Analysis of the prompt emission of *Fermi* Gamma-Ray Bursts with the Internal Shock Synchrotron Model (ISSM)

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The origin of the GRB prompt emission is a matter of open debate. The observed prompt spectra typically present a non-thermal component in the keV-MeV range, and possibly an additional thermal component at low energies. GRB spectra are usually reconstructed using phenomenological models, which adapt to the data with one or more components, such as the Band and the black-body functions. This work is rather based on numerical simulations of GRB prompt emission in internal shocks above the photosphere. The predicted spectra are well reproduced in the keV-MeV range by the four-parameter spectral function 'Internal Shock Synchrotron Model (ISSM)' proposed by Yassine et al. 2020. We perform time-integrated and time-resolved spectral analyses of the 460 most fluent bursts detected by *Fermi*-GBM in 10 years of observations. The ISSM spectral function significantly improves the goodness of the fits compared to the Band function, especially in time-integrated analysis. We compare the resulting distribution of the photon index below the peak energy with theoretical expectations in the internal shock scenario. Finally, using ISSM instead of Band to describe the non-thermal component of GRBs 100724B, 120323A and 131014A systematically reduces the significance of an additional thermal component, confirming that in this scenario the relativistic jet is initially magnetically dominated.

The ISSM function

- Fitting directly the internal-shock (IS) numerical model needs a complex analysis chain → feasibility study with the ISSM proxy function.
- **ISSM function built to reproduce the internal-shock synchrotron synthetic spectra** in the keV-MeV range [1].

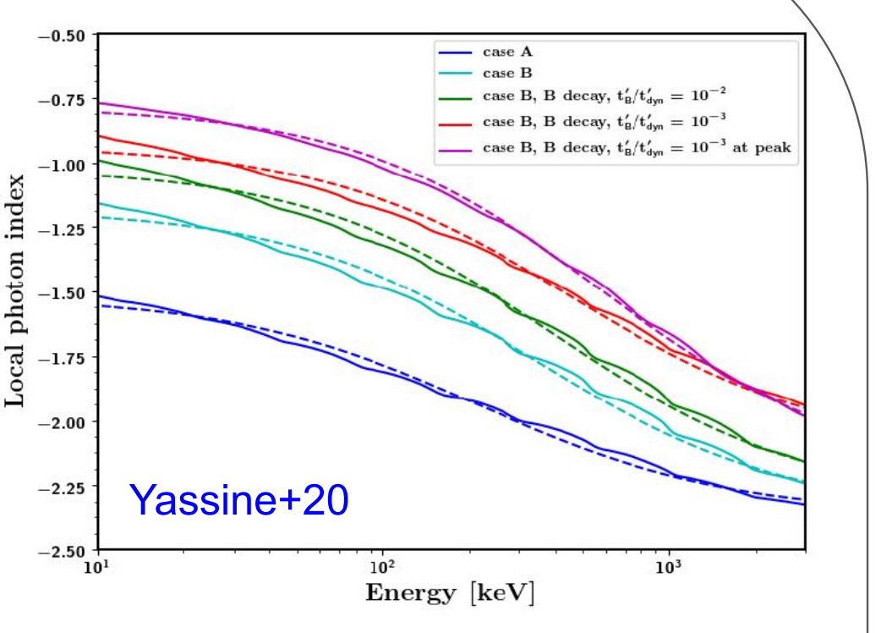
Differential photon flux:

$$f_{ISSM}(E) = \frac{A}{\left[1 - \frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}} \left(\frac{E}{E_r}\right)^{\alpha} \left[\frac{E}{E_r} - \frac{E_p}{E_r}\left(\frac{2+\beta}{2+\alpha}\right)\right]^{\beta-\alpha}$$

Local spectral index:

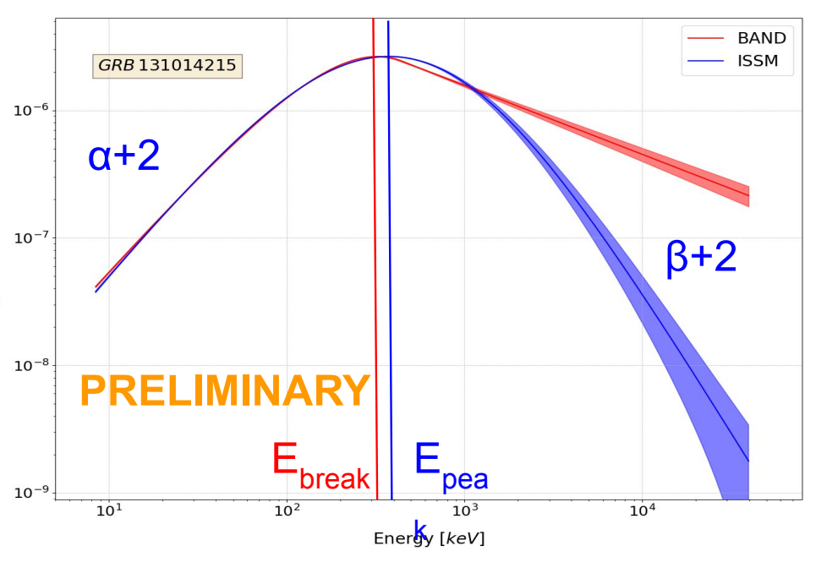
$$\Gamma_{ISSM}(E) = \alpha + (\beta - \alpha)\frac{E}{E - E_p\left(\frac{2+\beta}{2+\alpha}\right)}$$

- **4 parameters (like the Band function)**
  - Low and high-energy photon indices α and β
  - SED peak energy (E_p)
  - Flux normalization
- Unlike Band, **ISSM is continuously curved and more flexible in the spectral fits.**



Fit of Γ_{ISSM} to synthetic spectra produced by the IS numerical model.

SED = E^2 x f(E)



Fit of Band (red) and ISSM (violet) to the time-integrated spectrum of the bright GRB 131014A.

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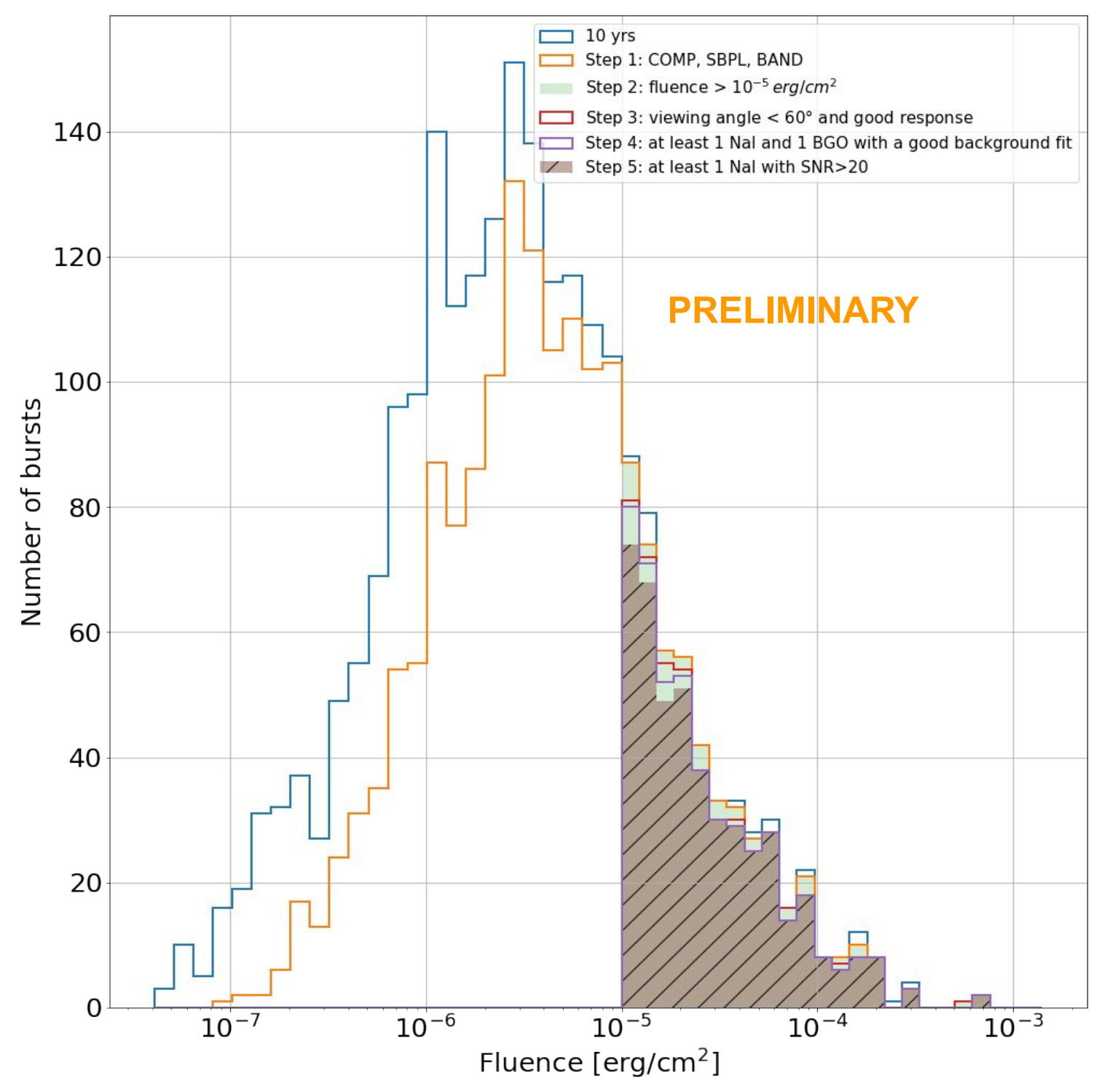
Selection of GBM fluent bursts



Step	Description	Excluded bursts	Selected bursts
-	10yr GBM Spectral Catalog[2]	-	2361
1	Exclude power-law spectra	583	1778
2	Fluence > 10^{-5} erg/cm^2	1264	514
3	Burst viewing angle < 60 degrees	29	485
4	≥ 1 NaI and ≥ 1 BGO with good background fit	11	474
5	≥ 1 NaI with SNR > 20	14	460

Final sample: 460 GBM fluent GRBs.

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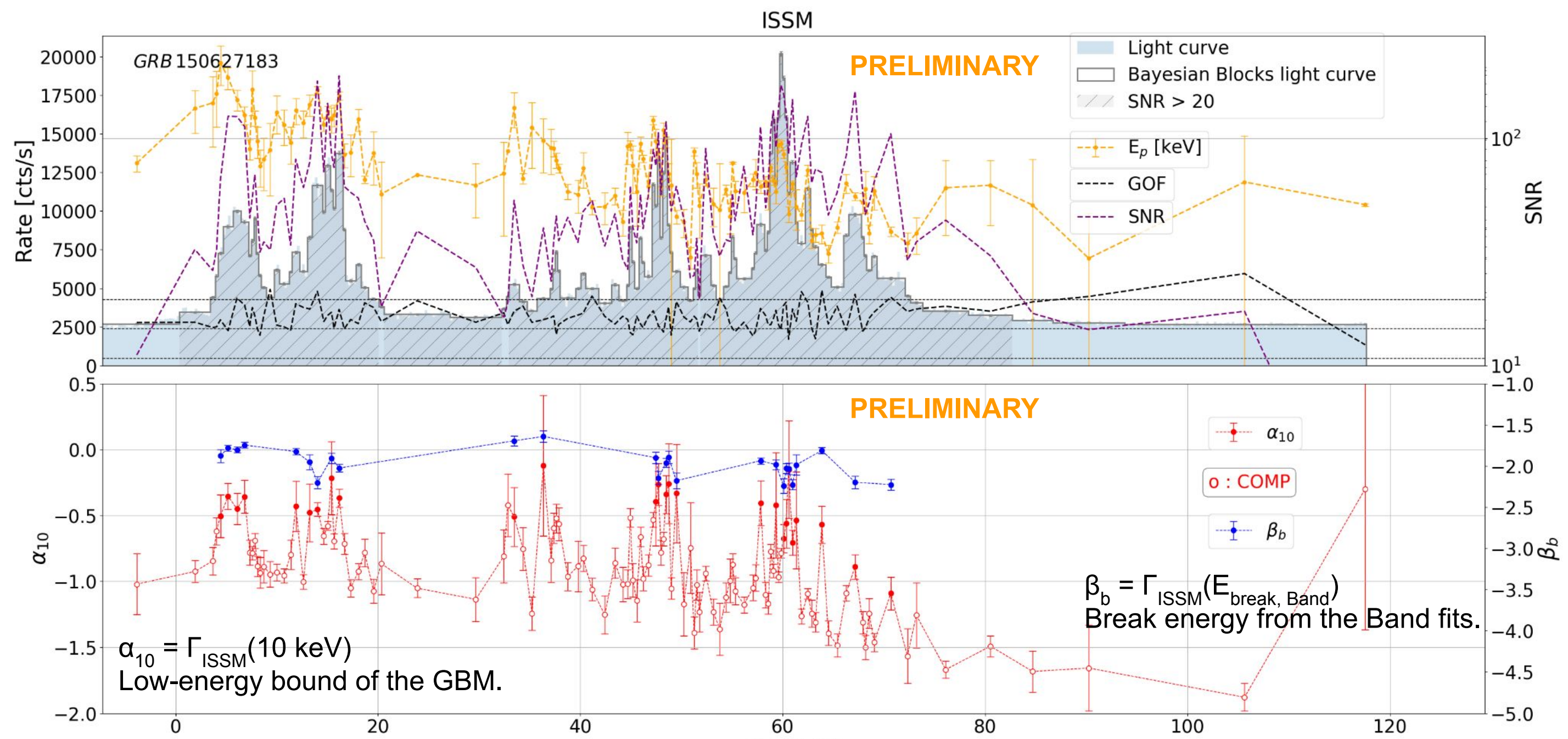
Spectral analysis

4 models fitted with pyXSPEC: COMP, SBPL, Band, ISSM:

- Time-integrated analysis over the duration of each burst (*Fluence* spectra in the GBM spectral catalog).
- For each burst, time-resolved analysis on the time-bins identified by the Bayesian blocks algorithm[3].



$\alpha_{10} = \Gamma_{ISSM}$(10 keV)
Low-energy bound of the GBM.

$\beta_b = \Gamma_{ISSM}(E_{break,\ Band})$
Break energy from the Band fits.

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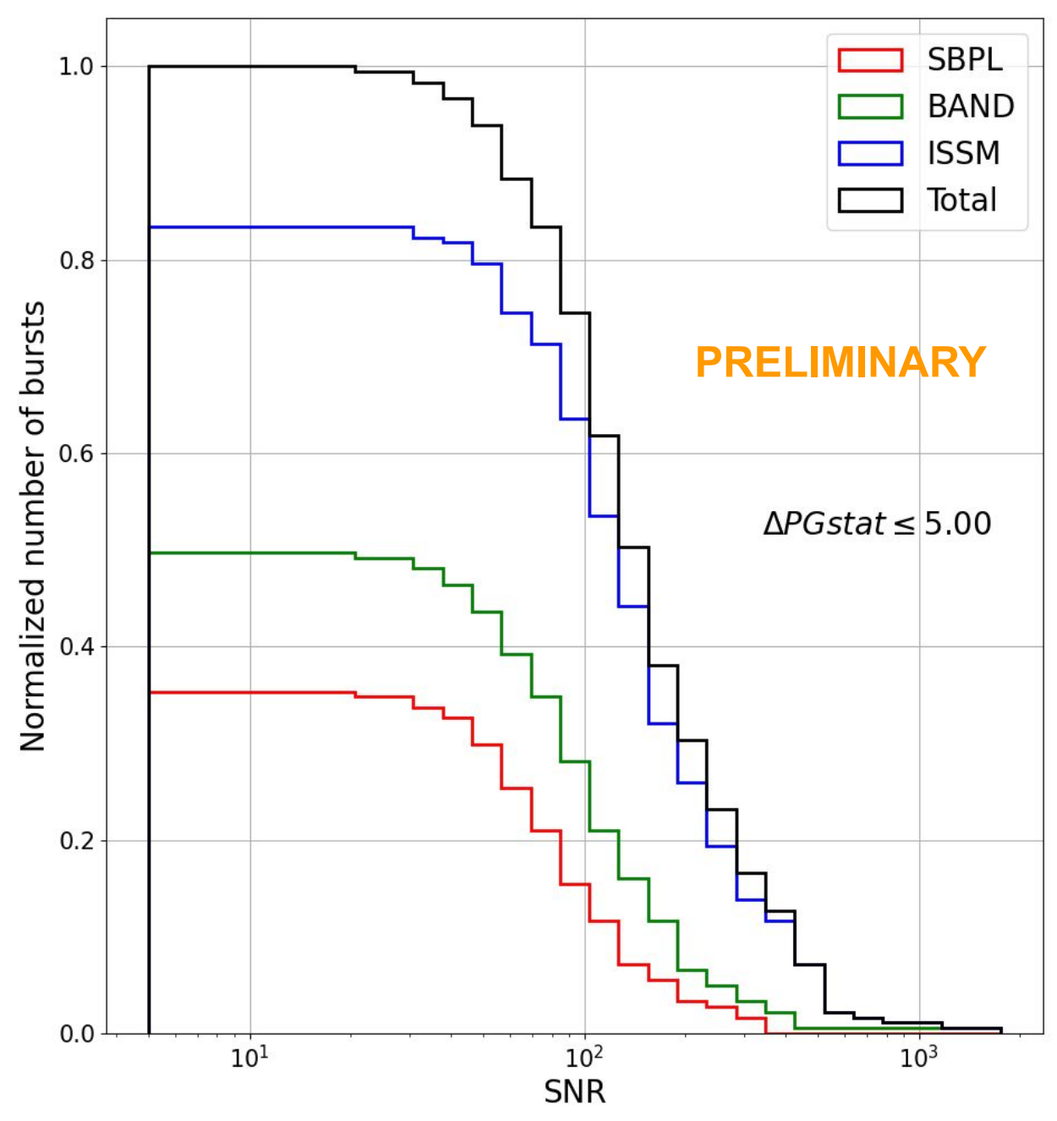
Model comparison

- $\Delta PGstat_{MODEL} = PGstat_{MODEL} - PGstat_{BEST}$
- Current model and best-fit model are equivalent and considered as good models if $\Delta PGstat_{MODEL} < 5$ (p-value < ~5σ) [1].



Selection	ΔPGstat < 5	ΔPGstat < 10
All bursts	(%)	(%)
COMP	0	0
SBPL	36	50
Band	49	60
ISSM	**83**	**89**
Highest SNR		
COMP	0	0
SBPL	12	18
Band	23	27
ISSM	**85**	**90**

Probability of being a good model.

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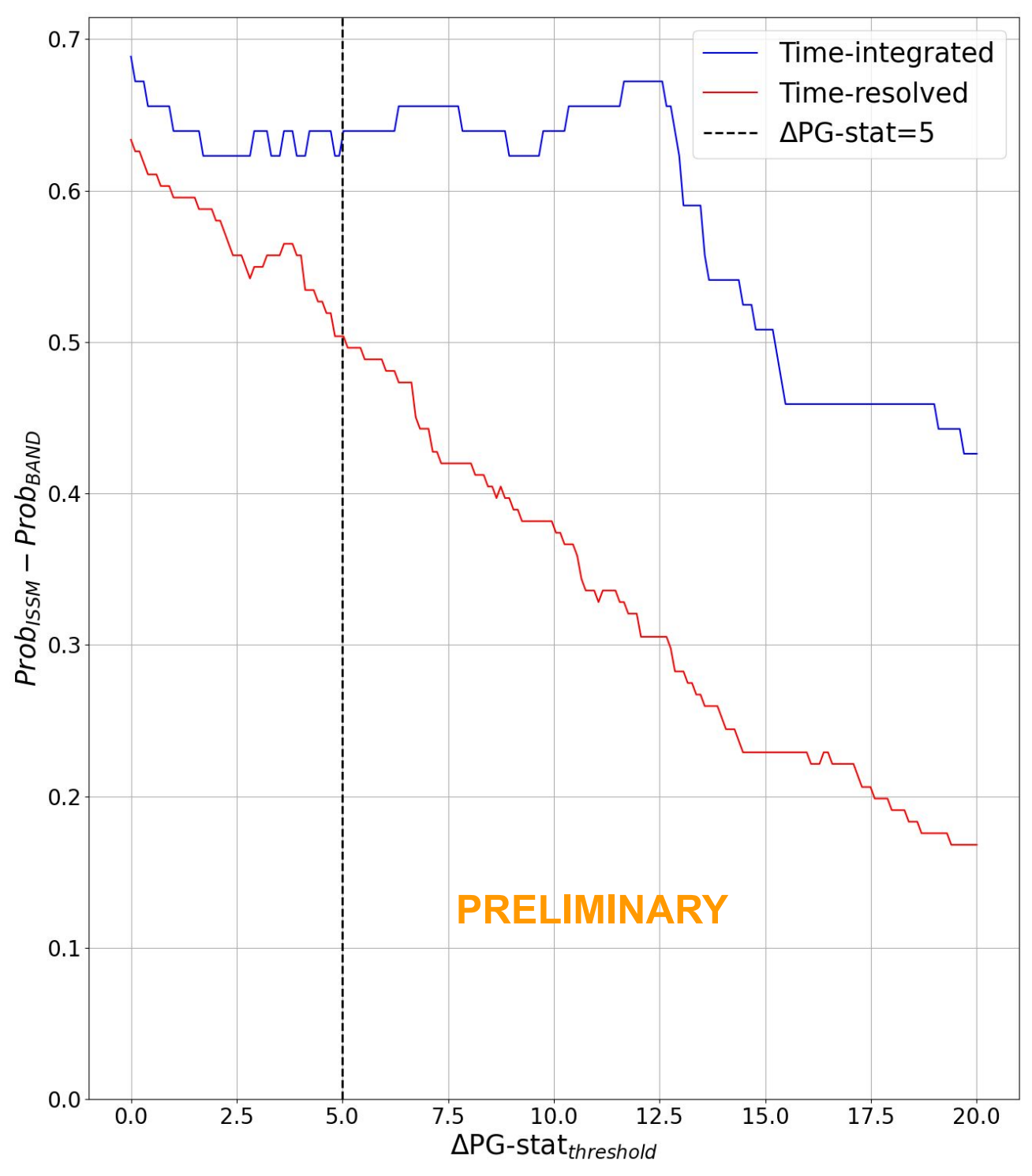
Time-integrated vs time-resolved analyses



$\Delta PGstat_{threshold}$ = variable threshold below which a model is considered good.

$Prob_{MODEL}$ = probability for a given model to have $\Delta PGstat_{MODEL} < \Delta PGstat_{threshold}$

- $\Delta Prob = Prob_{ISSM} - Prob_{Band} > 0$ always → ISSM is favored whatever the threshold.
- Time-integrated: ΔProb > 60%
- Time-resolved: ΔProb smoothly decreases with increasing $\Delta PGstat_{threshold}$

As time-integrated spectra are superposition of time-resolved spectra, this suggests that **Band is less suitable to fit time-integrated spectra with strong spectral evolution**.

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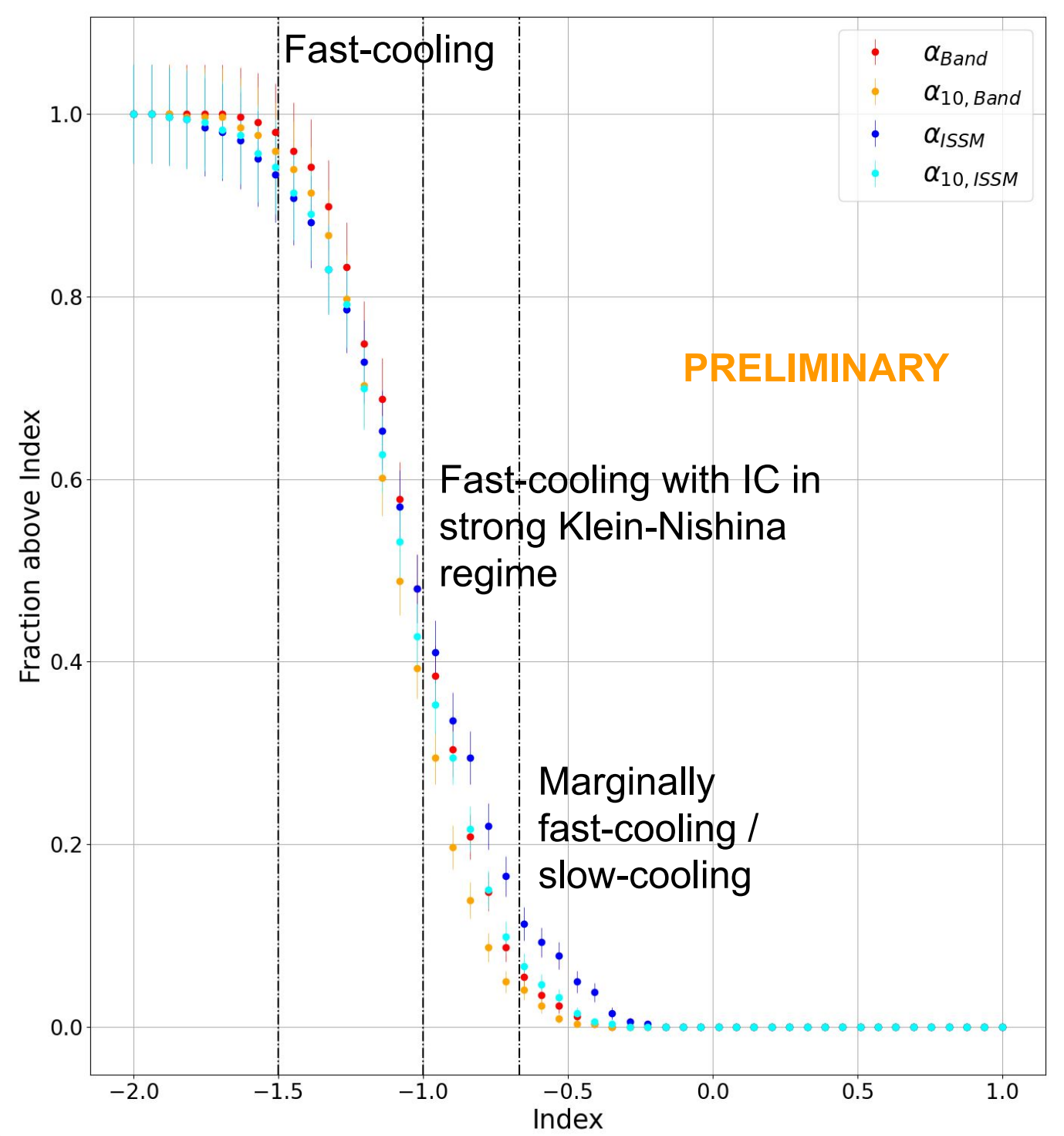
Low-energy photon index



The low-energy photon index is often used to discuss the compatibility of observed spectra with radiative processes. Here we compare the $\alpha_{10,MODEL} = \Gamma_{MODEL}$(10 keV) with expected values in fast-cooling synchrotron radiation.

	α_{Band}	$\alpha_{10,Band}$	α_{ISSM}	$\alpha_{10,ISSM}$
Fast-cooling: -3/2	98%	96%	93%	**94%**
Fast-cooling with IC in strong Klein-Nishina regime: -1	43%	35%	45%	**40%**
Marginally fast-cooling / slow-cooling: -2/3	**6%**	**4%**	**12%**	**7%**

Fraction of bursts above -3/2, -1, -2/3 at more than 2σ.

- $\alpha_{10,ISSM}$ always above pure fast-cooling regime.
- $\alpha_{10,ISSM}$ above slow-cooling value in 7% of cases → **line of death problem is not too severe.**
- **$\alpha_{10,ISSM}$ compatible with fast-cooling synchrotron in 60% of the cases and with marginally fast-cooling in 33% more cases.**

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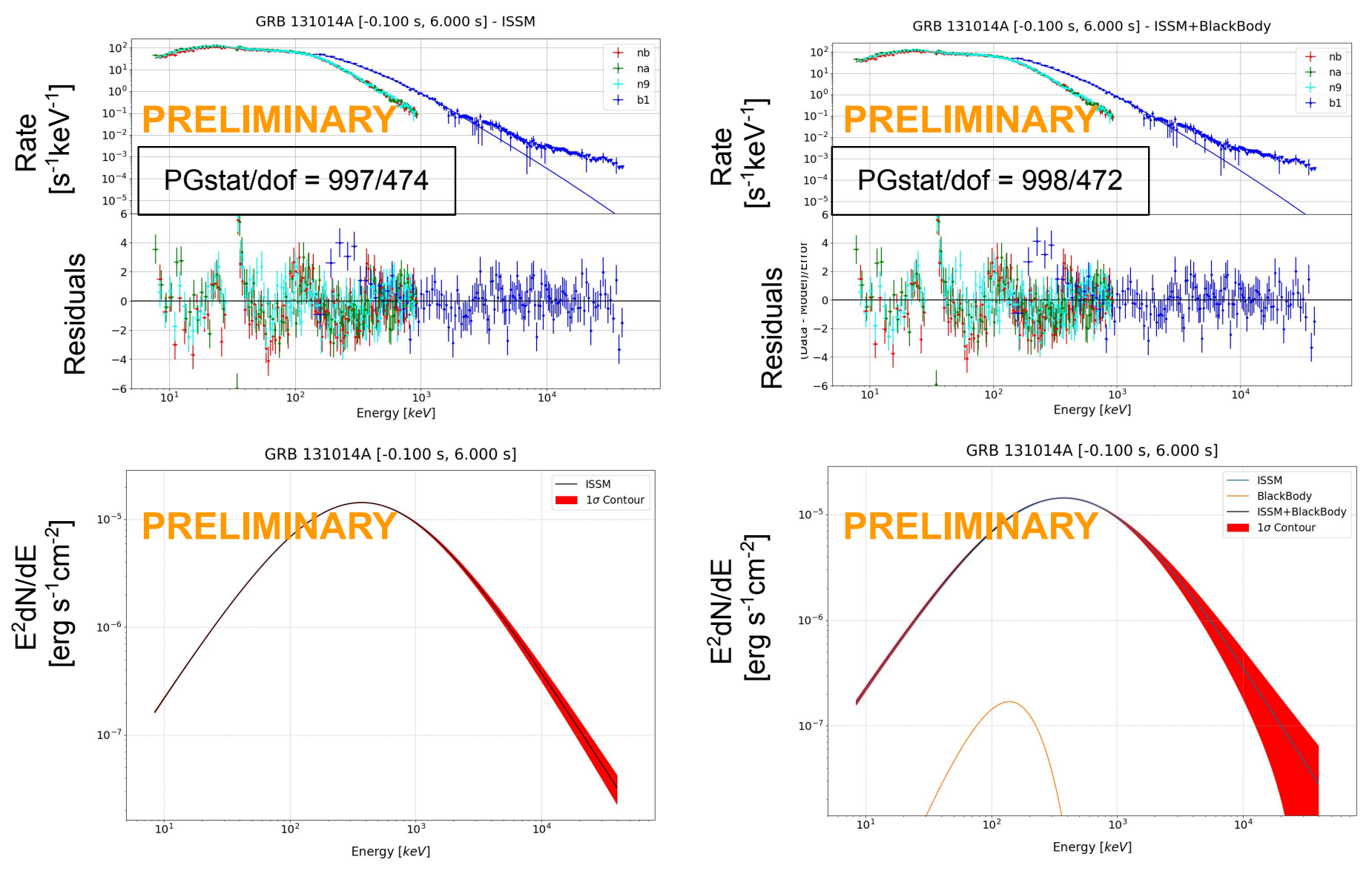
Photospheric emission

Even if the emission is mainly produced by synchrotron radiation in the optically thin regime, some emission is also expected at the photosphere. Its intensity depends on the composition of the relativistic jet, and especially its initial magnetization. For a non-dissipative photosphere, the predicted spectrum is quasi-thermal. A black-body (BB) component was detected in GRBs 100724B [4], 120323A [5], and 131014A [6] in addition to Band → what if the non-thermal component is fitted with ISSM?



- GRB 100724B and 120323A: **smaller BB significance when switching from Band to ISSM** (5.4σ → 2.8σ, 5.8σ → 4.3σ).
- **No additional thermal component is required for GRB 131014A when using ISSM (>8σ → 0σ).**

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Conclusions

In our sample of 460 GBM bright GRBs:

- **ISSM is almost always preferred to Band when fitting the GRB keV-MeV prompt spectra, especially in time-integrated analysis.**
- **The observed low-energy spectral index of ISSM is in most cases compatible with fast-cooling synchrotron radiation.**

In our analysis of GRBs 100724B, 120323A and 131014A, the detection of a photospheric component depends highly on the function that fits the non-thermal component. This work suggests that such photospheric component is weak and that the initial reservoir is partially constituted by Poynting flux.

References:
[1] Yassine, M., Piron, F., Daigne, F., et al. 2020, A&A, 640, A91.
[2] Poolakkil, S., Preece, R., Fletcher, C., et al. 2021, ApJ, 913.1, 60.
[3] Scargle, J. D. , Norris, J. P., Jackson, B., and Chiang, J., ApJ 764 167.
[4] Guiriec, S., Connaughton, V., Briggs, M. S., et al. 2011, ApJL 727.2, L33.
[5] Guiriec, S., Daigne, F., Hascoët, R., et al. 2013, ApJ 770.1, 32.
[6] Guiriec, S., Mochkovitch, R., Piran, T., et al. 2015, ApJ 814.1, 10.

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