Discovery of an evolving MeV emission line in the brightest GRB ever detected

Maria Edvige Ravasio
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in collaboration with
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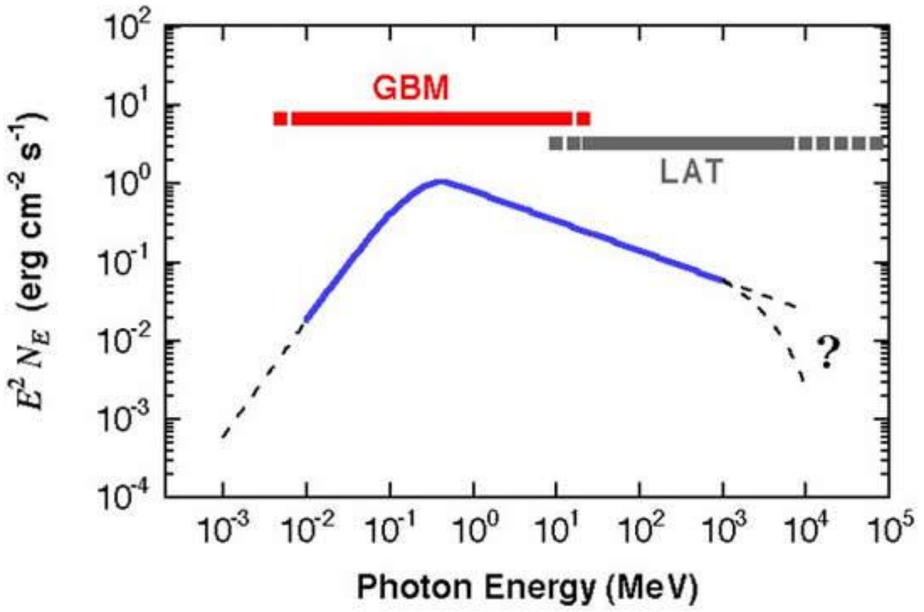
A typical GRB prompt spectrum



- keV-MeV
- non-thermal shape
- uncertain physical origin
- feature-less power-law segments
  [Band+1993]

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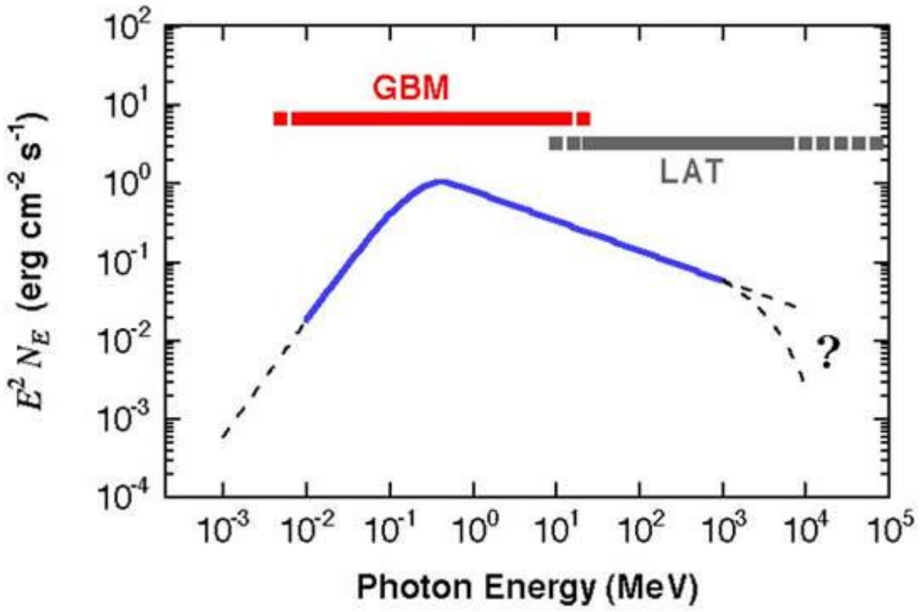

- keV-MeV
- non-thermal shape
- uncertain physical origin
- feature-less power-law segments $\boxed{\rightarrow \textbf{2 or more?}}$
  [Band+1993]

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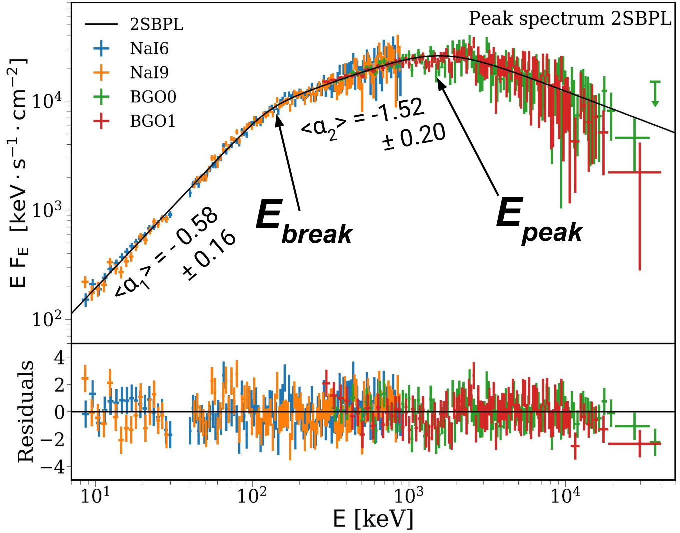
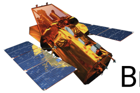
Recent results from Swift & Fermi



Ravasio et al. 2018, 2019

- keV-MeV
- non-thermal shape
- uncertain physical origin
  → synchrotron?
- feature-less power-law segments **→2 or more?**



Breaks discovered in Swift: Oganesyan et al. 2017, 2018, 2019

[see also Zhang, B.B. et al. 2011, 2016, Zhao et al. 2014, Burgess et al 2020]

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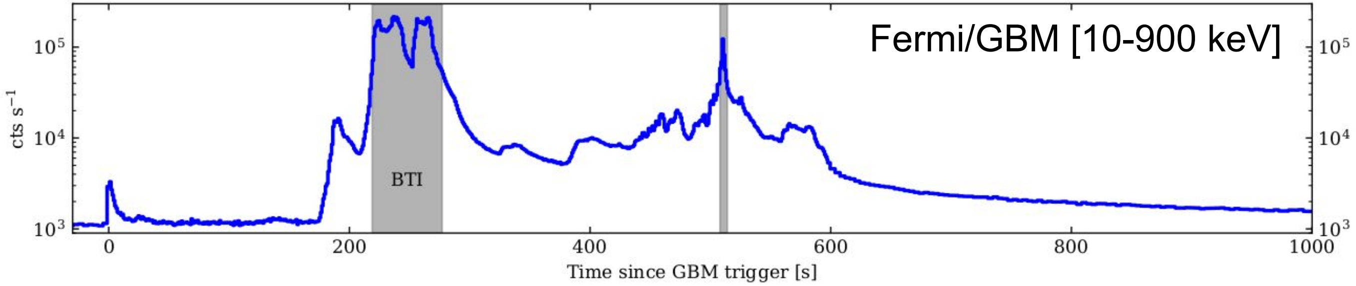
The extraordinary GRB 221009A



- Extraordinary fluence 0.2 erg/cm^2
  [Frederiks et al 2023, An et al 2023, Burns et al 2023]

E_{iso} = 1 x 10^{55} erg
L_{iso} = 9.9 x 10^{53} erg/s

- Nearby, z=0.151 [Malesani et al 2023]

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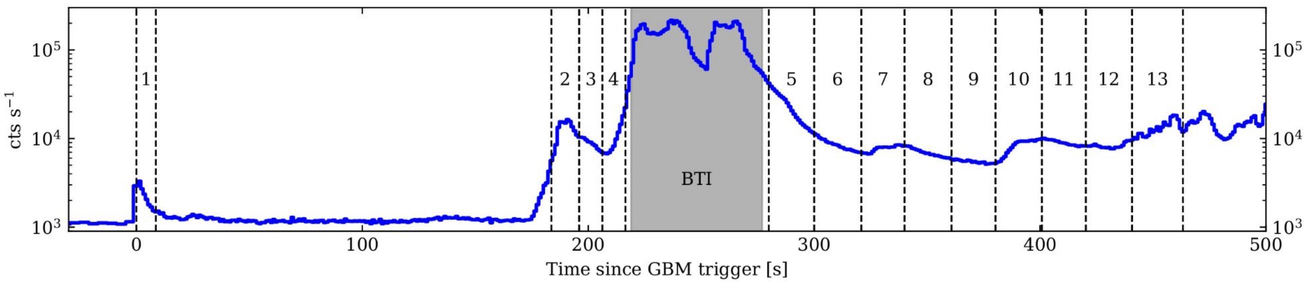
GRB 221009A: spectral analysis of Fermi/GBM data



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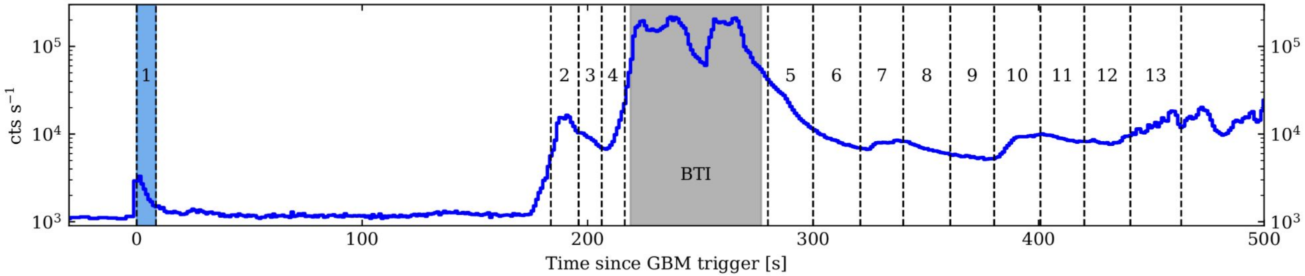

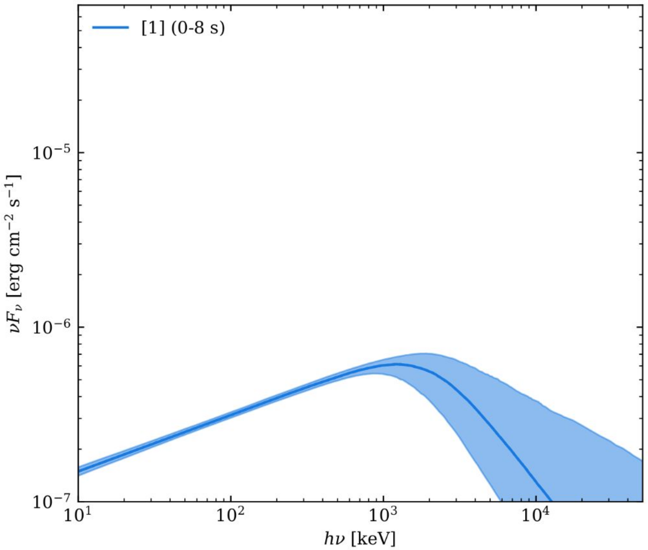

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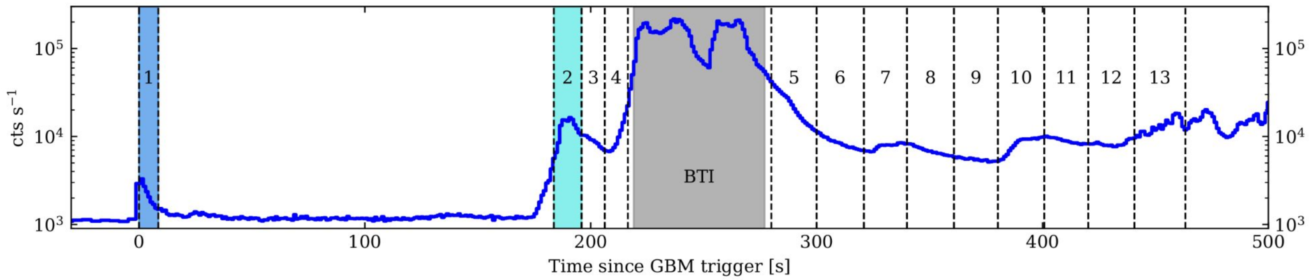

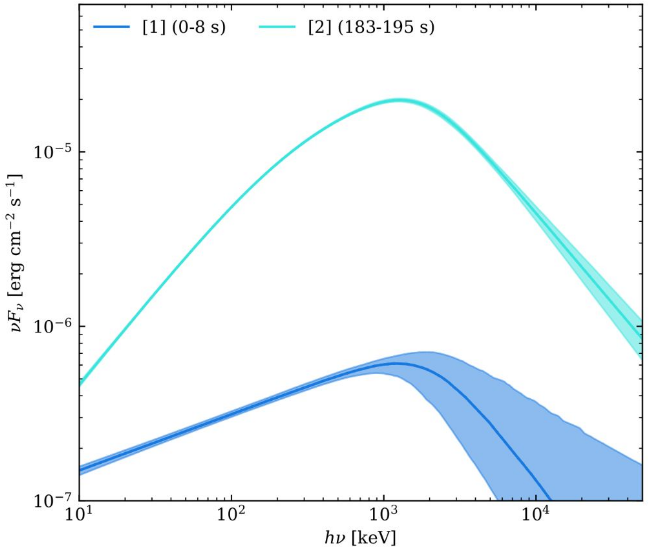

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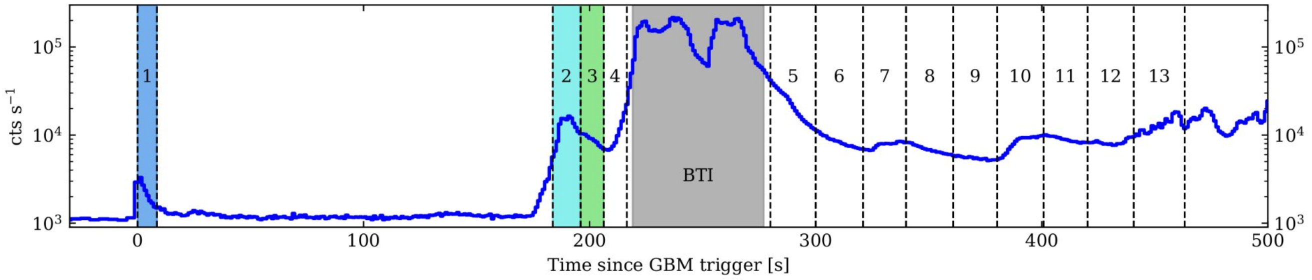

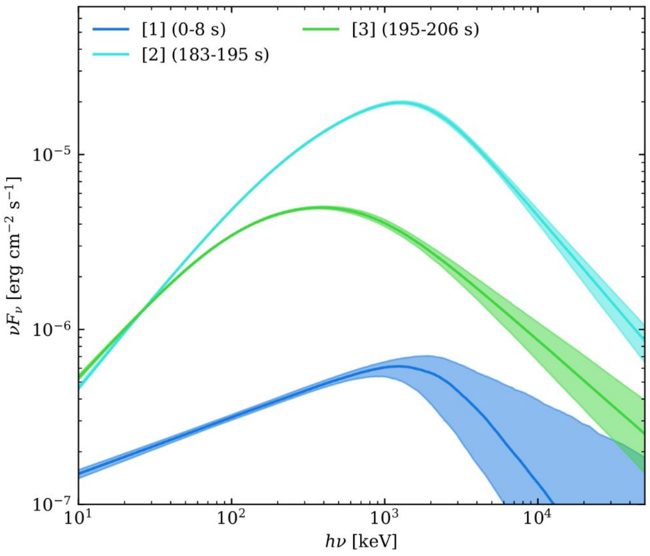

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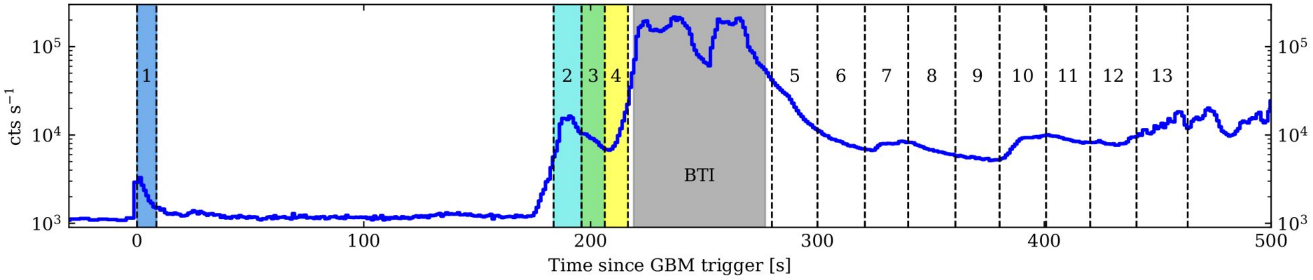

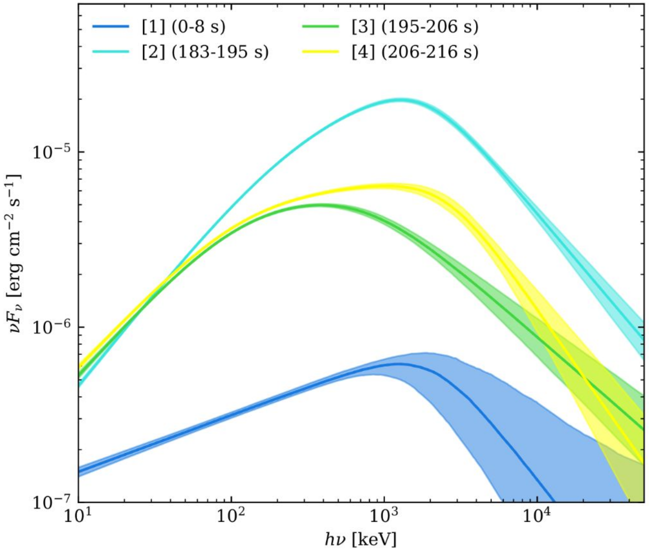

consistent with synchrotron emission

[see also Yang et al. 2023]

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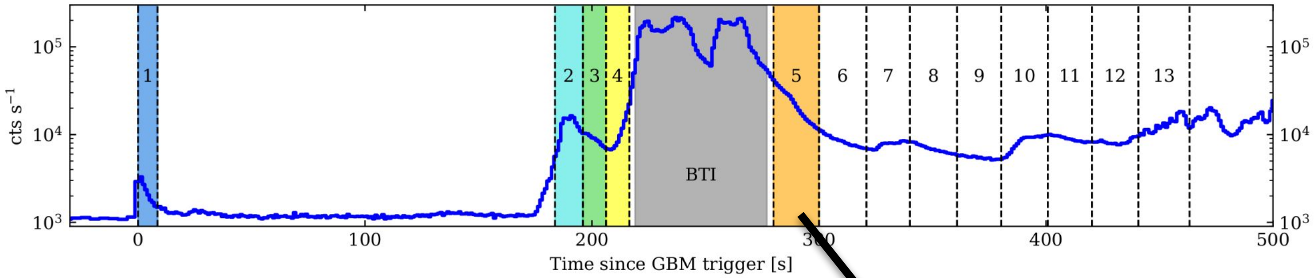

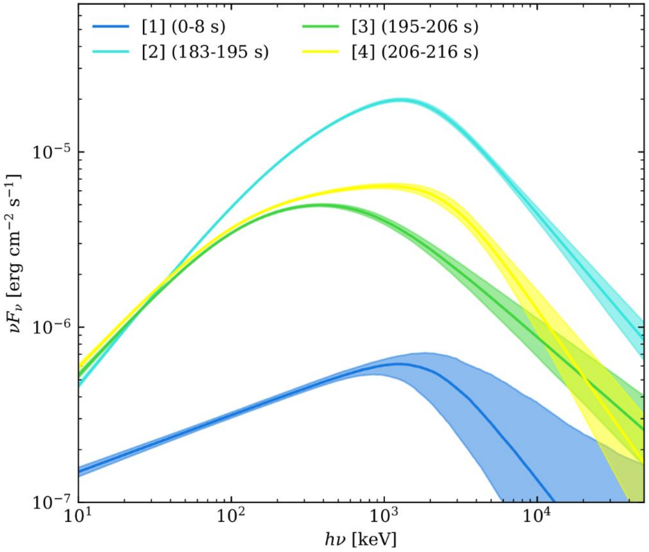

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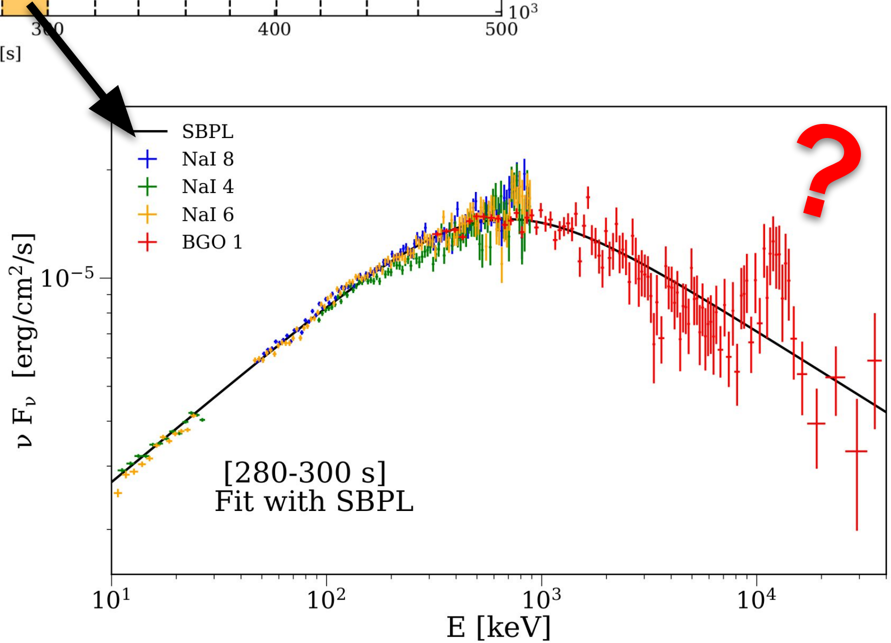

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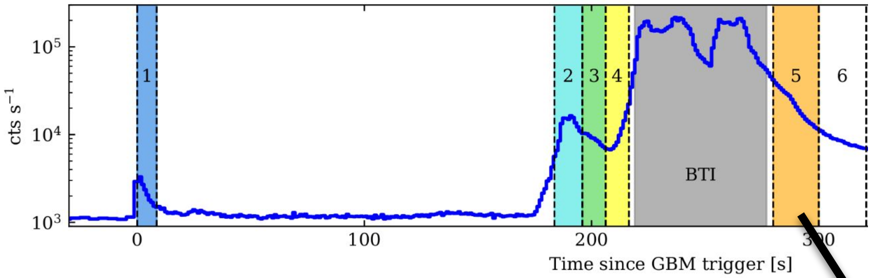
Spectral analysis of Fermi/GBM data

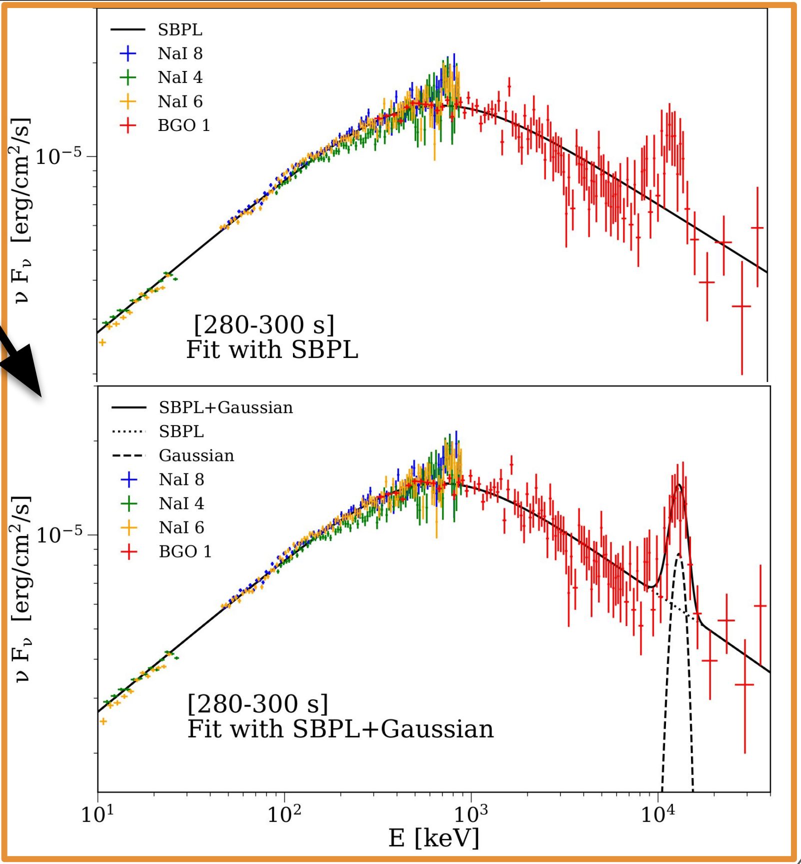


[280-300 s]

fitted with a Gaussian
on top of the continuum (SBPL)

high significance: ΔAIC = 49 → **6.6 σ**

E_{gauss} = 12.56 (±0.30) MeV
σ_{gauss} = 1.31 (±0.30) MeV
L_{gauss} = 1.12 (±0.19) x 10^{50} erg/s



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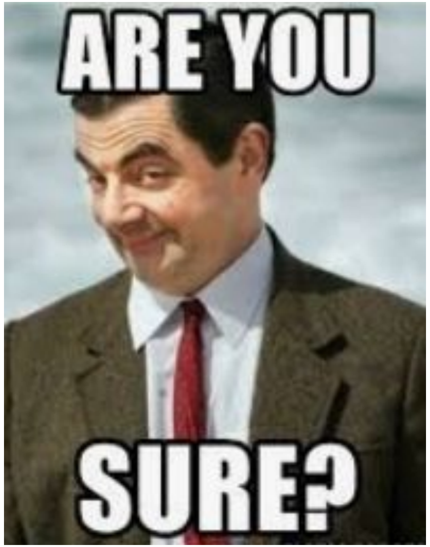
…a line in a GRB spectrum?



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…a line in a GRB spectrum? A long tortured history

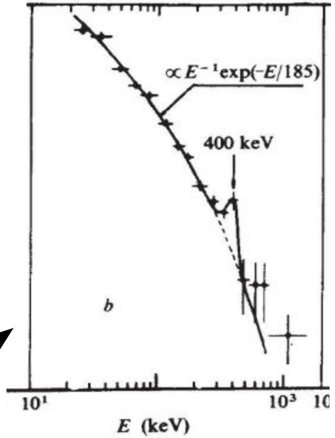
Lines during prompt have been searched for intensively in the past:

- ➔ **most of them in absorption**
- ➔ **most in the X-rays**

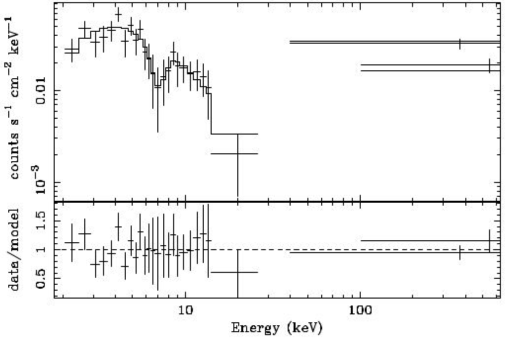
but no conclusive evidence so far

Mazets+1981	absorption @ 30 - 70 keV in KONUS
Mazets+1981	emission @ 400 keV in KONUS
Murakami+1988	absorption @ 20 & 40 keV in Ginga
Palmer+1994	no line (systematic search) in BATSE
Band+1996	no line (systematic search) in BATSE
Amati+2000	absorption @ 3.8 keV in BeppoSAX
Frontera+2004	absorption @ 6.9 keV in BeppoSAX

For the afterglow:
[Piro+1999, Antonelli+2000, Piro+2000, Yoshida+2001, Reeves+2002, Watson+2003, Butler+2003, Sako+2005, Campana+2016]



Emission line at ~400 keV in KONUS [Mazets et al. 1981]



Absorption line at ~6.9 keV in BeppoSAX 2.8-3.1 σ [Frontera et al. 2004]

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Mazets+1981,
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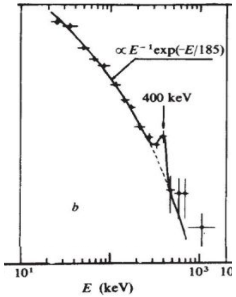
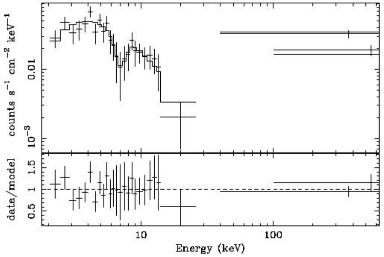
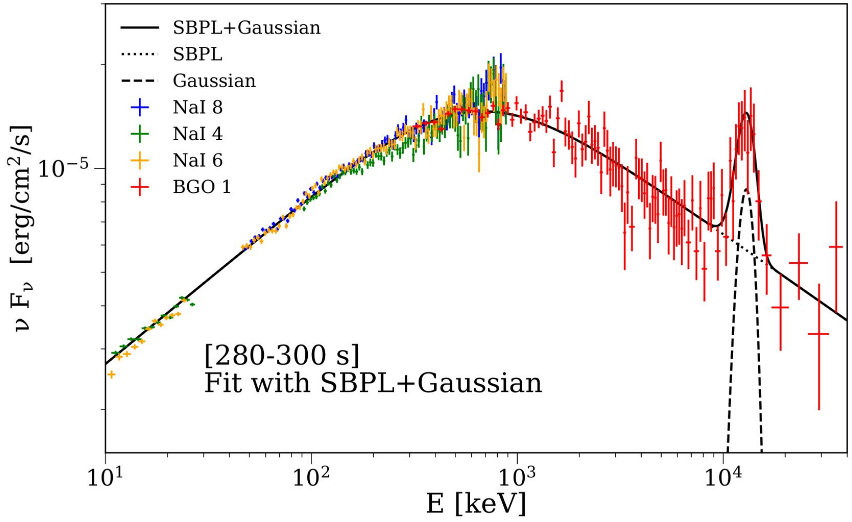




For the afterglow:
[Piro+1999, Antonelli+2000, Piro+2000, Yoshida+2001, Reeves+2002, Watson+2003, Butler+2003, Sako+2005, Campana+2016]

GRB 221009A represents the first burst where a bright and highly significant emission line, broader than instrumental resolution, is identified at several MeV energies in the Fermi/GBM spectral data



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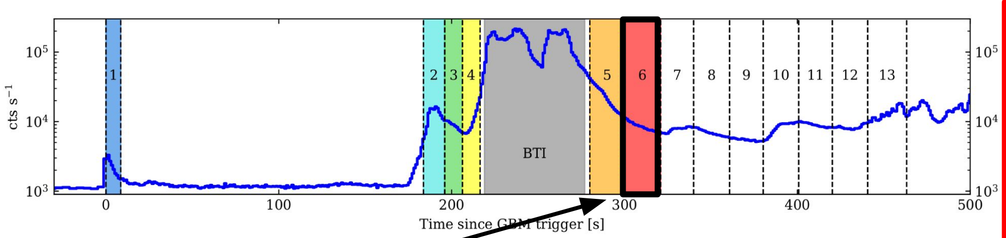
Spectral analysis: continuum + line



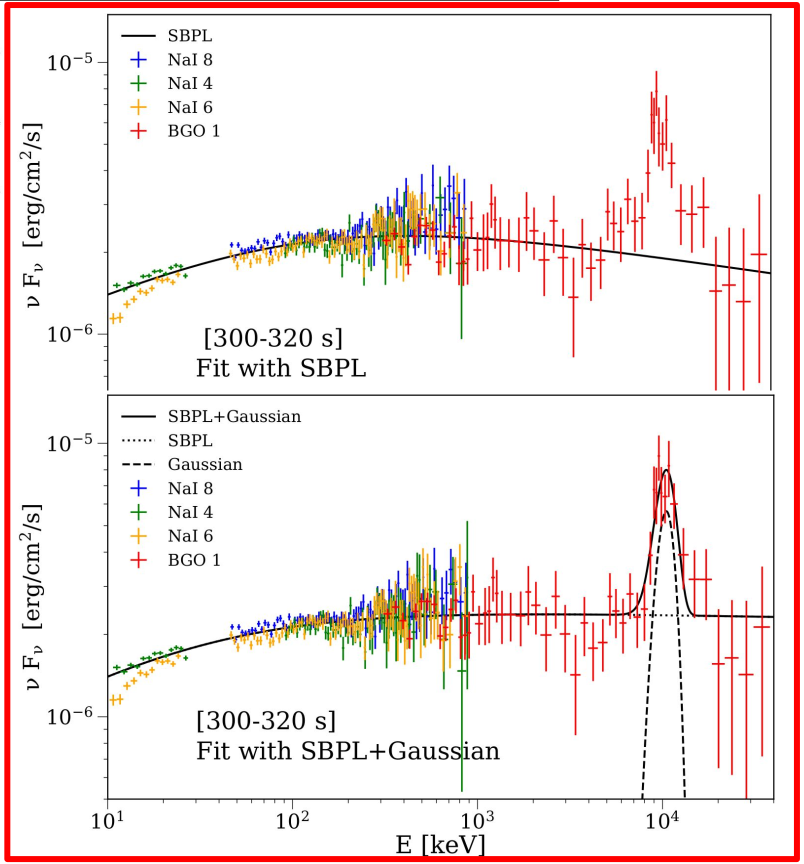
[300-320 s]

fitted with a Gaussian
on top of the continuum (SBPL)

high**er** significance! ΔAIC = 141→**11.5 σ**

the line is the highest peak of the νF_ν spectrum

E_{gauss} = 10.19 (±0.29) MeV
σ_{gauss} = 1.70 (±0.47) MeV
L_{gauss} = 1.14 (±0.19) x 10^{50} erg/s



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Simulations

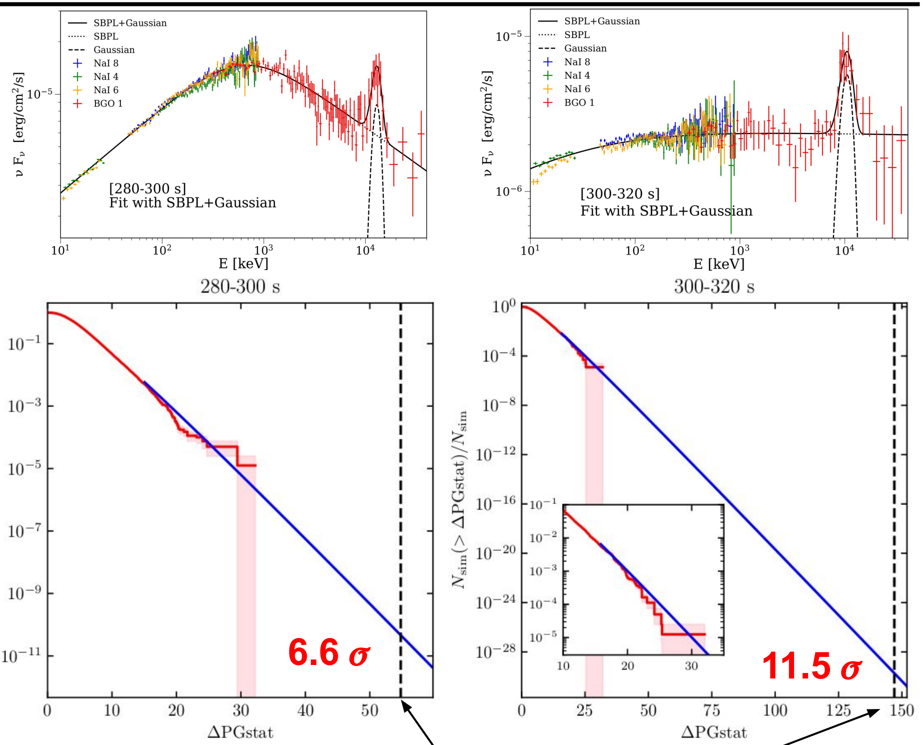
We performed 8 × 10^4 Monte Carlo simulations of spectra

- using our best-fit parameters of background+SBPL model

- then fitted each simulated spectrum with SBPL and SBPL+Gaussian

- all parameters free to vary

- repeated the SBPL + Gauss fit initializing each time from different E_{gauss} values



ΔPGstat obtained in the actual fit for spectrum 5 and spectrum 6

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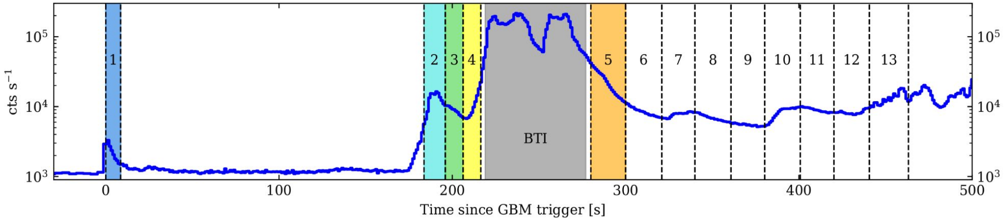
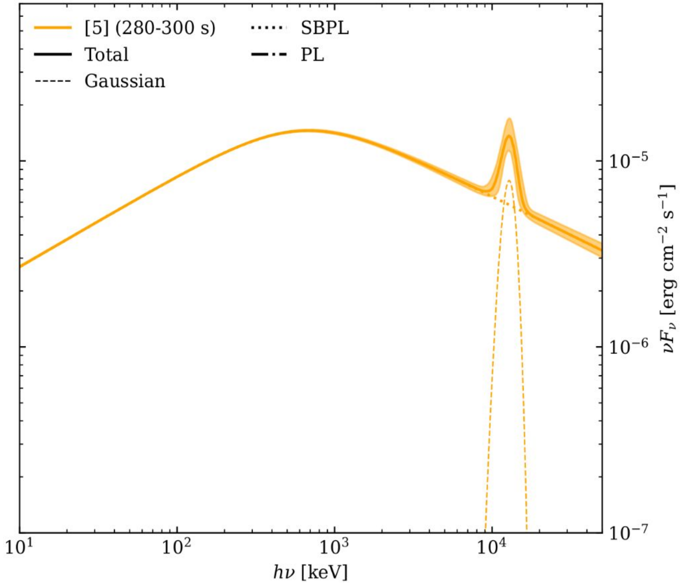
Spectral analysis: temporal evolution



The feature evolves both in energy E_{gauss} ~12 MeV to ~6 MeV and luminosity L_{gauss} ~10^{50} erg/s to ~2×10^{49} erg/s over ~80 s

Time interval [s]	L_{gauss} [10^{50} erg/s]	E_{gauss} [MeV]	σ_{gauss} [MeV]	ΔAIC
280 - 300 [5]	$1.12^{+0.19}_{-0.19}$	$12.56^{+0.30}_{-0.31}$	$1.31^{+0.31}_{-0.30}$	49
280 - 285 [5.1]	$0.77^{+0.42}_{-0.42}$	$14.40^{+0.86}_{-0.87}$	$0.99^{+0.66}_{-0.57}$	2.4
285 - 290 [5.2]	$0.43^{+0.33}_{-0.28}$	$13.21^{+6.36}_{-1.51}$	$1.14^{+0.59}_{-0.62}$	-1.2
290 - 295 [5.3]	$1.84^{+0.36}_{-0.33}$	$12.16^{+0.30}_{-0.30}$	$1.08^{+0.34}_{-0.30}$	42
295 - 300 [5.4]	$0.63^{+0.28}_{-0.27}$	$12.55^{+0.47}_{-1.45}$	$0.79^{+0.81}_{-0.45}$	5
300 - 320 [6]	$1.14^{+0.20}_{-0.18}$	$10.19^{+0.29}_{-0.28}$	$1.70^{+0.52}_{-0.42}$	141
300 - 310 [6.1]	$1.08^{+0.19}_{-0.17}$	$10.42^{+0.31}_{-0.30}$	$1.14^{+0.36}_{-0.29}$	45
310 - 320 [6.2][1]	$0.75^{+0.21}_{-0.19}$	$9.77^{+0.42}_{-0.49}$	$1.24^{+0.25}_{-0.21}$	30
320 - 340 [7][1]	$0.23^{+0.15}_{-0.13}$	$7.22^{+1.63}_{-1.72}$	$2.38^{+0.45}_{-0.83}$	-2
340 - 360 [8][1]	$0.21^{+0.12}_{-0.10}$	$6.12^{+0.74}_{-0.59}$	$1.35^{+1.08}_{-0.74}$	0

[a]These spectra require the presence of an extra power-law component.



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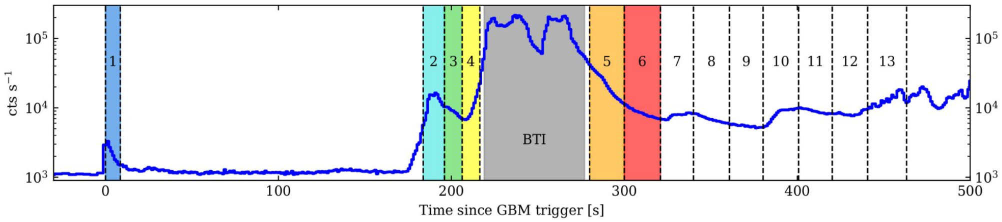
Spectral analysis: temporal evolution



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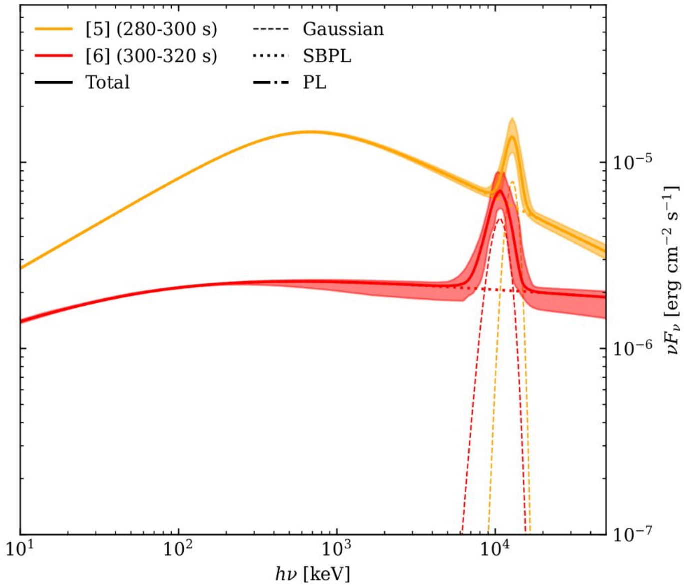

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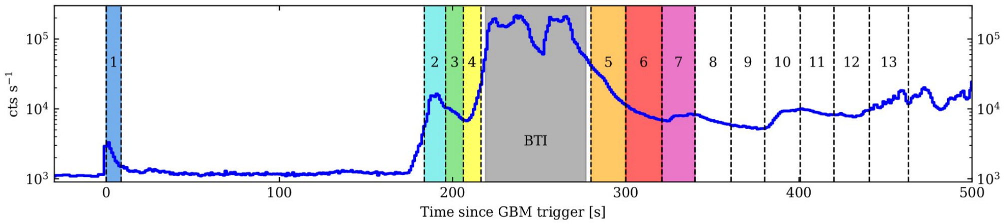

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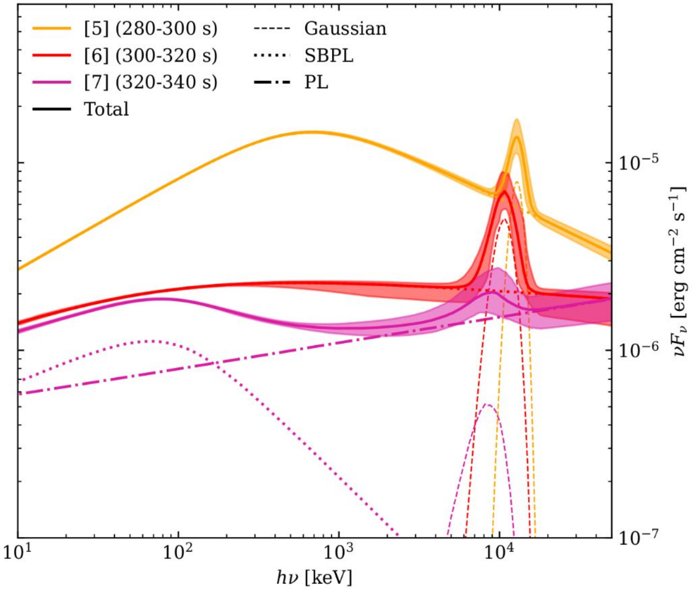

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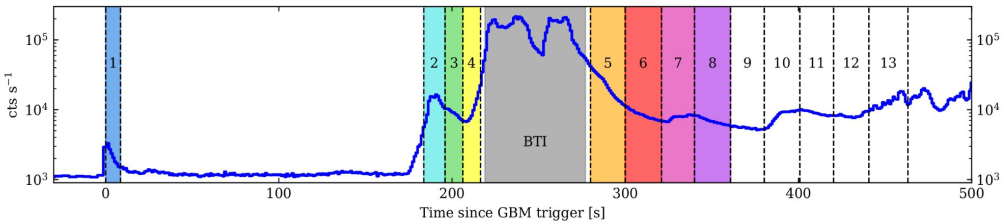

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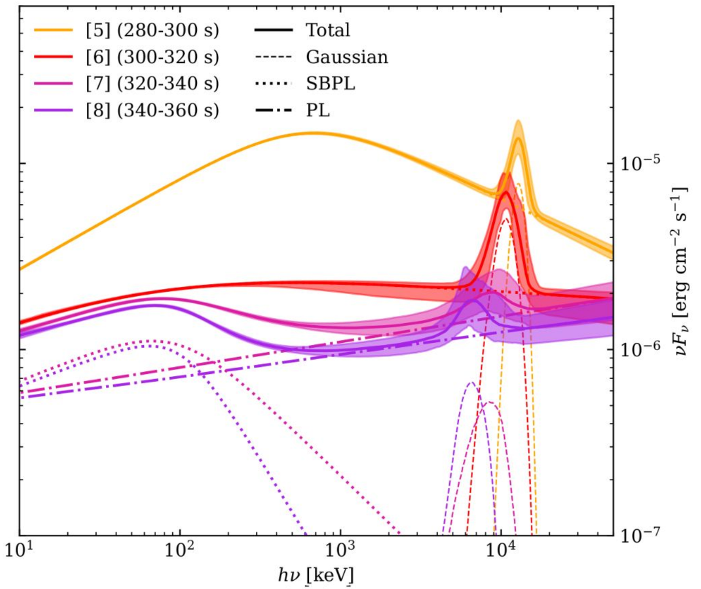
310 - 320 [6.2][1]	$0.75^{+0.21}_{-0.19}$	$9.77^{+0.42}_{-0.49}$	$1.24^{+0.25}_{-0.21}$	30
320 - 340 [7][1]	$0.23^{+0.15}_{-0.13}$	$7.22^{+1.63}_{-1.72}$	$2.38^{+0.45}_{-0.83}$	-2
340 - 360 [8][1]	$0.21^{+0.12}_{-0.10}$	$6.12^{+0.74}_{-0.59}$	$1.35^{+1.08}_{-0.74}$	0

[a]These spectra require the presence of an extra power-law component.



→ no evidence for this feature in the subsequent time intervals

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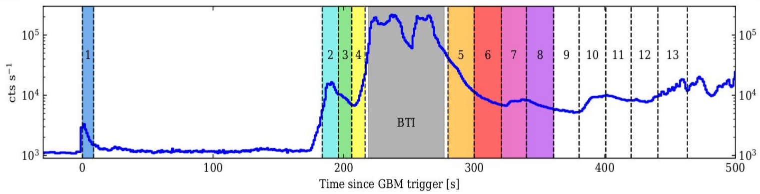
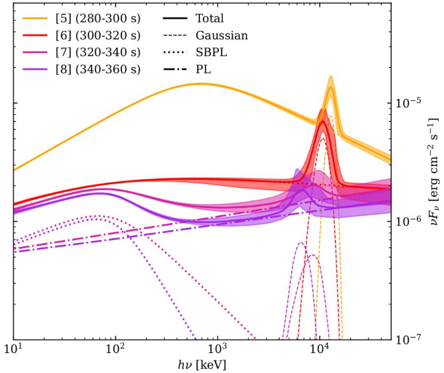
Interpretation





E_{gauss} ~12 MeV to ~6 MeV

L_{gauss} ~10^{50} erg/s to ~2×10^{49} erg/s

over ~80 s

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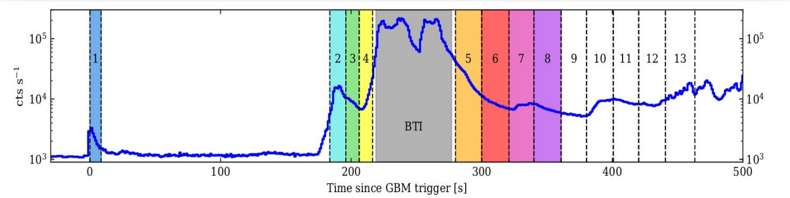
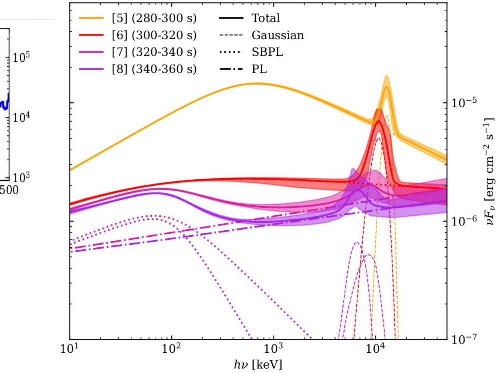
Interpretation: blue-shifted pair-annihilation line?





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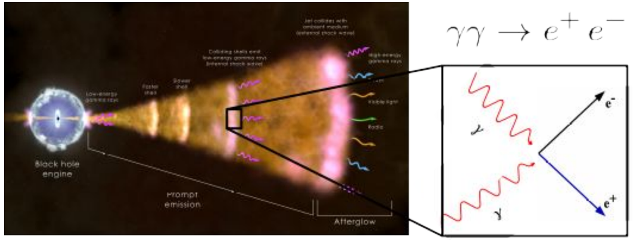
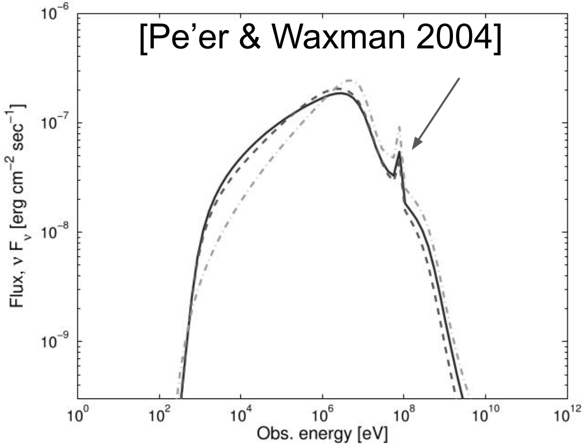
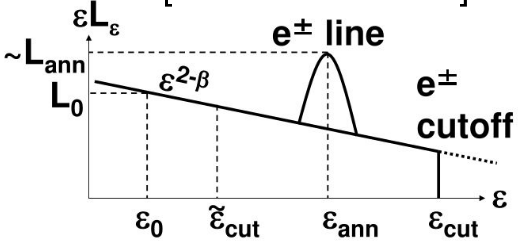




For bright synchrotron emission peaking at ~1 MeV and typical variability timescales (~10 ms) → high compactness ℓ' ~ 10^2-10^3

[Murase et al. 2008]



[see also Ioka et al. 2007]

observing it at 10 MeV implies either

- **Γ ~ 20**
- **Γ ~ 1000 in High-Latitude Emission scenario**

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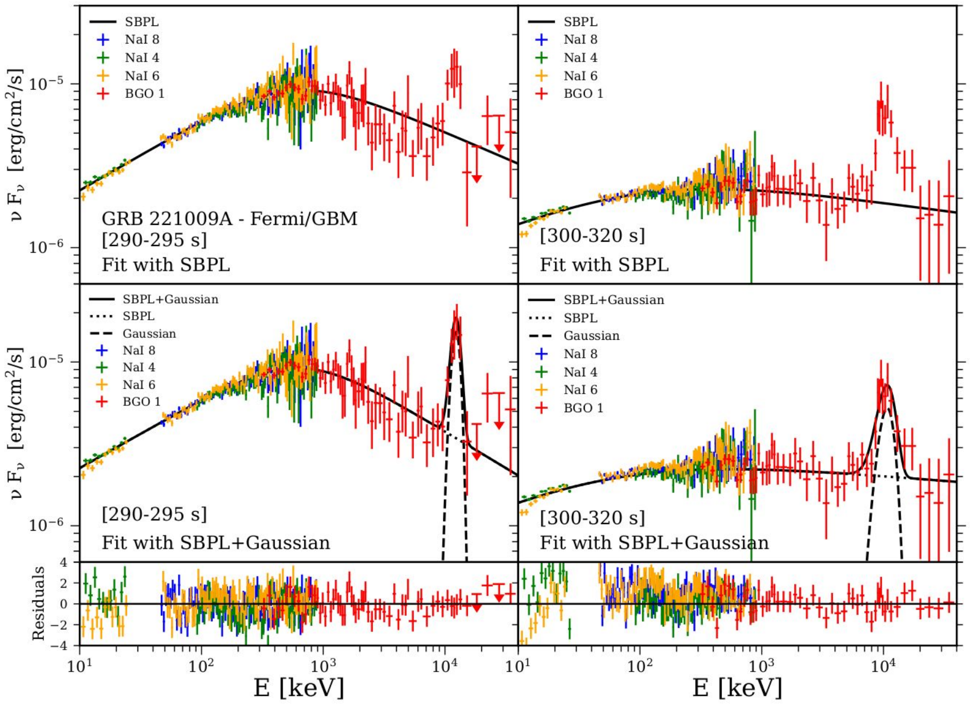
Take-home messages

Ravasio et al. 2023, Science (in press), arXiv:2303.16223



1. There is a highly significant (**> 6σ**), bright (**L~10^{50} erg/s**) and narrow (**width~1 MeV**) **emission** feature at **~10 MeV** in the **prompt** emission spectrum of the brightest ever GRB 221009A

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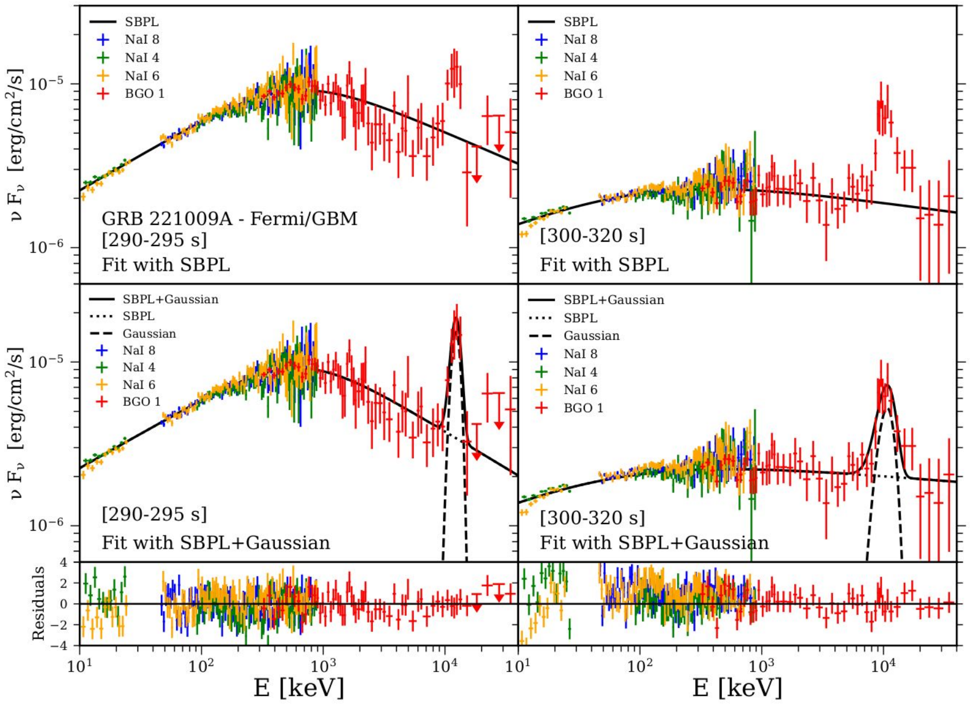

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2. This spectral feature is found in several time bins and it **evolves in time**, becoming softer and dimmer in ~80 s

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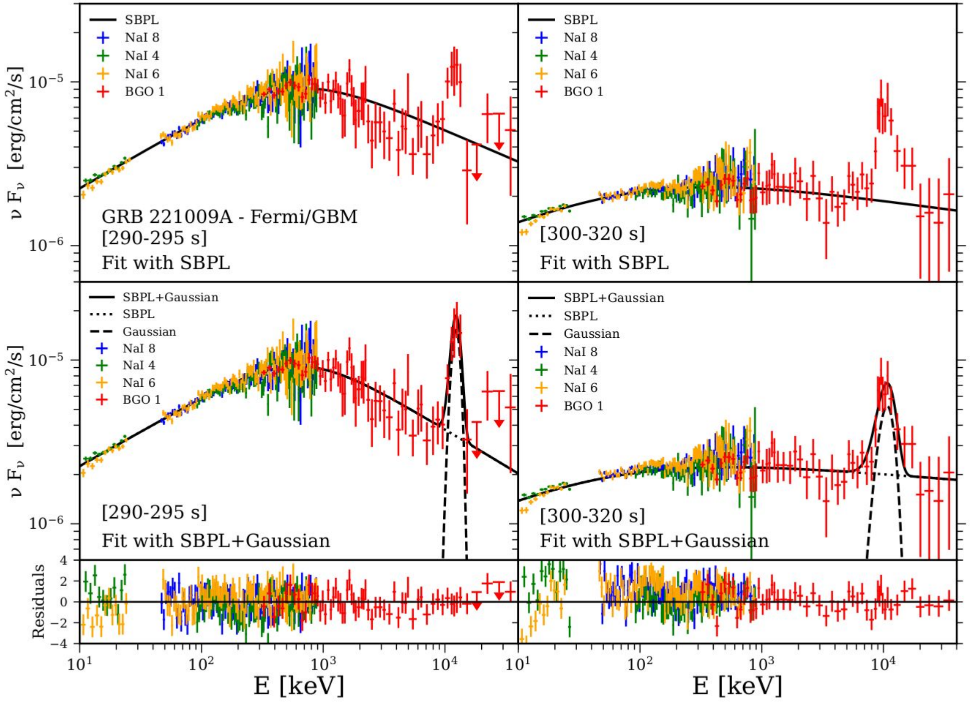

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3. Possible **interpretations**:
   - blue-shifted **annihilation line** [HLE?]
   - up-scattered atomic line [Fe?]

→ can shed light on the poorly understood jet properties!

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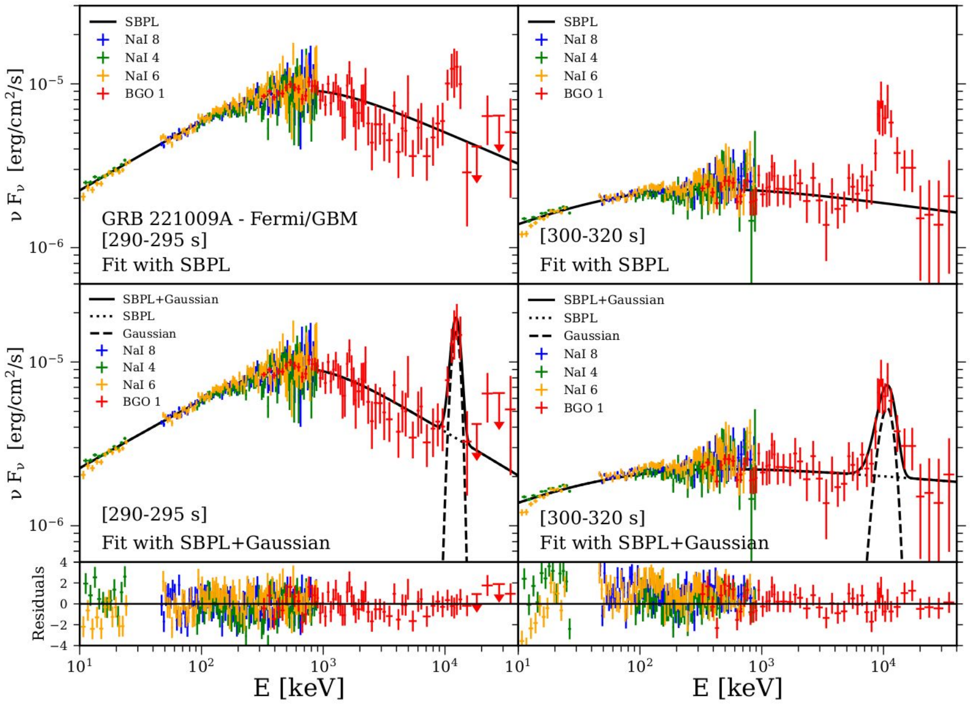

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4. Many **open question**: how common is this? When it is best visible in a GRB lightcurve (e.g. pulse decay)? What it can tell about the jet composition & energy dissipation mechanism? Are the formation conditions a prerogative of extreme bursts?

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