Constraints on GRB Lorentz factors from prompt and afterglow observations

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Lorentz factor Γ
A key parameter of GRB physics

Different methods to constrain Γ

- **From prompt emission**: e.g. compactness argument **(Rees 1966)**
  Δt_{var} and L_γ give an estimate of photon/plasma densities at emission
  The emission has to be transparent to Thomson opacity, $\gamma\gamma$ opacity (at high energy)
  → Lower bound on the Lorentz factor, $\Gamma_{min} \approx 100$ **(e.g. Lithwick & Sari 2001, Hascoet et al. 2012)**

- **From afterglow emission**: peak time of the afterglow
  (e.g. Meszaros & Rees 1997, Sari & Piran 1999)

Estimate of Γ from the afterglow peak time T_p

The afterglow dissipation peaks at the deceleration time T_{dec}

$$R_{\rm dec} = \left(\frac{3-s}{4\pi c^2} \frac{E_{\rm ej}}{\Gamma_{\rm bw}^2 \rho_{\rm dec}} \right)^{\frac{1}{3}}$$

$$T_{\rm p} \simeq T_{\rm dec} \simeq \frac{R_{\rm dec}}{2\Gamma_{\rm bw}^2 c}$$

$$\boxed{\Gamma_{\rm bw} = \left[\frac{3-s}{32\pi c^5} \frac{1-\eta}{\eta} \frac{E_\gamma}{\rho_{\rm dec} T_{\rm p}^3} \right]^{\frac{1}{8}}}$$

Measured quantities

- E_γ = γ-ray energy
- T_p = peak time

Unknown quantities

- s = density profile (s=0 uniform; s=2 wind)
- η = prompt efficiency
- **ρ_{dec} = external density at R_{dec} ($\rho_{dec}/m_p \approx 10^{-3} \rightarrow 10^{3}$ cm^{-3})**

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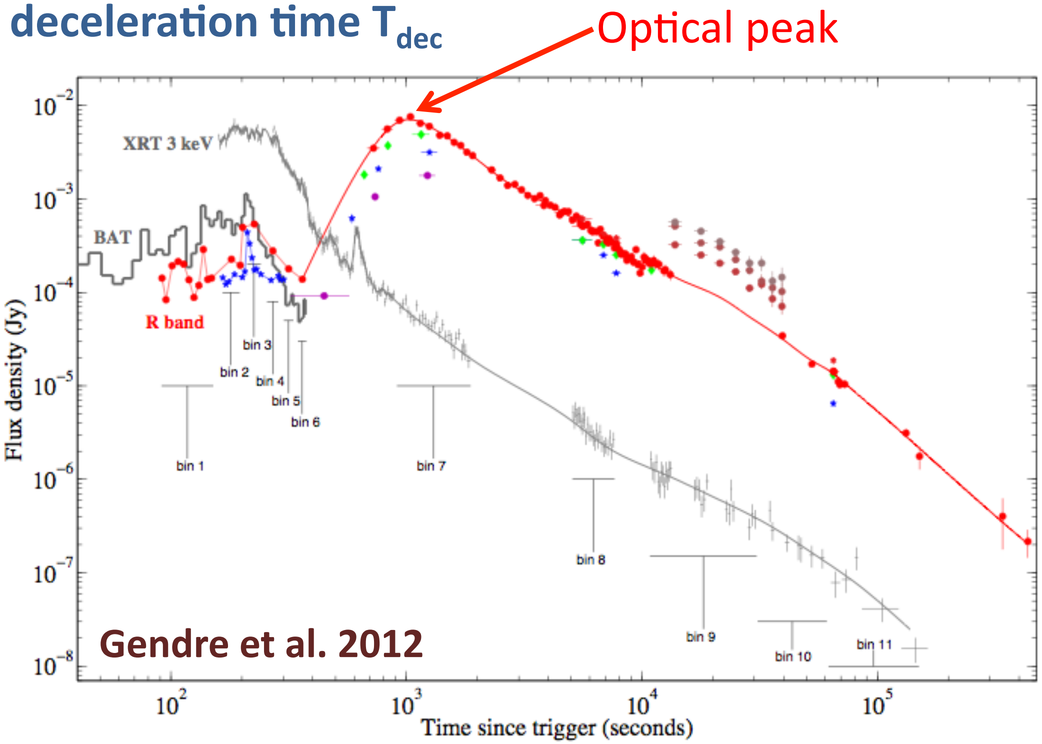


Optical peak

Gendre et al. 2012

Caveats

- Estimate for the blast wave Lorentz factor Γ_{bw}; not the ejecta Lorentz factor $\Gamma > \Gamma_{bw}$
  - ultra-relativisitic reverse shock $\Gamma >> \Gamma_{bw}$

    → $T_{GRB} \approx T_p$ ⟺ lower bound on Γ
  - newtonian to mildly relativisitic reverse shock $\Gamma \approx \Gamma_{bw}$

    → $T_{GRB} << T_p$ ⟺ estimate of Γ
- The phenomenology of the early afterglow is poorly understood (X-ray plateau, flares, bumps, achromatic behaviors)

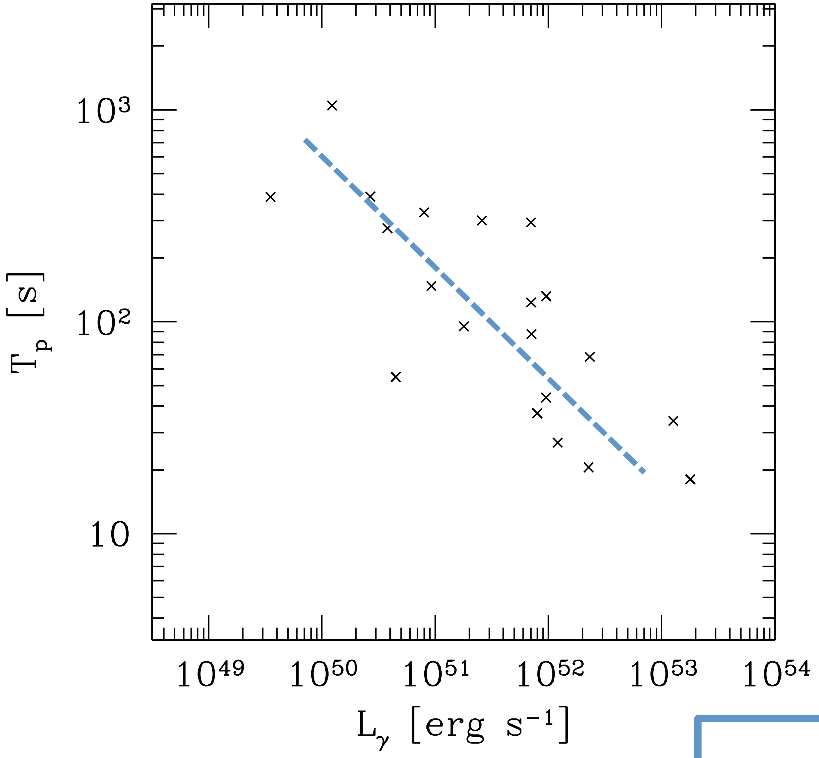
  → **key assumption: the optical peak traces the peak in blast wave dissipation**

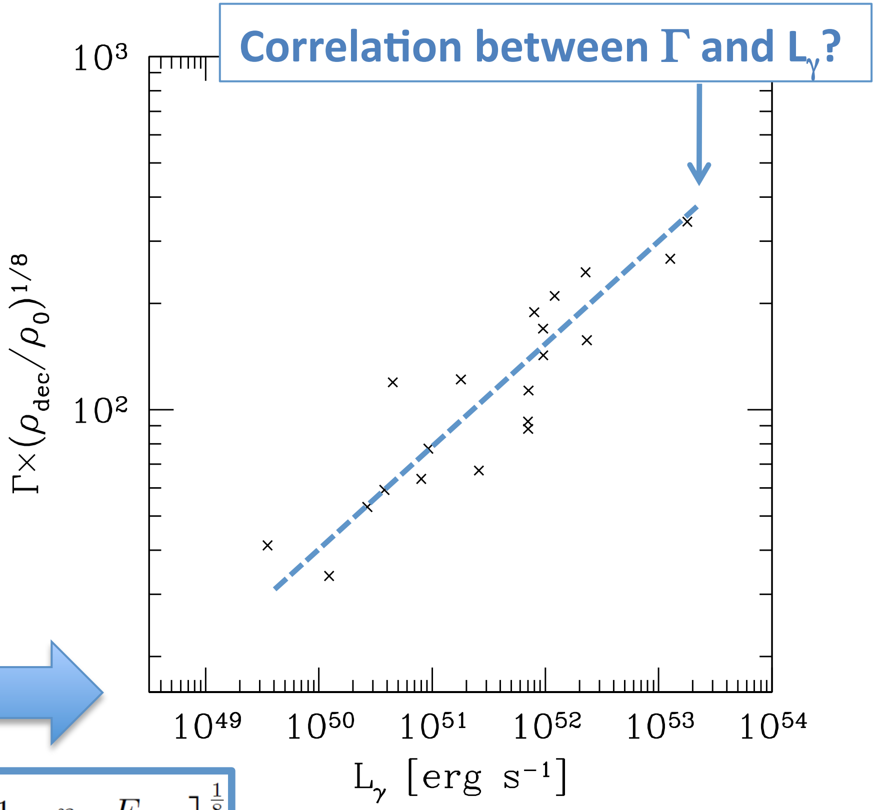
Constraining the Lorentz factor distribution of GRBs

Revisit previous studies

e.g. Liang et al. 2010, 2012
Ghirlanda et al. 2012

GRBs with detected optical afterglow peaks





Correlation between Γ and L_γ?

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$$\eta = 0.5\,,\, s=2\,,\, \rho_0/m_{\rm p} = 1~{\rm cm}^{-3}$$

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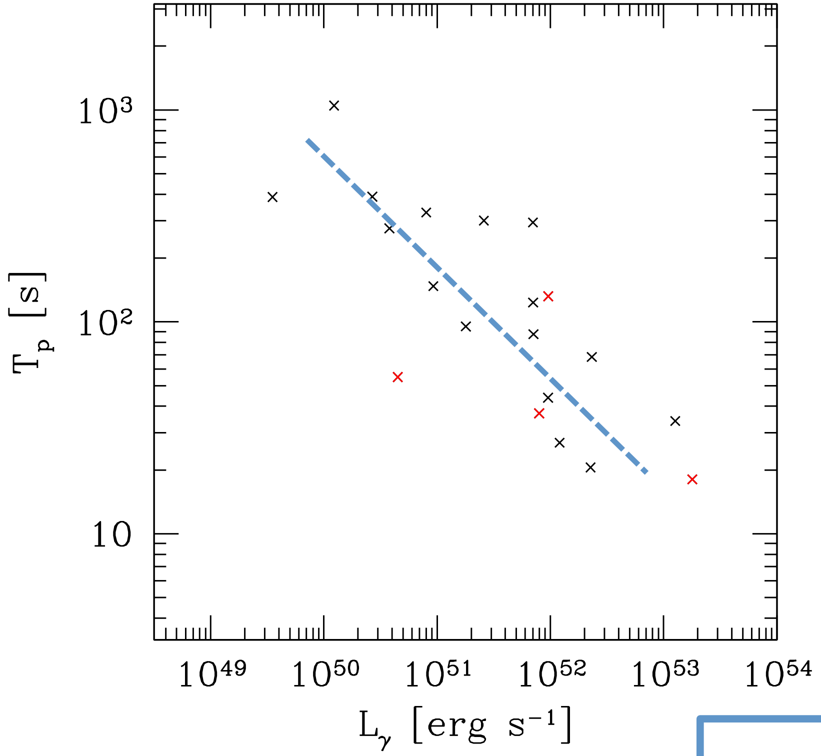
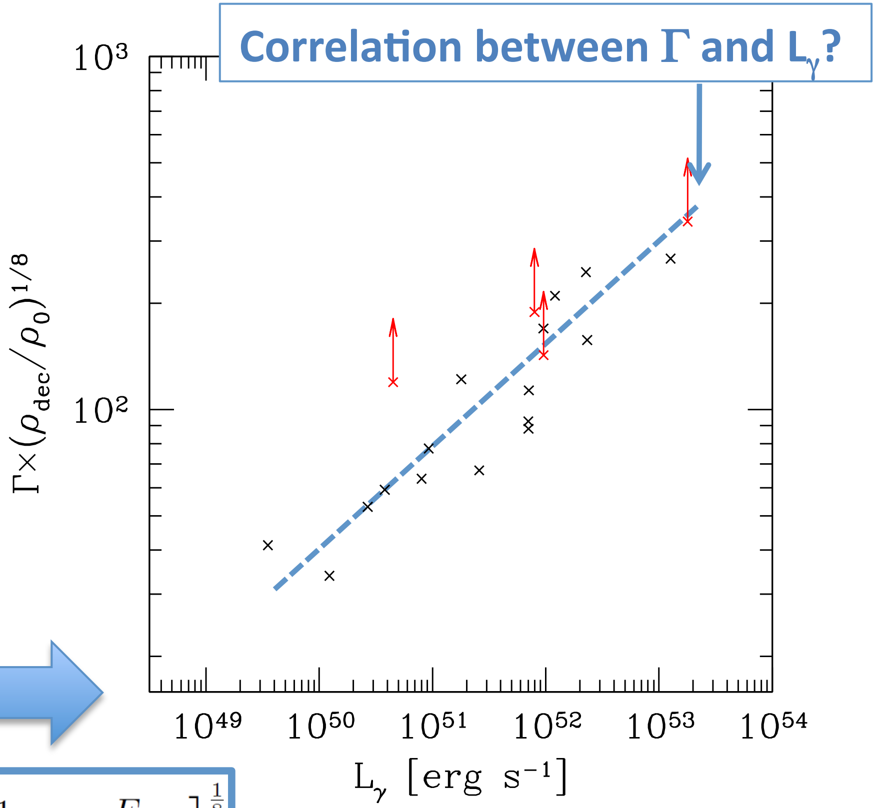
GRBs with detected optical afterglow peaks
GRBs with $T_p \approx T_{burst}$

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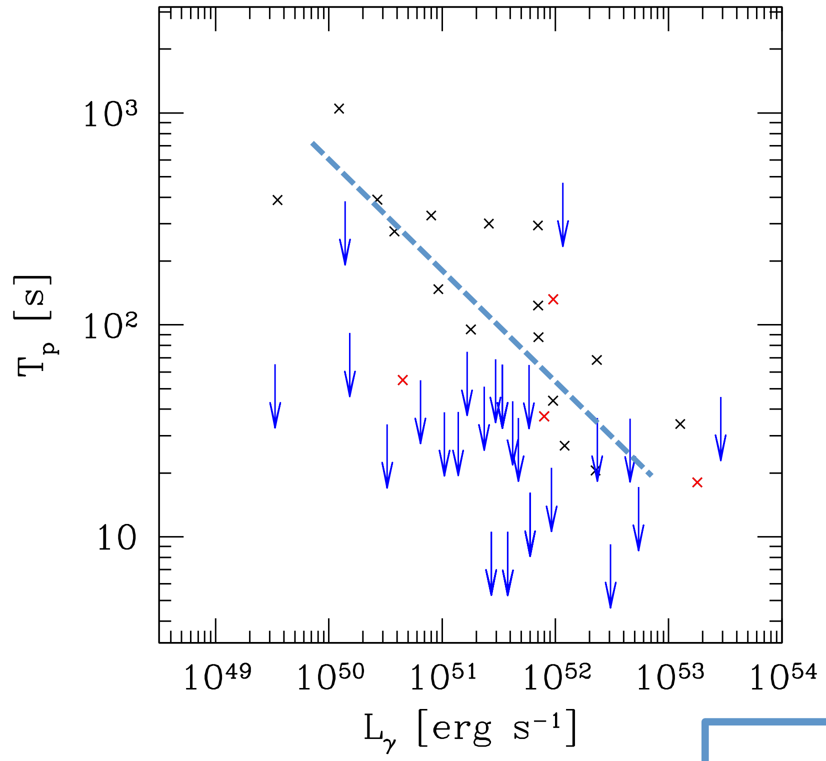
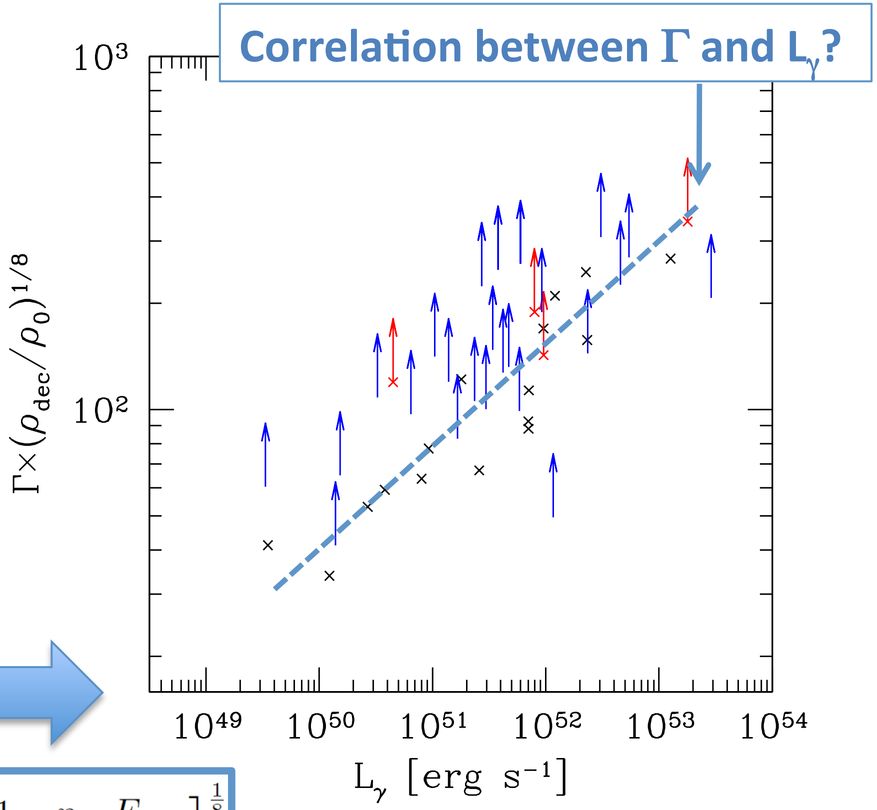
GRBs with detected optical afterglow peaks
GRBs with $T_p \approx T_{burst}$
GRBs with upper-limits on T_p

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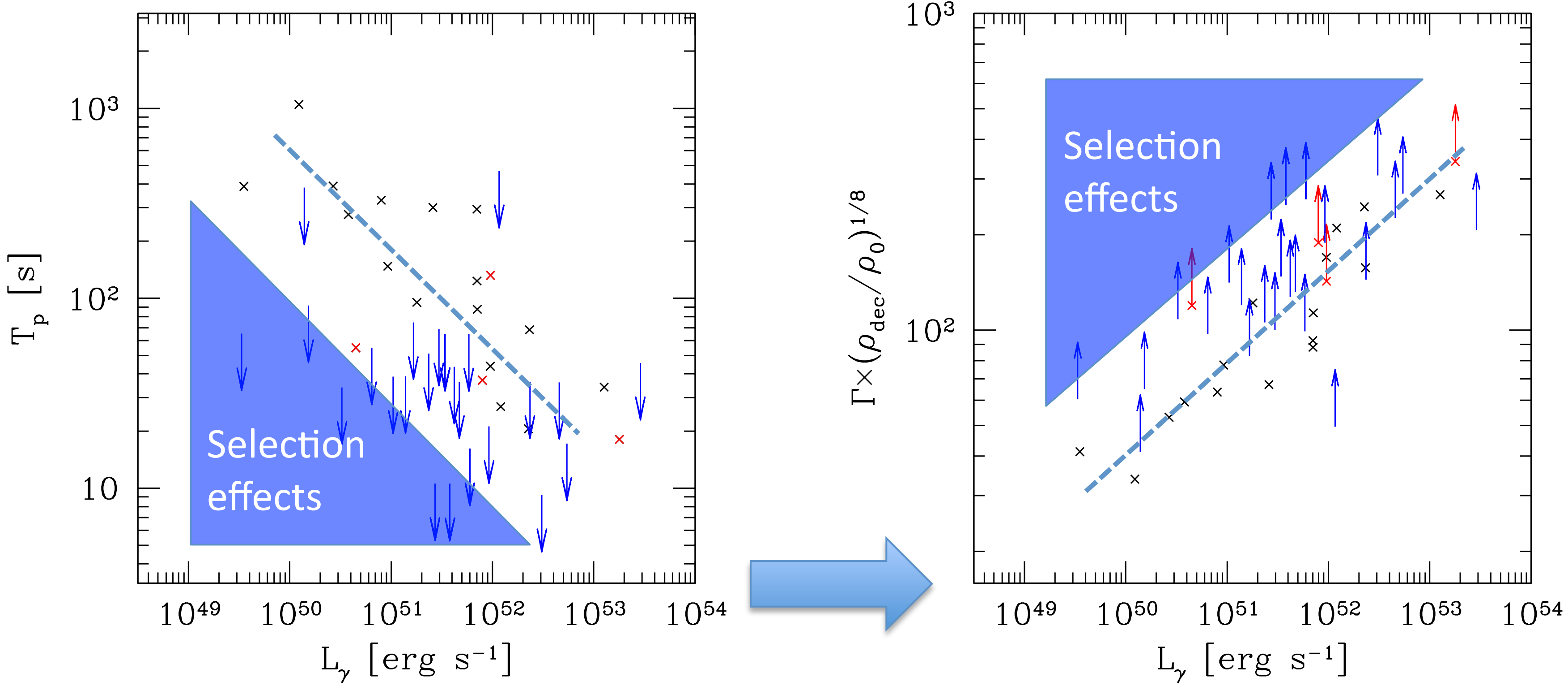

Selection effects: response delay of optical telescopes.

The correlation does not hold

Constraining the Lorentz factor distribution of GRBs

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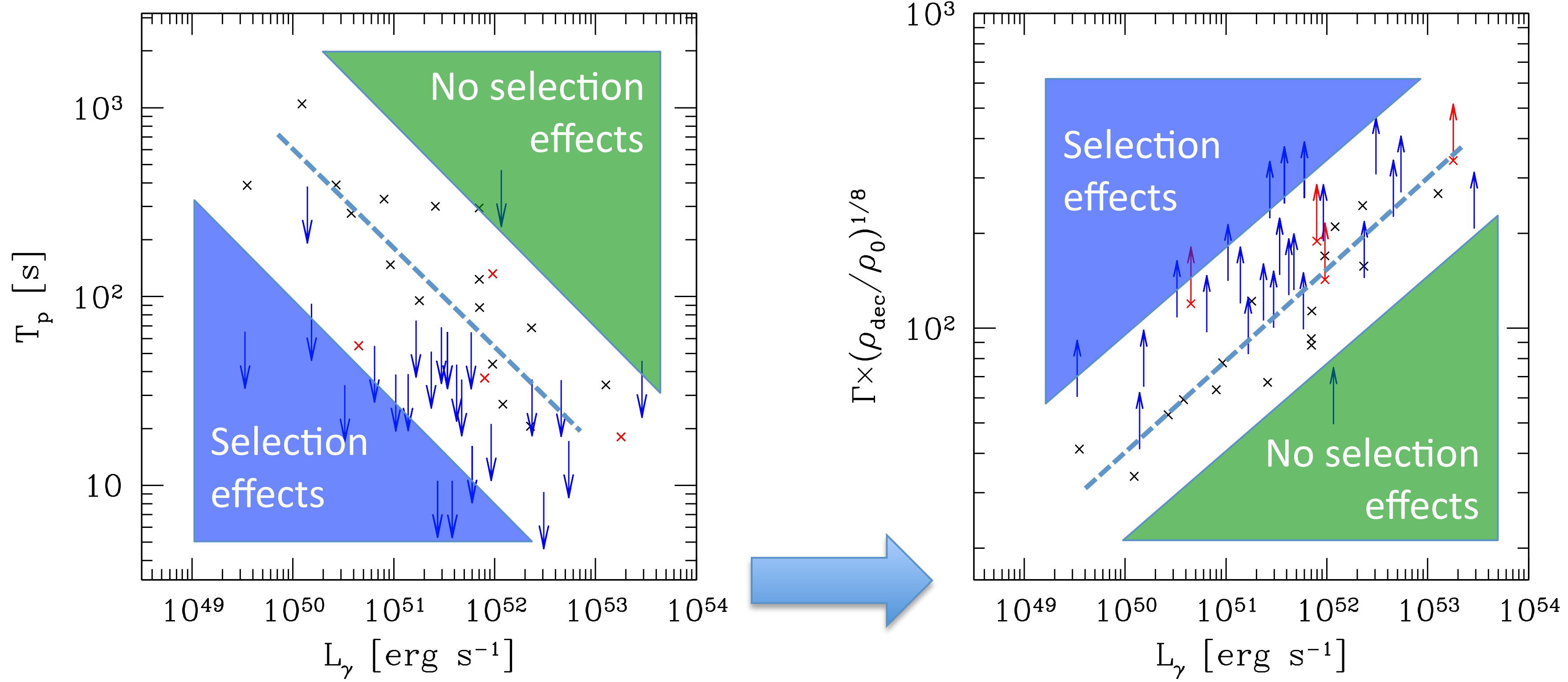


The lack of bright bursts with late T_p seems to be real

Bright burts cannot have low Lorentz factors?

Bright GRBs cannot have low Lorentz factors

An effect of adiabatic cooling?

- The prompt dissipation radius is expected to discrease with Γ
- The photospheric radius increases as Γ decreases

$$\boxed{R_{\rm diss} = \Gamma^2 R_0}$$

$$\boxed{R_* \simeq 2.9 \times 10^{12} \kappa_{0.2} L_{52} \Gamma_2^{-3}\ \mathrm{cm}}$$

- The dissipation can be burried far below the photosphere

$$\boxed{\tau_{\rm diss} = \frac{R_*}{R_{\rm diss}} \propto L\Gamma^{-5}}$$

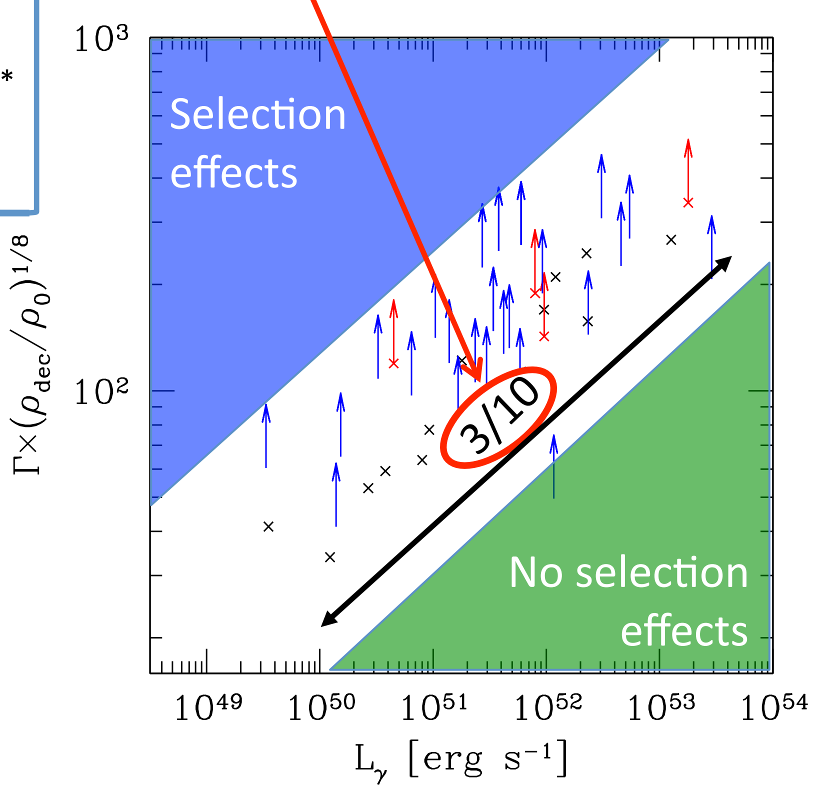
$$\boxed{\Gamma \propto L_\gamma^{3/10}}$$

- If $\tau_{\rm diss}$ >> 1, the emission is softened from $R_{\rm diss}$ to R_*
  - Adiabatic cooling

$$\boxed{L_\gamma \propto E_{\rm p} \propto \tau_{\rm diss}^{-2/3}}$$

  - High-energy cutoff due to Compton scatterings

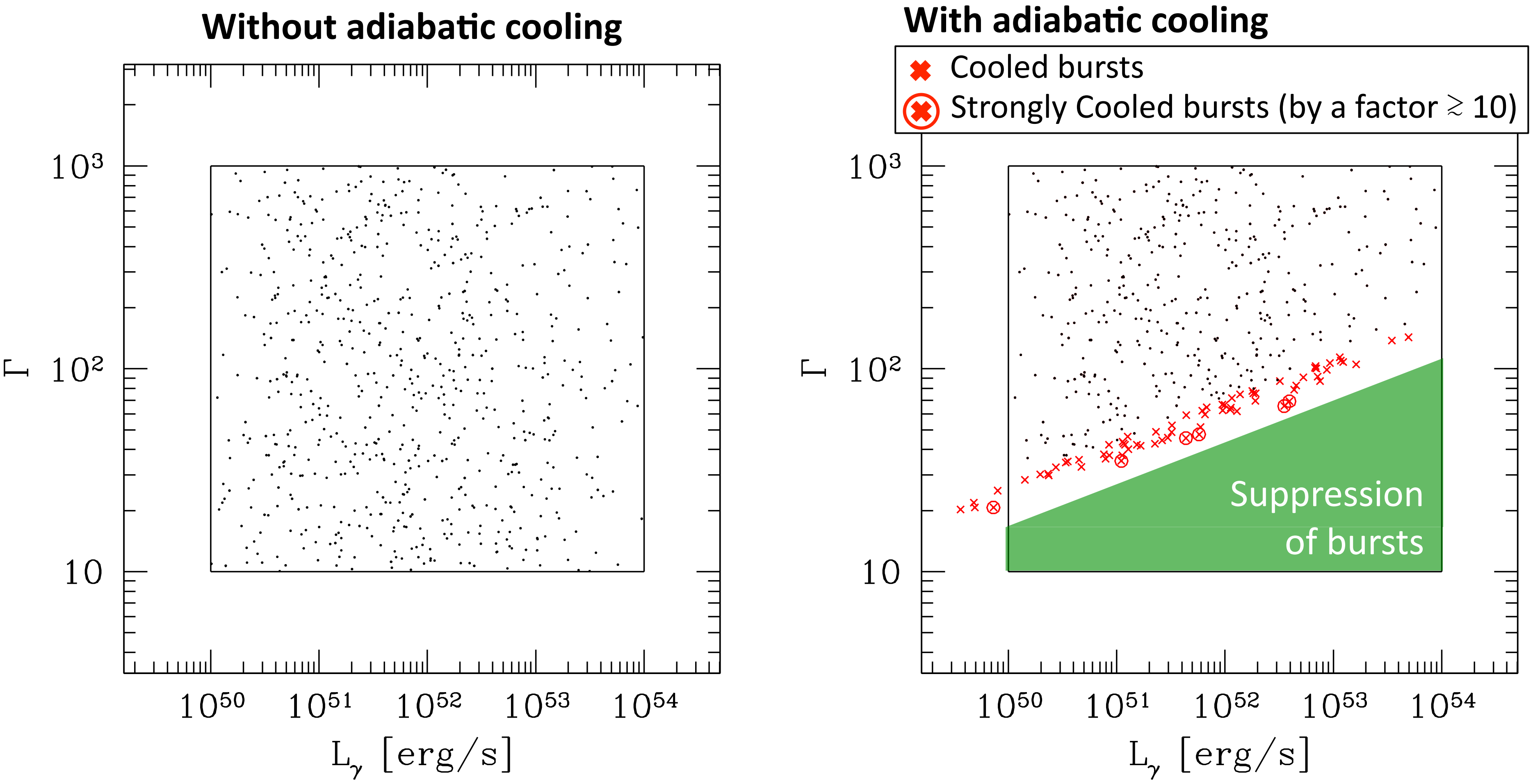
$$\boxed{E_{\rm max} \approx \frac{\Gamma m_e c^2}{\tau_{\rm diss}} \approx 511\ \frac{\Gamma}{\tau_{\rm diss}}\ \mathrm{keV}}$$



Bright GRBs cannot have low Lorentz factors

An effect of adiabatic cooling?

Synthetic GRB population - Bursts detected by Swift


Without adiabatic cooling

With adiabatic cooling

Most cooled GRBs avoid detection

Afterglow peak time + Compactness argument
Constraining the progenitor of long GRBs

$$\Gamma_{\rm bw} = \left[\frac{3-s}{32\pi c^5}\frac{1-\eta}{\eta}\frac{E_\gamma}{\rho_{\rm dec}T_{\rm p}^3}\right]^{\frac{1}{8}}$$

Afterglow peak time

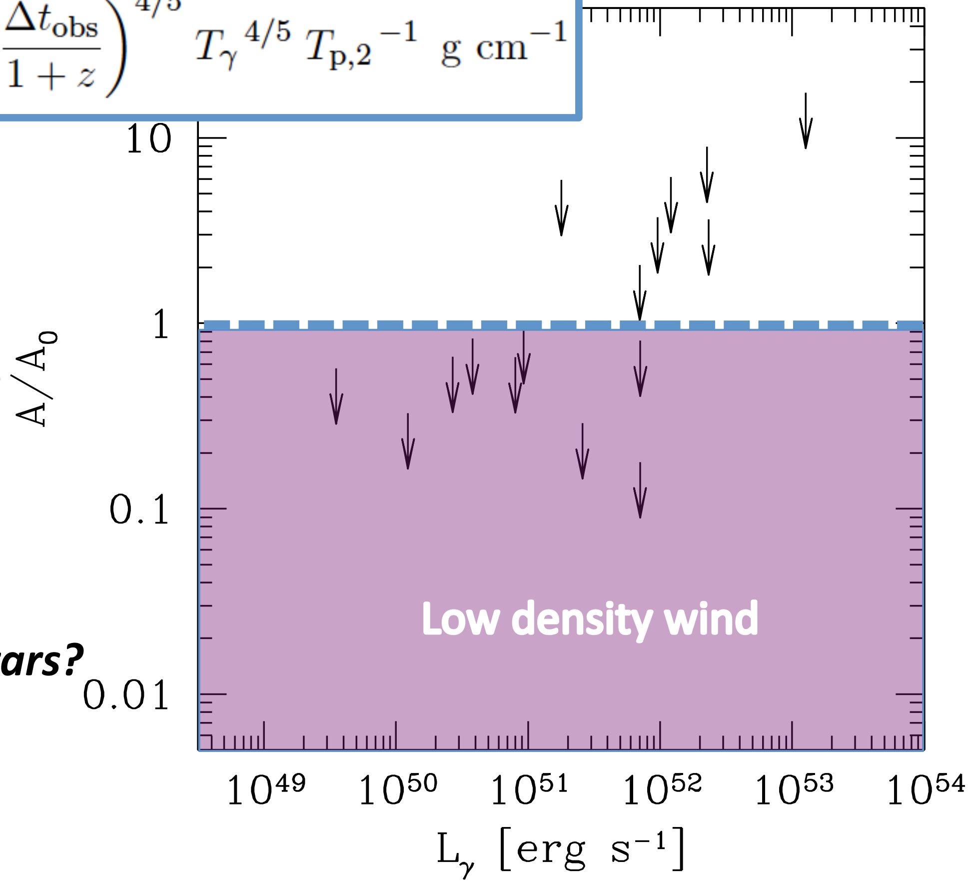
$$\frac{\Delta t_{\rm obs}}{1+z} \gtrsim \frac{R_*}{2\Gamma^2 c} \approx 5\,\kappa_{0.2}\frac{1-\eta}{\eta}L_{\gamma,52}\Gamma_2^{-5}\ \rm ms$$

Compactness argument

Thomson opacity

$$A < A_{\rm max} \approx 10^{11}\ {\kappa_{0.2}}^{-4/5}\left(\frac{1-\eta}{\eta}\right)^{1/5}\ {E_{\gamma,52}}^{1/5}\left(\frac{\Delta t_{\rm obs}}{1+z}\right)^{4/5}\ {T_\gamma}^{4/5}\ {T_{\rm p,2}}^{-1}\ \ \rm g\ cm^{-1}$$

Upper-bound on the wind density



ρ(R) = A/R²

A_0 = 5x10^{11} g/cm : typical Wolf-Rayet star

(e.g. Crowther 2007)

GRB progenitors are peculiar Wolf-Rayet stars?

Discussion I: Lack of bright bursts with low Lorentz factor

Observation
(key assumption: optical peak traces the peak in blast wave dissipation)

- Severe selection effects for weak bursts with high Lorentz factors

→ No evidence for a correlation between L_γ and Γ

- The lack of bright bursts with low Lorentz factors seems to be real

Interpretation

- Bright GRBs with low Lorentz factors are suppressed by adiabatic cooling ($R_{ph}/R_{diss} >> 1$)

Expected properties of (the few detected) adiabatically cooled bursts

- Most adibatically cooled bursts avoid detections
  GRBs cooled by a factor $\gtrsim$ 10 should represent (at most) a few % of detected bursts
  → prime candidates for orphan afterglows **(see Bradley Cenko et al. 2013)**
- Soft spectra (low E_p, high-energy cutoff)
- Low prompt efficiency $\eta = E_\gamma/E_{jet} << 1$
  → Bright afterglows (relative to prompt luminosity)
- Smooth γ-ray light-curve enforced by the large photospheric radius
  ($\Delta t_* = R_*/\Gamma^2 c \gtrsim$ 1-10 s)

Discussion II: progenitors of long GRBs have low density winds

Observation

- Combined constraints from afterglow peak time + transparency constraint (prompt compactness) give an upper-limit on the wind density
  → GRB progenitors have lower density winds than typical galactic Wolf-Rayet stars

Interpretation

- Only special Wolf-Rayet stars trigger a GRB: a low-metallicity is favorable
  low metallicity = low mass loss through stellar winds **(e.g. Vink et al. 2001)**
  - Observational evidence: from host galaxies
    (e.g. Perley et al. 2013)
  - Theoretical support: a low-metalicity star loses less angular momentum through winds
    (e.g. Woosley & Heger 2006)
  - Importance of selections effects?
    Sample based on optical afterglow detections: bias against high metallicity environments

- A low density ambient medium: a consequence of stellar evolution?
  → if stellar winds stall a few years before the GRB explosion