VHE GRB Afterglows: A story about Bactrians, Dromedaries and lots of Butterflies

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10.01.2023

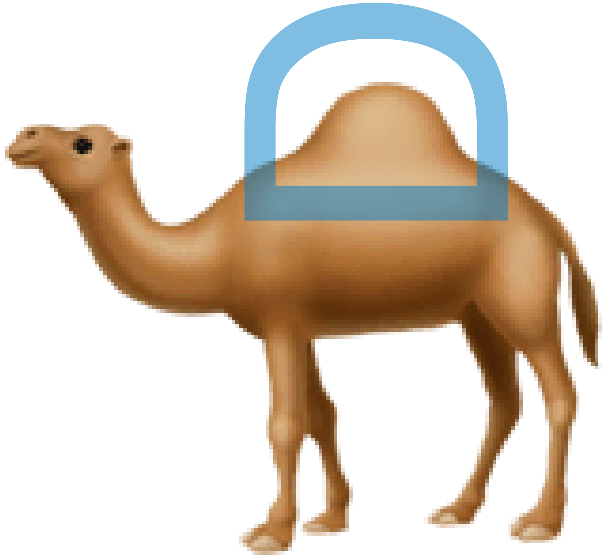
Transient Tuesday

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

HELMHOLTZ

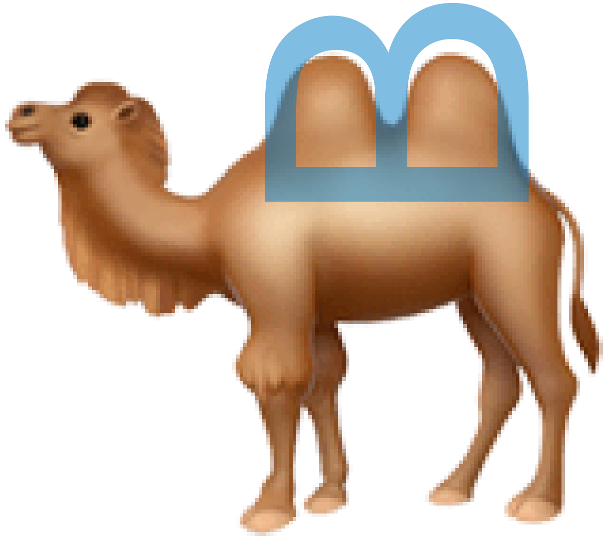
DESY.

Are gamma-ray bursts…



Dromedaries

or



Bactrians

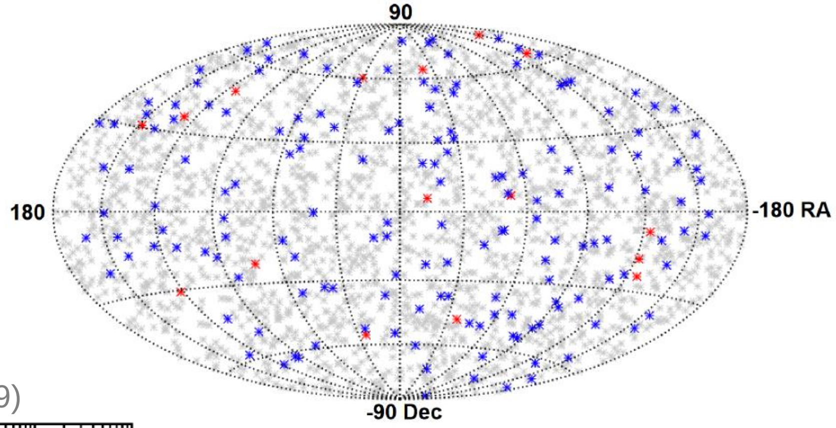
?

GRBs from two sides

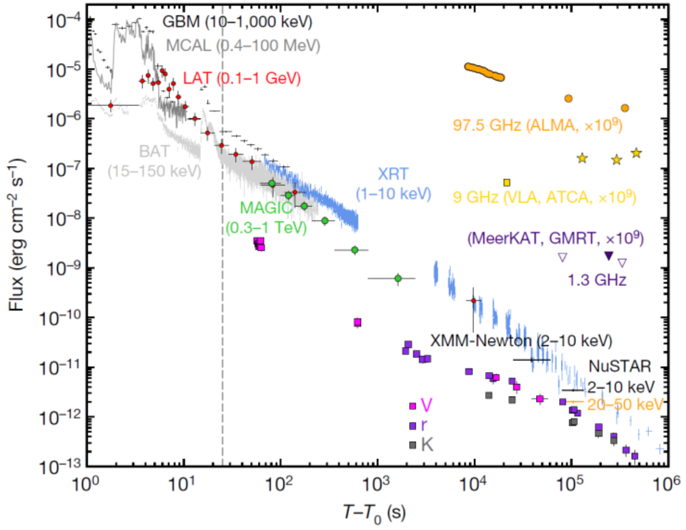
OBSERVATIONAL picture

- we observe flashes of X/γ-rays isotropically distributed on sky
- we find a complex prompt phase and smooth afterglow in the light curve
- we have associated one short burst to a NS-NS-merger and many long ones to SN
- short events → hard to follow up

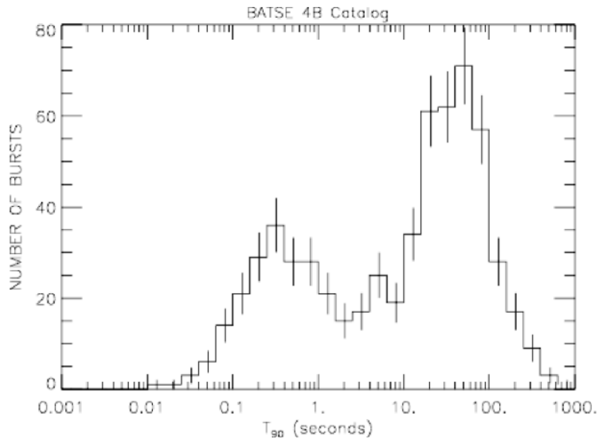
2. Fermi-LAT GRB Catalogue (2018)



MAGIC Nature 575 (2019)



Kouveliotou et al. (1993)



T_{90} [s]

GRBs from two sides

OBSERVATIONAL picture

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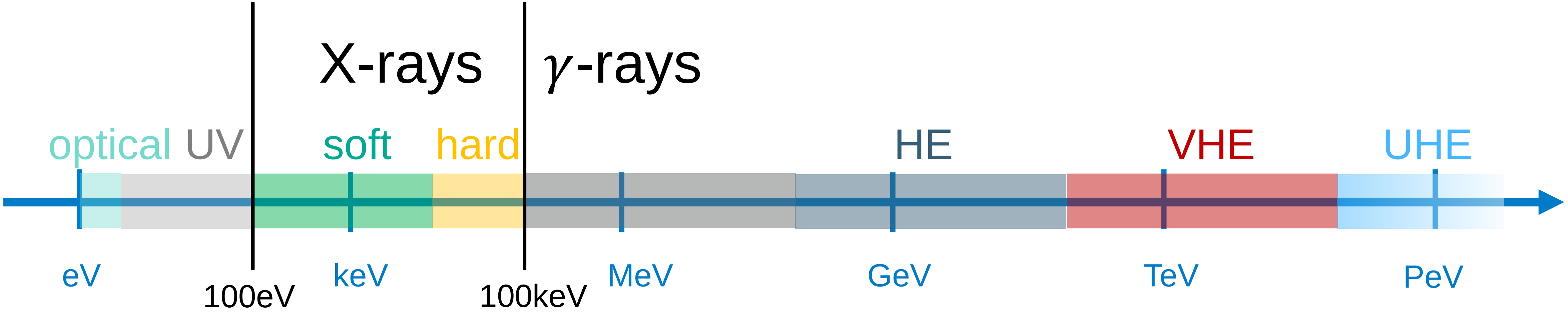
THEORETICAL picture

- accelerate a shell of hot 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?)

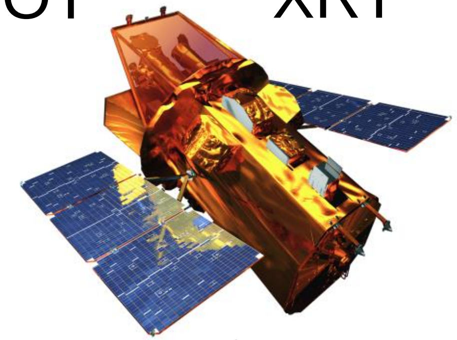
→ Fireball model

Instrument recap



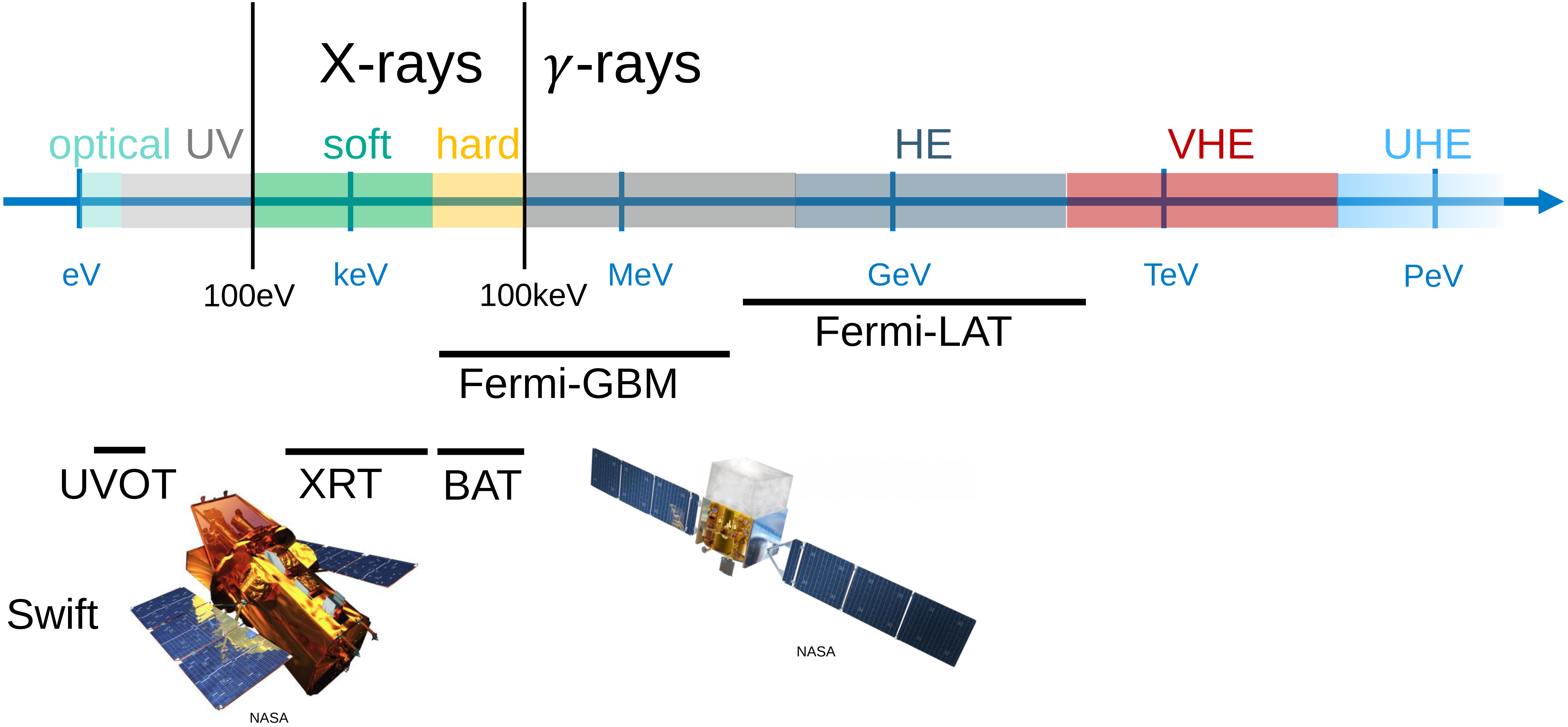
UVOT XRT BAT

Swift

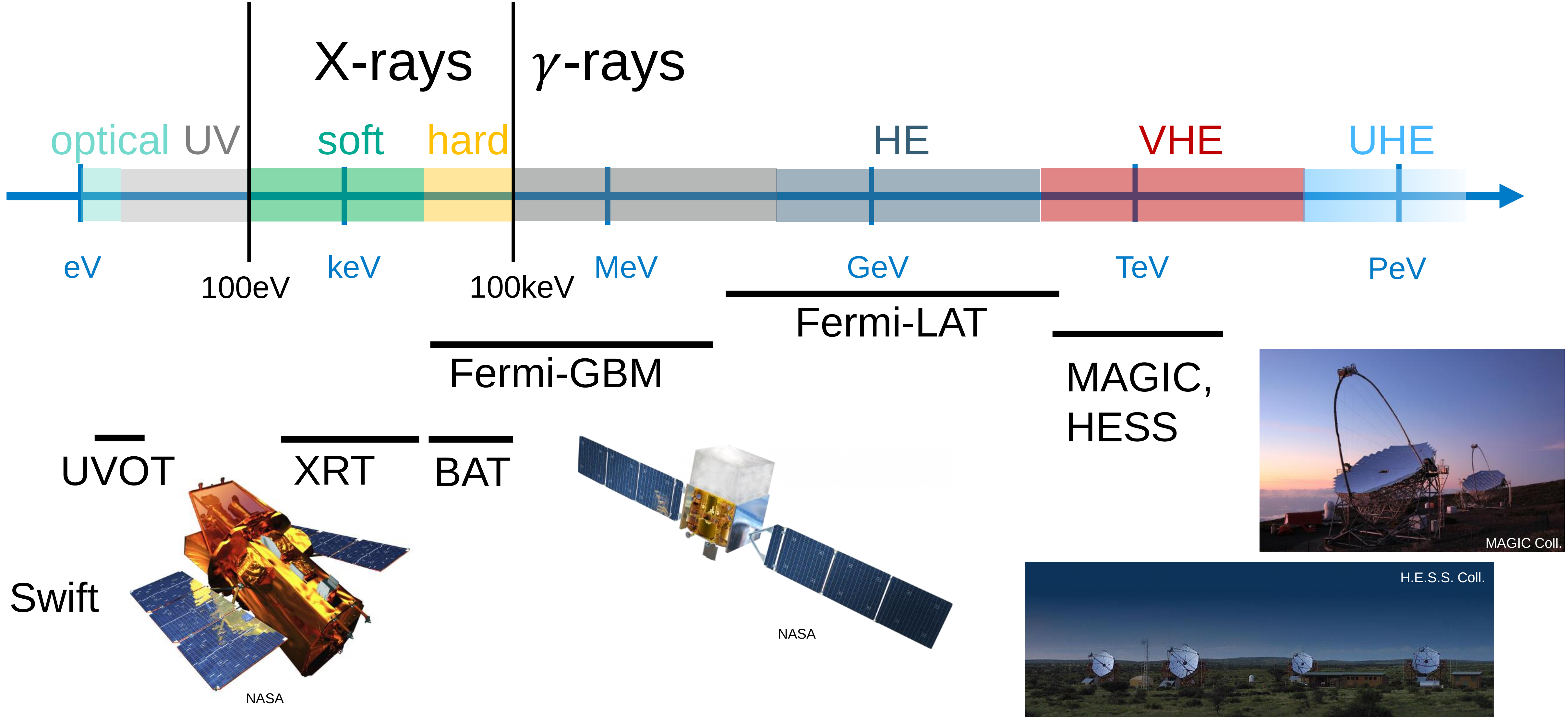


NASA

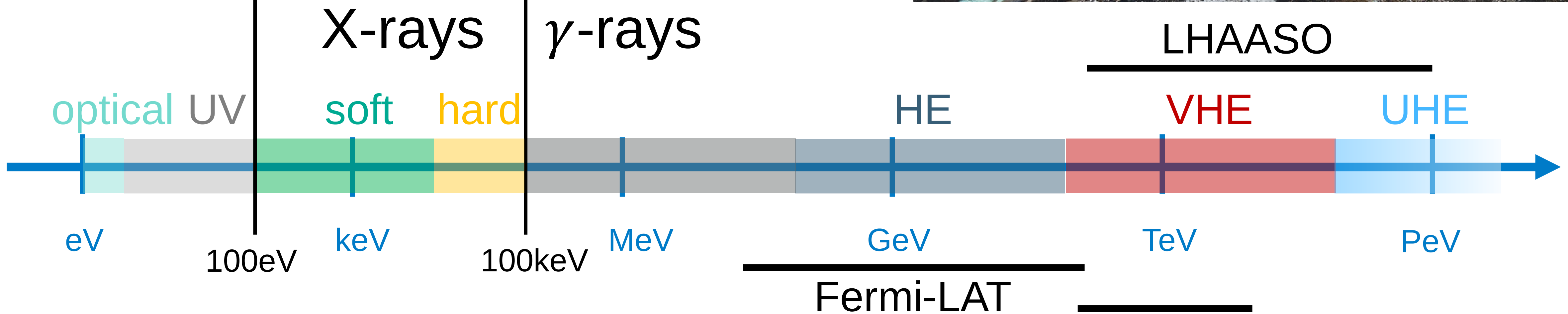
Instrument recap

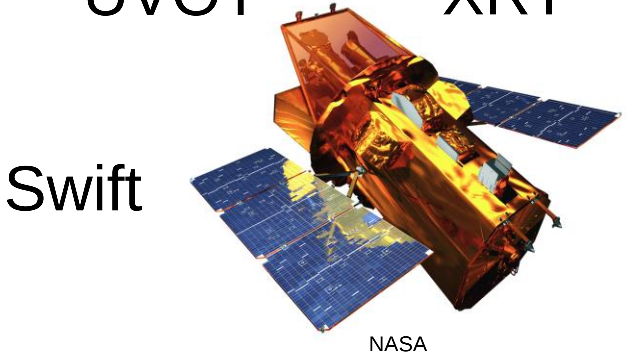


Instrument recap



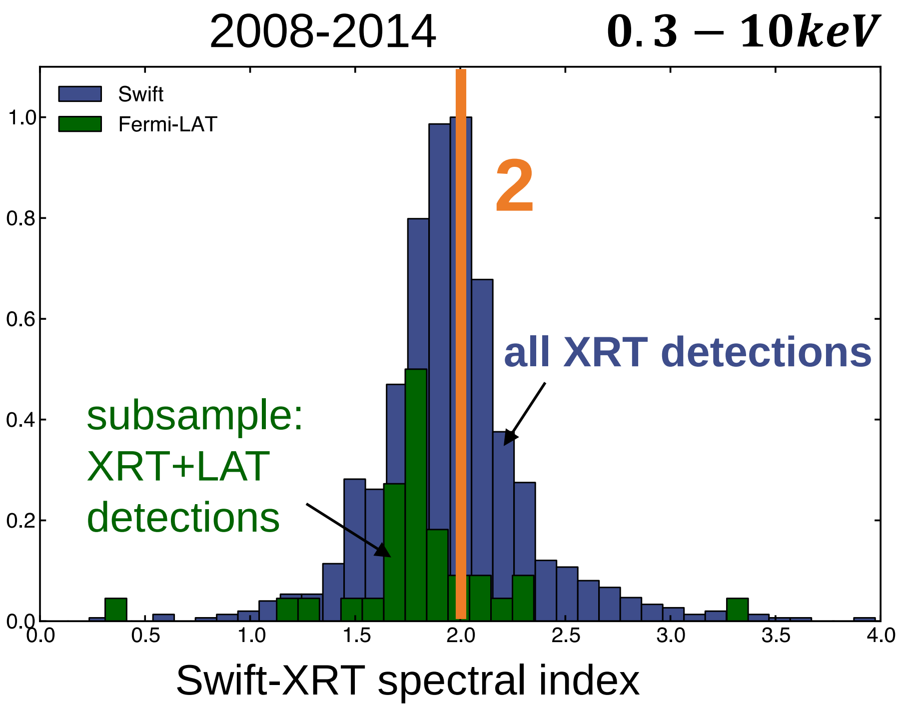
Instrument recap



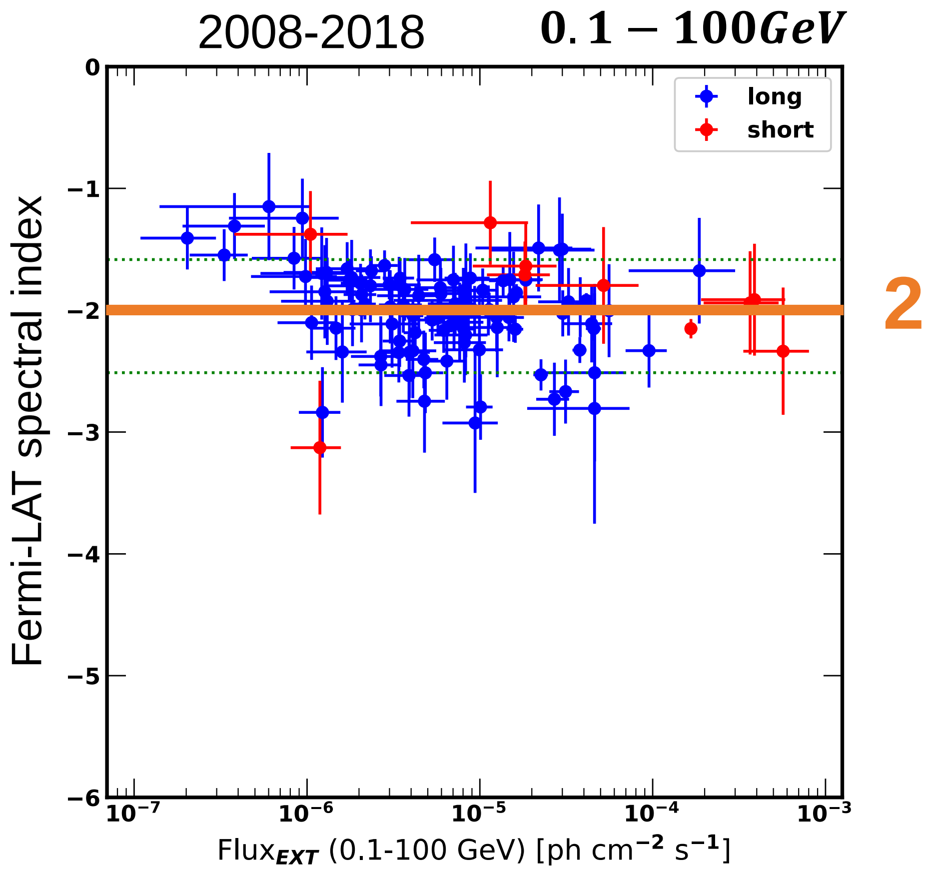


The afterglow picture before the VHE data

- spectral indices around $dN/dE_\gamma \sim E_\gamma^{-2}$



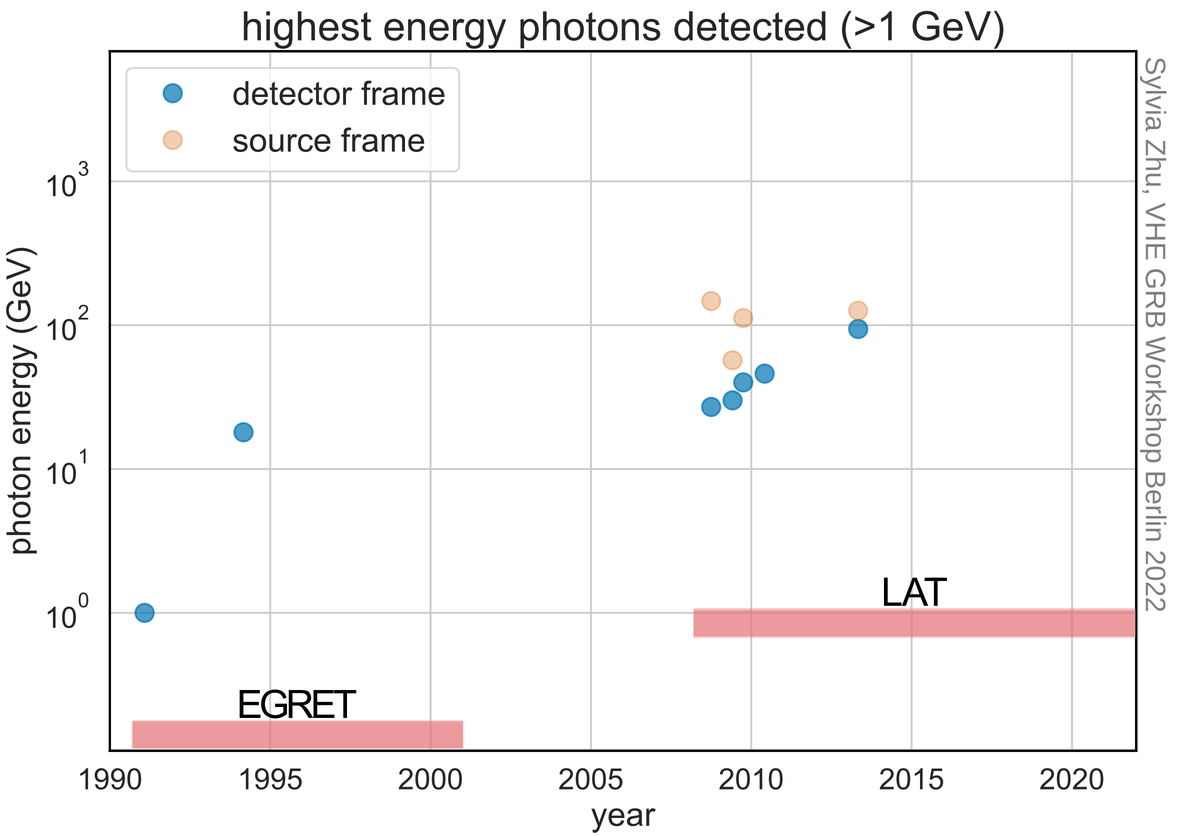
Ajello et al. 2018, joint Swift/Fermi analysis



Ajello et al. 2019, 2nd Fermi GRB catalogue

The afterglow picture before the VHE data

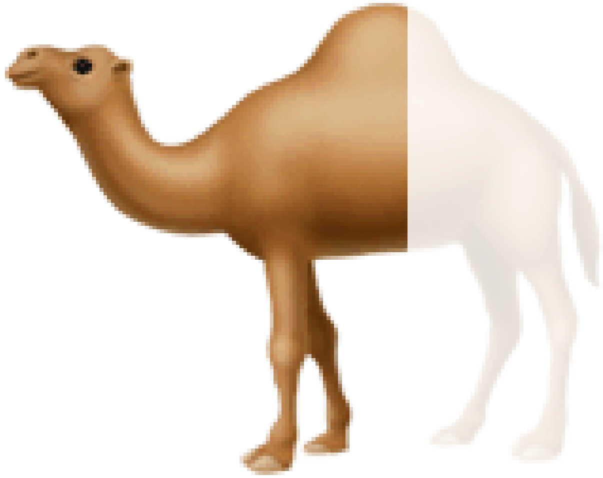
- spectral indices around $dN/dE_\gamma \sim E_\gamma^{-2}$
- highest energy detections up to 100 GeV (*Fermi*-LAT)



The afterglow picture before the VHE data

- spectral indices around $dN/dE_\gamma \sim E_\gamma^{-2}$
- highest energy detections up to 100 GeV (*Fermi*-LAT)
- no evidence for new component

→ not even GRB 130427A (Kouveliotou et al. 2013)



→ no second component for GRBs or only half the story?

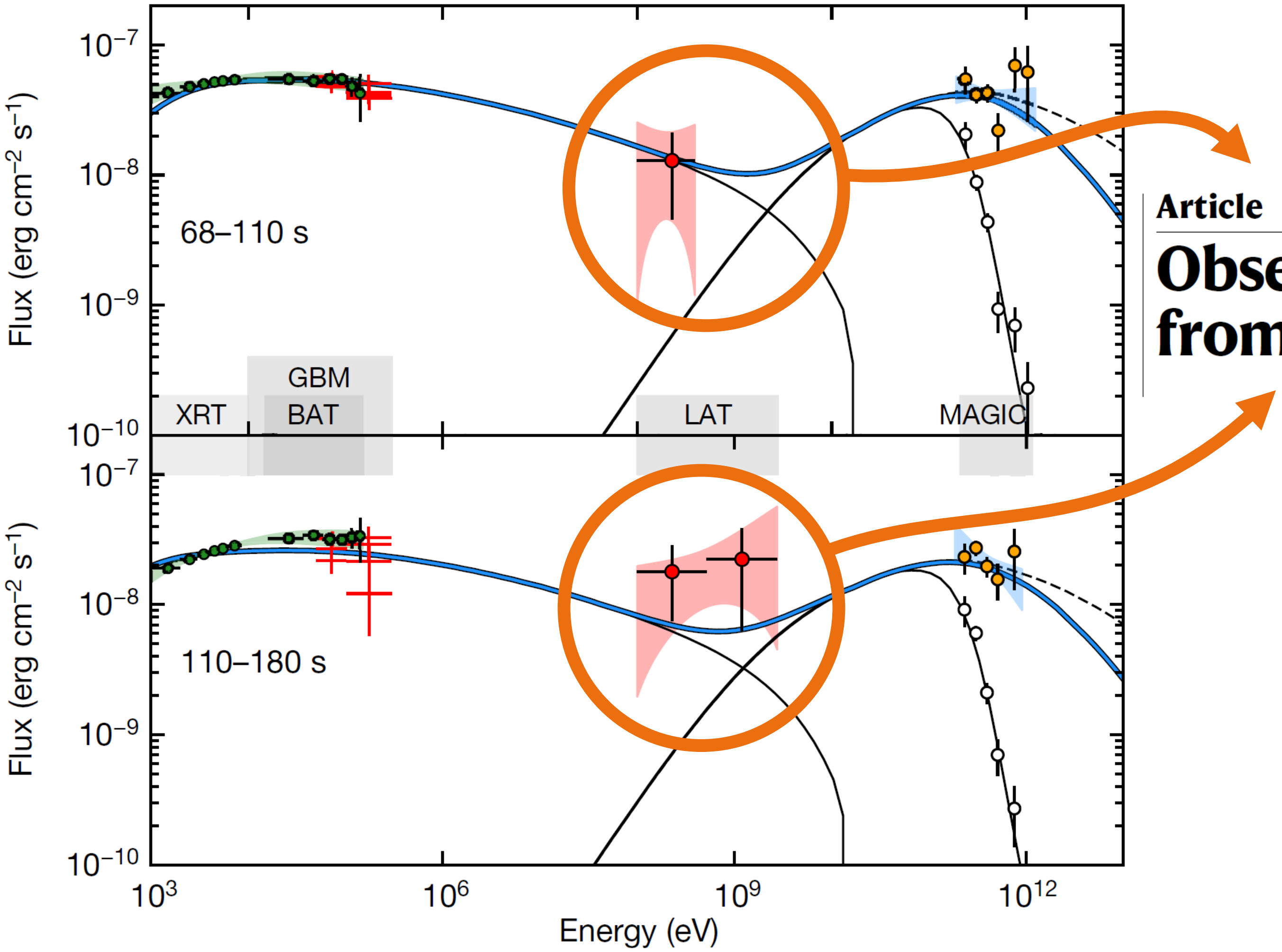
VHE GRB Afterglows?

- 180720B → no contemporaneous data at other energies
- **190114C → focus of my talk**
- **190829A → near by, strikingly flat VHE spectrum**
- 201015A → 3.5σ
- 201216C → z=1.1, strongly EBL absorbed
- 221009A → full moon, not published yet

→ **we can learn the most from the closest and brightest objects (that don't occur during full moon)**

1) GRB 190114C (detected by MAGIC)

MAGIC Nature 575 (2019)



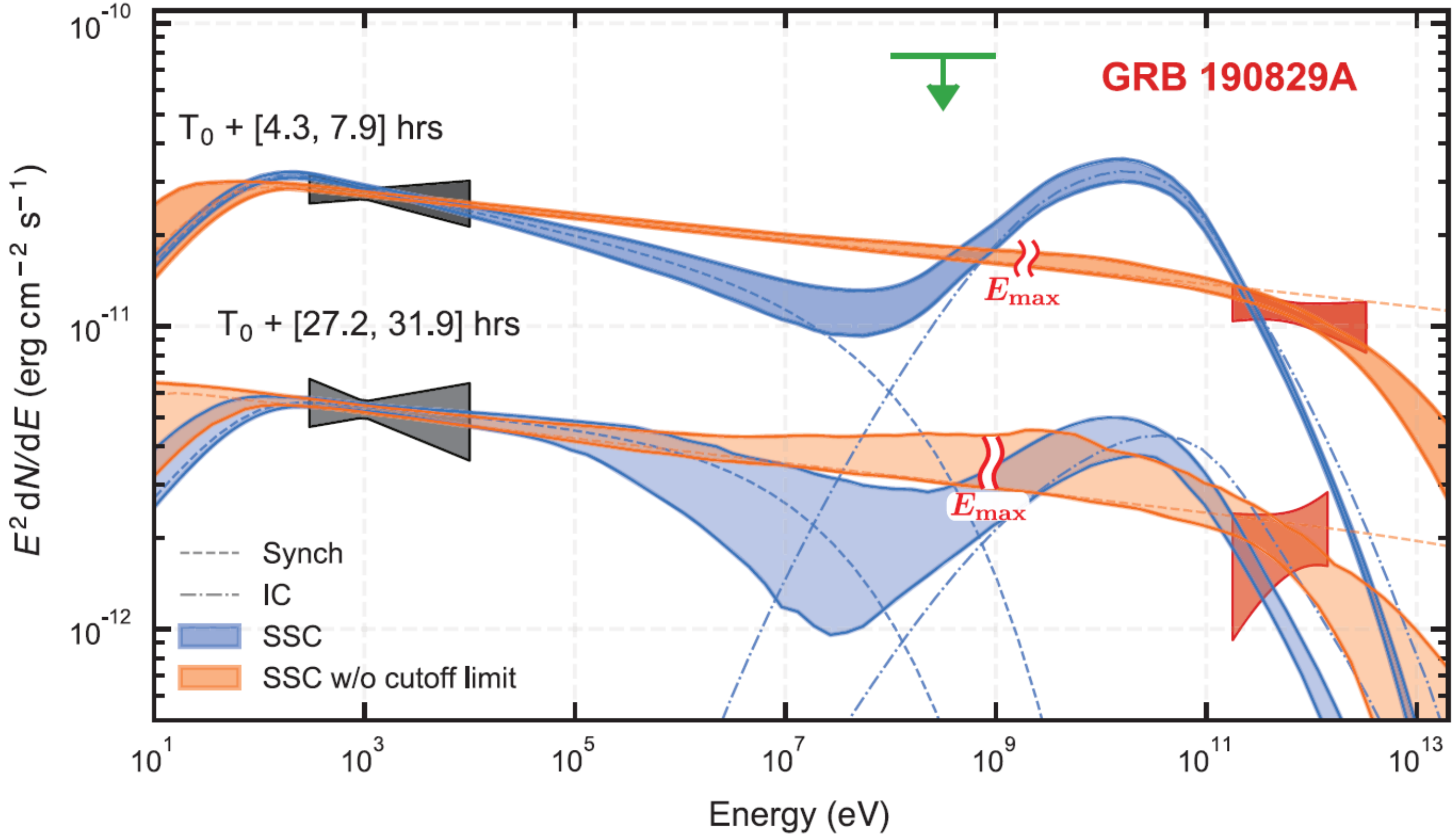
Article

Observation of inverse Compton emission from a long γ-ray burst

without proper statistical test: → **Bactrian**

2) GRB 190829A (detected by H.E.S.S.)

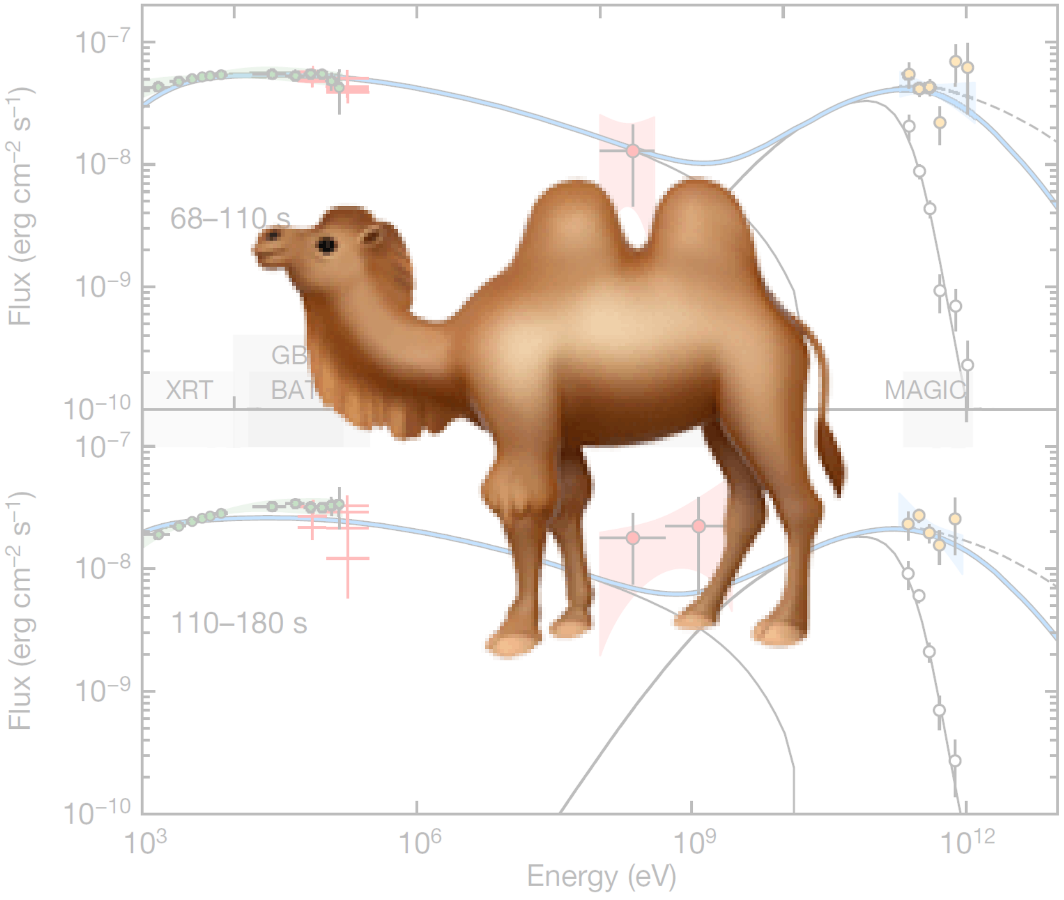
H.E.S.S. Science 372 (2021)



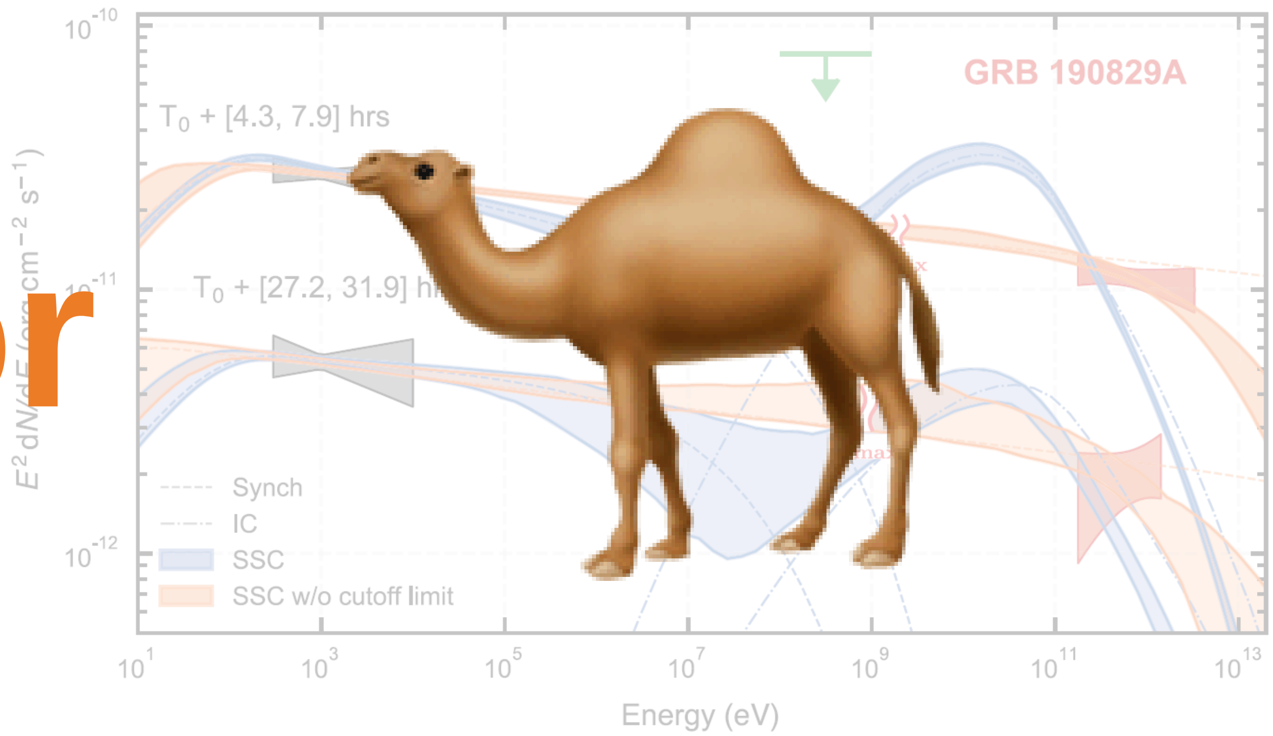
- preference for single component (5σ)

→ **Dromedary**

Now what?


68–110 s
110–180 s
XRT
MAGIC
Flux (erg cm^{-2} s^{-1})
Energy (eV)

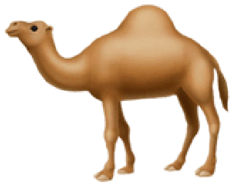
or


GRB 190829A
T_0 + [4.3, 7.9] hrs
Synch
IC
SSC
SSC w/o cutoff limit
Energy (eV)

Structure

- GRB modeling basics

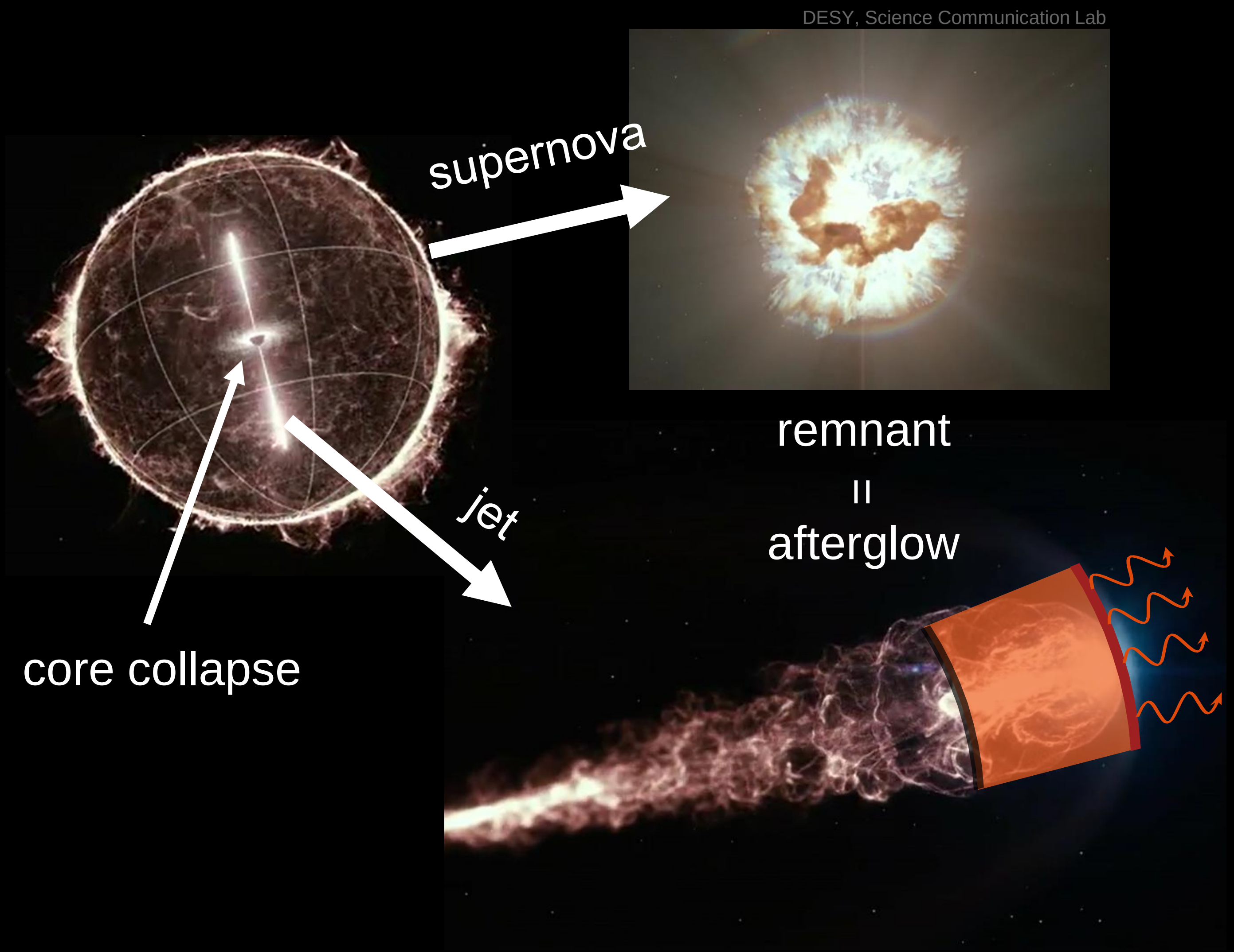
  → what do I actually mean by *Dromedary* and *Bactrian* ?

- How stable is the Bactrian claim for GRB 190114C (MAGIC) ?

Fireball model (GRB basics)

Fireball model: Long GRB



- Lorentz factors up to few 100

  → relativistic compression

- Quasi-isotropic outflow
- Energetics:

  → observed up to: $E_{\mathrm{iso}} \sim 10^{54} erg$

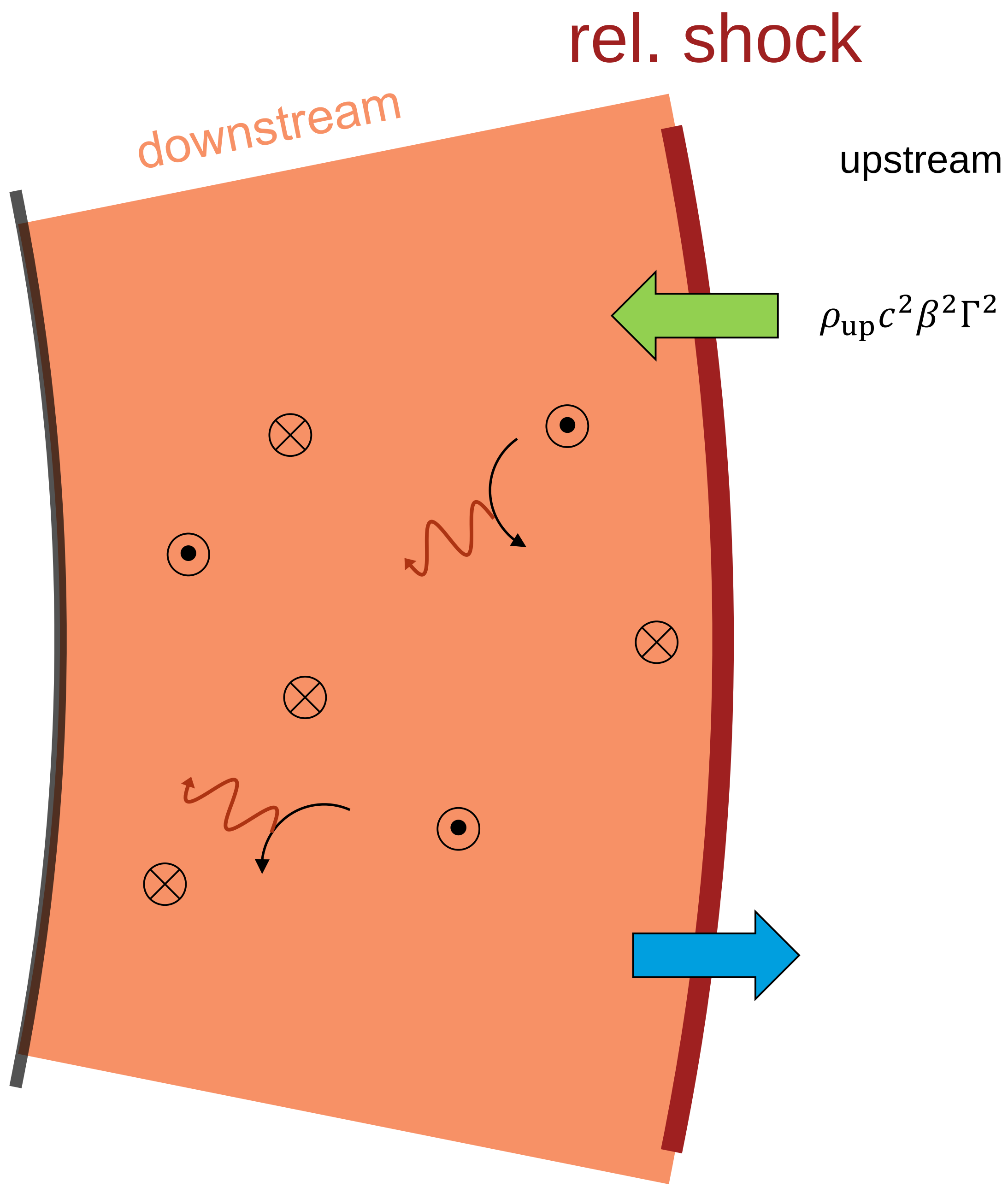
  → $E_{\mathrm{tot}} = \frac{\Omega}{4\pi} E_{\mathrm{iso}} \sim 10^{51} \mathrm{erg}$

  → comparable to SN !

- efficient converters of kinetic energy to radiation

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

One zone assumption

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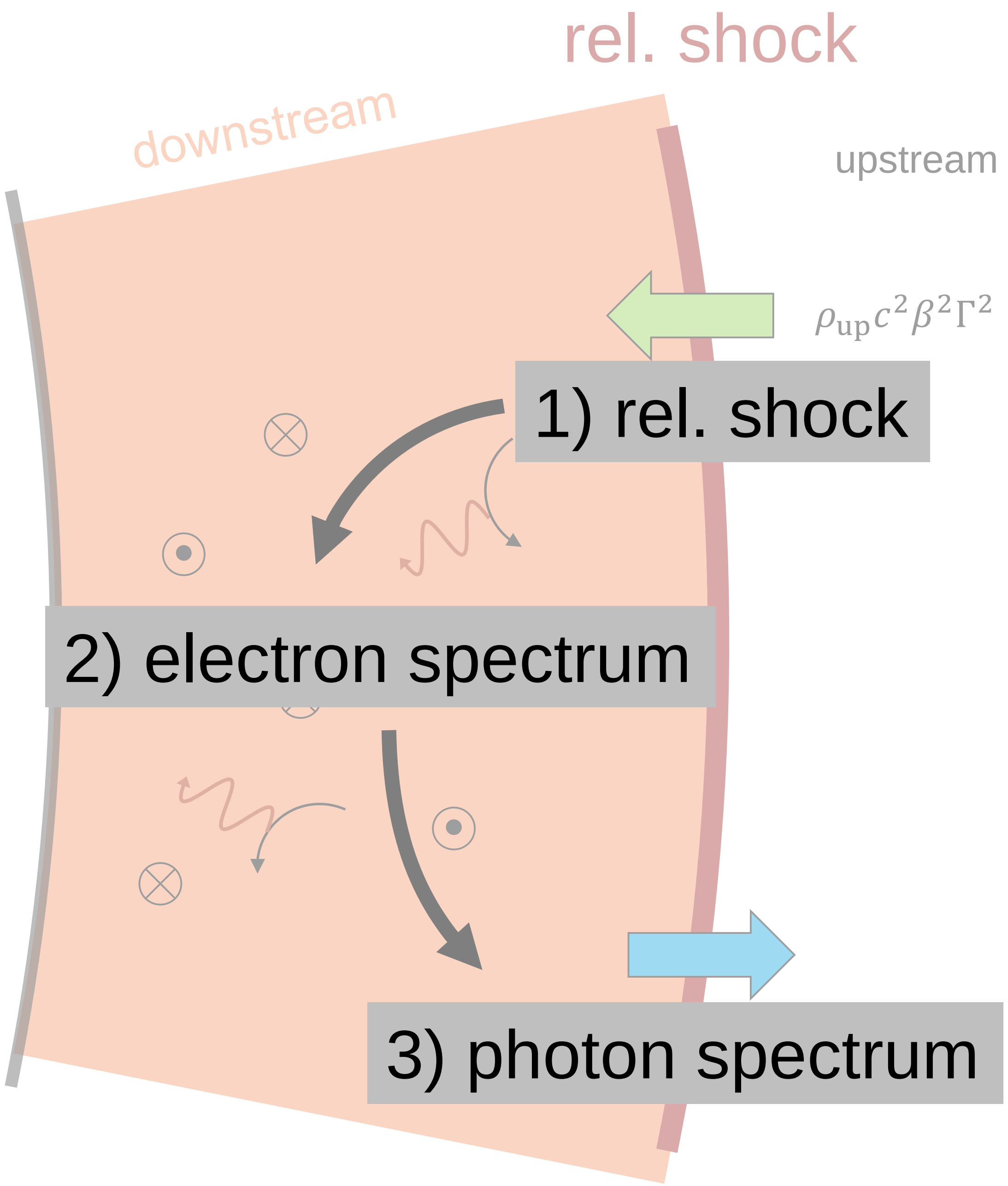
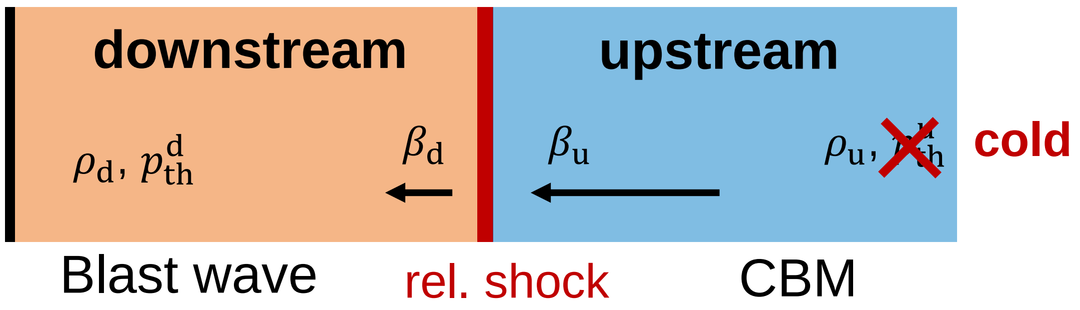


see e.g. Piran 2005 for a detailed review

1) Relativistic shocks



$$p^\mathrm{u}_\mathrm{ram} = c^2 \beta_\mathrm{u}^2 \Gamma_\mathrm{u}^2 w_\mathrm{u}$$

cold case:
enthalpy density $w_\mathrm{u} \approx \rho_\mathrm{u}$

$\rightarrow$

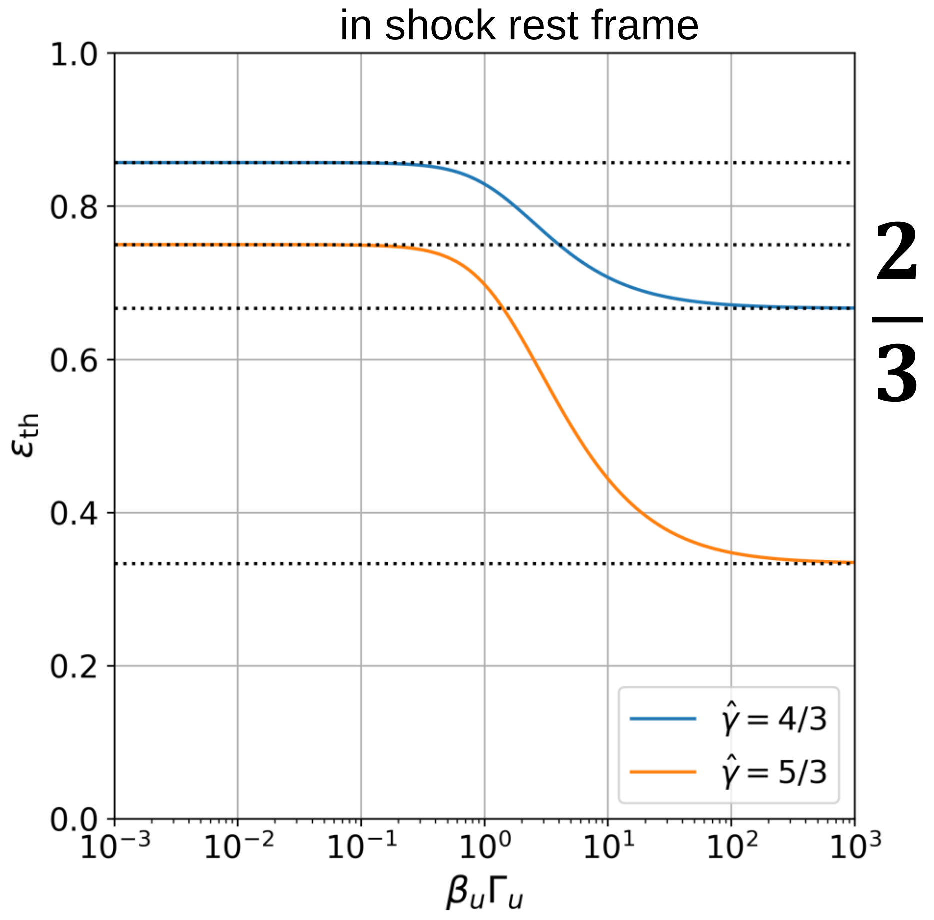
p^d_th $\quad \varepsilon_\mathrm{th} = \frac{2}{3}$

$p^\mathrm{d}_\mathrm{ram}$ $\quad \varepsilon_\mathrm{ram} = \frac{1}{3}$

$p^\mathrm{d}_\mathrm{e,non-th}$ $\quad \varepsilon_\mathrm{e}$ =few %?

$p^\mathrm{d}_\mathrm{p,non-th}$ $\quad \varepsilon_\mathrm{p}$ =few %?

p^d_B $\quad \varepsilon_\mathrm{B} = 10^{-4} - 10^{-2}$??



$$\varepsilon_\mathrm{X} = \frac{p^\mathrm{d}_\mathrm{X}}{p^\mathrm{u}_\mathrm{ram}}$$

(can also define ε via downstream energy density)

Magnetic field

- energy conservation:

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

  $\rightarrow t_{obs} = 90s, n_{ISM} = 1cm^{-3}$

  $\rightarrow \Gamma \sim 90$

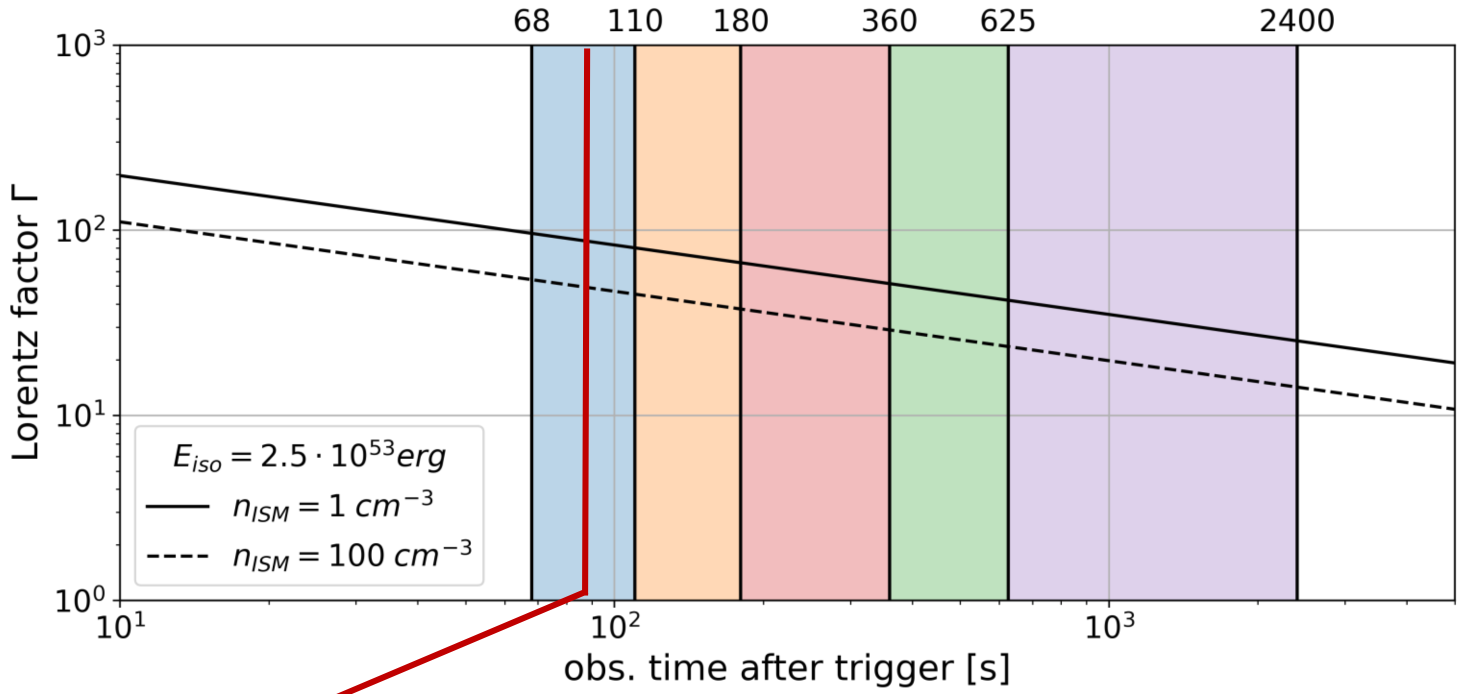
- ram pressure (SRF):

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

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

  $\rightarrow \varepsilon_B \sim 10^{-4} \rightarrow B \sim 0.1G$

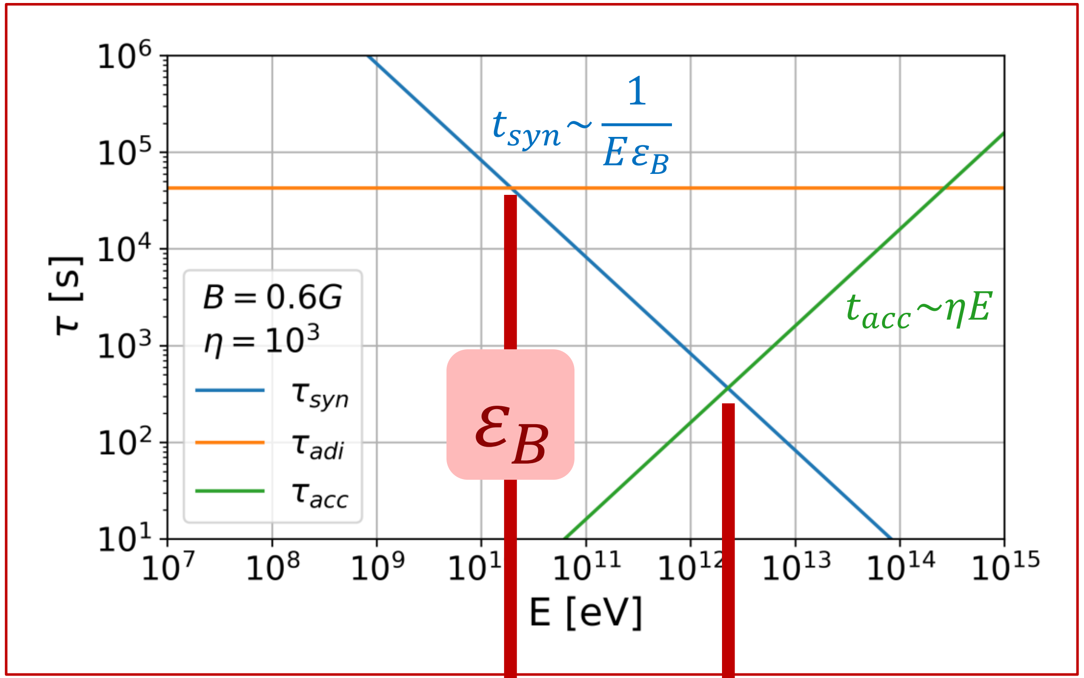
  $\rightarrow \varepsilon_B \sim 10^{-2} \rightarrow B \sim 1G$



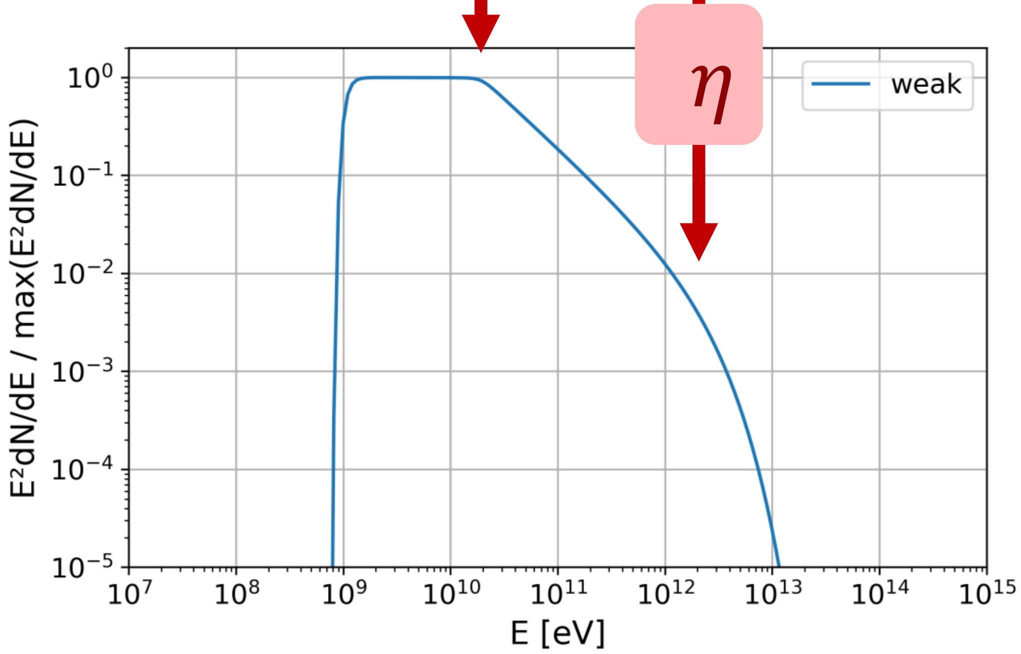
2) Electron spectrum

- quasi-steady state:

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

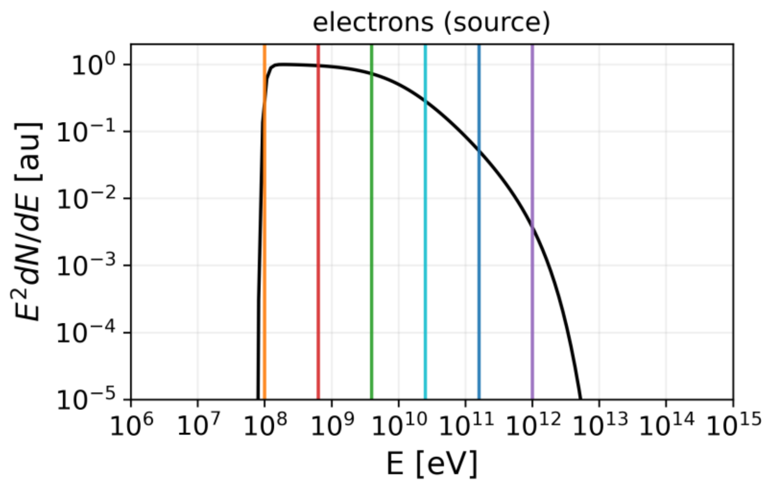


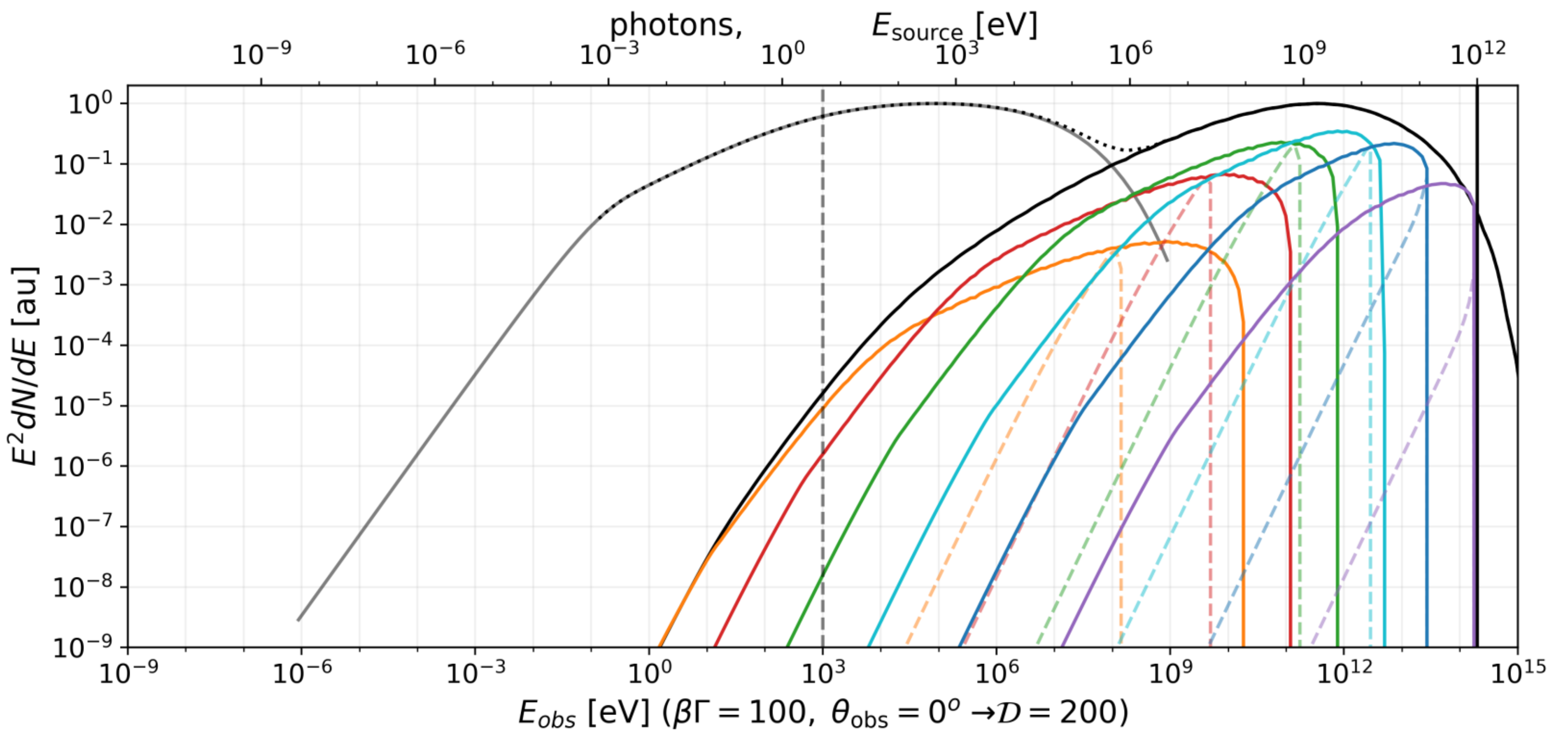
power law injection
spectral index $p \approx 2$



3) Photon Spectrum: Synchrotron Self-Compton (SSC)

→ Convolve electron spectrum with radiation kernel



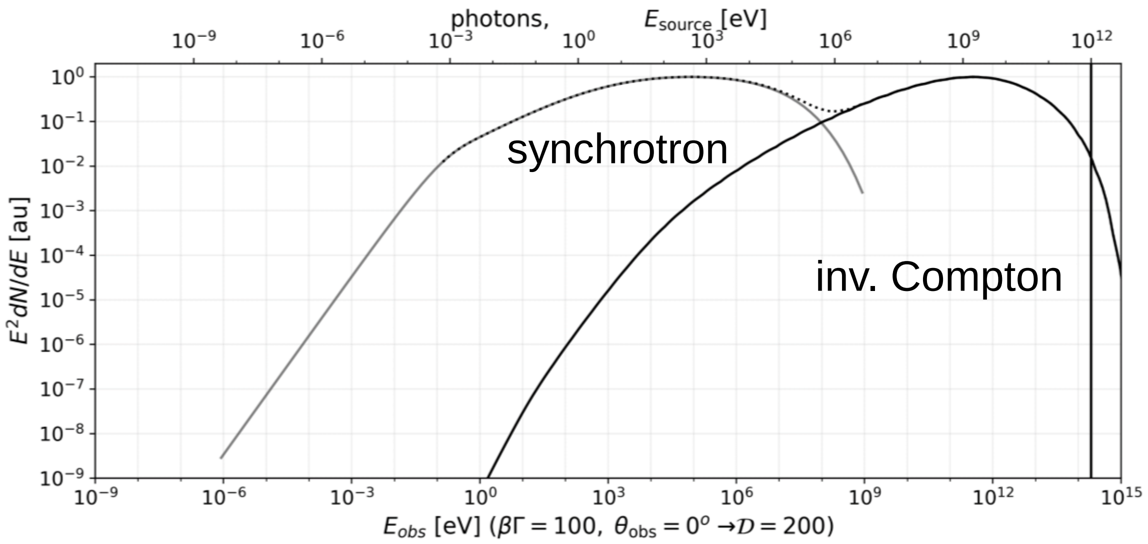


Reduced SSC model

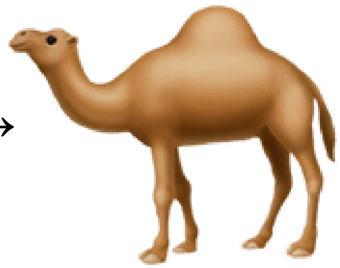
→ incorporates 2 types of solutions

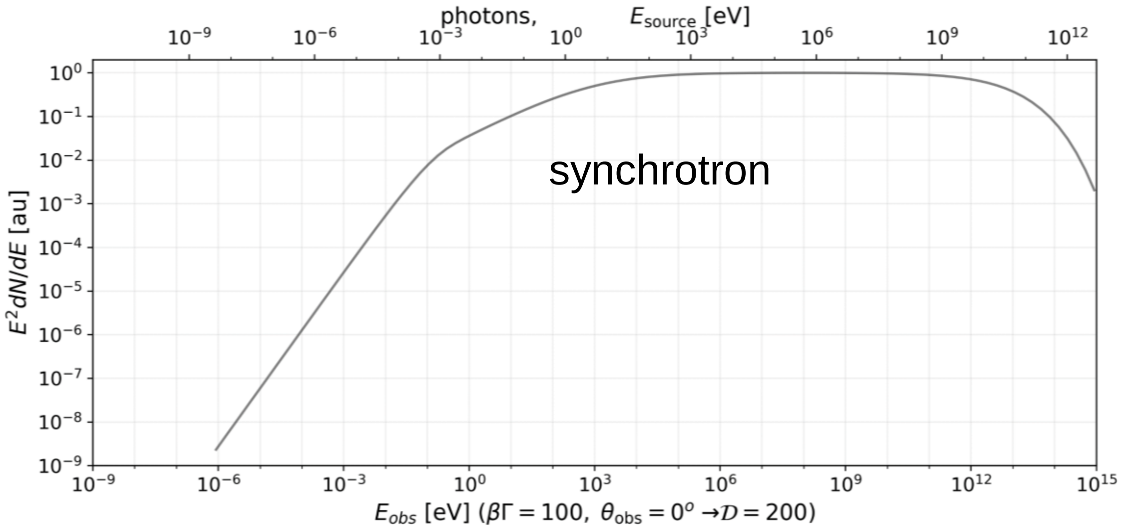
1. double hump solution (SSC):

→ 



2. single hump solution (syn. only)

→ 



Dromedary – single hump – syn. only – model

- extending a single synchrotron component up to TeV?

  → "just" increase max. electron energy

  → super-efficient acceleration $\eta \ll 1$

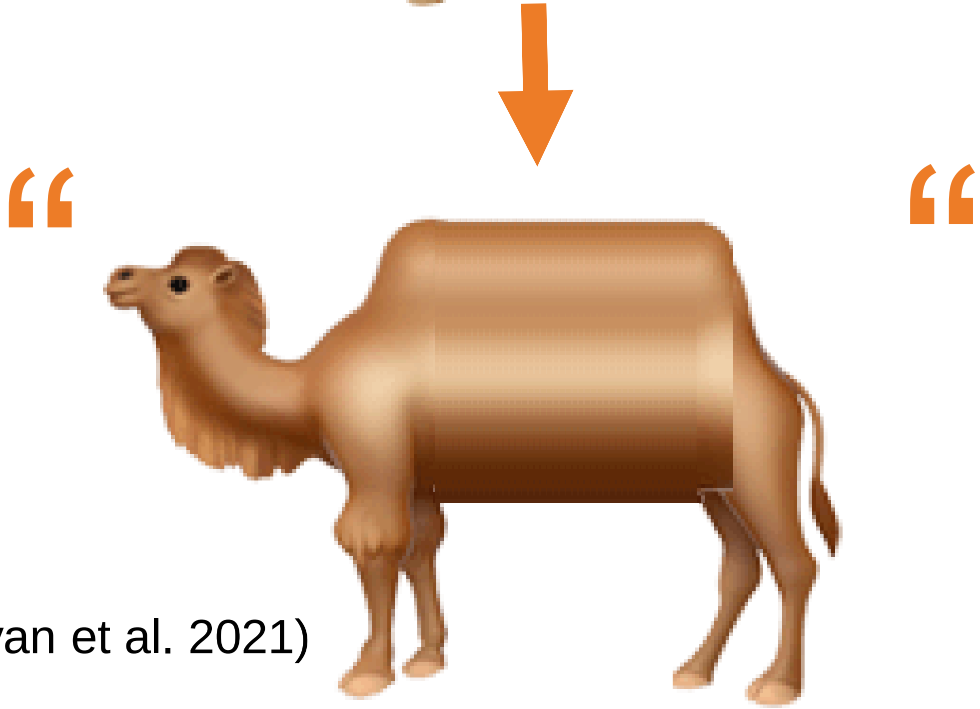
  → phenomenological description

- Problem: one zone model uses same magnetic field for

  1. confinement within acceleration zone
  2. creating radiation

  → **burn-off limit** $E^{\gamma}_{\max} \sim 100\ MeV$

- 2 zones – 2 field strengths? (e.g. Khangulyan et al. 2021)

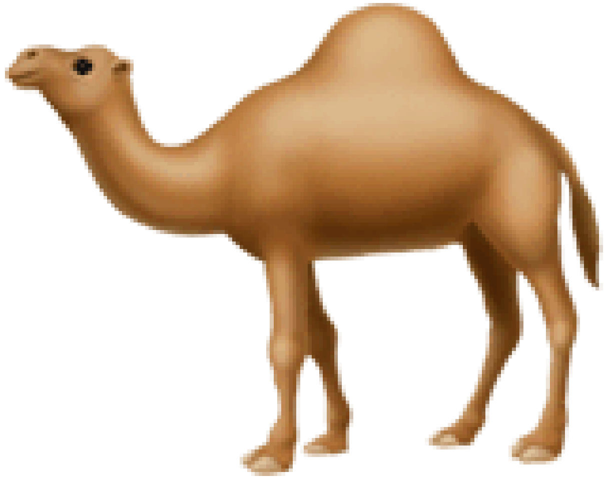


Specifying the Camel Question

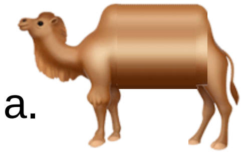
do we observe **two humps**

or

do we need to think about ways to **extend the single hump** to VHE energies?



a.k.a.



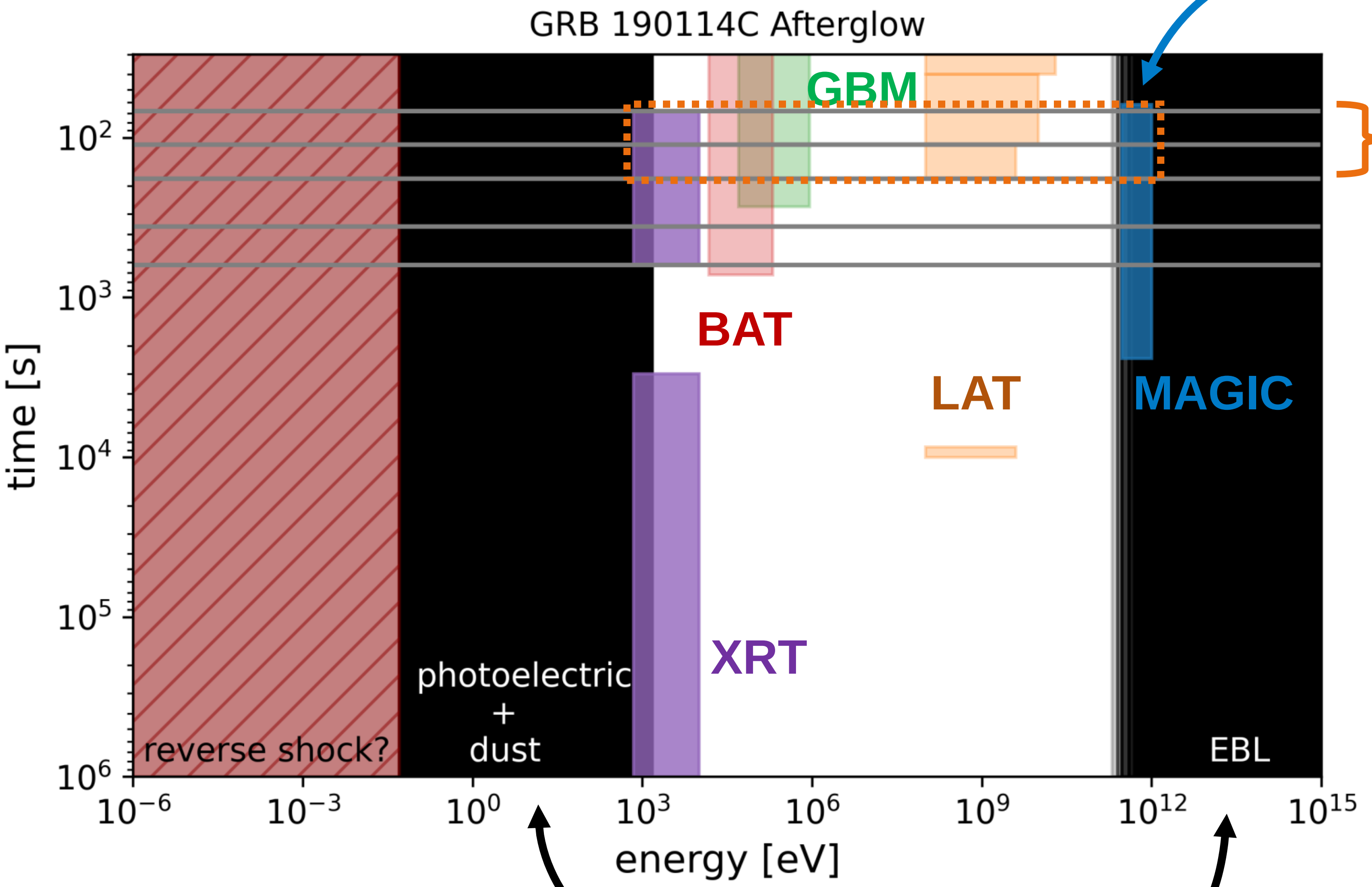
GRB 190114C

or

?

GRB 190114C (MAGIC 🐫)

rapid follow up from MAGIC (1-40min)

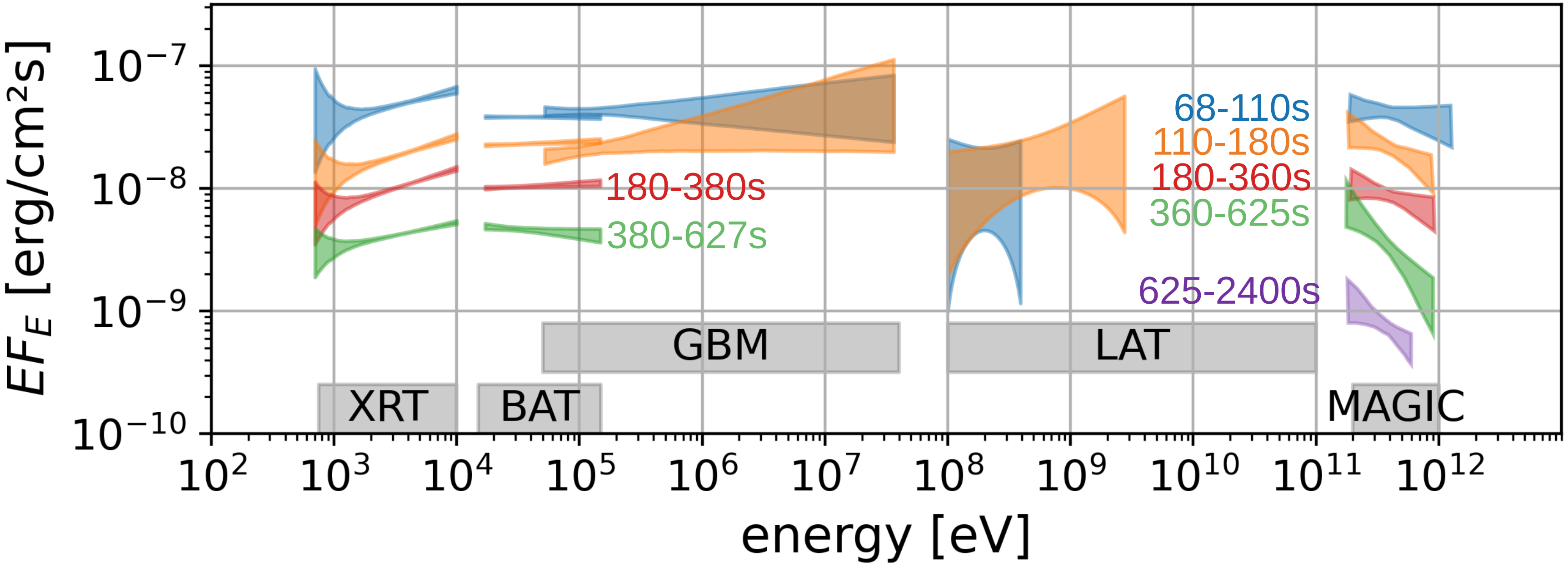


simultaneous data from 5 instruments!

exponentially absorbed!
(intermediate redshift $z = 0.42$)

GRB 190114C (MAGIC 🐫)

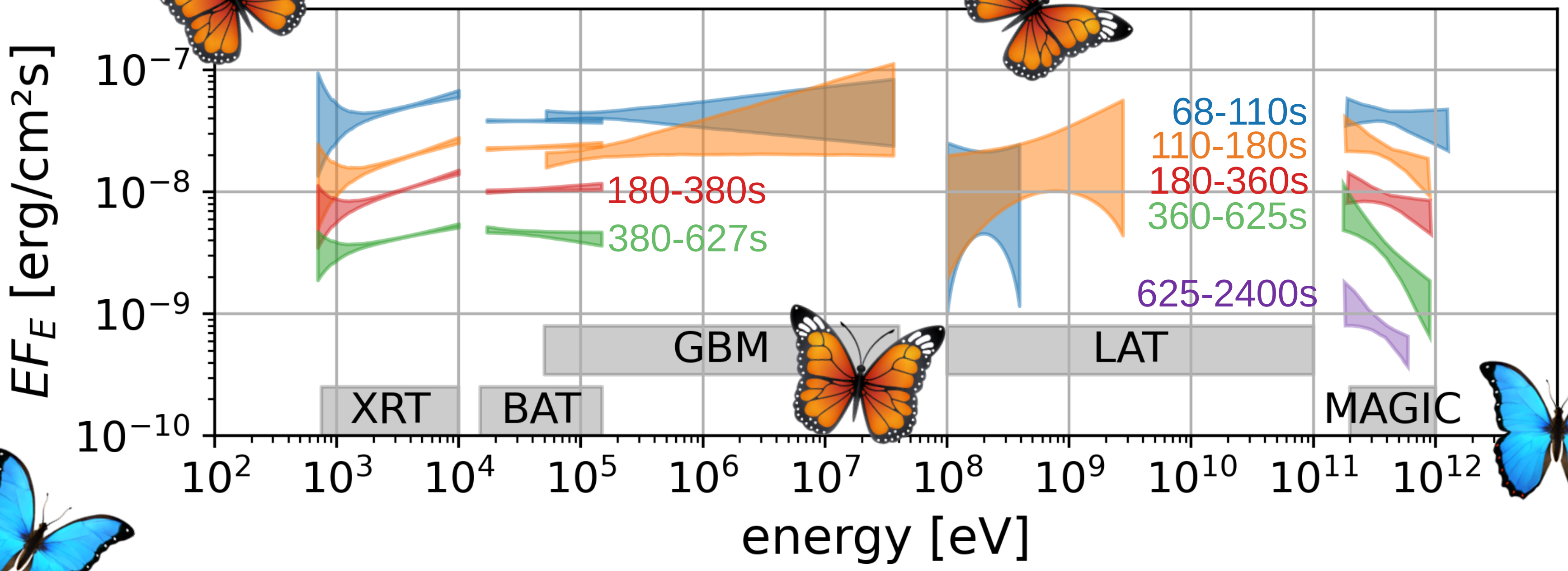
compare Ajello et al. 2020, MAGIC Coll. et al. 2020



Dromedary?

- remarkably flat over 9 orders of magnitude in energy!

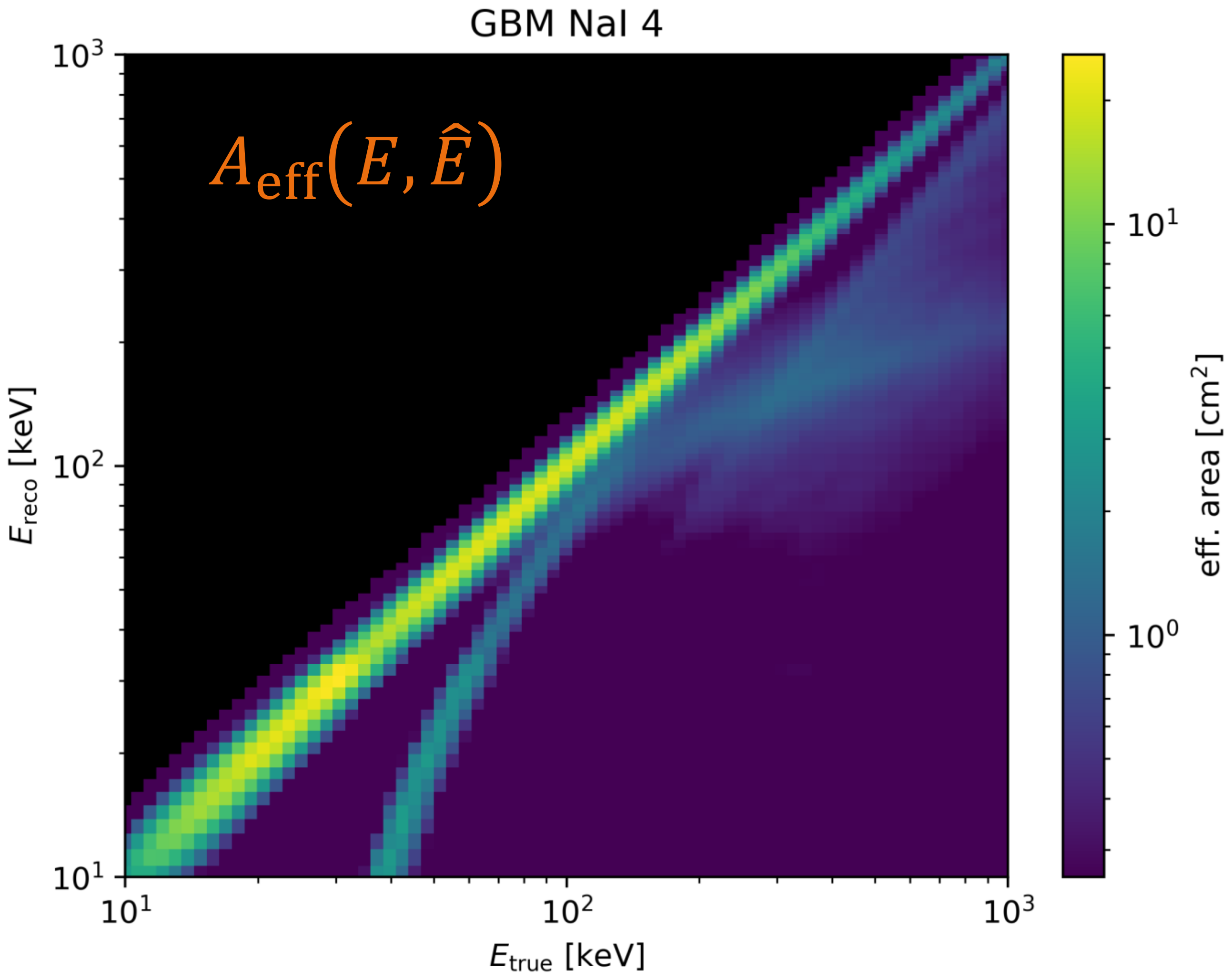
GRB 190114C (MAGIC 🐫)



- just looking at lovely butterflies has no statistical meaning…

→ combined fit of all instruments

Instrument response for single detector



- detector consists of many energy channels

  → **energy dispersion**

- we cannot simply invert (unfold) this matrix

  → **forward folding**

Statistical answer from forward folding

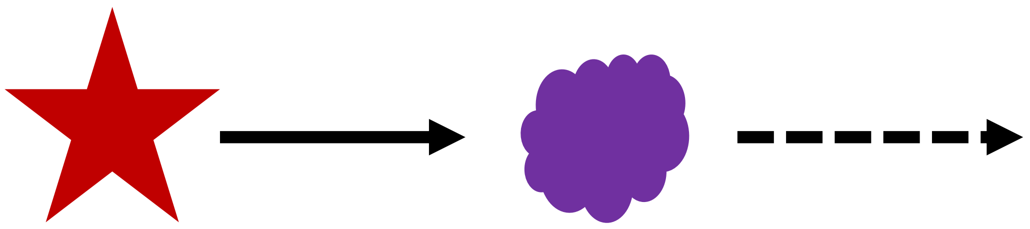
→ model

$$\frac{\mathrm{d}N_{\mathrm{source}}}{\mathrm{d}E\ \mathrm{d}t\ \mathrm{d}A}\left(\hat{E}\right)$$

Statistical answer from forward folding

→ model absorbed

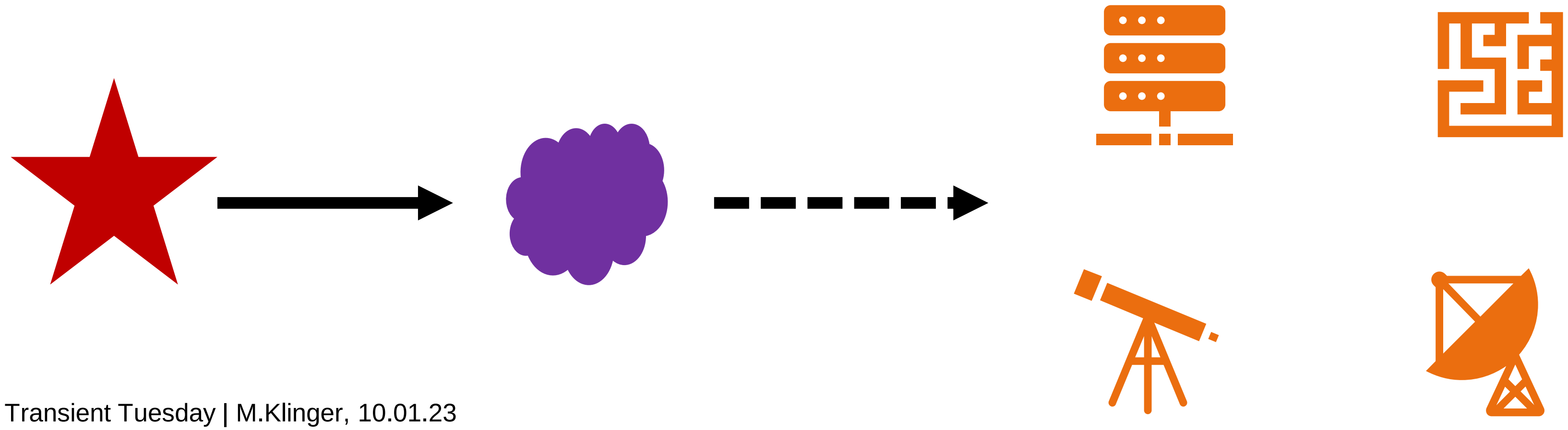
$$\frac{\mathrm{d}N_{\mathrm{source}}}{\mathrm{d}E\ \mathrm{d}t\ \mathrm{d}A}\left(\hat{E}\right)\ \exp\left(-\tau\left(\hat{E}\right)\right)$$



Statistical answer from forward folding

→ model absorbed measurements of detectors

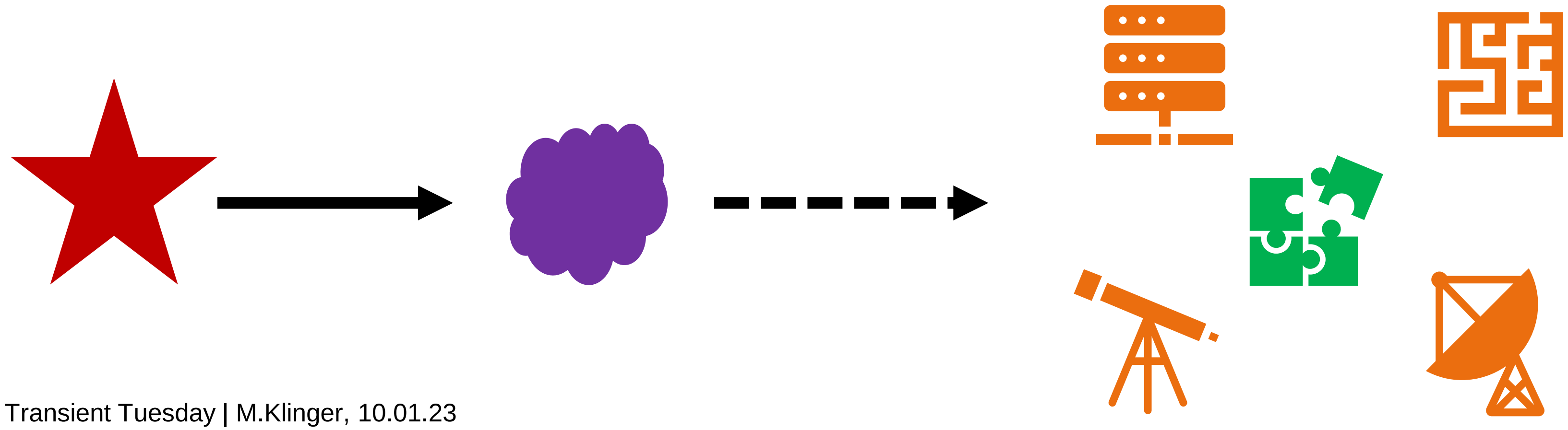
$$\text{Counts rate }(E) = \int \mathrm{d}\hat{E}\ \frac{\mathrm{d}N_{\mathrm{source}}}{\mathrm{d}E\ \mathrm{d}t\ \mathrm{d}A}\left(\hat{E}\right)\ \exp\left(-\tau\left(\hat{E}\right)\right)\ A_{\mathrm{eff}}\left(E,\hat{E}\right)$$



Statistical answer from forward folding

→ model absorbed measurements of multiple detectors

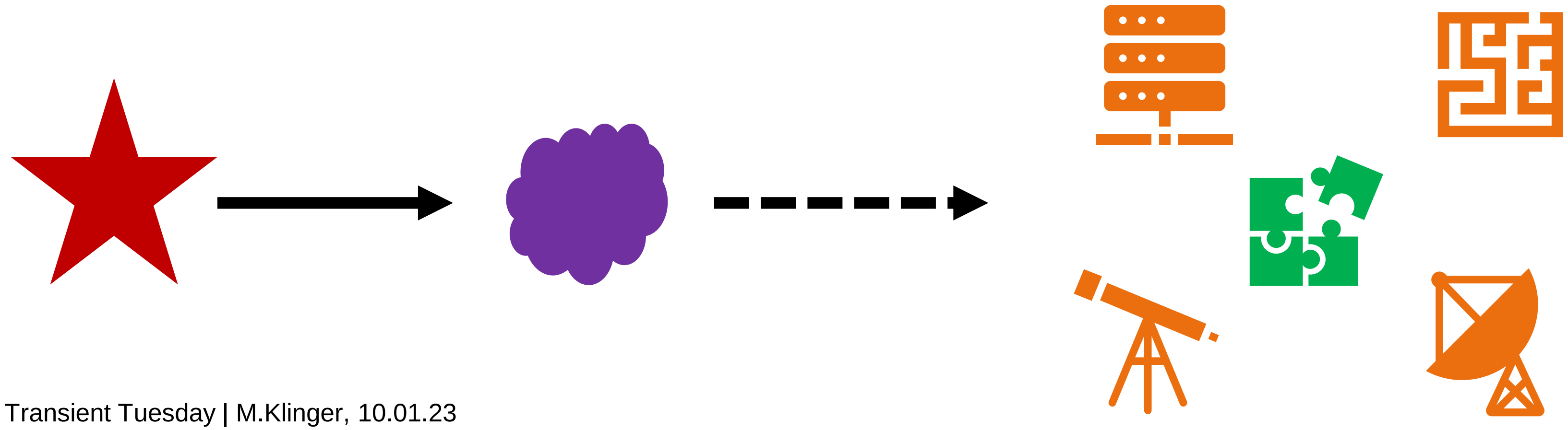
$$\text{Counts rate } (E) = \int \mathrm{d}\hat{E}\ \frac{\mathrm{d}N_{\mathrm{source}}}{\mathrm{d}E\ \mathrm{d}t\ \mathrm{d}A}(\hat{E})\ \exp\left(-\tau(\hat{E})\right)\ A_{\mathrm{eff}}(E,\hat{E})\ c_{\mathrm{sys}}$$



Statistical answer from forward folding

→ fit model to absorbed measurements of multiple detectors

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



Forward folding

→ fit model to absorbed measurements of multiple detectors

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

and

Background rate

different detectors have different statistics!

Open source software is already there

framework to fit

- multiple detectors
- on the counts level (proper statistics)
- with different fitting algorithms (Bayesian/Frequentist)
- …

3ML Multi-Mission Maximum Likelihood Framework

→ https://threeml.readthedocs.io/en/stable/index.html#

A **Python** package for **gamma-ray** astronomy

→ https://gammapy.org/

Fit ?

we used **UltraNest**
https://johannesbuchner.github.io/UltraNest/index.html

- Bayesian approach

  → $posterior = \frac{likelihood}{evidence} \cdot prior$

  → (sometimes log) uniform priors

  → evidence: $Z = \int d\vec{\theta}\ likelihood \cdot prior$
  (→ likelihood averaged over parameter space weighted with priors)

- sample posterior

  → detect multiple maxima?

- model comparison via Bayes factor Z_1/Z_2

  → quantitative way of measuring preference of model 1 over model 2

  → metric scale crucial

Structure for next few slides

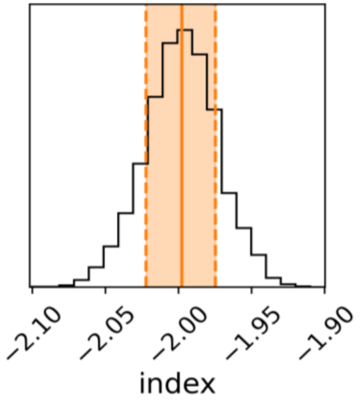
For first time bin (68-110s):

1. **Intuition:** Power law best fit for each instrument
2. **Full result:** Full likelihood analysis with all instruments, using reduced afterglow radiation model
3. **Stability:** examine significance of result from stability under perturbations

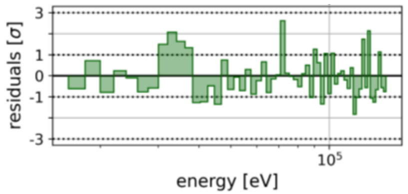
Intuition from power laws

BAT

15-150 keV



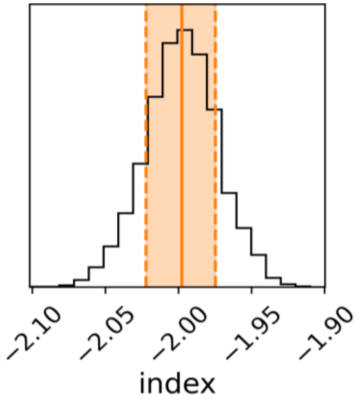
$-1.998^{+0.023}_{-0.024}$



Intuition from power laws

BAT

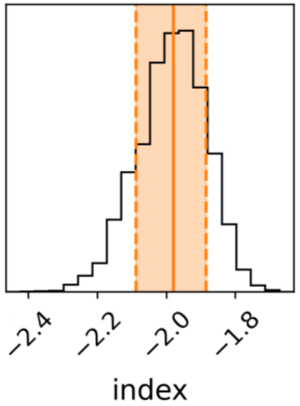
15-150 keV



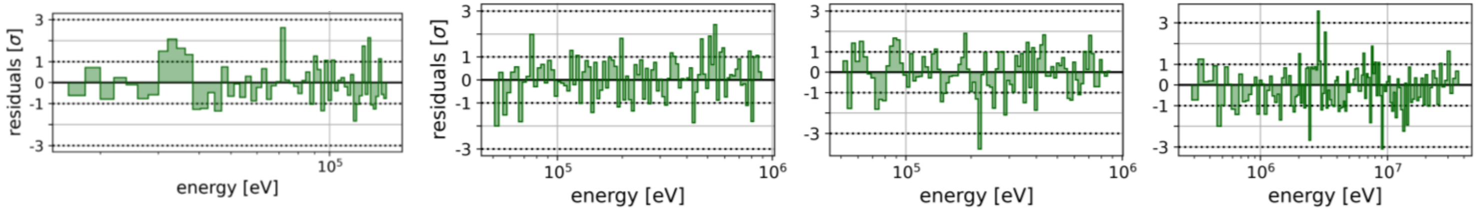
$-1.998^{+0.023}_{-0.024}$

GBM

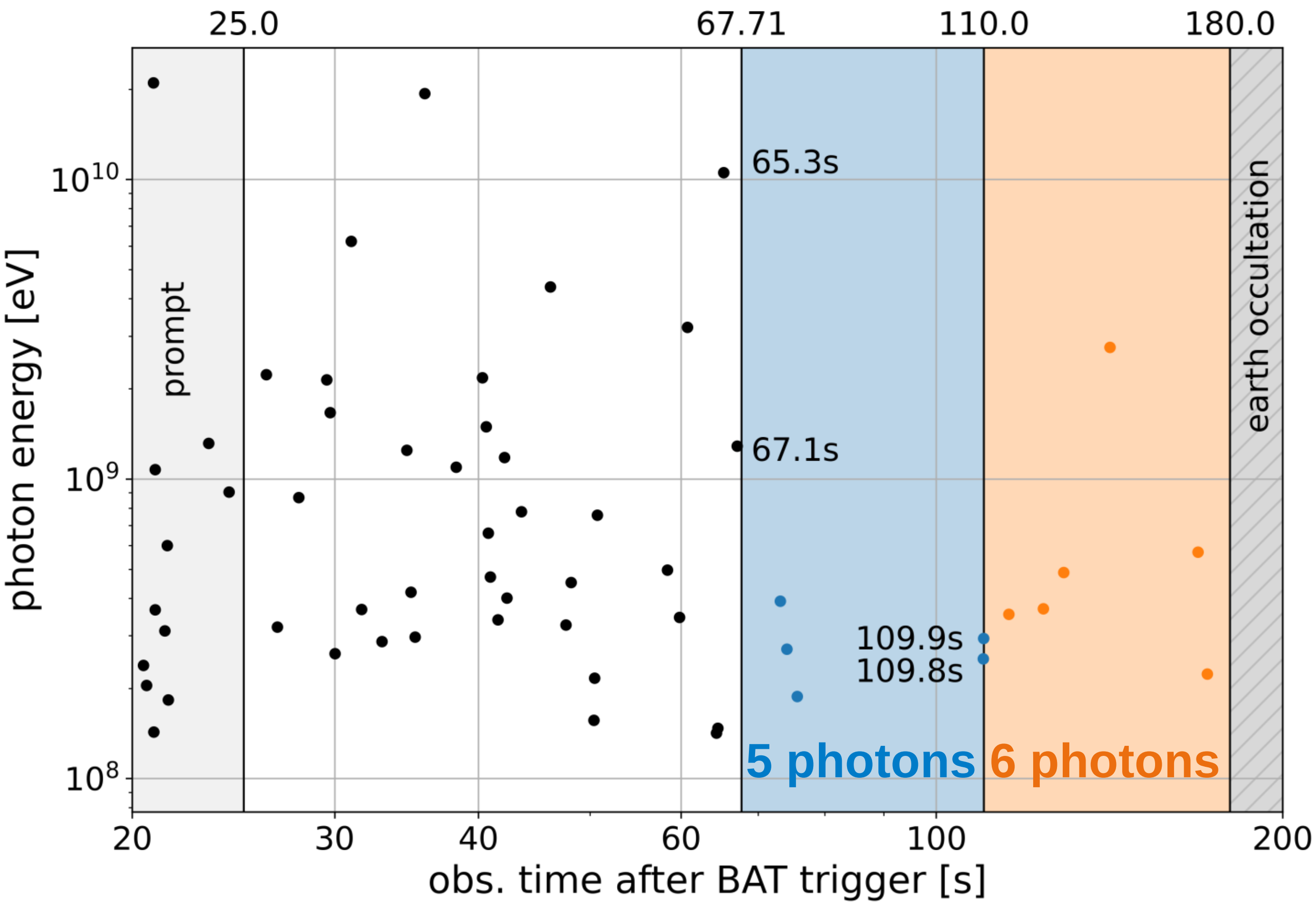
50 keV - 40 MeV



-1.98 ± 0.1

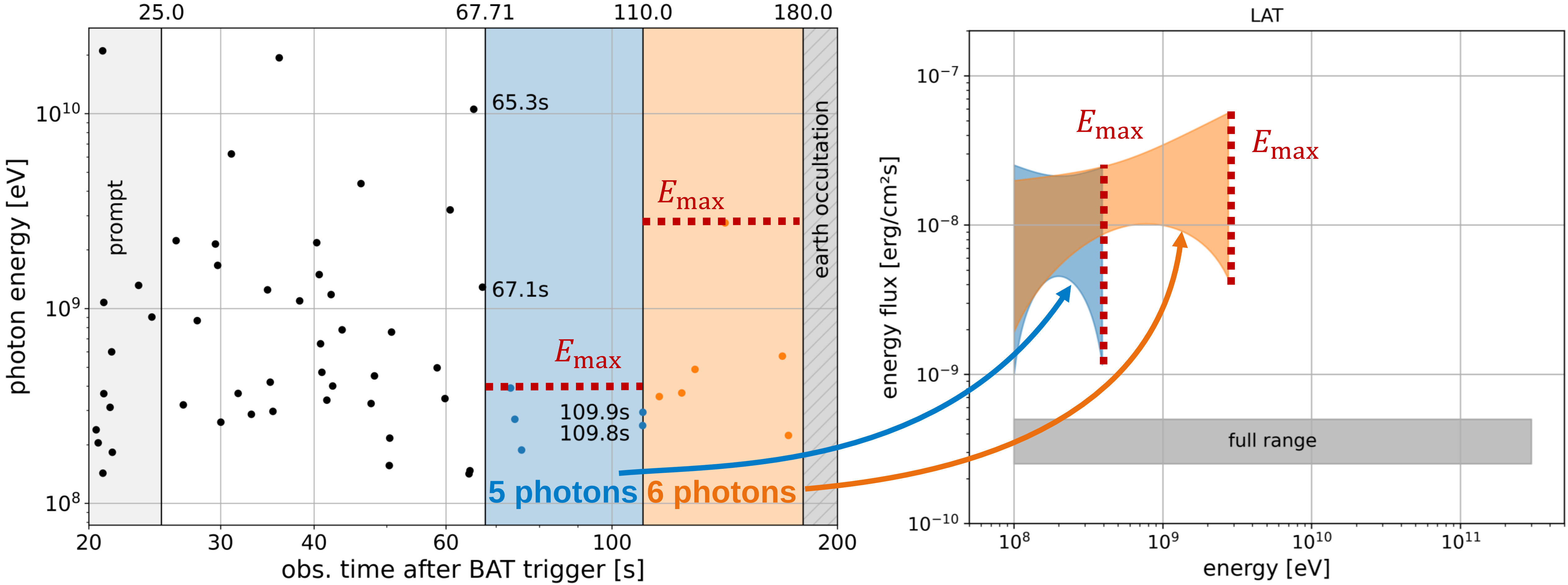


Fermi LAT



→ single photon counter

Fermi LAT



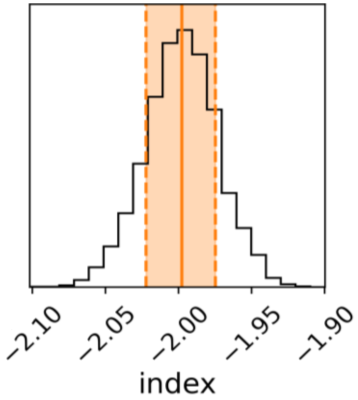
→ single photon counter

→ spectral index not really constrained

Intuition from power laws

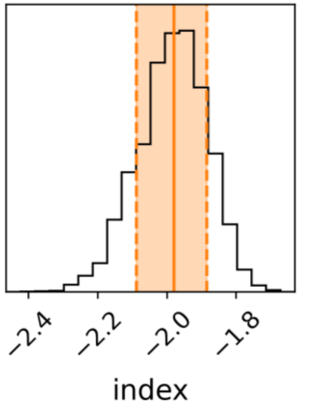
BAT

15-150 keV



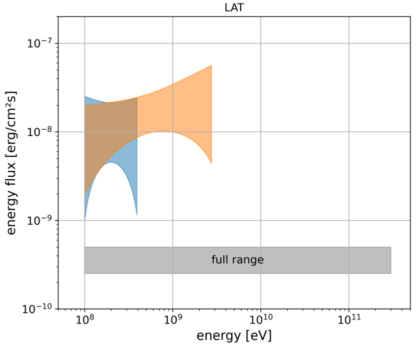
GBM

50 keV - 40 MeV



LAT

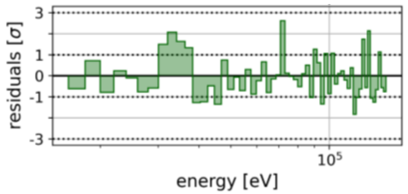
> 100 MeV

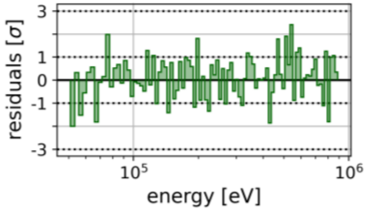


$-1.998^{+0.023}_{-0.024}$

-1.98 ± 0.1

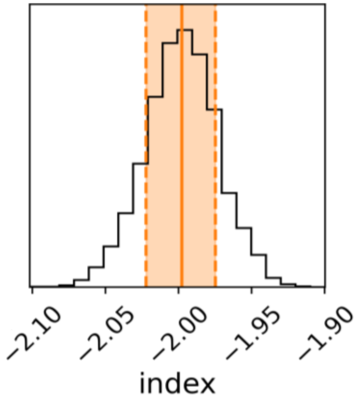
-2 ± 1

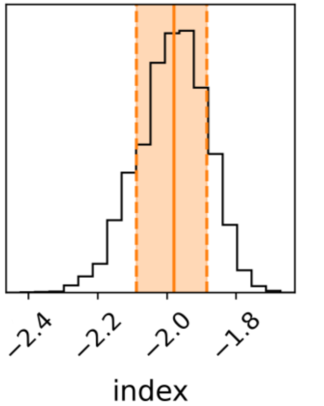


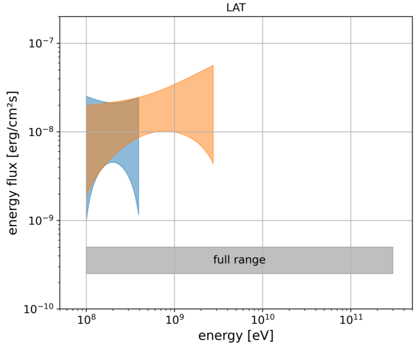


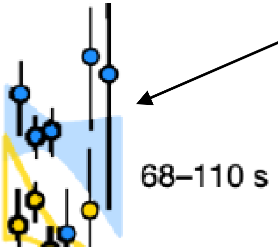
Intuition from power laws

BAT	**GBM**	**LAT**	**MAGIC**
15-150 keV	50 keV - 40 MeV	> 100 MeV	0.1-1 TeV





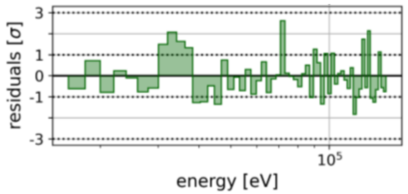


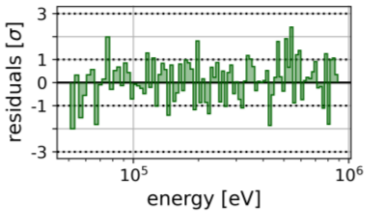


stat. uncertainties only!

MAGIC Nature 575 (2019)

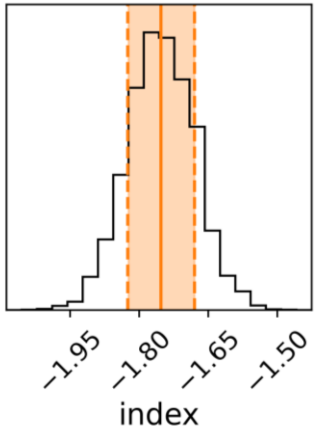
$$-1.998^{+0.023}_{-0.024} \qquad -1.98 \pm 0.1 \qquad -2 \pm 1 \qquad -2.16^{+0.29}_{-0.31}(\mathrm{stat}) \pm 0.2(\mathrm{sys})$$



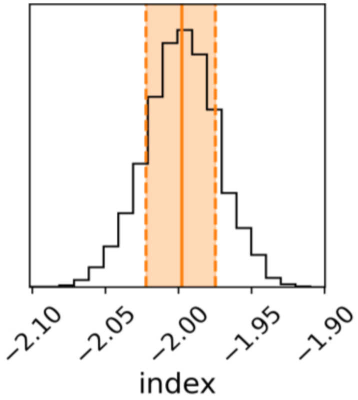


Intuition from power laws

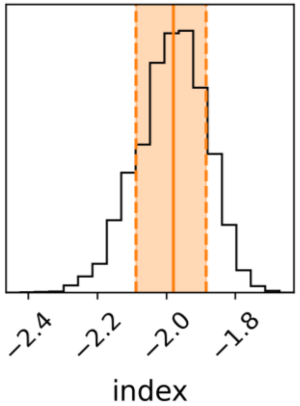
XRT
0.7-10 keV



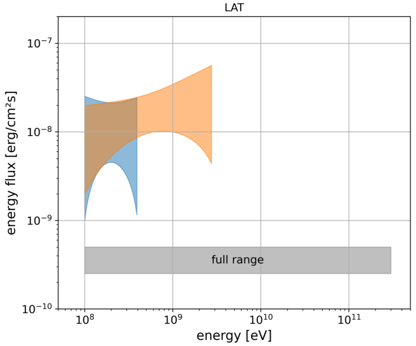
BAT
15-150 keV



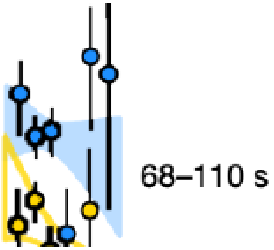
GBM
50 keV - 40 MeV



LAT
> 100 MeV



MAGIC
0.1-1 TeV



MAGIC Nature 575 (2019)

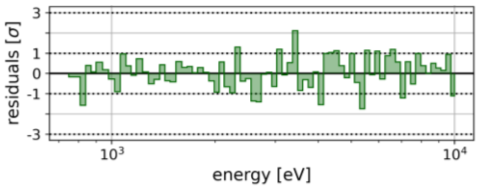
-1.75 ± 0.07

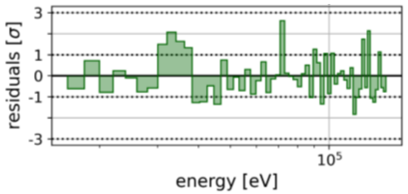
$-1.998^{+0.023}_{-0.024}$

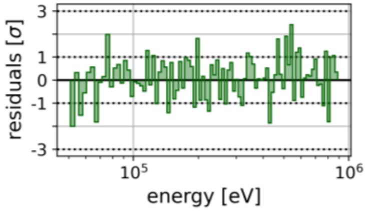
-1.98 ± 0.1

-2 ± 1

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





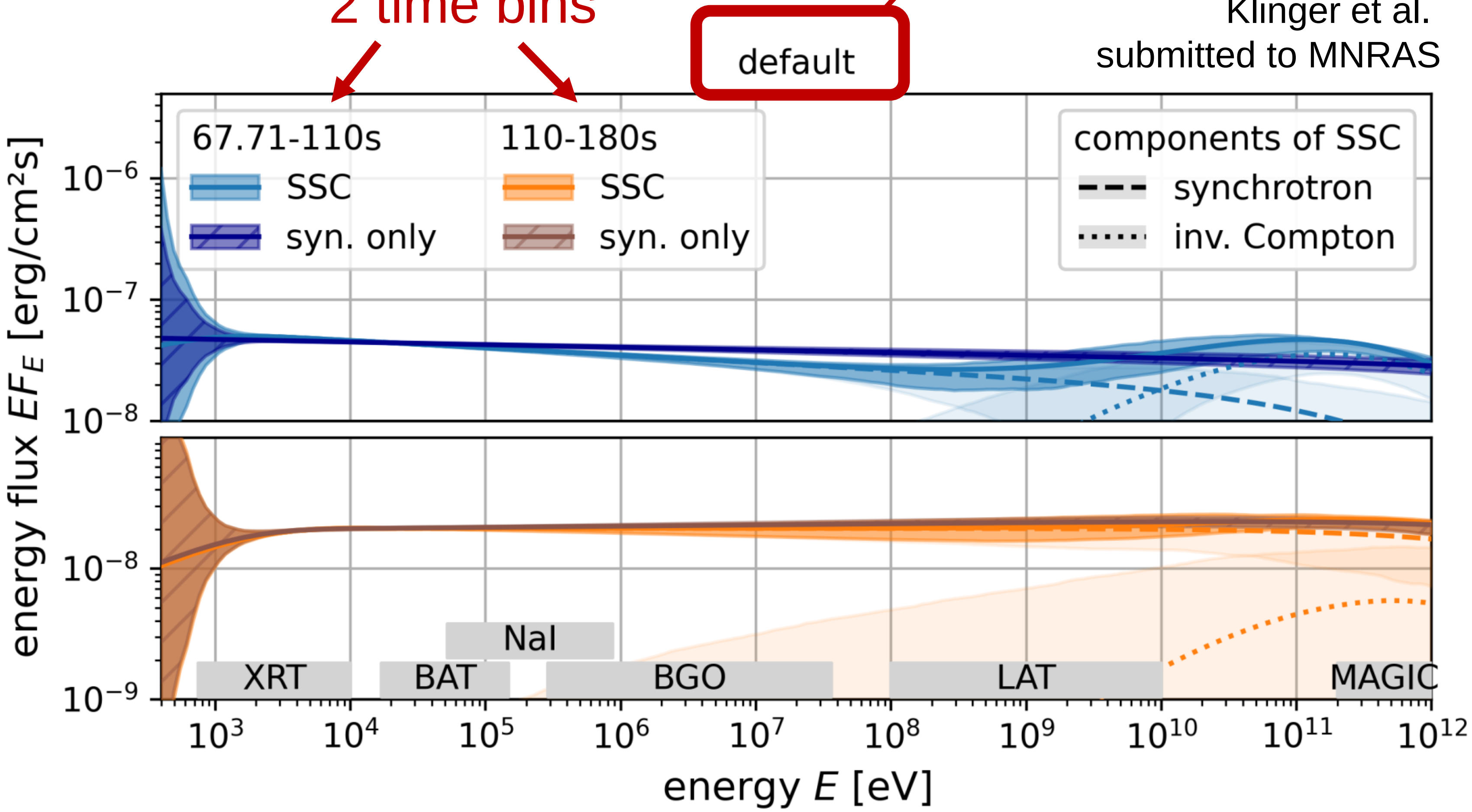


Fitting the reduced SSC model

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

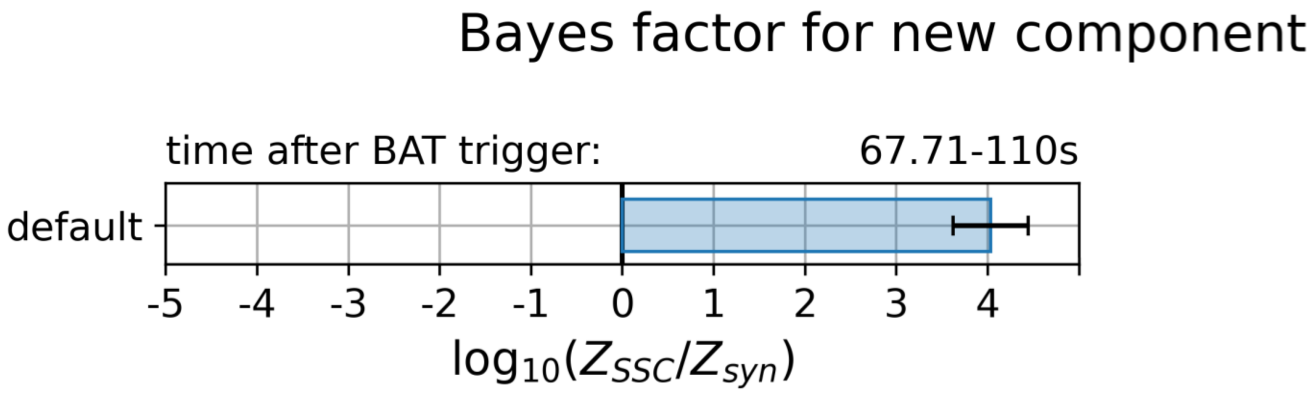
Klinger et al.
submitted to MNRAS

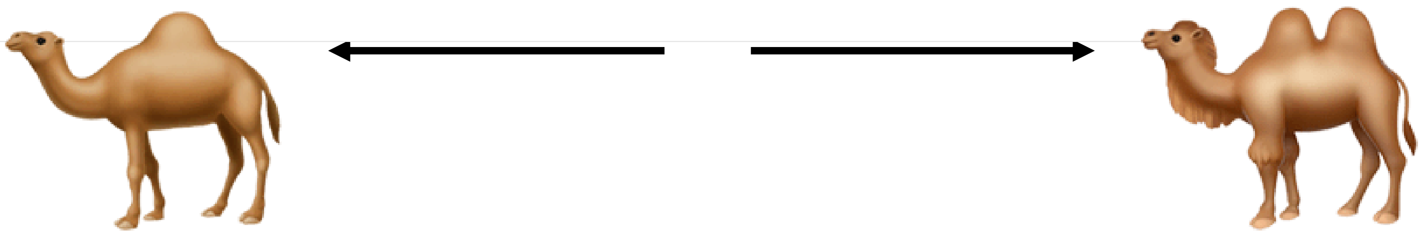
2 time bins



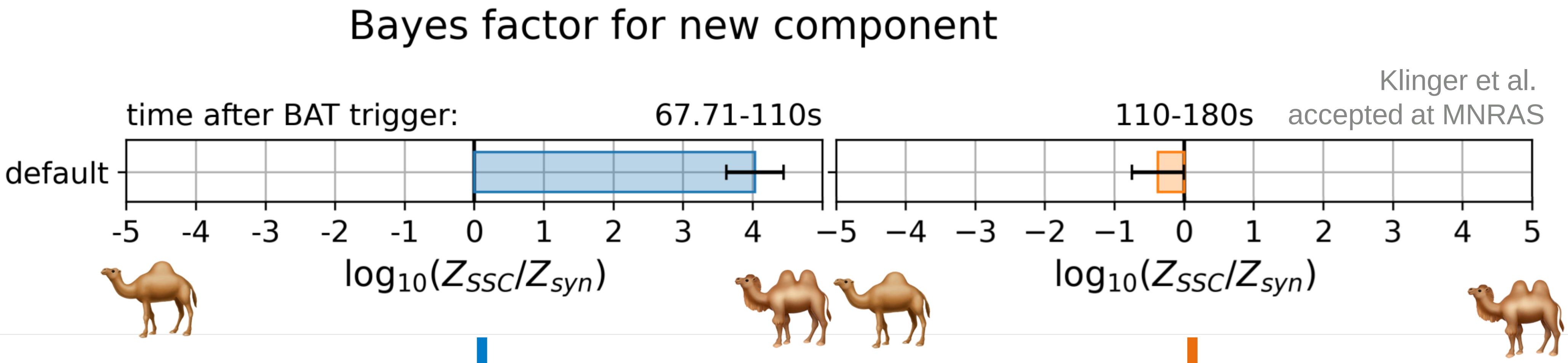
flat over 9 orders of magnitude!

Preference for new component?





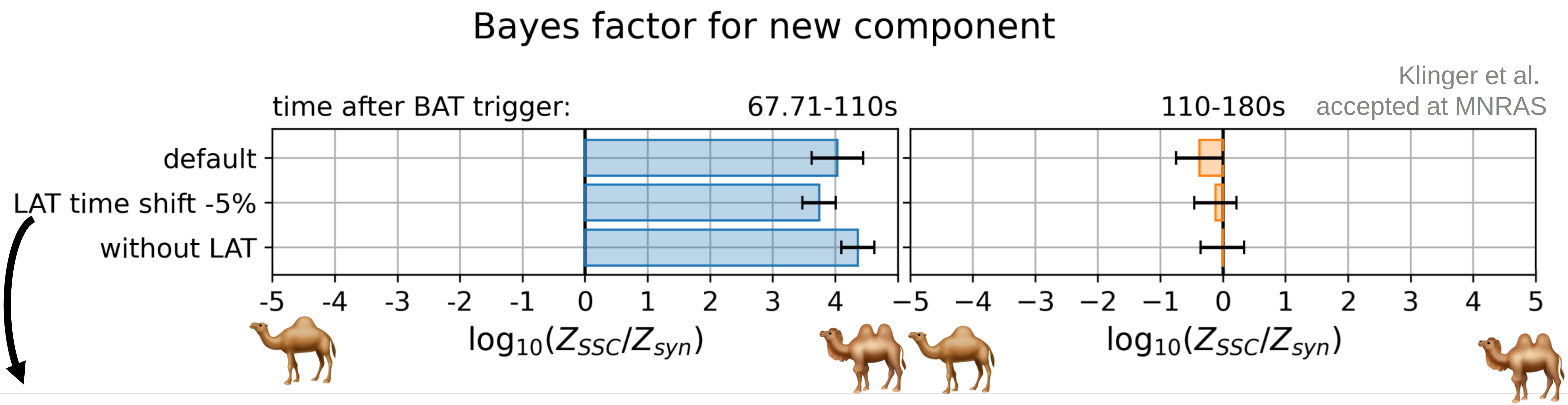
Preference for new component?



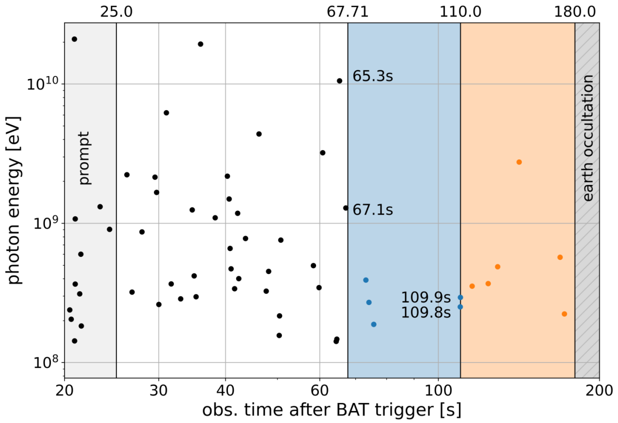
yes

no

Stability of Preference: LAT



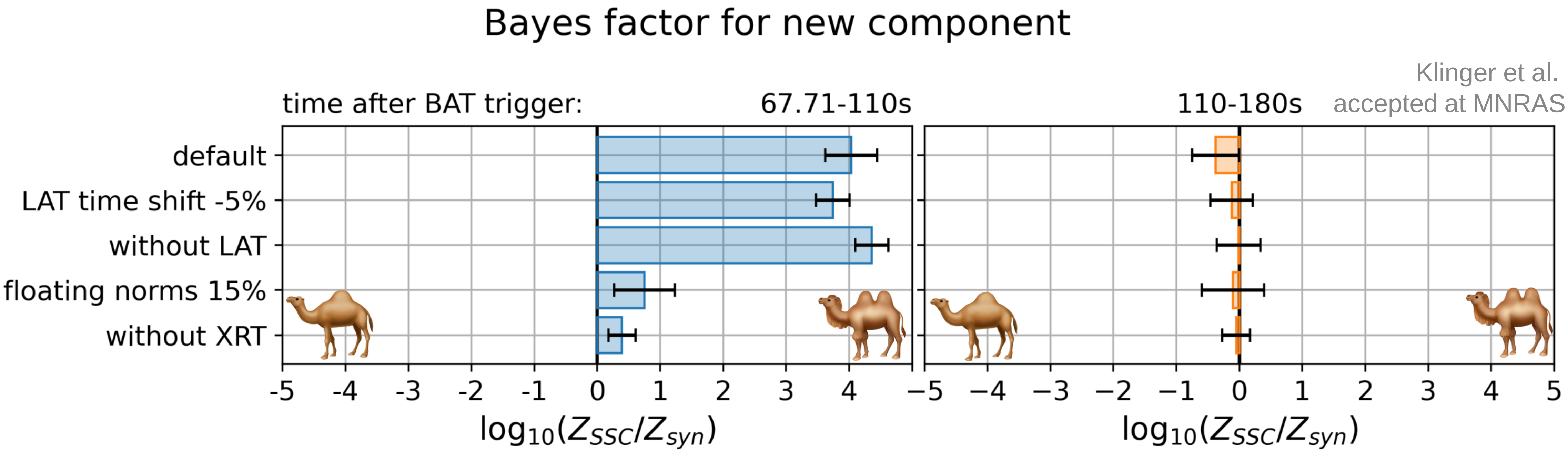
Klinger et al.
accepted at MNRAS



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

→**LAT not very strong**

Stability of Preference: XRT

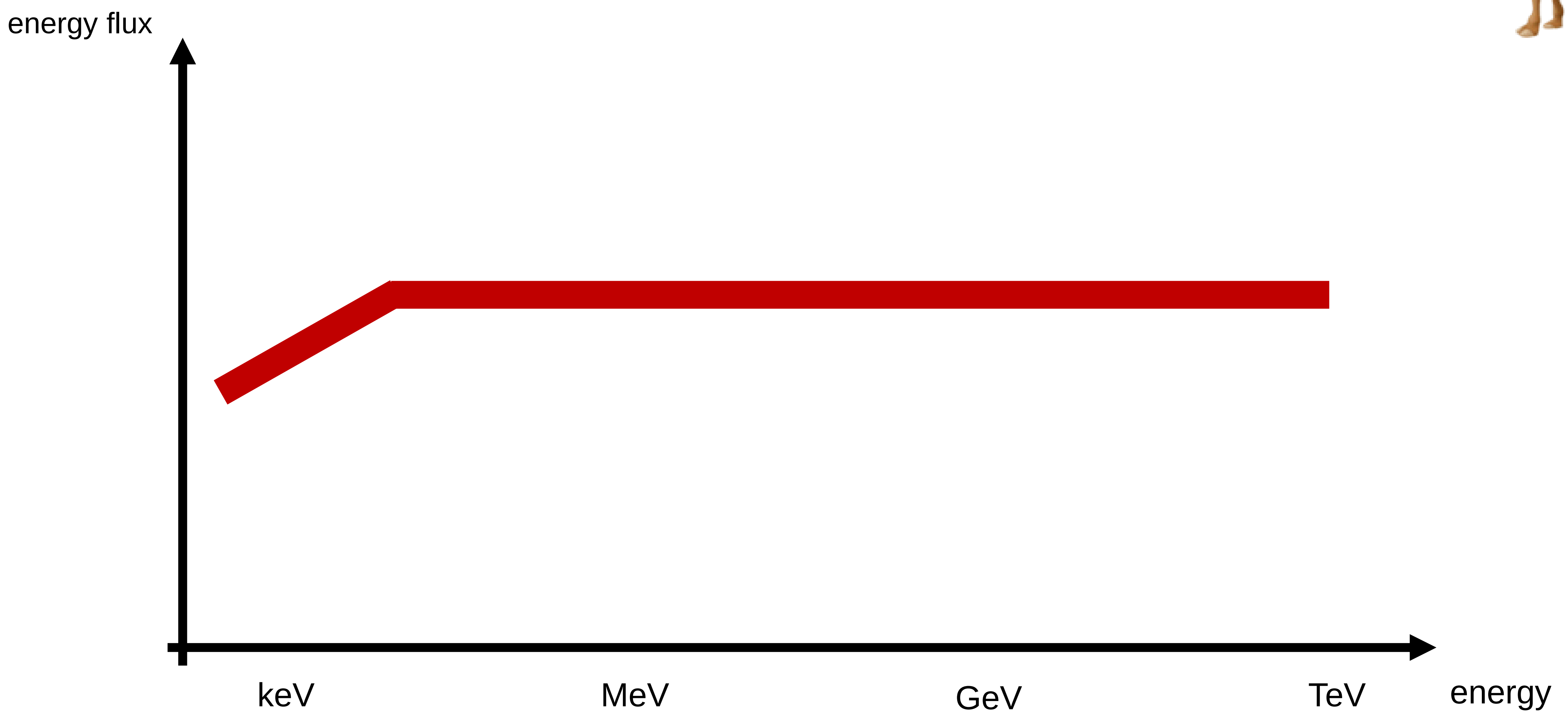


Klinger et al.
accepted at MNRAS

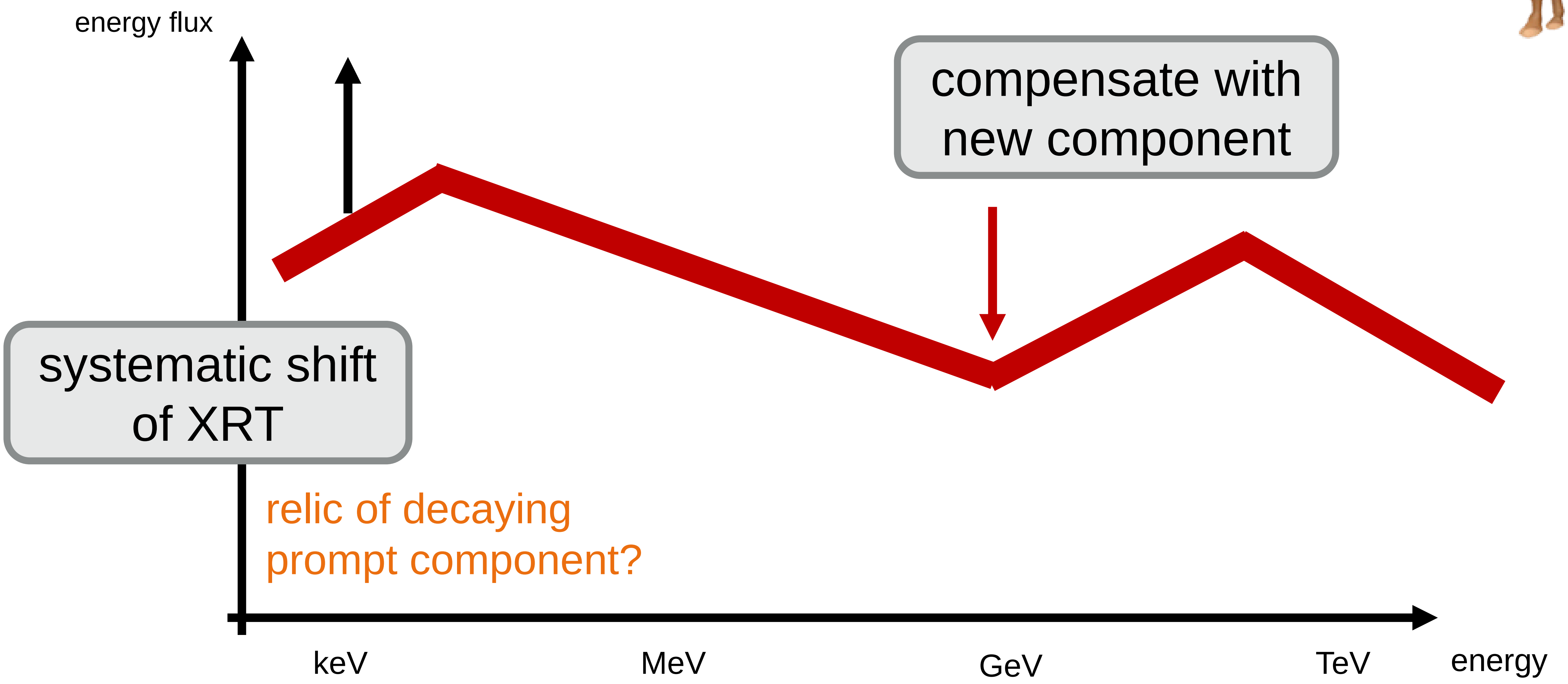
- systematic cross calibration uncertainty limited to 15% (a.k.a. floating norm or effective area correction)
- leave out XRT completely

→ **XRT drives new component!**

XRT driving the new component



XRT driving the new component



Conclusions on the Camel question

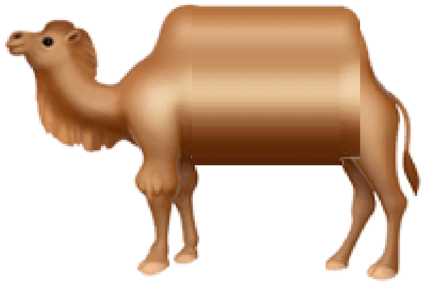
- do we observe **two humps** or do we need to think about ways to extend the single hump to VHE energies?

→ we can't tell clearly for GRB 190114C

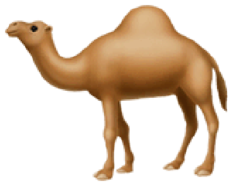
→ consistent with single hump preference for GRB 190829A

→ GRB 221009A seems to be flat as well

- why are bumps at same height?
  → Klein-Nishina suppression requires fine tuning/ regulating process in SSC picture
- second component of hadronic origin?



a.k.a.



- how does bump extend to such high energies?
- two zones?
- acceleration process?

Take away messages

- We need more **bright, nearby** GRBs (without moonlight!)
- We should get most out of the data by **fitting at the counts level**

  → we also need to share our instrument response functions…
- GRB 190114C is no clear camel type

  → **in particular no stable evidence for two bumps!**

  → **consistent with GRB 190829A**
- both models come with more questions
- lets see what GRB 221009A will tell us

Take away messages

- We need more **bright, nearby** GRBs (without moonlight!)
- We should get most out of the data by **fitting at the counts level**

  → we also need to share our instrument response functions…
- GRB 190114C is no clear camel type

  → **in particular no stable evidence for two bumps!**

  → **consistent with GRB 190829A**
- both models come with more questions
- lets see what GRB 221009A will tell us

Thank you!