High-redshift long GRBs

Their rate and production efficiency from modelling and observations

In collaboration with:
Susanna D. Vergani
Frédéric Daigne
Ruben Salvaterra
Jure Japelj

High-redshift Gamma-Ray Bursts in the *JWST* era
9th-13th of January 2023, Sexten, Italy

Outline

1. Long GRBs: a most promising probe of our Universe up to the highest redshifts
2. The issue of their progenitors and their production efficiency from stars
3. Deriving the rate and production efficiency of LGRBs by modelling their intrinsic population
4. Studying the factors driving this production efficiency through observations (at $z < 2$)

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GRBs: unique probes

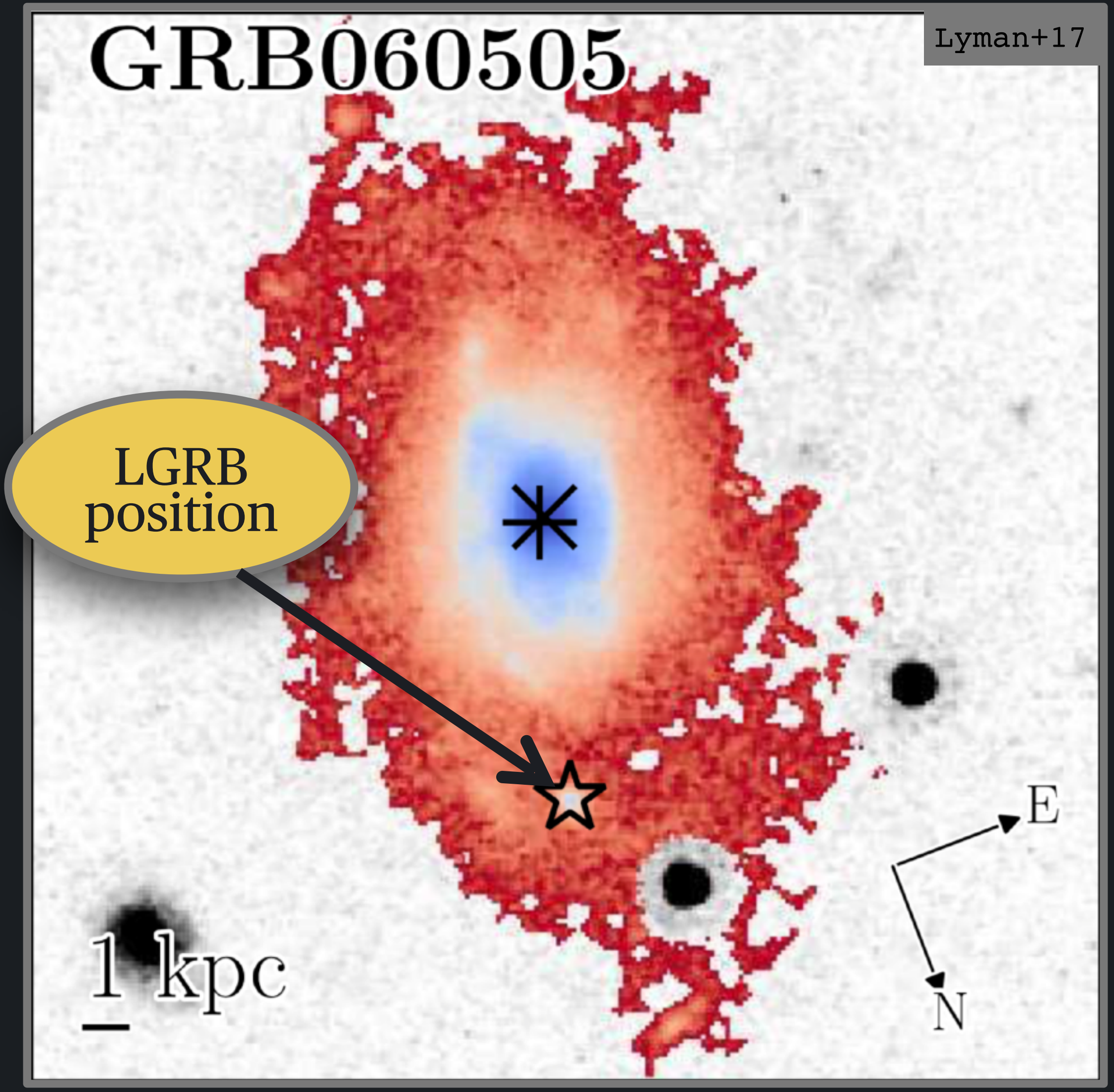
- Produced up to highest redshift
  $z = 8.2$ confirmed spectroscopically, predicted up to first stars at $z > 15$

- Detected in hard X-rays / soft γ-rays
  ➡ prompt is largely unaffected by dust/hydrogen

- Bright, transient, fading afterglow
  ➡ benefit from time dilation at high redshift

LGRBs and massive stars

- Long GRBs are associated to the deaths of (certain) massive stars: collapsar model



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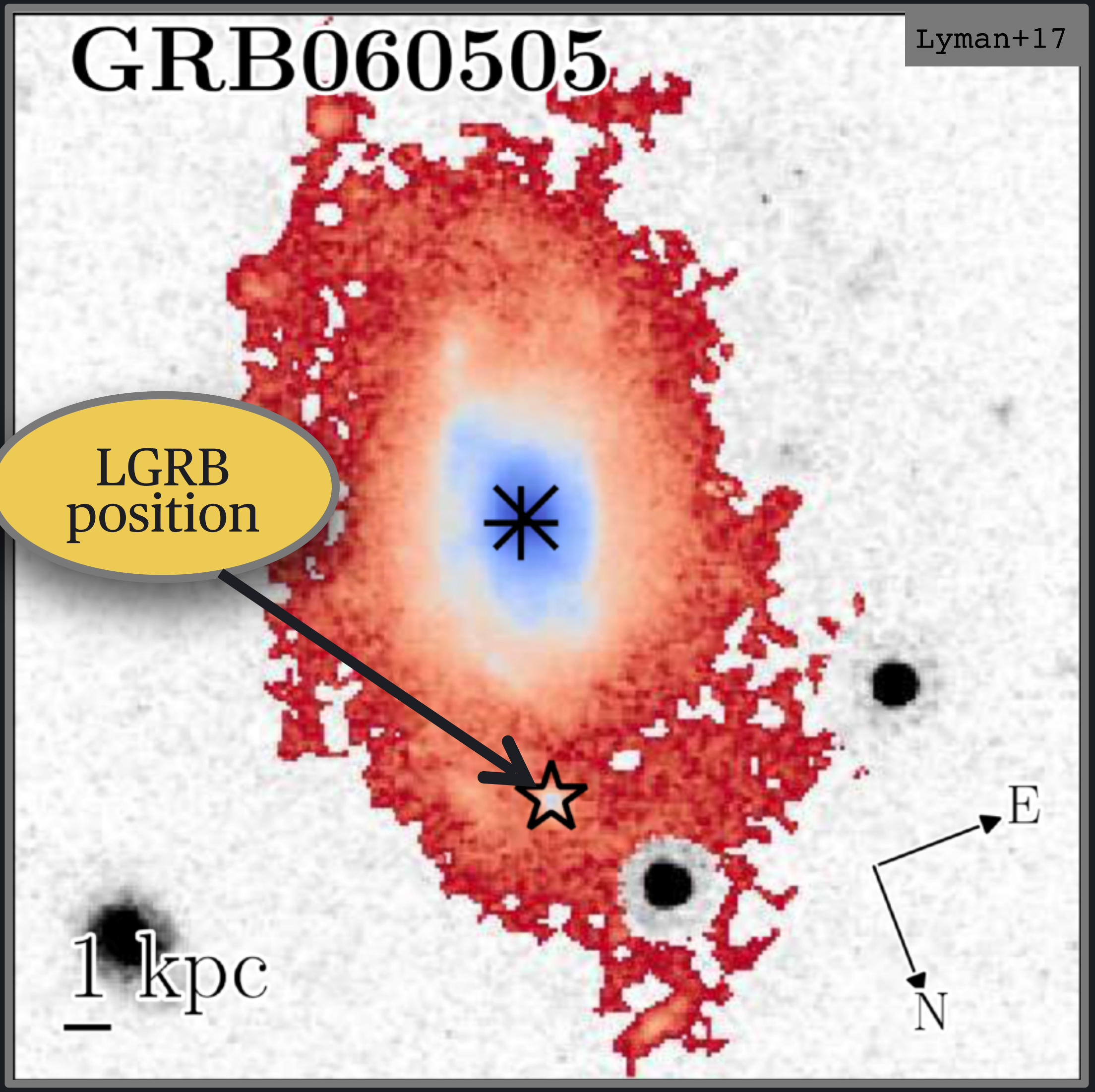
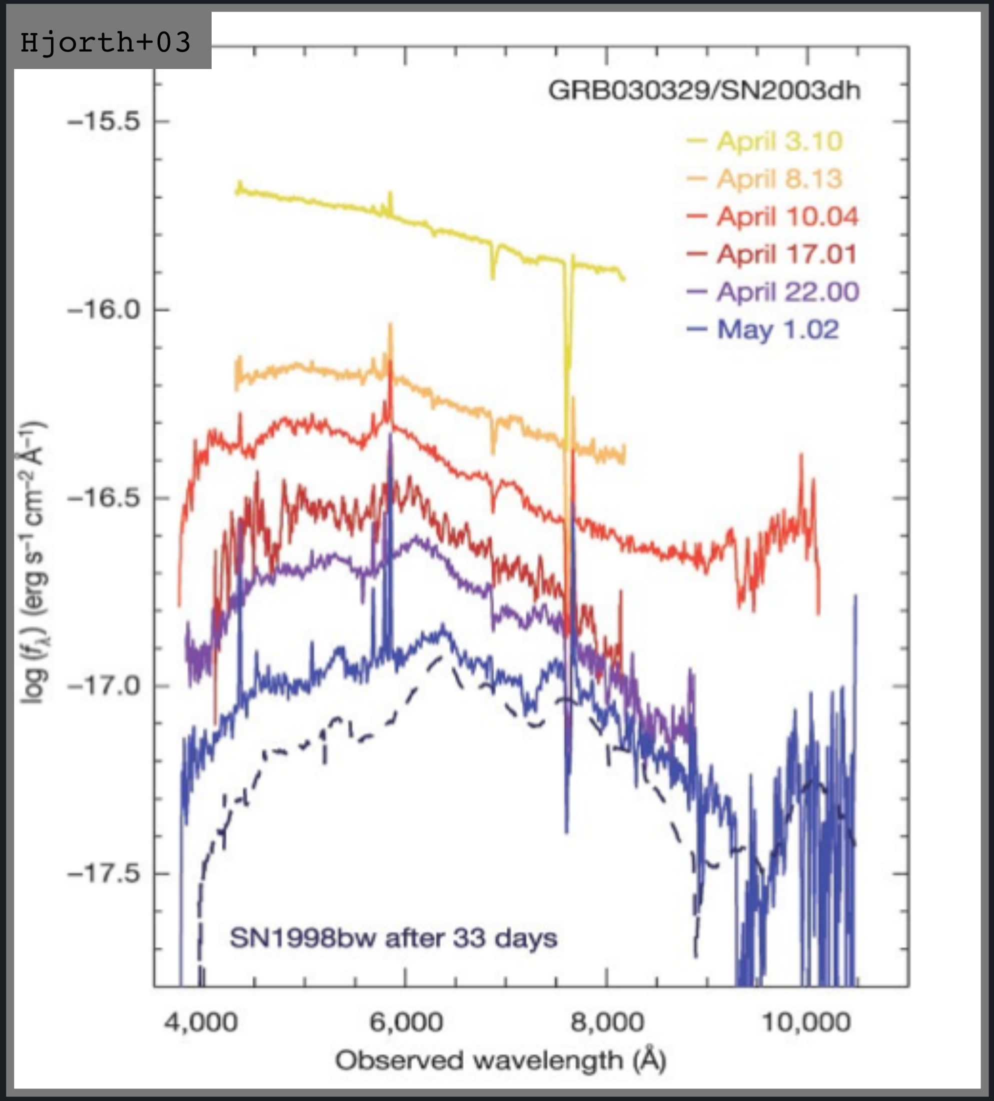
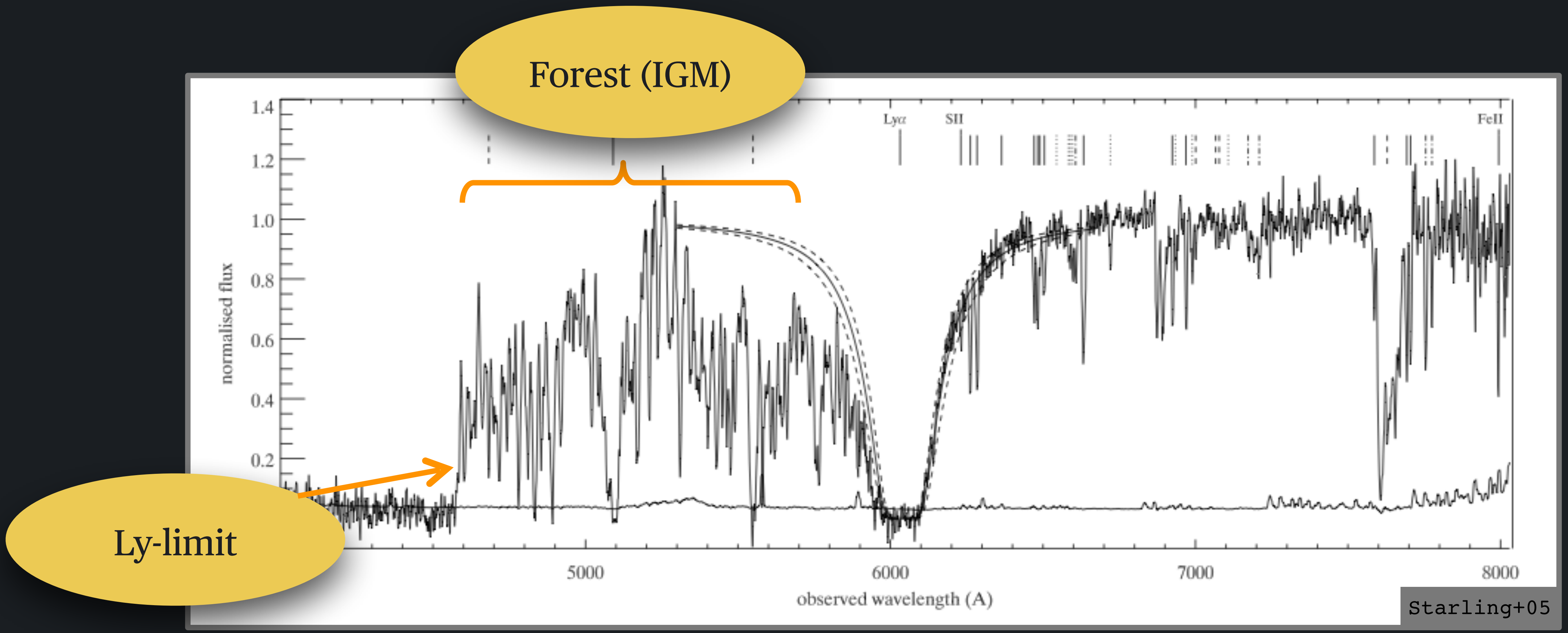




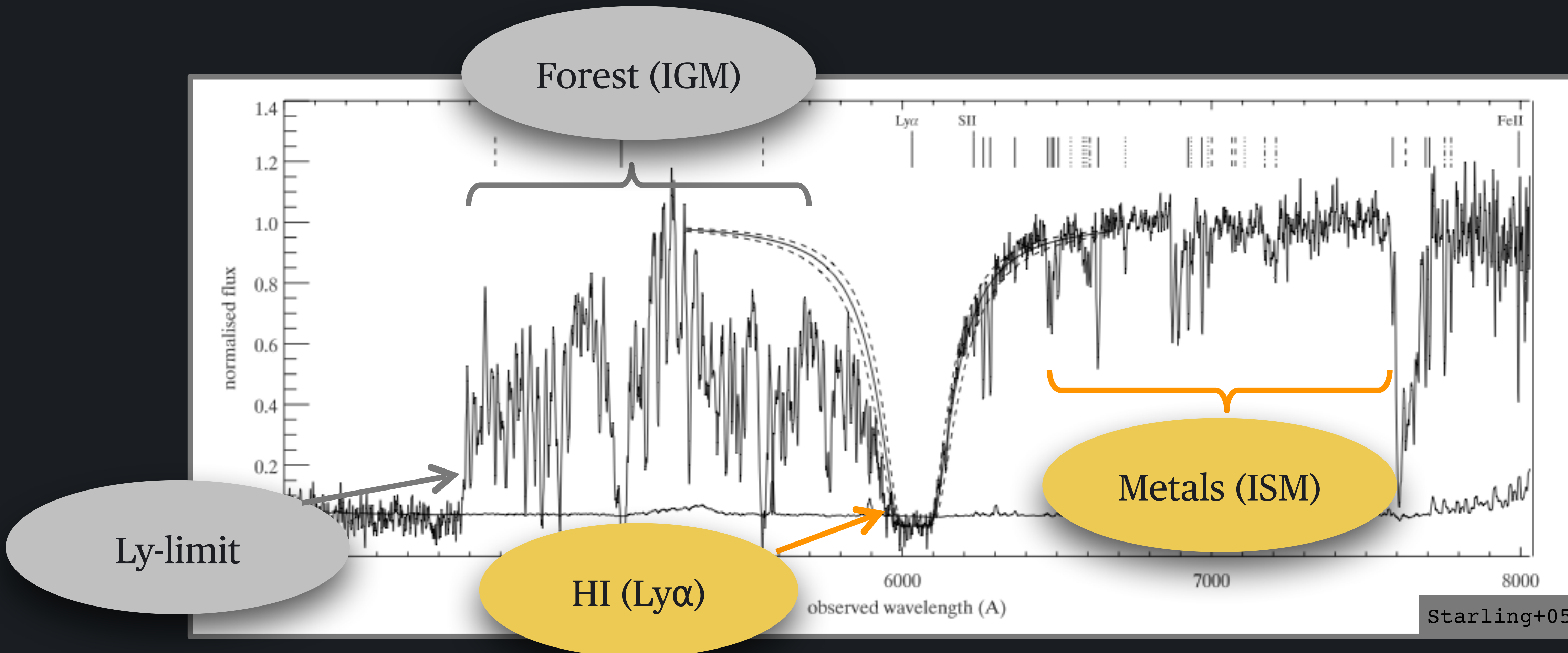
GRBs: case-by-case probes

- GRB afterglows allow to exquisitely study individual sightlines (like quasars)



GRBs: case-by-case probes

- GRB afterglows allow to exquisitely study individual sightlines (like quasars)
- But also uniquely the gas <u>inside</u> star forming regions at high redshift (see talk by A. Saccardi)



GRBs: statistical probes

- Populations/samples of GRBs can be used to study the Universe statistically
- Basic data: rate, sky position, duration, brightness/spectrum (in γ-rays)

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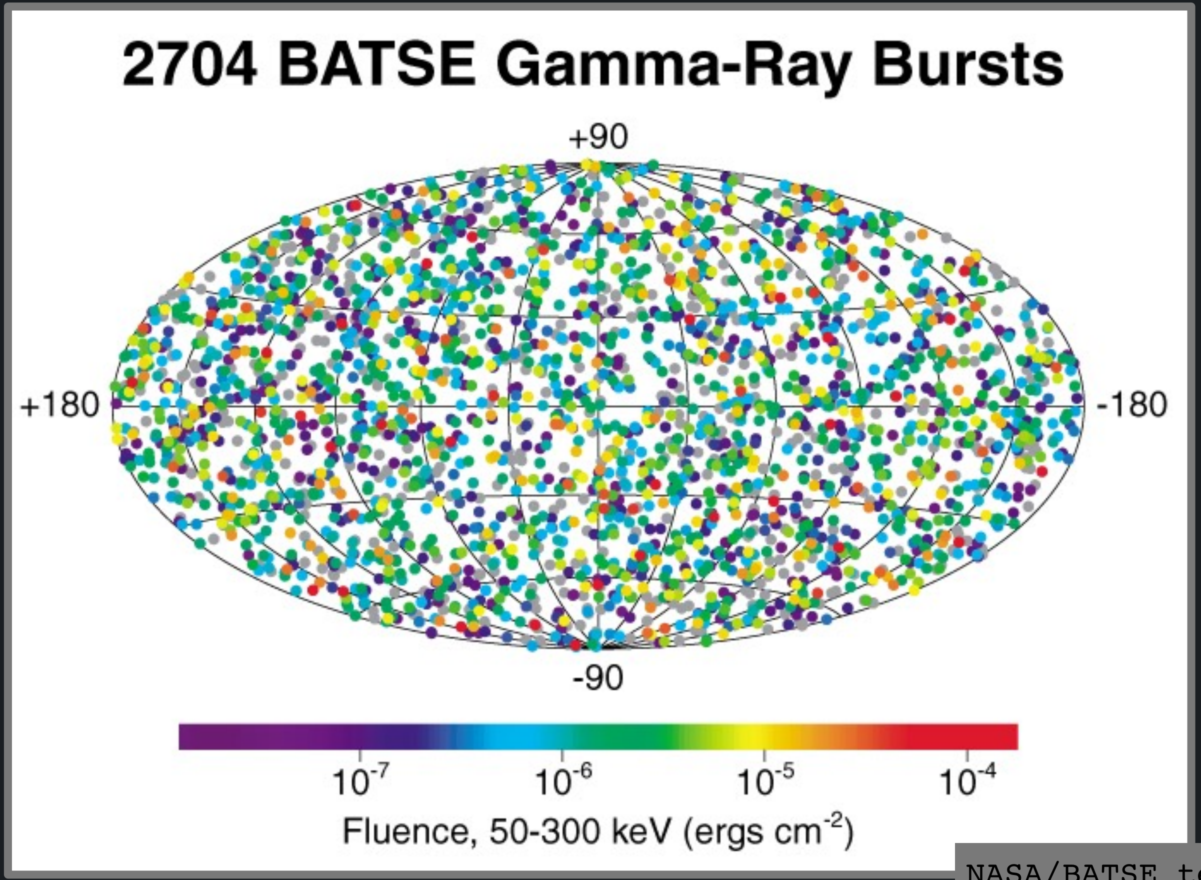

NASA/BATSE team

GRBs: statistical probes

- Populations/samples of GRBs can be used to study the Universe statistically
- Basic data: rate, sky position, duration, brightness/spectrum (in γ-rays)
- If successful optical/NIR follow-up: redshift/distance

➡ **Crucial** for full scientific potential of GRBs to be exploited

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- Statistically very powerful but **require** unbiasedness, completeness
(See talks by G. Ghirlanda or N. Tanvir for good examples)
- Can be limited by sample size

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LGRBs and star formation

- Long GRBs are associated to the deaths of (certain) massive stars: collapsar model
- Their rate is linked to the star-formation rate (SFR) since massive stars die rapidly (~1-10 Myr)
- By studying statistically the population of LGRBs and estimating their cosmic formation rate we could, in theory estimate the SFR
- But in order to do this we must understand this link (not trivial!)

Link between LGRB & SFR

- Properties of progenitor star:
  - mass range
  - initial rotation distribution
  - metallicity distribution
  - binarity

- Properties of the LGRB population:
  - luminosity evolution
  - spectrum evolution
  - jet opening angle

LGRB production efficiency

Production efficiency

LGRBs

Core-collapses

$$\dot{n}_{\mathrm{LGRB}}(z) = \eta(z)\, \dot{n}_{\mathrm{cc}}(z) \qquad [\mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}]$$

Comoving rate density
(number of events per year per comoving volume)

➡ Fraction of core-collapses that give rise to an LGRB (pointing in our direction)

LGRB production efficiency

Production efficiency

$$\dot{n}_{\mathrm{LGRB}}(z) = \eta(z)\,\dot{n}_{\mathrm{cc}}(z) \qquad [\mathrm{yr}^{-1}\,\mathrm{Mpc}^{-3}]$$

$$\dot{n}_{\mathrm{cc}}(z) \propto \dot{\rho}_*(z)$$ (see later for details)

➡ Core-collapse rate density is proportional to cosmic SFR density

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LGRB population model

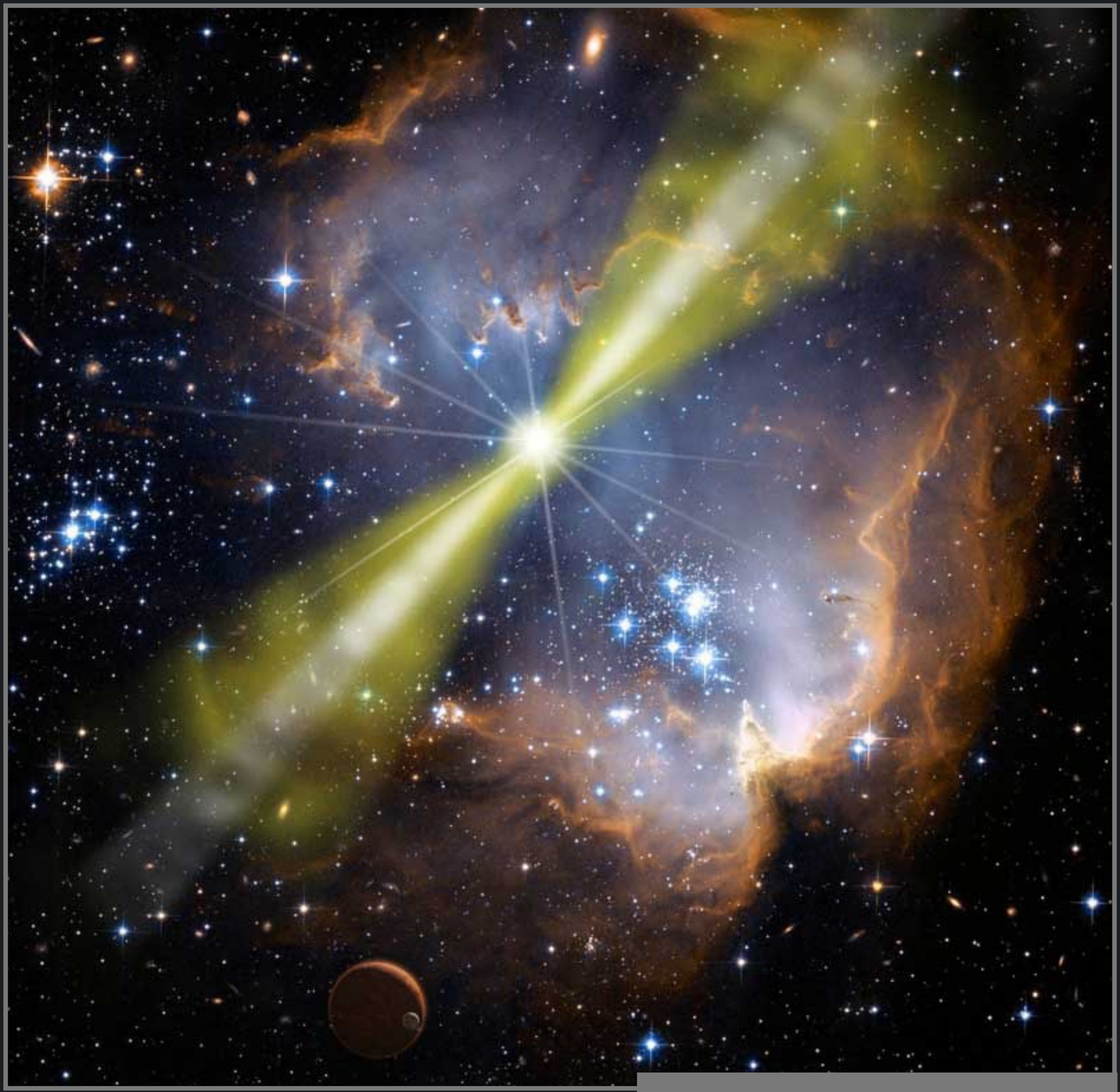
Palmerio & Daigne 2021

- Overcome the limitations of biased or incomplete samples by modelling the underlying intrinsic population and fitting it to carefully selected observational samples

- Forward-folding approach, flexible but parametric (limited by parameter space exploration)

- It allows us to address questions such as:
  - What is the intrinsic redshift distribution of LGRBs?
  - What does this imply for the LGRB production efficiency?

Describing an LGRB



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

- Luminosity: L_{iso}
- Spectrum: E_{peak} α β
- Redshift: z
- Temporal: T_{90} C_{var}

Population scheme

Schechter function

$$\phi(L) \propto \begin{cases} \left(\frac{L}{L_*}\right)^{-p} \times \exp\left(-\frac{L}{L_*}\right) & L > L_{\min} \\ 0 & L \leq L_{\min} \end{cases}$$

Redshift evolution?

$$\propto (1+z)^{k_{\mathrm{evol}}}$$

Log-Normal

$$\text{Log-}\mathcal{N}(E_{p0}, \sigma_{\mathrm{E_p}})$$

Intrinsic correlation

$$E_p = E_{p0} \left(\frac{L}{L_0}\right)^{\alpha_{\mathrm{A}}}$$

Luminosity: L_{iso}

Spectrum: E_{peak} α β

Redshift: z

Broken exponential

$$\dot{n}_{\mathrm{LGRB}}(z) \propto \begin{cases} e^{az} & z < z_m \\ e^{bz}\, e^{(a-b)z_m} & z \geq z_m \end{cases}$$

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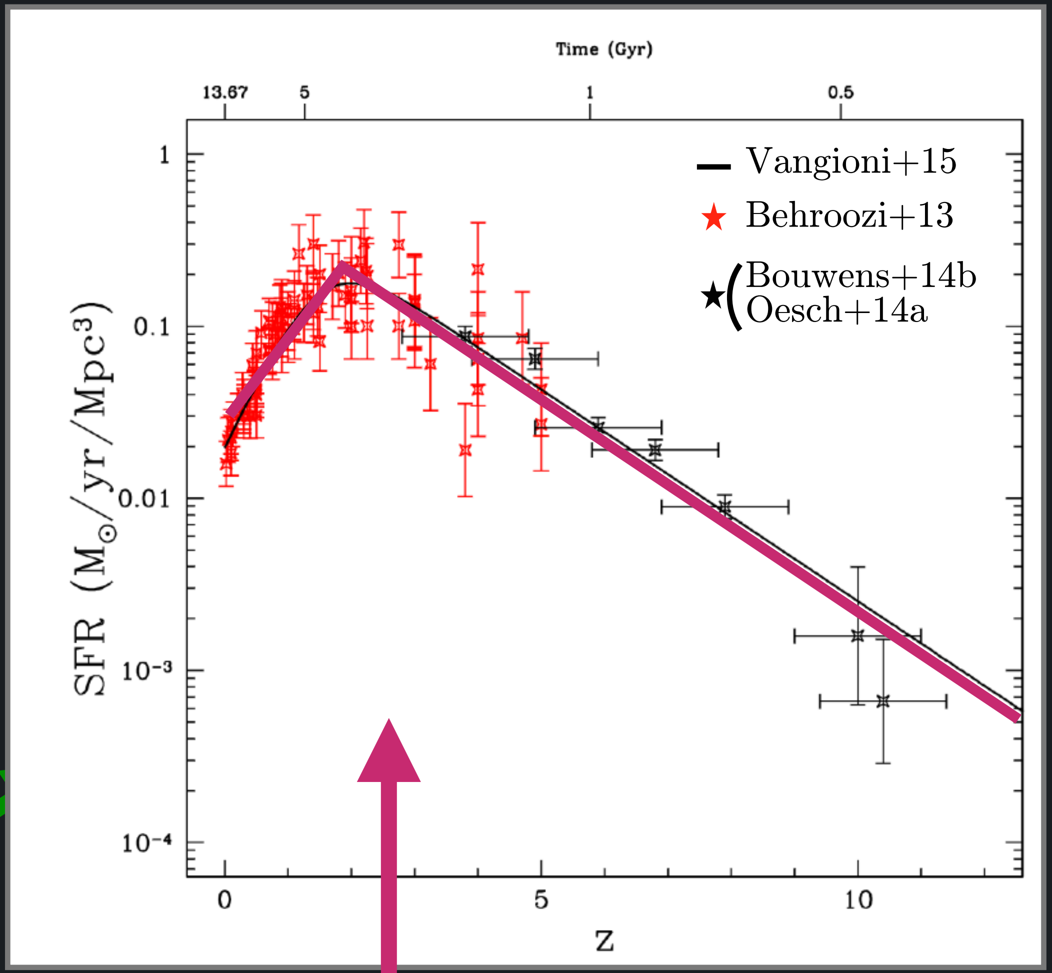

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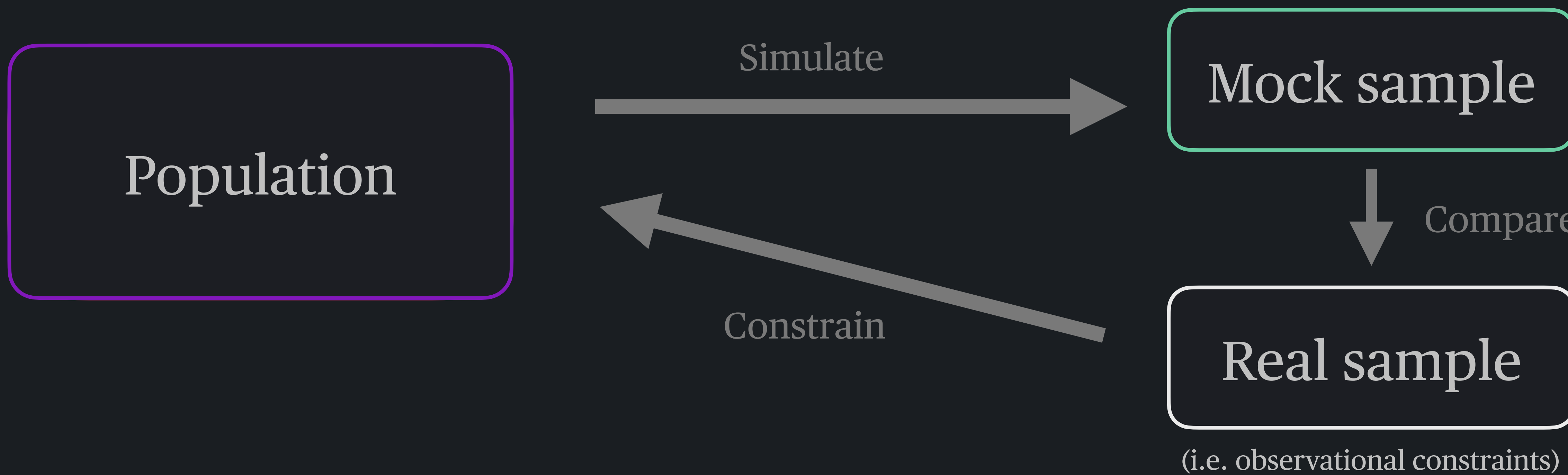

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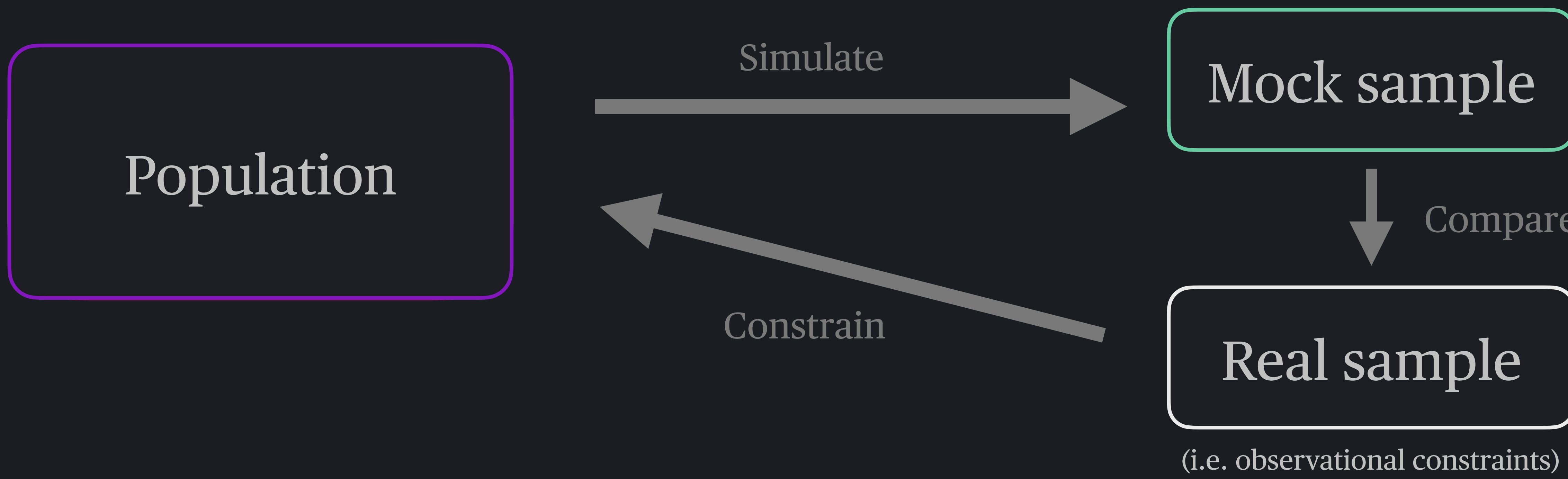


Luminosity: L_{iso}

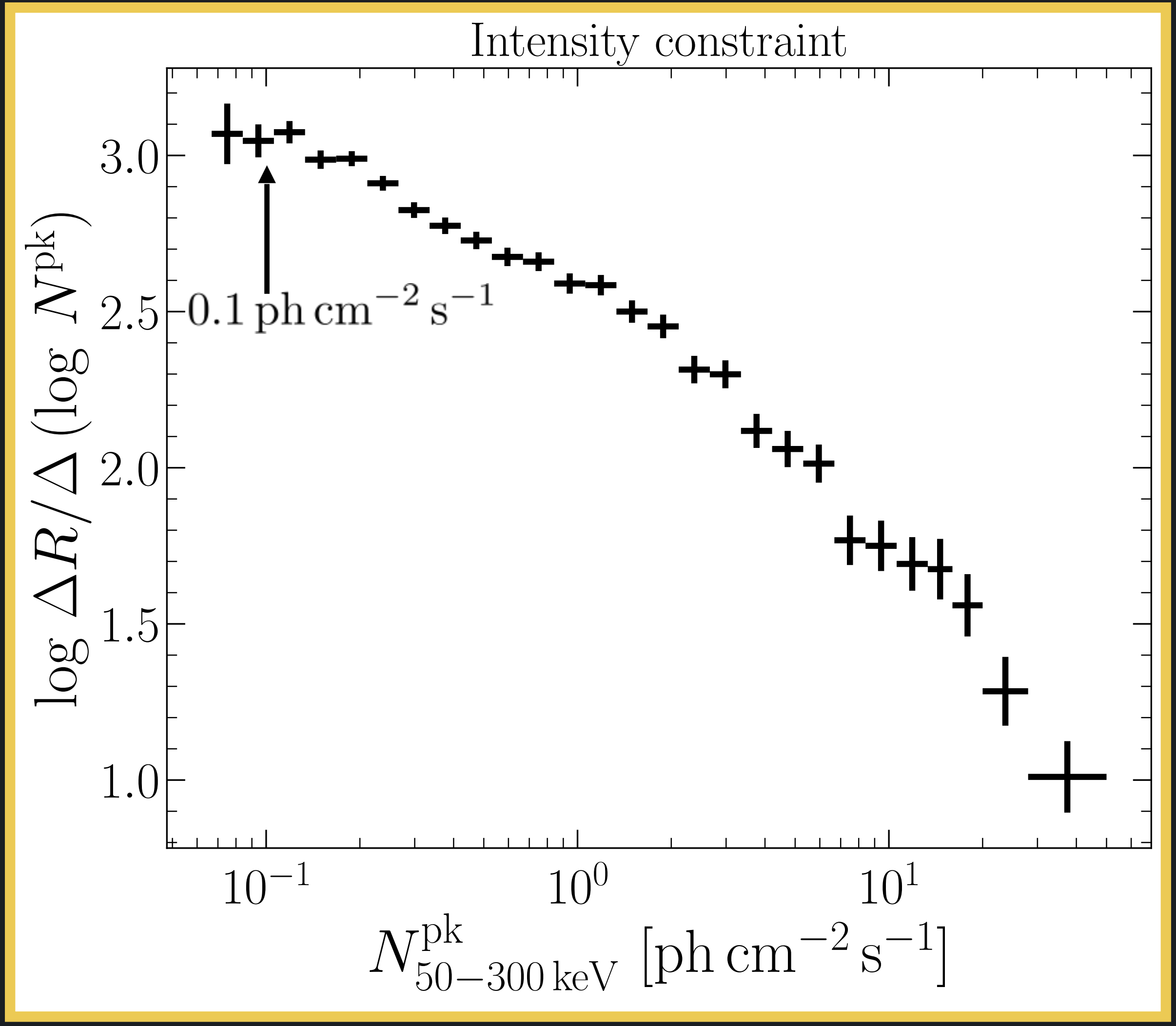
Spectrum: E_{peak} α β

Redshift: z

- Intensity
- Spectral
- Distance

Observational constraints

- Intensity constraint: $\log N$ - $\log P$
  - Observed peak flux distribution based on ~3300 LGRBs detected by *CGRO*/BATSE over 9.1 years (on board trigger + offline search, Stern+01)
  - Corrected for fraction of sky observed, live time of the search and detection efficiency



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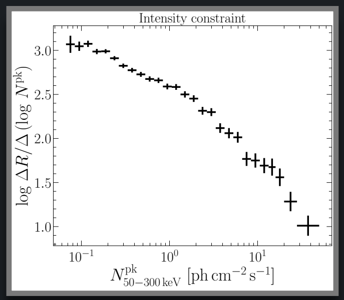
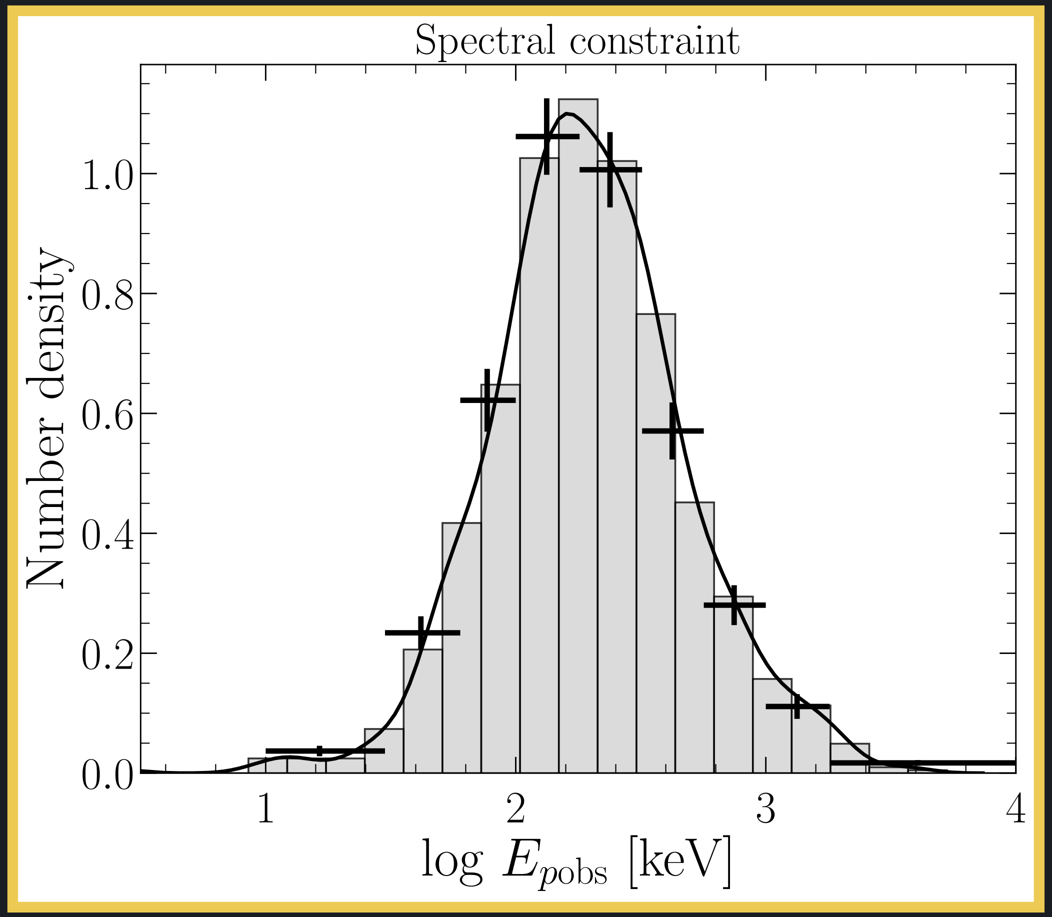


- Spectral constraint: E_{pobs}
  - Observed peak energy distribution of ~1000 bright LGRBs with $N^{pk}_{50-300\,\mathrm{keV}} \geq 0.9\,\mathrm{ph\,s^{-1}\,cm^{-2}}$ from *Fermi*/GBM (Gruber+14, Bhat+16)



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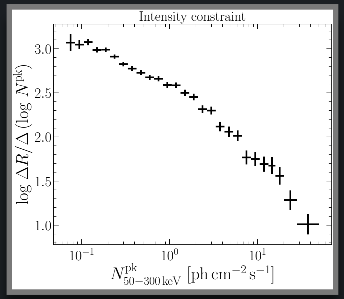

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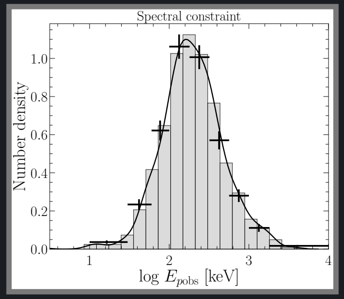
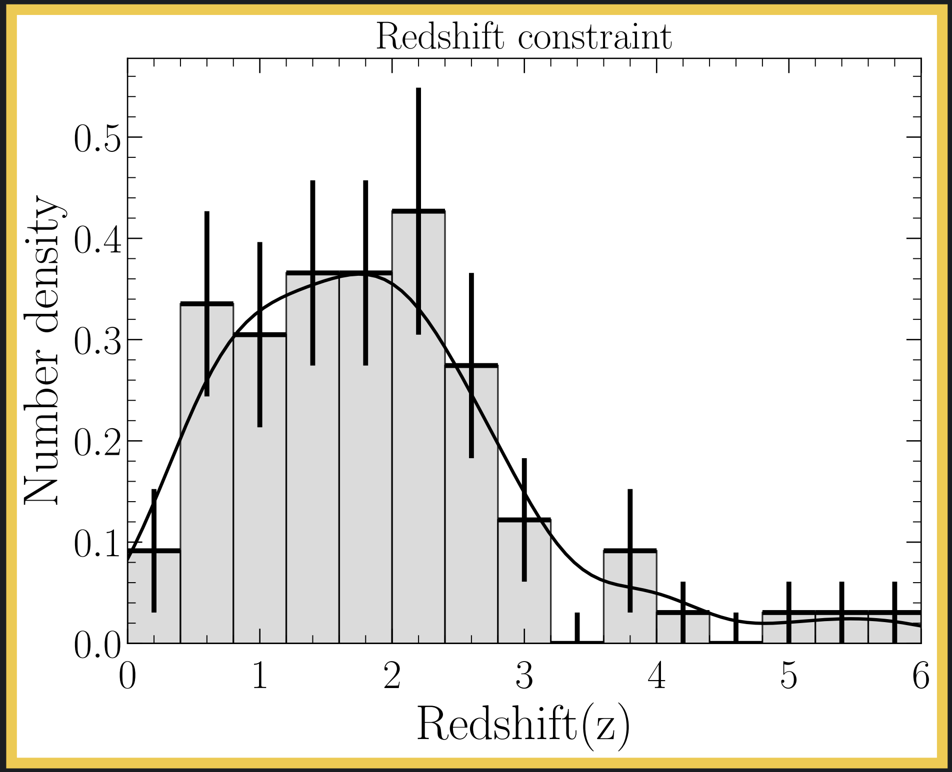
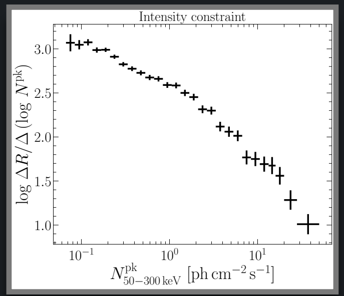


- Distance constraint: z
  - Redshift distribution of extended BAT6 (Pescalli+16)
  - 82 LGRBs (82% completeness) with $N^{\rm pk}_{15-150\,{\rm keV}} \geq 2.6\,{\rm ph\,s^{-1}\,cm^{-2}}$ detected by *Swift*/BAT and favorable observing conditions

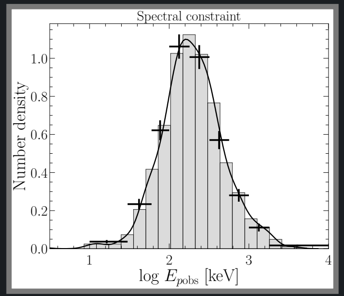


Observational constraints

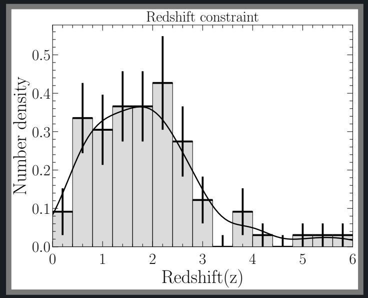
- Intensity constraint: $\log N$ - $\log P$



- Spectral constraint: $E_{p\mathrm{obs}}$



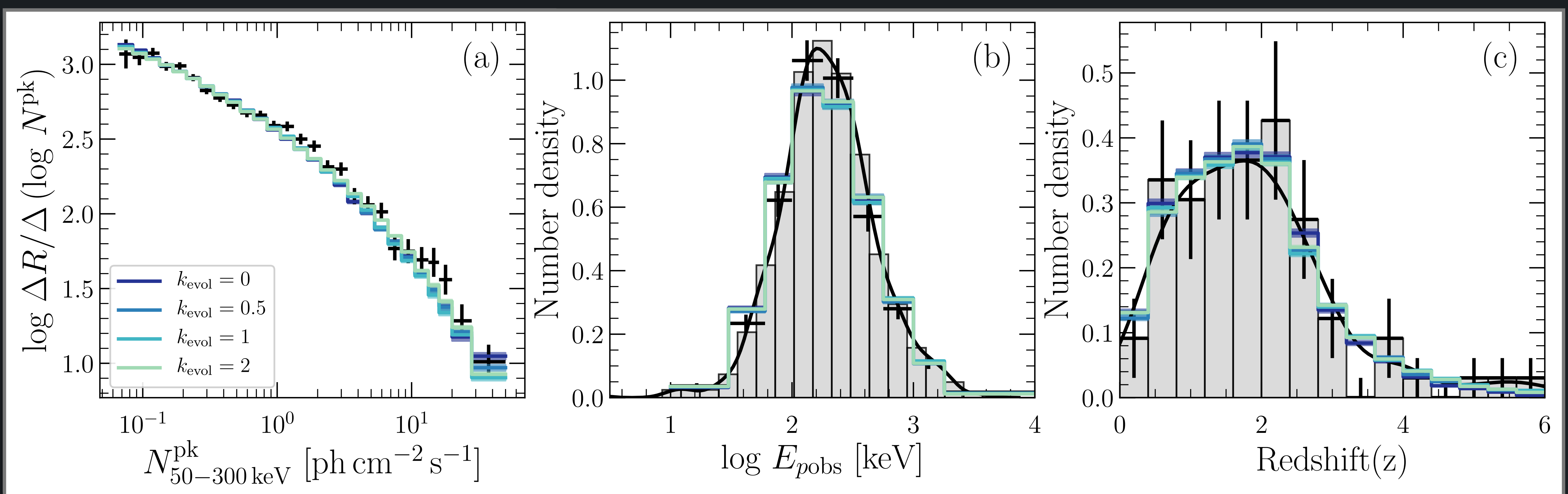
- Distance constraint: z



➡ We fit these constraints using MCMC and a Bayesian framework for a variety of different scenarios

Results

- We tested 4 different "strengths" of redshift evolution of the luminosity function: $k_{\mathrm{evol}} = 0,\ 0.5,\ 1,\ 2$
- All models can provide good fits to the data



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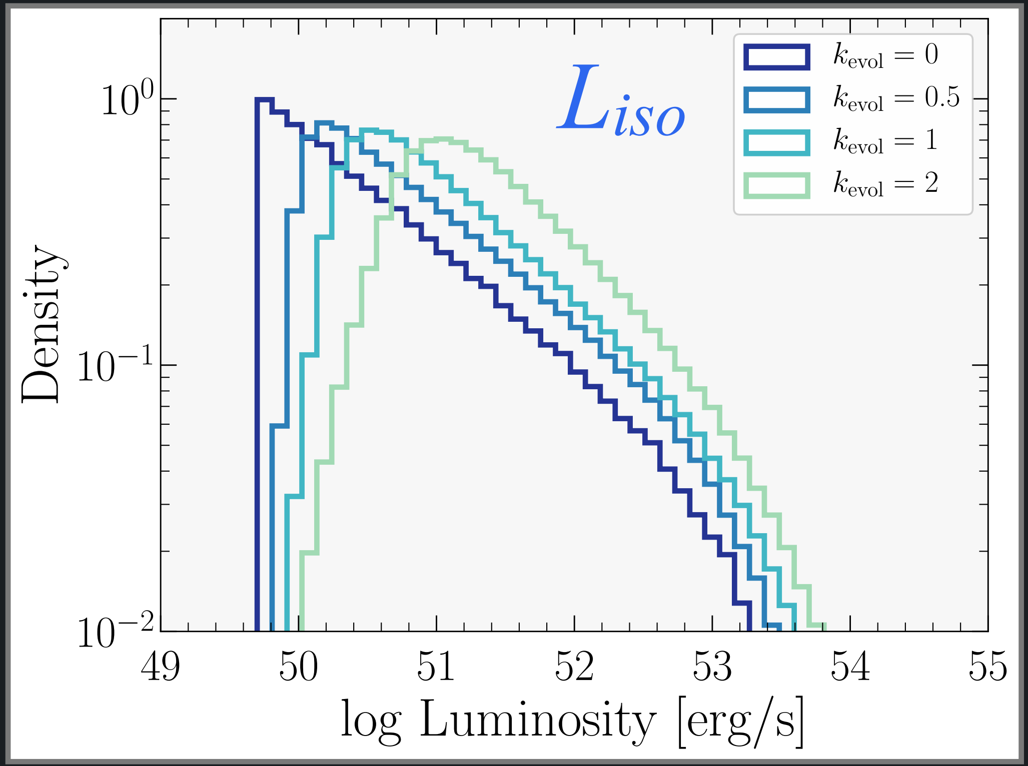
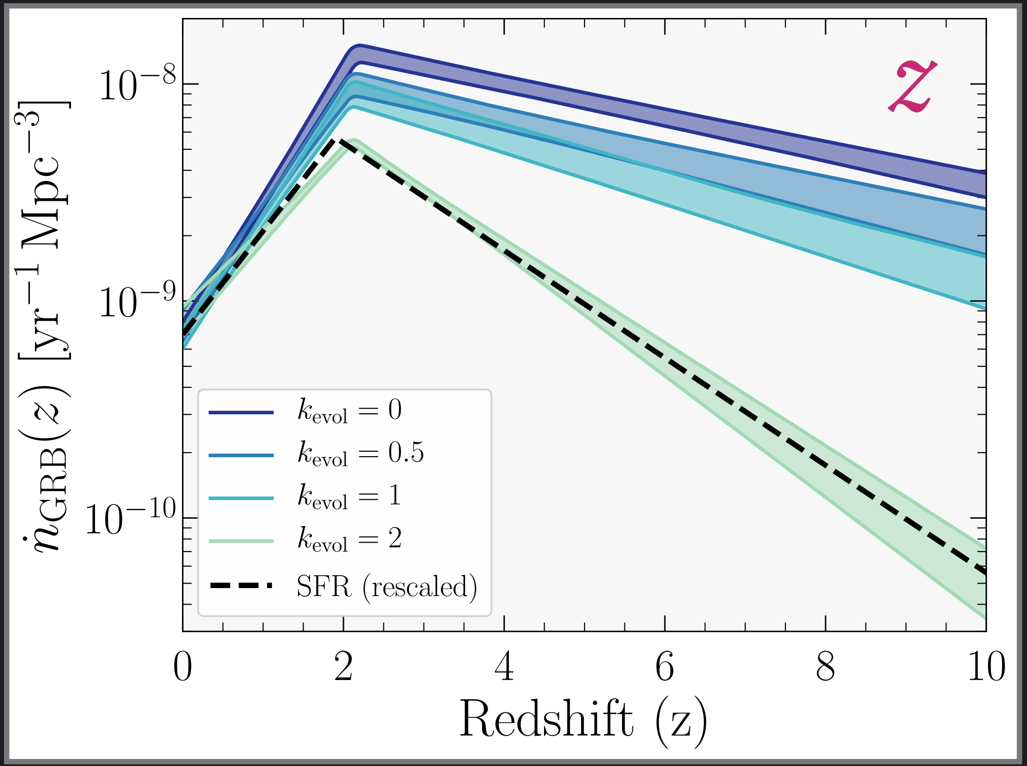
➡ Strong degeneracy between cosmic evolution of the LGRB luminosity function and cosmic evolution of the LGRB rate

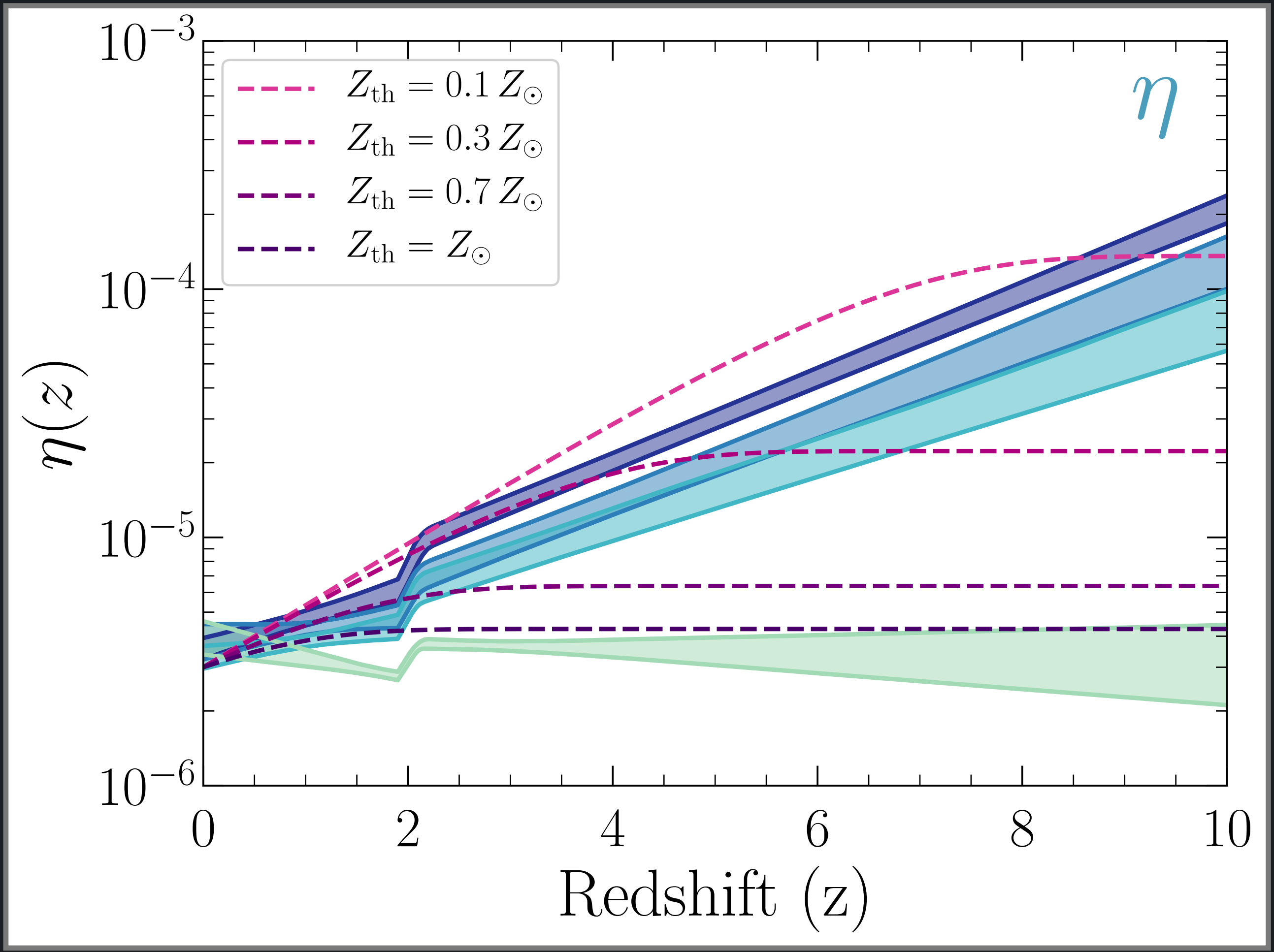




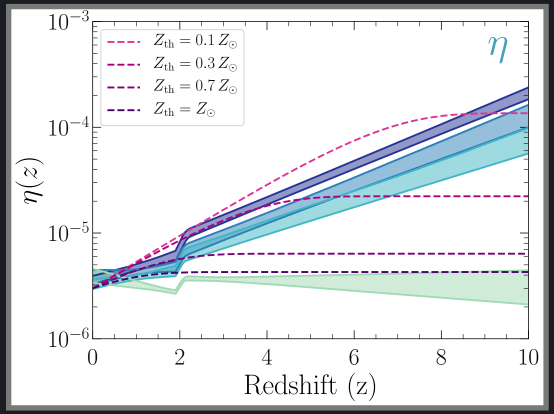
LGRB production efficiency

- Models suggest a higher production efficiency η at higher redshift
  (except for the case with strong luminosity evolution)

- Compare to the fraction of star-formation that occurs below a given metallicity threshold (Langer & Norman 2006)



Limitations



$$\dot{n}_{\rm LGRB}(z) = \eta(z)\,\dot{n}_{\rm cc}(z)$$

$$\dot{n}_{\rm cc}(z) \propto \dot{\rho}_*(z)$$

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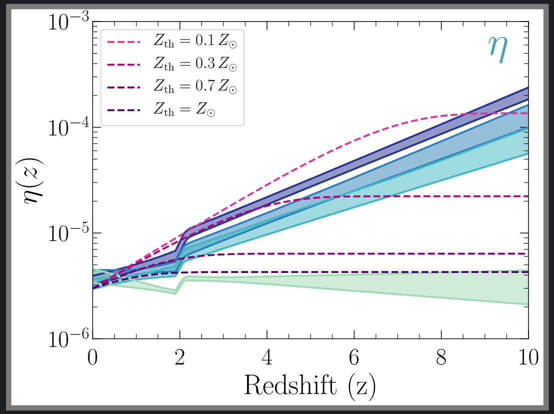

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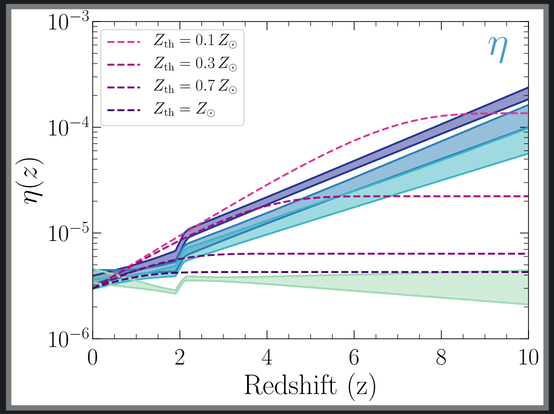
$$\dot{n}_{\rm cc}(z) = \boxed{\frac{p_{\rm cc}(z)}{\bar{m}(z)}}\dot{\rho}_*(z)$$

Number of core-collapses per unit of stellar mass produced

Limitations



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$$p_{\rm cc}(z) = \int_{m_{\rm cc}}^{m_{\rm sup}} I(m,z)\,{\rm d}m$$

$m_{\rm sup}$ → $100\,{\rm M}_\odot$

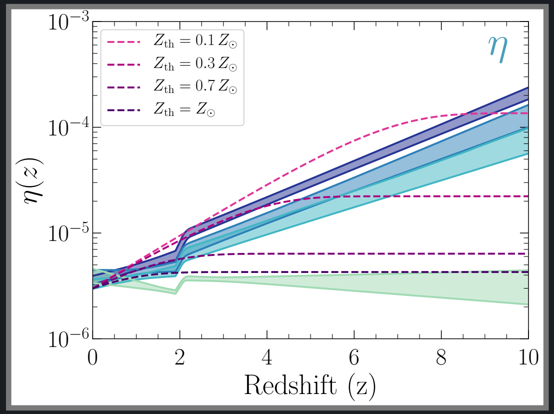
$m_{\rm cc}$ → $8\,{\rm M}_\odot$

$$\bar{m}(z) = \int_{m_{\rm inf}}^{m_{\rm sup}} m\,I(m,z)\,{\rm d}m$$

$m_{\rm sup}$ → $100\,{\rm M}_\odot$

$m_{\rm inf}$ → $0.1\,{\rm M}_\odot$

Limitations



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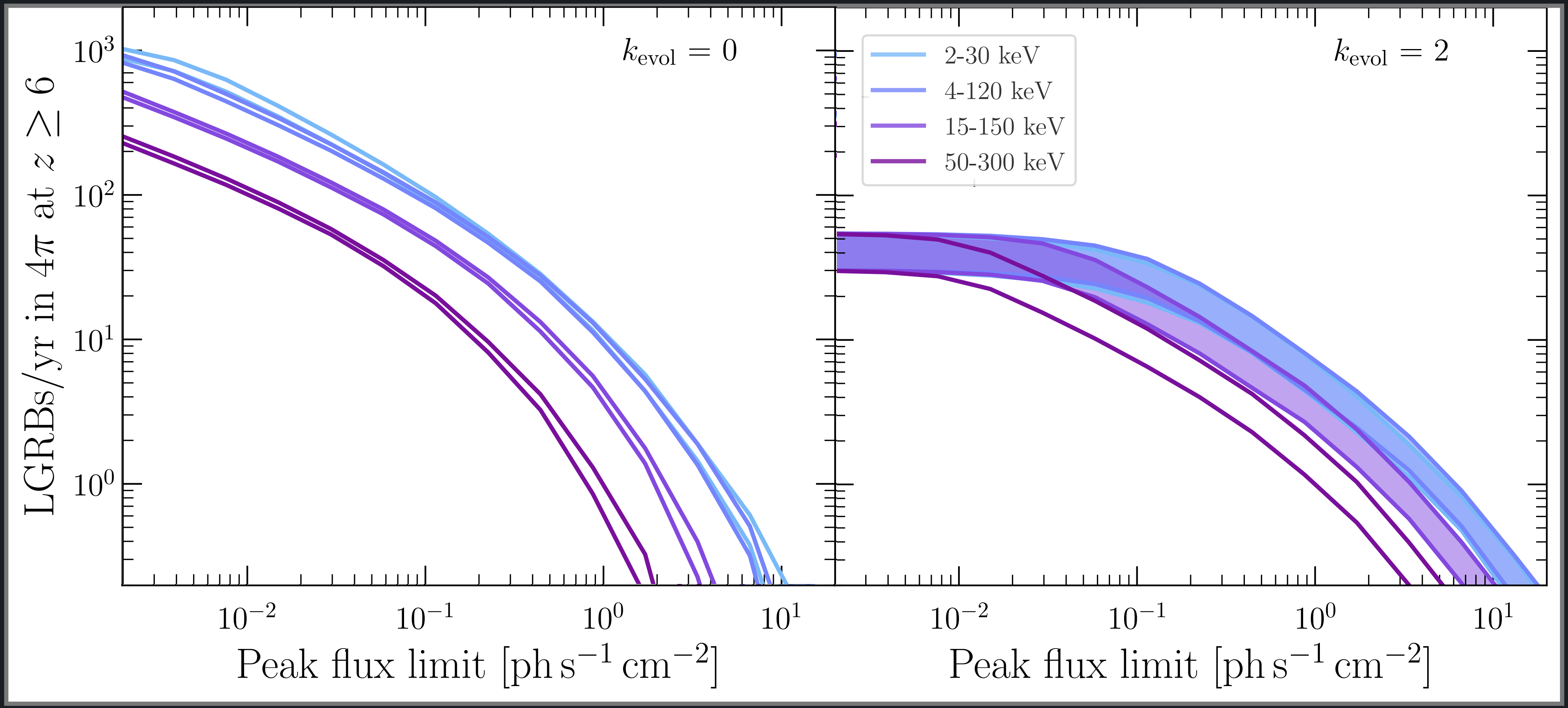
➡ Some evolution (but not all) could be due to the evolution of the IMF

High z LGRB rate



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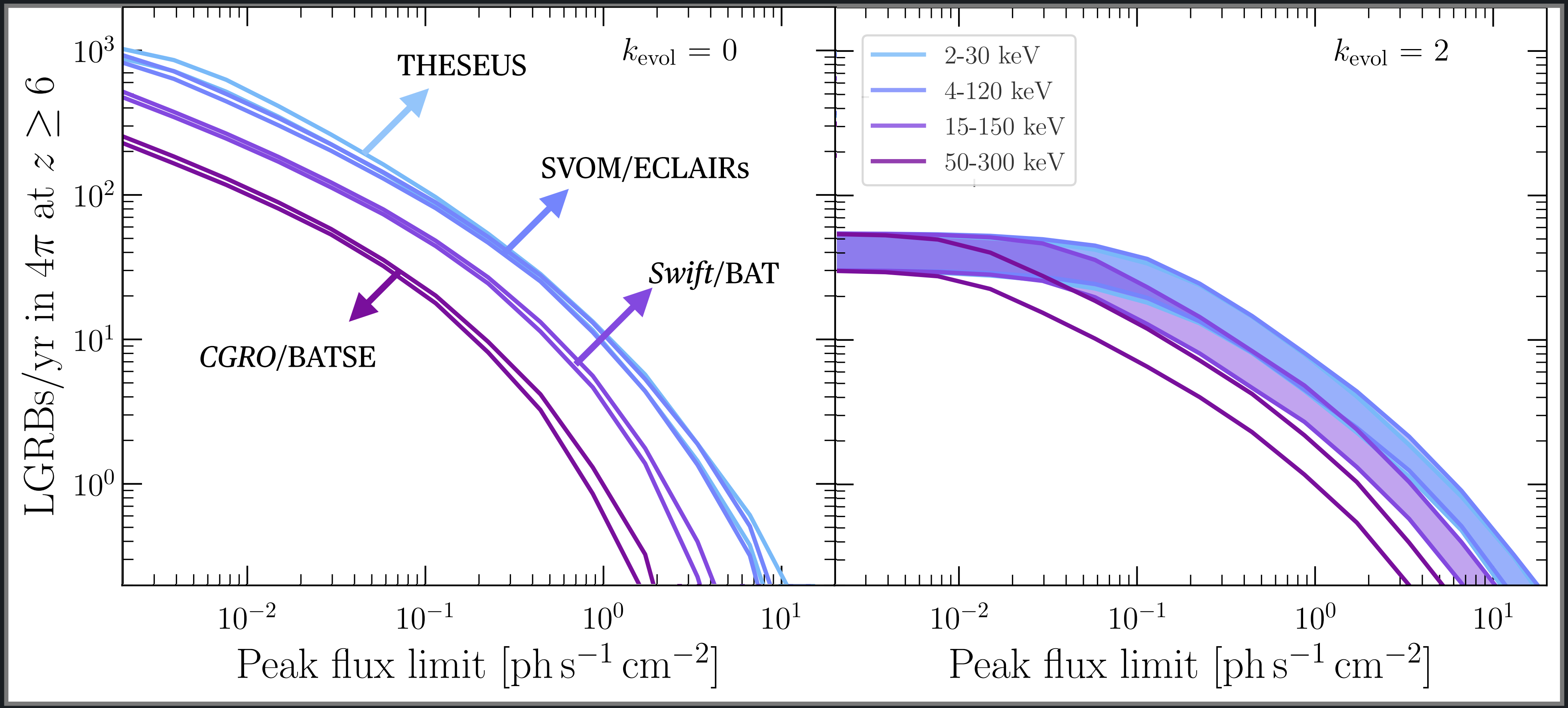
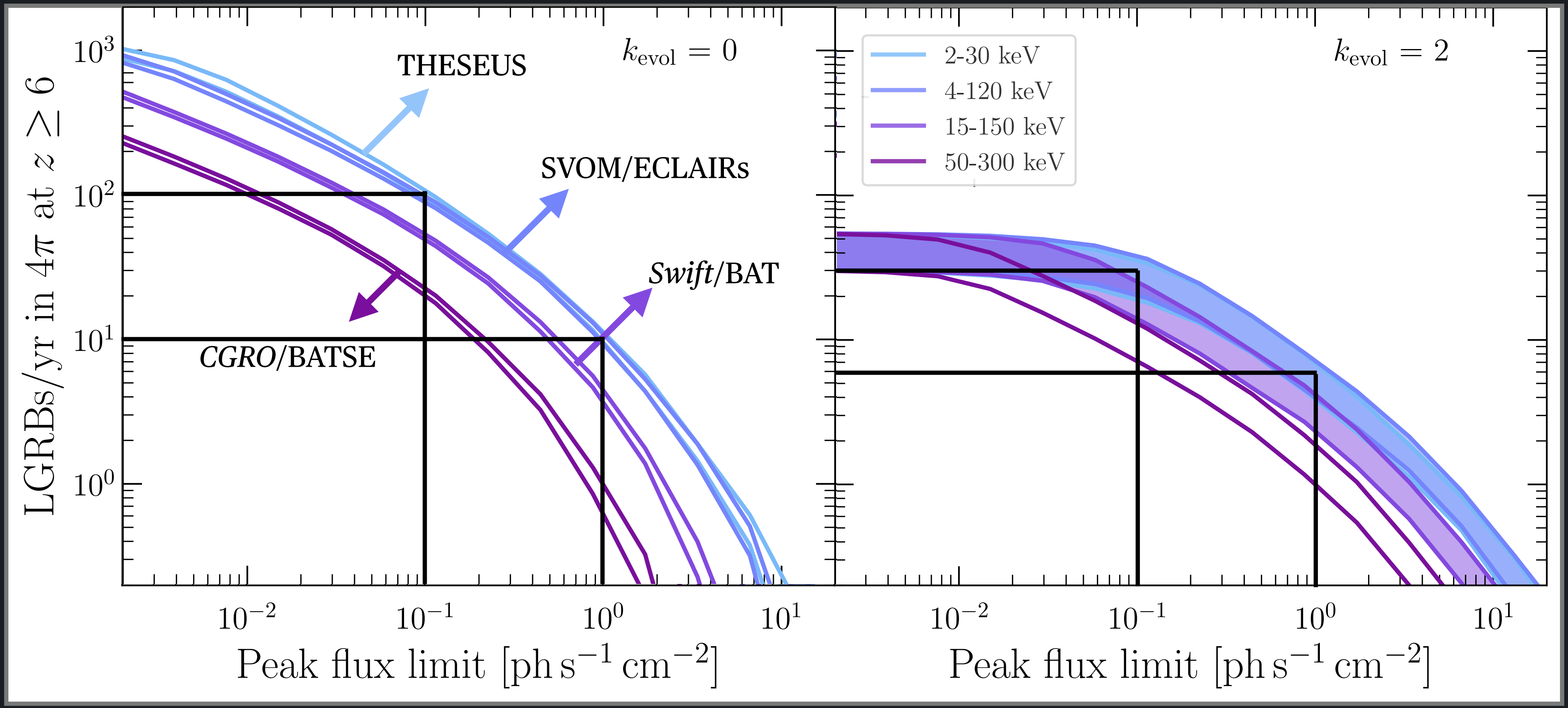


High z LGRB rate

- Number of LGRB per year in whole sky at $z > 6$:

Limiting peak flux (4-120 keV)	1 ph/s/cm²	0.1 ph/s/cm²
Optimist ($k_{evol} = 0$)	~ 10	~ 100
Pessimist ($k_{evol} = 2$)	6^{+1}_{-2}	30^{+20}_{-10}



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Factors driving production efficiency

- To determine the main factors driving the LGRB production efficiency we can statistically study their environment (i.e. their host galaxies)
- We must pay careful attention to selection to avoid biases and ensure high completeness
- Our sample: BAT6 (Salvaterra+12) with a selection on peak flux of γ-ray prompt emission and unbiasing favorable observing conditions* (Jakobsson+06)

➡ 58 LGRBs with 97% redshift completeness extends up to $z = 6$

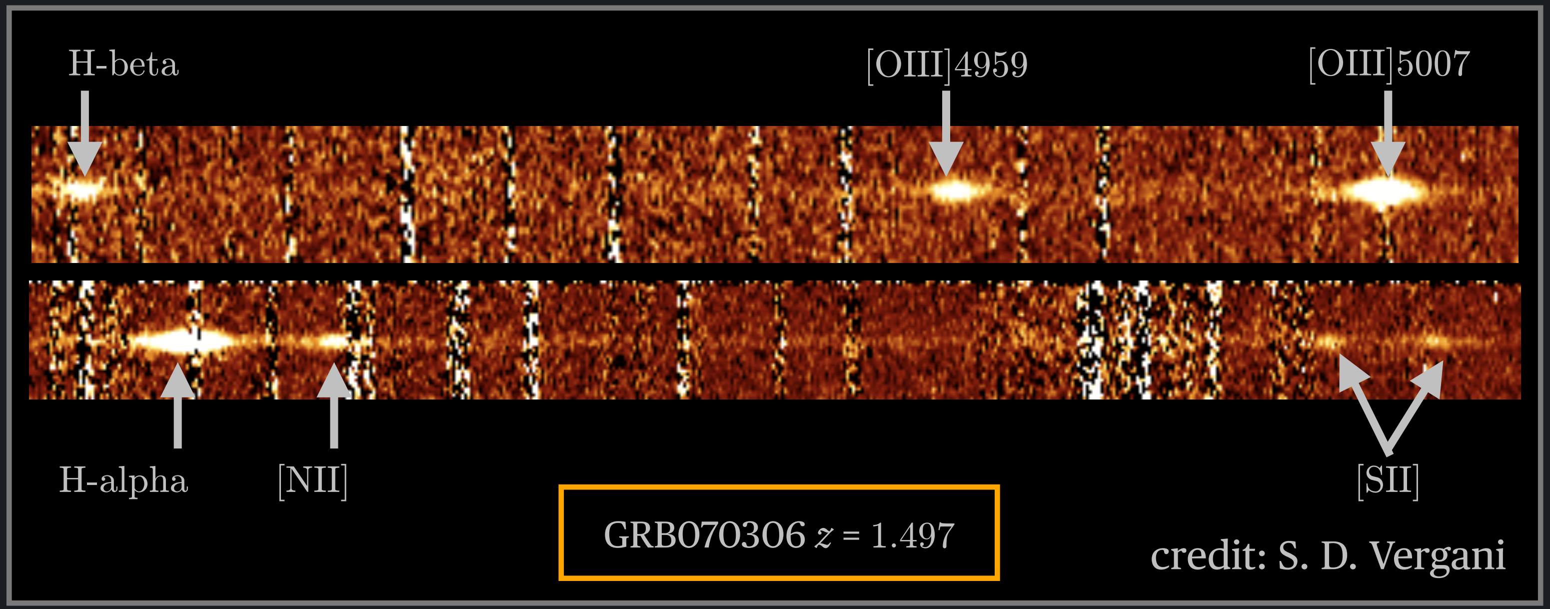
➡ We study the host galaxies of these LGRBs up to $z = 2$ (N=28)

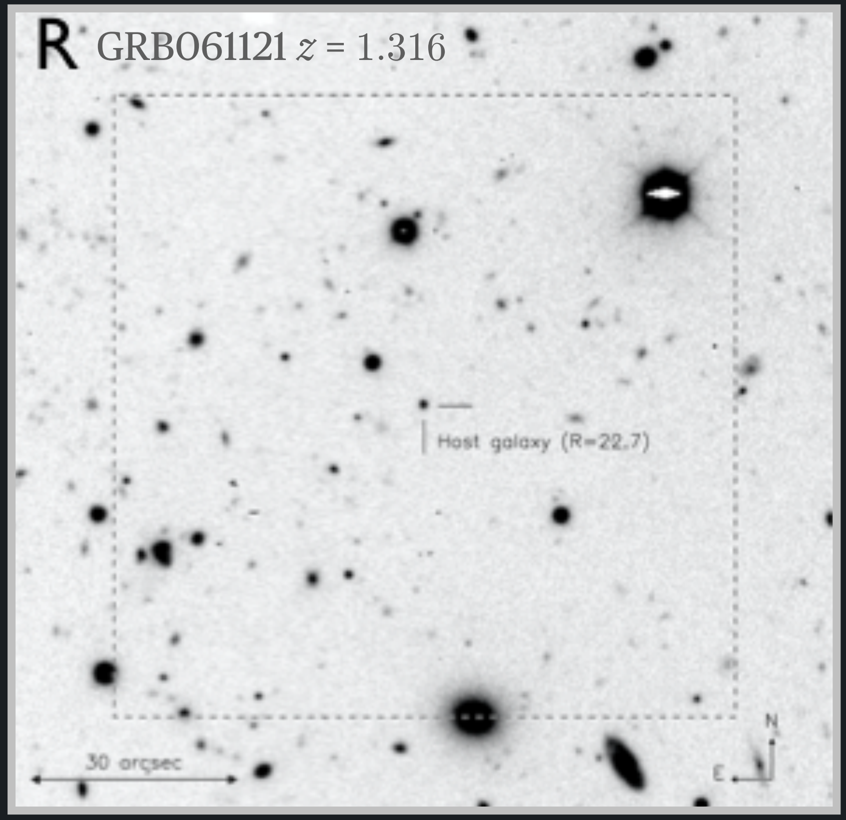
➡ Hosts are not selected according to their flux and thus unbiased

*see backup slide

LGRB hosts sample

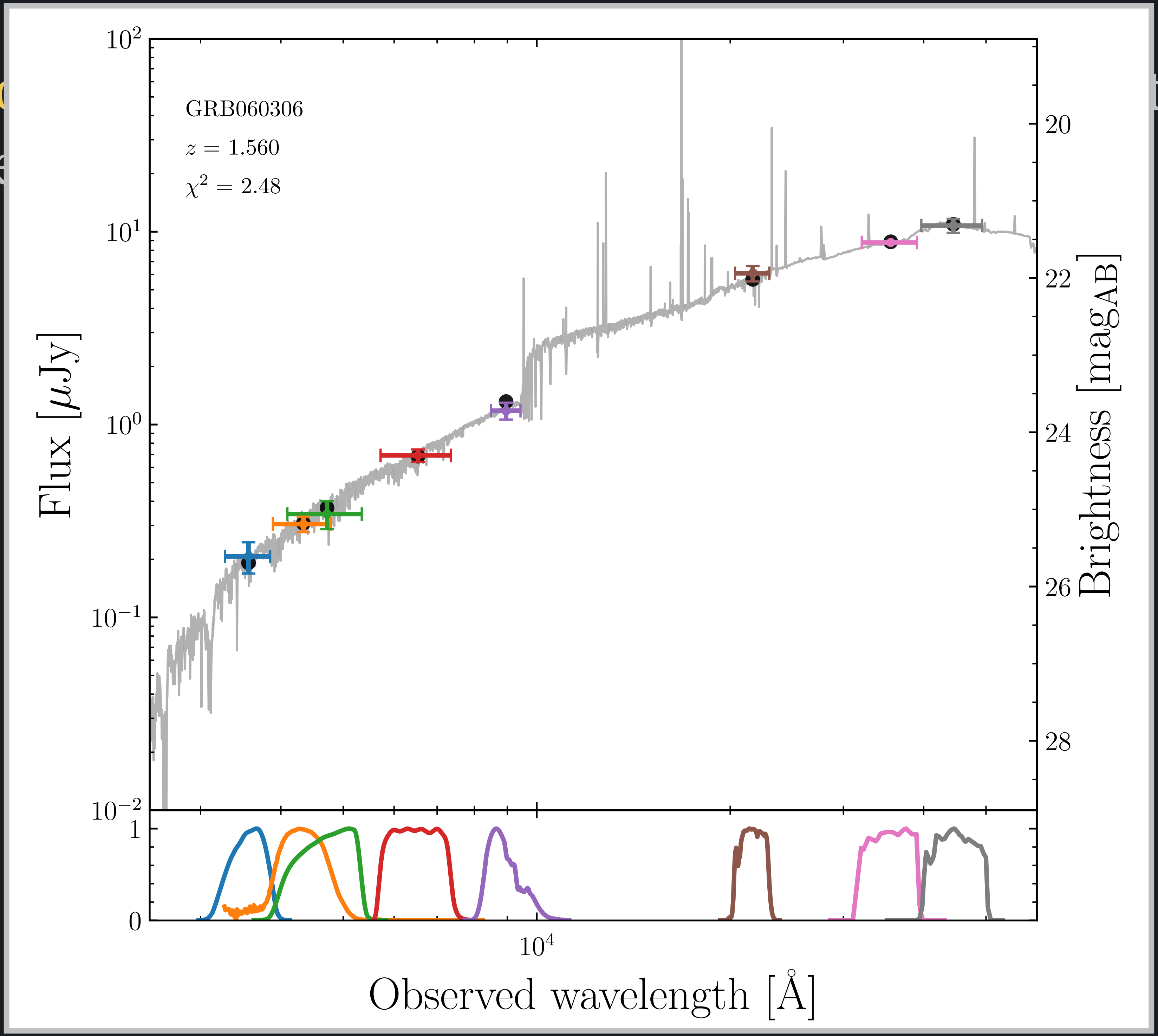
- Deep medium resolution spectra and photometry for all 28 hosts to characterize their properties:





LGRB hosts sample

- Deep medium reso[...]ts to characterize the[...]
  - Stellar mass



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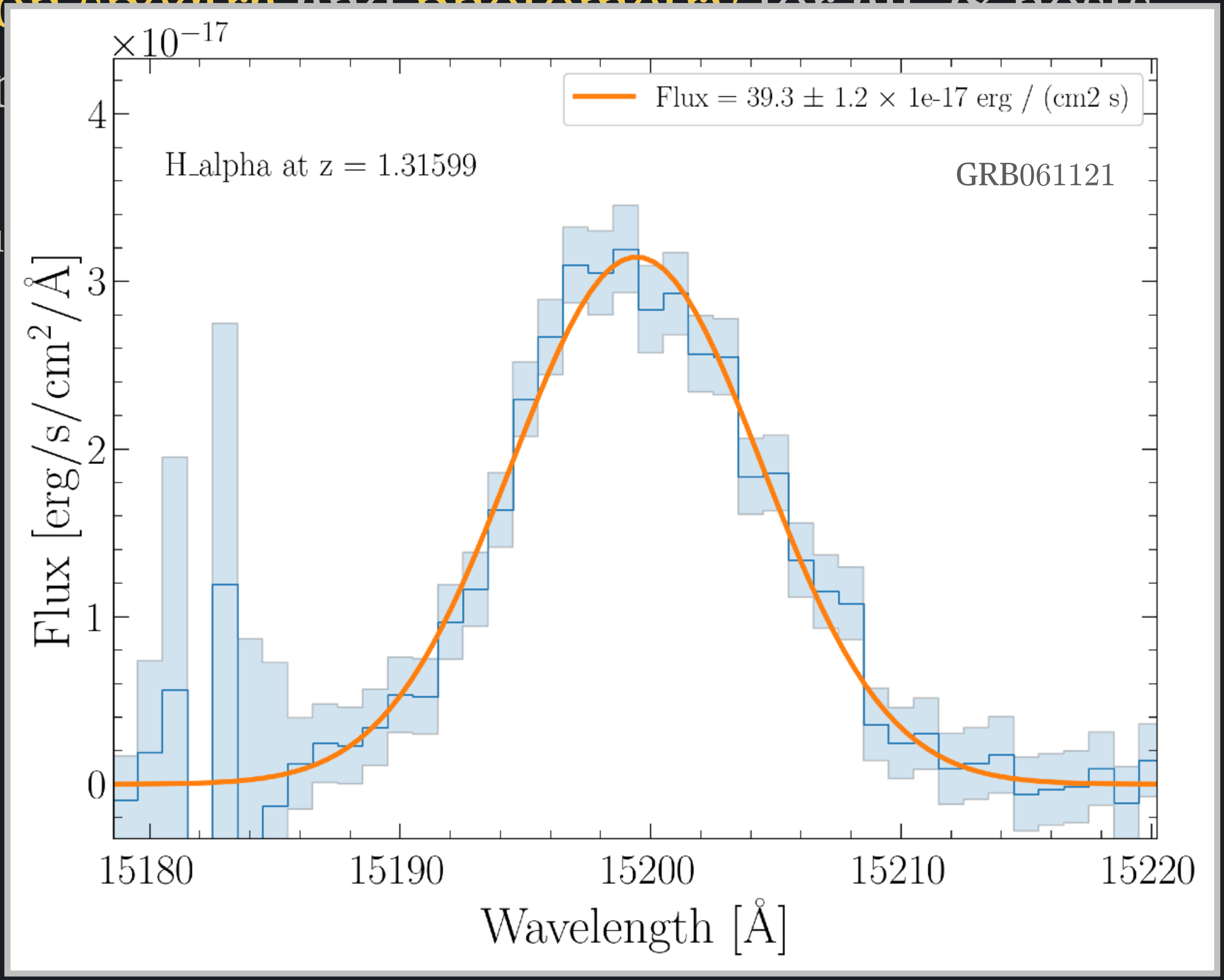

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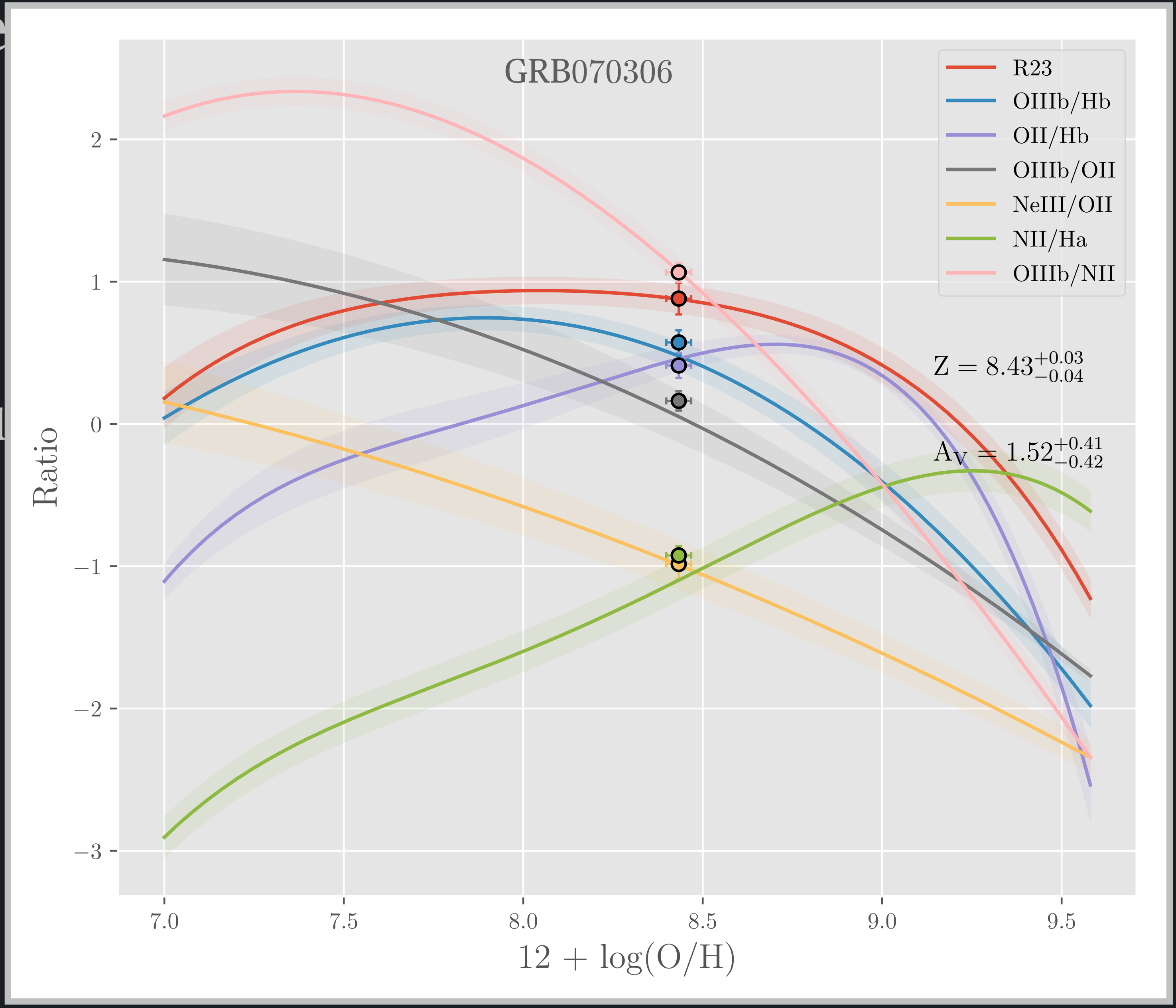
  - Star formation rate (from d

  - Metallicities



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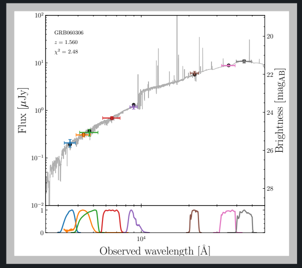
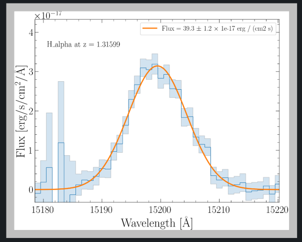
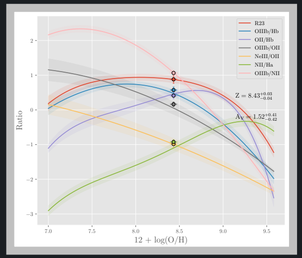


  - Star formation rate (from dust-corrected Hα)



  - Metallicities (from strong-line ratios)



Comparison sample

- MOSFIRE Deep Evolution Field (MOSDEF) is a deep ($H \leq 24$) near-infrared spectroscopic survey at medium z

Kriek+15
Shivaei+15
Sanders+18

- 133 galaxies at $1.37 < z < 1.7$, with rest-frame optical emission lines

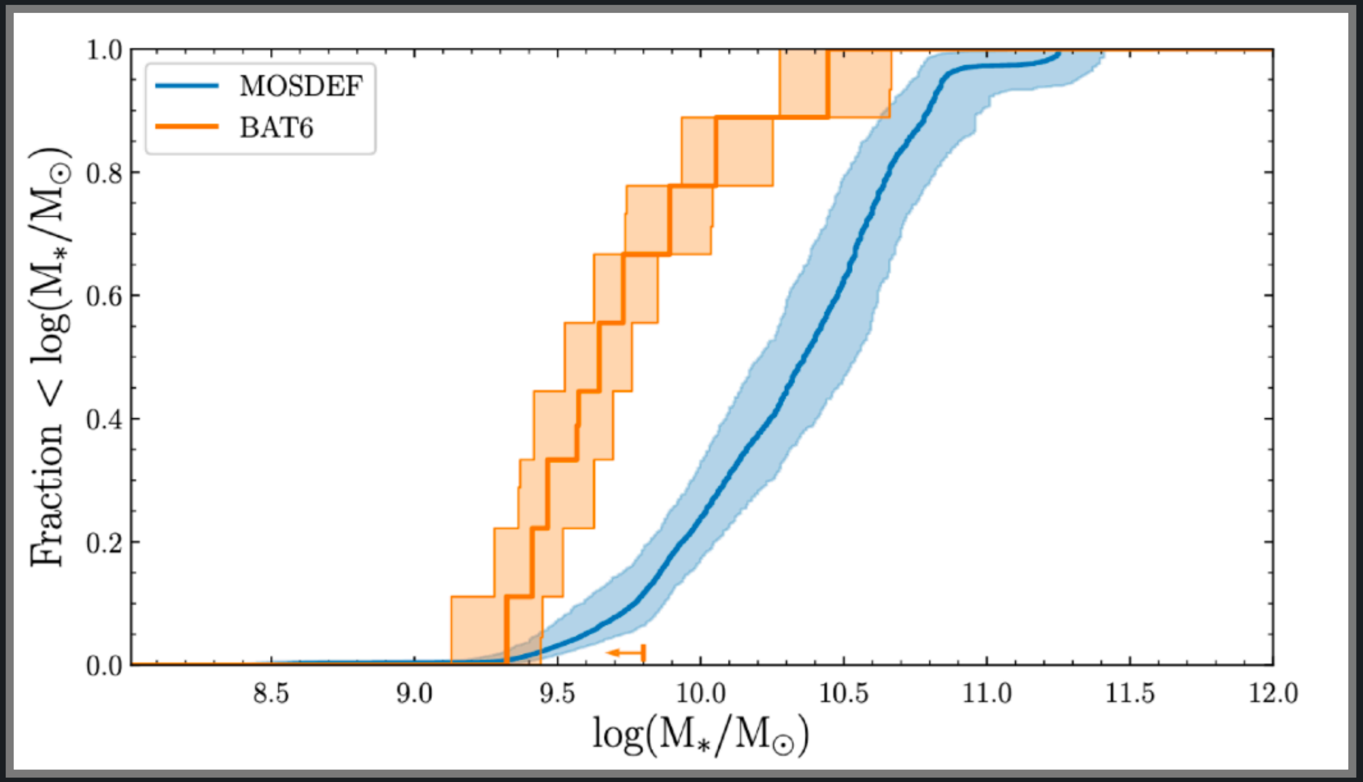
Image Credit: Ethan Tweedie

Methodology

- Similar redshift range
- Same cosmology
- Same stellar mass completeness
- Same stellar Initial Mass Function (IMF) for determining the stellar mass and SFR (Chabrier+03)
- Same SFR diagnostic (dust-corrected Hα)
- Same strong-line ratios to determine the metallicity (Maiolino+08) (using [OII]3727; [OIII]4059,5007; Balmer lines; [NII]6583)

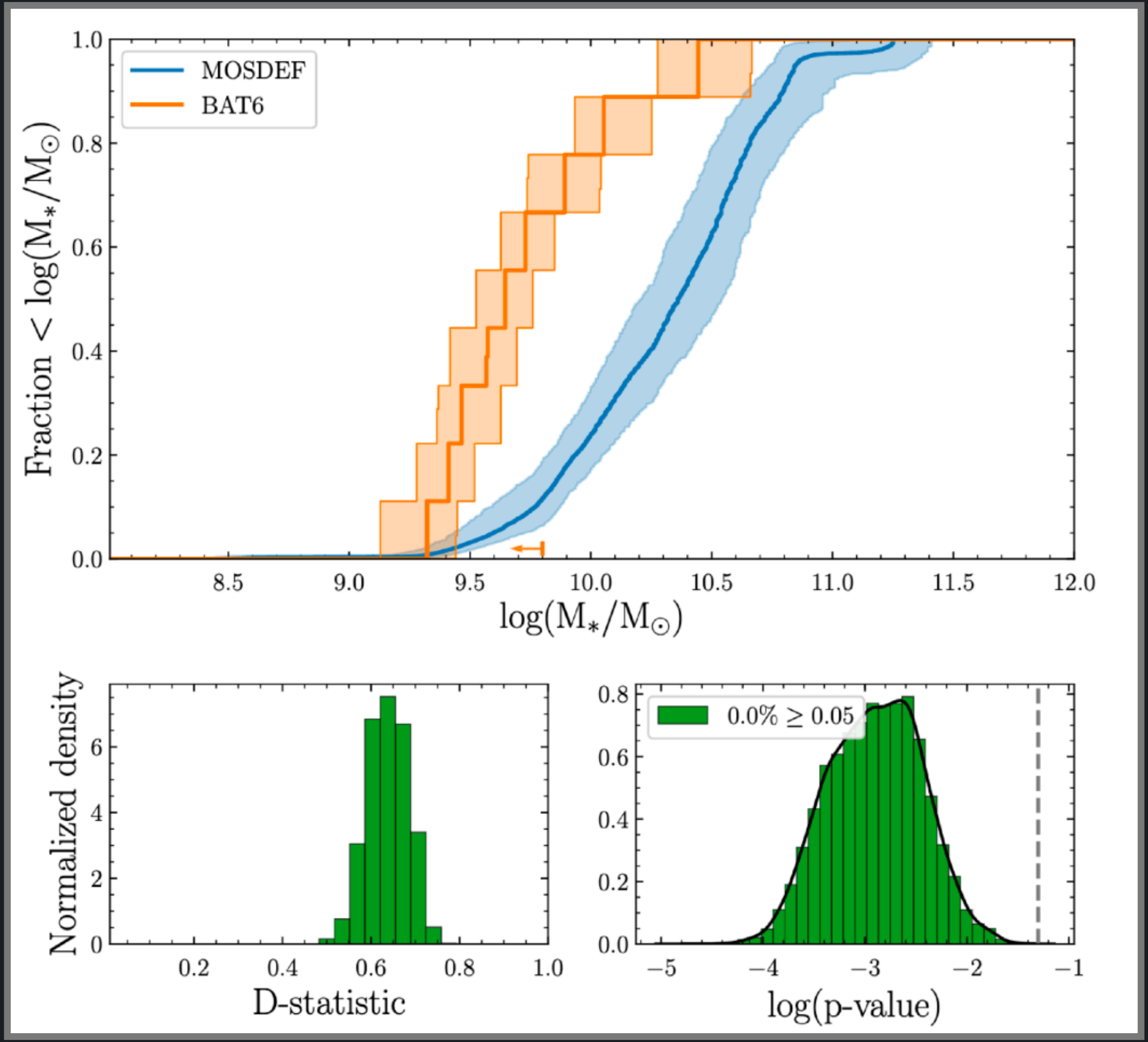
Results at $1 < z < 2$

- Compared CDF of LGRB hosts to SFR-weighted CDF of typical star-forming galaxies



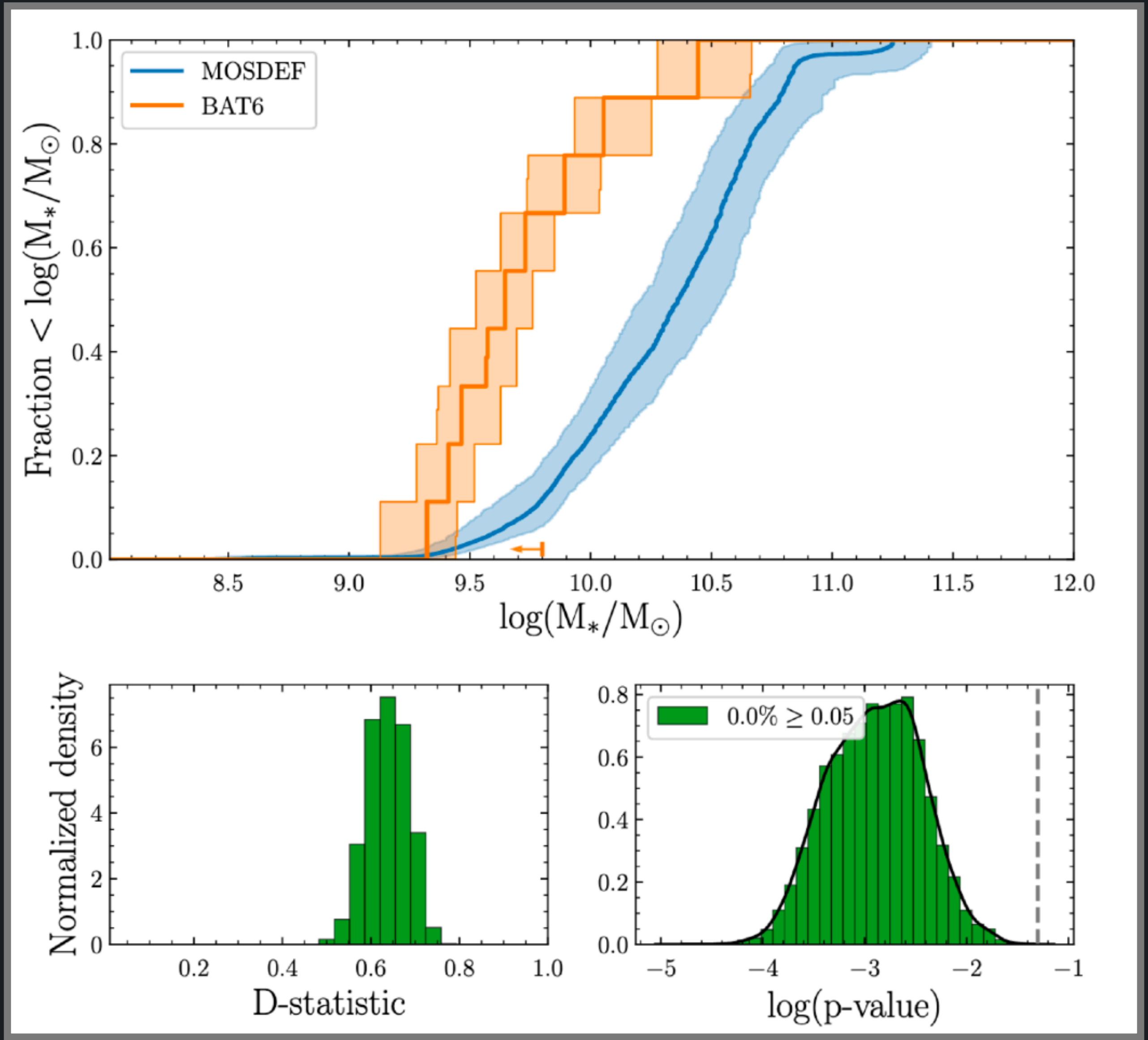
Results at $1 < z < 2$

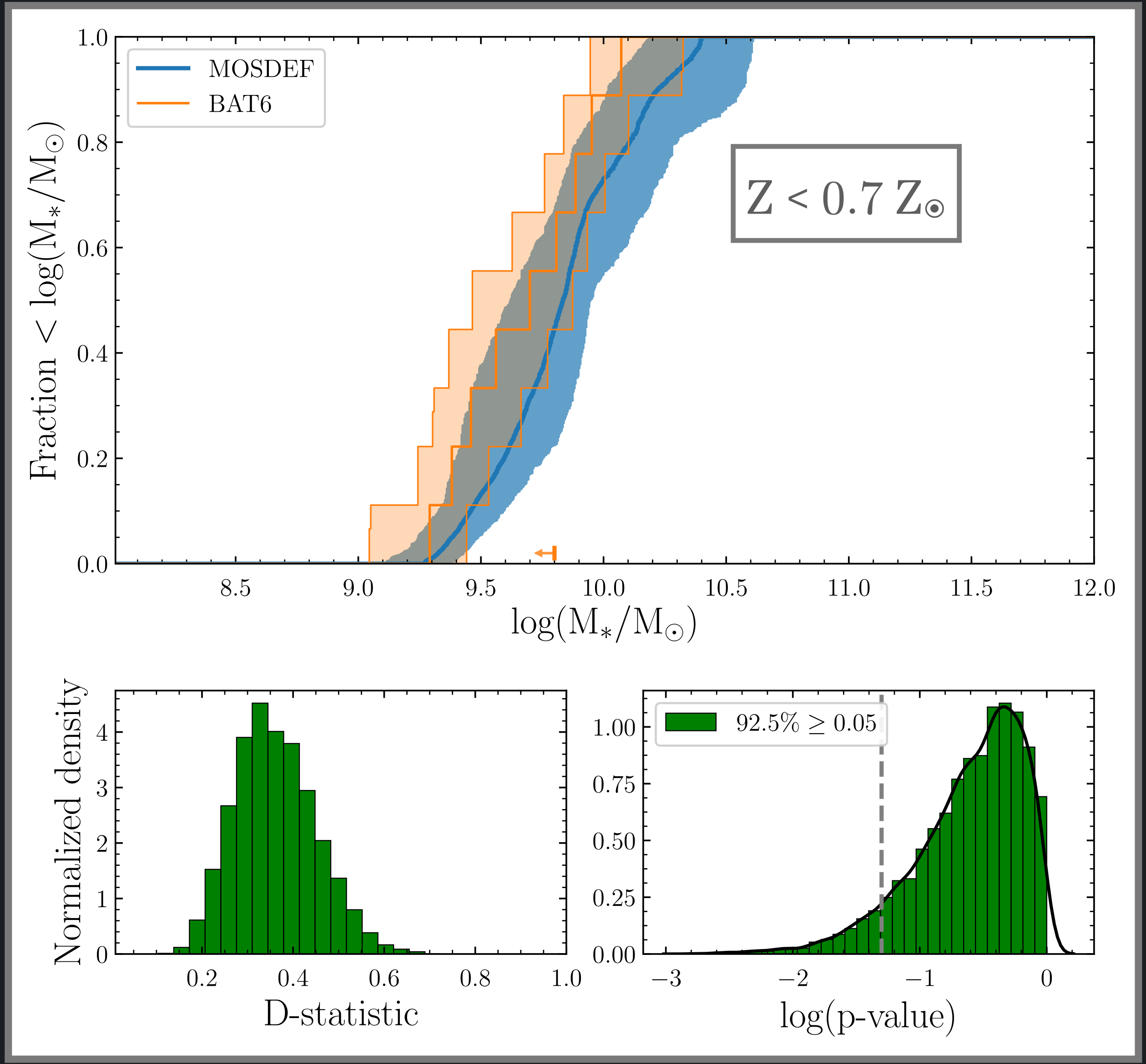
- Bayesian approach coupled with Monte Carlo sampling to take into account measurement uncertainty



Results at $1 < z < 2$

- Metallicity is a driving factor of the LGRB production efficiency
  (Kruehler+15, Japelj+16, Perley+16)





Conclusions

- LGRBs are not direct tracers of star formation at $z < 2$
- Applying a metallicity cut of 70% solar resolves the discrepancy implying metallicity is a driving factor behind the LGRB efficiency
- We therefore expect LGRBs to trace SF at $z > 3\text{-}4$
- Interpreted in the context of LGRB progenitors, the metallicity threshold is higher than expected from single star models ($Z < 0.7\ Z_\odot$ vs $Z < 0.2\ Z_\odot$)

  ➡ Binary star LGRB progenitor? Multiple channels?

Discussion

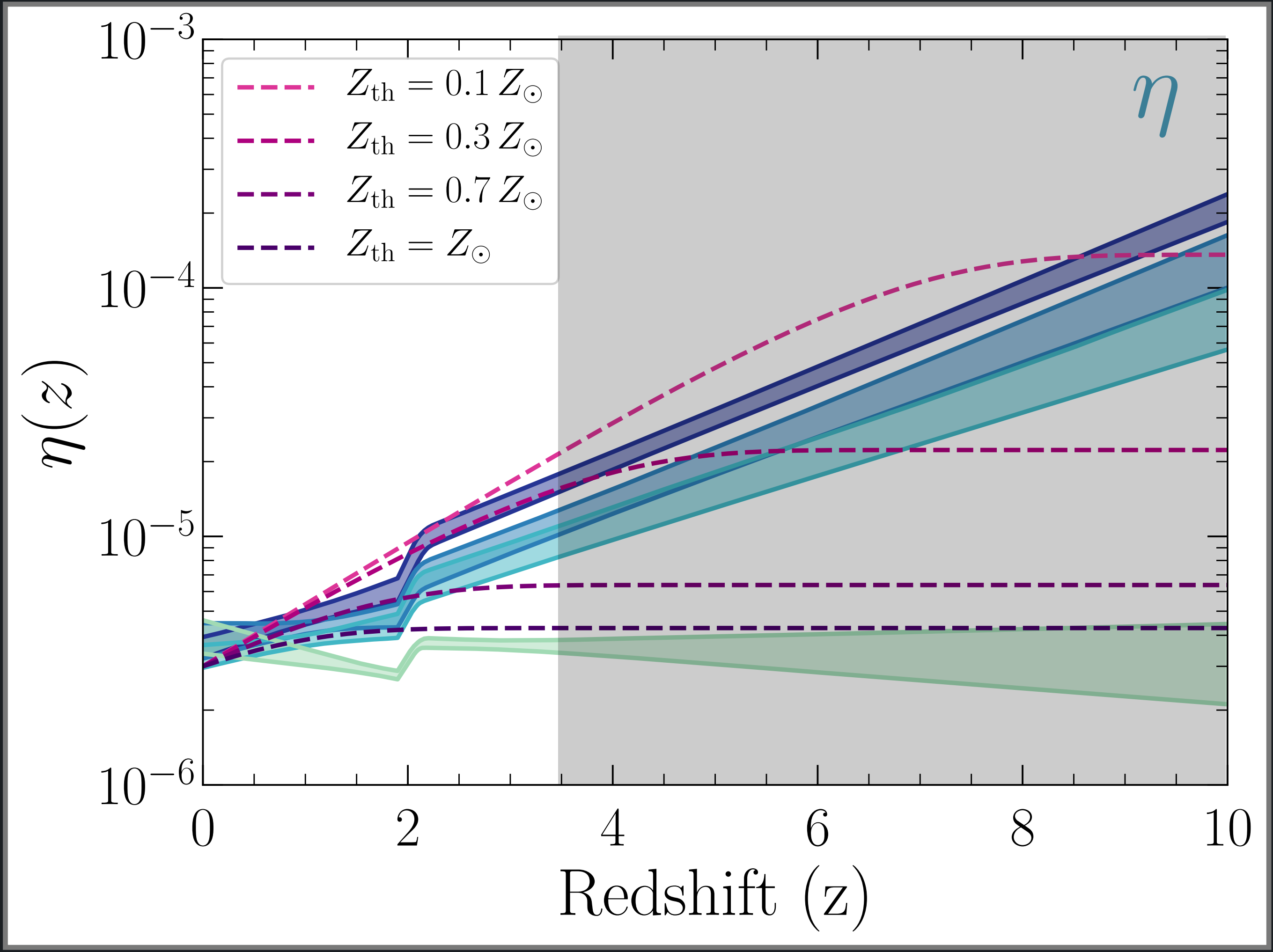
- There is uncertainty on strong line calibrators absolute metallicity values (dependence on photoionisation models)
- Oxygen measured and Z obtained by assuming solar scaling
- Fe is driver of winds for WR in single star progenitor models. Young galaxies with [O/Fe] > 0.5 could reconcile high metallicity threshold
  (Hashimoto+18)

➡ Absolute metallicity threshold ($Z < 0.7\ Z_\odot$) is uncertain

➡ BUT same methodology means robust results for metallicity being driving factor of the LGRB efficiency

Discussion

- Discrepancy at $z > 3$-4 with metallicity as driver of production efficiency
- Redshift distribution of intrinsic population requires additional break?
  (hard to constrain with current samples/datasets)
- Other factors become dominant at this redshift?
  (sSFR, binarity, initial rotation…)
- IMF evolution?
- Underestimating cosmic SFRD?



Summary

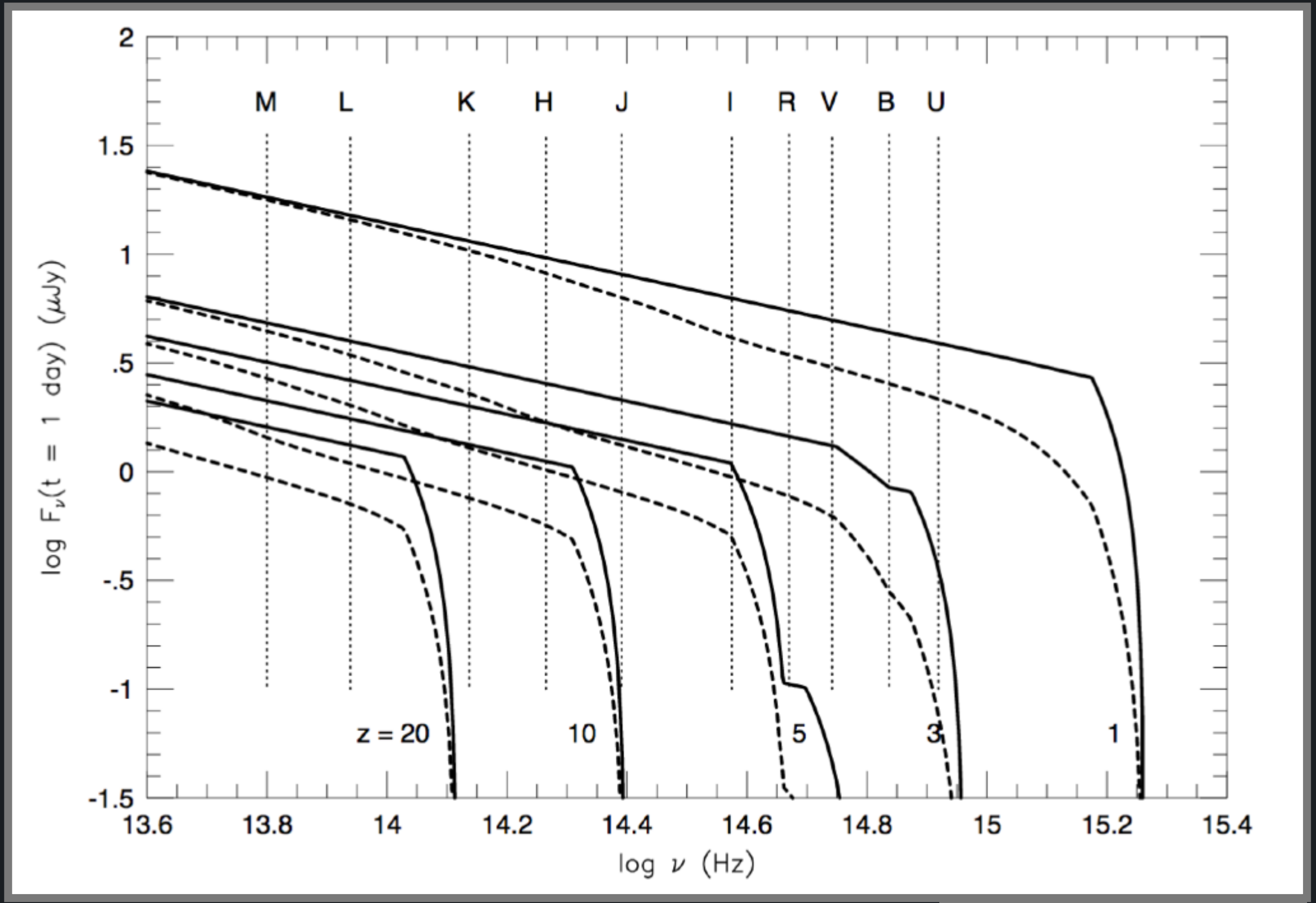
- GRBs are powerful unique probes of the Universe, up to high redshift
- If we want to go beyond case-by-case studies, we need large-enough, unbiased, complete statistical samples. This is **hard** and requires well-designed, efficient follow-up (SVOM is expected to help)
- Rate of high redshift LGRBs remains uncertain because of degeneracies with the evolution of the luminosity function (SVOM, THESEUS?)
- LGRB production efficiency seems to evolve with redshift and (at least) at $z < 2$, metallicity is its main driving factor
- If this holds at higher z and other factors don't play a significant role, LGRB rate could be used to estimate the SFR at these redshifts

Extra slides

Benefit of fading at high z

Observing 1 day after the prompt emission on Earth corresponds to, in the source frame:

- 6h if the source is at $z = 3$
- 2h if the source is at $z = 10$



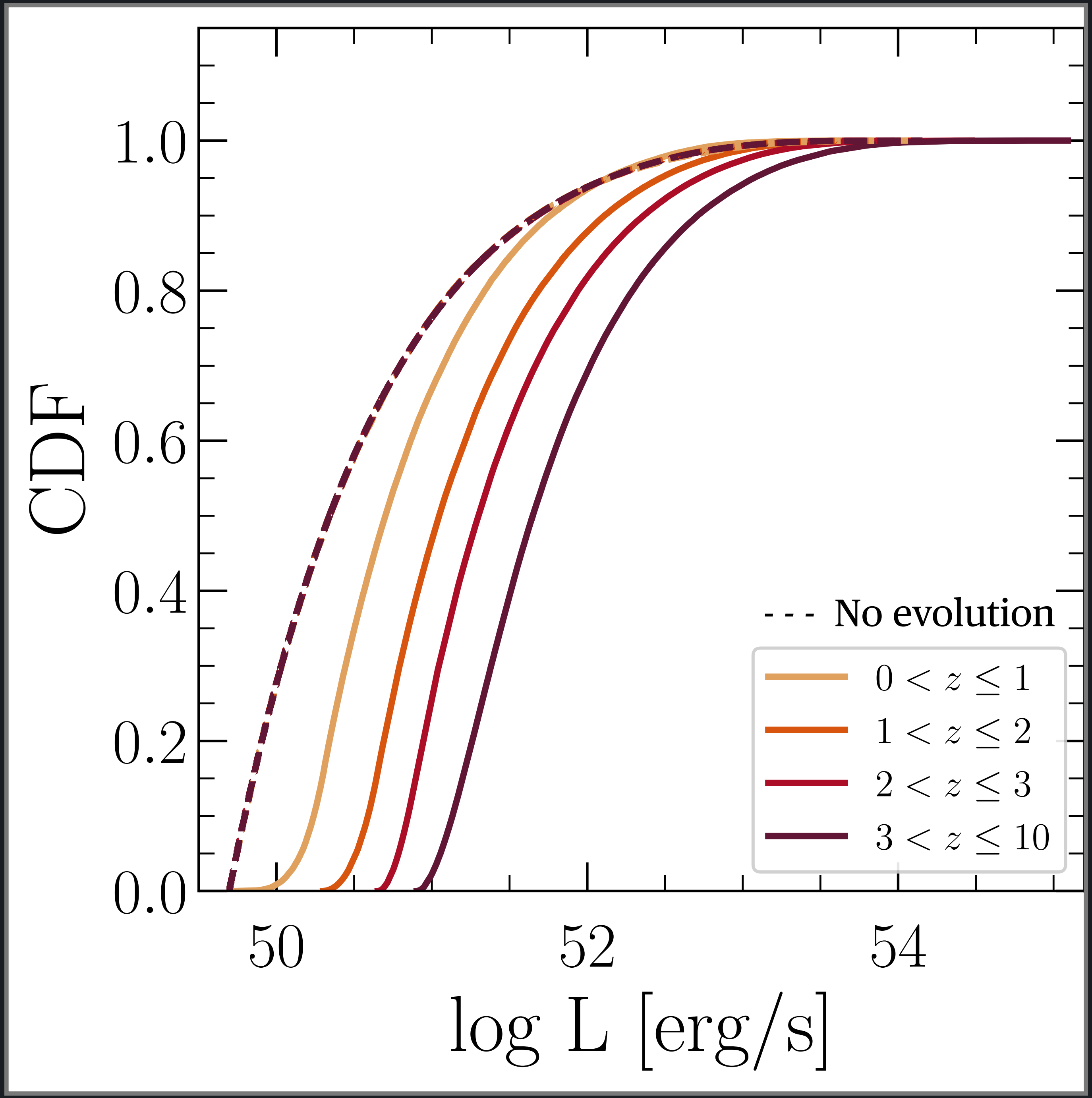
Lamb & Reichart+00

We are therefore catching the afterglow earlier in its light curve (and thus brighter since it is fading) as redshift increases

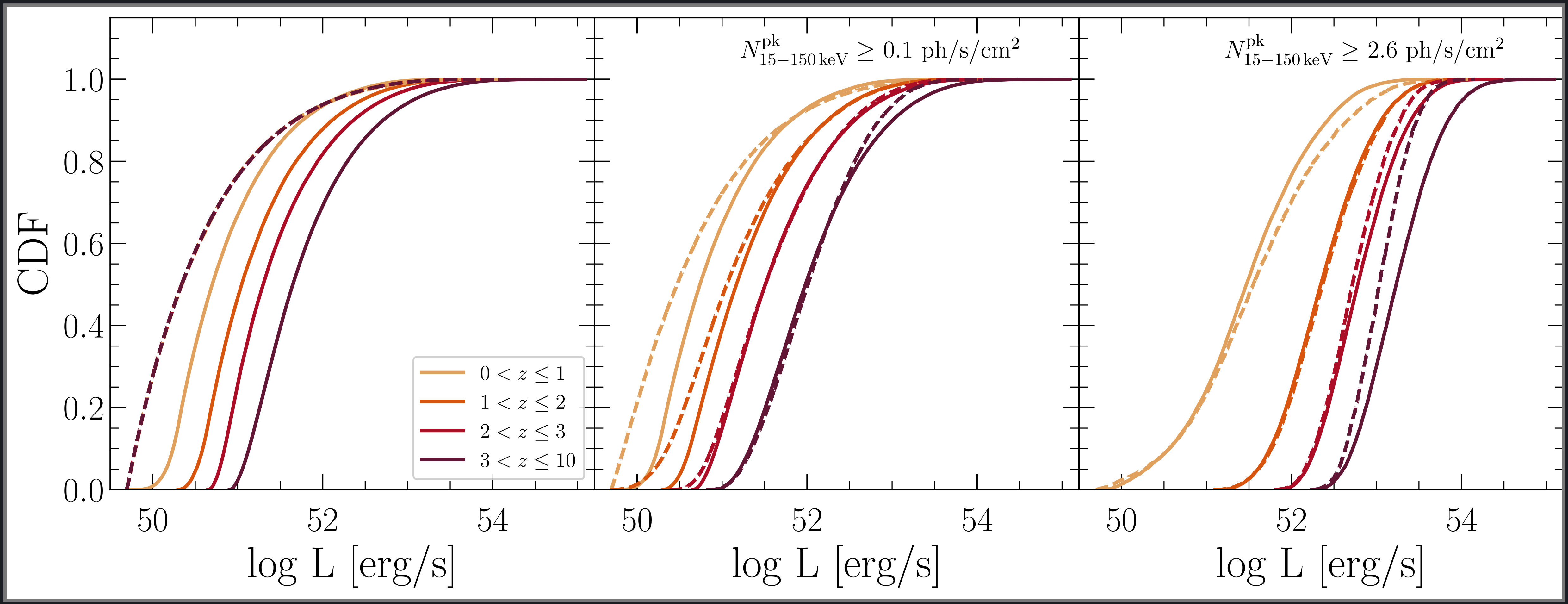
This almost compensates cosmological dimming

Population model extras

Separating into z bins

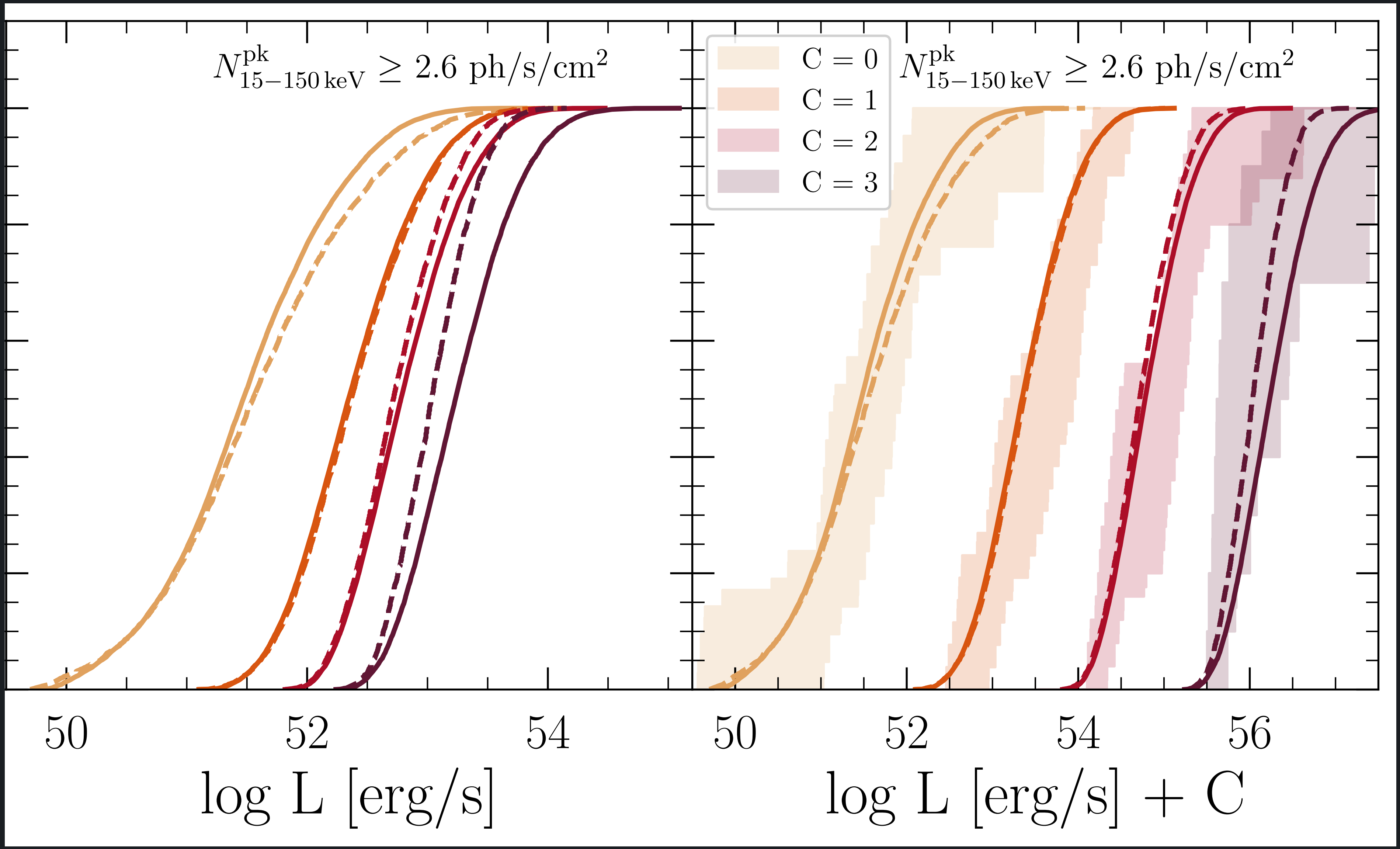


Separating into z bins

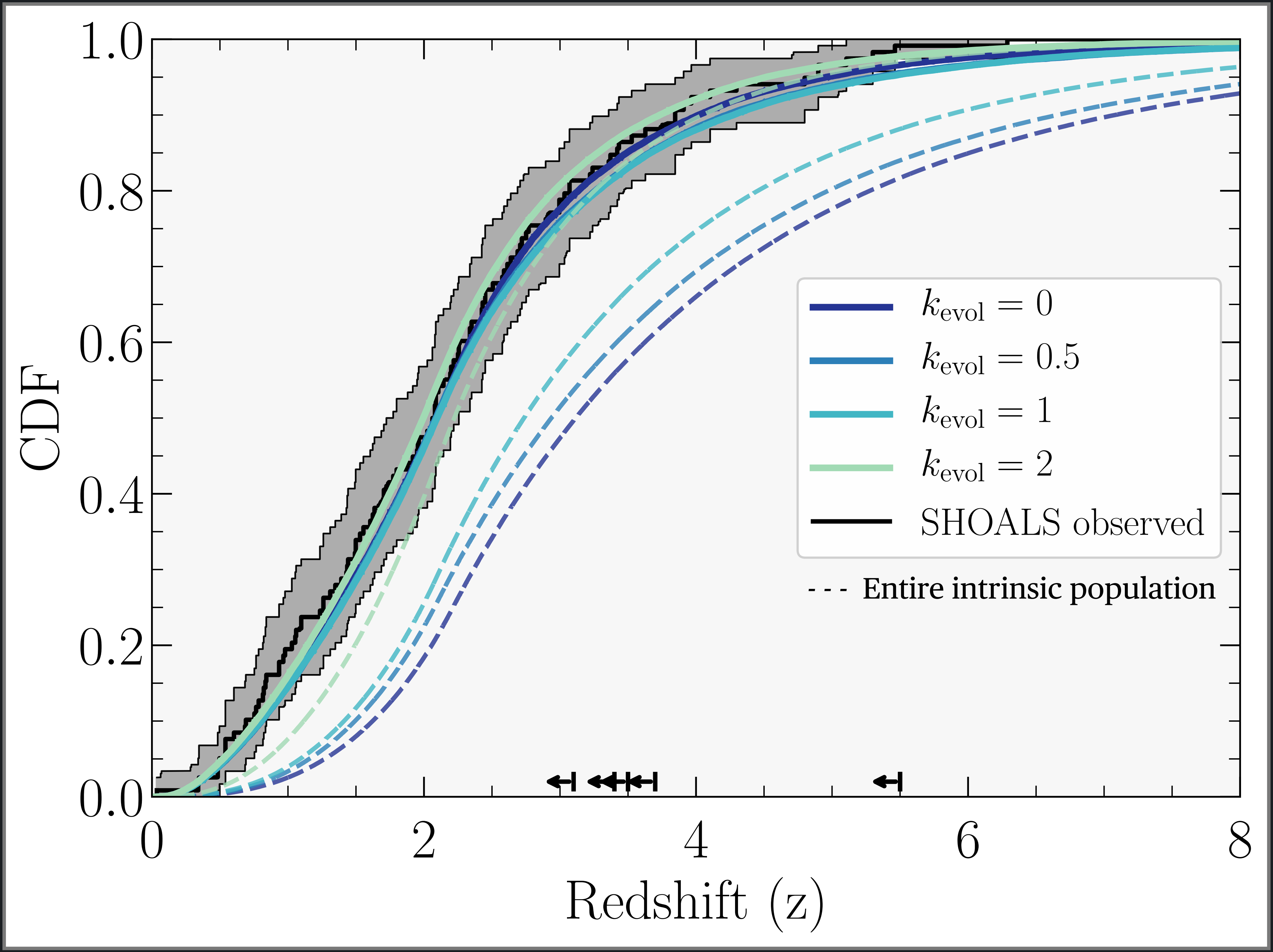


Peak flux/fluence cut mimics the effect of luminosity evolution

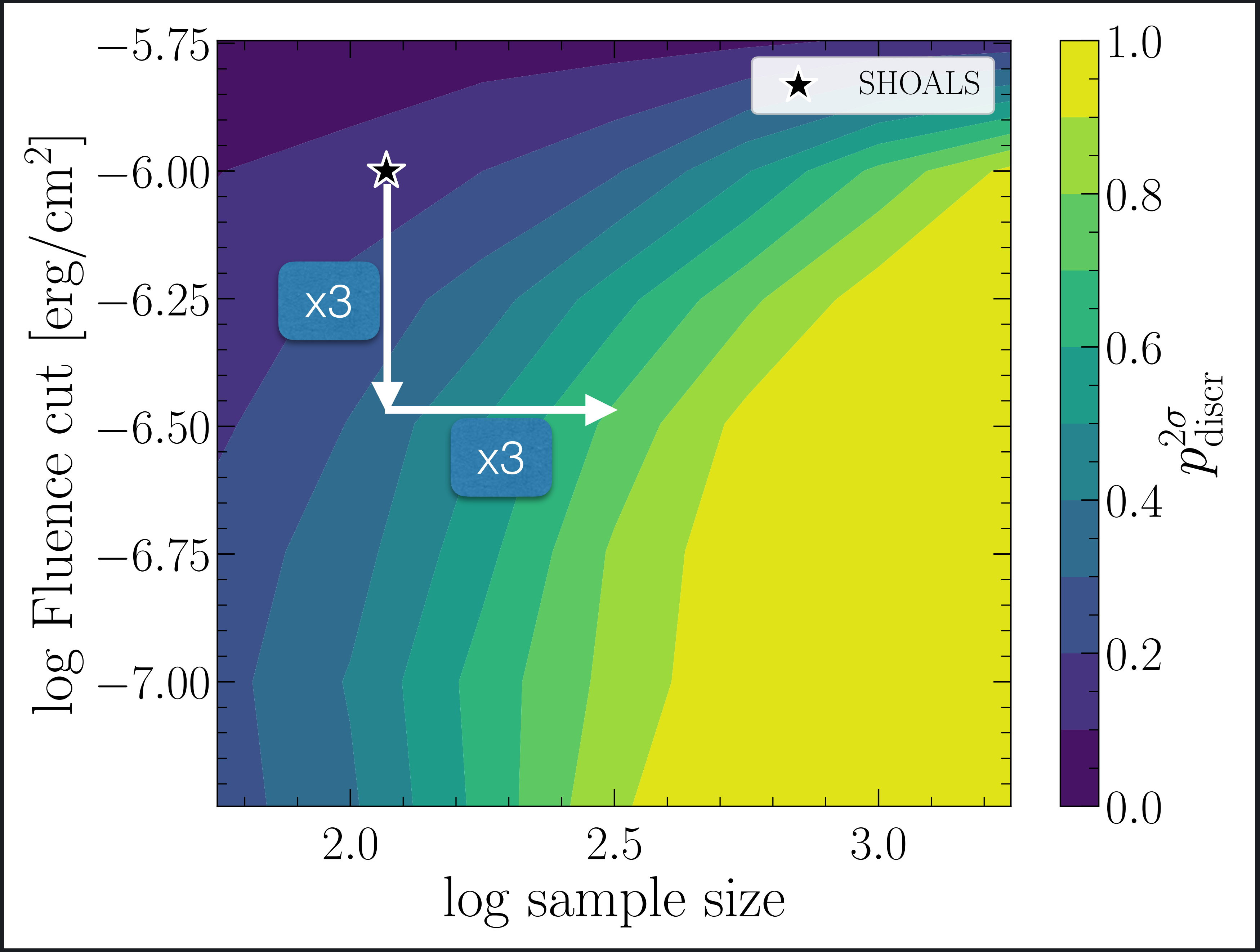
Separating into z bins



Using SHOALS

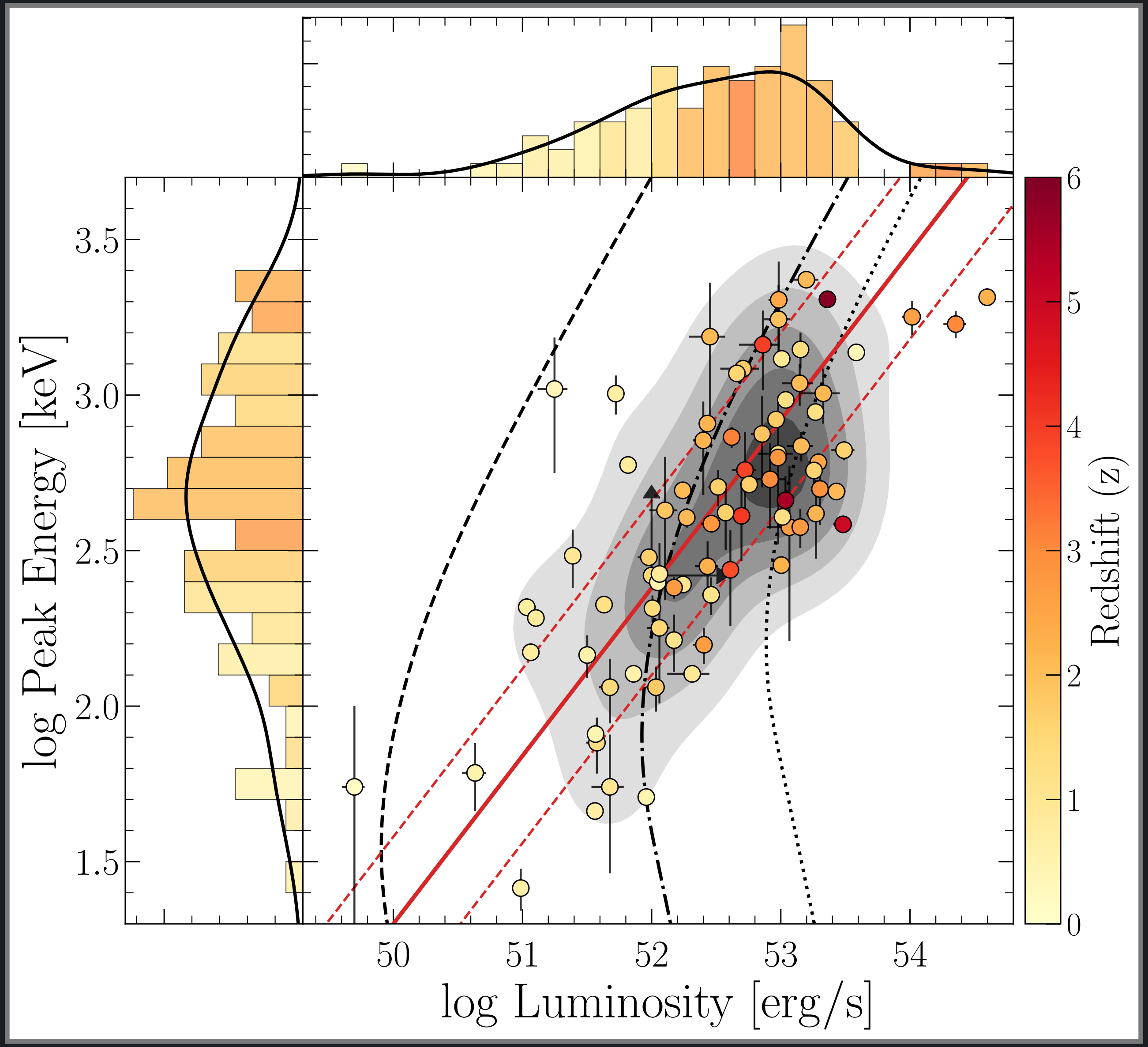


How to lift the degeneracy?



Spectral correlations

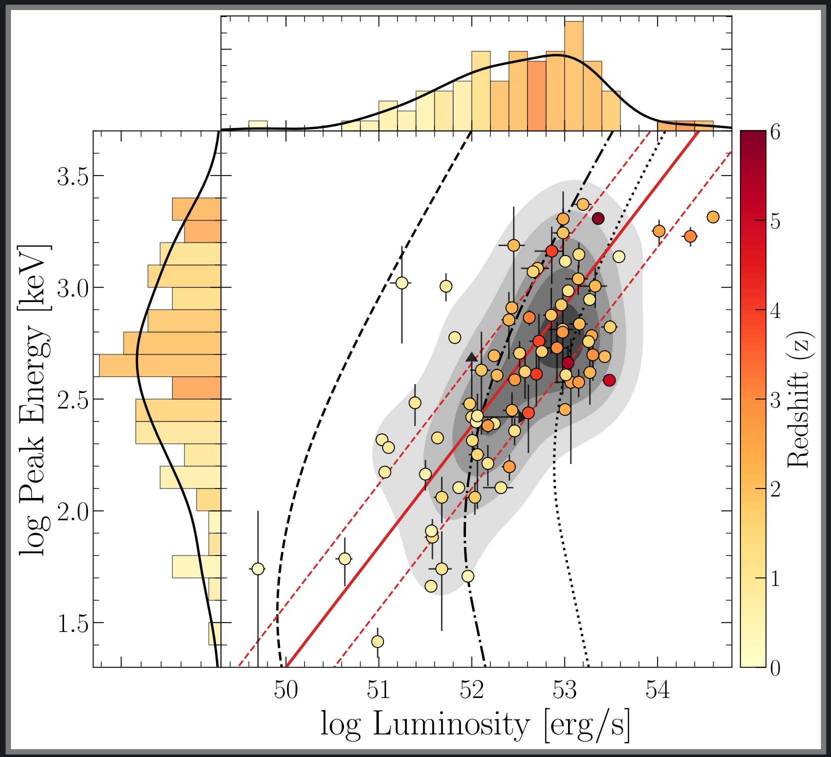
eBAT6 observed Ep - L plane



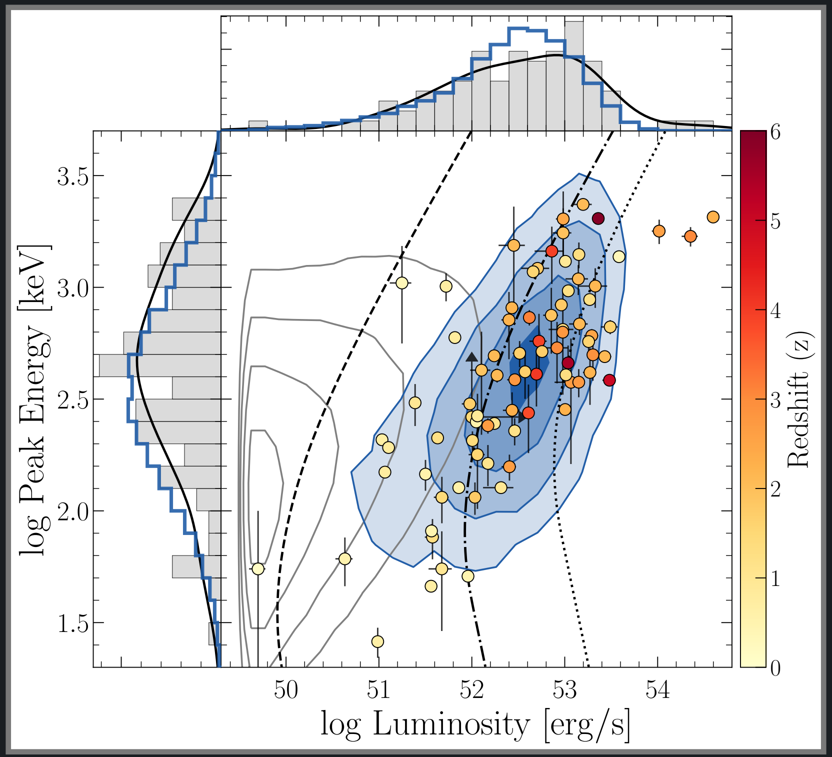
Spectral correlations

Mock eBAT6 predicted Ep - L plane

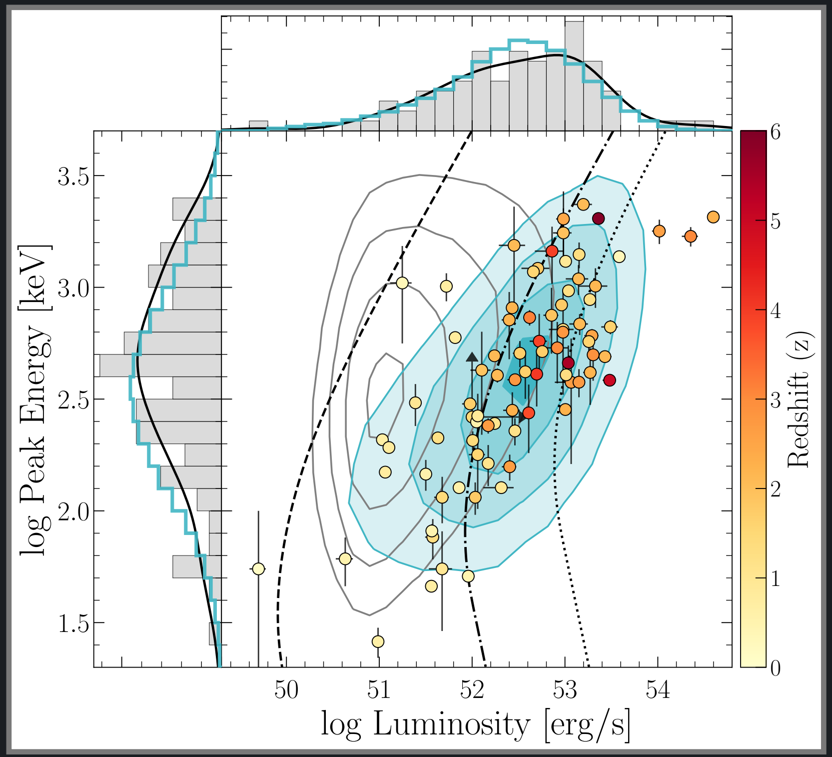
Observed



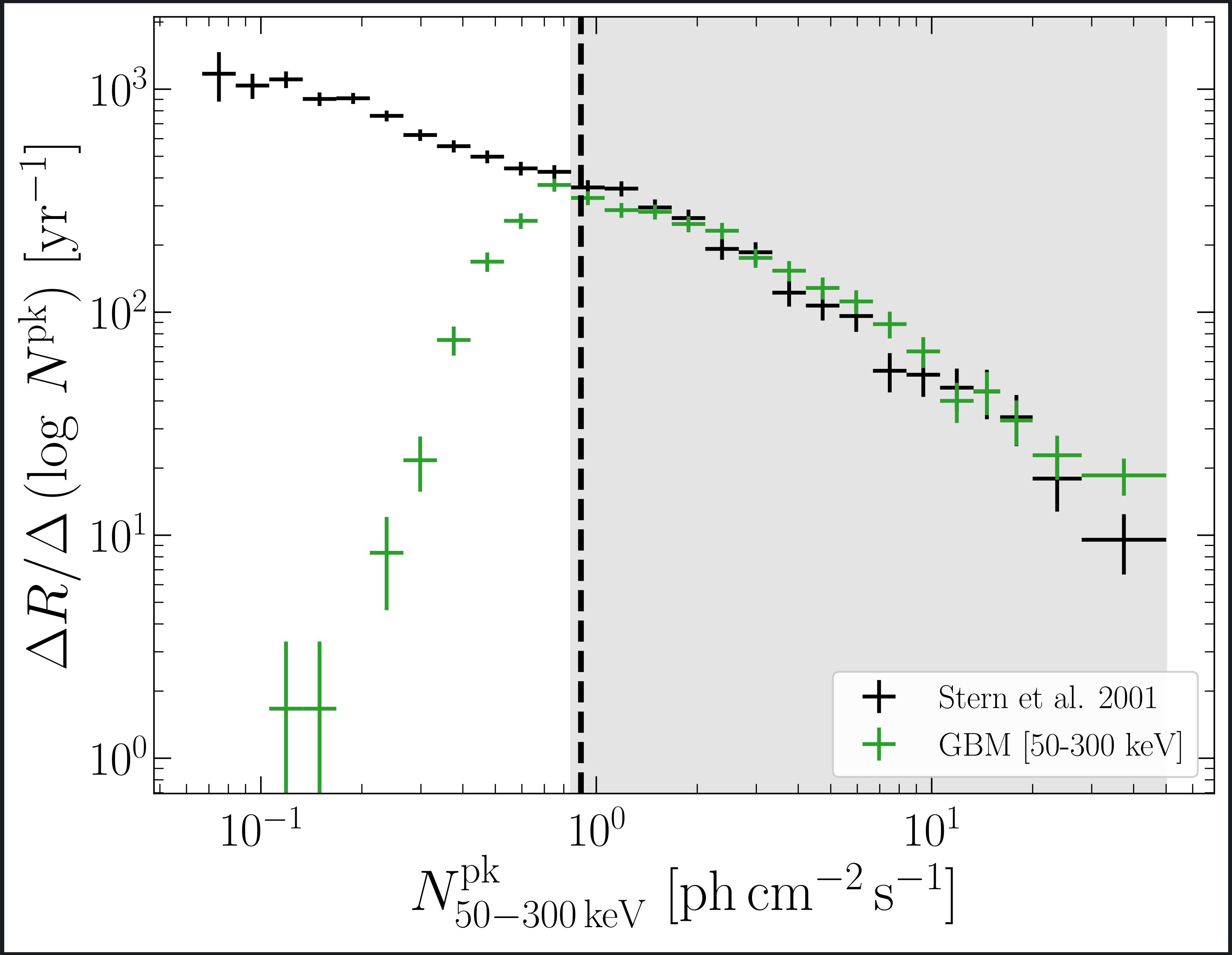
$k_{\mathrm{evol}} = 0$



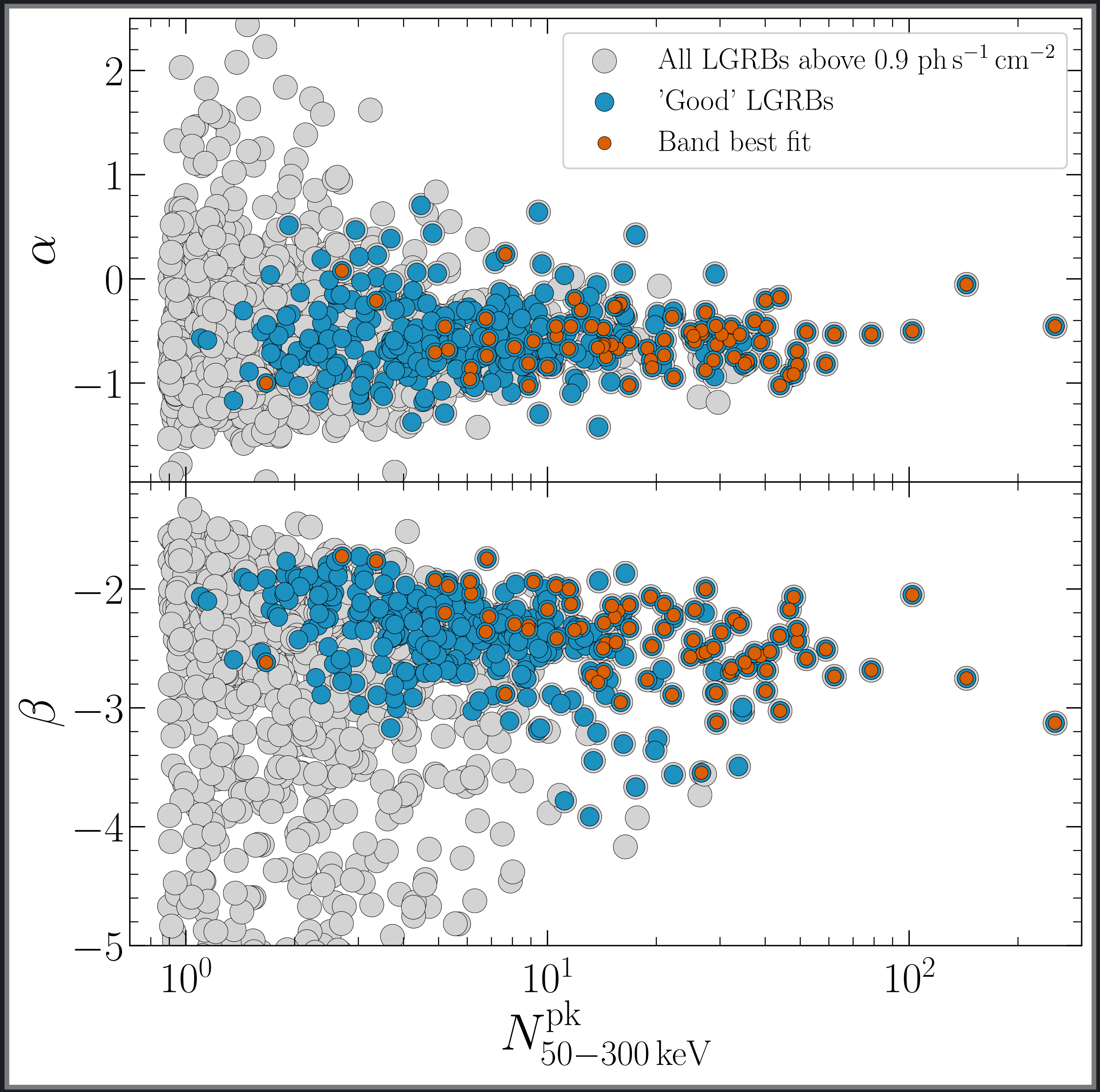
$k_{\mathrm{evol}} = 2$

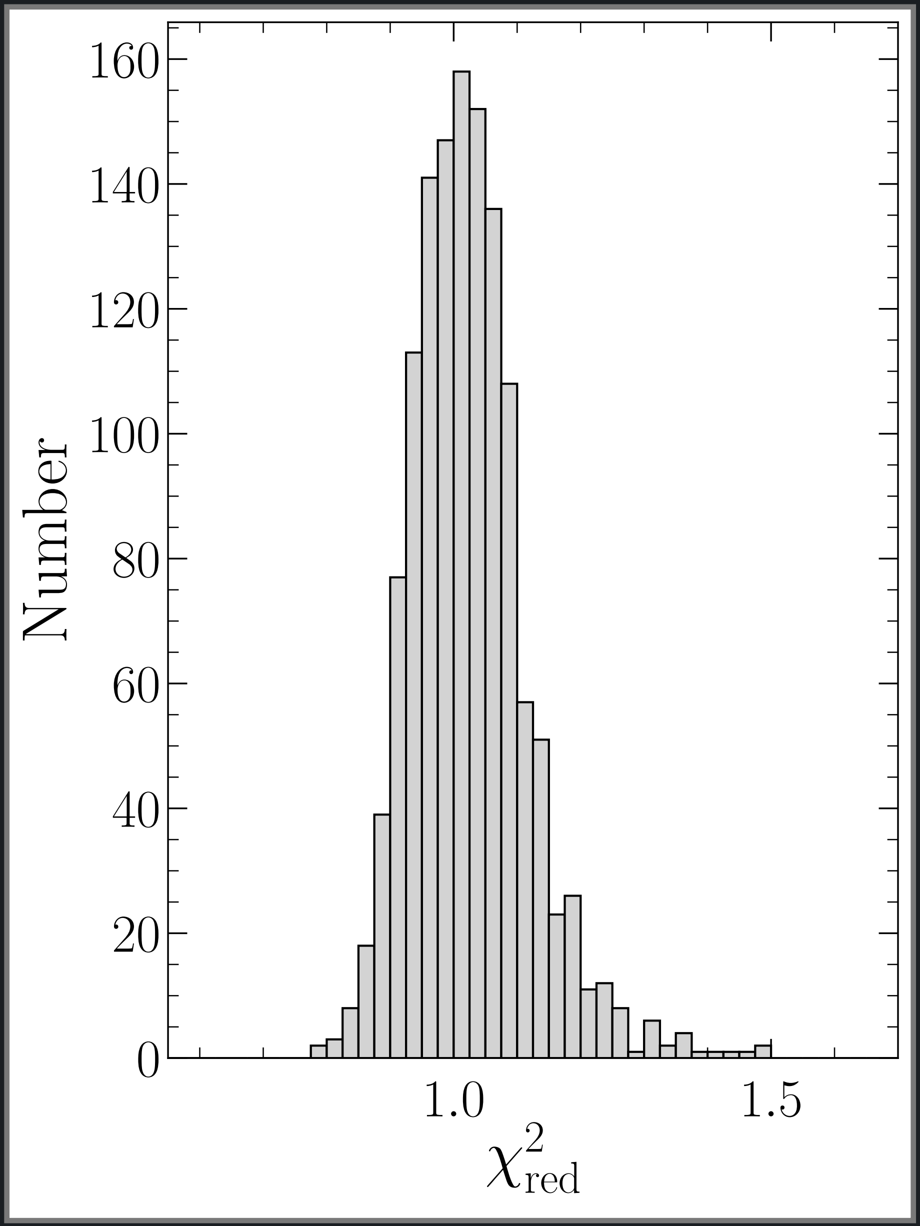


Peak flux threshold for spectral constraint

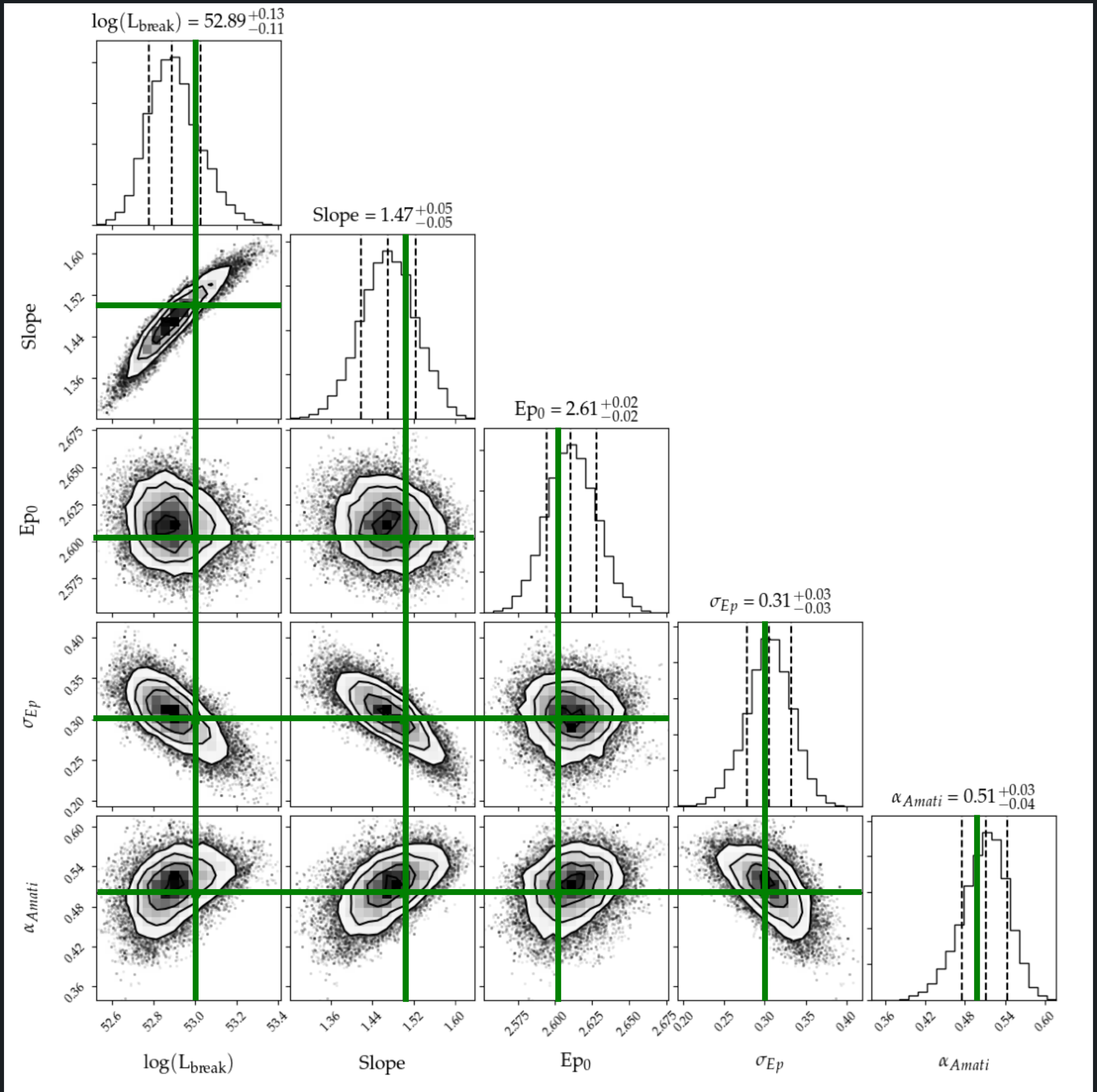


Band spectral model





MCMC exploration

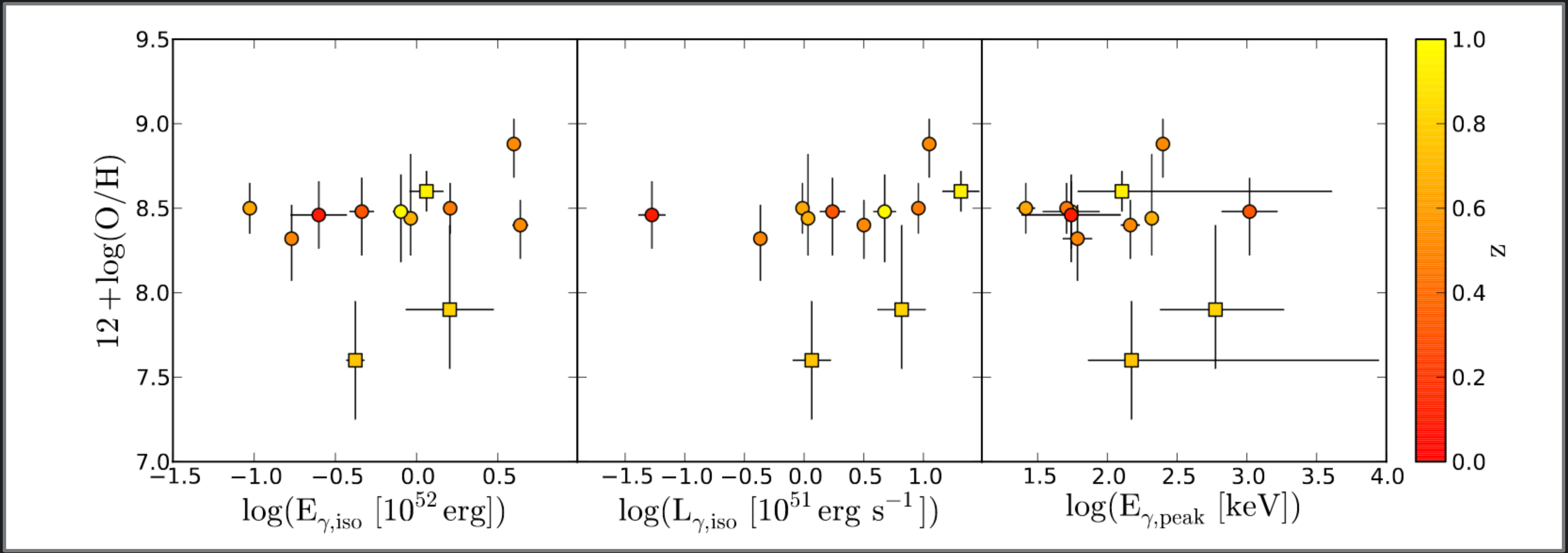


Challenges of statistical studies

- Selection biases
- Completeness
- Sample size

LGRB host galaxies extras

Prompt/host correlation



Favorable observing conditions

- Burst was well localised by *Swift*/XRT and the information was distributed quickly
- Low galactic extinction (A_v < 0.5)
- Burst declination is between -70° and +70°
- Its angular distance to the sun is greater than 55°
- No nearby bright stars

Metallicity gradients in nearby LGRB hosts