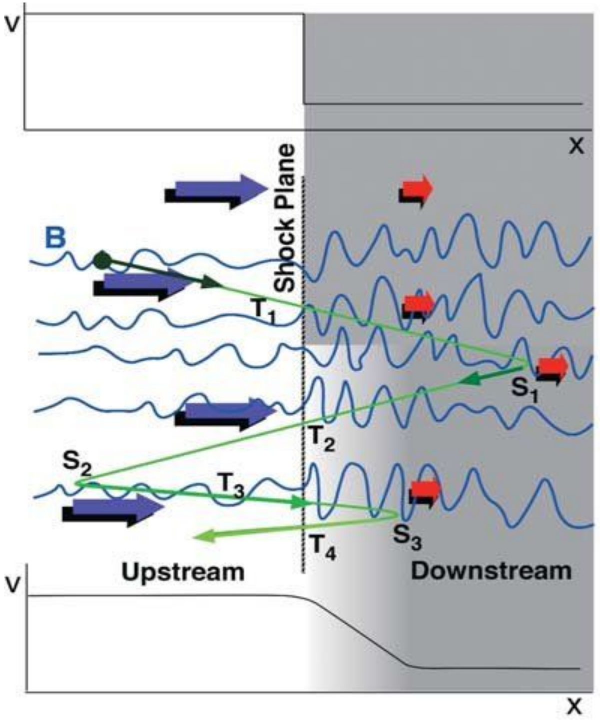




Radiative processes



Particle acceleration



Möbius & Kallenbach, 2005
ISSI Scientific Reports Series

- Shocks dissipate bulk kinetic energy → internal energy, non-thermal particle energy
- **Fermi** acceleration → particles gain energy via multiple scatterings across a velocity gradient (there is also shock-drift, …)
- **Scatterings mediated by magnetic fields** → generated by instabilities
- Shocks can accelerate particles into **power-law** distributions.
- Inefficient acceleration in
  - Superluminal shocks
  - High - σ plasmas

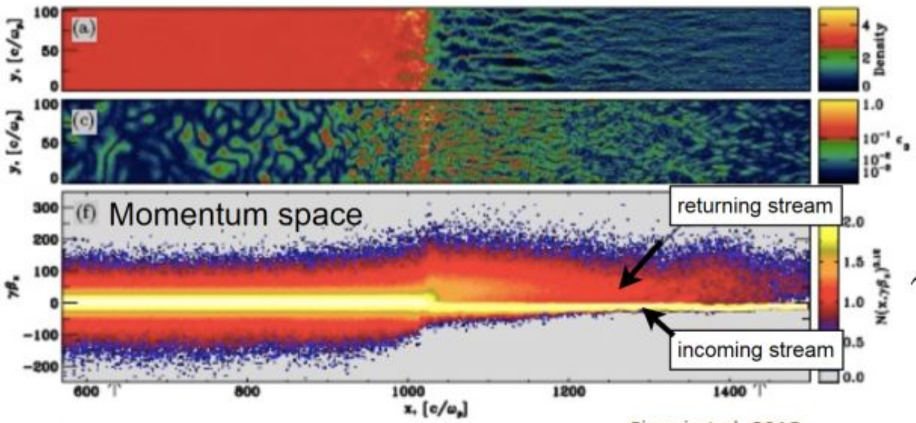
Drury 1983, *ApJ*; Bell 1987, *MNRAS*; Blandford & Eichler 1987, *Phys. Rep.*; Begelman & Kirk 1990; Bell 2004, *MNRAS*, Blasi 2013, *A&ARv* +++

Relativistic shock acceleration

$\sigma = 0$

$\gamma_0 = 15$

Low-σ shocks:
- returning particles
- filamentation instabilities



n ε_B $\gamma\beta_x$

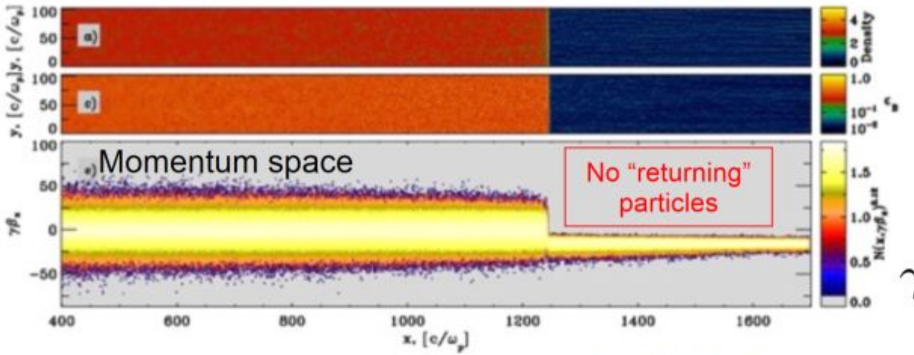
Sironi et al. 2013

← weakly magnetized
(relevant to GRB blast waves)

$\sigma = 0.1$

$\gamma_0 = 15$

High-σ shocks:
- no returning particles
- no turbulence

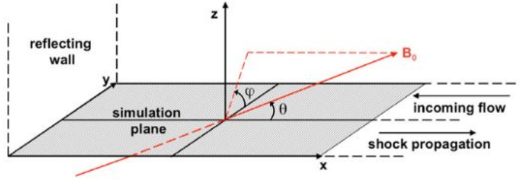


n ε_B $\gamma\beta_x$

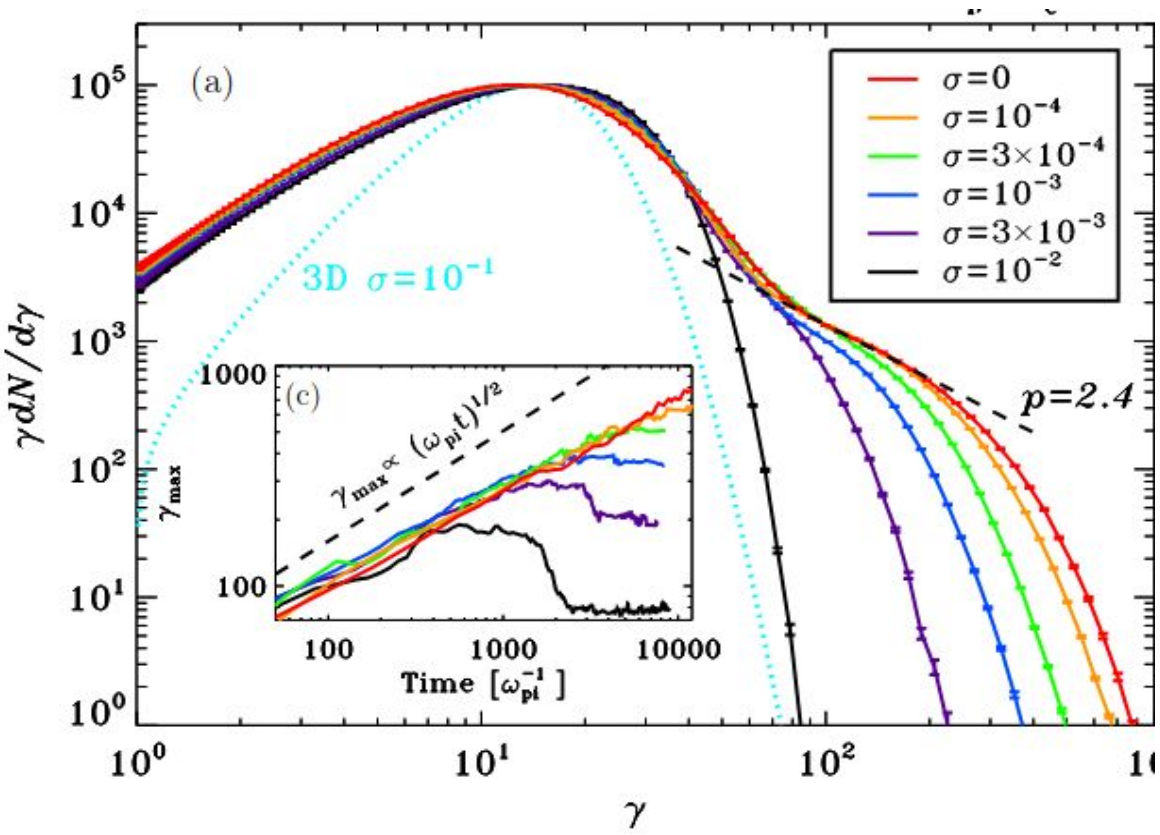
Sironi & Spitkovsky 2011

← strongly magnetized
(relevant to internal shocks in jets)

θ = 15 deg



Relativistic shock acceleration



Sironi & Spitkovsky 2013, *ApJ*, **771**, 54

Diffusion coefficient and maximal energy depend on typical scale λ of turbulent magnetic field :

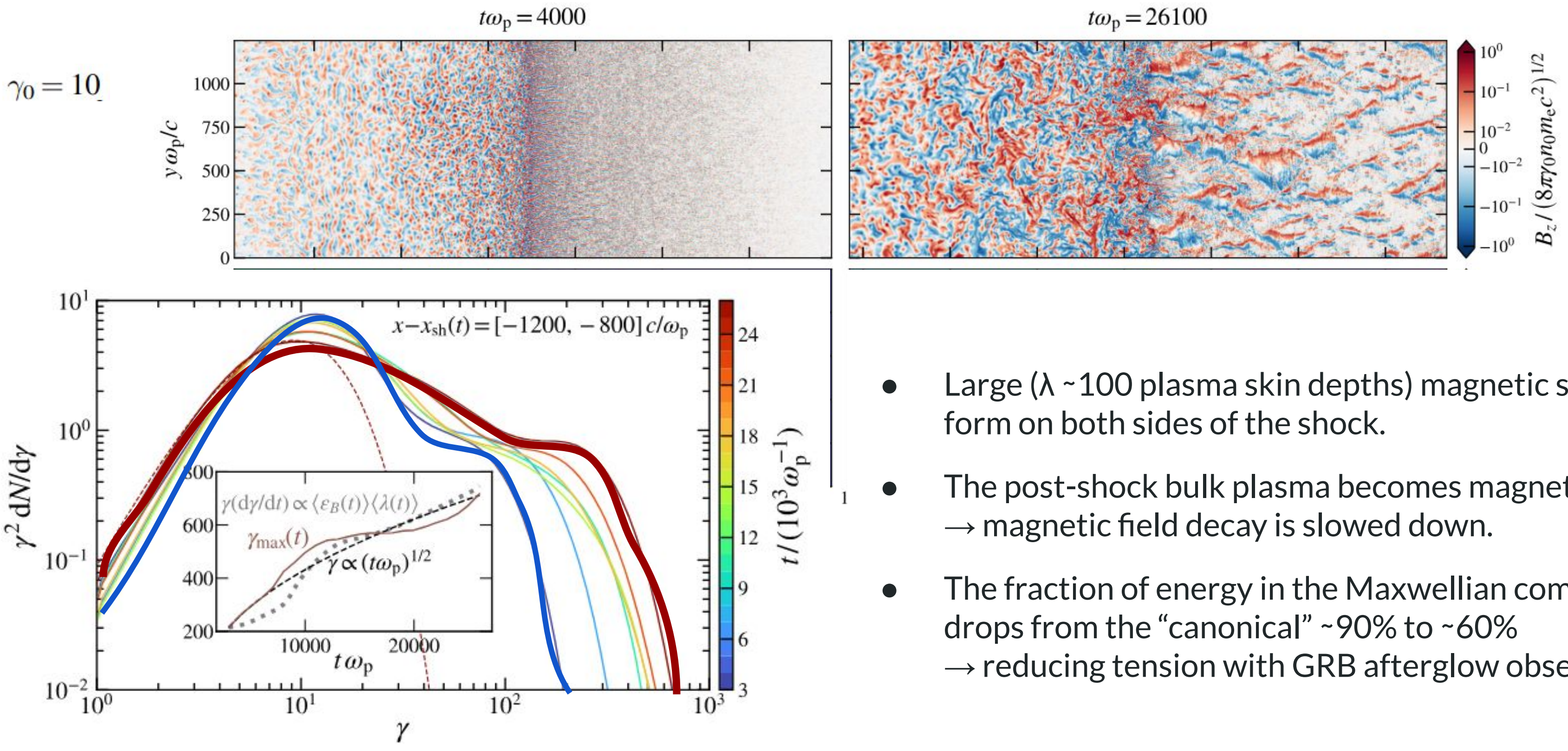
$$D(\varepsilon) \sim c\lambda \left[\frac{r_L(\varepsilon)}{\lambda}\right]^2 = c\lambda \left(\frac{\varepsilon}{eB\lambda}\right)^2$$

$$\gamma_{\max} m_i c^2 \sim eB\lambda \left(\frac{ct}{\lambda}\right)^{1/2}$$

Some problems:

1. Slow increase of γmax
2. Prominent Maxwellian component in particle distribution
3. Turbulent magnetic field decays far from shock

Long term evolution of relativistic shocks



- Large (λ ~100 plasma skin depths) magnetic structures form on both sides of the shock.
- The post-shock bulk plasma becomes magnetized → magnetic field decay is slowed down.
- The fraction of energy in the Maxwellian component drops from the "canonical" ~90% to ~60% → reducing tension with GRB afterglow observations.

Grošelj, Sironi, Spitkovsky, 2024, *ApJL*, **963**, 44

The standard GRB afterglow model

ε_B, ε_e are key free parameters!

Power entering the shocked plasma:

$$\frac{dE}{dt} = \beta c \cdot (\Gamma - 1)\,\Gamma \rho c^2 \cdot 4\pi r^2$$

Electron distribution:

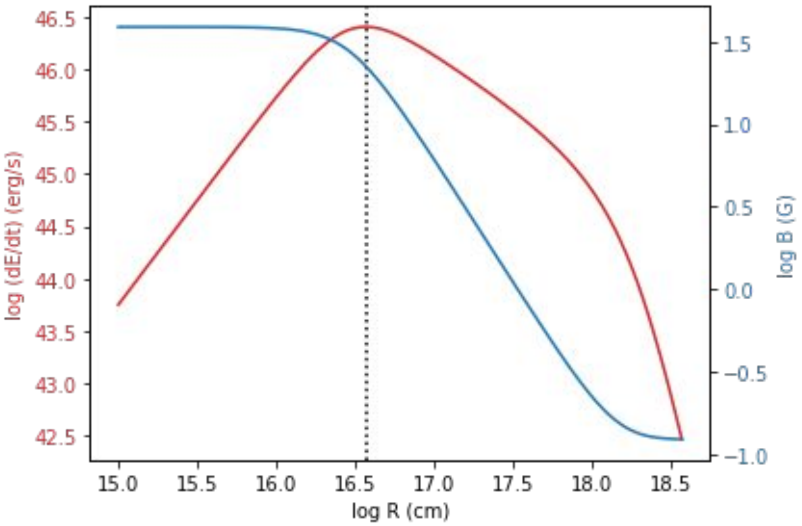
$$\frac{dN}{dt d\gamma} = K_e \gamma^{-\mathrm{p}}, \quad \gamma_{min} \leq \gamma \leq \gamma_{max}, \quad \gamma_{min} \sim \frac{m_p}{m_e} \Gamma(\mathrm{r})$$

Power injected into relativistic electrons:

$$L_e = m_e c^2 \int_{\gamma_{min}}^{\gamma_{max}} d\gamma (\gamma - 1) \frac{dN}{dt d\gamma} = \boldsymbol{\varepsilon}_{\mathrm{e}} \frac{dE}{dt}$$

Magnetic field strength:

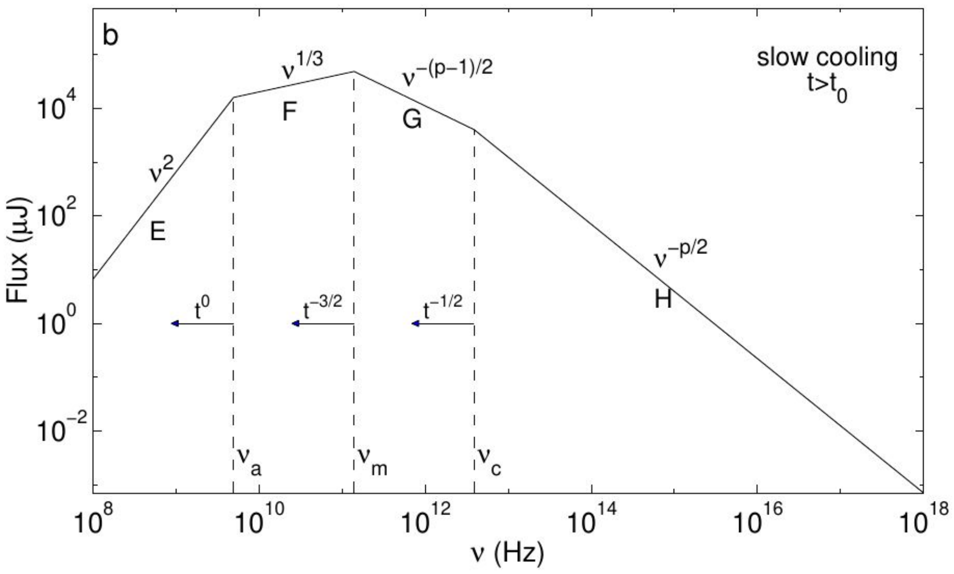
$$\frac{B^2}{8\pi} = \boldsymbol{\varepsilon}_{\mathrm{B}} u_{sh} = \boldsymbol{\varepsilon}_{\mathrm{B}} 4\Gamma(r)\, \rho\, (\Gamma - 1)\, c^2$$



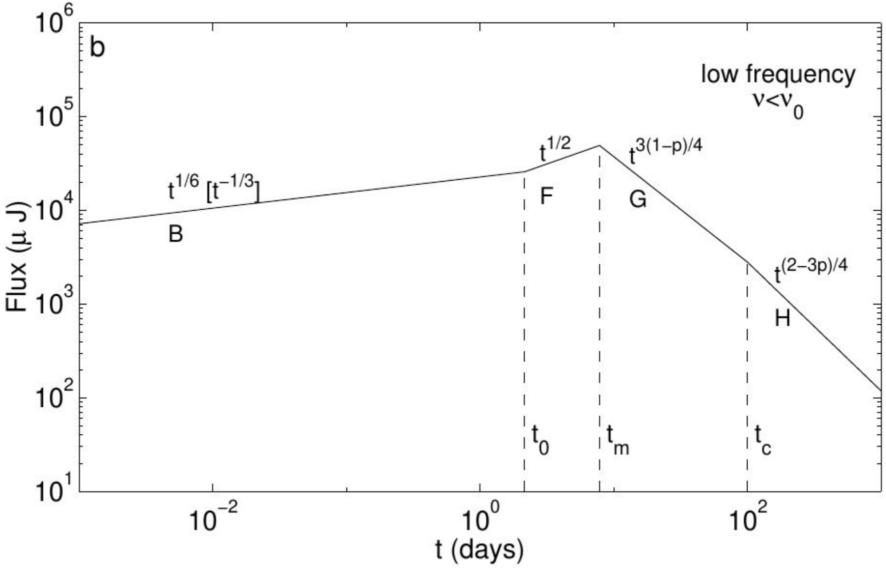
The Synchrotron GRB afterglow model

Analytical results

Synchrotron spectrum



Synchrotron light curve



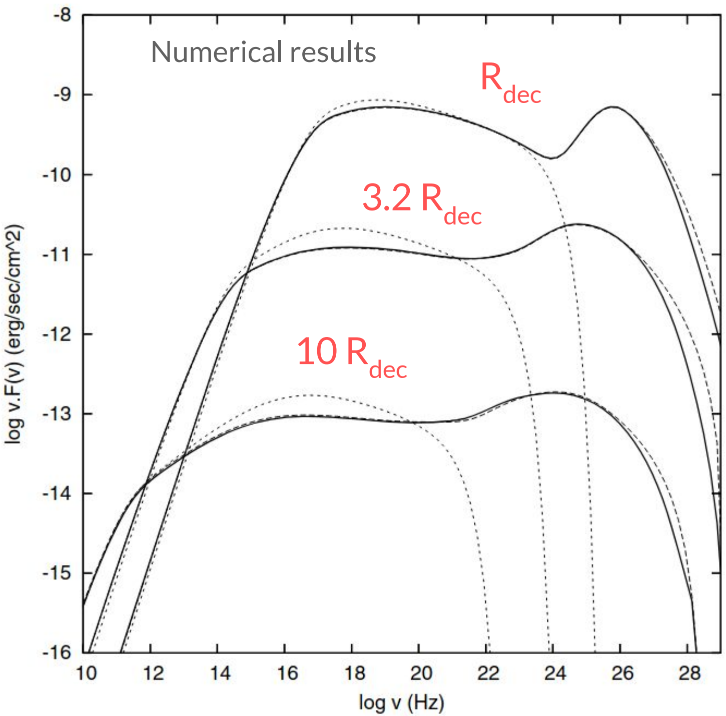
Sari, Piran, Narayan 1998, ApJL

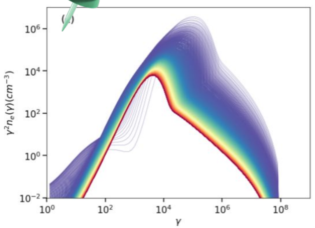
The SSC afterglow models

$$\frac{\partial n_e}{\partial t} + c\frac{3n_e}{r} = Q_e^{(inj)} + Q_e^{(\gamma\gamma)} + \mathcal{L}_e^{(ad)} + \mathcal{L}_e^{(syn)} + \mathcal{L}_e^{(ics)} \quad (9)$$

$$\frac{\partial n_\gamma}{\partial t} + c\frac{3n_\gamma}{r} + c\frac{n_\gamma}{r} = Q_\gamma^{(syn)} + Q_\gamma^{(ics)} + \mathcal{L}_\gamma^{(\gamma\gamma)} + \mathcal{L}_\gamma^{(ssa)} \quad (10)$$

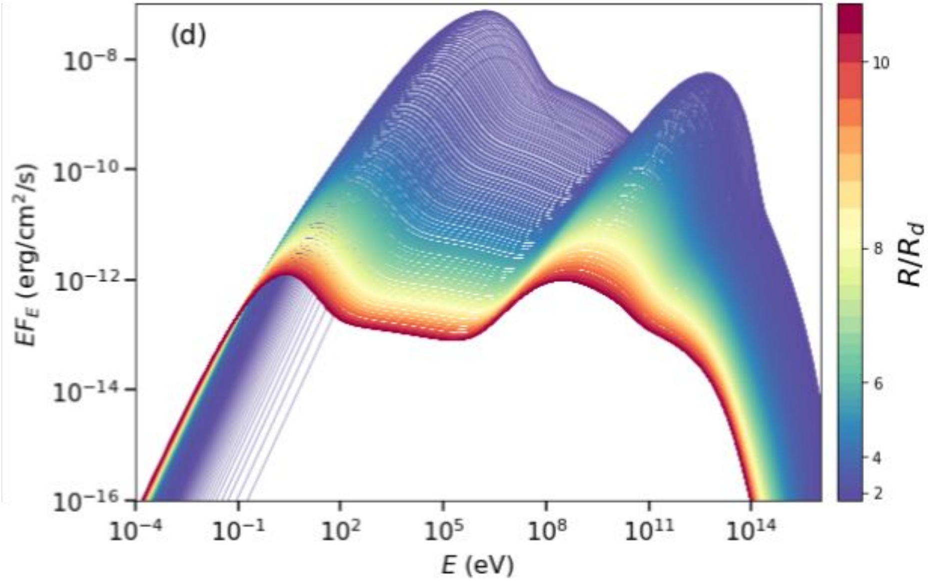
Synchrotron self-Compton (SSC)





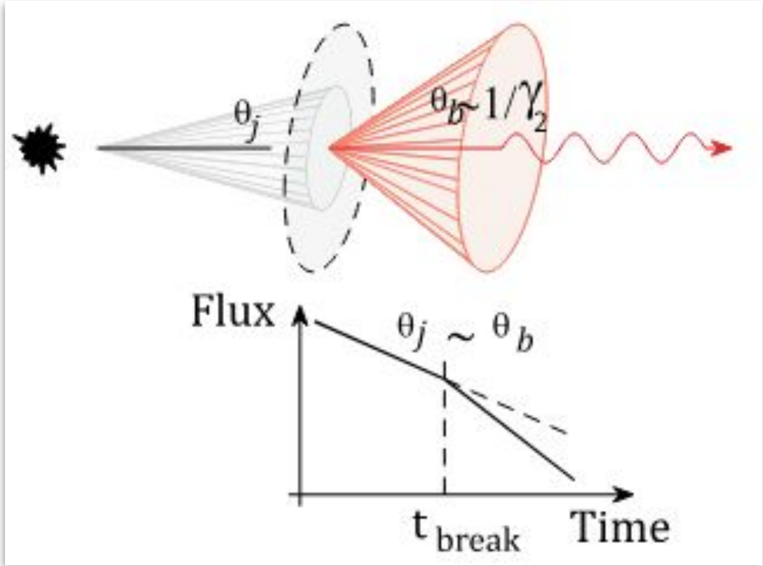
Thermal + Non-thermal electron distribution

(Giannios & Spitkovsky 2009, Warren et al. 2022)



Petropoulou & Mastichiadis 2009, A&A

Relativistic beaming - Jet breaks



Relativistically moving plasma with Γ >> 1 emits radiation within a cone of half opening-angle:

$$\theta_b \sim \frac{1}{\Gamma} \sim \frac{0.29 \text{ deg}}{\Gamma_2}$$

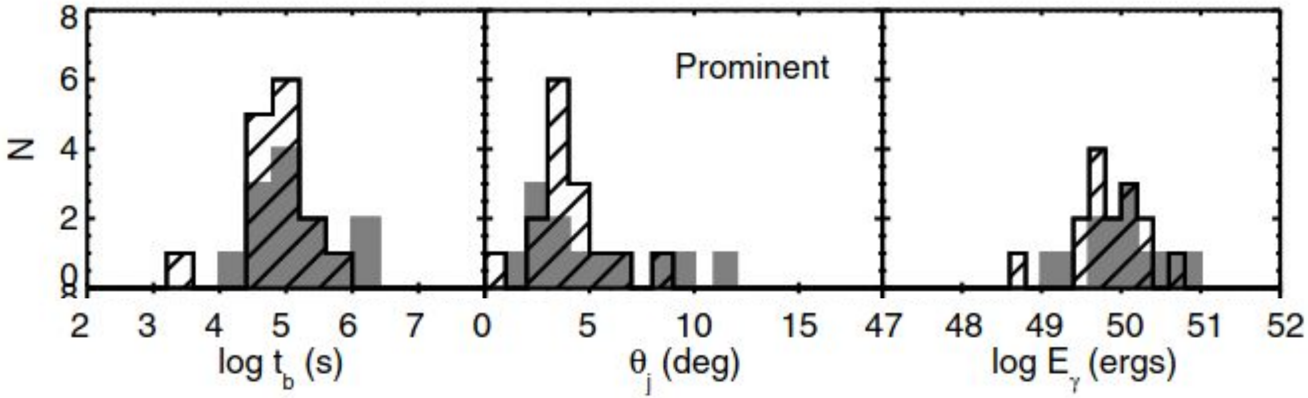
Beaming angle > jet opening angle → rapid decrease in flux (jet break)

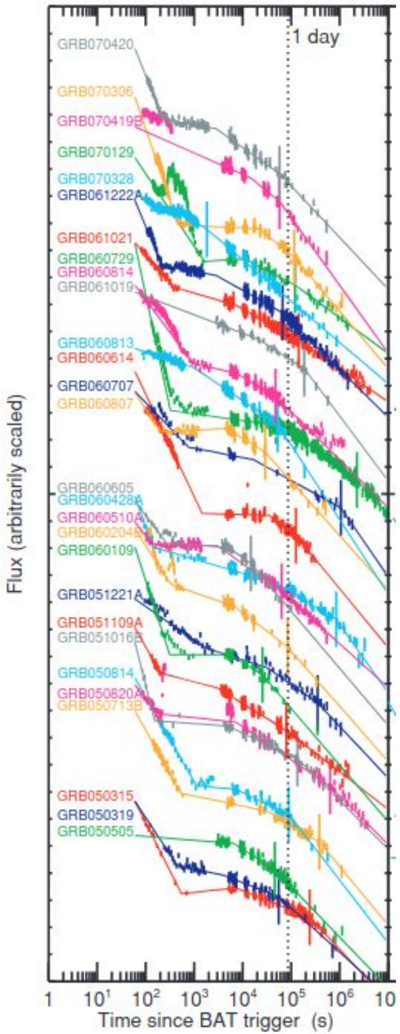
$$\theta_j = 0.057 \left(\frac{t_j}{1 \text{ day}}\right)^{3/8} \left(\frac{1+z}{2}\right)^{-3/8} \left[\frac{E_{\rm iso}(\gamma)}{10^{53} \text{ ergs}}\right]^{-1/8} \times \left(\frac{\eta_\gamma}{0.2}\right)^{1/8} \left(\frac{n}{0.1 \text{ cm}^{-3}}\right)^{1/8},$$

Sari et al. 1999, ApJ

GRB jet breaks

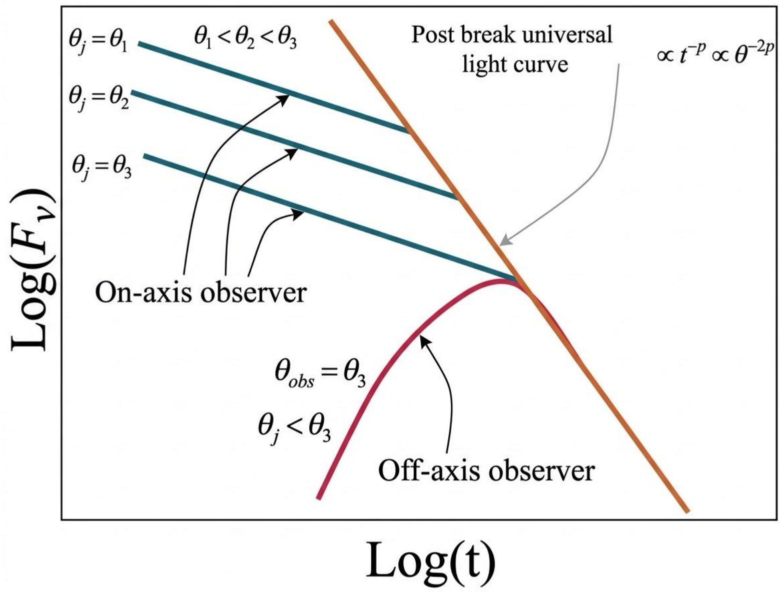
- GRB jets are very well collimated outflows !
- Geometrical beaming is important $f_b = (1 - \cos\theta_b) \xrightarrow{\theta_b << 1} \frac{\theta_b^2}{2}$
- Reduced true energetics $E_\gamma = f_b E_{\gamma,\,iso} = \frac{\theta_b^2}{2} E_{\gamma,\,iso}$



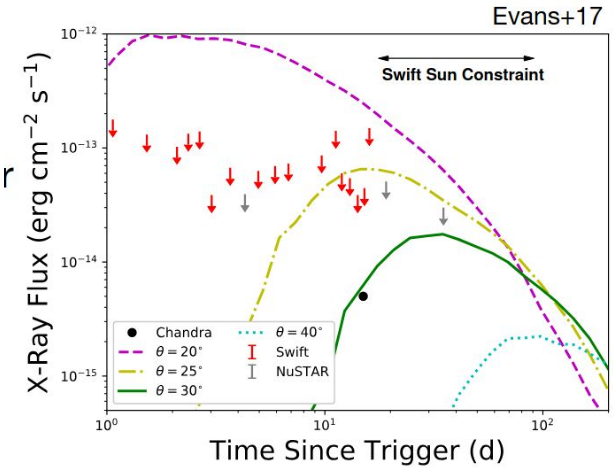


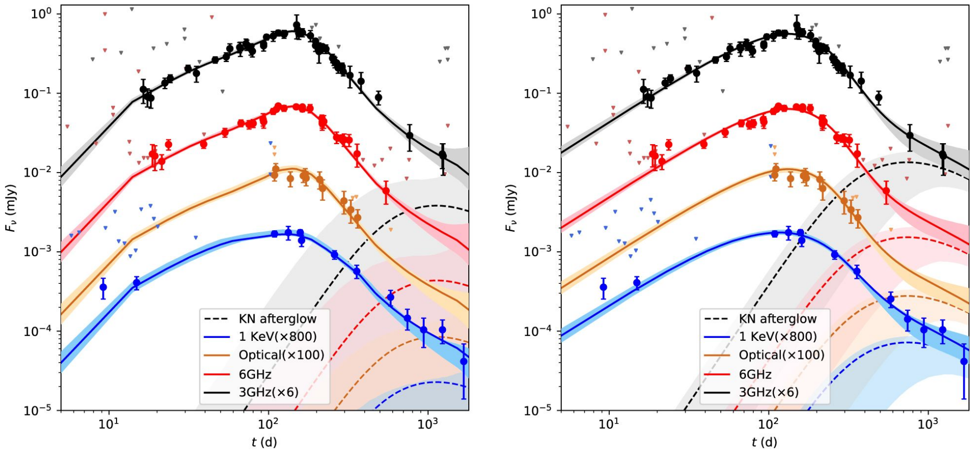
Racusin et al. 2009, ApJ

Off-axis GRB afterglows



GRB 170817A ($z = 0.099$)

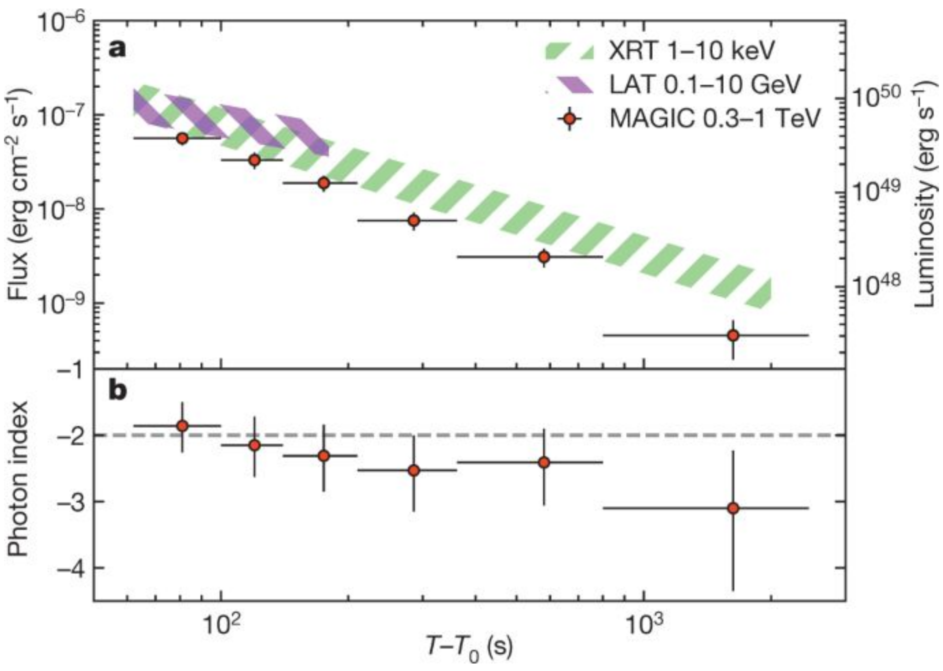




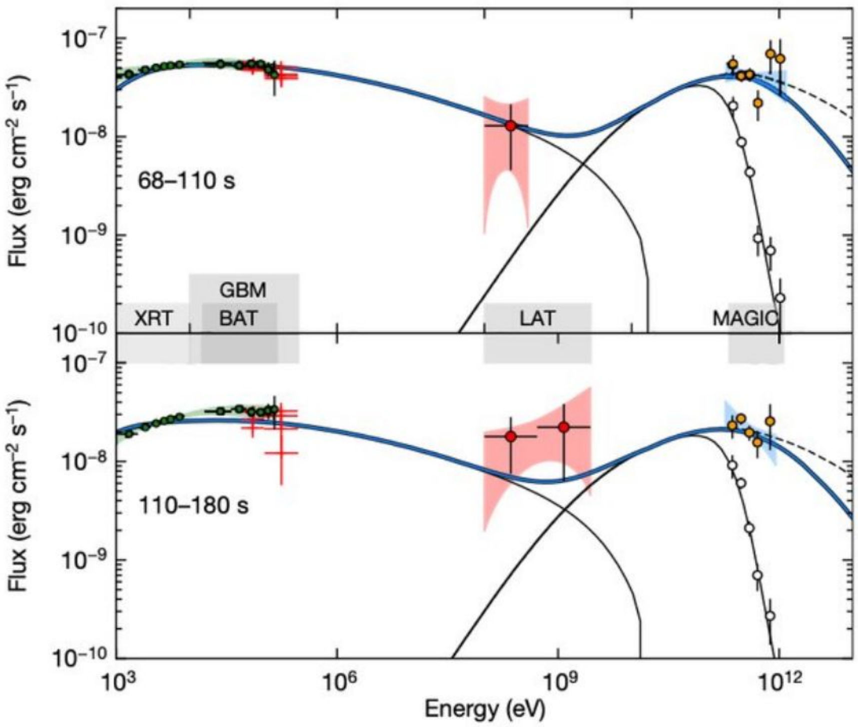
(a) (b)

Wang et al. 2 023, ApJ

GRBs detected at VHE energies



GRB 190114C ($z = 0.4245 \pm 0.0005$)



MAGIC Collaboration 2019, Nature

Open questions & Outlook

Part 1: Prompt emission

1. What causes the observed variability?
2. Are GRB jets magnetic or kinetic dominated flows?
3. What is the baryonic loading (protons/neutrons) of the jet?
4. How are particles accelerated?
5. What produces low-energy spectral breaks in GRB spectra?

Part 2: Afterglow emission

1. What produces flares and plateaus in X-ray afterglows ?
2. What are the expected ε_B, ε_e parameters for relativistic shocks?
3. Do the shock microphysical parameters evolve with time?
4. How does the pair loading affect the afterglow emission?

Outlook: TeV prompt emission, γ-ray polarization, neutrinos + GWs ??

Useful References

1. Ruderman 1975, AAS
2. Cavallo & Rees 1997, MNRAS
3. Goodman 1986, ApJL
4. Paczynski 1986, ApJL
5. Burgess et al. 2020, Nature Astronomy
6. Abbott et al. 2017, ApJ
7. Troja et al 2017,Nature
8. Piran 2004, Review of Modern Physics (theoretical review)
9. Vigliano & Longo 2024, Universe (recent review on observations)
10. Blandford & McKee 1976, Phys. Fluids
11. Sari, Piran, Narayan 1998, ApJL
12. Chiang & Dermer 1999, ApJ
13. Miceli & Nava 2022, Galaxies (recent review)

Part 4: AfterglowPy

https://github.com/geoffryan/afterglowpy

https://afterglowpy.readthedocs.io/en/stable/quickstart.html

AfterglowPy: Installation

https://afterglowpy.readthedocs.io/en/stable/quickstart.html

https://github.com/geoffryan/afterglowpy

Installation/Building

afterglowpy is available via `pip`:

```
$ pip install afterglowpy
```

afterglowpy is compatible with Numpy v1 and v2, Python 3.8+, and runs on MacOS, Linux, and Windows.

If you are working on a local copy of this repo and would like to install from source, you can the run the following from the top level directory of the project.

```
$ pip install -e .
```

Ryan et al. 2020 , ApJ

AfterglowPy: Numerical GRB Afterglow Models

https://afterglowpy.readthedocs.io/en/stable/quickstart.html

https://github.com/geoffryan/afterglowpy

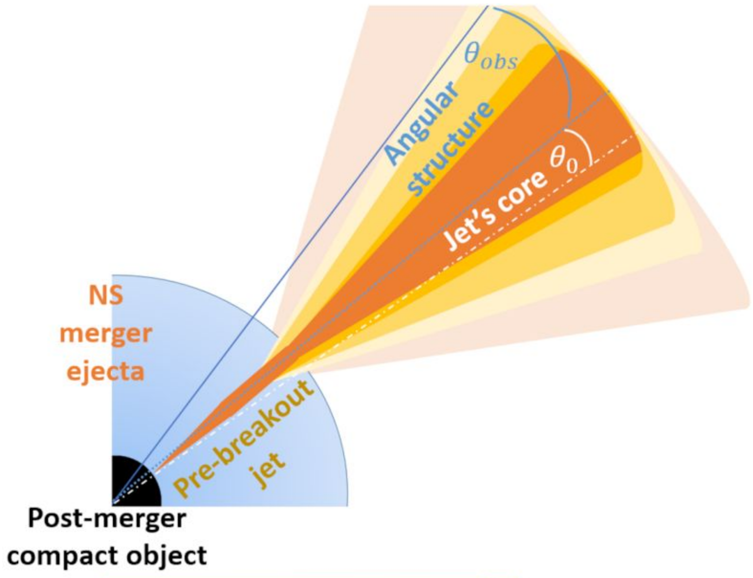
Features

afterglowpy computes synchrotron emission from the forward shock of a relativistic blast wave. It includes:

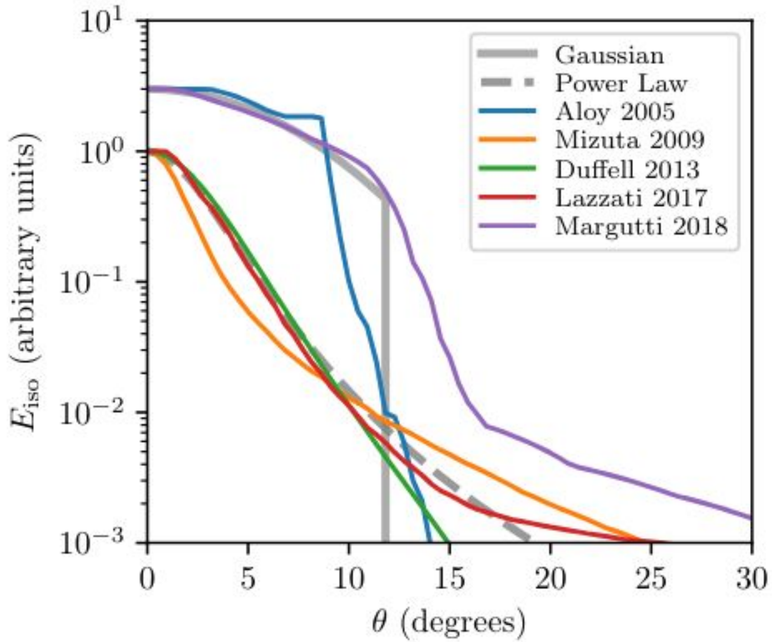
- Fully trans-relativistic shock evolution through a constant density medium.
- On-the-fly integration over the equal-observer-time slices of the shock surface.
- Approximate prescription for jet spreading.
- Arbitrary viewing angles.
- Angularly structured jets, ie. $E(\theta)$
- Spherical velocity-stratified outflows, ie. $E(u)$
- Counter-jet emission.
- Deep Newtonian emission.
- Image moments suitable for astrometry: centroid position and image size.

Ryan et al. 2020 , ApJ

Afterglow light curves from structured jets

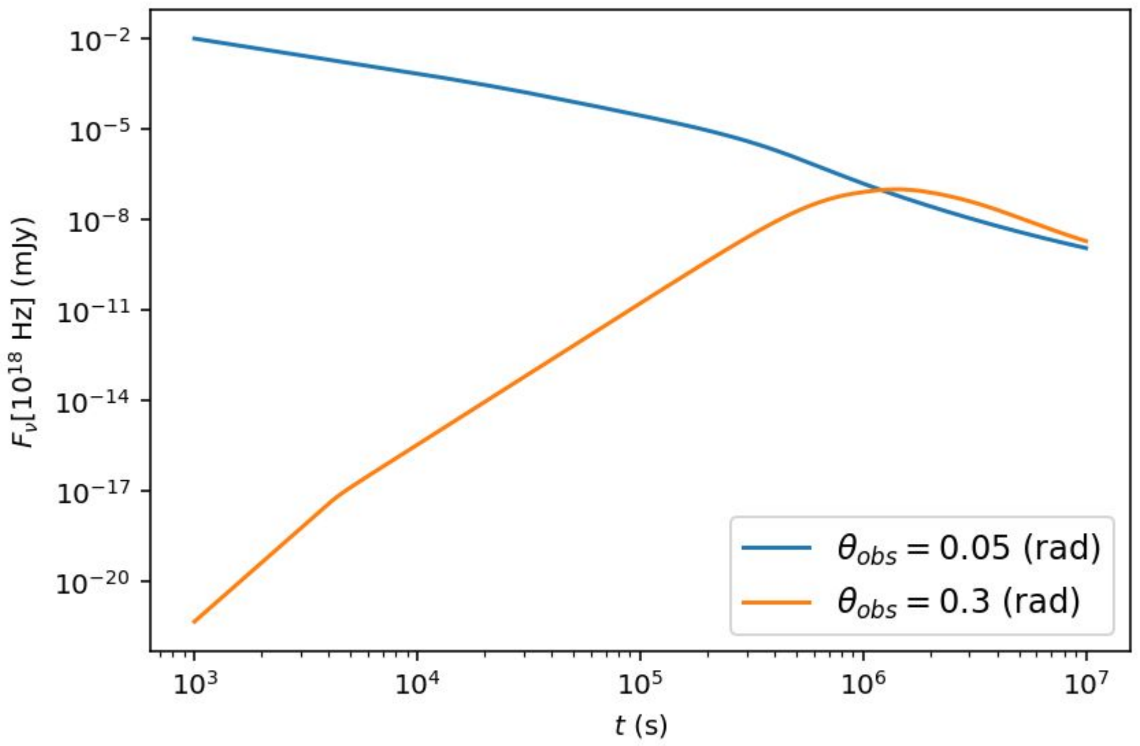


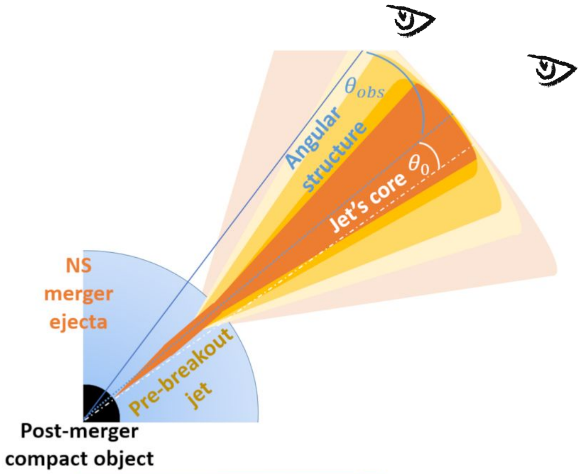
Beniamini et al. 2019, ApJ



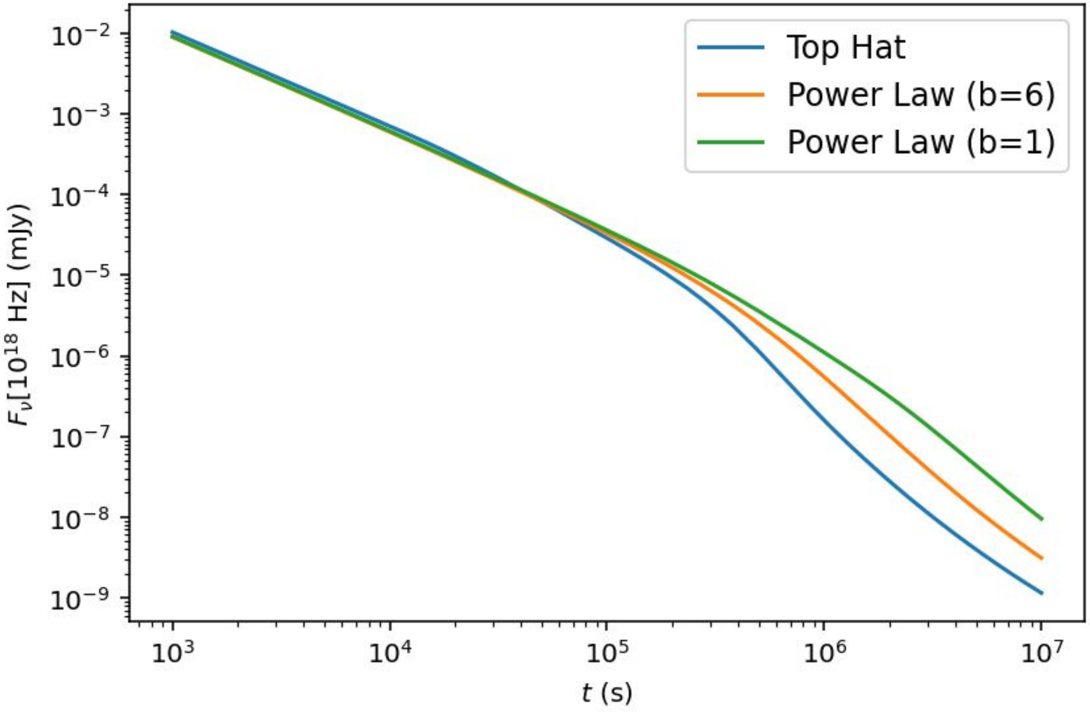
Ryan et al. 2020 , ApJ

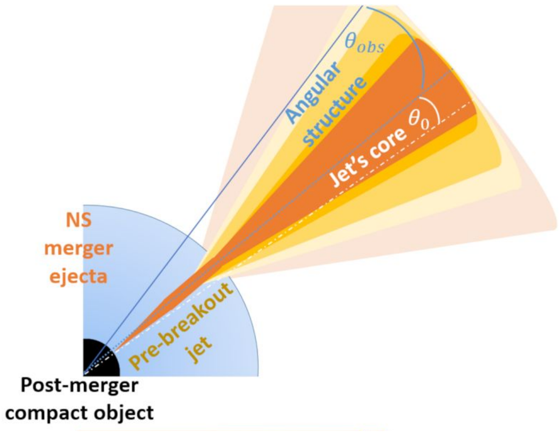
Example 1: On axis vs. Off axis observer





Example 2: Top-Hat vs. Power-Law

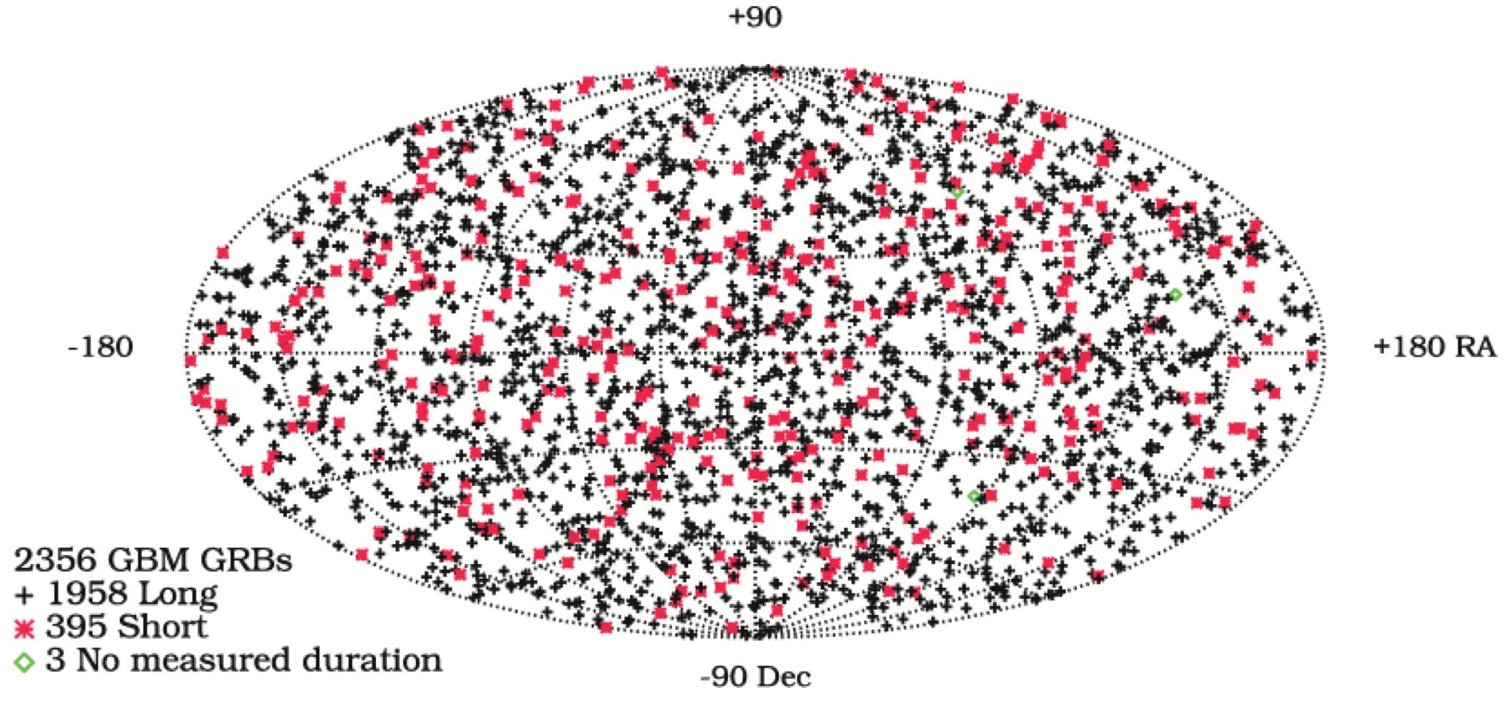




Backup slides

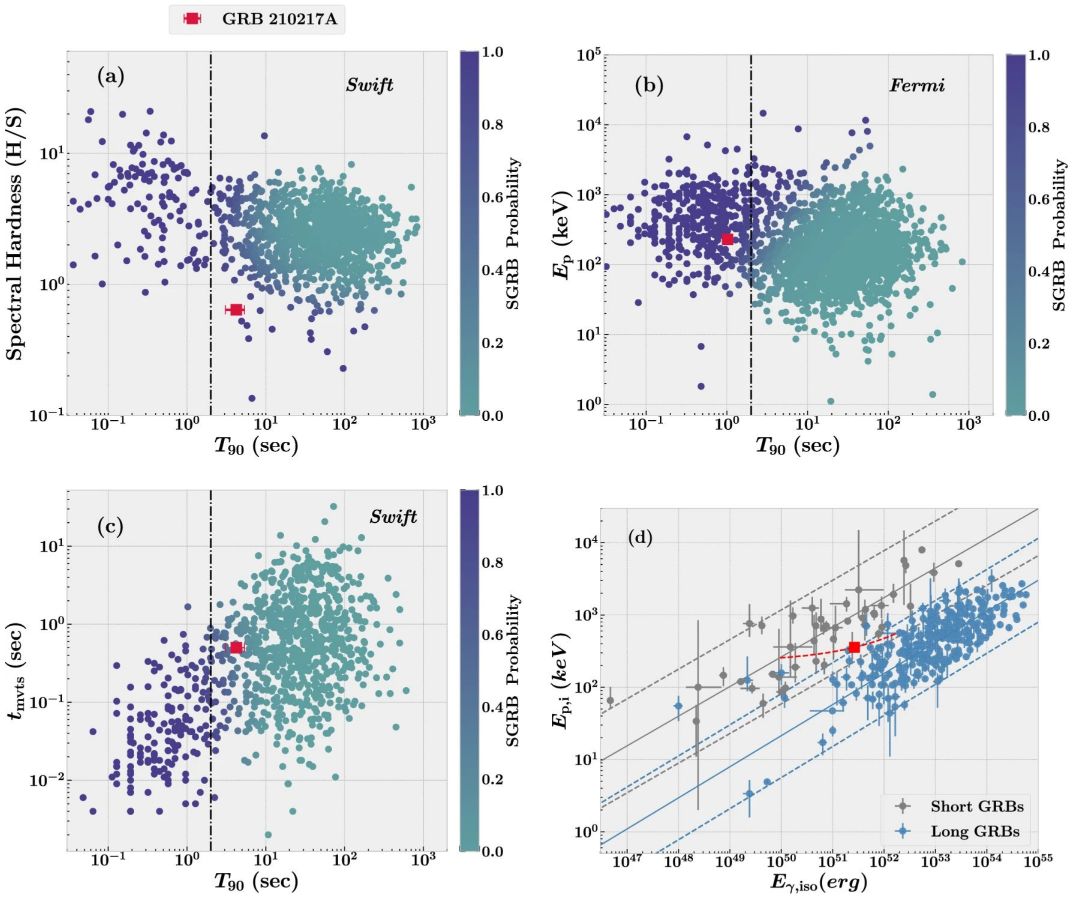
The Fermi era (2008 - today)

2356 bursts



von Kienlin et al. 2020, ApJ

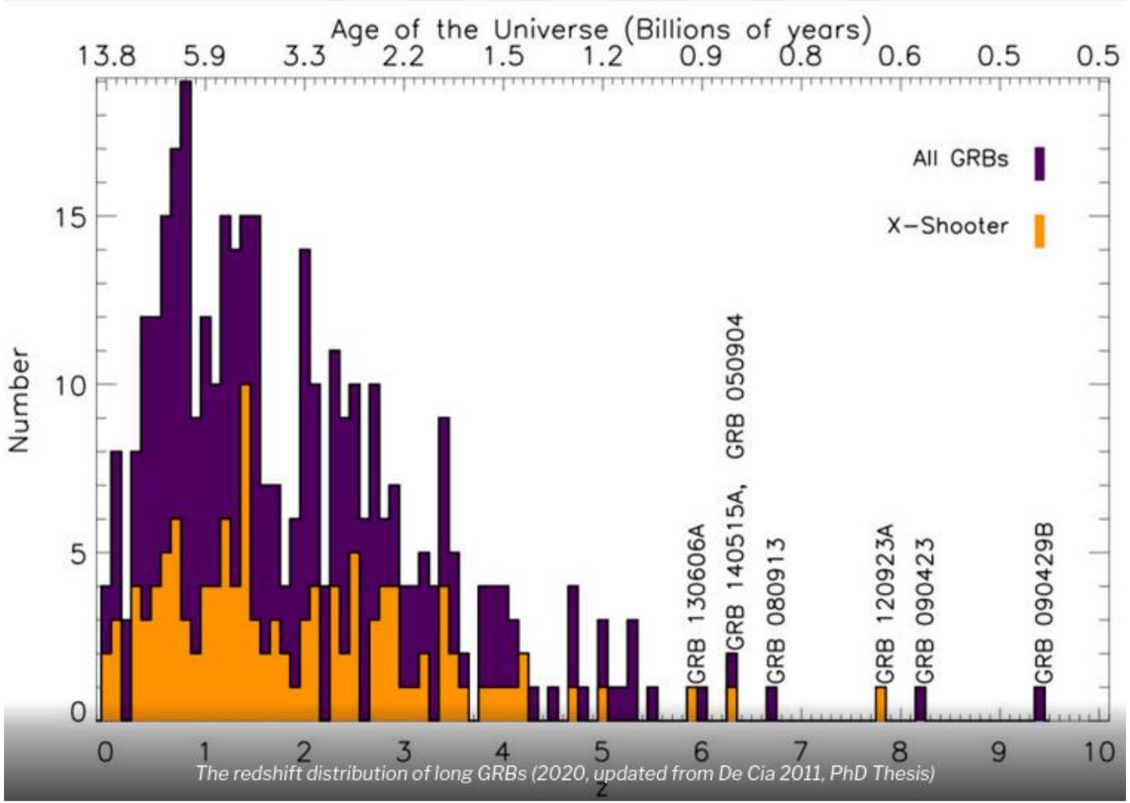
GRB observations with modern observatories



- Similar distributions with BATSE
- Variability is shorter for short GRBs
- Spectral peak energy correlates with total γ-ray energy
- No common explanation for all these trends !

Dimple *et al.* 2022, *J Astrophys Astron* **43**, 39

GRB redshift distribution



The redshift distribution of long GRBs (2020, updated from De Cia 2011, PhD Thesis)