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

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AP seminar

HELMHOLTZ WEIZMANN
RESEARCH SCHOOL
MULTIMESSENGER ASTRONOMY

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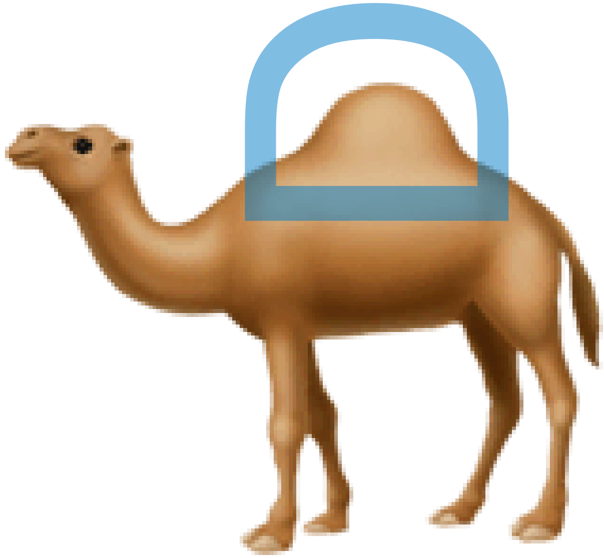
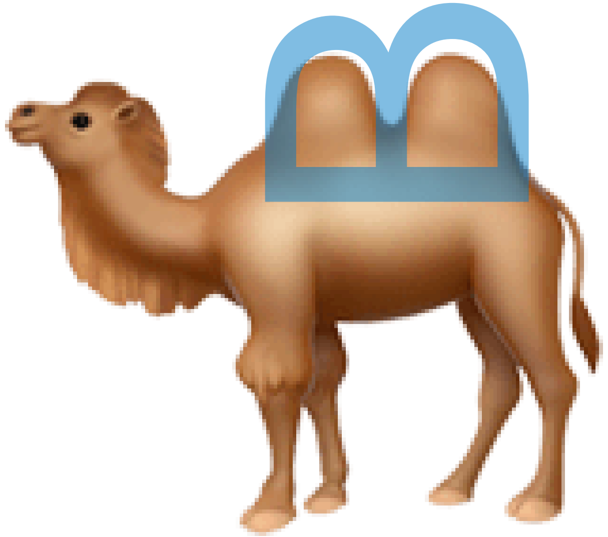
DESY.

Are gamma ray bursts…



Dromedaries

or



Bactrians

?

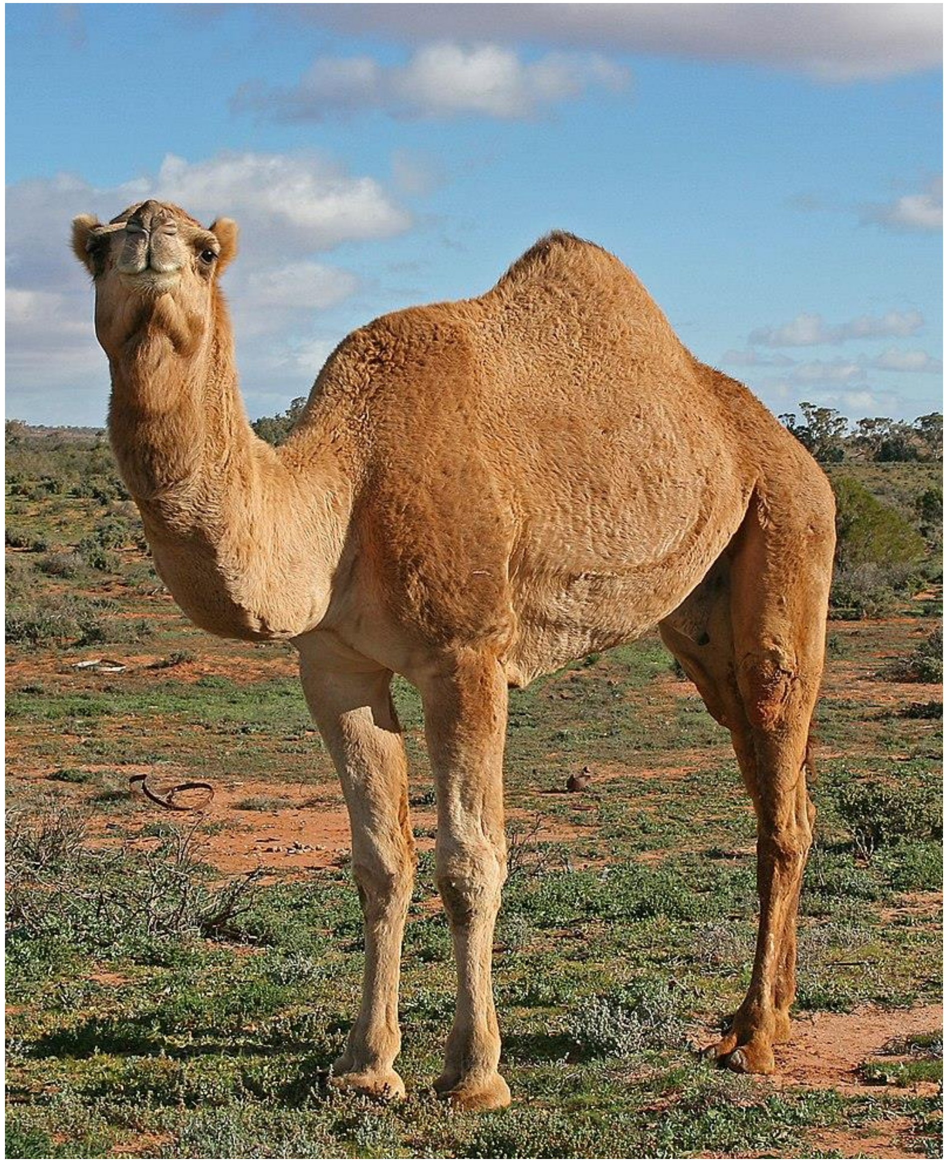
Bactrian or Dromedary?

Bactrian or Dromedary?

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

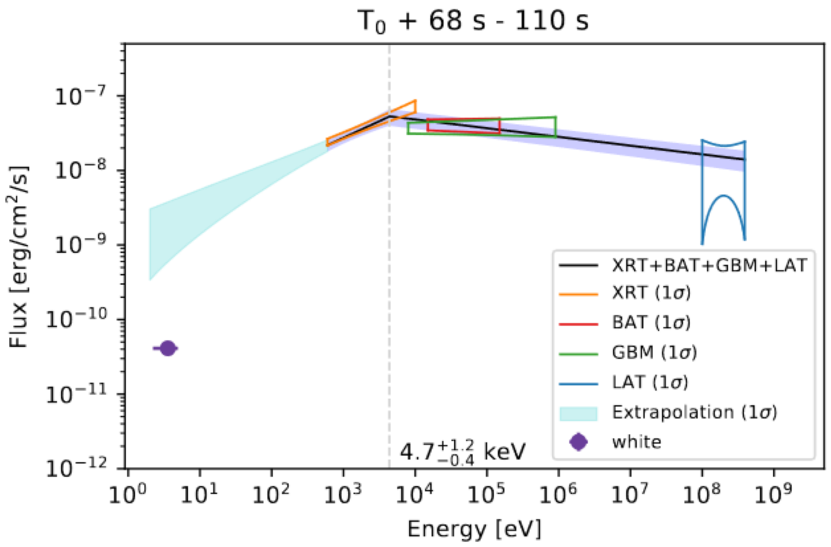
Bactrian or Dromedary?

Bactrian or Dromedary?



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

Bactrian or Dromedary?



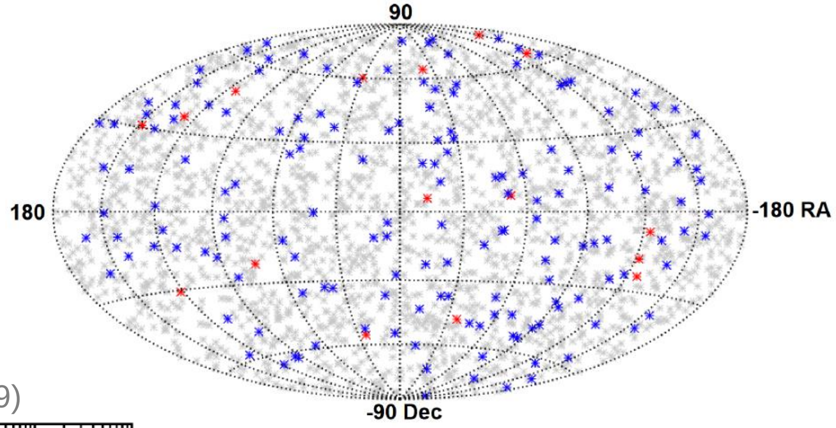
Swift Fermi ApJ 890 (2020)

GRBs from two sides

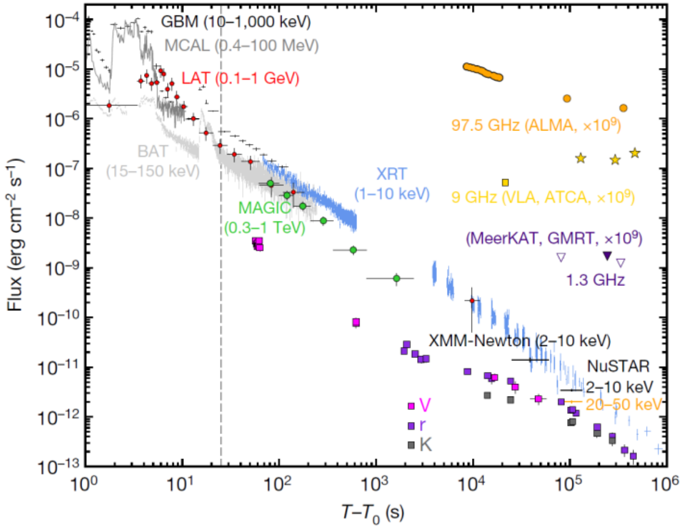
OBSERVATIONAL picture

- 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 some long ones to SN
- short events → hard to follow up

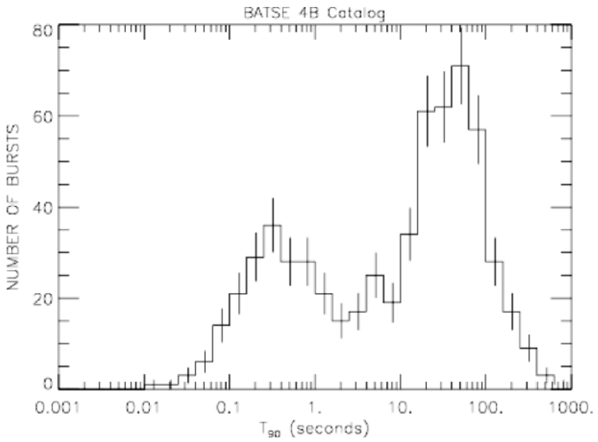
2. Fermi-LAT GRB Catalogue (2018)



MAGIC Nature 575 (2019)



Kouveliotou et al. (1993)



T_{90} [s]

GRBs from two sides

OBSERVATIONAL picture

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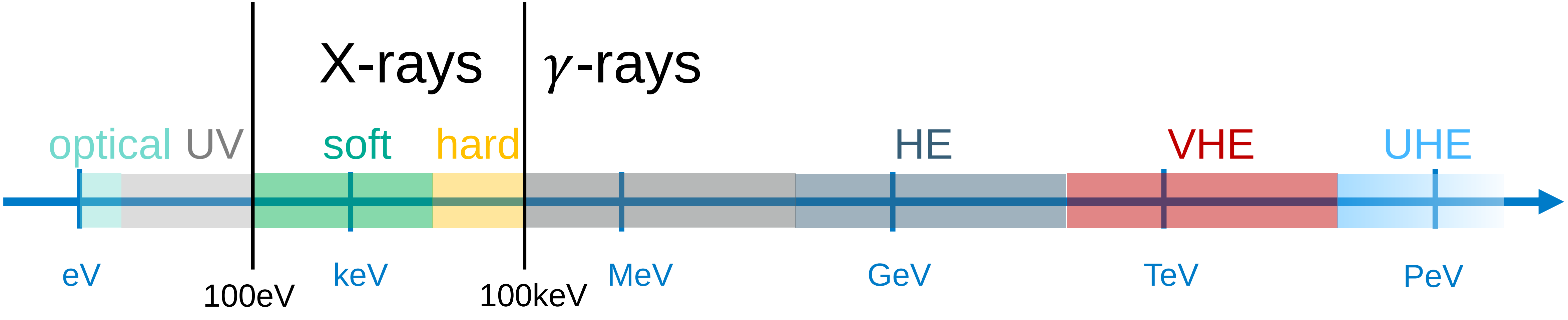
THEORETICAL picture

- 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?)

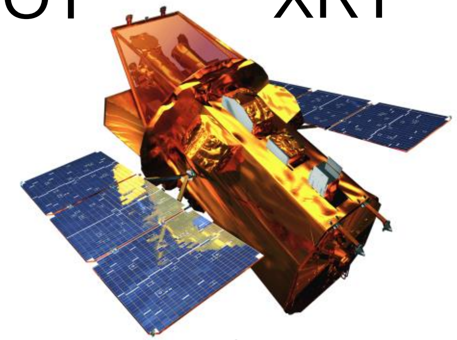
→ Fireball model

Instrument recap



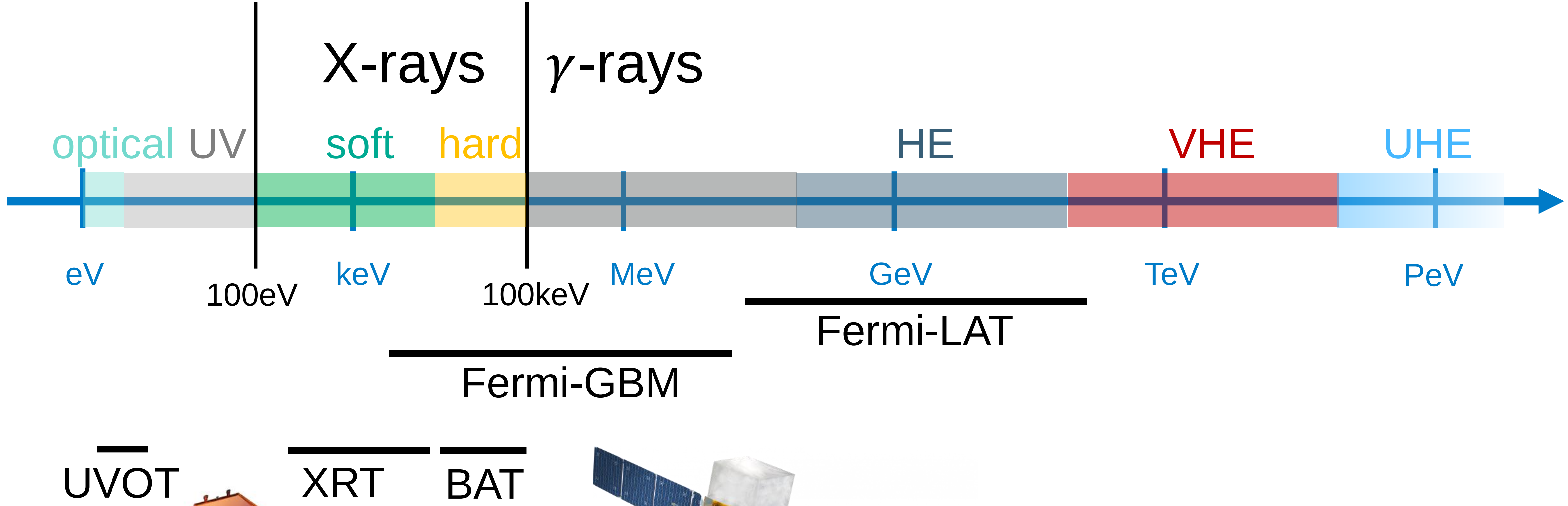
UVOT XRT BAT

Swift

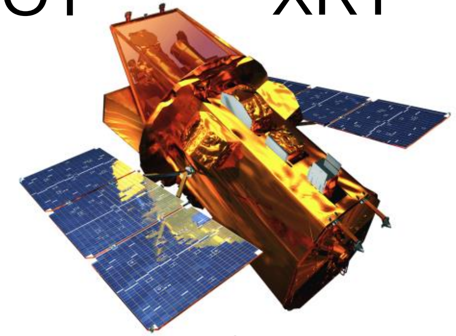


NASA

Instrument recap



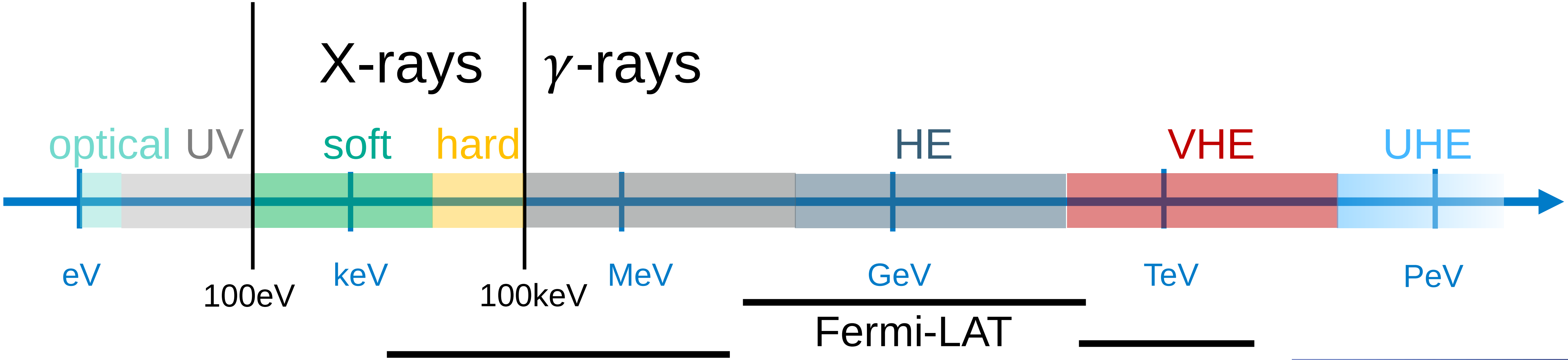
Swift



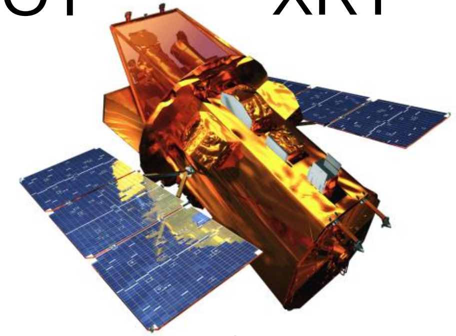
NASA

NASA

Instrument recap



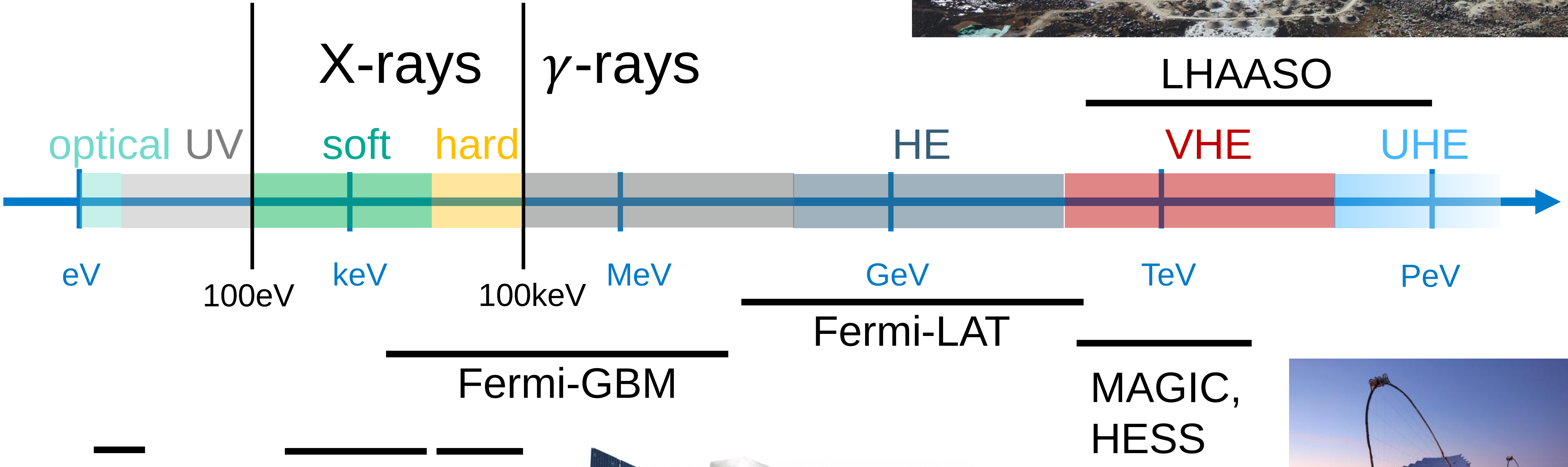
Swift

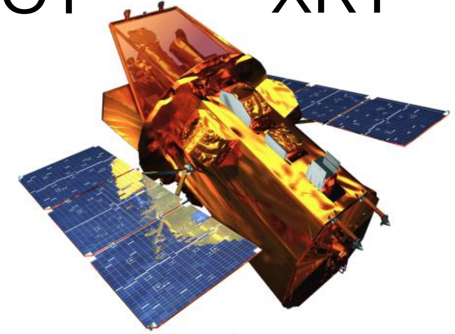


NASA

NASA

Instrument recap





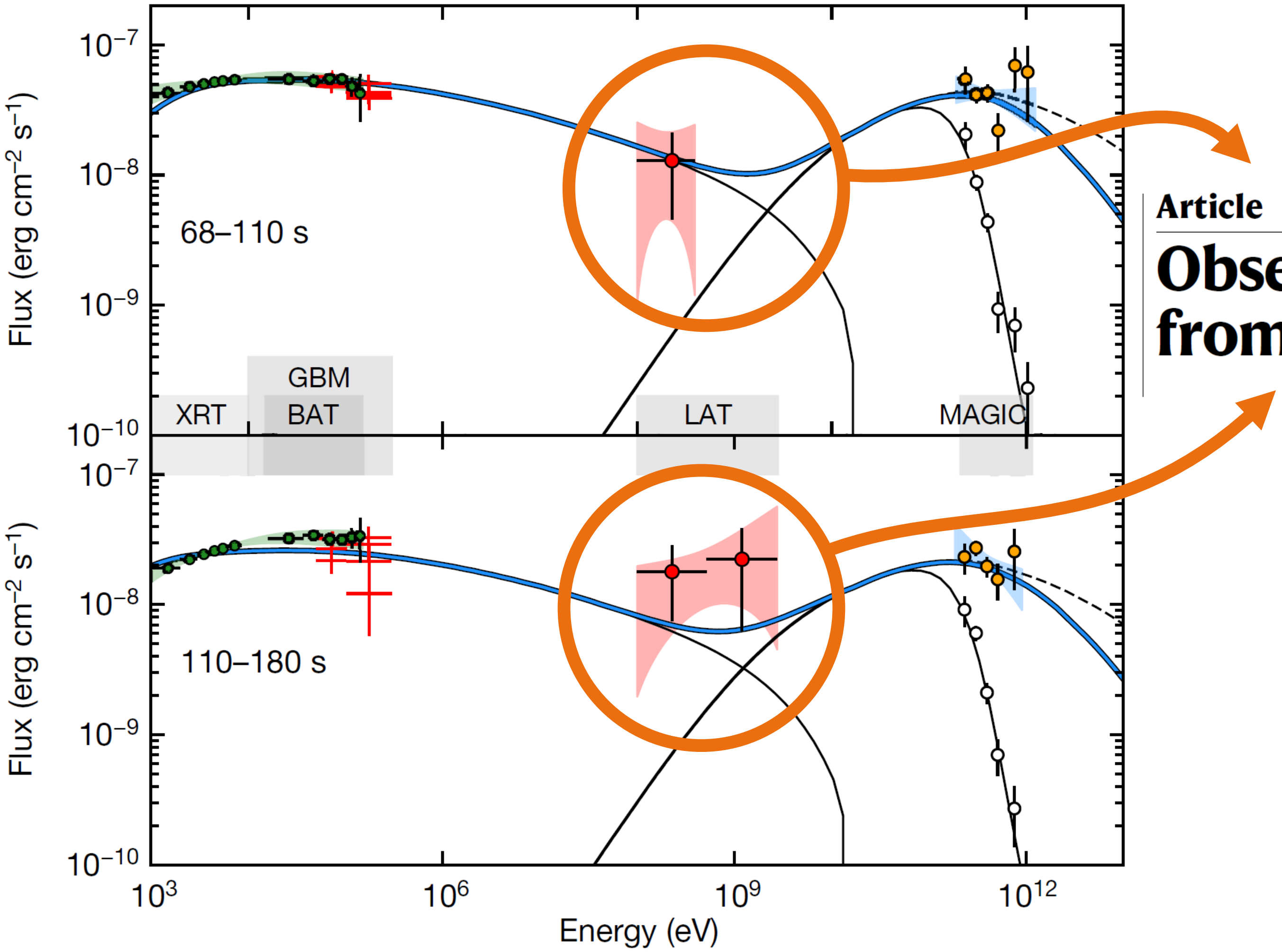
Swift

NASA

NASA

GRB 190114C (detected by MAGIC)

MAGIC Nature 575 (2019)



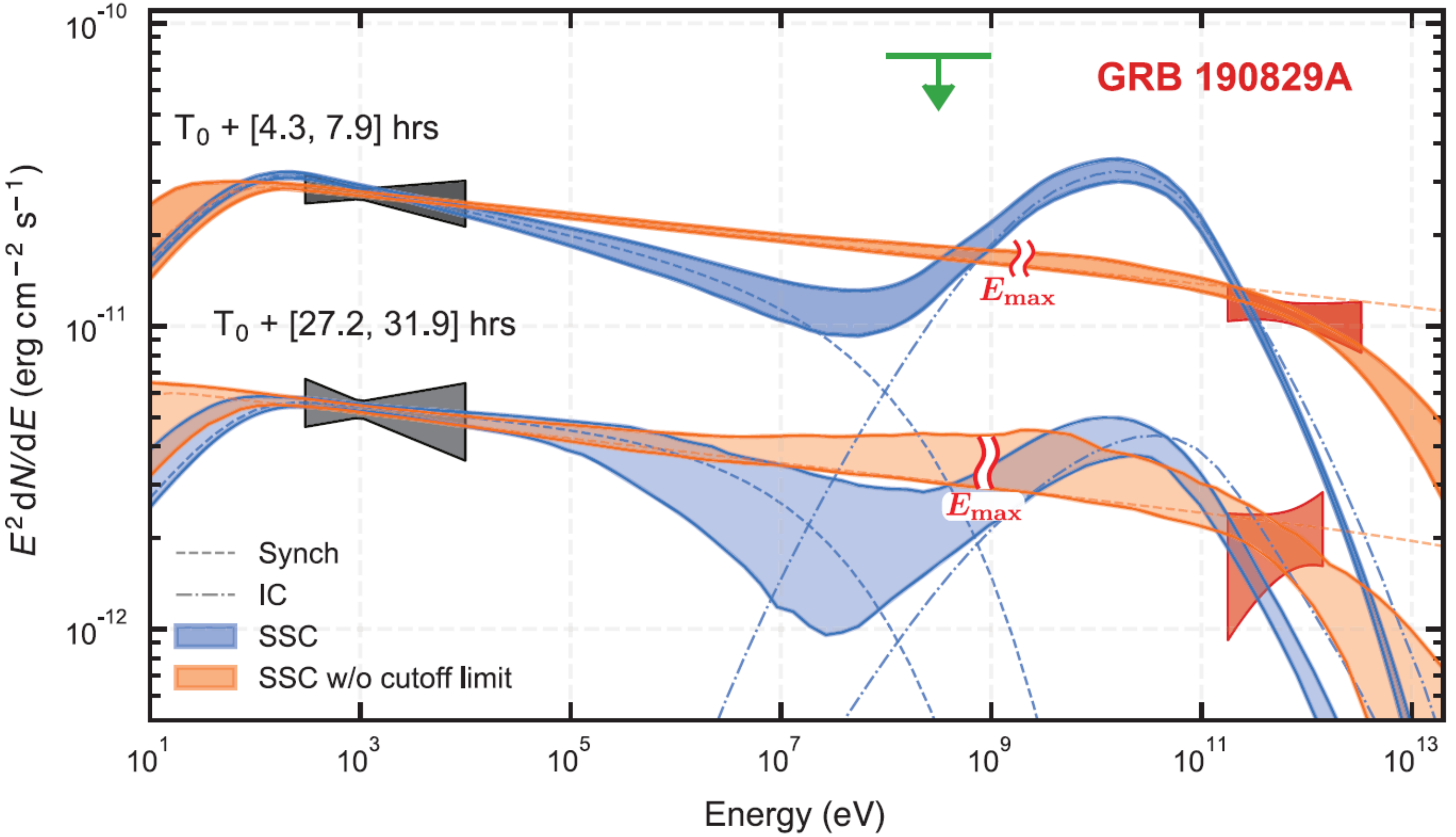
Article

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

→ Bactrian

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

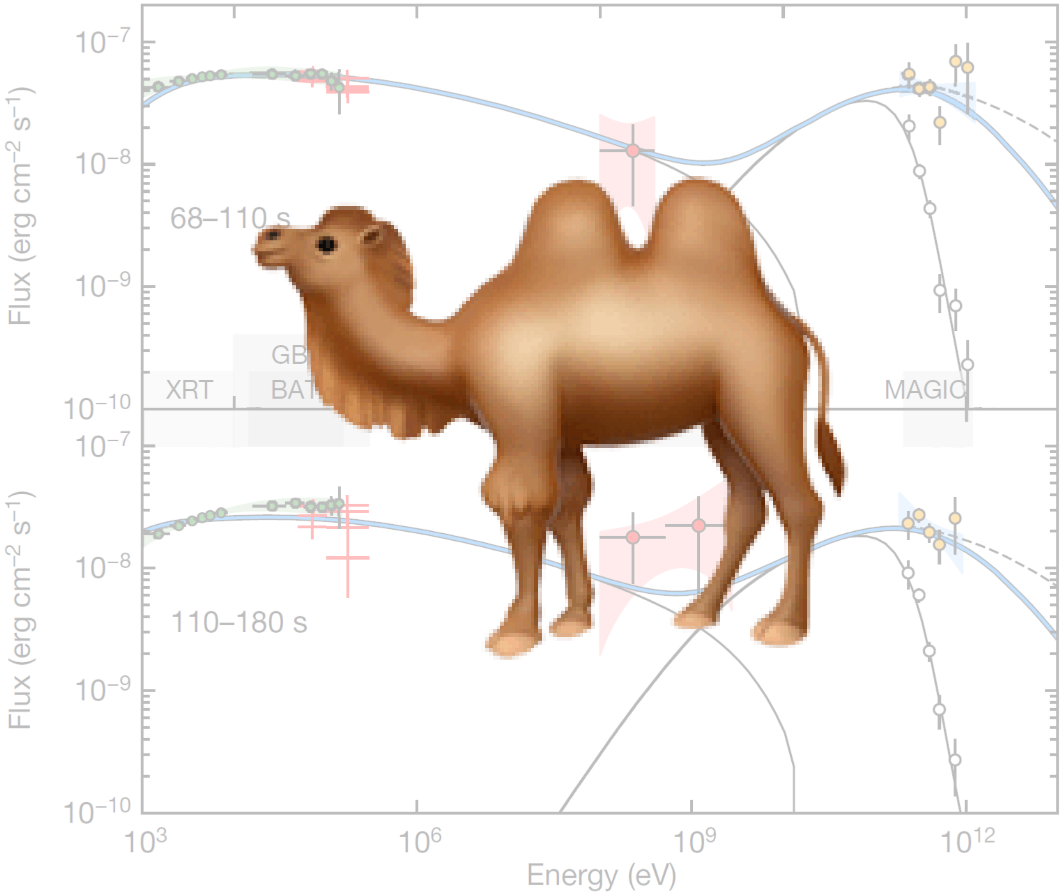
H.E.S.S. Science 372 (2021)



- preference for single component (5σ)

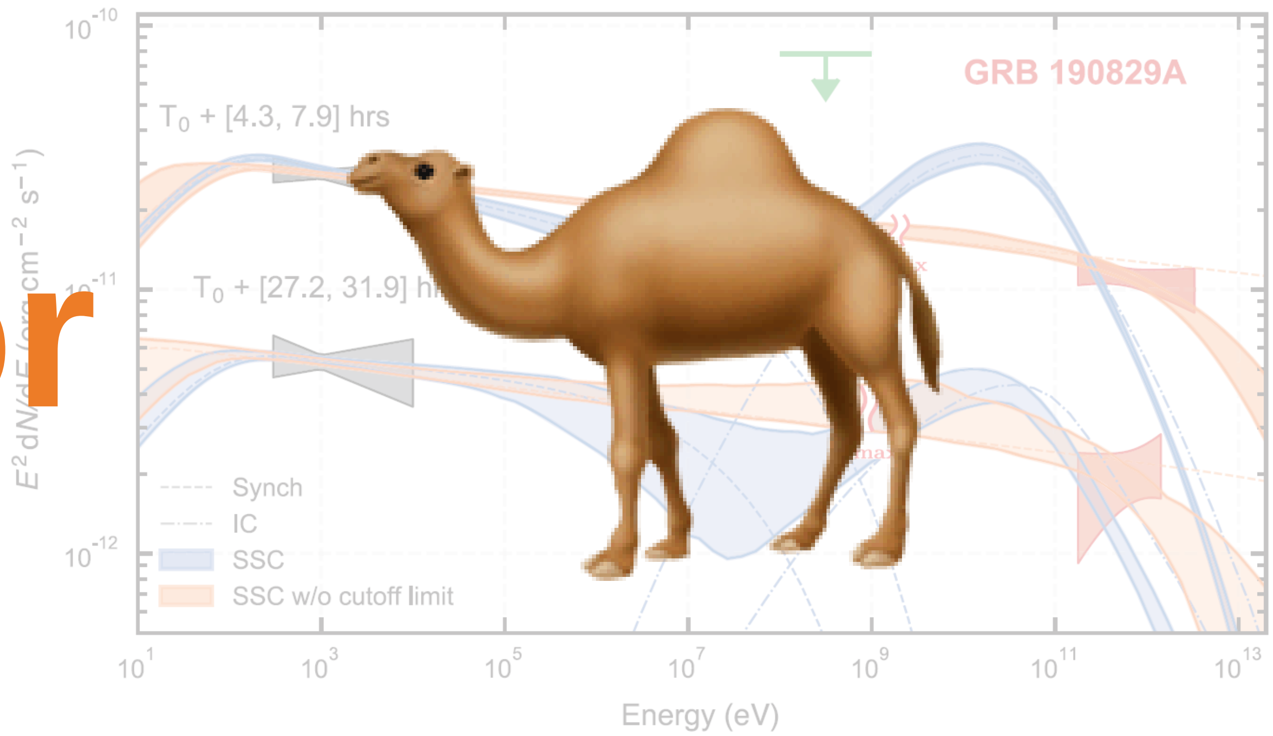
→ **Dromedary**

Now what?



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

or

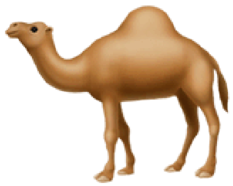


GRB 190829A
T$_0$ + [4.3, 7.9] hrs
T$_0$ + [27.2, 31.9] hrs
Synch
IC
SSC
SSC w/o cutoff limit
Energy (eV)

Outline

- GRB modeling basics

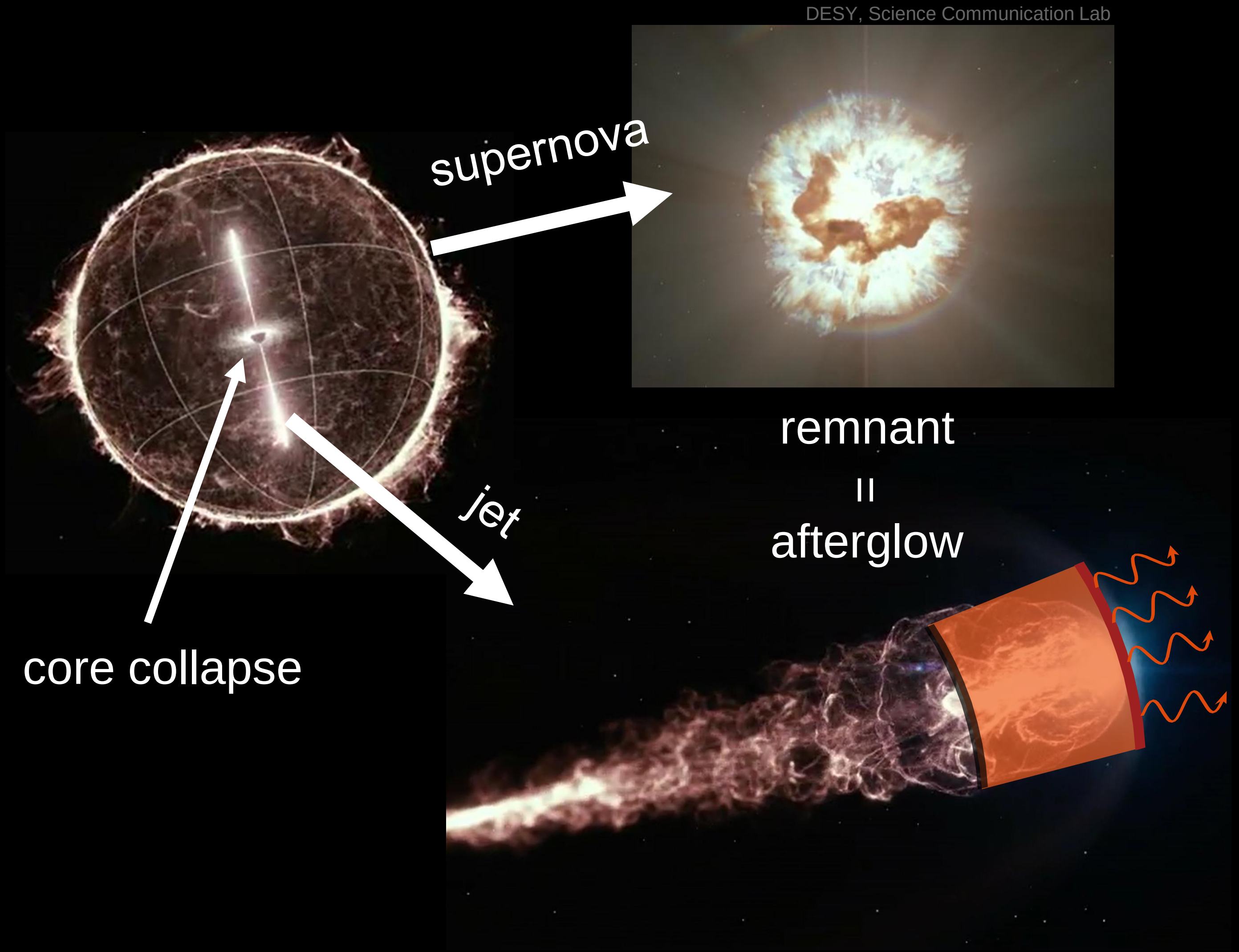
  → what do I actually mean by *Dromedary* and *Bactrian* ?

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

Fireball model (GRB basics)

Fireball model: Long GRB



- Lorentz factors up to few 100

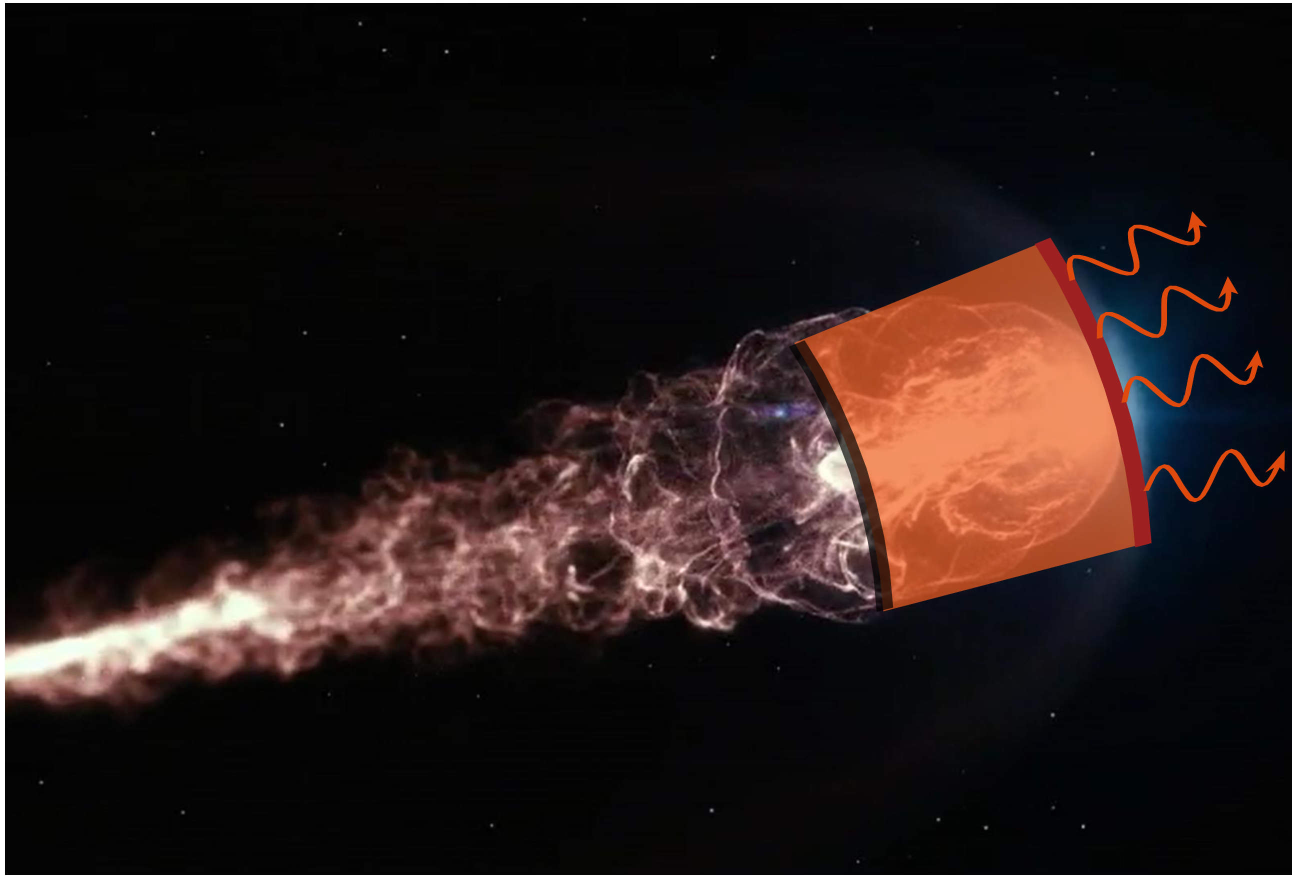
  → relativistic compression
- Quasi isotropic outflow
- Energetics:

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

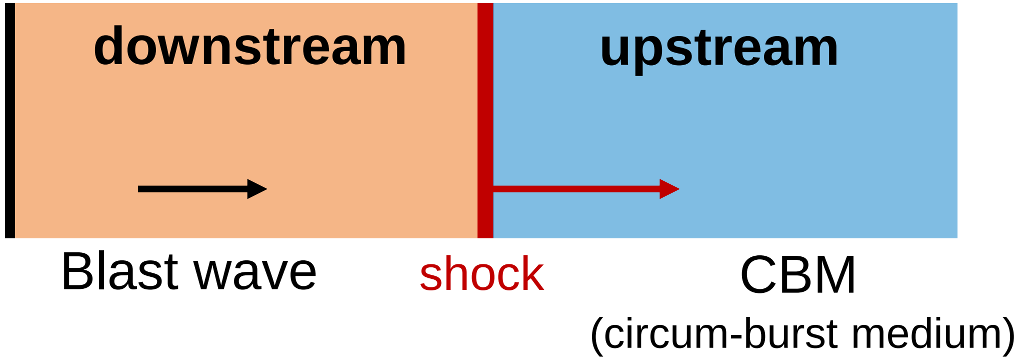
  → $E_{\text{tot}} = \frac{\Omega}{4\pi} E_{\text{iso}} \sim 10^{51} \text{erg}$

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

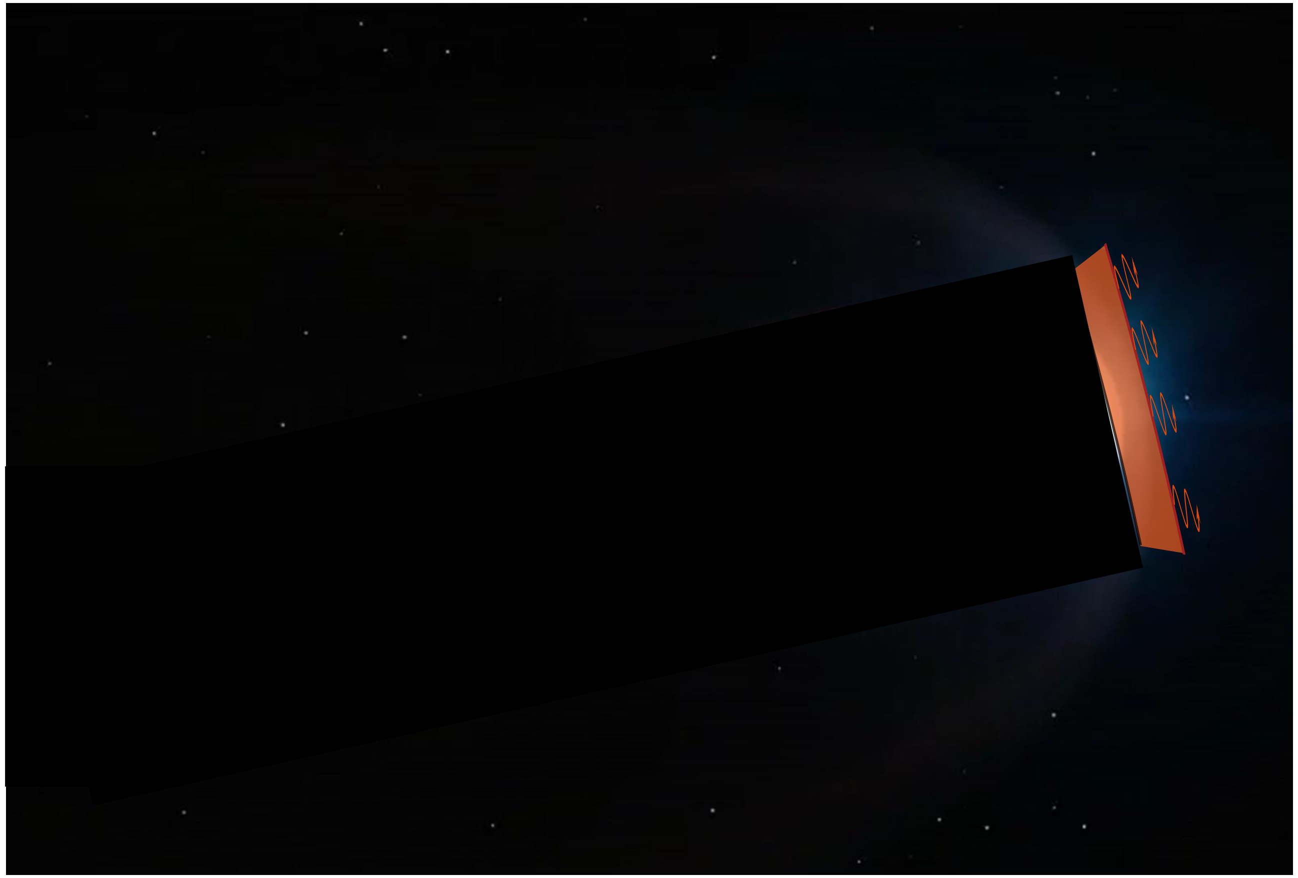
Forward shock and blast wave



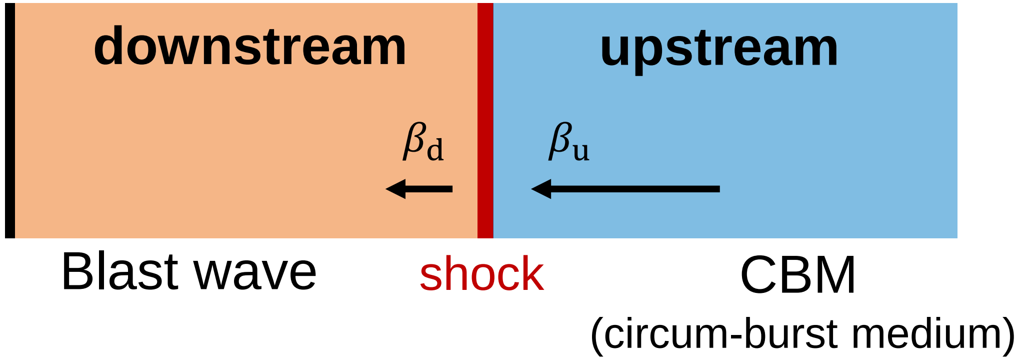
Forward shock and blast wave



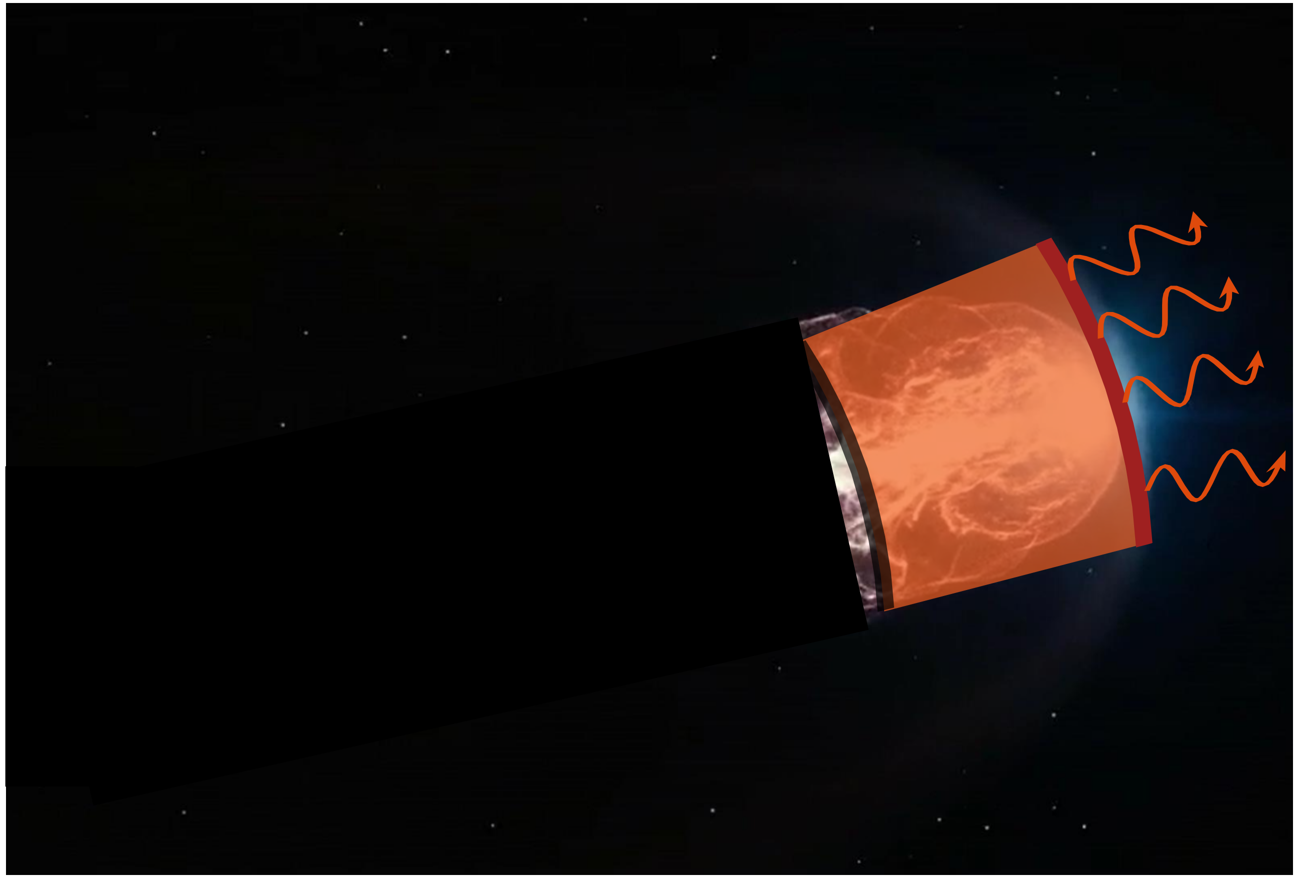
observer's frame



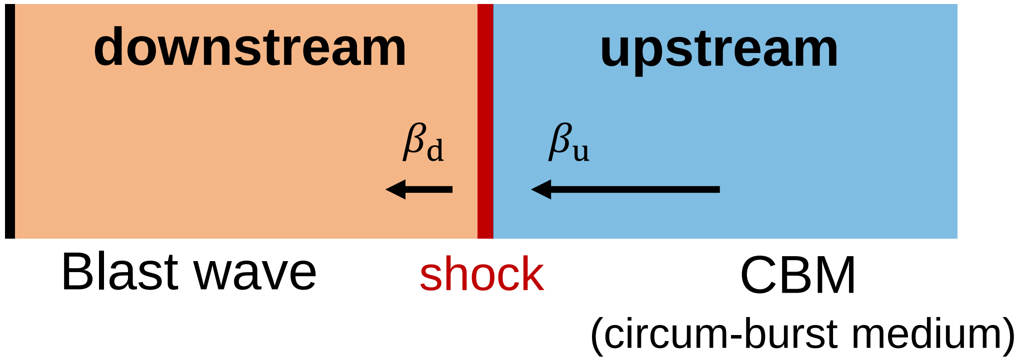
Shock redistributes upstream ram pressure



shock rest frame



Shock redistributes upstream ram pressure



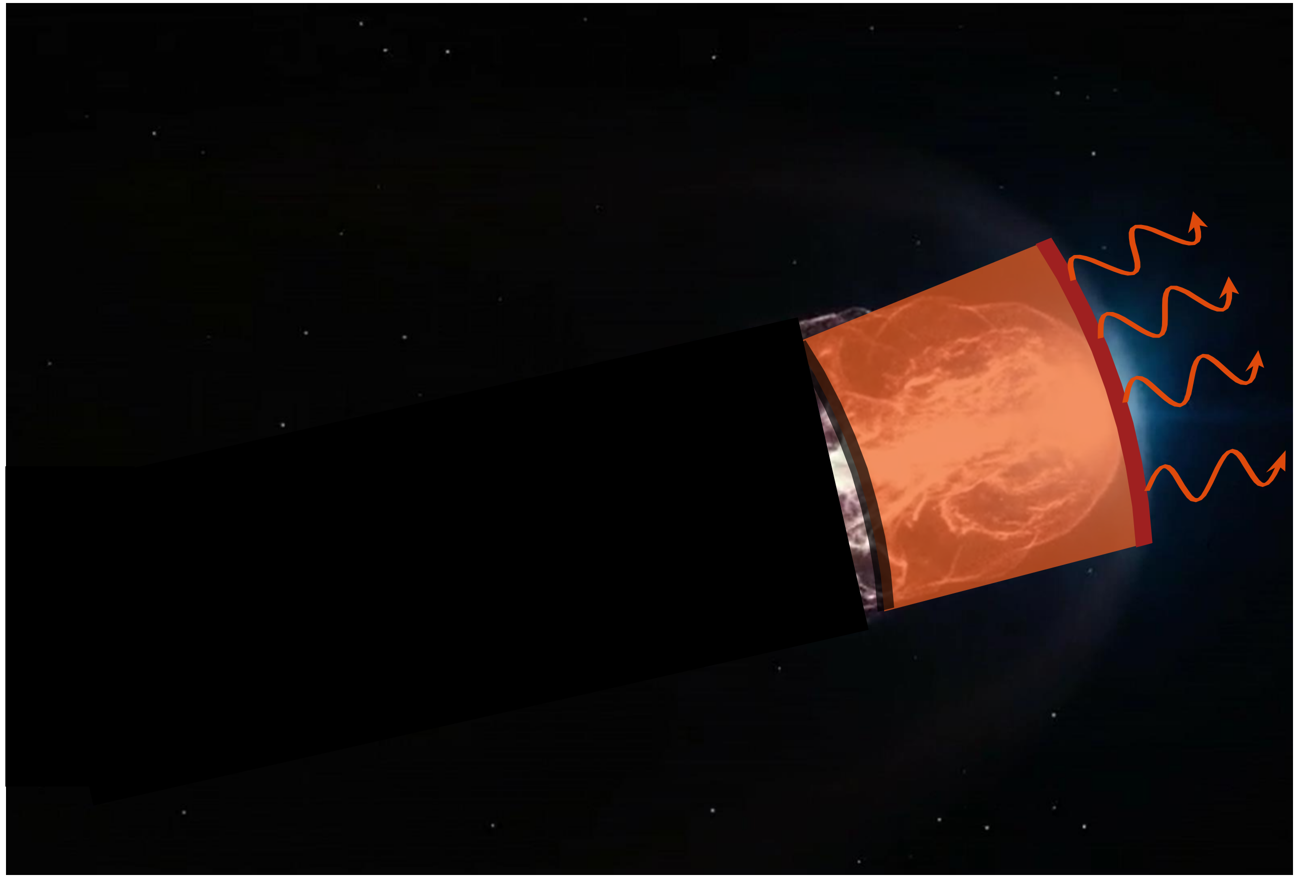
$\varepsilon_{th} = \frac{2}{3}$ p_{th}^{d}

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

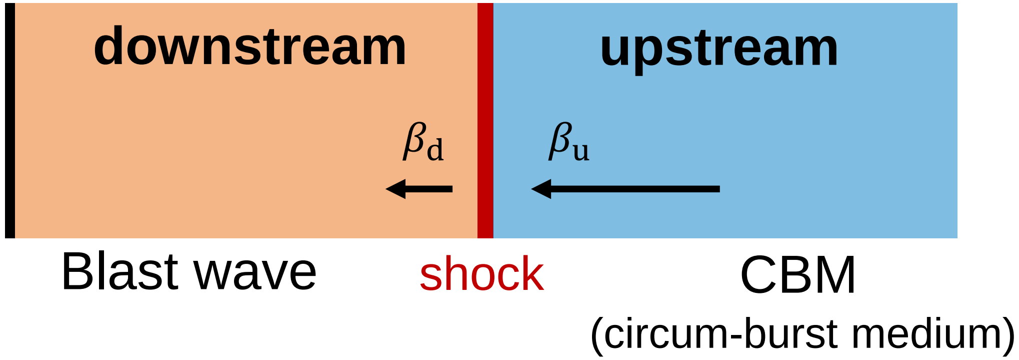
$$p_{ram}^{u} = \beta_u^2 \Gamma_u^2 \rho_u c^2$$

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

shock rest frame



Shock redistributes upstream ram pressure



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

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

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

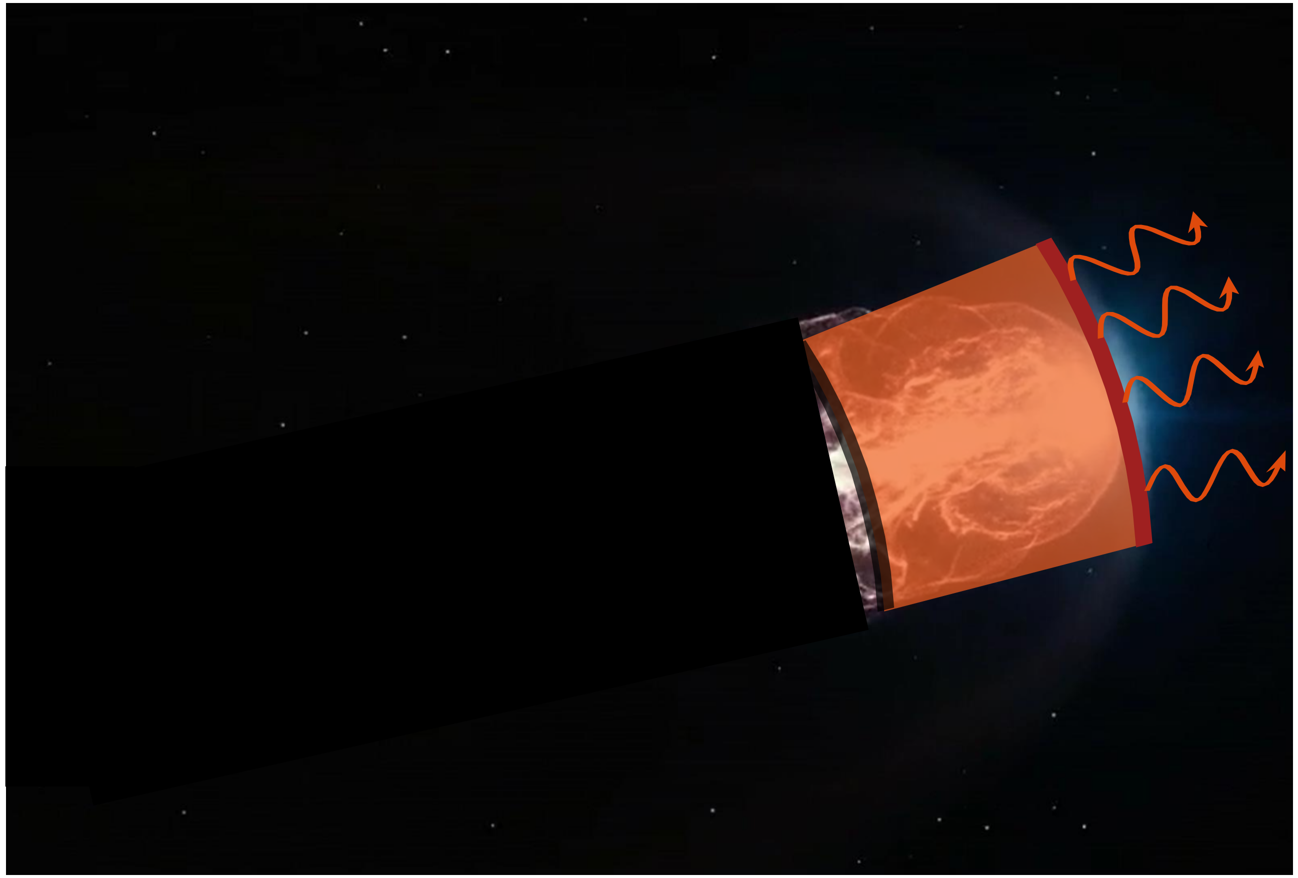
ε_p =few %? — $p^\mathrm{d}_\mathrm{p,non-th}$

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

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

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

shock rest frame



Shock redistributes upstream ram pressure

$\varepsilon_B = 10^{-4} - 10^{-2}$?? p^d_B

shock rest frame

at $t_{obs} = 100s$

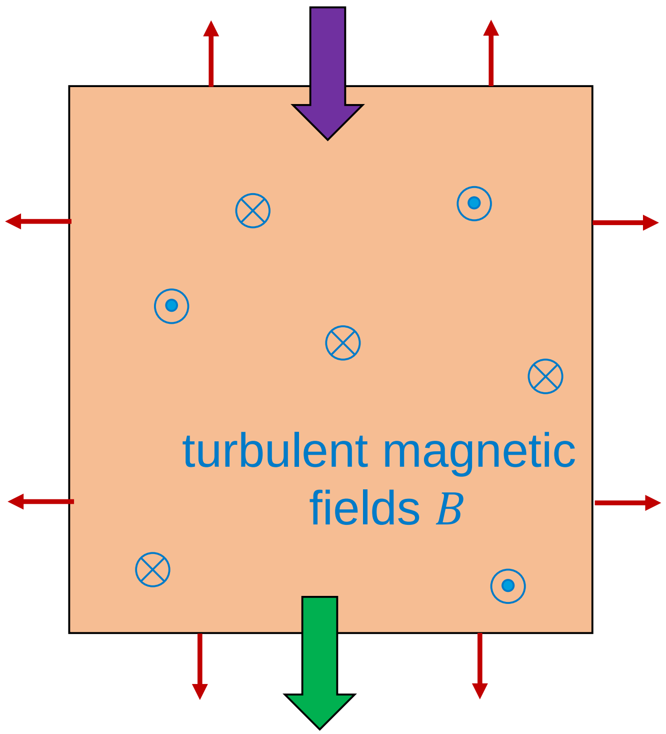
$\varepsilon_B = 10^{-4} \rightarrow \; B \approx 0.3G$

$\varepsilon_B = 10^{-2} \rightarrow \; B \approx 3G$

→ magnetic fields at Gauss level

Leptonic one zone modelling

injection Q



escape τ_{esc}

electrons drive expansion of box

shock injects relativistic particles

electron number

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

synchrotron

inverse Compton scattering

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

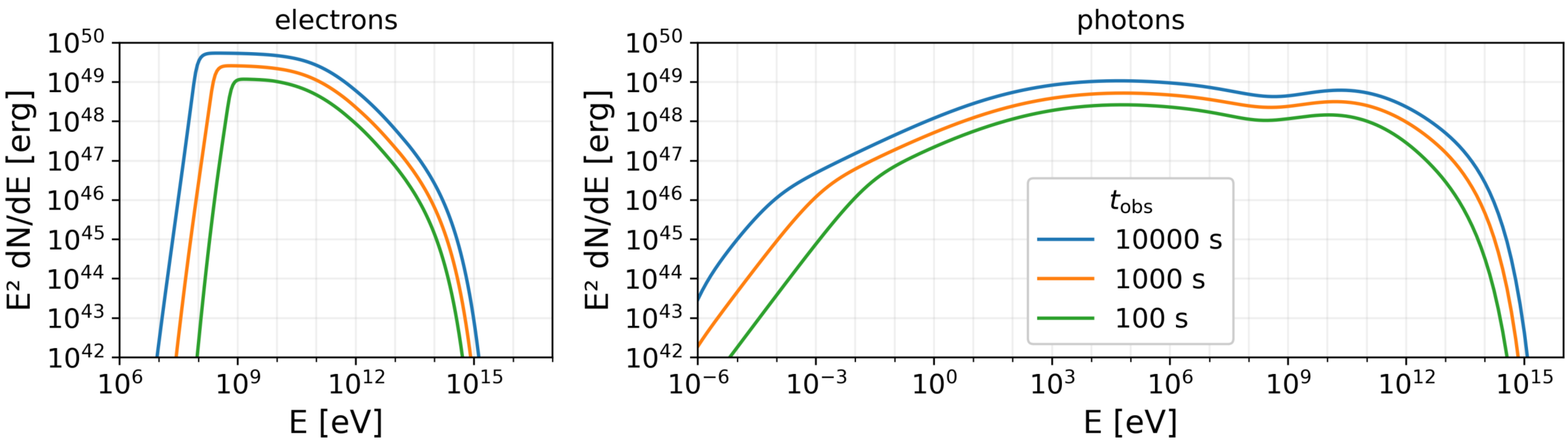
$\gamma\gamma \rightarrow e^-e^+$

photon number

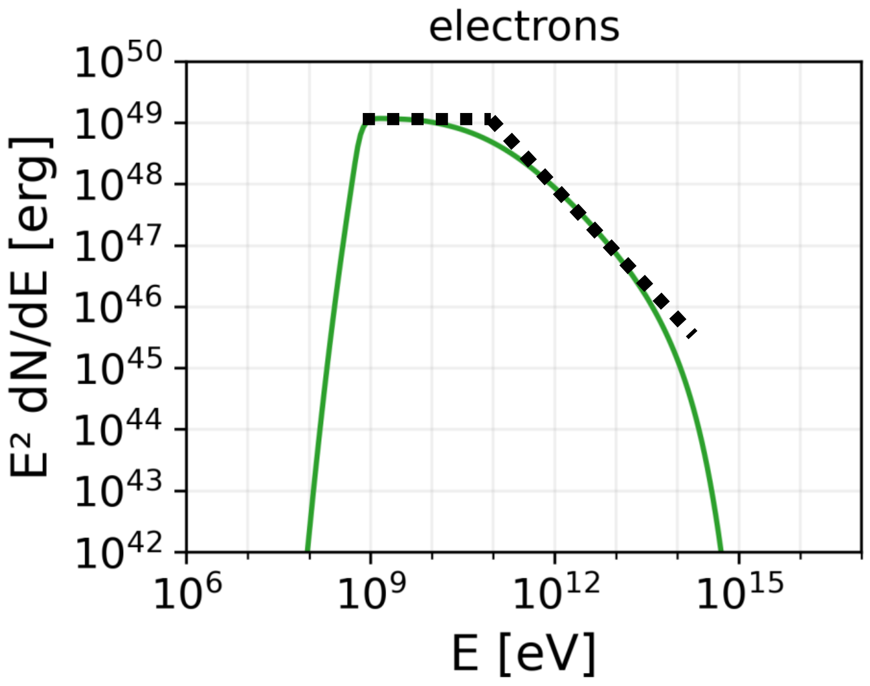
$$\partial_t N_{E,\gamma} = -\frac{N_{E,\gamma}}{\tau_{esc}(t)} + Q_{syn}(E,t) + Q_{iC}(E,t) + Q_{pp}(E,t) - \frac{N_{E,\gamma}}{\tau_{pa}(E,t)}$$

photons can escape from box

Fiducial set of parameters



Fiducial set of parameters



- electron spectrum in **quasi-steady state**

  → smoothly broken power law

  → slope dictated by dominant cooling process

- steady state for const. $\tau(E), Q_E(E)$:

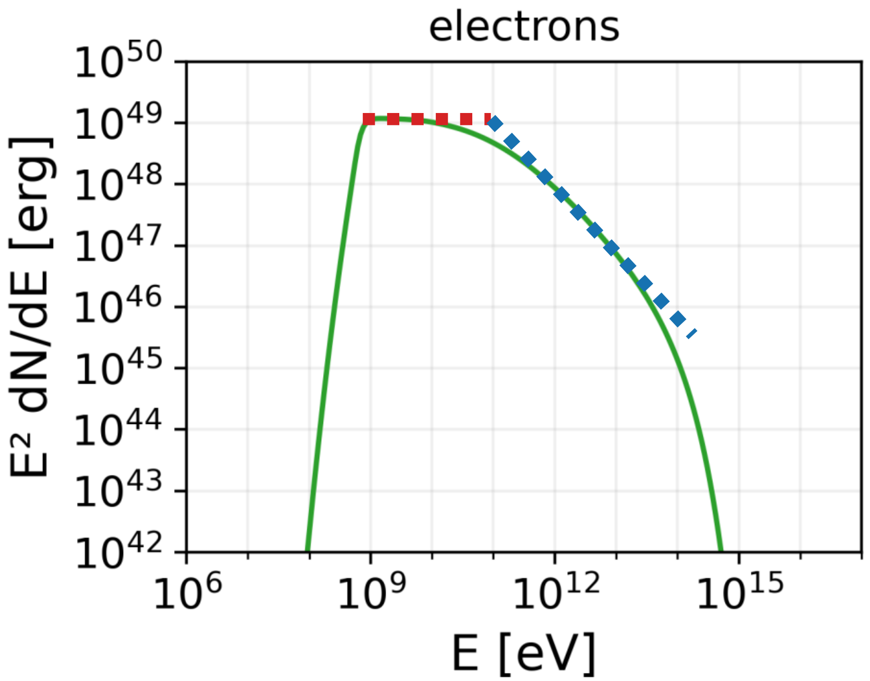
  $\rightarrow \partial_t N_E = -\frac{N_E}{\tau} + Q_E = 0 \;\; \rightarrow \;\; N_E = \boldsymbol{Q_E \tau}$

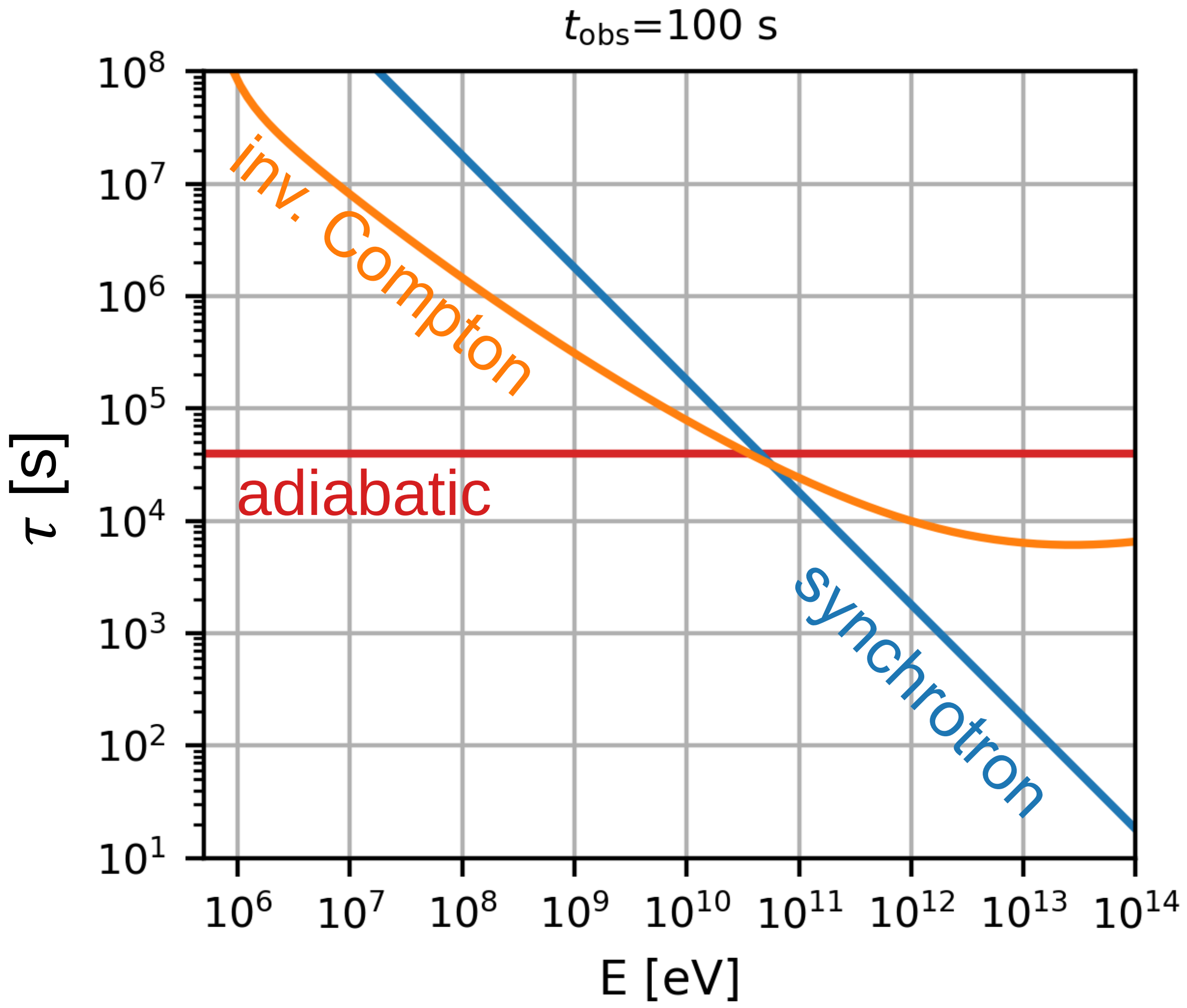
- here: time dependent $\tau(t, E), Q_E(t, E)$

  → same result with numerical factor of order unity

  $\rightarrow N_E(t) \propto Q_E(t)\,\tau(t)$

Fiducial set of parameters

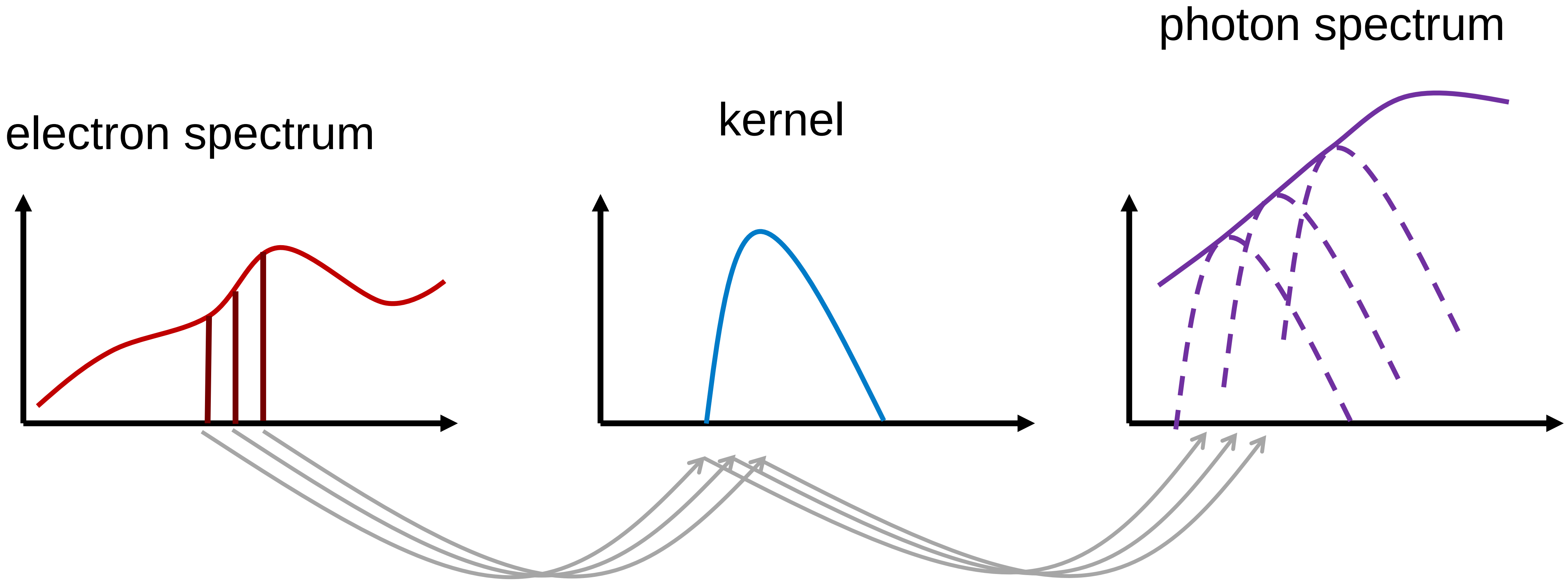




$$\rightarrow N_E(t) \propto Q_E(t)\,\tau(t)$$

Photons Spectrum: Synchrotron Self-Compton (SSC)

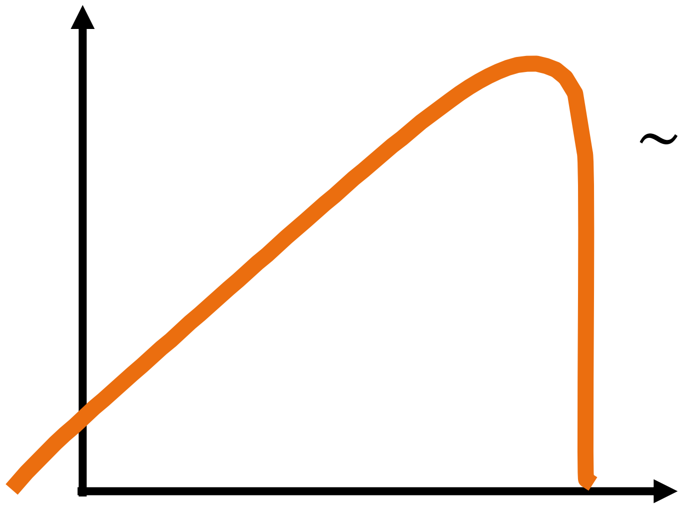
- just another example of convolutions



Radiation processes: Synchrotron

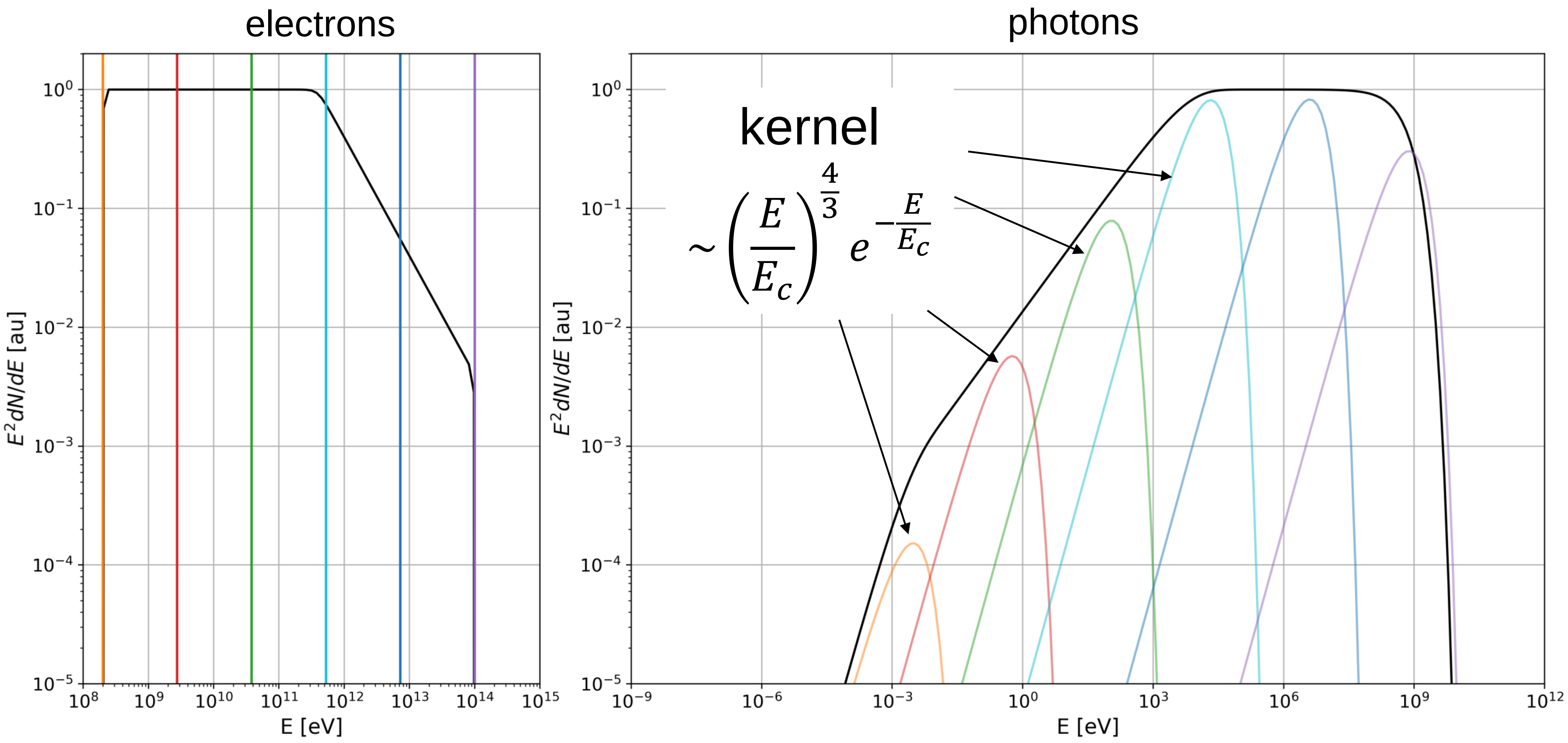
- electrons gyrate in magnetic field

Synchrotron

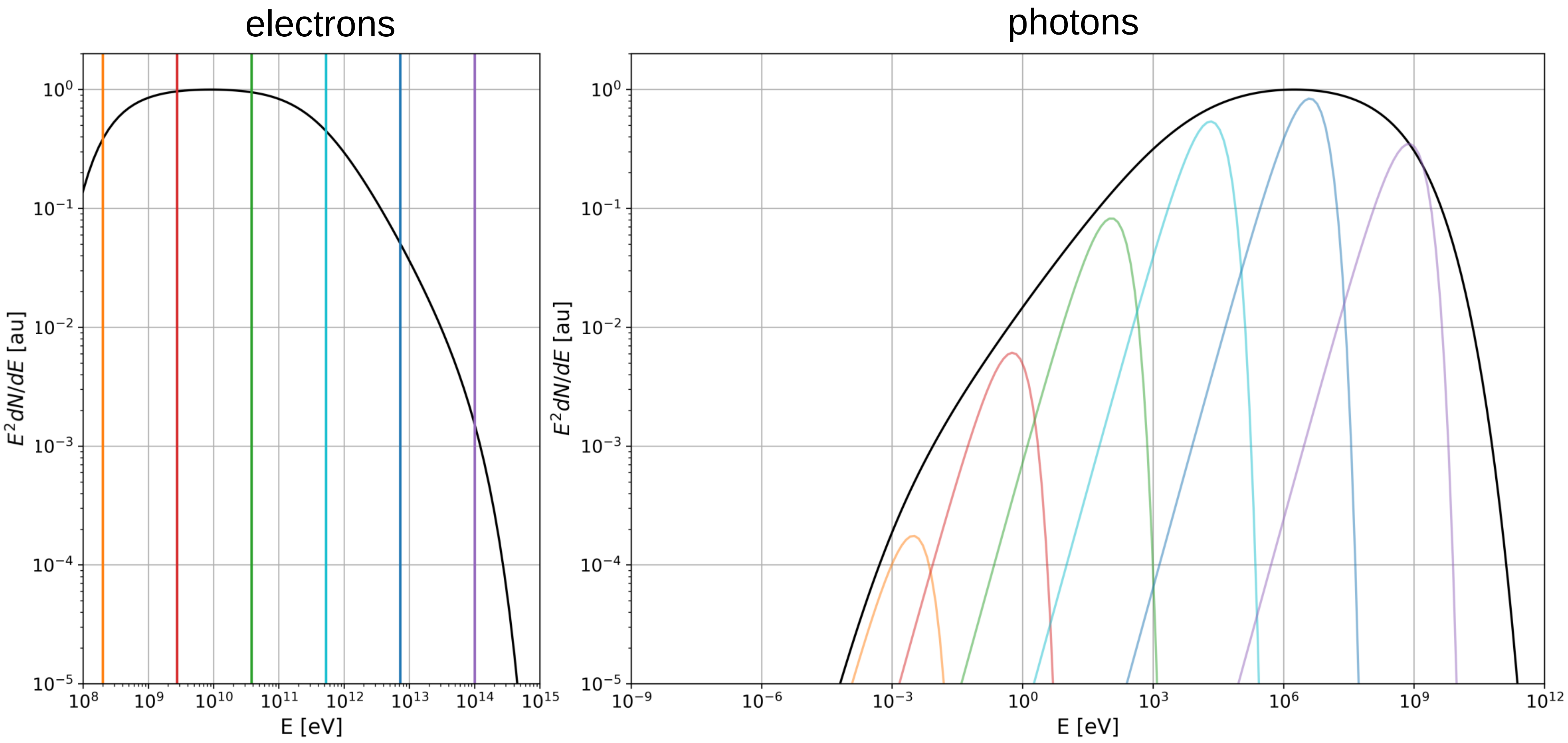


$$\sim \left(\frac{E}{E_c}\right)^{\frac{4}{3}} e^{-\frac{E}{E_c}}$$

Photon spectrum: Synchrotron toy spectrum

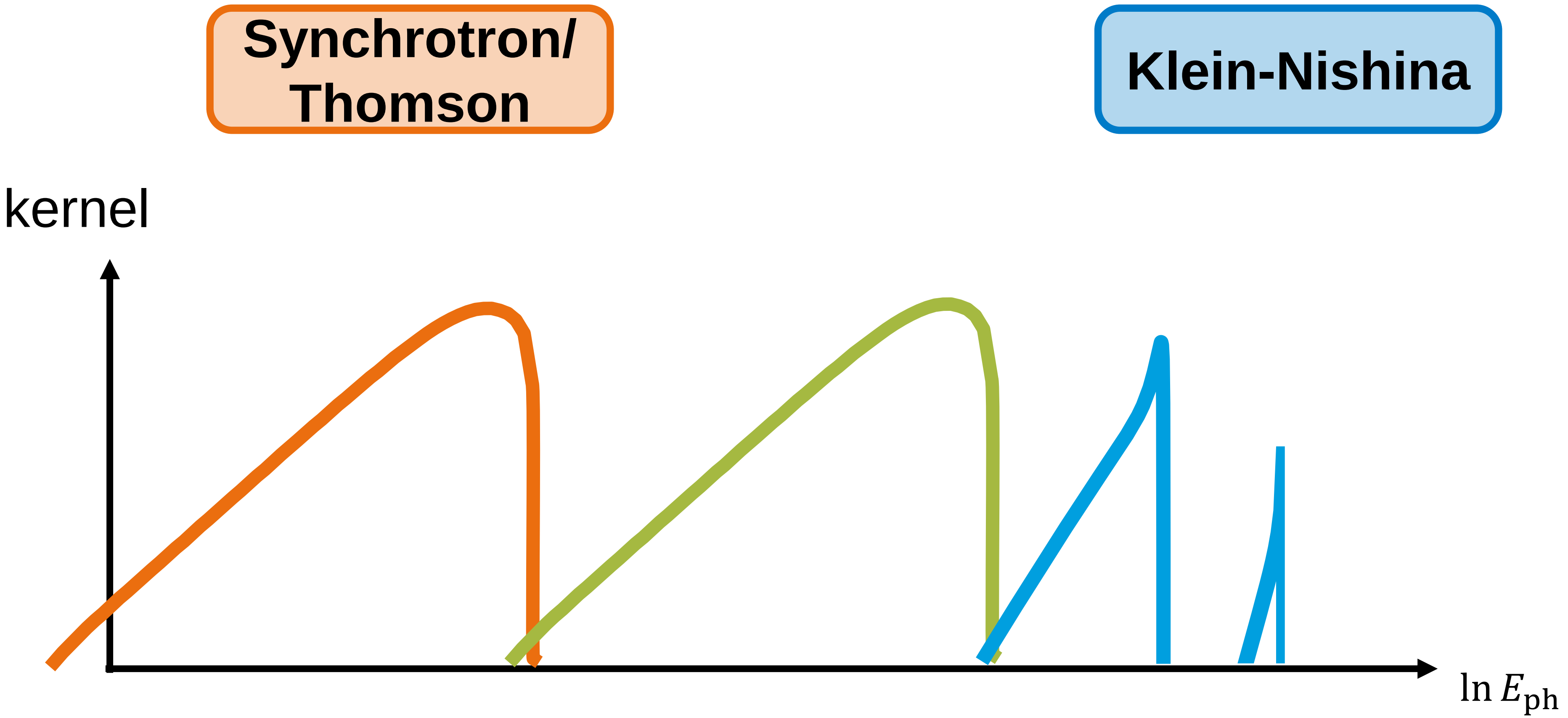


Photon spectrum: Synchrotron smooth electrons



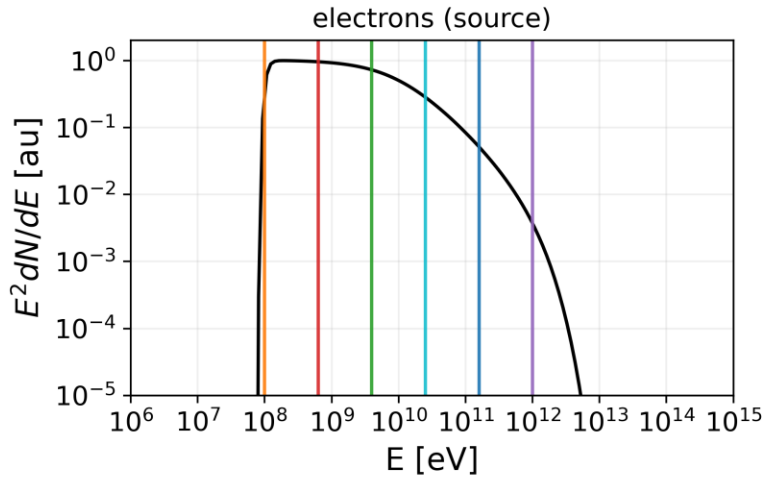
Radiation processes: Inverse Compton

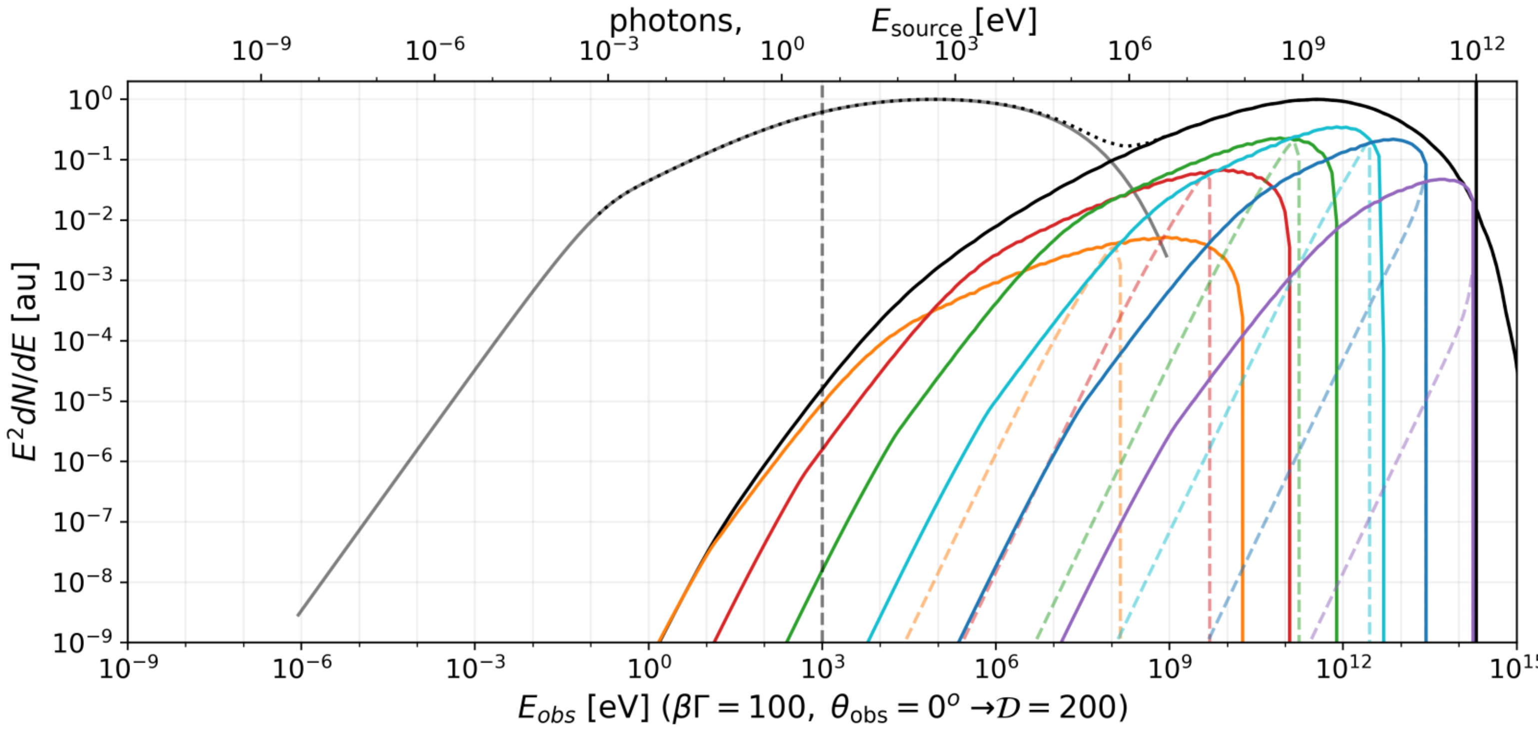
- electron up-scatters photon (energy transfer to photon)



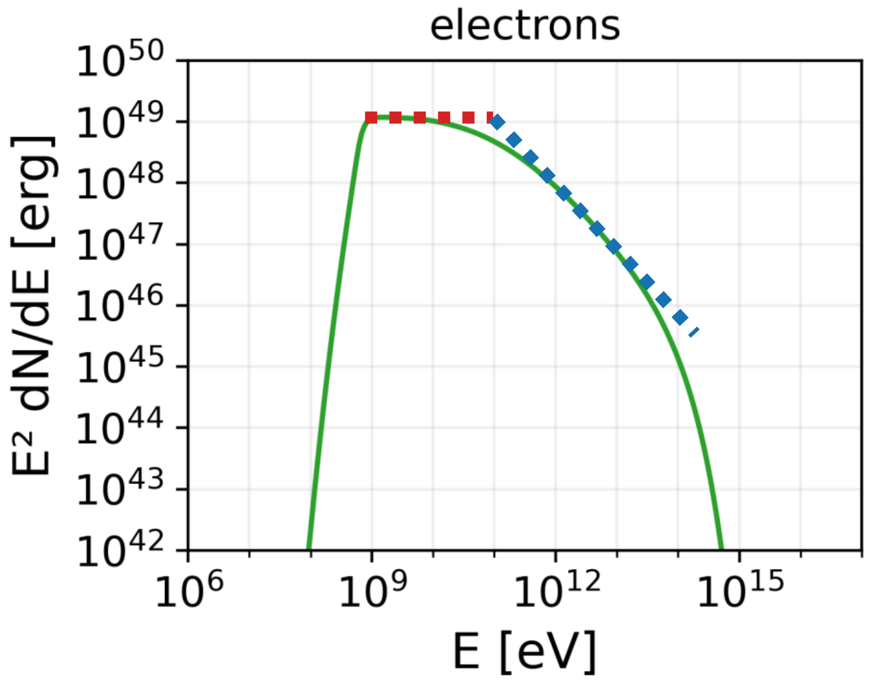
Photon spectrum: Synchrotron Self-Compton (SSC)

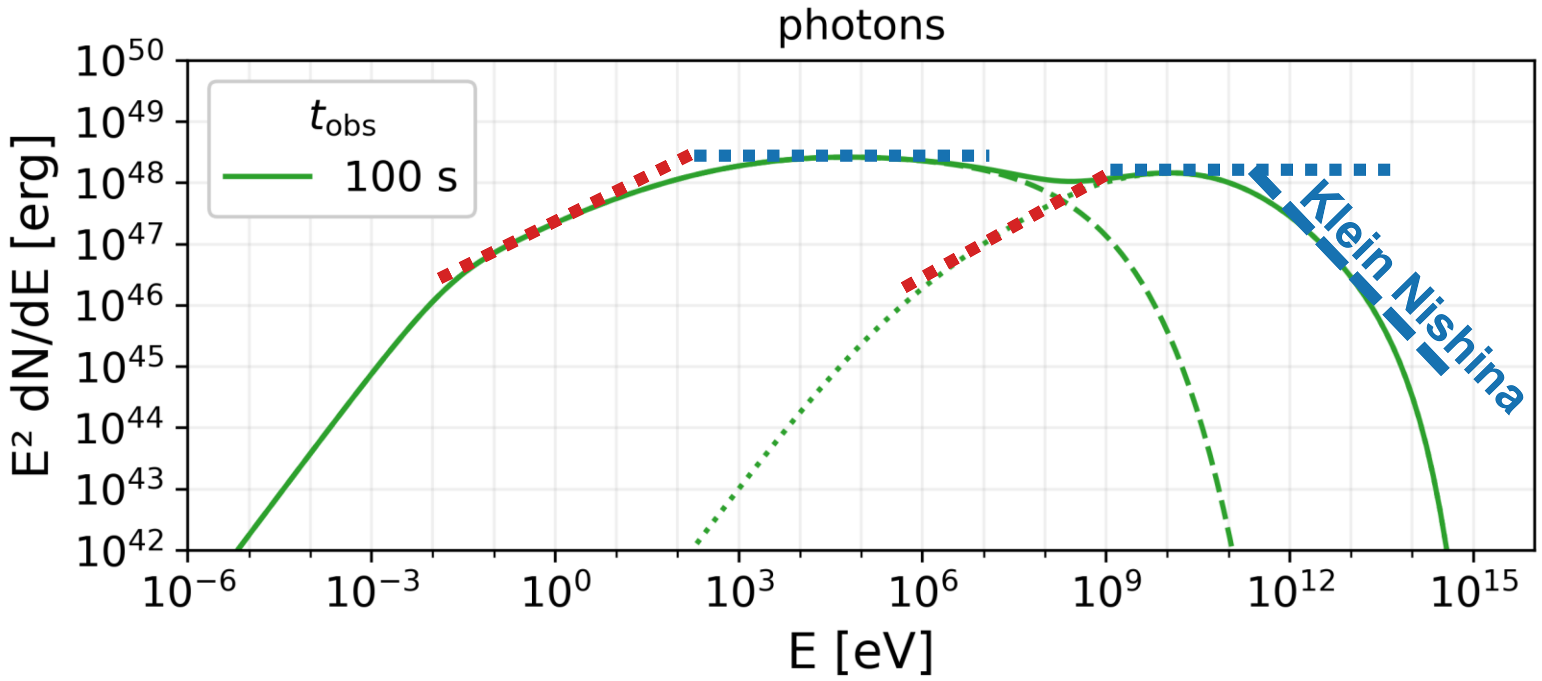
→ Convolve electron spectrum with radiation kernel





Bactrian – two hump – SSC – model





Dromedary – single hump – Syn. – model

- how about extending a single synchrotron component up to TeV?

  → "just" increase max. electron energy

- leptonic one zone model uses same magnetic field for

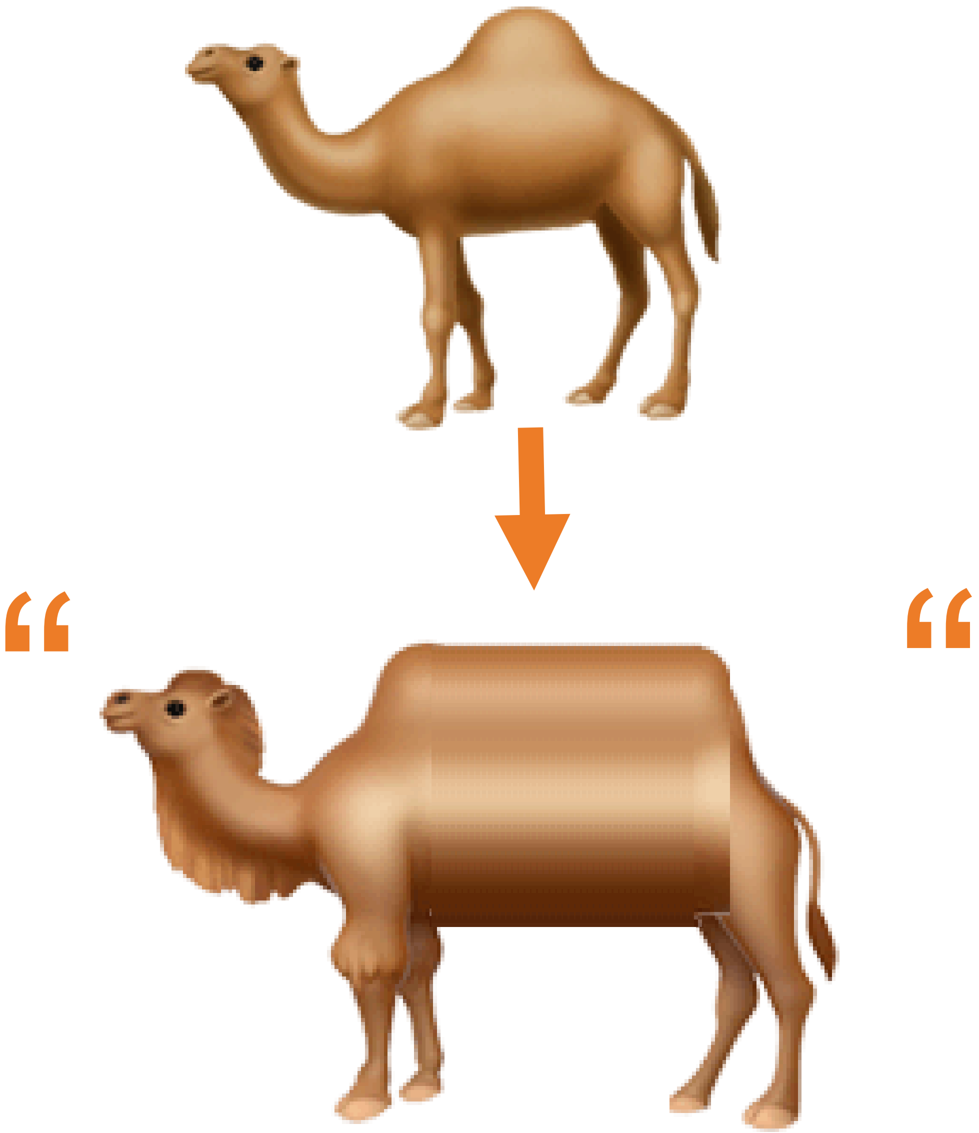
  → confinement within acceleration zone

  → creating radiation

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

- split 2 zones

- hadronic components?



Specifying the Camel Question

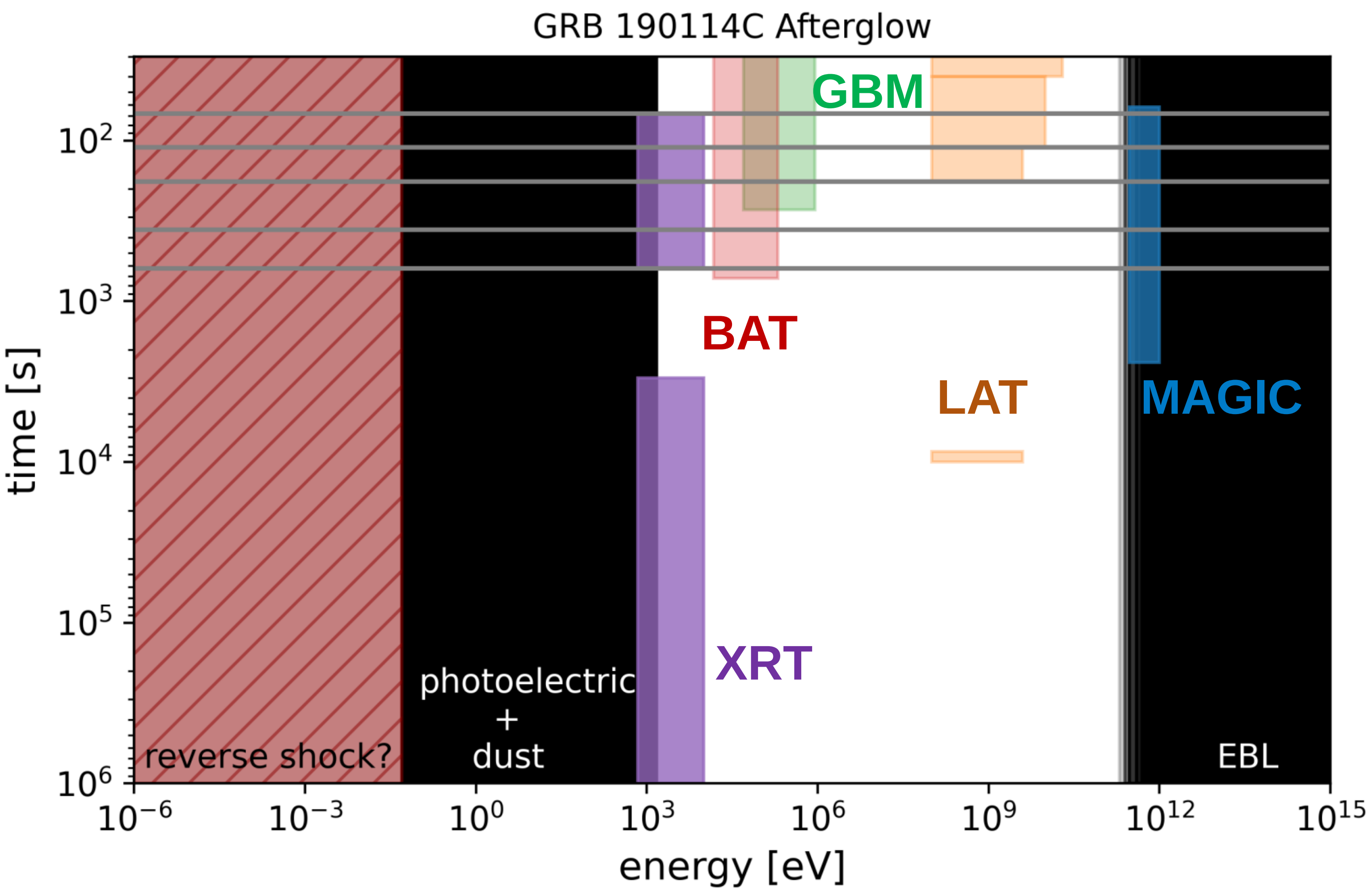
- do we observe a two hump model or do we need to think about ways to extend the single hump to VHE energies?

GRB 190114C

or

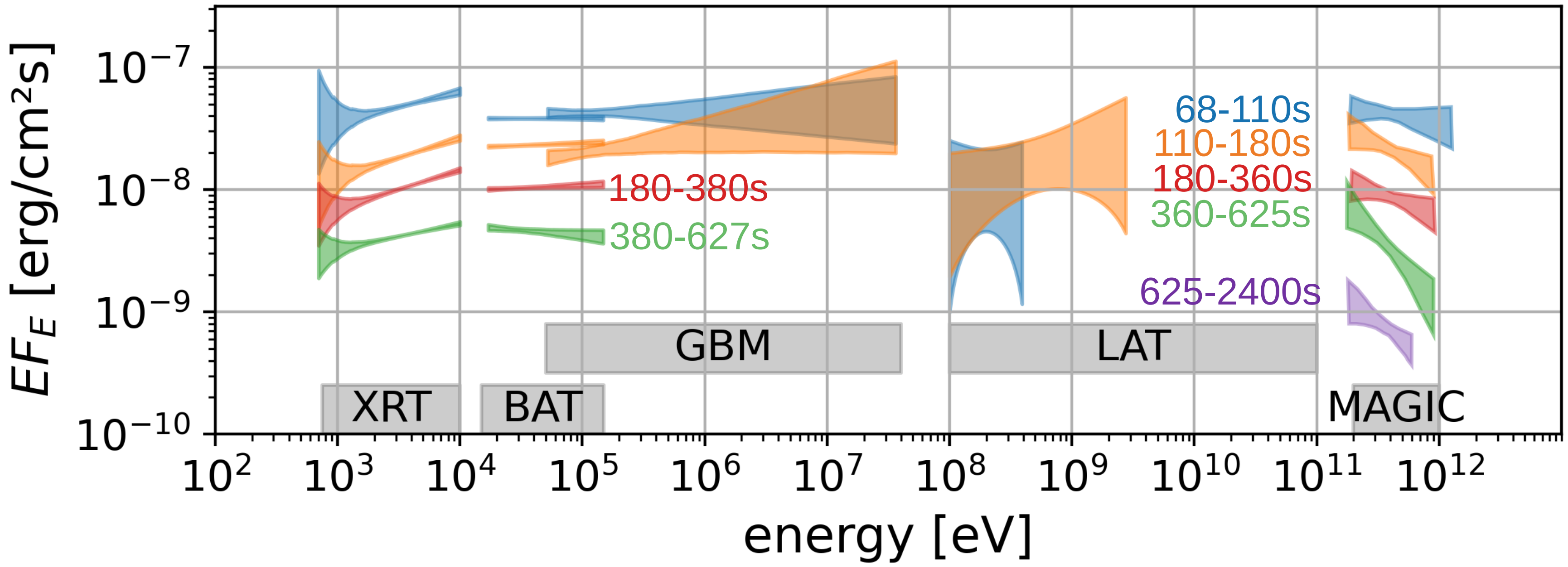
?

Observational window



- triggered:
  - → Swift satellite (**BAT**, XRT)
  - → Fermi satellite (**GBM**, LAT)
- rapid follow up by MAGIC
  - → **VHE afterglow** observed up to 40 min
- intermediate redshift $z = 0.42$

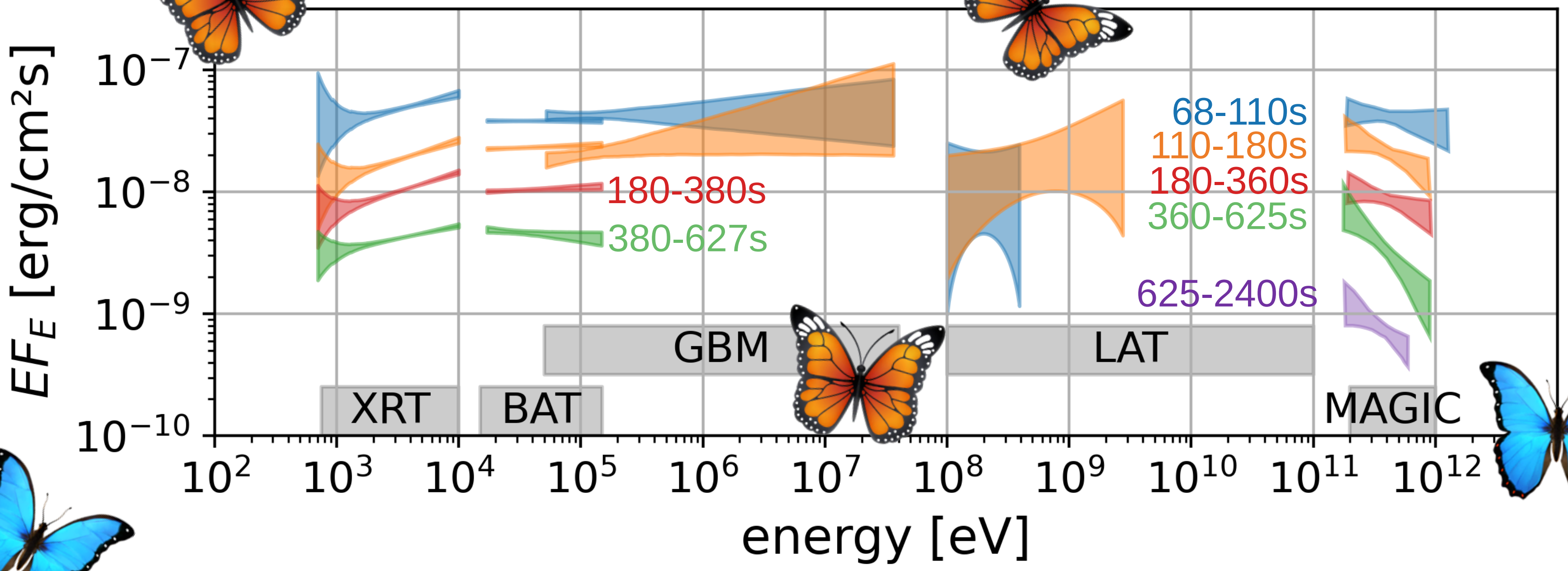
GRB 190114C (MAGIC 🐫)



Dromedary?

- remarkably flat over 9 orders of magnitude in energy!

GRB 190114C (MAGIC 🐫)



- just looking at lovely butterflies has no statistical meaning…

What is the task? Forward folding

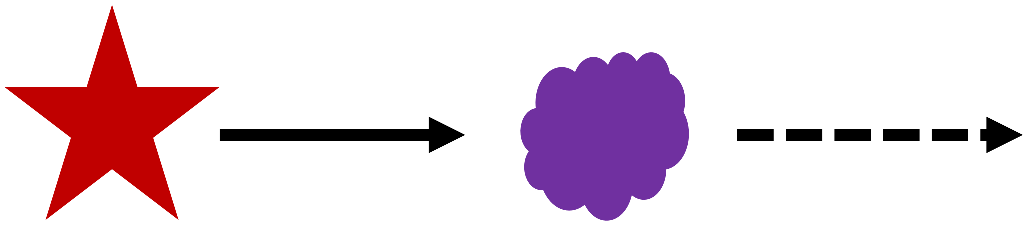
→ model

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

What is the task? Forward folding

→ model absorbed

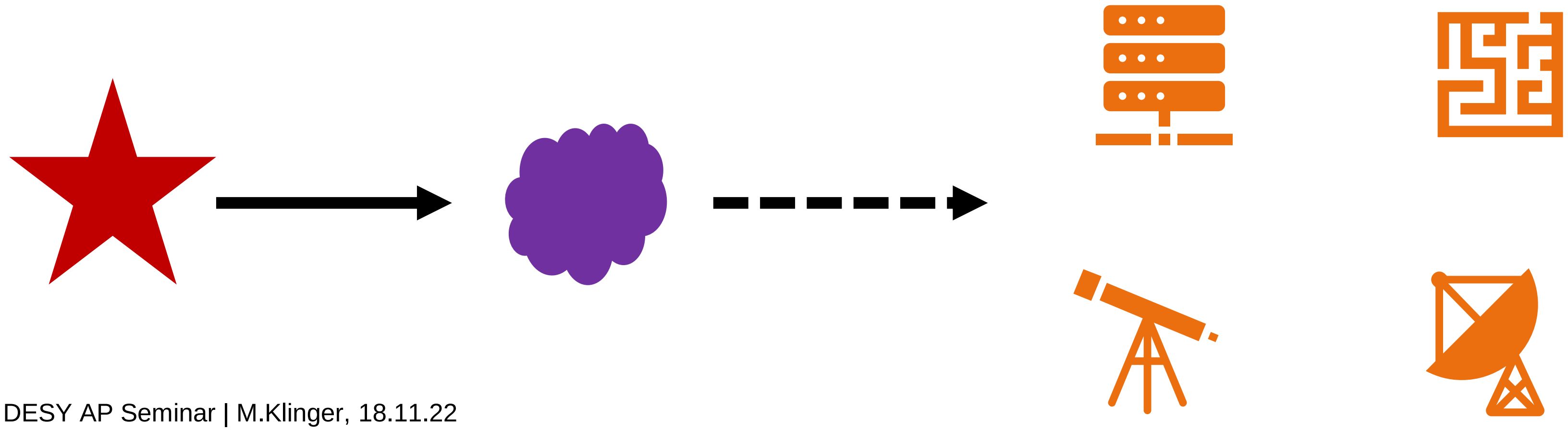
$$\frac{\mathrm{d}N_{\mathrm{source}}}{\mathrm{d}E\,\mathrm{d}t\,\mathrm{d}A}(\hat{E})\ \exp\left(-\tau(\hat{E})\right)$$



What is the task? Forward folding

→ model absorbed measurements of multiple detectors

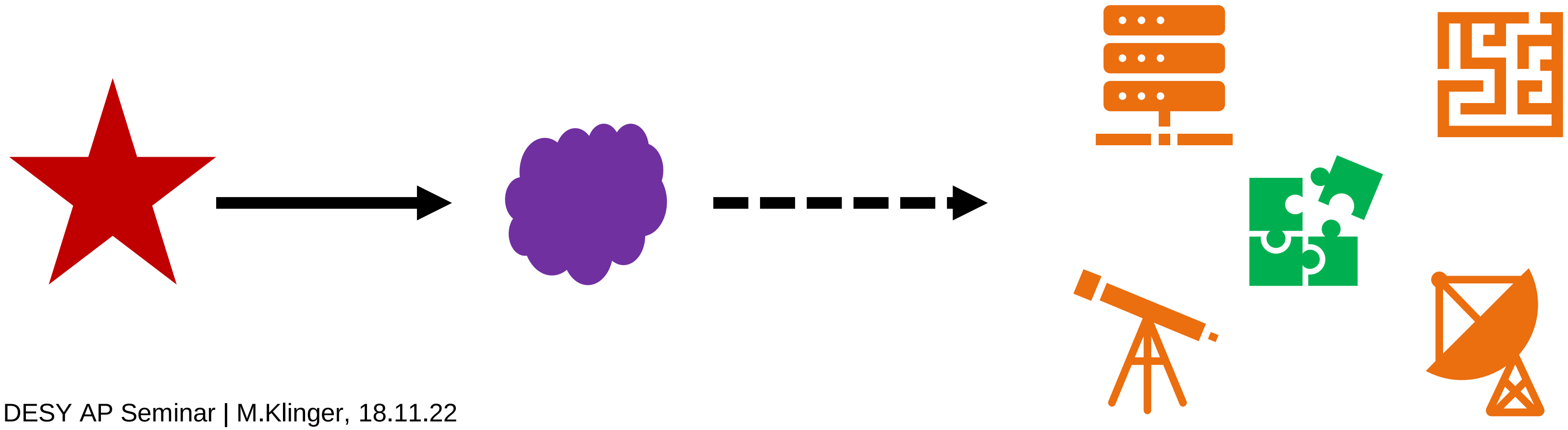
$$\text{Counts rate } (E) = \int \mathrm{d}\hat{E} \; \frac{\mathrm{d}N_{\text{source}}}{\mathrm{d}E \; \mathrm{d}t \; \mathrm{d}A}(\hat{E}) \; \exp\left(-\tau(\hat{E})\right) \; A_{\text{eff}}(E,\hat{E})$$



What is the task? Forward folding

→ model absorbed measurements of multiple detectors

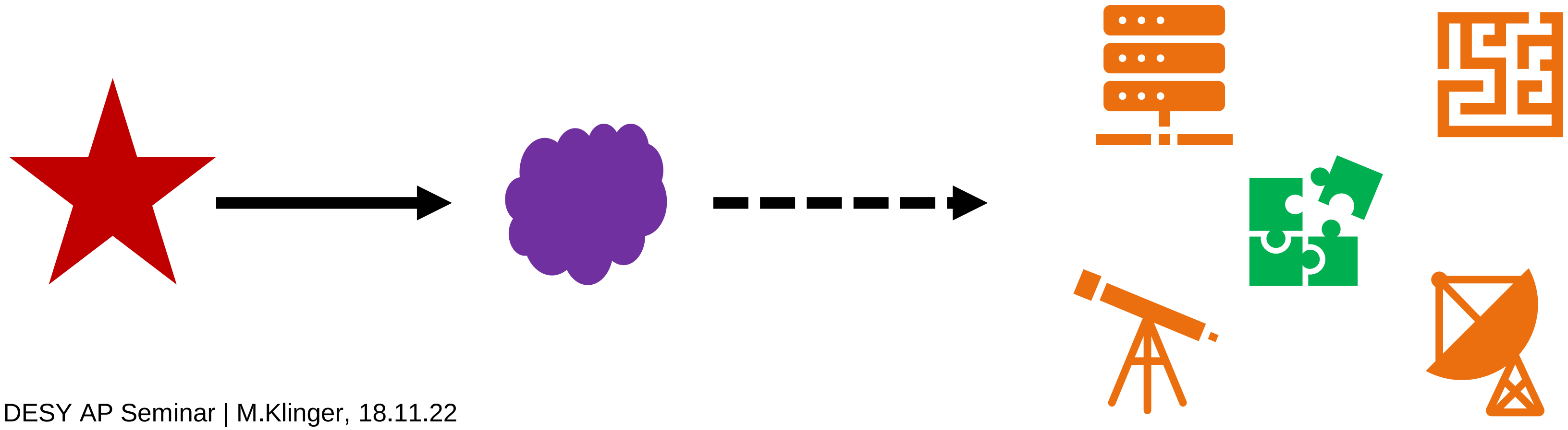
$$\text{Counts rate } (E) = \int \mathrm{d}\hat{E}\ \frac{\mathrm{d}N_{\mathrm{source}}}{\mathrm{d}E\ \mathrm{d}t\ \mathrm{d}A}\left(\hat{E}\right)\ \exp\left(-\tau\left(\hat{E}\right)\right)\ A_{\mathrm{eff}}\left(E,\hat{E}\right)\ c_{\mathrm{sys}}$$



What is the task? Forward folding

→ fit model to absorbed measurements of multiple detectors

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



Fit ?

- 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

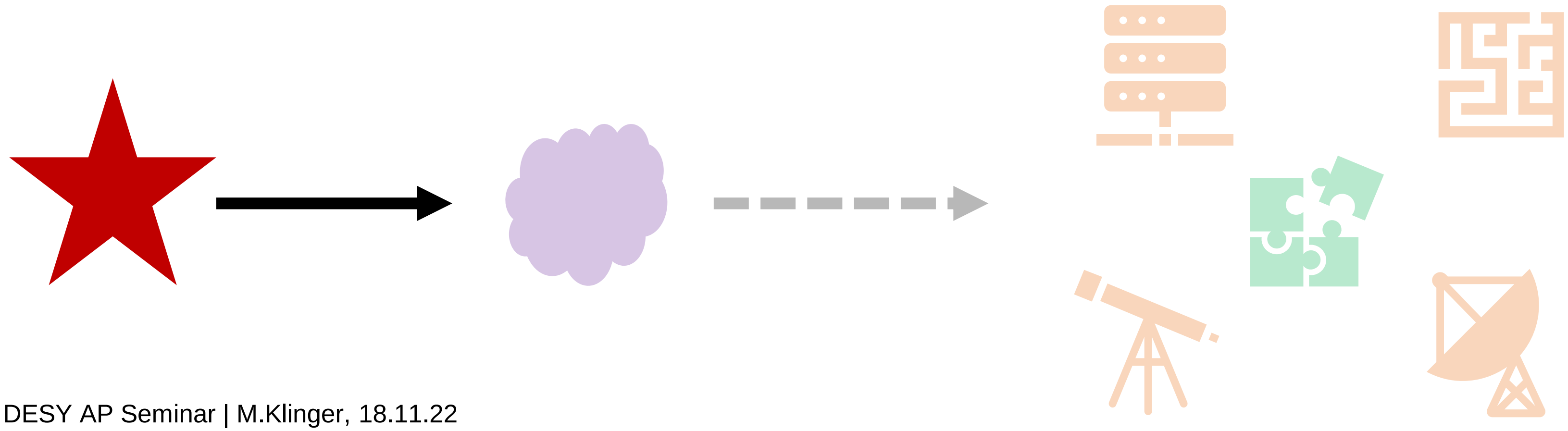
  → quantitative way of measuring preference of model 1 over model 2

  → metric scale crucial

Forward folding

→ fit **model** to absorbed measurements of multiple detectors

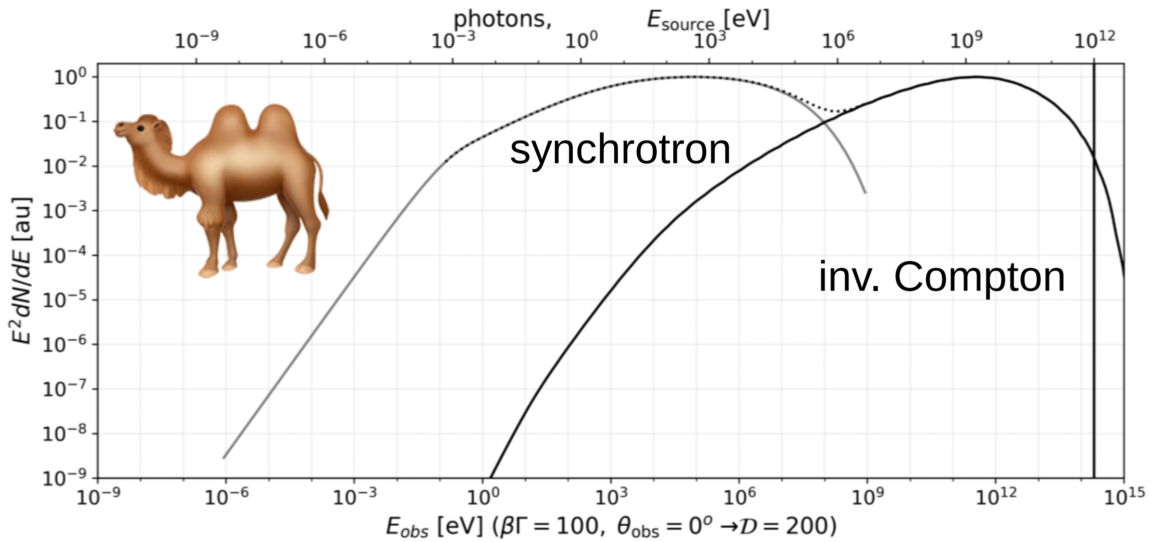
$$\text{Counts rate } (E) = \int \mathrm{d}\hat{E}\ \frac{\mathrm{d}N_{source}}{dE\ \mathrm{d}t\ \mathrm{d}A}(\hat{E})\ exp\left(-\tau(\hat{E})\right)\ A_{\mathrm{eff}}(E,\hat{E})\ c_{\mathrm{sys}}$$



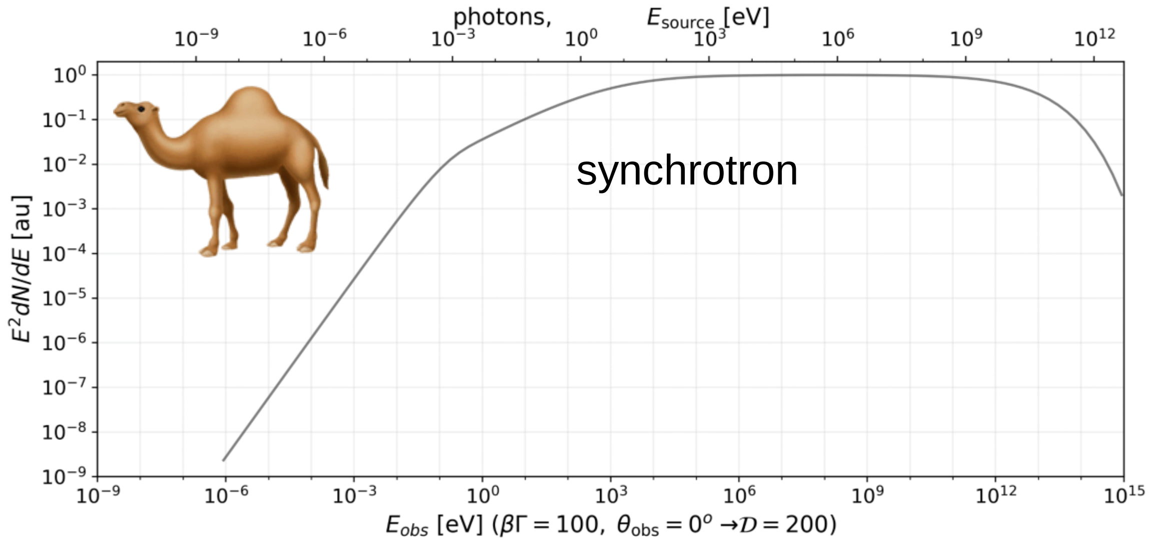
Reduced SSC model

→ incorporates 2 types of solutions

1. double hump solution (SSC):



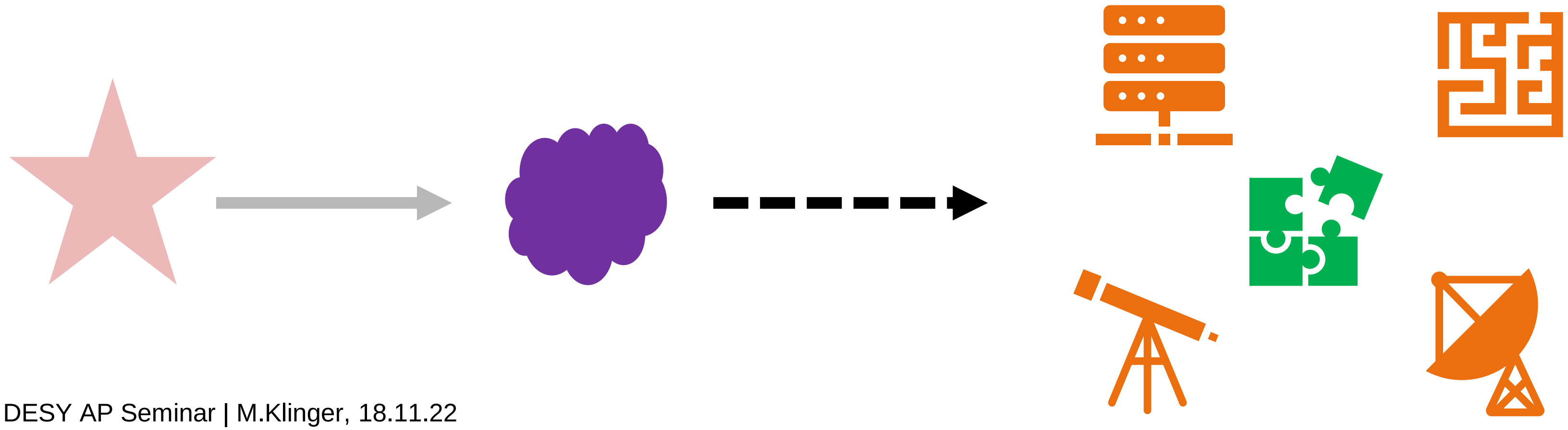
2. single hump solution (syn. only)



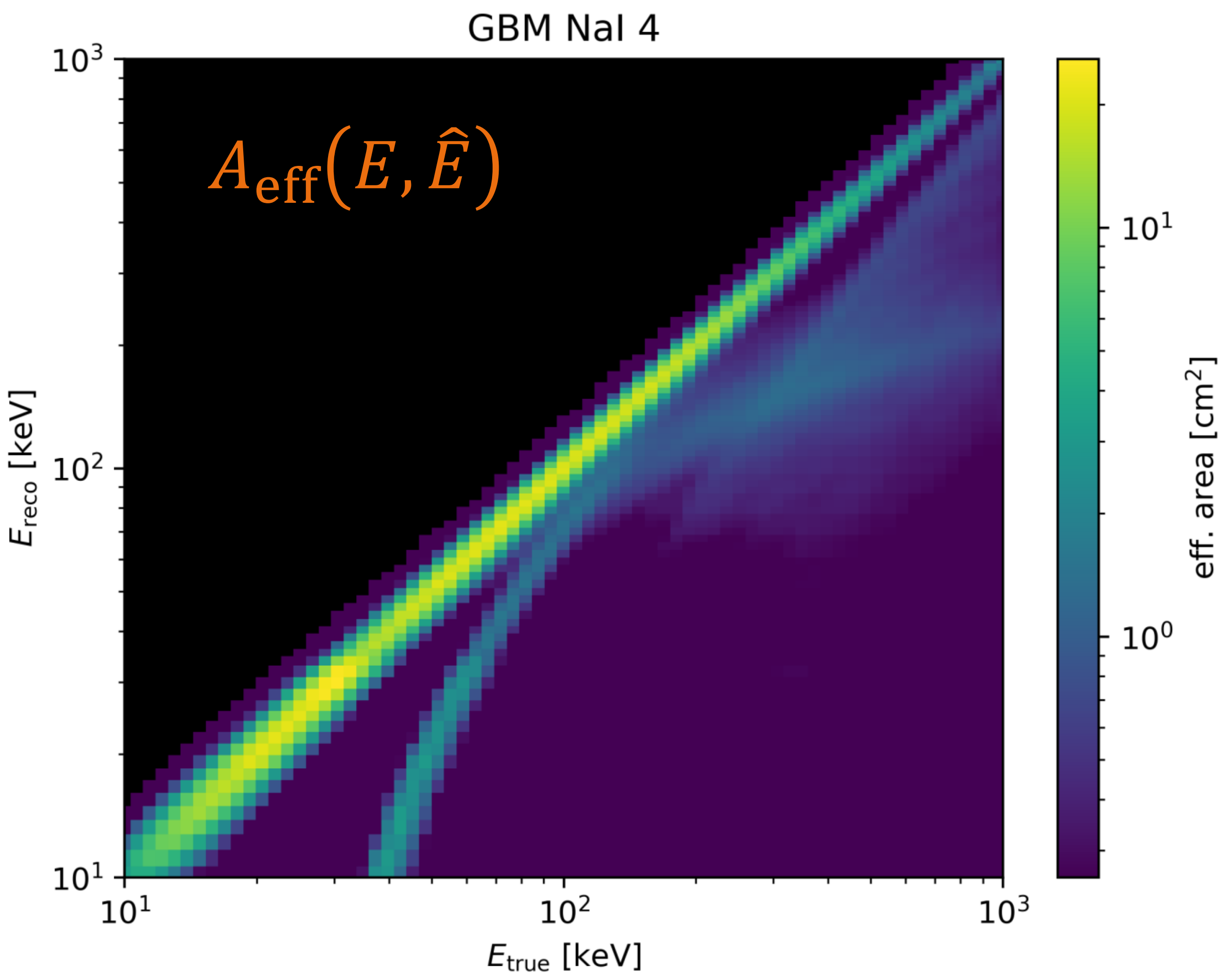
Forward folding

→ fit model to absorbed measurements of multiple detectors

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



Instrument response for single detector

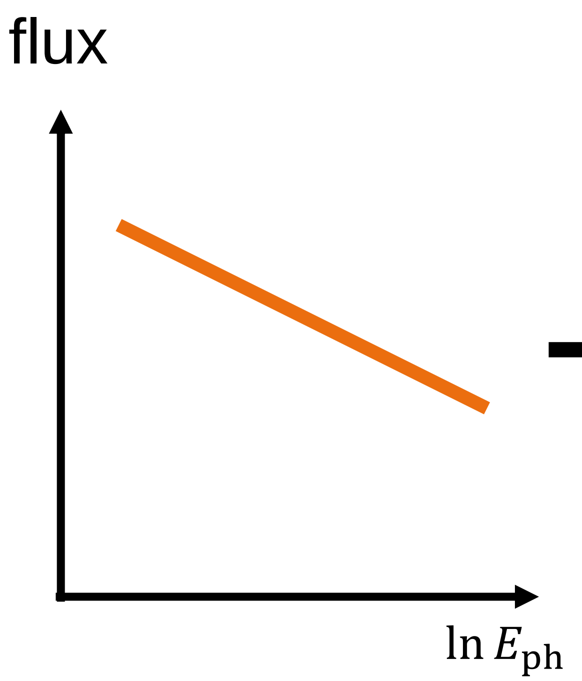


- detector consists of many energy channels

  → **energy dispersion**
- we cannot simply invert (unfold) this matrix

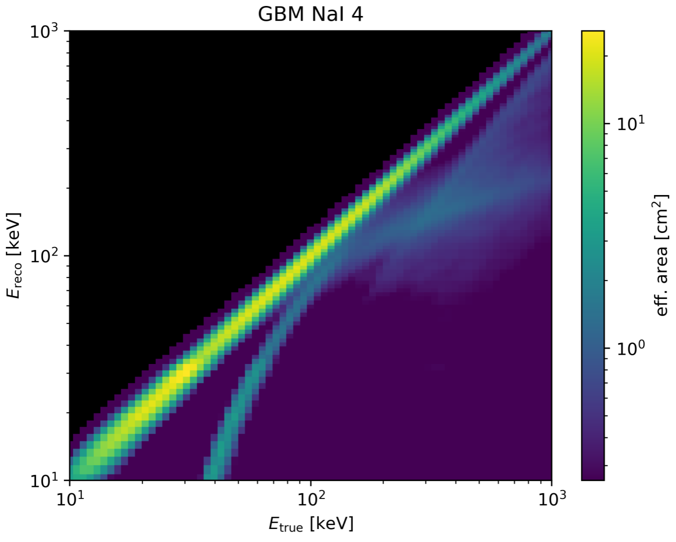
  → **forward folding**

Instrument response for single detector



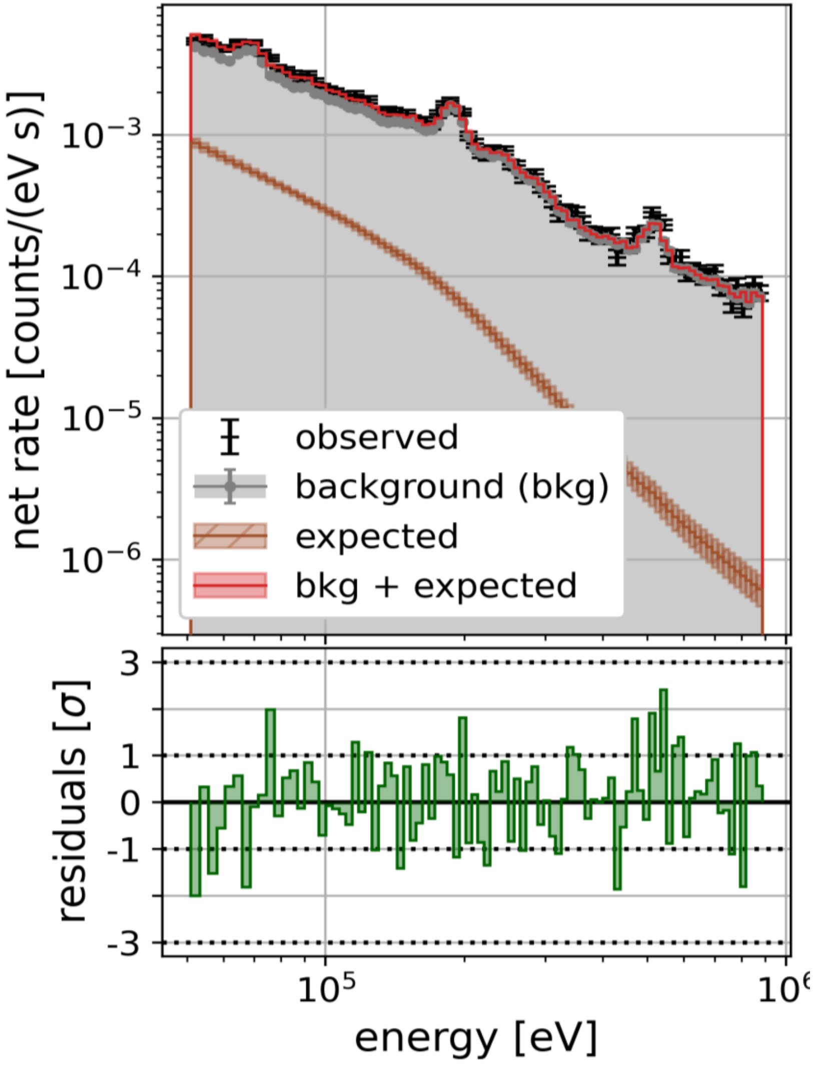
model

+



$A_{\mathrm{eff}}(E, \hat{E})$

=



count rate

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

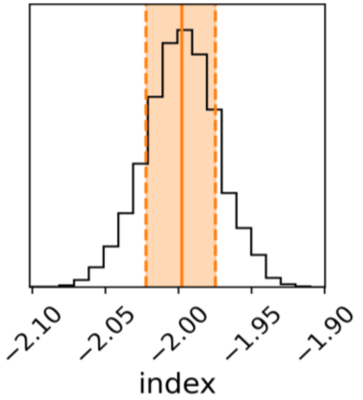
Background rate

different detectors have different statistics!

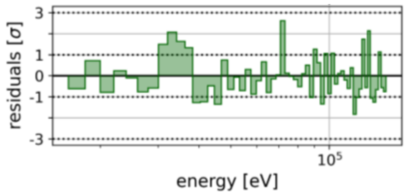
Building up the picture

BAT

15-150 keV



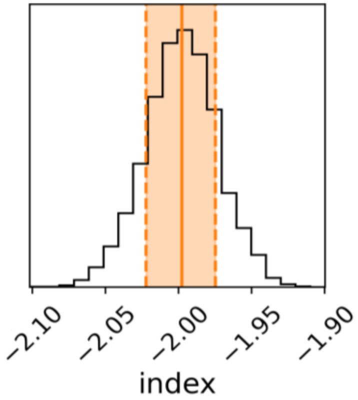
$$-1.998^{+0.023}_{-0.024}$$



Building up the picture

BAT

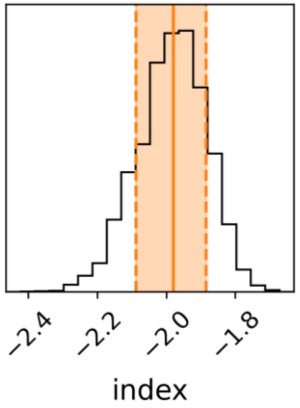
15-150 keV



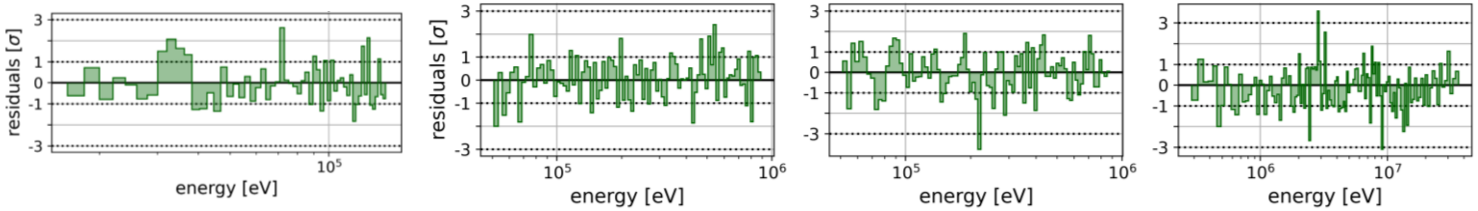
$$-1.998^{+0.023}_{-0.024}$$

GBM

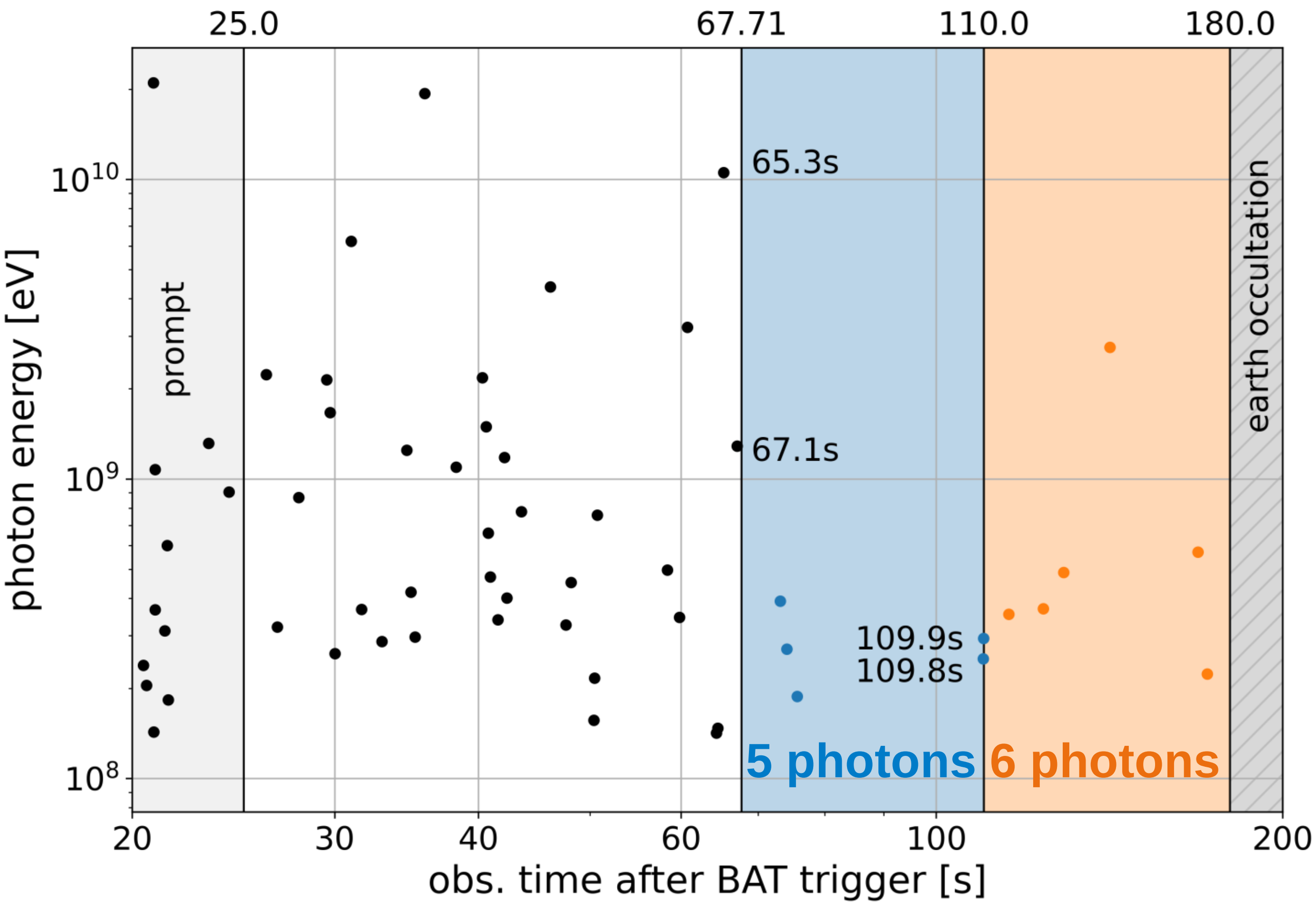
50 keV - 40 MeV



$$-1.98 \pm 0.1$$

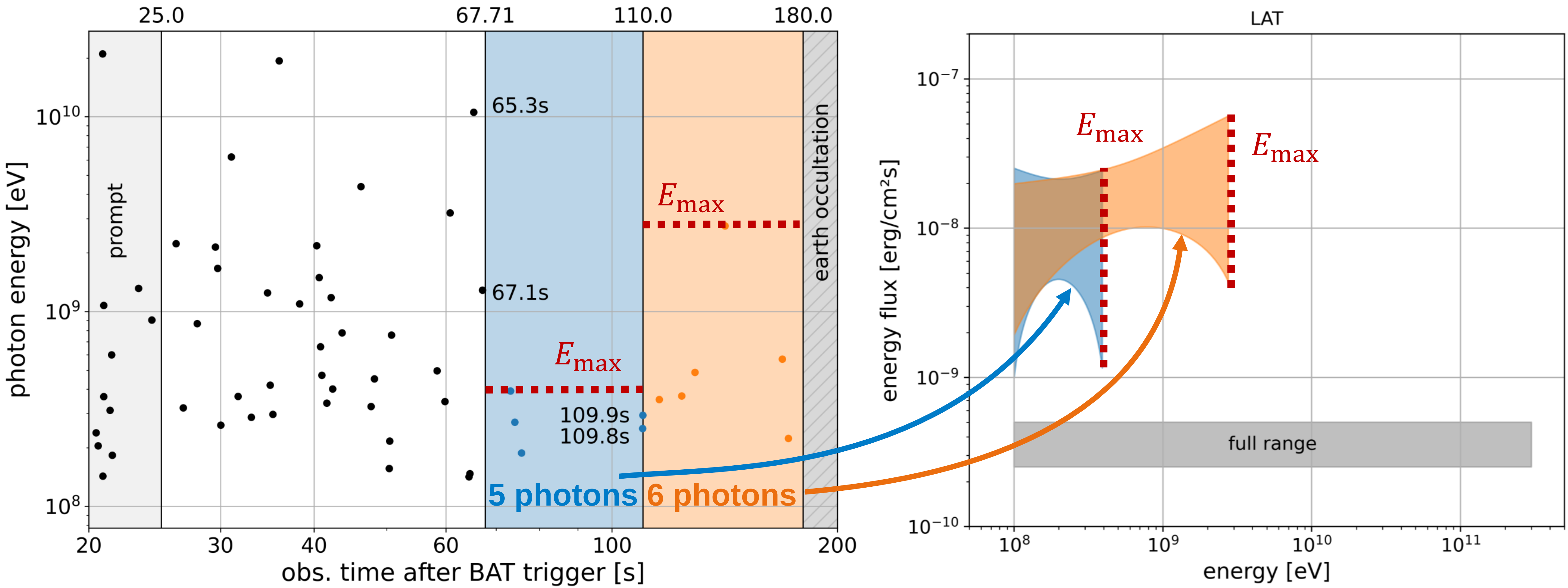


Fermi LAT



→ single photon counter

Fermi LAT

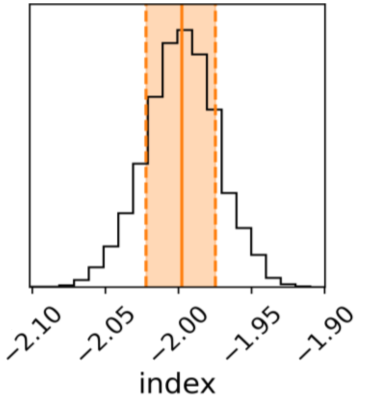


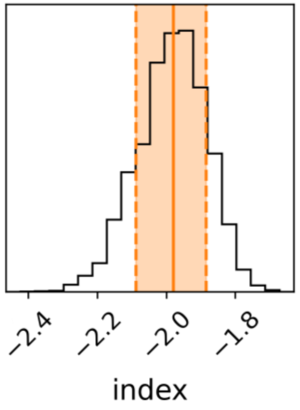
→ single photon counter

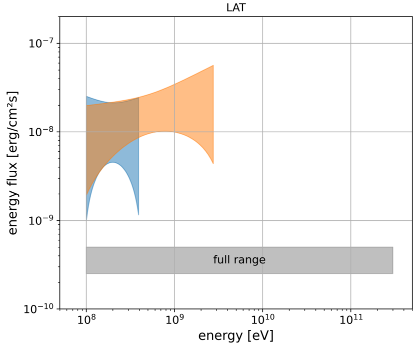
→ spectral index not really constrained

Building up the picture

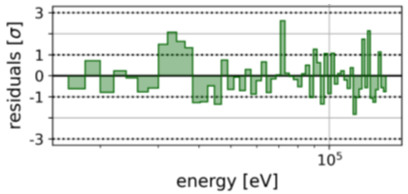
BAT	GBM	LAT
15-150 keV	50 keV - 40 MeV	> 100 MeV

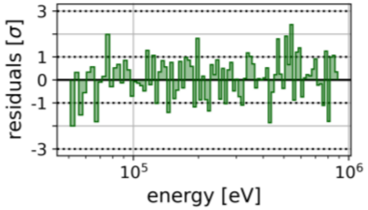






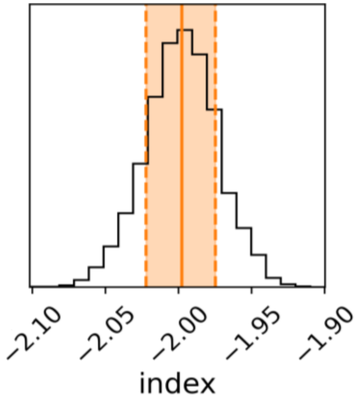
$-1.998^{+0.023}_{-0.024}$ $\quad$ -1.98 ± 0.1 $\quad$ -2 ± 1

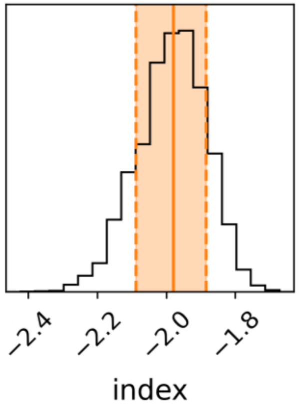


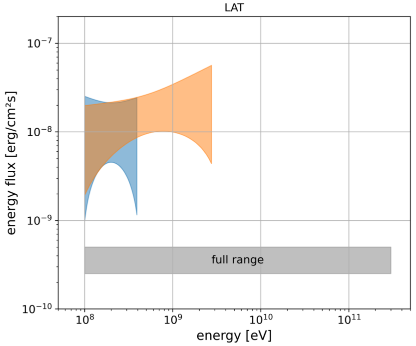


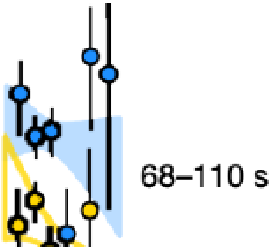
Building up the picture

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



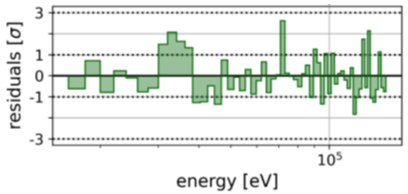


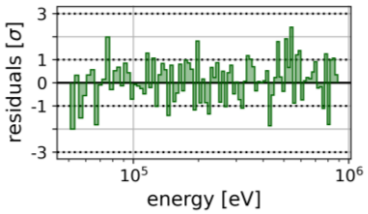




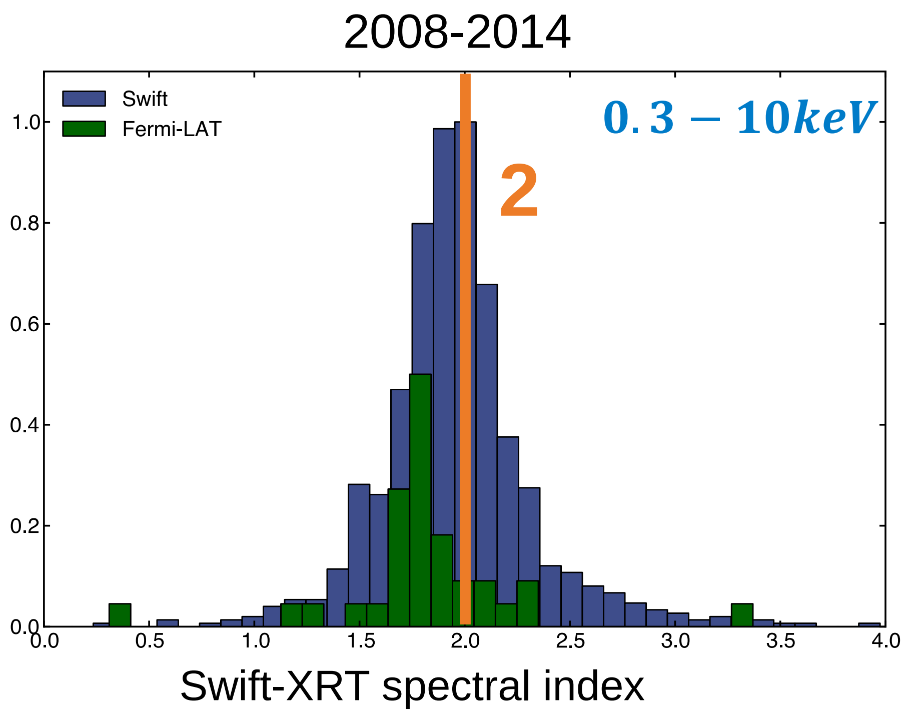
MAGIC Nature 575 (2019)

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

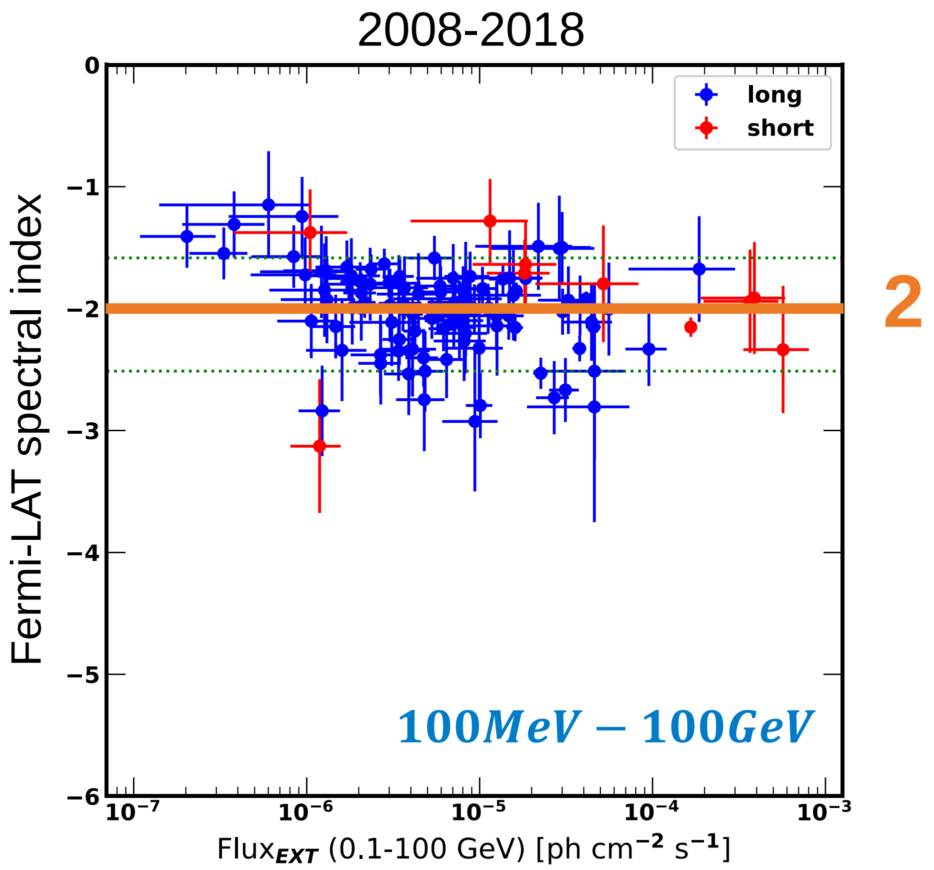




Flat Energy Flux Spectra?



Ajello et al. 2018, joint Swift/Fermi analysis

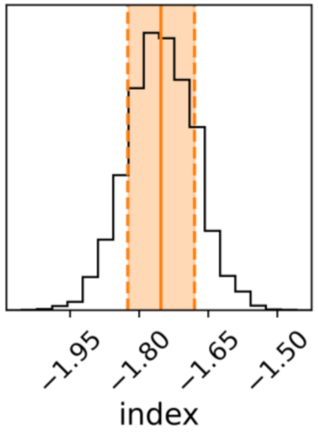


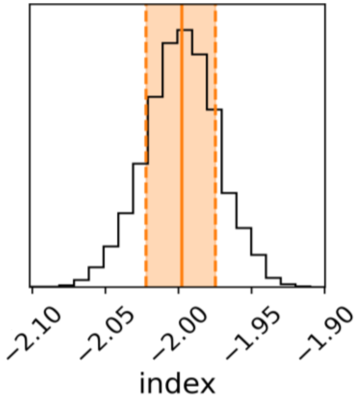
Ajello et al. 2019, 2nd Fermi GRB catalogue

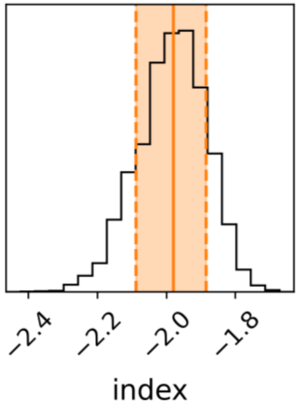
- flat spectra (spectral index ≈ 2) are not uncommon!

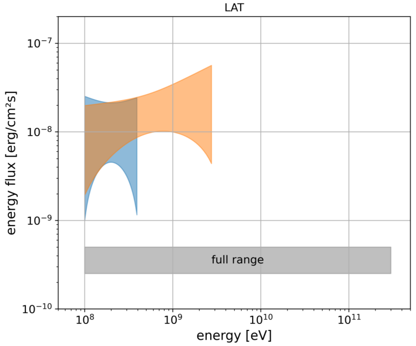
Building up the picture

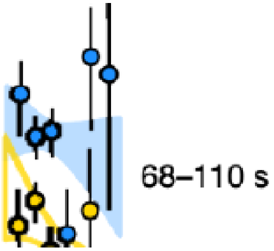
XRT	BAT	GBM	LAT	MAGIC
0.7-10 keV	15-150 keV	50 keV - 40 MeV	> 100 MeV	0.1-1 TeV











MAGIC Nature 575 (2019)

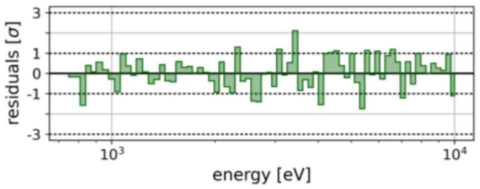
-1.75 ± 0.07

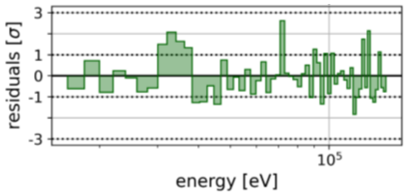
$-1.998^{+0.023}_{-0.024}$

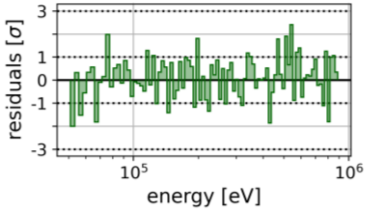
-1.98 ± 0.1

-2 ± 1

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

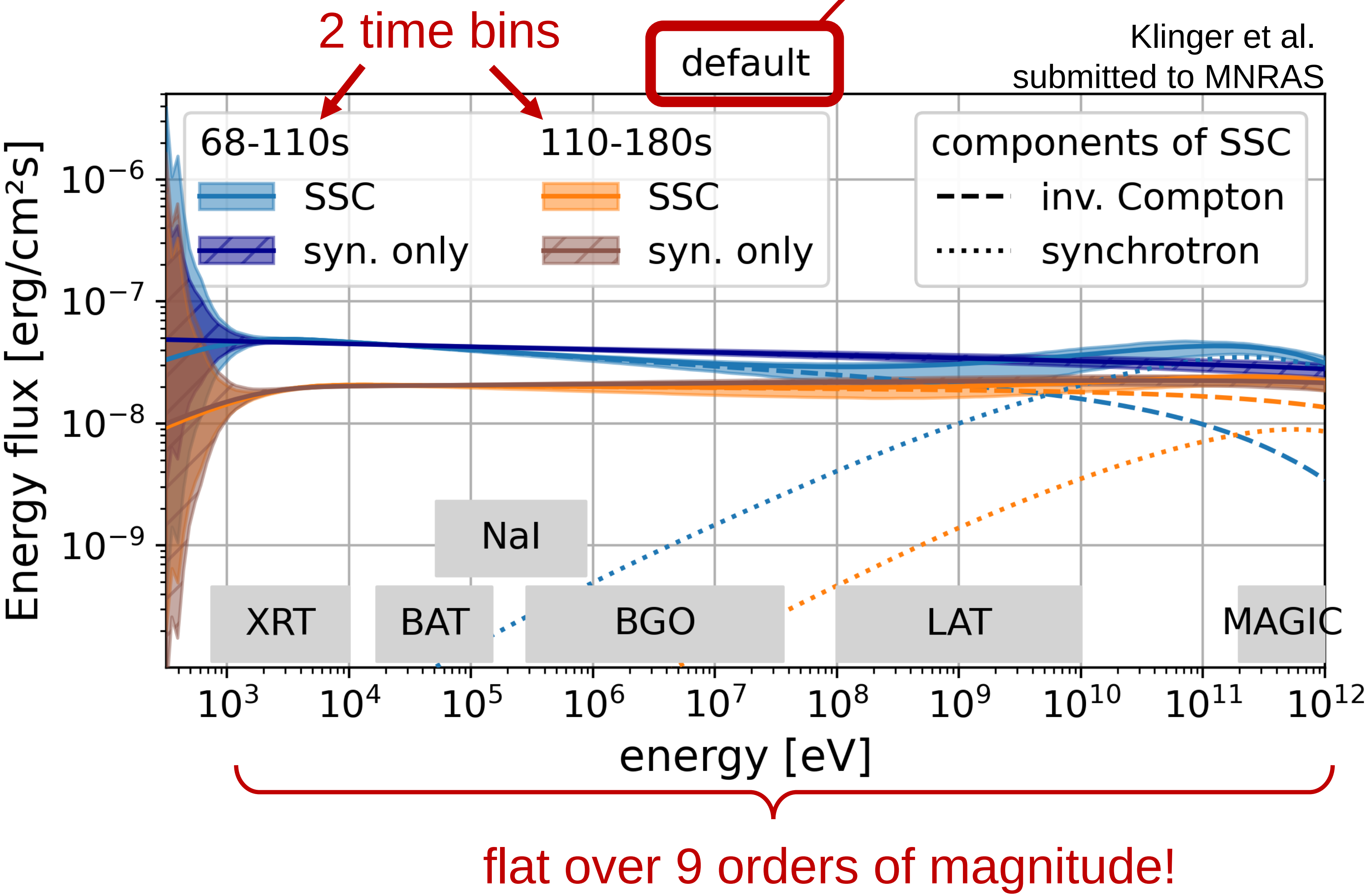




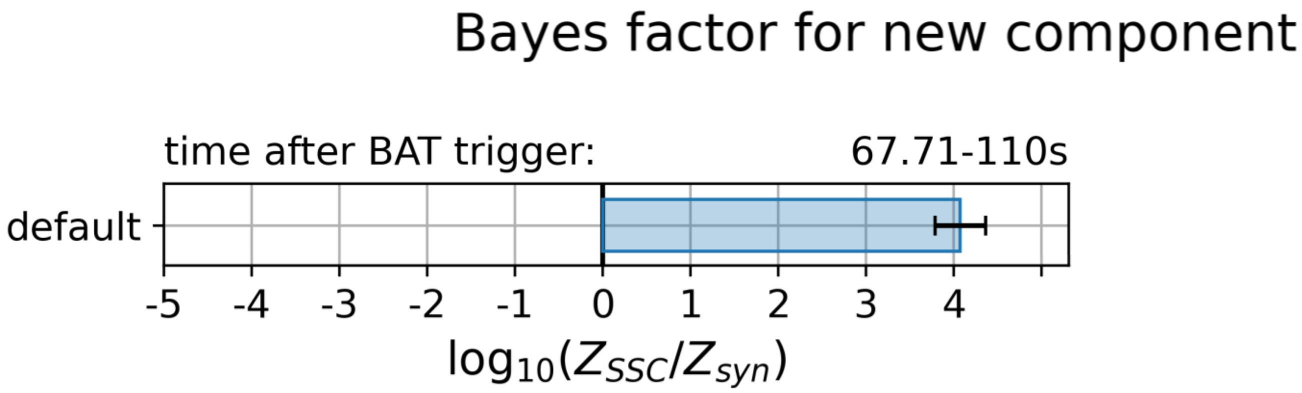


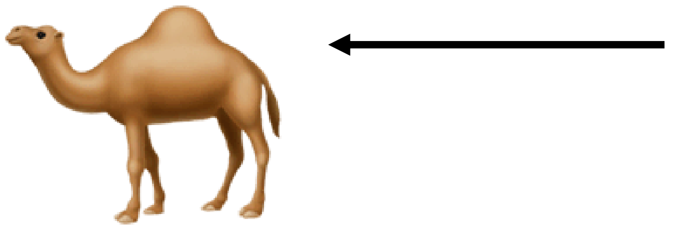
Fitting the reduced SSC model

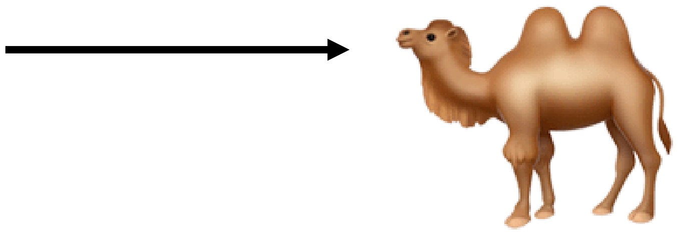
as in Ajello et al. 2020 (joint Swift+Fermi)
→ only BAT-GBM cross calibration included



Preference for new component?







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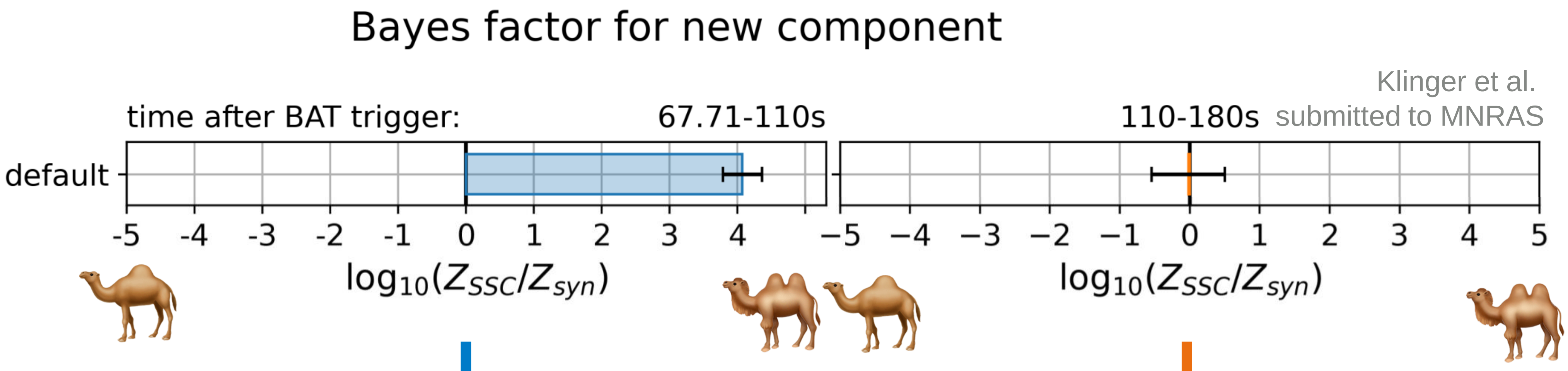


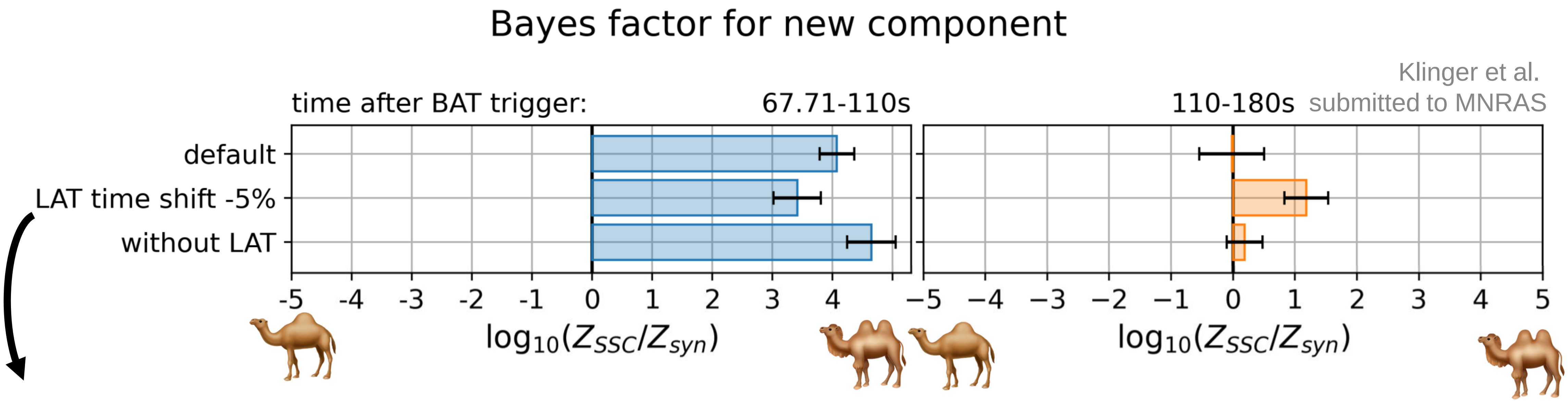
Klinger et al.
submitted to MNRAS

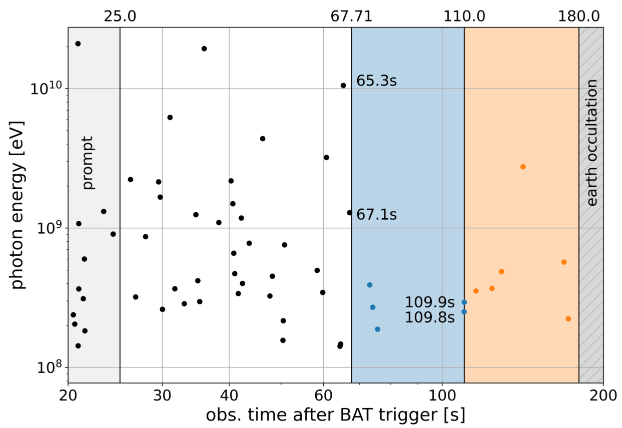
yes

no

Stability of Preference: LAT

Klinger et al.
submitted to MNRAS

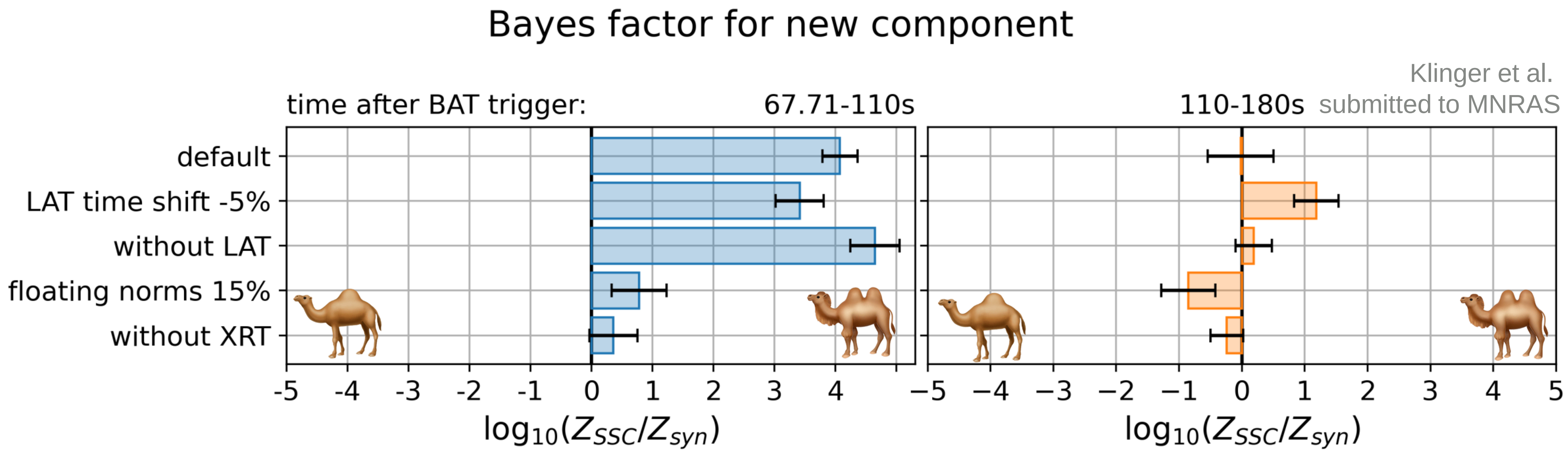




- shift LAT time selection window by 5% (2.1s)
- leave out LAT completely

→LAT not very strong

Stability of Preference: XRT



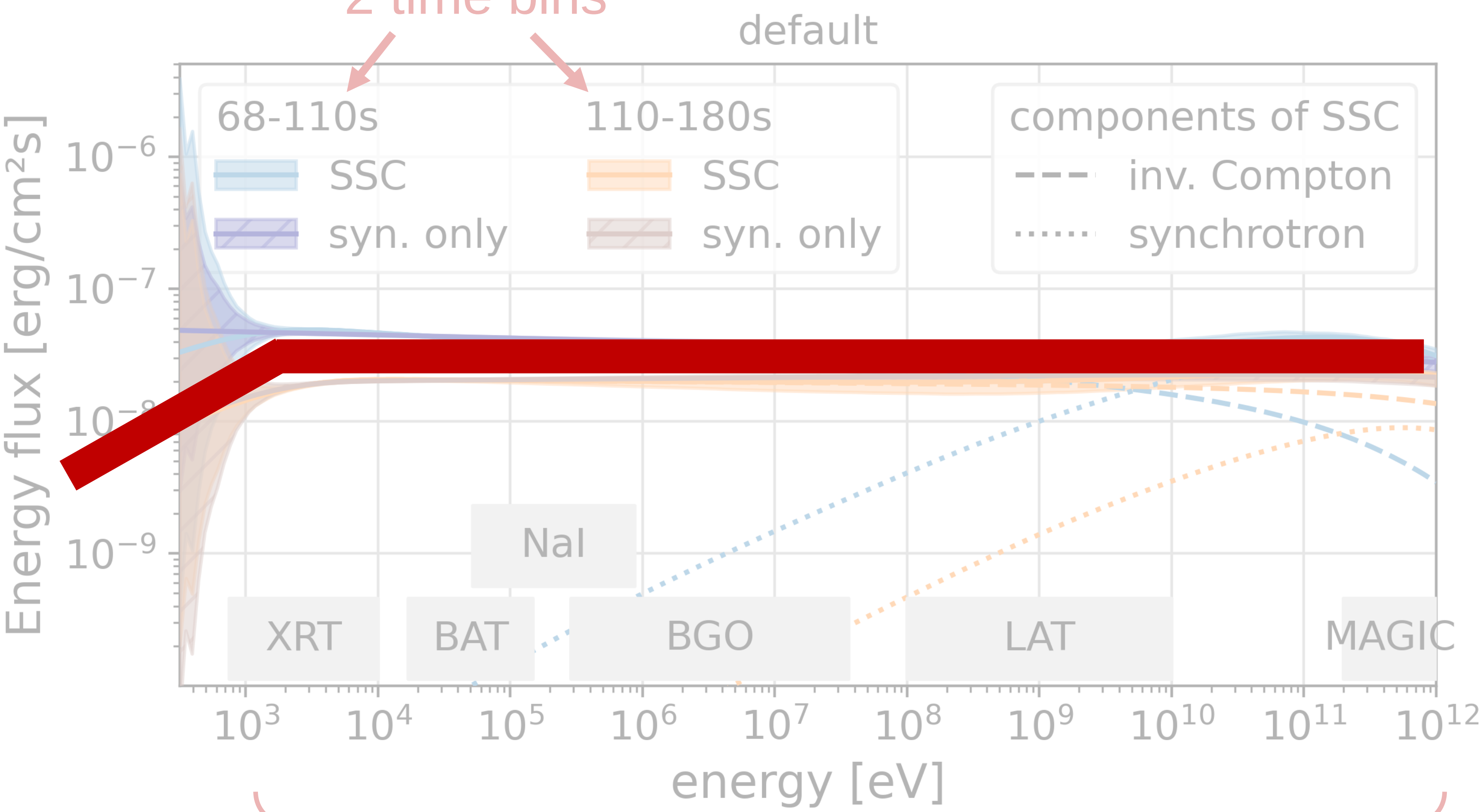
Klinger et al. submitted to MNRAS

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

→ **XRT drives new component!**

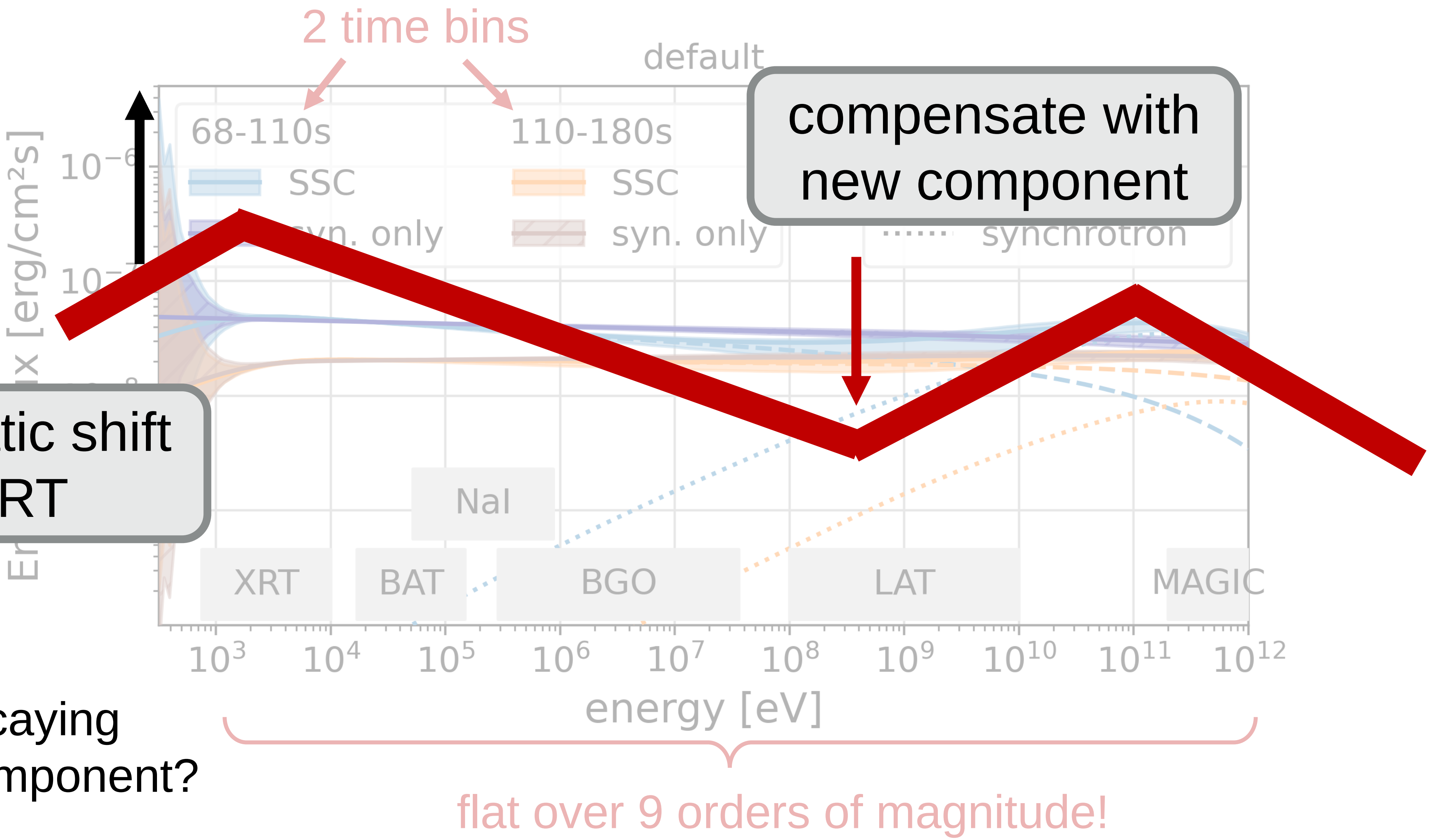
Fitting a reduced SSC model

2 time bins



flat over 9 orders of magnitude!

Fitting a reduced SSC model



compensate with new component

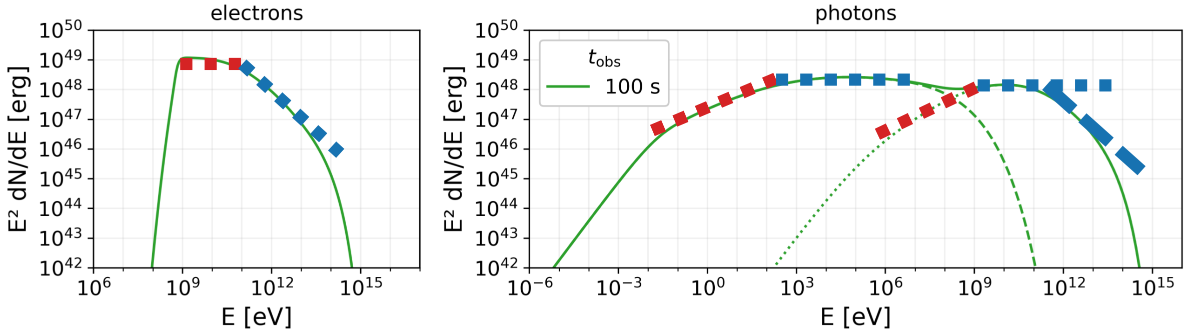
systematic shift of XRT

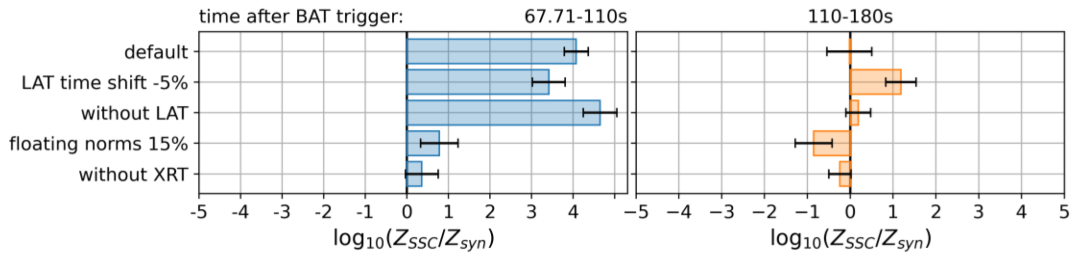
relic of decaying prompt component?

Take away messages

- SSC spectra are mirroring a smoothly BPL electron distribution
- We need more **bright, nearby** GRBs (without moonlight!)
- GRB 190114C is no clear camel type

  →**in particular no clear dromedary!**





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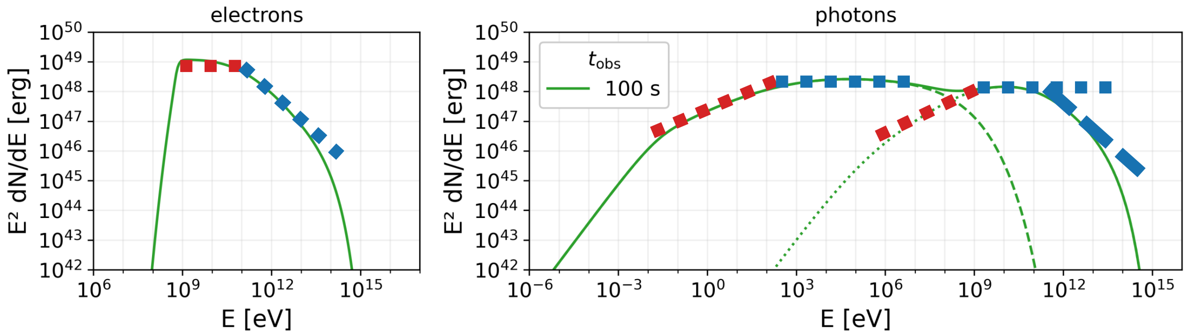

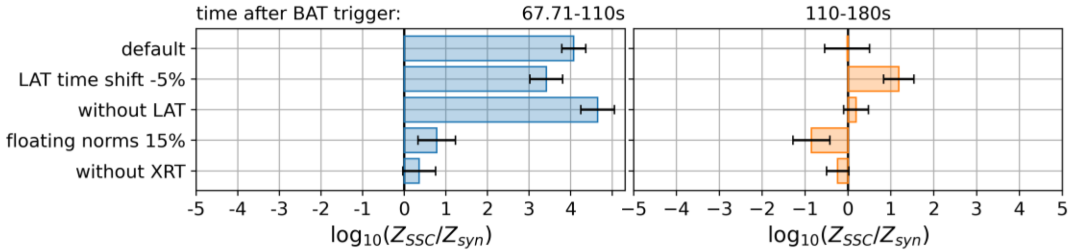

Thank you!