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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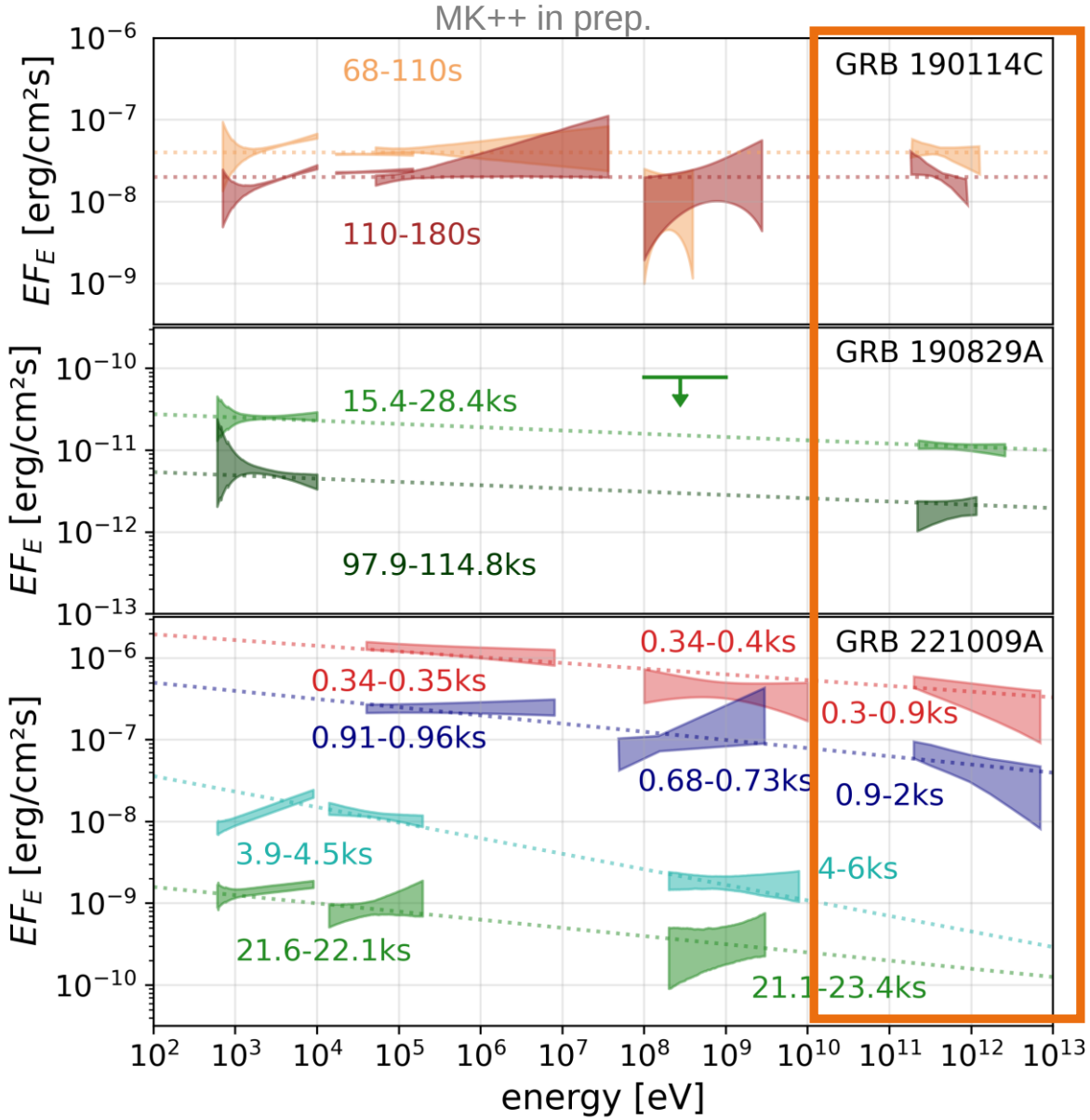
https://maklinger.github.io/

GRB afterglows detected at VHE!



→ **MAGIC**

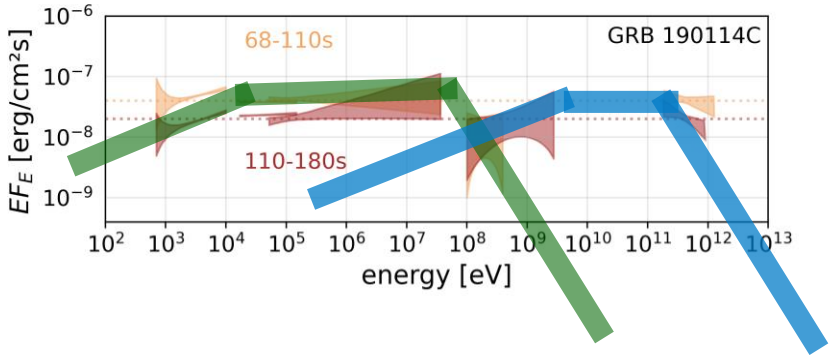
→ **HESS**

→ **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:

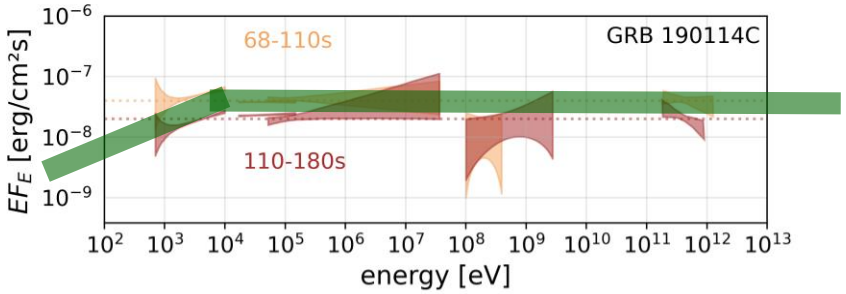
Current models struggle to predict TeV photon spectra of the early afterglow of long GRBs!

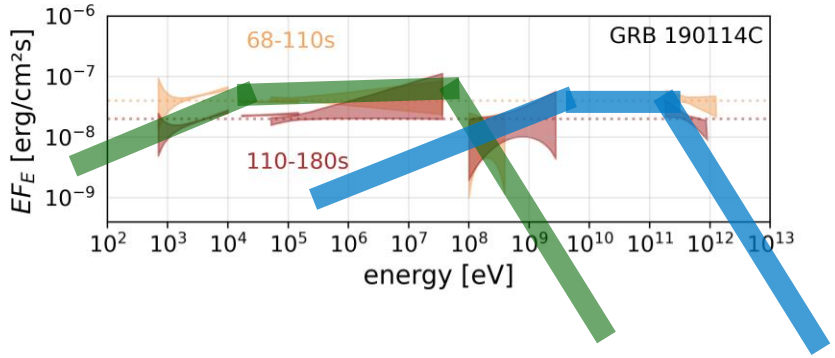


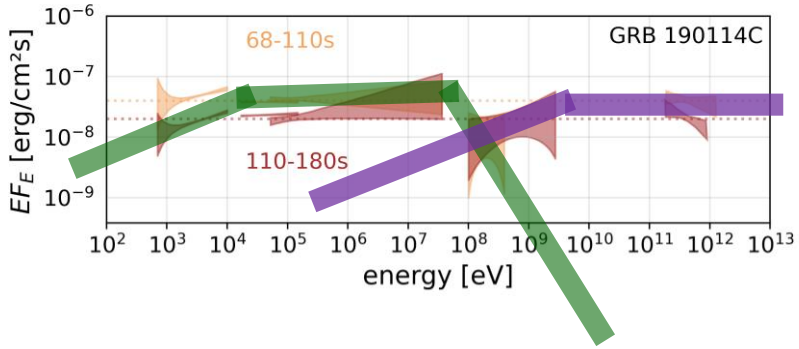
standard in community:
2 component SSC

Problem:

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





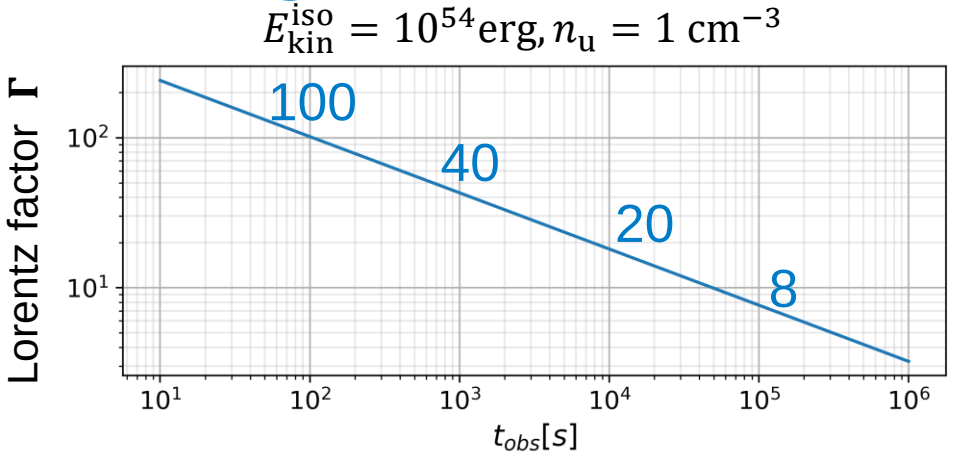


?

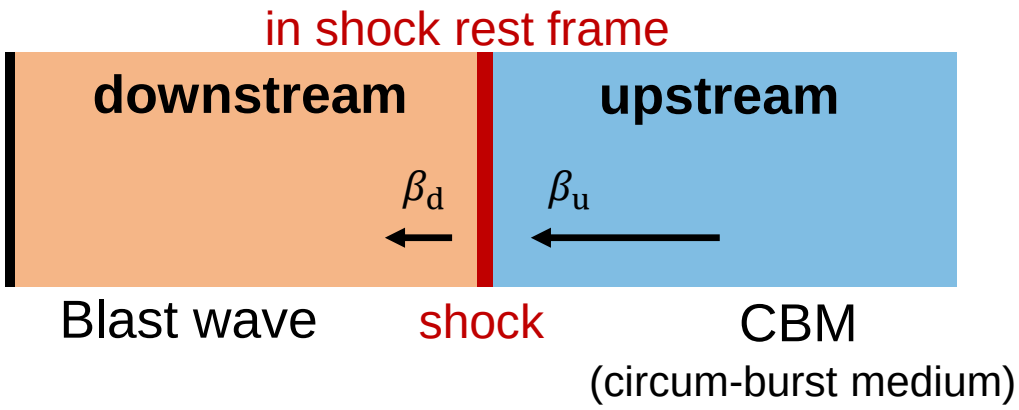
standard in community:
2 component SSC

?

Afterglows: Radiation from a relativistic shock



Blandford & McKee 1976



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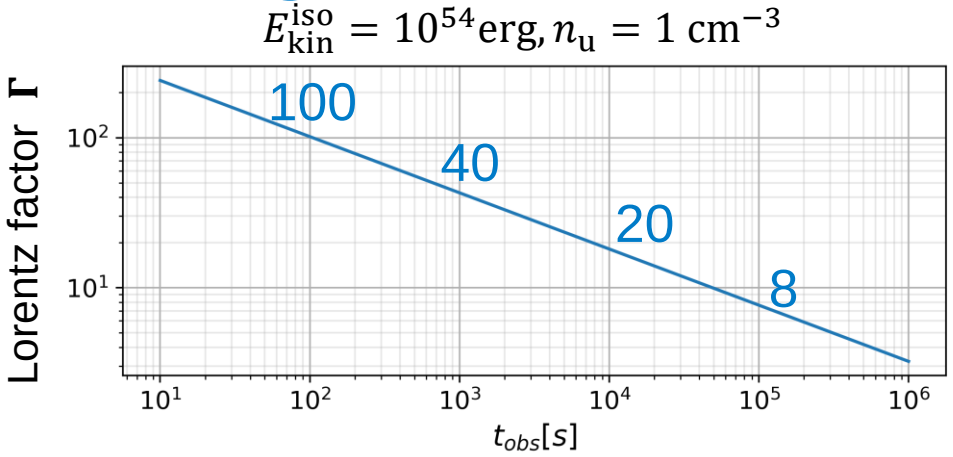
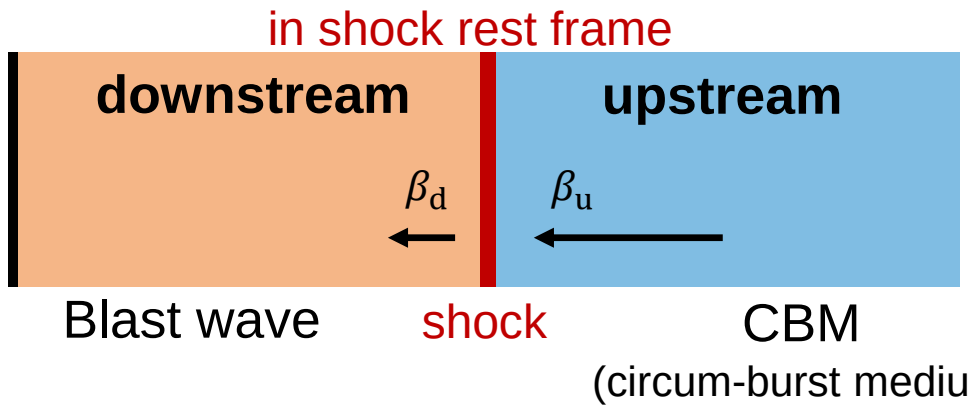




thermal (e, p)

ram

non-thermal (e, p)

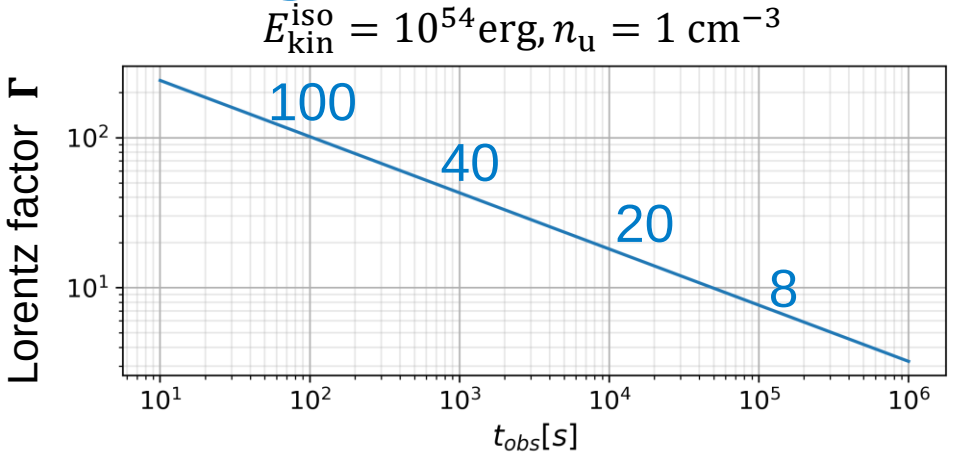
magnetic fields (B)

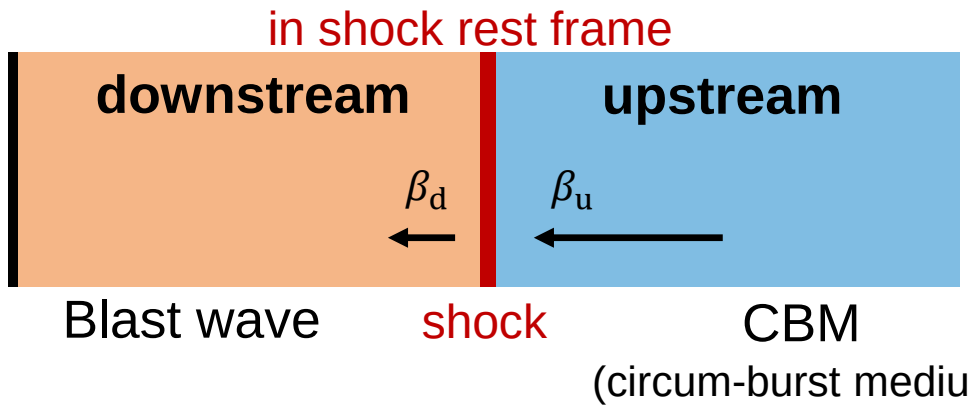
$$p_{\rm ram}^{\rm u} = \beta_{\rm u}^2 \Gamma_{\rm u}^2 \rho_{\rm u} c^2$$

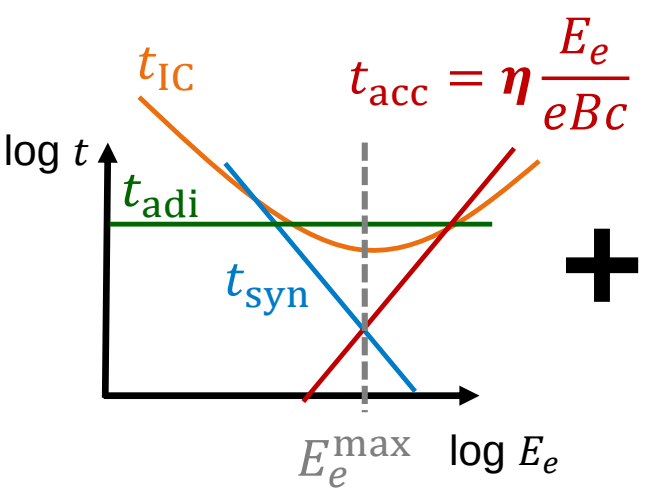
with $\rho_{\rm u} = n_{\rm u} m_p c^2$

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

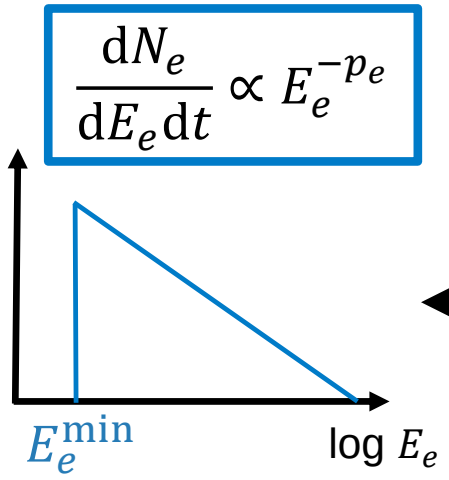
Afterglows: Radiation from a relativistic shock

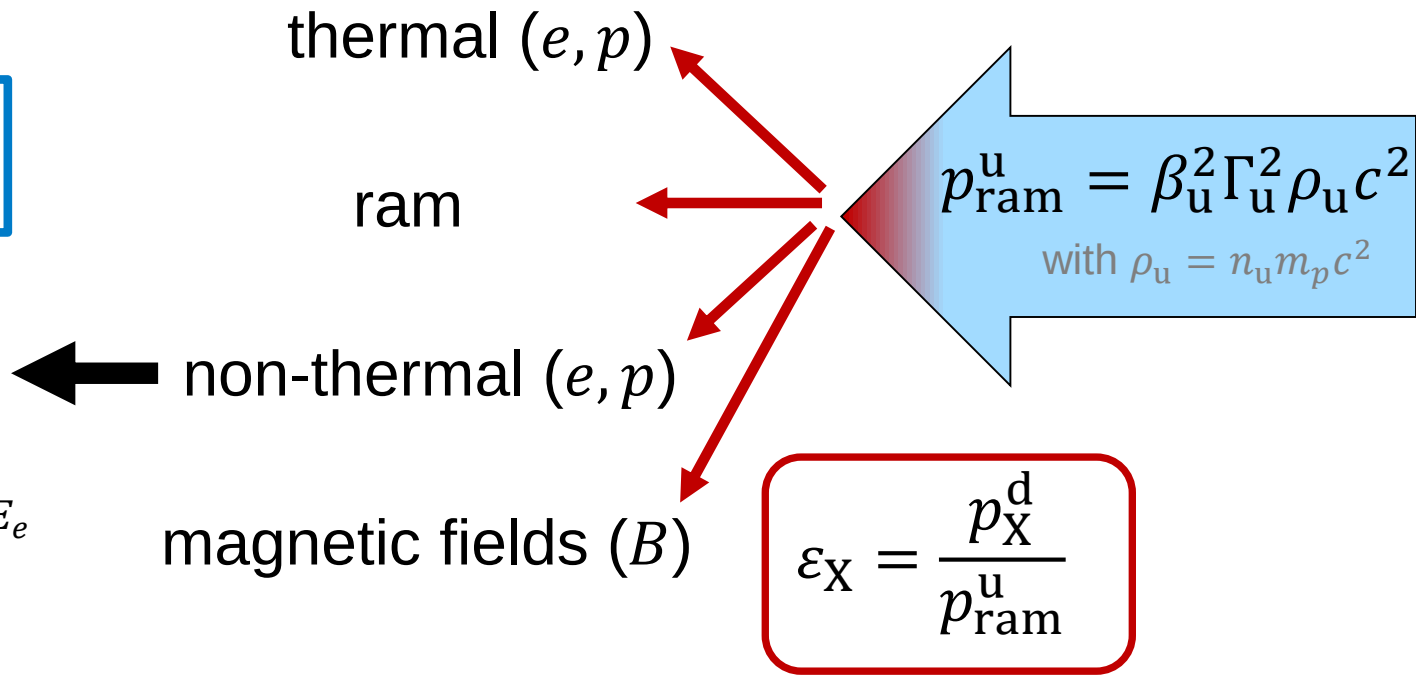




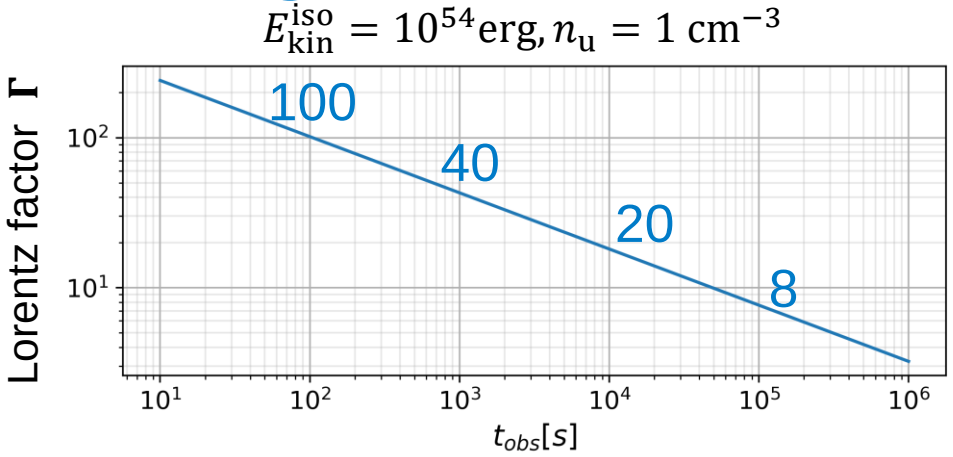


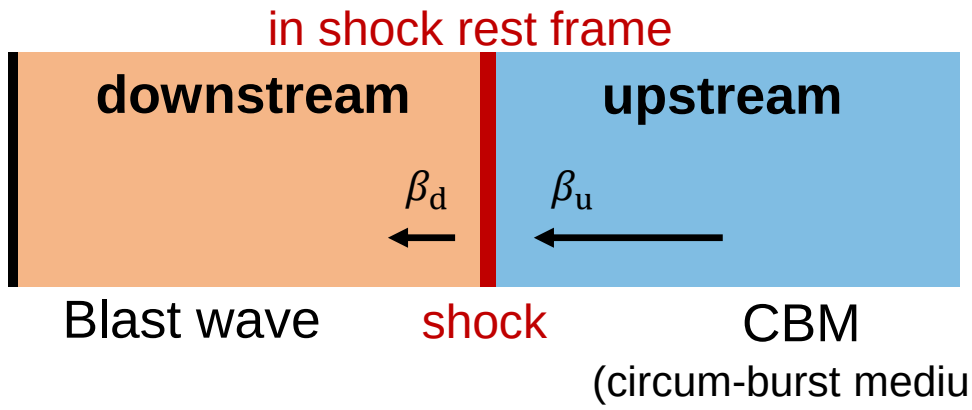
+





Afterglows: Radiation from a relativistic shock





→ quasi-steady state

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

thermal (e, p)

ram

non-thermal (e, p)

magnetic fields (B)

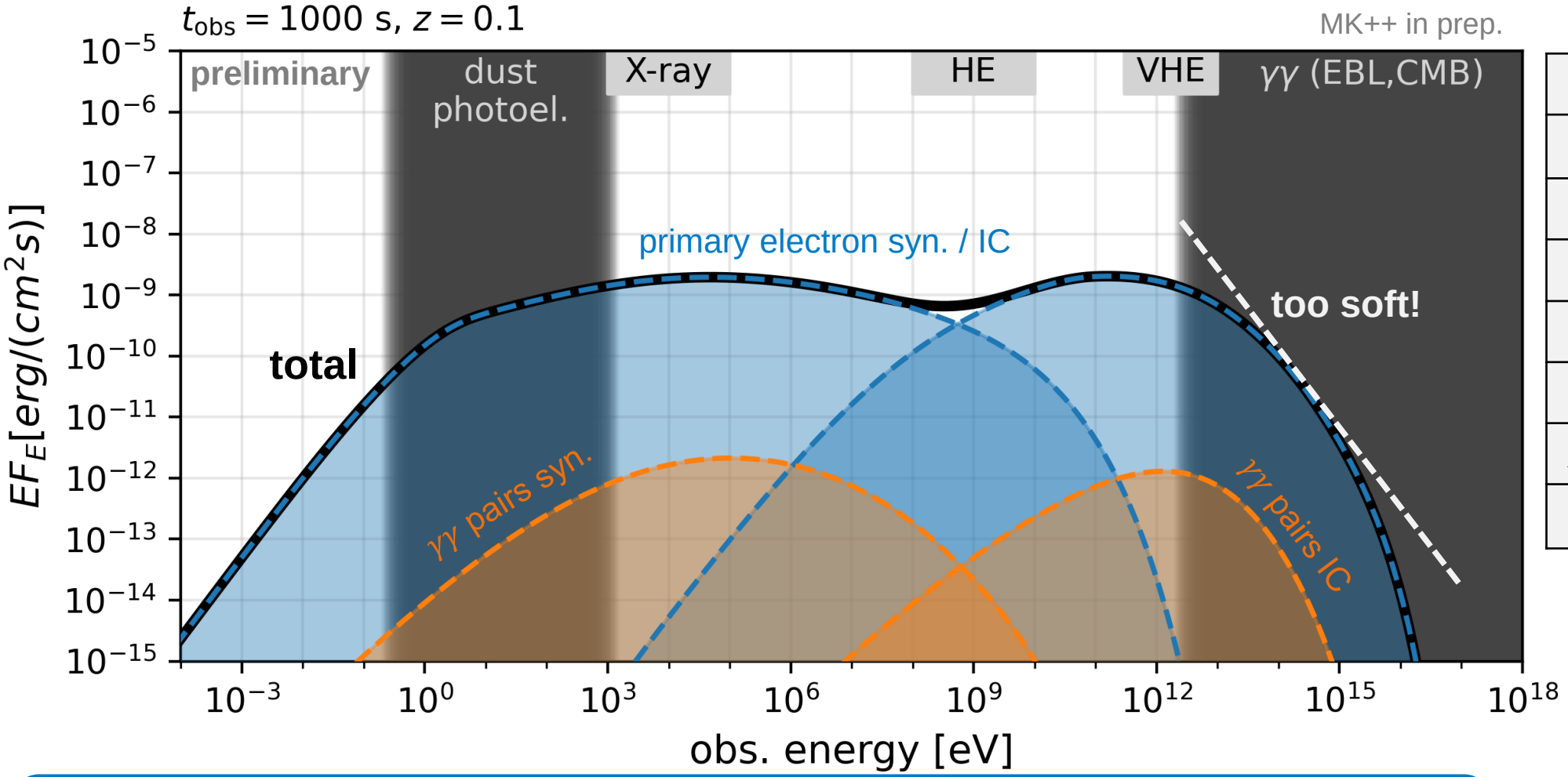
$$p_{\rm ram}^{\rm u} = \beta_{\rm u}^2 \Gamma_{\rm u}^2 \rho_{\rm u} c^2$$

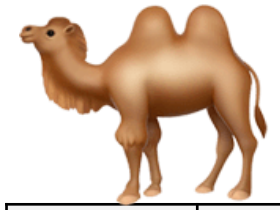
with $\rho_{\rm u} = n_{\rm u} m_p c^2$

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

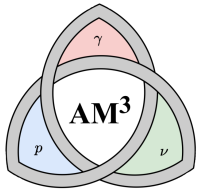
→ similar to time-dependent modeling

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
$E_{\text{kin iso}}$	10^{54}erg
n_{up}	1cm^{-3}



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

Ideas:

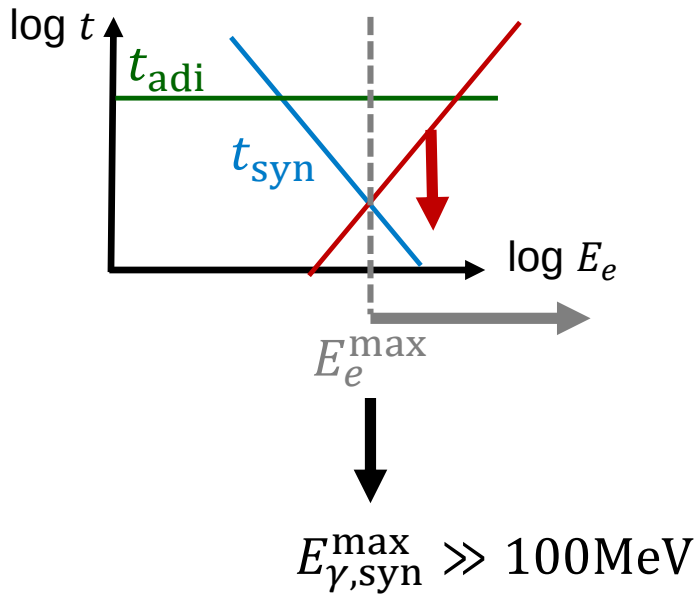
- faster than Bohm acceleration: $\eta \ll 1$

  → 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)

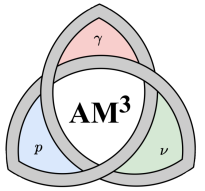
  → **extended electron synchrotron component**

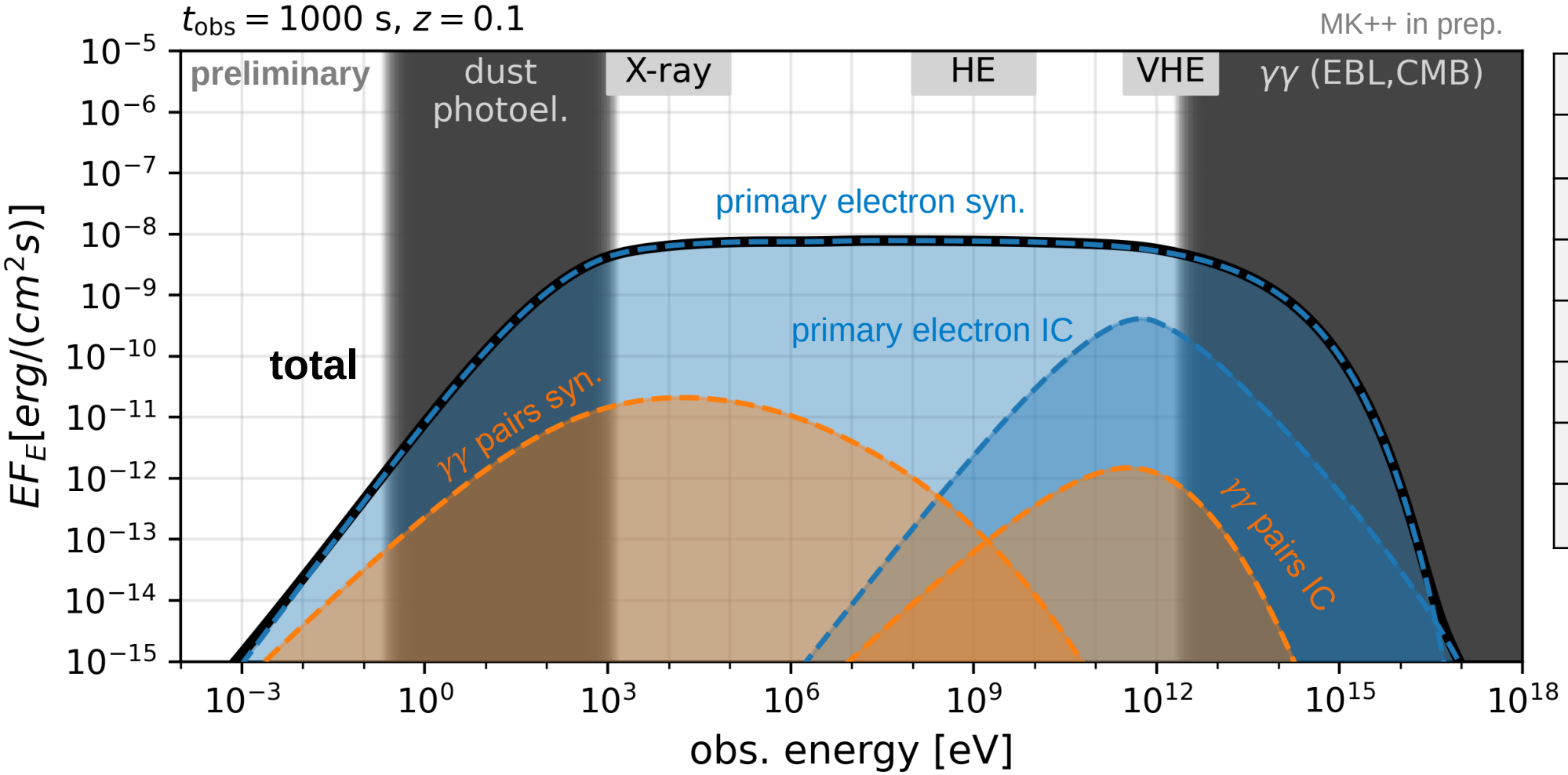
$$t_{\mathrm{acc}} = \eta \frac{E_e}{eBc}$$



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

Extended synchrotron spectrum

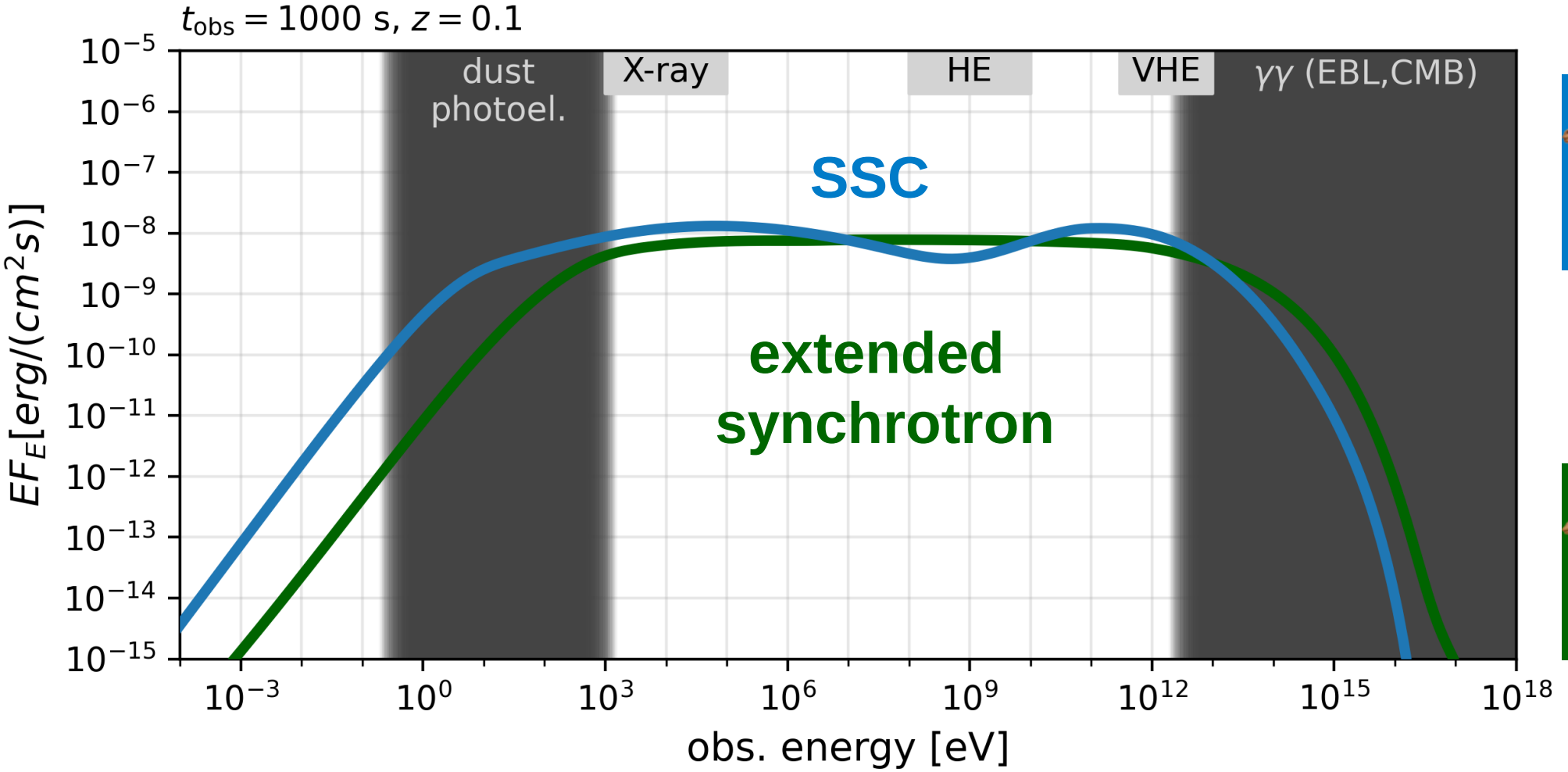




ε_e	$10^{-1.5}$
ε_p	0
ε_B	10^{-3}
$E_{\min}$	30GeV
p_e	2
η	10^{-4}
$E_{\rm iso}$	10^{54}erg
$n_{\rm up}$	$1\mathrm{cm}^{-3}$

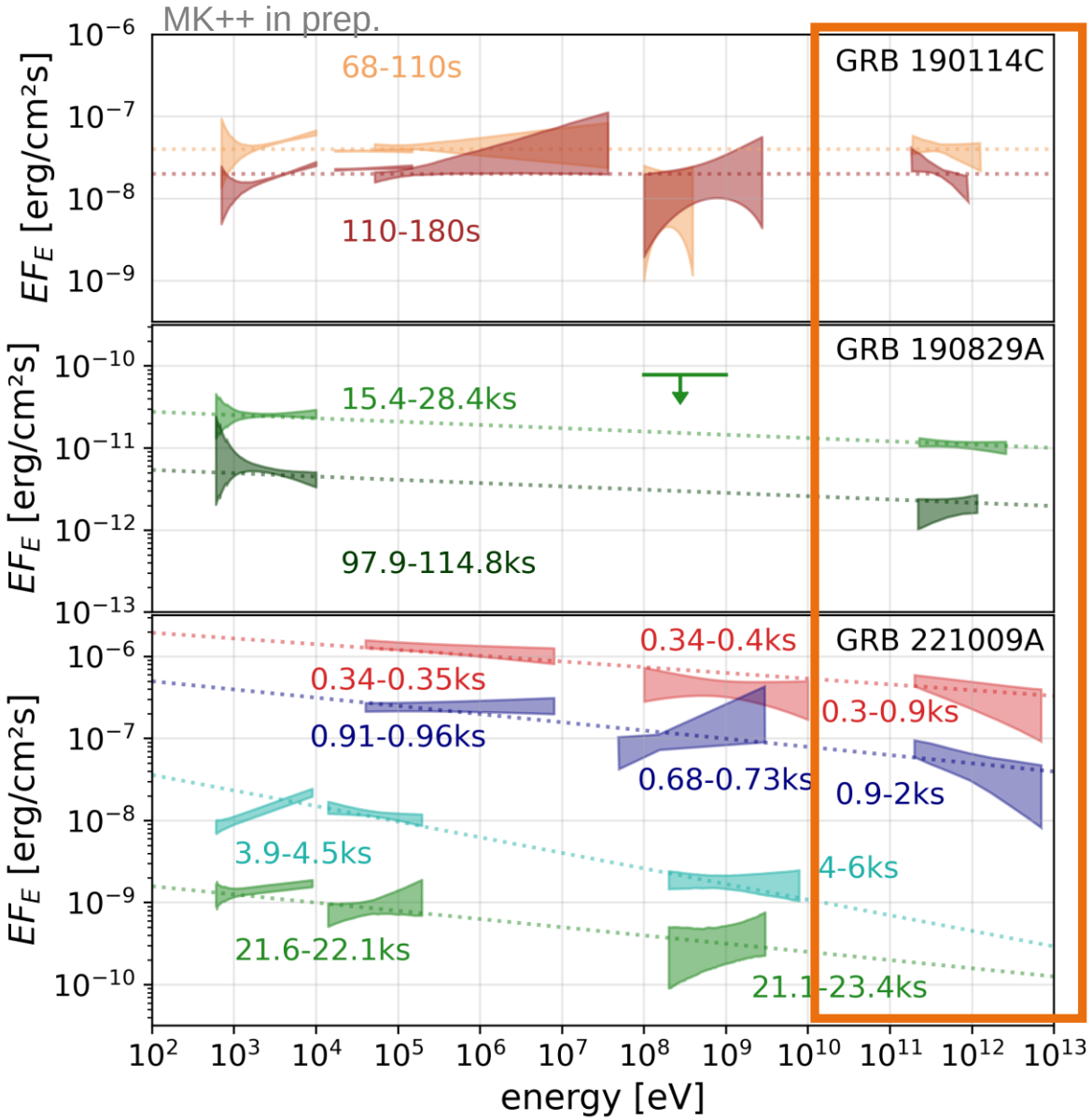
Problem: how to explain $\eta \ll 1$?

Extended synchrotron vs SSC



What about data?

Comparison to data

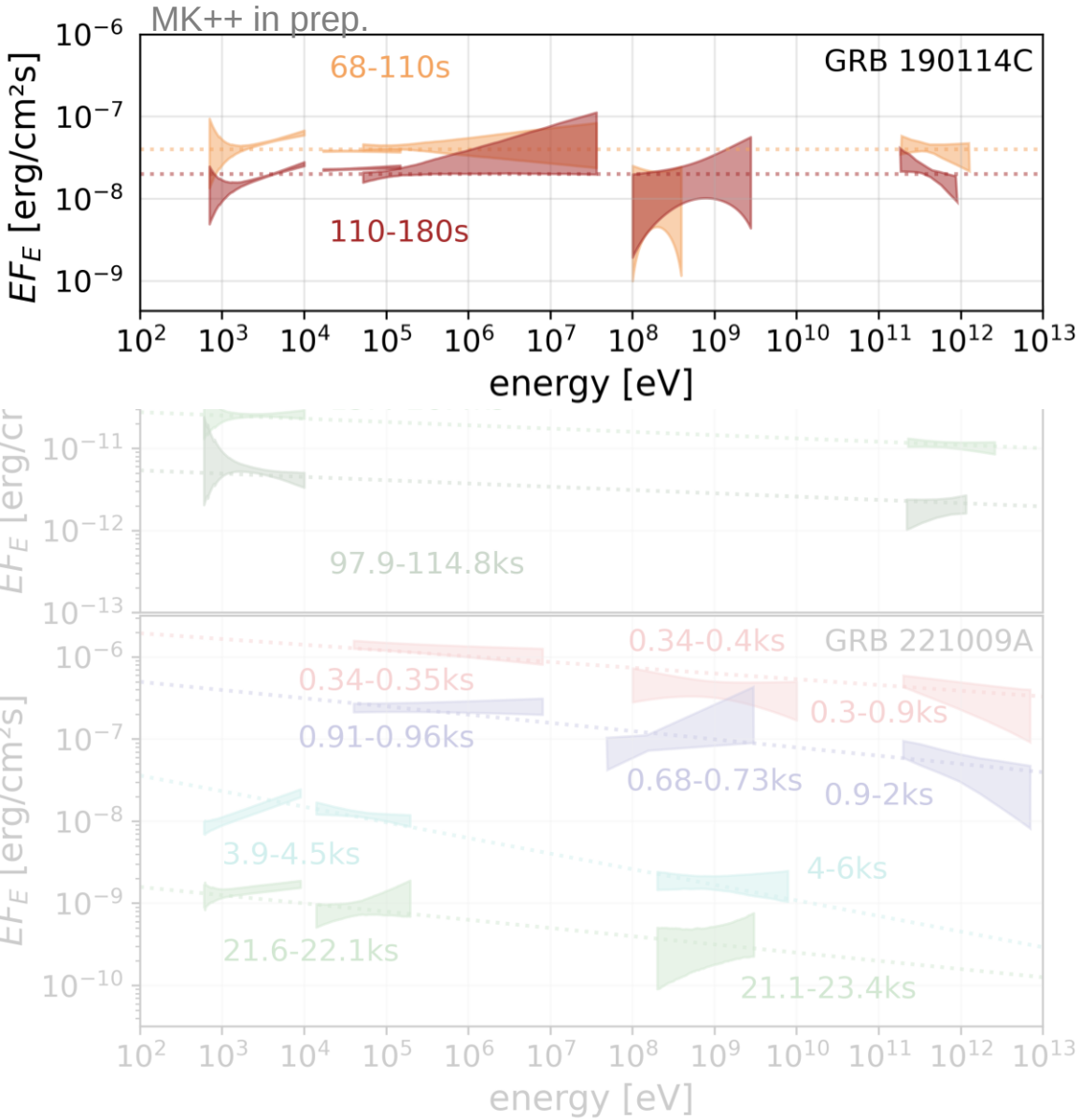


→ **MAGIC:**

→ **HESS:**

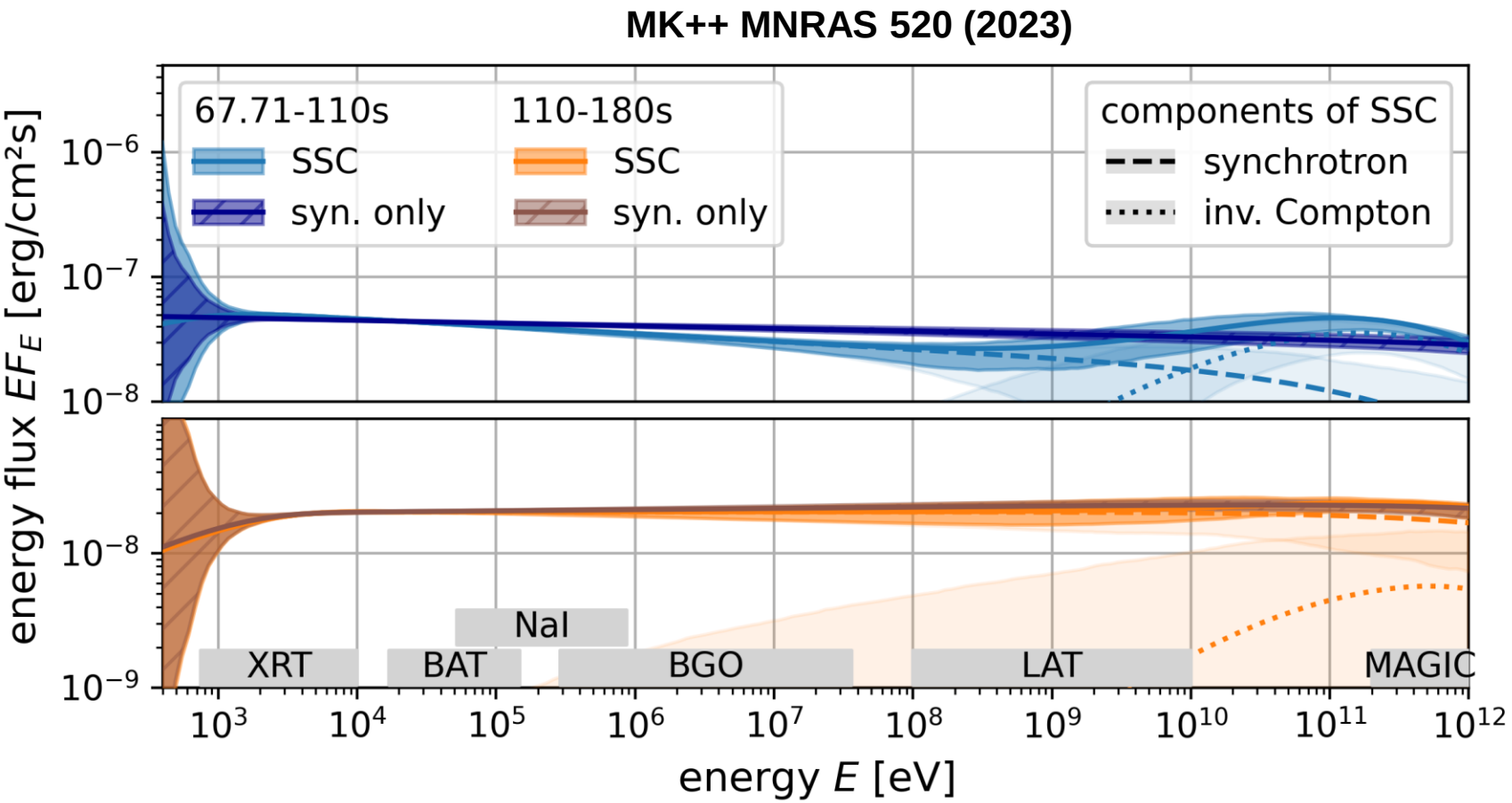
→ **LHAASO:**

Comparison to data



→ **MAGIC:**

GRB 190114C: SSC vs extended syn



- MAGIC observation:

$z = 0.43$ (EBL) + moonlight

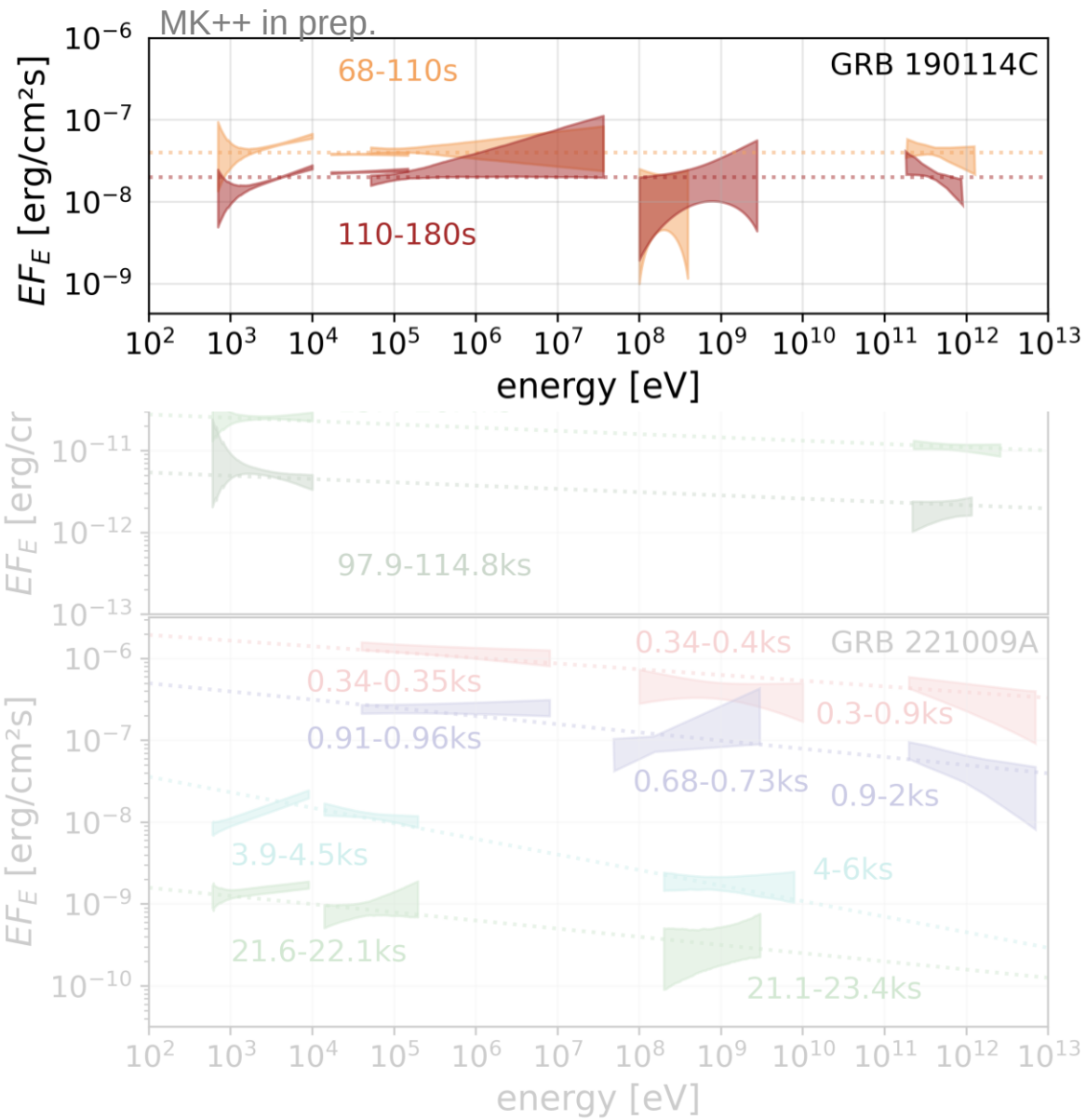
→ uncertain spectral index at TeV $-2.2 \pm 0.3 \pm 0.2$
(stat) (sys)
MAGIC Nature 575 (2019)

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

- counts level fit:

→ no robust preference for SSC!

Comparison to data

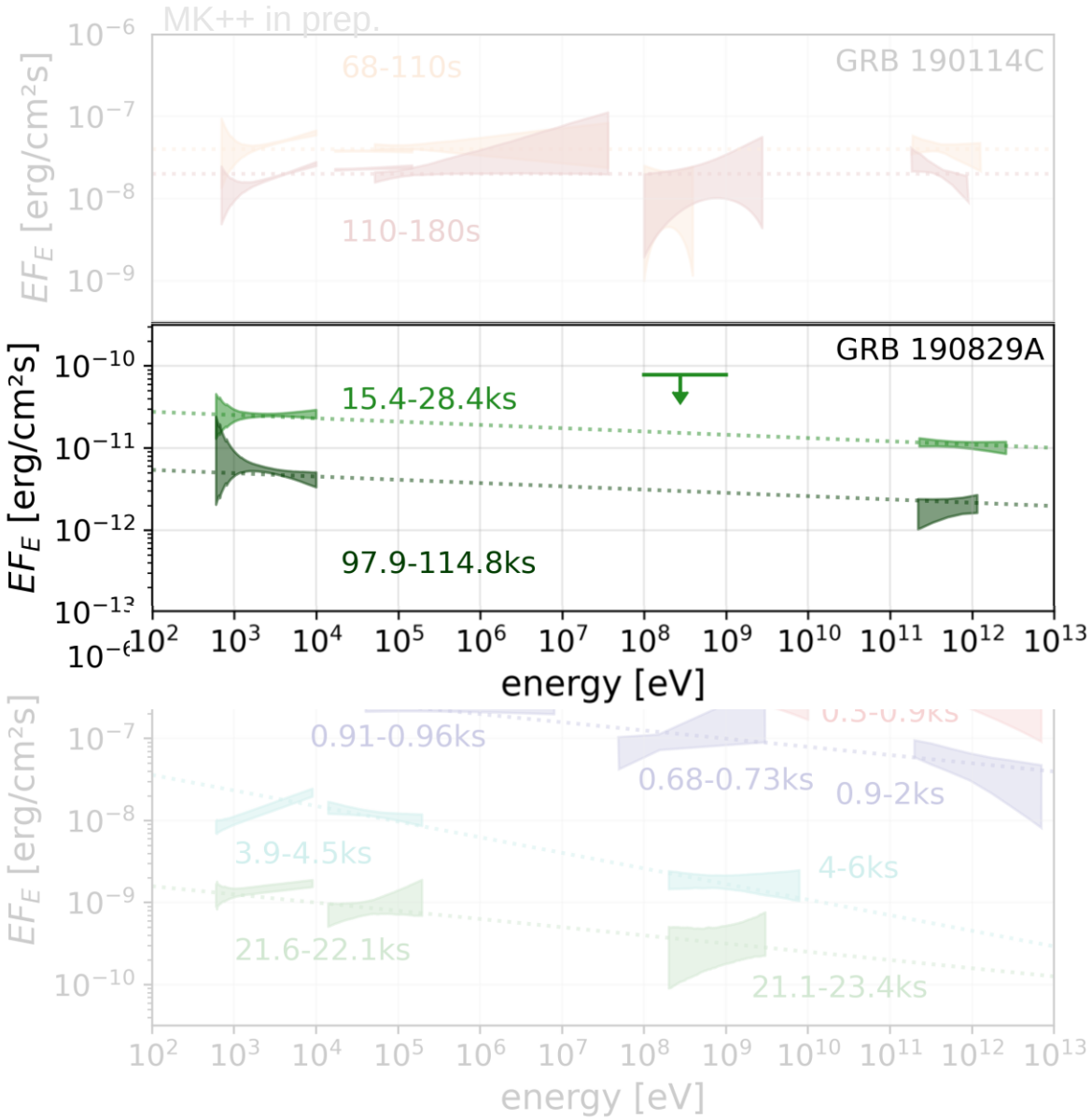


→ **MAGIC:**

?

→ **inconclusive on syn vs. SSC**

Comparison to data

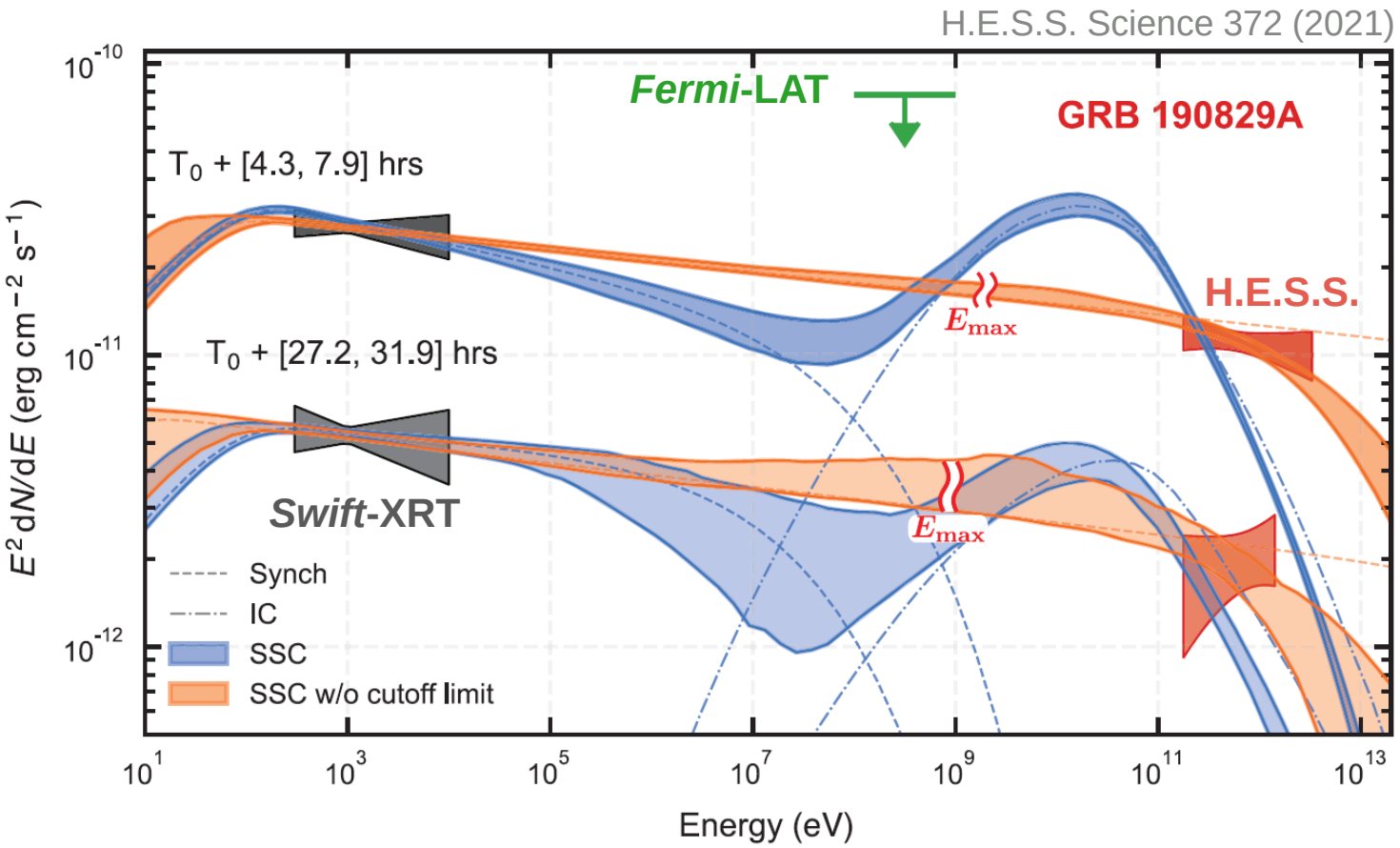


→ MAGIC:

→ inconclusive on syn vs. SSC

→ **HESS:**

GRB 190829A: SSC vs extended syn



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

→ spectral index at TeV:

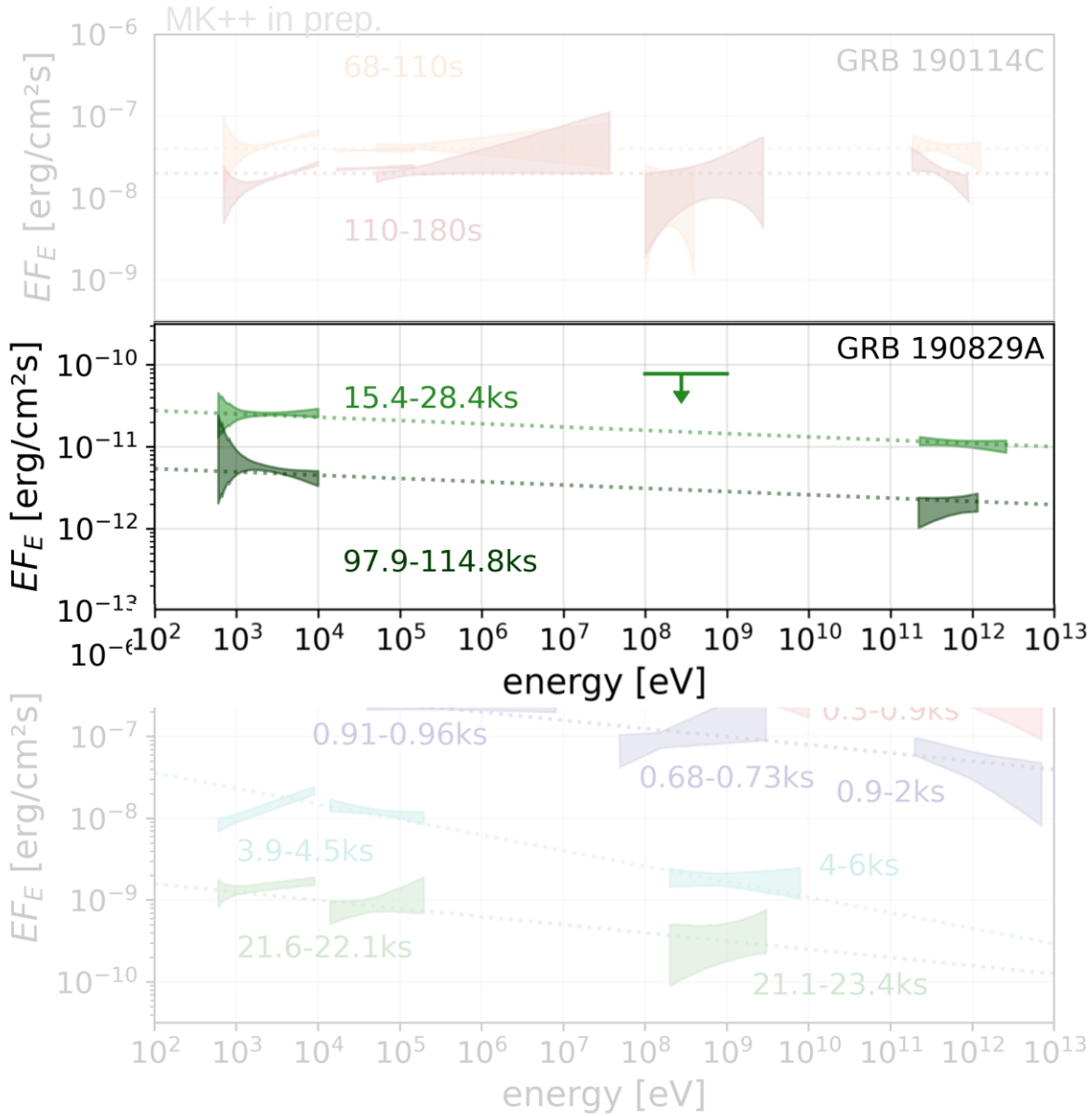
$$\approx -2 \pm 0.1_{\text{(stat)}} \pm 0.26_{\text{(sys)}}$$

- poor MWL coverage

- counts level fit:

→ preference for single component!

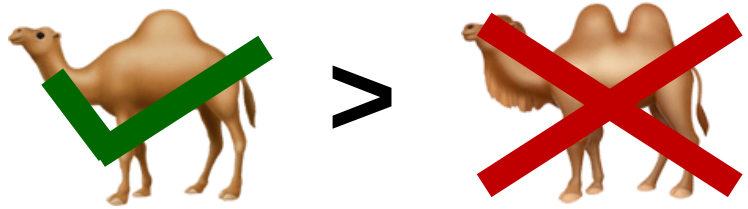
Comparison to data



→ MAGIC:

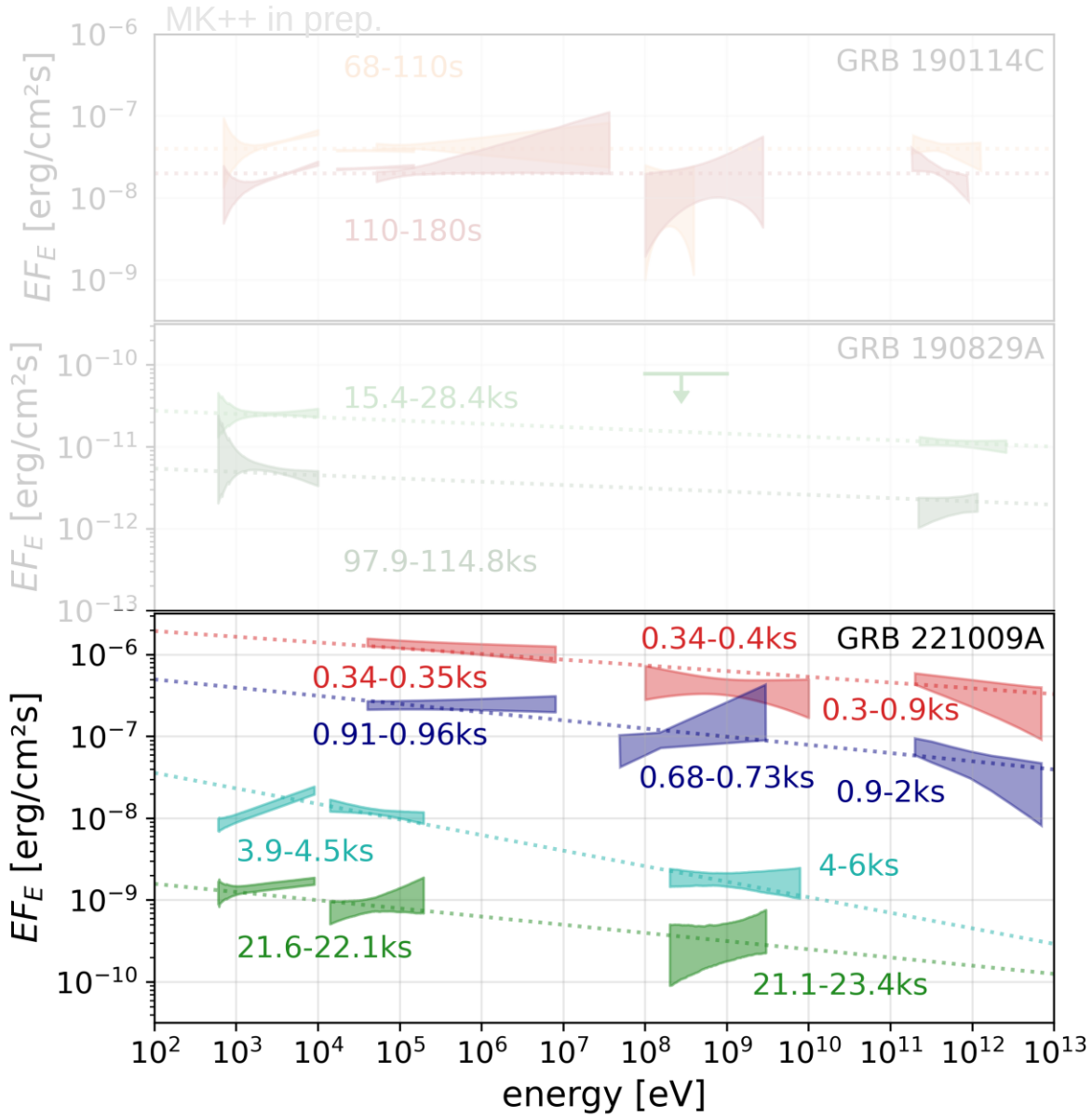
→ inconclusive on syn vs. SSC

→ HESS:



→ in tension with SSC

Comparison to data



→ MAGIC:

→ inconclusive on syn vs. SSC

→ HESS:

→ in tension with SSC

→ **LHAASO:**

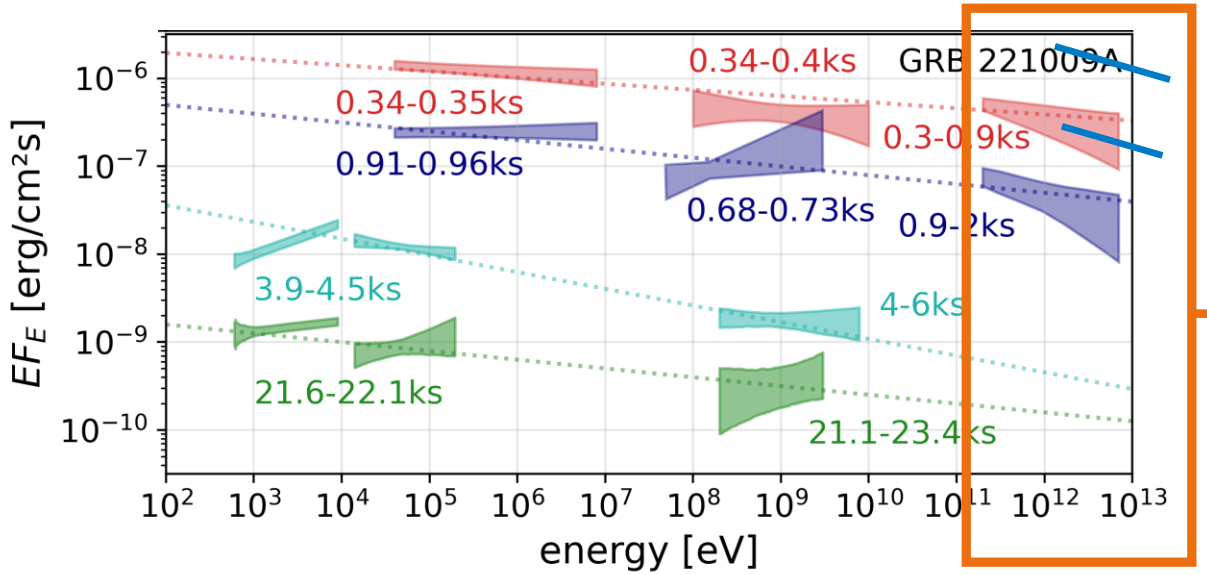
GRB 221009A

LHAASO Collaboration 2023:

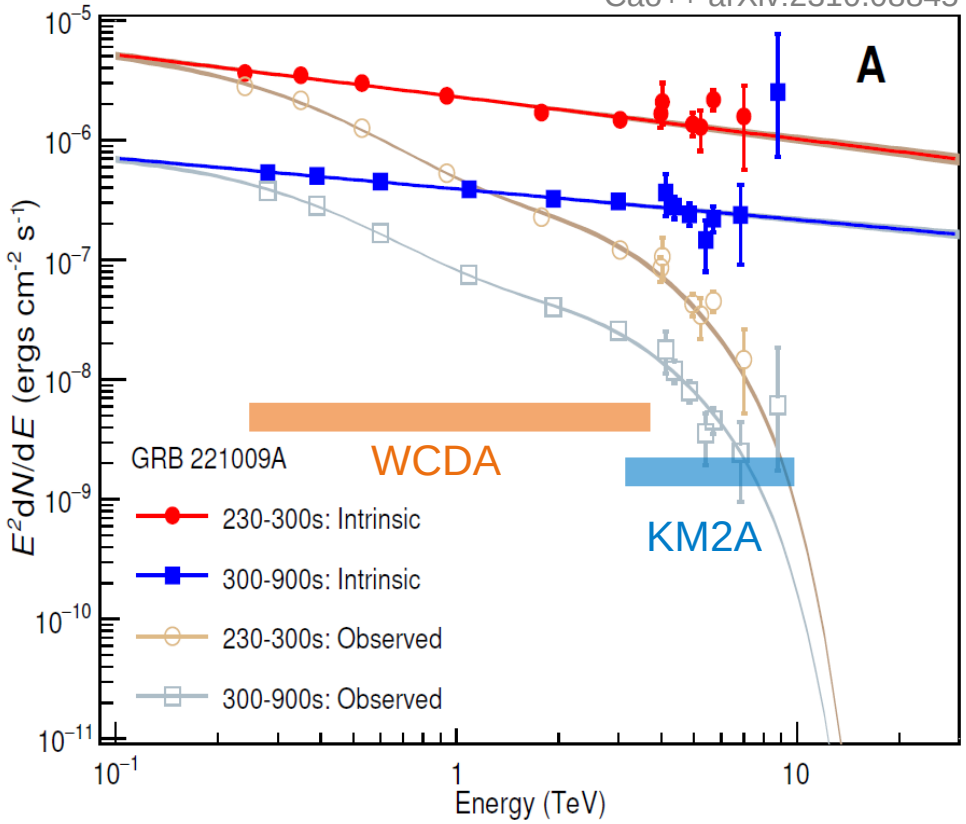
No softening up to at least 10 TeV!

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

→ incompatible with SSC



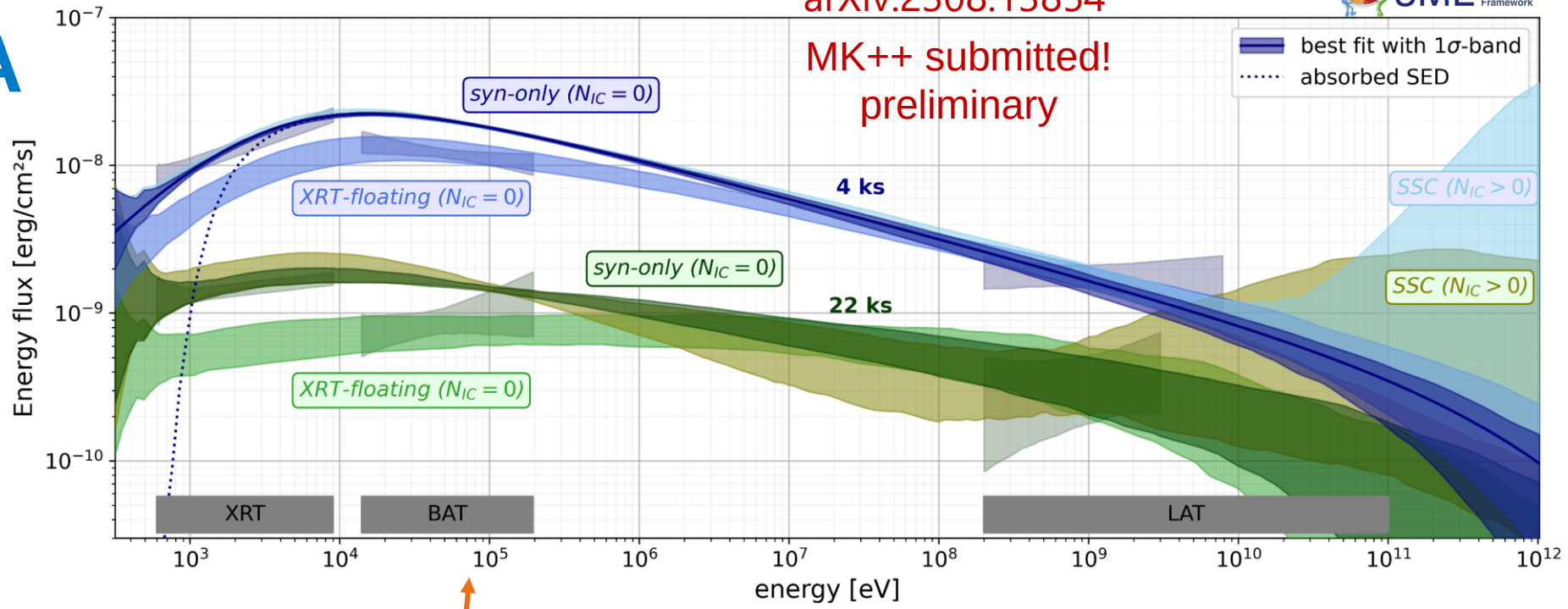
Cao++ arXiv:2310.08845

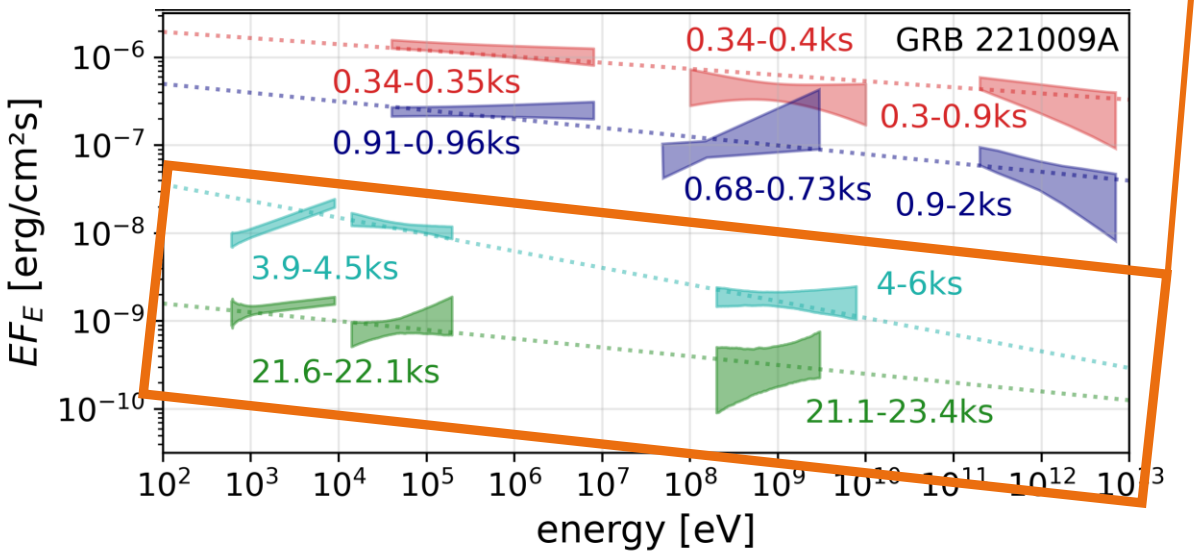


GRB 221009A

arXiv:2308.13854

MK++ submitted!
preliminary



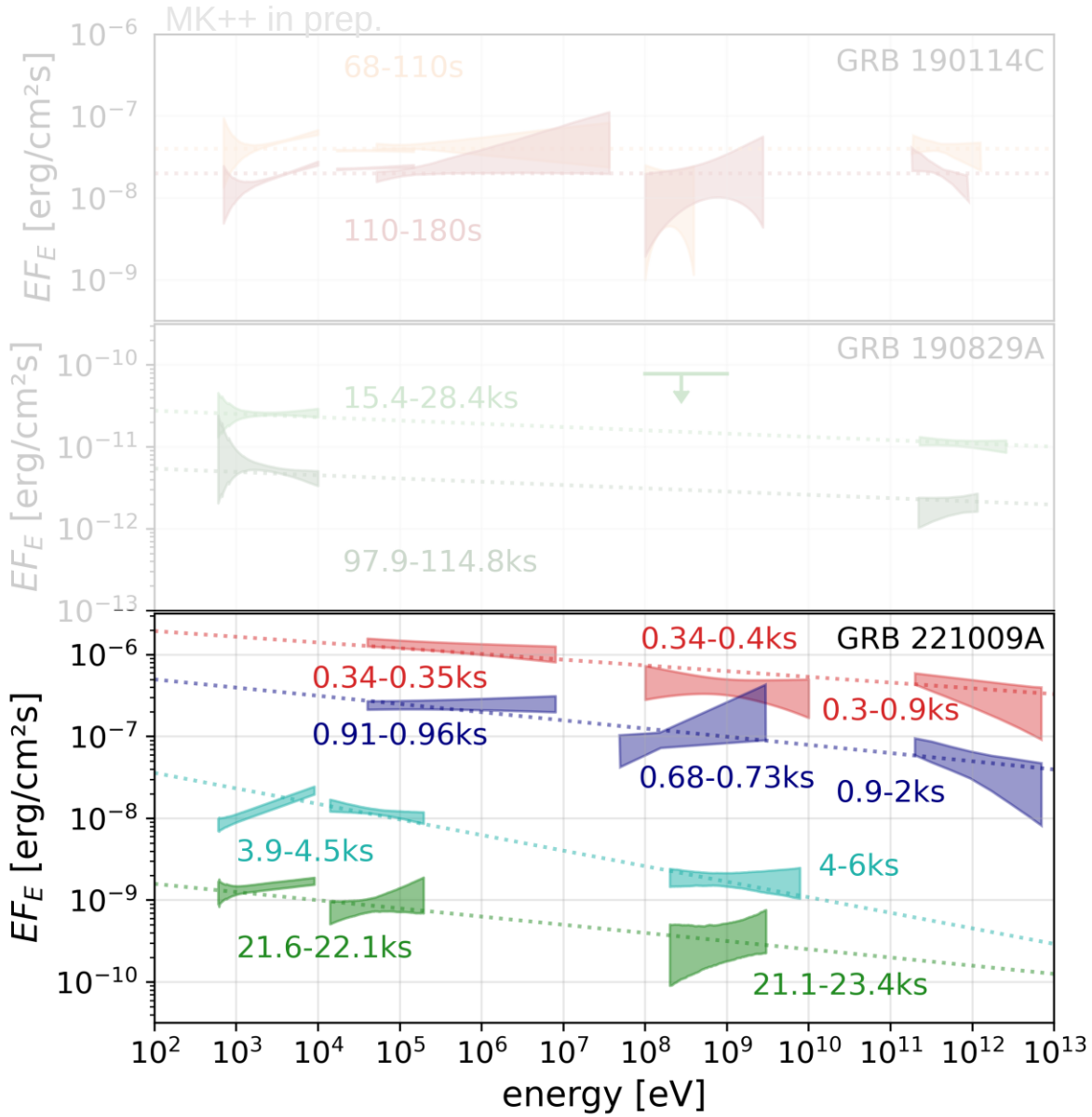


after LHAASO (> 2 ks):

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

→ consistent with LHAASO

Comparison to data



→ MAGIC:

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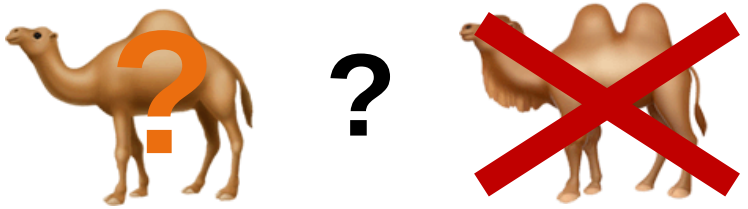
→ HESS:

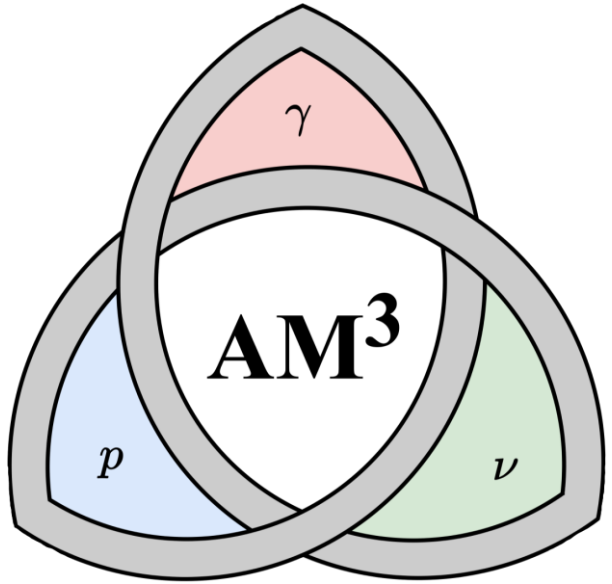
→ in tension with SSC

→ **LHAASO:**



→ in tension with SSC

There is more beyond the SSC model



Ideas:

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

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

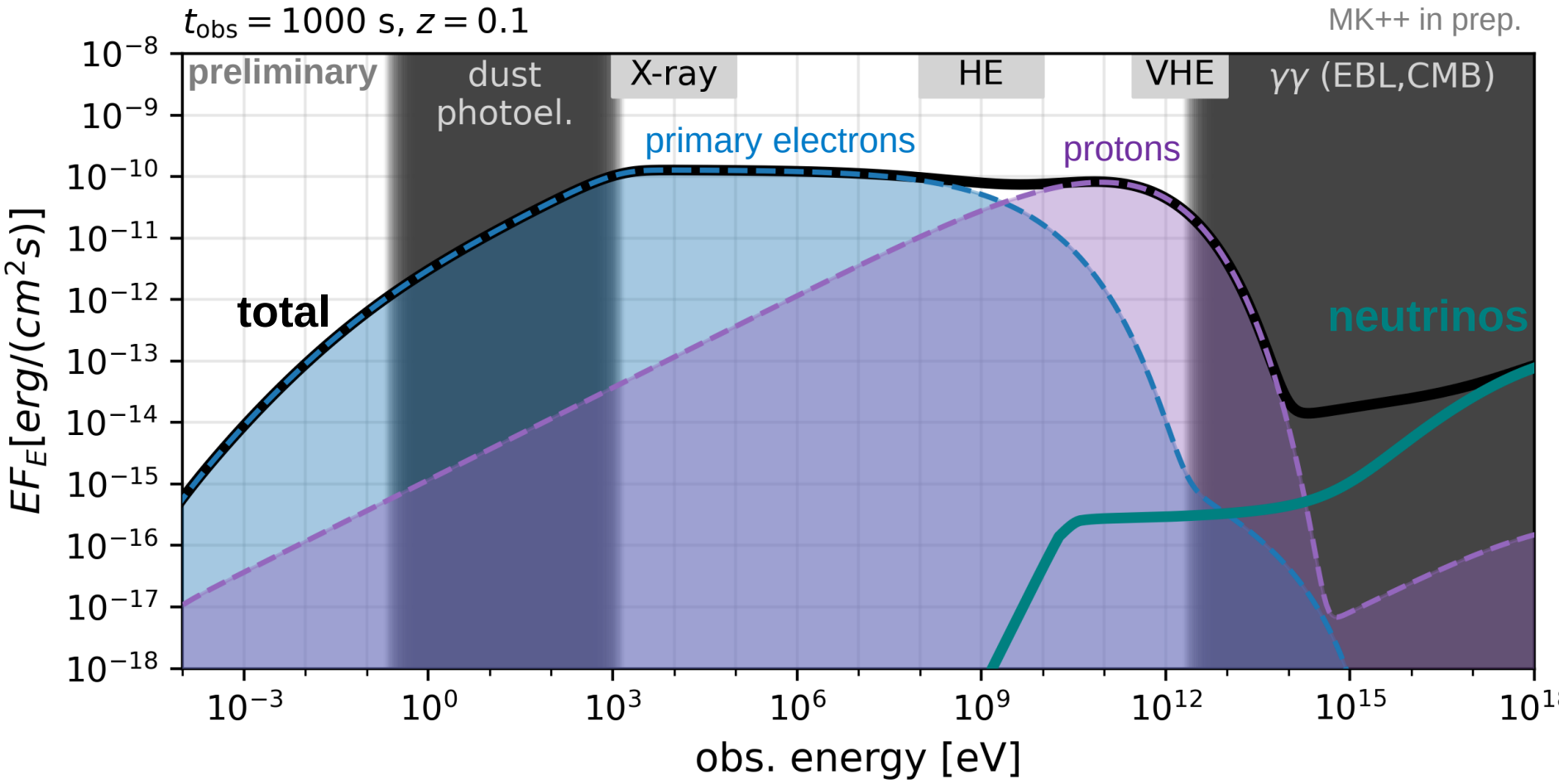
  → 2 zone: decouple acceleration zone from radiation zone
  Khangulyan++ APJ 947 (2021)

  → **extended electron synchrotron component**

- involve hadrons

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

Proton-Synchrotron model

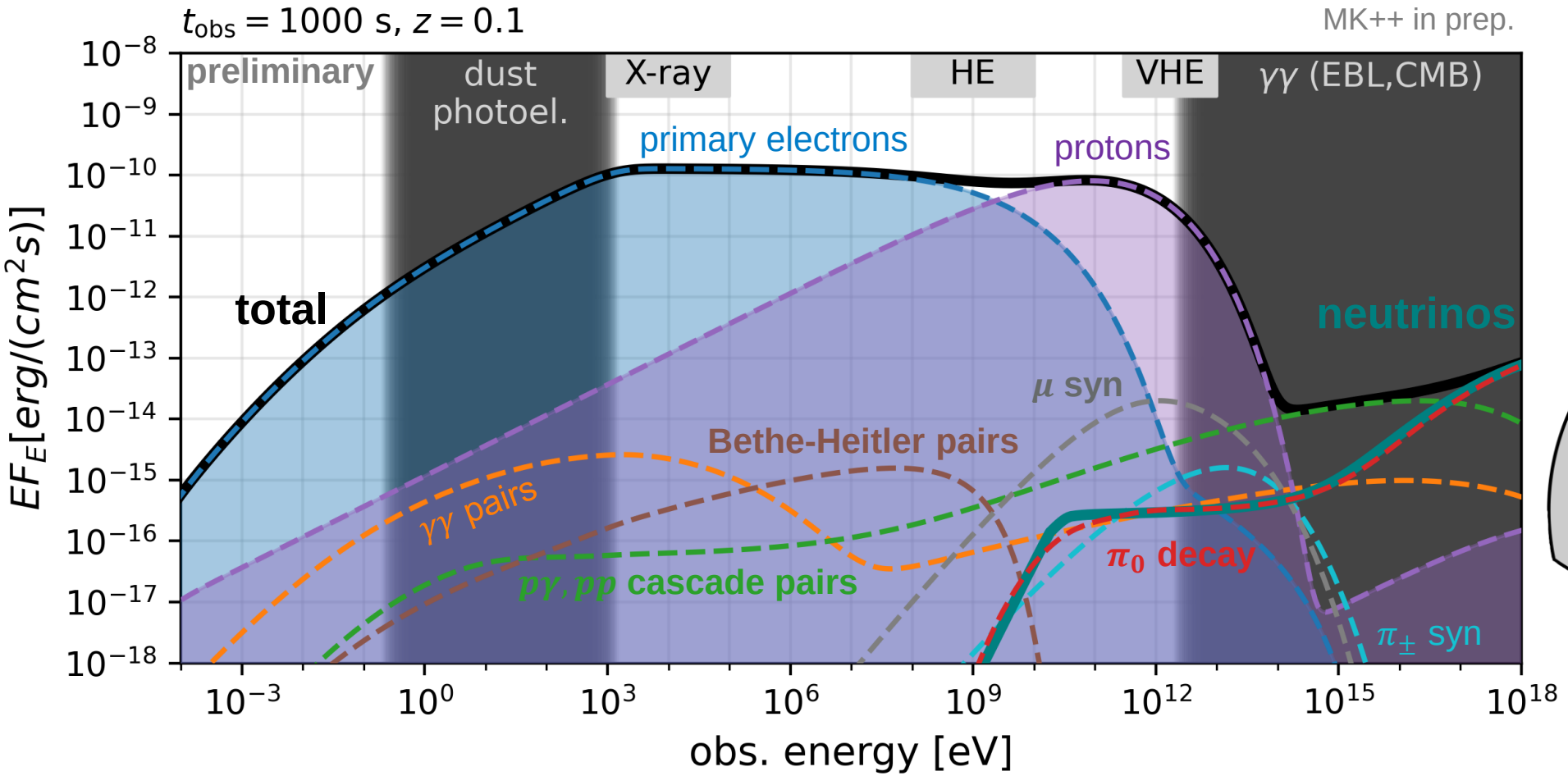


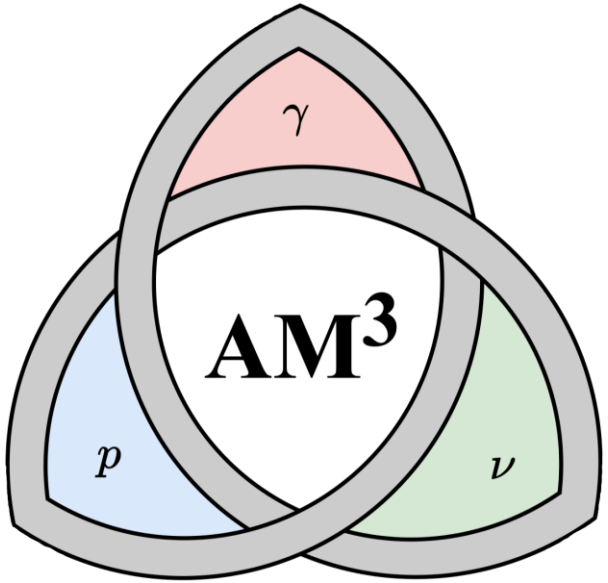
ε_e	10^{-3}
ε_p	$10^{-0.5}$
ε_B	$10^{-0.5}$
$E_{\min}$	10GeV
p	2
η	1
$E_{\rm iso}$	10^{55}erg
$n_{\rm up}$	$1\mathrm{cm}^{-3}$

$\varepsilon_B, \varepsilon_p \lesssim 1$

Problem: proton synchrotron component at exponential cut-off!

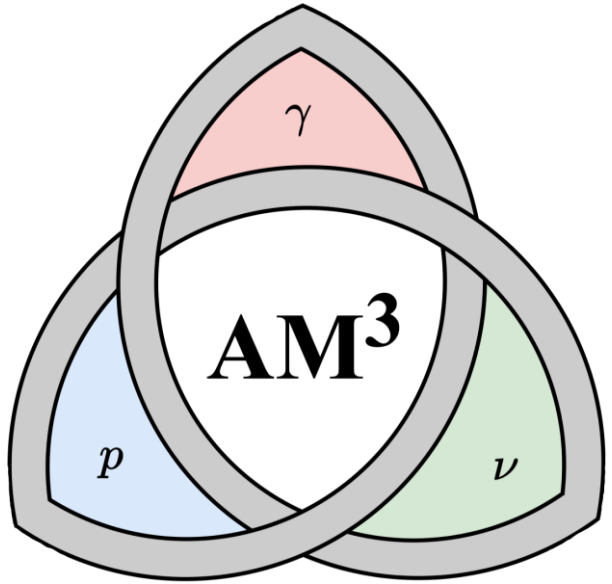
Proton-Synchrotron model





Interesting: neutrinos! But fluence not too high…

There is more beyond the SSC model



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  → **extended electron synchrotron component**

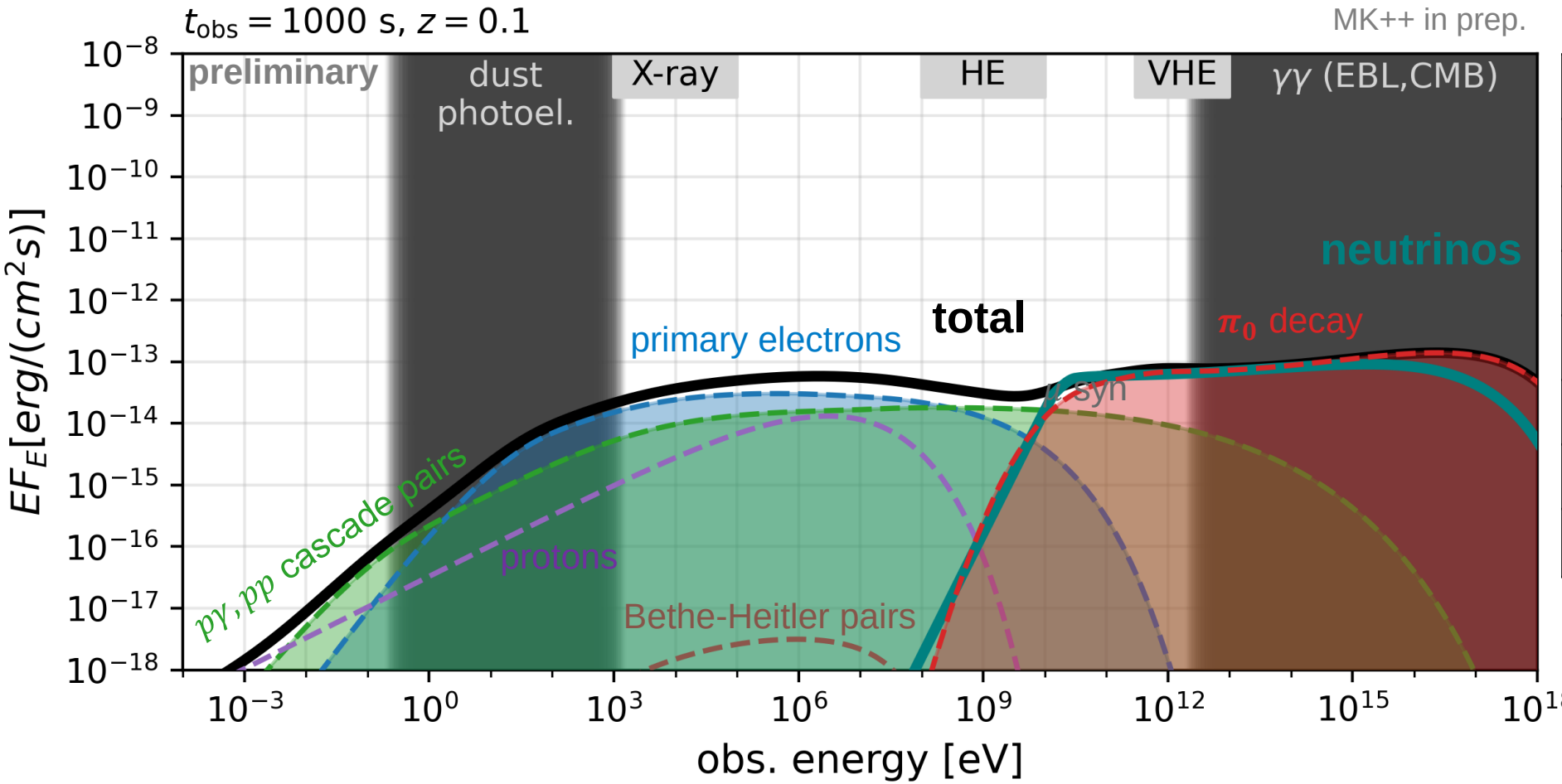
- involve hadrons

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

  → **cascade from pγ interactions** for prompt VHE emission (Cao++ arXiv:2310.11821)

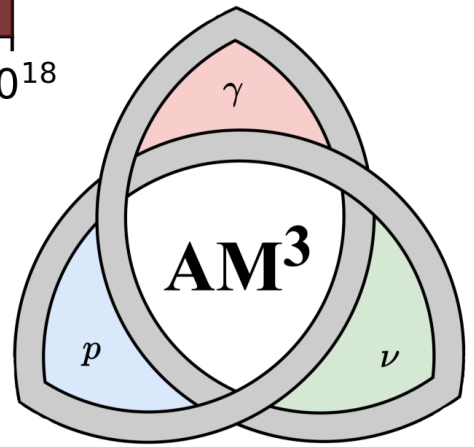
  → **cascade from pp interactions**

pp-cascade



ε_e	10^{-8}
ε_p	10^{-1}
ε_B	10^{-5}
$E_{\rm min}$	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

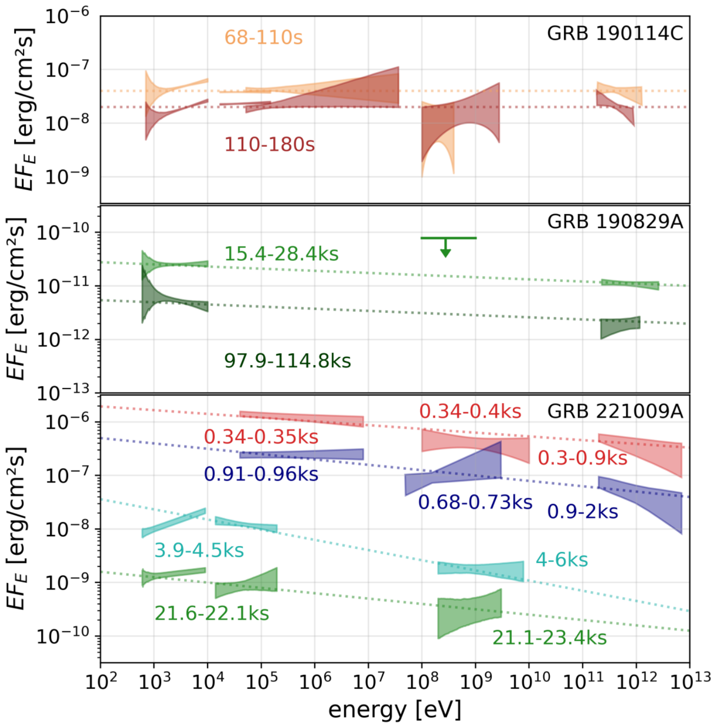
  → in particular for SSC scenario

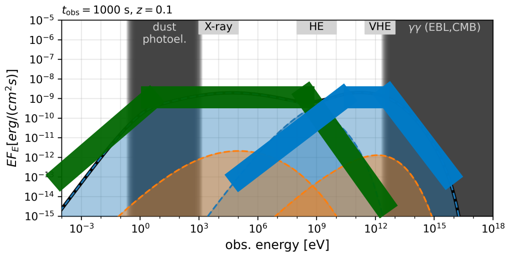
- Need to think about other scenarios:

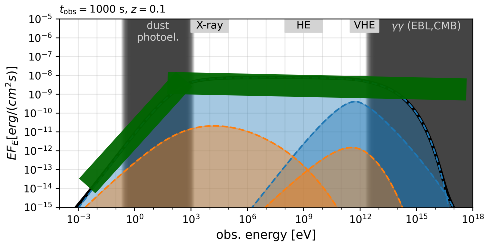
  → extended synchrotron model

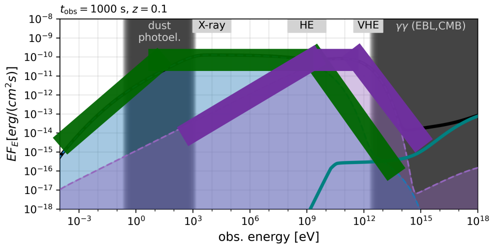
  → proton synchrotron

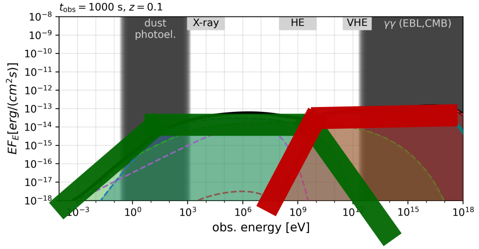
  → cascade from pp interactions







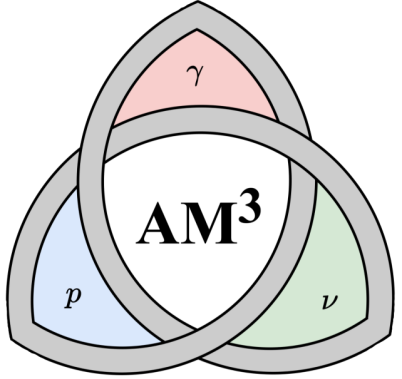


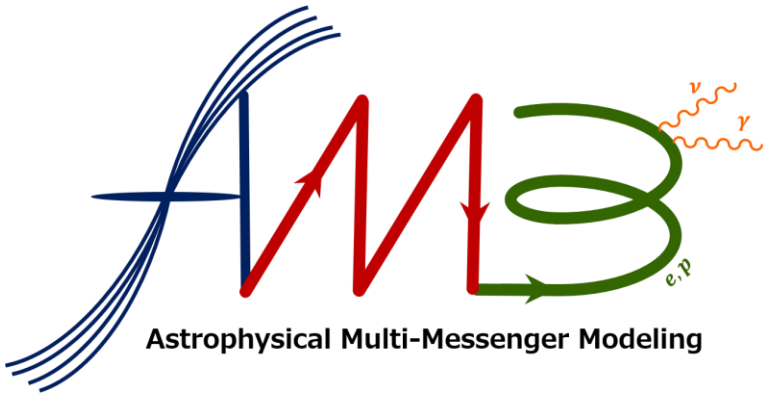


Thank you!

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

Gao++ APJ 843 (2017)

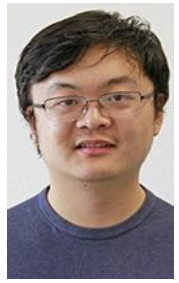
- including documentation!


Gao


Klinger


Rudolph


Rodrigues


Yuan


Fichet De Clairfontaine


Fedynitch


Winter

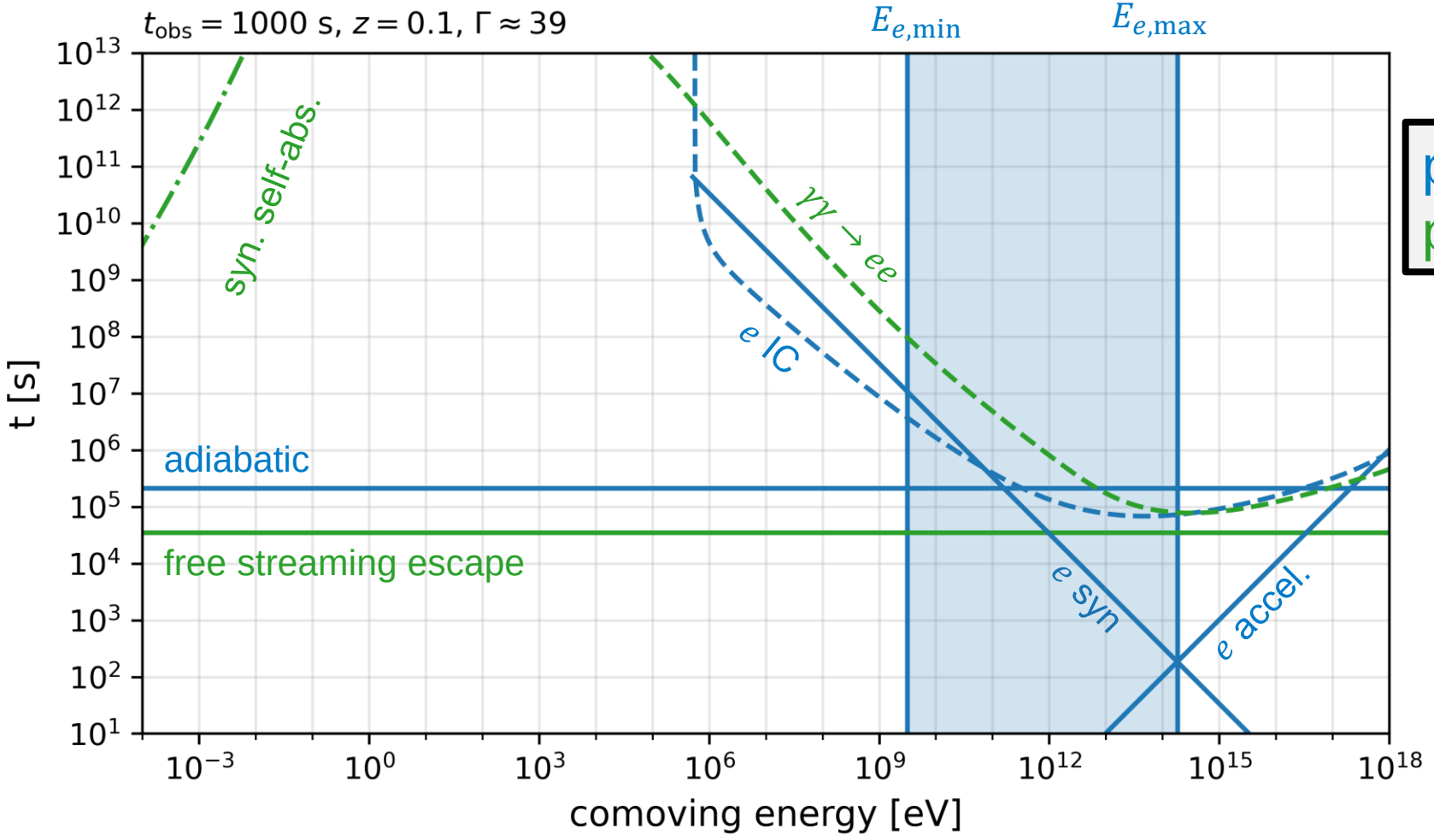

Pohl

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

Backup

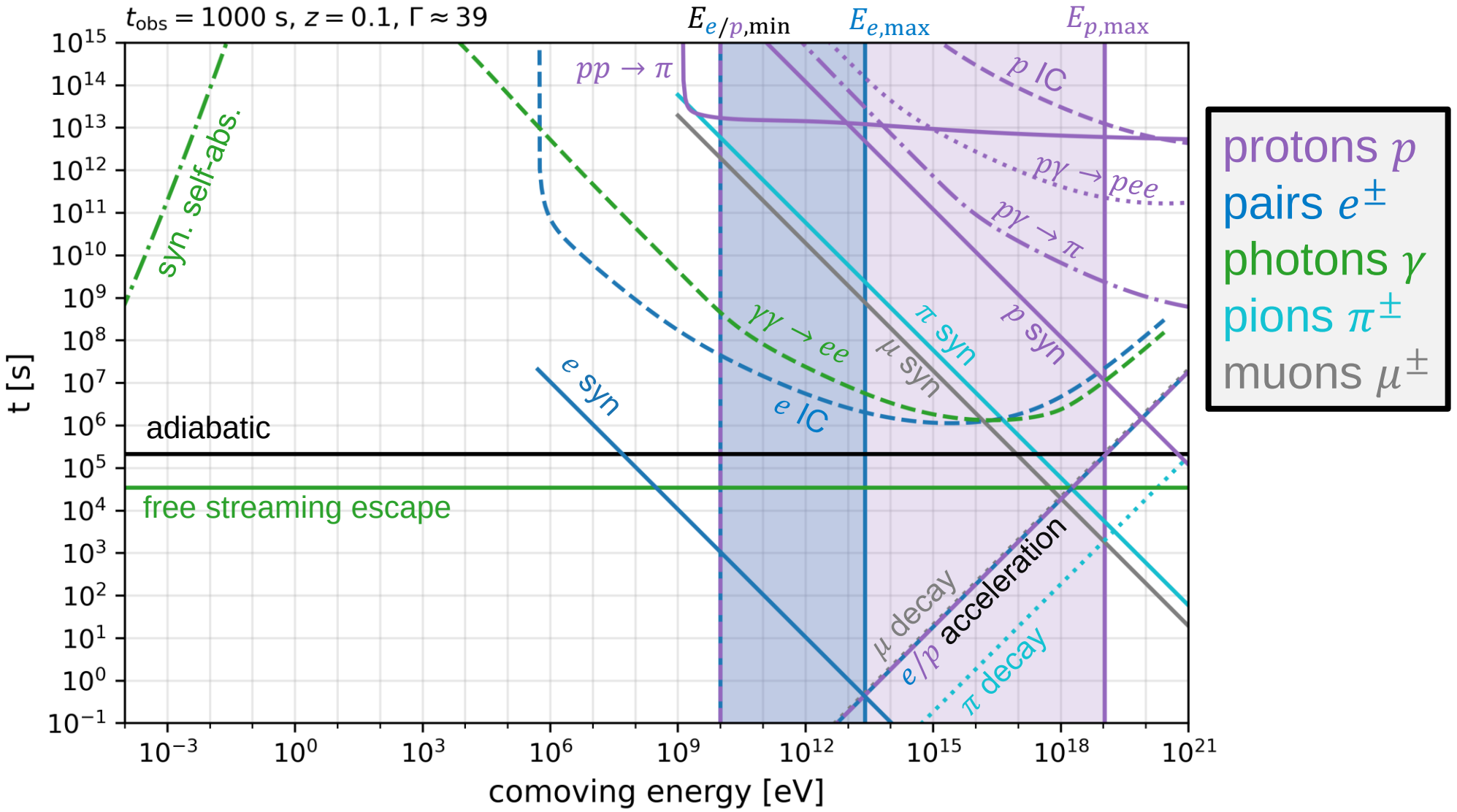
Hadronic scenarios

SSC model time scales

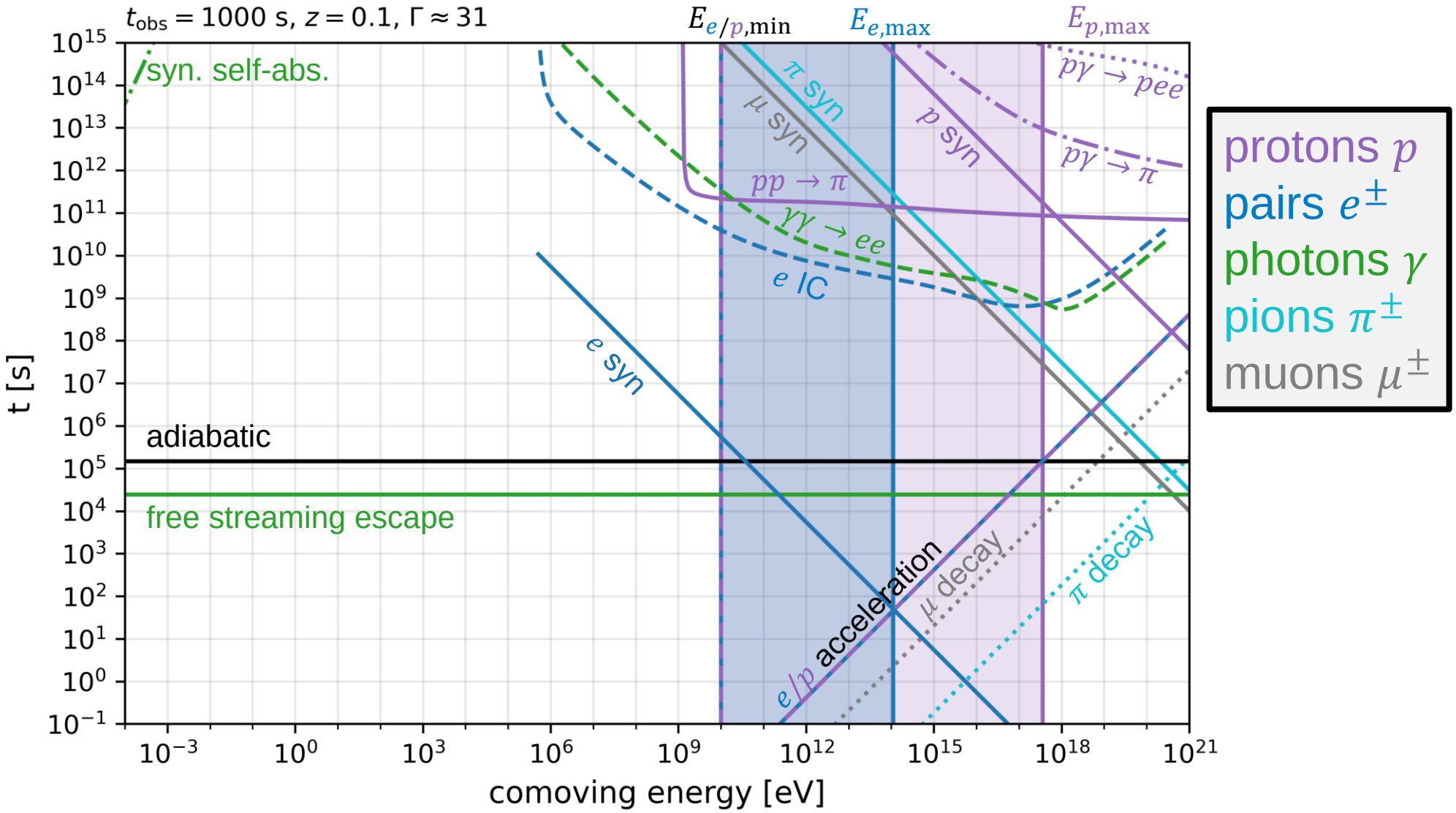


pairs $e^{\pm}$
photons γ

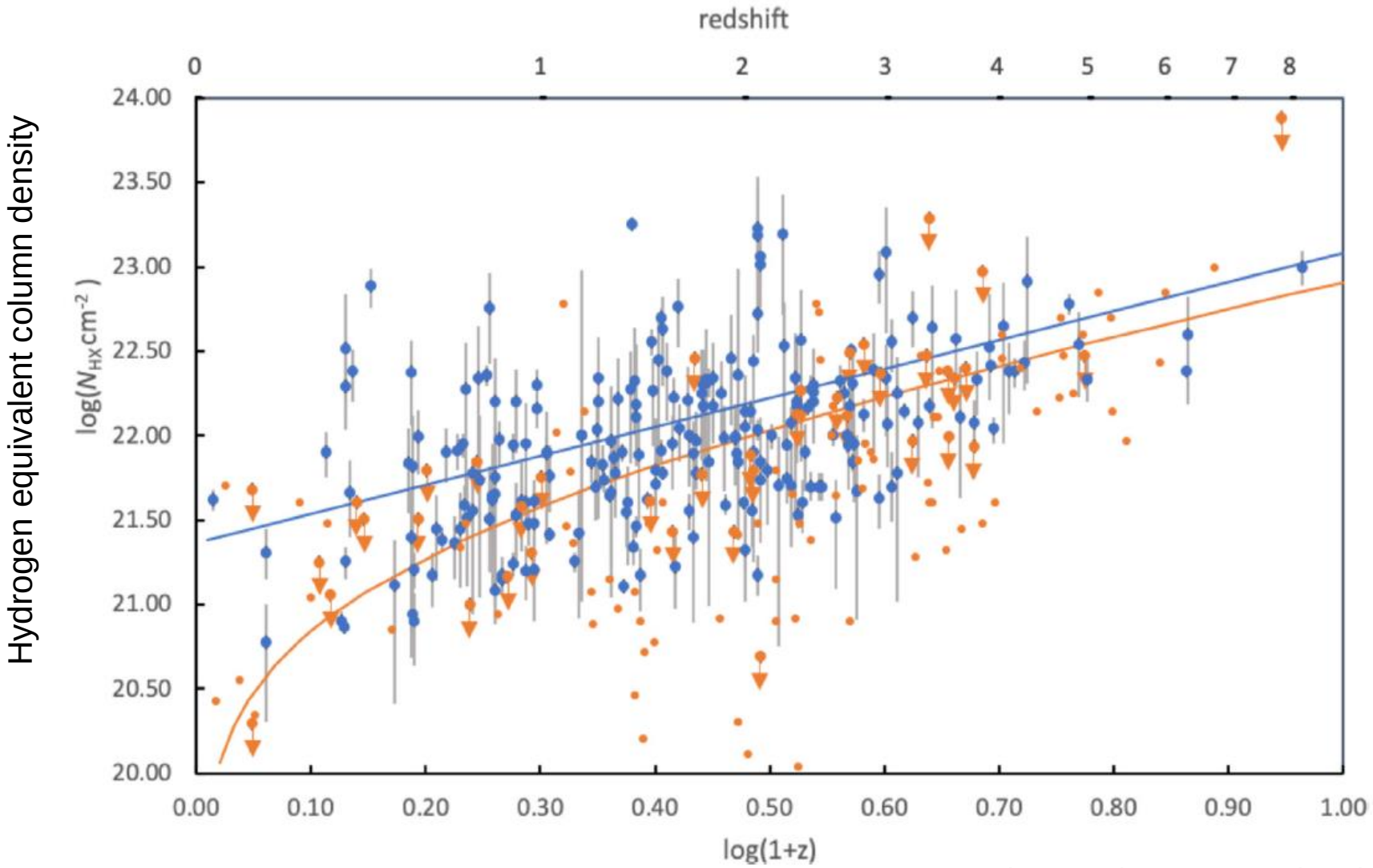
Proton Synchrotron model time scales



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