Les Houches 14-18 Mai 2018

How to constrain the nature of GRB progenitors: the example of long GRBs

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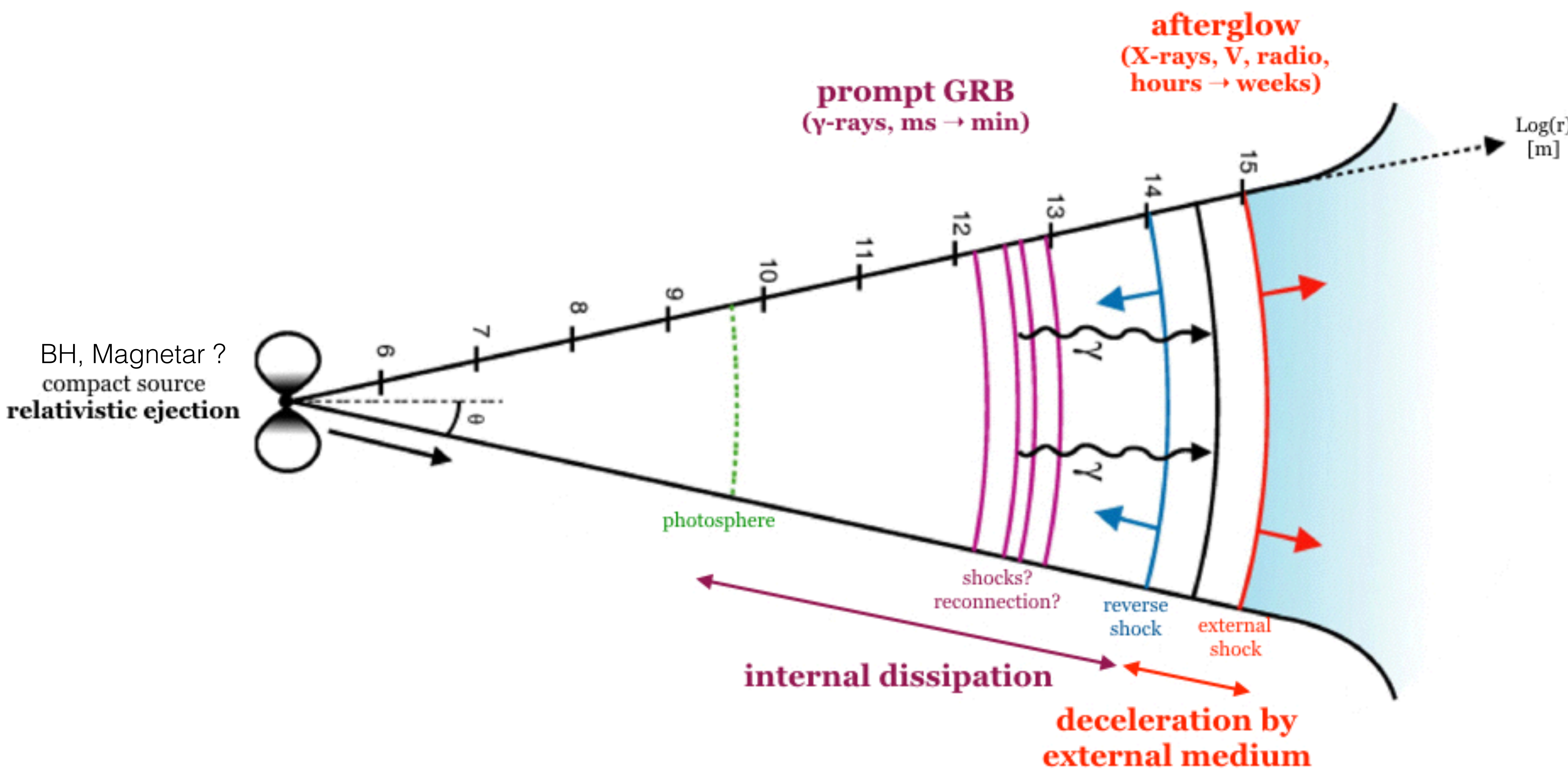
What are Gamma-Ray Bursts?

Ultra relativistic jet associated with the formation of a stellar mass black hole



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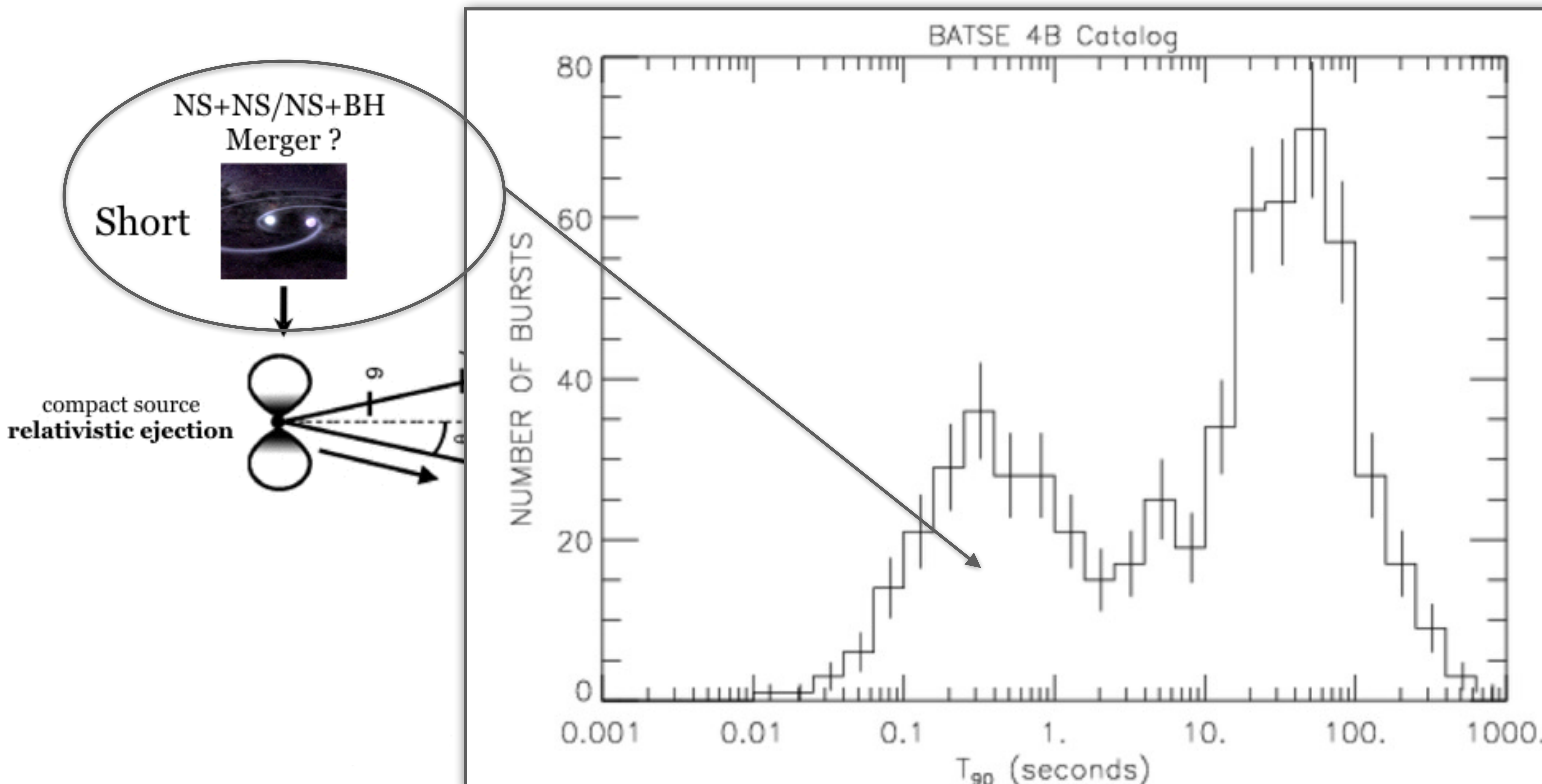

credit : http://gammaray.nsstc.nasa.gov/batse/grb/duration/

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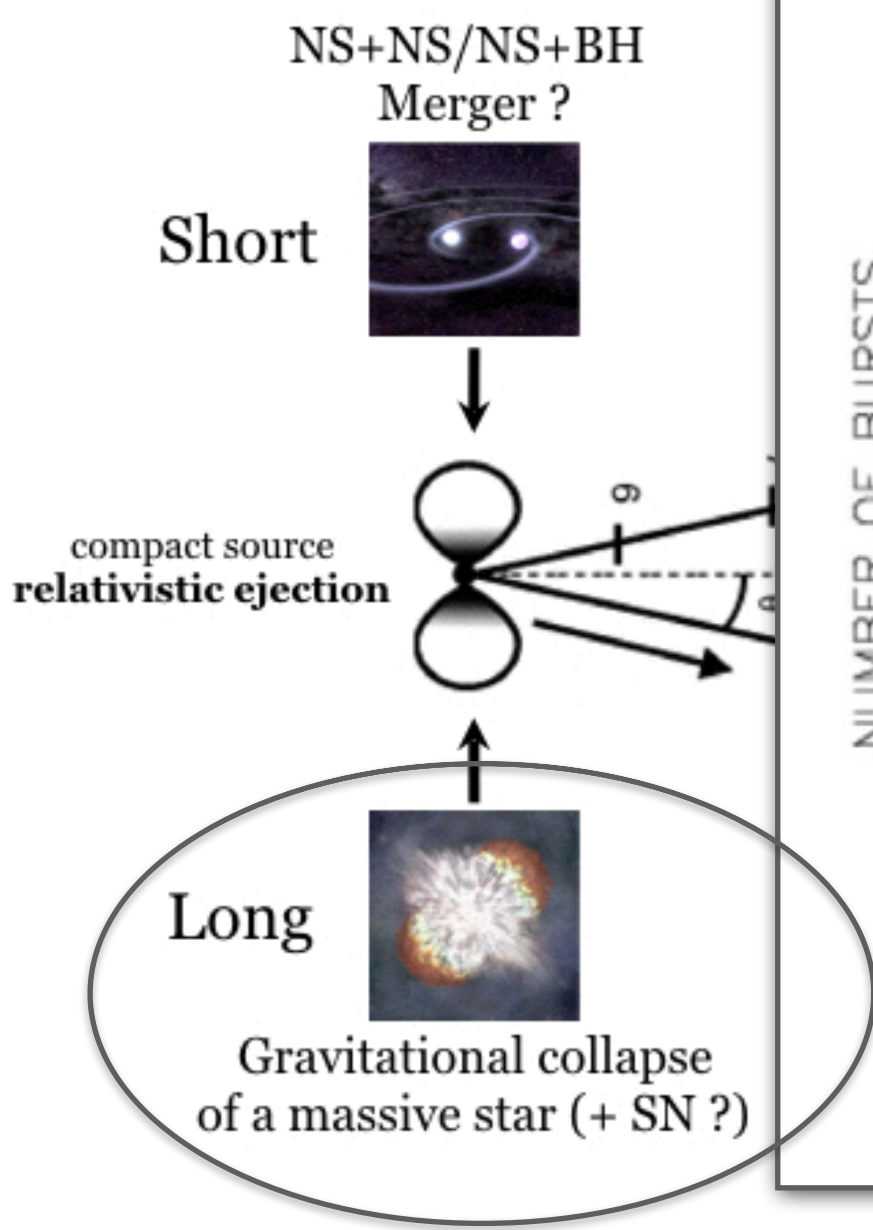
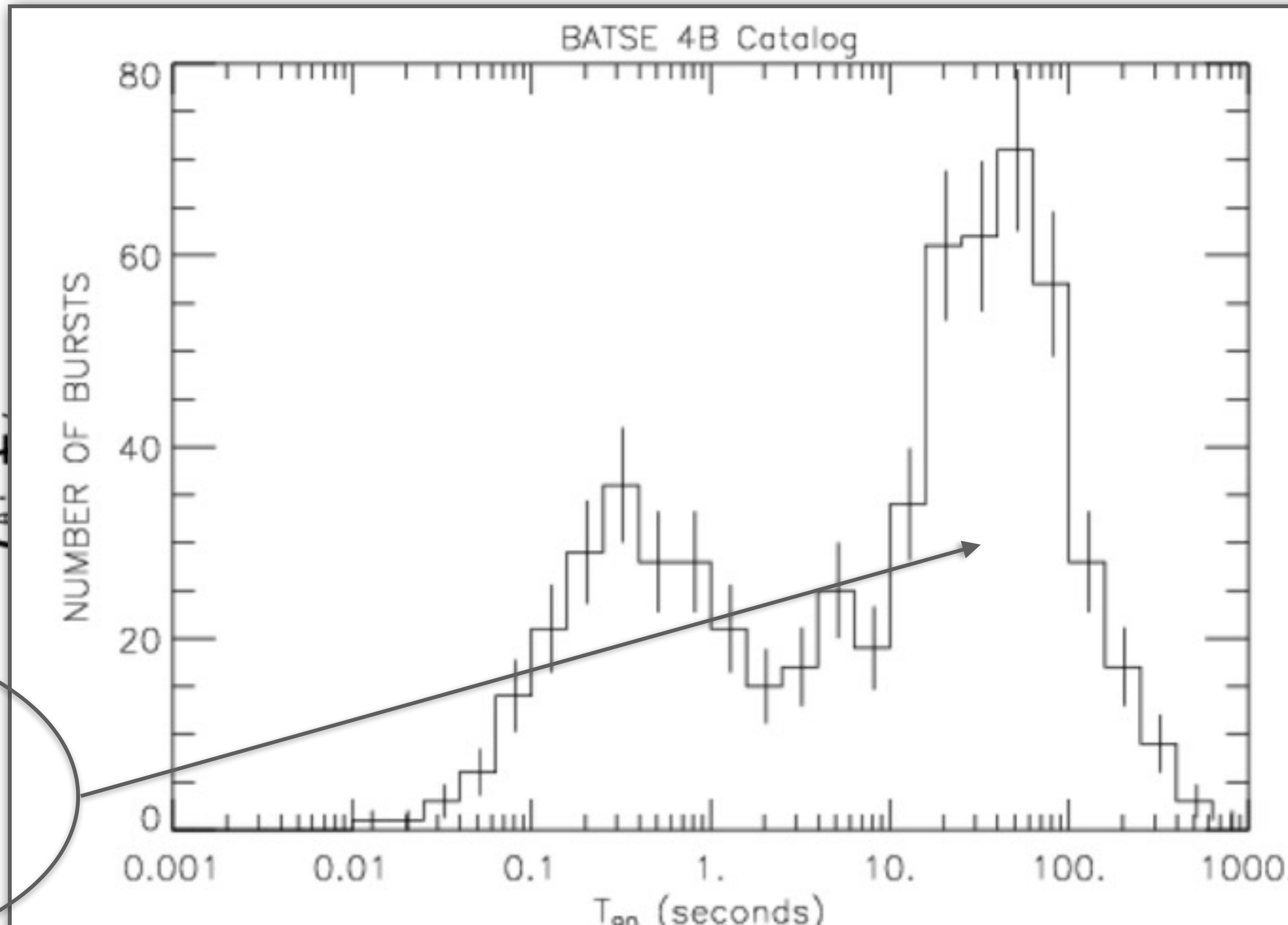




credit : http://gammaray.nsstc.nasa.gov/batse/grb/duration/

Context

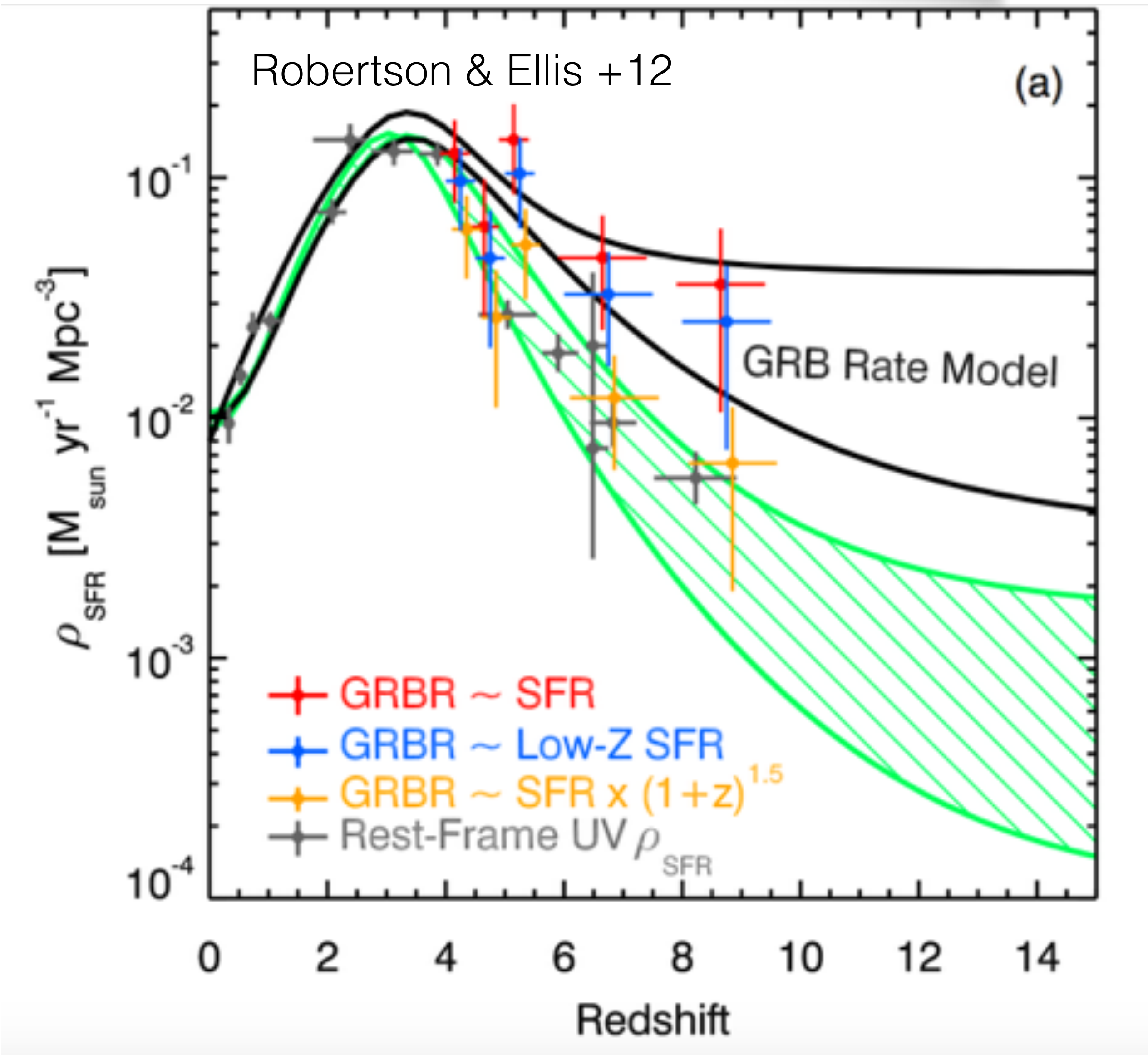
Interest of studying Long GRBs (LGRBs)?

- LGRBs allow us to **study the Universe** up to high redshift
  - Detected by **gamma rays** which are easily observable at high z (and largely unaffected by dust)
  - Afterglow is **bright** at high-z compared to other sources and benefits from time dilation

➡ In particular, LGRBs offer a powerful, **unique tool** to probe the SFR at high-z

Link between SFR and LGRB rate: LGRB efficiency

- Studies compared LGRB rate to SFR but using biased or incomplete samples
- To date, only about **30%** of *Swift* GRBs have a redshift



➡ Need for **complete samples** of LGRBs (*e.g.* TOUGH (Hjorth+12), SHOALS (Perley+16a,b), BAT6 (Salvaterra+12))

LGRB efficiency: proper definition

- Number of core-collapses per year per comoving volume : $\dot{n}_{coll}$ $[\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}]$
- Number of LGRBs per year per comoving volume : $\dot{n}_{GRB}$ $[\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}]$

➡ $\dot{n}_{GRB} = \eta(z)\,\dot{n}_{coll}$

with $\eta(z)$ the fraction of core-collapses that form a LGRB

- Collapse rate : $R_{coll} = \int_0^{z_{max}} \dot{n}_{coll}(z)\,\frac{dV}{dz}\,\frac{1}{1+z}dz$ $[\mathrm{yr}^{-1}]$
- GRB rate : $R_{GRB} = \int_0^{z_{max}} \eta(z)\,\dot{n}_{coll}(z)\,\frac{dV}{dz}\,\frac{1}{1+z}dz$ $[\mathrm{yr}^{-1}]$

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LGRB population model

- To gain insight into their progenitors, one method is to constrain the **global statistical properties** of LGRBs and their **rate** via a population model
- Take advantage of the **wide variety of observational constraints** available on the GRB **prompt** emission, with careful selection (*e.g.* from *CGRO*/BATSE, *Swift*/BAT, *Fermi*/GBM…)
- **Test various correlations** between parameters (*e.g.* E_{peak} - L_{iso}: intrinsic correlation and/or observational bias?)

LGRB rates and luminosity

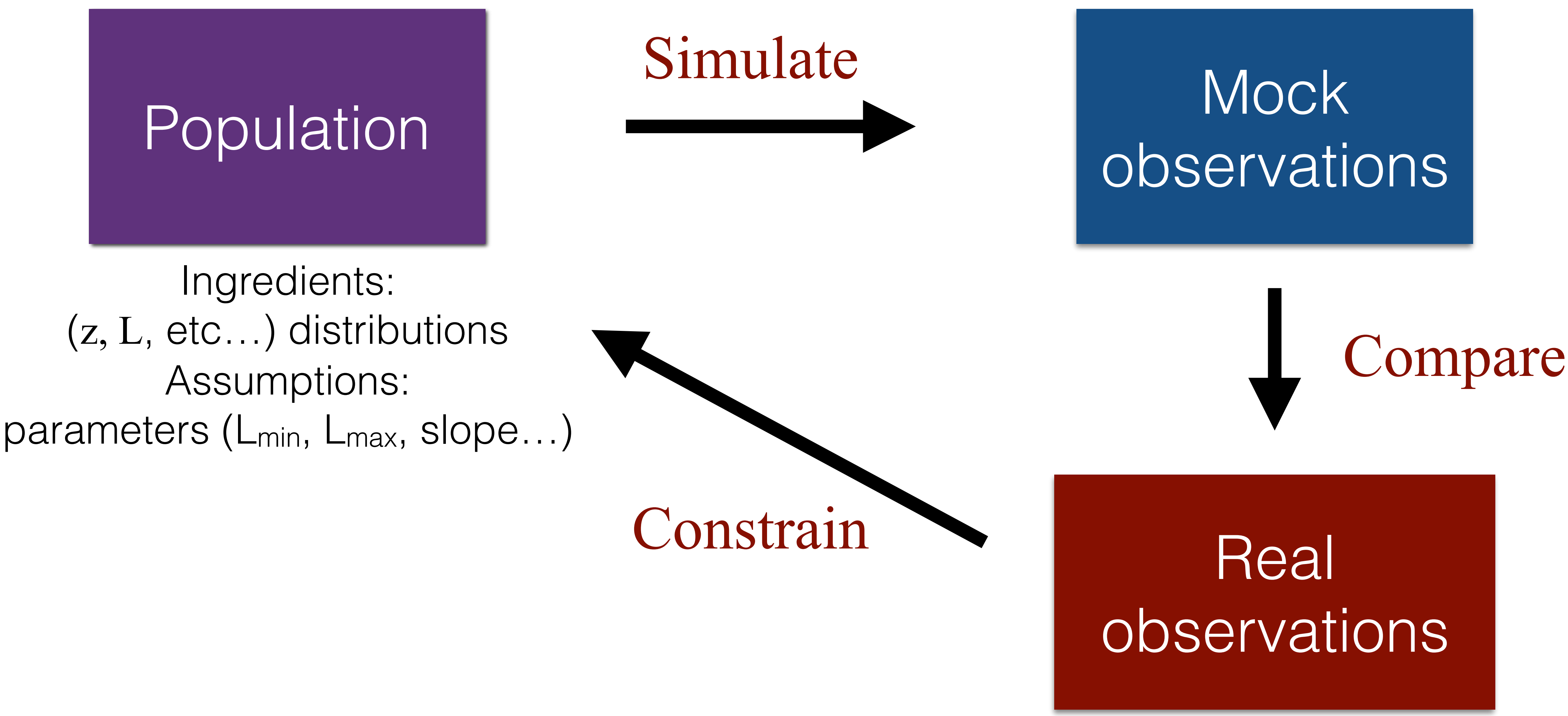
- What is the **Luminosity Function** (*e.g.* Pescalli+16)?
  Does it **evolve with redshift** (*e.g.* Petrosian+15)?

- What is the **redshift distribution** (*e.g.* Wanderman & Piran 10)?
  How does it **compare to the Cosmic Star Formation Rate** (*e.g.* Daigne+06)?
  What does this mean for the **LGRB efficiency** and **progenitors**?

- Are there **correlations** between physical quantities, pointing to some underlying physics? (*e.g.* "Amati-like" correlations)

Population model scheme

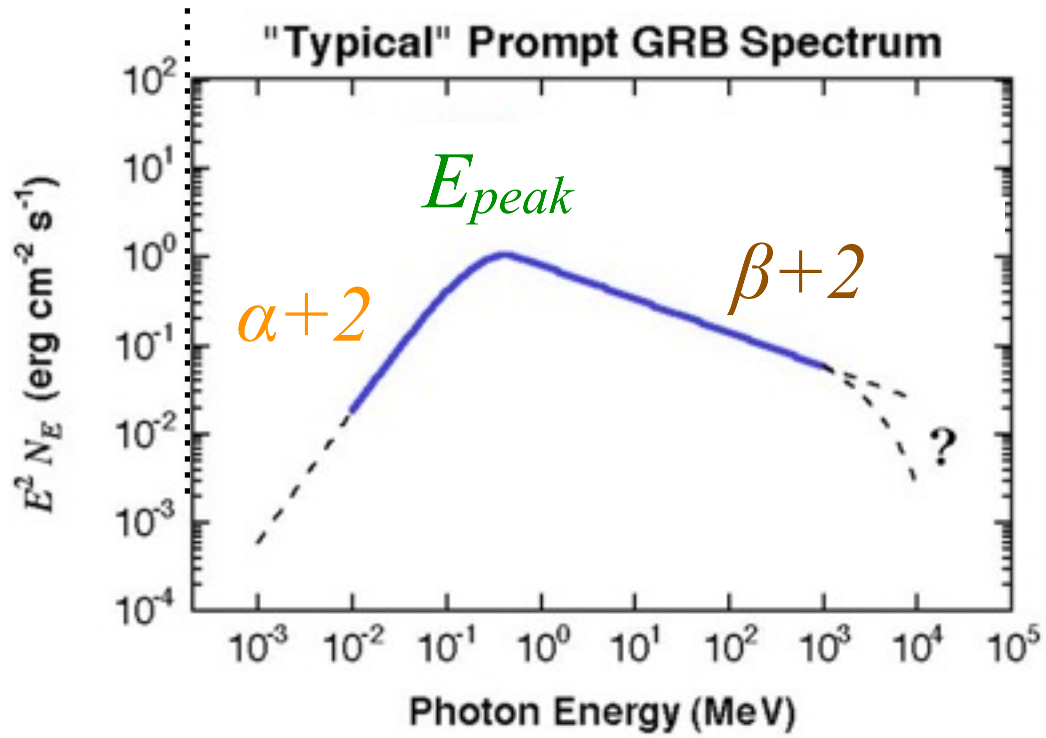
Based on MC model from Daigne et al. 2006



Ingredients for the population model

credit : NASA/Swift/Mary Pat Hrybyk-Keith and John Jones

- Redshift : z
- Luminosity : L_{iso}
- Spectrum : E_{peak} α β



Luminosity distribution

Functional form

- Power law

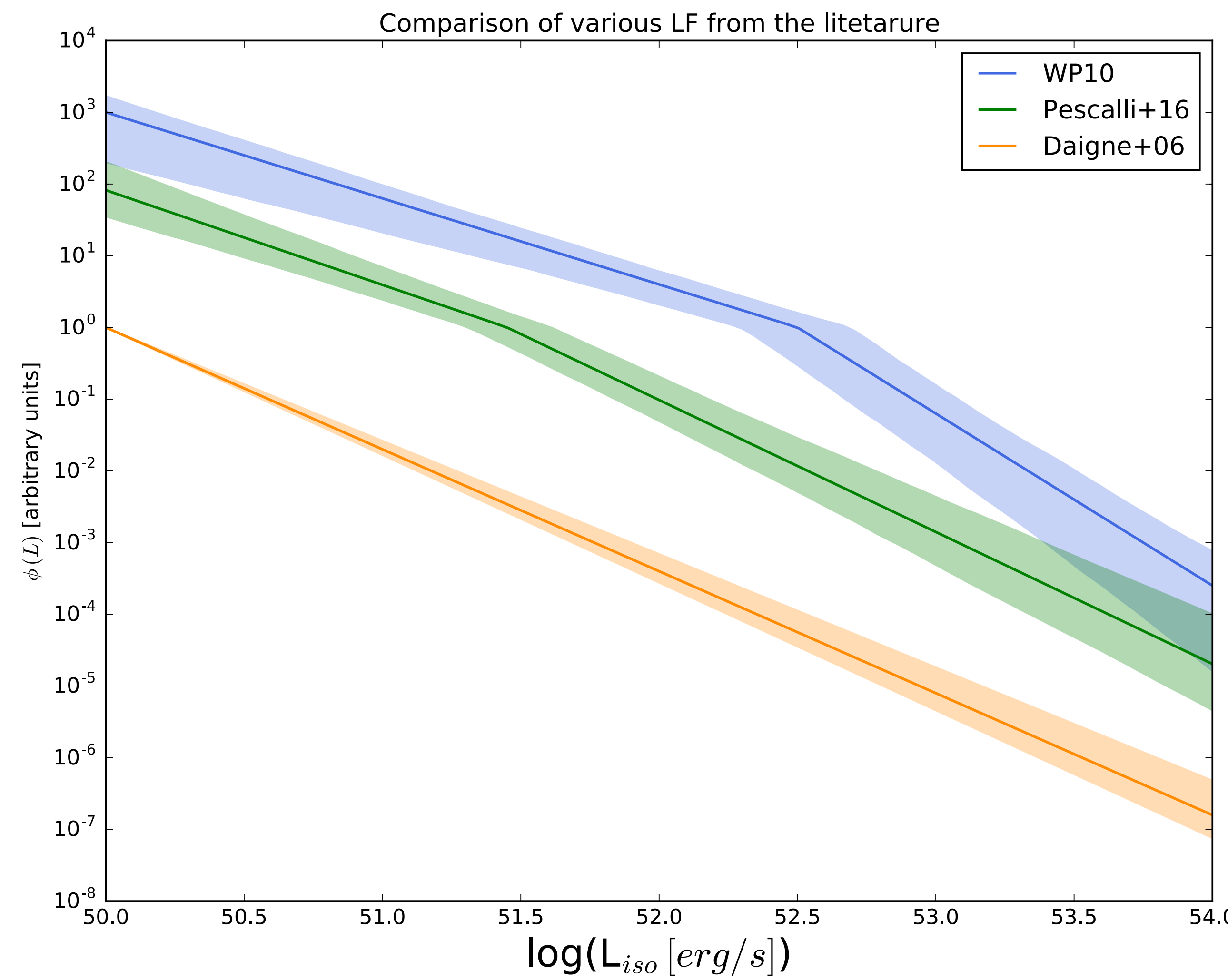
$$\phi(L) = A\,L^{-p}$$

- Schechter function

$$\phi(L) = A\left(\frac{L}{L_{break}}\right)^{-p} \times \exp\left(-\frac{L}{L_{break}}\right)$$

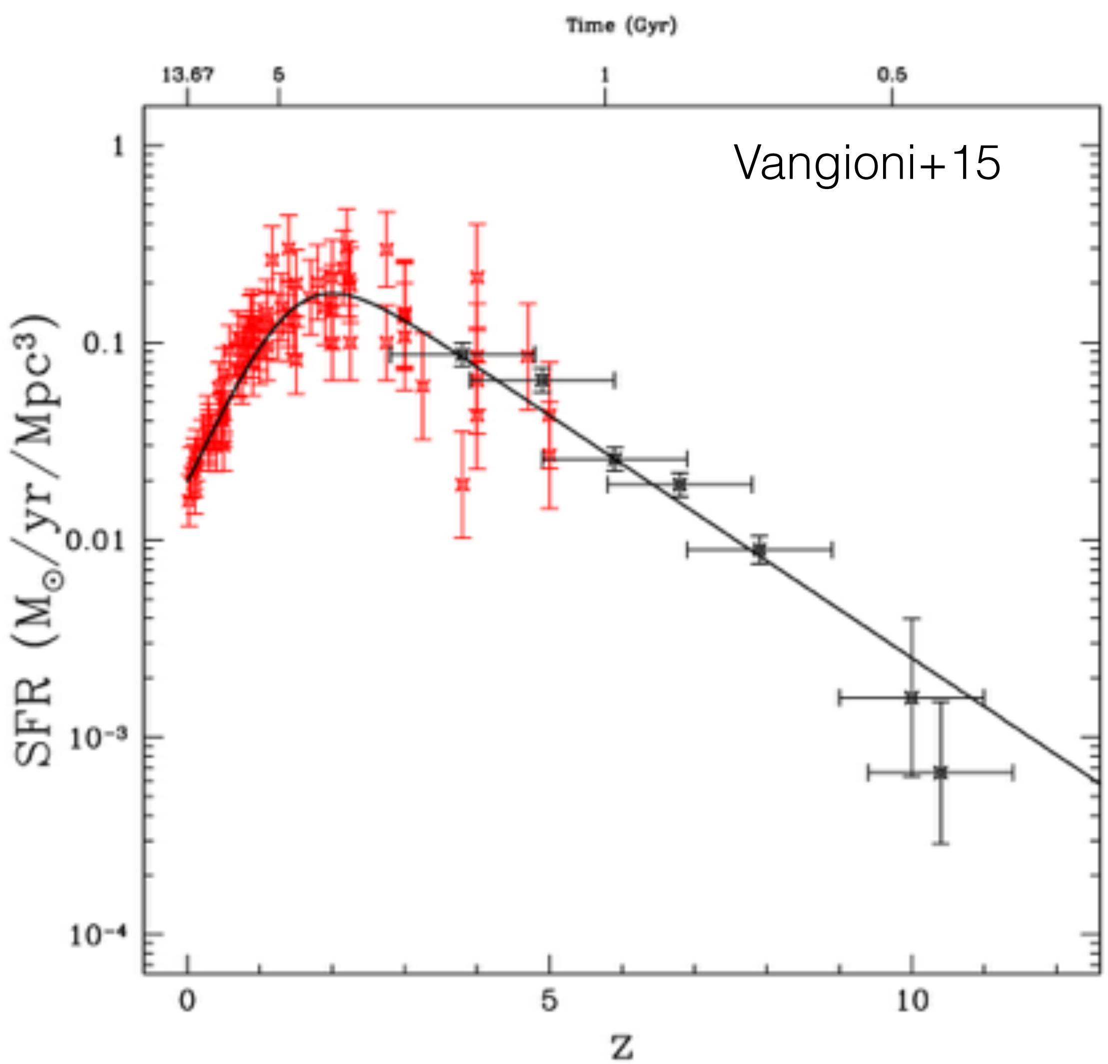
- Evolution ?

$$\propto (1+z)^k$$



Redshift distribution

- Fundamental to understanding the **LGRB production efficiency** of stars
- Assume $$\dot{n}_{GRB} = A \begin{cases} e^{a\,z} & z < z_m \\ e^{b\,z}\, e^{(a-b)\,z_m} & z \geq z_m \end{cases}$$



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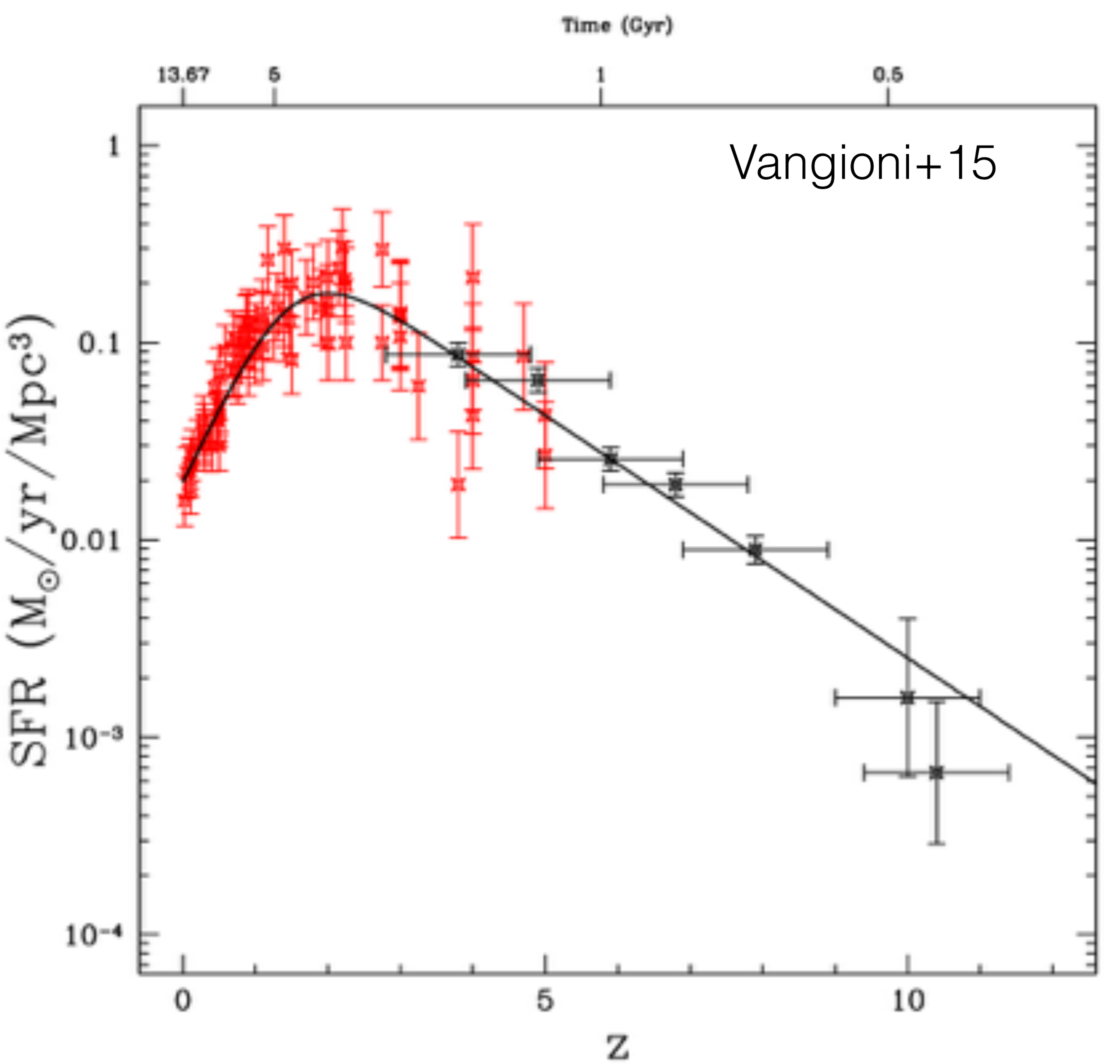
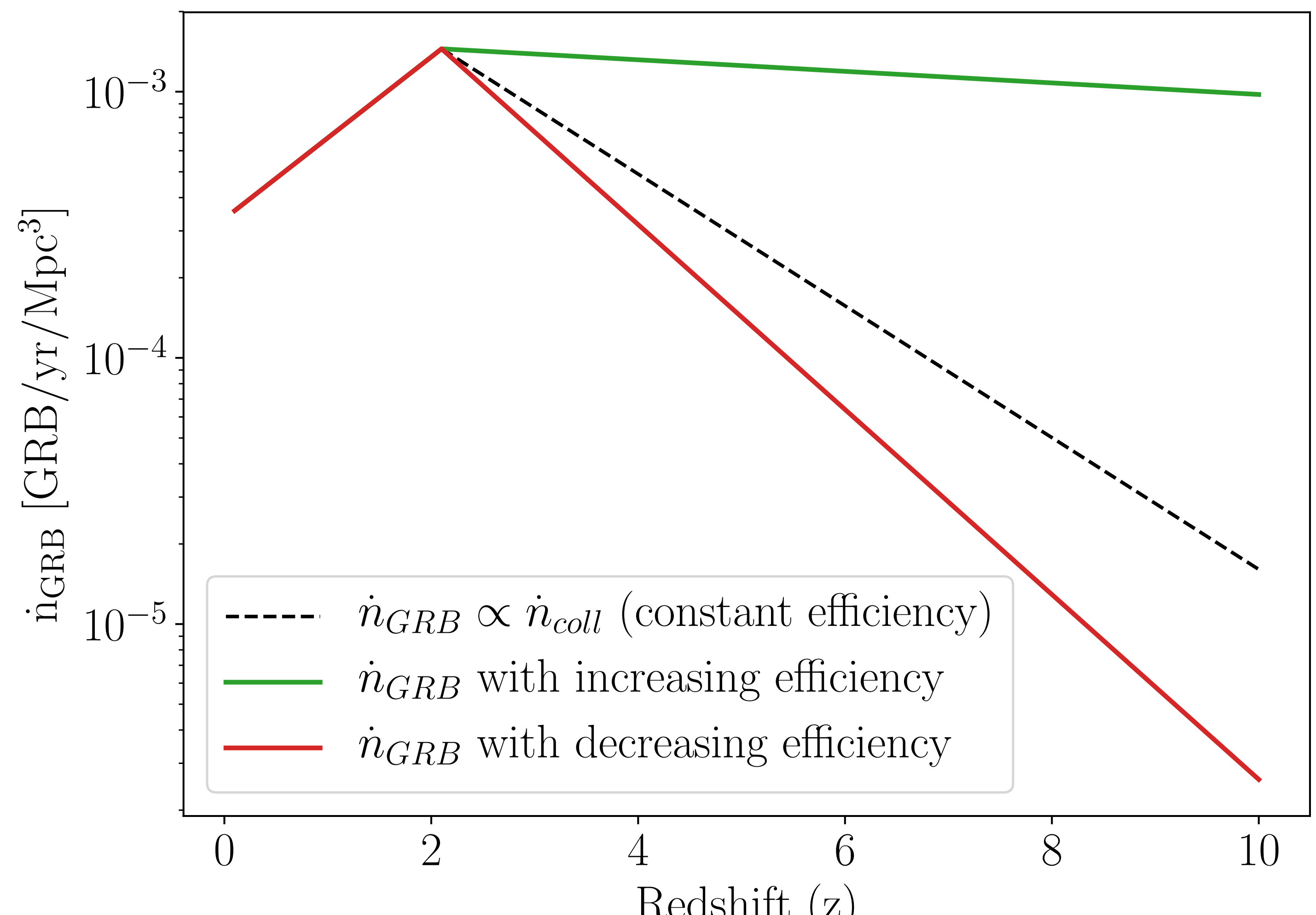
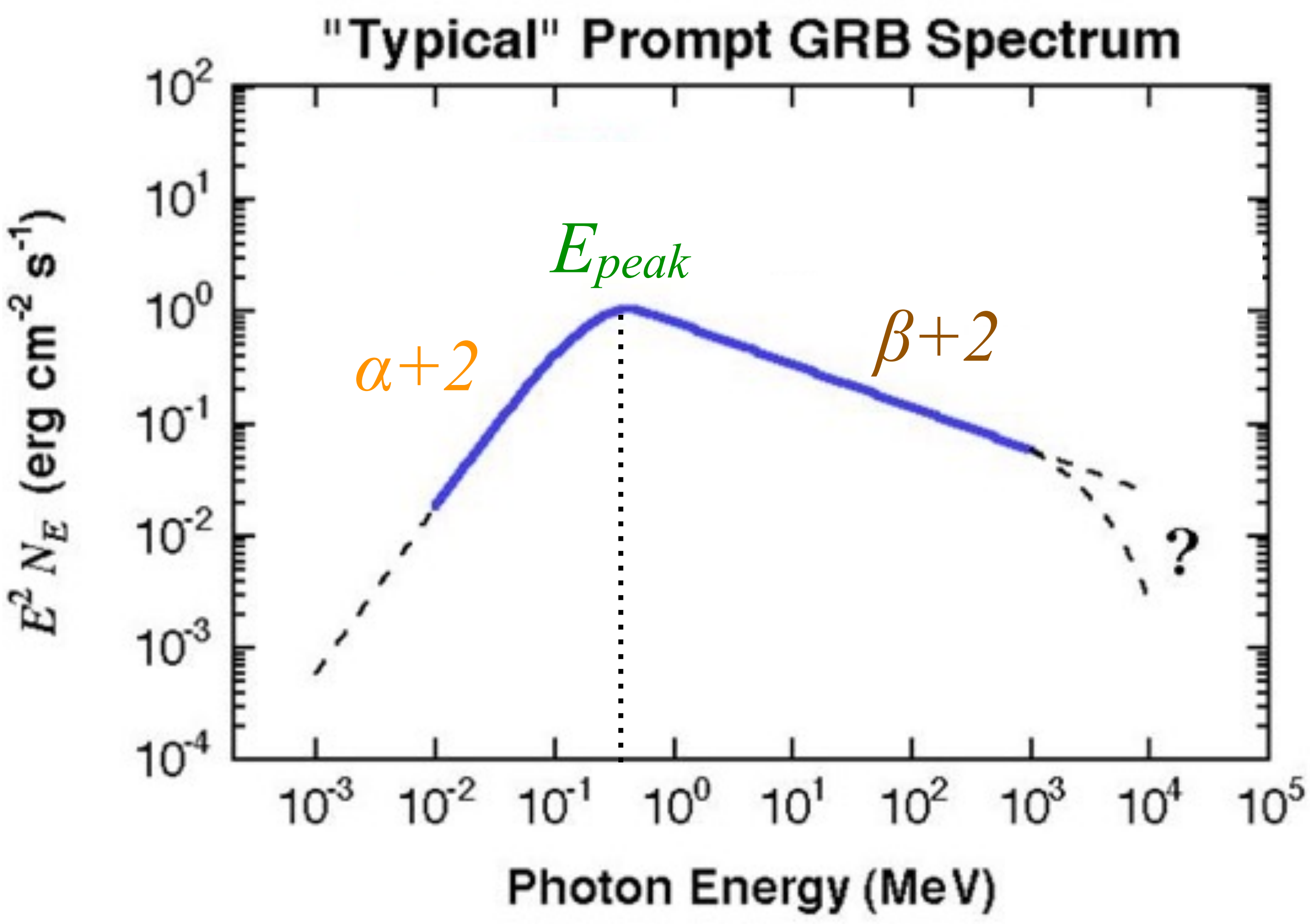




Spectral parameters

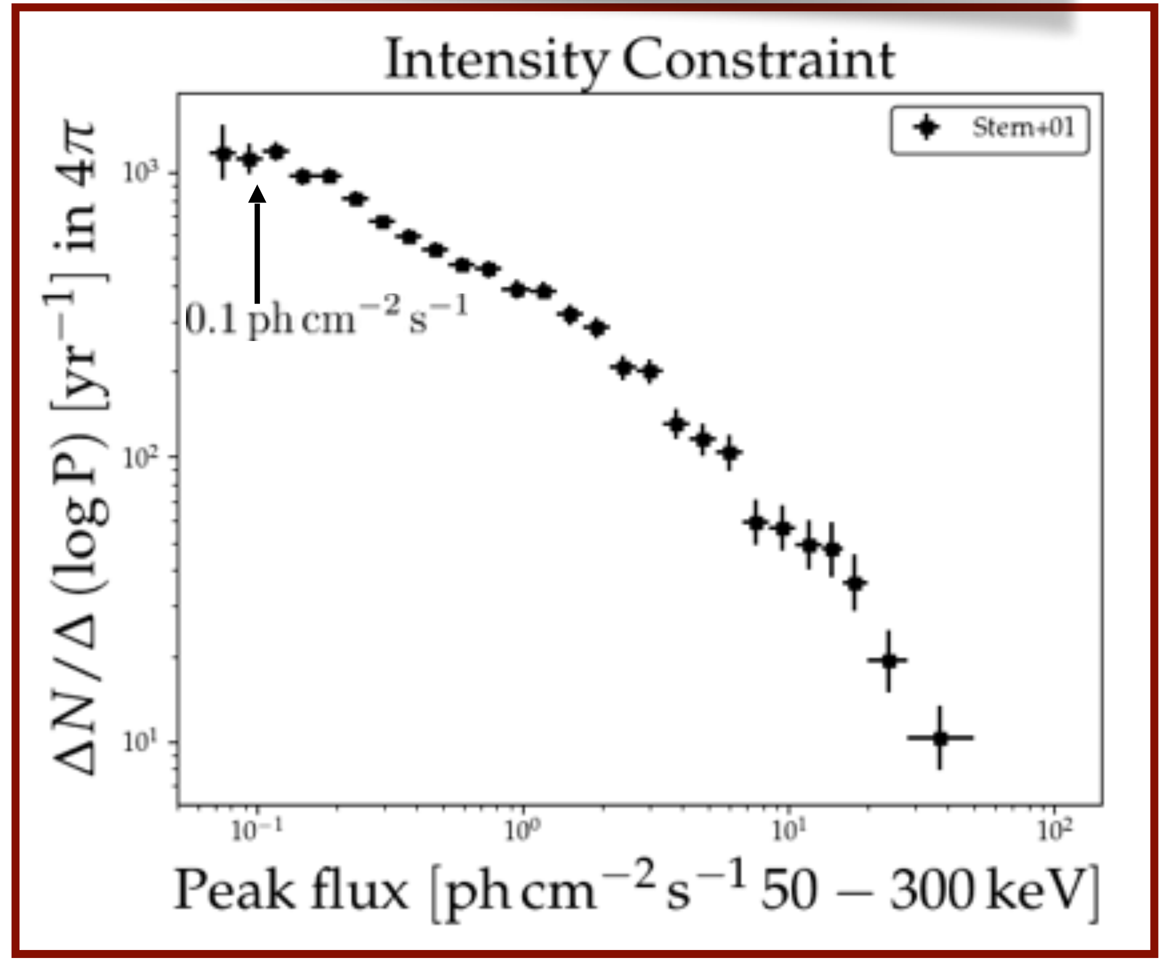
- α : low-energy index
- β : high-energy index
- E_{peak} : peak in the νF_ν spectrum
- Different functional forms (Band et al. 1993, exponential cut-off, power-law…)



credits : http://fermi.gsfc.nasa.gov

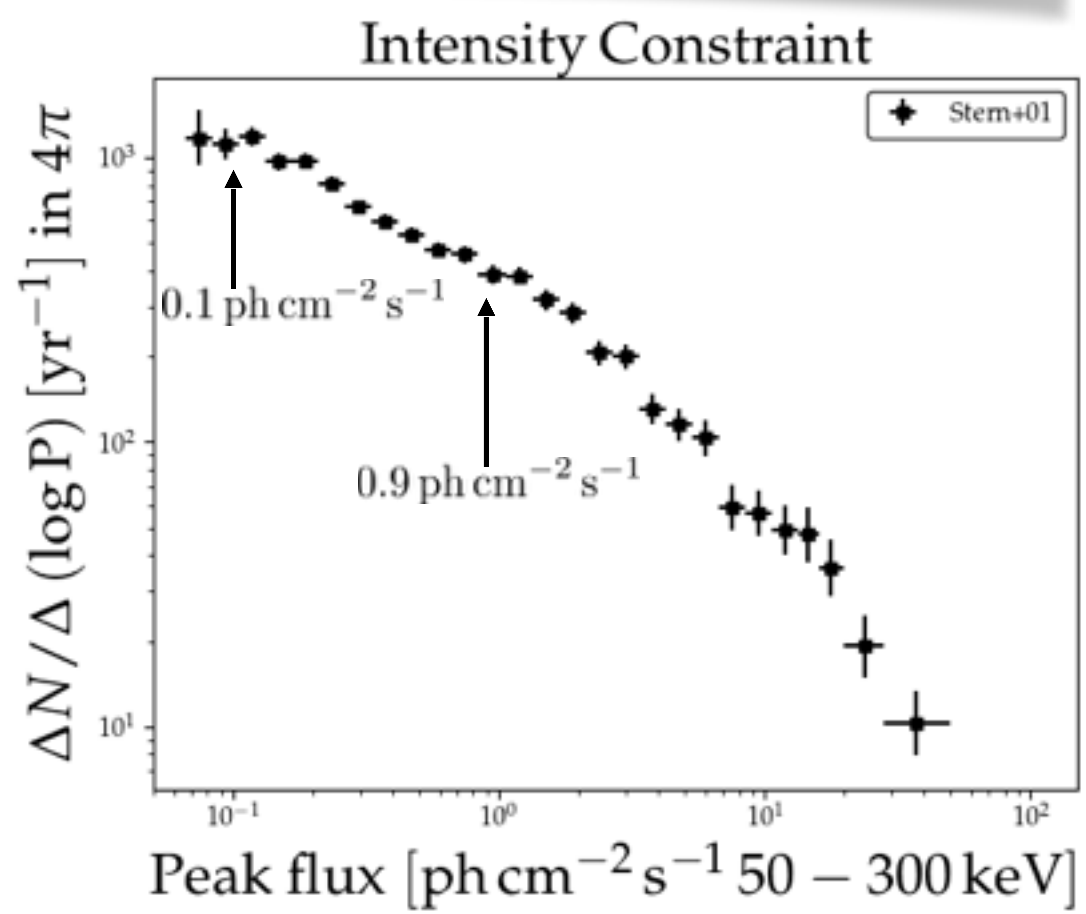
Observational constraints I: Intensity

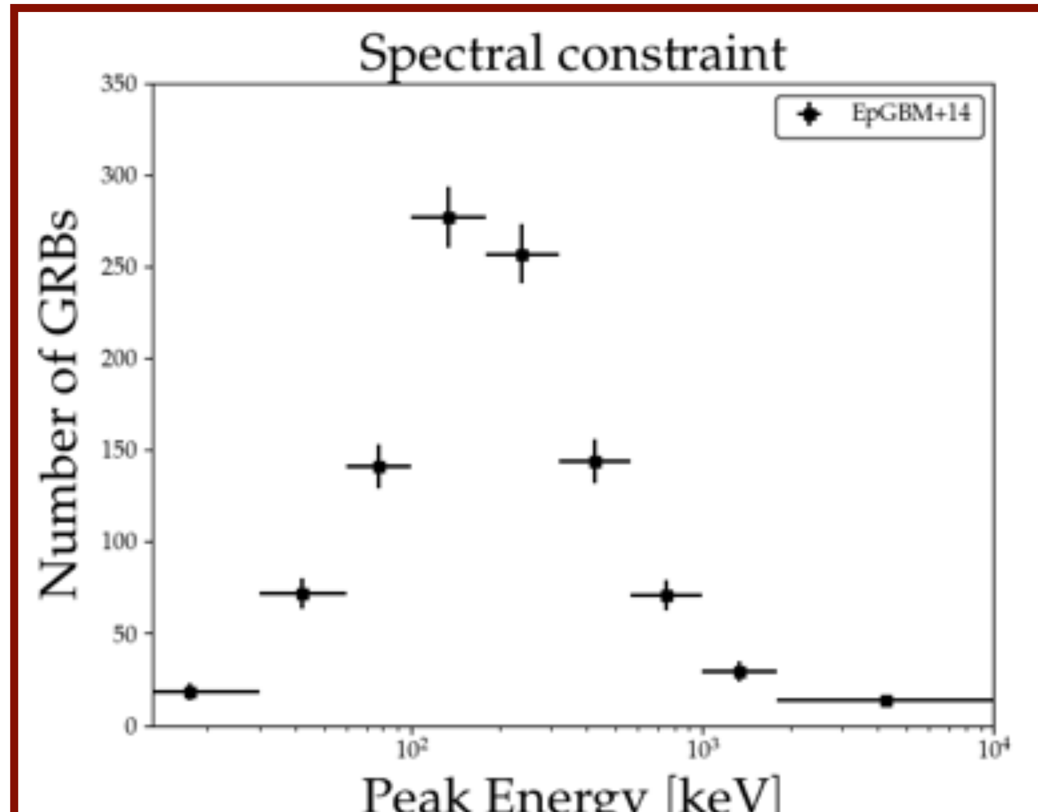
- Intensity constraint (Stern+01) : **Log N - Log P diagram**
- Based on **~3300** LGRBs detected by *CGRO*/BATSE over 9.1 years (on board trigger + offline search)
- **Corrected** for fraction of sky observed, live time of the search and detection efficiency
- **Normalization** of our model to this constraint yields the physical **duration** of our simulation: t_{sim}



Observational constraints II: Spectrum

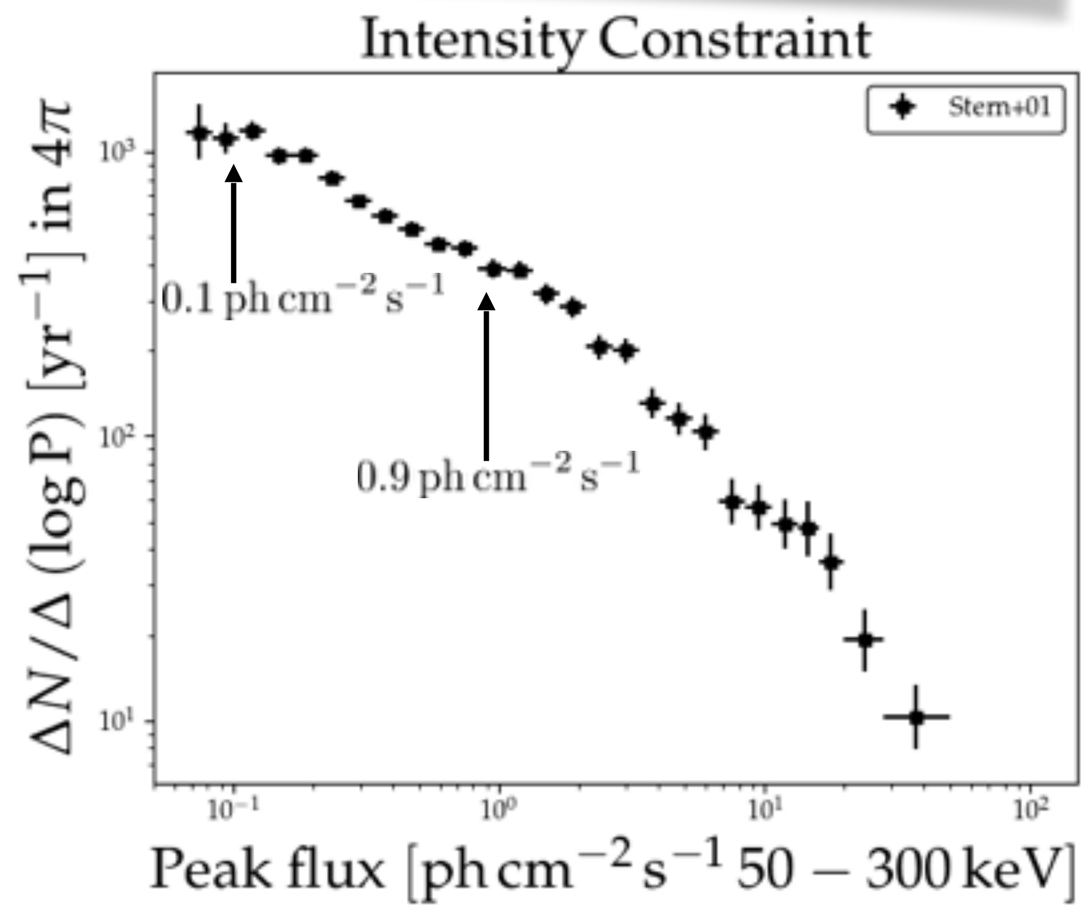
- Spectral constraint : **Peak energy distribution** of GBM (Gruber+14)
- Based on **~1000** LGRBs with $P_{50-300\,\mathrm{keV}} \geq 0.9\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ detected by *Fermi*/GBM
- Uses the peak energy at the peak flux, derived from a Band spectral model fit to the GRB spectrum

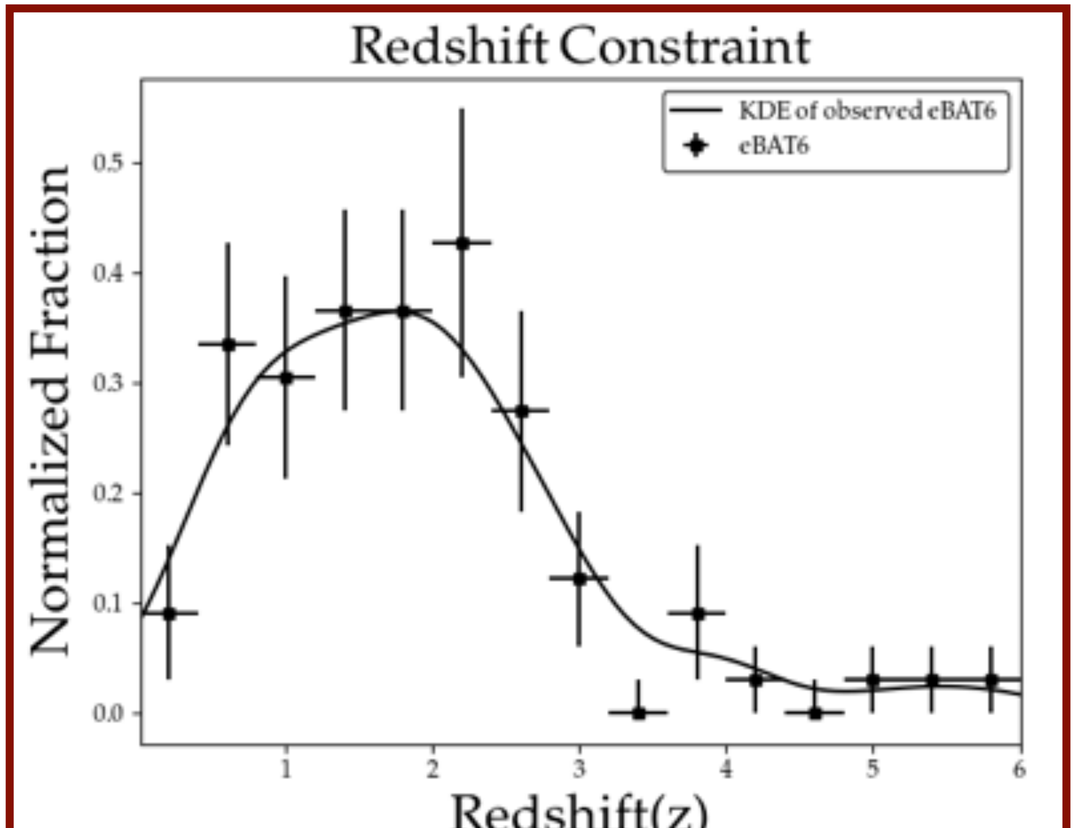


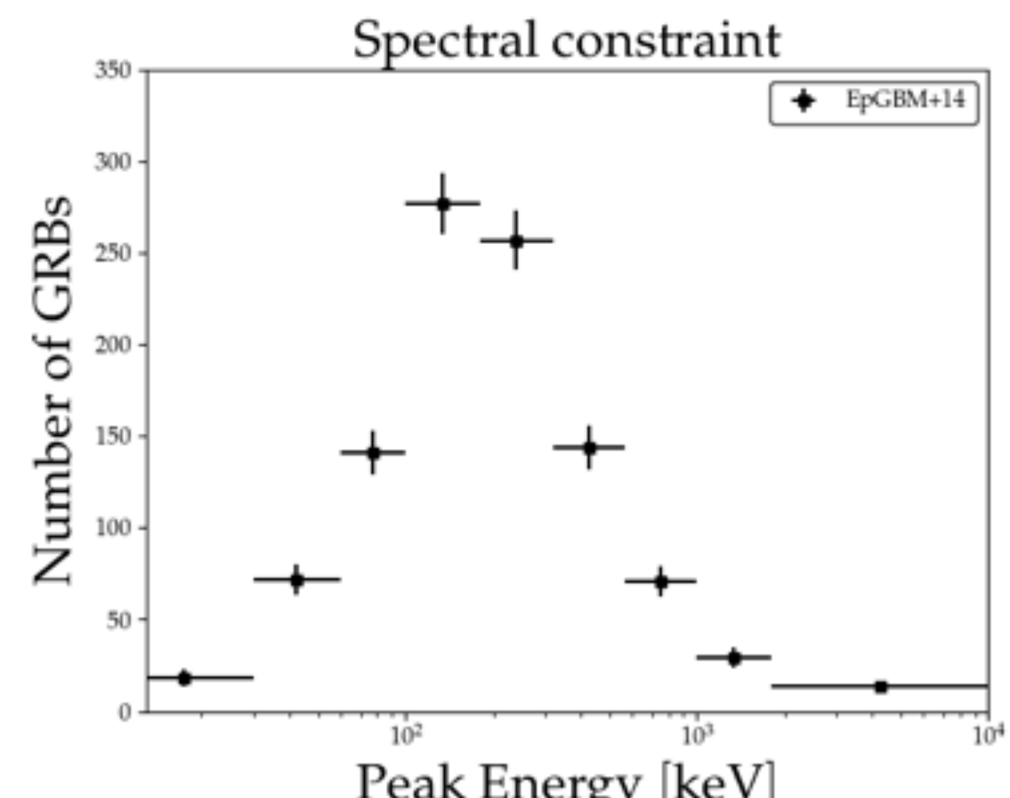


Observational constraints III: Redshift

- Redshift constraint : **Redshift distribution** of extended BAT6 sample (Pescalli+16)
- Based on **82** LGRBs with $P_{15-150\,\mathrm{keV}} \geq 2.6\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ detected by *Swift*/BAT and favorable observing conditions

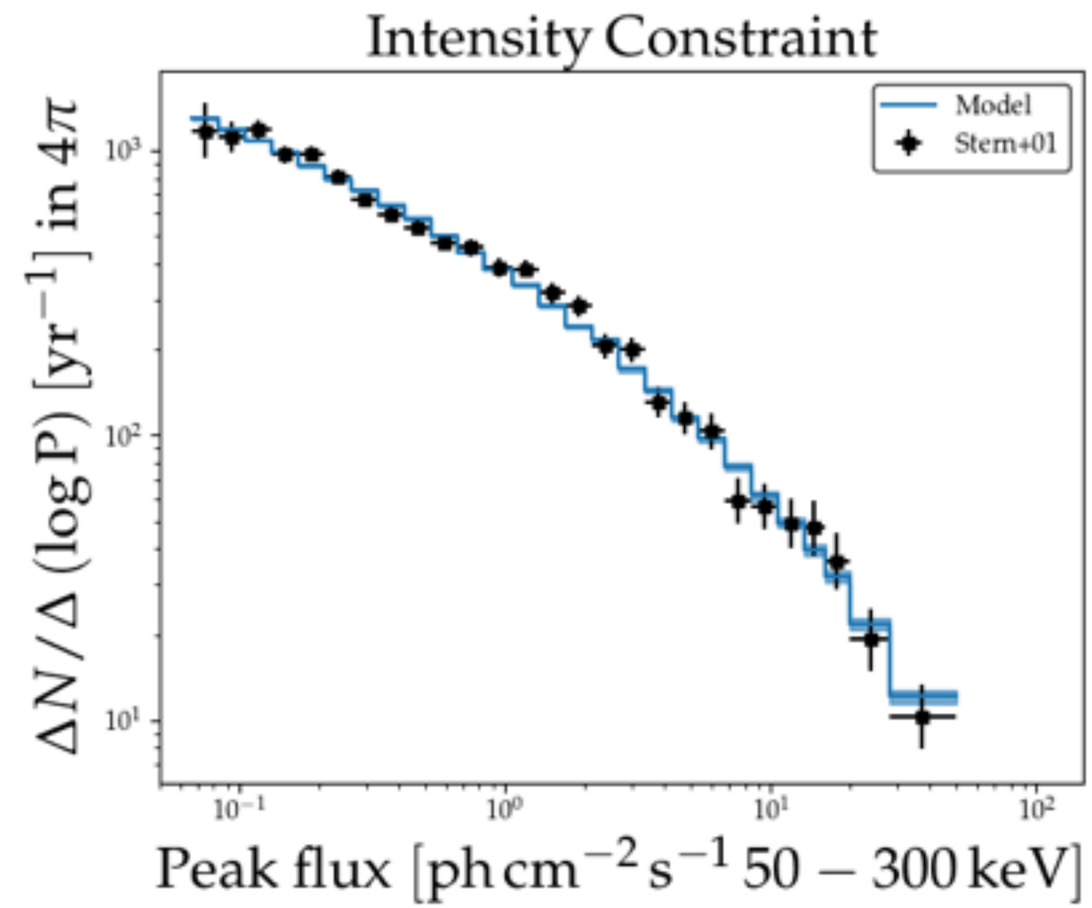


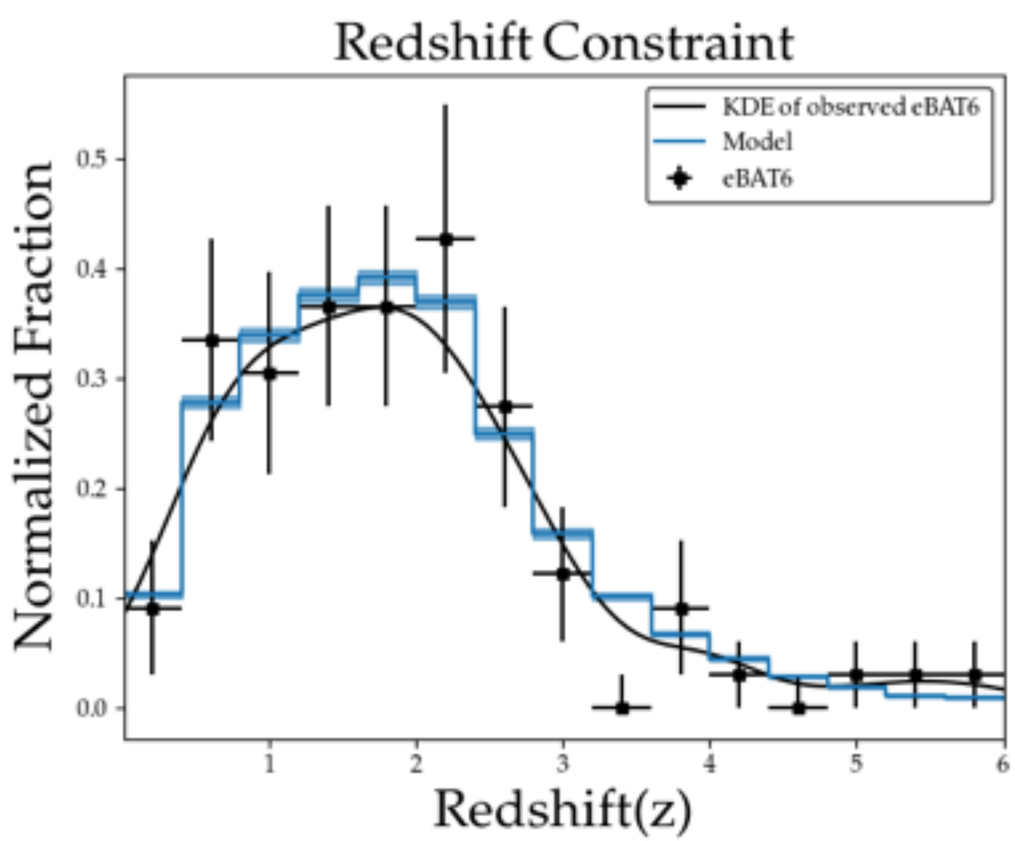


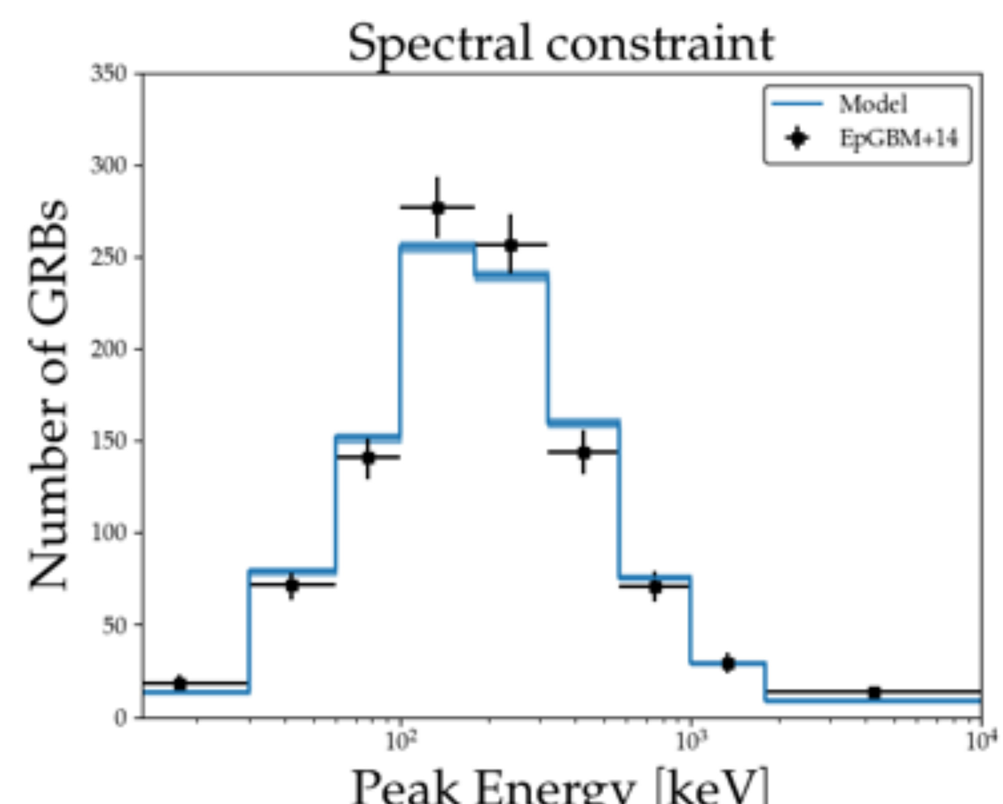


Results

- Best fit from Schechter Luminosity Function
- LogNormal Peak Energy distribution
- Broken exponential Redshift distribution
- No LF evolution (k = 0)

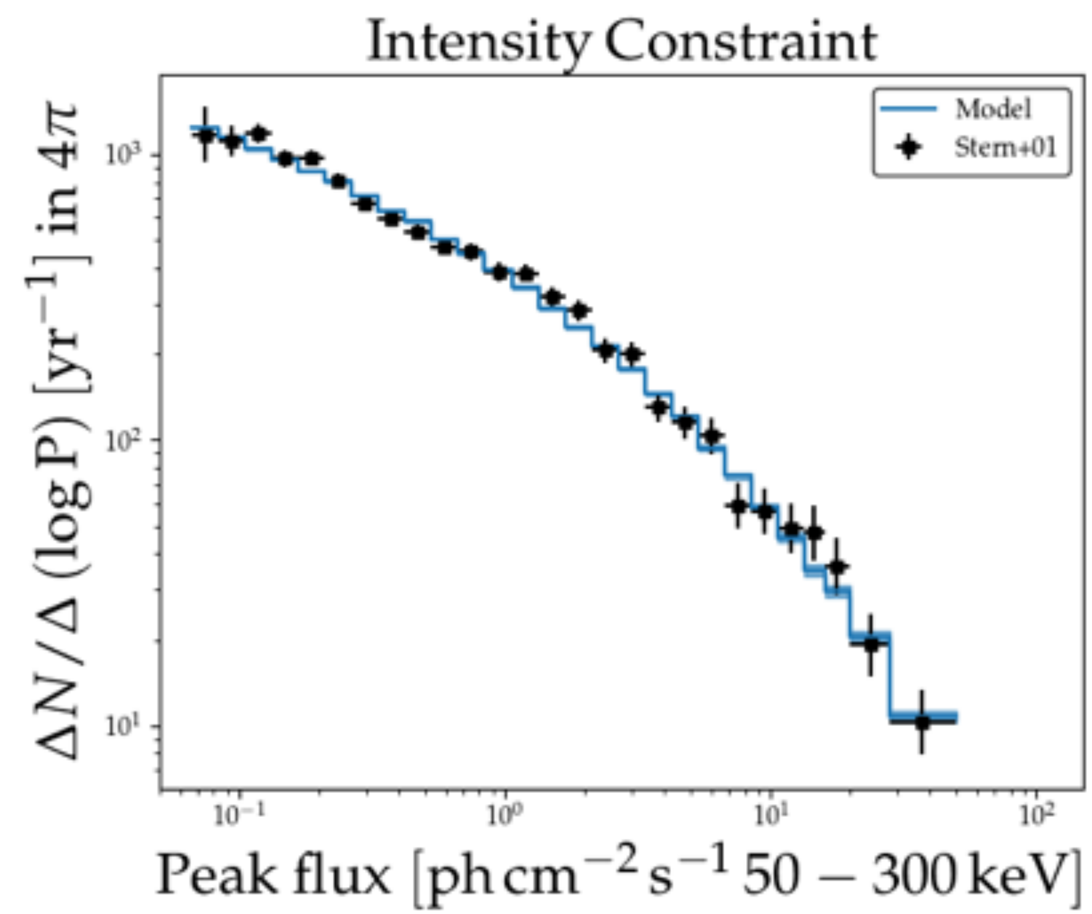


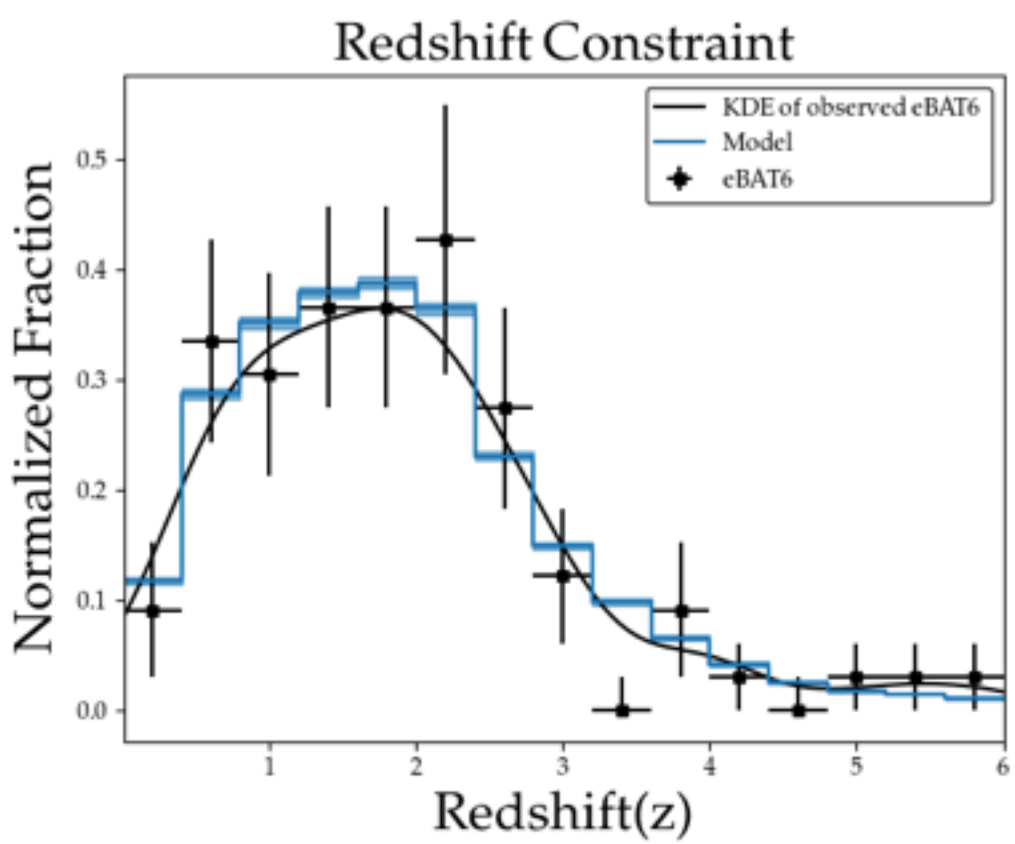


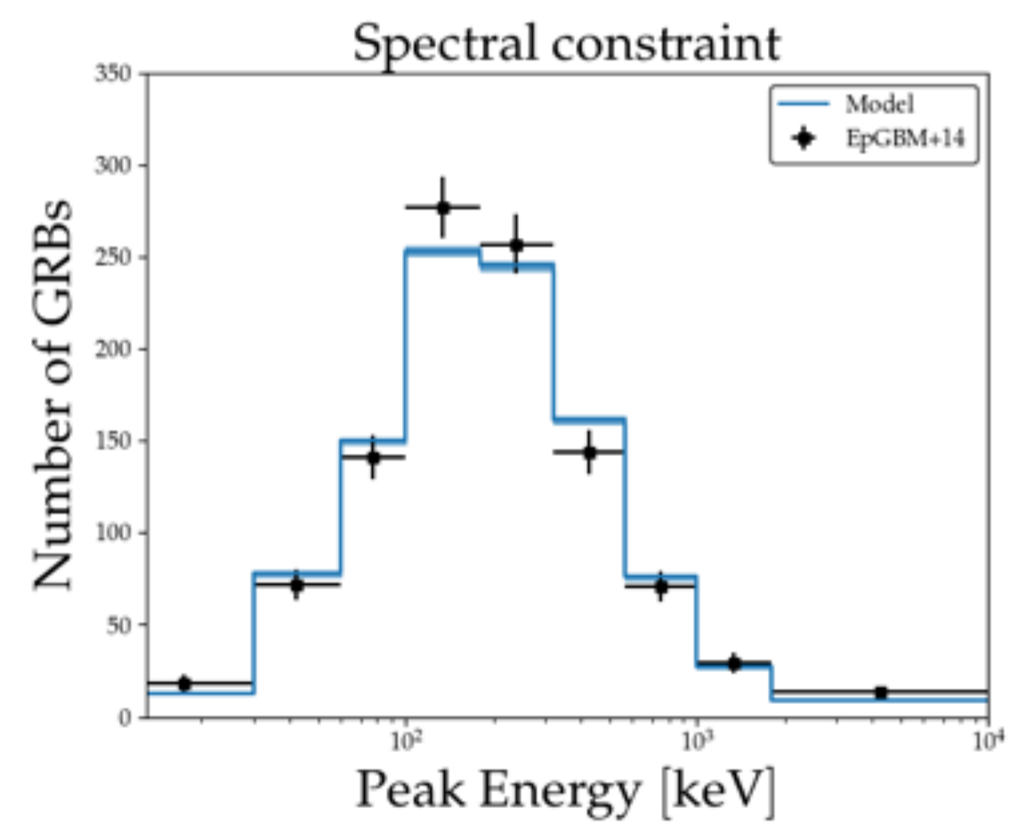


Results

- Best fit from Schechter Luminosity Function
- LogNormal Peak Energy distribution
- Broken exponential Redshift distribution
- mild LF evolution (k = 0.5)

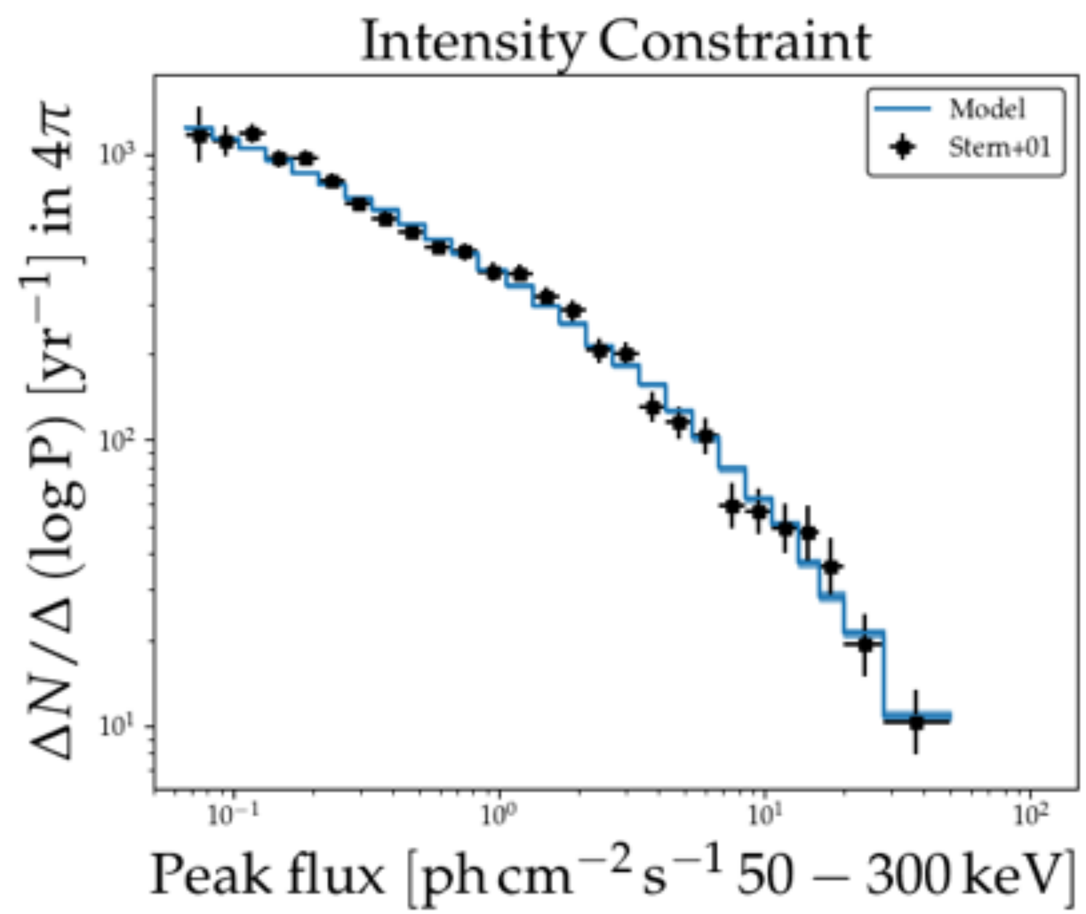


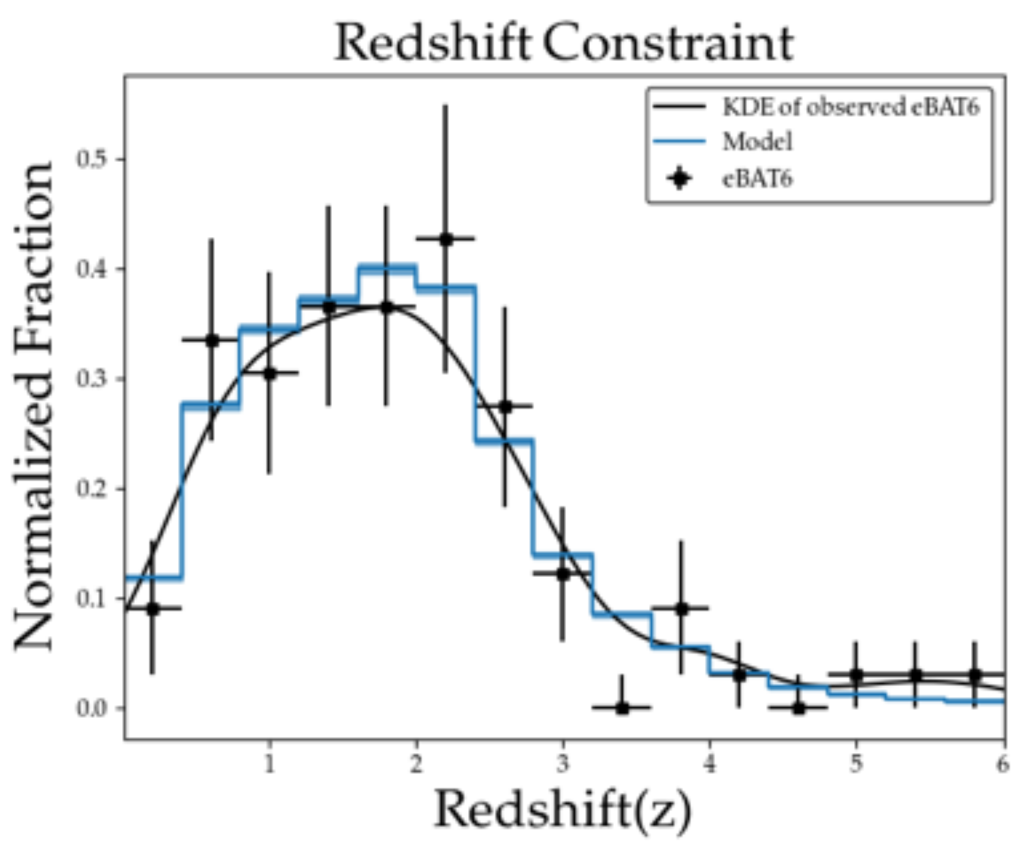


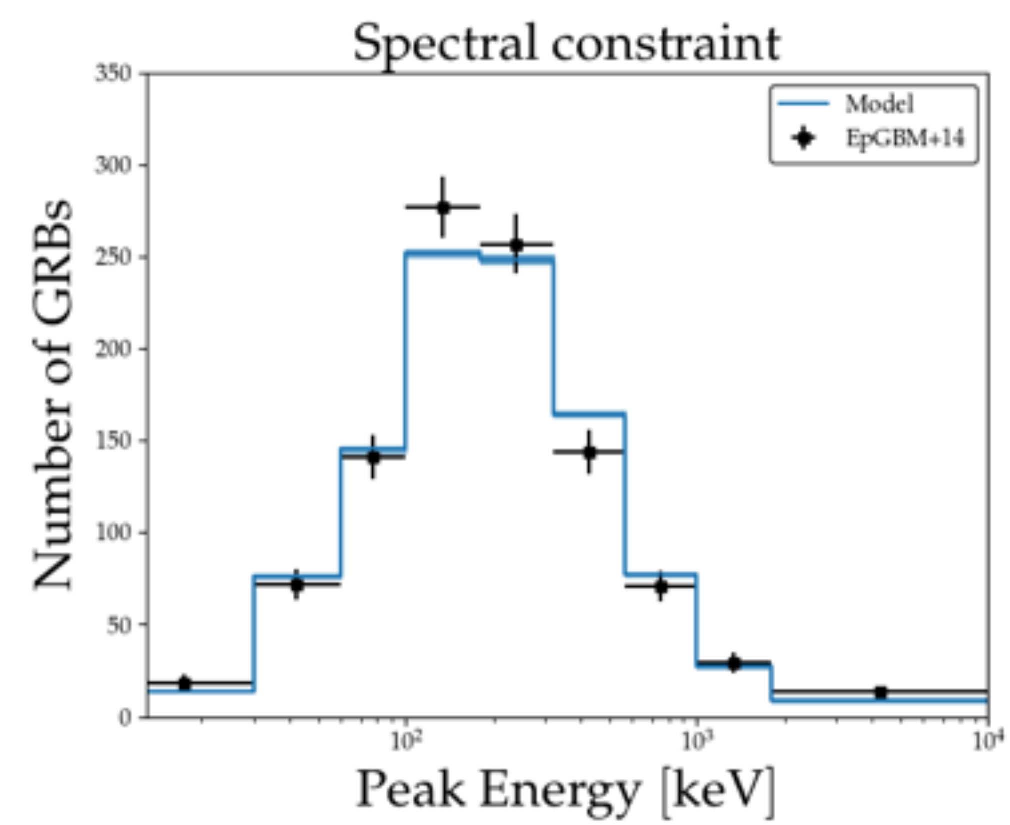


Results

- Best fit from Schechter Luminosity Function
- LogNormal Peak Energy distribution
- Broken exponential Redshift distribution
- LF evolution (k = 1.0)

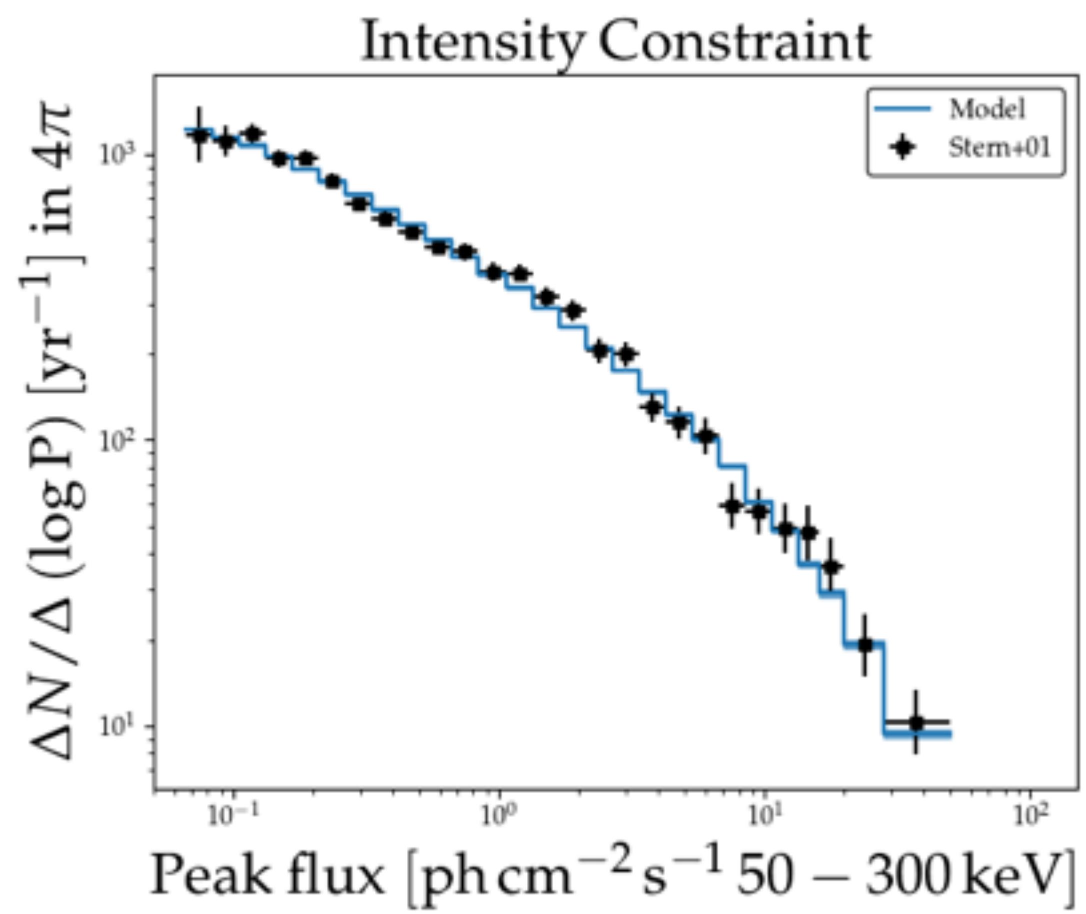


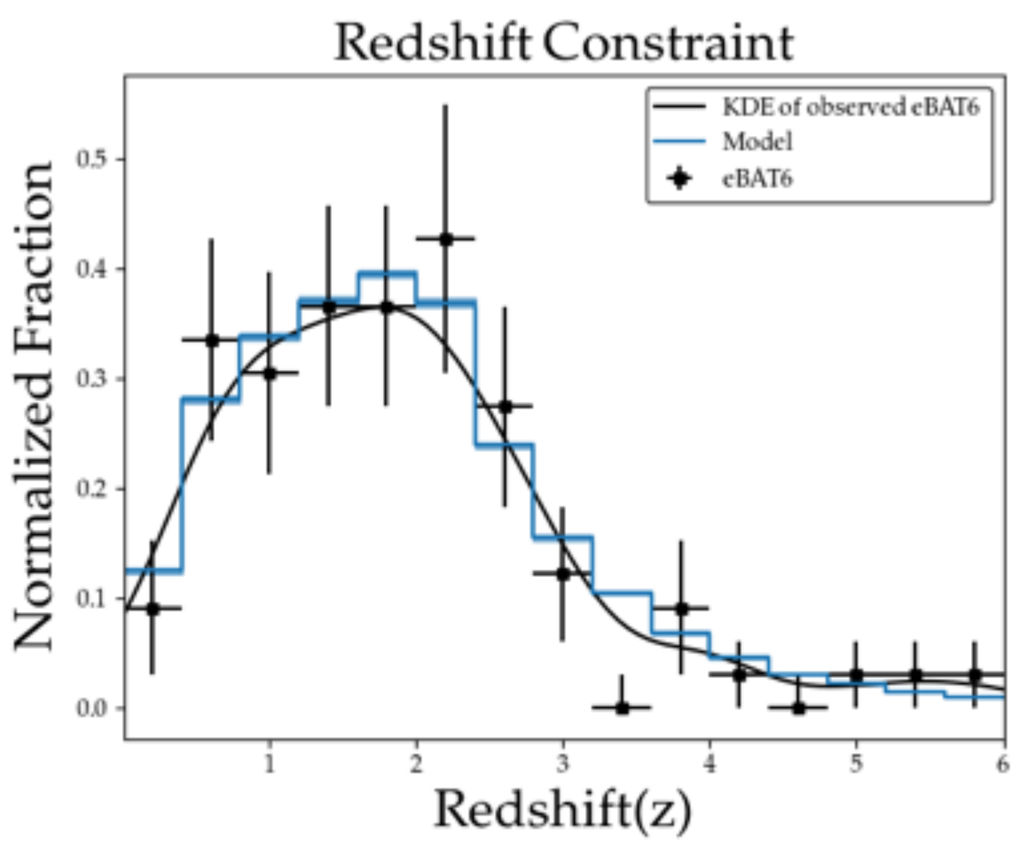


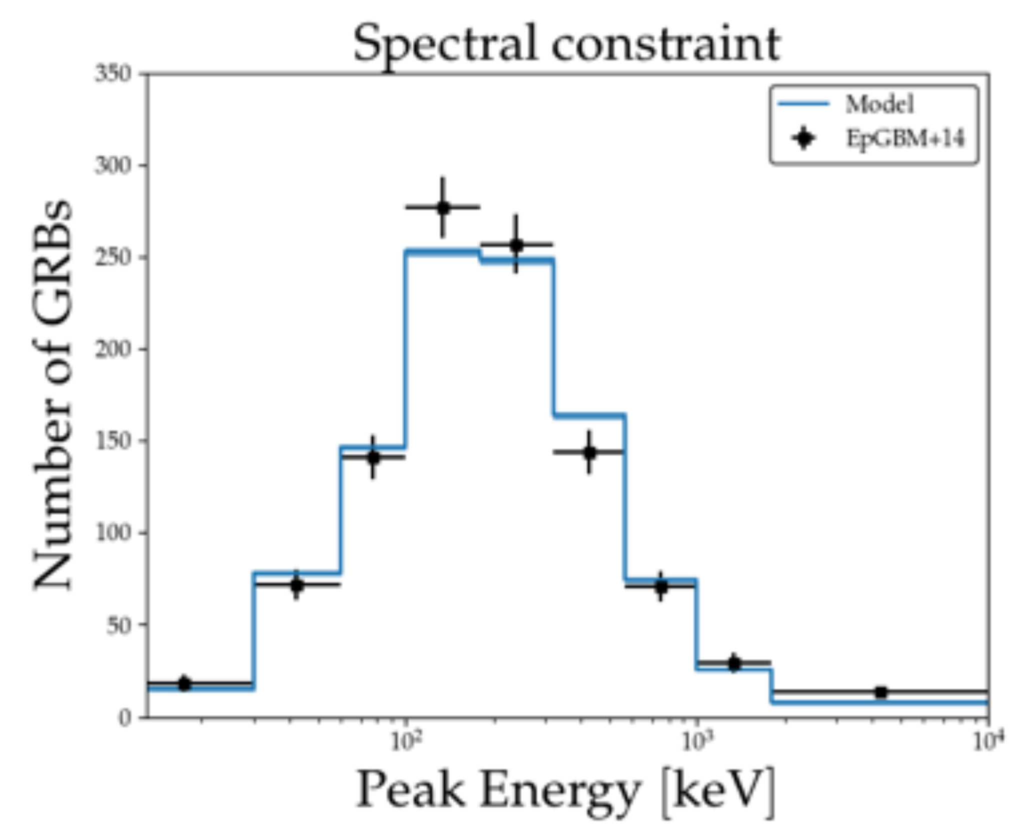


Results

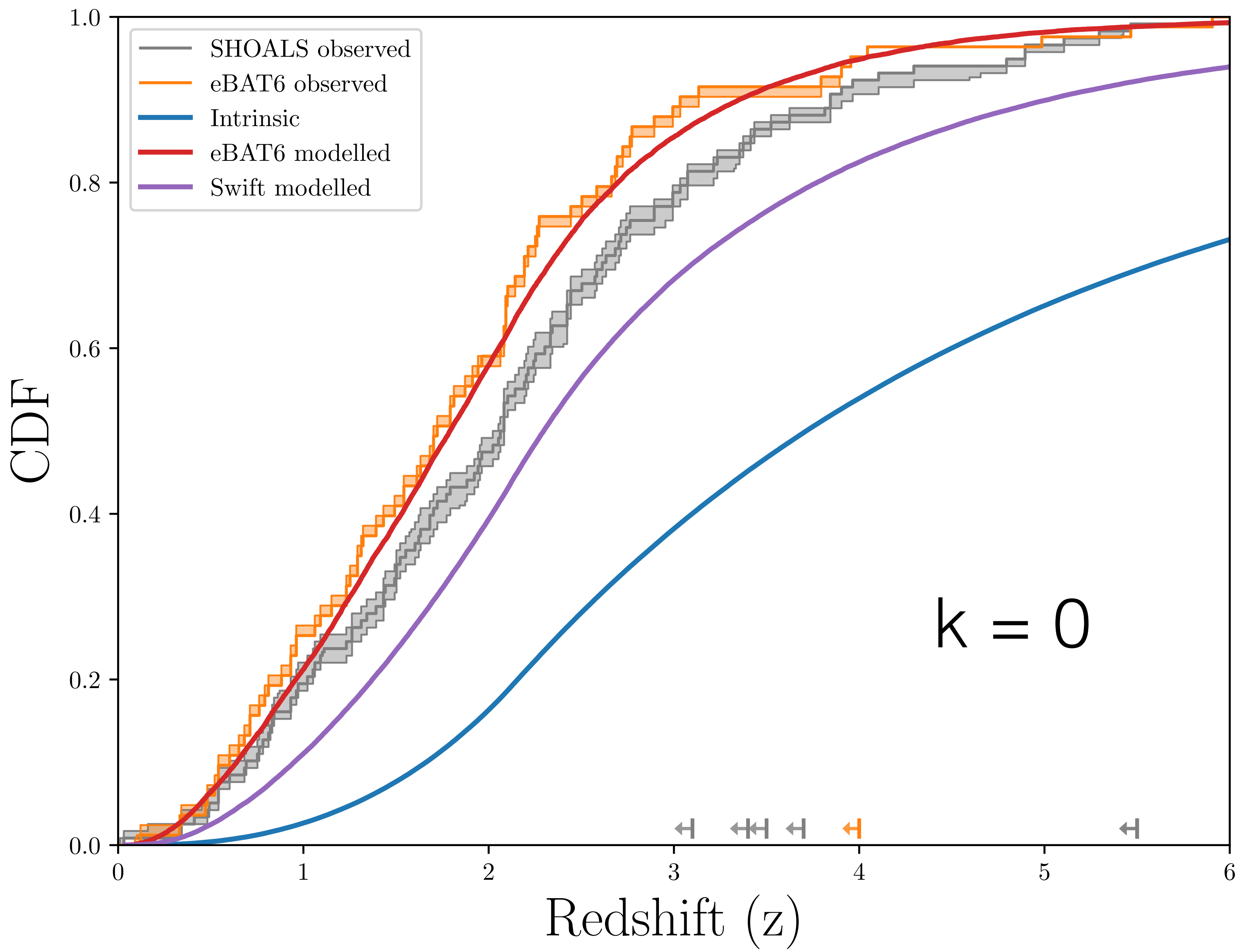
- Best fit from Schechter Luminosity Function
- LogNormal Peak Energy distribution
- Broken exponential Redshift distribution
- strong LF evolution (k = 2.0)







Breaking the degeneracy



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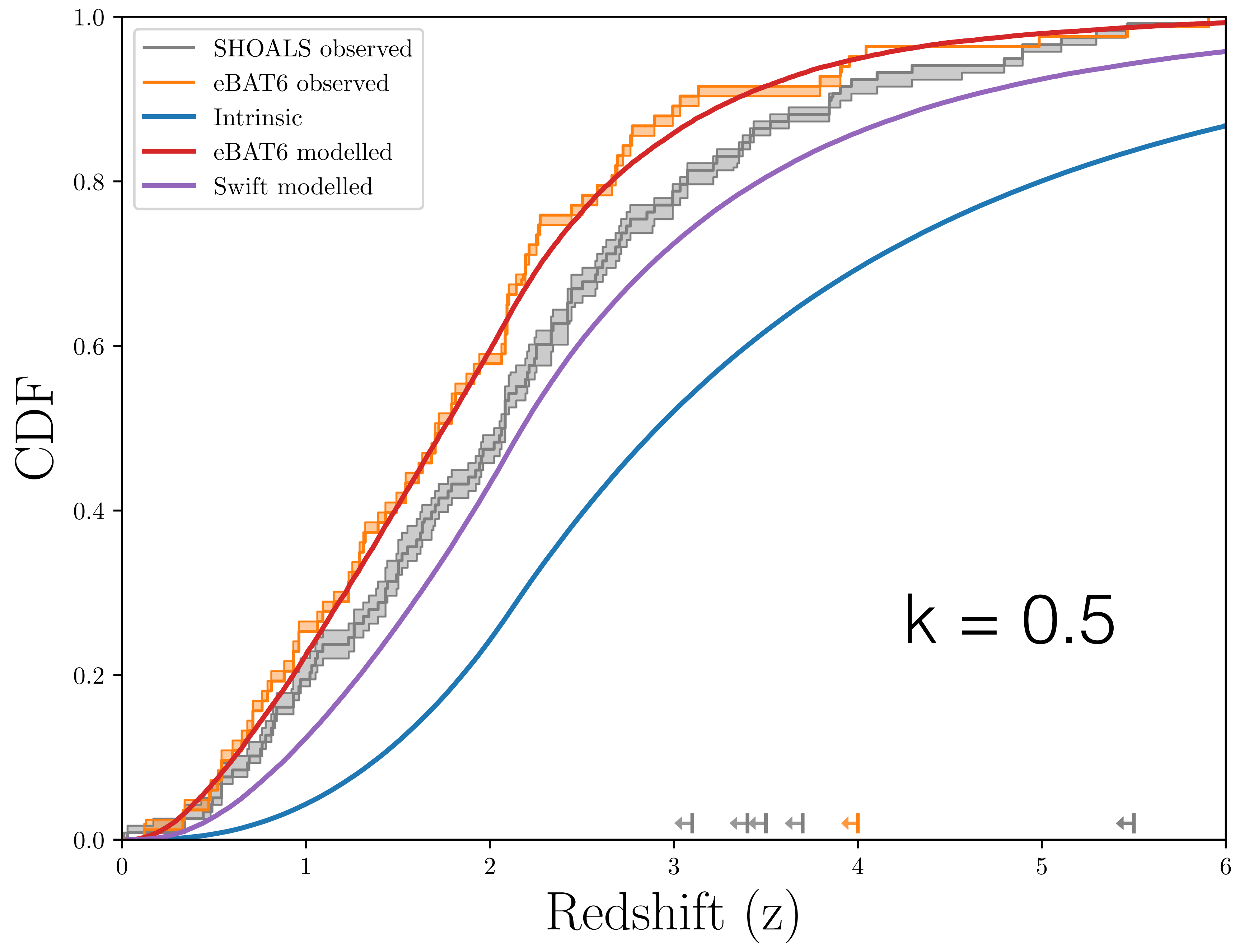

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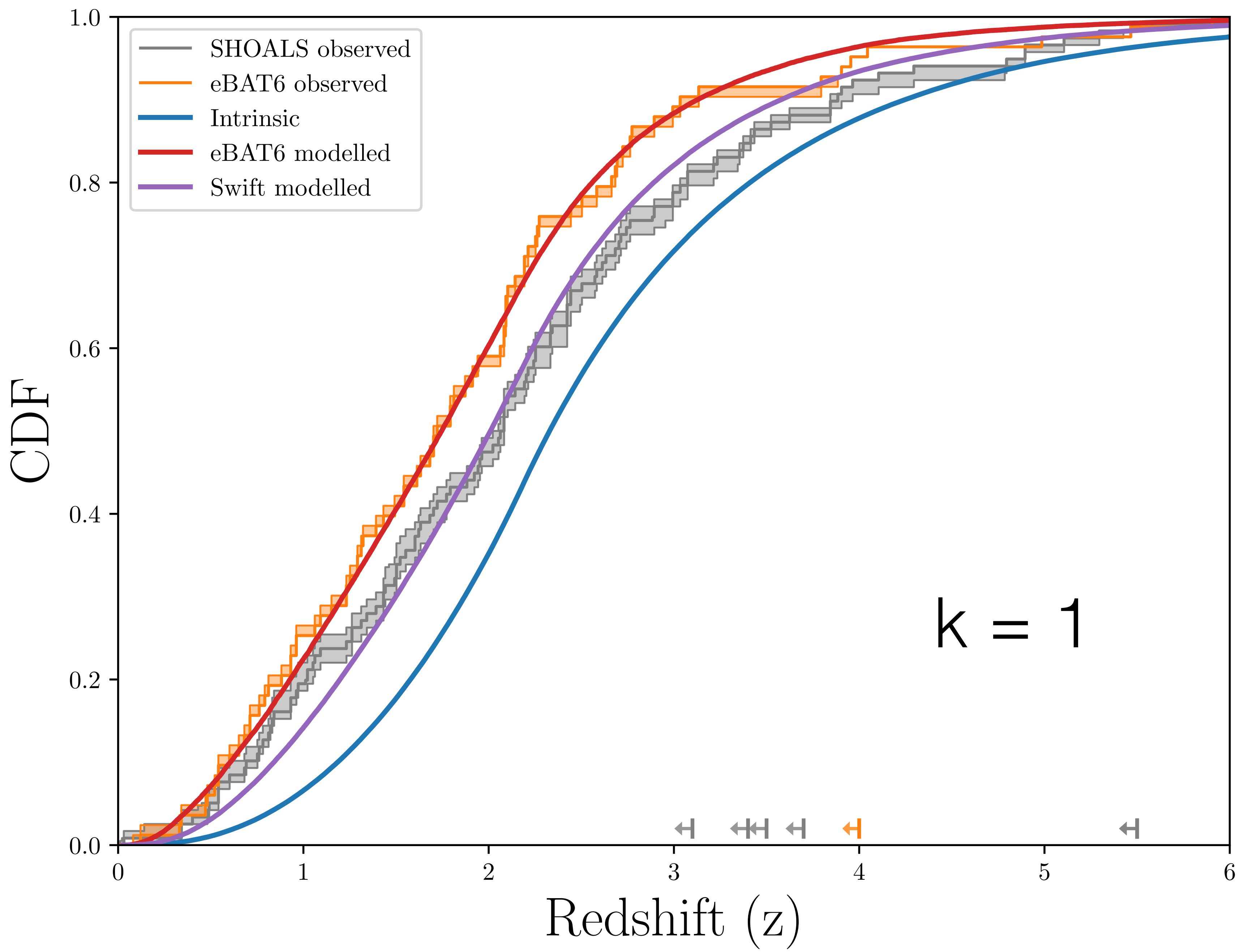
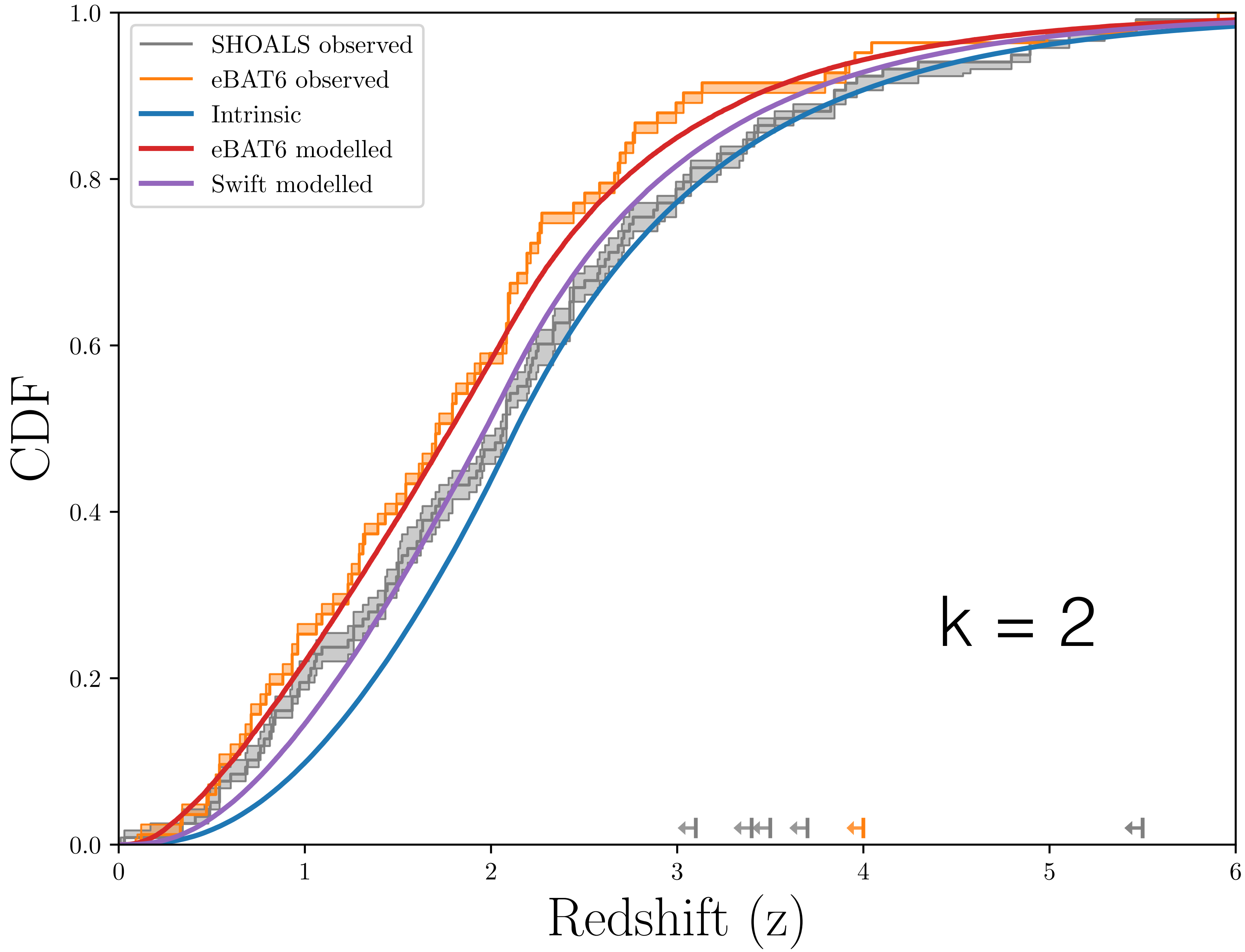


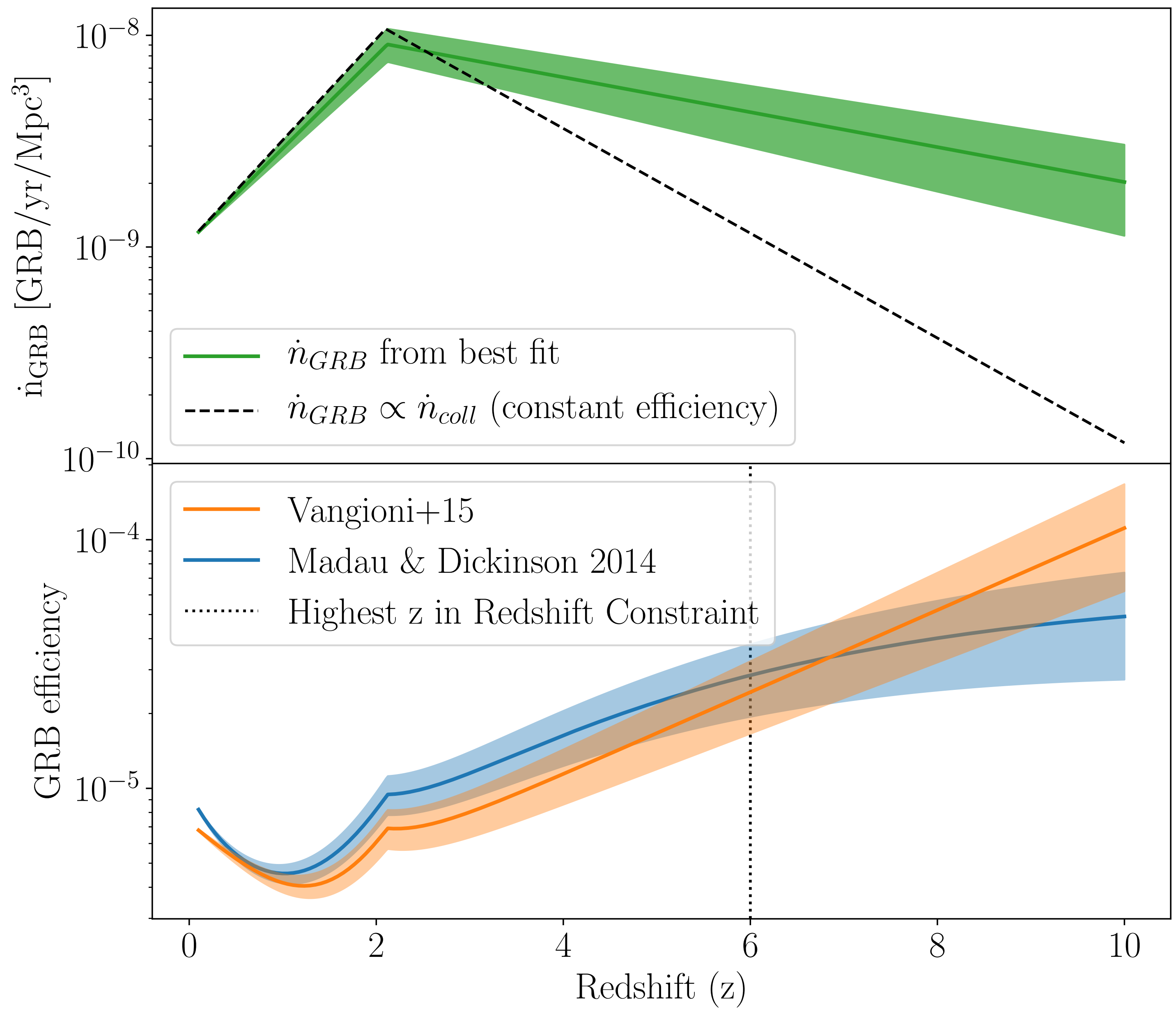
Breaking the degeneracy

- Model with **mild luminosity evolution** best fits the observations



Implication for GRB efficiency

- Model with **mild luminosity evolution** has **increasing LGRB efficiency** with redshift



True rate:

$$\frac{4\pi}{<\Omega>}$$

Open questions

- What are the implications for the progenitors?
- Are the observed “Amati-like” correlations intrinsic or caused by selection?
- What about X-Ray Flashes and X-Ray Rich GRBs?
- What does this mean for *SVOM* ?

Predicting *SVOM*/ECLAIRs' detection rate

- A naïve model for detection based on the **peak flux**
  - On-axis: $P_{on} = \int_{4\,keV}^{150\,keV} N(E_{obs})\,A(E_{obs})\,dE_{obs}$ Peak flux

    $B = \int_{4\,keV}^{150\,keV} b(E_{obs})\,dE_{obs}$ Noise

- Detection at n sigma if: $P_{on}\,\Delta t > n\,\sqrt{B\,\Delta t}$ ← 1 second

  - Off-axis: $P_{ij} = P_{on}\,\underbrace{\cos(\theta_{ij})\,D_{ij}}_{O_{ij}}$ Peak flux for pixel (i,j)

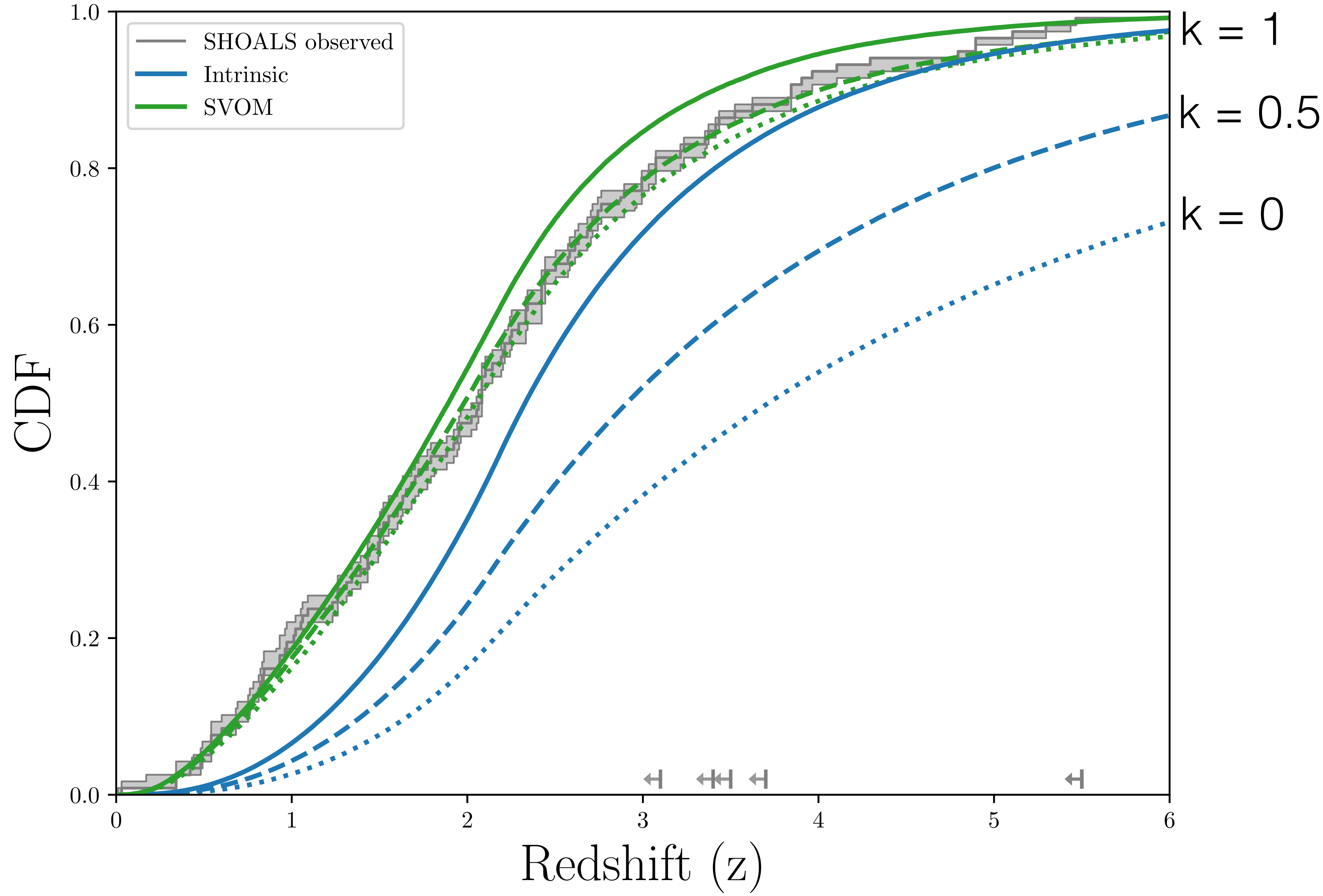
    D_{ij} ← Illuminated fraction of the detector

    O_{ij}: correction off-axis

- Detection at n sigma if: $P_{on}\,\Delta t > \frac{n\,\sqrt{B\,\Delta t}}{O_{ij}}$ ← 1 second

➡ Working to add image mode

Preliminary *SVOM* redshift distribution



- Challenge for *SVOM*:
  increase fraction of GRBs followed-up (1/3 -> 2/3)

Conclusion

- First model that uses such a wide variety of observational constraints with a careful, controlled selection
- Results seem to indicate a **mild luminosity evolution** and an **increasing LGRB efficiency** with redshift. (Palmerio & Daigne in prep.)
  - Could be **linked to metallicity threshold** of host galaxy studies. Other factors (binarity…) ?
  - **Important bias** to understand before using LGRBs as tracers of Star Formation

Perspectives

- In progress:
  - test intrinsic “Amati-like” correlations
  - compare with other studies
- Added value:
  - use model to **predict *SVOM’s* GRB detection rate (in progress)**
- Extend this method to **short GRBs** (but lower statistics…)

Merci

谢谢

Number of collapses

- Number of collapses per year per comoving volume is given by :

$$\dot{n}_{core-collapse}(z) = P_{core-collapse}(z)\,\frac{\dot{\rho}_*(z)}{\bar{m}(z)} \quad [\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}]$$

where $\dot{\rho}_*(z)$ is the Star Formation Rate Density $[\mathrm{M}_\odot\,\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}]$

and $\bar{m}(z)$ is the mean mass deduced from the IMF of stars:

$$\bar{m}(z) = \int_{m_{inf}}^{m_{sup}} m\,p(m)\,dm \qquad [\mathrm{M}_\odot]$$

and $P_{core-collapse}(z)$ is the core-collapse probability:

$$P_{core-collapse}(z) = \int_{8\,M_\odot}^{m_{sup}} p(m)\,dm$$

Predicting *SVOM*'s detection rate

- Two detection modes: **flux** and **fluence**

- Fluence mode:

$$P'_{on} = P_{on}\, C_{var}$$

$$C_{var} = \frac{\bar{P}}{P_{peak}}$$

Average flux ($\bar{P}$)

Peak flux (P_{peak})

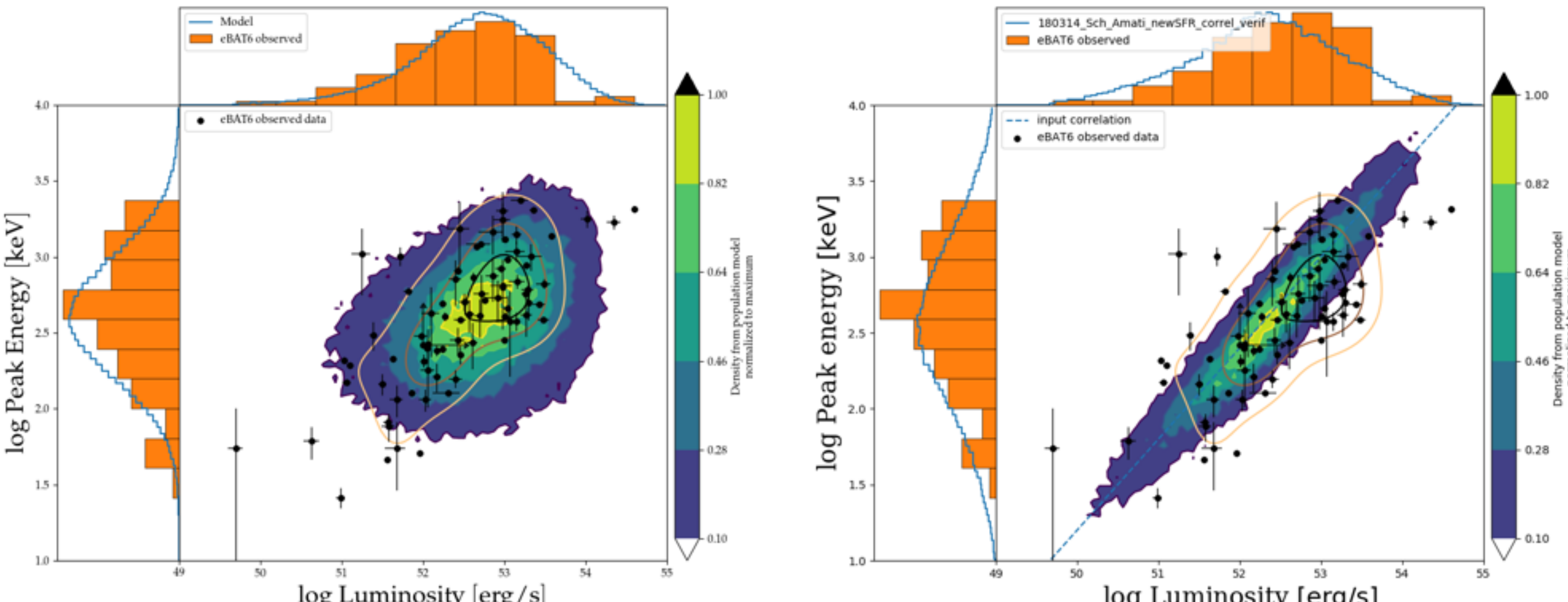
Variability indicator (C_{var})

- Detection at n sigma if: $P'_{on}\, \Delta t > \dfrac{n\,\sqrt{B\,\Delta t}}{O_{ij}}$

Burst duration (Δt)

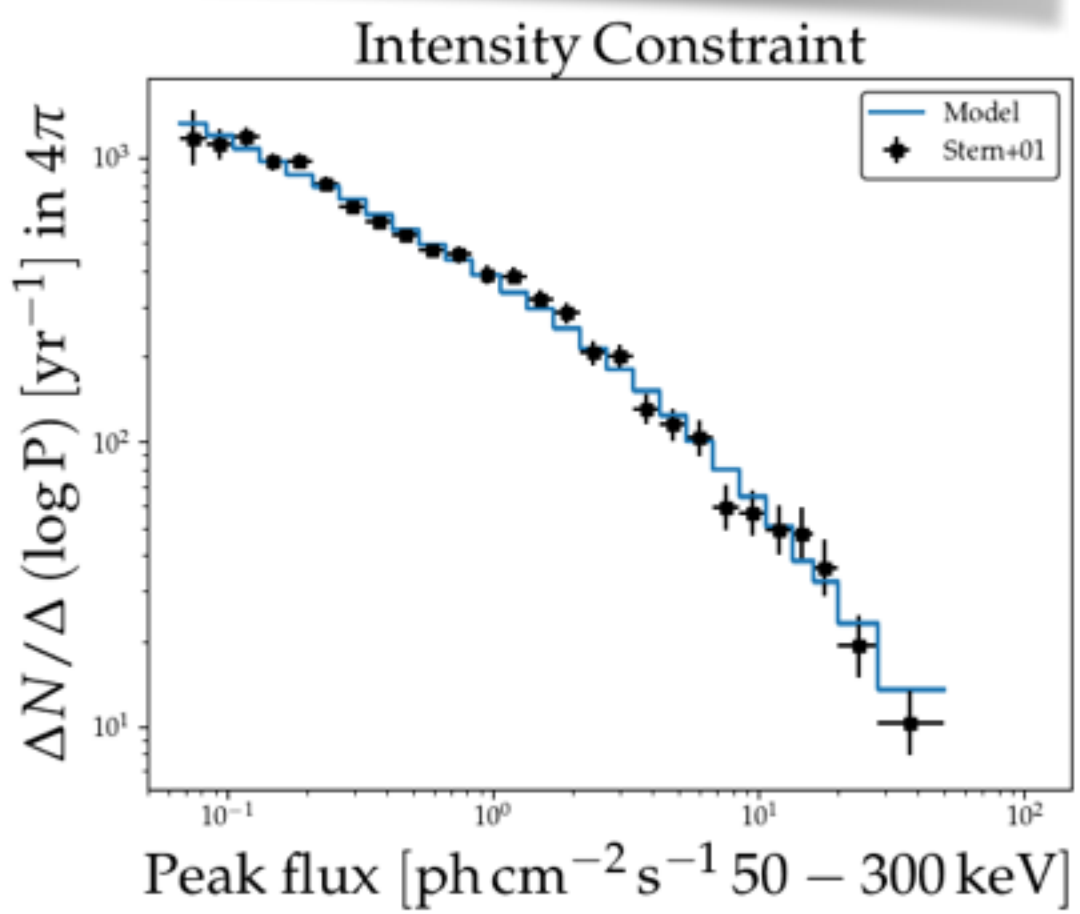
Other observable outputs

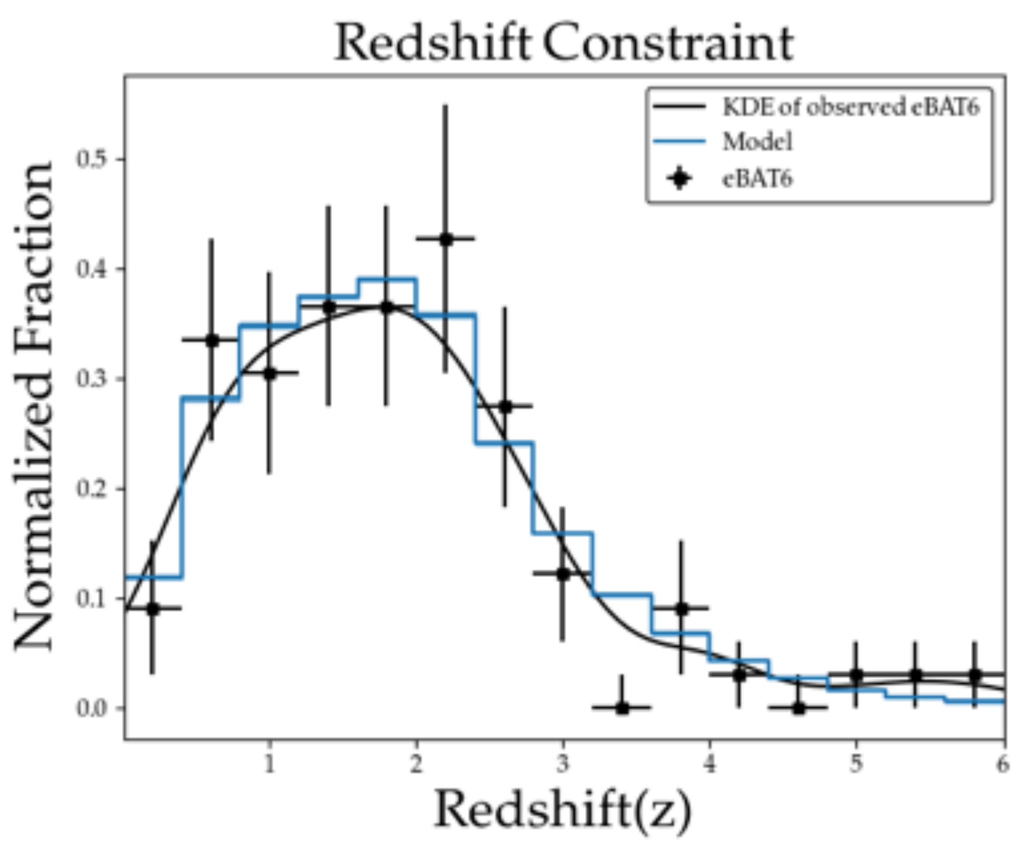
- Test for the presence of **intrinsic correlations** in LGRBs

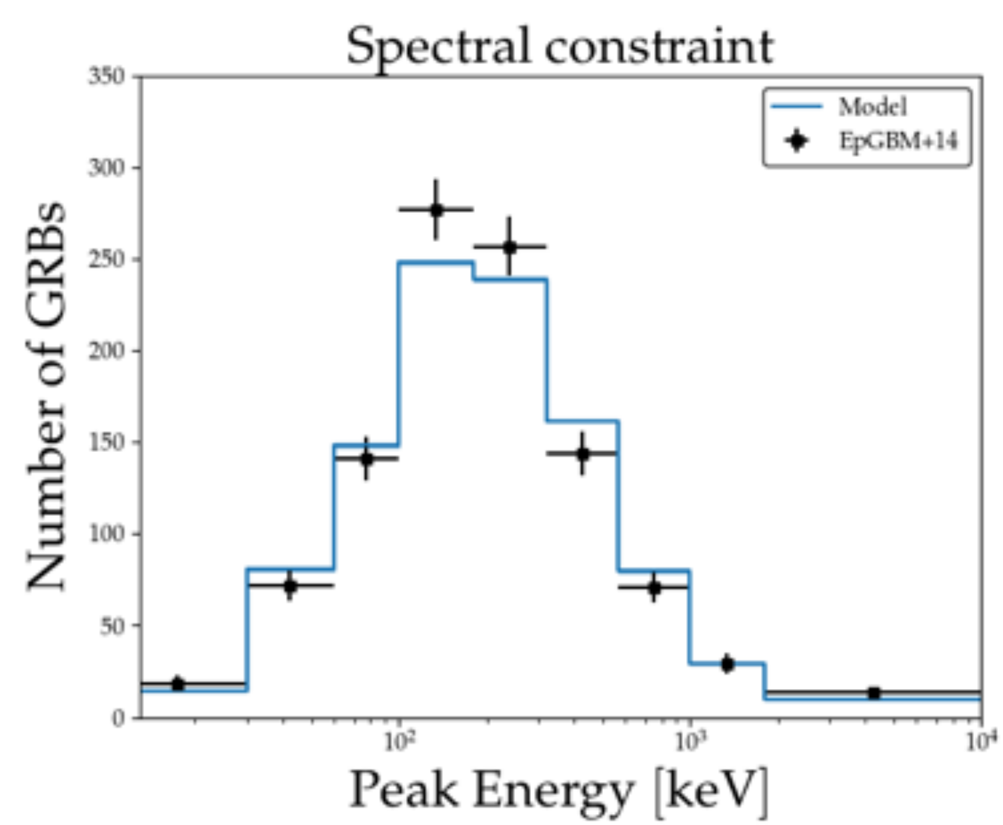


Results

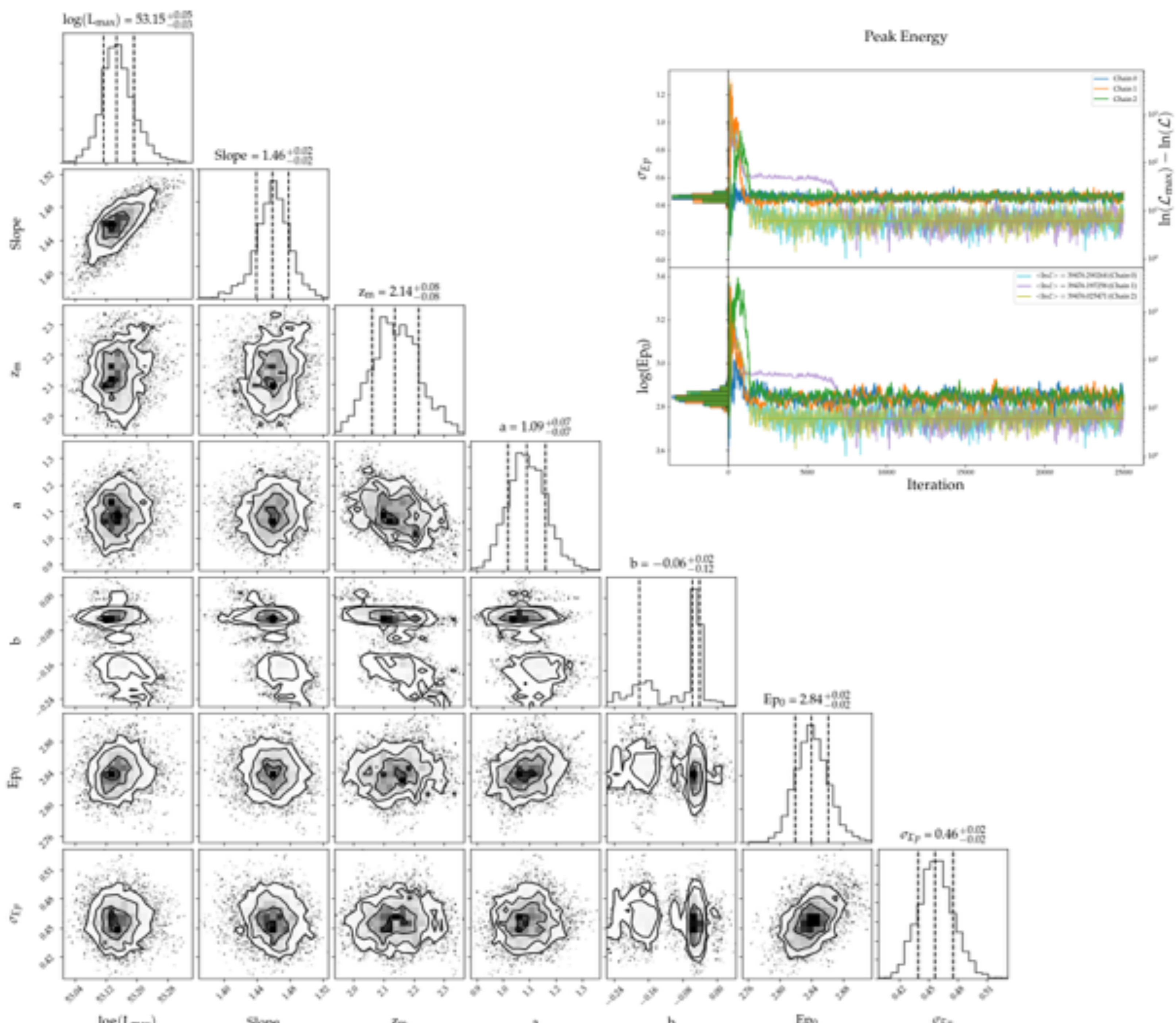
- Best fit from power law Luminosity Function
- LogNormal Peak Energy distribution
- Broken exponential Redshift distribution

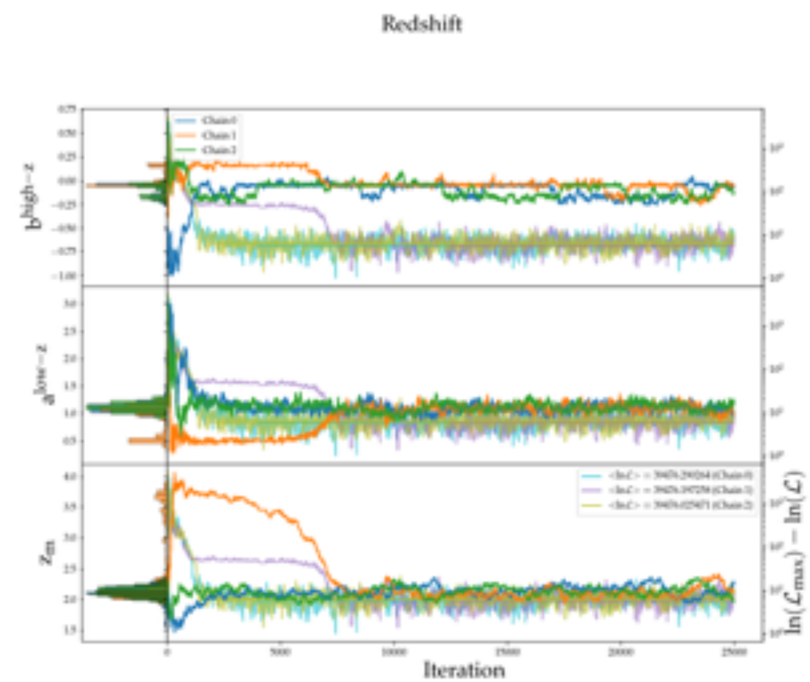


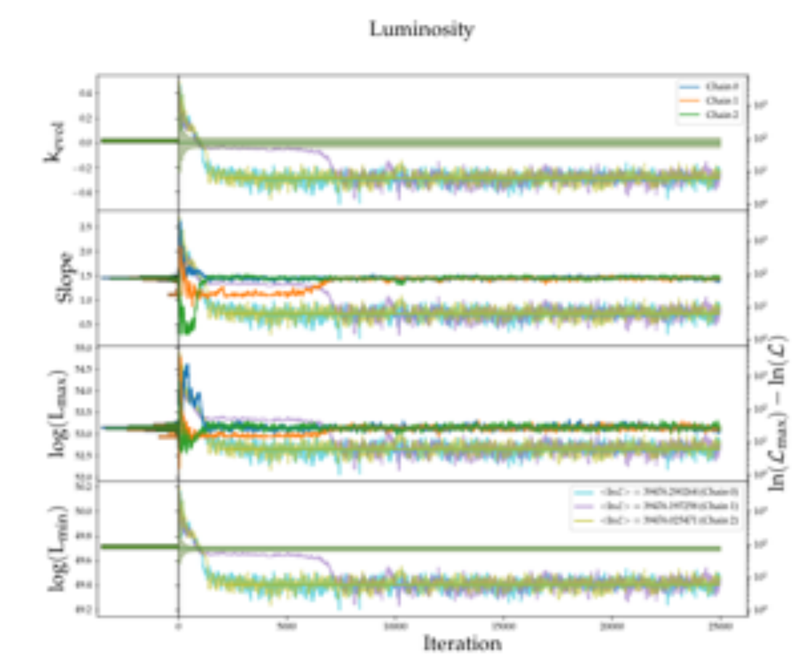




MCMC performance

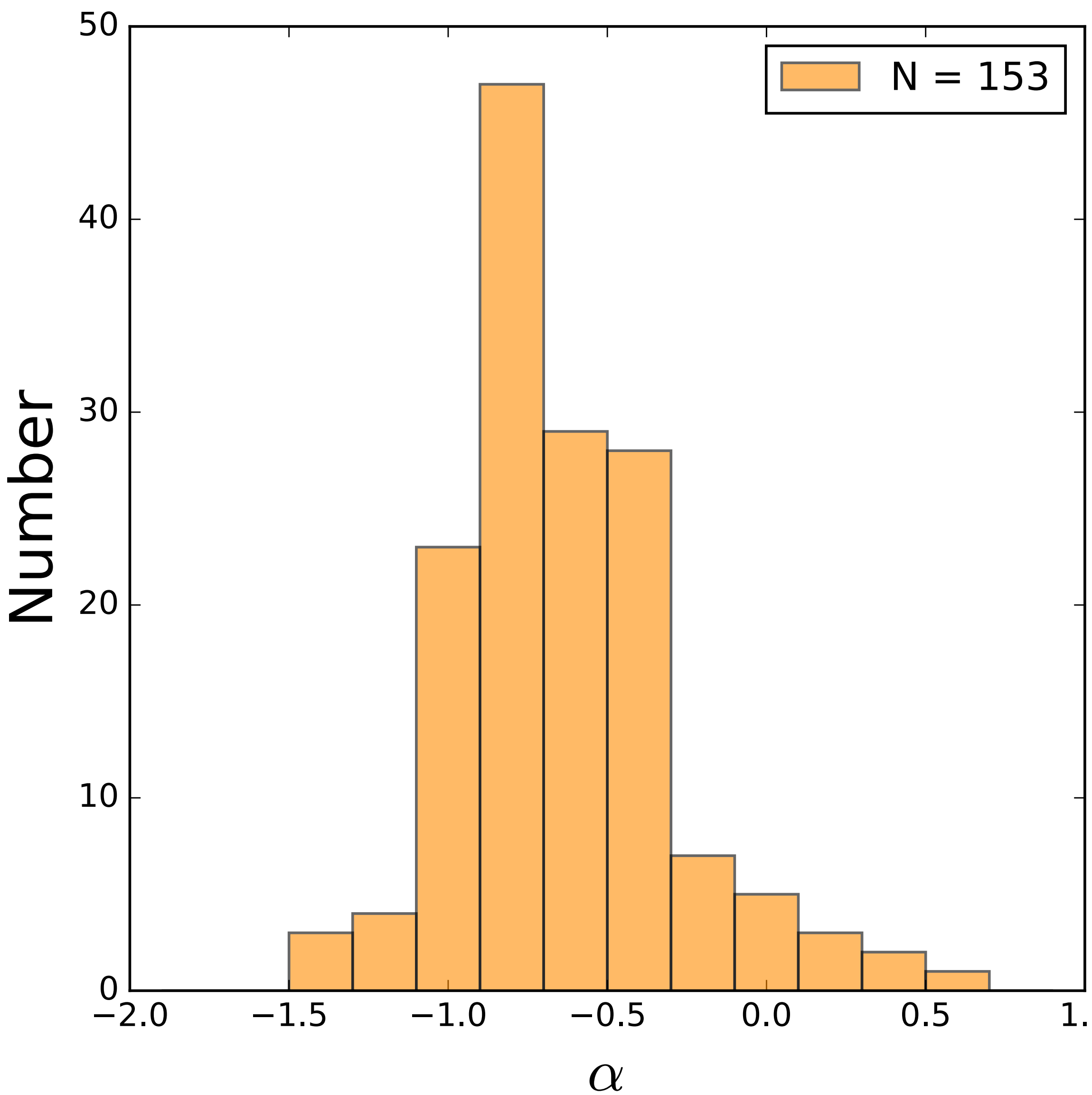


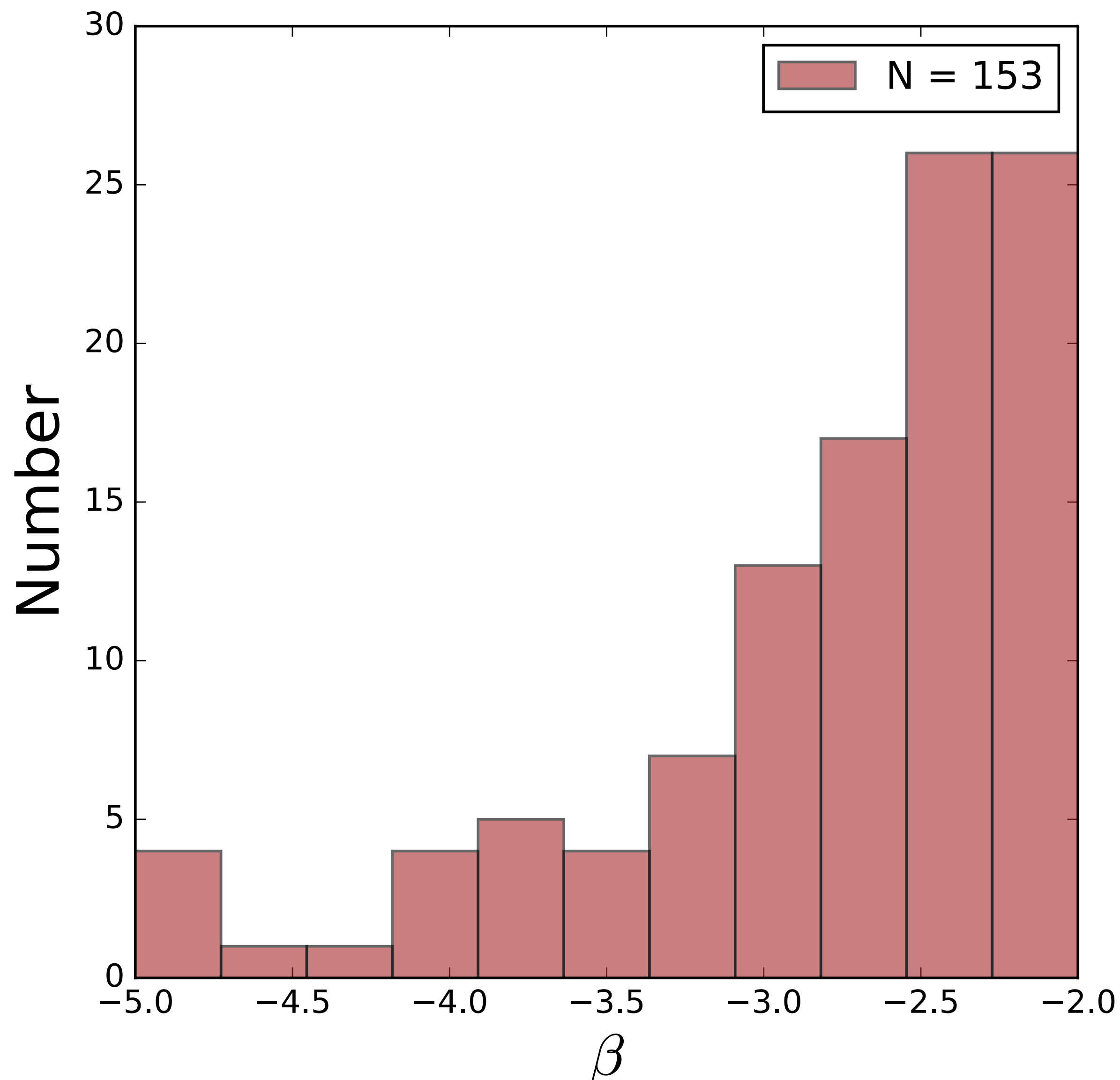




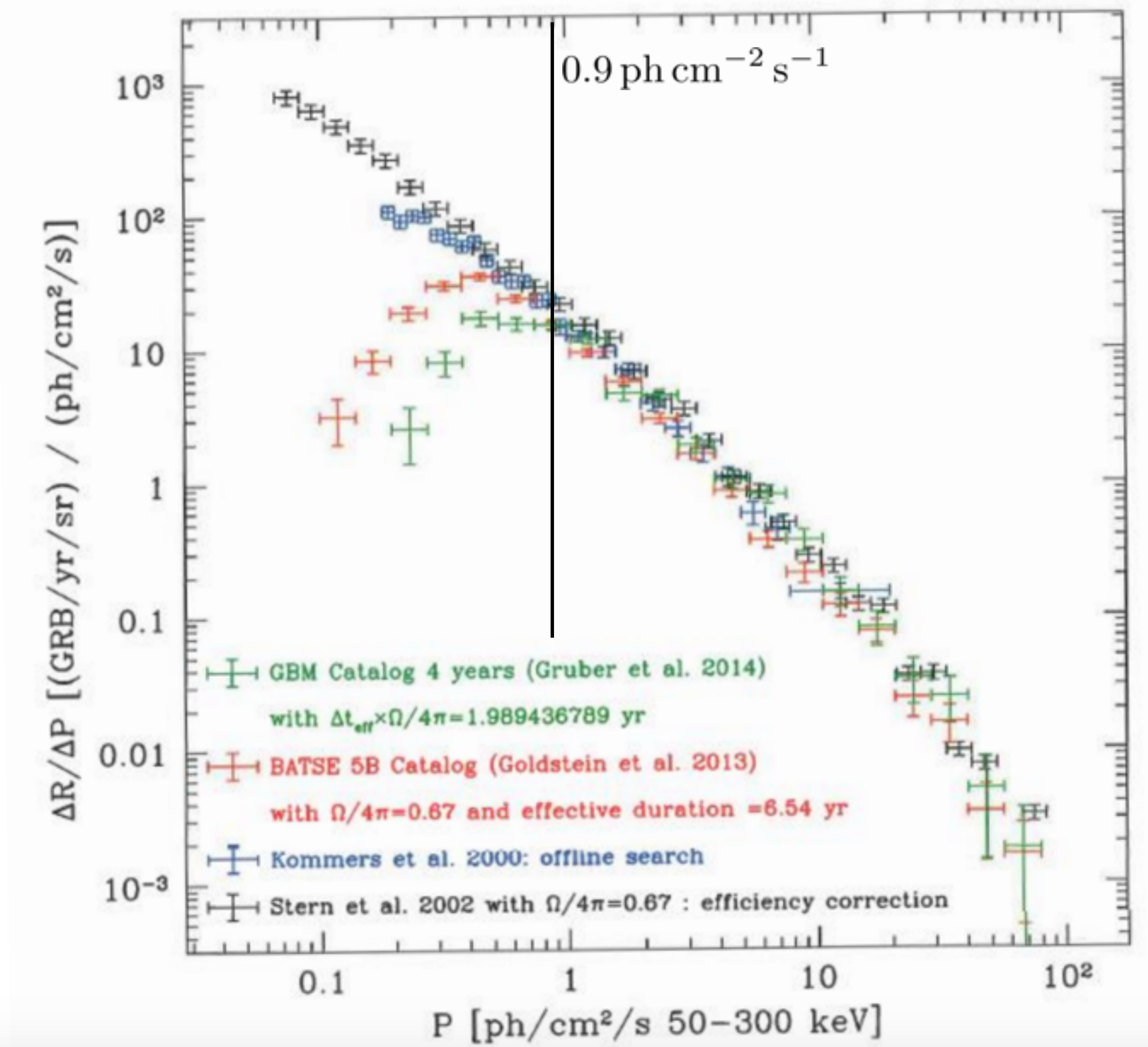
Spectral parameter distribution

α and β are drawn from the latest GBM spectral catalog (Gruber+14), with certain selection criteria



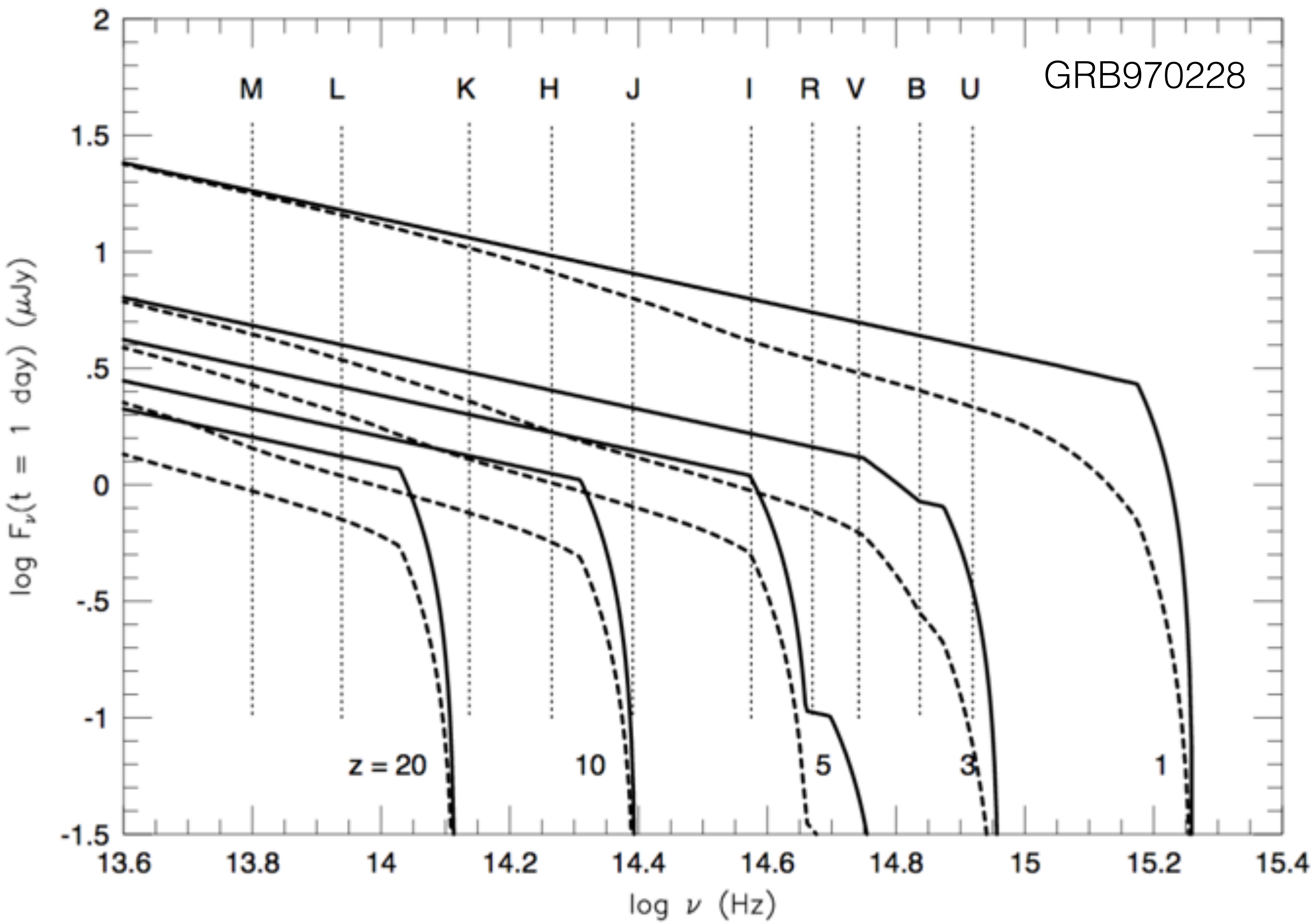


Ep GBM cut selection



S. Antier, PhD thesis

High redshift detectability

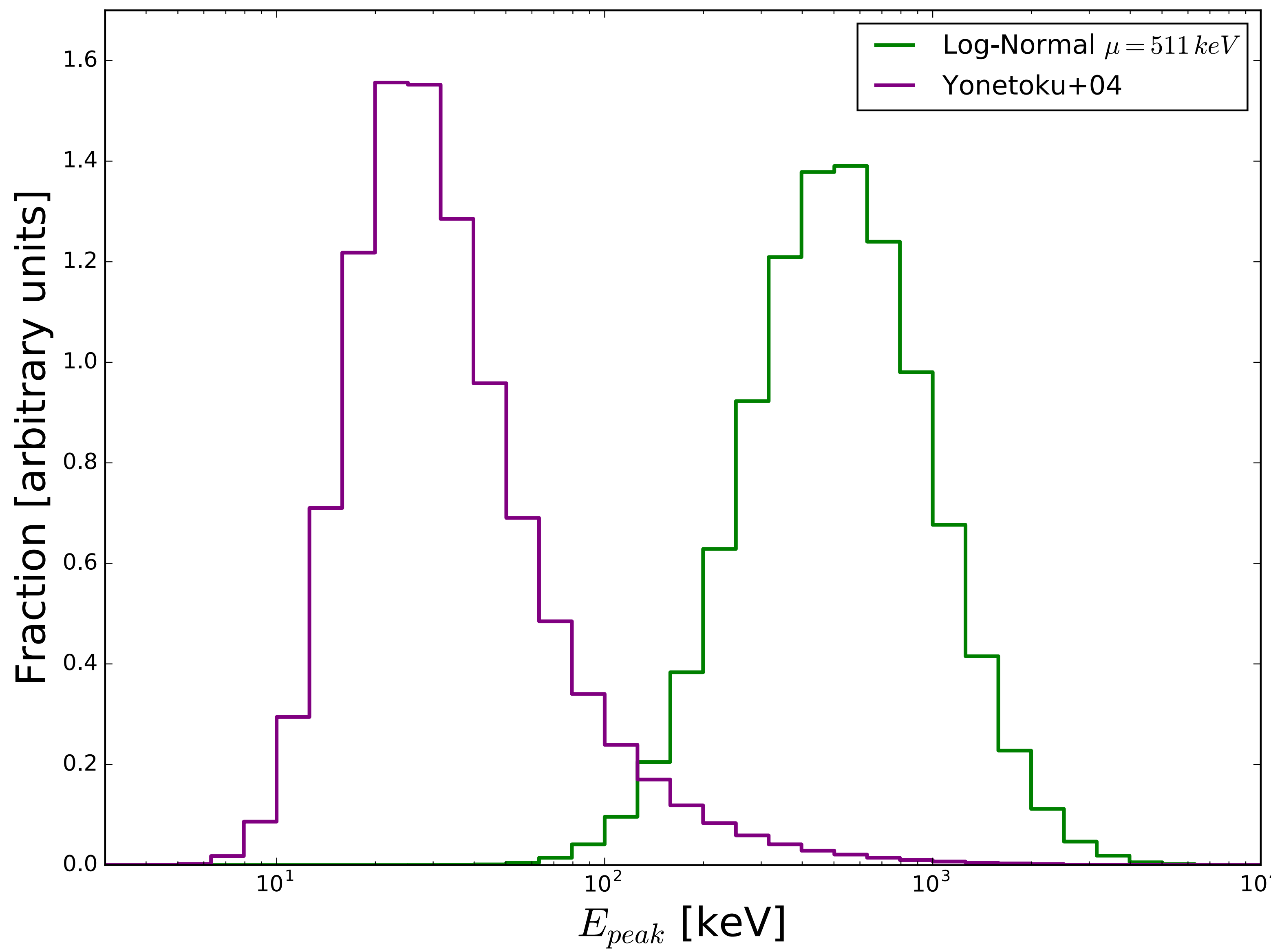


credits : Lamb & Reichart+00

Spectral parameter distribution

We explore two different distributions regarding E_{peak} :

- E_{peak} - L_{iso} correlation from Yonetoku+04
- Independent lognormal distribution.



LGRBs and Star Formation

- LGRBs occur in faint blue galaxies (*e.g.* Le Floc'h+03)
- When resolved, they occur in (UV-)bright regions of their host, with low galactocentric offset (*e.g.* Lyman+17)
- CCSN features appear at later times in the afterglow spectrum (*e.g.* Hjorth+03)

➡ **Link** between **Star Formation Rate** and **LGRB rate?**

➡ **GRB efficiency:** fraction of core collapses that form LGRBs