Lepto-Hadronic Very-High-Energy GRB Afterglows

Marc Klinger*, 24.10.2023, at HEPRO VIII in Paris

In Collaboration with Andrew Taylor, Walter Winter, Sylvia Zhu, Chengchao Yuan, Donggeun Tak, Andrew Beardmore, Tyler Parsotan, Sebastian Heinz

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

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DESY.

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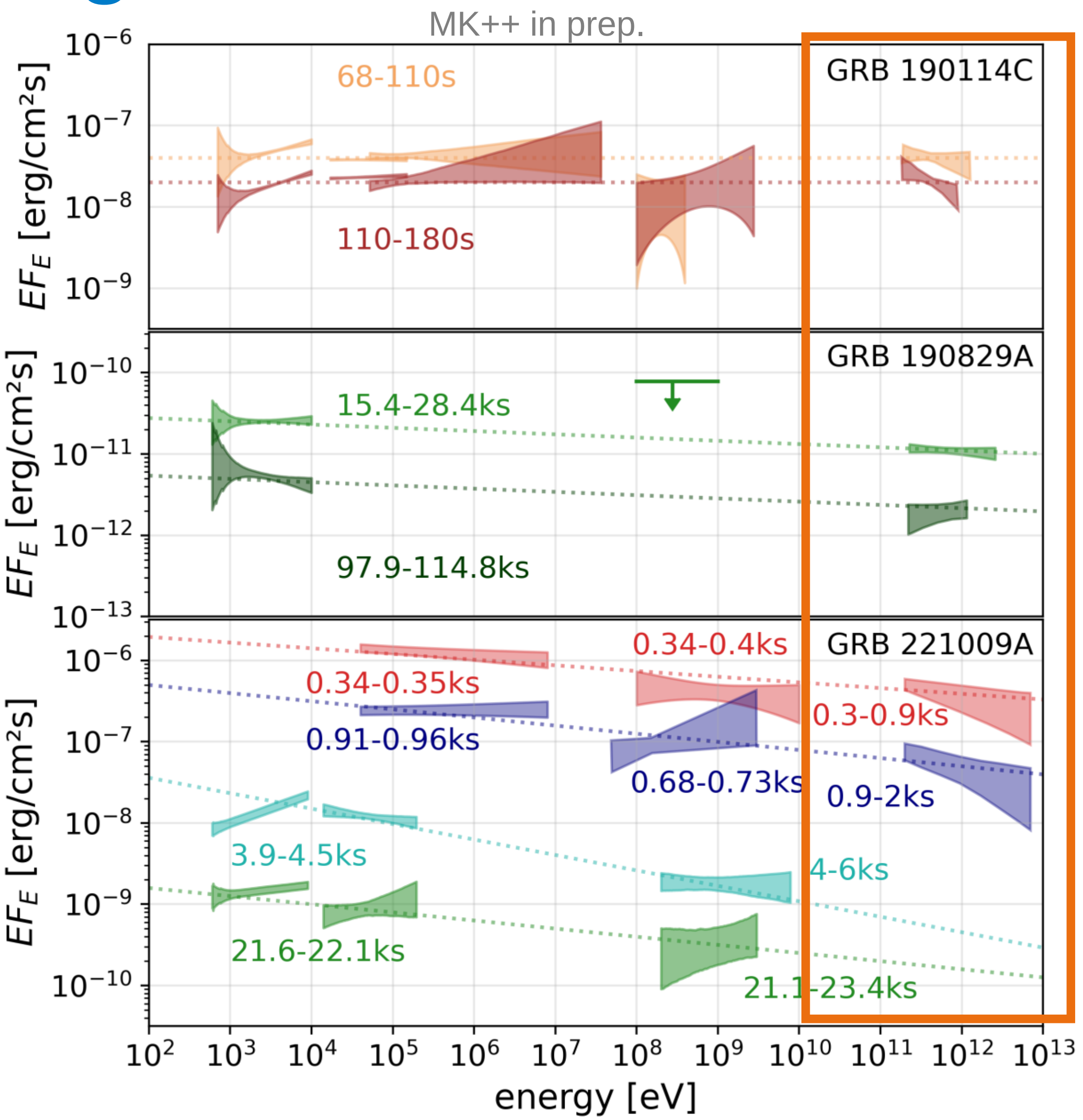
https://maklinger.github.io/

GRB afterglows detected at VHE!



→ **MAGIC**

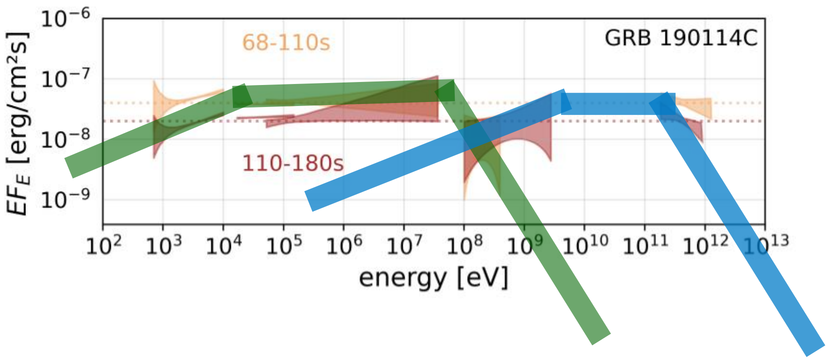
→ **HESS**

→ **LHAASO**

data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ arXiv:2309.10515
LHAASO Science 380 (2023)
MK++ subm. arXiv:2308.13854

Problem:

Current models struggle to predict TeV photon spectra of the early afterglow of long GRBs!



standard in community:
2 component SSC

Problem:

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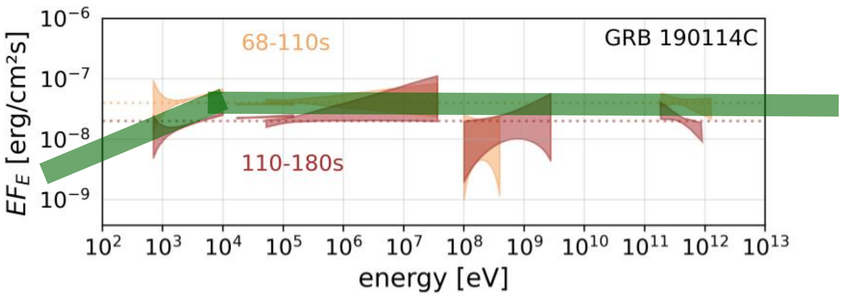
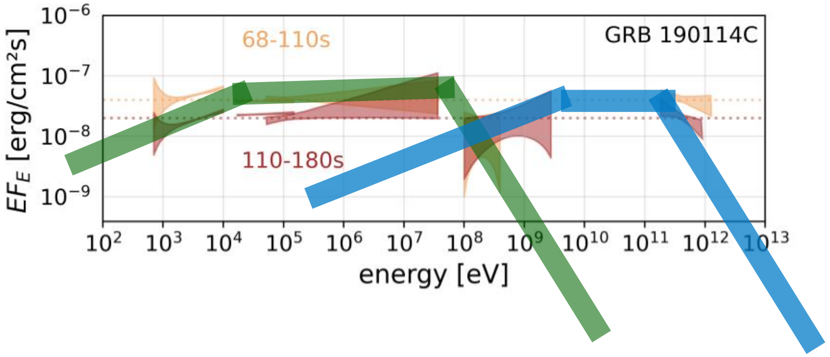
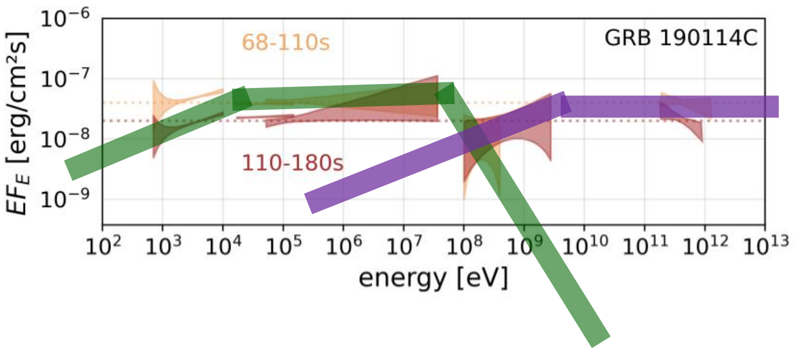
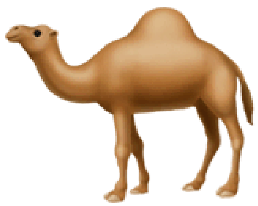






?



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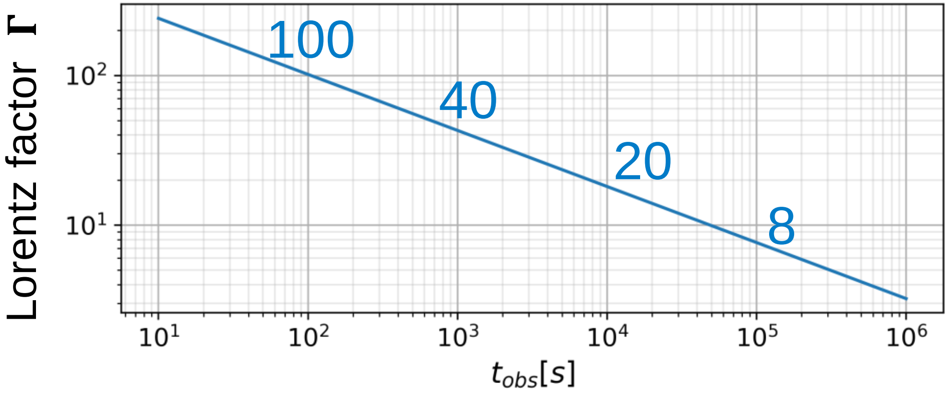
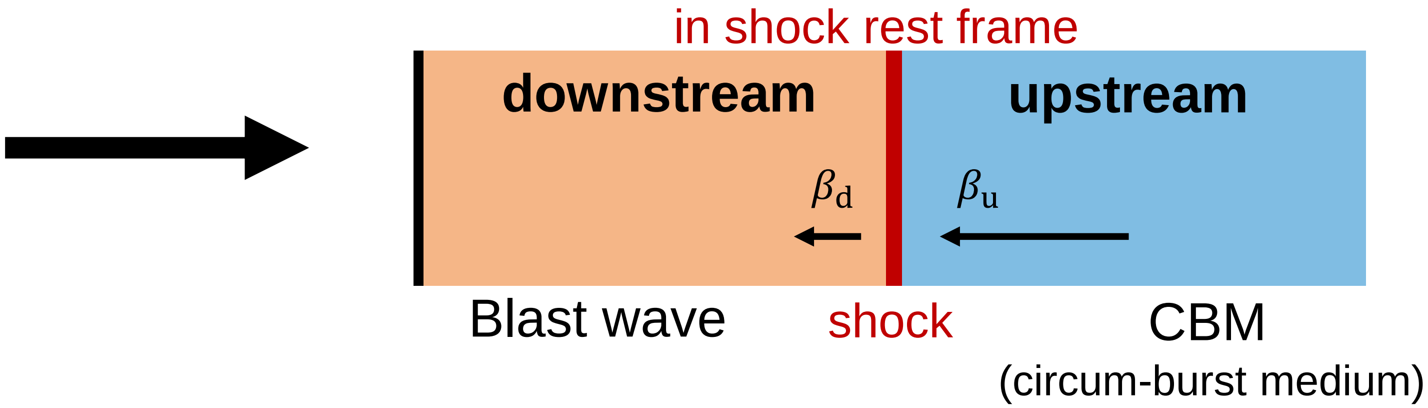
Afterglows: Radiation from a relativistic shock

$E_{\mathrm{kin}}^{\mathrm{iso}} = 10^{54}\mathrm{erg}, n_{\mathrm{u}} = 1\ \mathrm{cm}^{-3}$



Blandford & McKee 1976



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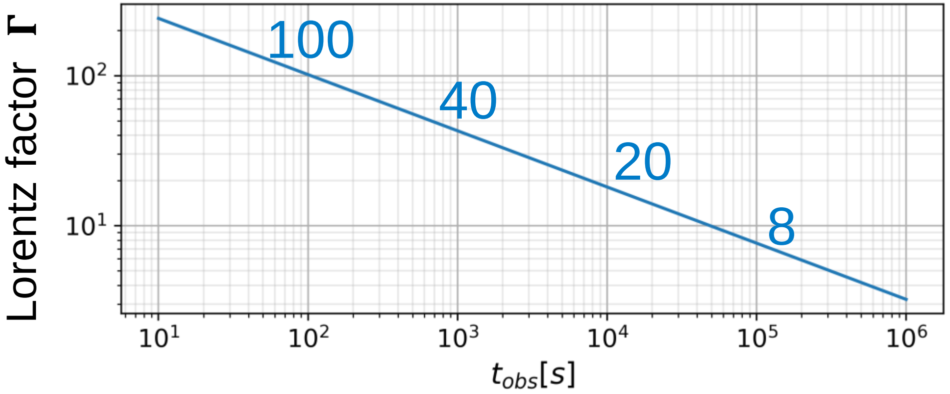

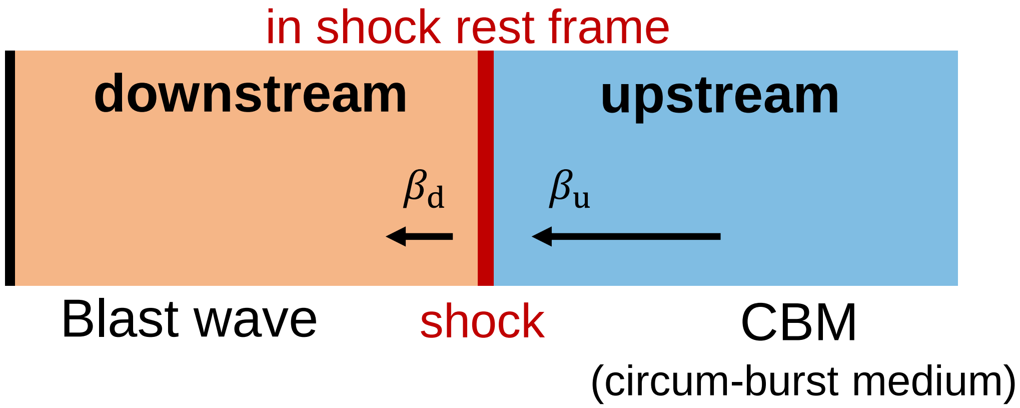

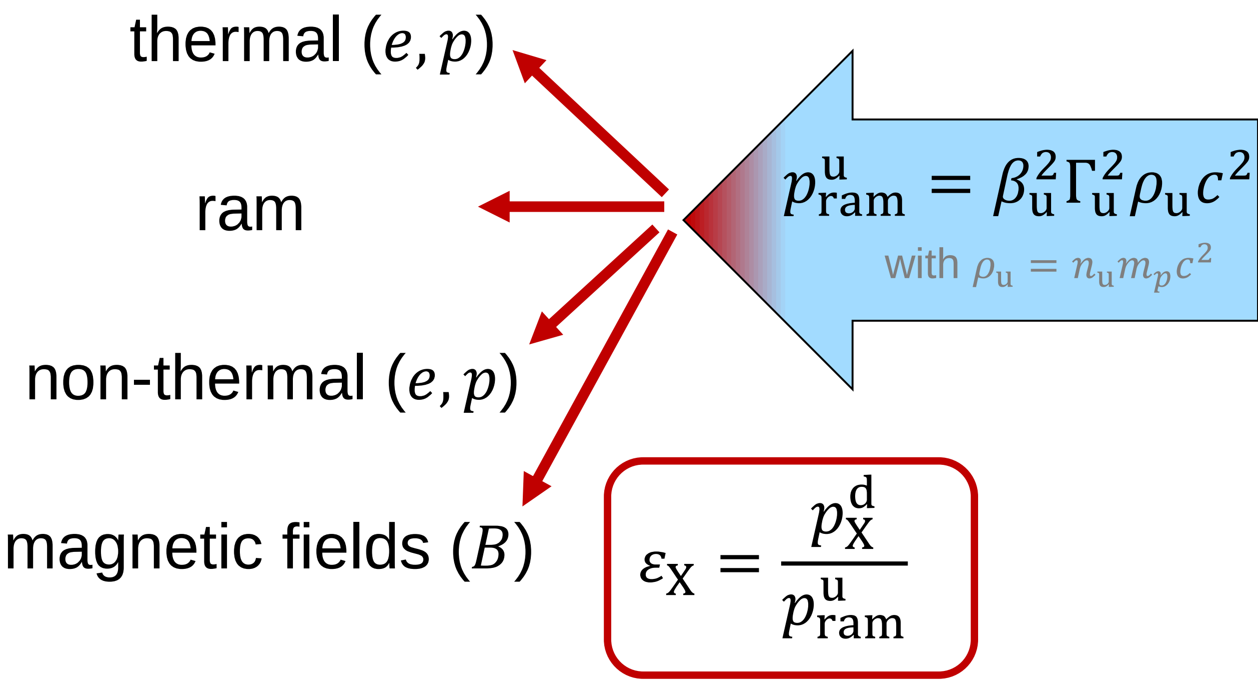

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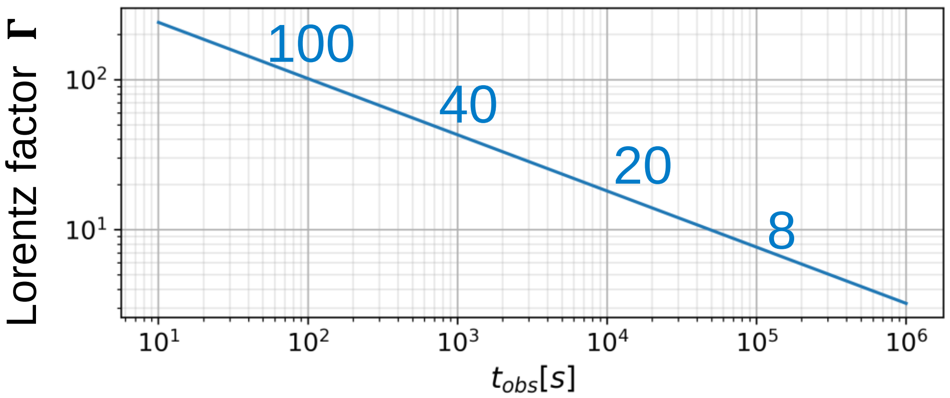
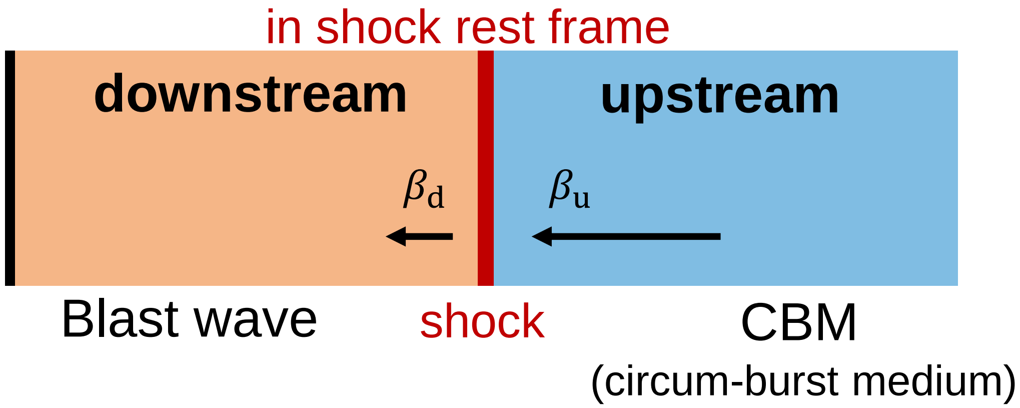
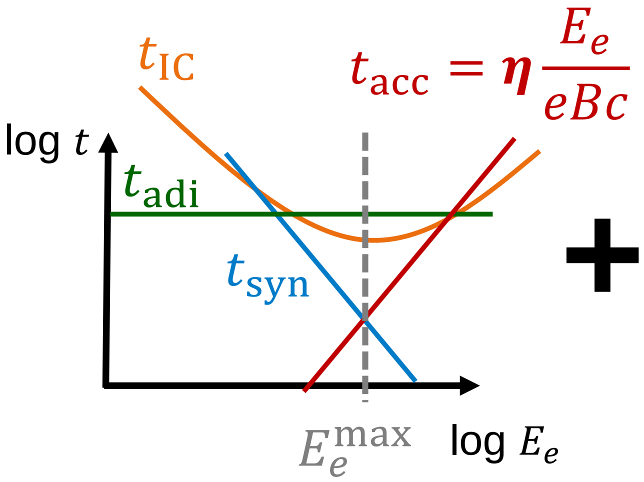
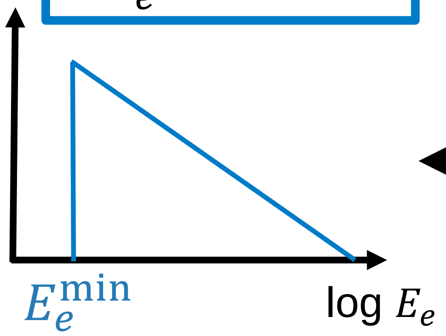






+

$$\frac{{\rm d}N_e}{{\rm d}E_e{\rm d}t} \propto E_e^{-p_e}$$



thermal (e, p)

ram

non-thermal (e, p)

magnetic fields (B)

$$p_{\rm ram}^{\rm u} = \beta_{\rm u}^2 \Gamma_{\rm u}^2 \rho_{\rm u} c^2$$

with $\rho_{\rm u} = n_{\rm u} m_p c^2$

$$\varepsilon_{\rm X} = \frac{p_{\rm X}^{\rm d}}{p_{\rm ram}^{\rm u}}$$

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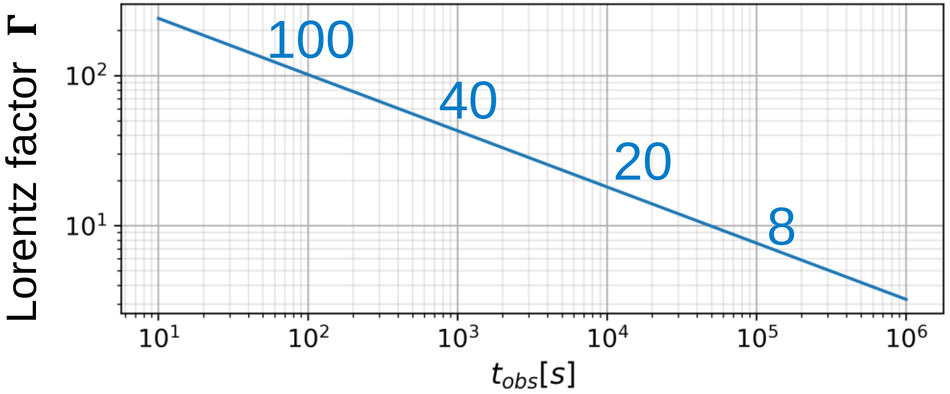

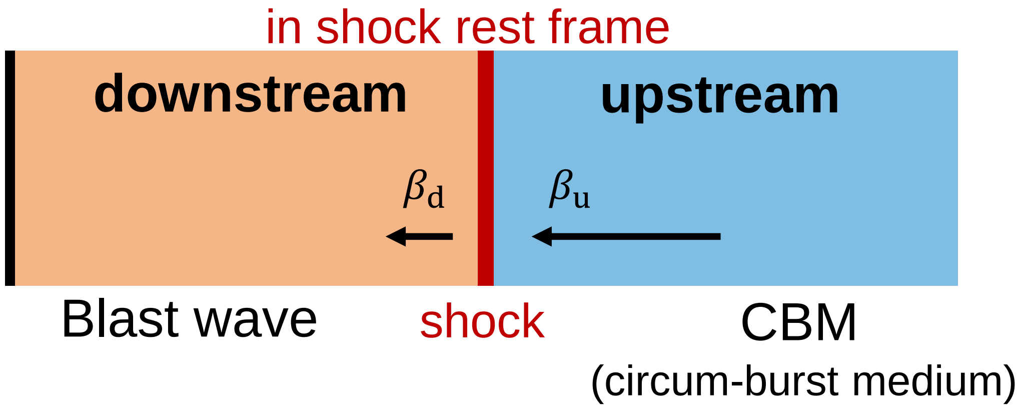

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with $\rho_{\mathrm{u}} = n_{\mathrm{u}} m_p c^2$

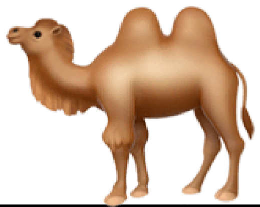
$$\boxed{\varepsilon_{\mathrm{X}} = \frac{p_{\mathrm{X}}^{\mathrm{d}}}{p_{\mathrm{ram}}^{\mathrm{u}}}}$$

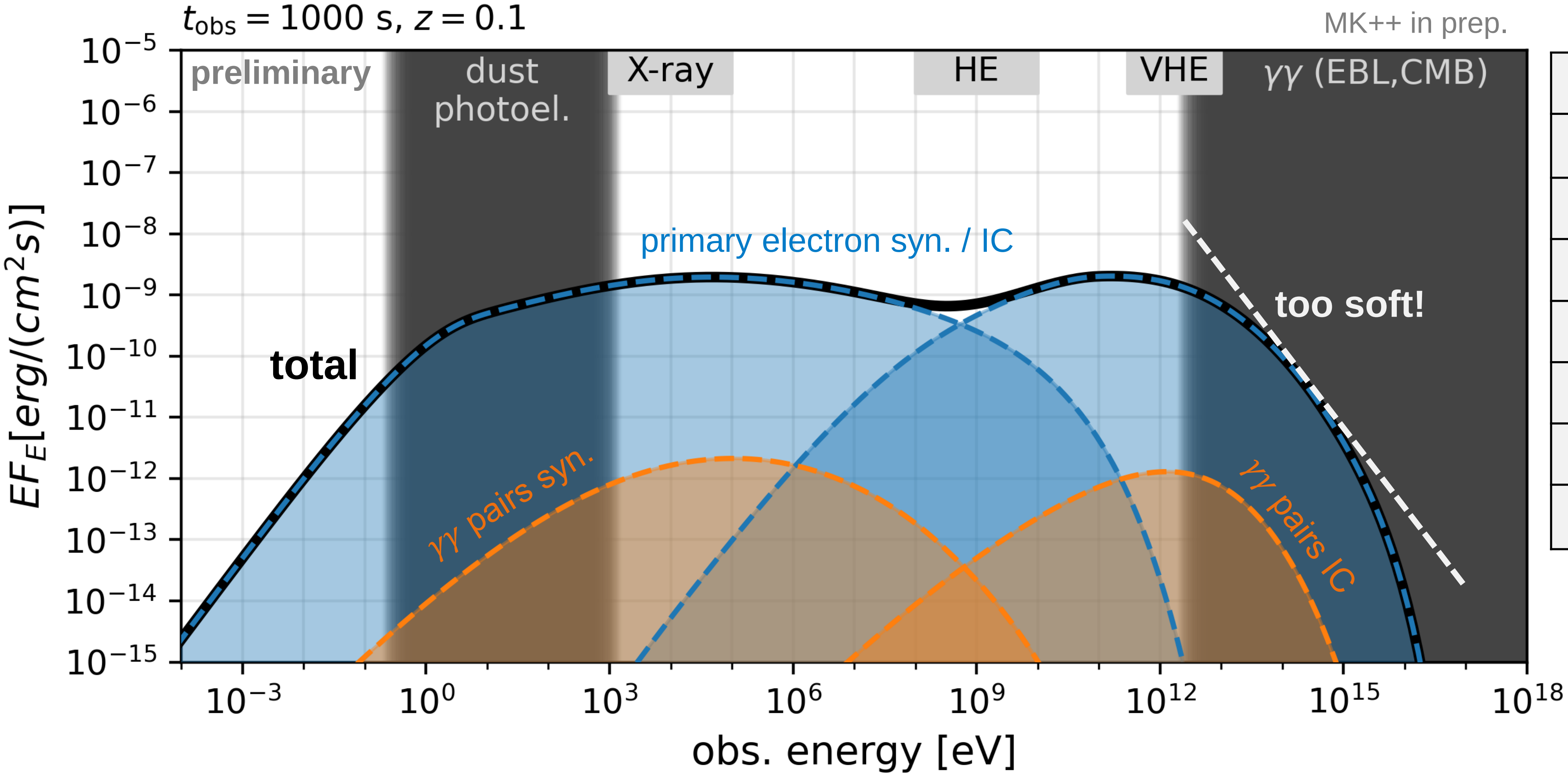
→ quasi-steady state

$$\frac{\mathrm{d}N}{\mathrm{d}E} \sim \tau \times \frac{\mathrm{d}N_e}{\mathrm{d}E_e \mathrm{d}t}$$

→ similar to time-dependent modeling

Synchrotron Self-Compton (SSC) model





ε_e	$10^{-1.5}$
ε_p	0
ε_B	10^{-4}
E_e^{min}	3GeV
p_e	2.4
η	1
$E_{kin\ iso}$	10^{54}erg
n_{up}	1cm^{-3}

AM³

time dependent modeling with AM³!

Problem: Klein-Nishina suppression tricky!

(1) slope at VHE very soft (2) parameter fine tuning to get peaks at ~ same height

Beyond the SSC model

$$t_{\rm acc} = \boldsymbol{\eta}\frac{E_e}{eBc}$$

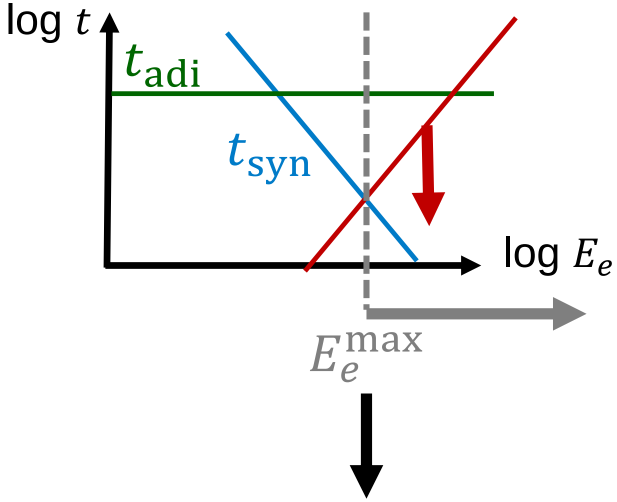
Ideas:

- faster than Bohm acceleration: $\eta \ll 1$

  → 1 zone: violation of MHD conditions
  Kumar++ MNRAS 427 (2012), Huang++ APJ 925 (2022)

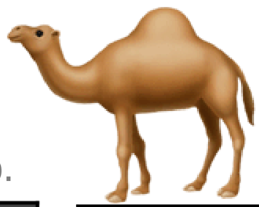
  → 2 zone: decouple acceleration zone from radiation zone
  Khangulyan++ APJ 947 (2021)

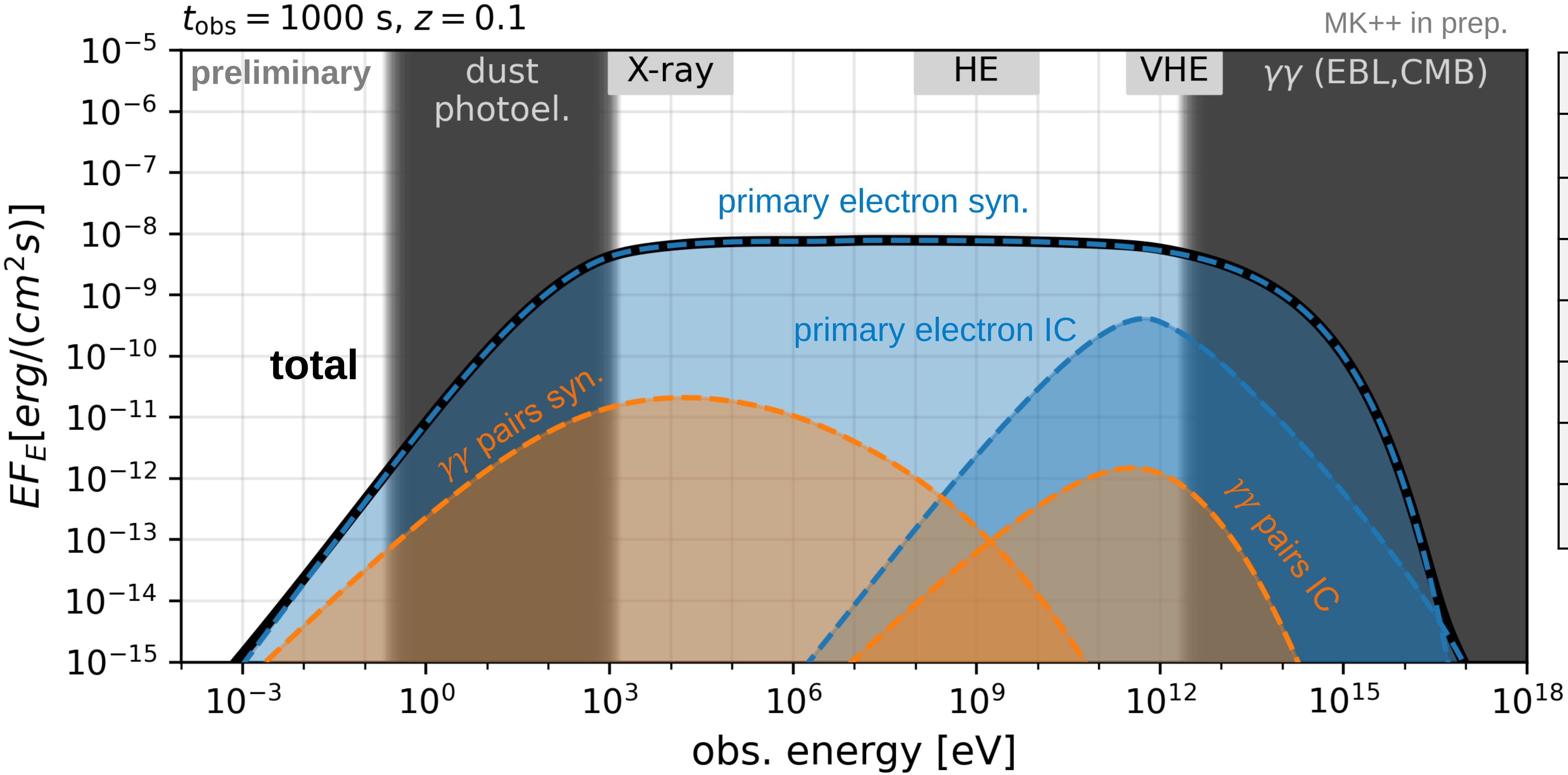
  → **extended electron synchrotron component**



$$E_{\gamma,\rm syn}^{\rm max} \gg 100\rm MeV$$

Extended synchrotron spectrum

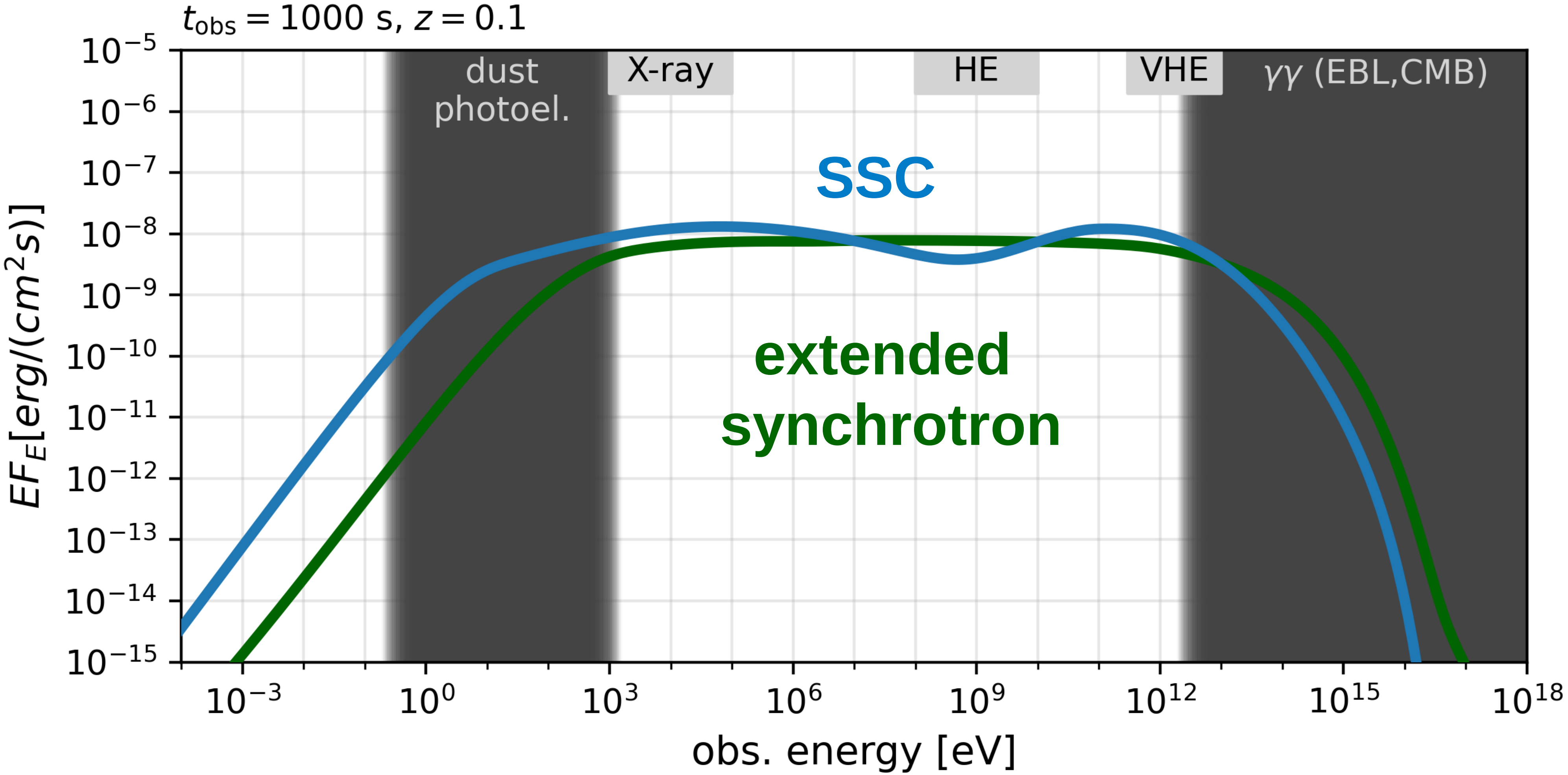


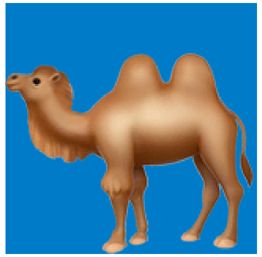


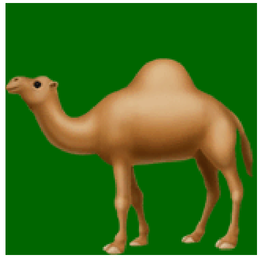
ε_e	$10^{-1.5}$
ε_p	0
ε_B	10^{-3}
E_{min}	30GeV
p_e	2
η	10^{-4}
E_{iso}	10^{54}erg
n_{up}	$1\mathrm{cm}^{-3}$

Problem: how to explain $\eta \ll 1$?

Extended synchrotron vs SSC

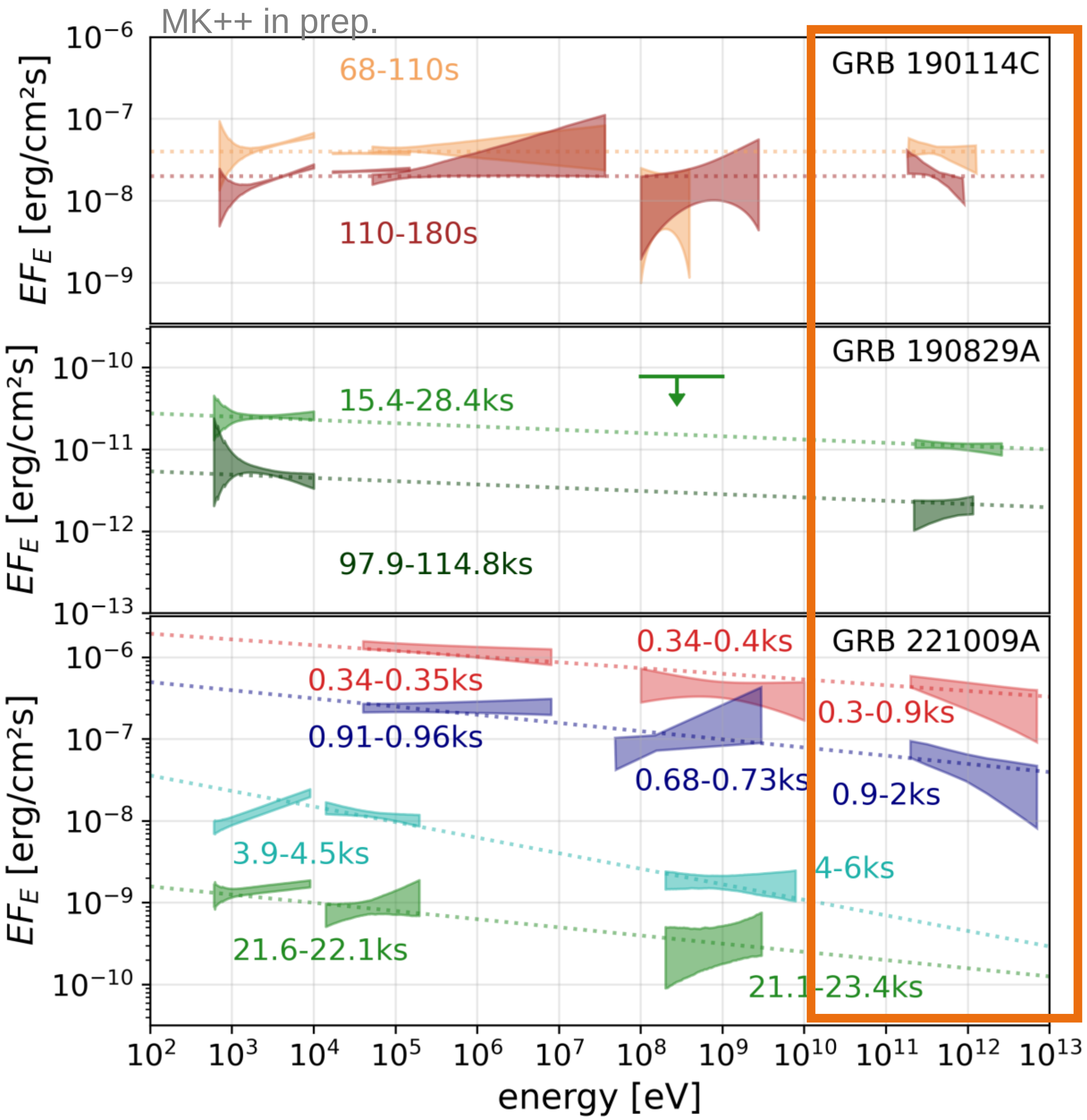






What about data?

Comparison to data

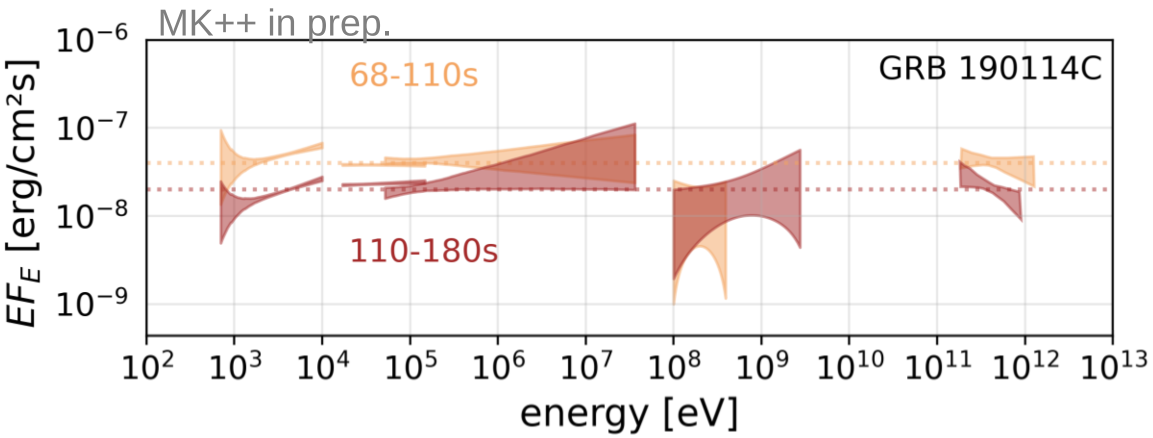


→ **MAGIC:**

→ **HESS:**

→ **LHAASO:**

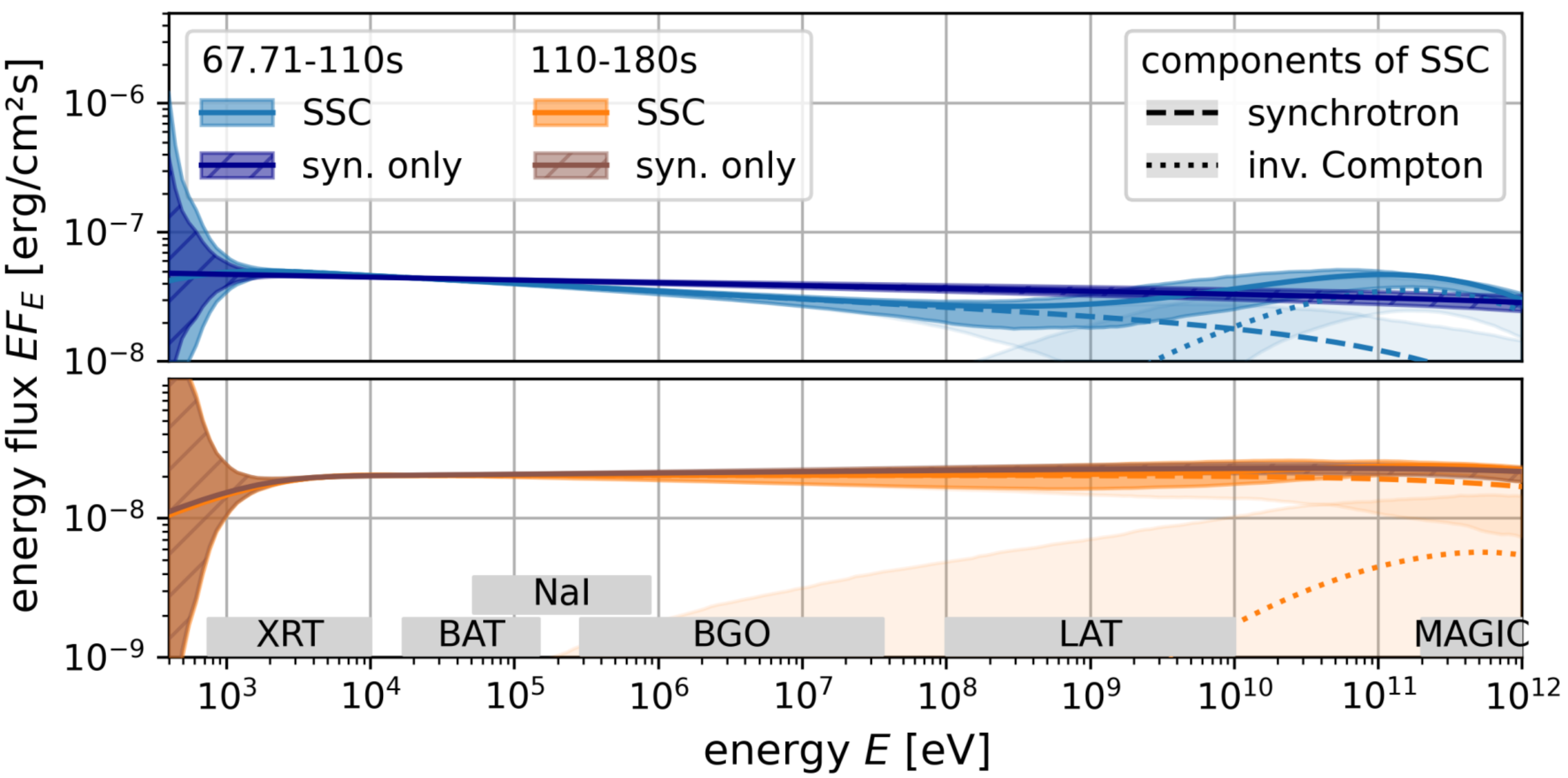
Comparison to data



→ **MAGIC:**

GRB 190114C: SSC vs extended syn

MK++ MNRAS 520 (2023)



- MAGIC observation:

  $z = 0.43$ (EBL) + moonlight

  → uncertain spectral index at TeV $-2.2 \pm 0.3 \pm 0.2$ (stat) (sys)

  MAGIC Nature 575 (2019)

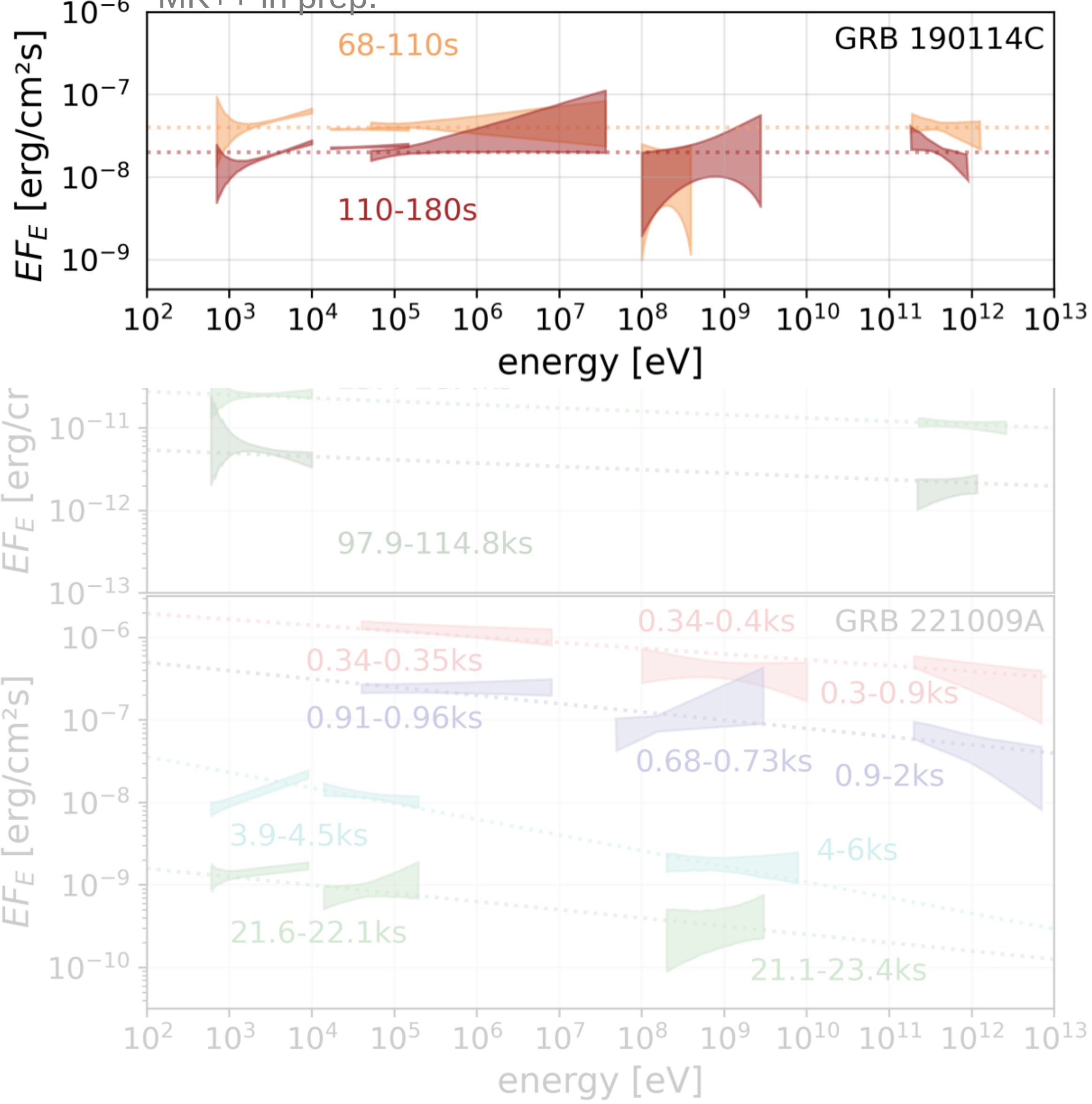
- *Fermi*-LAT not constraining (5+6 photons)

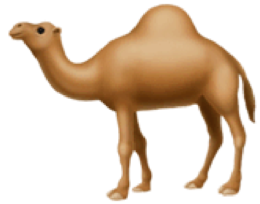
- counts level fit:

  → no robust preference for SSC!

Comparison to data

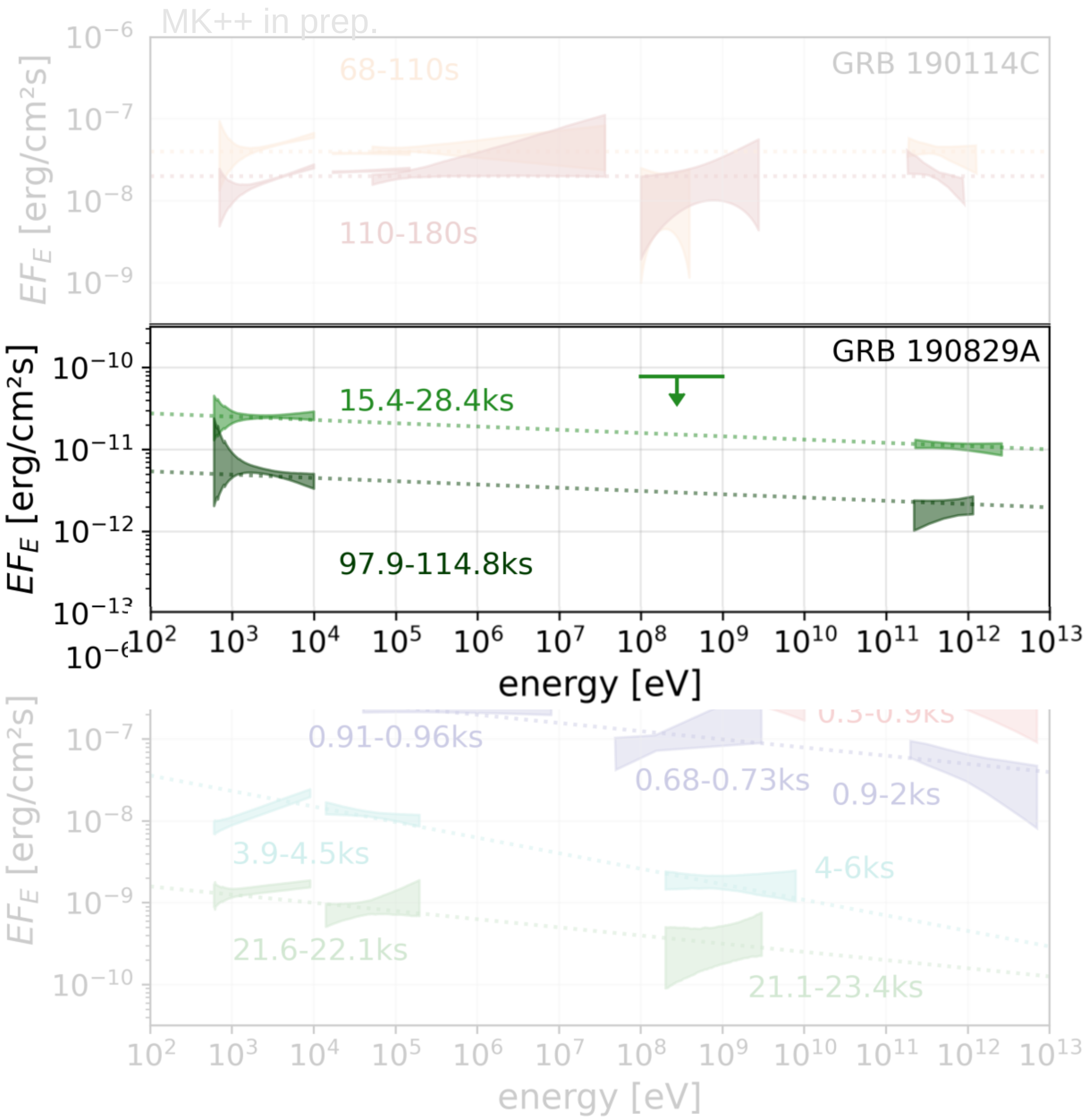
MK++ in prep.



→ **MAGIC:**  **?** 

→ **inconclusive on syn vs. SSC**

Comparison to data



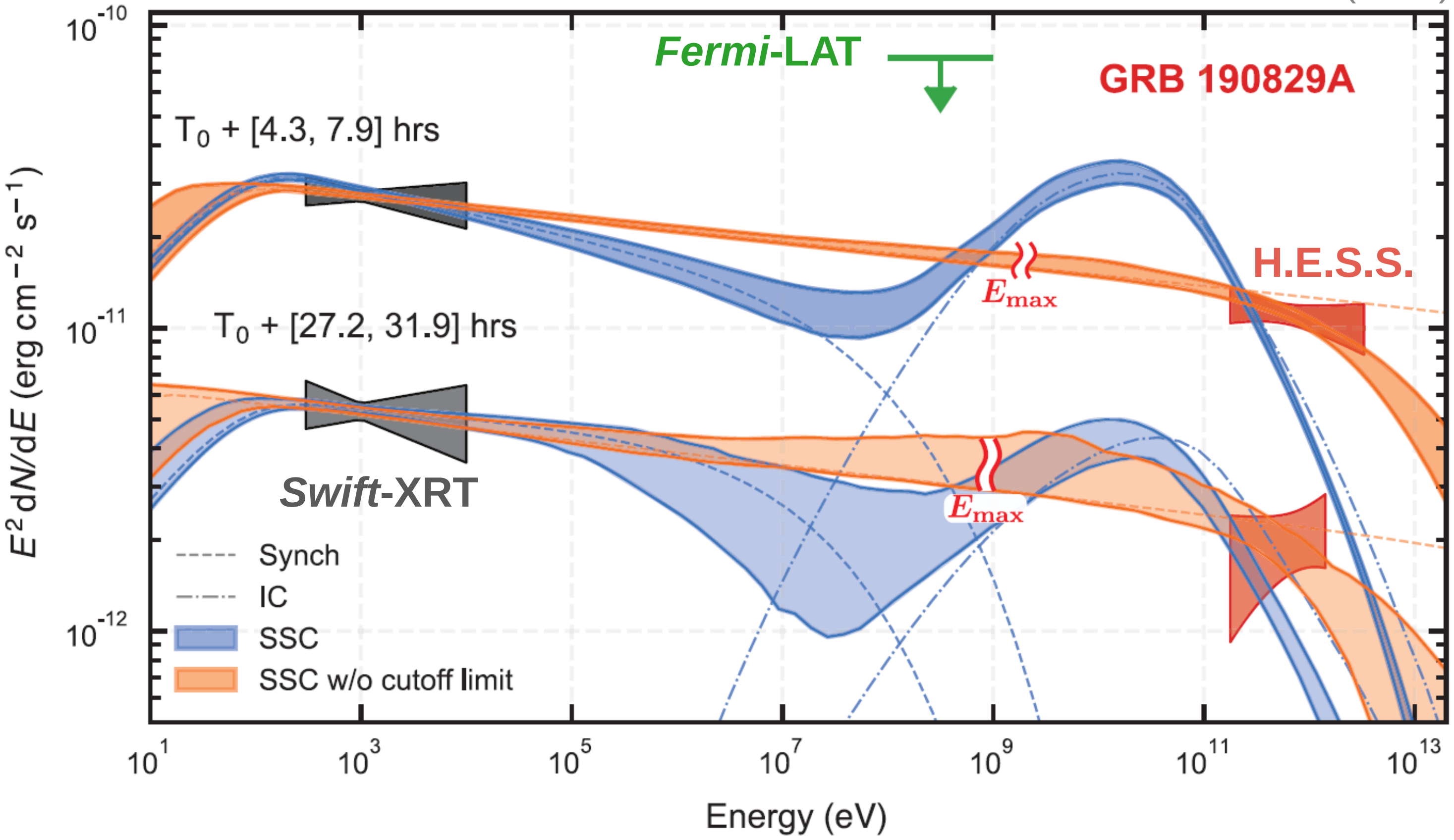
→ **MAGIC:**

→ **inconclusive on syn vs. SSC**

→ **HESS:**

GRB 190829A: SSC vs extended syn

H.E.S.S. Science 372 (2021)



- $z = 0.08 \rightarrow$ low EBL abs.

$\rightarrow$ spectral index at TeV:

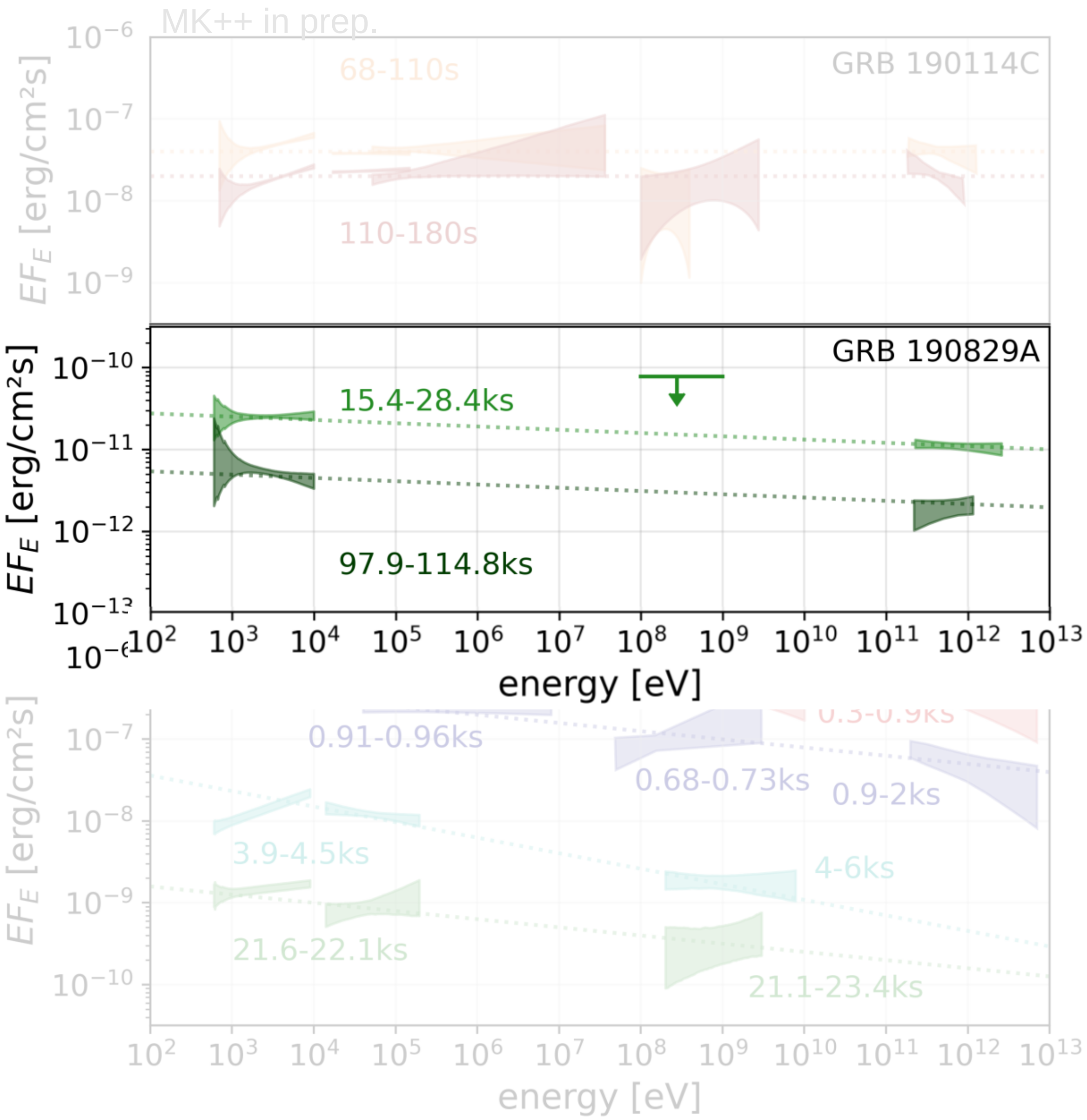
$$\approx -2 \underset{\text{(stat)}}{\pm 0.1} \underset{\text{(sys)}}{\pm 0.26}$$

- poor MWL coverage

- counts level fit:

$\rightarrow$ preference for single component!

Comparison to data



→ MAGIC:

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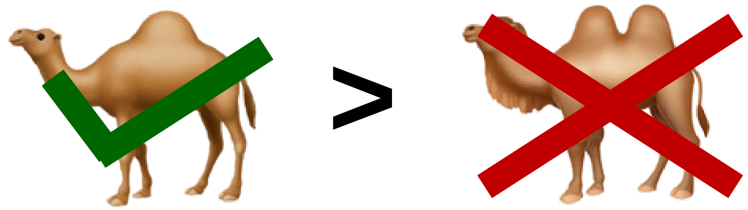
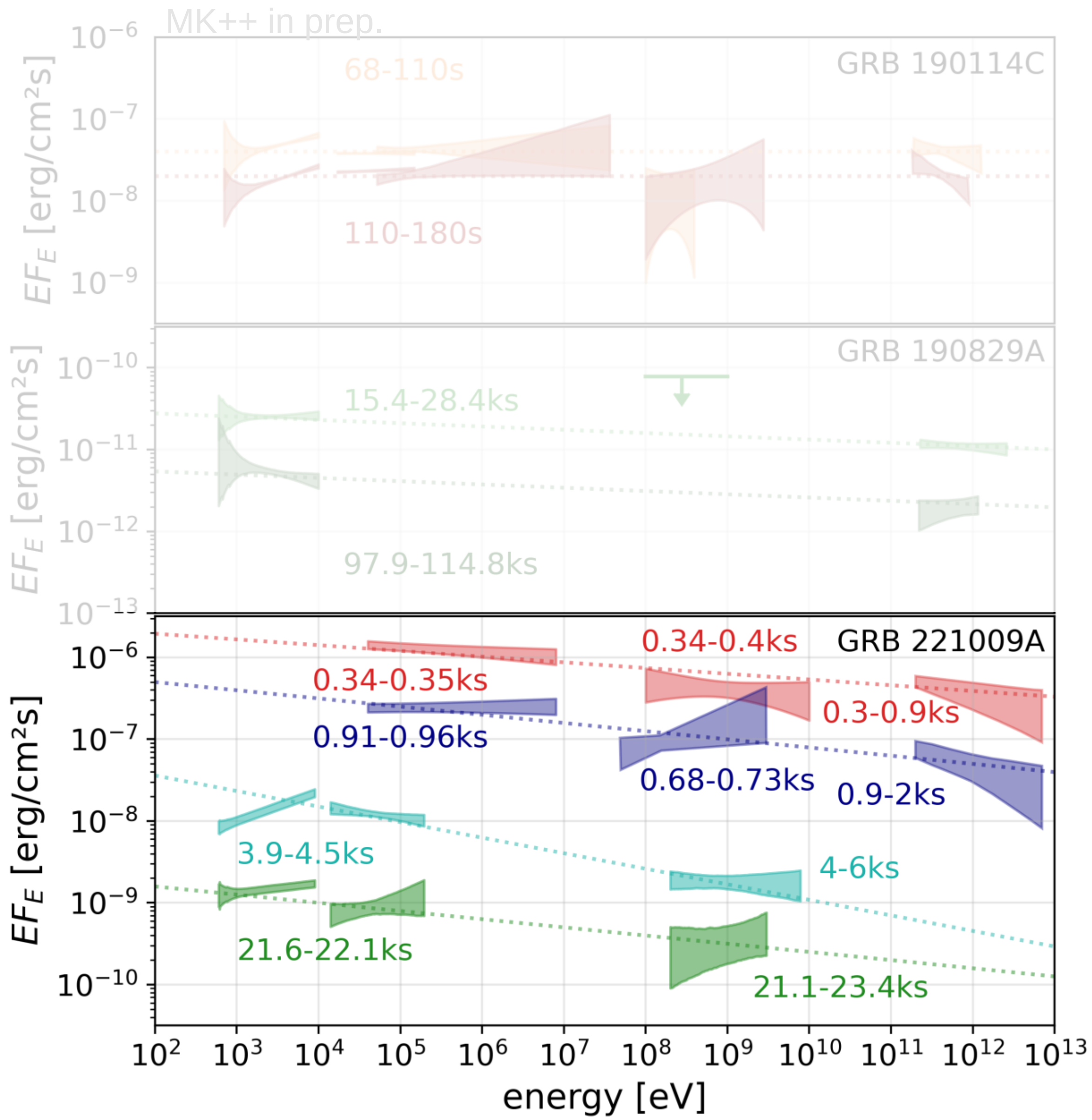


→ in tension with SSC

Comparison to data



→ MAGIC:

→ inconclusive on syn vs. SSC

→ HESS:

→ in tension with SSC

→ LHAASO:

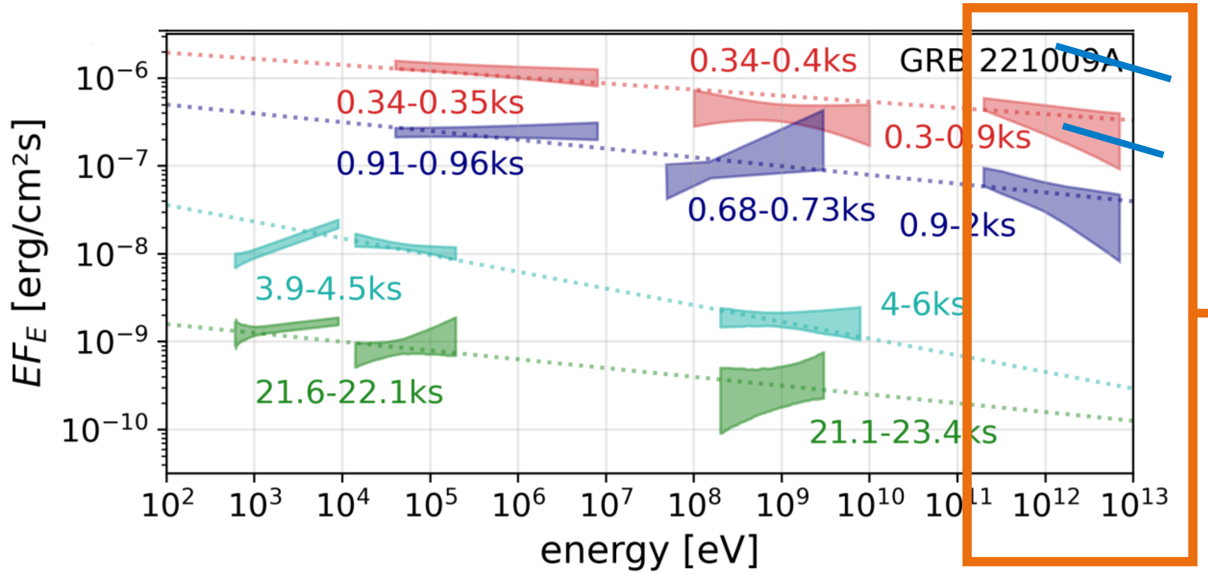
GRB 221009A

LHAASO Collaboration 2023:

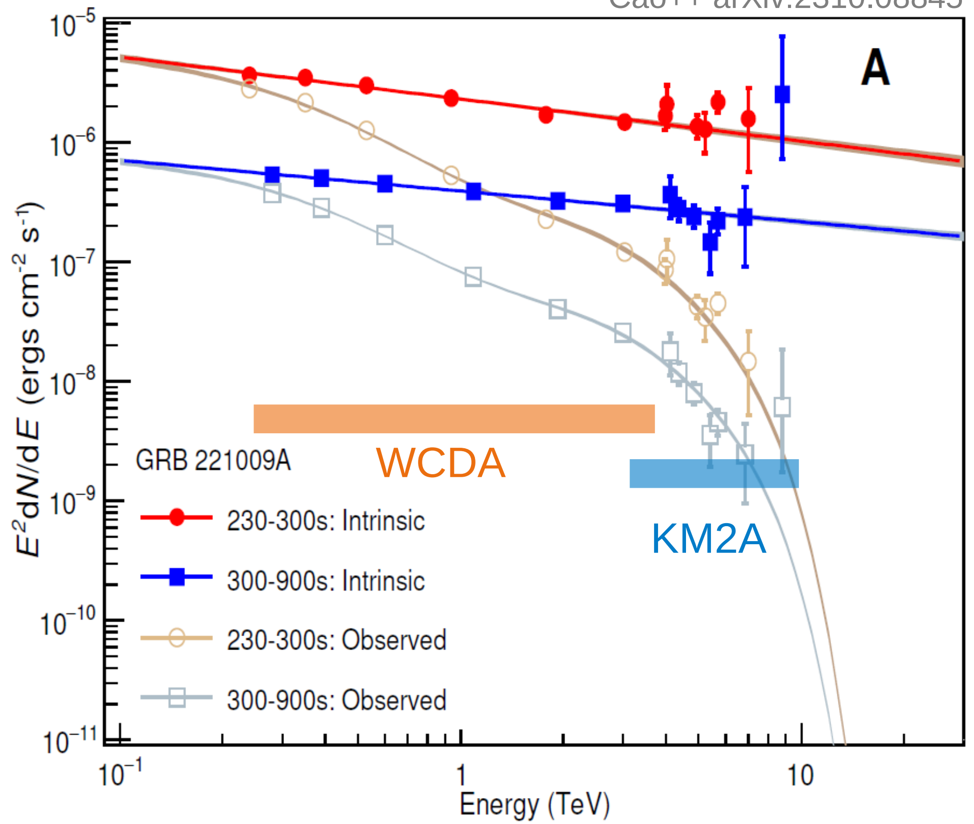
No softening up to at least 10 TeV!

(note $z = 0.15 \rightarrow$ EBL abs. > few TeV)

→ incompatible with SSC



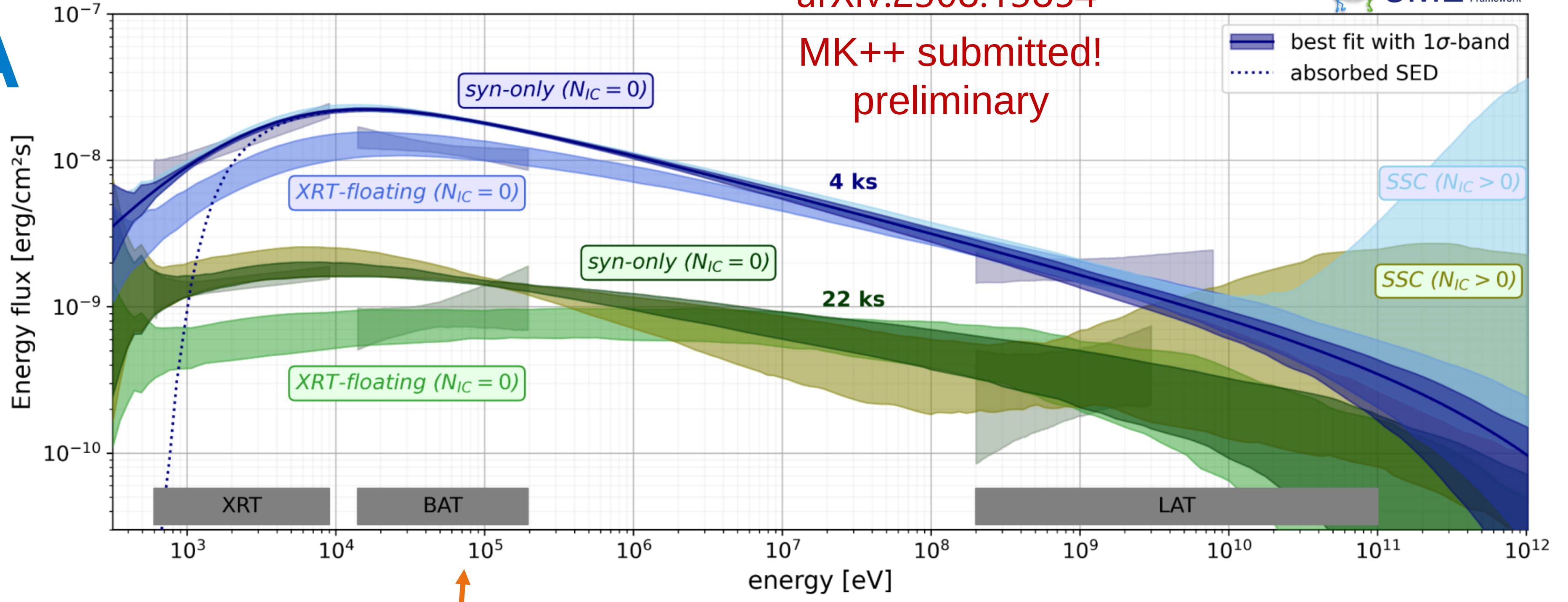
Cao++ arXiv:2310.08845

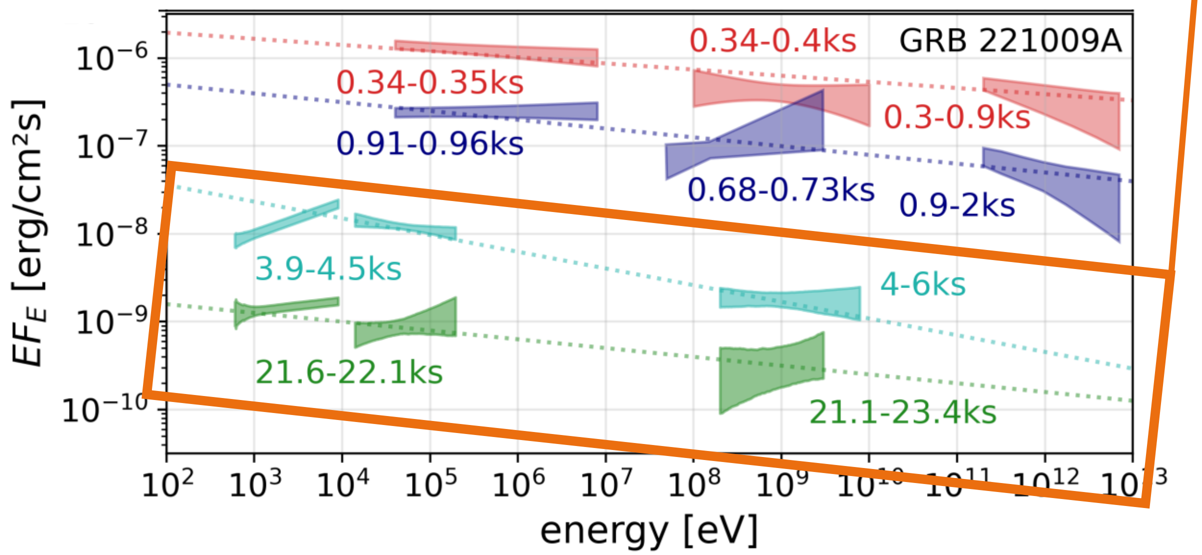


GRB 221009A

arXiv:2308.13854

MK++ submitted!
preliminary



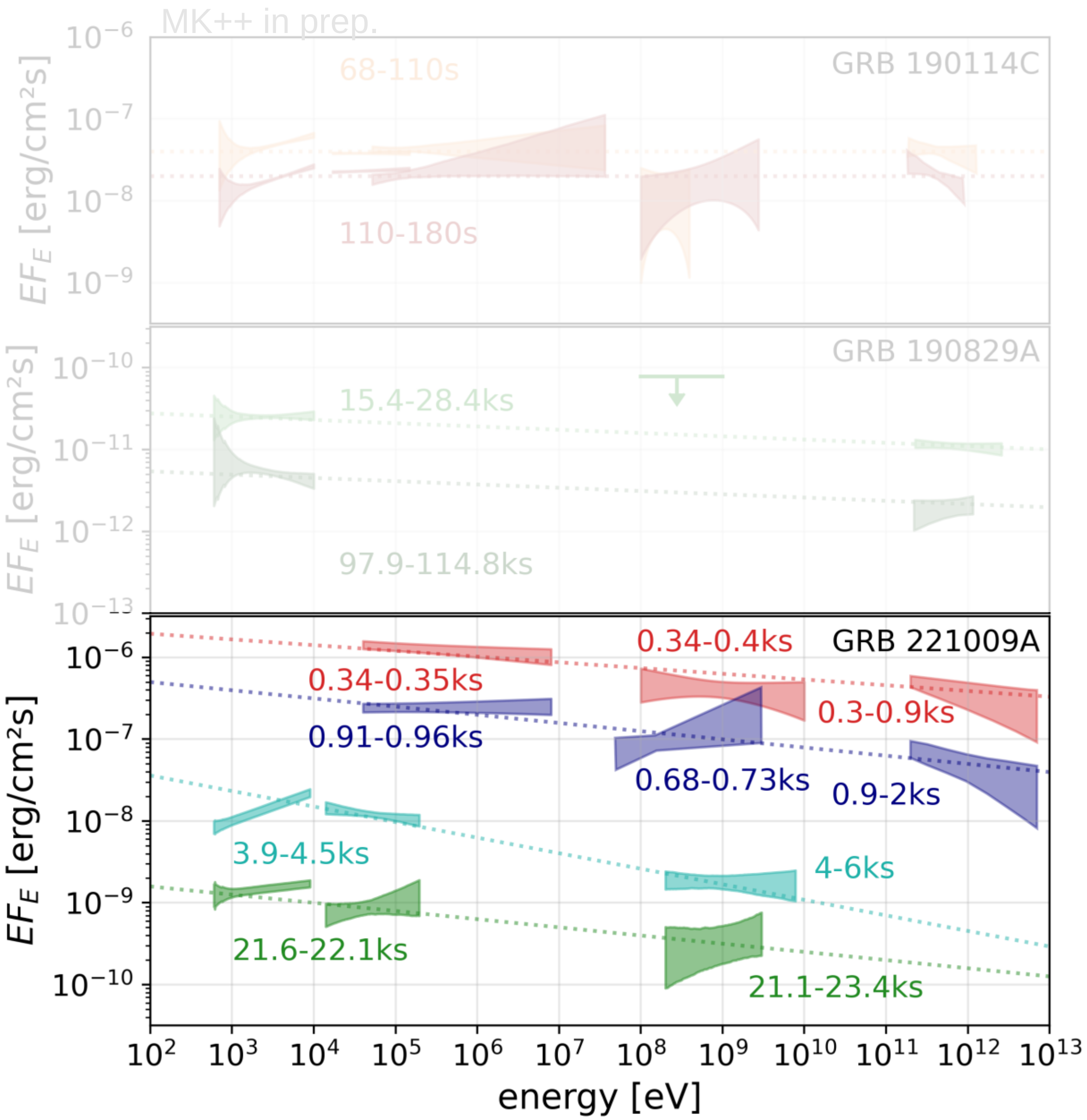


after LHAASO (> 2 ks):

- brightest GRB + in galactic plane
  → **problematic backgrounds (XRT, LAT)!**
- power-law with spectral index -2.2

→ consistent with LHAASO

Comparison to data



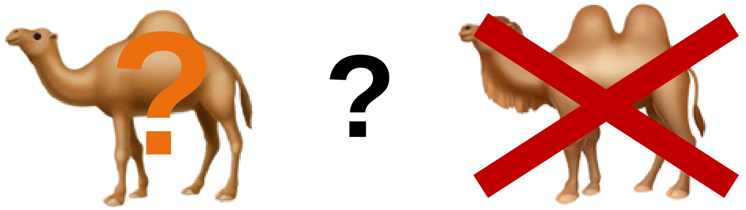
→ MAGIC:

→ inconclusive on syn vs. SSC

→ HESS:

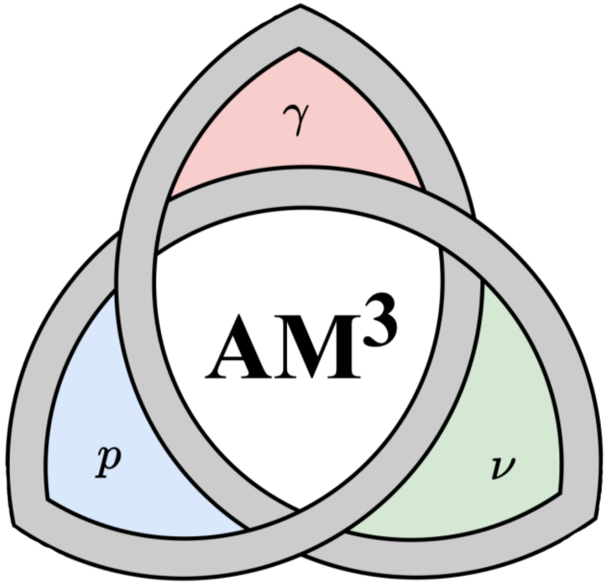
→ in tension with SSC

→ LHAASO:



→ in tension with SSC

There is more beyond the SSC model



Ideas:

- faster than Bohm acceleration: $\eta \ll 1$

  $\longrightarrow$ 1 zone: violation of MHD conditions
  Kumar++ MNRAS 427 (2012), Huang++ APJ 925 (2022)

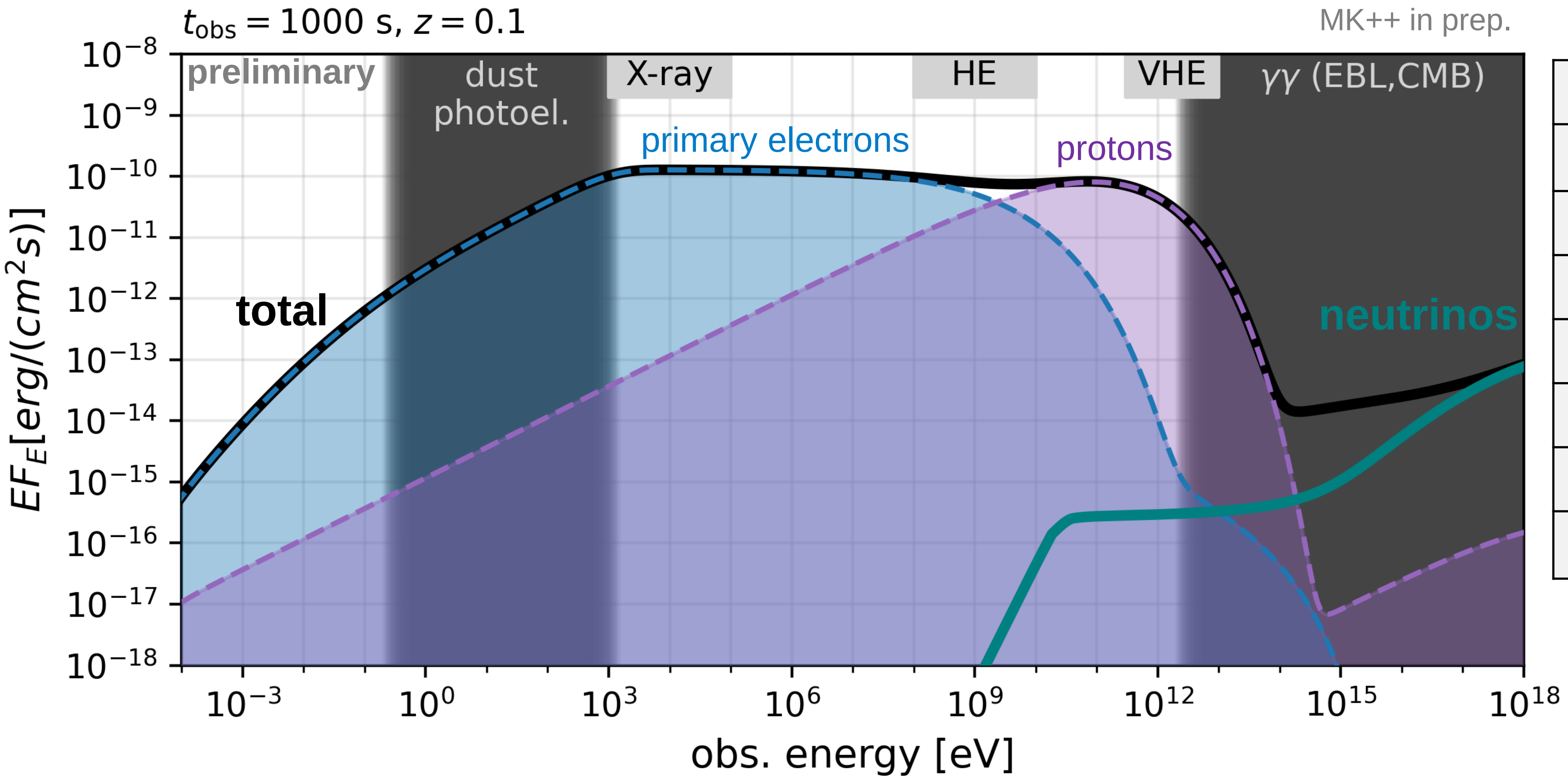
  $\longrightarrow$ 2 zone: decouple acceleration zone from radiation zone
  Khangulyan++ APJ 947 (2021)

  $\longrightarrow$ **extended electron synchrotron component**

- involve hadrons

  $\longrightarrow$ **proton synchrotron** component for VHE emission (Isravel++ ApJ 955 (2023), Cao++ arXiv:2310.08845)

Proton-Synchrotron model

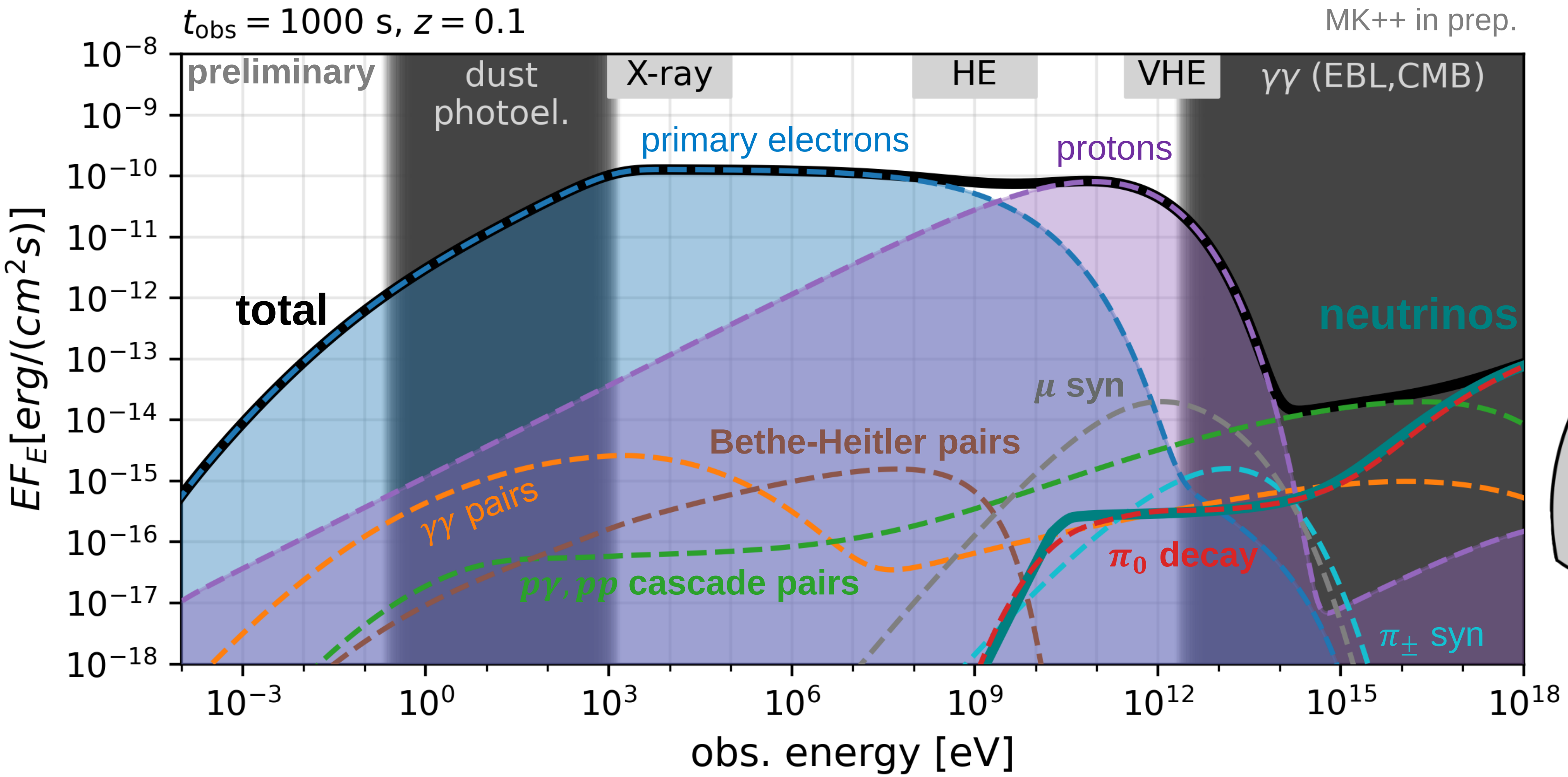


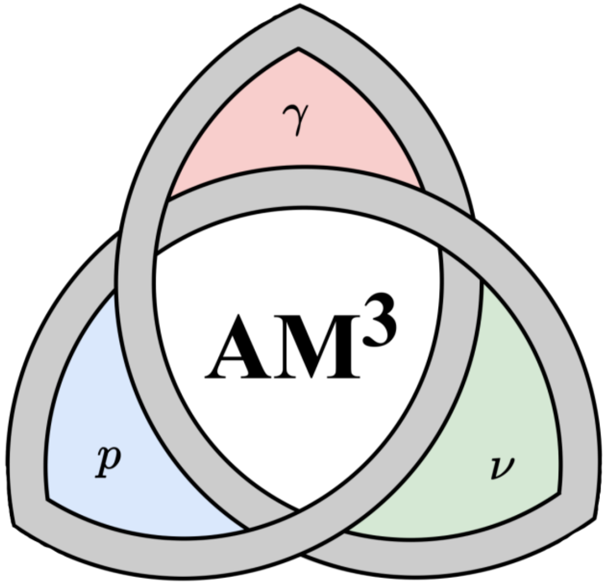
ε_e	10^{-3}
ε_p	$10^{-0.5}$
ε_B	$10^{-0.5}$
E_{min}	10GeV
p	2
η	1
E_{iso}	10^{55}erg
n_{up}	$1\mathrm{cm}^{-3}$

$\varepsilon_B, \varepsilon_p \lesssim 1$

Problem: proton synchrotron component at exponential cut-off!

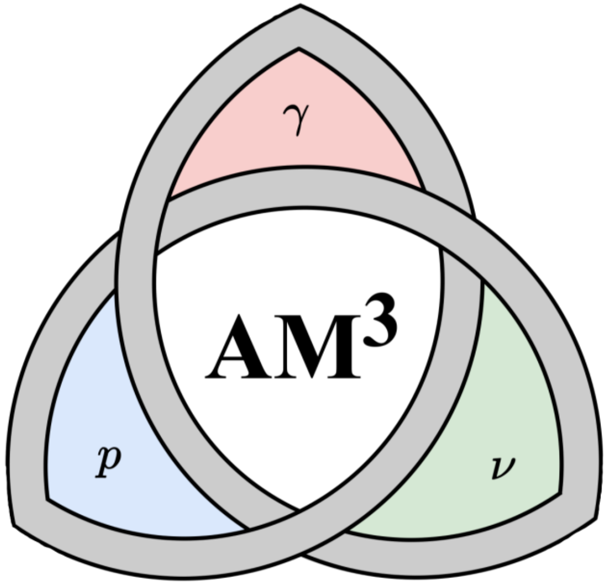
Proton-Synchrotron model





Interesting: neutrinos! But fluence not too high…

There is more beyond the SSC model



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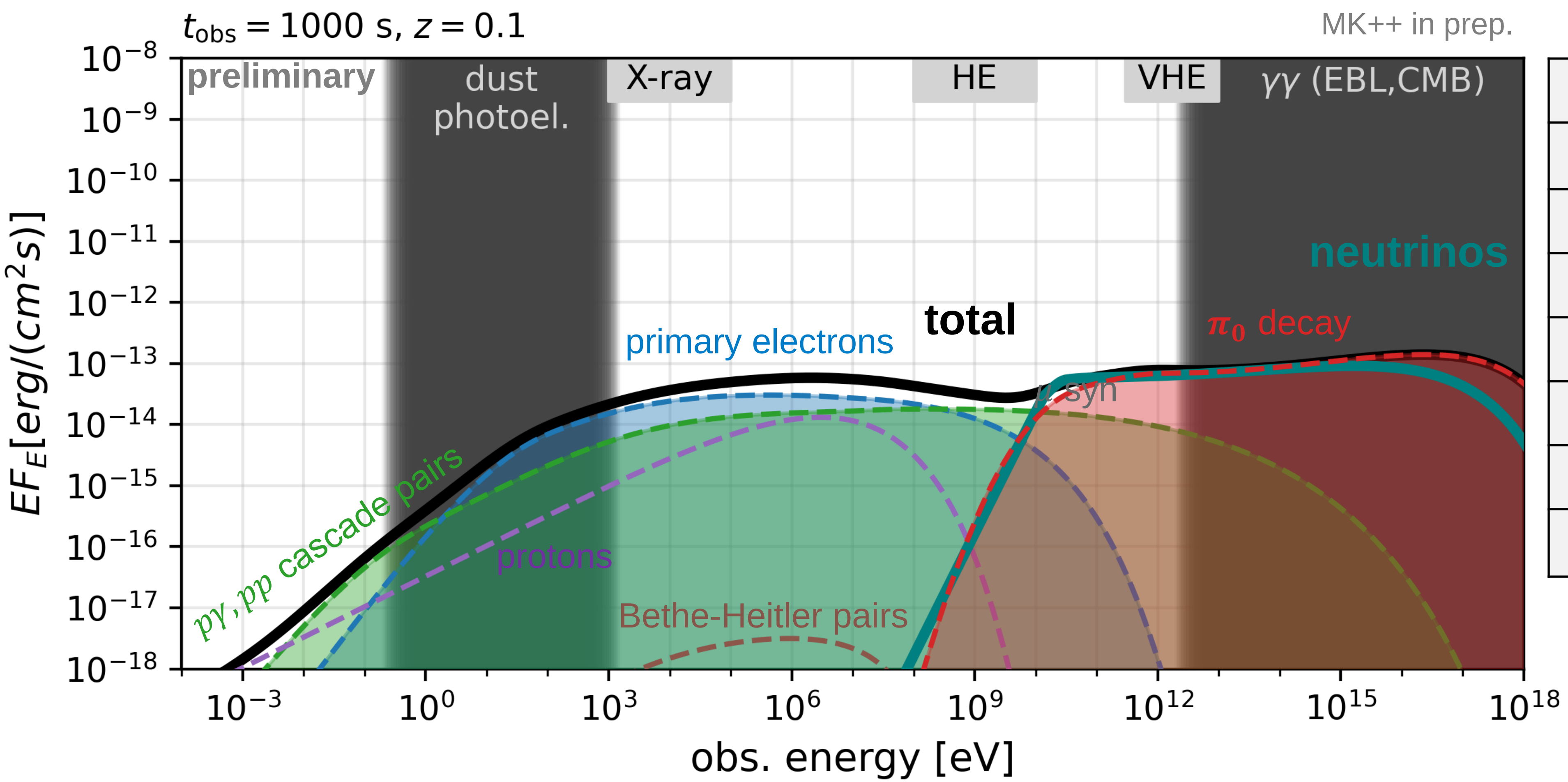
  - $\rightarrow$ **extended electron synchrotron component**
- involve hadrons
  - $\rightarrow$ **proton synchrotron** component for VHE emission (Isravel++ ApJ 955 (2023), Cao++ arXiv:2310.08845)
  - $\rightarrow$ **cascade from pγ interactions** for prompt VHE emission (Cao++ arXiv:2310.11821)
  - $\rightarrow$ **cascade from pp interactions**

pp-cascade



ε_e	10^{-8}
ε_p	10^{-1}
ε_B	10^{-5}
$E_{\min}$	10GeV
p	2
η	1
$E_{\rm iso}$	10^{55}erg
$n_{\rm up}$	$100{\rm cm}^{-3}$

Not very bright, high densities,
extreme baryonic loading, **but flat!**

Conclusions

- Long GRB afterglows show flat spectra extending to more than 10TeV

  → challenging to explain with current models

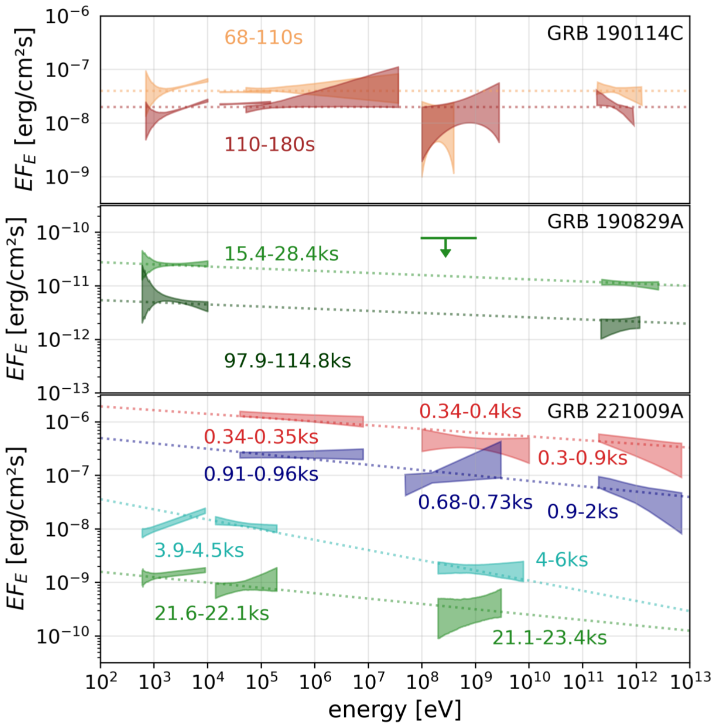
  → in particular for SSC scenario

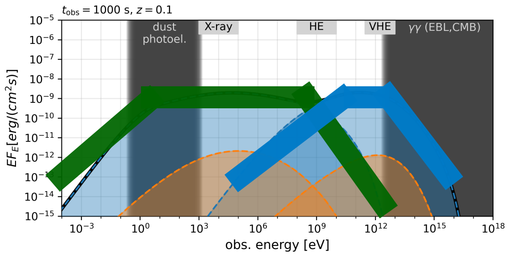
- Need to think about other scenarios:

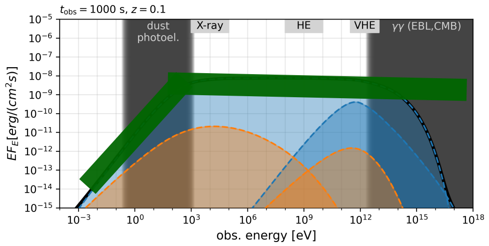
  → extended synchrotron model

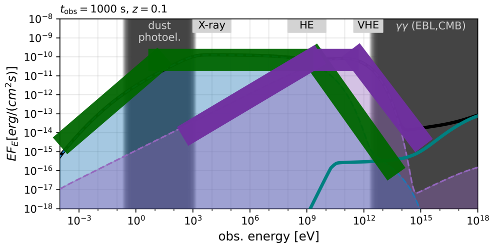
  → proton synchrotron

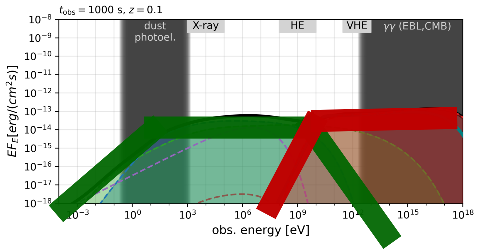
  → cascade from pp interactions











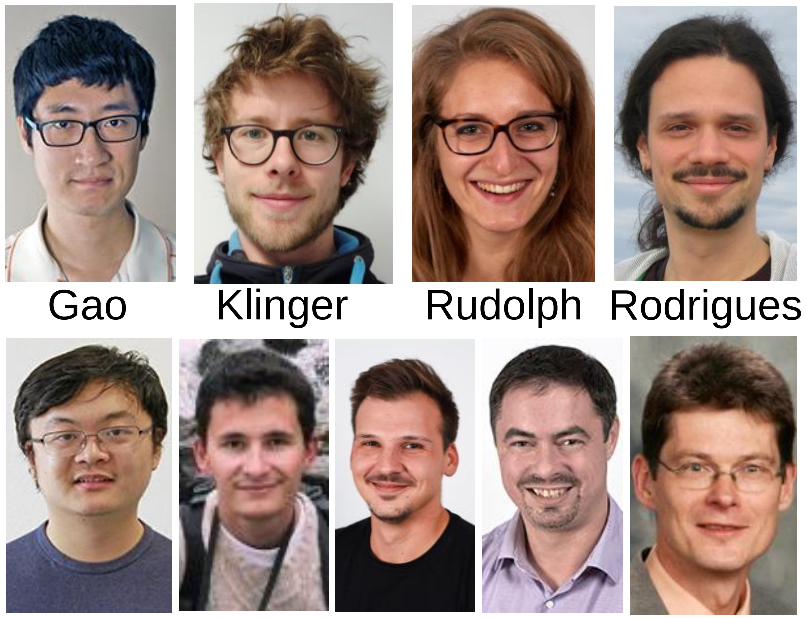
Thank you!

AM³ - finally public!

Astrophysical Multi-Messenger Modeling

- solve transport equations - time dependent!
- for protons, electrons, photons
  + pions, muons, neutrinos
- Syn, IC, pair-prod., $p\gamma$, pp, Bethe-Heitler, decays,..
- speed optimized (steady state in ~10s)
- written in C++, interface to python
- used already for blazars (initially Gao++ 2017), GRBs, TDEs
- including documentation!

Gao++ APJ 843 (2017)



Gao Klinger Rudolph Rodrigues

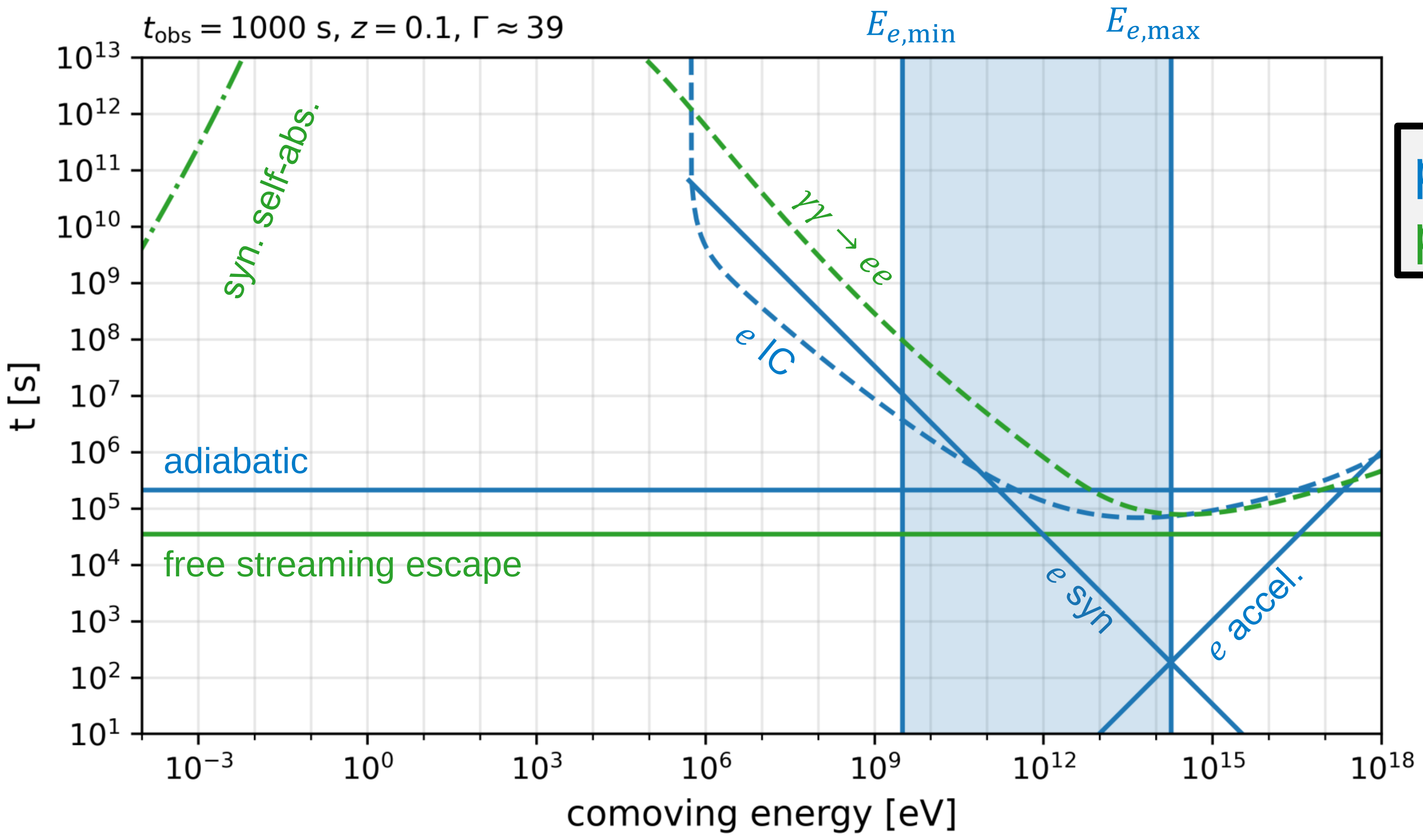
Yuan Fichet De Clairfontaine Fedynitch Winter Pohl

https://gitlab.desy.de/am3/am3

Backup

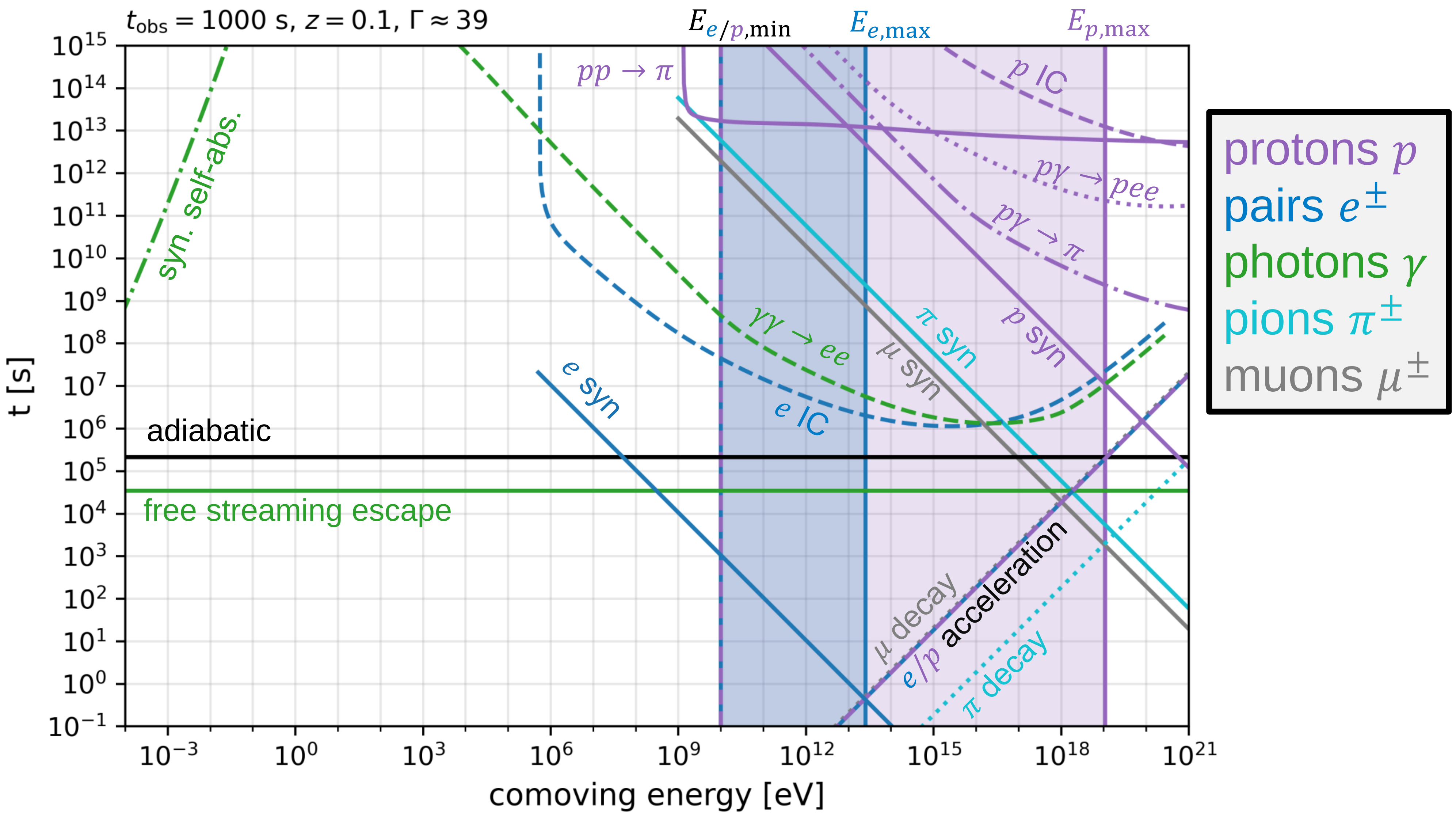
Hadronic scenarios

SSC model time scales

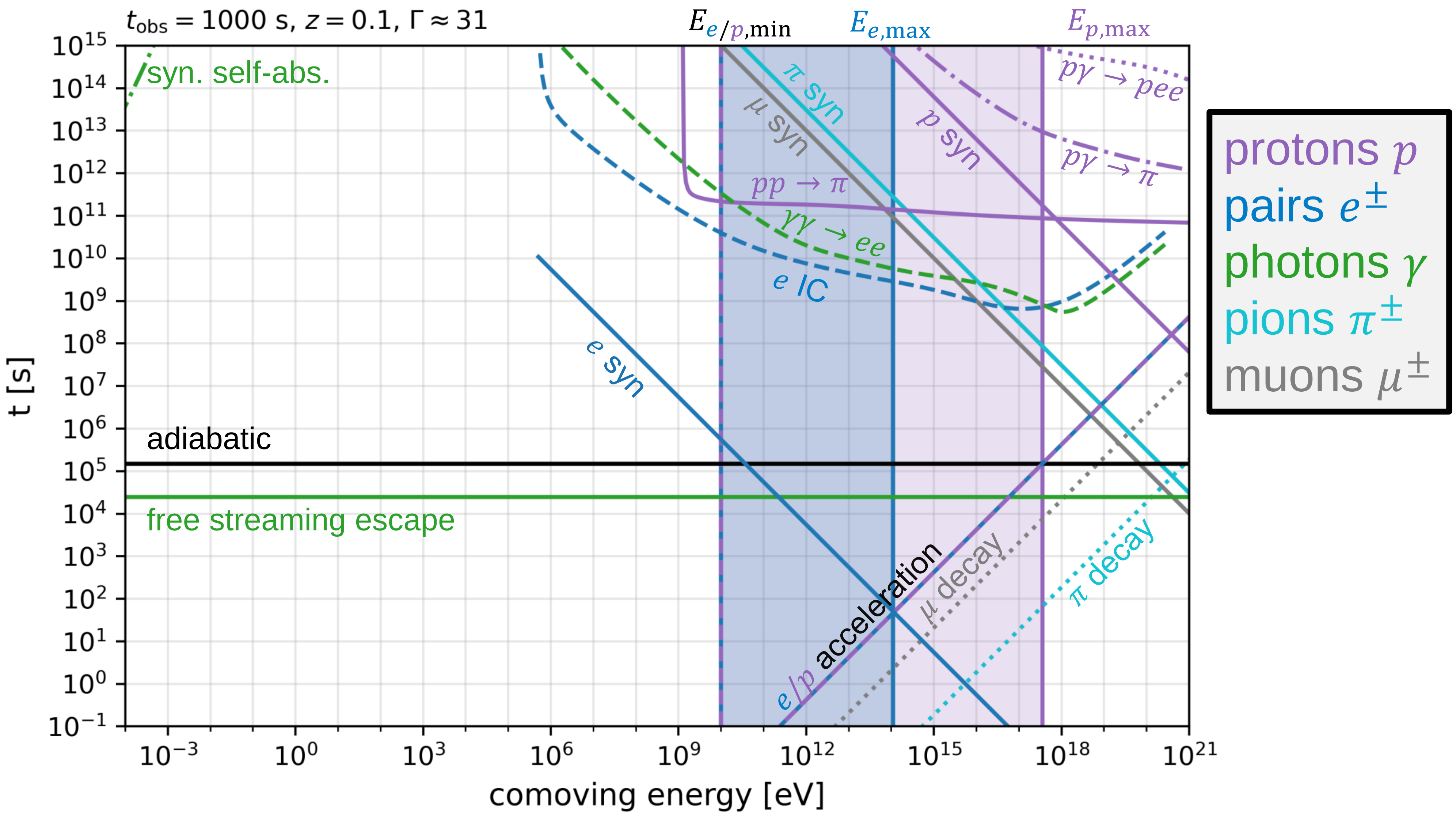


pairs $e^{\pm}$
photons γ

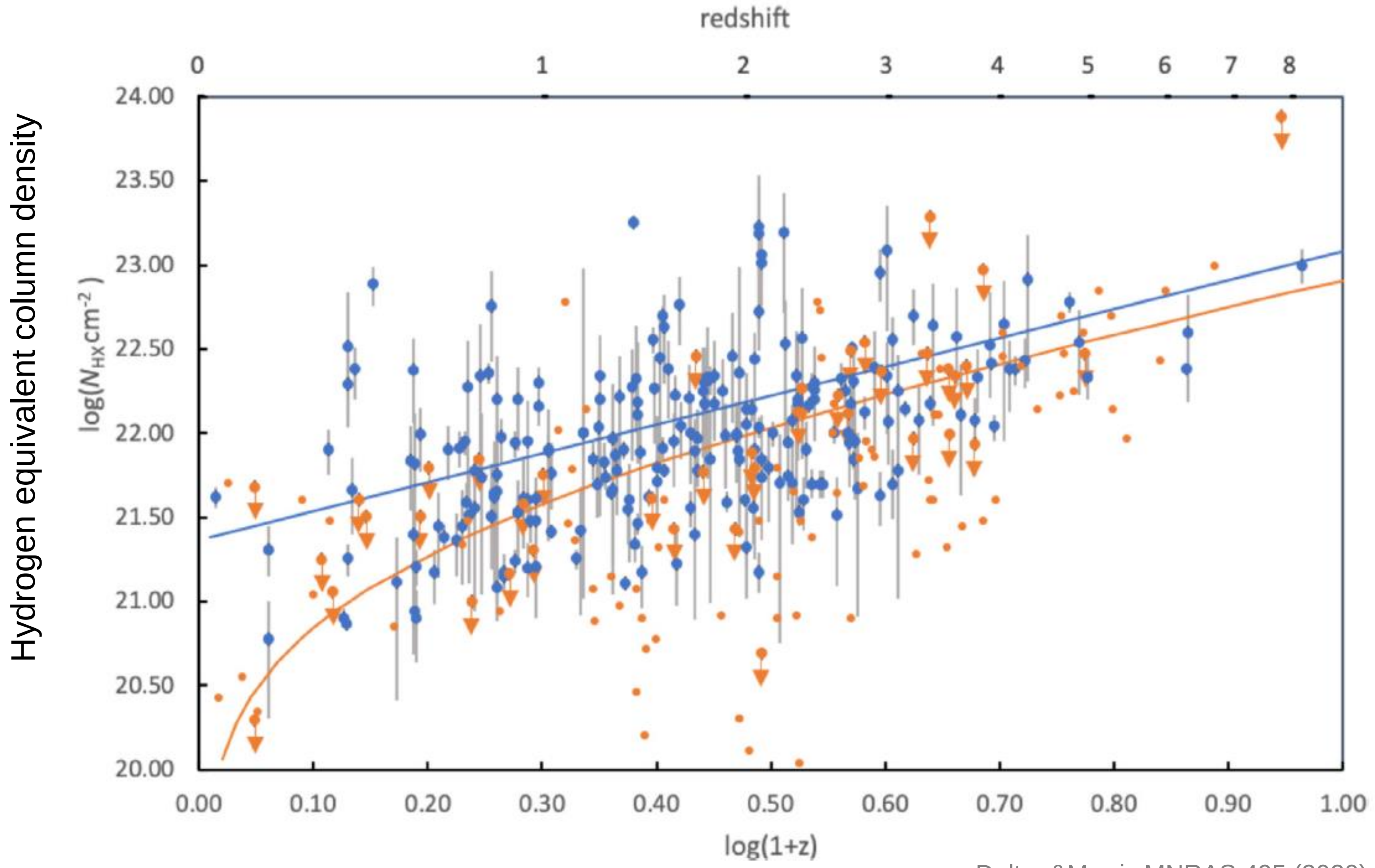
Proton Synchrotron model time scales



PP model time scales



Photoelectric absorption N_H for GRBs



Dalton&Morris MNRAS 495 (2020)

350 Swift GRBs
→ there is some extra material in the way!

VHE GRBs

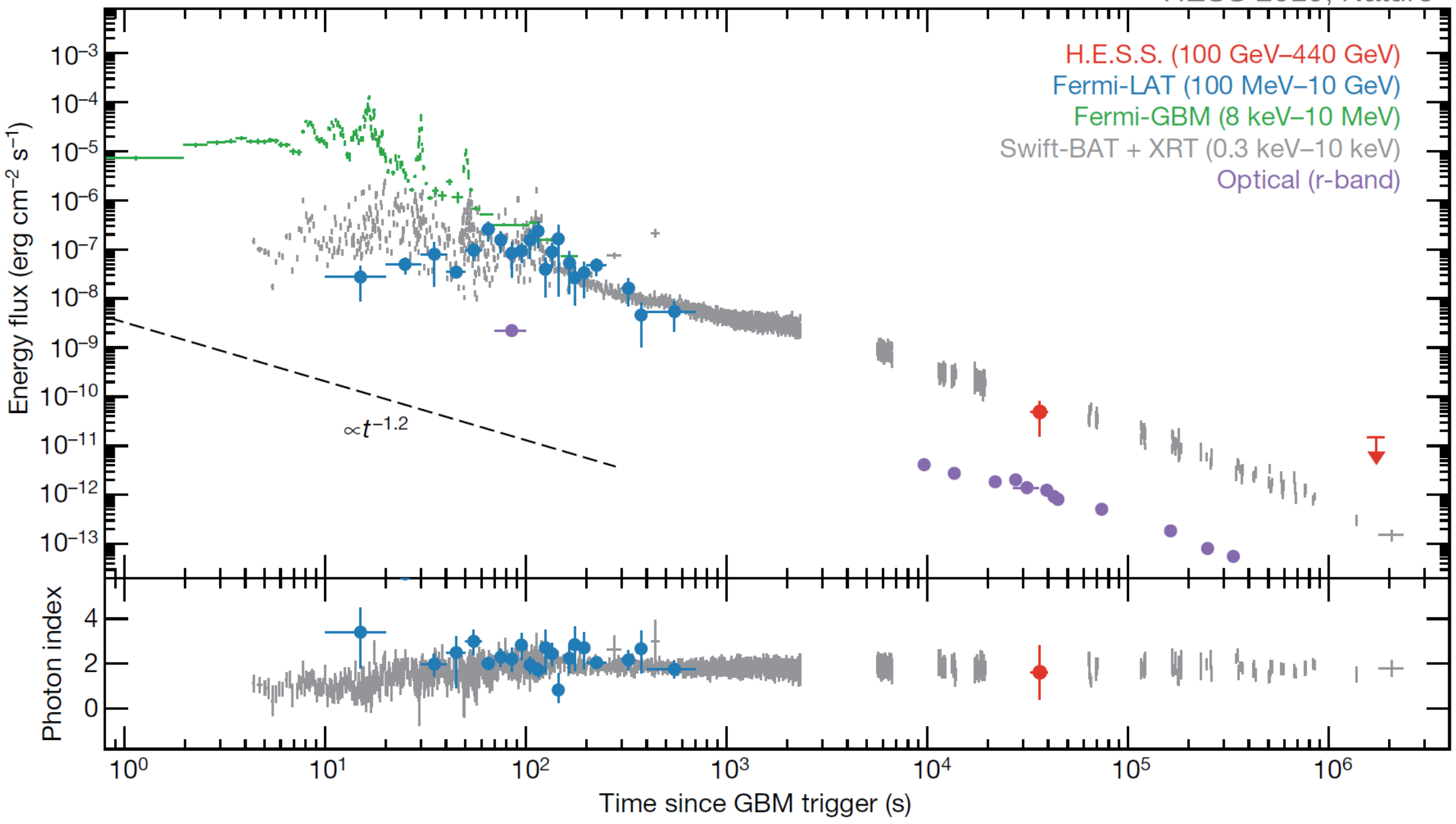
Long GRB afterglows detected at VHE

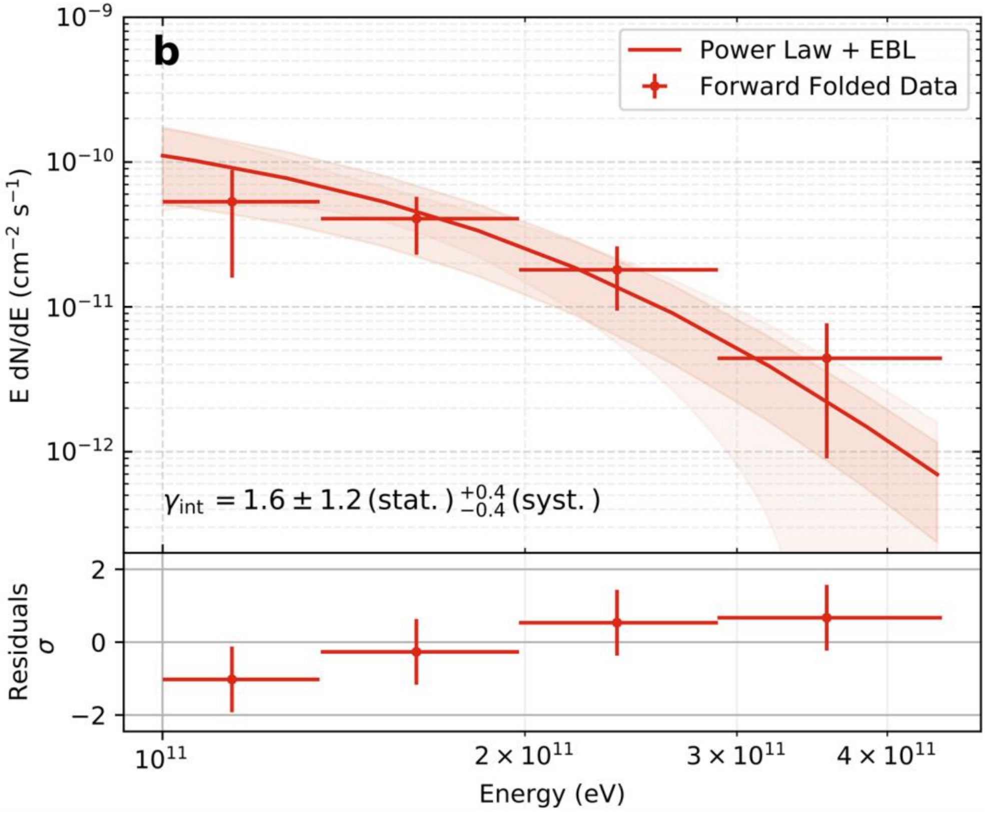
GRB #	z	VHE observations		comment
180720B	0.65	H.E.S.S.	10-12 hrs	sparse simultaneous data
190114C	0.42	MAGIC	1-40 min	rich MWL data set
190829A	0.08	H.E.S.S.	4-8 hrs, 27-32 hrs	very close
201015A	0.43	MAGIC	33 s – 4hrs	3.5σ
201216C	1.1	MAGIC	1 min – 2.2 hrs	6σ, EBL attenuated >150GeV
221009A	0.15	LHAASO	0-2000s	brightest GRB

GRB 180720B (observed by H.E.S.S.)

- redshift $z = 0.65$
- observed from $10 - 12h$

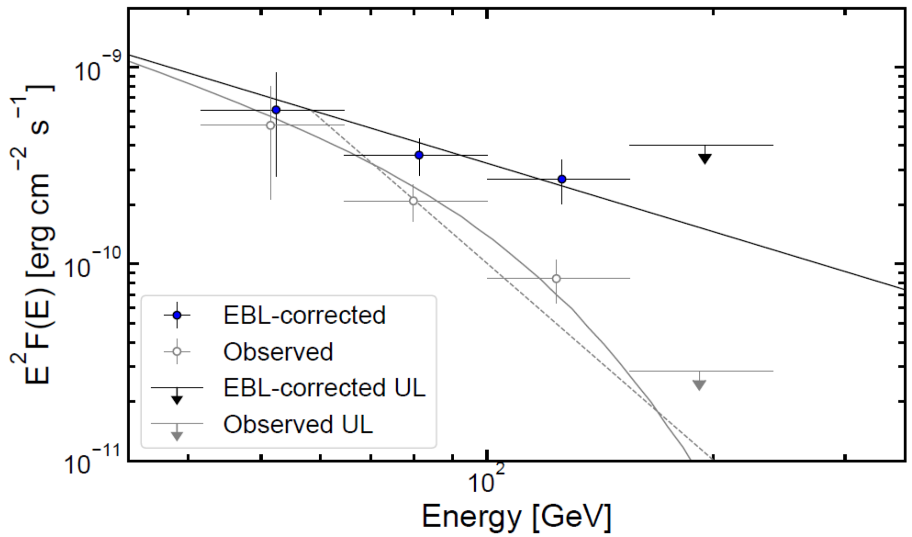
HESS 2019, Nature



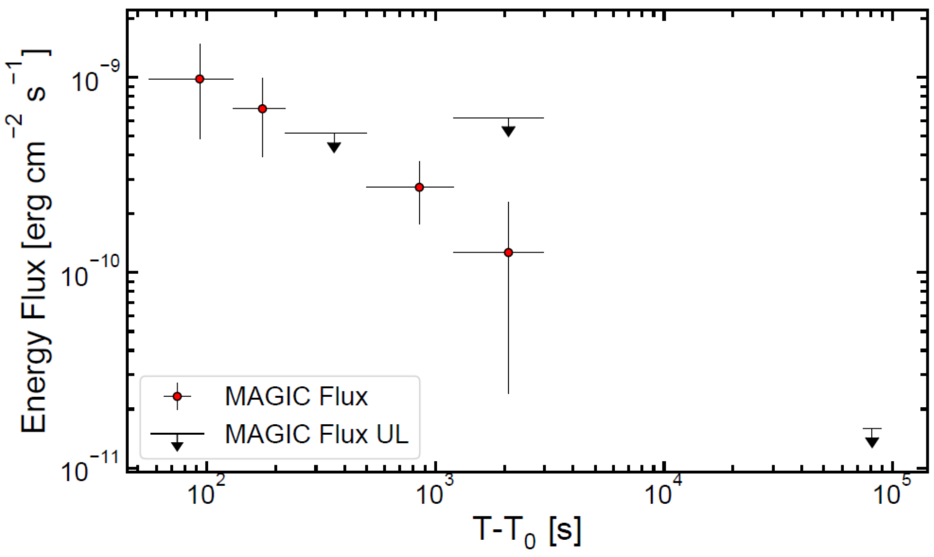


GRB 201216C (observed by MAGIC)

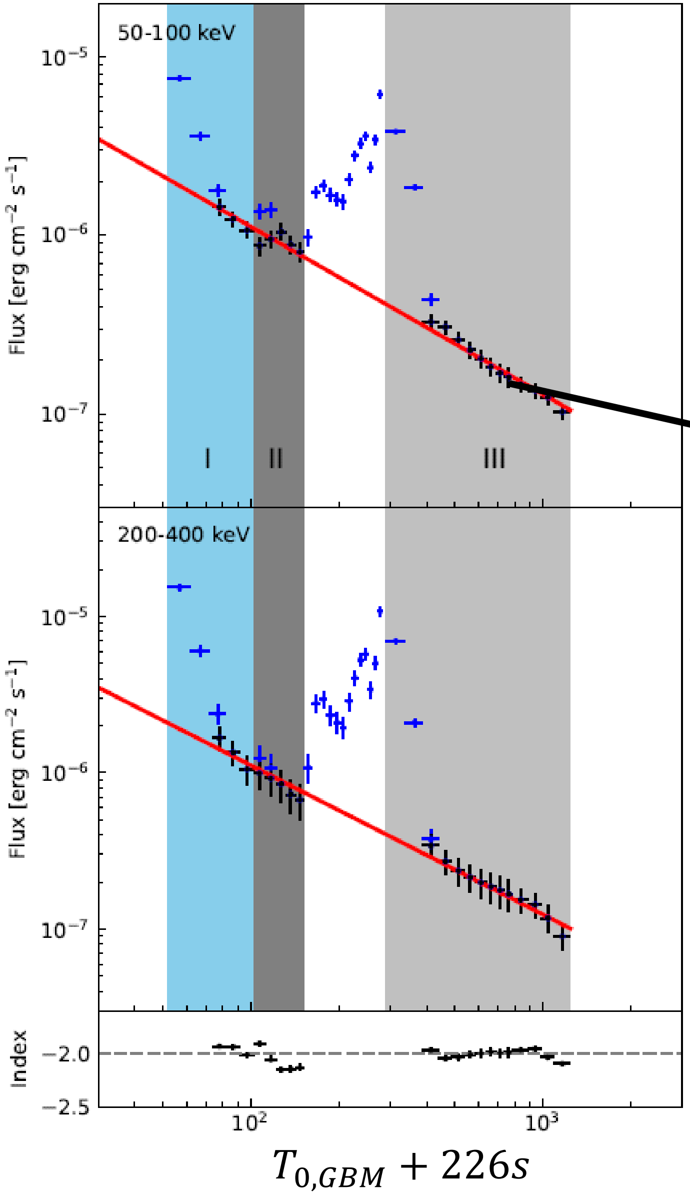
- $z = 1.1 \rightarrow$ strong EBL absorption
  - $\rightarrow$ no robust spectral information at VHE
- strong dust absorption
  - $\rightarrow$ optical data not robust



light scale	EBL	normalization [$\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$]	index
nominal	D11	$(2.03 \pm 0.39) \times 10^{-8}$	-3.15 ± 0.70
-15%	D11	$(1.14 \pm 0.25) \times 10^{-8}$	-3.19 ± 0.52
+15%	D11	$(2.99 \pm 0.53) \times 10^{-8}$	-2.17 ± 0.57
nominal	F08	$(1.95 \pm 0.38) \times 10^{-8}$	-3.19 ± 0.70
nominal	FI10	$(2.76 \pm 0.54) \times 10^{-8}$	-2.65 ± 0.73
nominal	G12	$(3.99 \pm 0.77) \times 10^{-8}$	-2.45 ± 0.71



GRB 221009A: Early afterglow in *Fermi*-GBM?



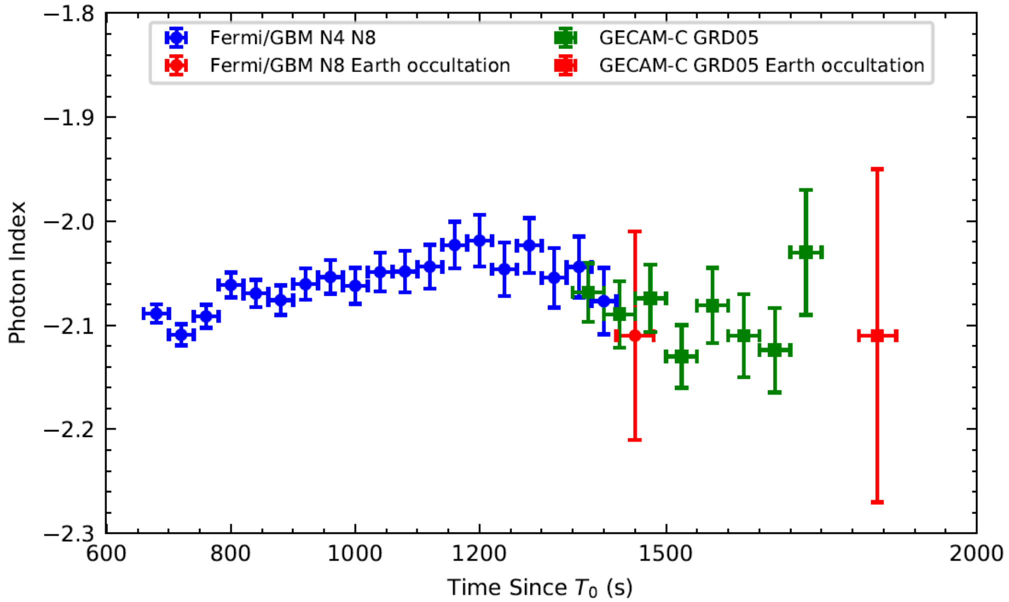
Zhang++ arXiv:2307.12623

Zhang++ 2023: between “prompt” peaks

→ light curve seems to follow power law

→ spectrum changes to similar power law with spectral index -2

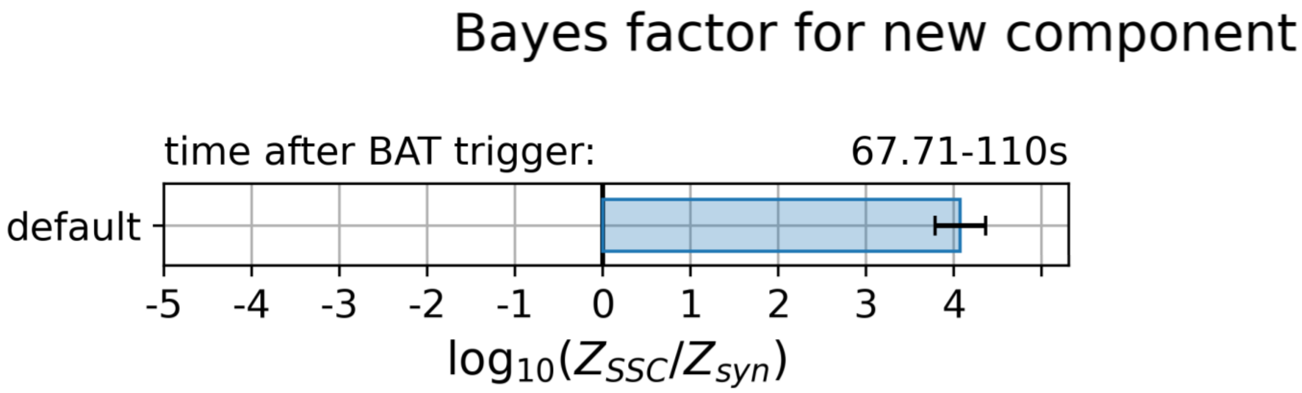
Zheng++ arXiv:2310.10522

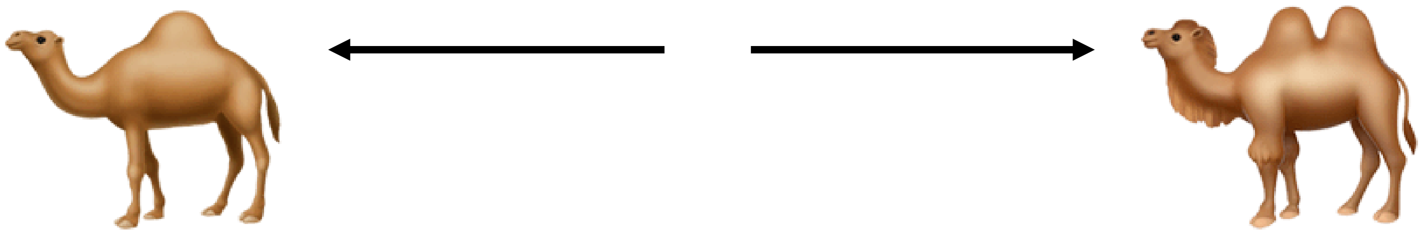


Fermi/GBM N8 and GECAM-C GRD05 in 20-300 keV

GRB 190114C
counts level fits

Preference for new component?

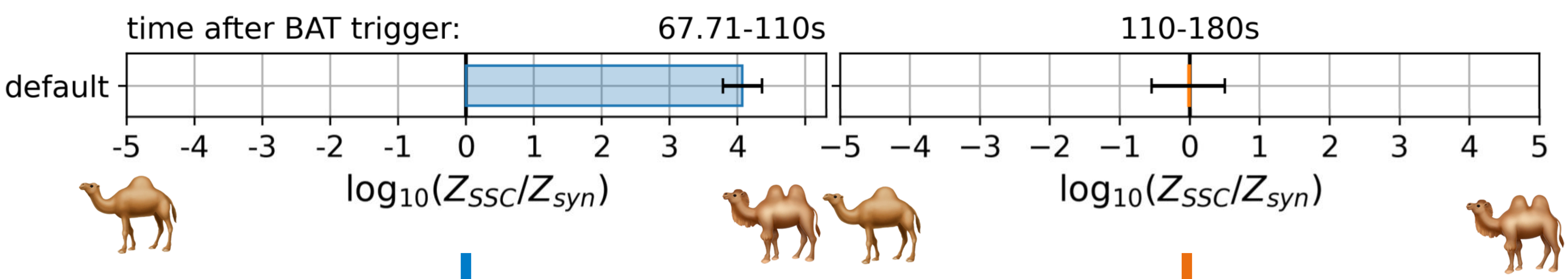




Preference for new component?

Bayes factor for new component

MK++ MNRAS 520 (2023)

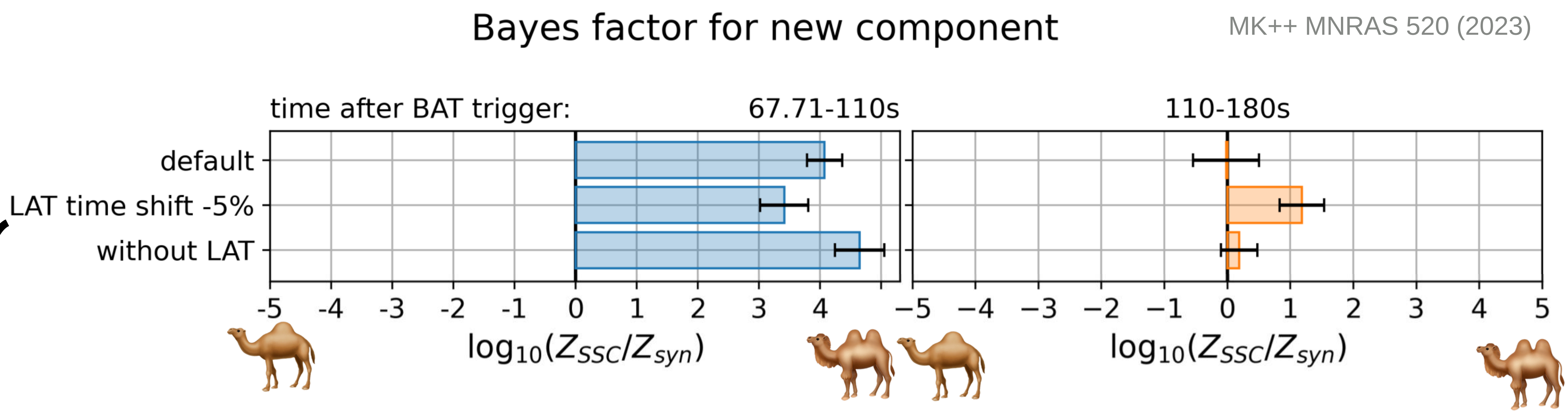


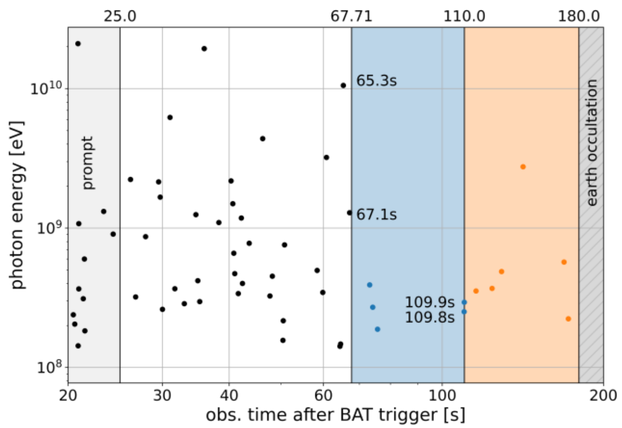
yes

no

Stability of Preference: LAT

MK++ MNRAS 520 (2023)



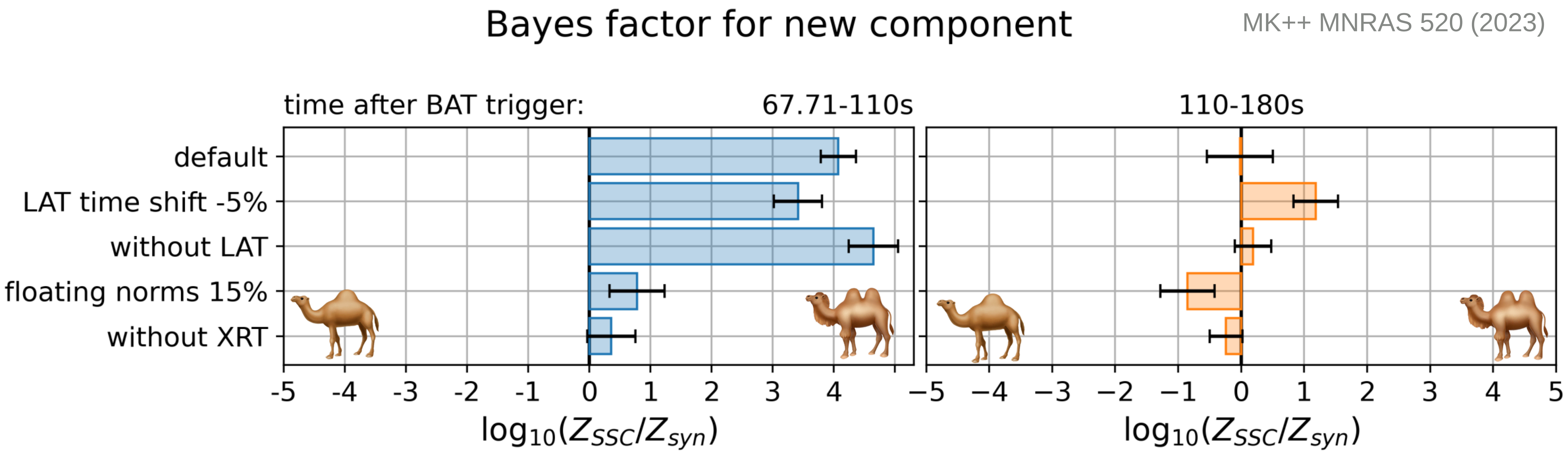


- shift LAT time selection window by 5% (2.1s)
- leave out LAT completely

→**LAT not very strong**

Stability of Preference: XRT

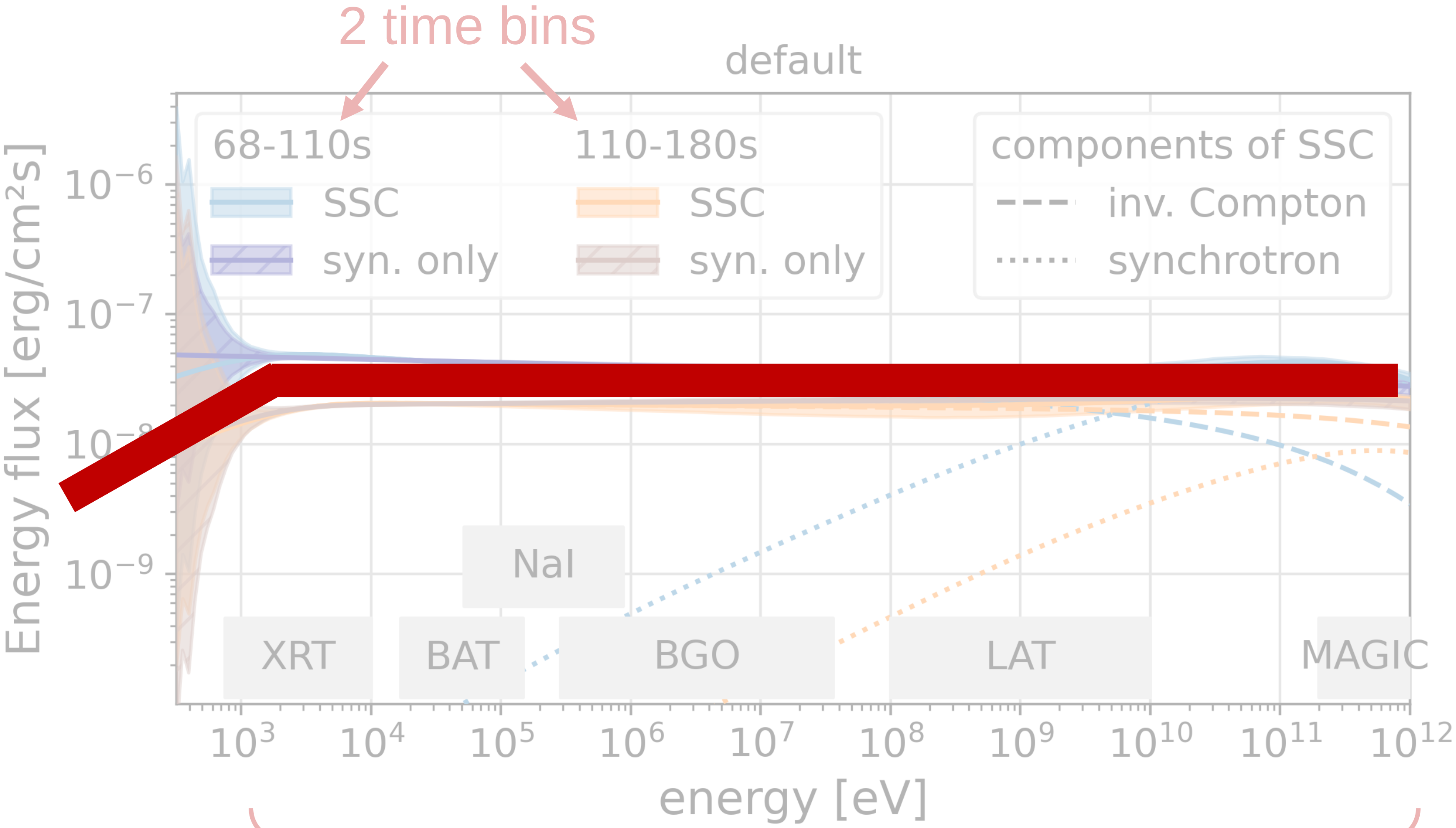
MK++ MNRAS 520 (2023)



- systematic cross calibration uncertainty limited to 15% (a.k.a. floating norm or effective area correction)
- leave out XRT completely

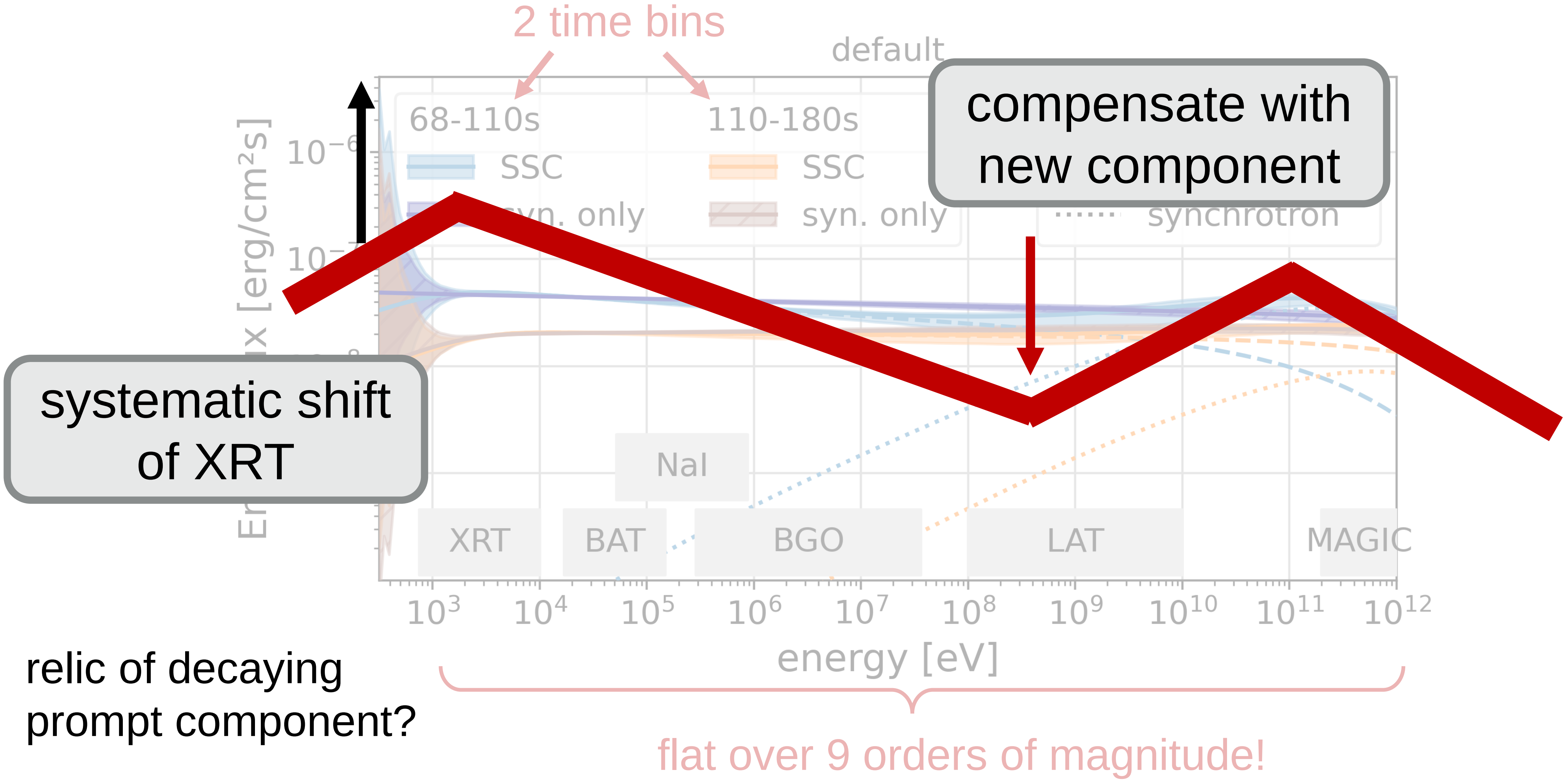
→ **XRT drives new component!**

Fitting a reduced SSC model



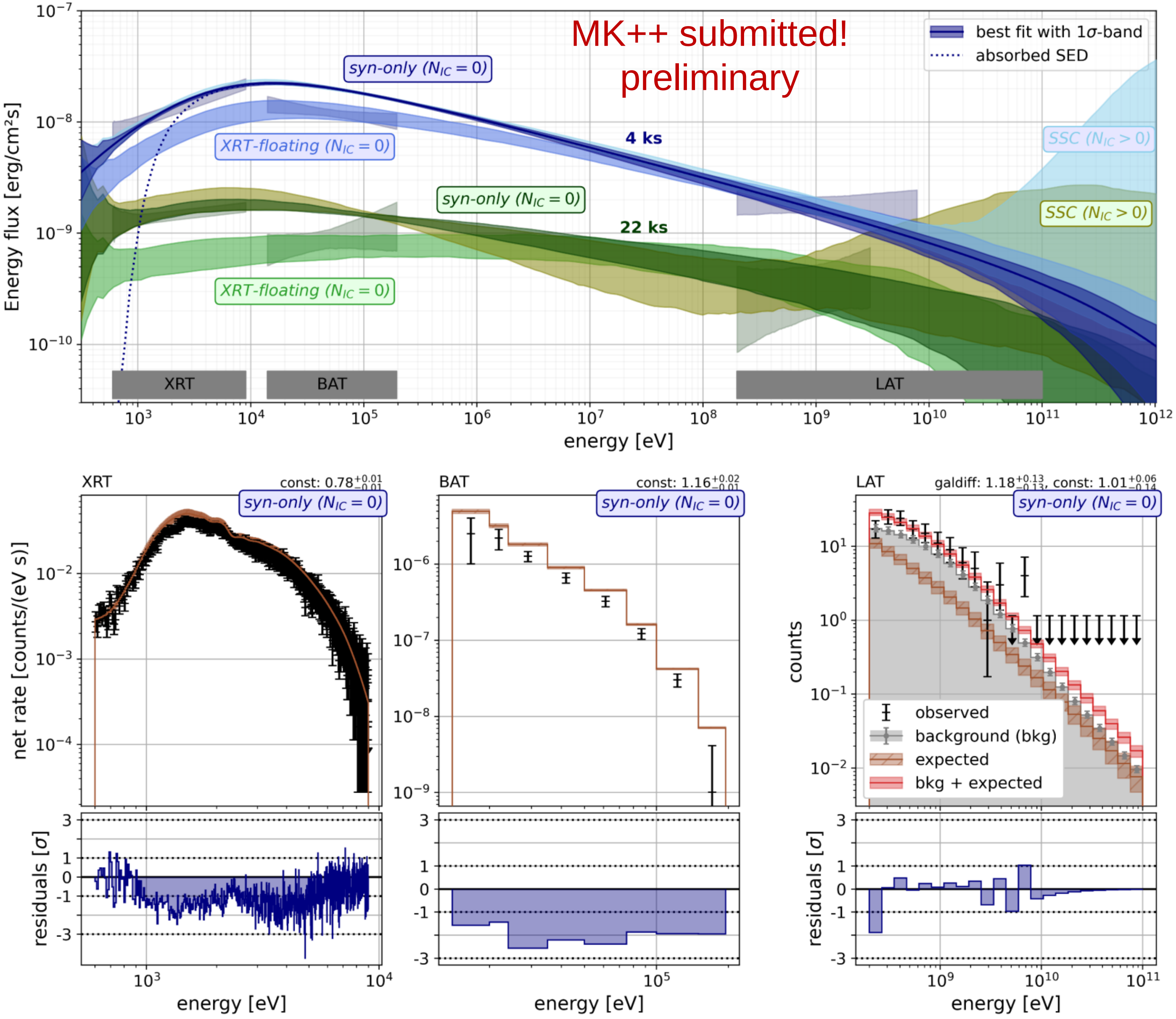
flat over 9 orders of magnitude!

Fitting a reduced SSC model



relic of decaying prompt component?

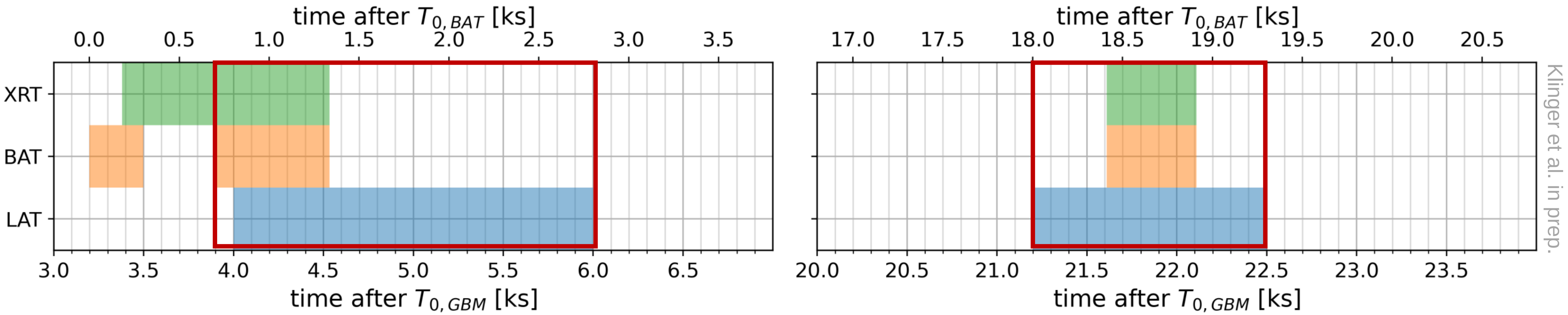
GRB 221009A counts level fits



arXiv:2308.13854

GRB 221009A

Multiwavelength fit – 2 overlapping intervals



4ks window

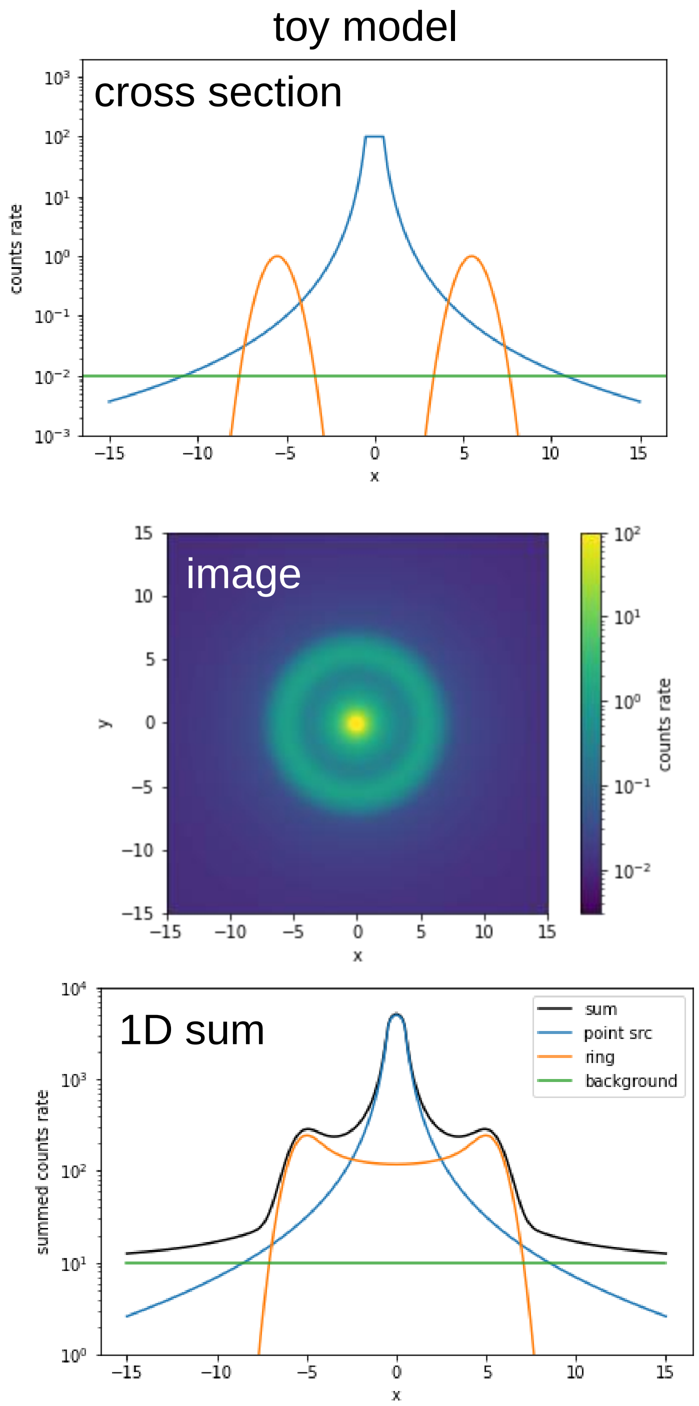
22ks window

LHAASO-WCDA
(KM2A even earlier)

→ focus of our fit results to early afterglow

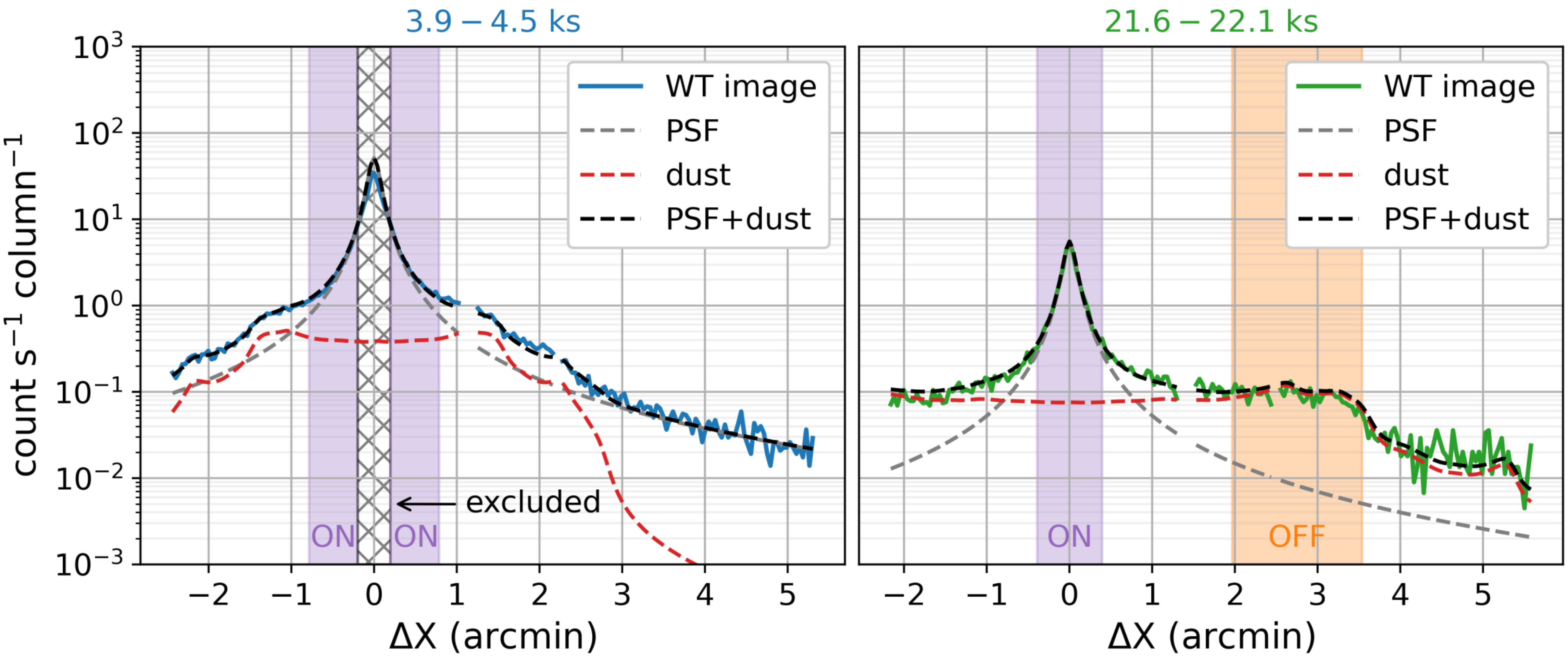
Dust ring problematic

- 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

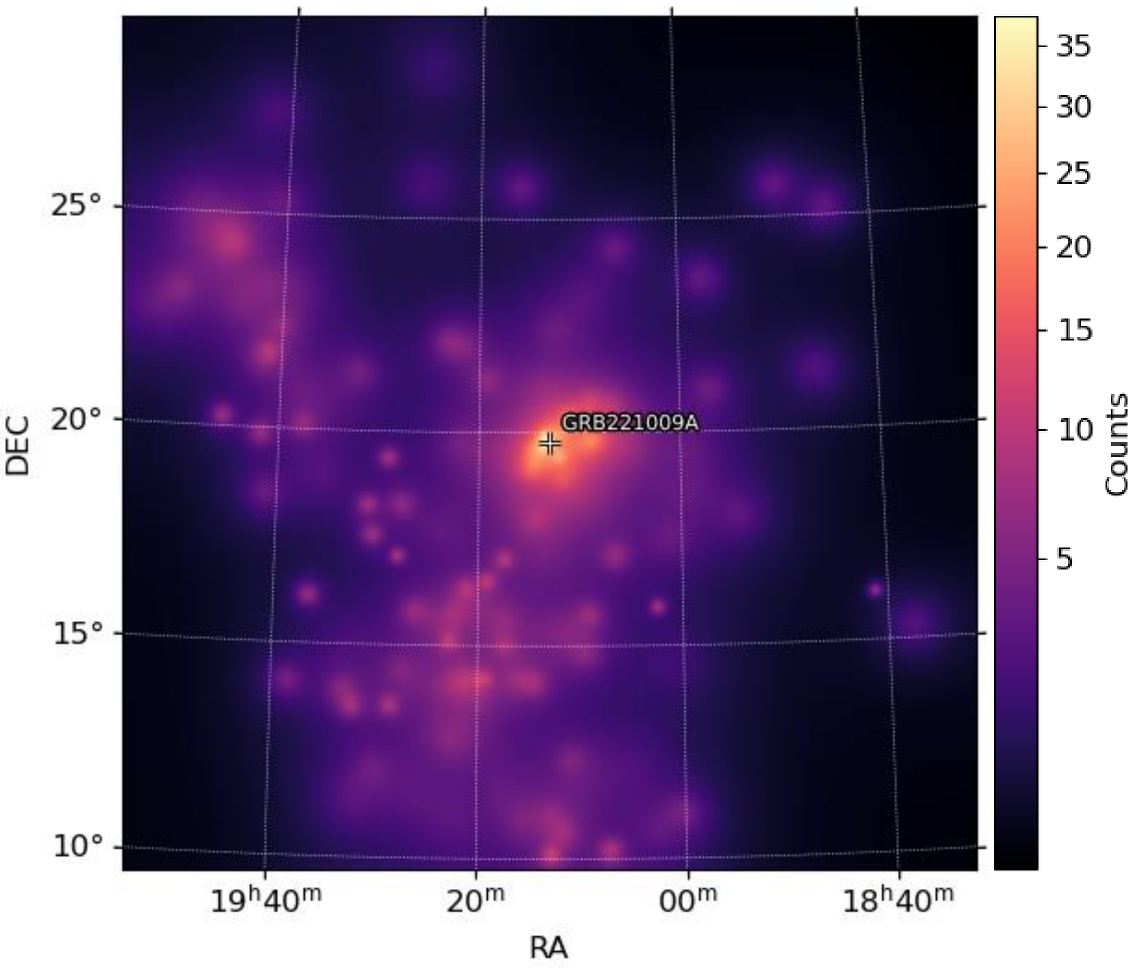
arXiv:2308.13854



Fermi-LAT: a GRB in the galactic plane

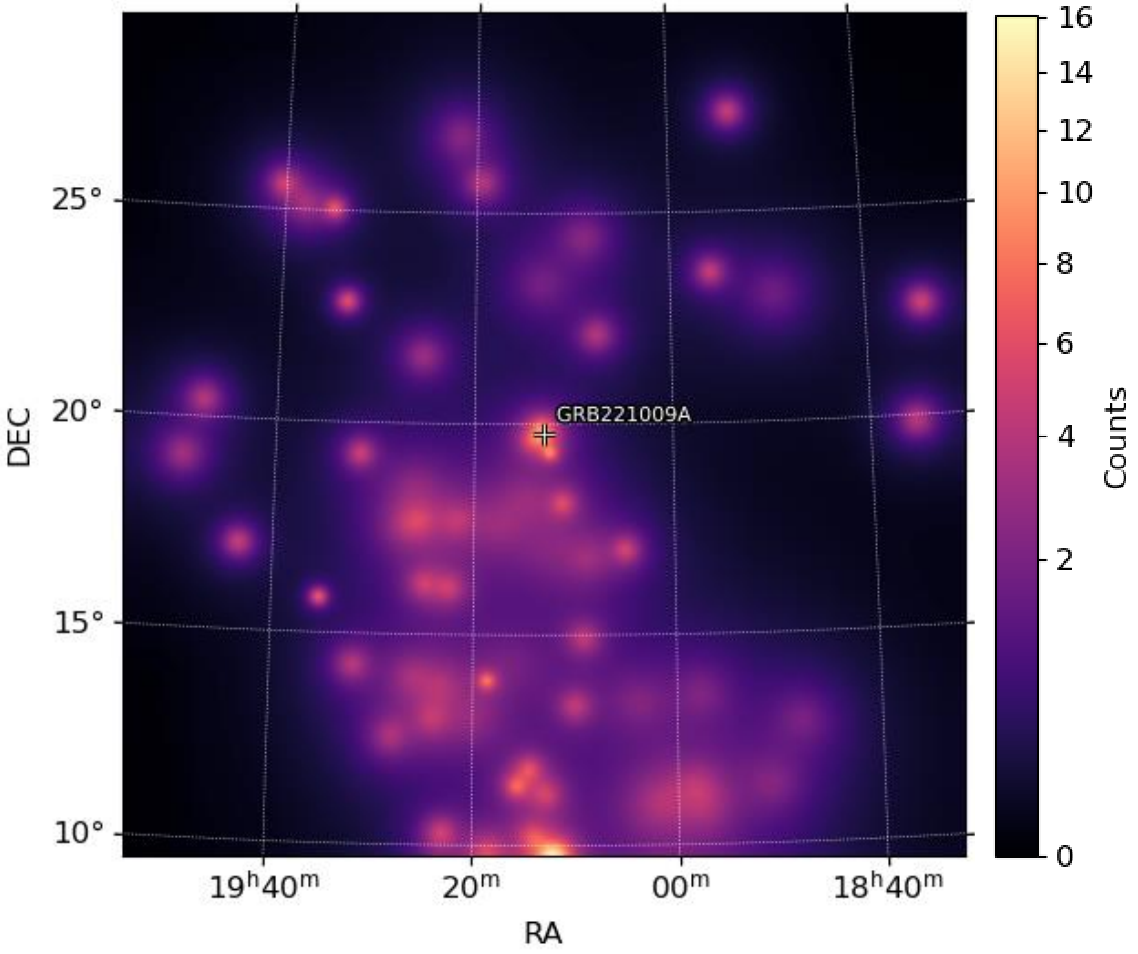
4ks

total:
137 photons

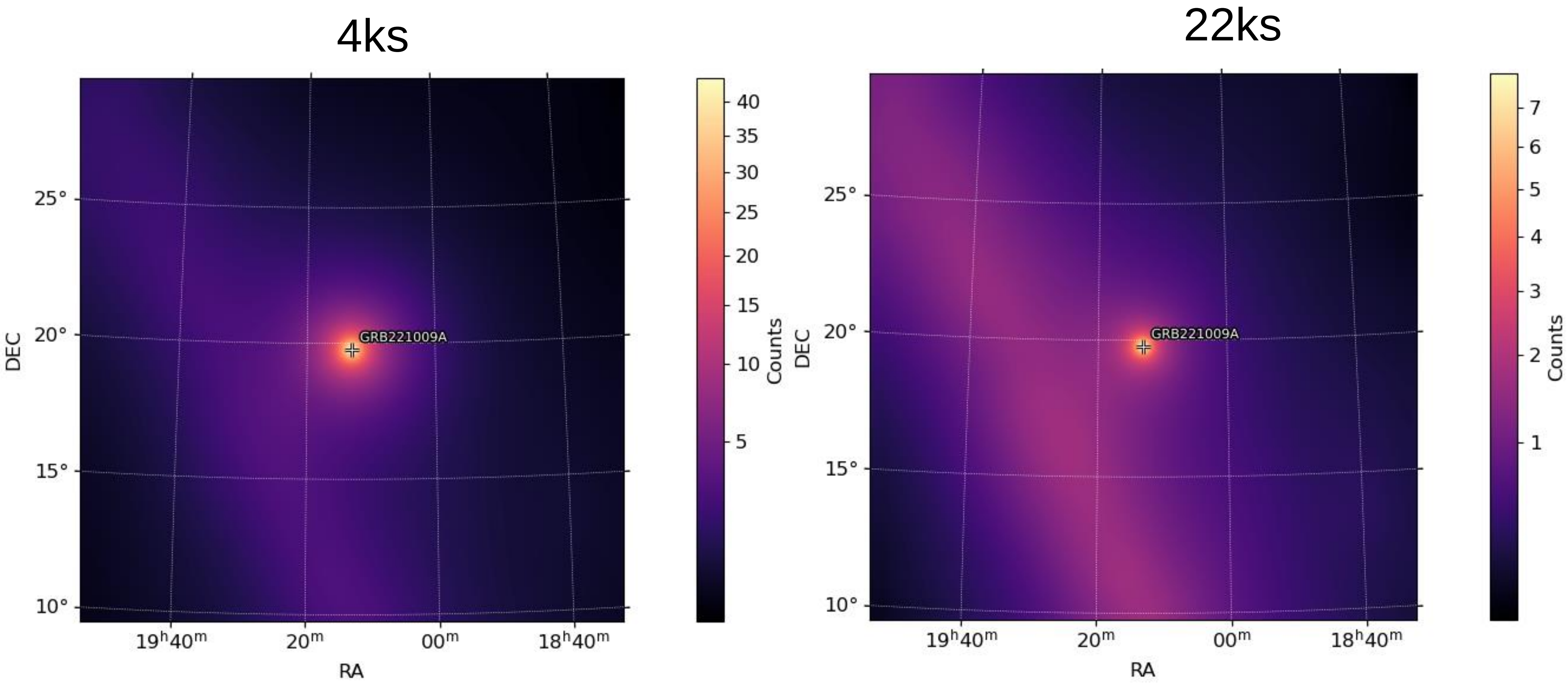


22ks

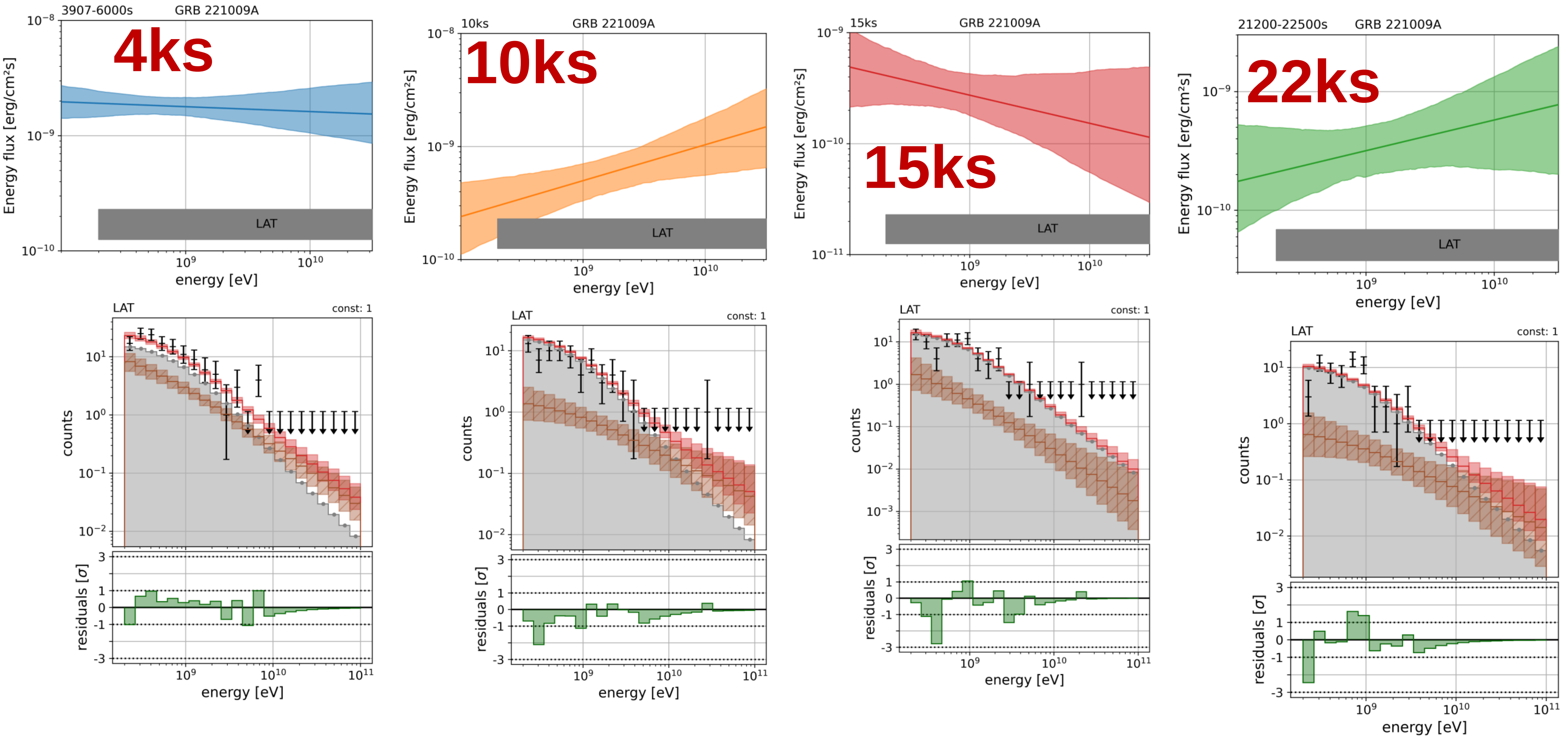
total:
62 photons



Model in a map → galactic background

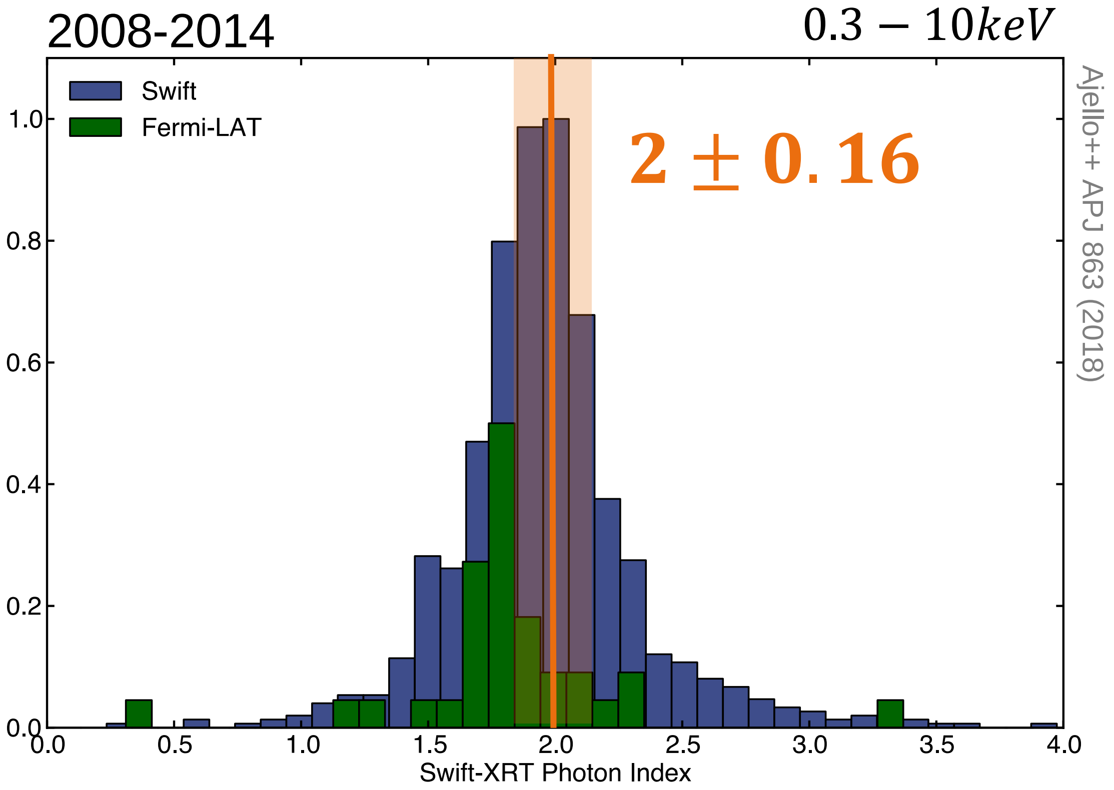


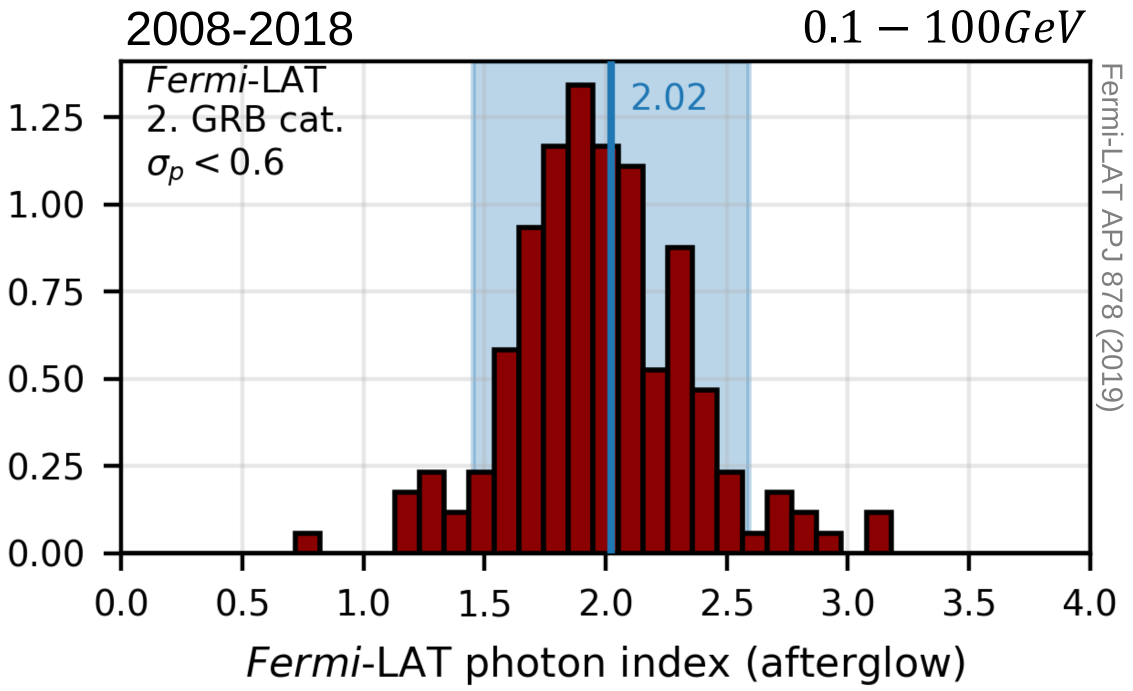
4 orbits of Fermi-LAT: galactic diffuse background!



Observational picture from keV-TeV

GRB afterglow population at keV and TeV energies





Fermi-LAT observed GRB afterglows have **harder spectrum at keV ($p_\gamma \lesssim 2$)**

2. Fermi-LAT GRB catalogue:

Fermi-LAT observed GRB afterglows have **hard spectrum at GeV ($p_\gamma \approx 2$)**

Observational picture: VHE GRBs' early afterglows

1. we see flat spectra from keV to TeV
2. roughly described by a single power law