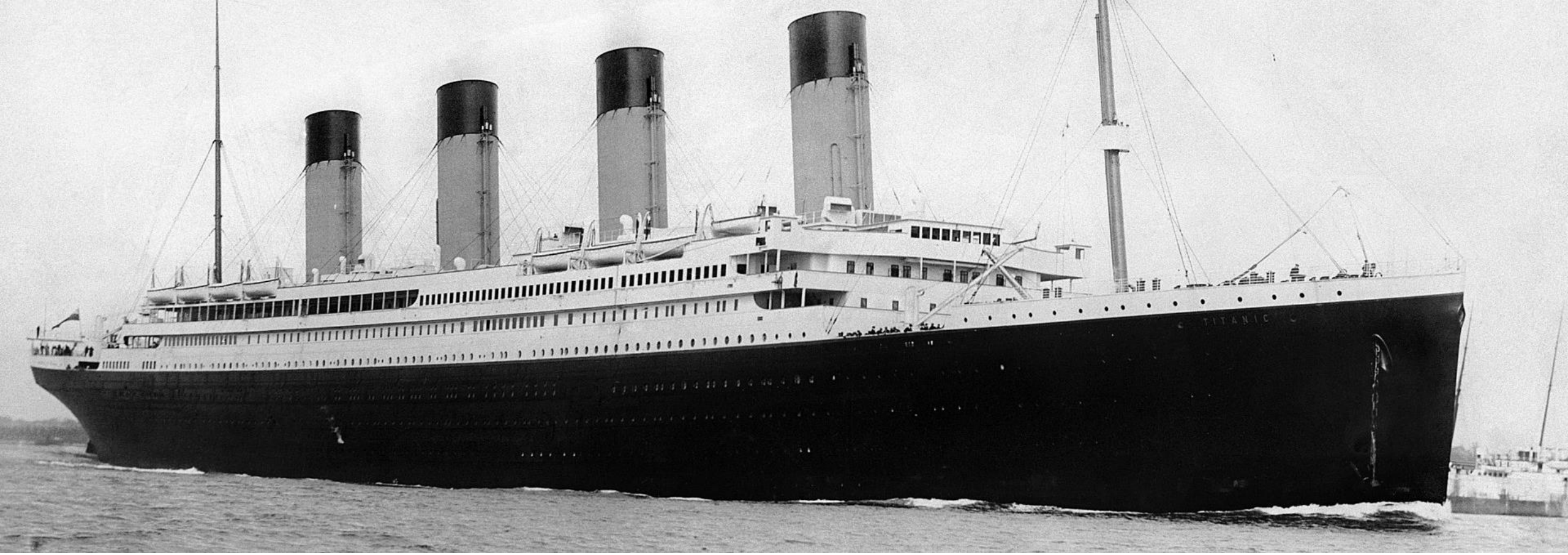


GRB 221009A: Afterglow spectrum

Gamma group meeting 30.06.2023

Marc Klinger, Andrew Taylor, Tyler Parsotan, Andy Beardmore, Sebastian Heinz, Sylvia Zhu, Donggeun Tak

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

HELMHOLTZ

DESY.

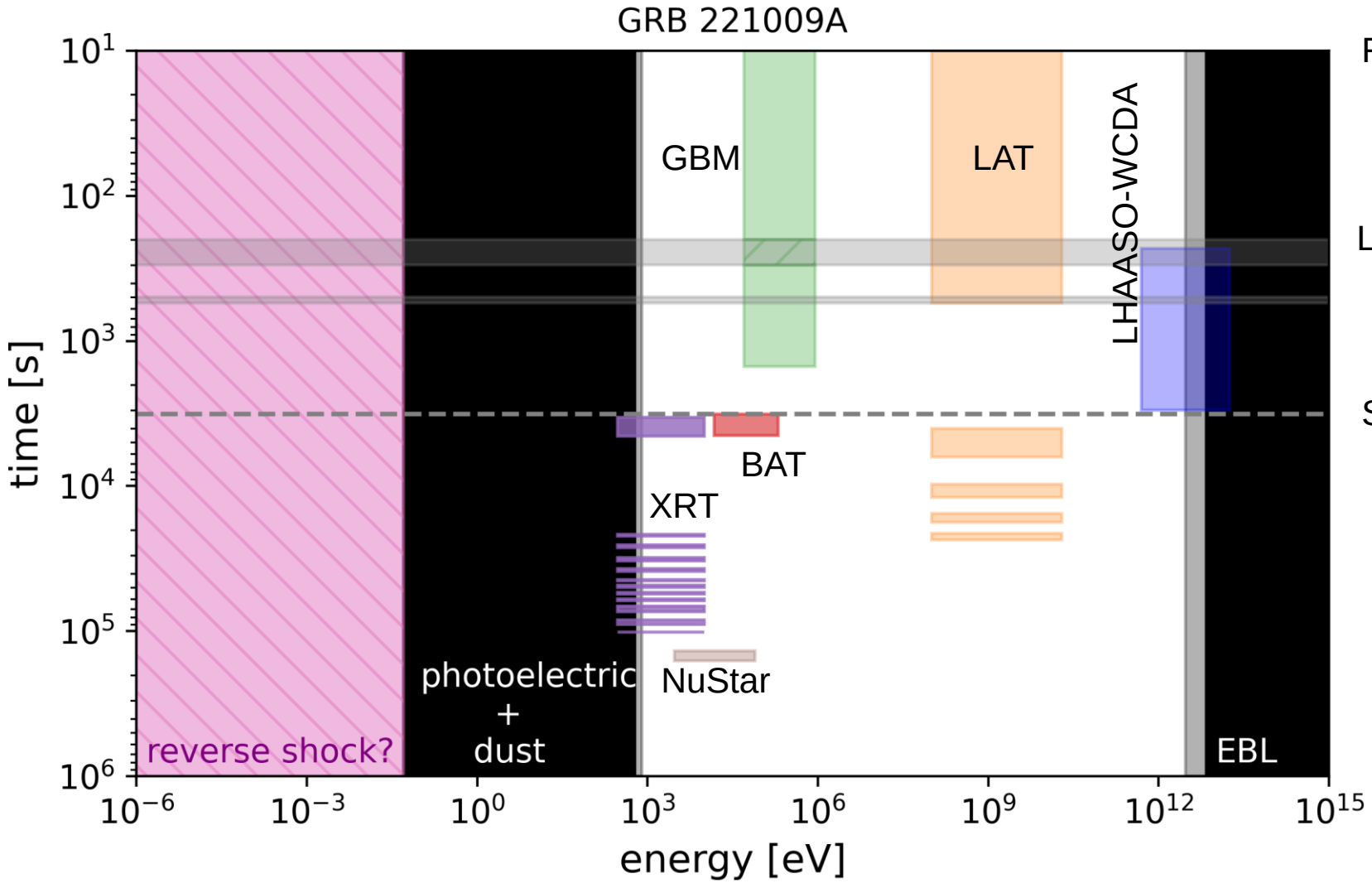
THE ASTROPHYSICAL JOURNAL LETTERS, 946:L31 (14pp), 2023 March 20 https://doi.org/10.3847/2041-8213/acc39c

GRB 221009A: The BOAT

- the Brightest Of All Times!... all times?
- everyone looked at it!... fantastic MWL coverage?
- even LHAASO saw 18TeV photons! … or 10TeV?
- best data set we have! Really …?
- not so straight forward..

Time – energy window

Time-Energy-Window



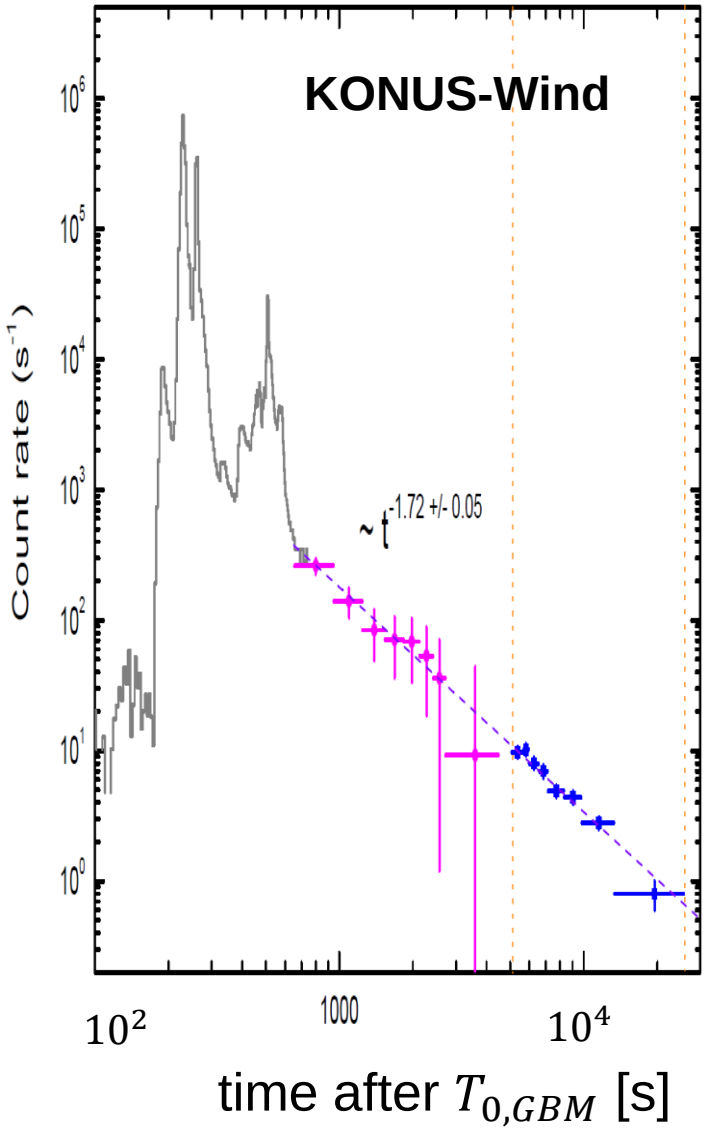
Fermi-GBM trigger T_0

LHAASO-WCDA onset $T_* = 226s$

Swift-BAT trigger (enters field of view)

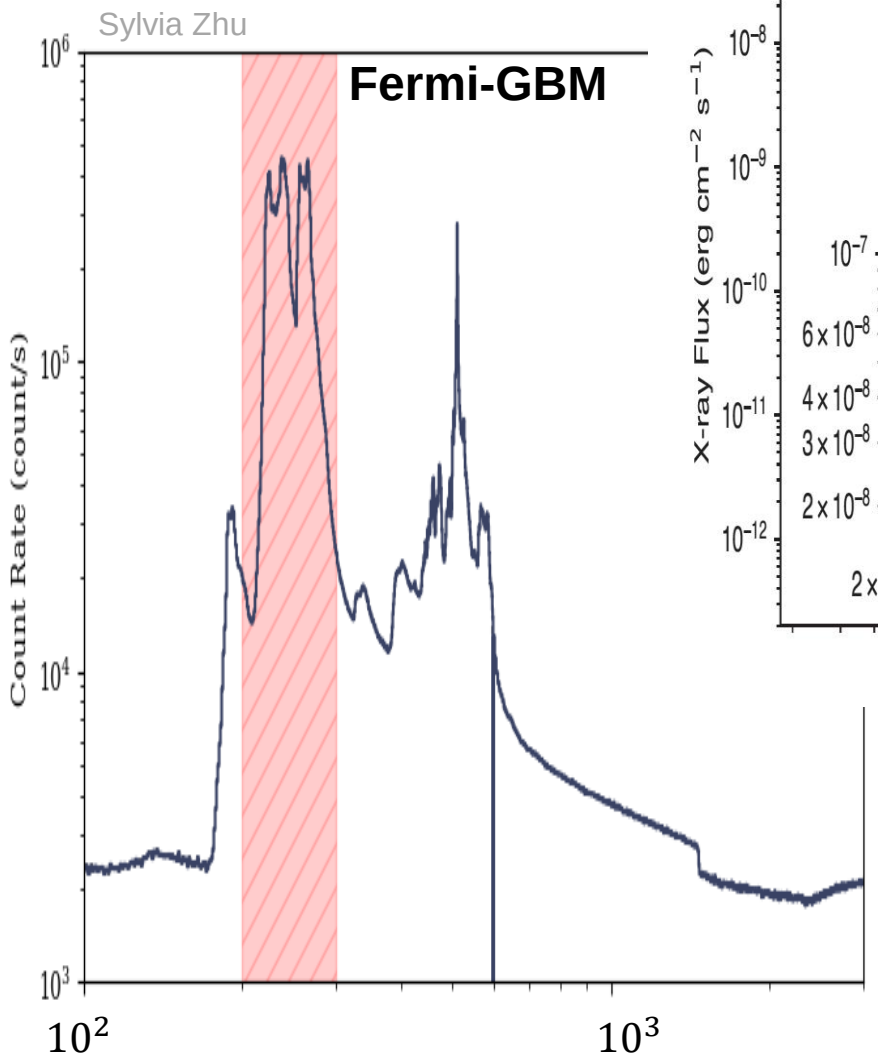
Start of afterglow? ~800s

Fredericks et al. 23



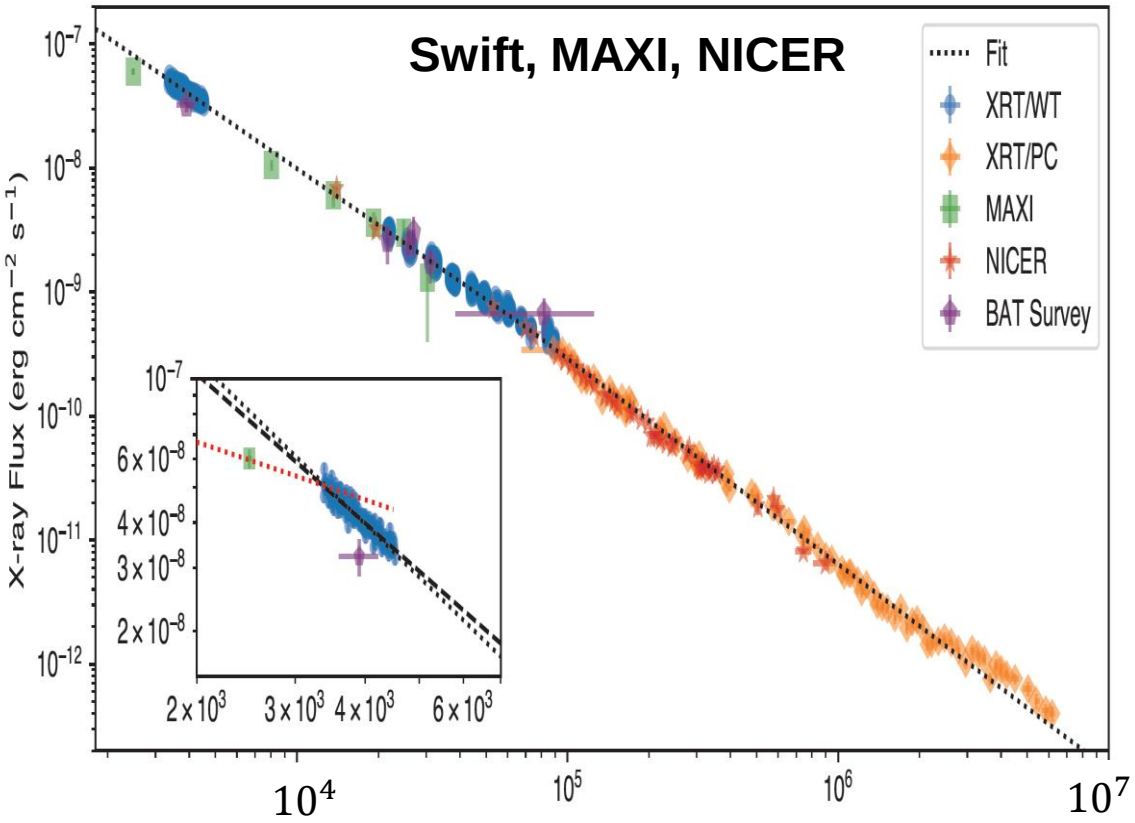
time after $T_{0,GBM}$ [s]

Sylvia Zhu



time after $T_{0,GBM}$ [s]

Williams et al. 23

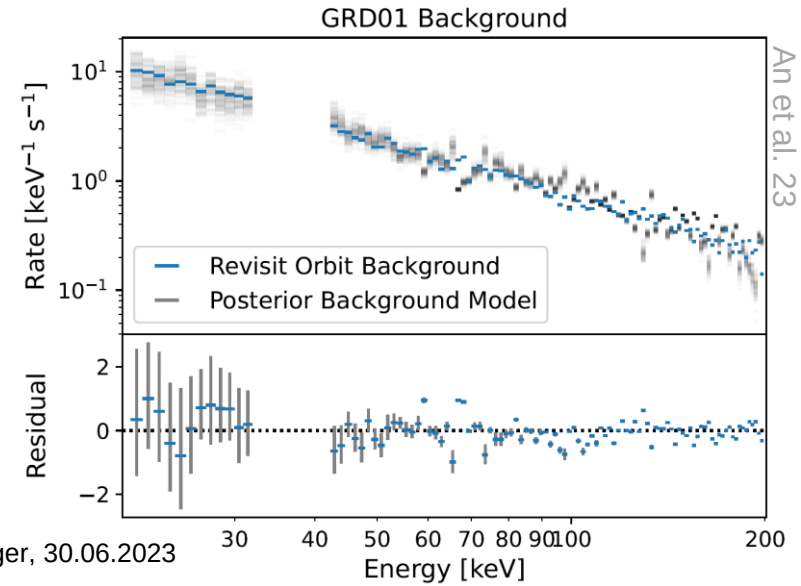


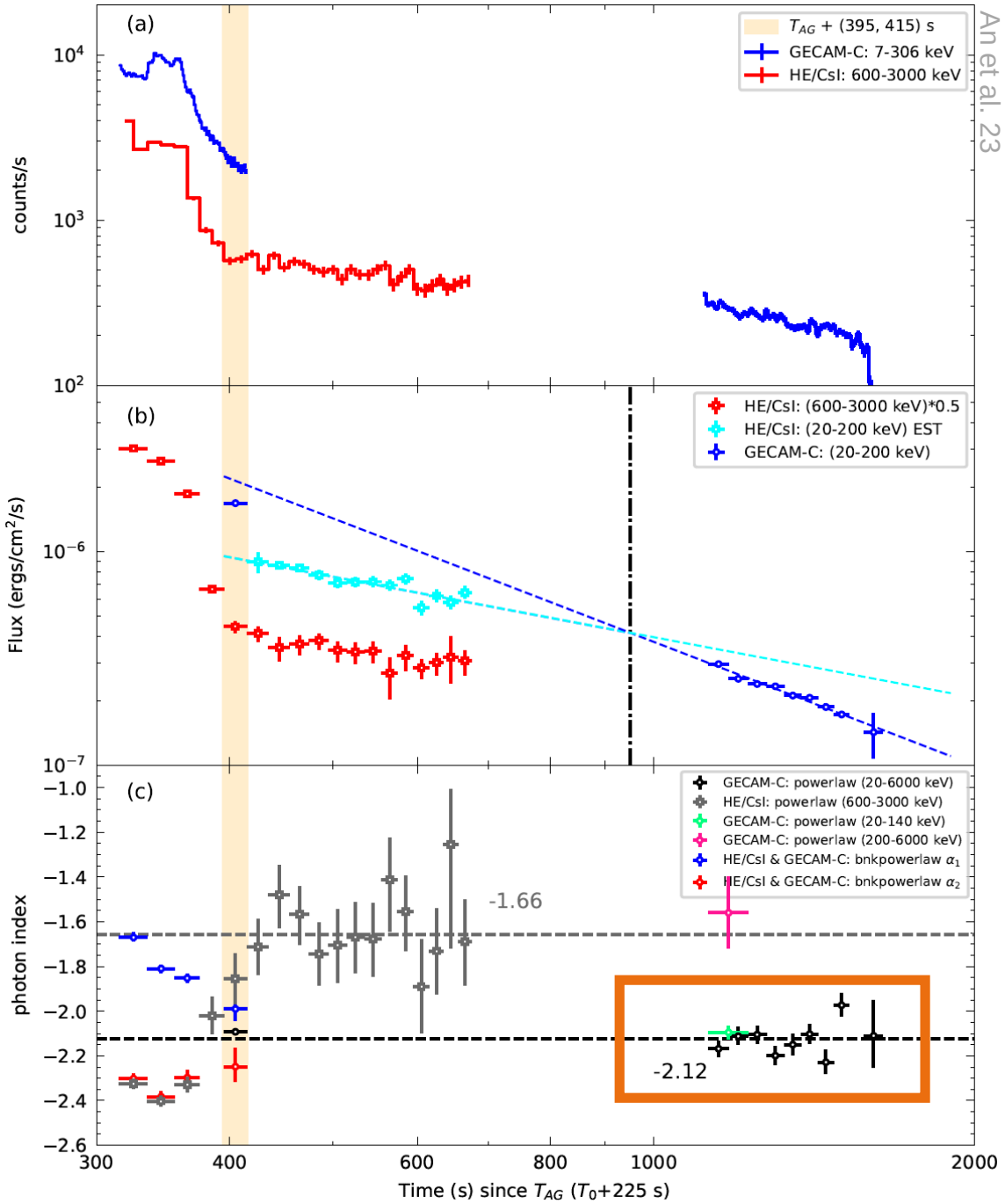
time after $T_{0,GBM}$ [s]

Insight-HXMT, GECAM-C

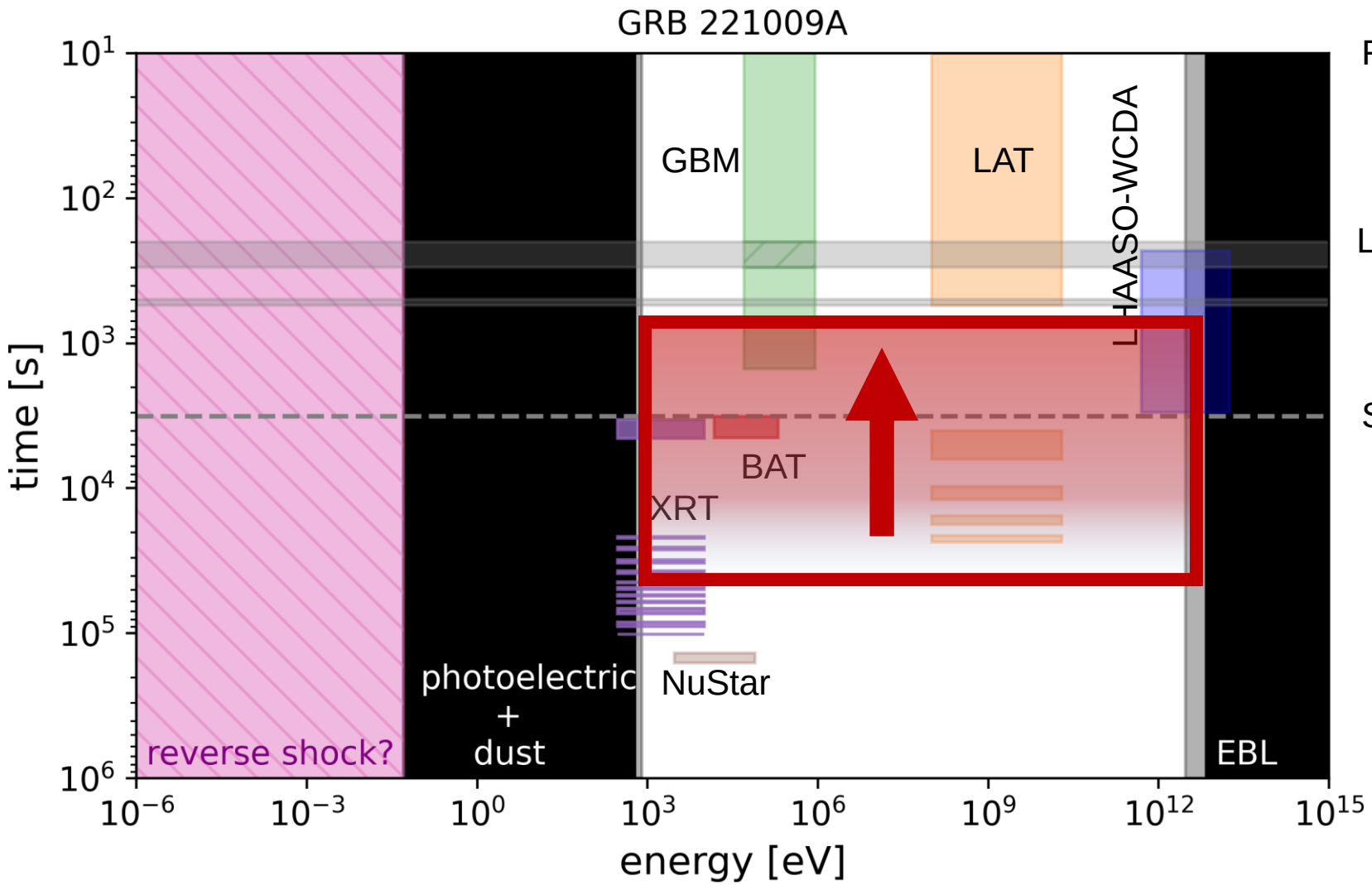
- data up to 2ks
- GECAM-C: 20keV – 6MeV
- spectral index ~ 2.1 (1.35-1.86ks)
- high energy band (>200keV) harder (~1.6)

EOT spectrum
2.1±0.15 (20-200keV)





Time-Energy-Window

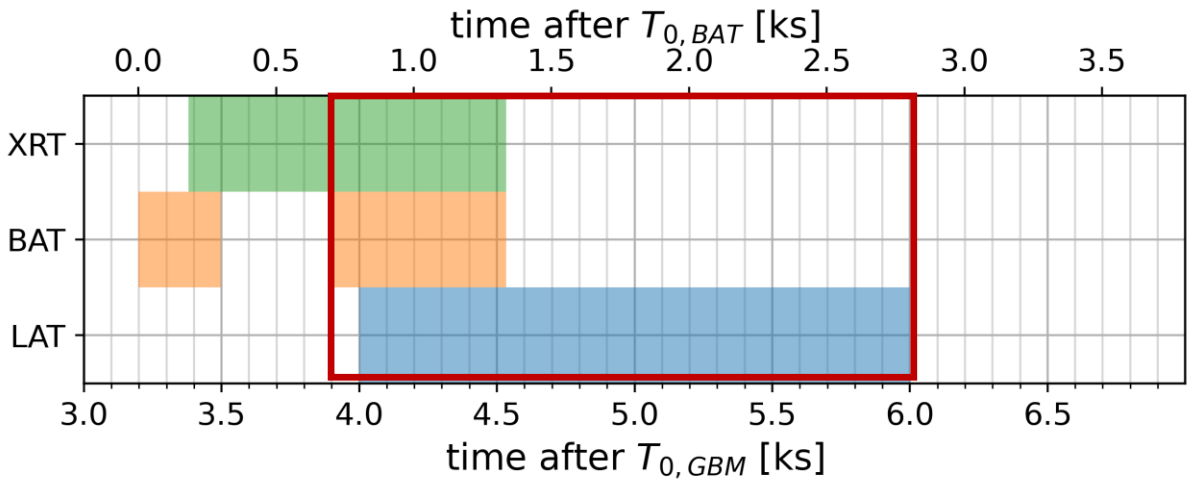


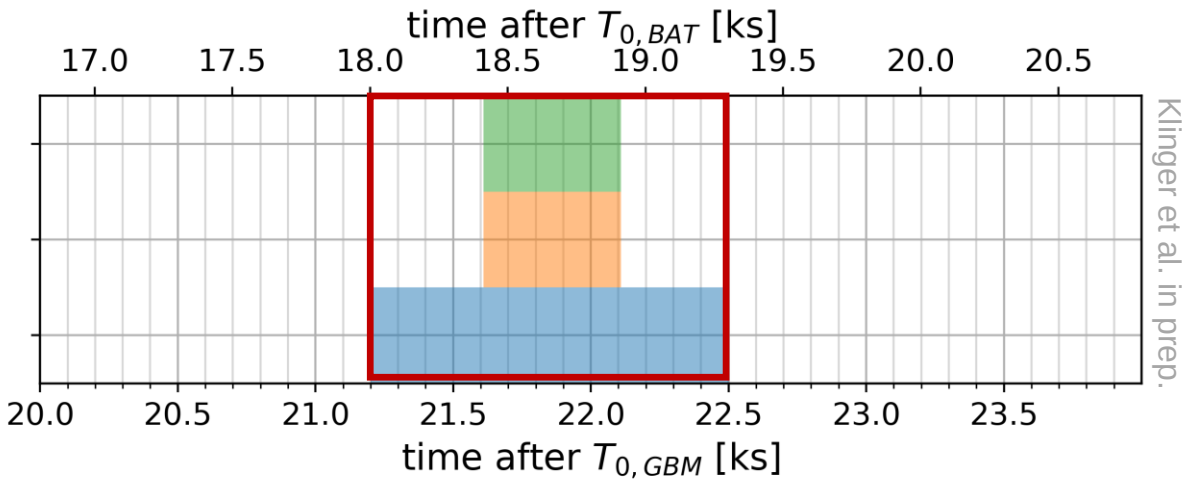
Fermi-GBM trigger T_0

LHAASO-WCDA onset $T_* = 226s$

Swift-BAT trigger (enters field of view)

Multiwavelength fit – 2 overlapping intervals





4ks window

22ks window

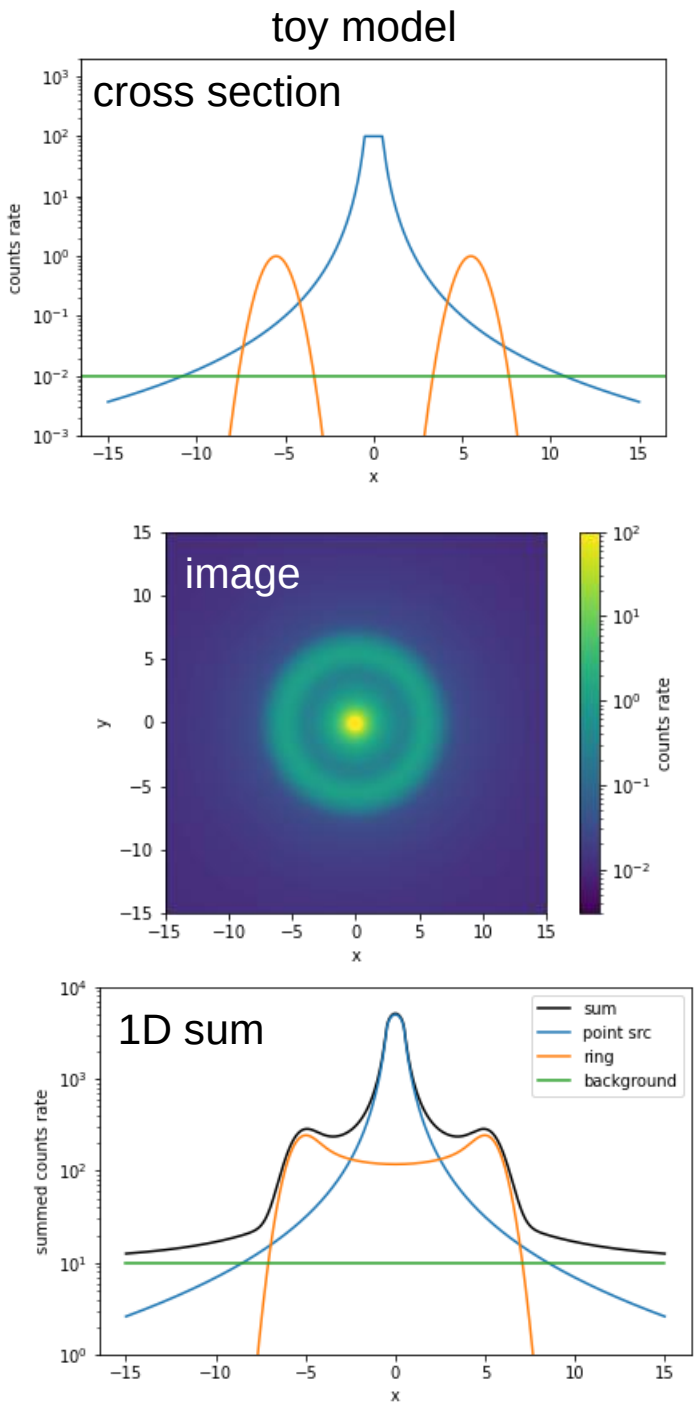
LHAASO-WCDA
(KM2A even earlier)

→ focus of our fit results to early afterglow

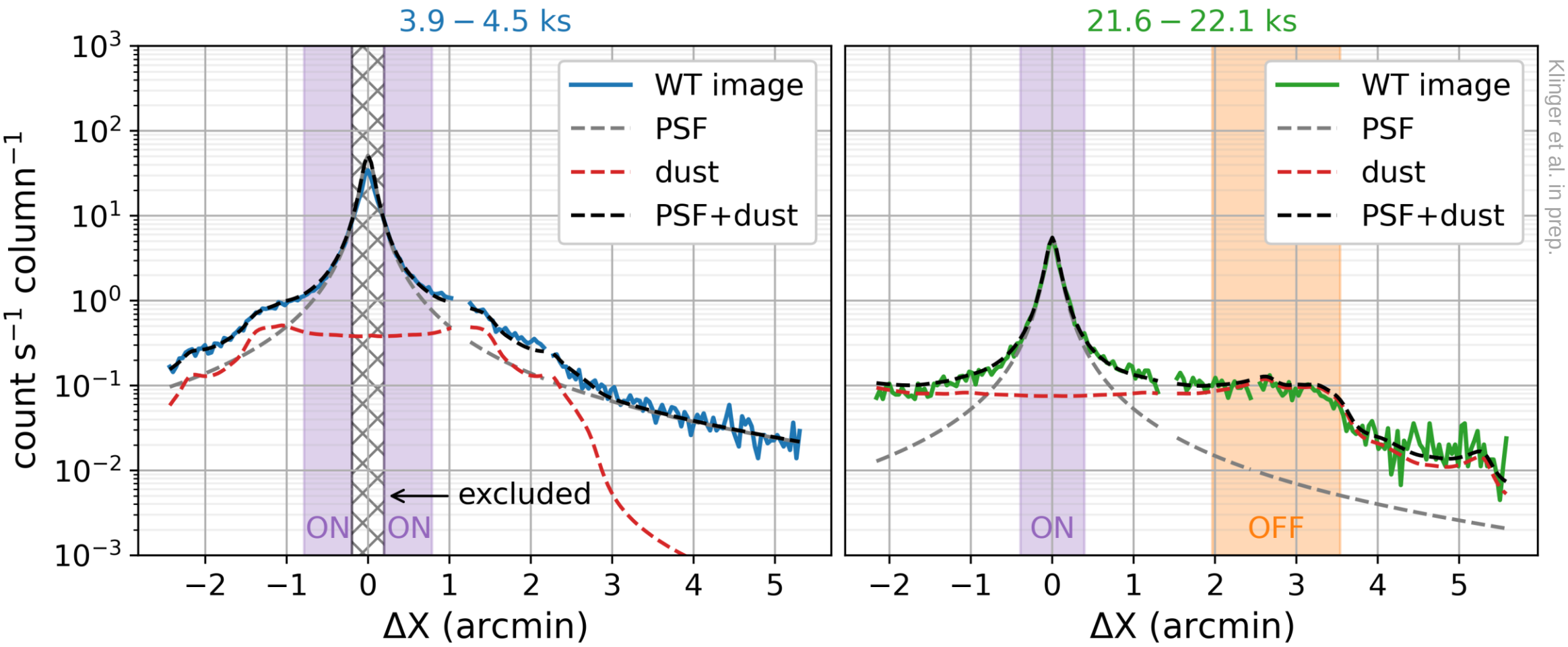
Data quality – how much can we trust the data?

Dust ring problematic

- XRT has 2 read-out modes
  - → WT: windowed timing (fast read-out)
  - → PC: photon counting (slow read-out)
- XRT observed in WT mode until ~90ks
  - → image read-out column-wise to 1D
  - → more complex source/background estimation



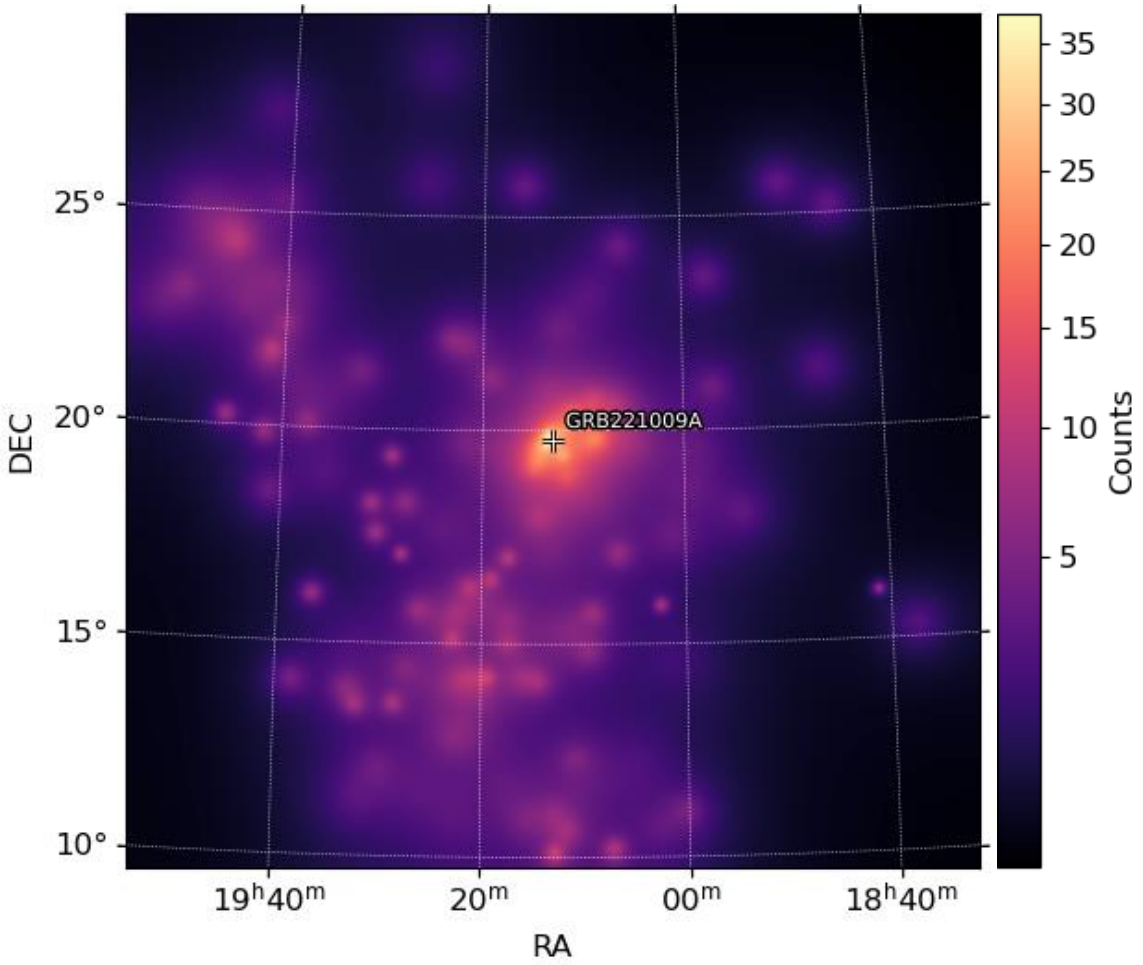
WT images – actual observations



Fermi-LAT: a GRB in the galactic plane

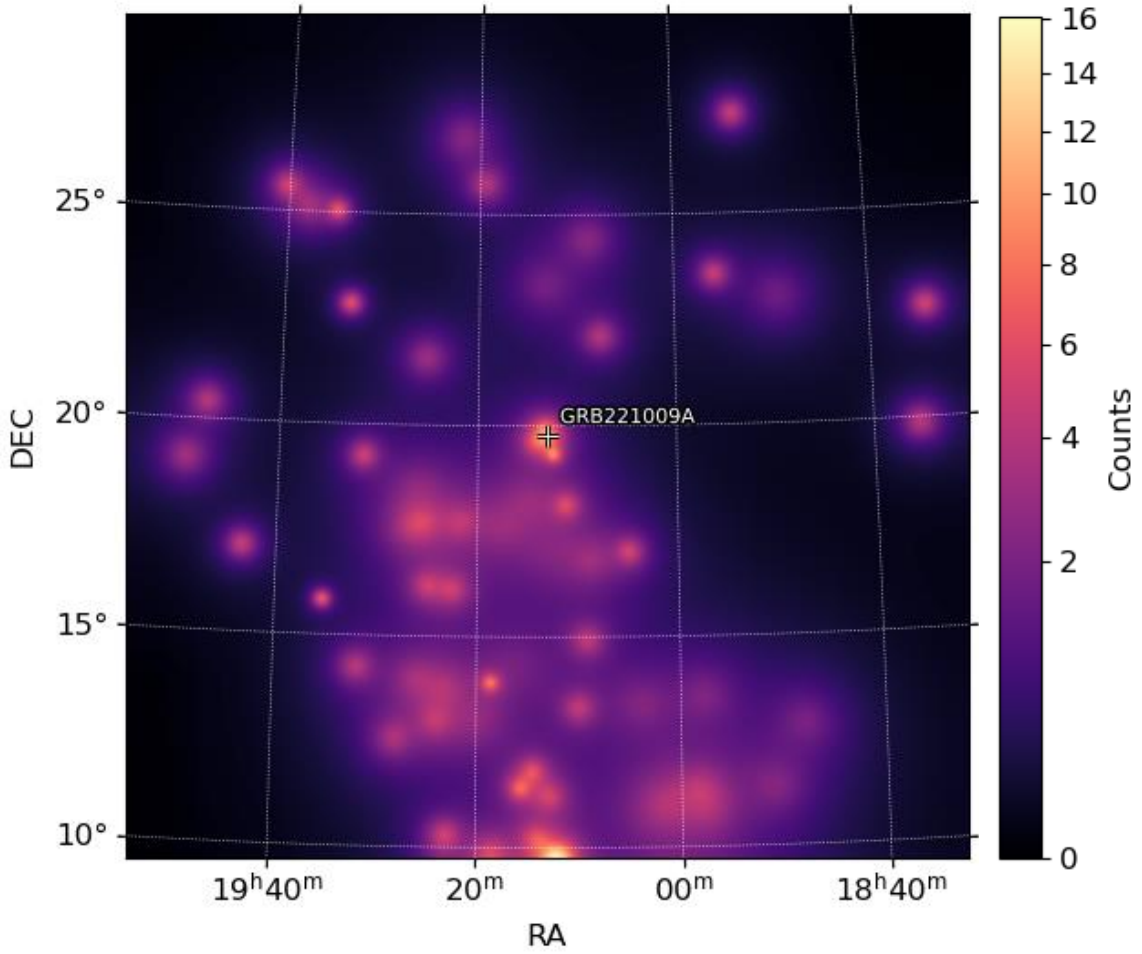
4ks

total:
137 photons



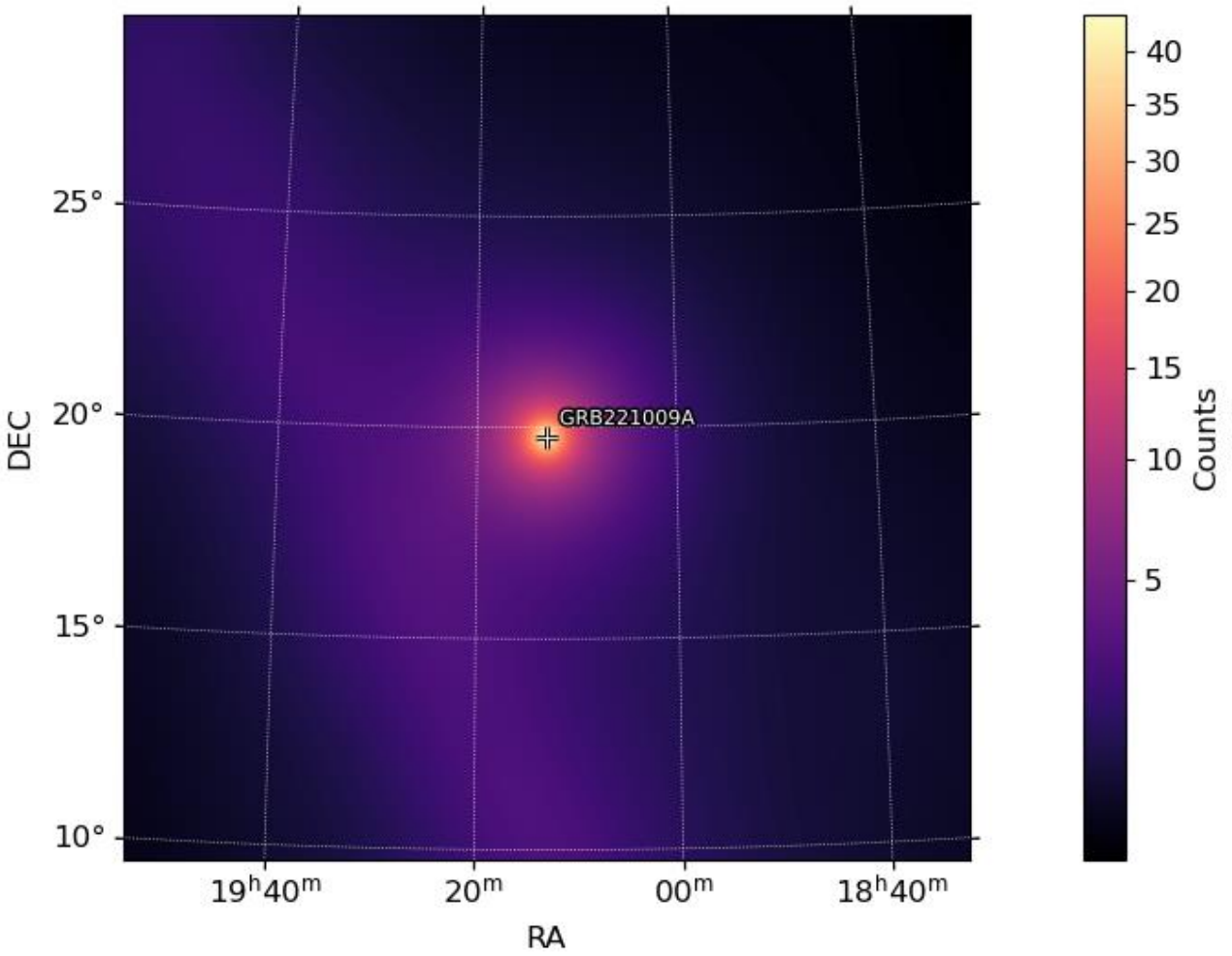
22ks

total:
62 photons

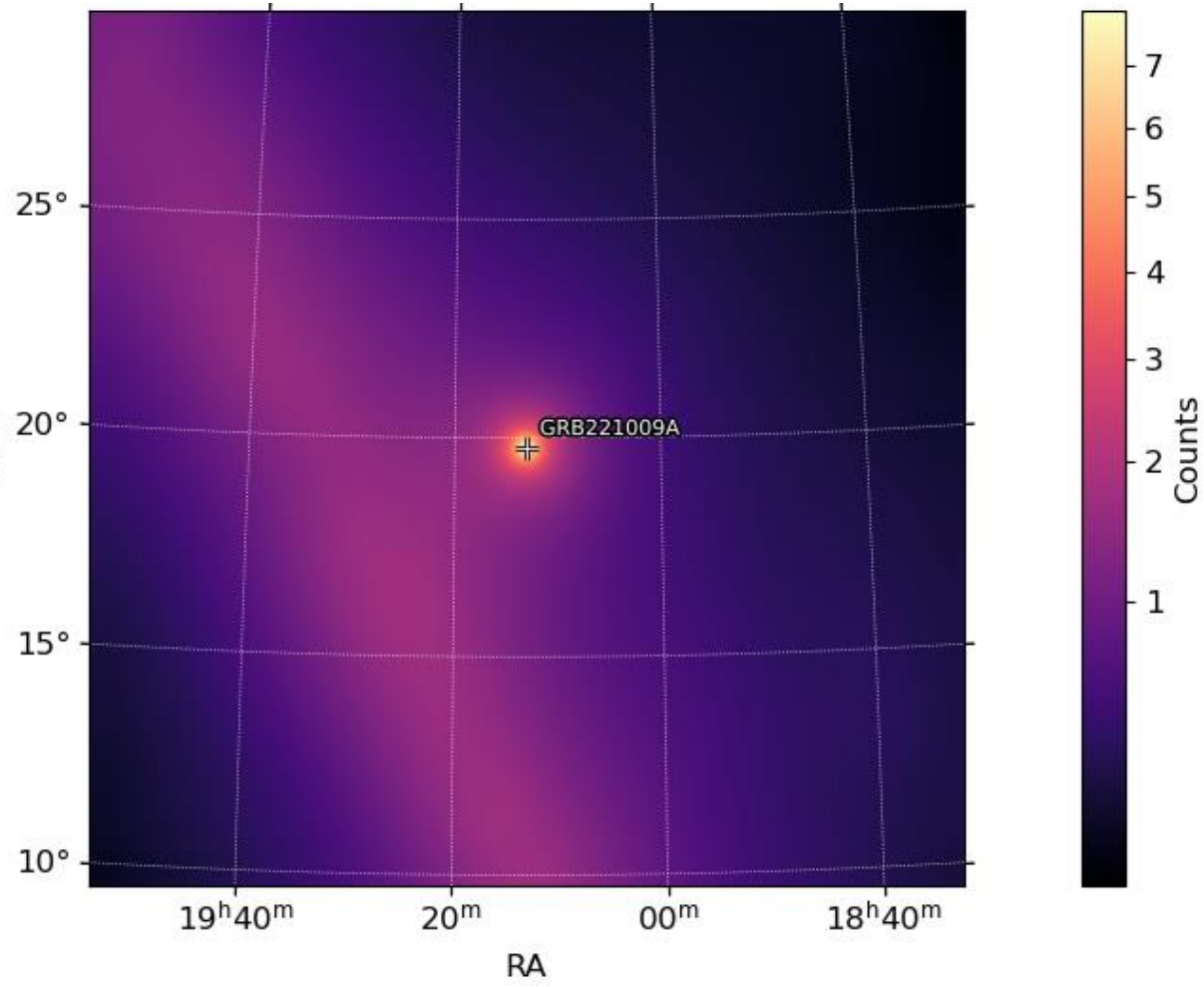


Model in a map → galactic background

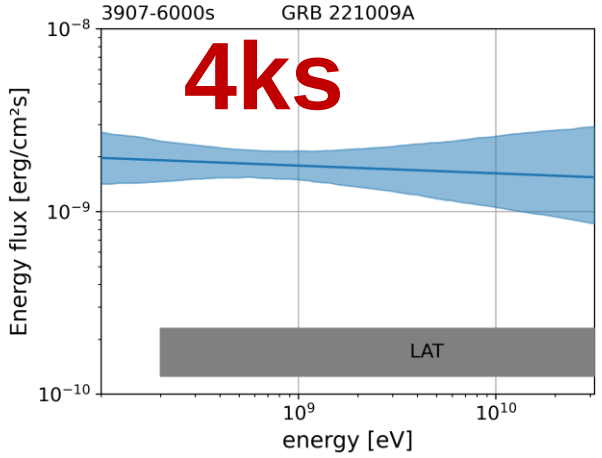
4ks

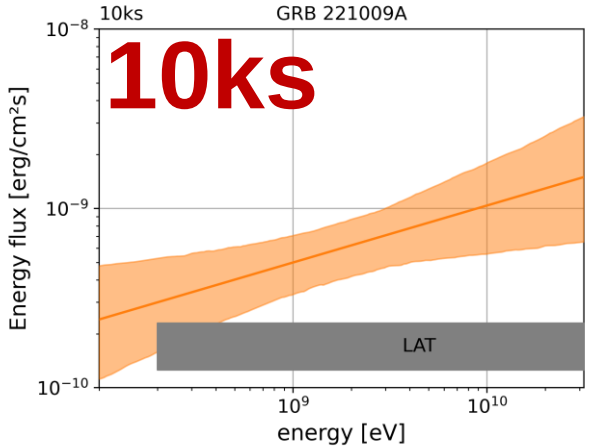


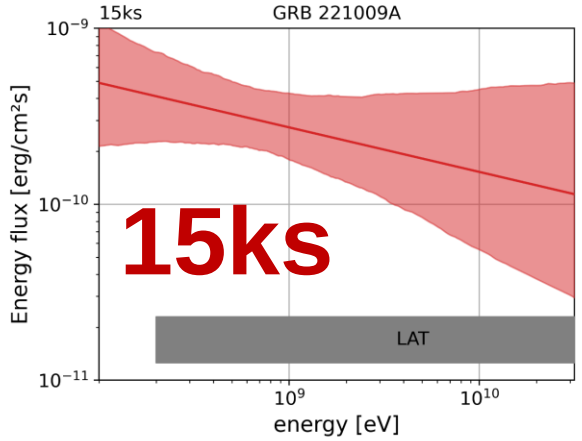
22ks

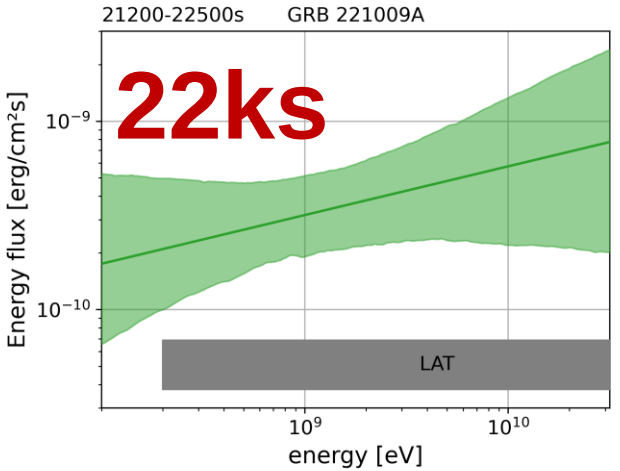


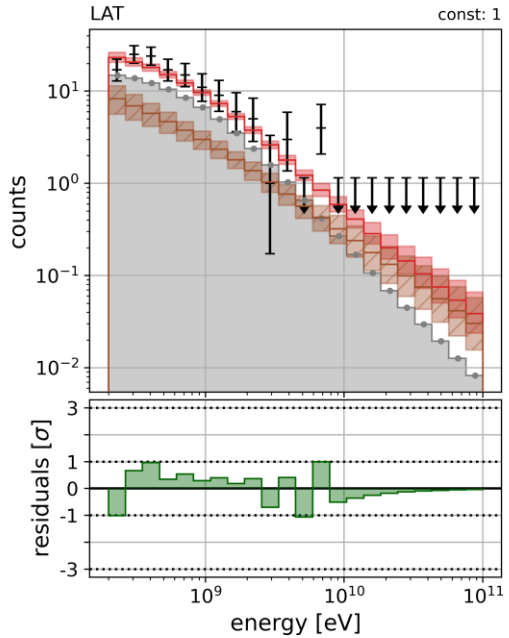
4 orbits of Fermi-LAT: galactic diffuse background!

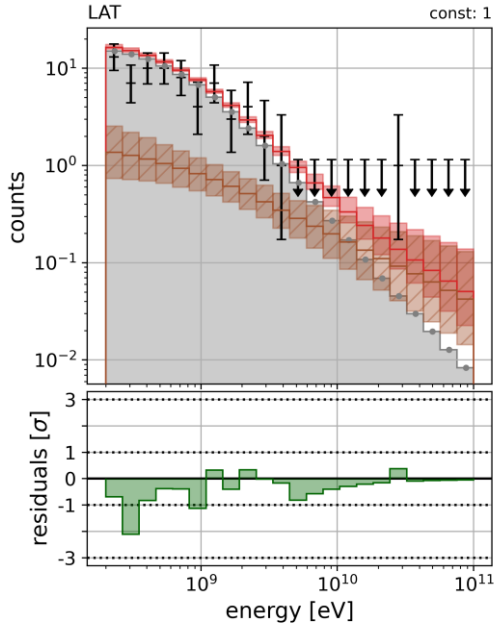


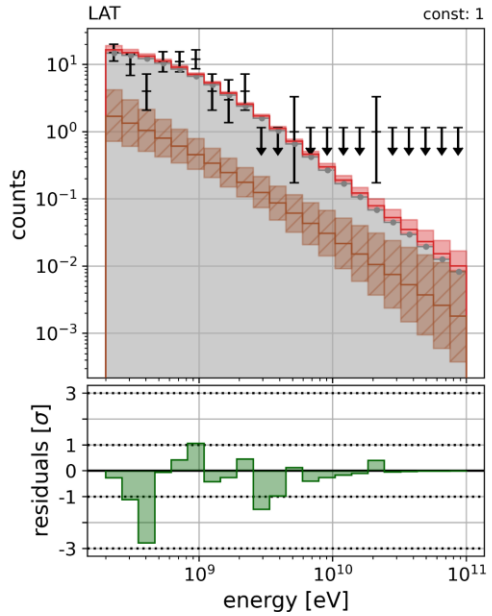


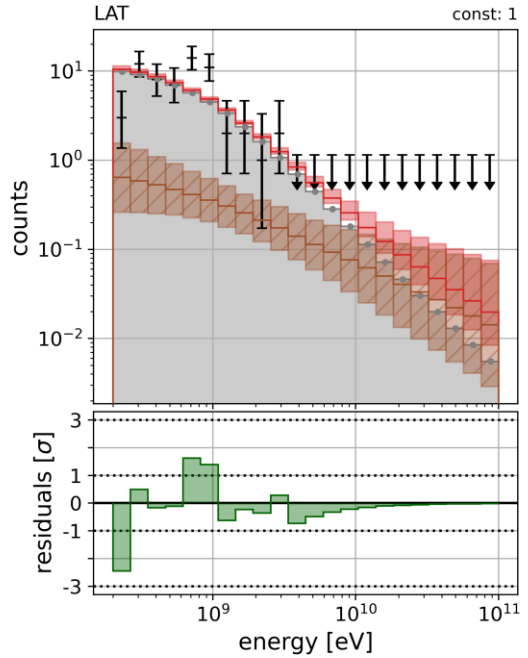






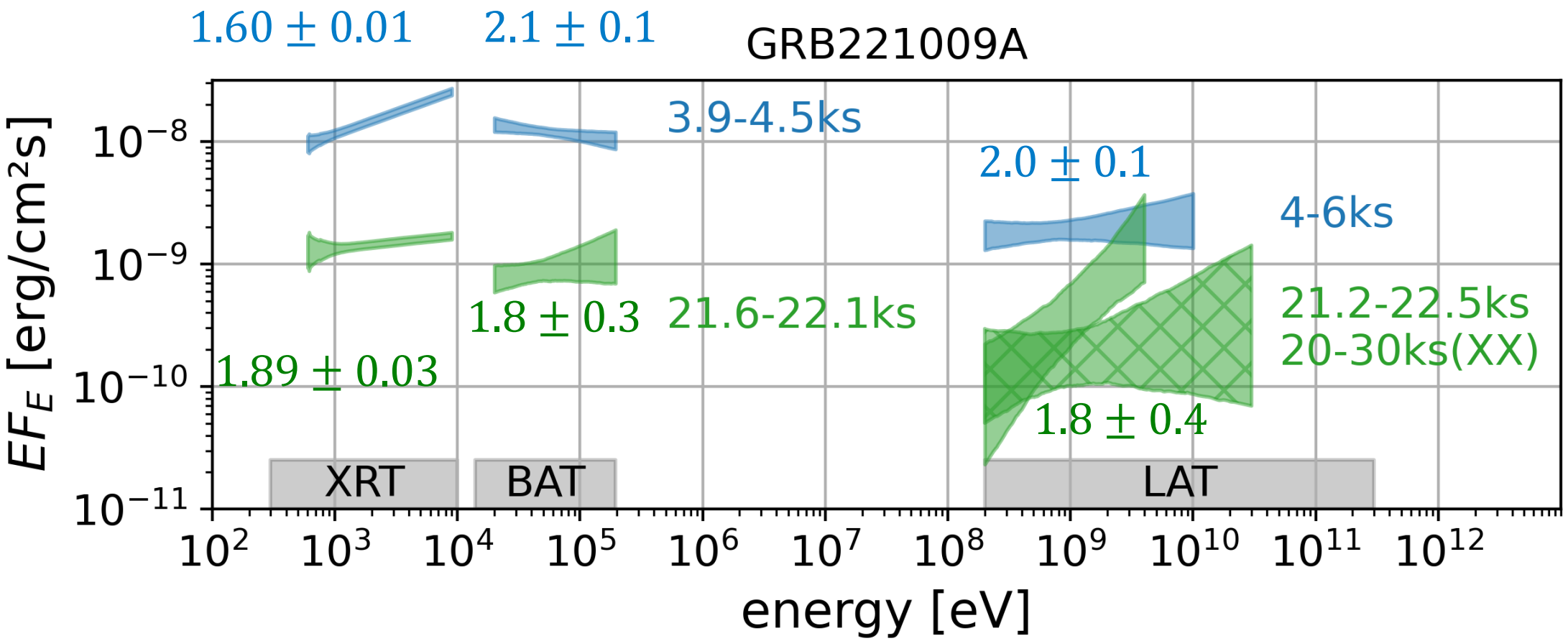




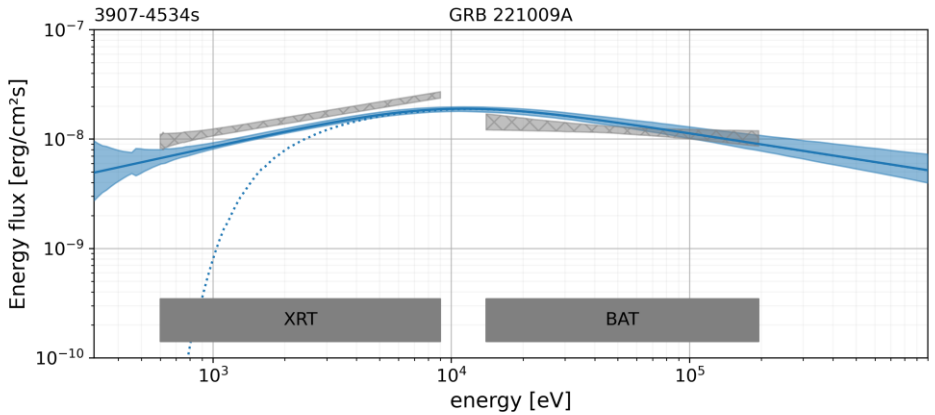


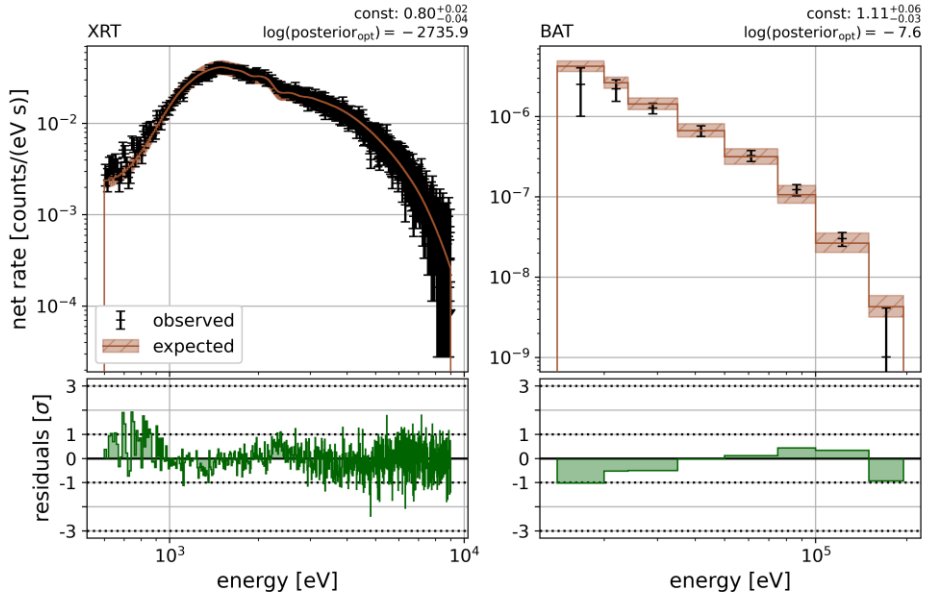
Phenomenological Picture

Putting things together: XRT, BAT, LAT

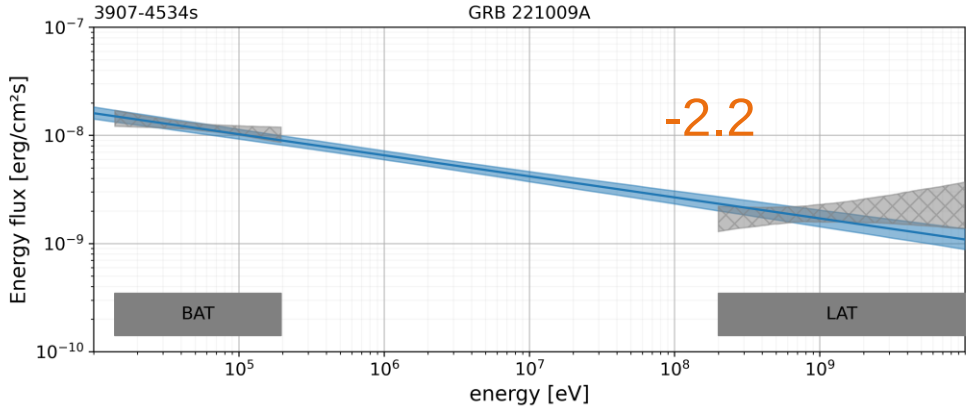


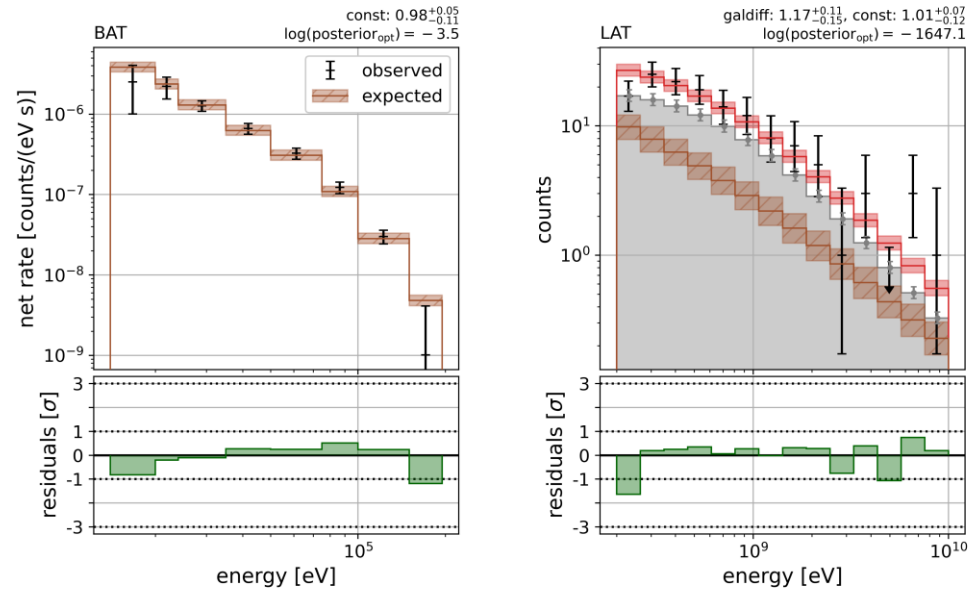
Combined fits at 4ks: phenomenological picture





→ break!

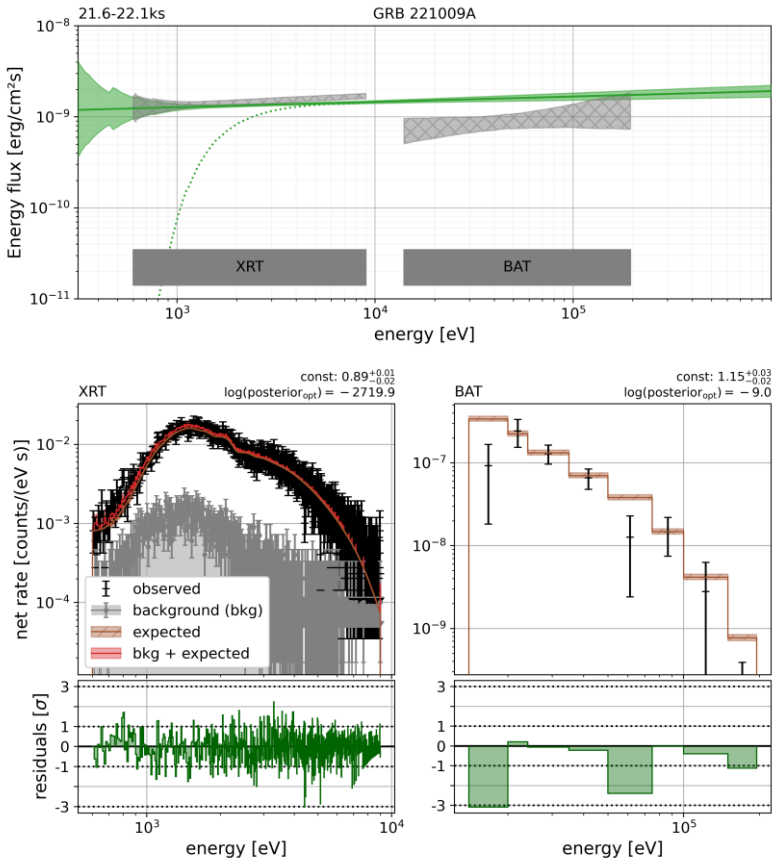




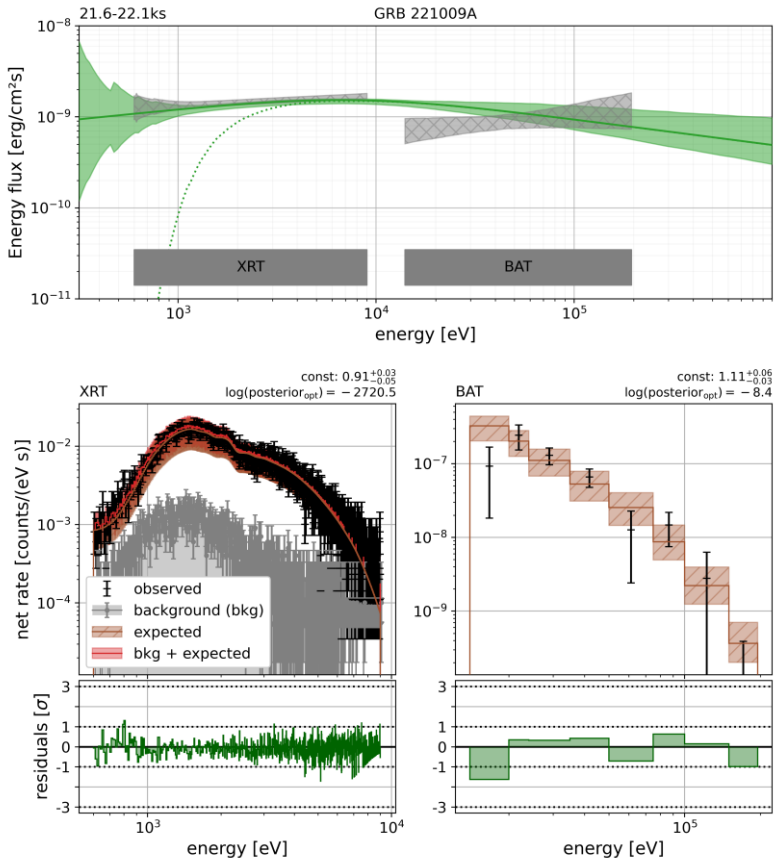
→ power law!

Combined fits at 22ks: phenomenological picture

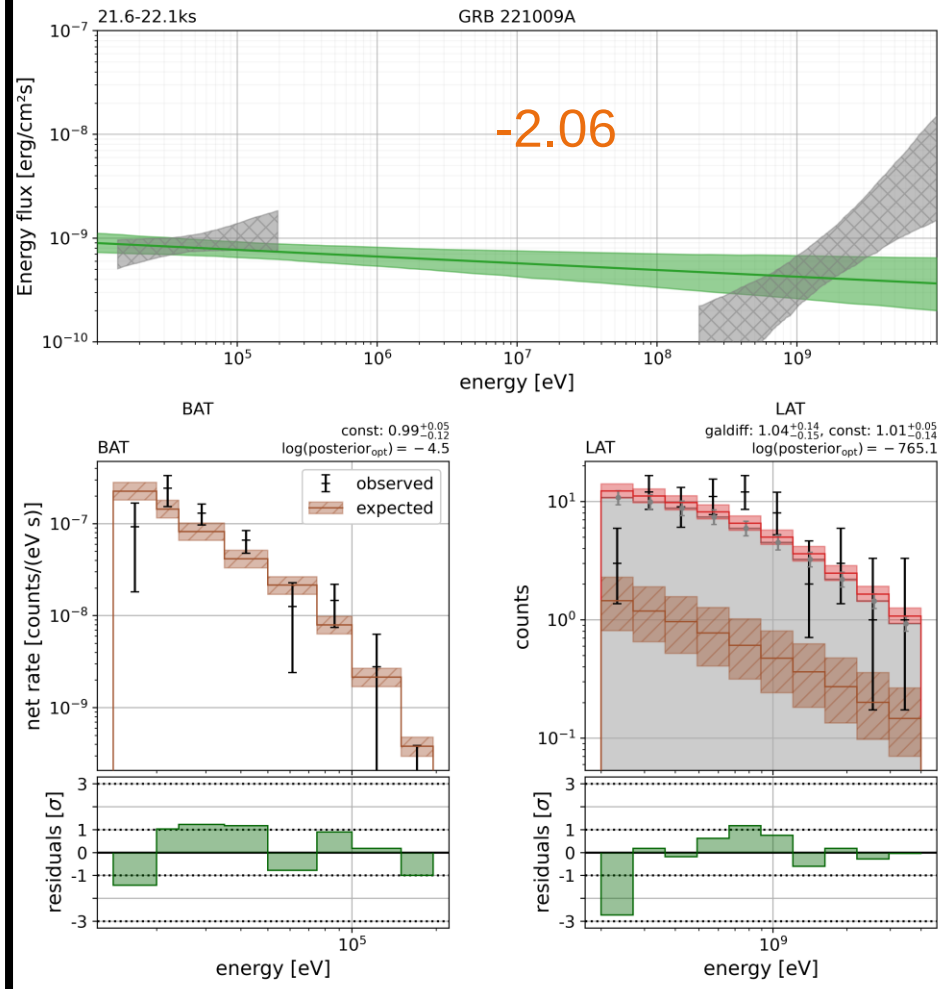
power law with extra floating



smoothly broken power law



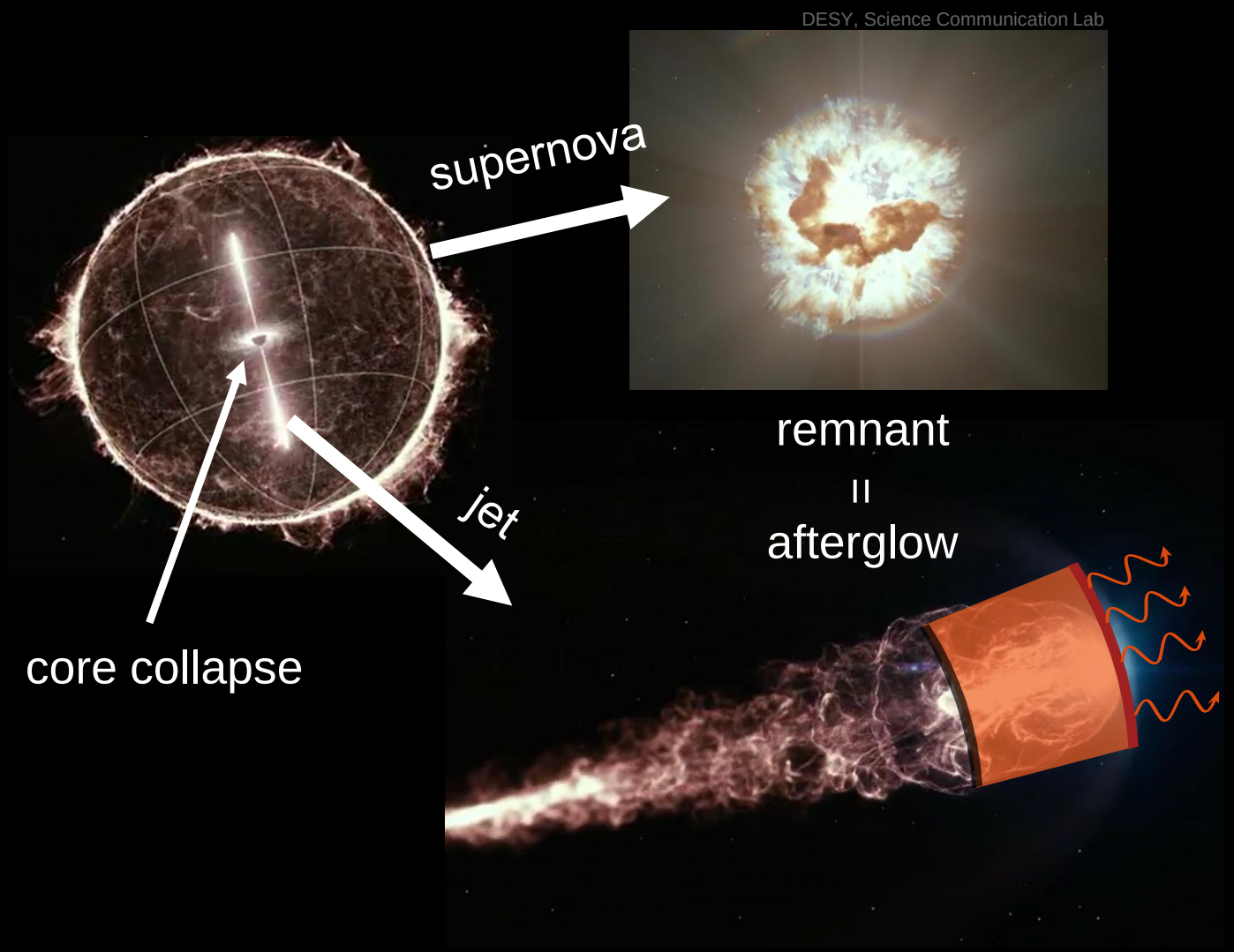
→ break less clear..



→ power law!

Reduced SSC model

Fireball model: Long Gamma-Ray Burst



- Lorentz factors up to few 100

  → relativistic compression
- Quasi isotropic outflow
- Energetics:

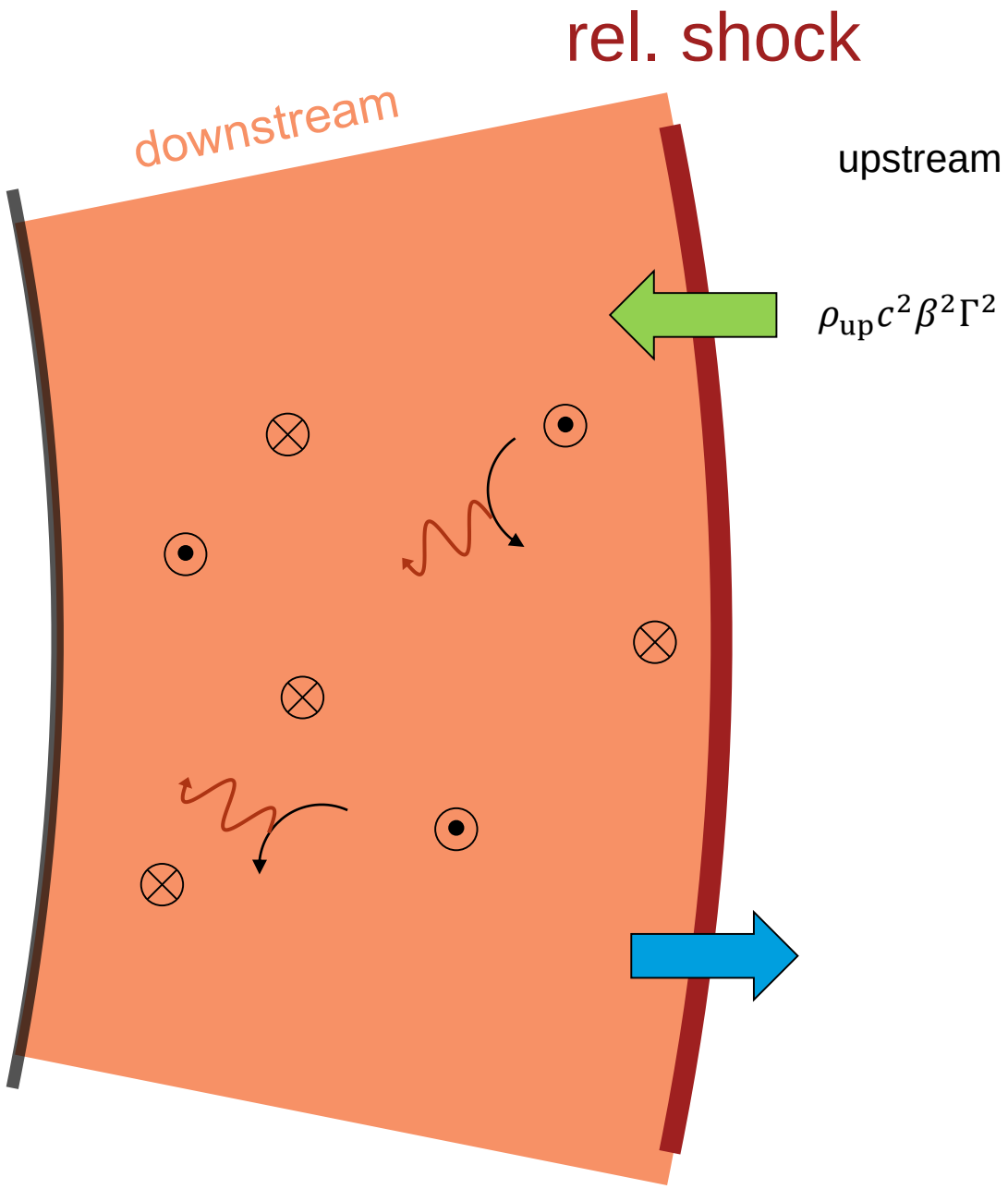
  → $E_{\gamma,\mathrm{iso}} = 10^{55} erg$ in $1 - 10^{4} keV$

  → $E_{\mathrm{tot}} > \frac{\Omega}{4\pi} E_{\gamma,\mathrm{iso}}$

  → comparable to SN !
- efficient converters of kinetic energy to radiation

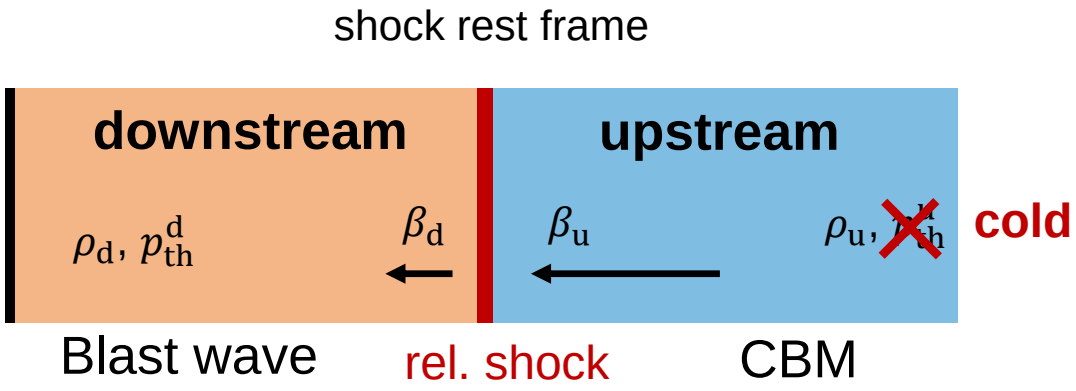
One zone assumption

- Homogeneous shell of electrons/positrons and photons
- relativistic shock
  - → injection of non-thermal particles (ε_e, ζ_e)
  - → turbulent magnetic fields (ε_B)
- particles cool
- photons escape



see e.g. Piran 2005 for a detailed review

Relativistic shocks



$$p_{ram}^u = \beta_u^2 \Gamma_u^2 w_u$$

cold case:
enthalpy density $w_u \approx \rho_u$

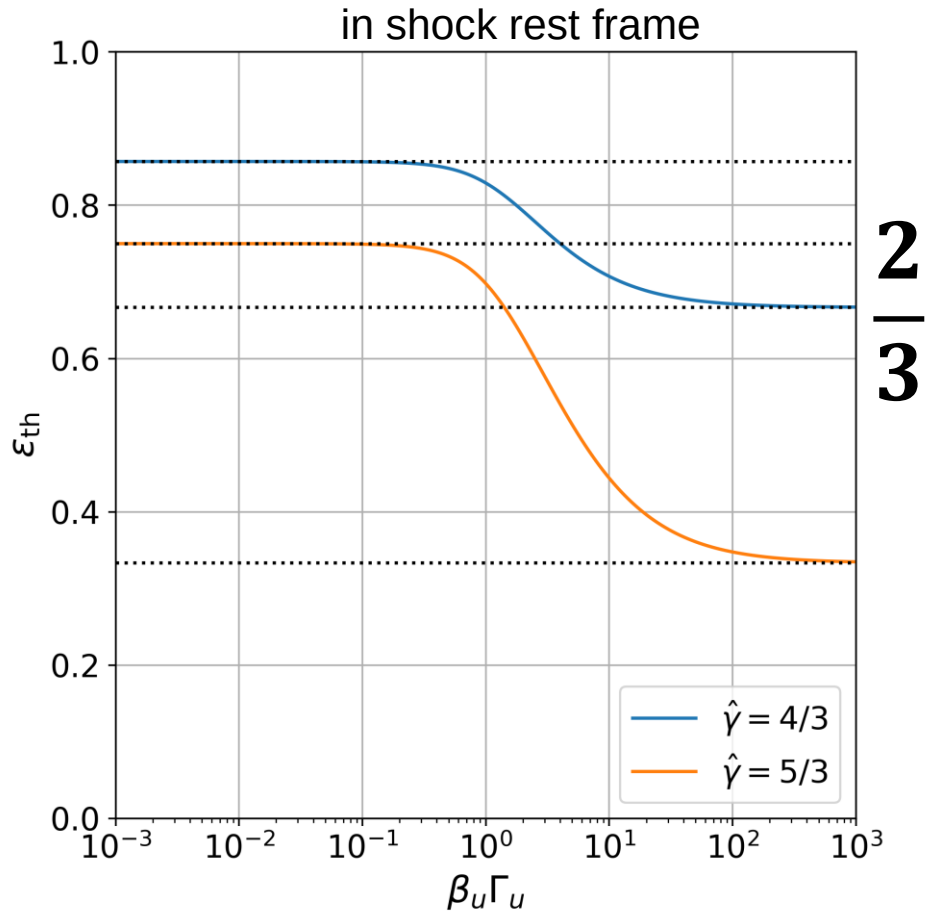
p_{th}^d $\quad \varepsilon_{th} = \frac{2}{3}$

p_{ram}^d $\quad \varepsilon_{ram} = \frac{1}{3}$

$p_{e,non-th}^d$ $\quad \varepsilon_e$ =few %?

$p_{p,non-th}^d$ $\quad \varepsilon_p$ =few %?

p_B^d $\quad \varepsilon_B = 10^{-4} - 10^{-2}$??



$$\varepsilon_X = \frac{p_X^d}{p_{ram}^u}$$

(can also define ε via energy density)

Characteristic values of blast wave parameters

- energy conservation:

  $\rightarrow E_{iso} = \Gamma^2(t_{obs})\, M_{sw}(t_{obs})\, c^2$

  $\rightarrow t_{obs} = 4ks, n_{ISM} = 1cm^{-3}$

  $\rightarrow \boxed{\Gamma \sim 34}$

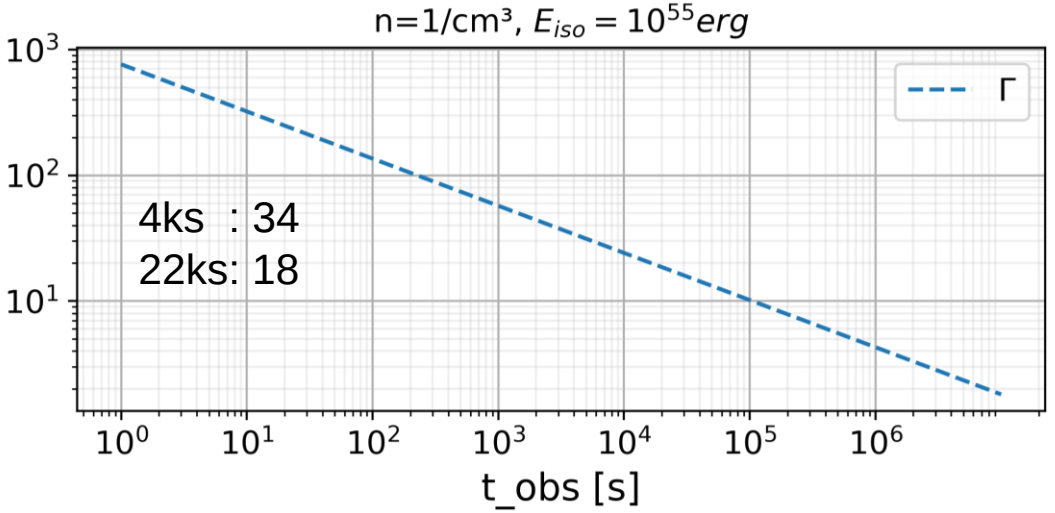
- ram pressure (SRF):

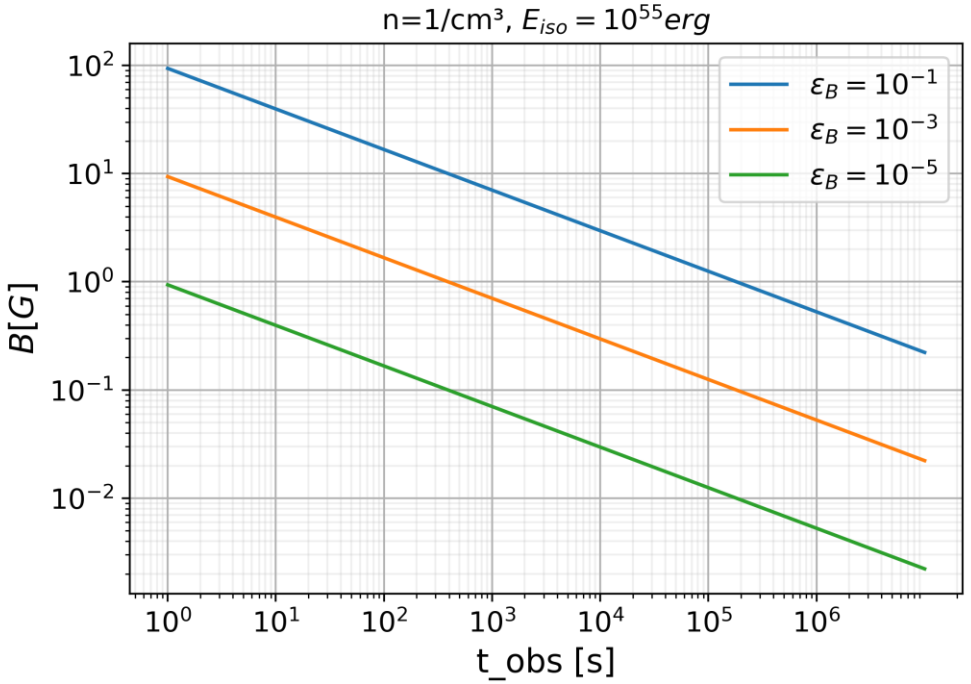
  $\rightarrow p_{ram} \approx m_p c^2 n_{up} \Gamma^2$

- magnetic field: $\frac{B^2}{8\pi} = \varepsilon_B\, p_{ram}$

  $\rightarrow \boxed{\varepsilon_B \sim 10^{-5} \rightarrow B \sim 0.03G}$

  $\rightarrow \boxed{\varepsilon_B \sim 10^{-3} \rightarrow B \sim 0.3G}$





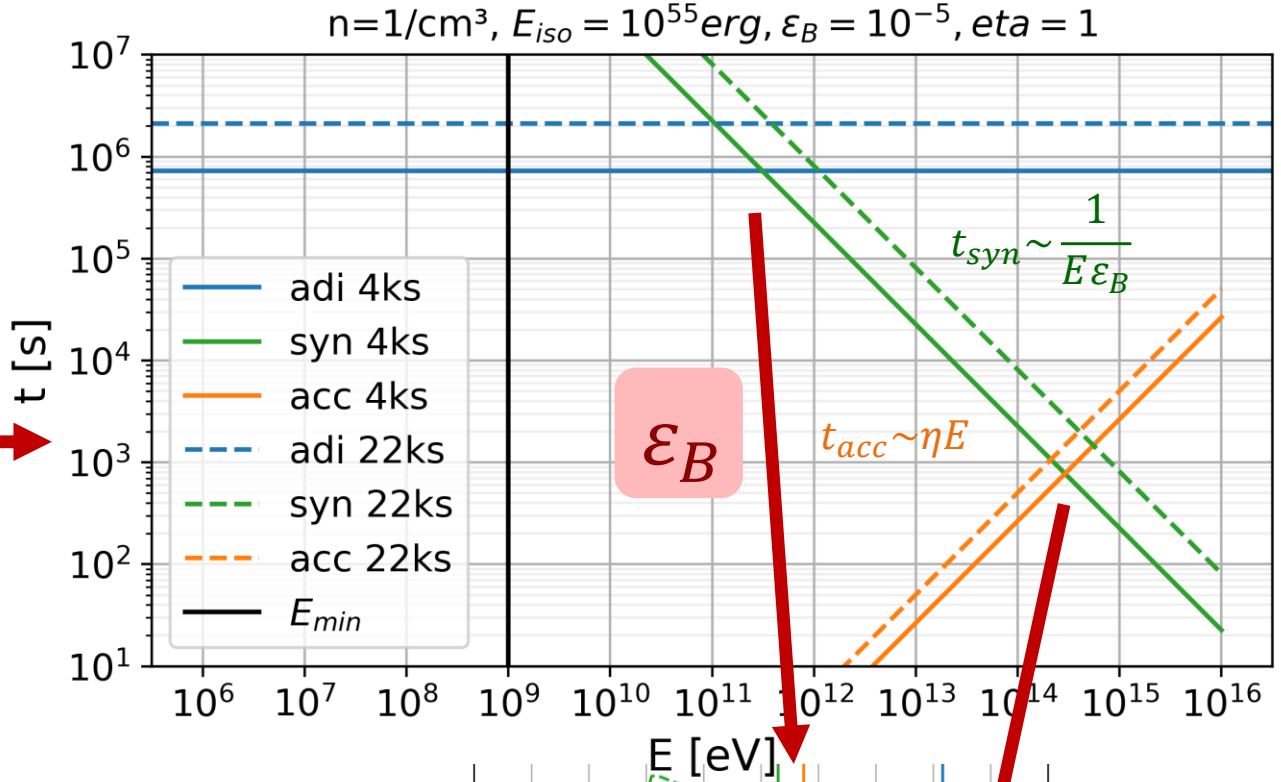
Electron spectrum

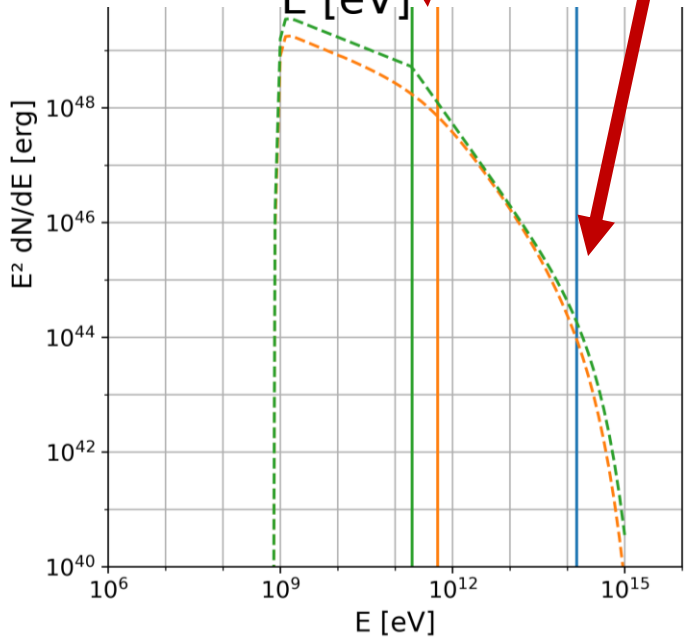
- quasi-steady state:

$$\rightarrow N \sim Q(E)\,\tau(E)$$

power law injection
spectral index $p \approx 2$

“injection washes away old particles”





η

One zone modelling → AM3 to be public soon!

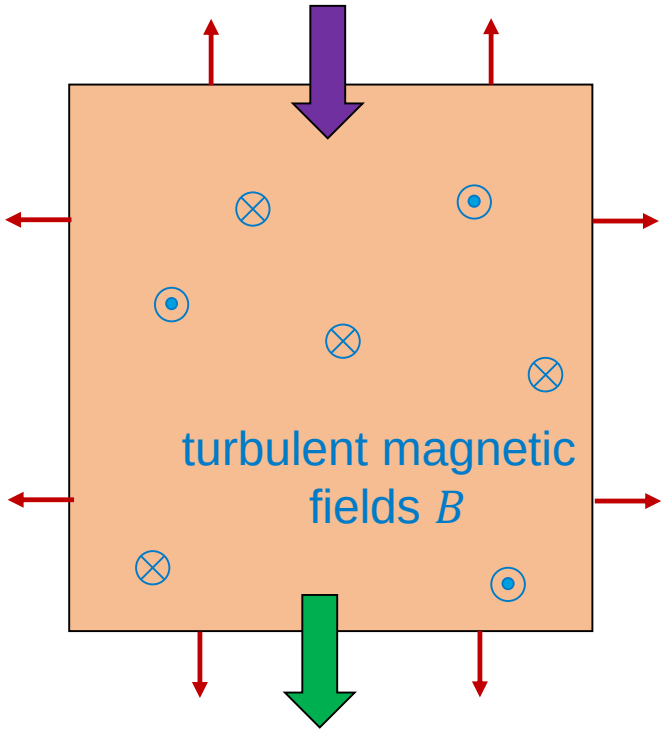
electrons drive expansion of box

shock injects relativistic particles

electron number

$$\partial_t N_{E,el} = \partial_E \left[\left(\frac{E}{\tau_{syn}(E,t)} + \frac{E}{\tau_{iC}(E,t)} + \frac{E}{\tau_{adi}(t)} \right) N_{E,el} \right] + Q_{inj}(E,t) - \frac{N_{E,el}}{\tau_{pp}(E,t)} + Q_{pa}(E,t)$$

injection Q



escape τ_{esc}

synchrotron

inverse Compton scattering

$e^- e^+ \rightarrow \gamma\gamma$

$\gamma\gamma \rightarrow e^- e^+$

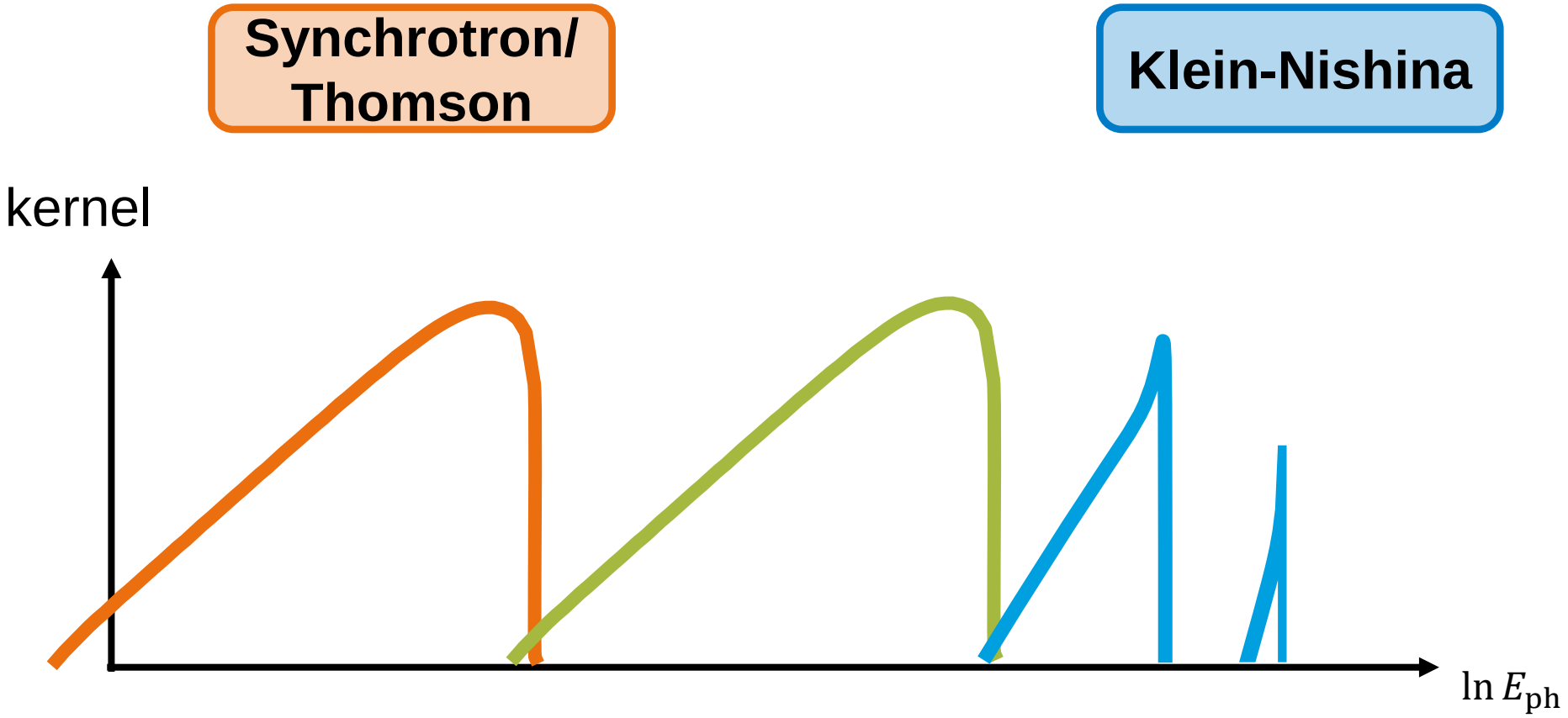
photon number

$$\partial_t N_{E,\gamma} = -\frac{N_{E,\gamma}}{\tau_{esc}(t)} + Q_{syn}(E,t) + Q_{iC}(E,t) + Q_{pp}(E,t) - \frac{N_{E,\gamma}}{\tau_{pa}(E,t)}$$

photons can escape from box

Photon Spectrum: Synchrotron Self-Compton (SSC)

→ Convolve electron spectrum with radiation kernel



Photon Spectrum: Synchrotron Self-Compton (SSC)

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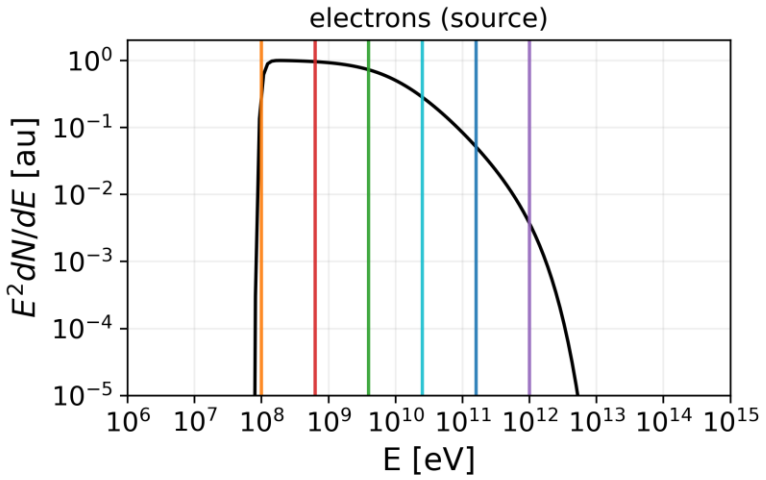
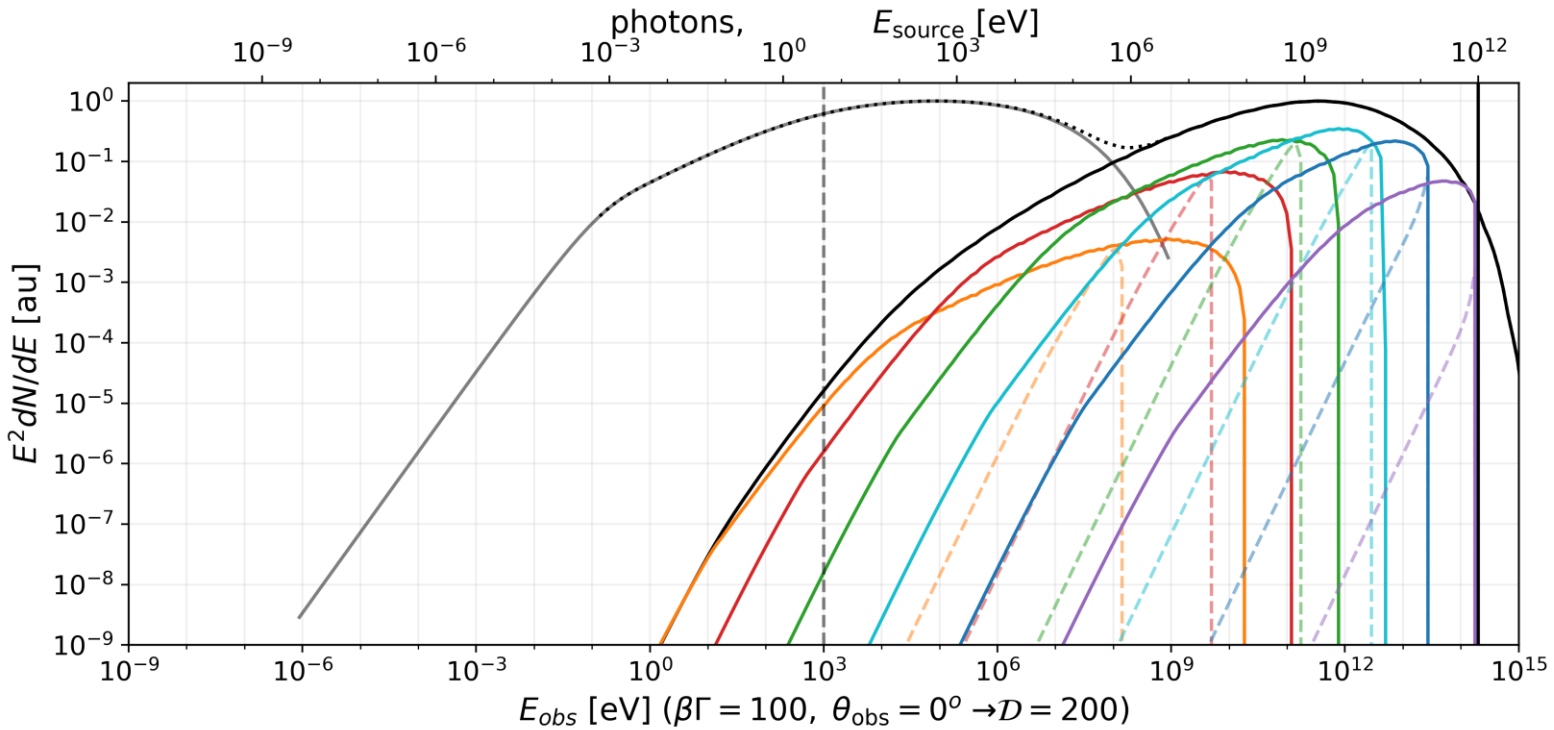
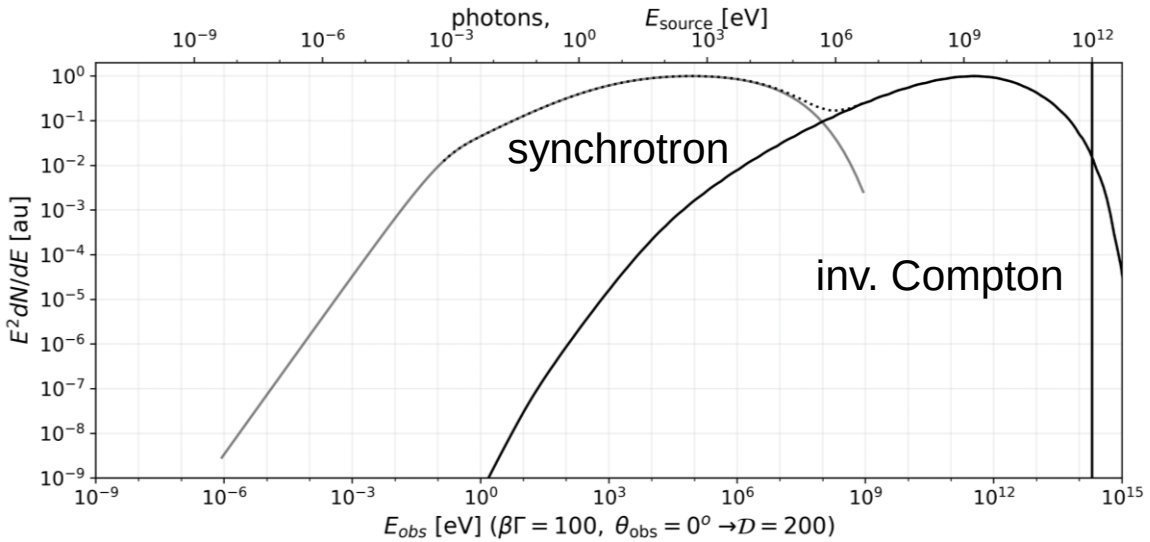




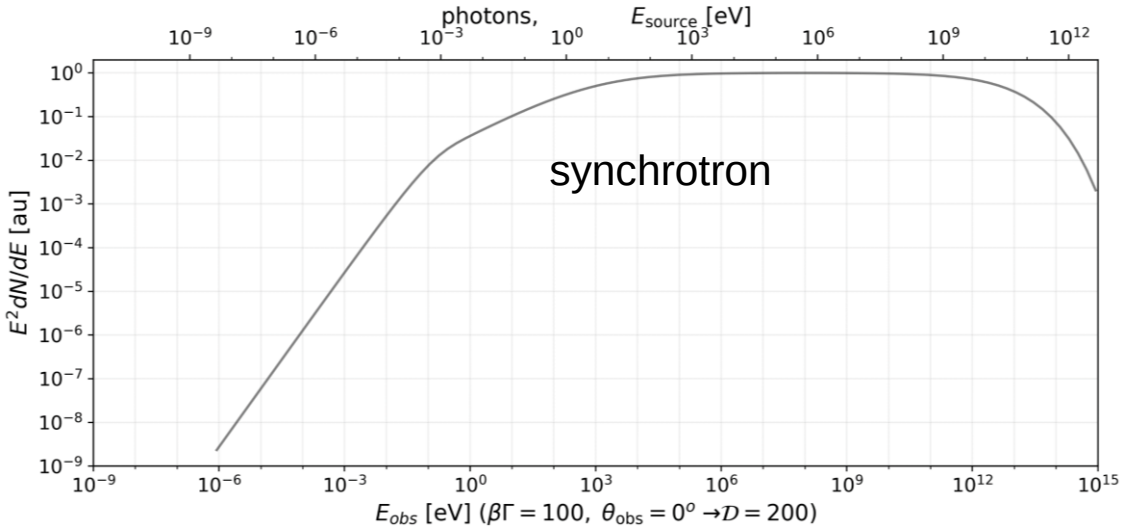
Reduced SSC model

→ incorporates 2 types of solutions

1. double hump solution (SSC):

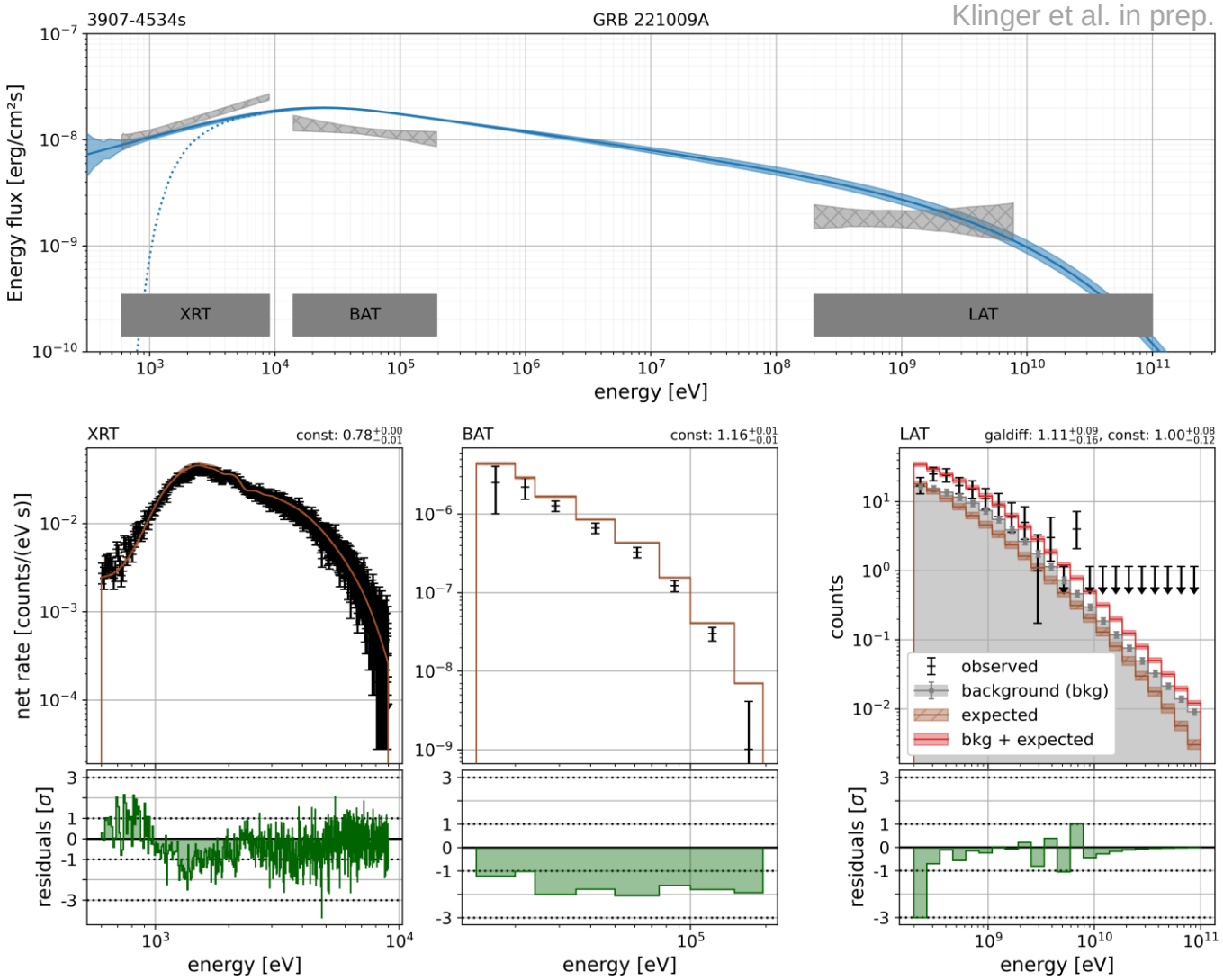


2. single hump solution (syn. only)



Synchrotron model fits

4ks: synchrotron model - simple fit



- break at few keV

  → low magnetic field $\varepsilon_B \sim 10^{-5}$
- power law regime from BAT to LAT

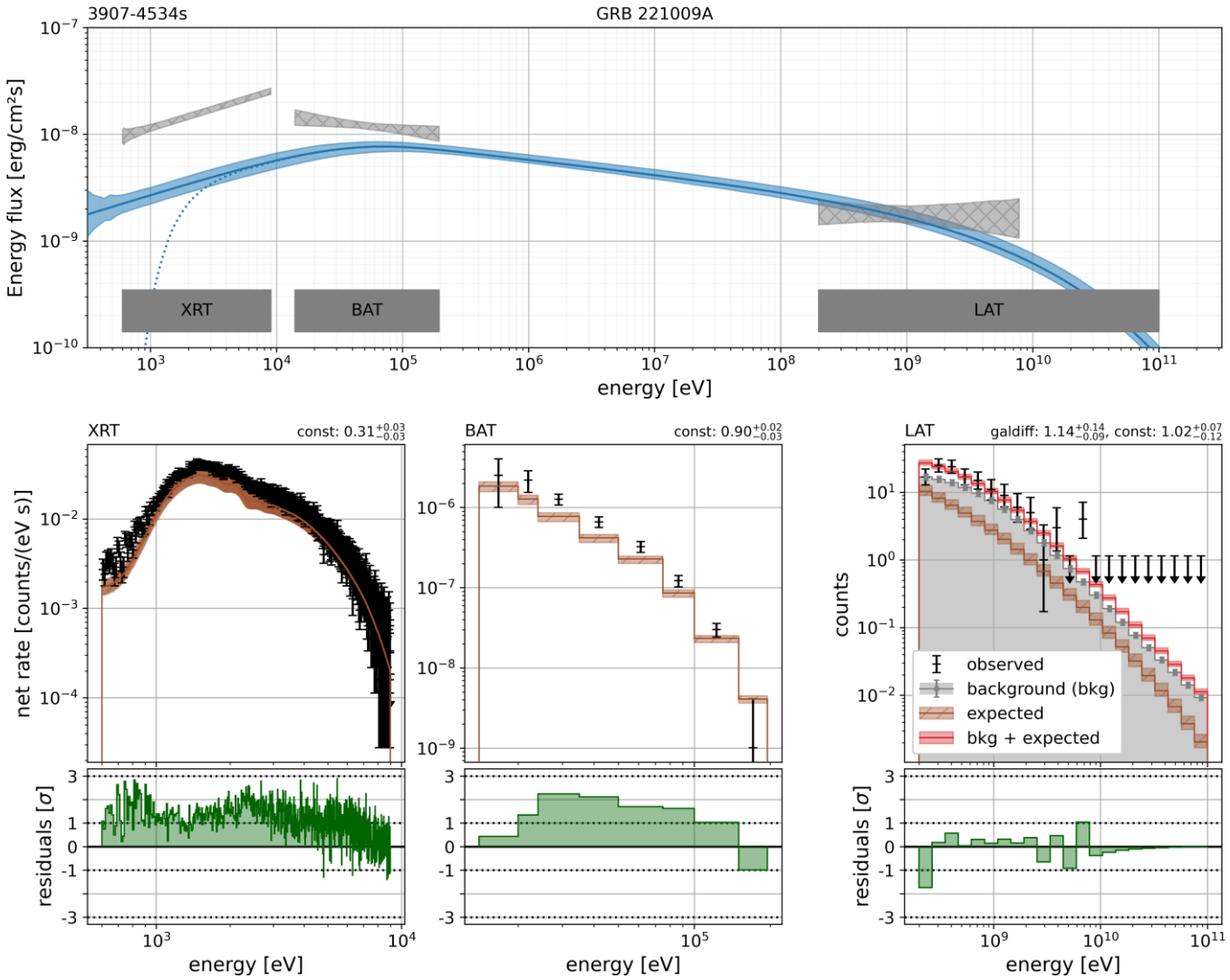
  → photon spectral index 2.15

  → electron spectral index 2.3
- BAT overshot

  → XRT floating norm
- cut-off position fixed ($\eta = 1$)

  → correlated to photoelectric absorption

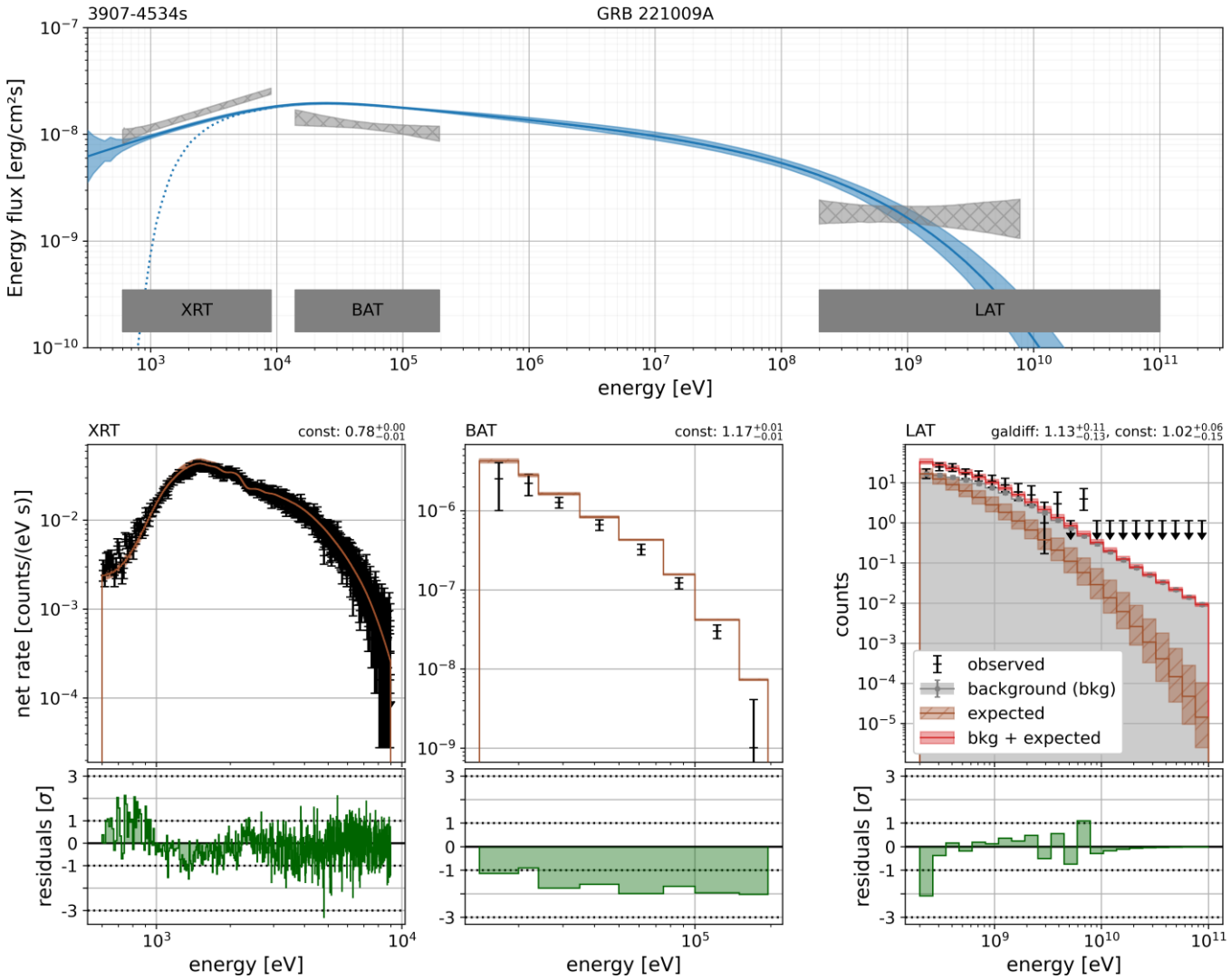
4ks: departure 1 – XRT floating



- seems to overdo it
- slight shift of peak + hardening + absorption

  → at 10% level (log)
- does not affect main conclusions dramatically

4ks: departure 2 – free η



fit seems to get unstable:

- XRT prefers extremely hard spectrum below break energy

  → overestimates quality of photoelectric absorption

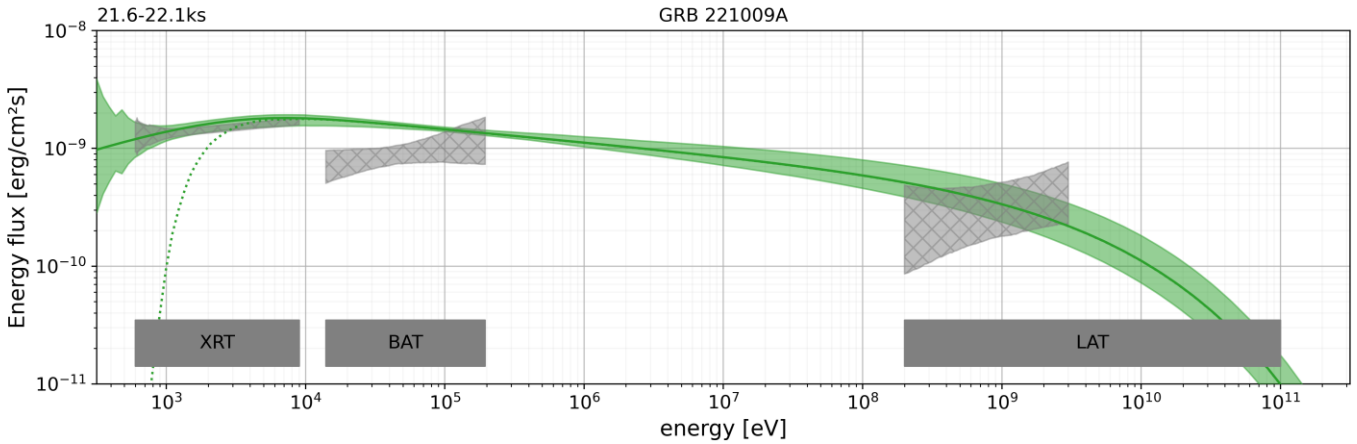
- spectral index below and above break energy linked

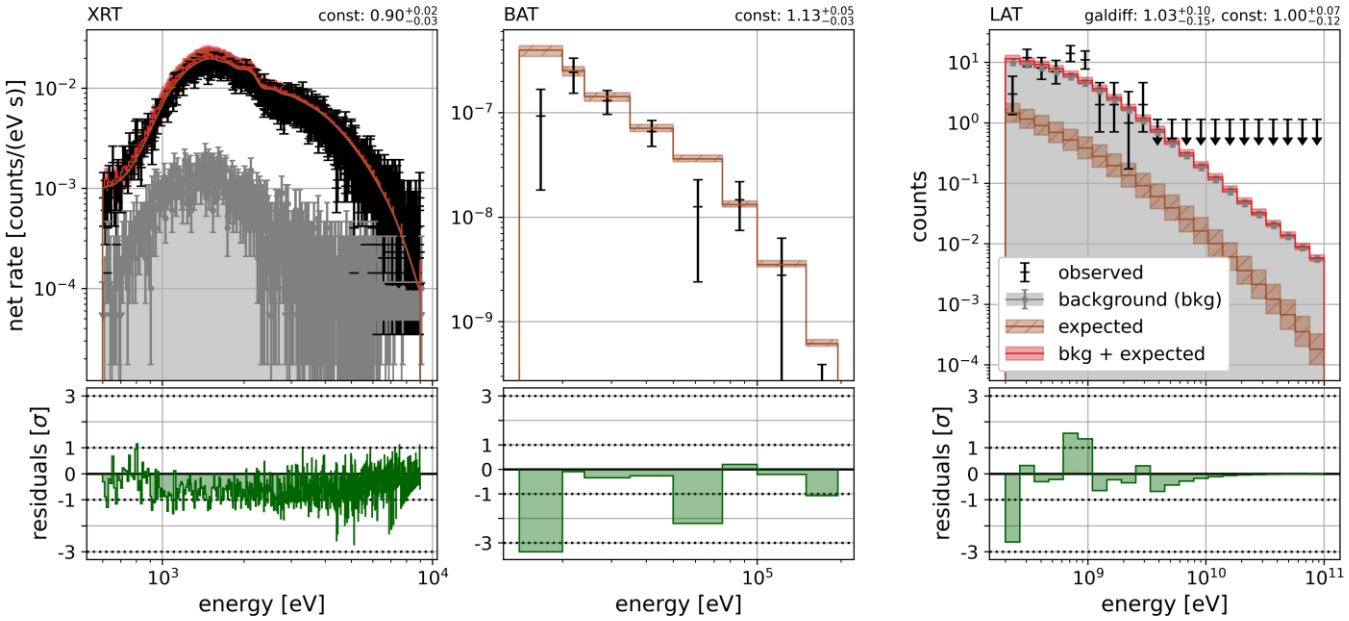
  → hardening of spectrum above break

- compensated by early cut-off

  → much softer LAT spectrum

22ks: synchrotron model - simple fit





- lower statistics
- similar picture:

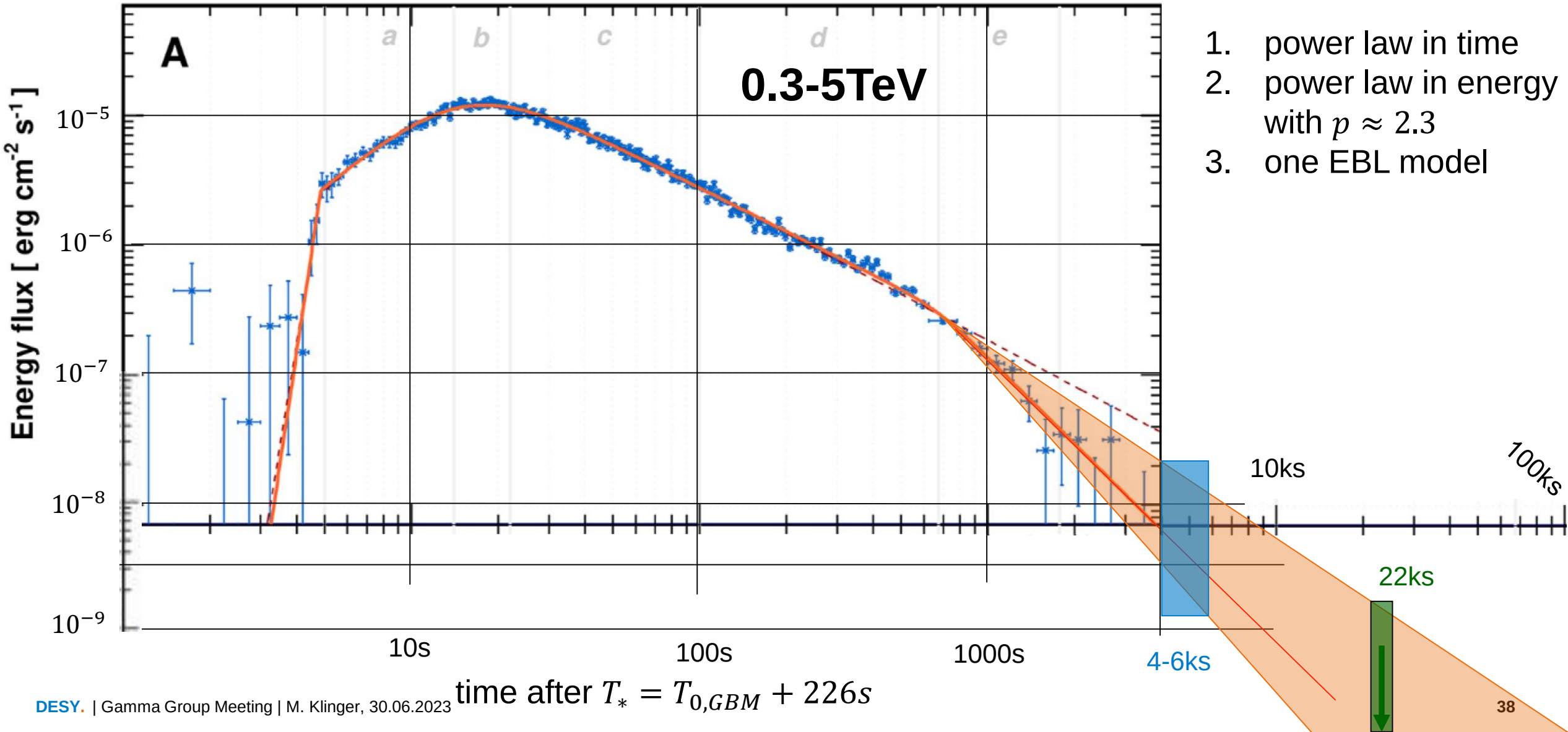
  → spectral index slightly softer than 2

  → break at few keV less clear
- prefers $\eta < 1$ anyways
- extended floating drives it towards one single power law

  → large uncertainties

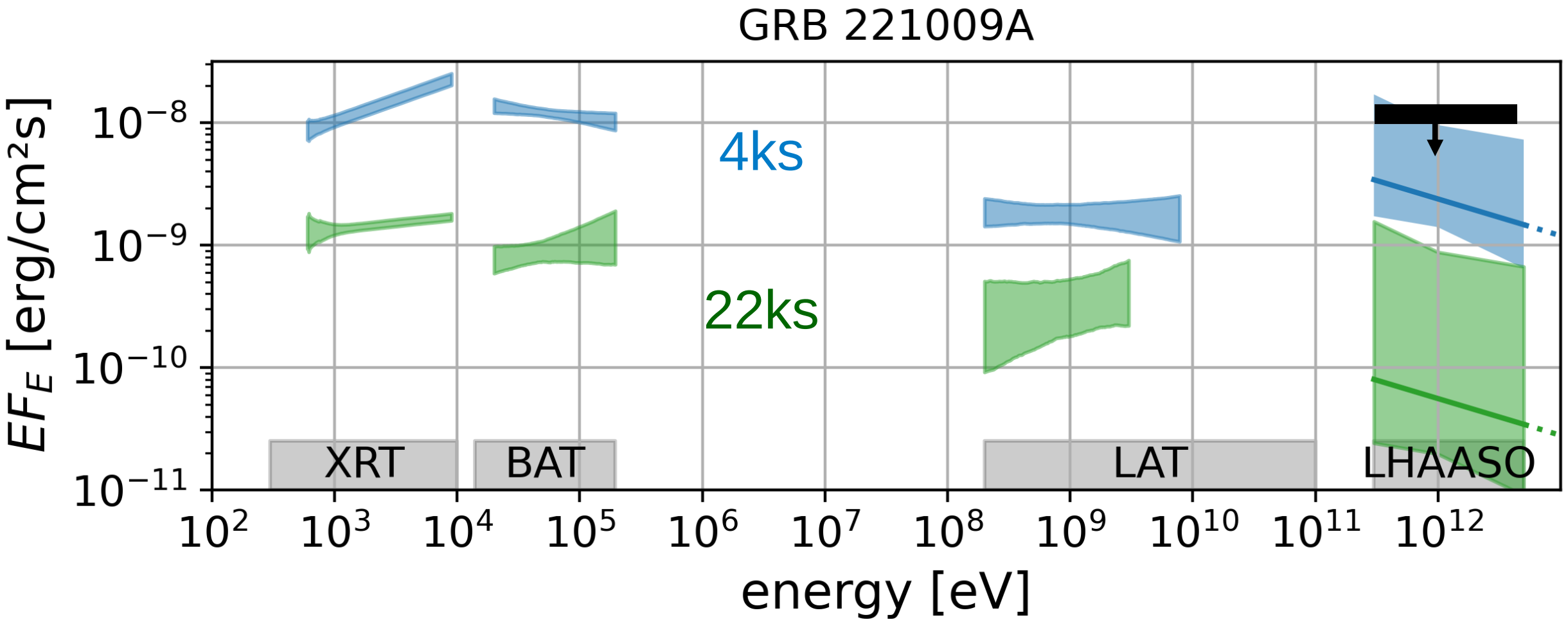
on the SSC component

LHAASO light curve extrapolation acrobatics



1. power law in time
2. power law in energy with $p \approx 2.3$
3. one EBL model

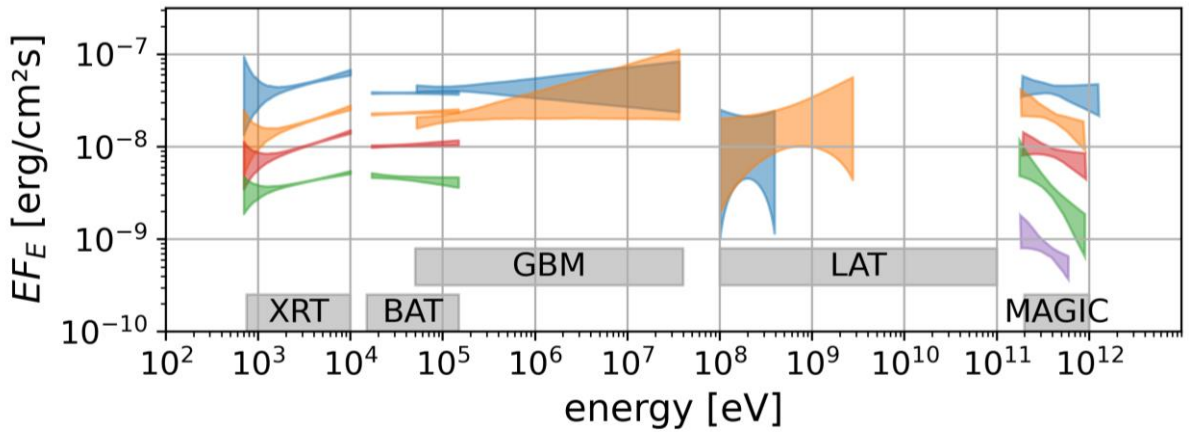
LHAASO light curve extrapolation acrobatics



Other VHE GRB afterglows

Observational picture- all VHE GRBs flat up to TeV

$t_{obs} \approx 10^2, \Gamma \sim 90$ **GRB 190114C**



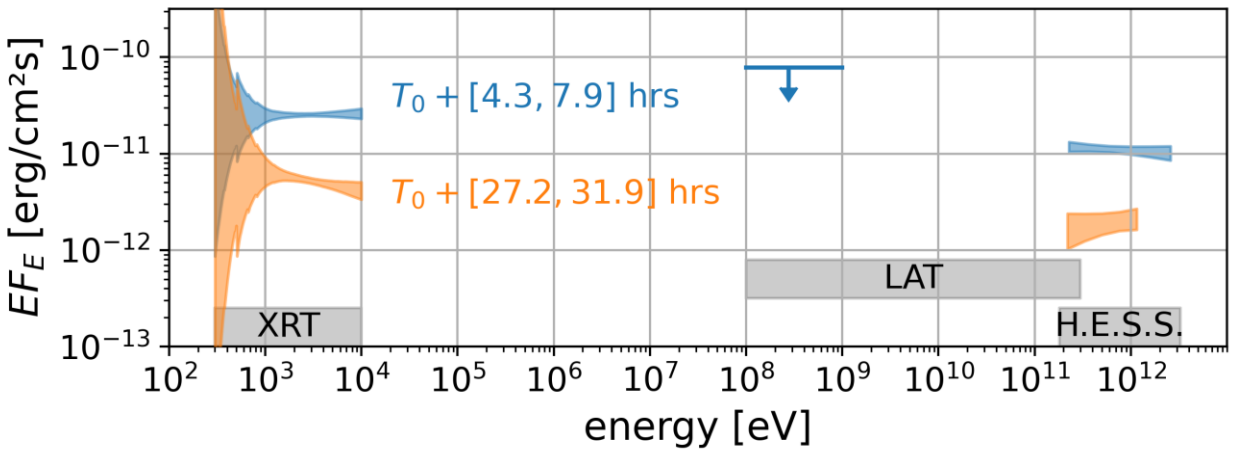
GRB 180720B

XRT/BAT(earlier), HESS
flat ? , flatish(1.6±1.6)

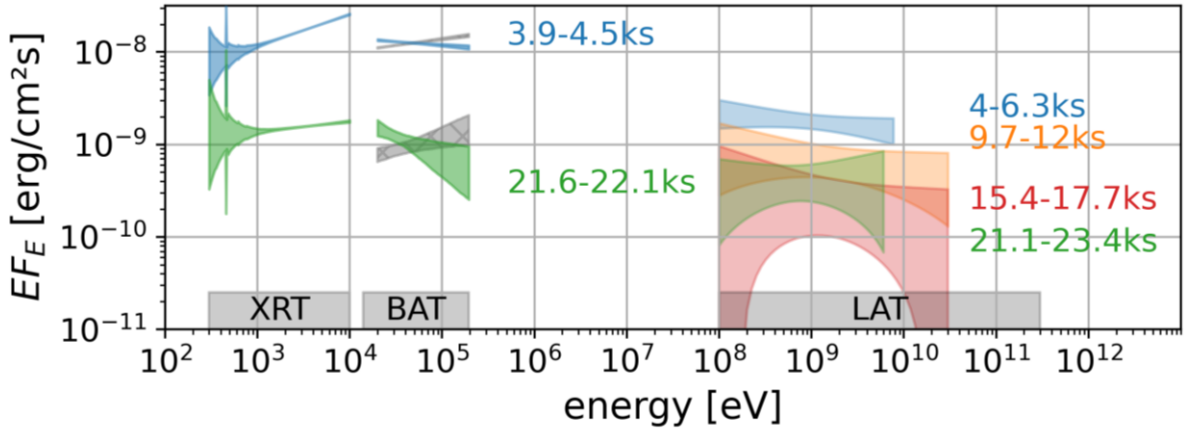
GRB 201216C

MAGIC -> z=1.1 -> EBL absorbed

$t_{obs} \approx 10^4 s, \Gamma \sim 6$ **GRB 190829A**

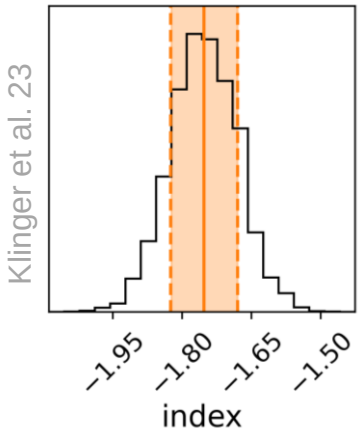


$t_{obs} \approx 10^3 - 10^4 s, \Gamma \sim 30$ **GRB 221009A**



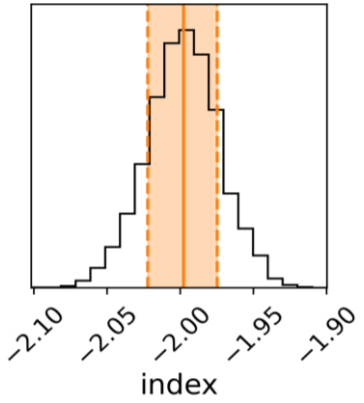
GRB 190114C

XRT
0.7-10 keV



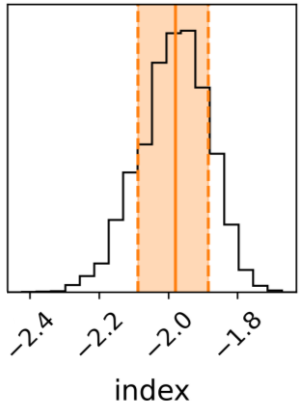
-1.75 ± 0.07

BAT
15-150 keV



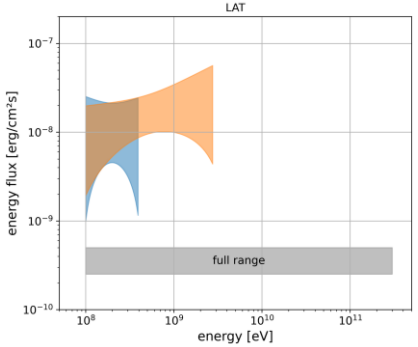
$-1.998^{+0.023}_{-0.024}$

GBM
50 keV - 40 MeV



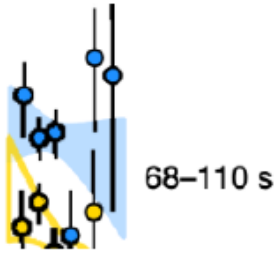
-1.98 ± 0.1

LAT
> 100 MeV



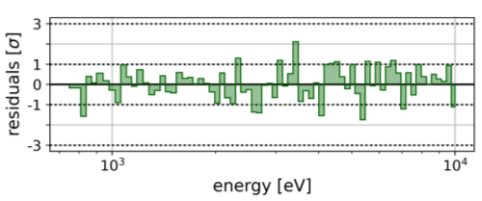
-2 ± 1

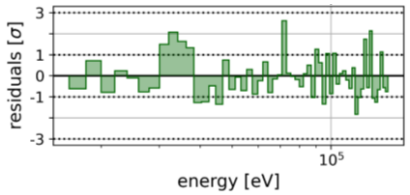
MAGIC
0.1-1 TeV

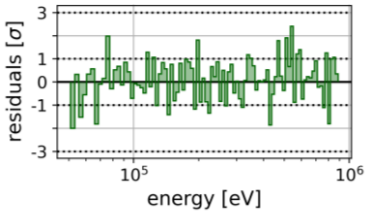


MAGIC Nature 575 (2019)

$-2.16^{+0.29}_{-0.31}(\mathrm{stat}) \pm 0.2(\mathrm{sys})$

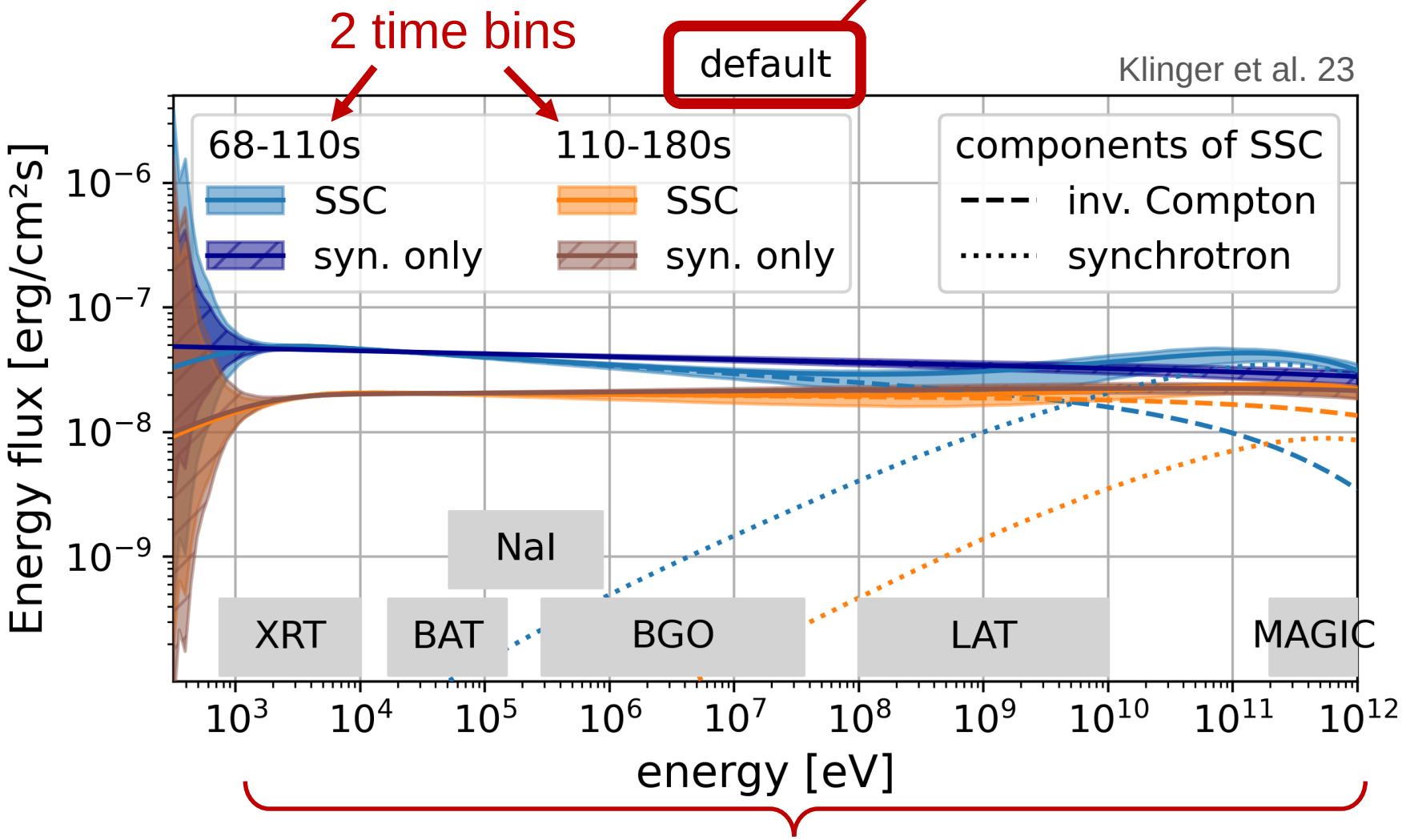






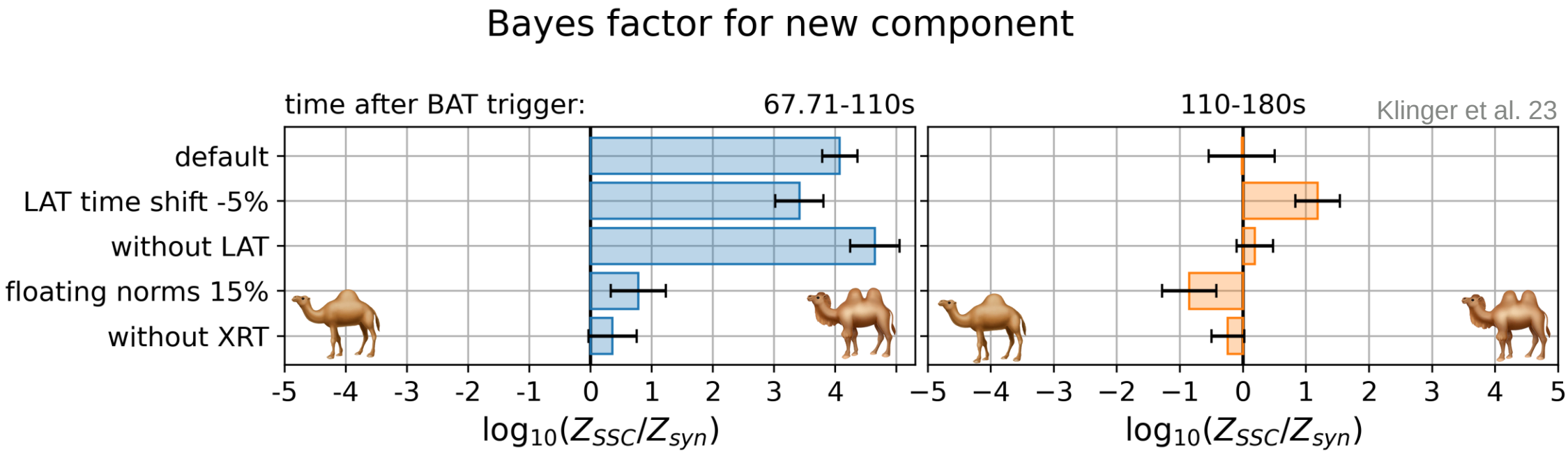
Fitting the reduced SSC model

as in Ajello et al. 2020 (joint Swift+Fermi)
→ only BAT-GBM cross calibration included



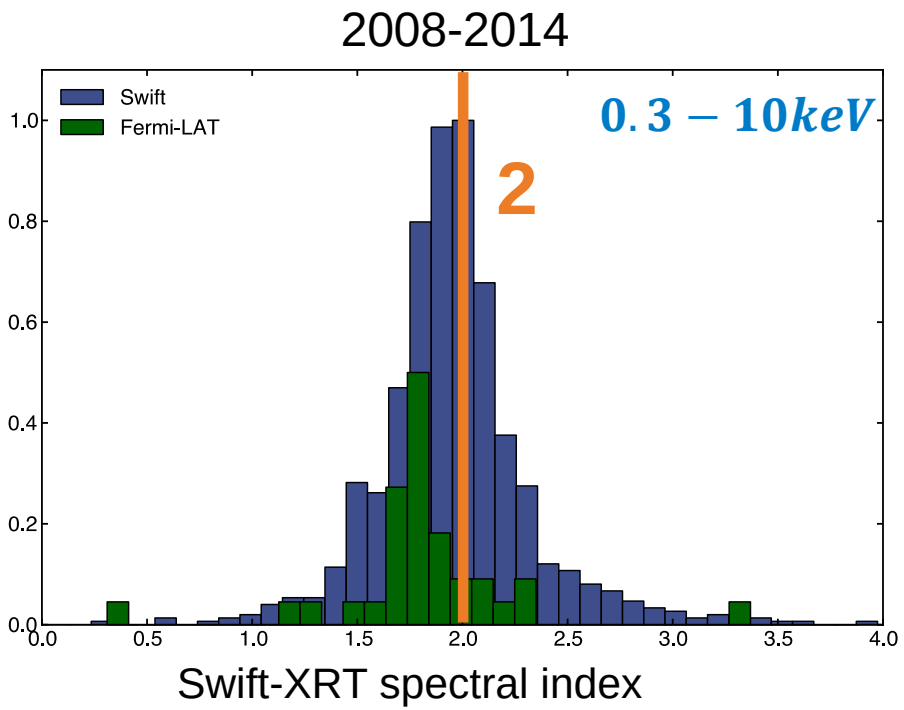
flat over 9 orders of magnitude!

Stability of Preference: XRT

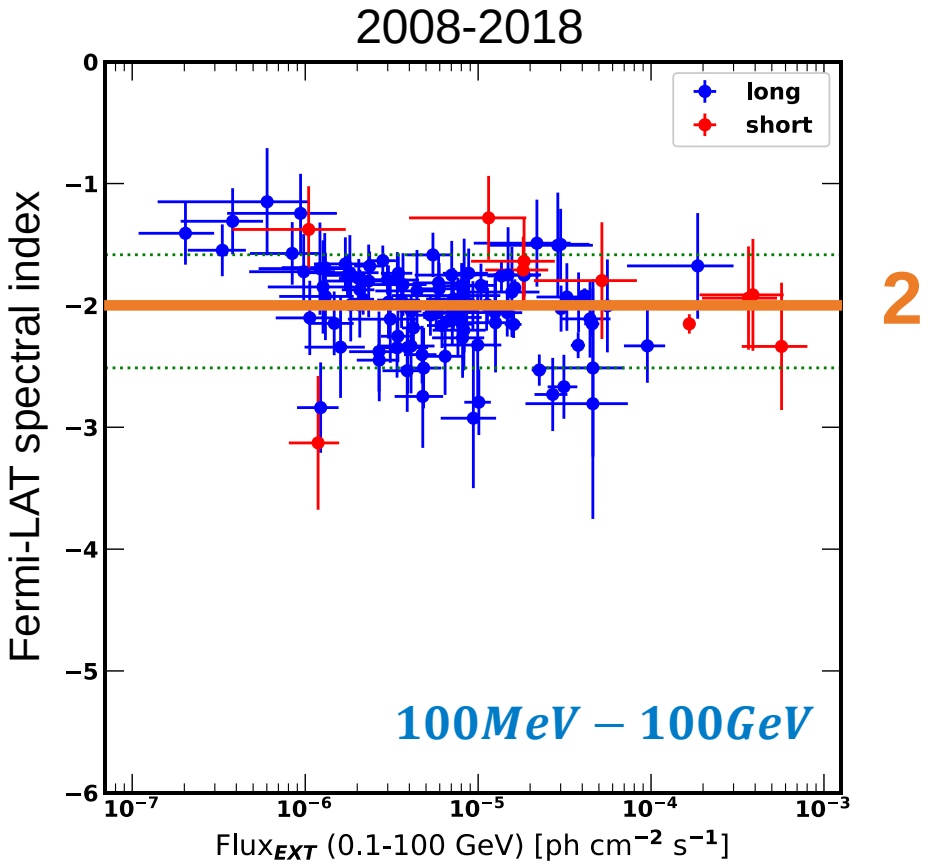


- systematic cross calibration uncertainty limited to 15% (a.k.a. floating norm or effective area correction)
- **LAT no crucial role!**
- **XRT drives new component!**

Flat Energy Flux Spectra?



Ajello et al. 2018, joint Swift/Fermi analysis



Ajello et al. 2019, 2nd Fermi GRB catalogue

- flat spectra (spectral index ≈ 2) are not uncommon!