On the camel nature of GRB Afterglows

Marc Klinger*, 28.10.2023, at SPIMAX, Oxford

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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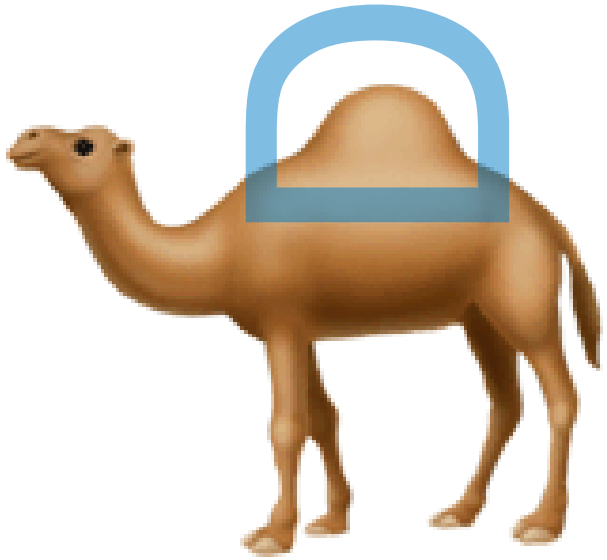
https://maklinger.github.io/

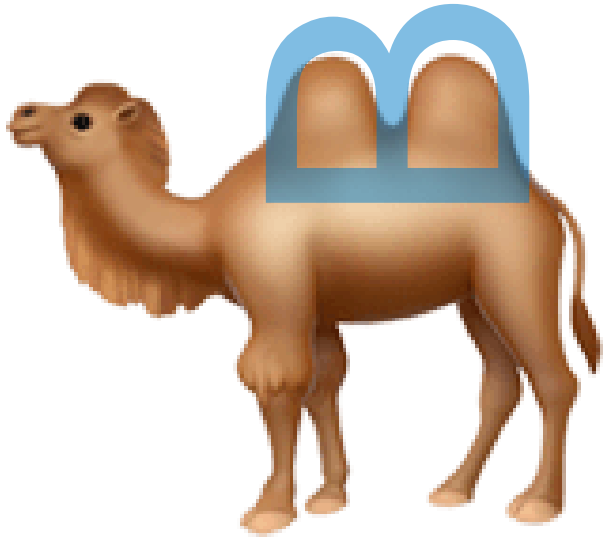
DESY.

Are gamma ray burst afterglows…



Dromedaries

or



Bactrians

?

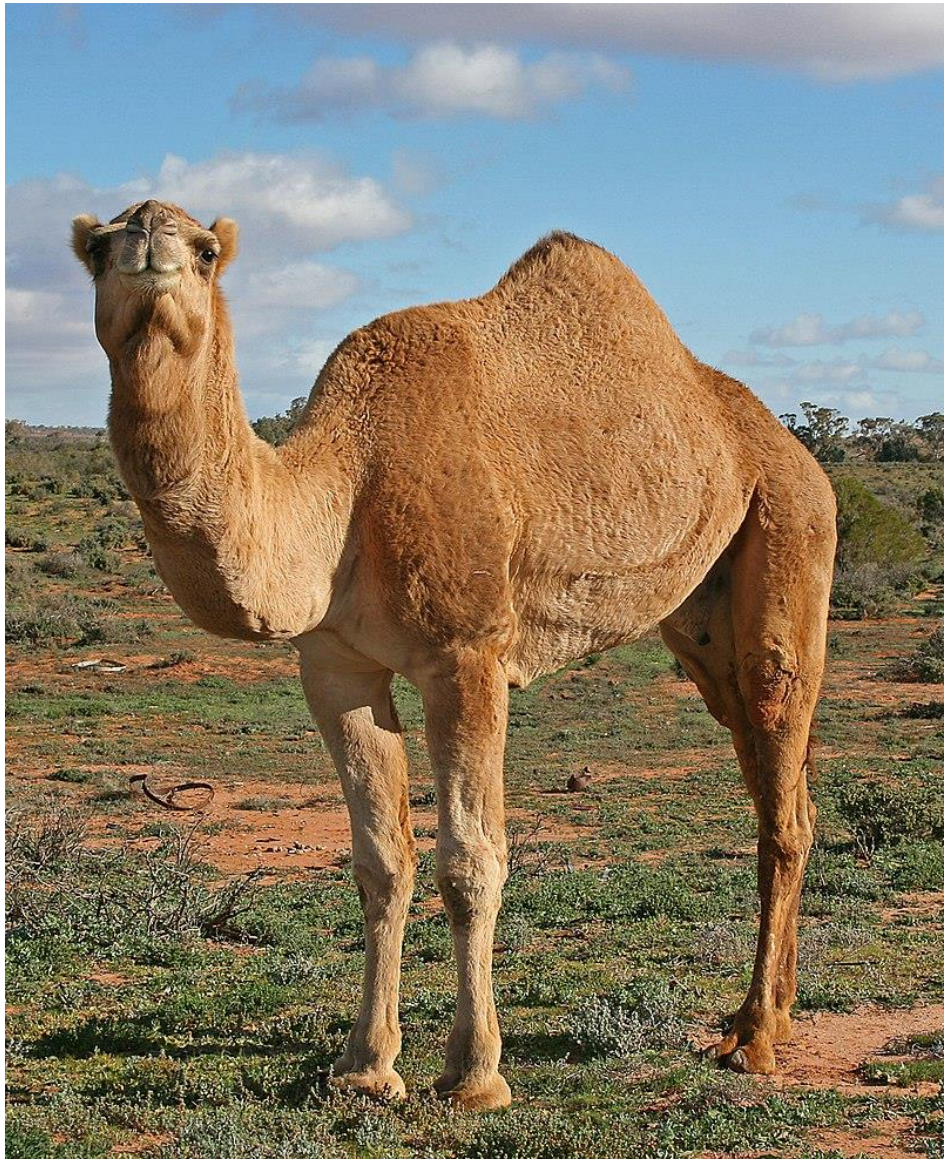
Bactrian or Dromedary?

Bactrian or Dromedary?

https://www.balisafarimarinepark.com/what-makes-camel-became-a-unique-animal/

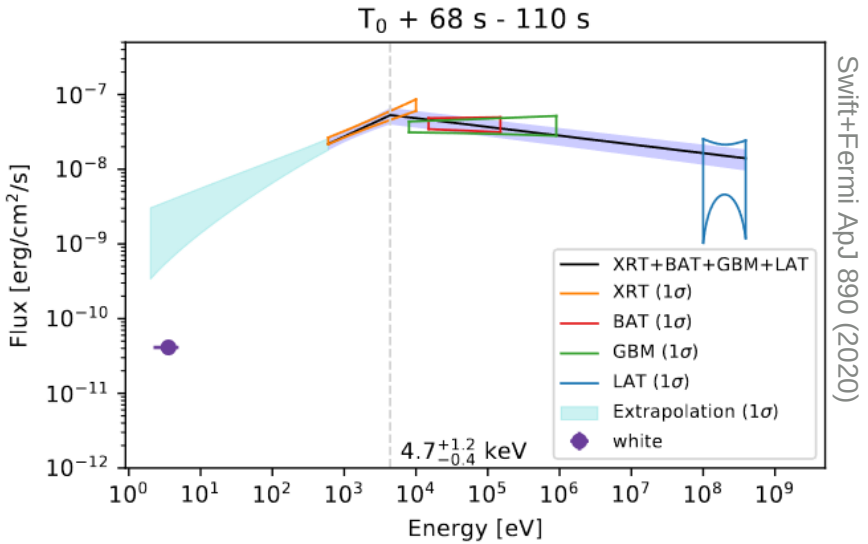
Bactrian or Dromedary?

Bactrian or Dromedary?

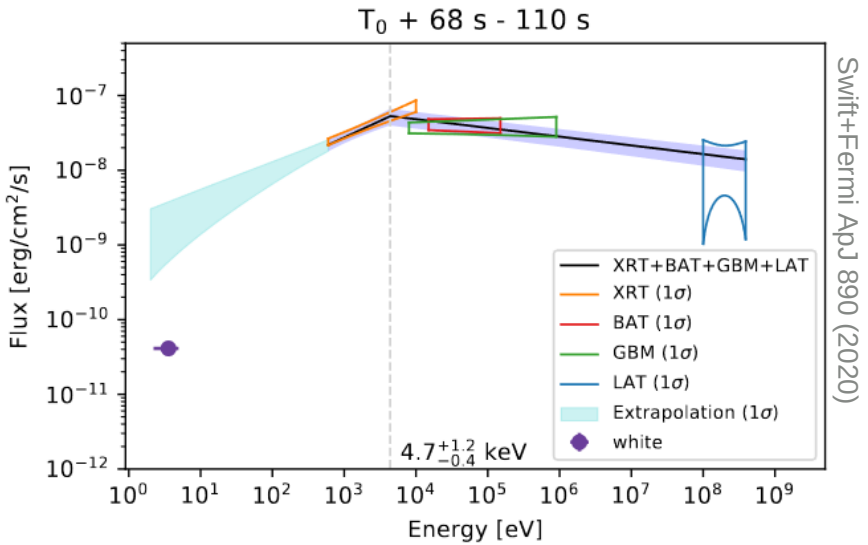


https://en.wikipedia.org/wiki/File:07._Camel_Profile,_near_Silverton,_NSW,_07.07.2007.jpg

Bactrian or Dromedary?

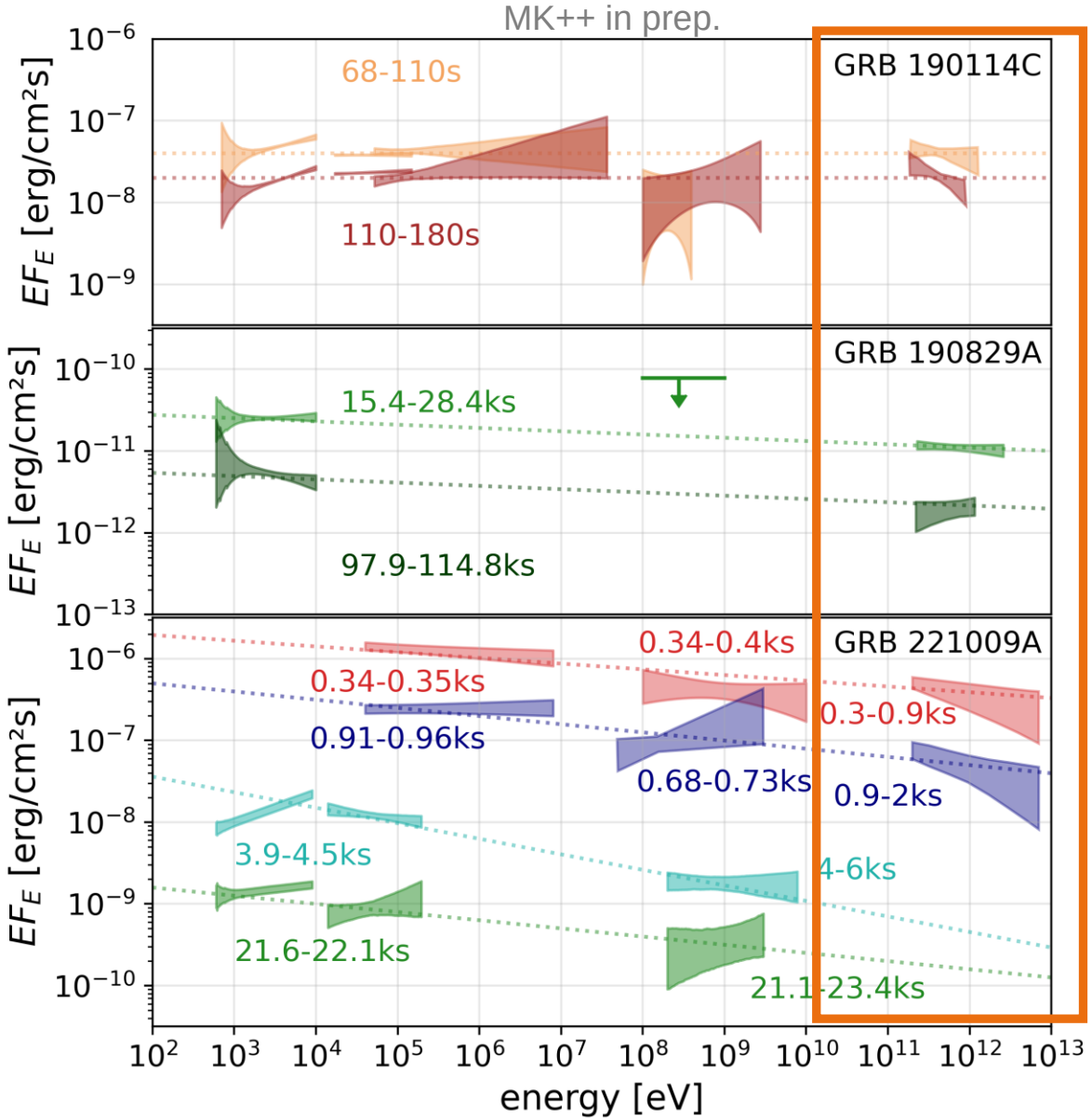


Bactrian or Dromedary?



→ would be nice to see more of the camel!

GRB afterglows detected at VHE!



→ **MAGIC**

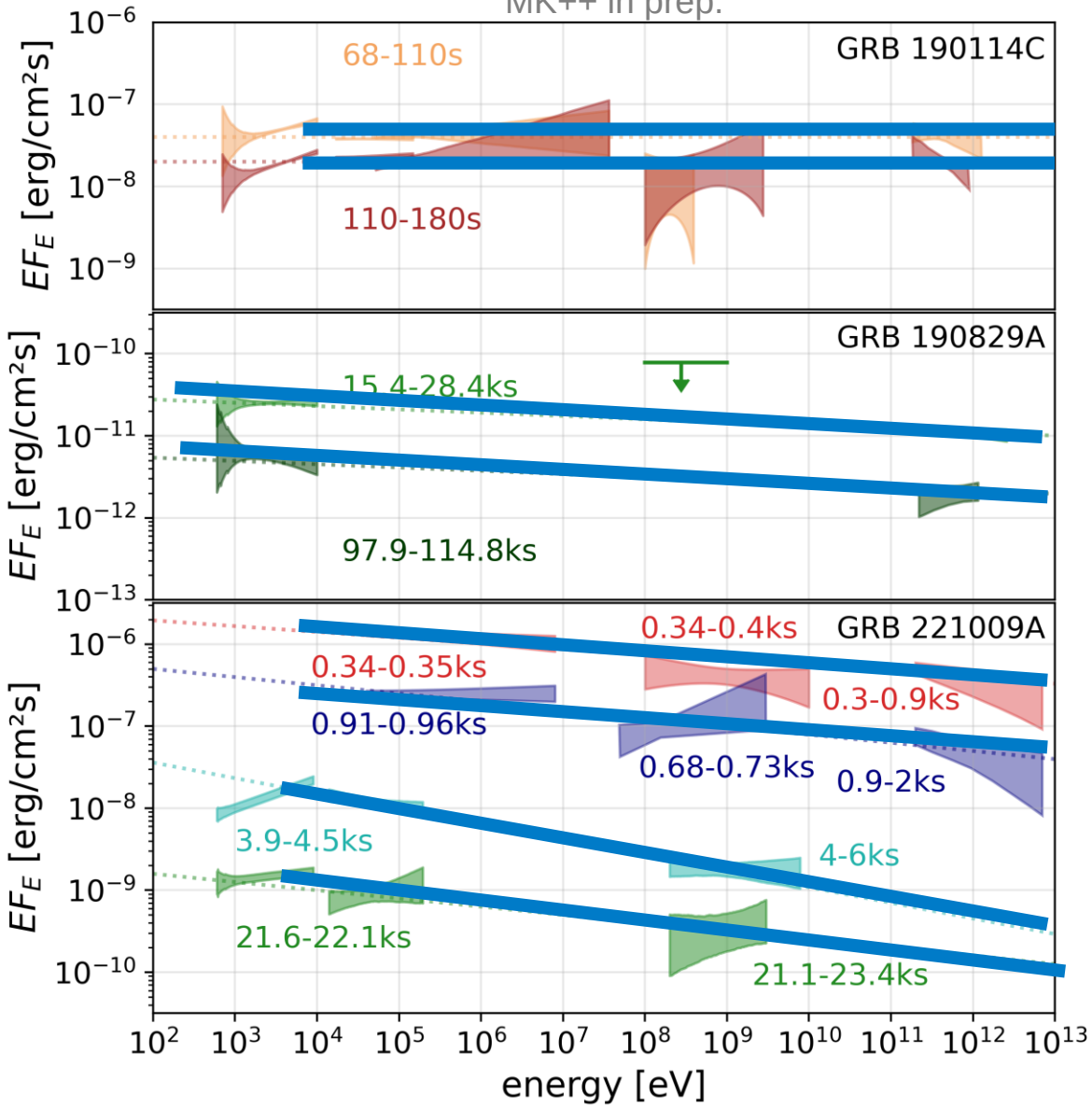
→ **H.E.S.S.**

→ **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

GRB afterglows detected at VHE!

MK++ in prep.



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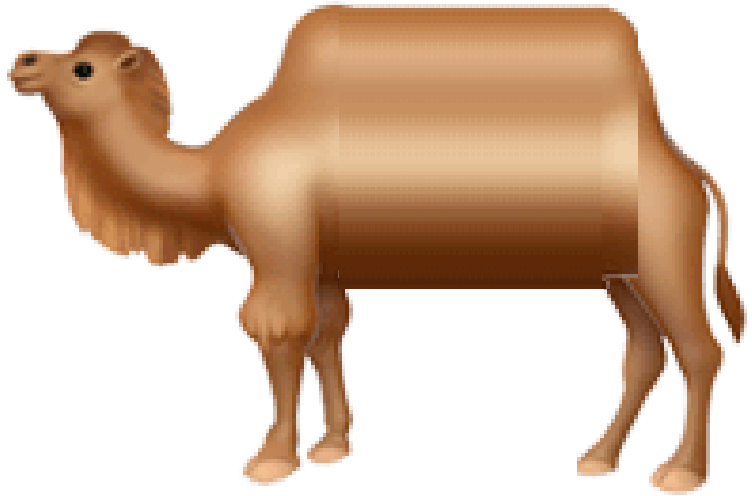
→ LHAASO



flat spectra extending up to >TeV

data from:
MAGIC Nature 575 (2019)
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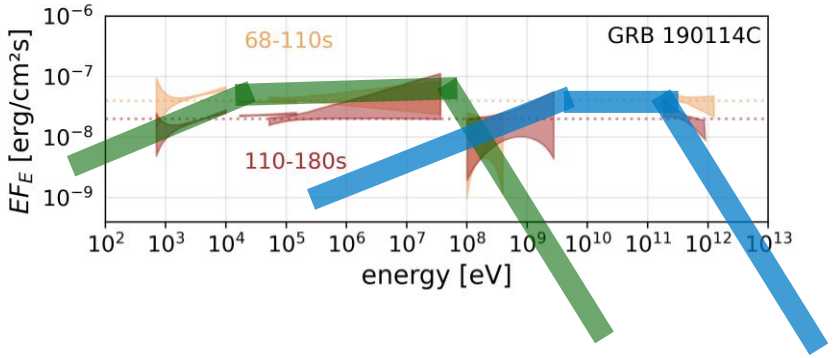
Why to care about GRBs?

- **non-thermal particle acceleration** at **shocks** ?
- **relativistic** realisation: afterglow of a gamma-ray burst
- **observational handle: photon spectra**
- connection of observed photon spectra to underlying physics based on **many assumptions** → room for improvement
- new observational window at VHE

  → crisis (= we can learn something new!)

Crisis:

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



standard in community:
2 component SSC

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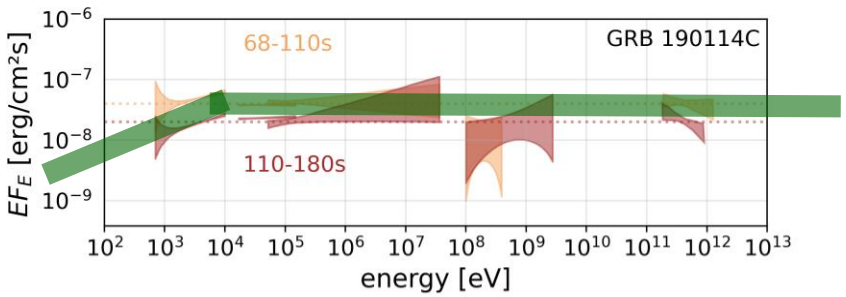
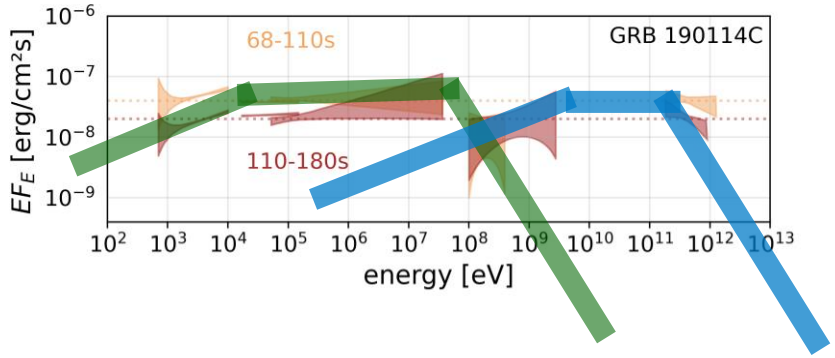
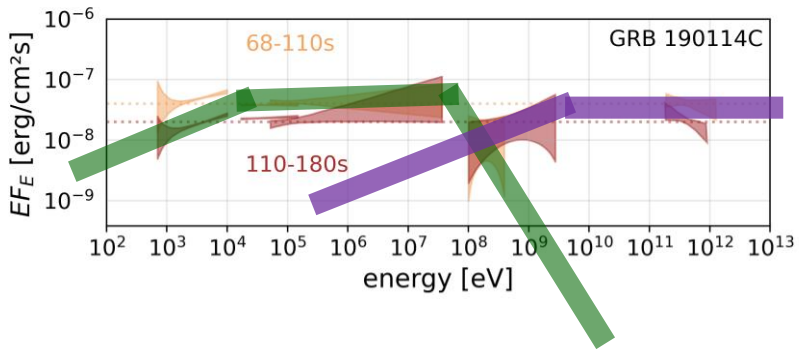






?

standard in community:
2 component SSC

?

Outline

- GRB afterglow modeling basics

  → what do I actually mean by *Dromedary* and *Bactrian* ?


- observational picture at high energies

  → GRB 190114C, GRB 190829A, GRB 221009A

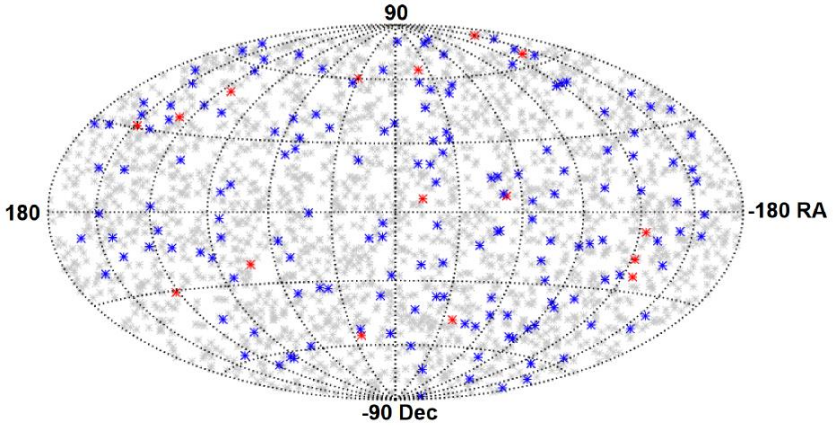
- hadronic ways out of crisis

GRBs from two sides

OBSERVATIONAL picture

- we observe flashes of X/γ-rays isotropically distributed on sky

2. Fermi-LAT GRB Catalogue (2018)



T_{90} [s]

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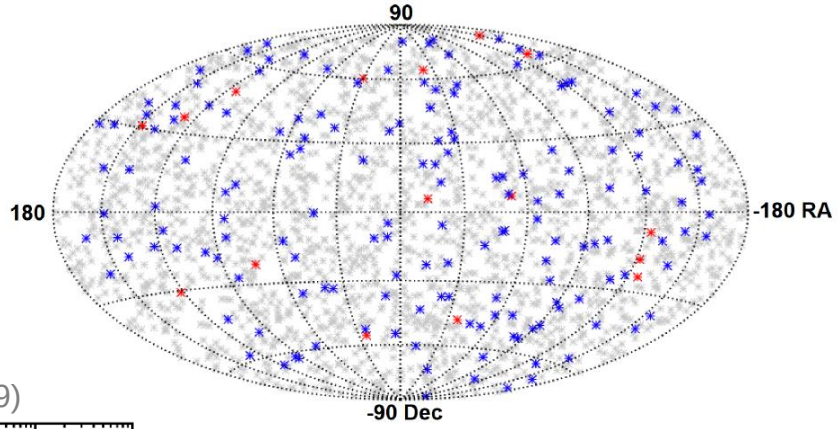

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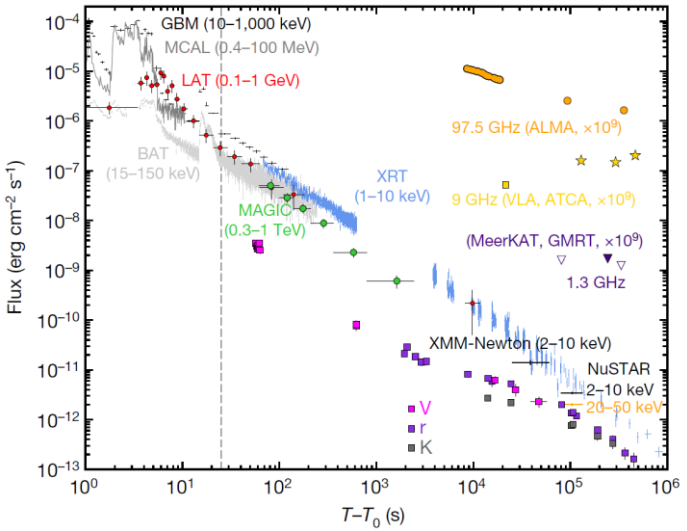

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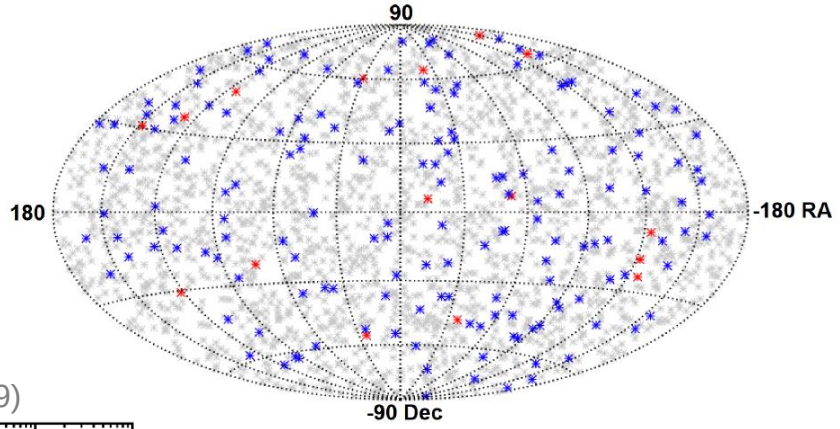

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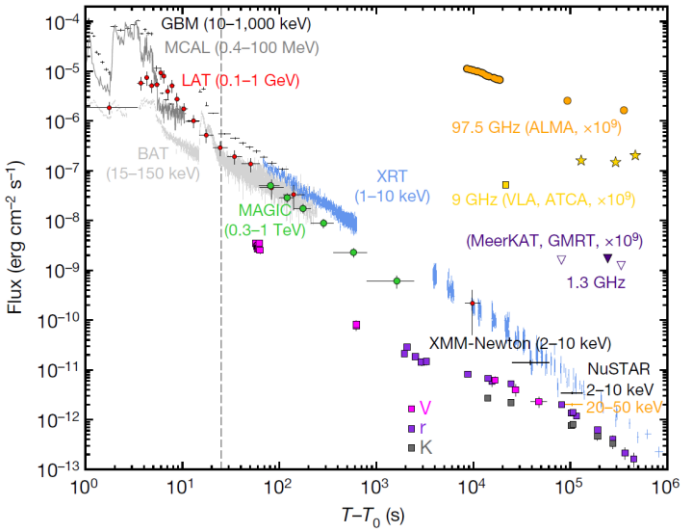
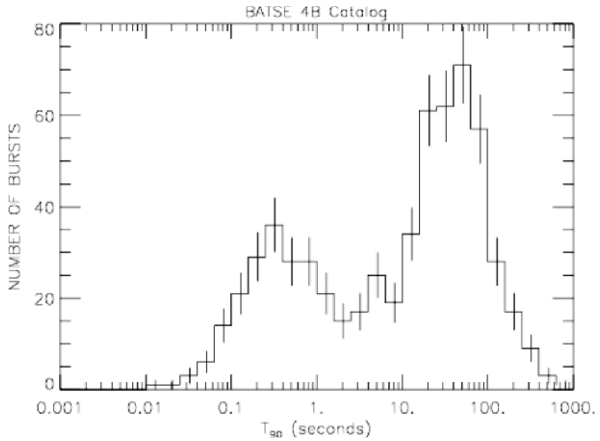


Kouveliotou et al. ApJ 413 (1993)



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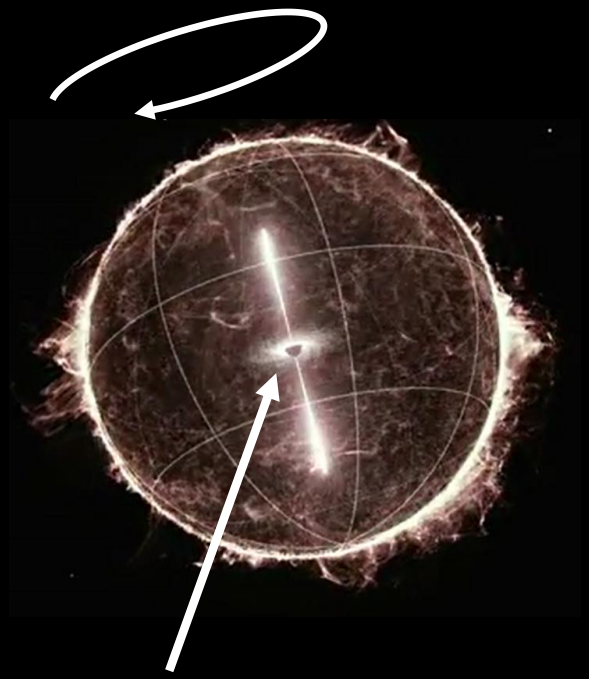
THEORETICAL picture

- accelerate a shell of plasma (jet) and dump it into a circum-burst medium
- different mechanisms convert the kinetic energy eventually into photons that we can observe at Earth (and other messengers?)

→ Fireball model

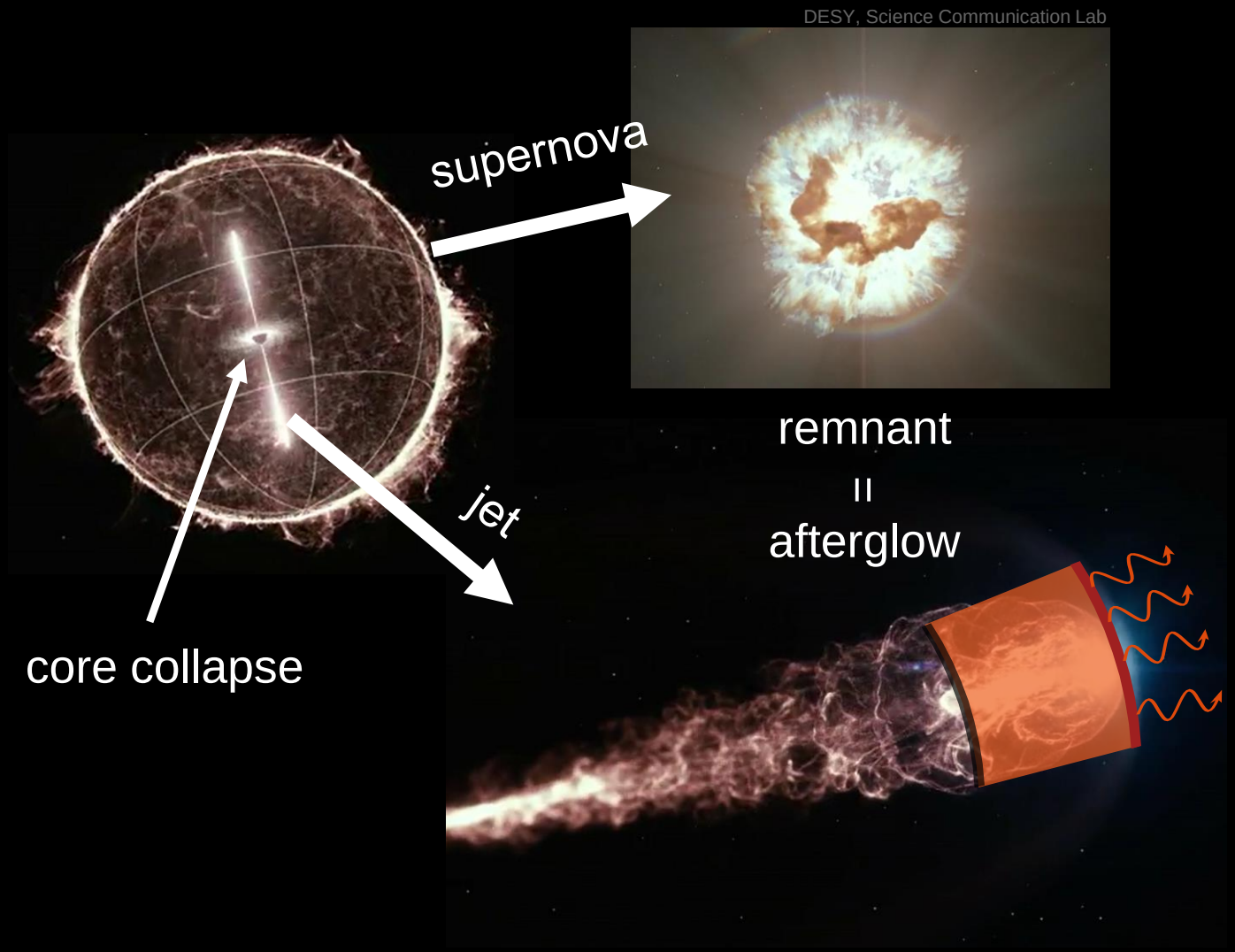
Fireball model: Long GRB

DESY, Science Communication Lab



core collapse

Fireball model: Long GRB



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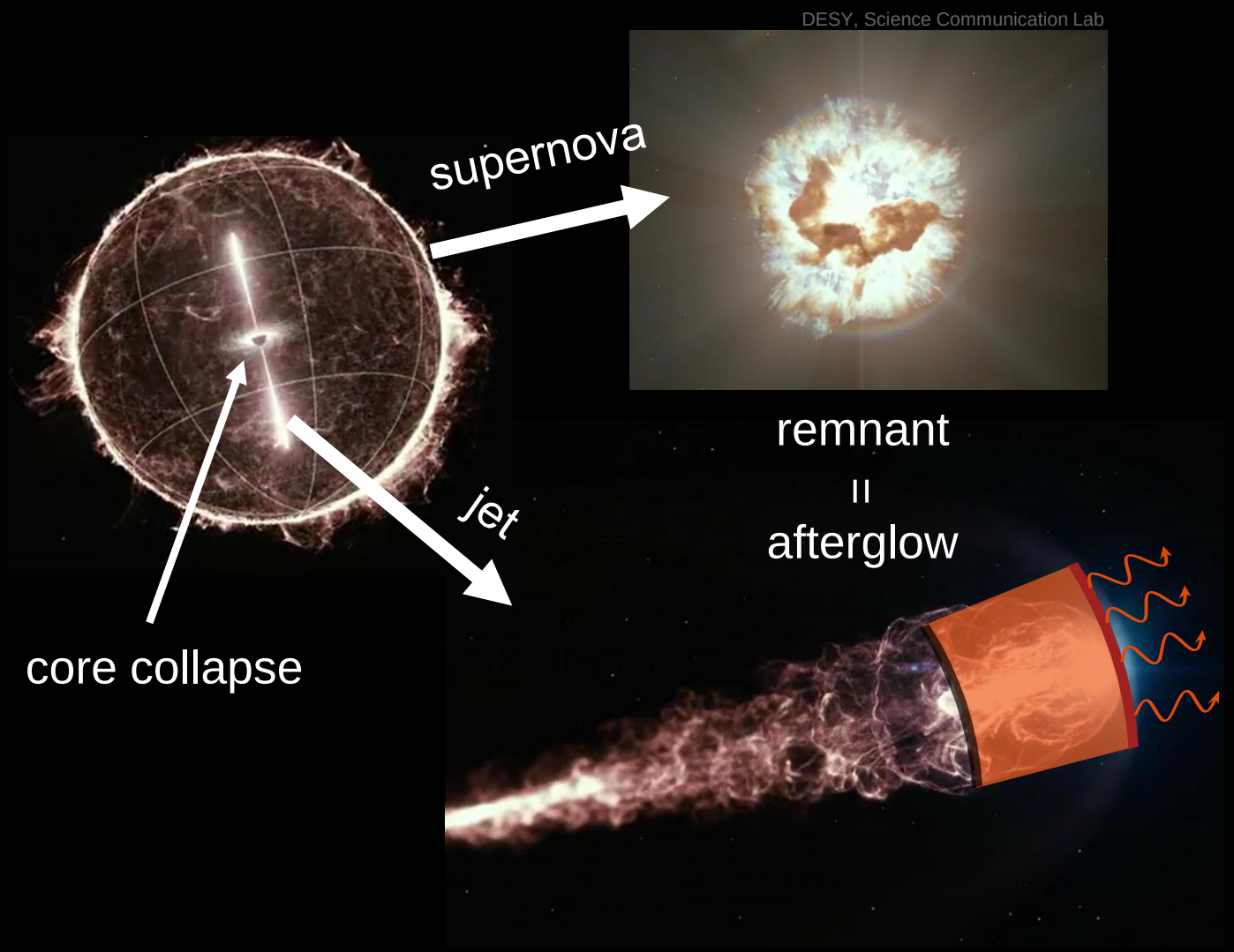
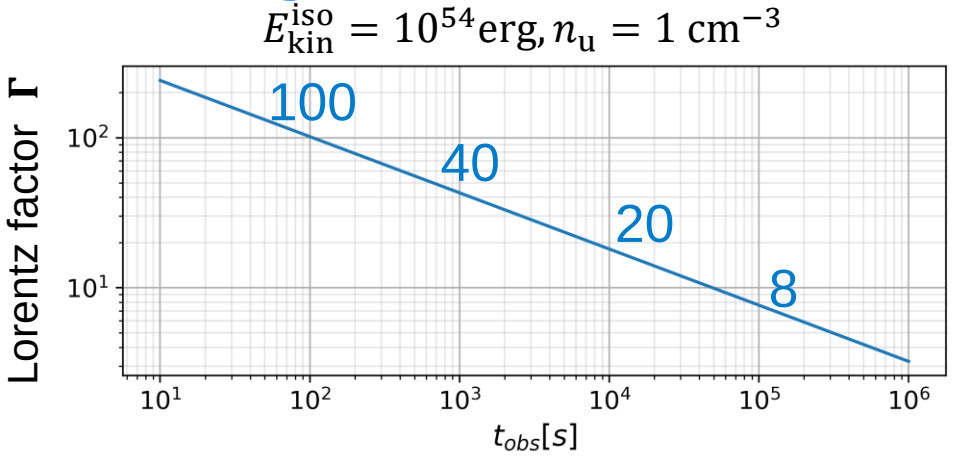
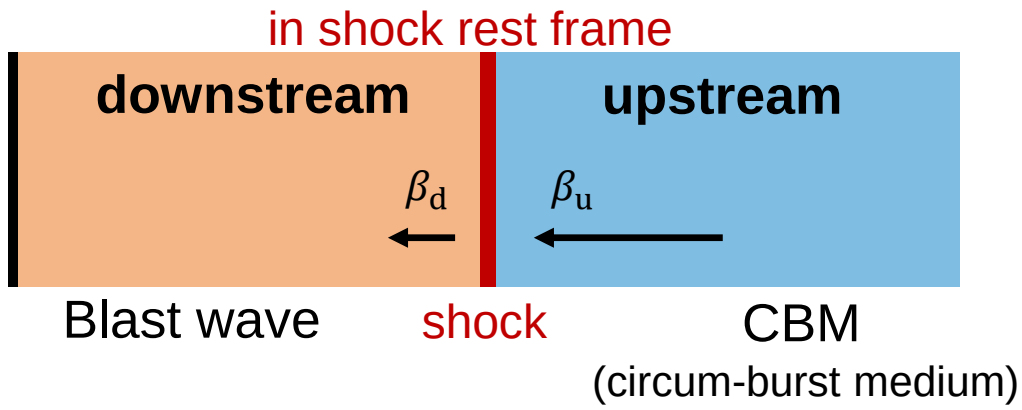


- Lorentz factors up to few 100
  → relativistic compression
- Quasi isotropic outflow
- Energetics:
  → observed up to: $E_{\mathrm{iso}} \sim 10^{55}\,\mathrm{erg}$
  → $E_{\mathrm{tot}} = \frac{\Omega}{4\pi} E_{\mathrm{iso}} \sim 10^{51}\,\mathrm{erg}$
  → comparable to SN !
- efficient converters of kinetic energy to radiation

Afterglows: Radiation from a relativistic shock



Blandford & McKee 1976



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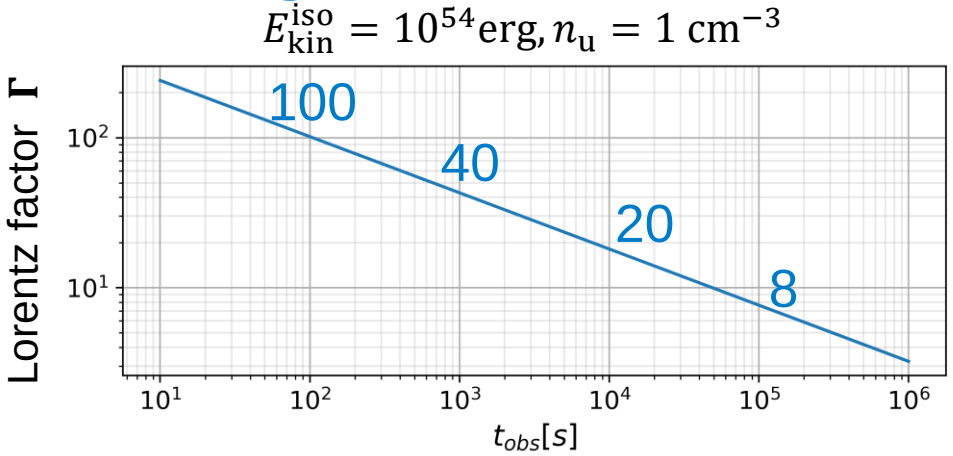

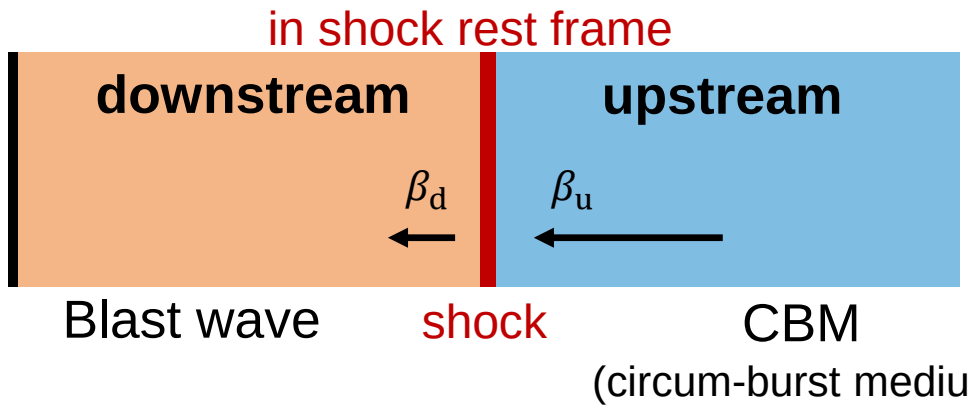

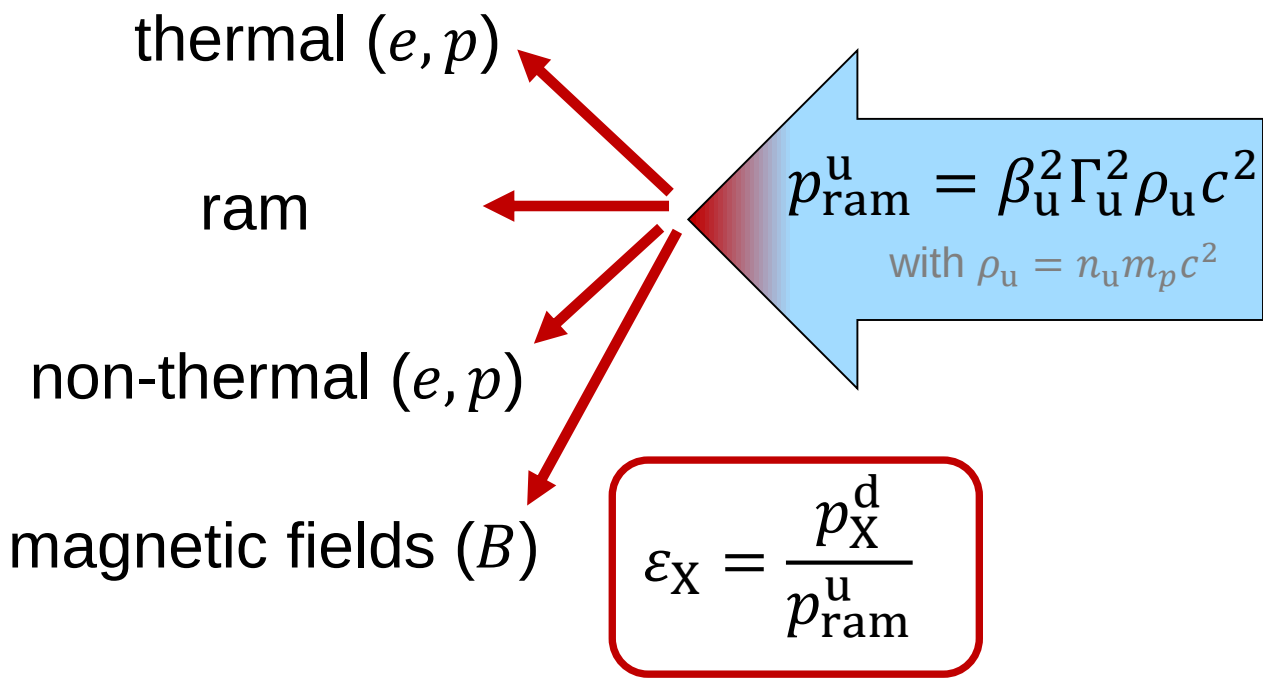

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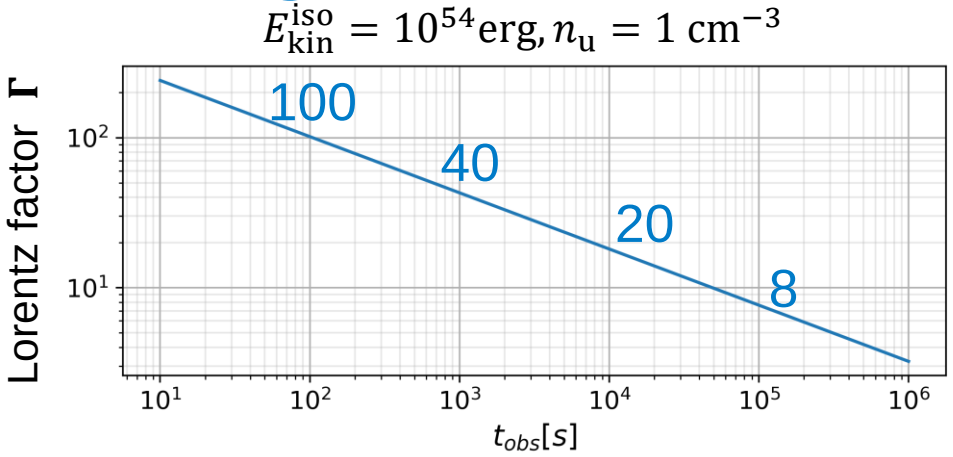

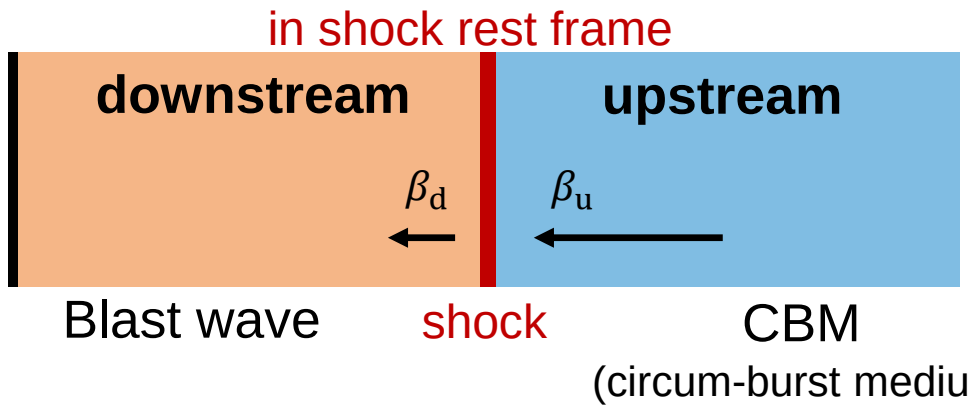

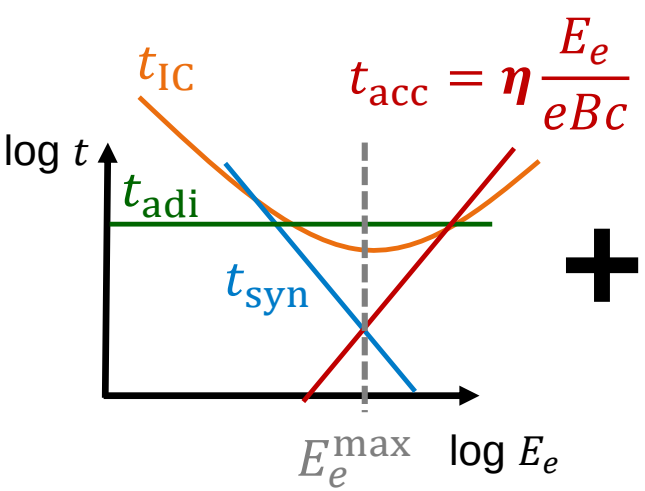

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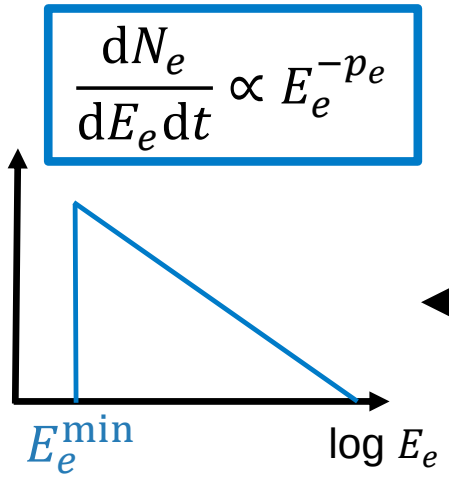
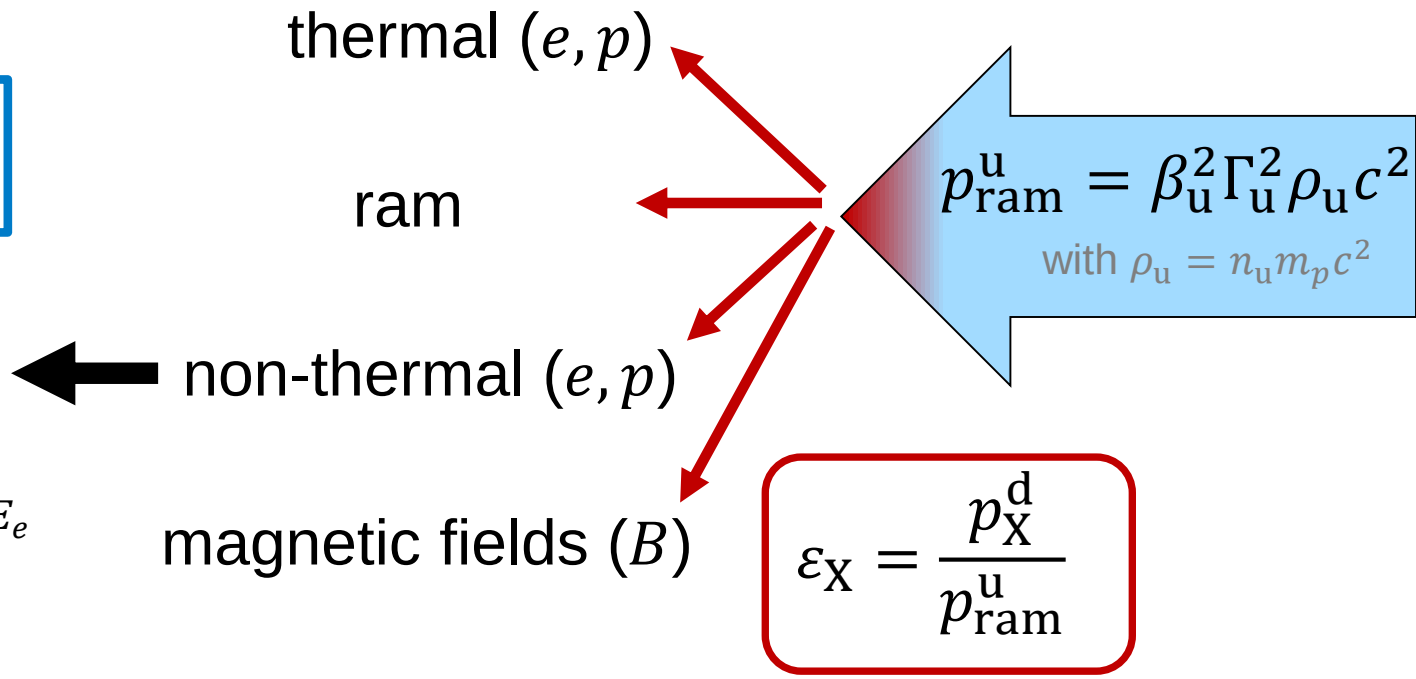
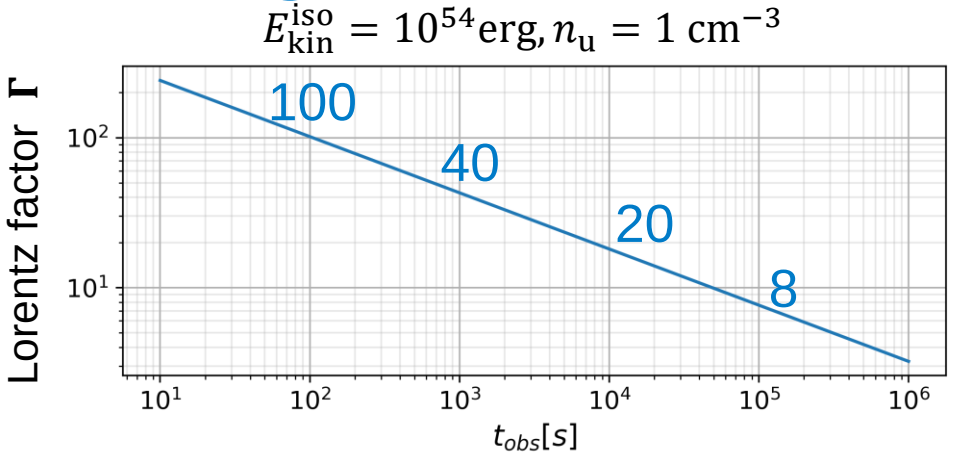
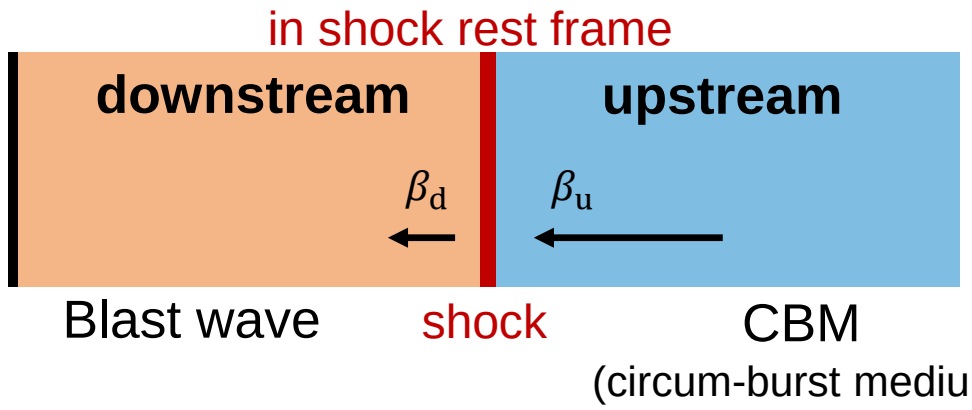




Afterglows: Radiation from a relativistic shock





→ quasi-steady state

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

← non-thermal (e, p)

thermal (e, p)

ram

magnetic fields (B)

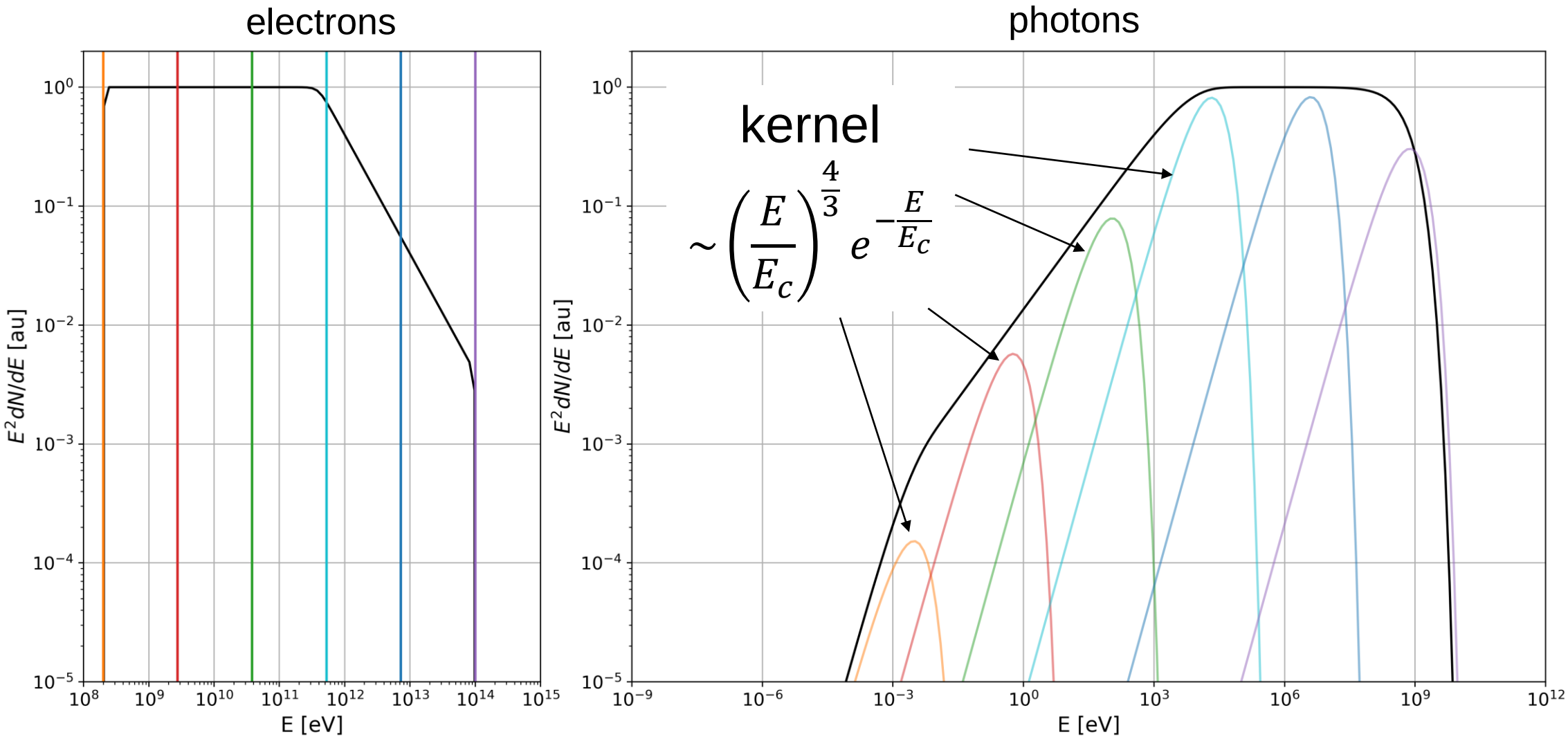
$$p_{\rm ram}^{\rm u} = \beta_{\rm u}^2 \Gamma_{\rm u}^2 \rho_{\rm u} c^2$$

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

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

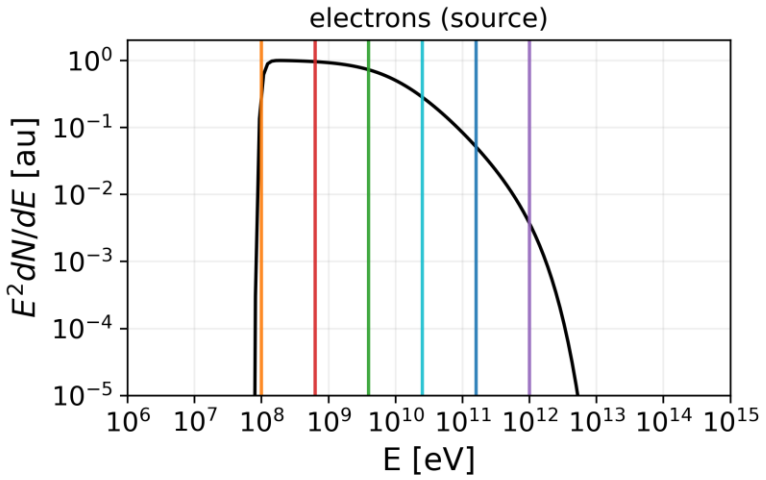
→ good for intuition

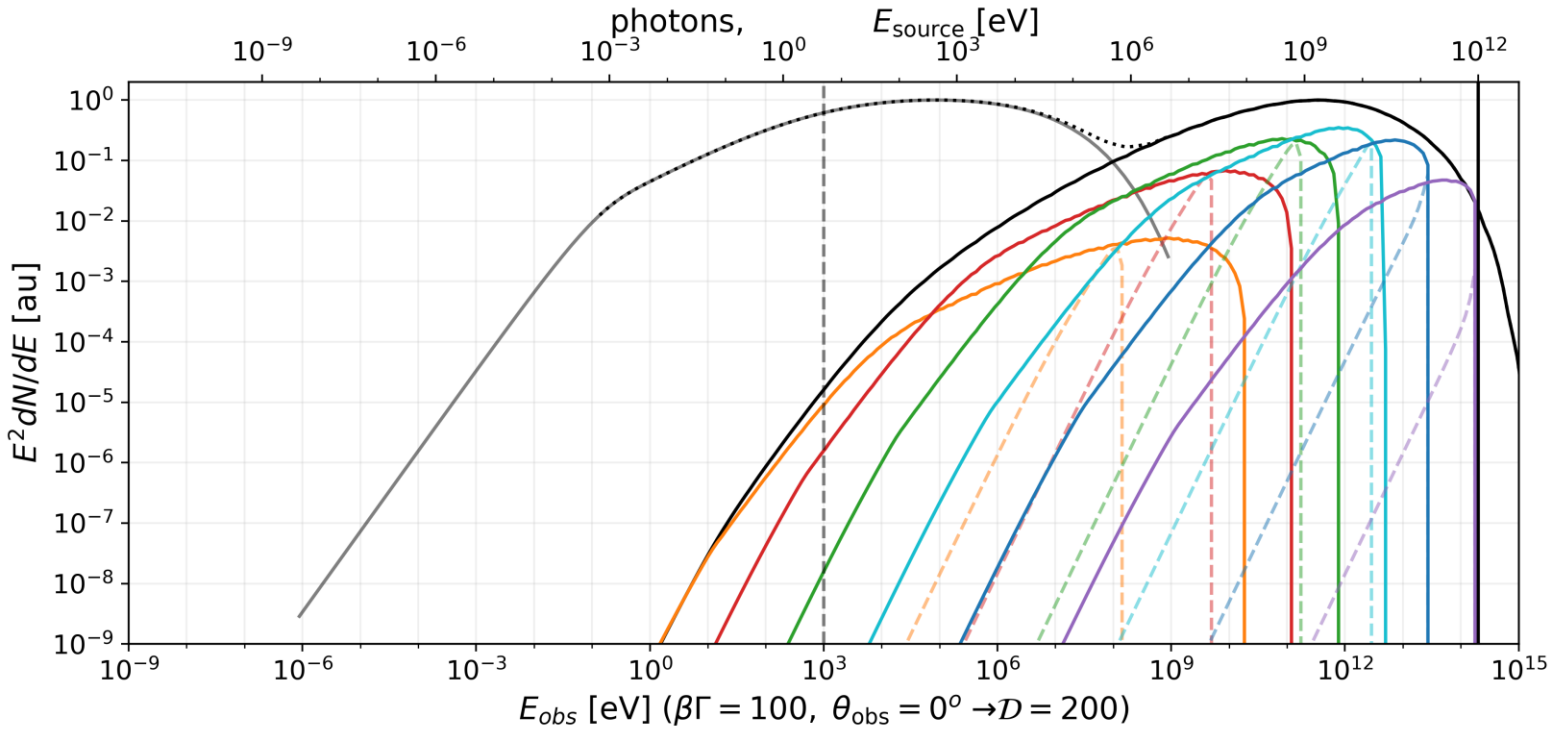
Photon spectrum: Synchrotron from a convolution



Photon spectrum: Synchrotron Self-Compton (SSC)

→ Convolve electron spectrum with radiation kernel





Time-dependent one zone modelling

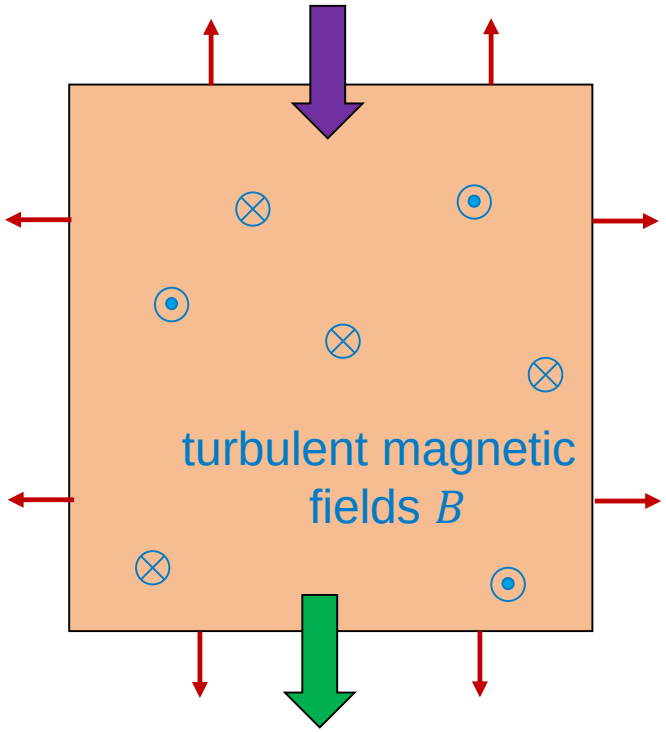
electrons drive expansion of box

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

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

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

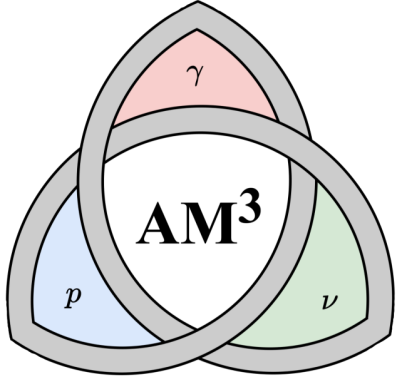
photon number

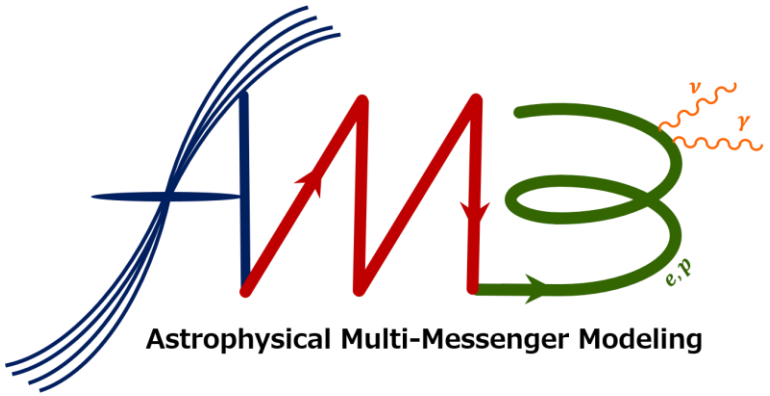
$$\partial_t N_{E,\gamma} = -\frac{N_{E,\gamma}}{\tau_{esc}(t)} + Q_{syn}(E,t) + Q_{iC}(E,t) + Q_{pp}(E,t) - \frac{N_{E,\gamma}}{\tau_{pa}(E,t)}$$

photons can escape from box

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)

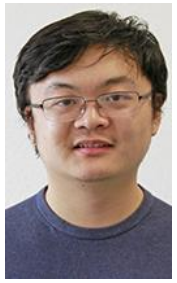
- including documentation!


Gao


Klinger


Rudolph


Rodrigues


Yuan


Fichet De Clairfontaine

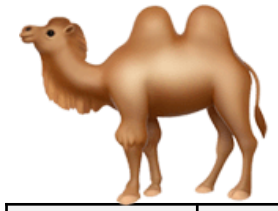

Fedynitch

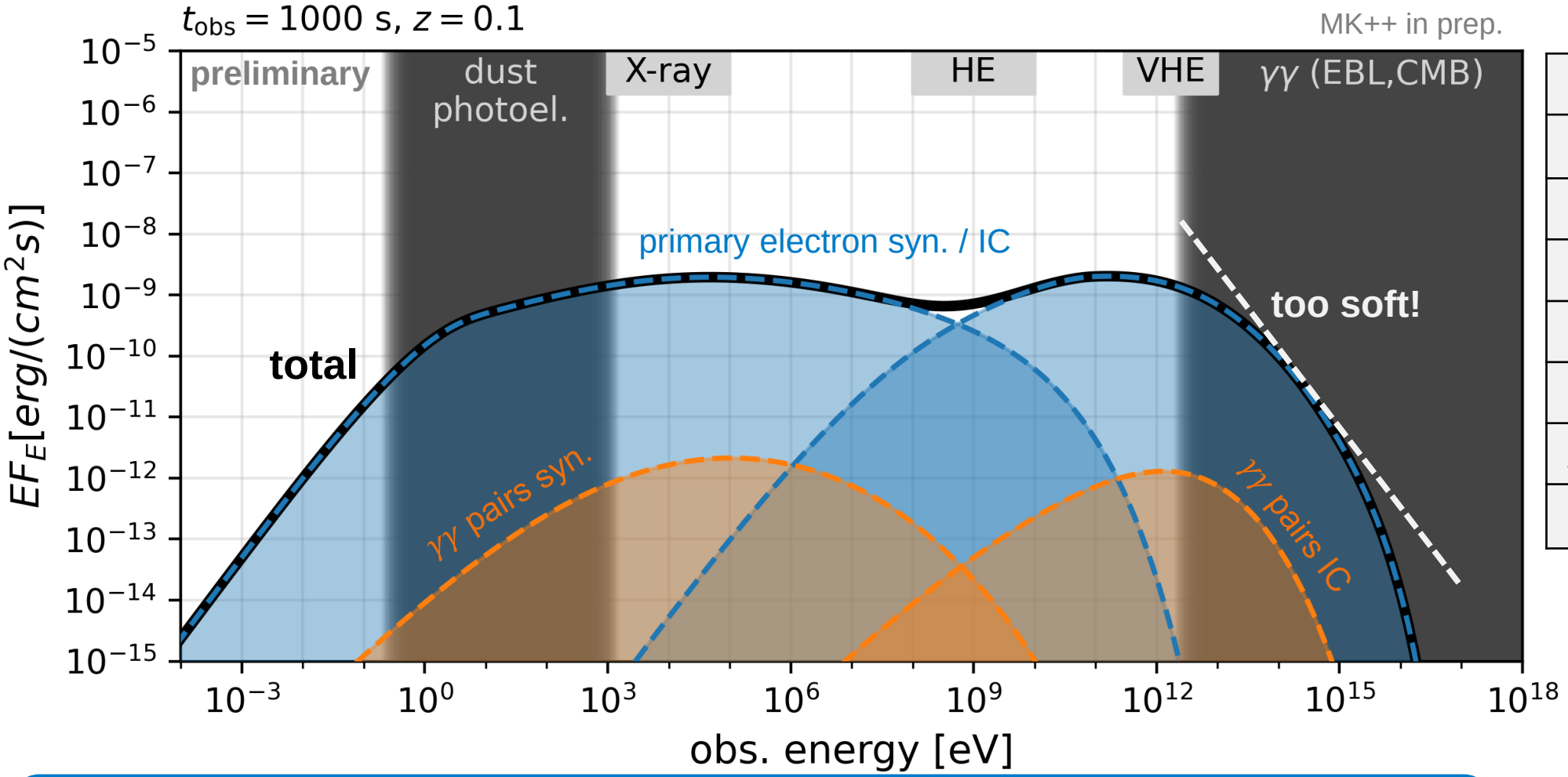

Winter


Pohl

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

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:

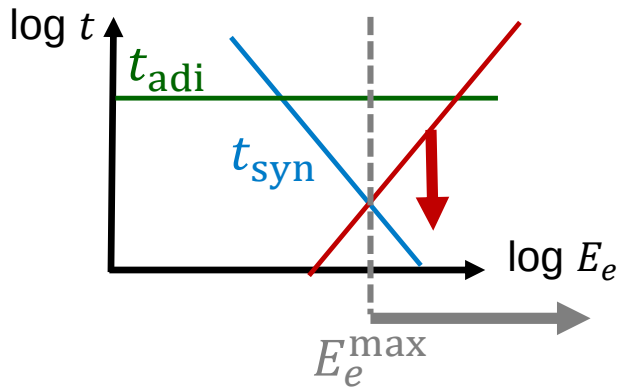
- faster than Bohm acceleration: $\eta \ll 1$

  → 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)

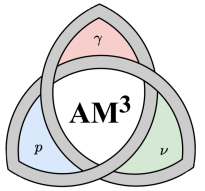
  → **extended electron synchrotron component**

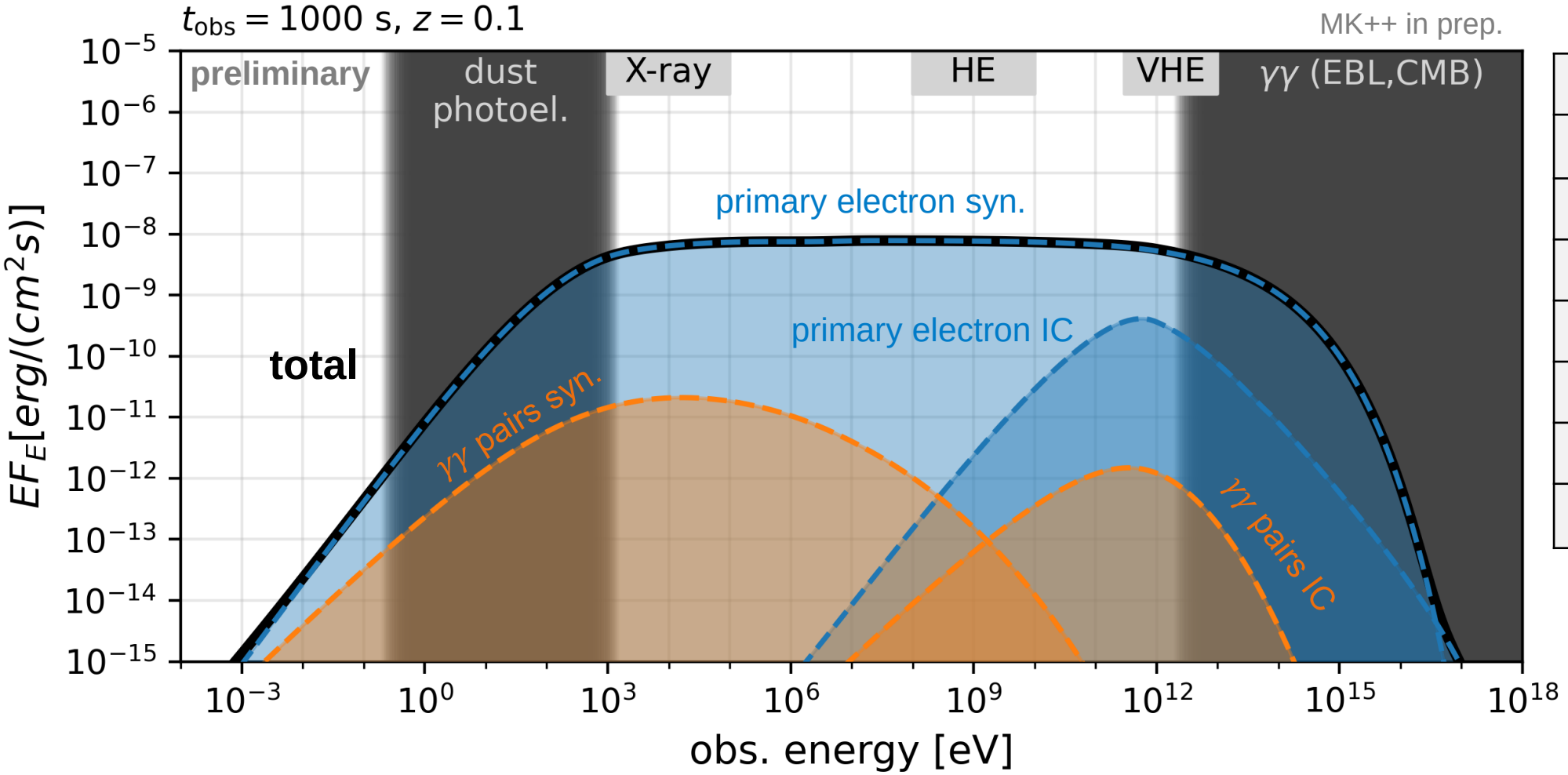
$$t_{\mathrm{acc}} = \eta \frac{E_e}{eBc}$$



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

Extended synchrotron spectrum

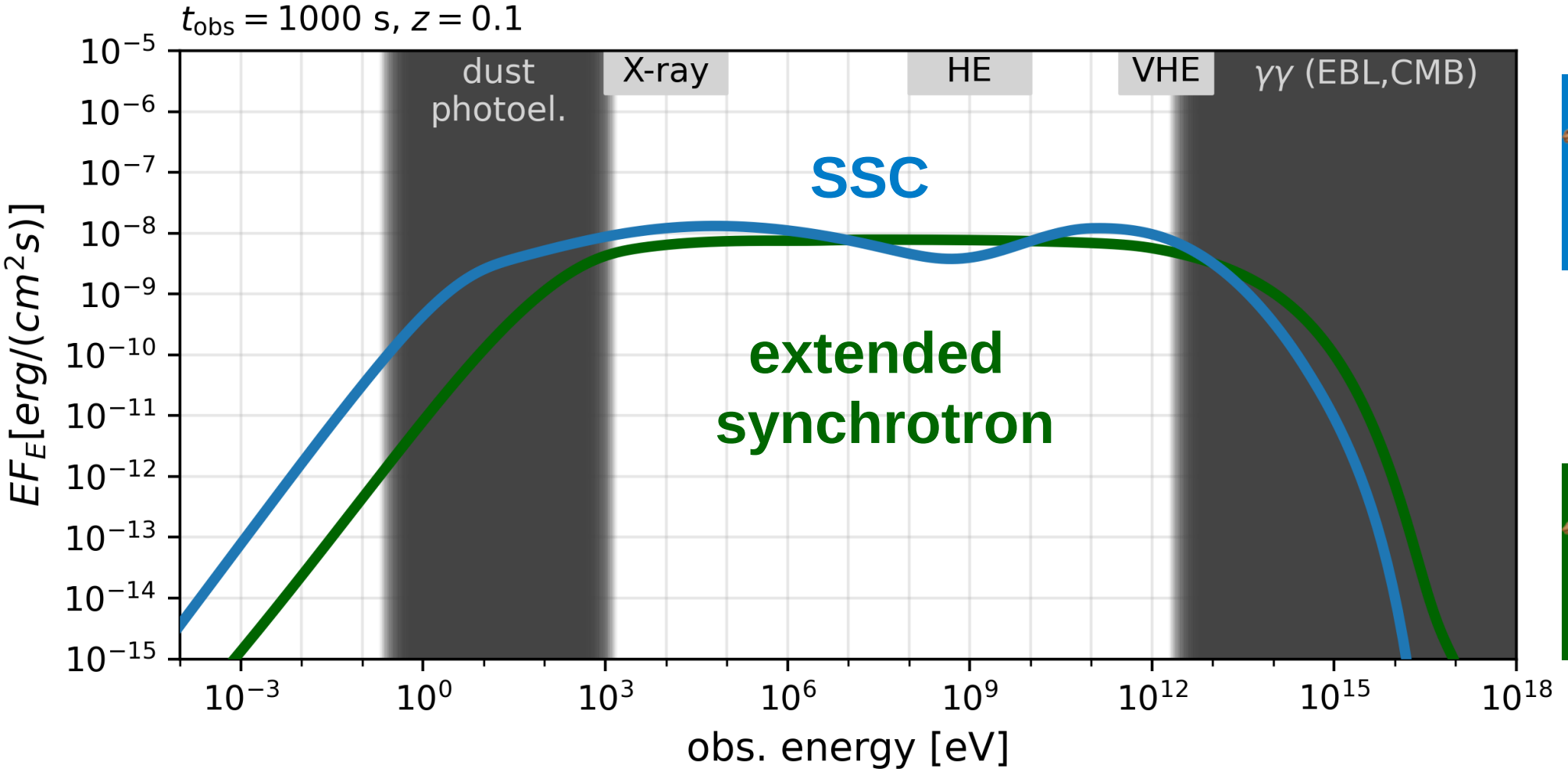




ε_e	$10^{-1.5}$
ε_p	0
ε_B	10^{-3}
$E_{\rm min}$	30GeV
p_e	2
η	10^{-4}
$E_{\rm iso}$	10^{54}erg
$n_{\rm up}$	$1{\rm cm}^{-3}$

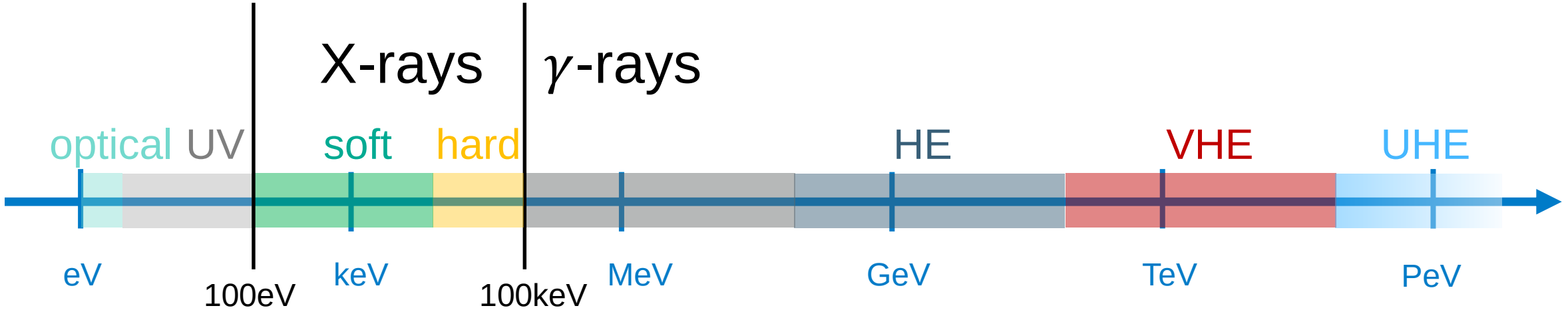
Problem: how to explain $\eta \ll 1$?

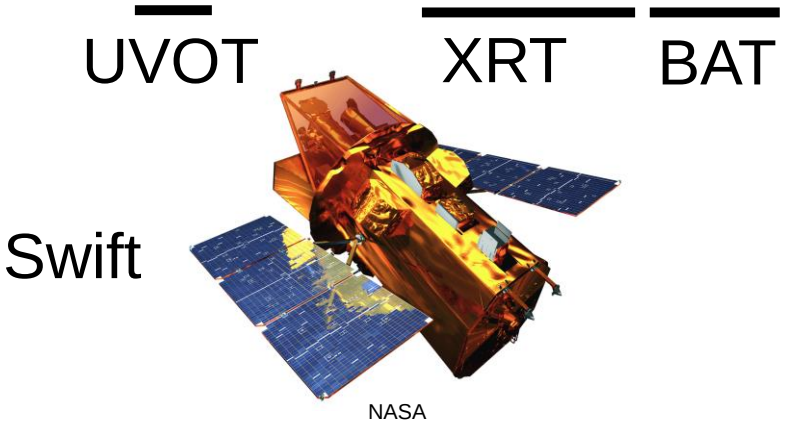
Extended synchrotron vs SSC



What about data?

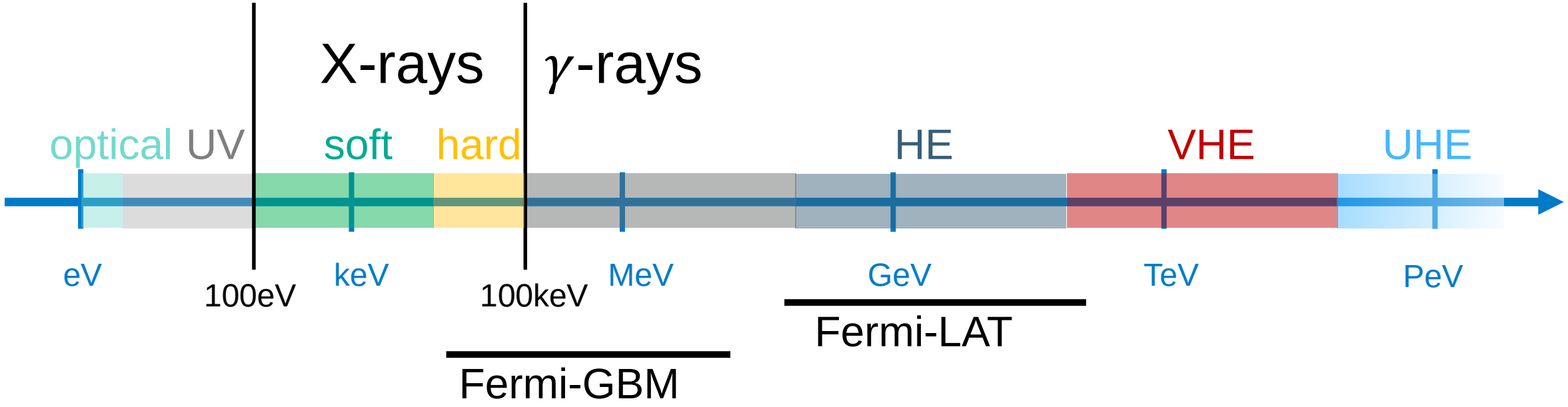
Instrument recap





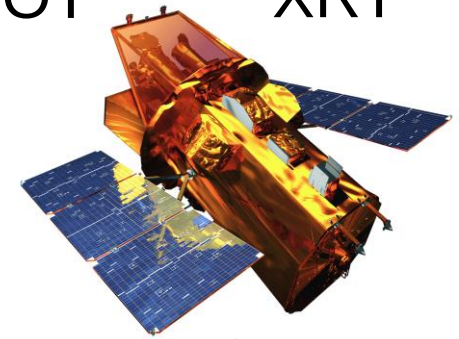
NASA

Instrument recap



UVOT XRT BAT

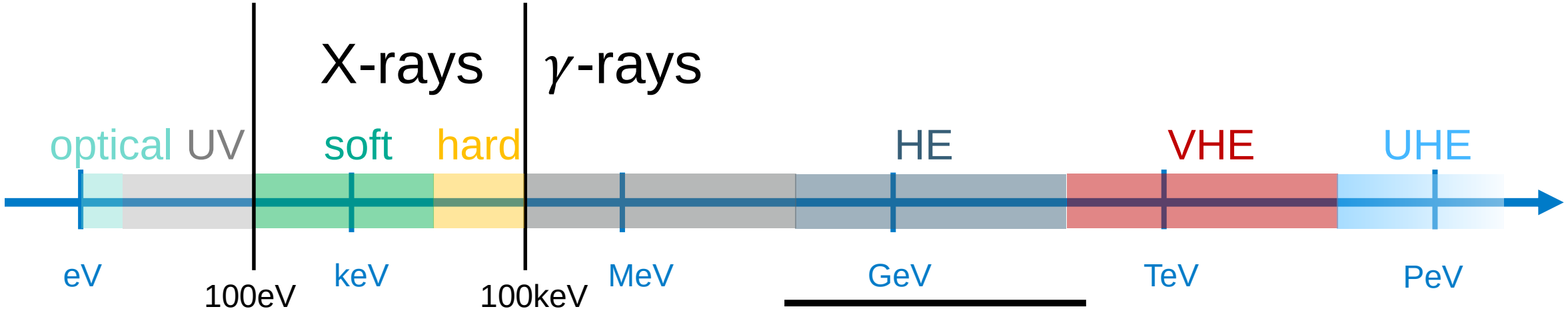
Swift

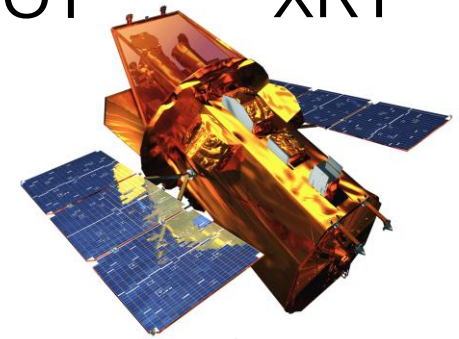


NASA

NASA

Instrument recap

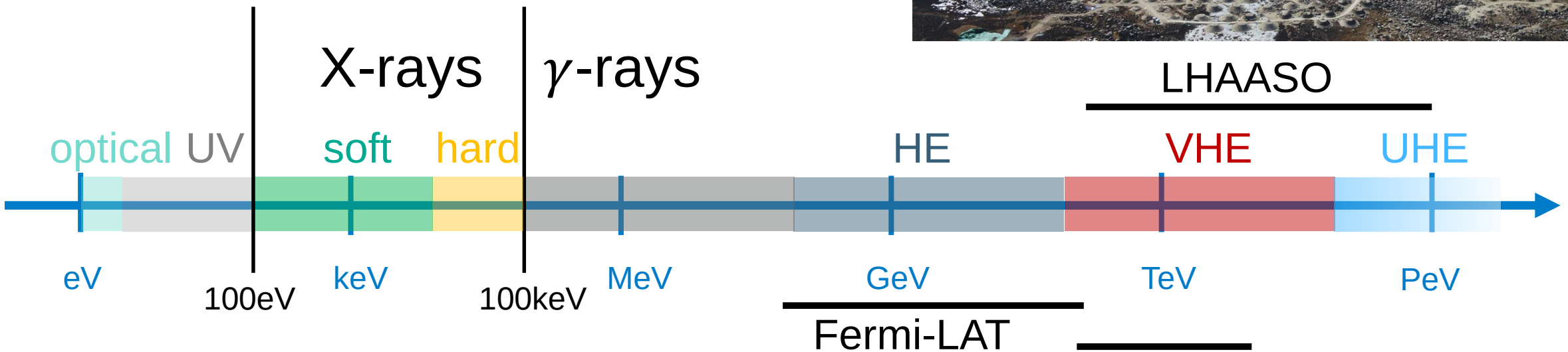




NASA

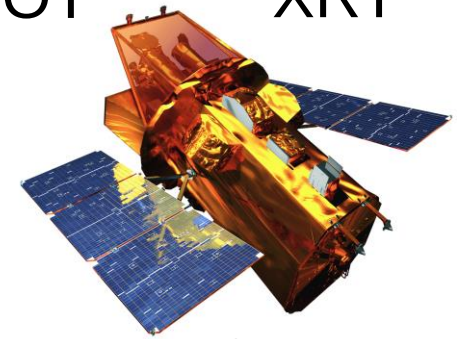
NASA

Instrument recap



UVOT XRT BAT

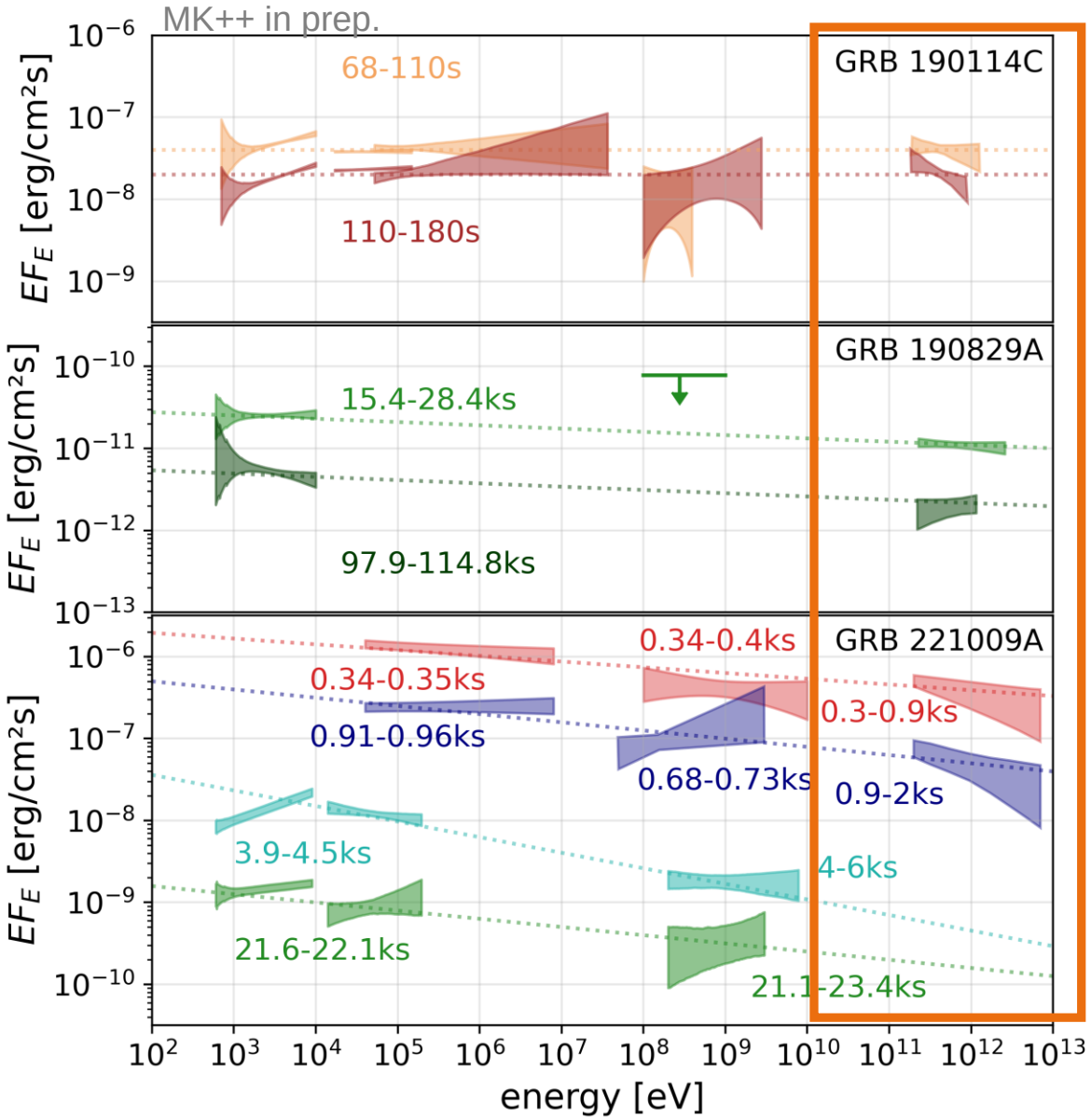
Swift



NASA

NASA

Comparison to data

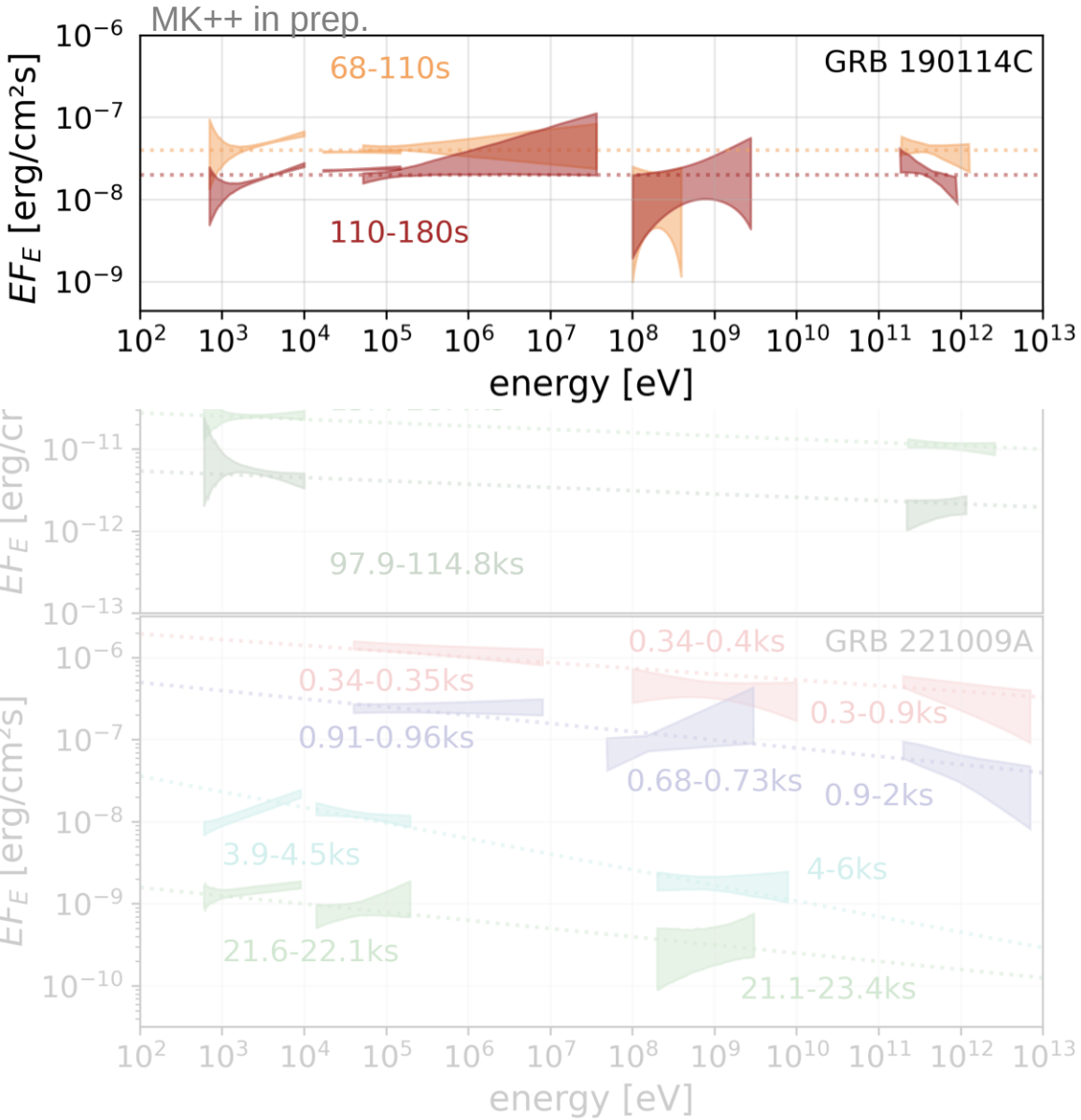


→ **MAGIC:**

→ **H.E.S.S.:**

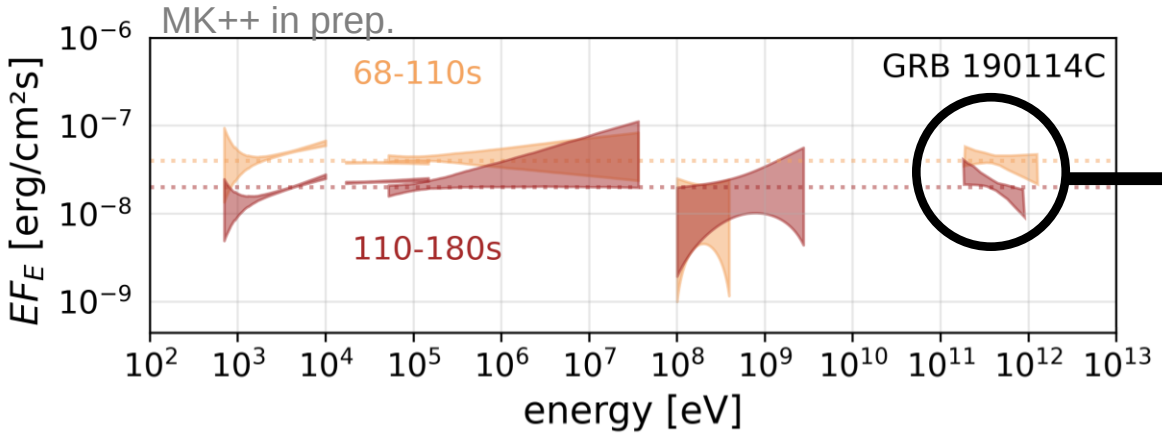
→ **LHAASO:**

Comparison to data



→ **MAGIC:**

Comparison to data

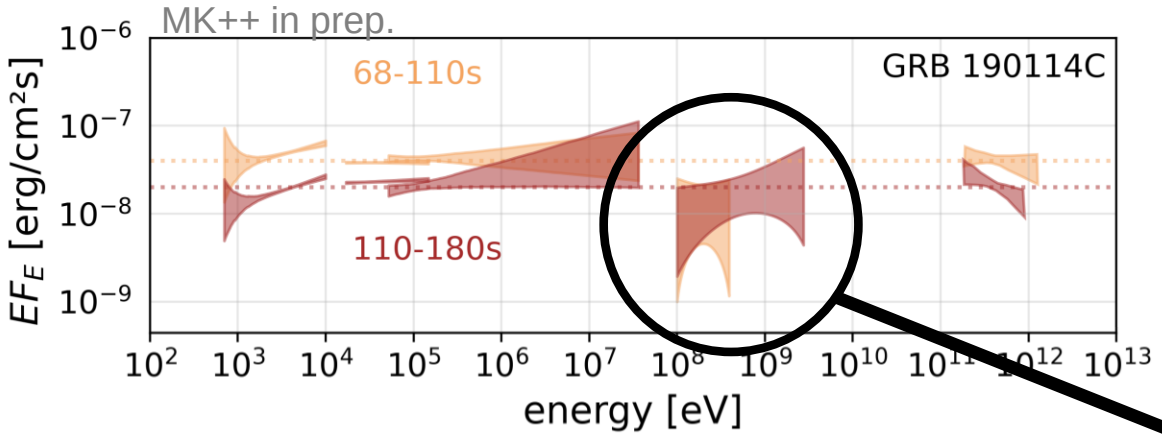


- **MAGIC observation:**

$z = 0.43$ (EBL) + moonlight

→ uncertain spectral index at TeV $-2.2 \pm 0.3 \pm 0.2$

Comparison to data



- MAGIC observation:

$z = 0.43$ (EBL) + moonlight

→ uncertain spectral index at TeV $-2.2 \pm 0.3 \pm 0.2$

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

GRB 190114C: SSC vs extended syn

3ML Multi-Mission Maximum Likelihood Framework

$$\text{Counts rate}\,(E) = \int \mathrm{d}\hat{E}\ \frac{\mathrm{d}N_{\text{source}}}{\mathrm{d}E\ \mathrm{d}t\ \mathrm{d}A}\left(\hat{E}\right)\ \exp\left(-\tau\left(\hat{E}\right)\right)\ A_{\text{eff}}\left(E,\hat{E}\right)\ c_{\text{sys}}$$

and

Background rate → **different detectors have different statistics!**

- MAGIC observation:

  $z = 0.43$ (EBL) + moonlight

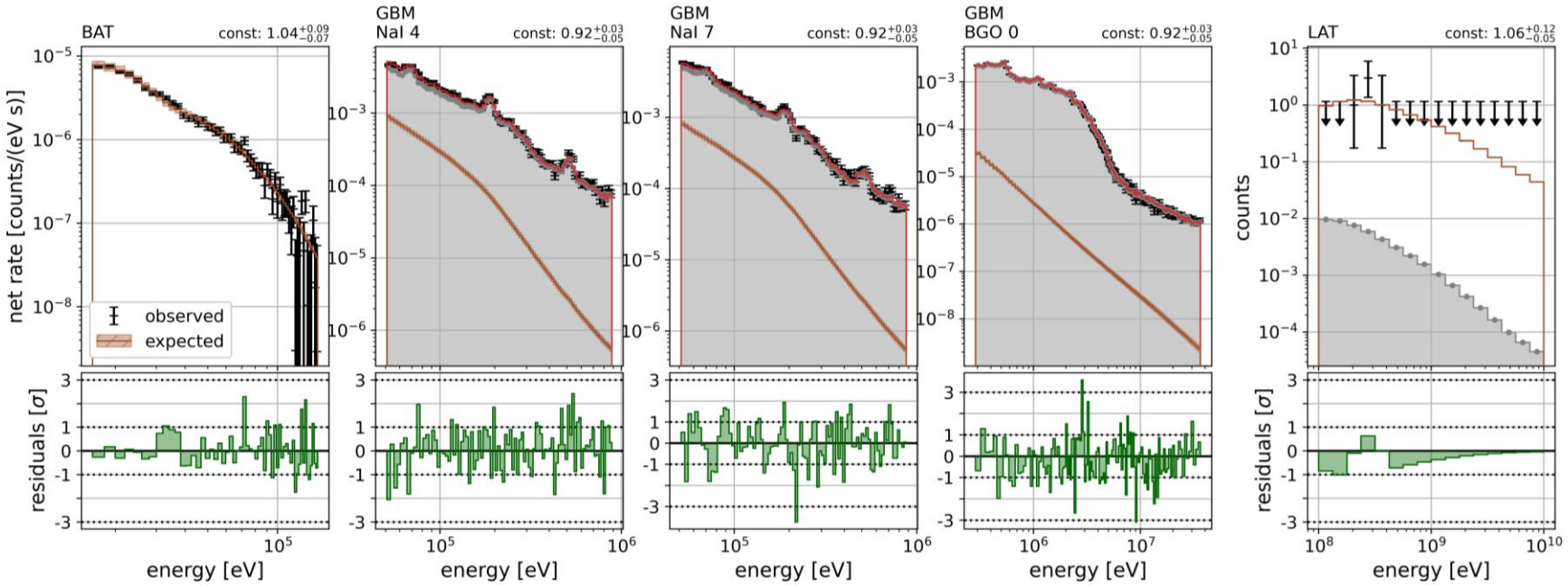
  → uncertain spectral index at TeV $-2.2 \pm 0.3 \pm 0.2$ (stat) (sys)

  MAGIC Nature 575 (2019)

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

- **counts level fit to reduced SSC model**

GRB 190114C: SSC vs extended syn



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MAGIC Nature 575 (2019)

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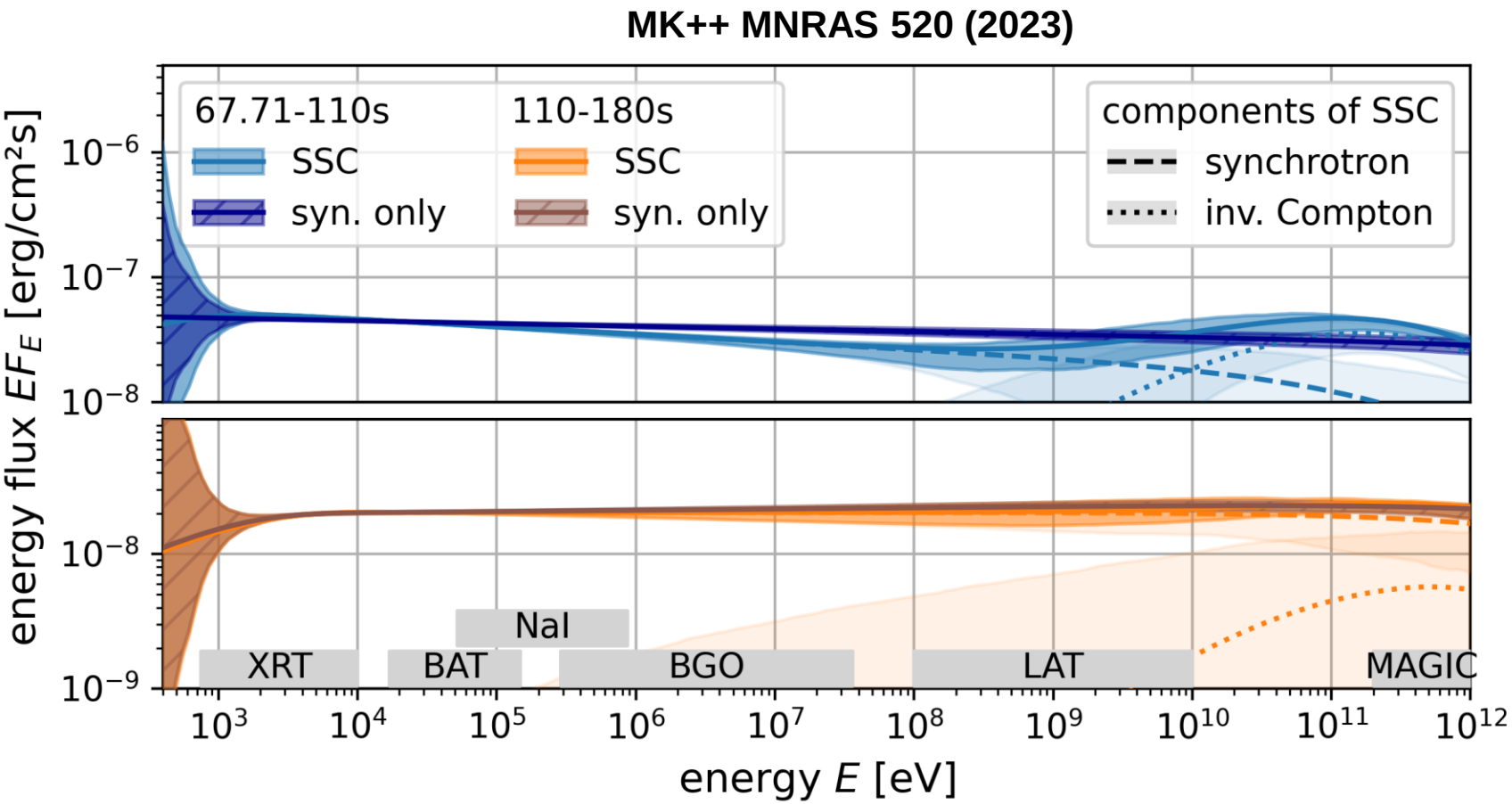
GRB 190114C: SSC vs extended syn



- MAGIC observation:

  $z = 0.43$ (EBL) + moonlight

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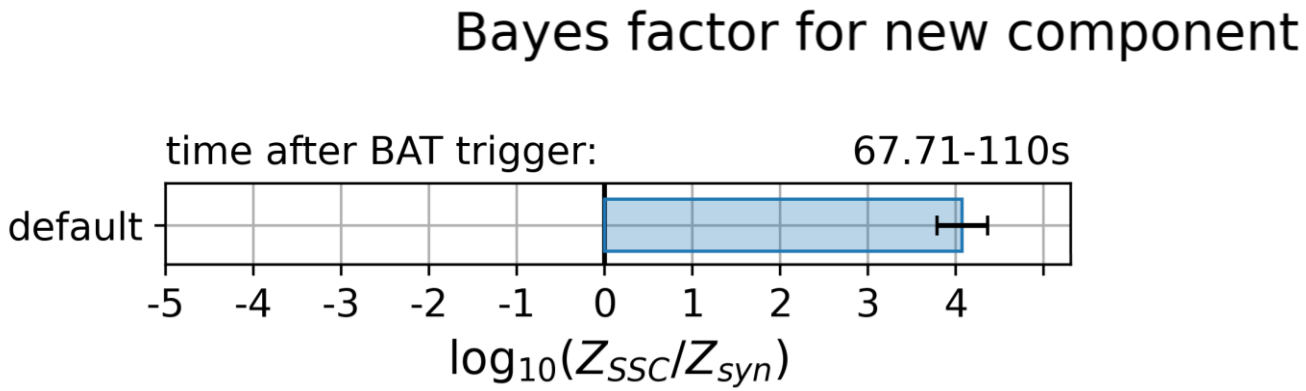
at TeV $-2.2 \pm 0.3 \pm 0.2$
(stat) (sys)
MAGIC Nature 575 (2019)

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

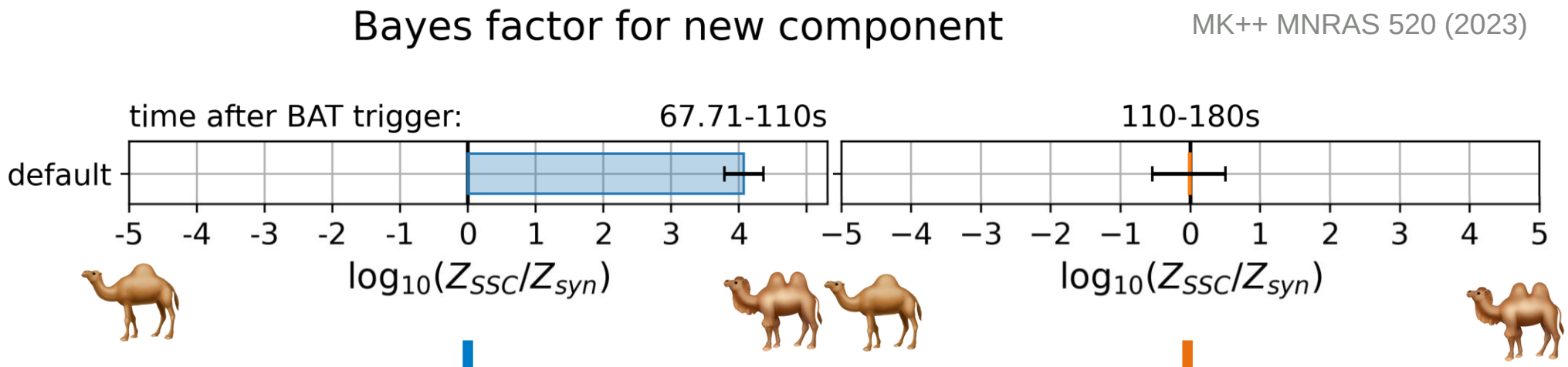
- **counts level fit to reduced SSC model**

→ statistical test of preference?

Preference for new component?



Preference for new component?

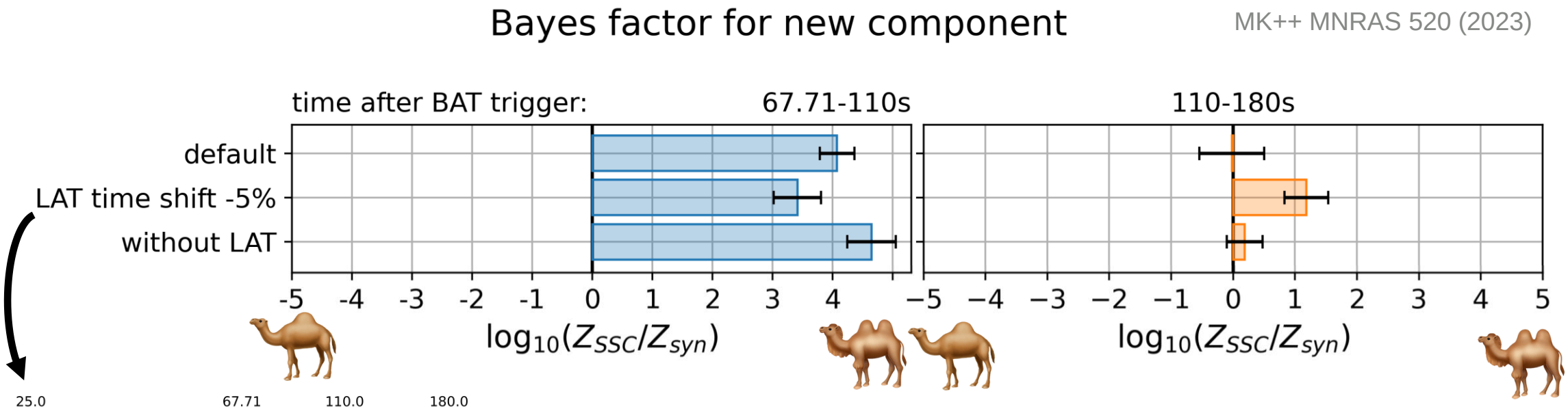


MK++ MNRAS 520 (2023)

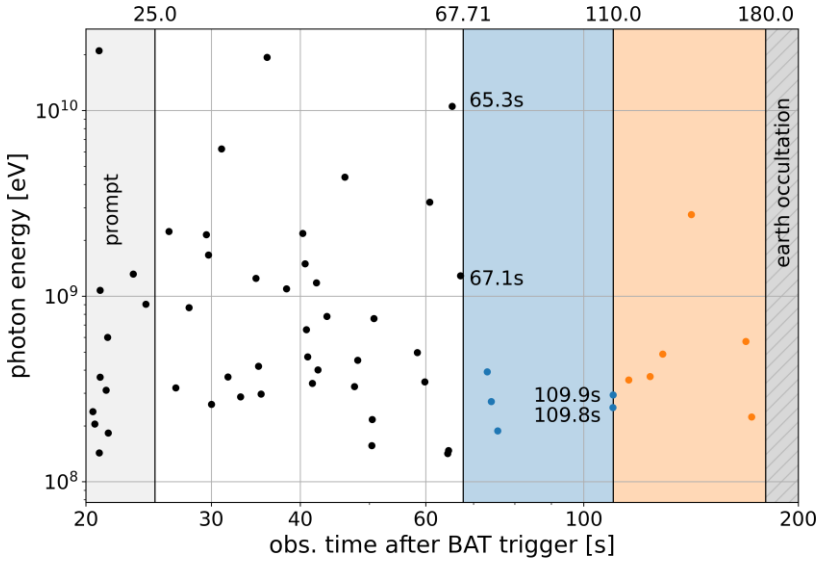
yes

no

Stability of Preference: LAT



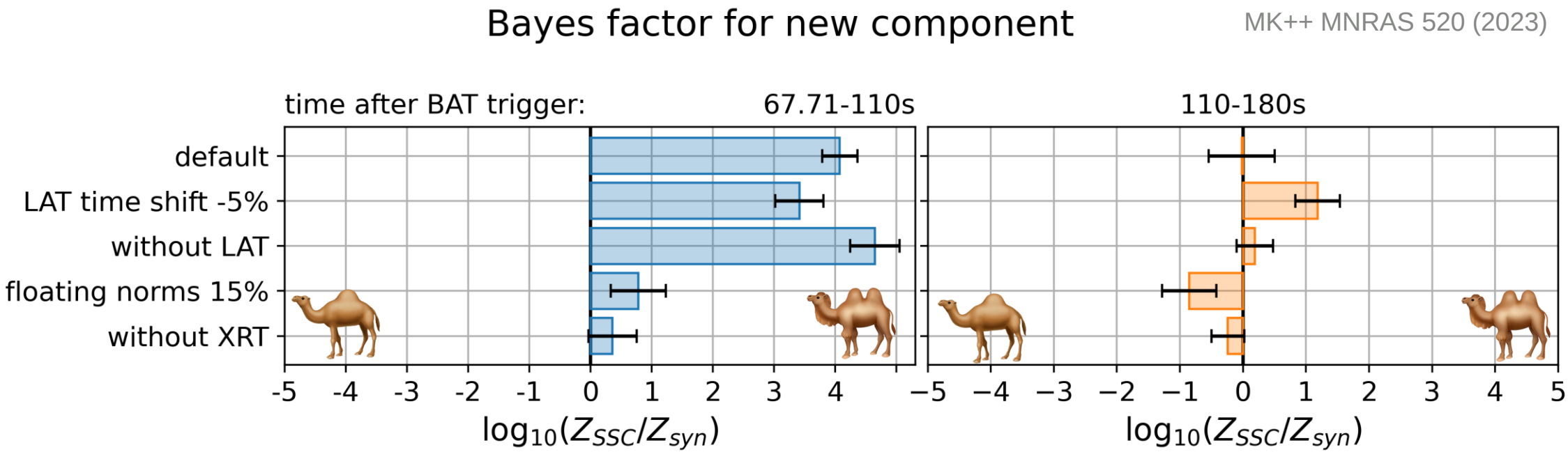
MK++ MNRAS 520 (2023)



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

→LAT not very strong

Stability of Preference: XRT

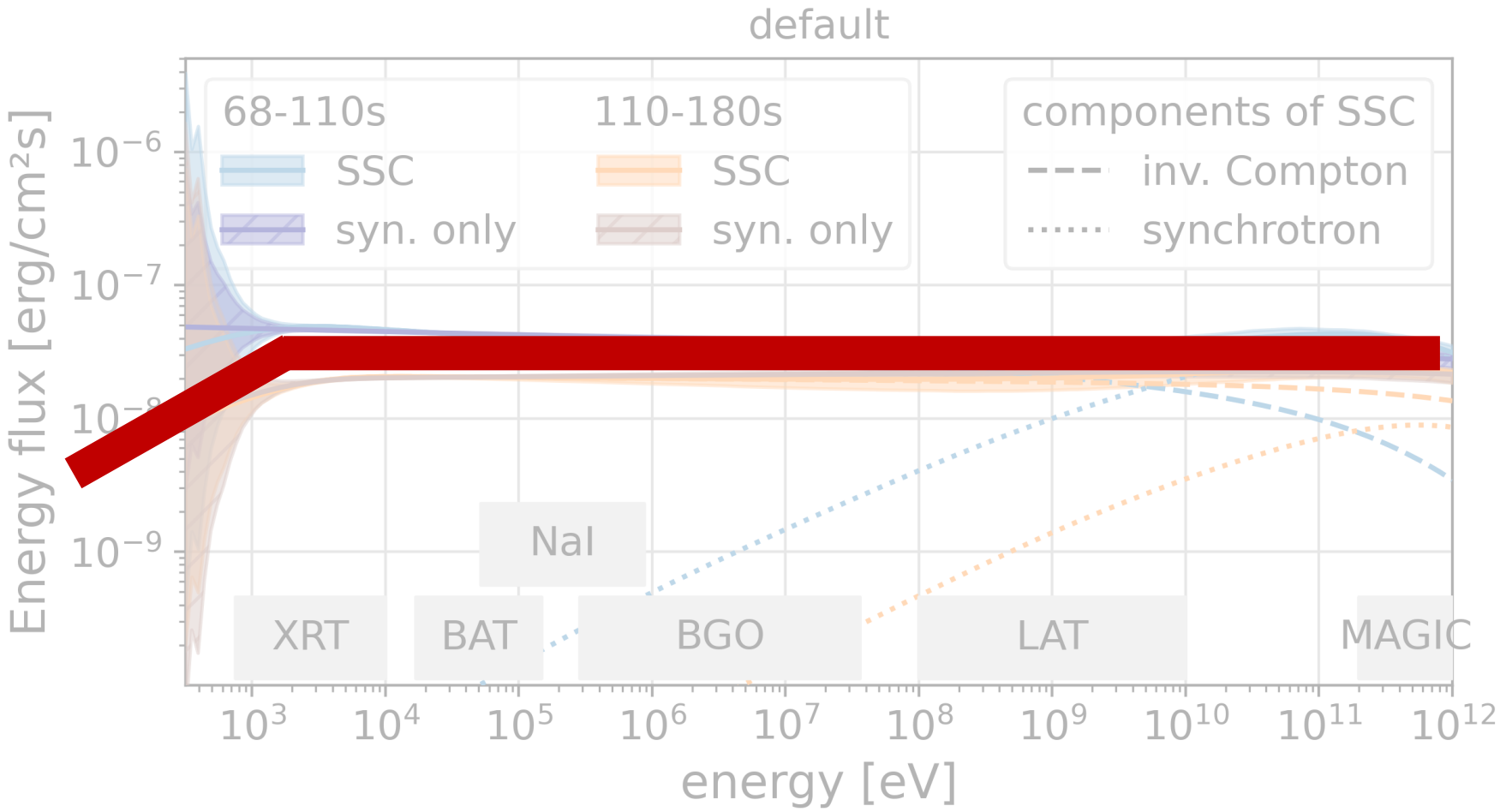


MK++ MNRAS 520 (2023)

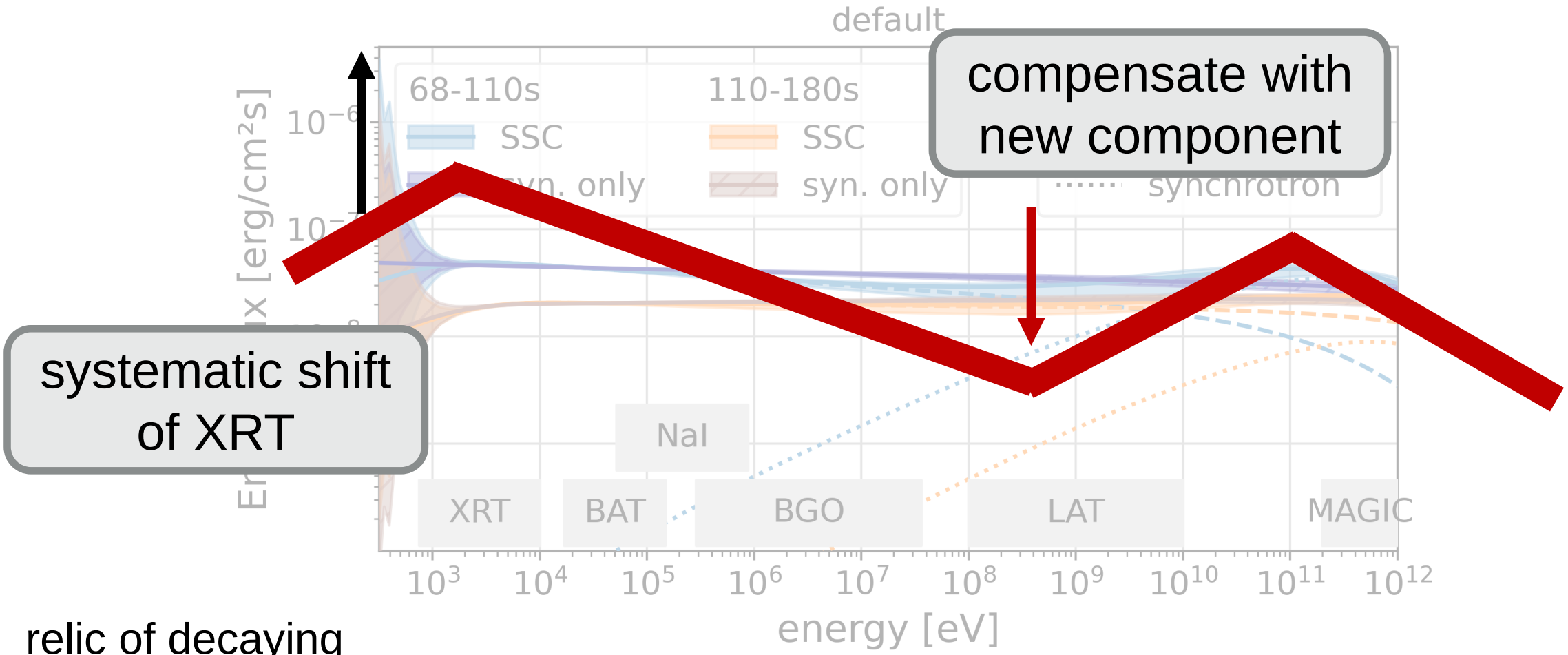
- systematic cross calibration uncertainty limited to 15% (a.k.a. floating norm or effective area correction)
- leave out XRT completely

→ **XRT drives new component!**

Fitting a reduced SSC model

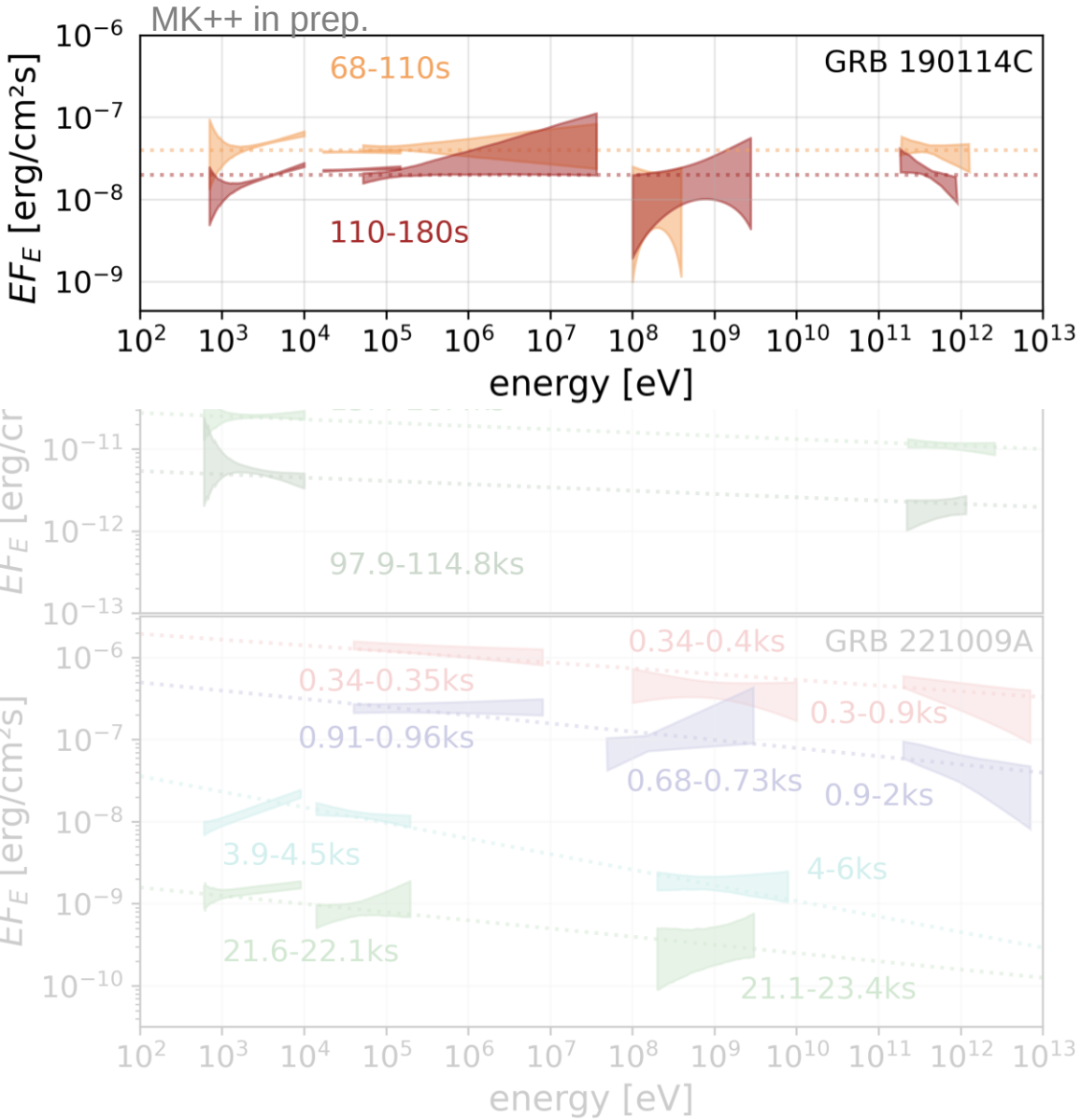


Fitting a reduced SSC model



relic of decaying prompt component?

Comparison to data

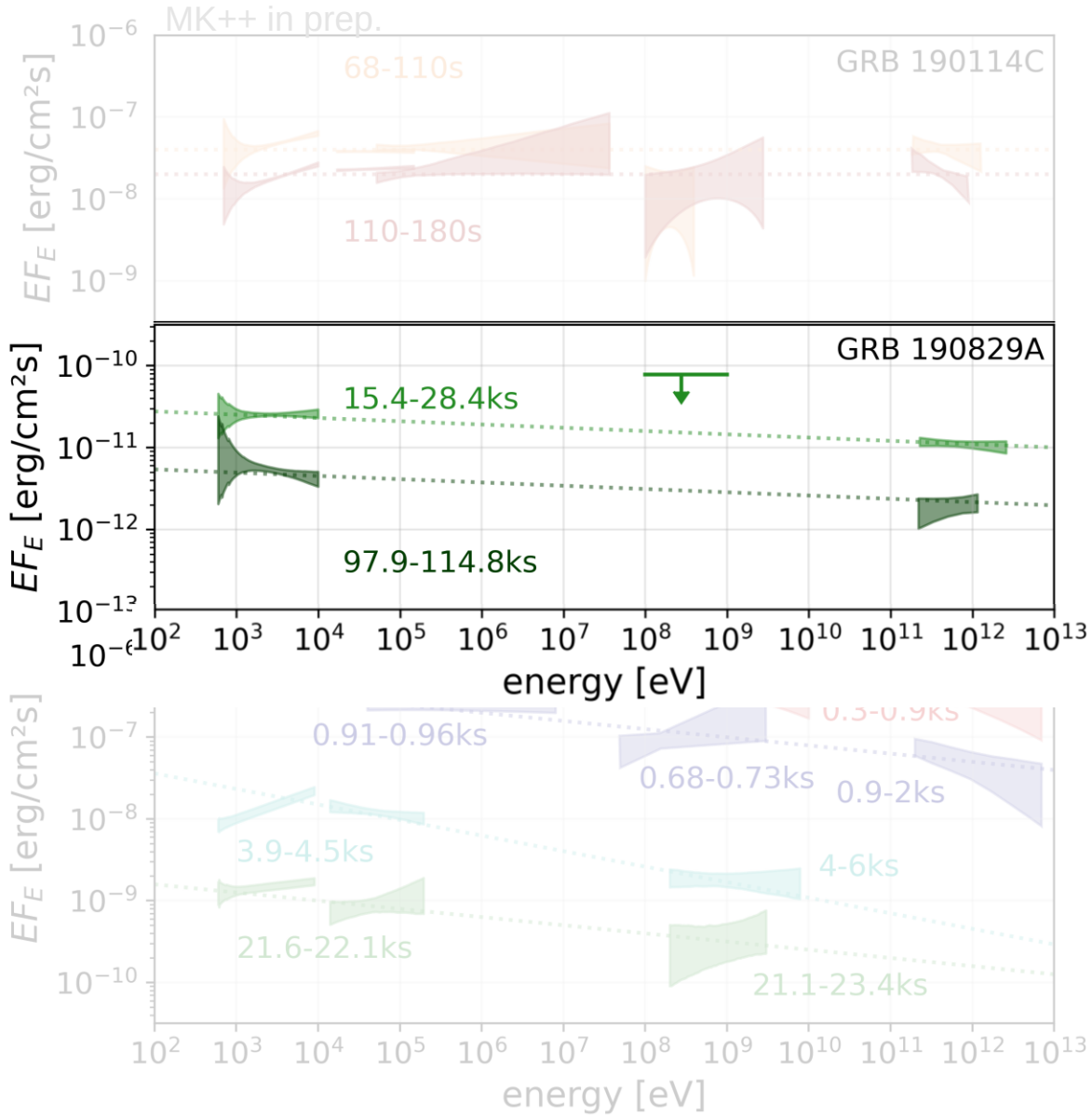


→ **MAGIC:**

?

→ inconclusive on syn vs. SSC

Comparison to data

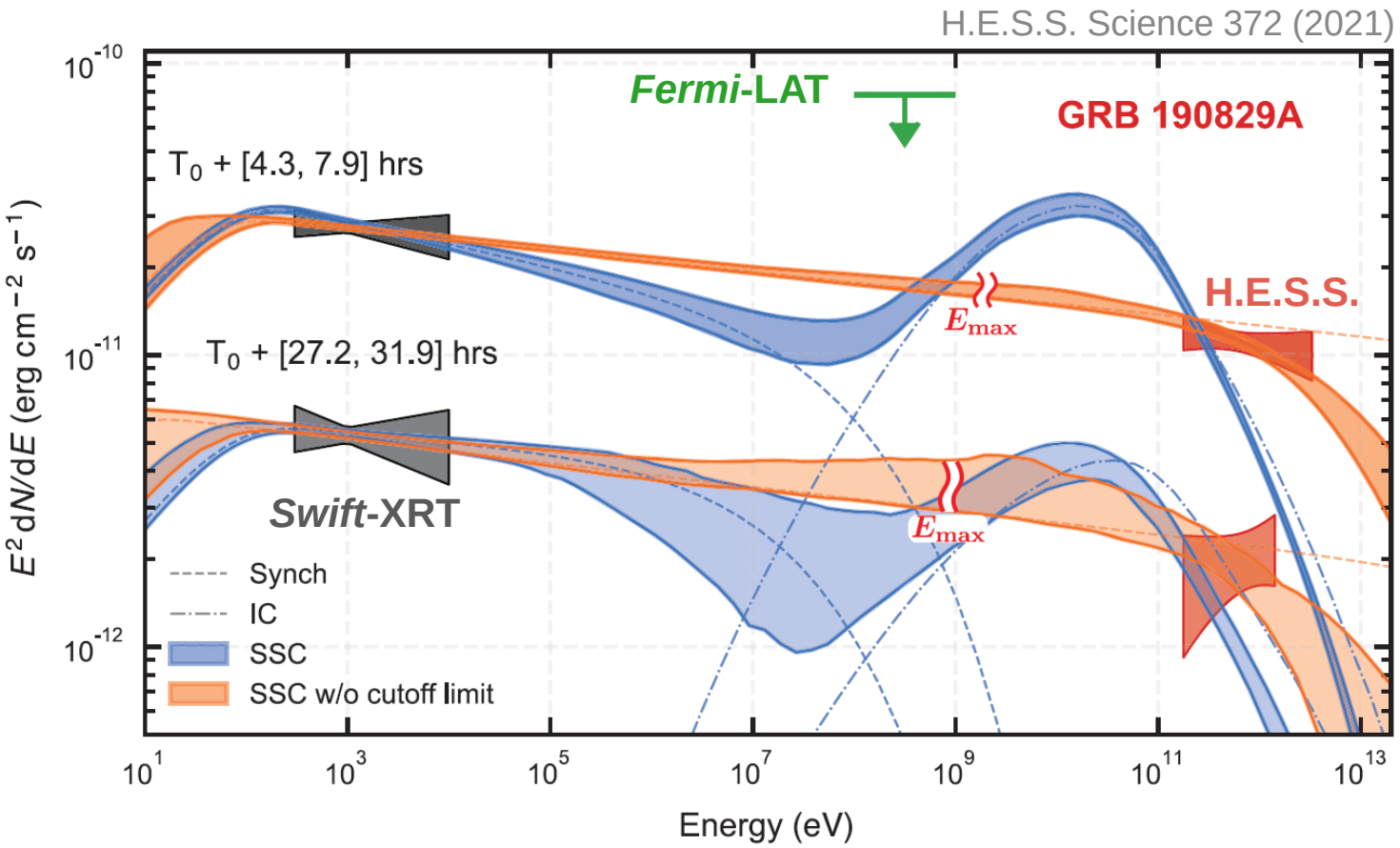


→ MAGIC:

→ inconclusive on syn vs. SSC

→ **H.E.S.S.:**

GRB 190829A: SSC vs extended syn



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

$\rightarrow$ spectral index at TeV:

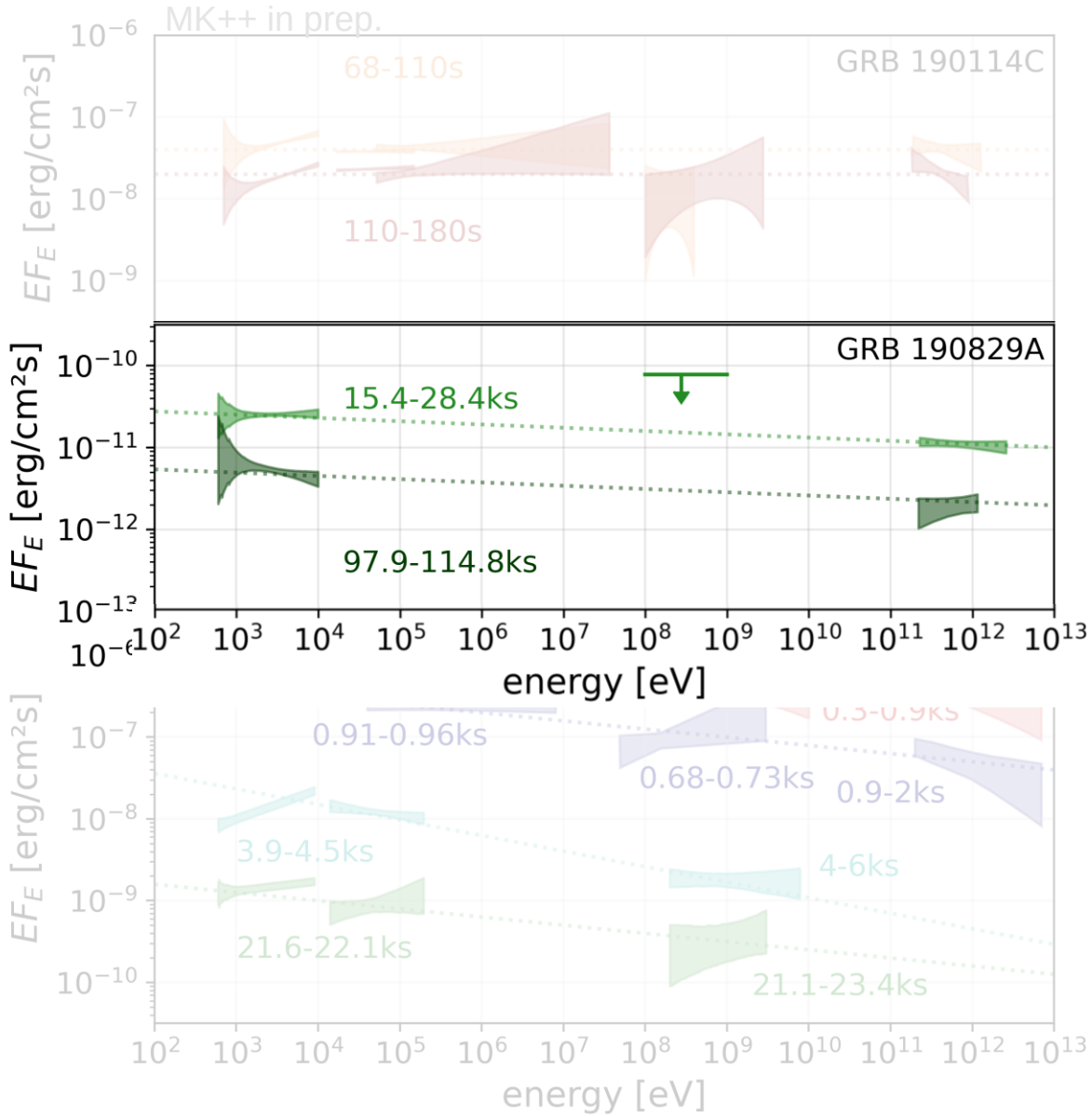
$$\approx -2 \pm 0.1_{(\text{stat})} \pm 0.26_{(\text{sys})}$$

- poor MWL coverage

- counts level fit:

$\rightarrow$ preference for single component!

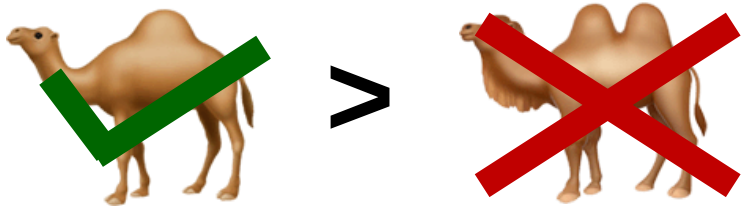
Comparison to data



→ MAGIC:

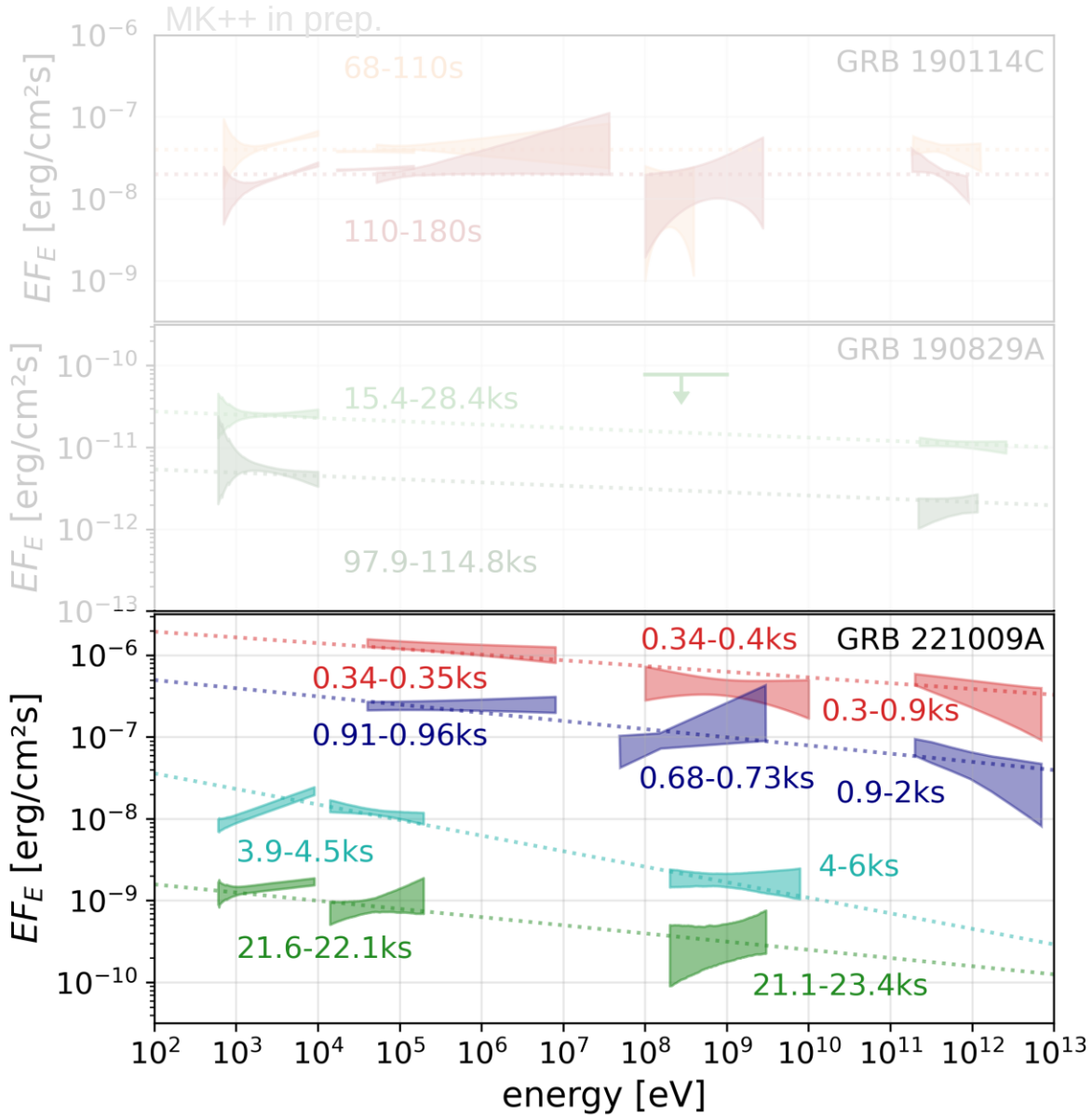
→ inconclusive on syn vs. SSC

→ H.E.S.S.:



→ in tension with SSC

Comparison to data



→ MAGIC:

→ inconclusive on syn vs. SSC

→ H.E.S.S.:

→ in tension with SSC

→ **LHAASO:**

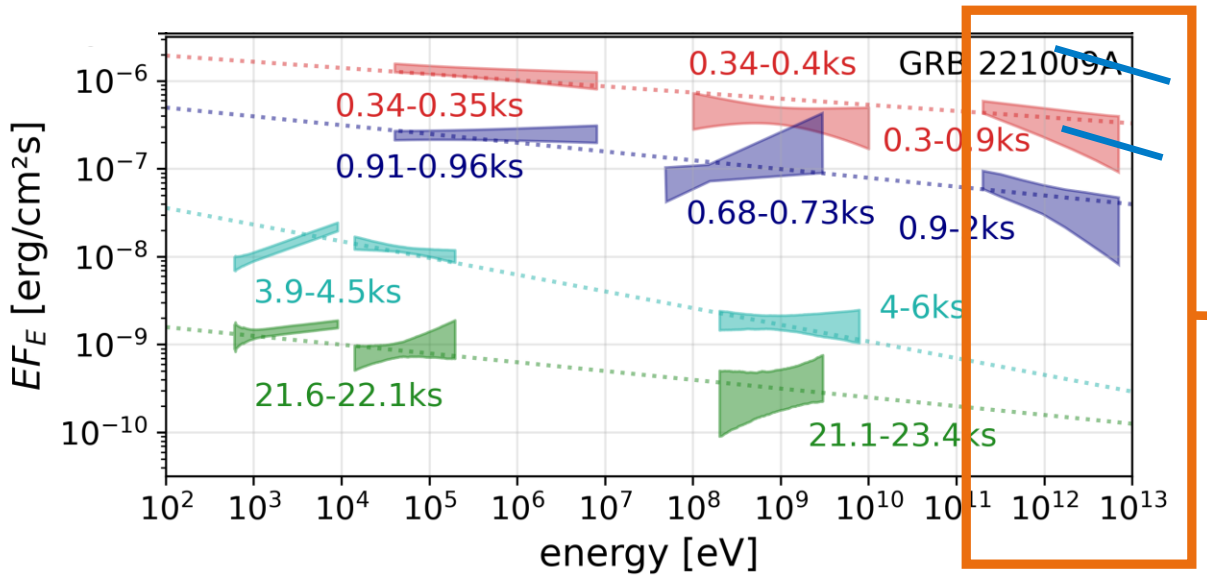
GRB 221009A

LHAASO Collaboration 2023:

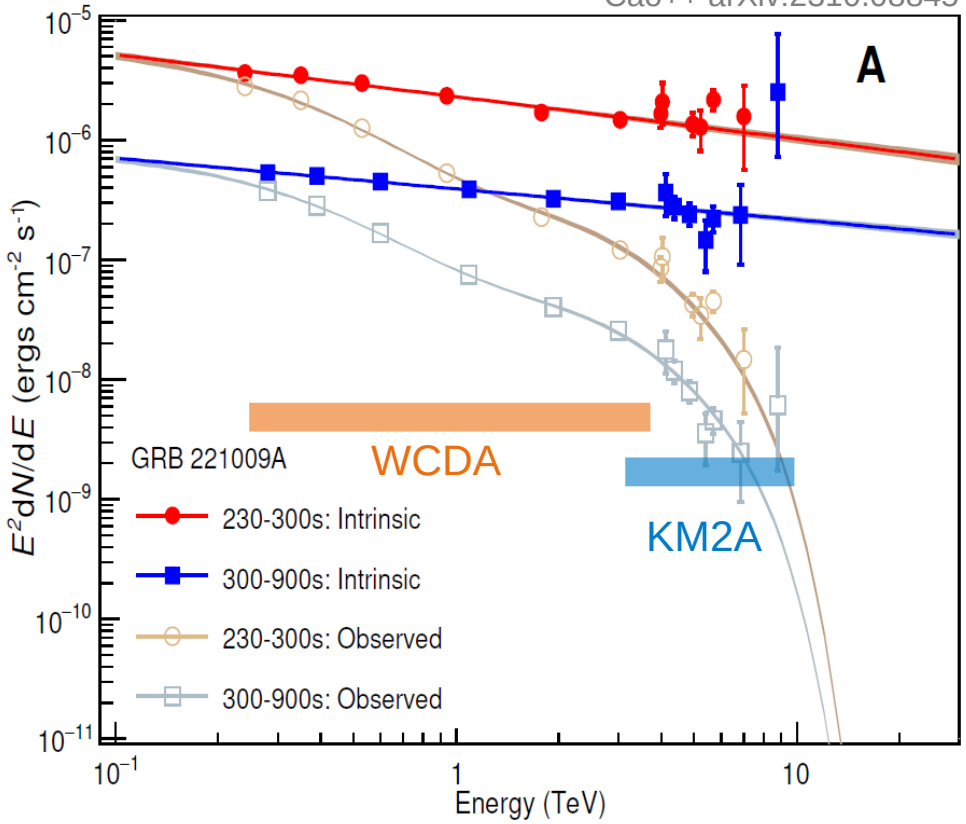
No softening up to at least 10 TeV!

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

→ incompatible with SSC

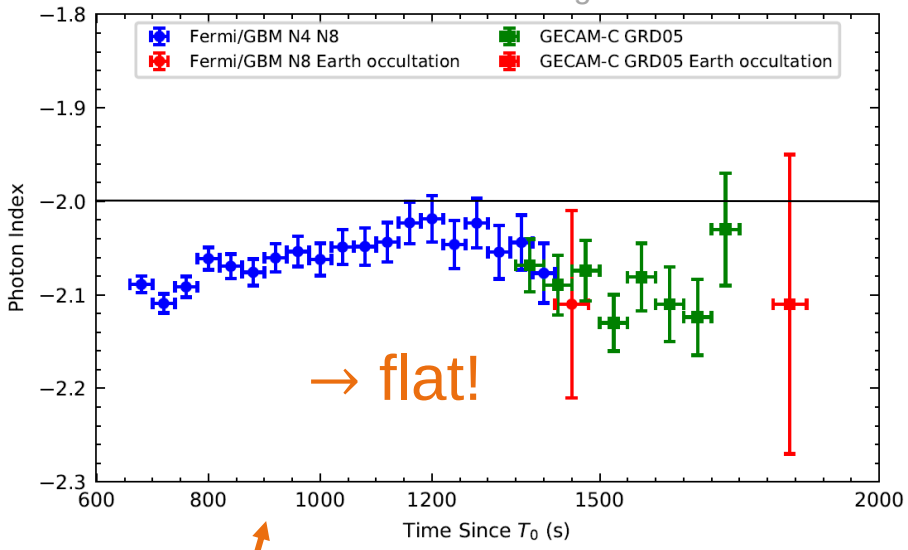


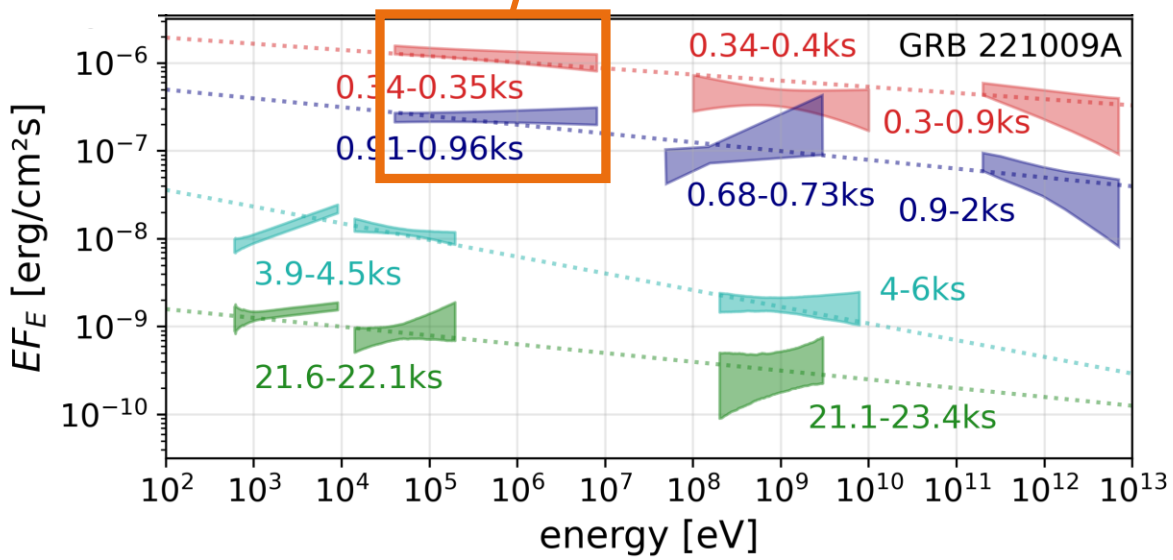
Cao++ arXiv:2310.08845



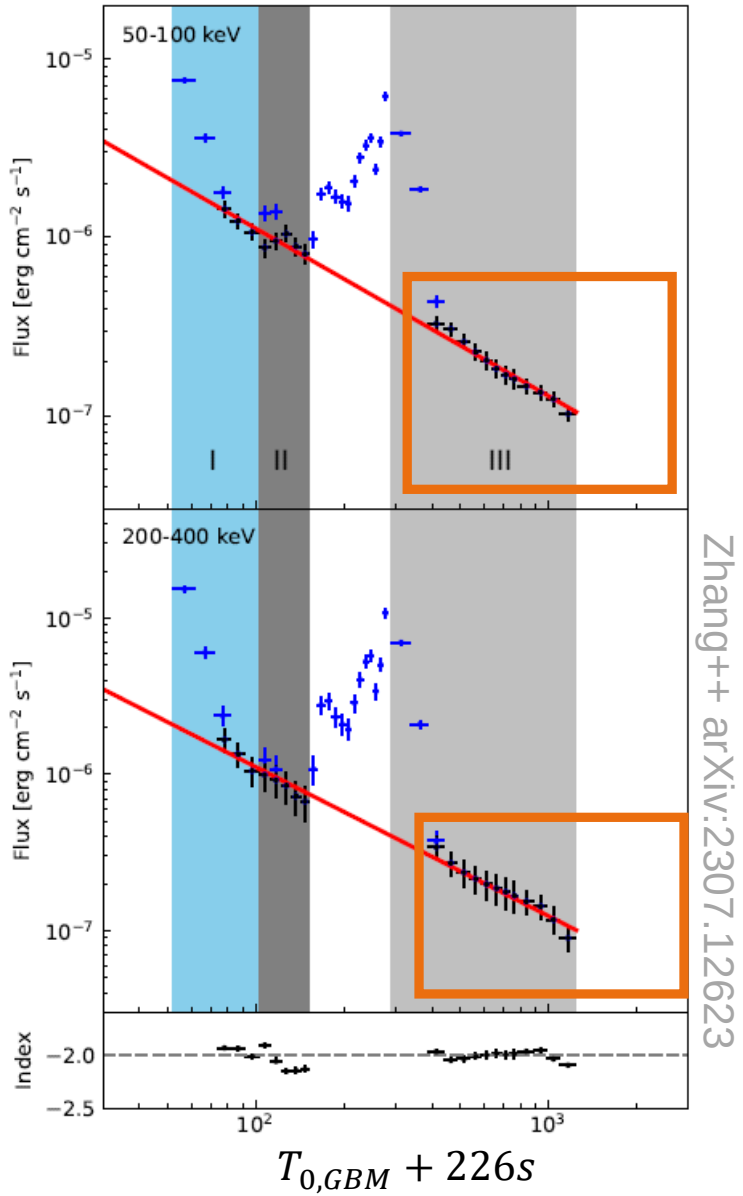
GRB 221009A

Zheng++ arXiv:2310.10522





Fermi-GBM light curve

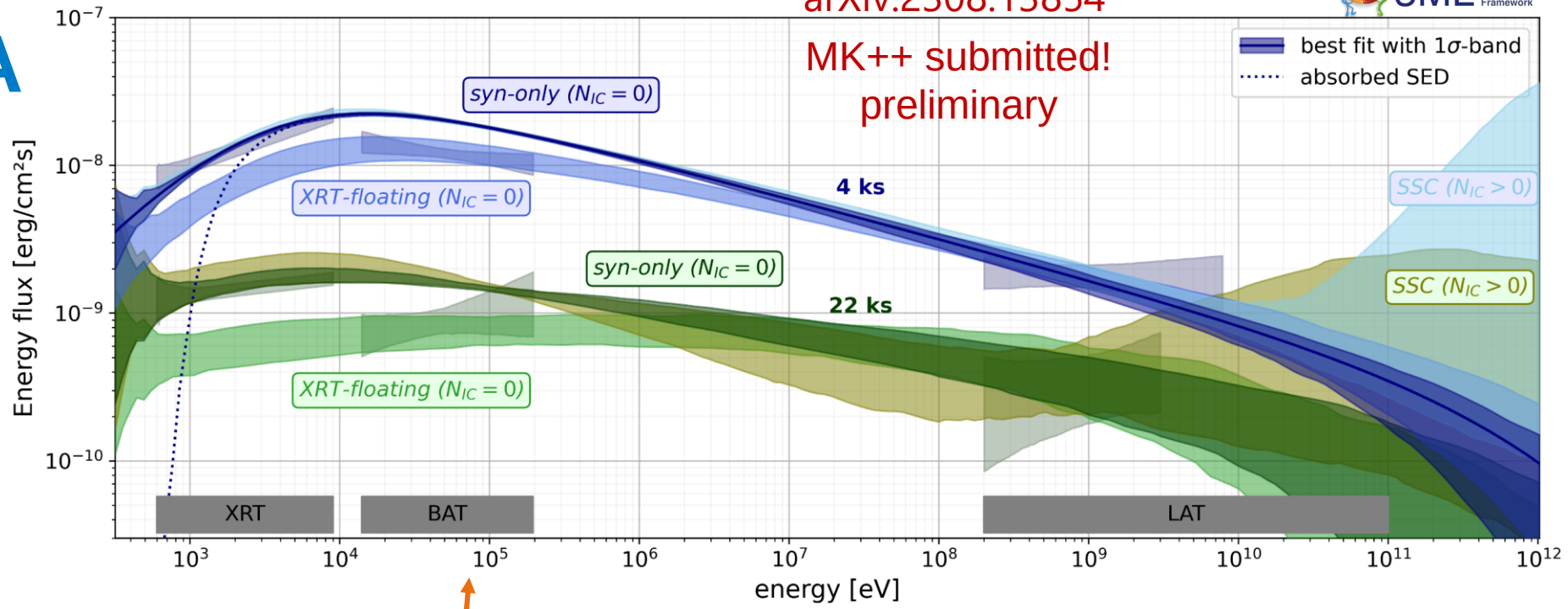


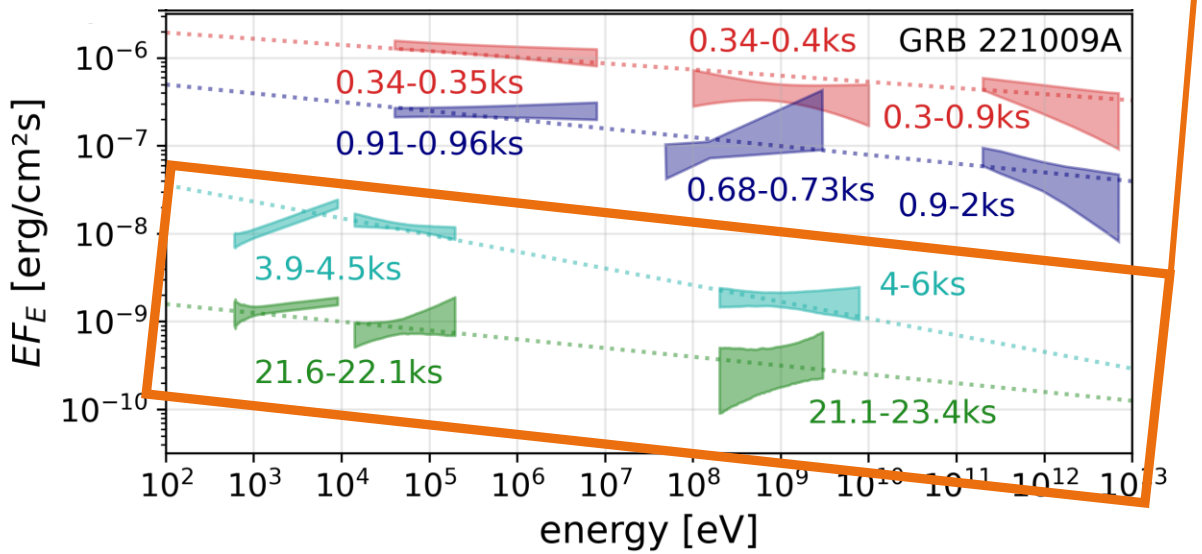
Zhang++ arXiv:2307.12623

GRB 221009A

arXiv:2308.13854

MK++ submitted!
preliminary



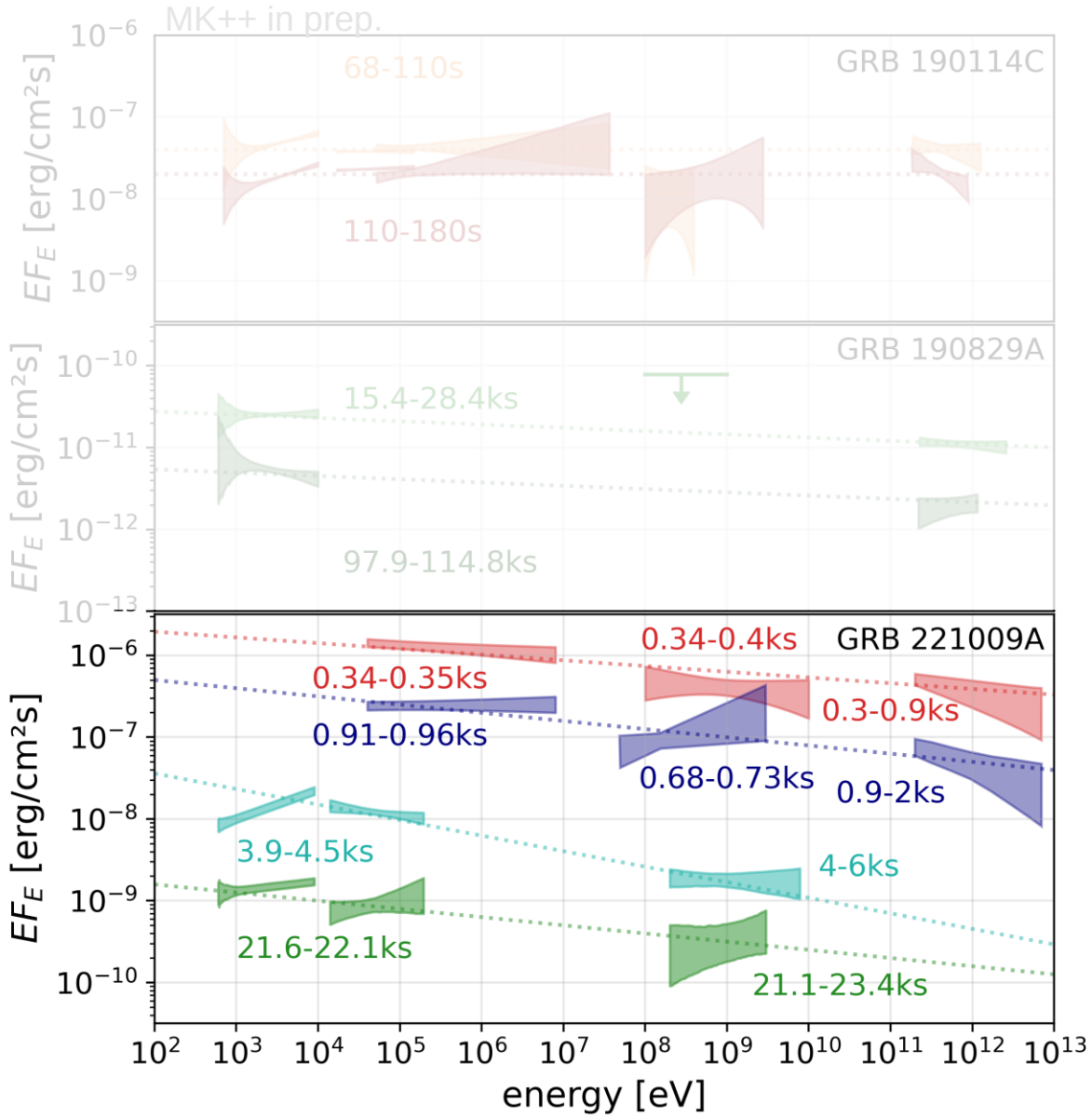


after LHAASO (> 2 ks):

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

→ consistent with LHAASO

Comparison to data



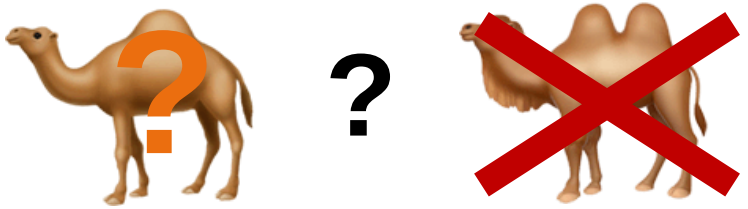
→ MAGIC:

→ inconclusive on syn vs. SSC

→ H.E.S.S.:

→ in tension with SSC

→ LHAASO:



→ in tension with SSC

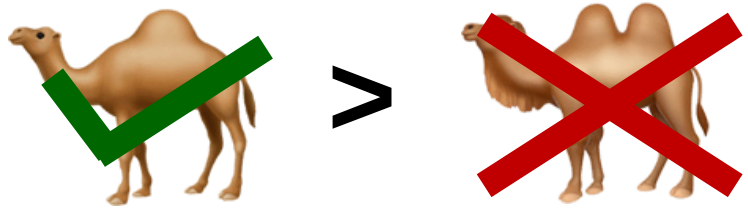
Comparison to data

→ 1 zone SSC crisis!

→ MAGIC:

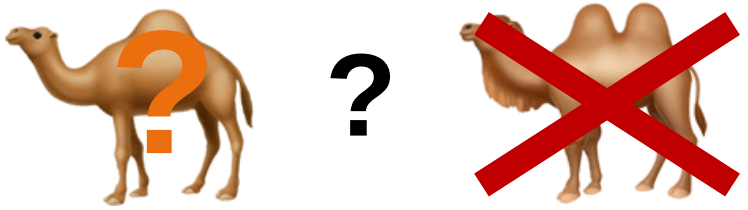
→ inconclusive on syn vs. SSC

→ H.E.S.S.:



→ in tension with SSC

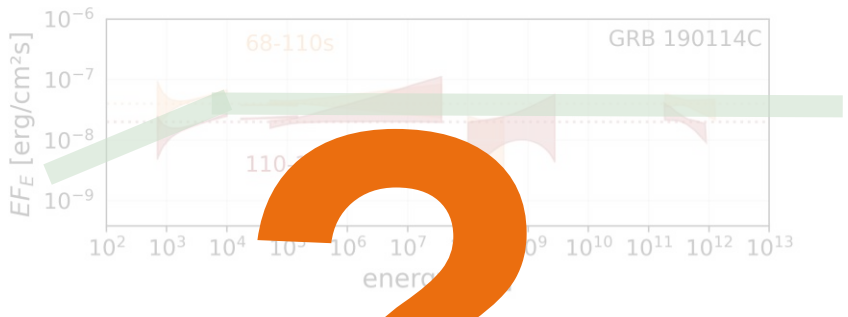
→ LHAASO:

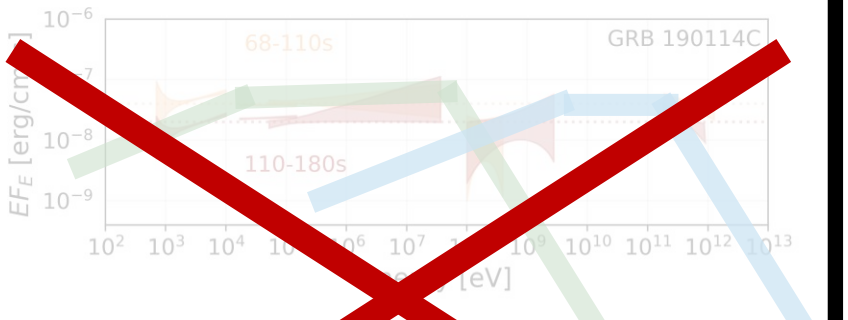


→ in tension with SSC

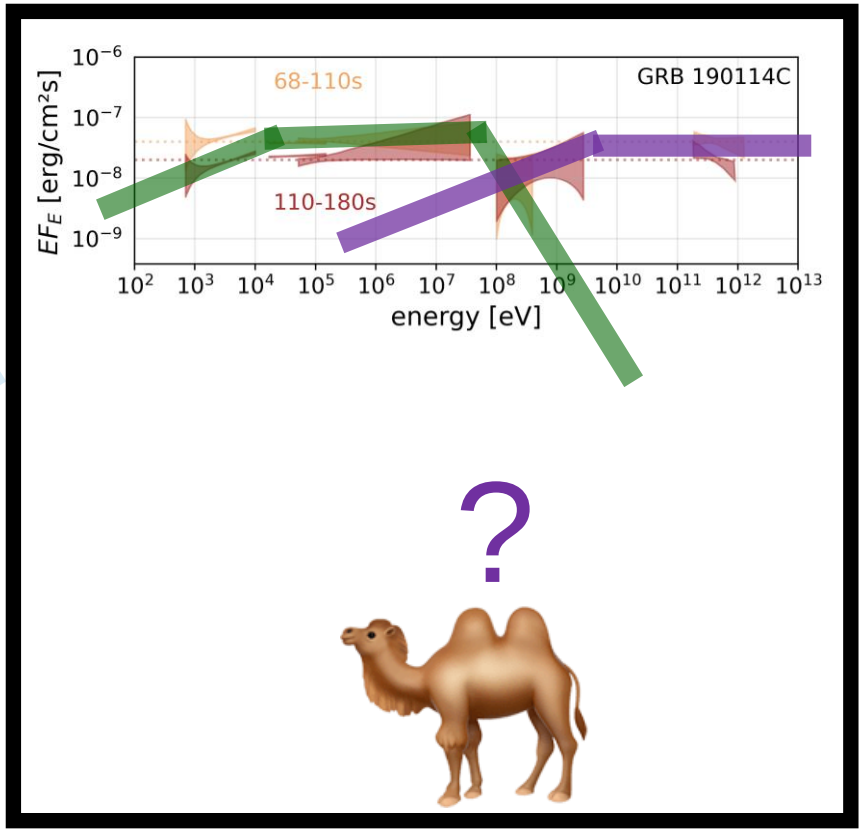
Crisis:

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

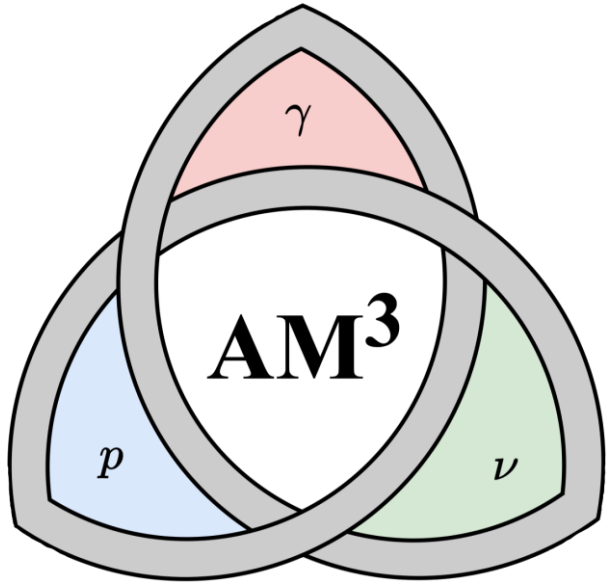




standard in community:
2 component SSC



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)

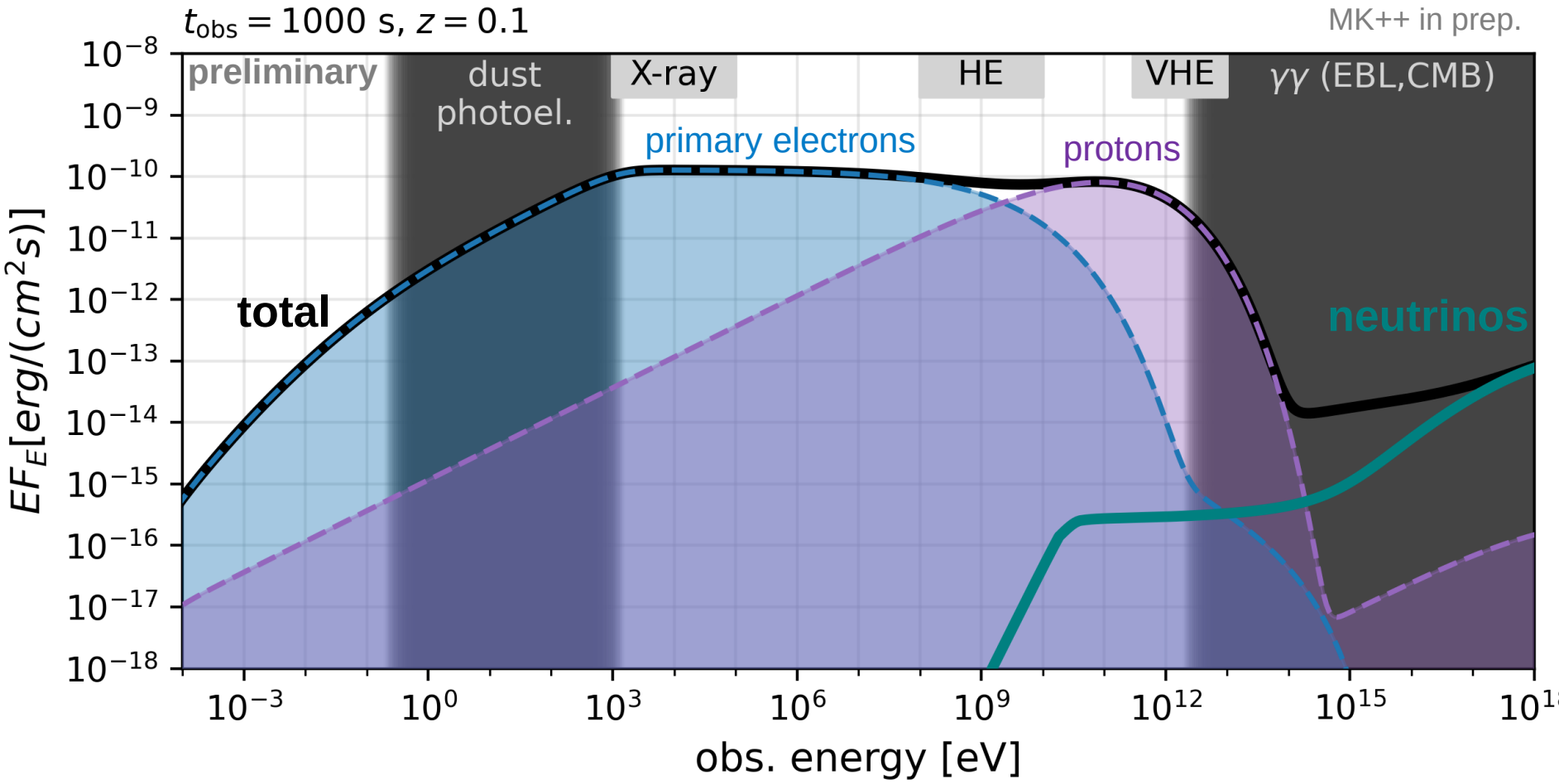
  → 2 zone: decouple acceleration zone from radiation zone
  Khangulyan++ APJ 947 (2021)

  → **extended electron synchrotron component**

- involve hadrons

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

Proton-Synchrotron model

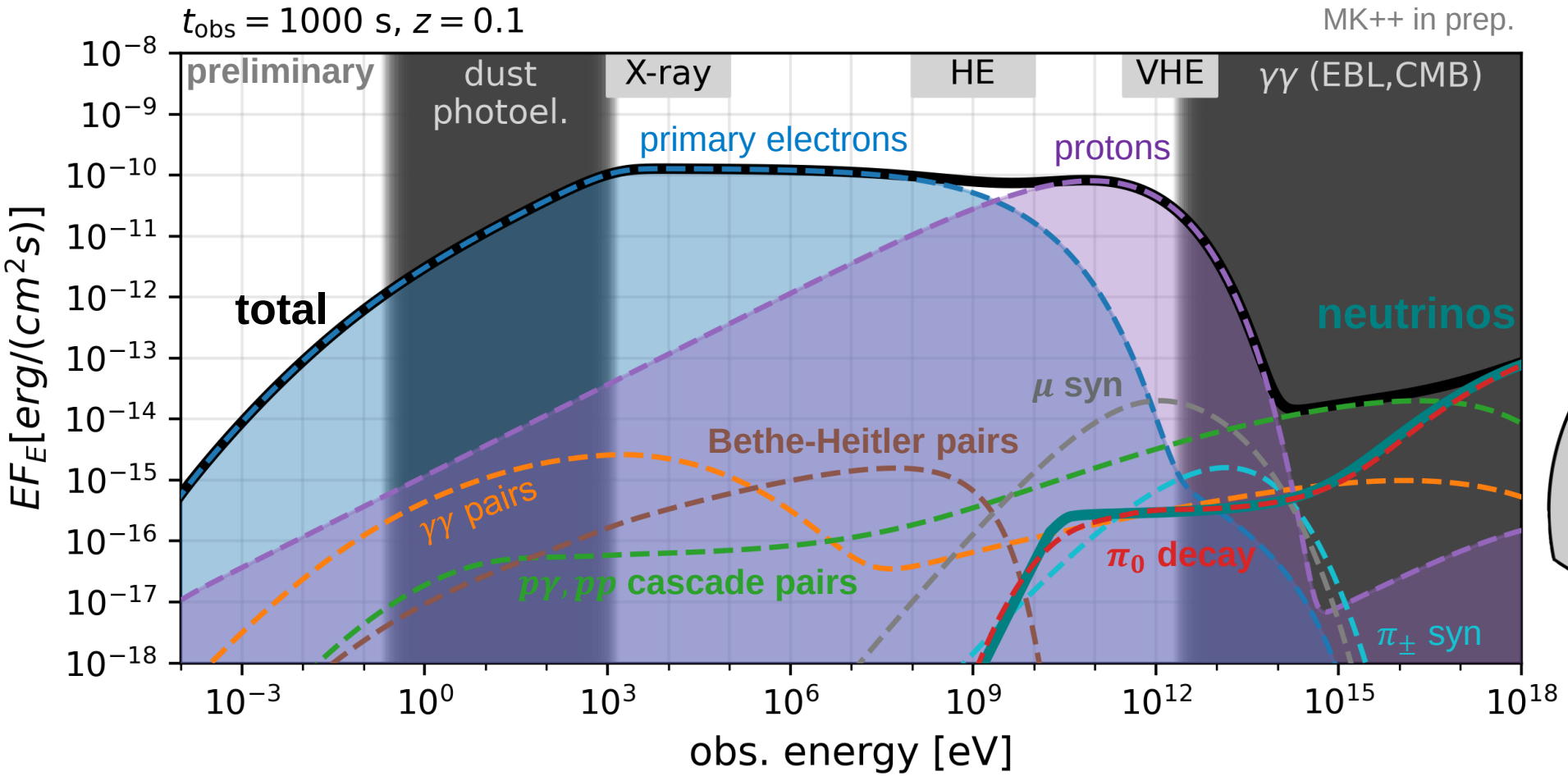


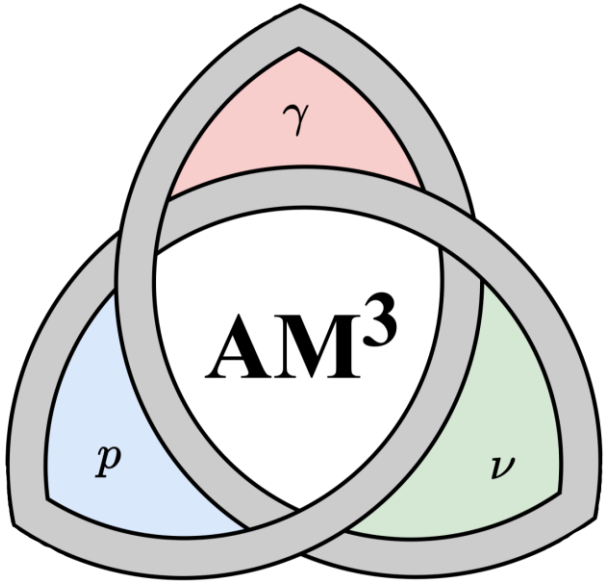
ε_e	10^{-3}
ε_p	$10^{-0.5}$
ε_B	$10^{-0.5}$
$E_{\min}$	10GeV
p	2
η	1
$E_{\rm iso}$	10^{55}erg
$n_{\rm up}$	$1\mathrm{cm}^{-3}$

$\varepsilon_B, \varepsilon_p \lesssim 1$

Problem: proton synchrotron component at exponential cut-off!

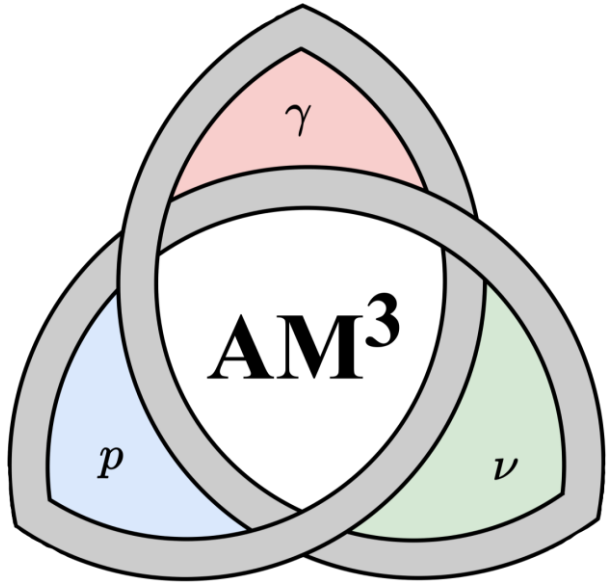
Proton-Synchrotron model





Interesting: neutrinos! But fluence not too high…

There is more beyond the SSC model



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**

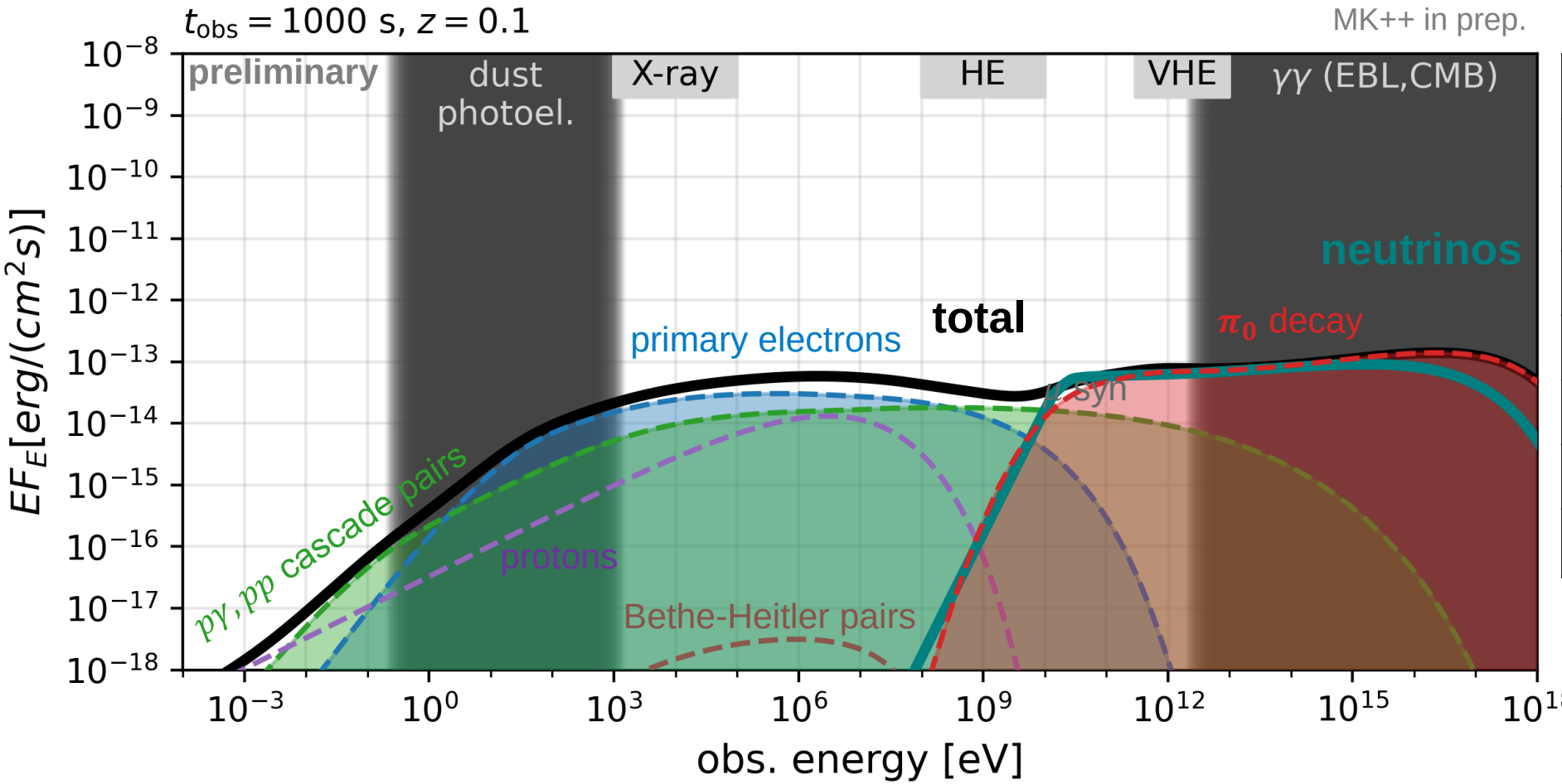
- involve hadrons

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

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

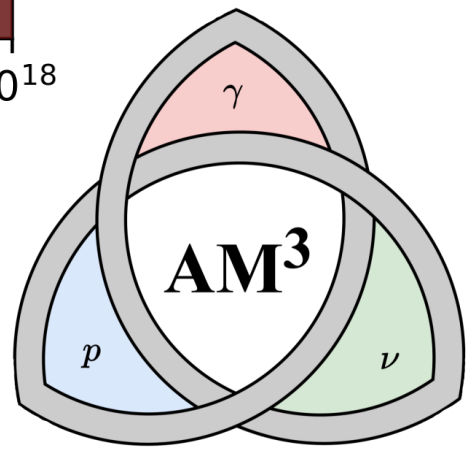
  → **cascade from pp interactions**

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!**



Other points with room for improvement

- high energy spectra

  → maximum energy? confinement?

- low energy injection spectra

  → thermal particles? → low energy spectra?

- magnetic fields (generation, decay, scales,…)

  → more than "ε_B"

- description of systematic absorption effects

  → dust+photoel. @ optical - x-ray, EBL @ VHE

Conclusions

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

  → challenging to explain with current models

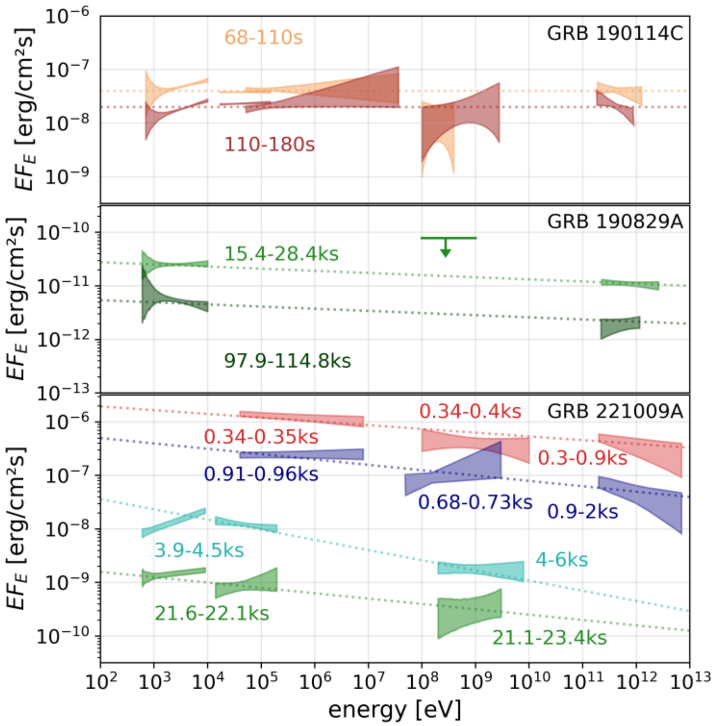
  → in particular for SSC scenario

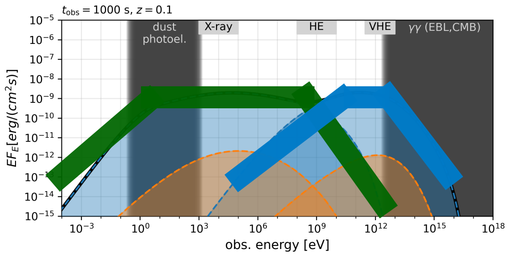
- Need to think about other scenarios:

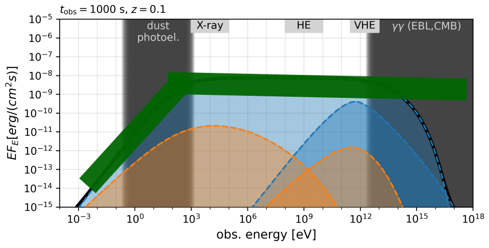
  → extended synchrotron model

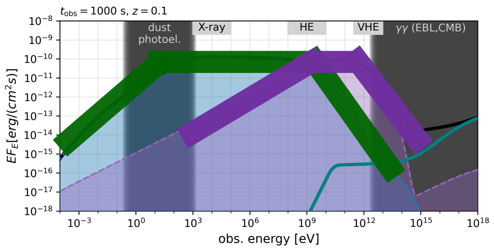
  → proton synchrotron

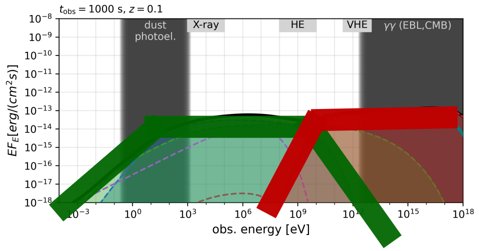
  → cascade from pp interactions











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Thank you!