The role of internal shocks in prompt gamma-ray burst emission: implications for synchrotron radiation and spectral breaks

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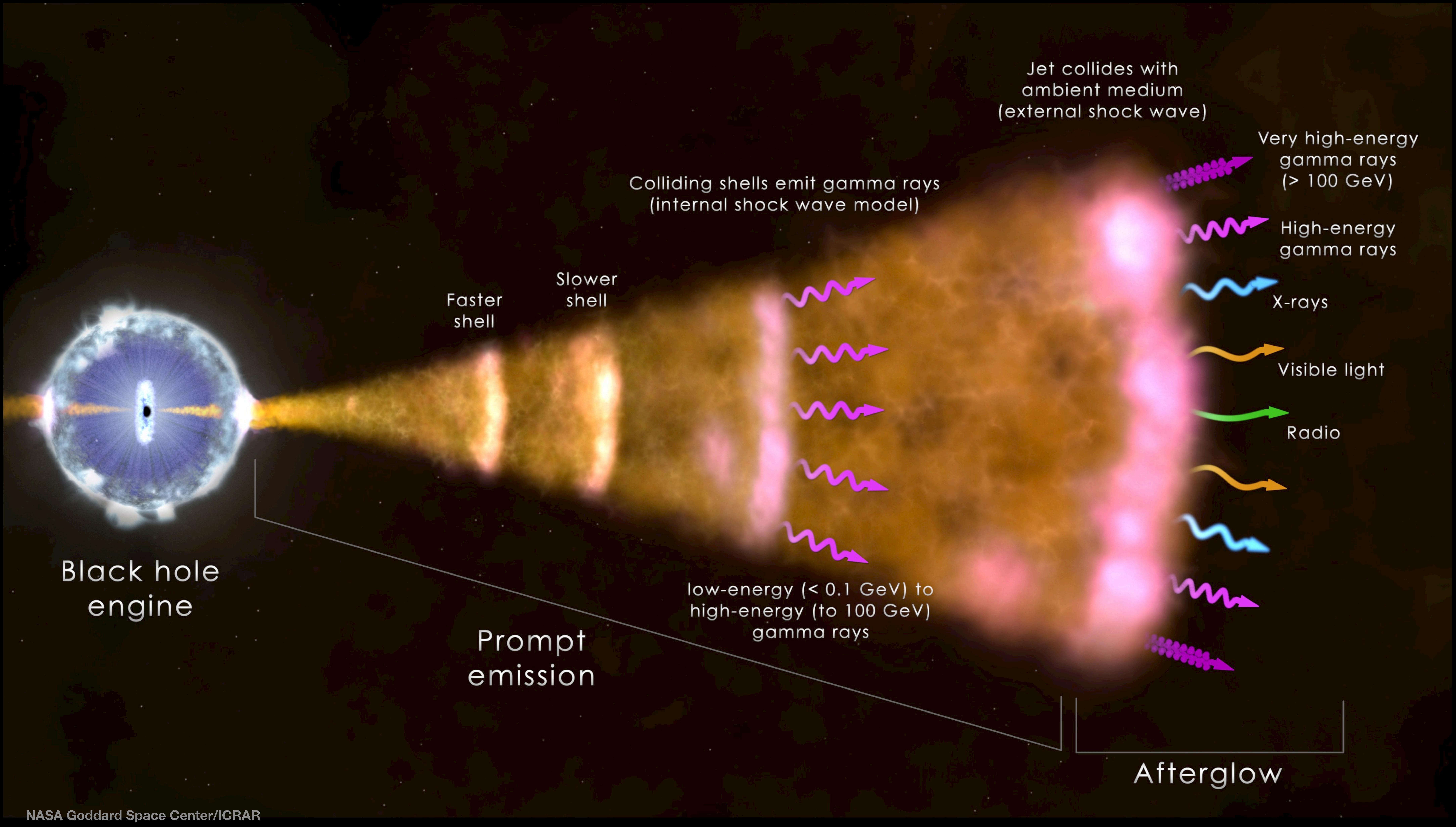
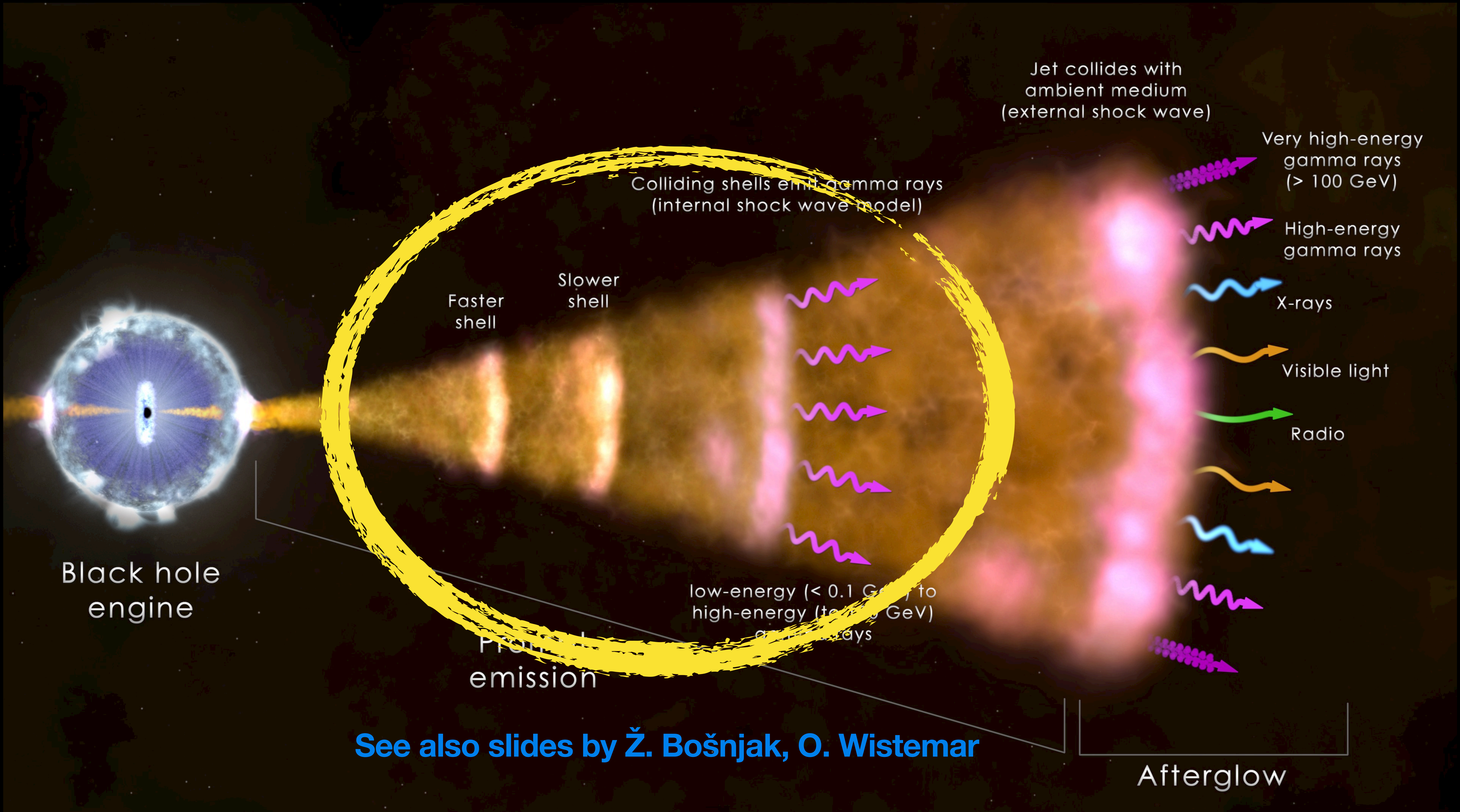
with Lara Nava, Giancarlo Ghirlanda, Om Sharan Salafia

Sexten, 02/07/2025


Jet collides with
ambient medium
(external shock wave)
Very high-energy
gamma rays
(> 100 GeV)
Colliding shells emit gamma rays
(internal shock wave model)
High-energy
gamma rays
Slower
shell
Faster
shell
X-rays
Visible light
Radio
Black hole
engine
low-energy (< 0.1 GeV) to
high-energy (to 100 GeV)
gamma rays
Prompt
emission
Afterglow
NASA Goddard Space Center/ICRAR

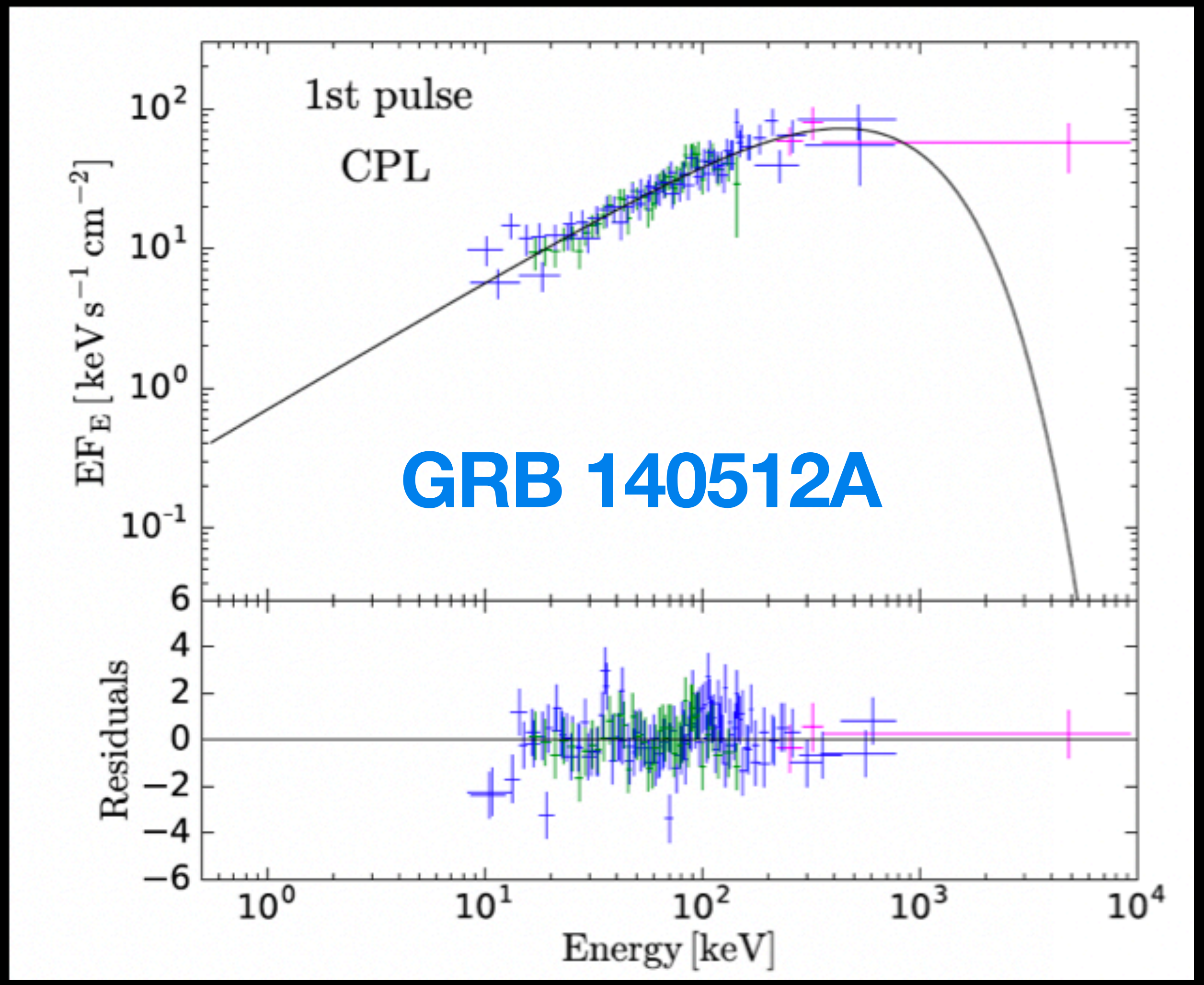


See also slides by Ž. Bošnjak, O. Wistemar

NASA Goddard Space Center/ICRAR

What is the (main) mechanism responsible for prompt emission in gamma-ray bursts?

A prompt emission spectral break is consistent with synchrotron emission, α_1 = -2/3, based on Swift and Fermi-GBM data



Oganesyan+ 2017

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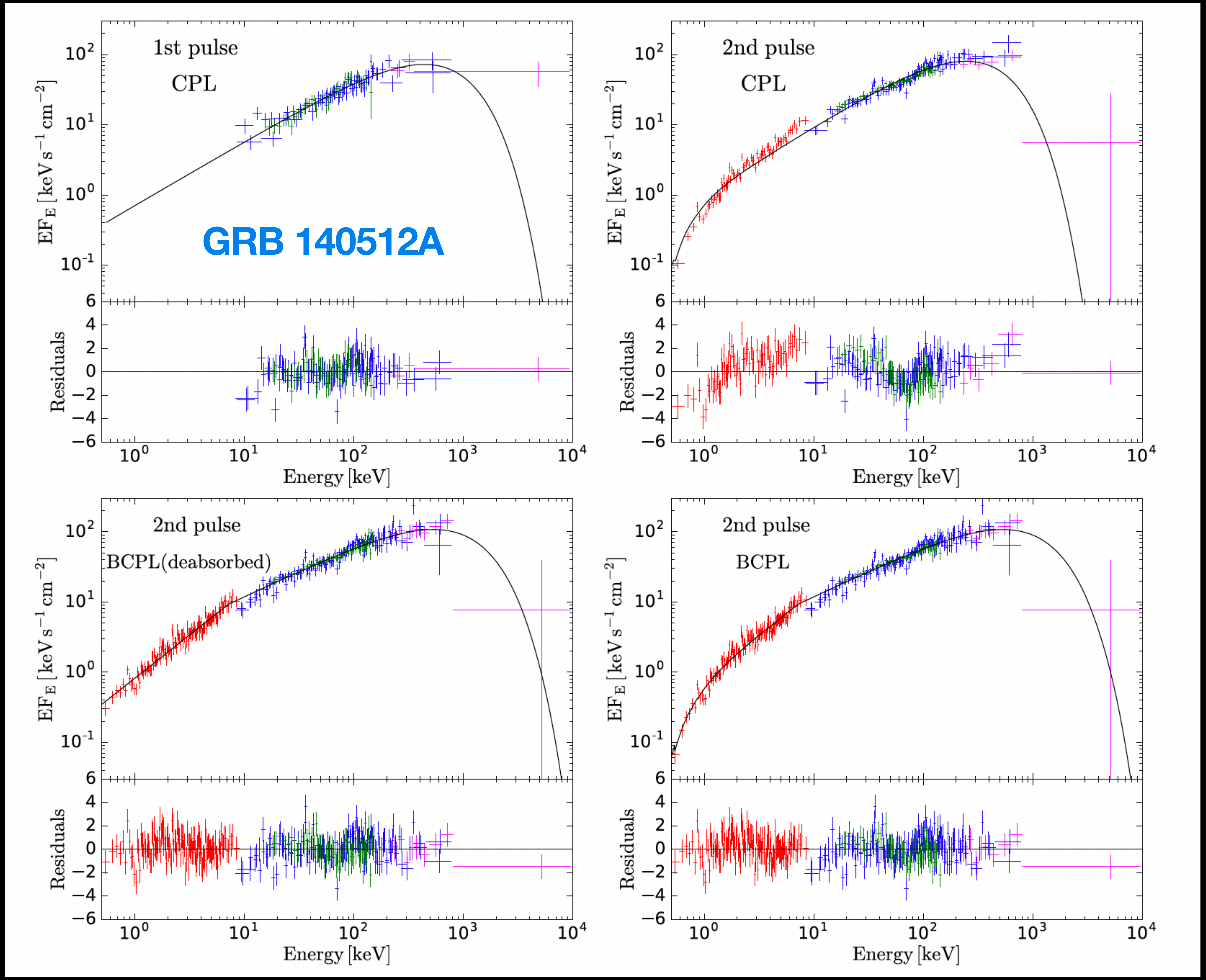
2nd pulse includes XRT observations



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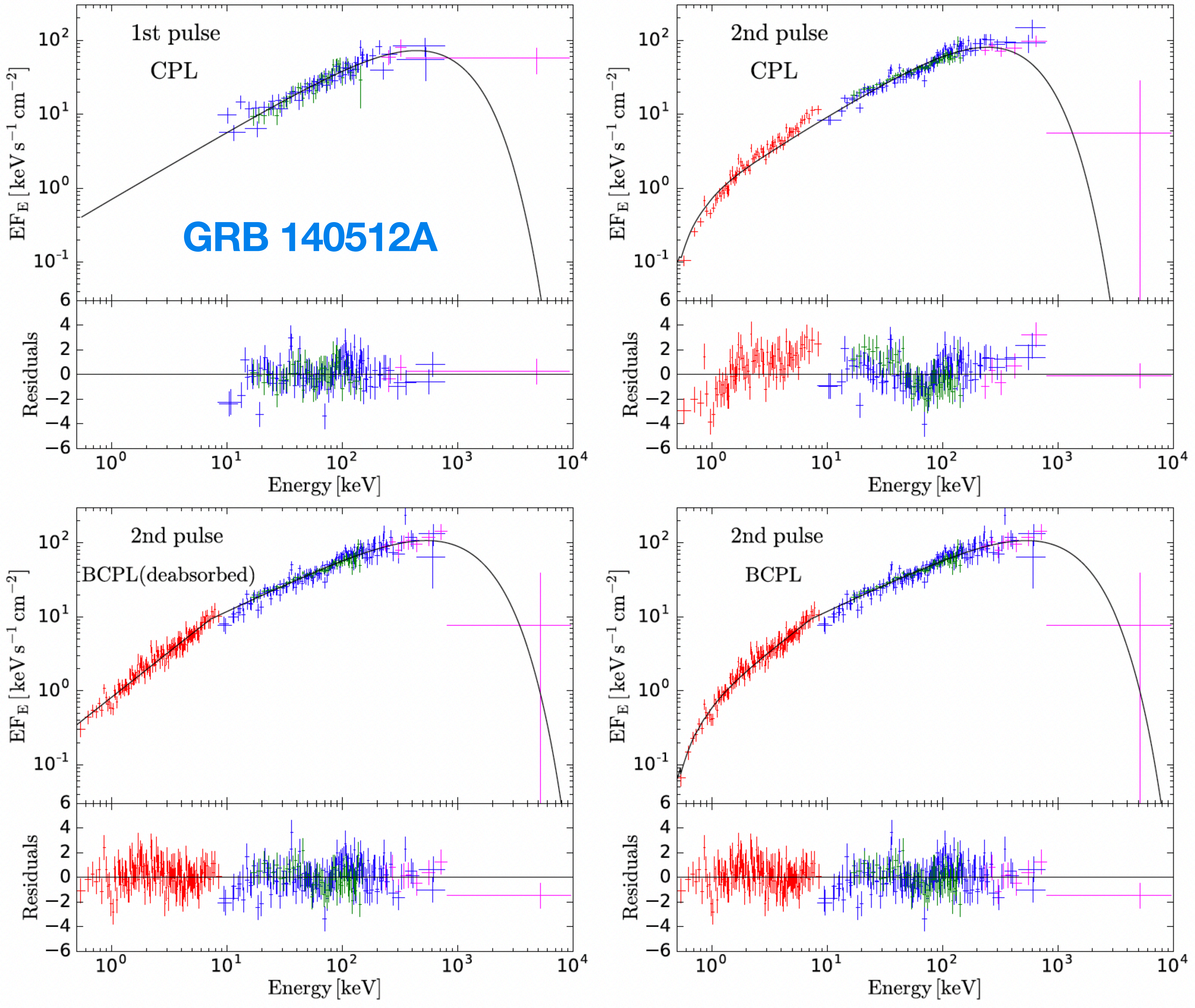

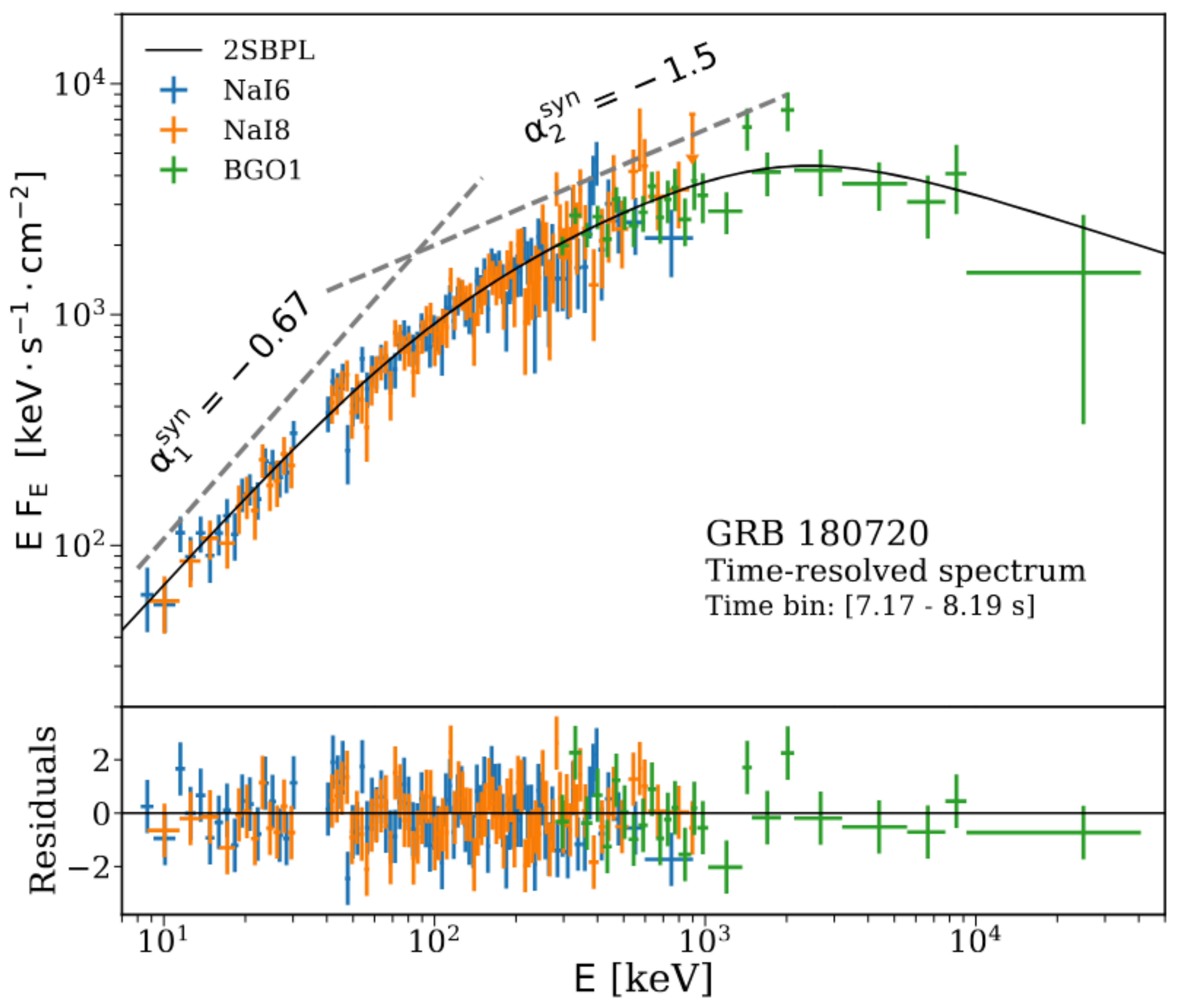

Oganesyan+ 2017

Ravasio+ 2019

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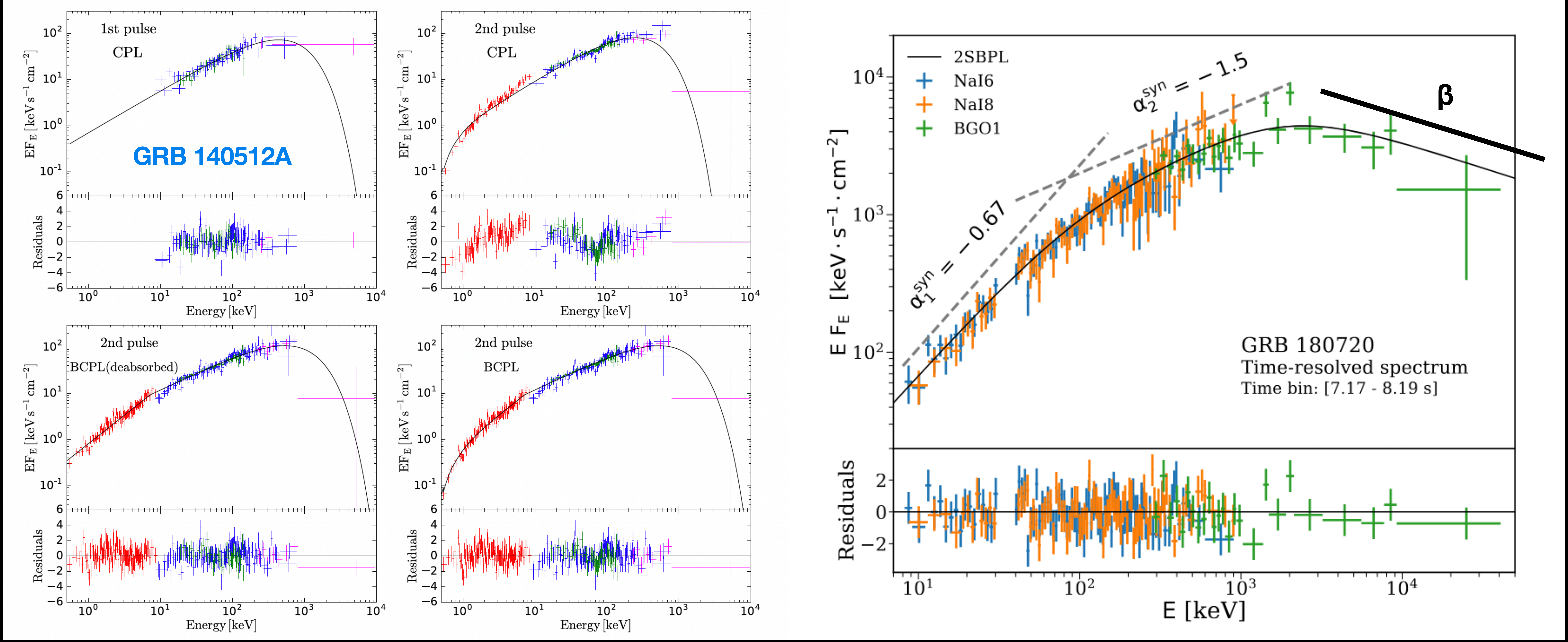
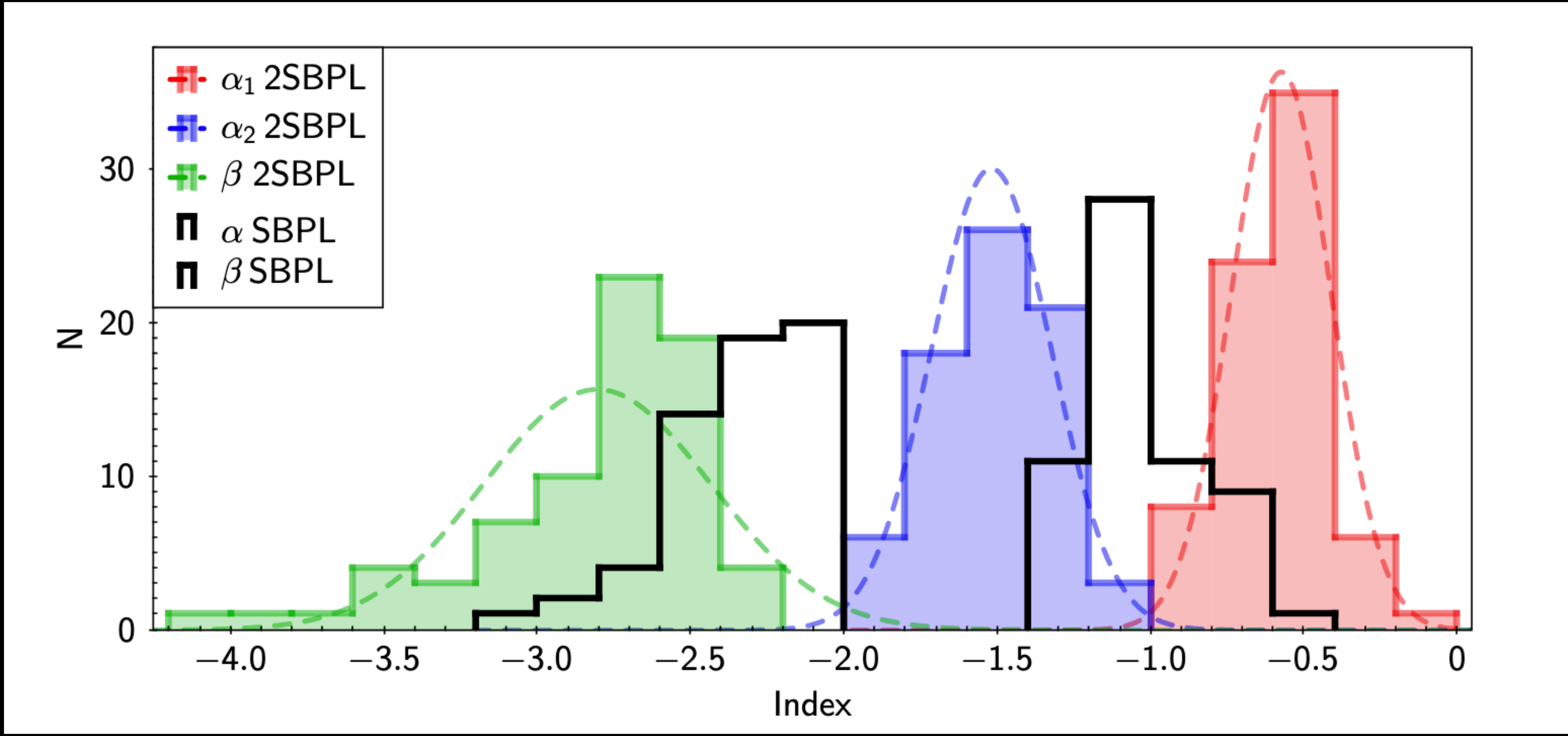


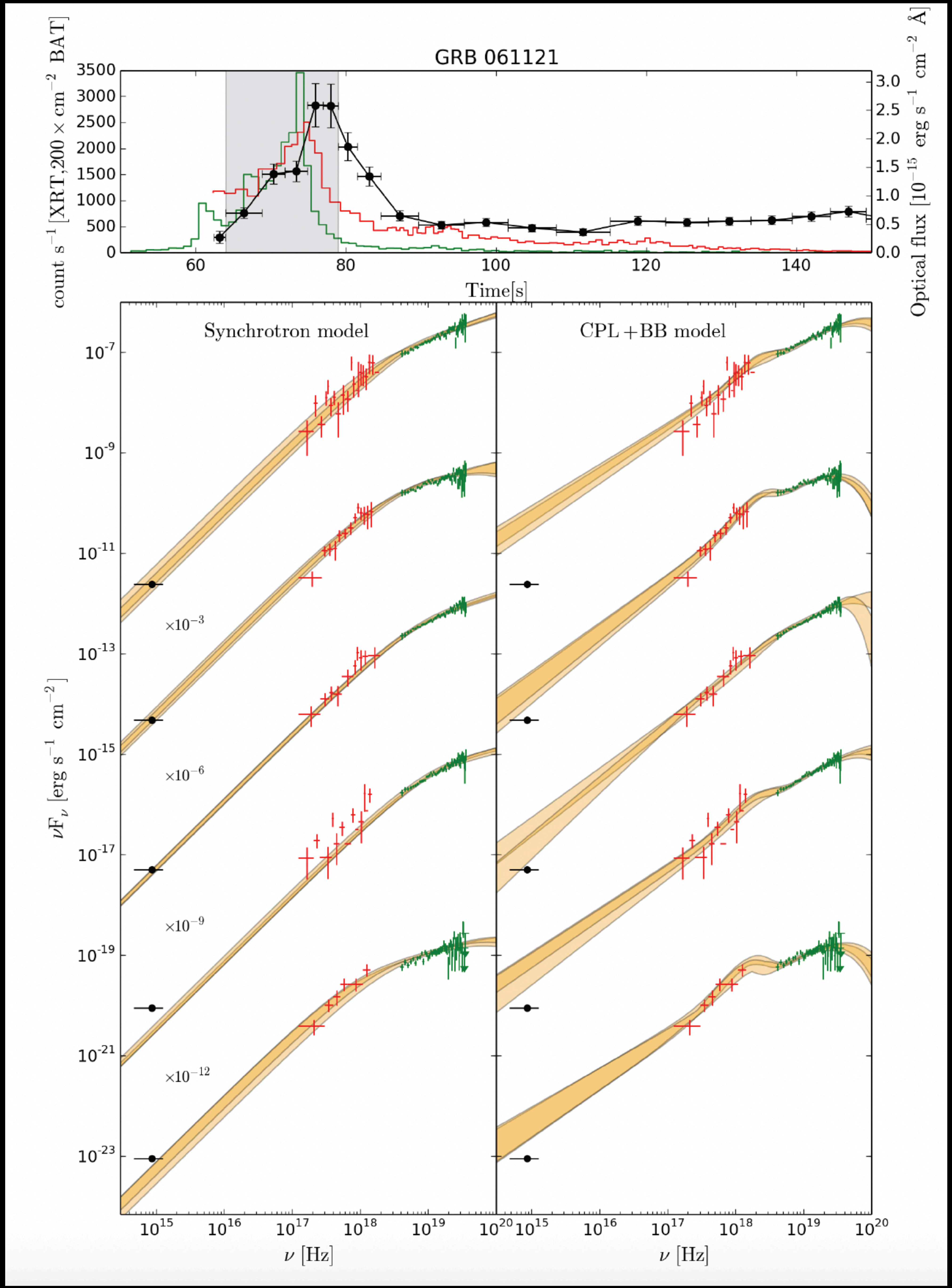
Oganesyan+ 2017

Ravasio+ 2019

Further analysis with Fermi-GBM and Swift confirms the spectral break at low energies

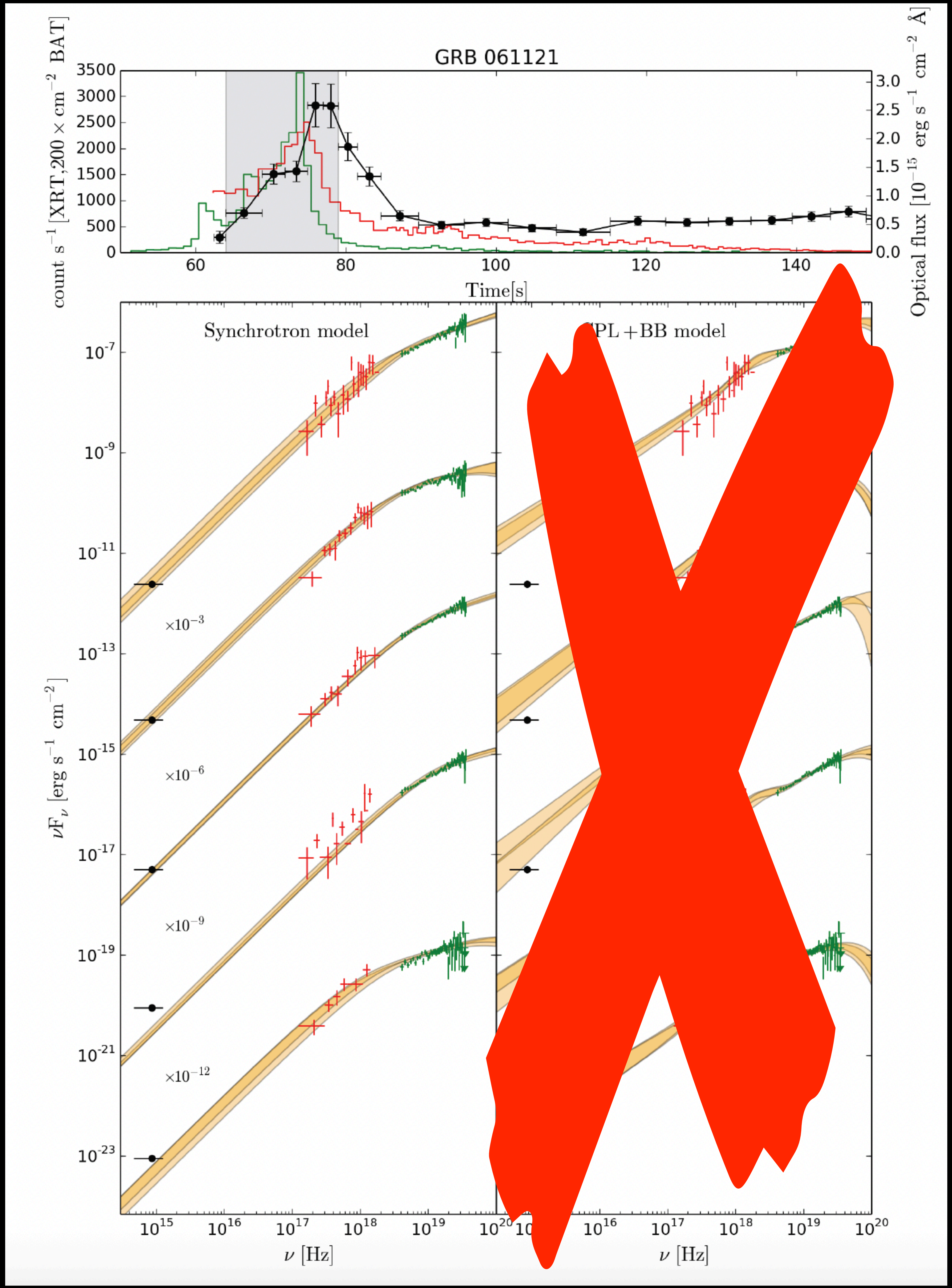


Ravasio+ 2019



Additional optical observations consistent with synchrotron model with α_1 = -2/3; rule out or severely constrain other models

Oganesyan+ 2019



Additional optical observations consistent with synchrotron model with α_1 = -2/3; rule out or severely constrain other models

Oganesyan+ 2019

A summary so far…

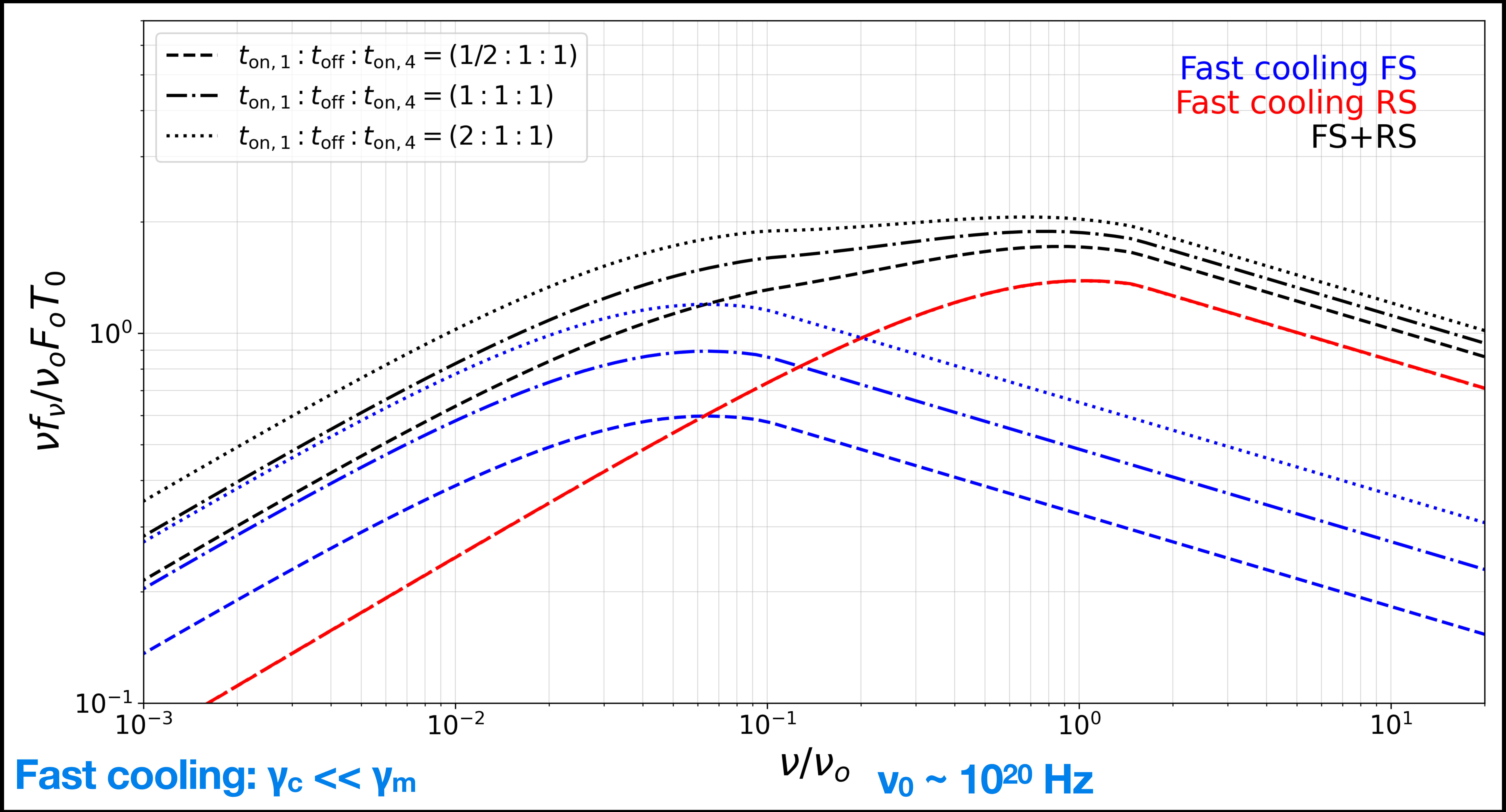
- GRB observations show an **additional spectral break at low energies**
- **Synchrotron radiation a promising candidate** mechanism to explain breaks
- Additional **optical data essential to further constrain models**, spectral index $\alpha_1 = -2/3$

Modeling the emission as the sum of contributions from forward and reverse shocks

GS+ in prep

See also Rahaman+ 2023, 2024

Synchrotron radiation where both shocks are in fast cooling is ruled out as it is unable to reproduce the spectral index inferred from observations



GS+ in prep

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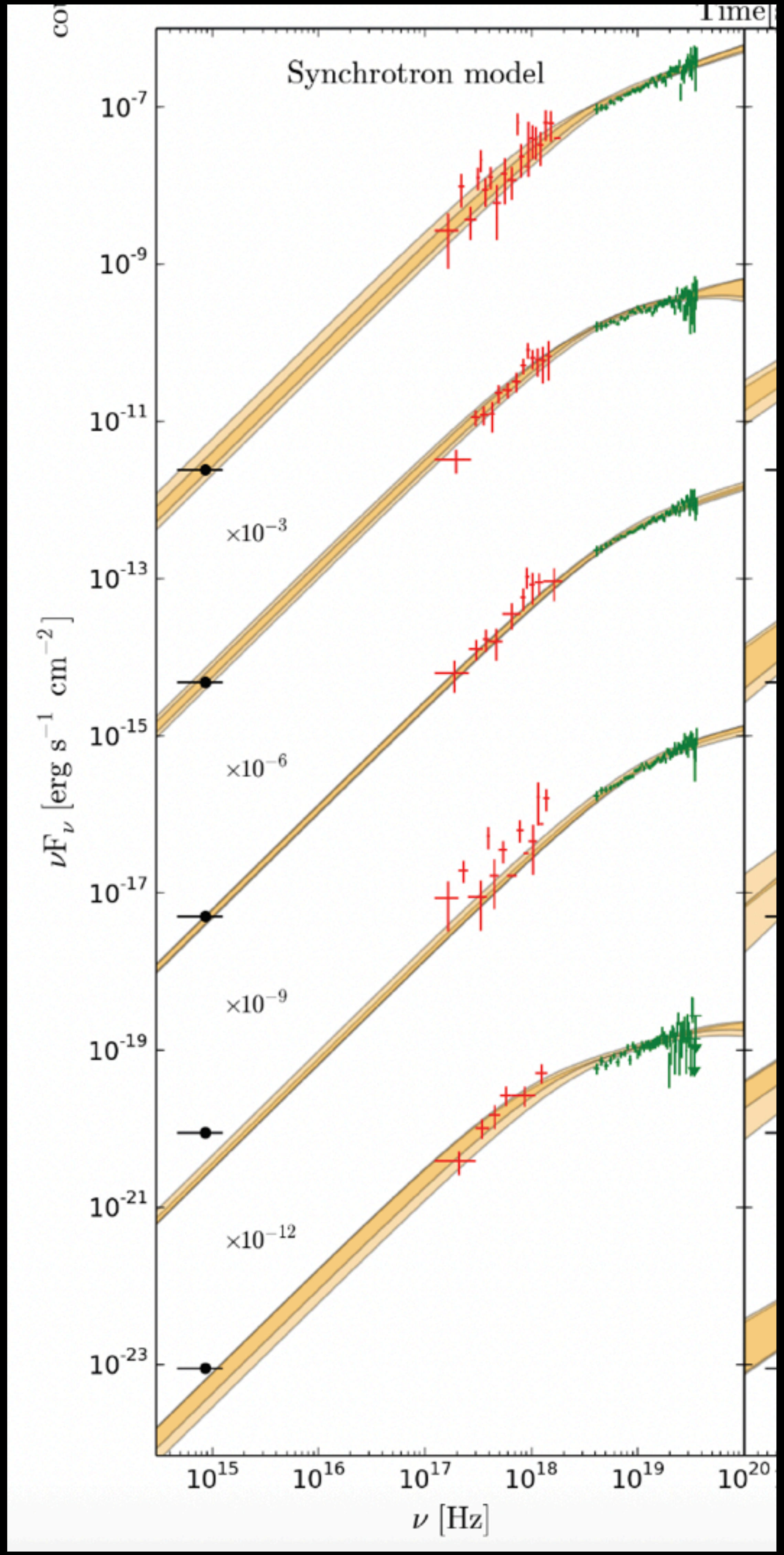
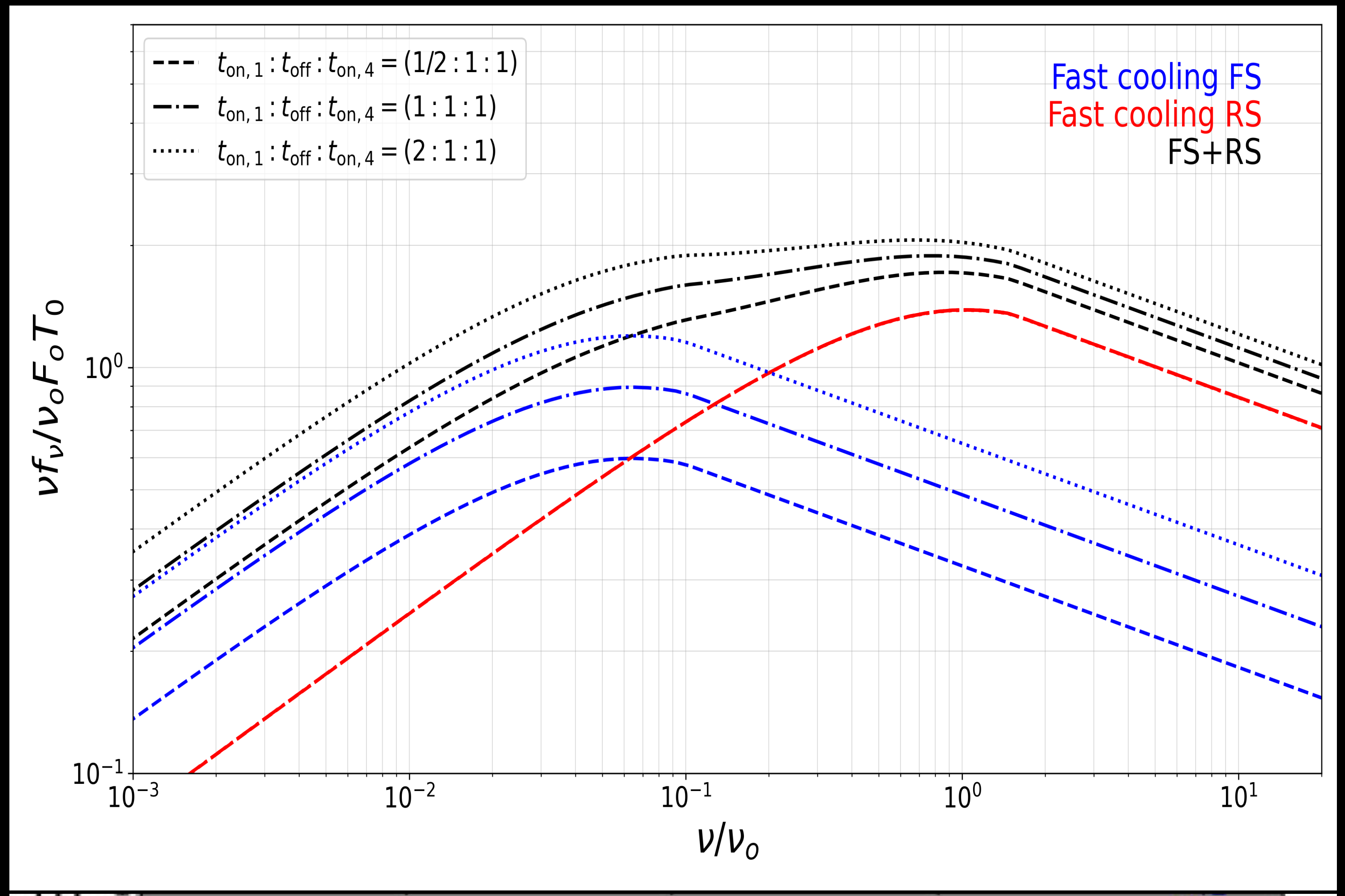
What if the forward shock is in the marginally fast cooling regime?

GS+ in prep

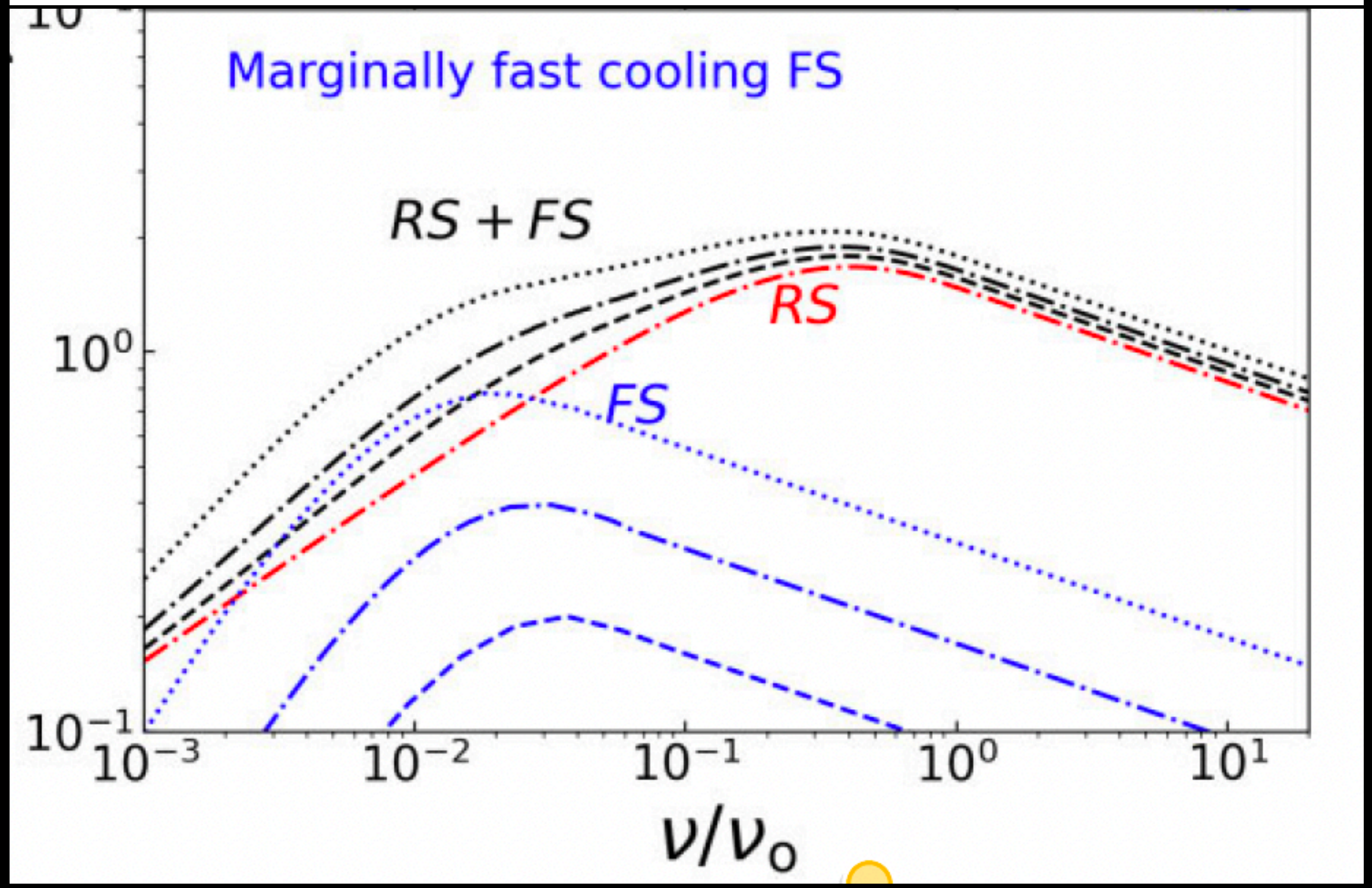


Oganesyan+ 2019

Fast cooling: $\gamma_c << \gamma_m$



Marginally FC : $\gamma_c \sim \gamma_m$

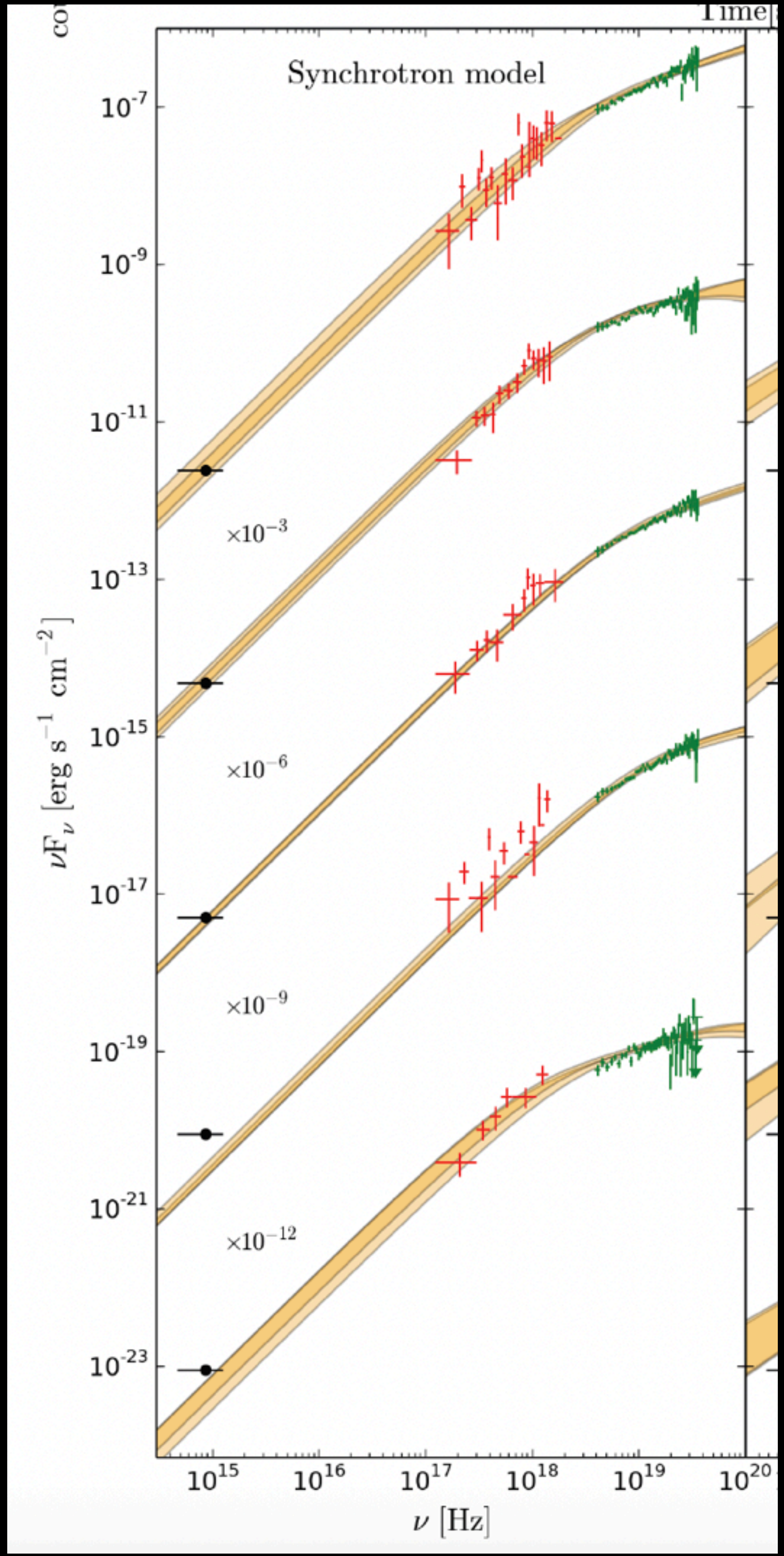


$\nu_0 \sim 10^{20}$ Hz

Rahaman+ 2024

Extrapolating to lower energies indicates RS (fast cooling) would dominate again, softening the spectrum

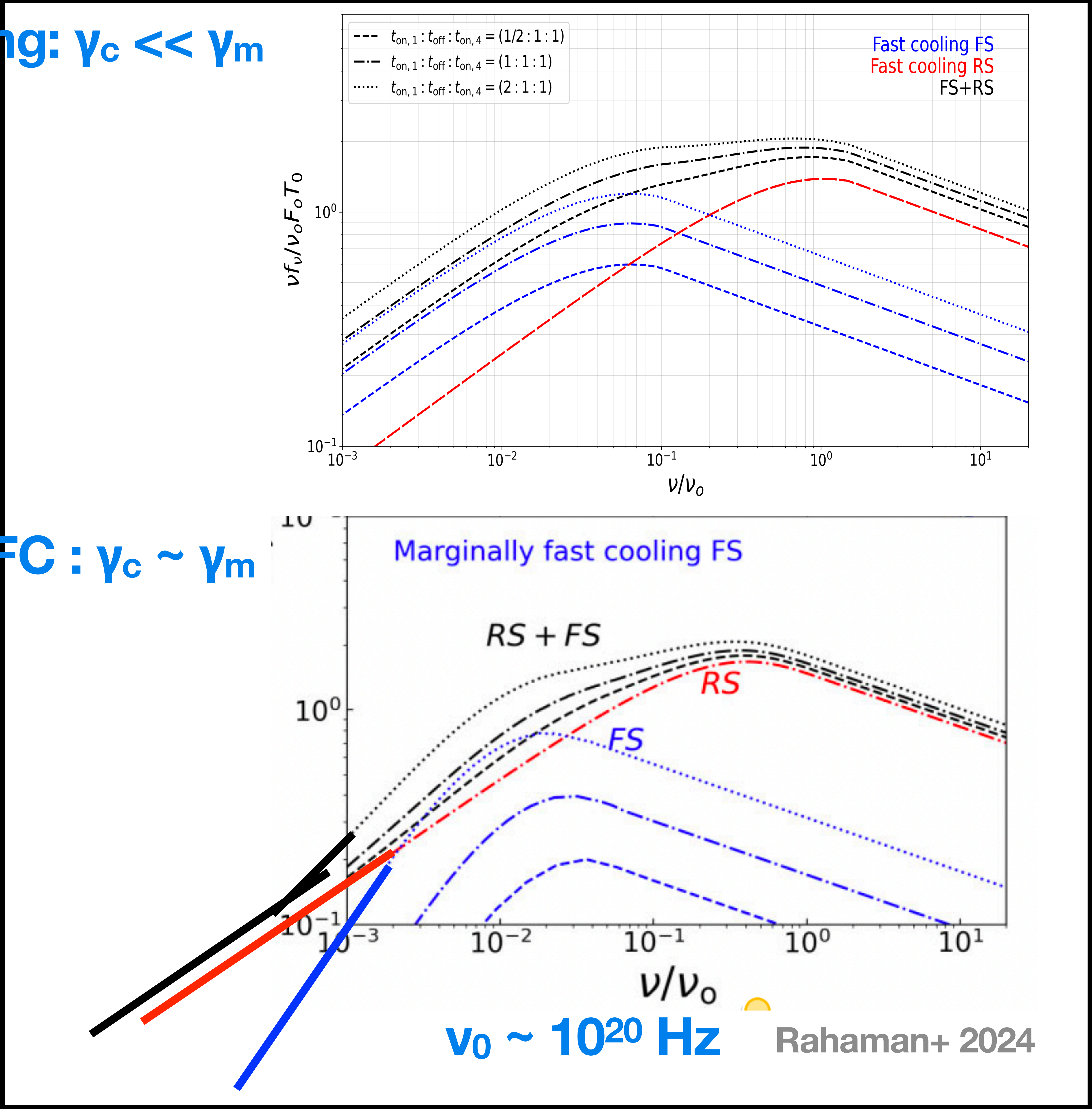
GS+ in prep



Oganesyan+ 2019

Fast cooling: $\gamma_c \ll \gamma_m$

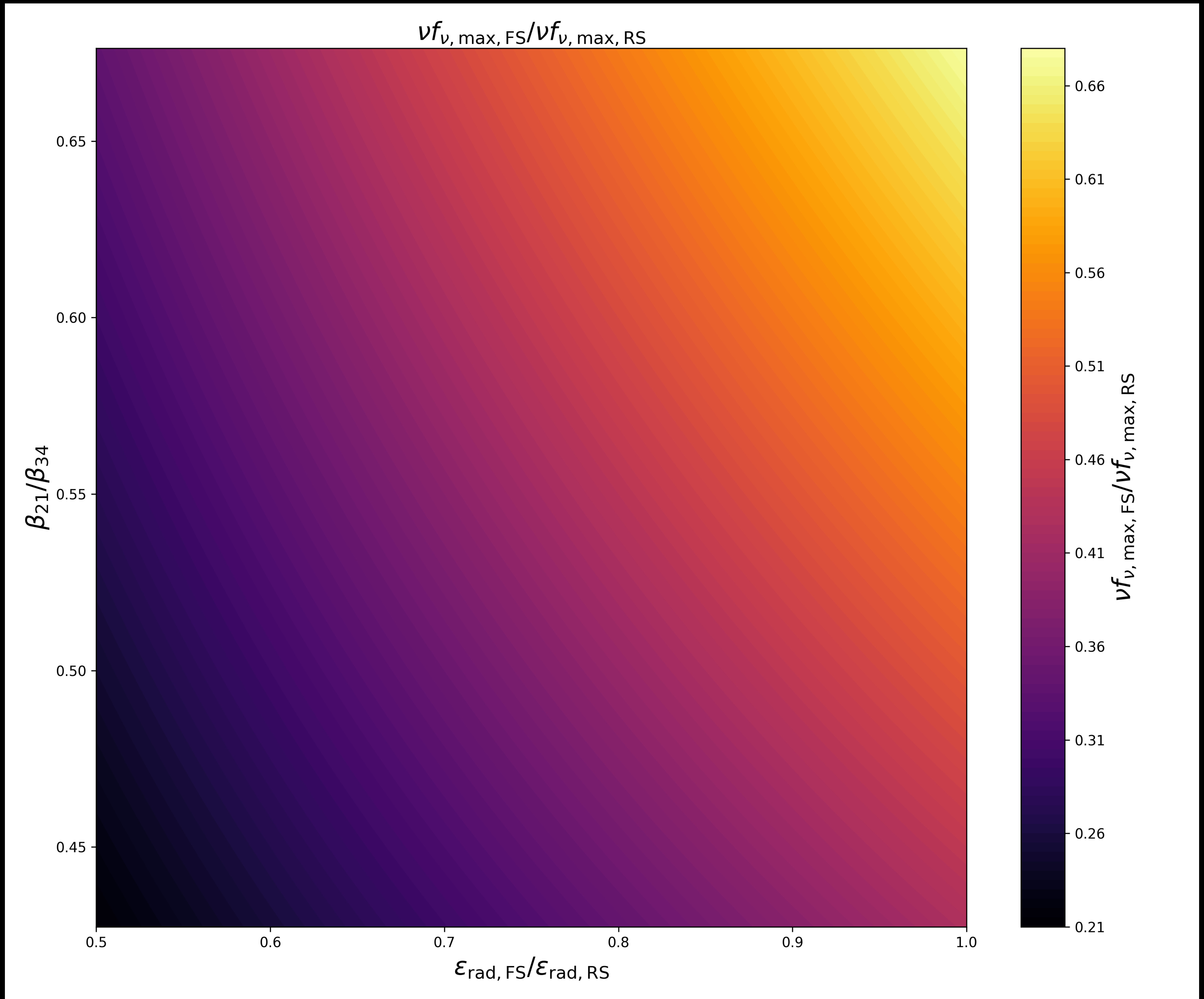
Marginally FC : $\gamma_c \sim \gamma_m$



$\nu_0 \sim 10^{20}$ Hz

Rahaman+ 2024

A full parameter exploration could shed light on quantitative limits of physical parameters and help constrain models



GS+ in prep

So, what have we learned?

- GRB observations show an **additional spectral break at low energies**
- Fermi GBM and Swift data show a **low-energy slope consistent with α = -2/3**
- Modeling the spectra as the composition of two synchrotron-dominated components (forward and reverse shocks) is able to **qualitatively** describe the low-energy spectral breaks, but an extrapolation of the spectra towards lower energies leads to a **spectral softening that conflicts with observational data**
- Ongoing **parameter space exploration might hint at quantitative limits** of such kind of modeling
- **Additional physics likely needed**: Inverse Compton effects on electron cooling? Decaying magnetic fields? Microphysical parameters?

Extras

$$\Gamma_{21} = \Gamma_2\Gamma_1(1 - \beta_2\beta_1),$$
$$\Gamma_{34} = \Gamma_3\Gamma_4(1 - \beta_3\beta_4).$$

$$\boxed{\gamma_{\mathrm{c,i}} = \frac{3m_e c}{4\sigma_{\mathrm{T}} U'_B t'_{\mathrm{syn,i}}}},$$

$$\boxed{\gamma_{\mathrm{m}} = \frac{p-2}{p-1}\frac{\epsilon_{\mathrm{e}}}{\xi_{\mathrm{e}}}\frac{m_{\mathrm{p}}}{m_{\mathrm{e}}}(\Gamma - 1)}.$$

$$j'_\nu = j'_{\nu,\max} \times \begin{cases} (\nu/\nu_c)^{1/3} & \text{if } \nu < \nu_c \\ (\nu/\nu_c)^{-1/2} & \text{if } \nu_c < \nu < \nu_m \\ (\nu_m/\nu_c)^{-1/2}(\nu/\nu_m)^{-p/2} & \text{if } \nu > \nu_m. \end{cases}$$

$$j'_\nu = j'_{\nu,\max} \times \begin{cases} (\nu/\nu_m)^{1/3} & \text{if } \nu < \nu_m \\ (\nu/\nu_m)^{-(p-1)/2} & \text{if } \nu_m < \nu < \nu_c \\ (\nu_c/\nu_m)^{-(p-1)/2}(\nu/\nu_c)^{-p/2} & \text{if } \nu > \nu_c, \end{cases}$$

$$N(E) = A \begin{cases} \left(\frac{E}{100\,\mathrm{keV}}\right)^{\alpha} \mathrm{e}^{-\left(\frac{E}{E_0}\right)}, & \text{for } E < (\alpha-\beta)E_0 \\ \left[\frac{(\alpha-\beta)E_0}{100\,\mathrm{keV}}\right]^{\alpha-\beta} \left(\frac{E}{100\,\mathrm{keV}}\right)^{\beta} \mathrm{e}^{\beta-\alpha}, & \text{for } E \geq (\alpha-\beta)E_0, \end{cases}$$