PhD Defence

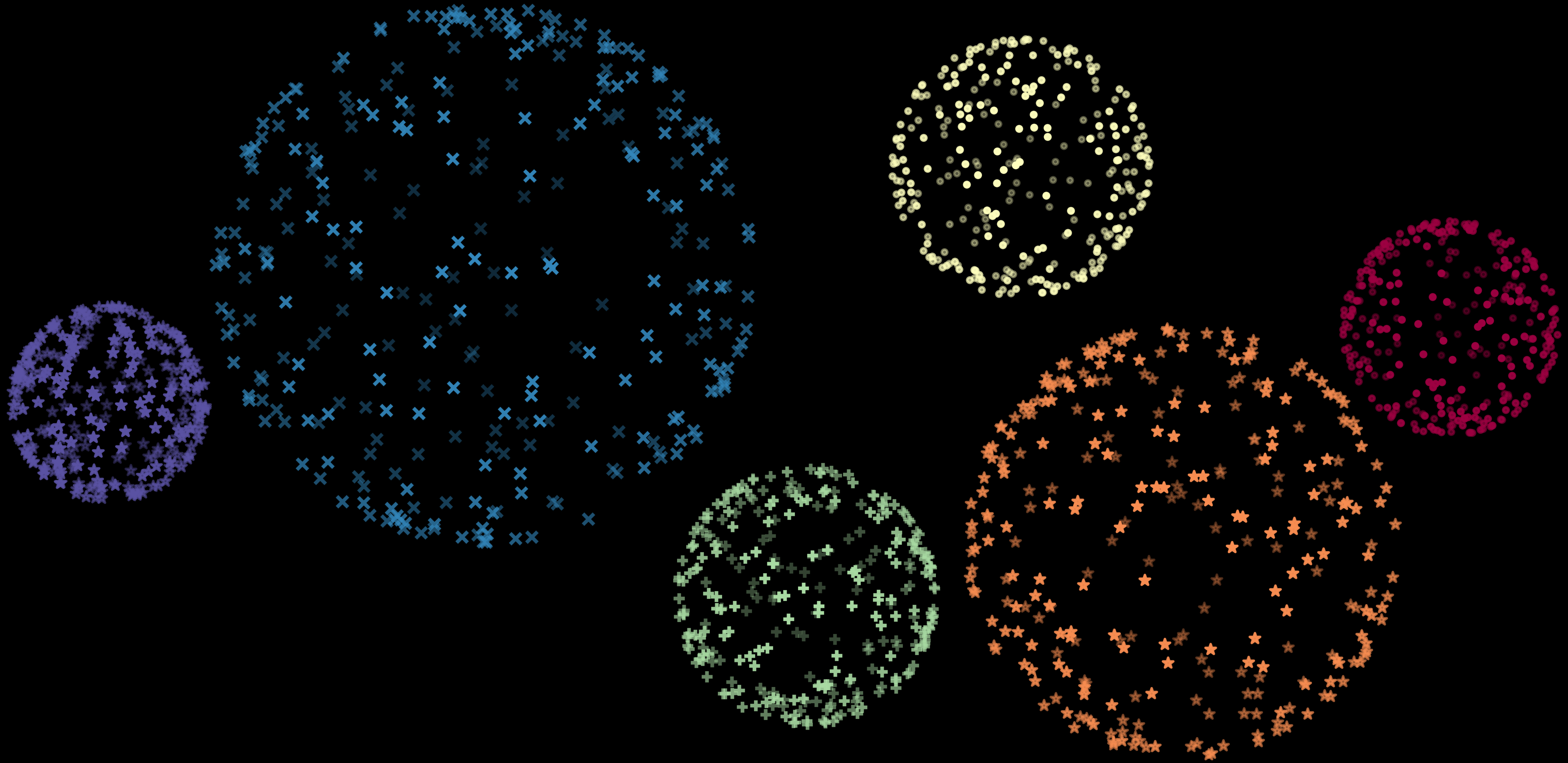
Marc Klinger

01.11.2024

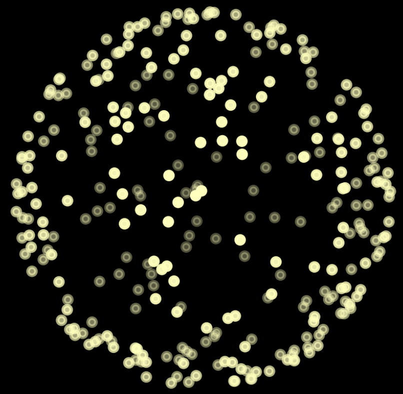
Time-dependent Modelling of Gamma-Ray Burst Afterglows

Supervised by Walter Winter & Andrew Taylor

in collaboration with A. Beardmore, A. Fedynitch, G. Fichet de Clairfontaine, S. Gao, S. Heinz, T. Parsotan, M. Pohl, X. Rodrigues, A. Rudolph, D. Tak, E. Waxman, C. Yuan, S. Zhu



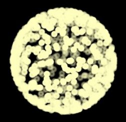
fireworks on new year's sky ⟷ astrophysical explosions in universe



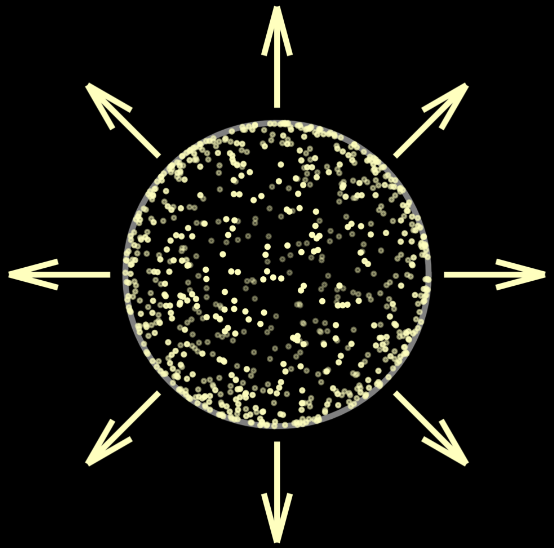
gamma-ray bursts (GRBs)

fireworks on new year's sky ⟷ astrophysical explosions in universe

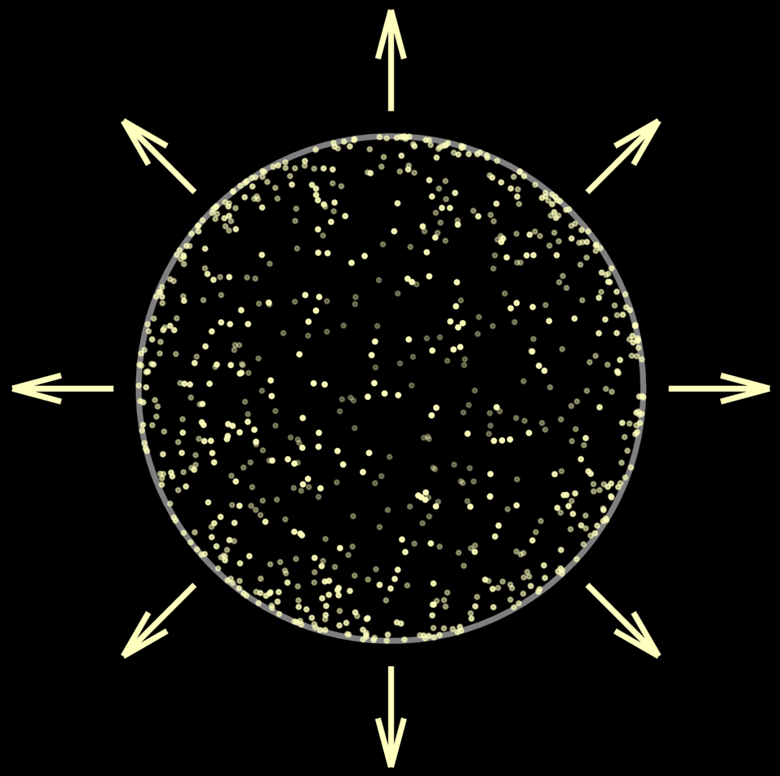
Astrophysical explosions



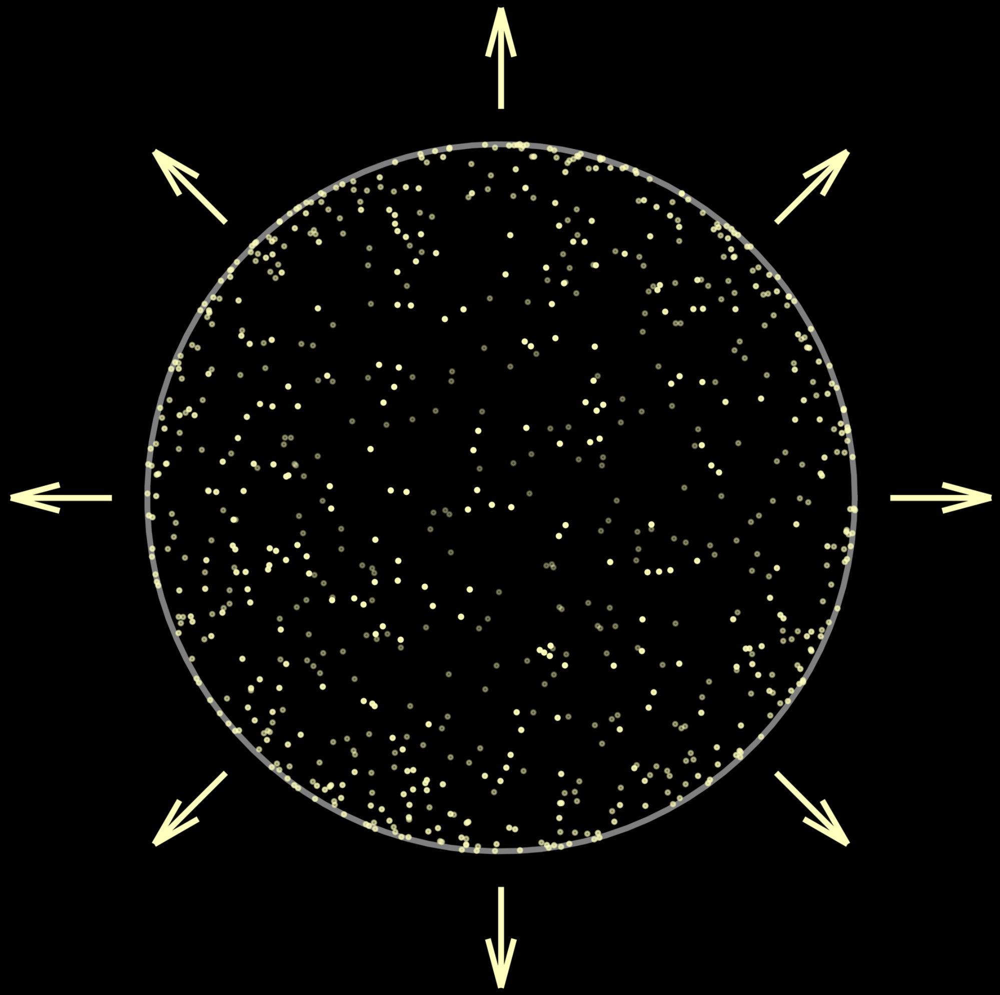
Astrophysical explosions



Astrophysical explosions

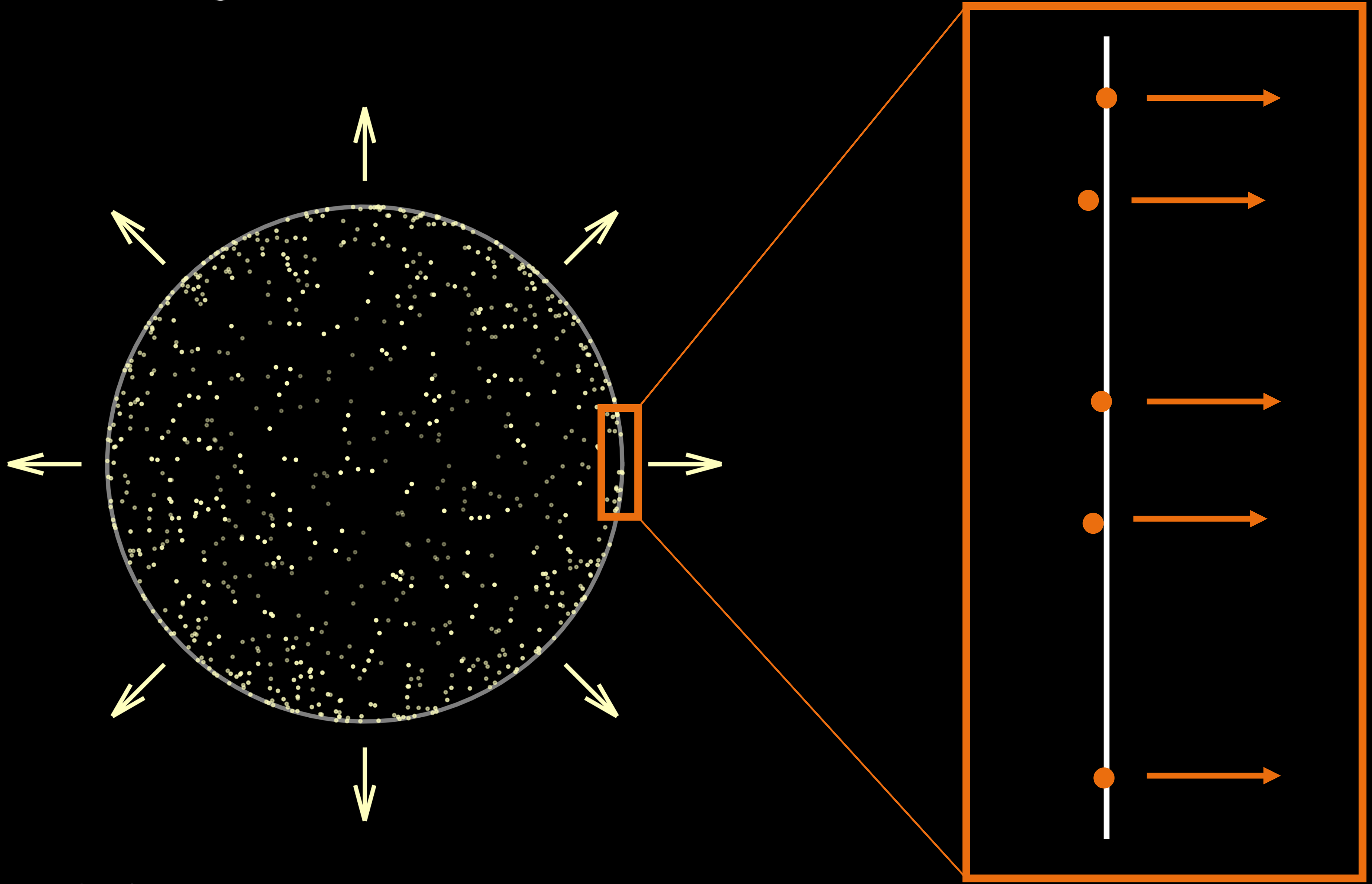


Astrophysical explosions

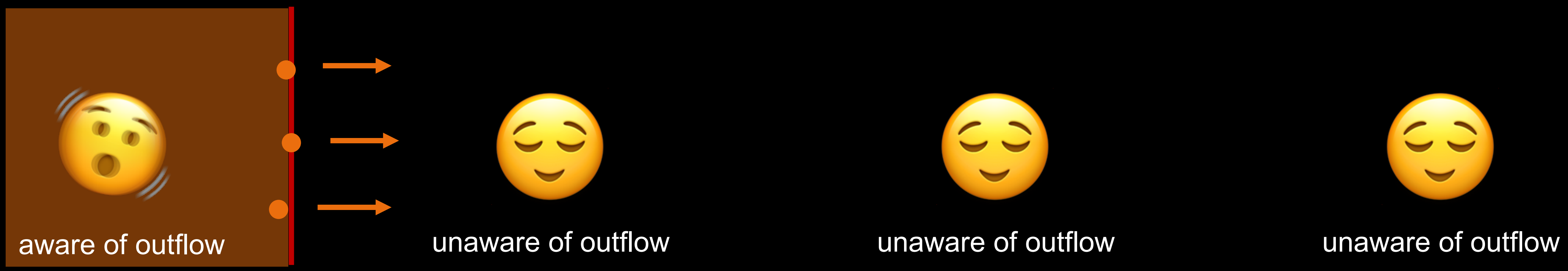


→ outflow

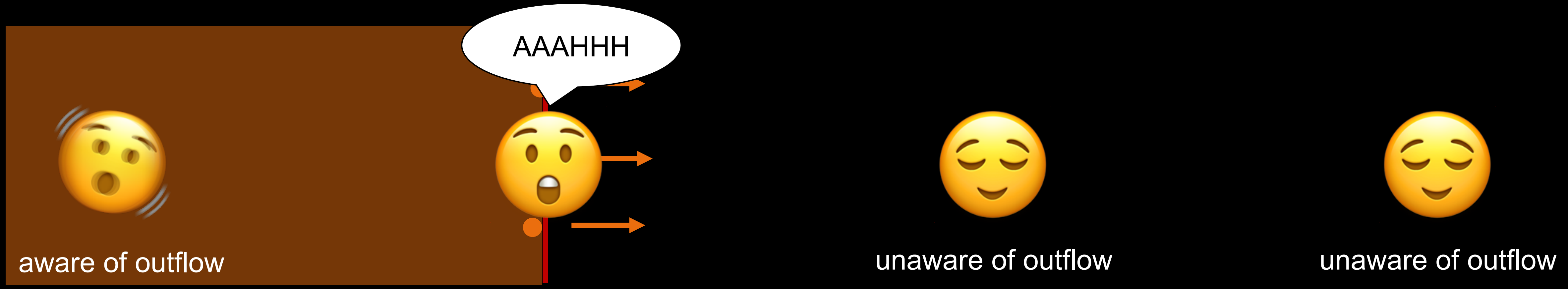
Astrophysical explosions



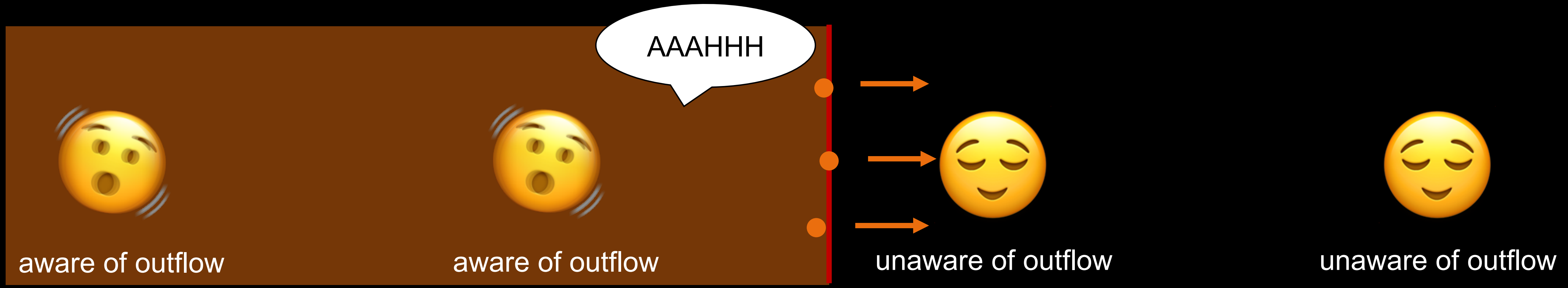
Astrophysical outflows



Astrophysical outflows

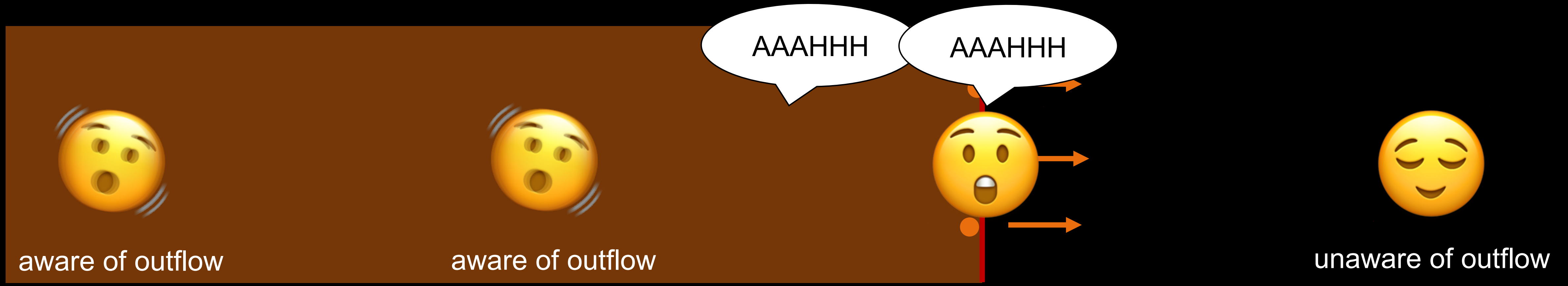


Astrophysical outflows

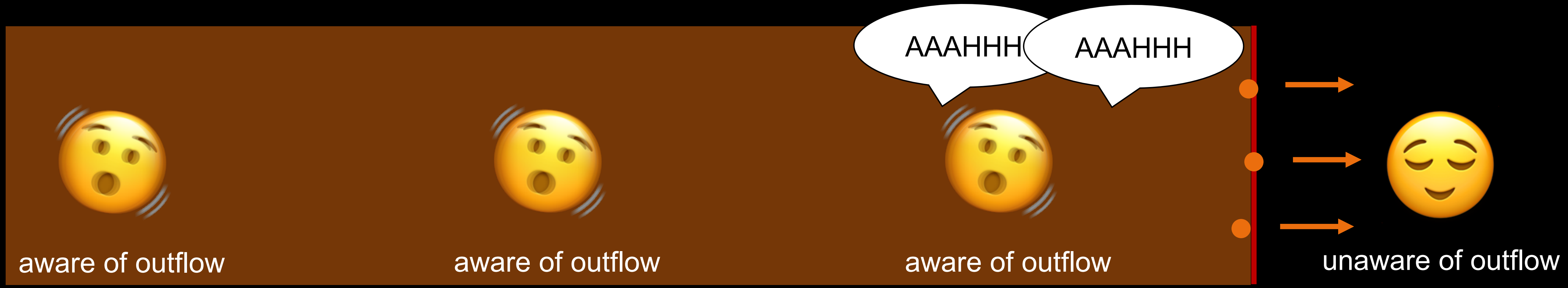


Astrophysical outflows

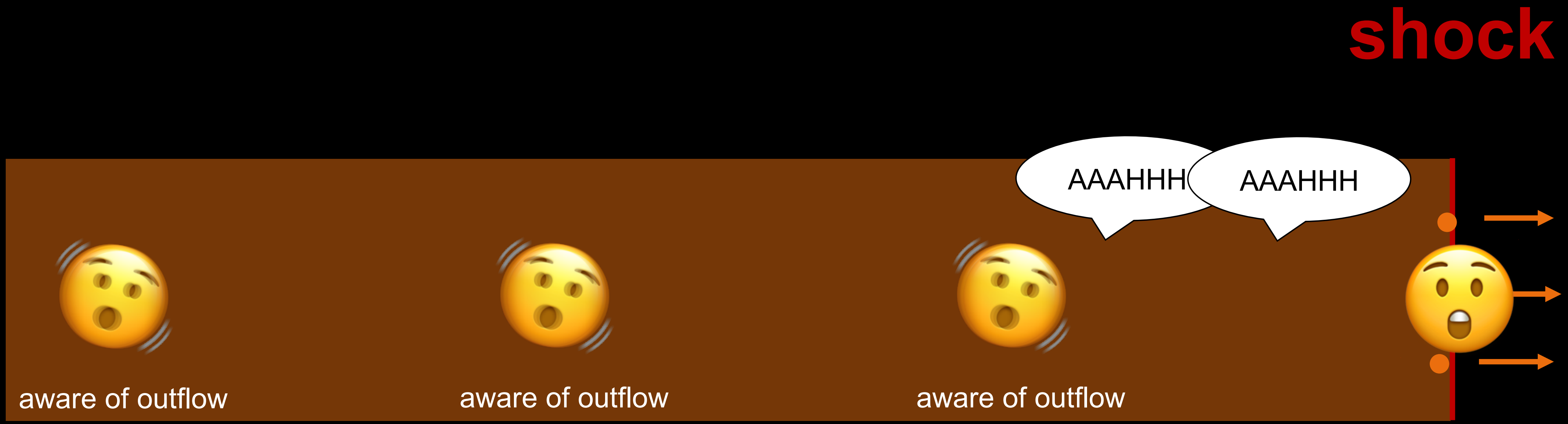
outflow
faster than
speed of information



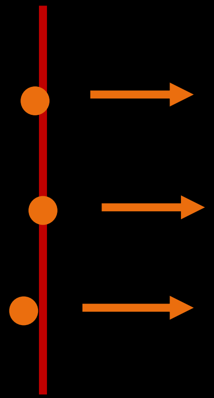
Astrophysical outflows



Astrophysical outflows



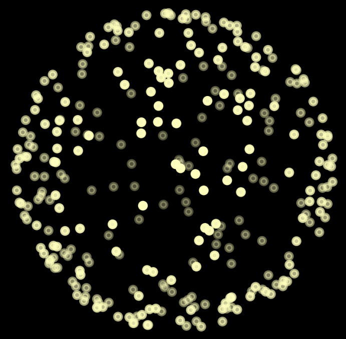
Astrophysical shocks shine too



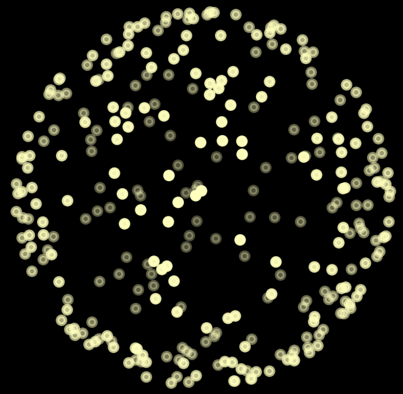
outflow
→ shock

particle acceleration &
radiation mechanism

uncertain assumptions



observations



gamma-ray bursts (GRBs)

fireworks on new year’s sky ⟷ astrophysical explosions in universe

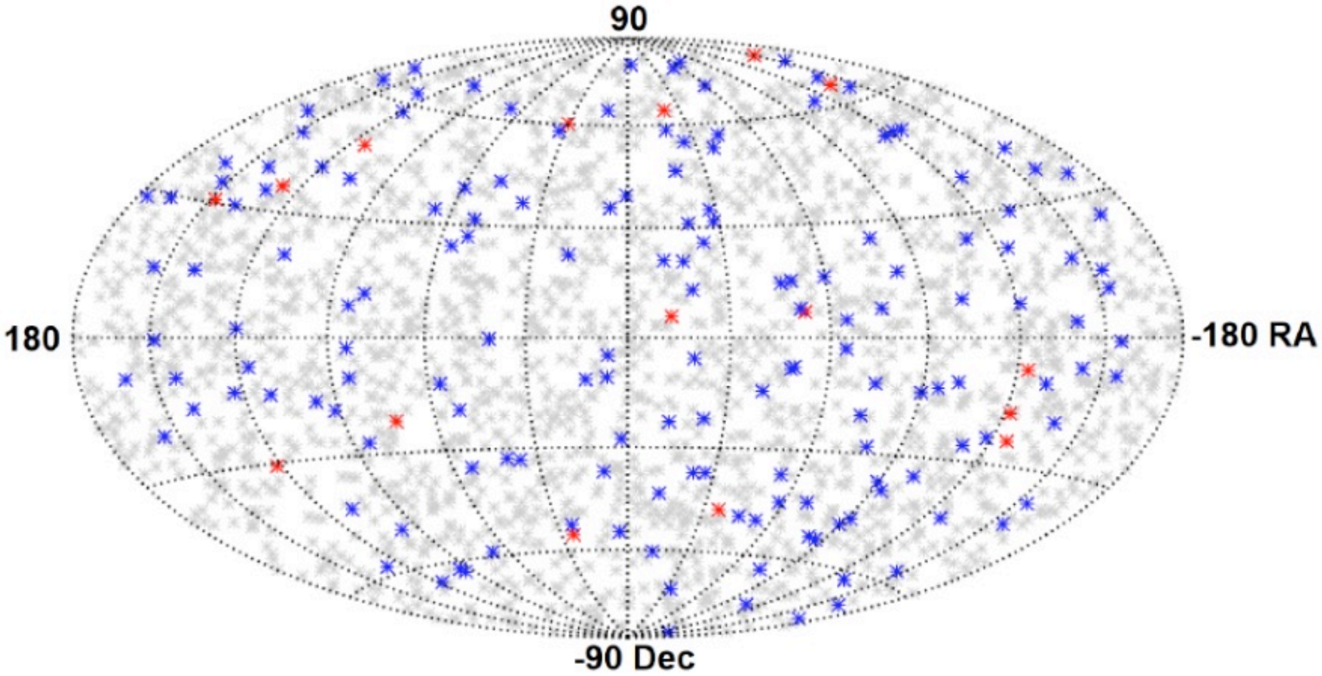
Gamma-ray bursts (GRBs)

Observational picture

Gamma-ray bursts (GRBs)

Observational picture

- **flashes of X/γ-rays isotropically distributed on sky**



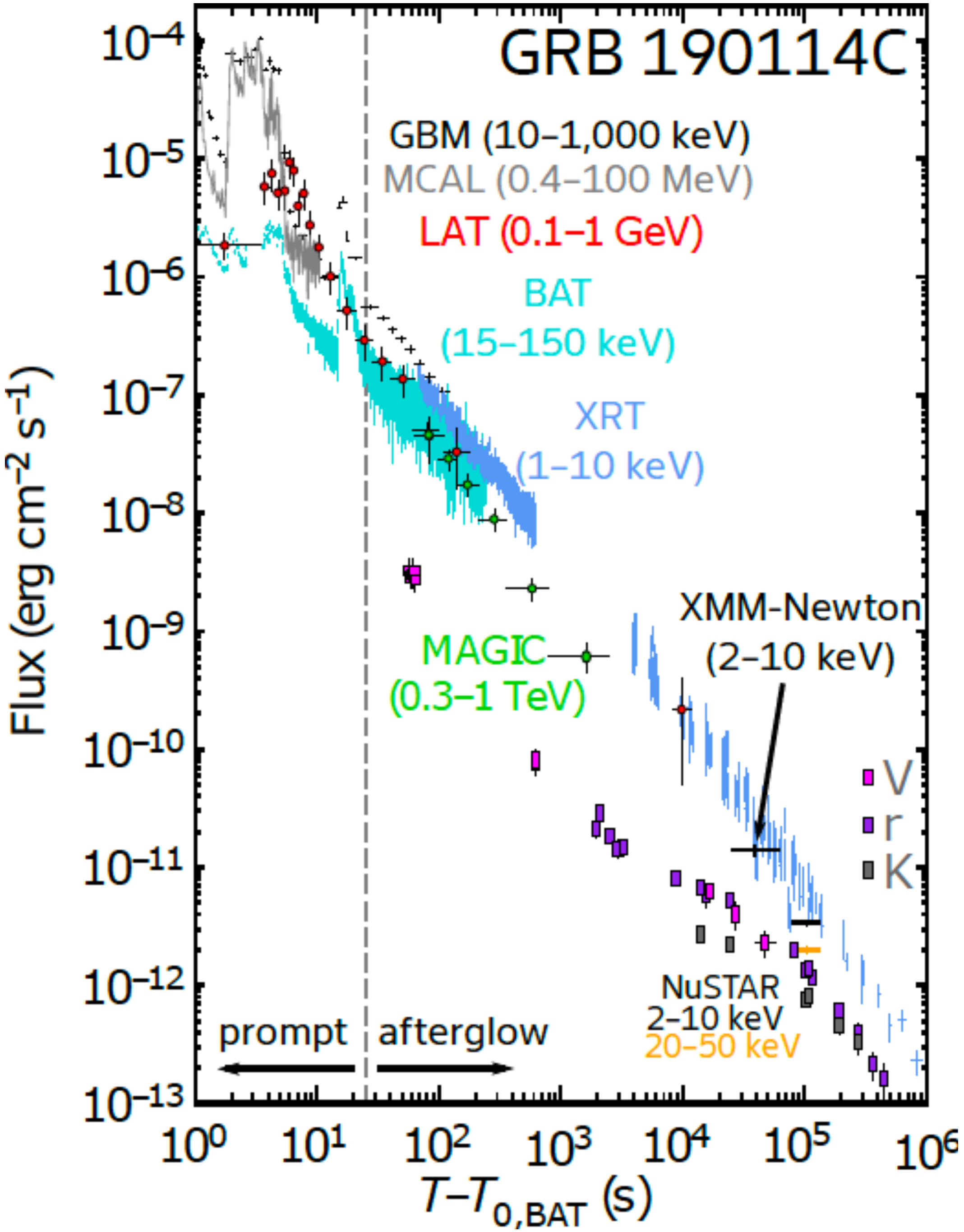
2. Fermi-LAT GRB Catalogue
[Ajello et al. ApJ 878 52 (2019)]

Gamma-ray bursts (GRBs)

Observational picture

- flashes of X/γ-rays isotropically distributed on sky
- **complex prompt phase and smooth afterglow in the light curve**

adapted from MAGIC Collab. Nature 575 (2019)

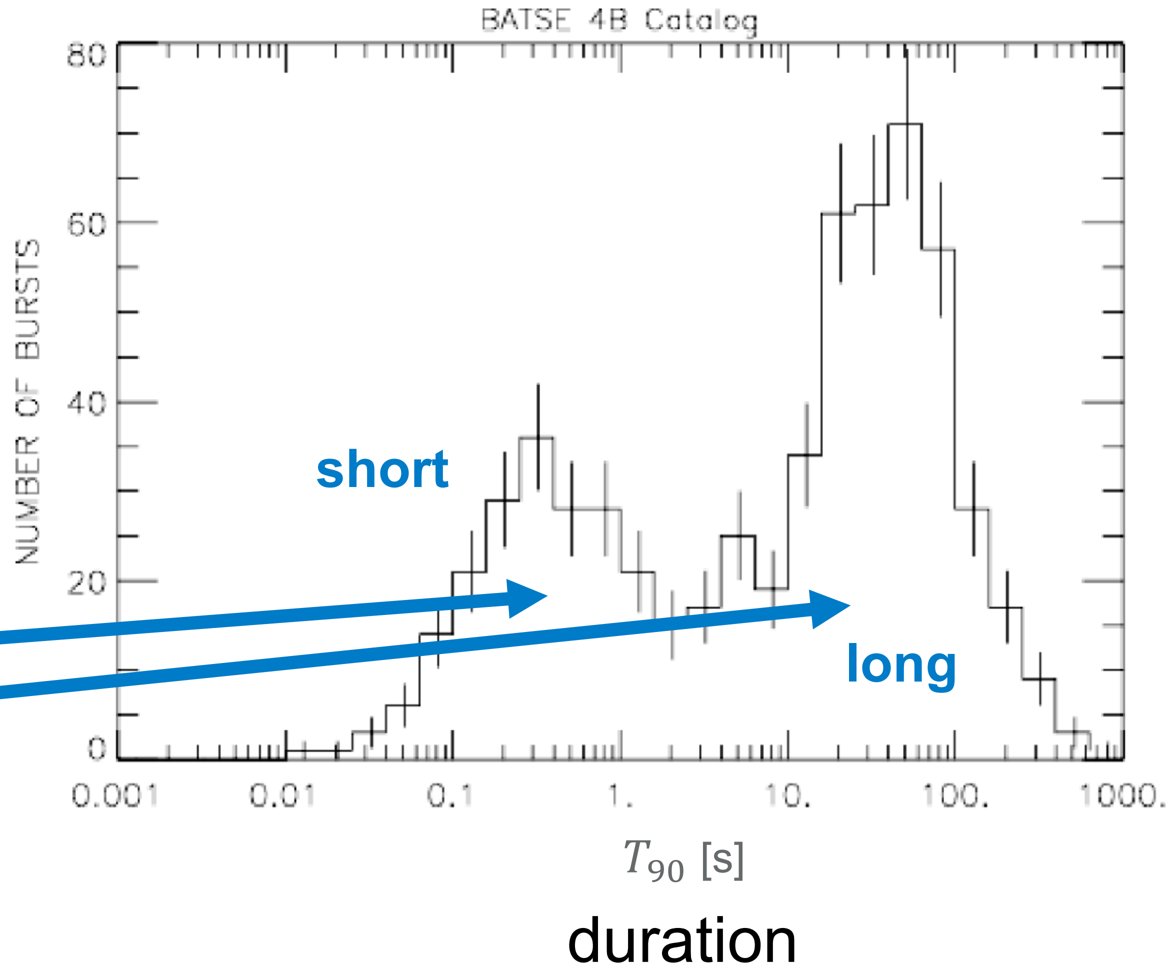


Gamma-ray bursts (GRBs)

Observational picture

- flashes of X/γ-rays isotropically distributed on sky
- complex prompt phase and smooth afterglow in the light curve
- **duration: long vs. short**
  - 1x short → merger of 2 neutron stars
  - many long → supernovae

Kouveliotou et al. ApJ 413 (1993)

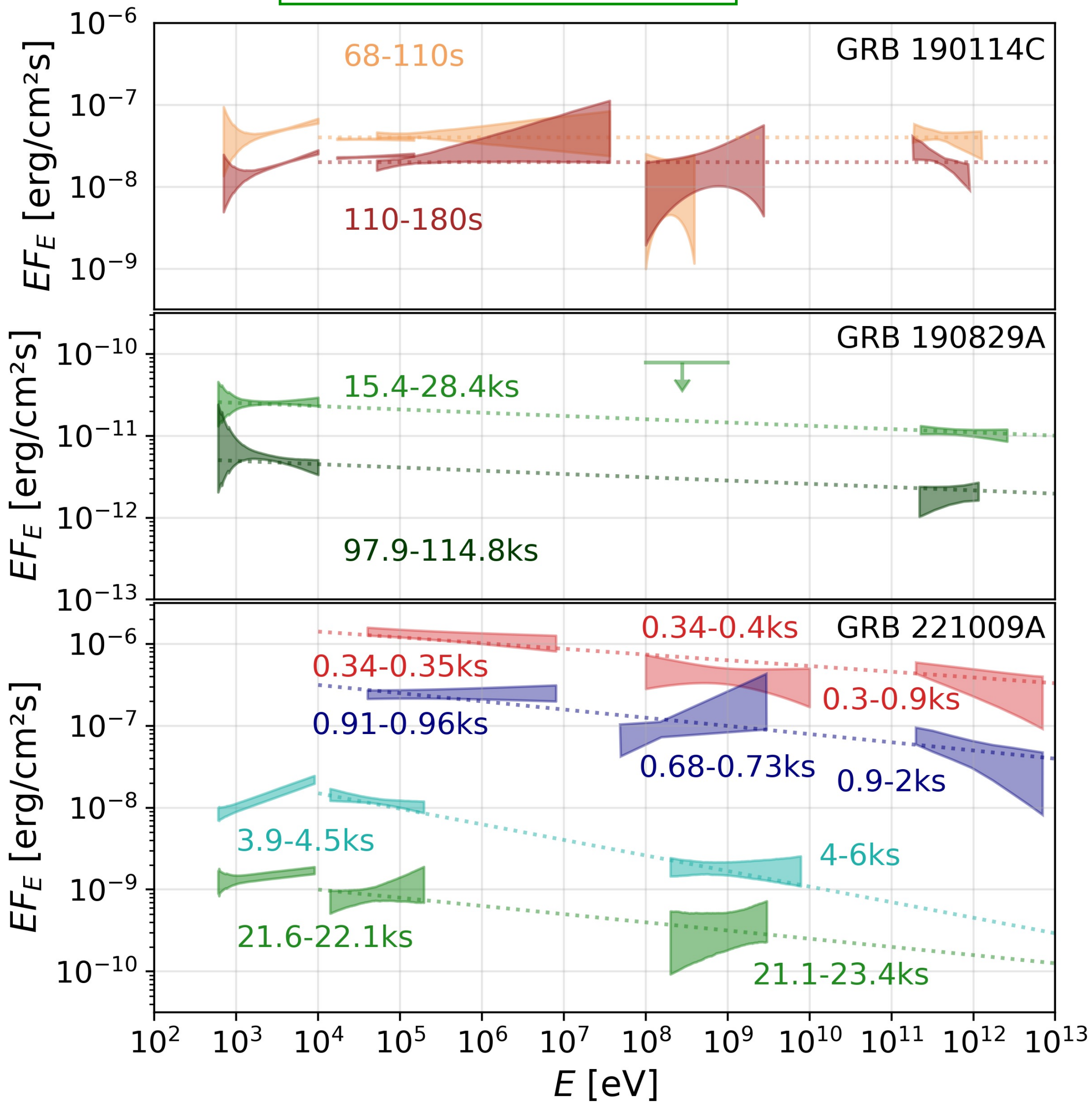


Gamma-ray bursts (GRBs)

Observational picture

- flashes of X/γ-rays isotropically distributed on sky
- complex prompt phase and smooth afterglow in the light curve
- duration: long vs. short
  - 1x short → merger of 2 neutron stars
  - many long → supernovae
- **power-law energy spectra**

"Modelling" paper

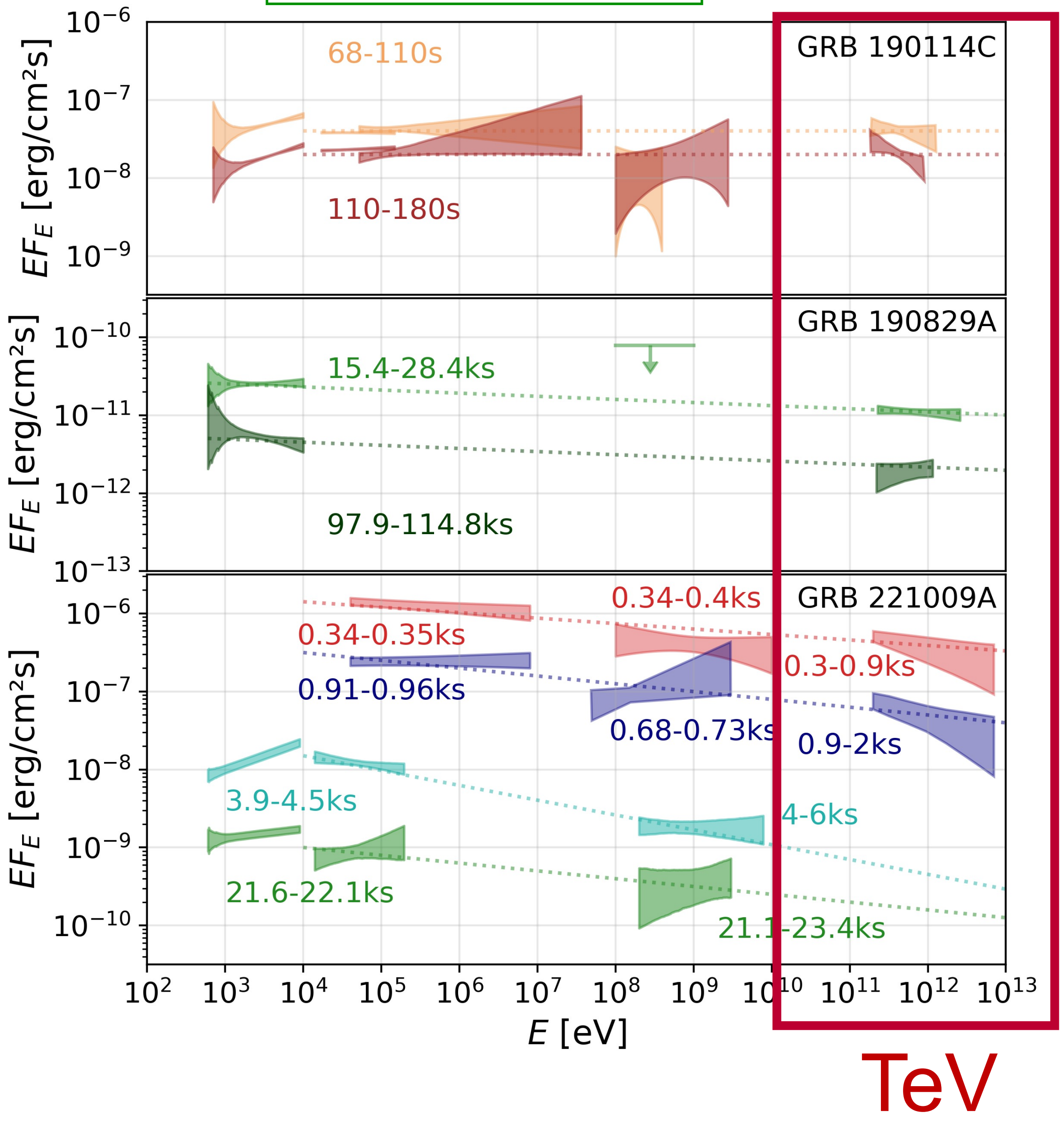


Gamma-ray bursts (GRBs)

Observational picture

- flashes of X/γ-rays isotropically distributed on sky
- complex prompt phase and smooth afterglow in the light curve
- duration: long vs. short
  - 1x short → merger of 2 neutron stars
  - many long → supernovae
- power-law energy spectra
- **recent detections up to TeV γ-rays**

"Modelling" paper



Gamma-ray bursts (GRBs)

Observational picture

- flashes of **X/γ-rays** isotropically distributed on sky
- complex prompt phase and smooth **afterglow** in the light curve
- duration: **long** vs. short
  - 1x short → merger of 2 neutron stars
  - many long → supernovae
- **power-law energy spectra**
- recently **detected up to TeV γ-rays**

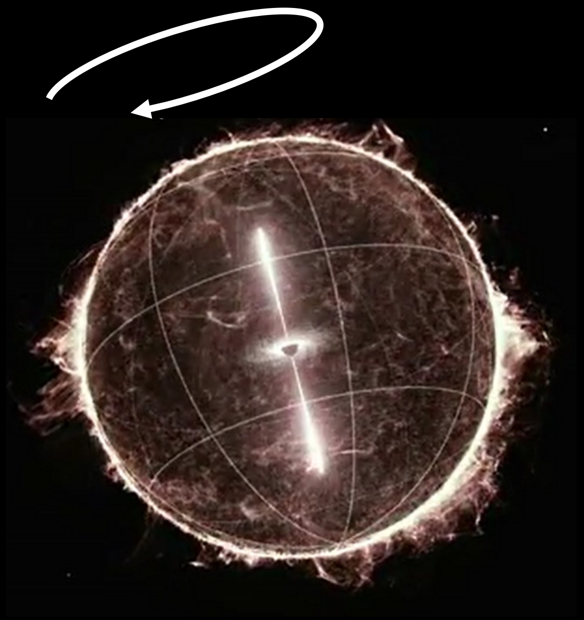
My PhD:

Interpretation of the observed **power-law energy spectra** of the **afterglows** of **long GRBs** with **TeV detection**

Publications

1. *“Fitting MAGIC”* – Klinger et al. MNRAS 520 (2023)
2. *“Fitting LHAASO”* – Klinger et al. MNRAS 529L (2024)
3. *“AM^3”* – Klinger et al. ApJS 275 4 (2024)
4. *“Modelling”* – Klinger et al. subm. to ApJ (2024) [arXiv:2403.13902]

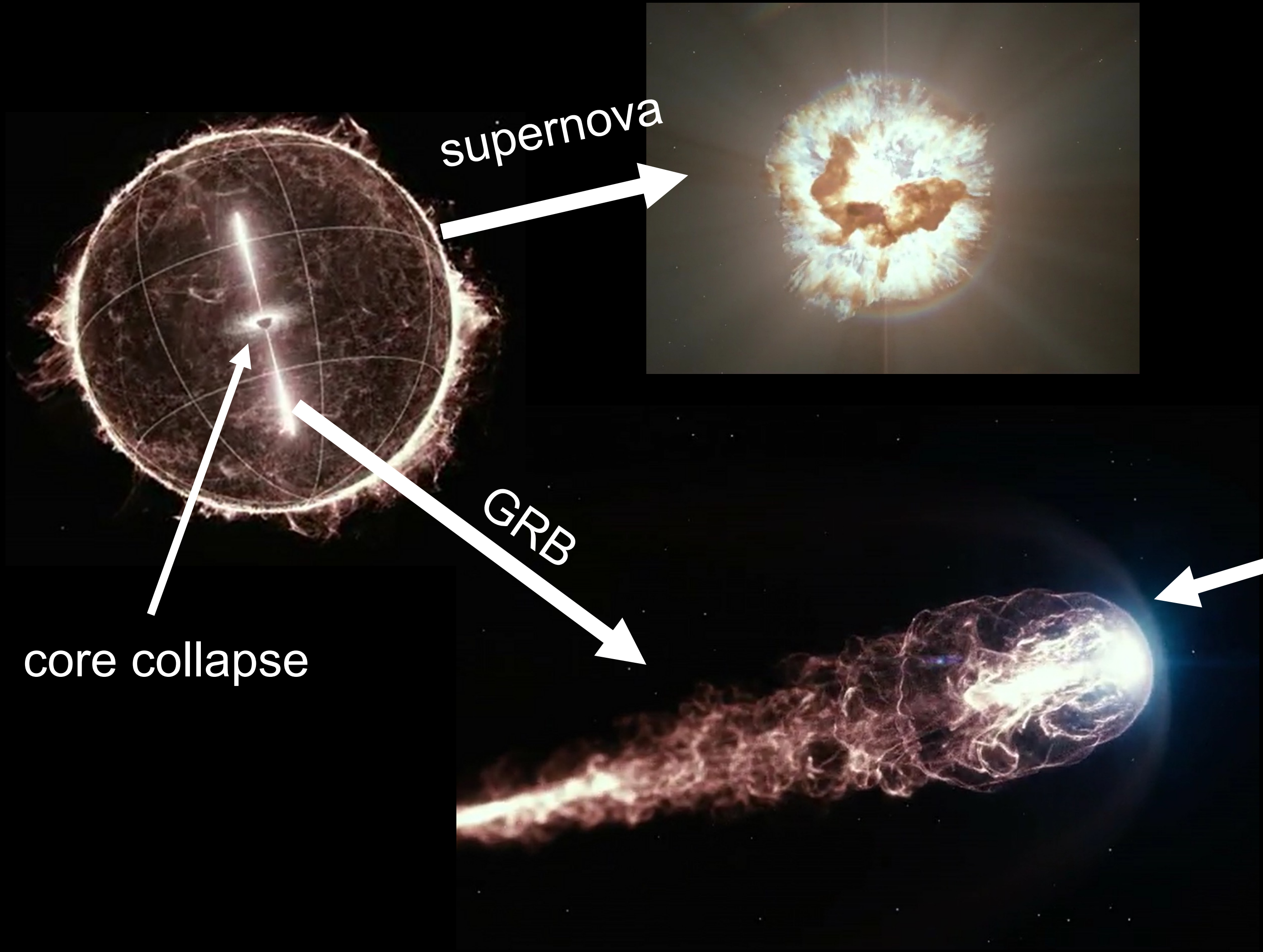
Long GRBs



massive, rotating star

images: DESY, Science Communication Lab

Long GRBs

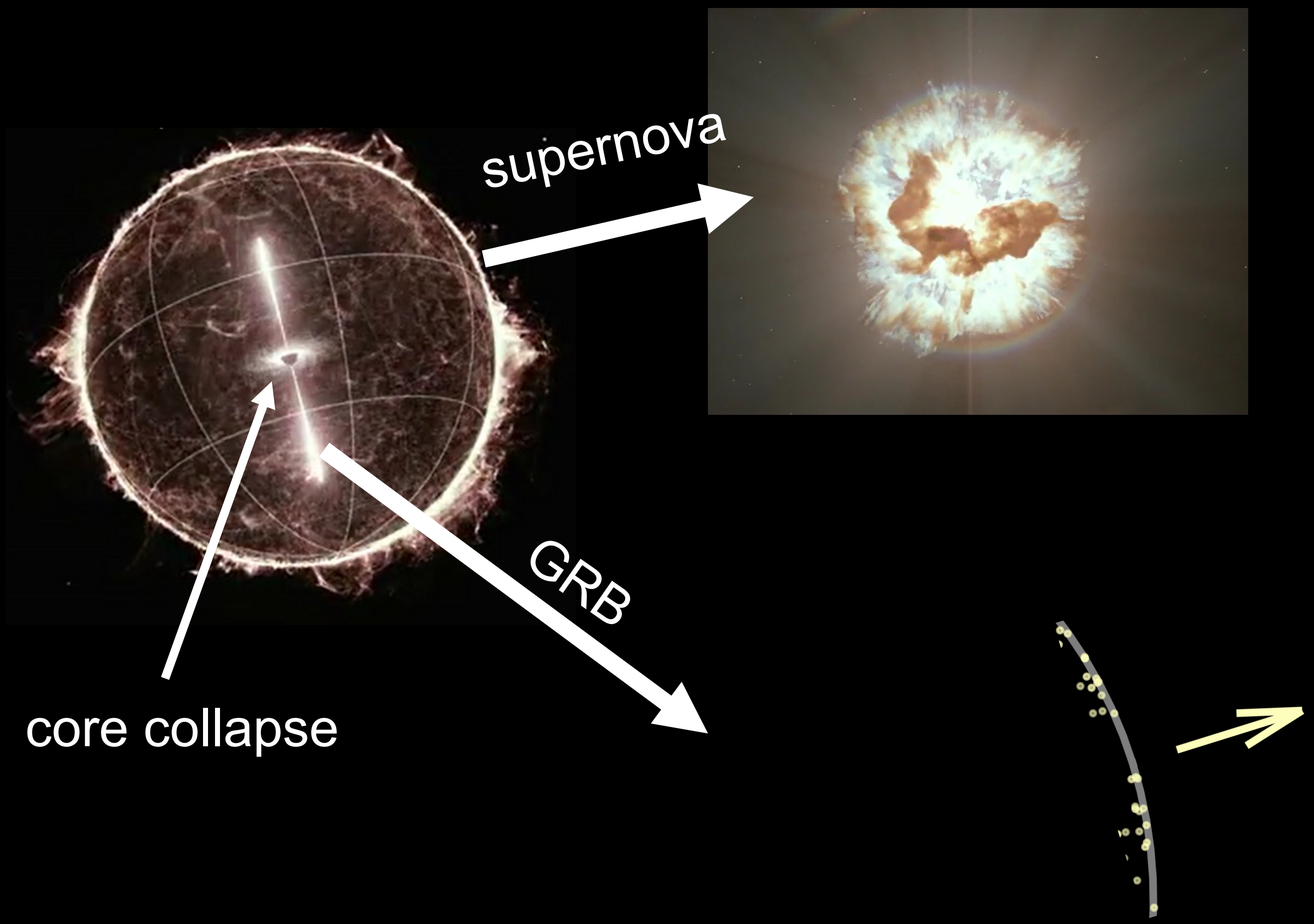


Lorentz factors up to few 100

→ quasi-isotropic outflow

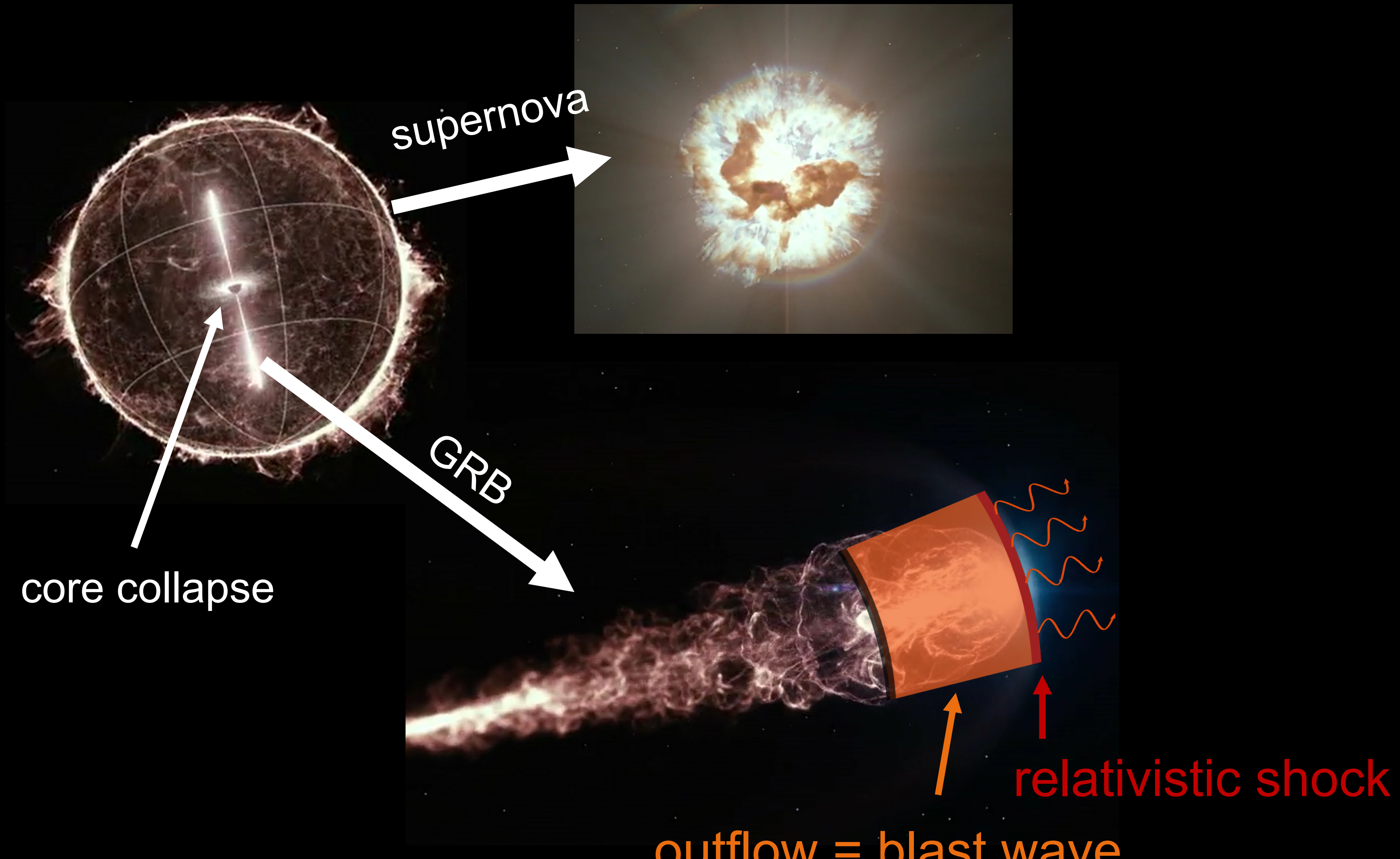
images: DESY, Science Communication Lab

Long GRBs



images: DESY, Science Communication Lab

Long GRBs



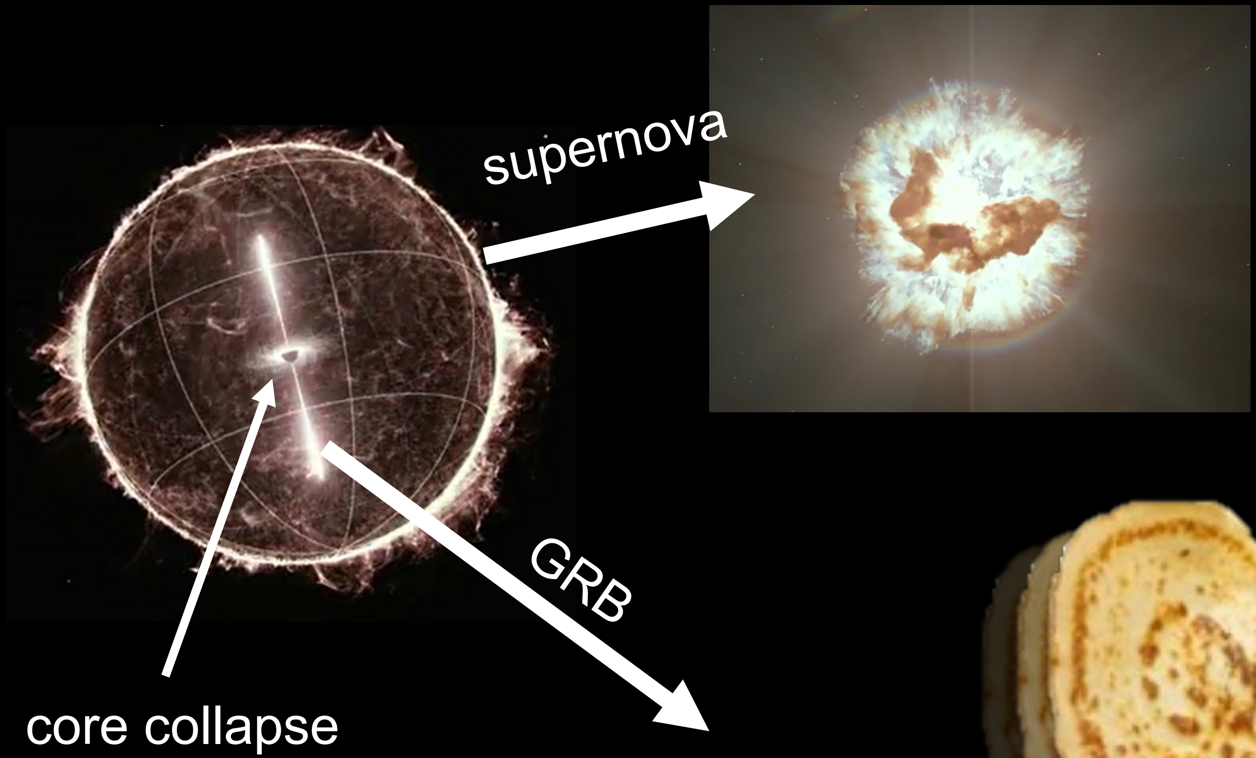
images: DESY, Science Communication Lab

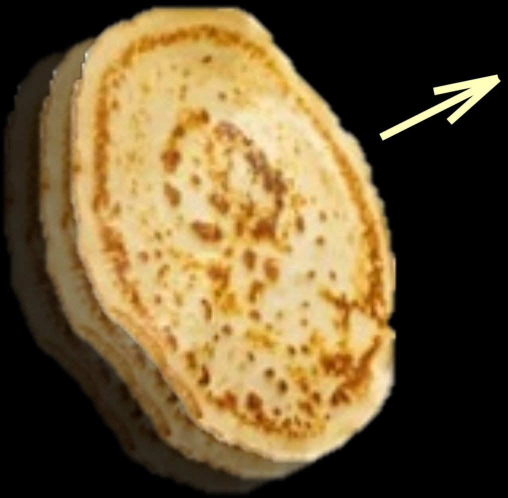
Long GRBs

afterglow = radiation from blast wave behind shock

images: DESY, Science Communication Lab

Long GRBs





afterglow = radiation from blast wave behind shock

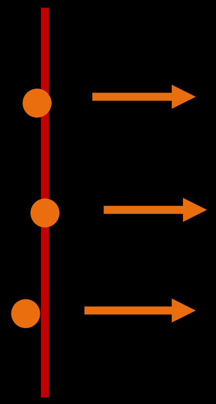
↓

compressed into pancake shape

images: DESY, Science Communication Lab

Piran Rev. Mod. Phys. **76**, 1143 (2005)

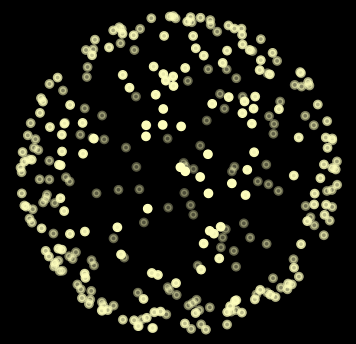
Long GRB afterglow shocks shine



relativistic outflow
→ **relativistic** shock

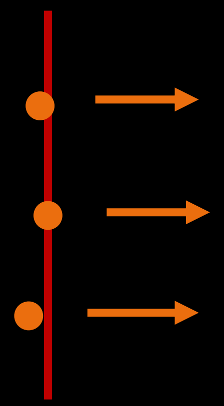
particle acceleration &
radiation mechanism

uncertain assumptions



observations
→ **power-law spectra**

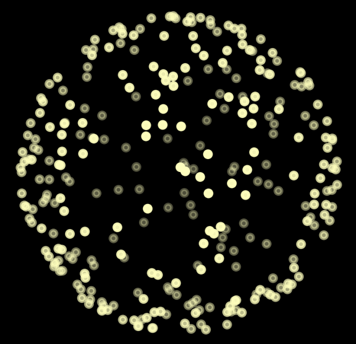
Long GRB afterglow shocks shine



relativistic outflow
→ relativistic shock

particle acceleration &
radiation mechanism

uncertain assumptions

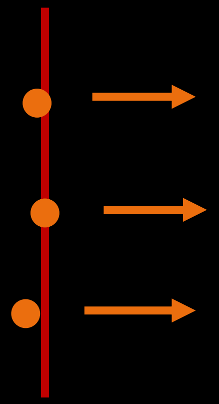


observations
→ power-law
spectra

**enables
new tests of**

**New observational
window at TeV**

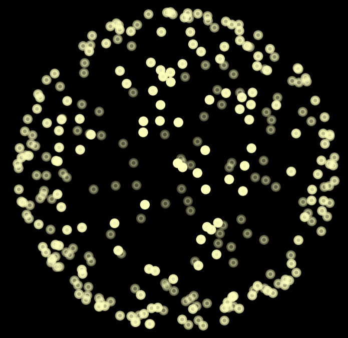
Long GRB afterglow shocks shine



relativistic outflow
→ relativistic shock

1-zone SSC model

uncertain assumptions

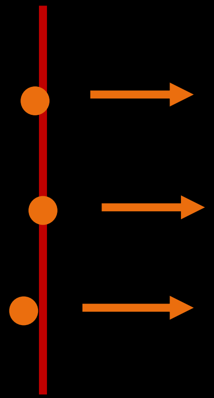


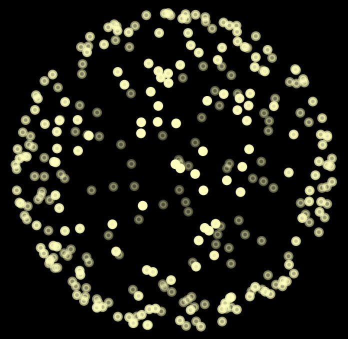
observations
→ power-law spectra

enables new tests of

New observational window at TeV

Long GRB afterglow shocks shine





1-zone SSC model

rel. outflow
→ rel. shock

blast wave deceleration

energy conversion at shock

electron spectrum

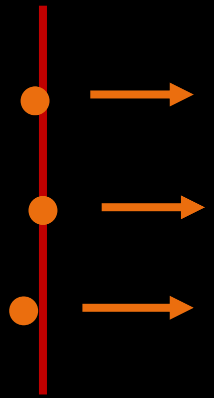
mapping to photon spectrum

relativistic motion

propagation

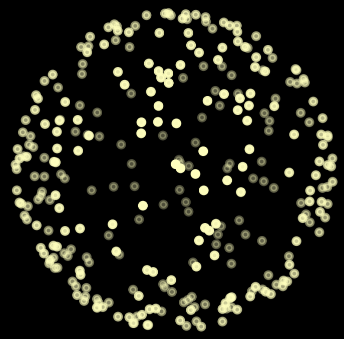
observations
→ power-law spectra

Long GRB afterglow shocks shine



rel. outflow
→ rel. shock

1-zone SSC model



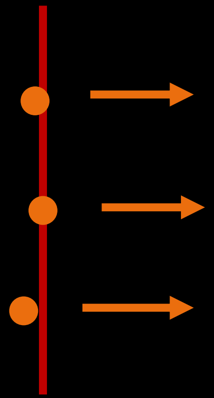
observations
→ power-law spectra

blast wave deceleration

energy conservation:
$E_{\mathrm{kin}}^{\mathrm{iso}}, n_{\mathrm{u}}, t \leftrightarrow \Gamma$

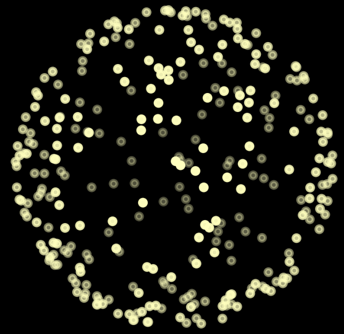
energy conversion at shock → electron spectrum → mapping to photon spectrum → relativistic motion → propagation

Long GRB afterglow shocks shine



rel. outflow
→ rel. shock

1-zone SSC model



observations
→ power-law
spectra

blast wave
deceleration

energy
conversion
at shock

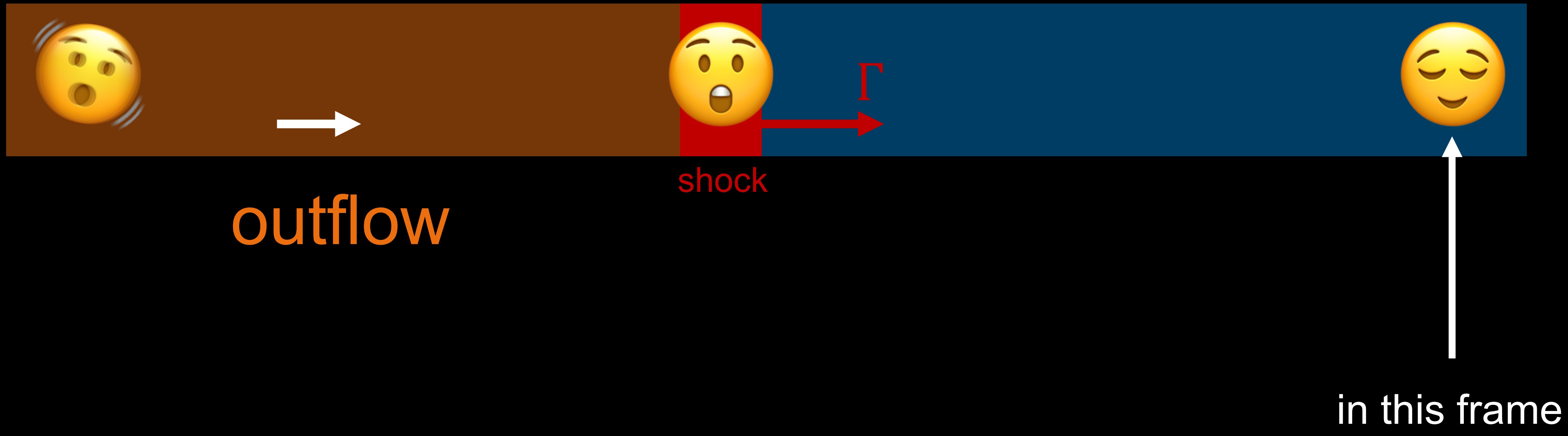
electron
spectrum

mapping to
photon
spectrum

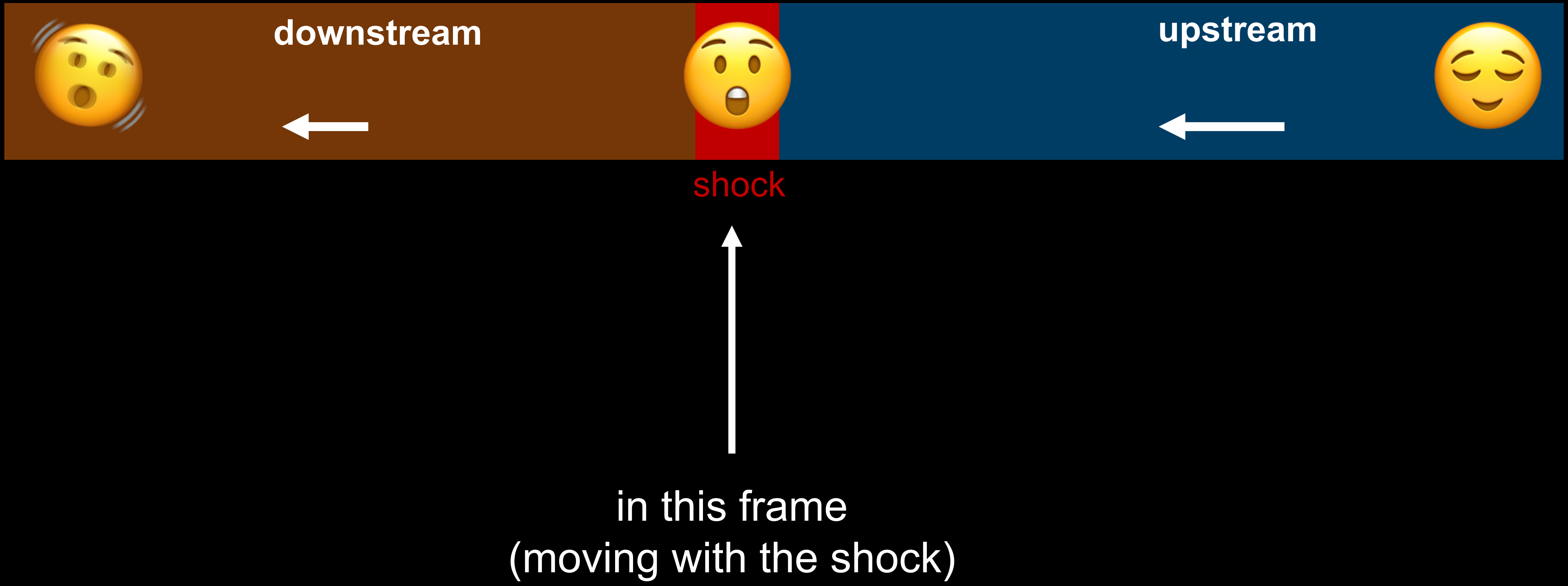
relativistic
motion

propagation

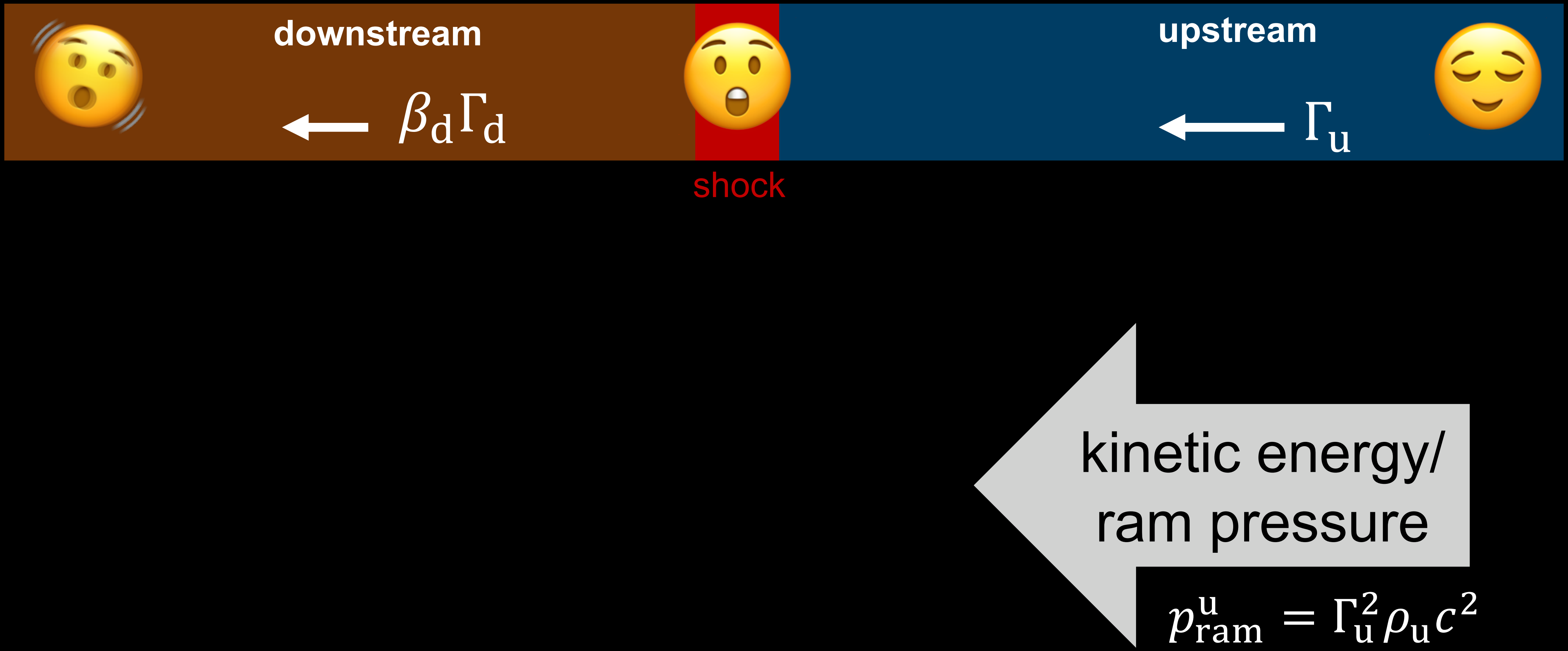
Energy conversion at the shock



Energy conversion at the shock



Energy conversion at the shock



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

with $\rho_{\mathrm{u}} = n_{\mathrm{u}} m_p$

Energy conversion at the shock

heat (isotropic)

slower outflow (anisotropic)

kinetic energy/
ram pressure

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

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

Energy conversion at the shock

heat (isotropic)

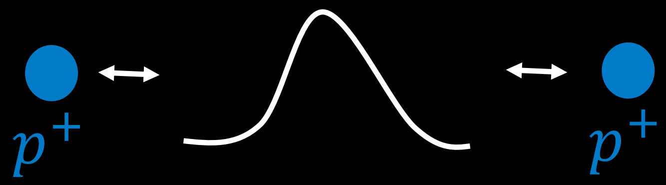
slower outflow (anisotropic)

turbulent magnetic fields

kinetic energy/ ram pressure

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

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



Energy conversion at the shock

heat (isotropic)

slower outflow (anisotropic)

turbulent magnetic fields

non-thermal particles

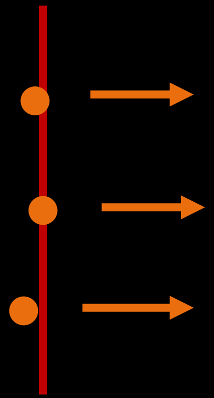
kinetic energy/ ram pressure

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

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

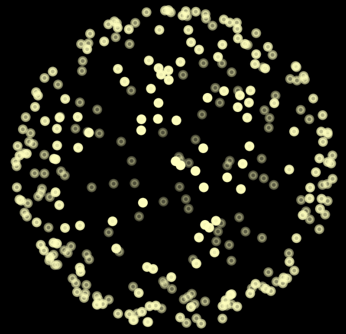
with $\rho_\mathrm{u} = n_\mathrm{u} m_p c^2$

Long GRB afterglow shocks shine



rel. outflow
→ rel. shock

1-zone SSC model



observations
→ power-law
spectra

blast wave
deceleration

energy
conversion
at shock

electron
spectrum

mapping to
photon
spectrum

relativistic
motion

propagation

Electron spectrum

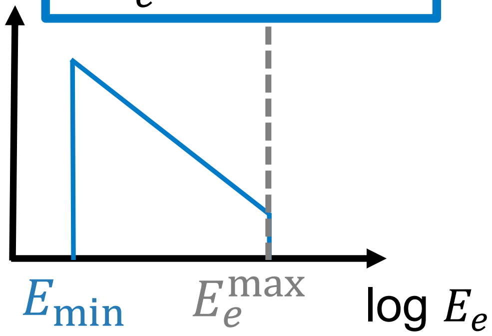
+

continuous injection

energy losses

Electron spectrum

$$\frac{\mathrm{d}n_e}{\mathrm{d}E_e\mathrm{d}t} \propto E_e^{-s_{\mathrm{inj}}}$$



+

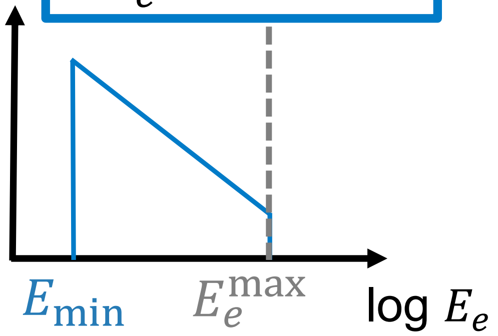
continuous injection

→ power-law

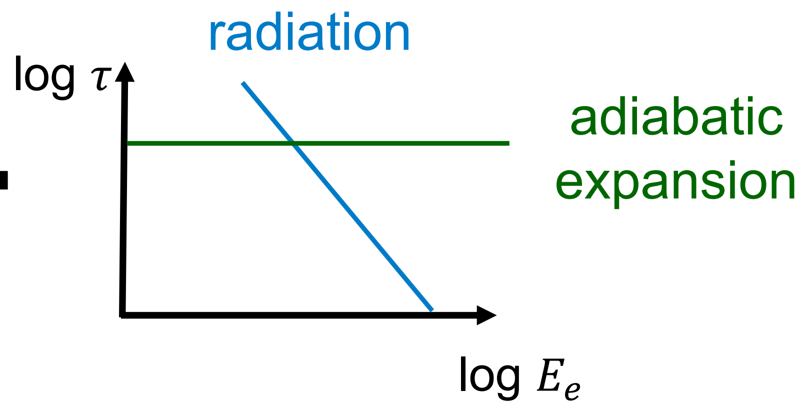
energy losses

Electron spectrum

$$\frac{dn_e}{dE_e dt} \propto E_e^{-s_{\rm inj}}$$

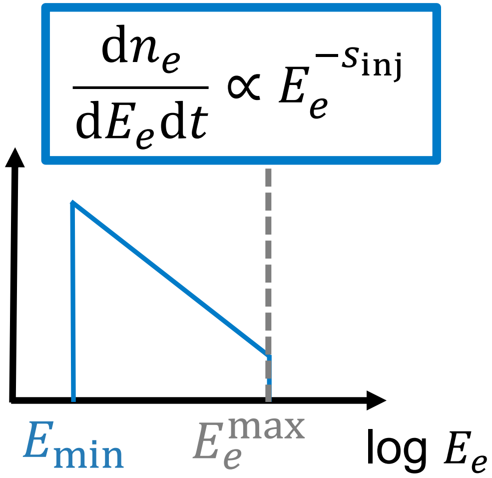


continuous injection

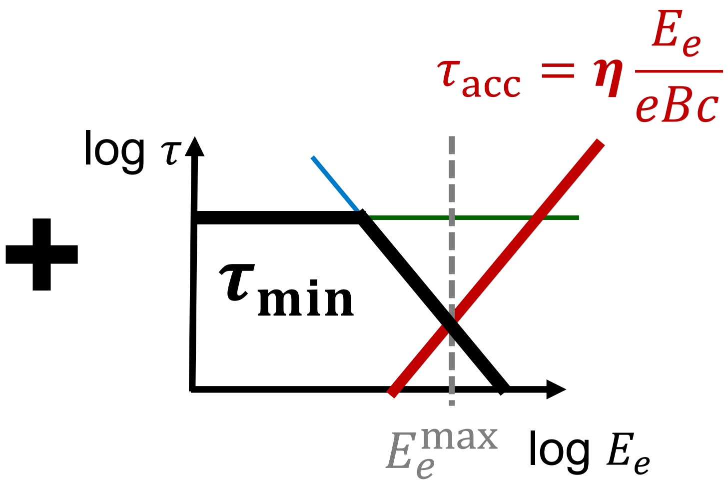


energy losses

Electron spectrum



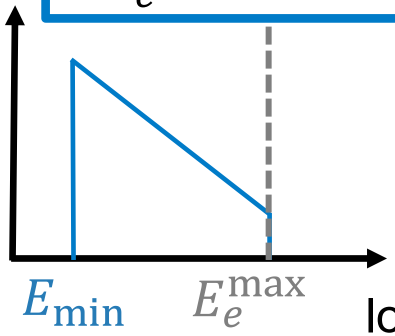
continuous injection



energy losses

Electron spectrum

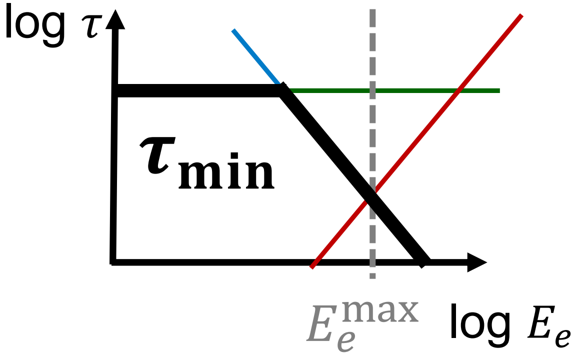
$$\frac{\mathrm{d}n_e}{\mathrm{d}E_e\mathrm{d}t} \propto E_e^{-s_{\mathrm{inj}}}$$



continuous injection

+

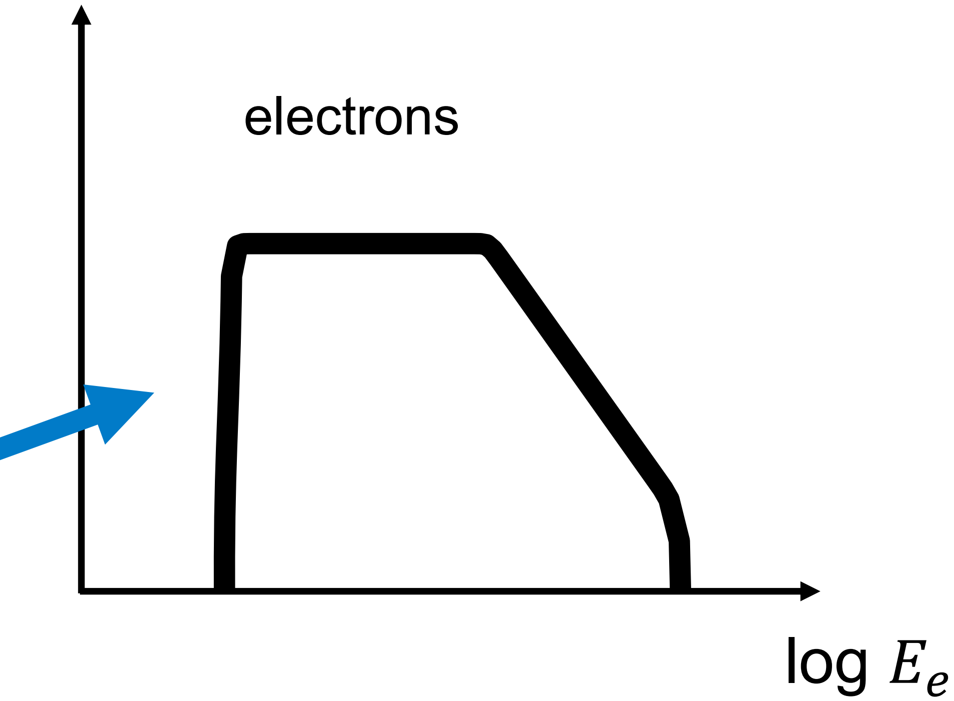
$$\tau_{\mathrm{acc}} = \eta \frac{E_e}{eBc}$$



energy losses

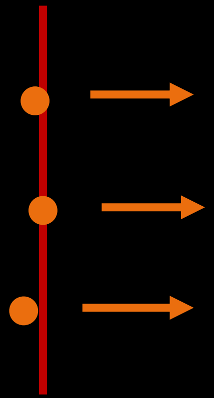
steady-state approximation

$$\frac{\mathrm{d}N_e}{\mathrm{d}E_e} \sim \frac{\mathrm{d}N_e}{\mathrm{d}E_e\mathrm{d}t} \times \tau_{\mathrm{min}}$$



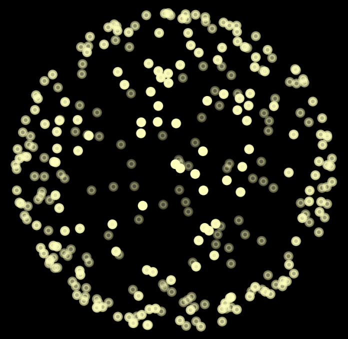
e.g., Sari et al. ApJ 497 L17 (1998)

Long GRB afterglow shocks shine



rel. outflow
→ rel. shock

1-zone SSC model



observations
→ power-law
spectra

blast wave
deceleration

energy
conversion
at shock

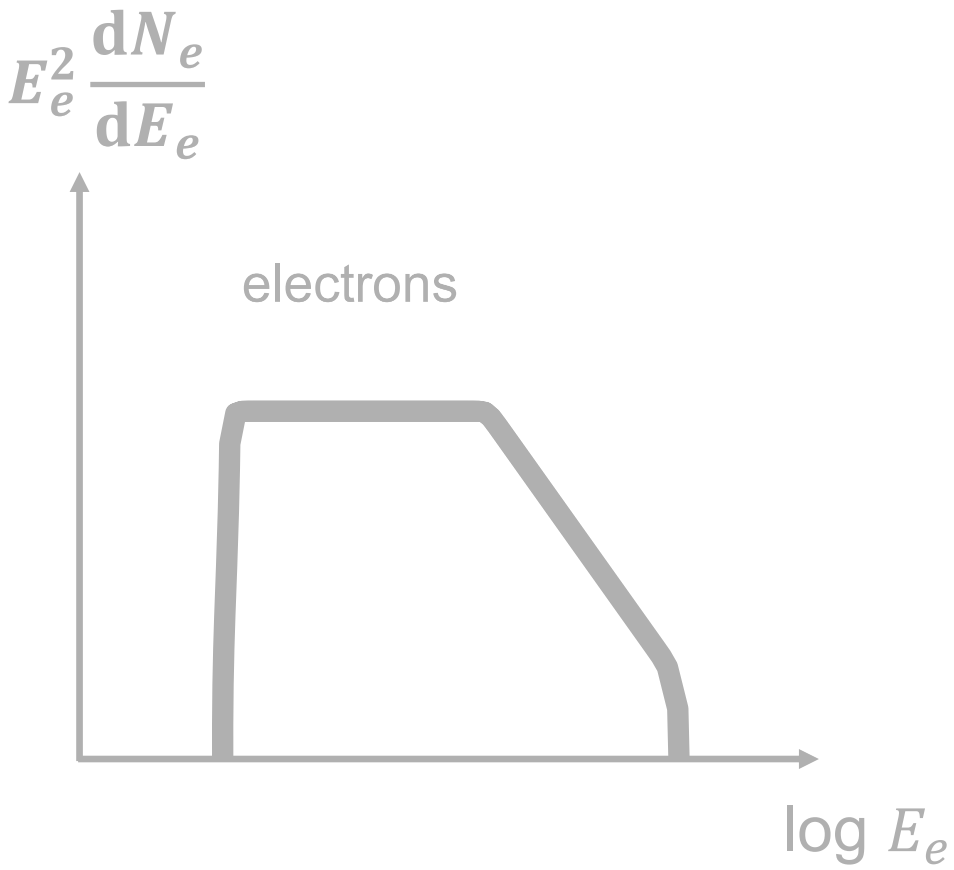
electron
spectrum

mapping to
photon
spectrum

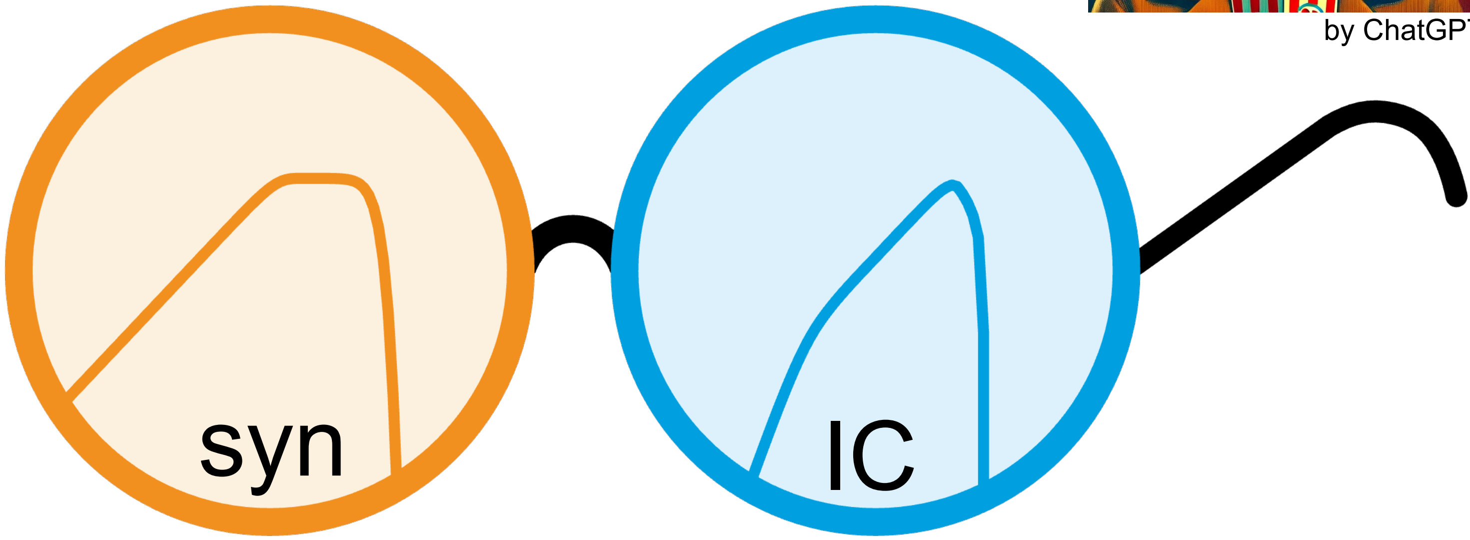
relativistic
motion

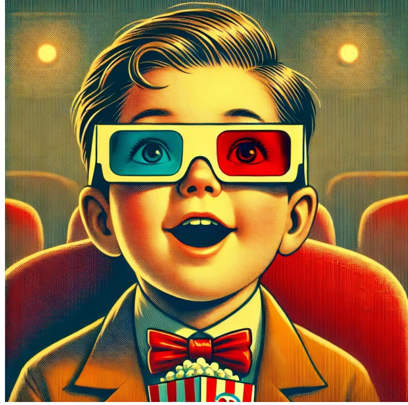
propagation

Mapping to photon spectrum



invisible



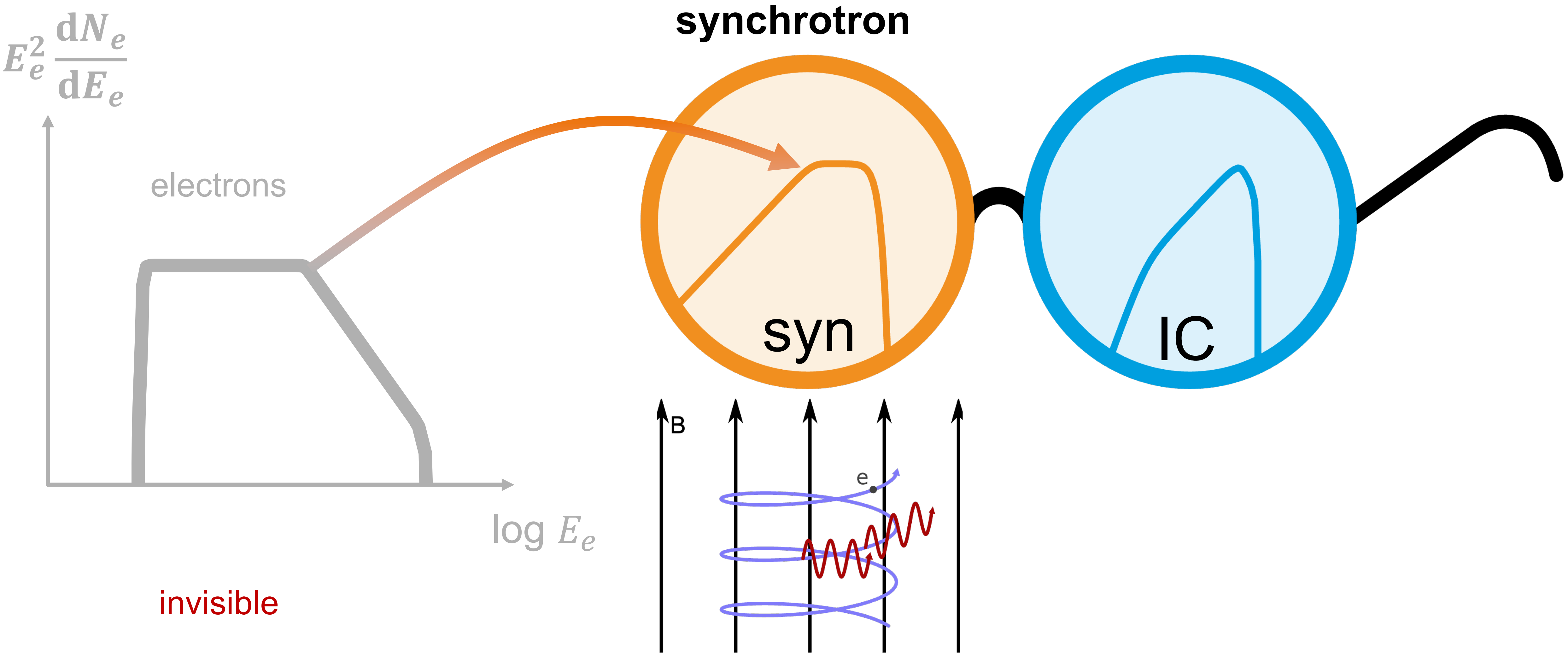


by ChatGPT

indirect observation through

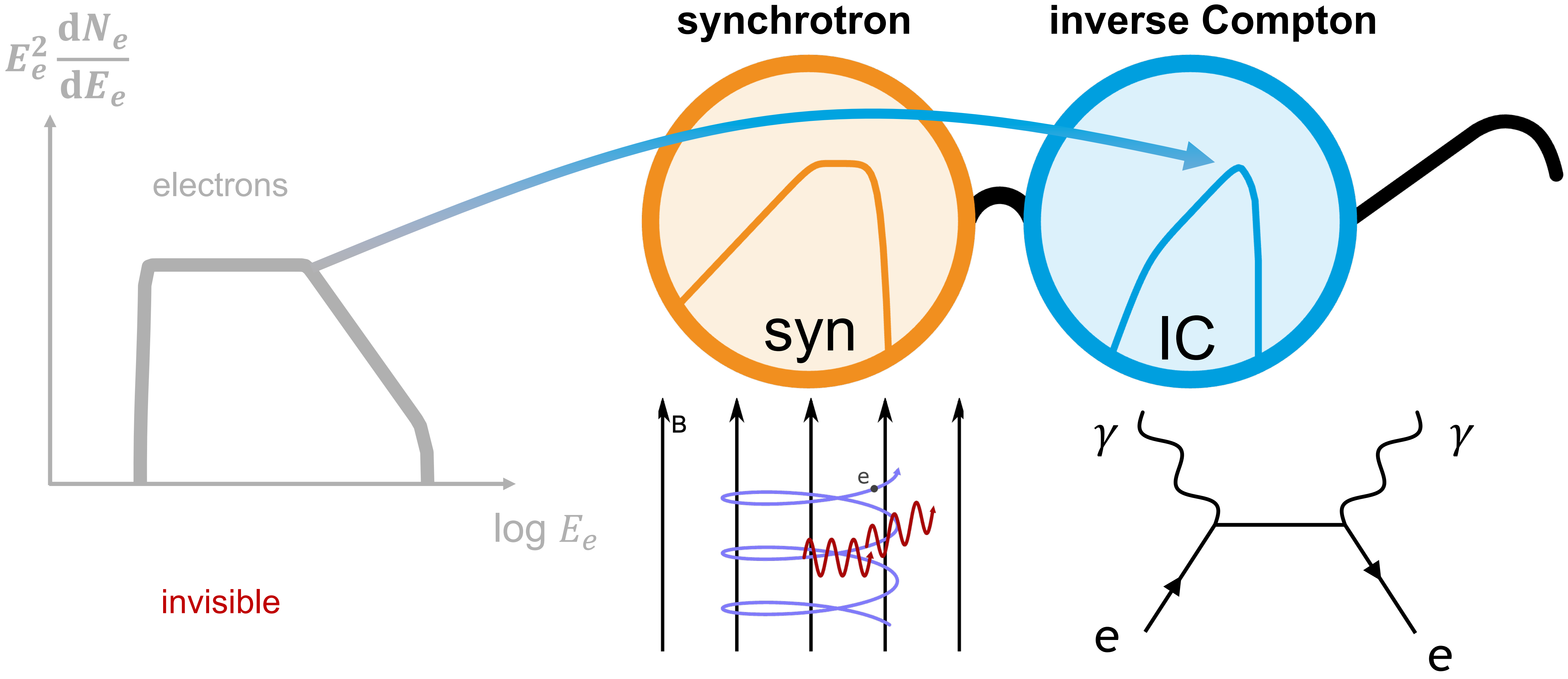
SSC goggles!

Mapping to photon spectrum

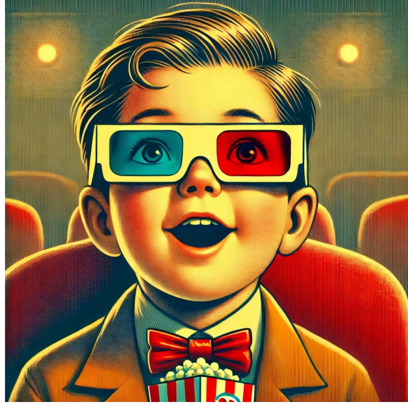


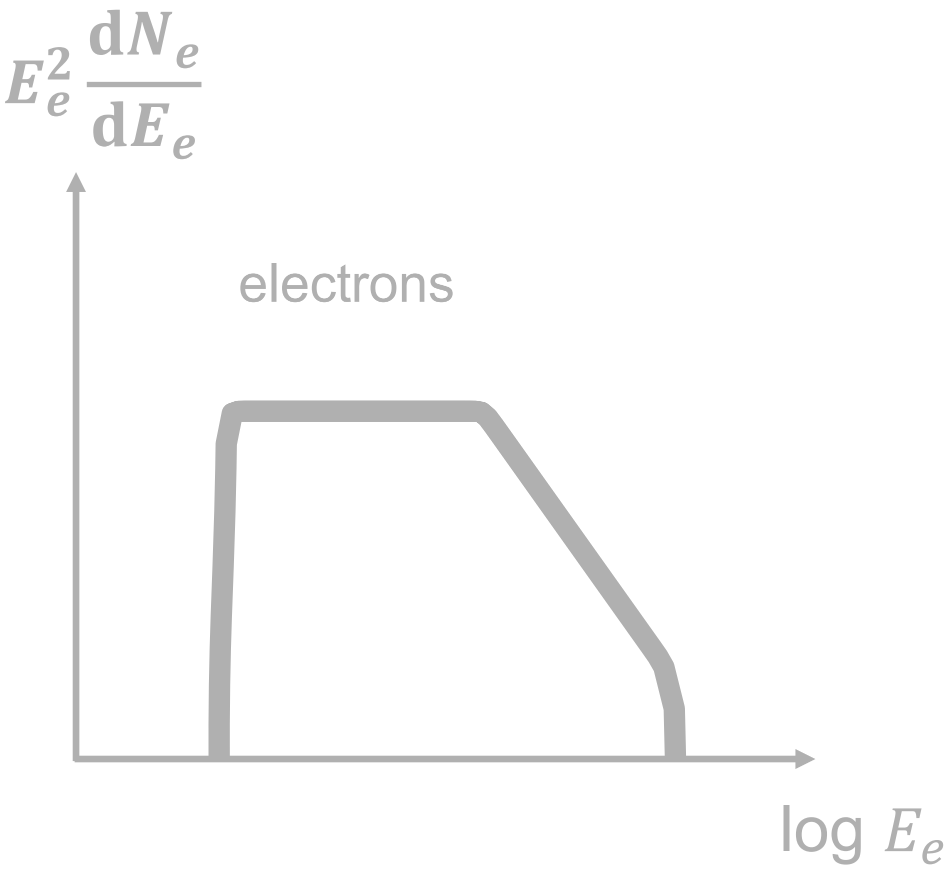
invisible

Mapping to photon spectrum

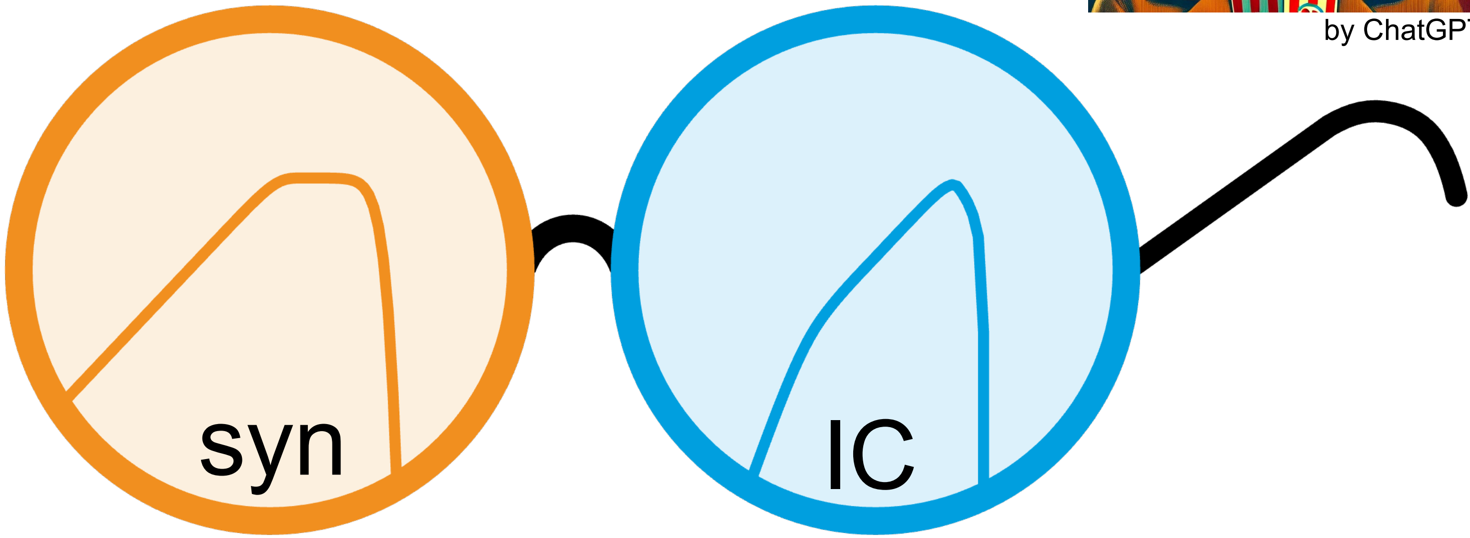


Mapping to photon spectrum





invisible

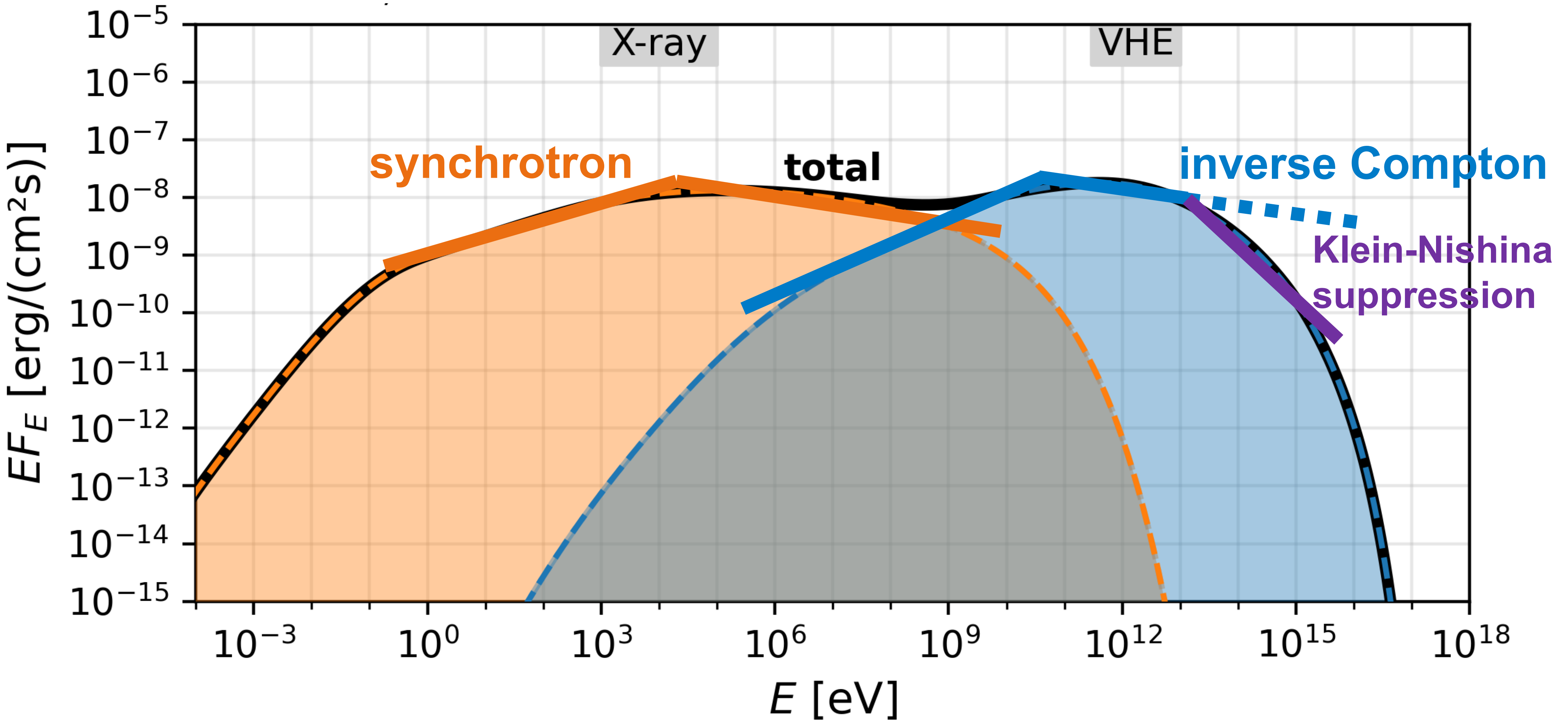


indirect observation through

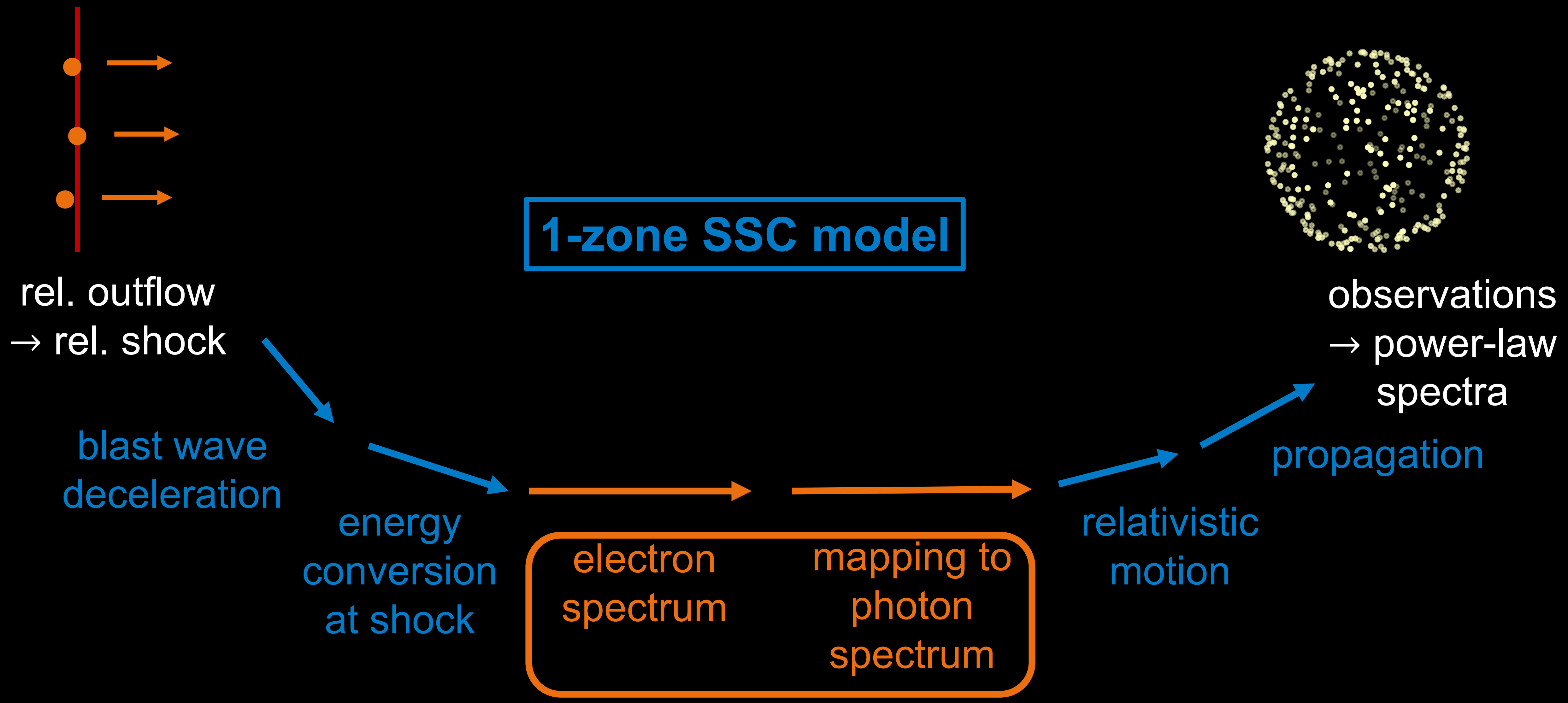
SSC goggles!

synchrotron self-Compton

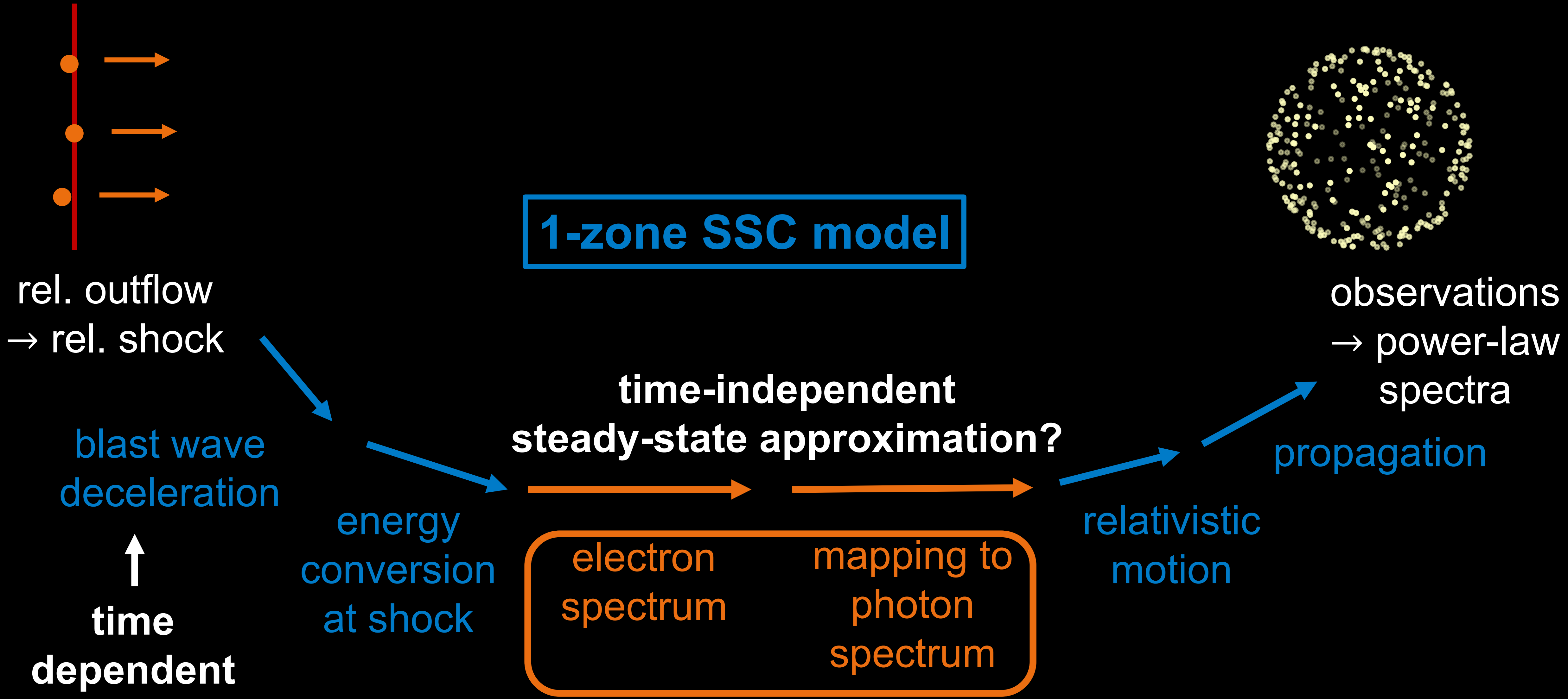
Mapping to photon spectrum



Long GRB afterglow shocks shine



Long GRB afterglow shocks shine



Steady-state approximation?

→ solve set of **coupled transport equations** like

$$\partial_t n_i = Q + \partial_E\left(\dot{E} n_i\right) - \alpha n_i$$

for species i

depend in general on E, t, n_j

particle number density

$$n_i(E,t) = \frac{\partial^2 N_i}{\partial E \, \partial V}$$

Steady-state approximation?

→ solve set of **coupled transport equations** like

$$\partial_t n_i = Q + \partial_E(\dot{E} n_i) - \alpha n_i$$

for species i

depend in general on E, t, n_j

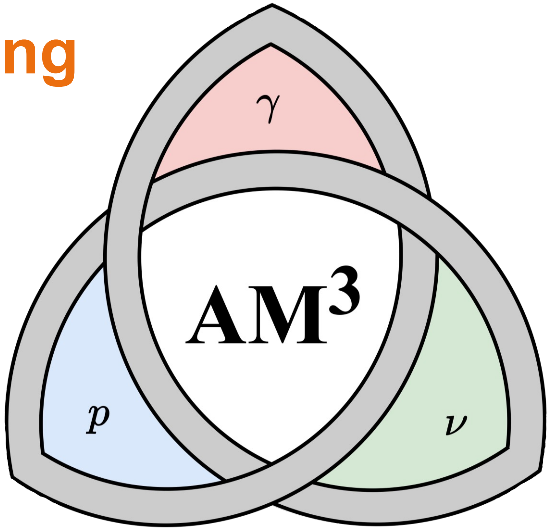
particle number density

$$n_i(E,t) = \frac{\partial^2 N_i}{\partial E\, \partial V}$$

→ I developed a framework to perform time-dependent modelling of GRB afterglows

AM³ software

Astrophysical Multi-Messenger Modeling



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

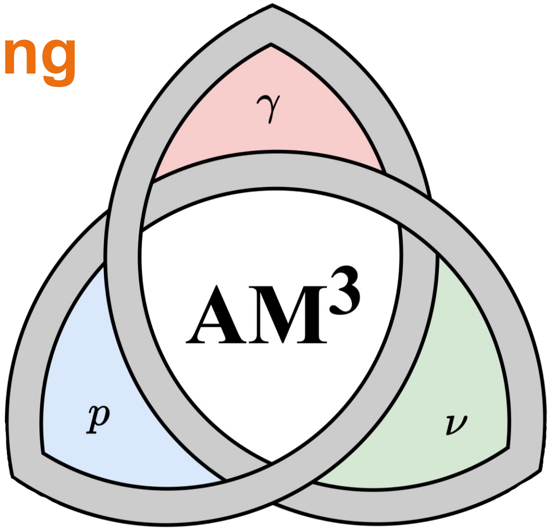
- improved* original version of former group members
- major contributions to the publication team-effort

→ *"AM3" paper*

*co-implemented pp-interactions, made solver algorithm faster and more robust

AM³ software

Astrophysical Multi-Messenger Modeling



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

- improved* original version of former group members
- major contributions to the publication team-effort

→ *"AM³" paper*

- AM³ solves transport equations

→ lepto-hadronic interactions

→ fast, trackable, FAIR** trendsetter

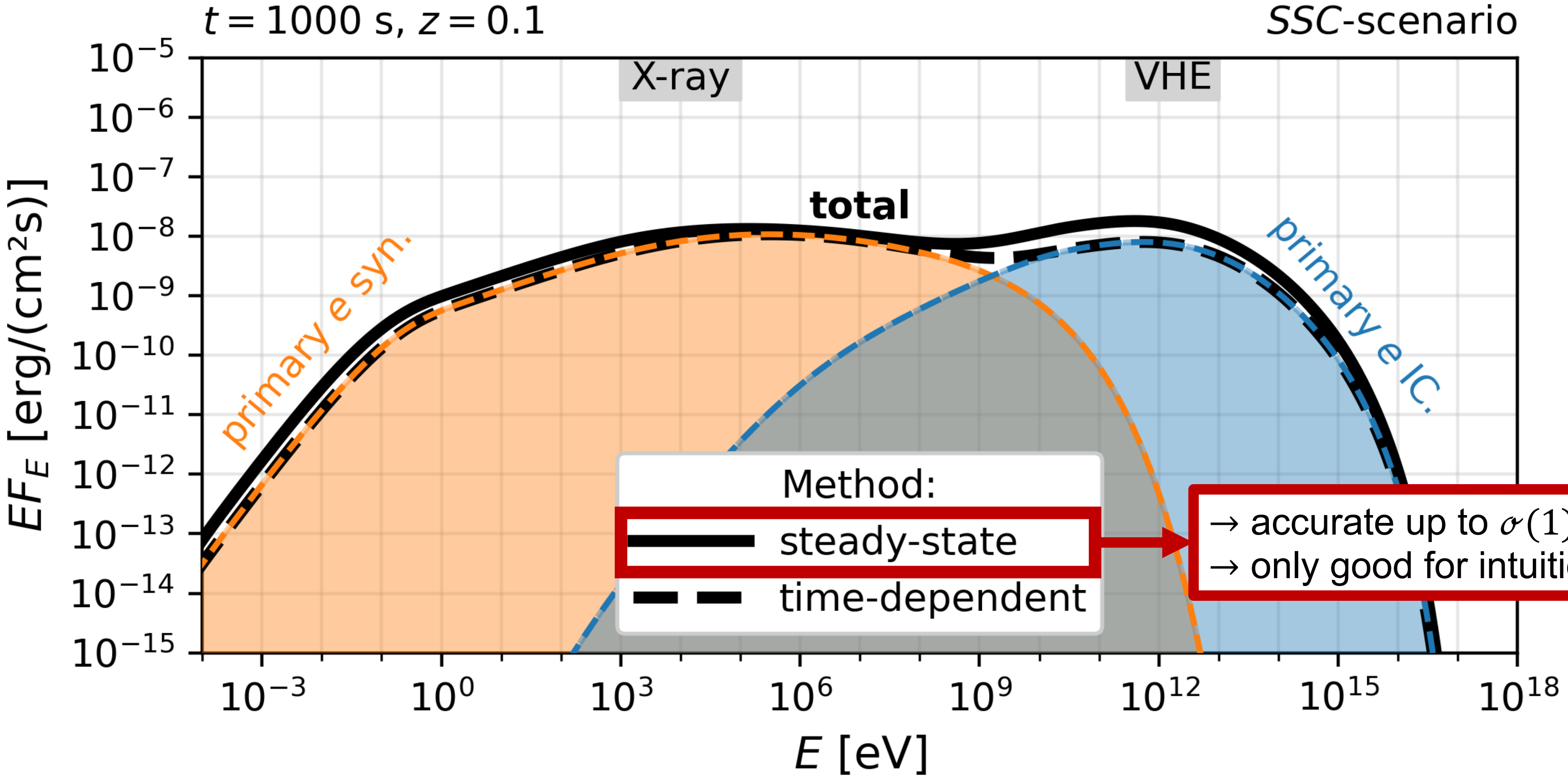
→ applied to other source types

*co-implemented pp-interactions, made solver algorithm faster and more robust

**findable, accessible, interoperable, reusable

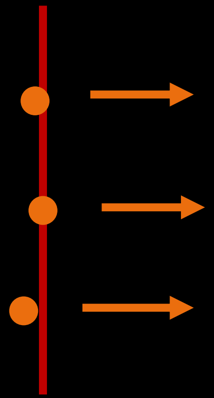
Time-dependent = quasi-steady state

"*Modelling*" paper



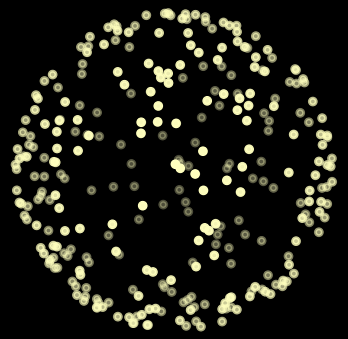
→ accurate up to $\mathcal{O}(1)$ factors
→ only good for intuition!

Long GRB afterglow shocks shine



rel. outflow
→ rel. shock

1-zone SSC model



observations
→ power-law
spectra

blast wave
deceleration

energy
conversion
at shock

electron
spectrum

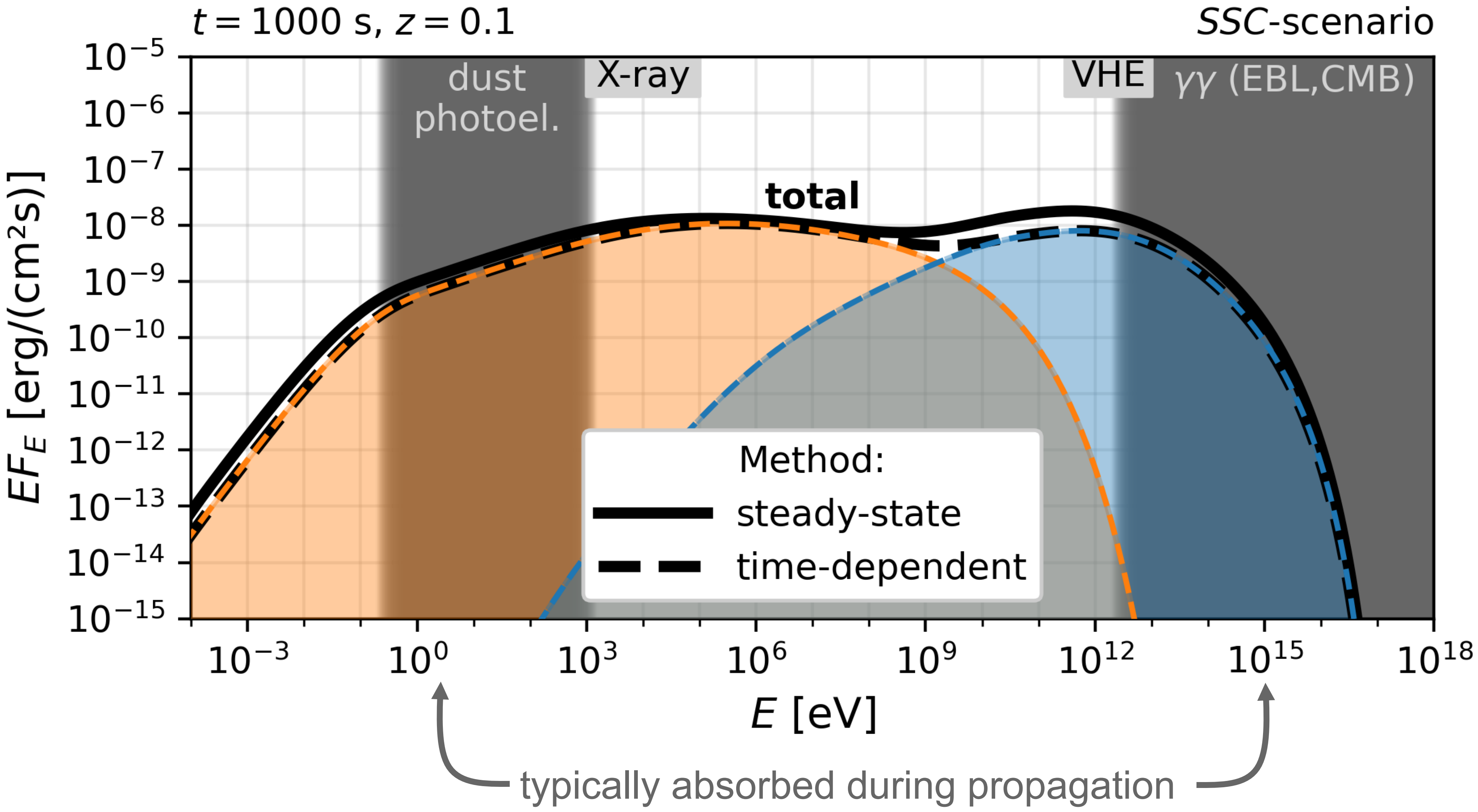
mapping to
photon
spectrum

relativistic
motion

propagation

Time-dependent quasi-steady state

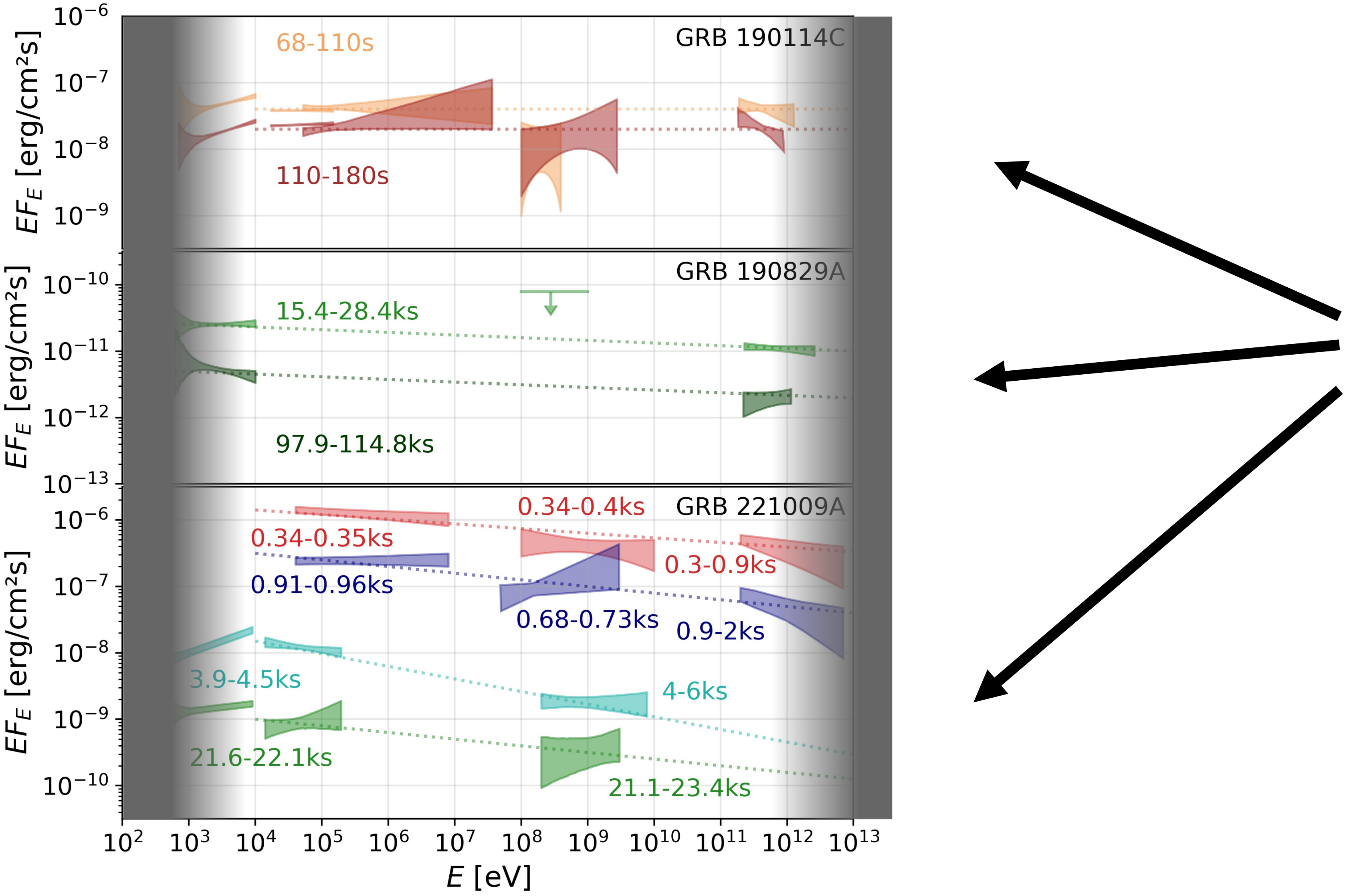
"*Modelling*" paper



Do the observations show the two bumps of the 1-zone SSC model?

Observations

“*Modelling*” paper

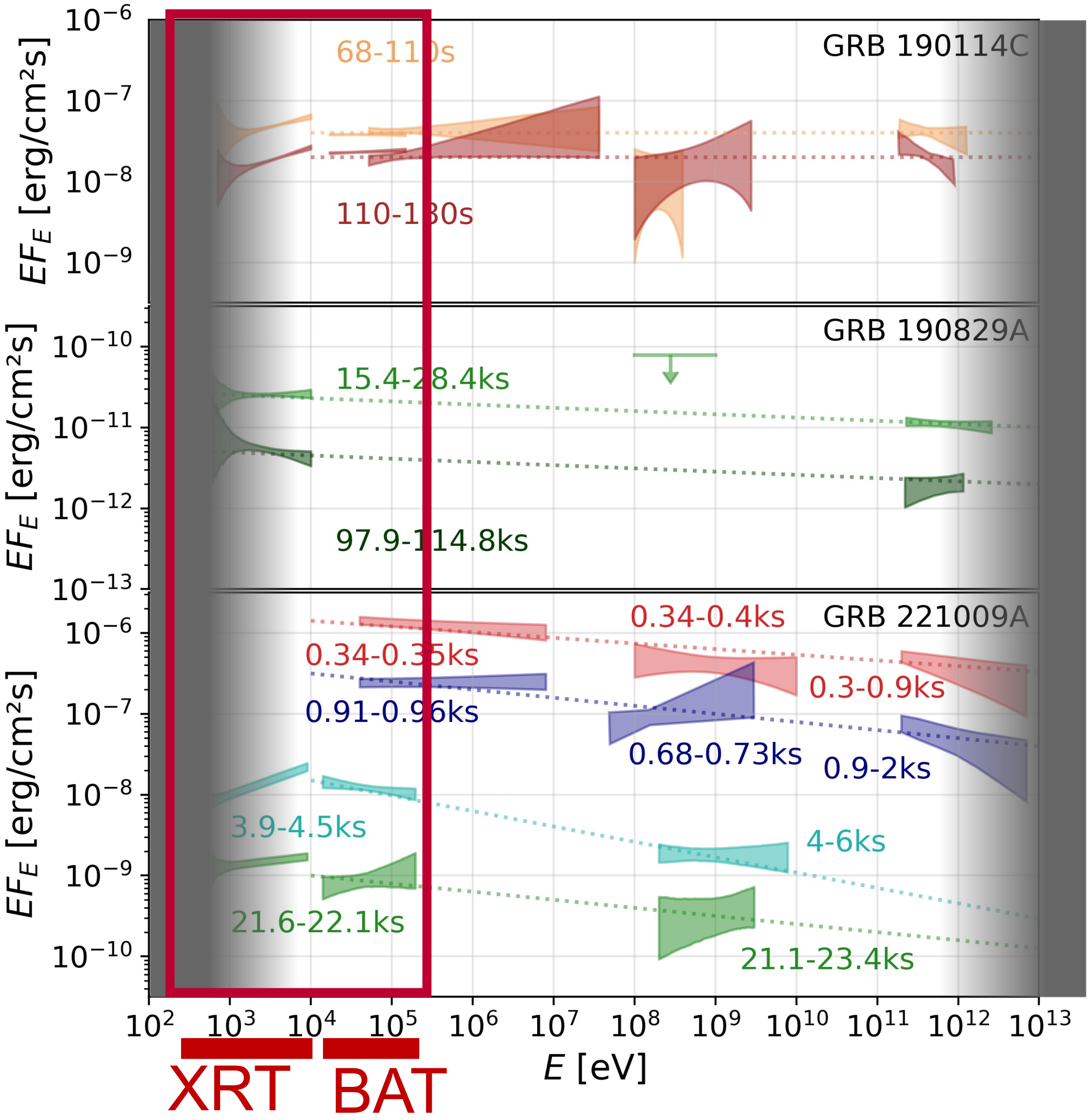


3 GRBs

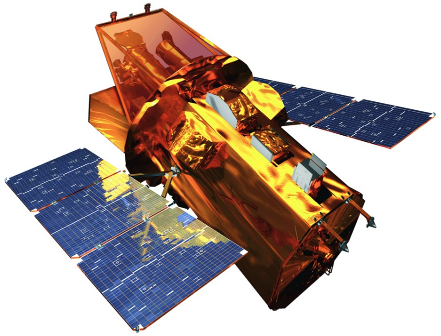
data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

Observations

"Modelling" paper



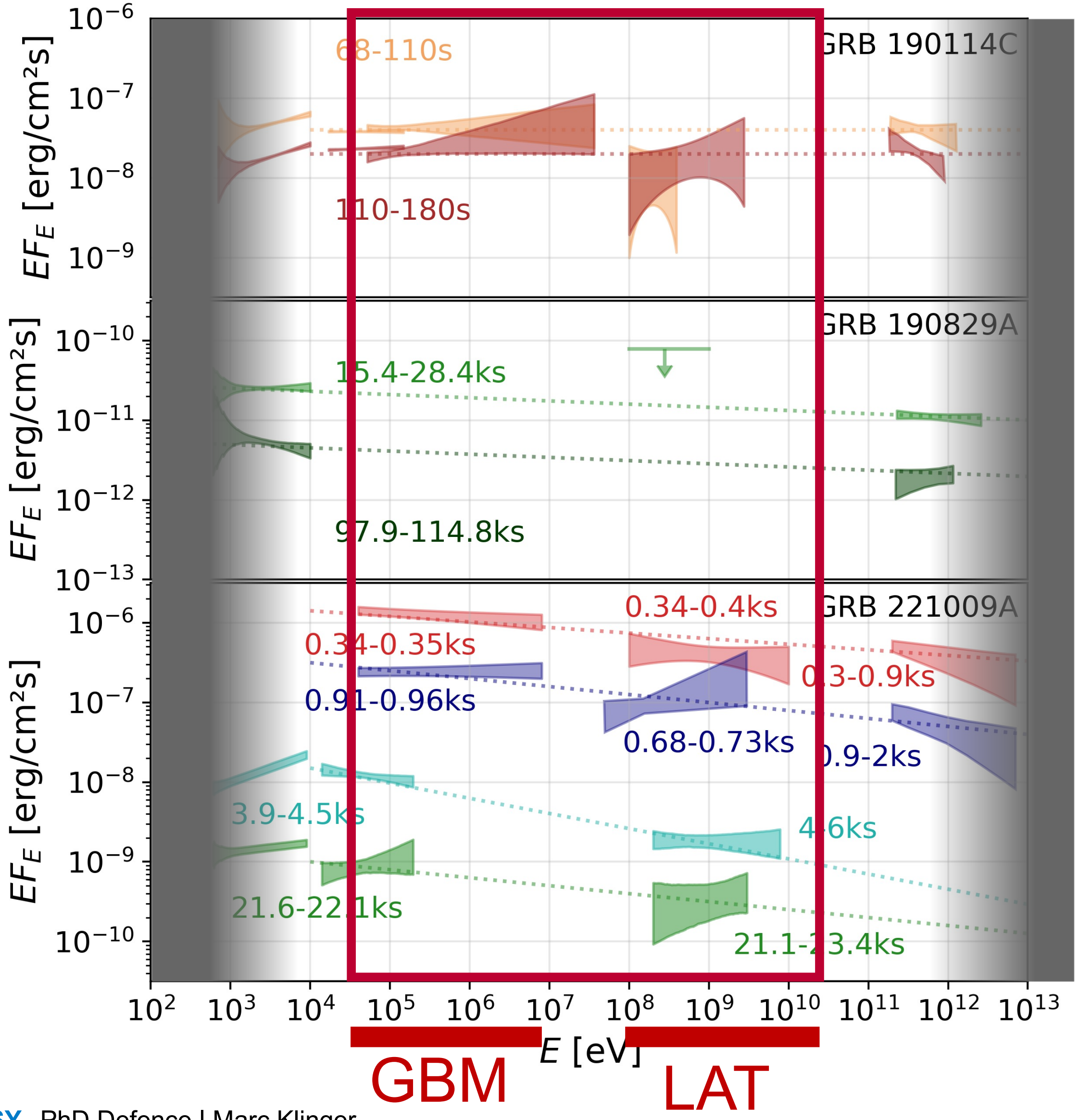
Swift satellite


NASA

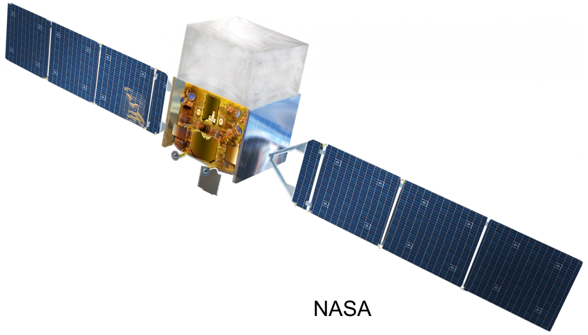
data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

Observations

"Modelling" paper



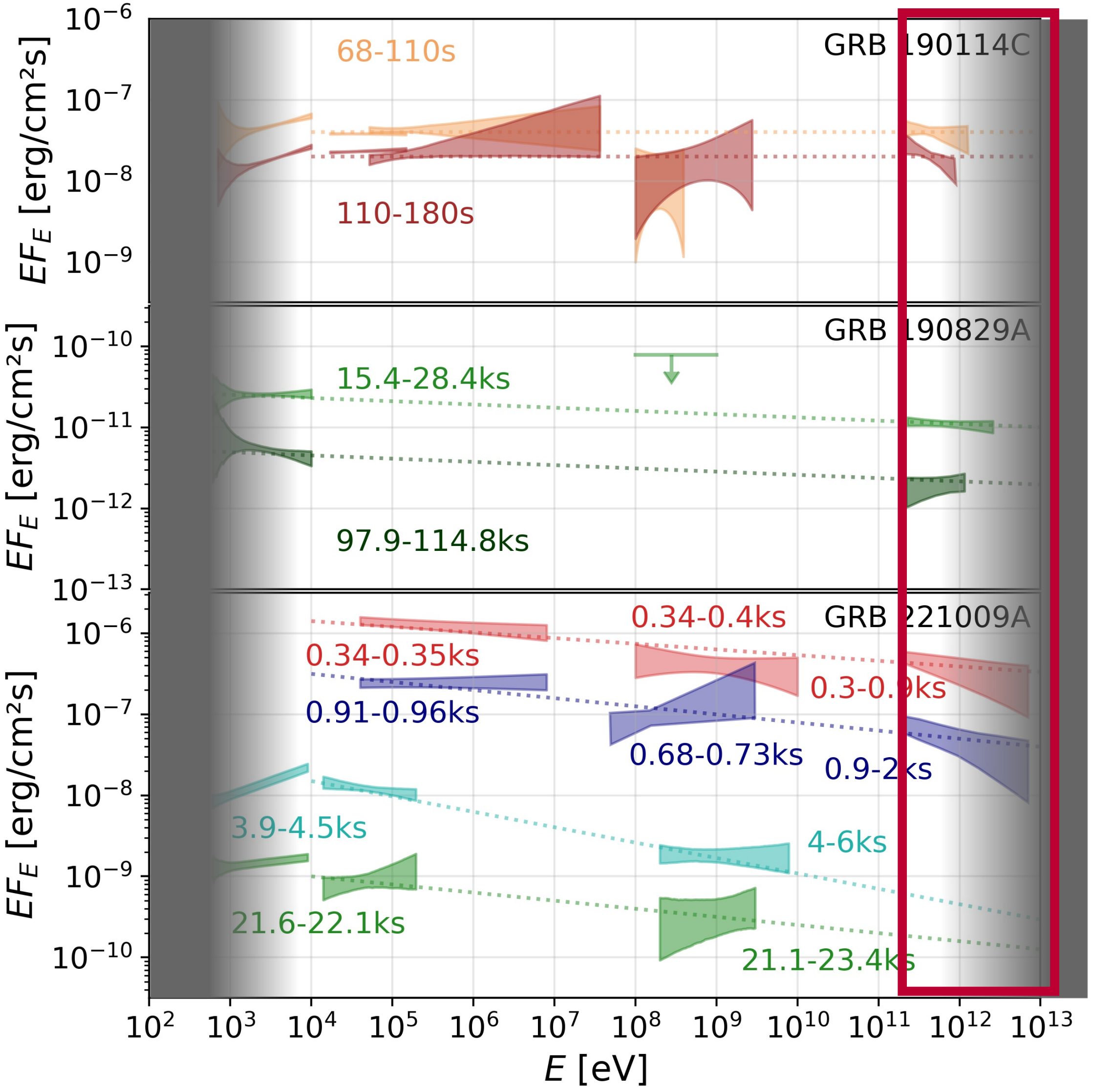
Fermi satellite



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++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

Observations

very-high energy
VHE ($E_\gamma > 0.1\,TeV$)



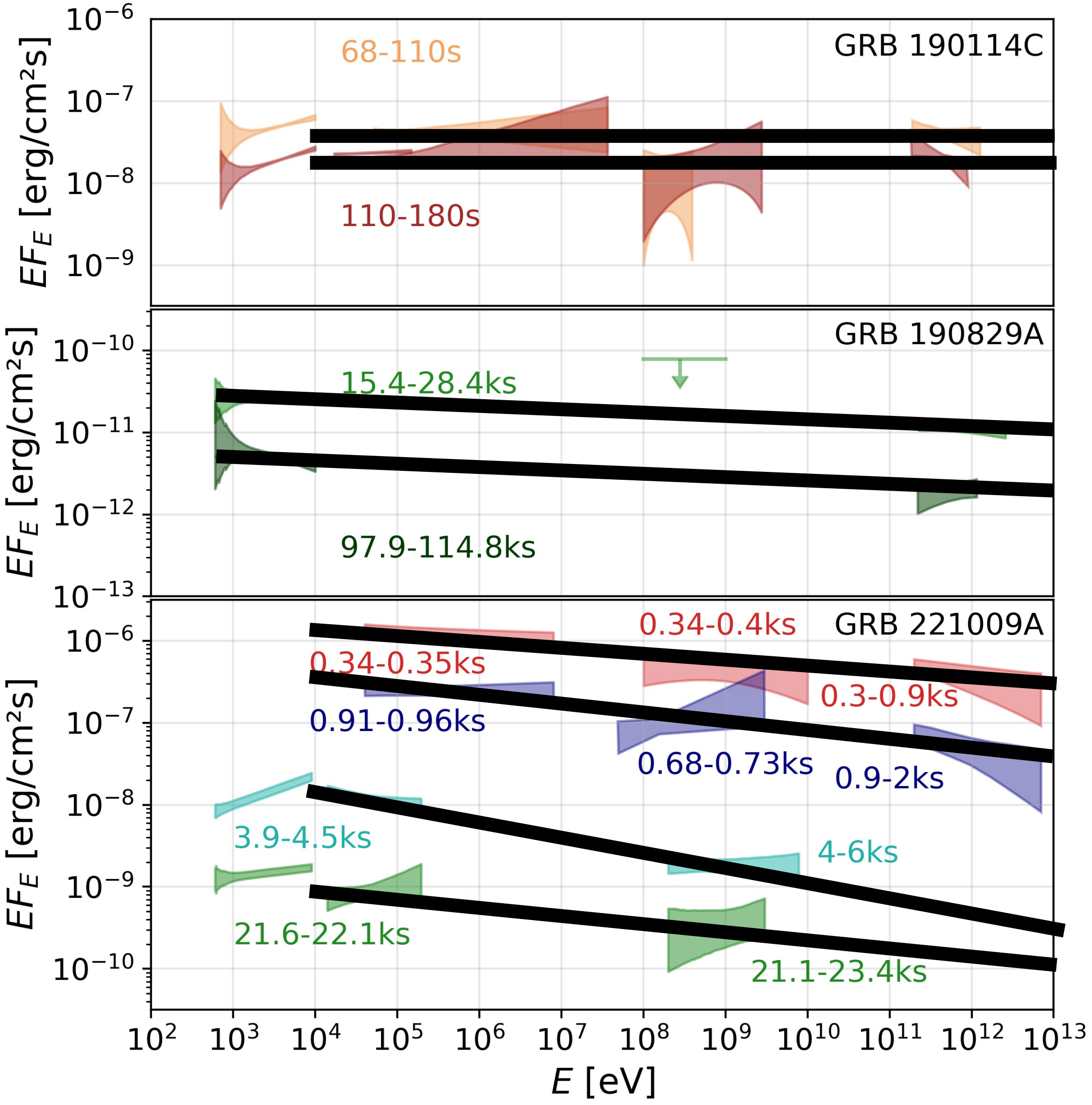
→ **MAGIC**

→ **H.E.S.S.**

→ **LHAASO**

Observations

"*Modelling*" paper



→ **MAGIC**

→ **H.E.S.S.**

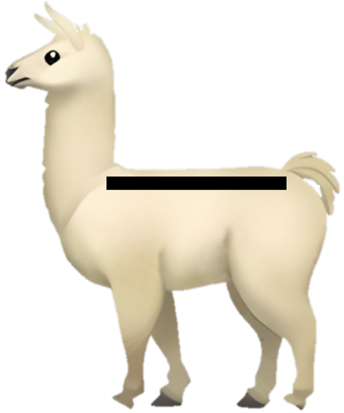
→ **LHAASO**

single power-law component up to TeV energies?

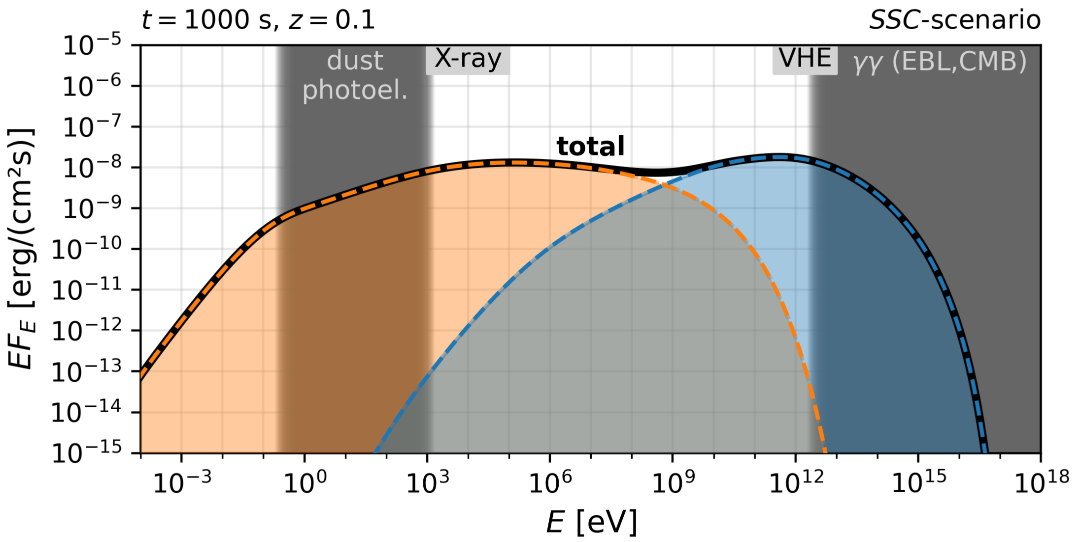
data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

SSC and ideas beyond

observations:
something
close to

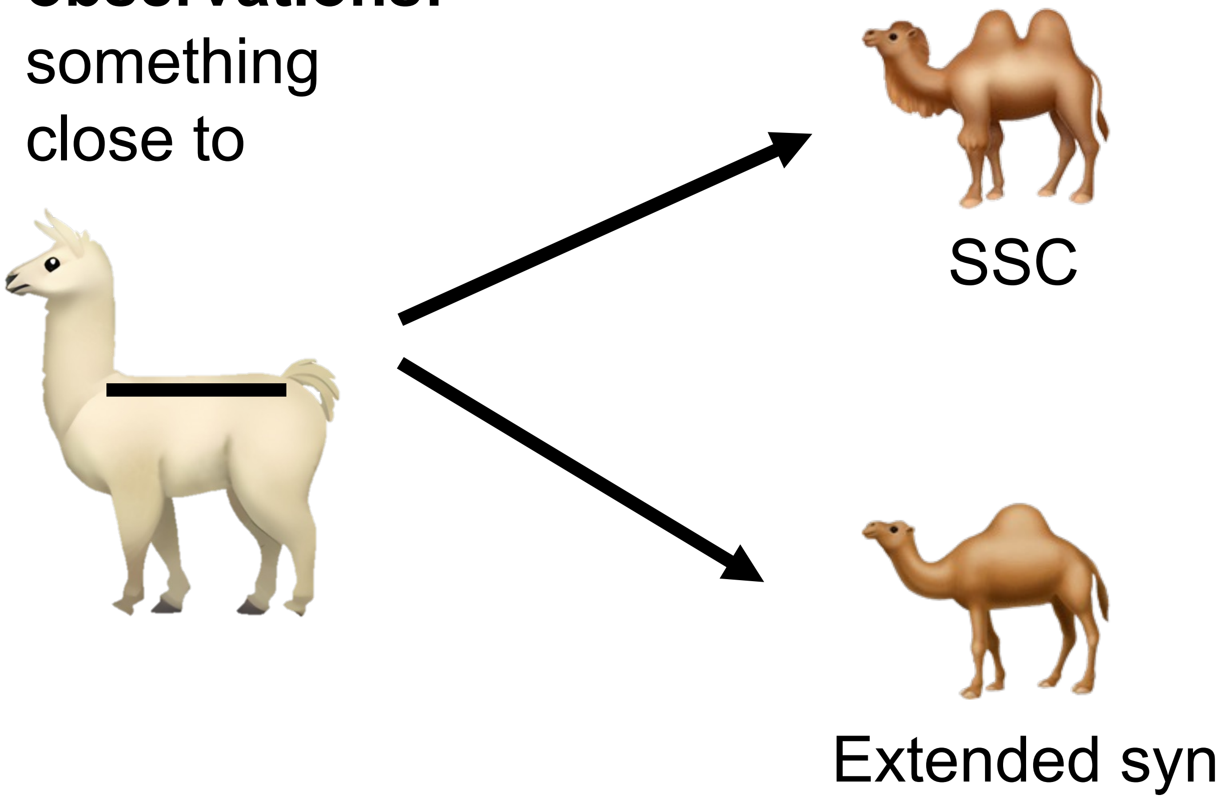


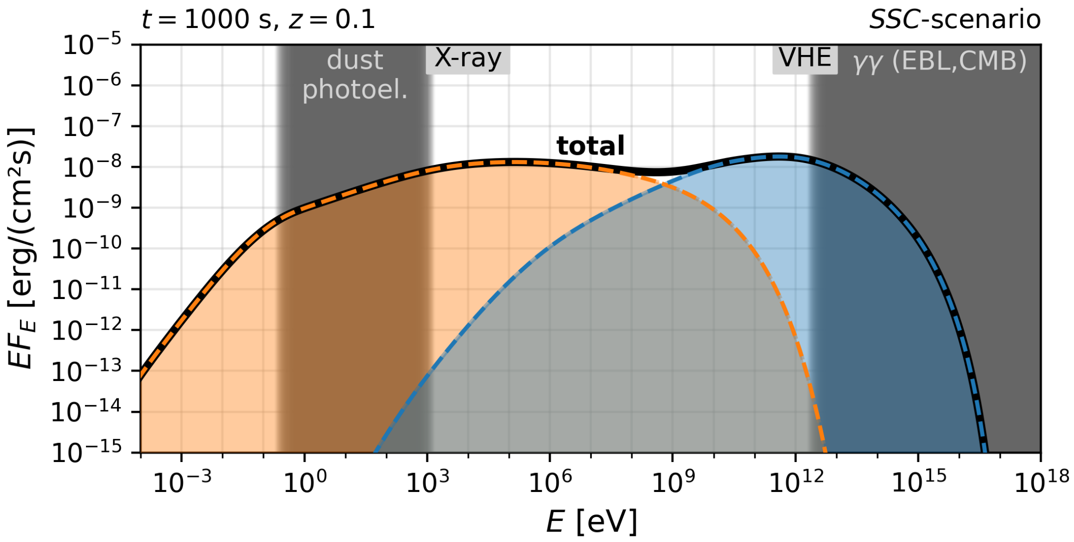
SSC

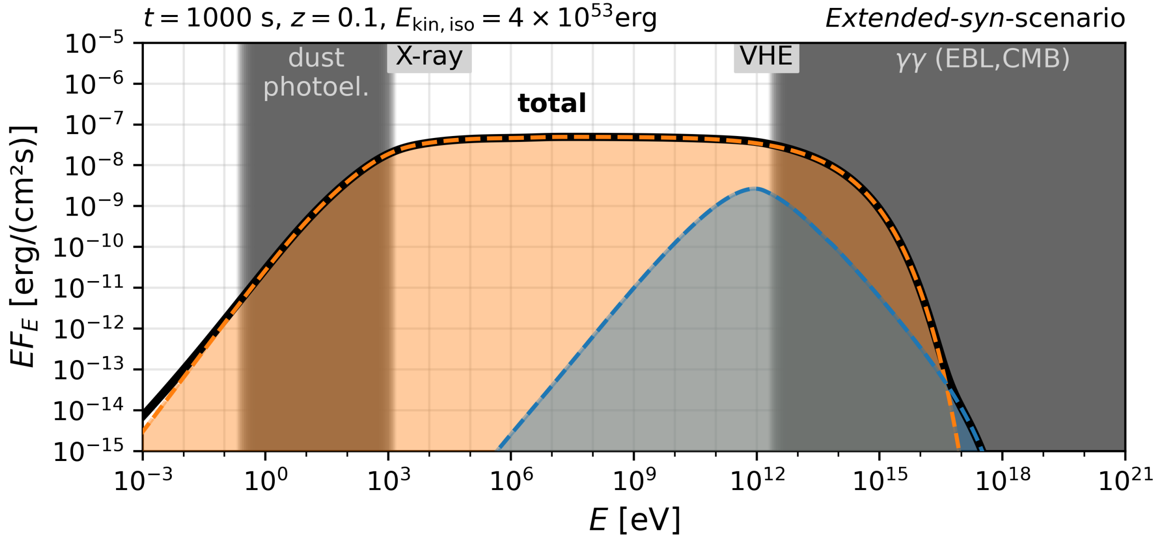


SSC and ideas beyond

observations:
something
close to



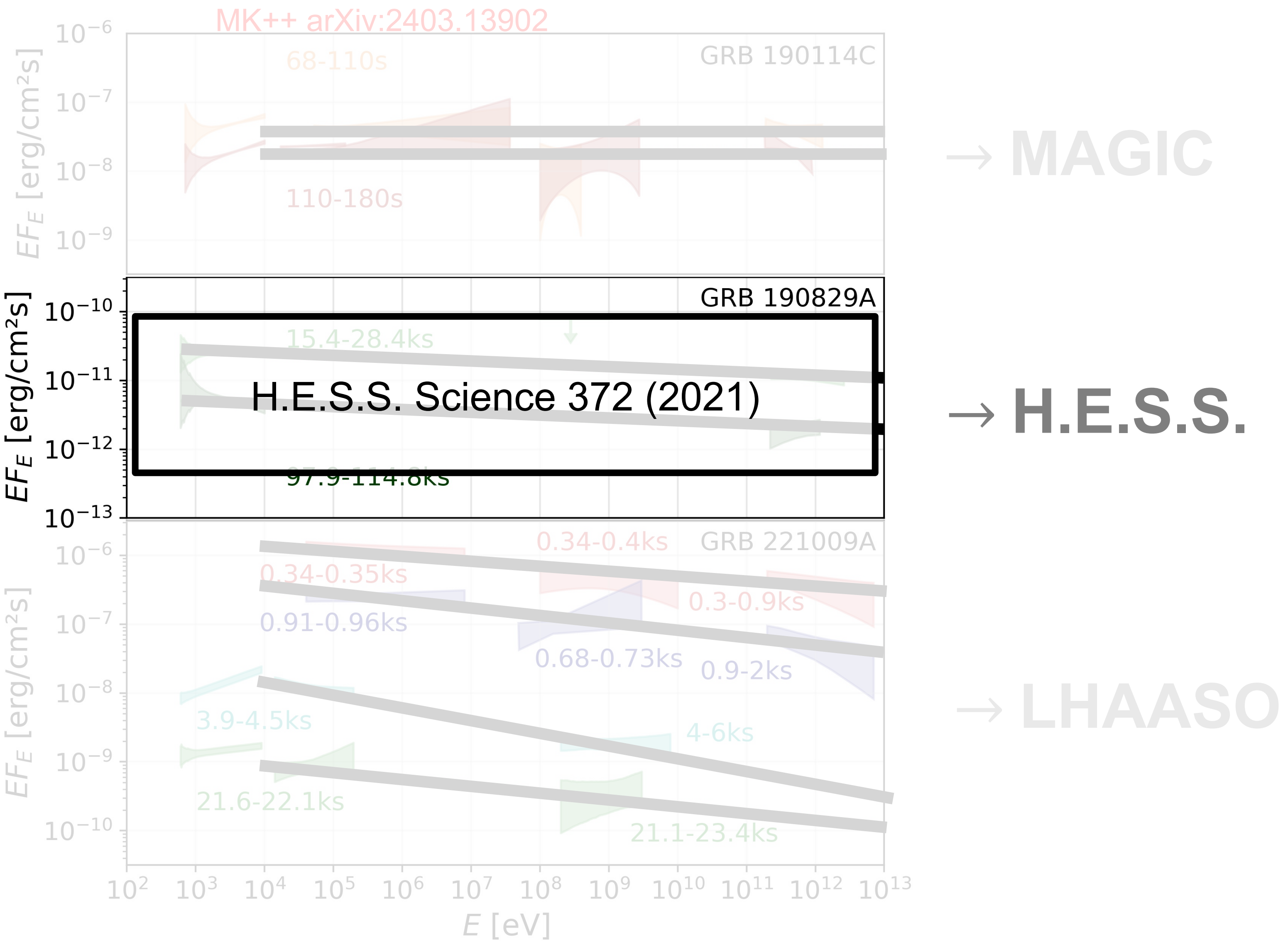




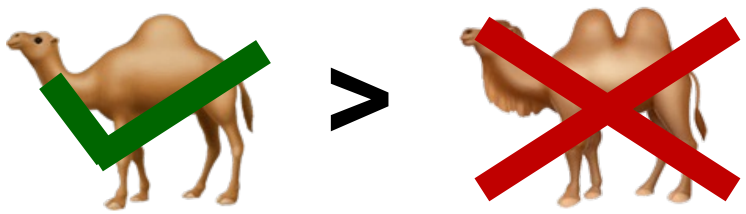
→ faster than Bohm acceleration: $\eta \ll 1$ → needs careful justification!

e.g. Kumar++ MNRAS 427 (2012) , Khangulyan++ APJ 947 (2021), Huang++ APJ 925 (2022), Groslj++ ApJL 963 L44 (2024)

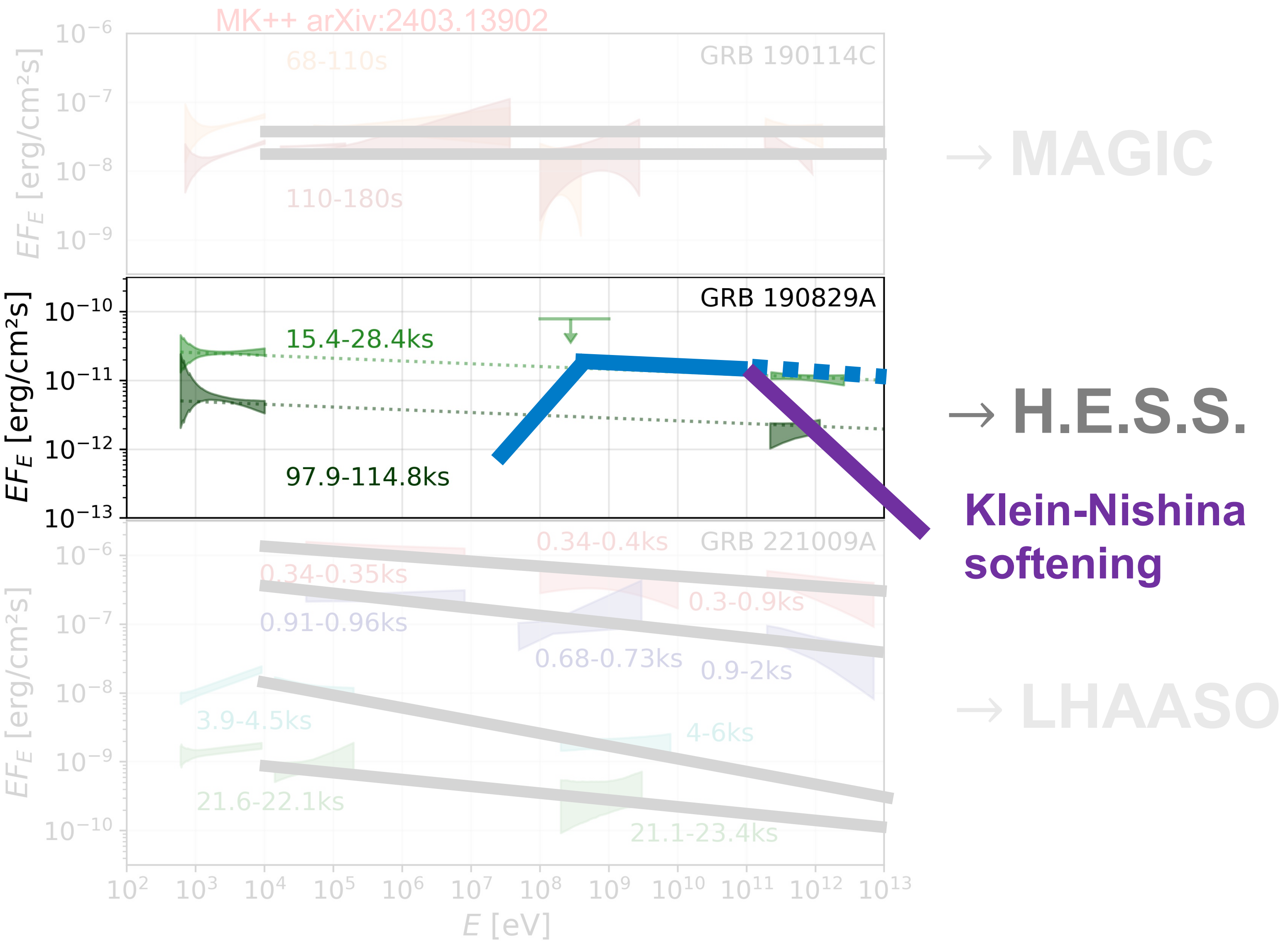
Observations



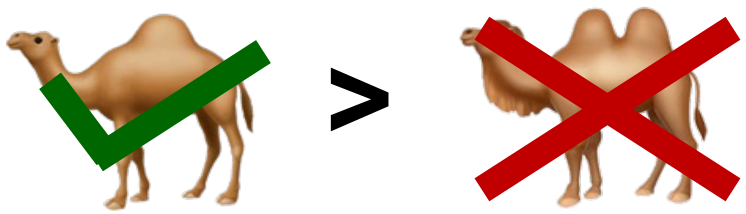
statistical preference for single component!



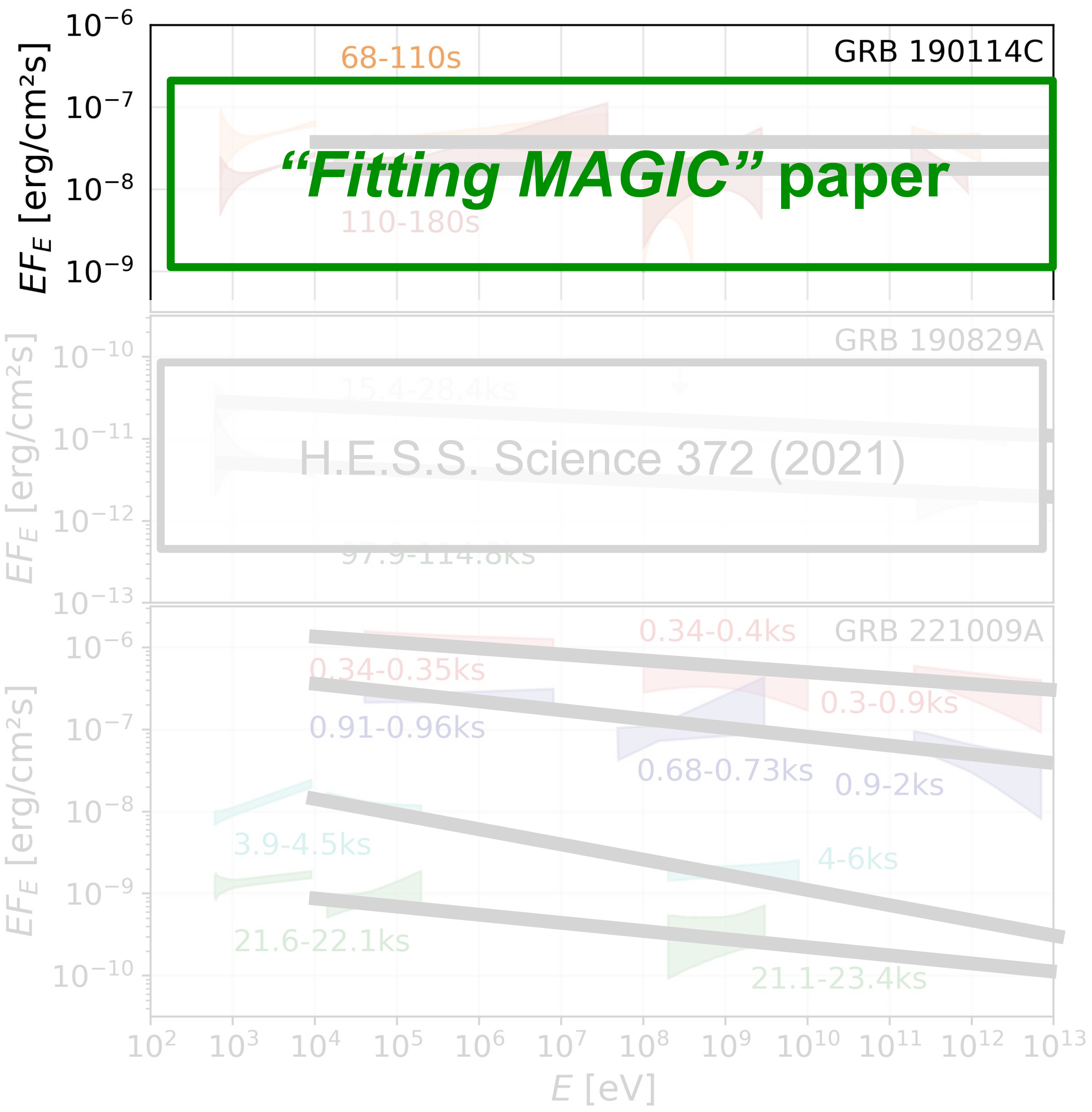
Observations



statistical preference for single component!



Observations



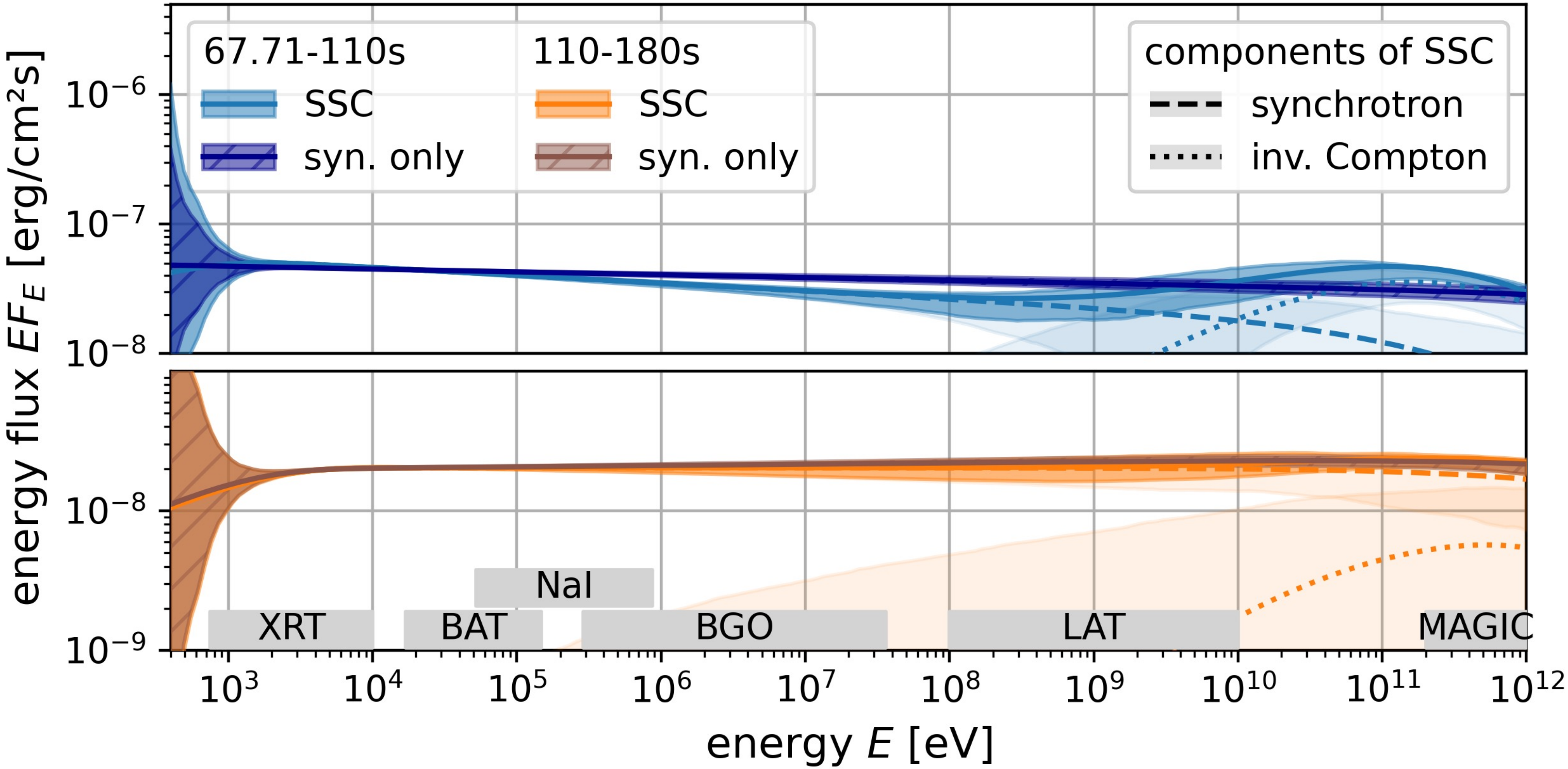
→ MAGIC

→ H.E.S.S.

→ LHAASO

MAGIC GRB 190114C

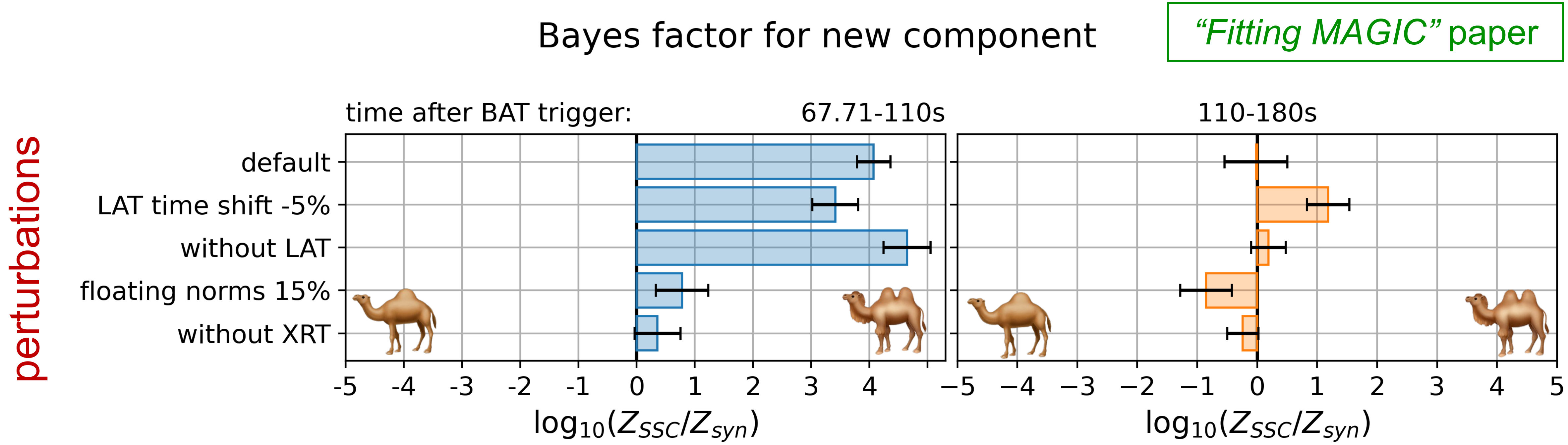
"Fitting MAGIC" paper



→ combined counts-level fit → statistical test of preference?

MAGIC GRB 190114C – preference for a 2. component?

"Fitting MAGIC" paper

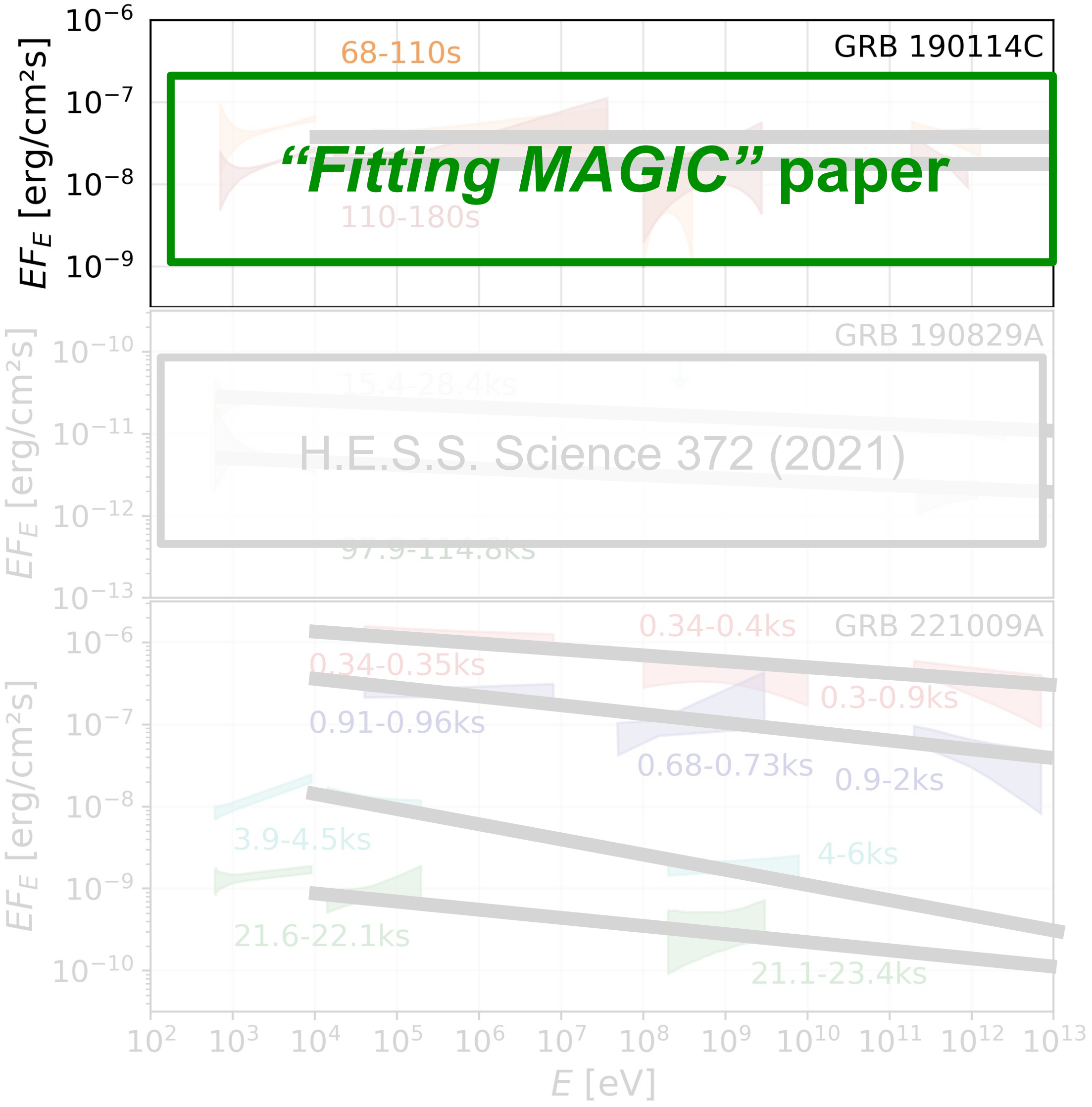


→ XRT/cross calibration drives new component!

no stable preference for either scenario!

→ different from claim by MAGIC collaboration [MAGIC Nature 575 (2019)]

GRB afterglow observations up to TeV energies



→ MAGIC

?

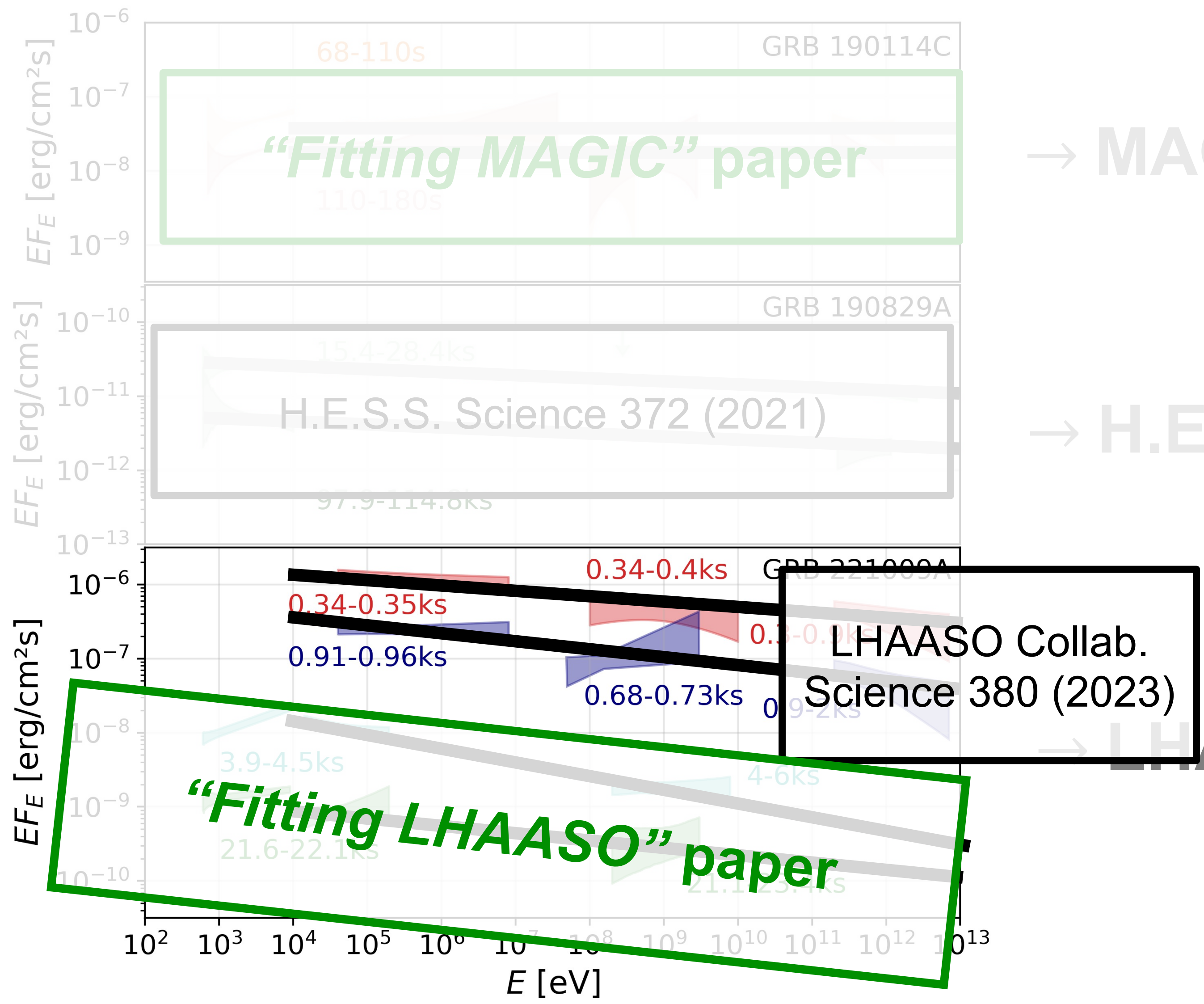
→ inconclusive on syn vs. SSC

→ H.E.S.S.

>

→ LHAASO

GRB afterglow observations up to TeV energies



→ MAGIC

→ H.E.S.S.

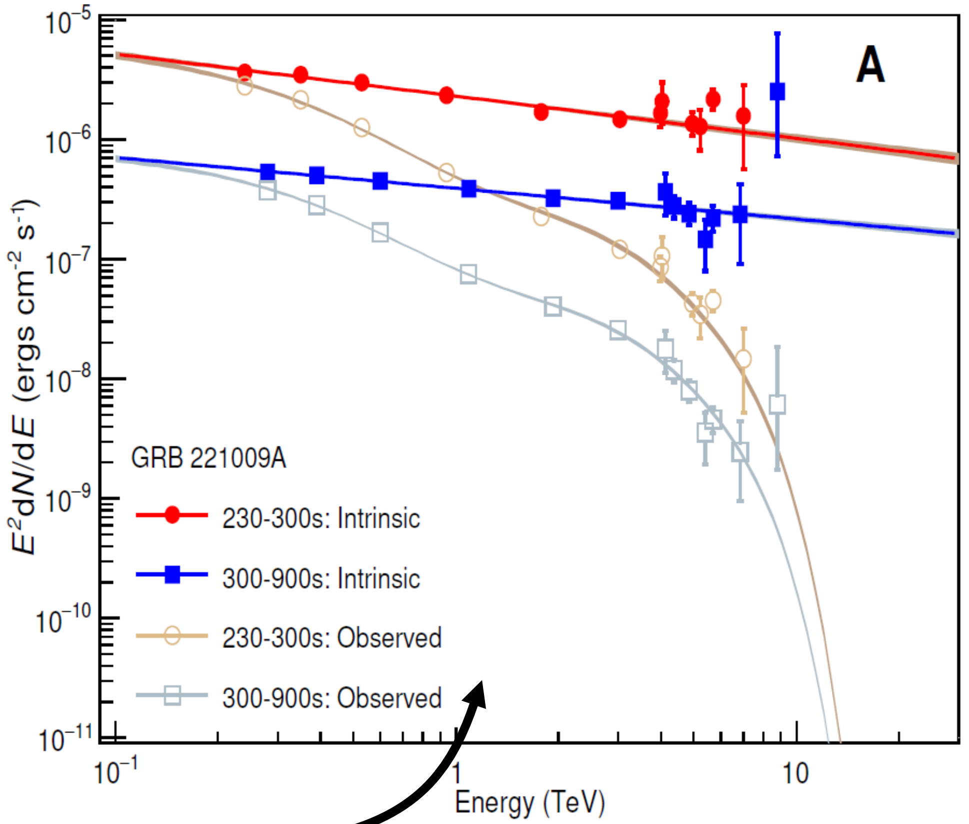
→ LHAASO

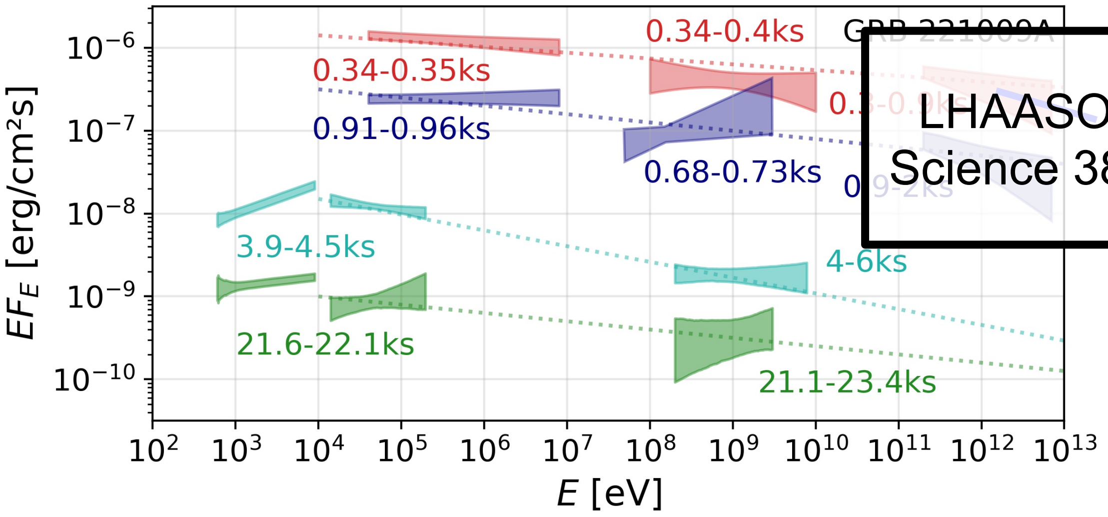
LHAASO GRB 221009A

→ **power law with $\gamma_{\mathrm{TeV}} \approx 2.2$**

→ **No softening up to at least 10 TeV**

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





LHAASO Collab.
Science 380 (2023)

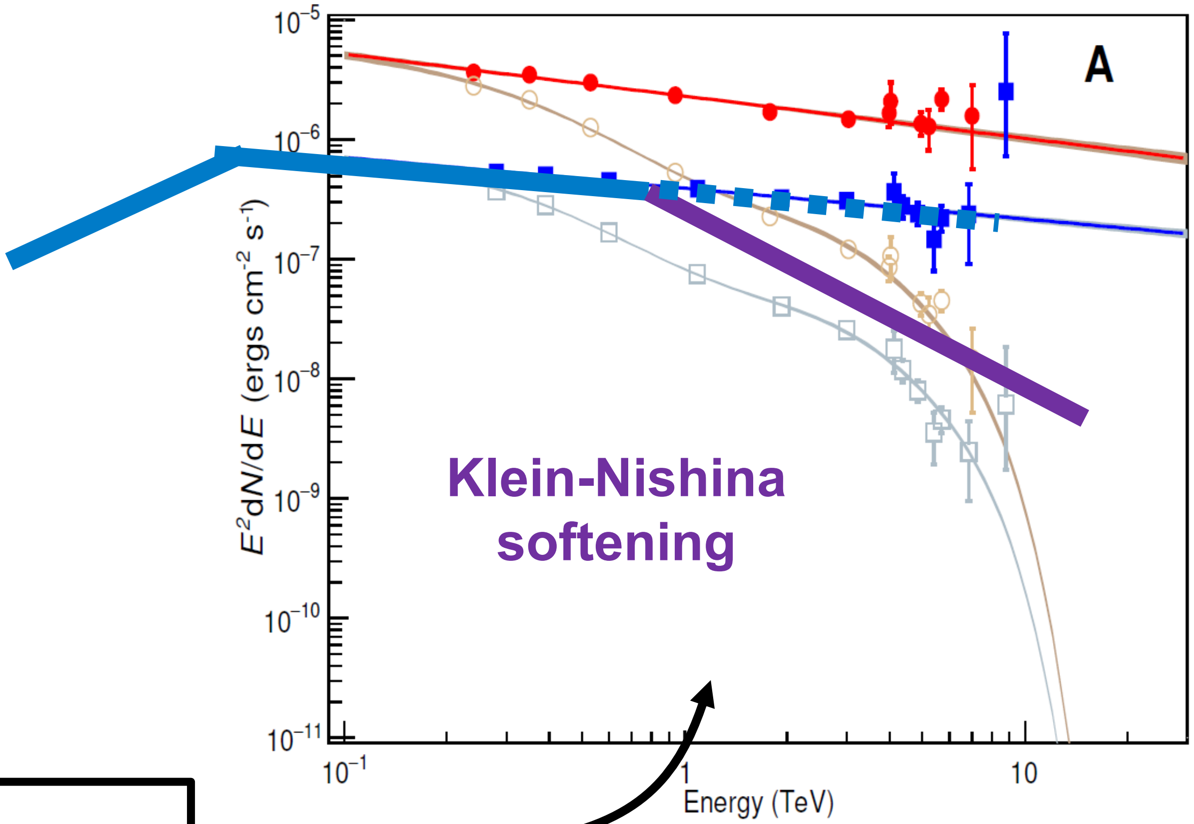
LHAASO GRB 221009A

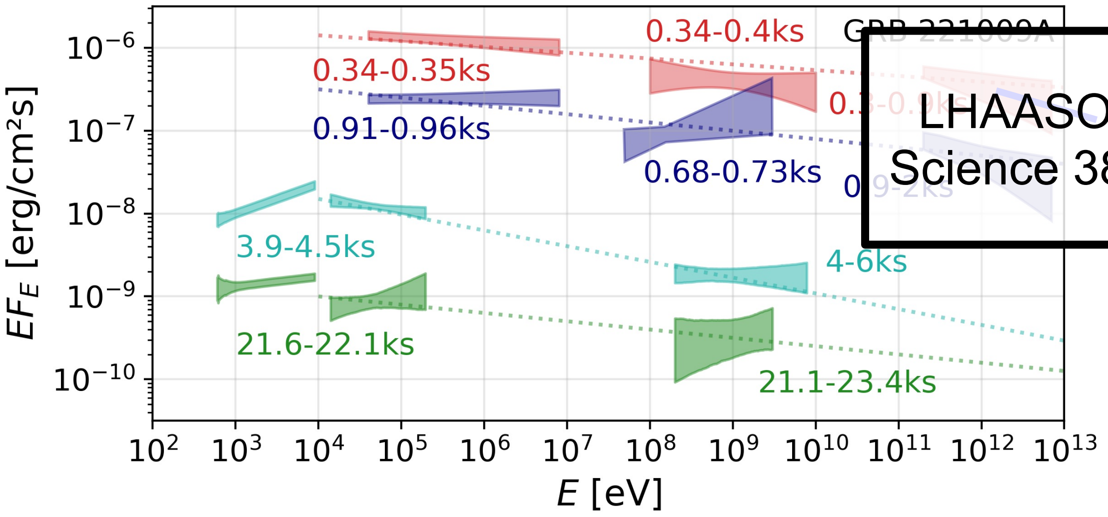
→ power law with $\gamma_{\mathrm{TeV}} \approx 2.2$

→ No softening up to at least 10 TeV

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

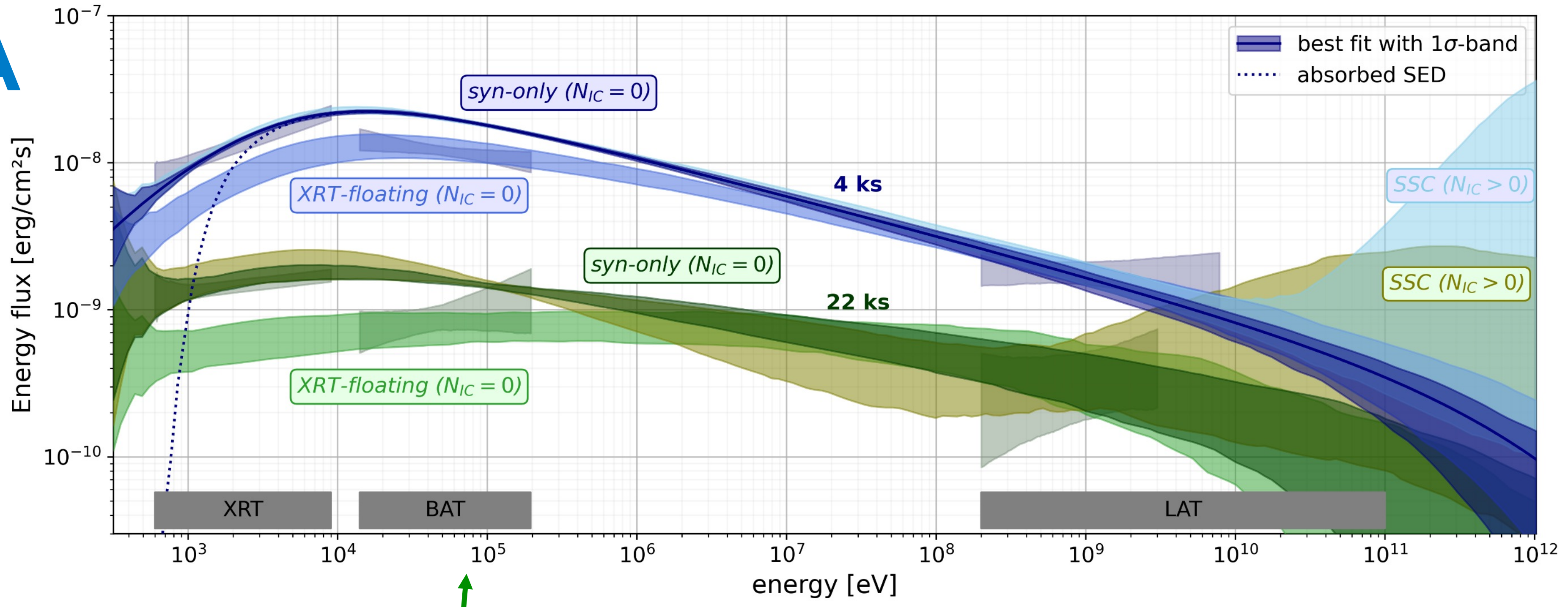
→ in tension with SSC

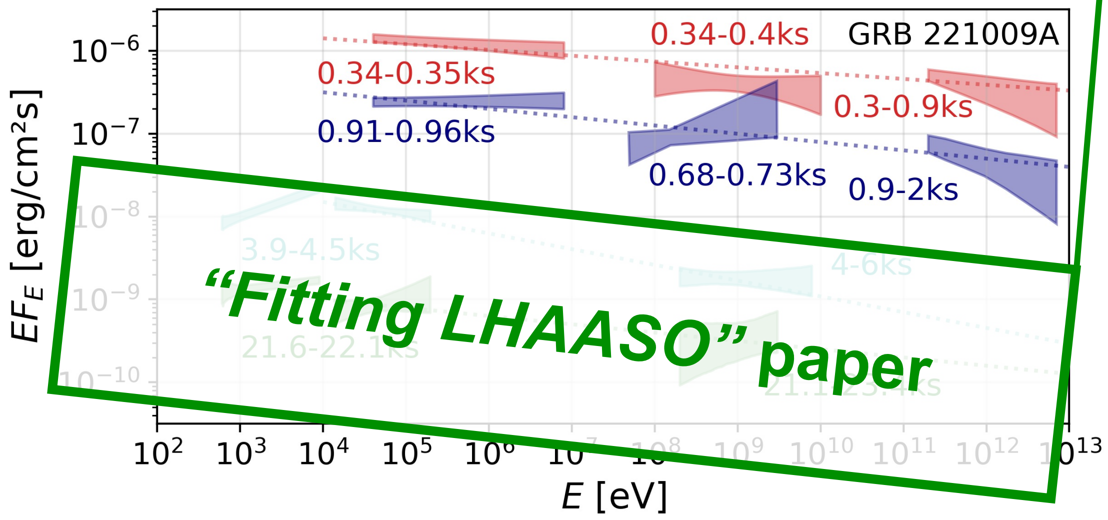




LHAASO Collab.
Science 380 (2023)

GRB 221009A (LHAASO)



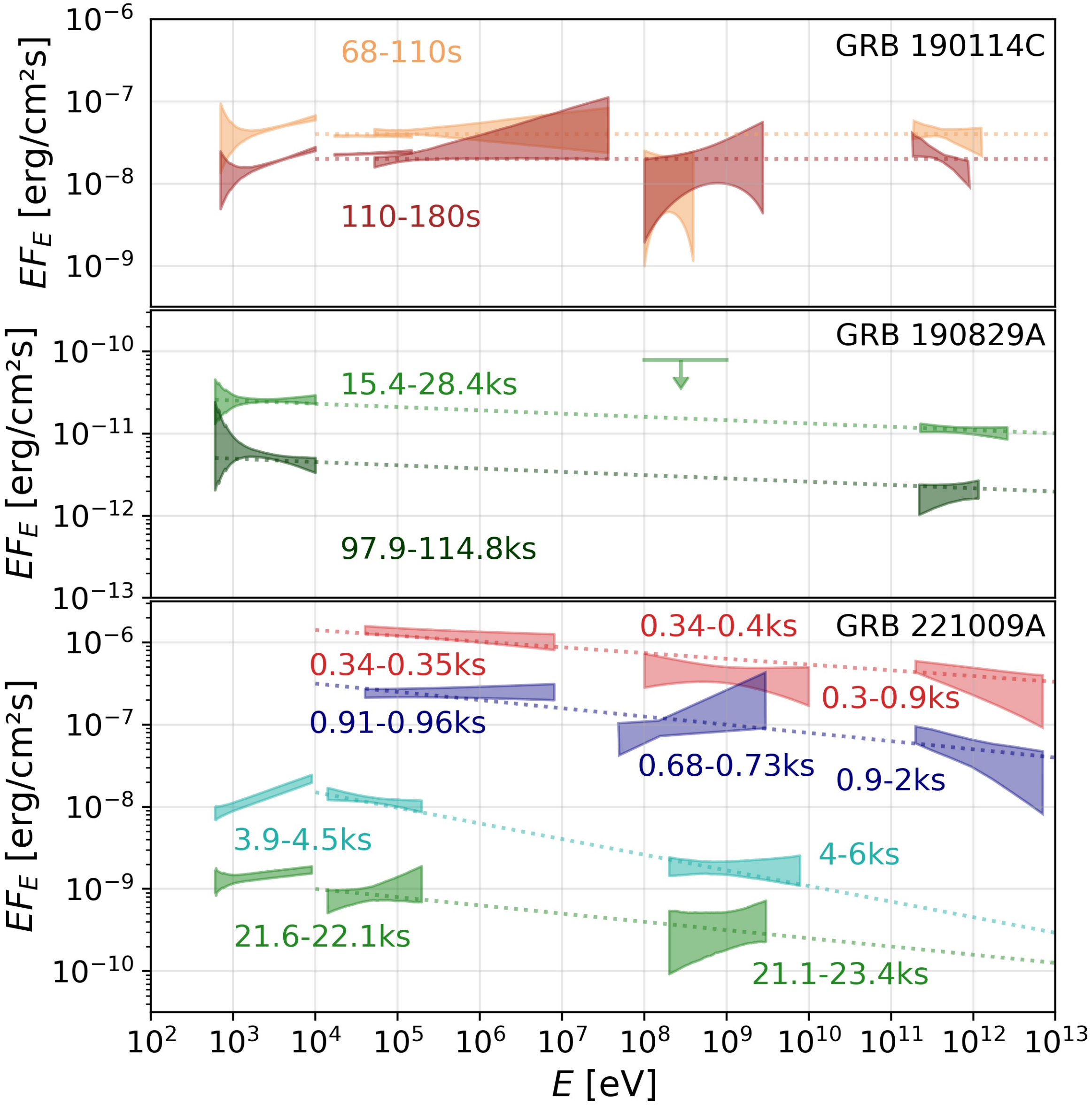


after LHAASO (> 2 ks):

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

→ consistent with LHAASO

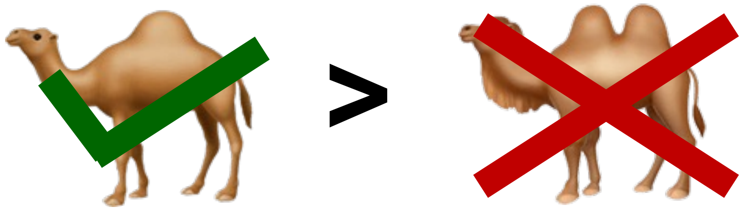
Observational summary



→ **MAGIC:**

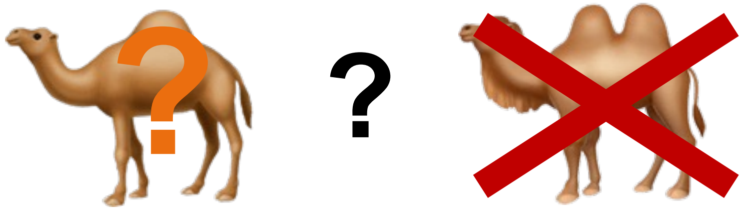
→ **inconclusive on syn vs. SSC**

→ **H.E.S.S.:**



→ **preference against SSC**

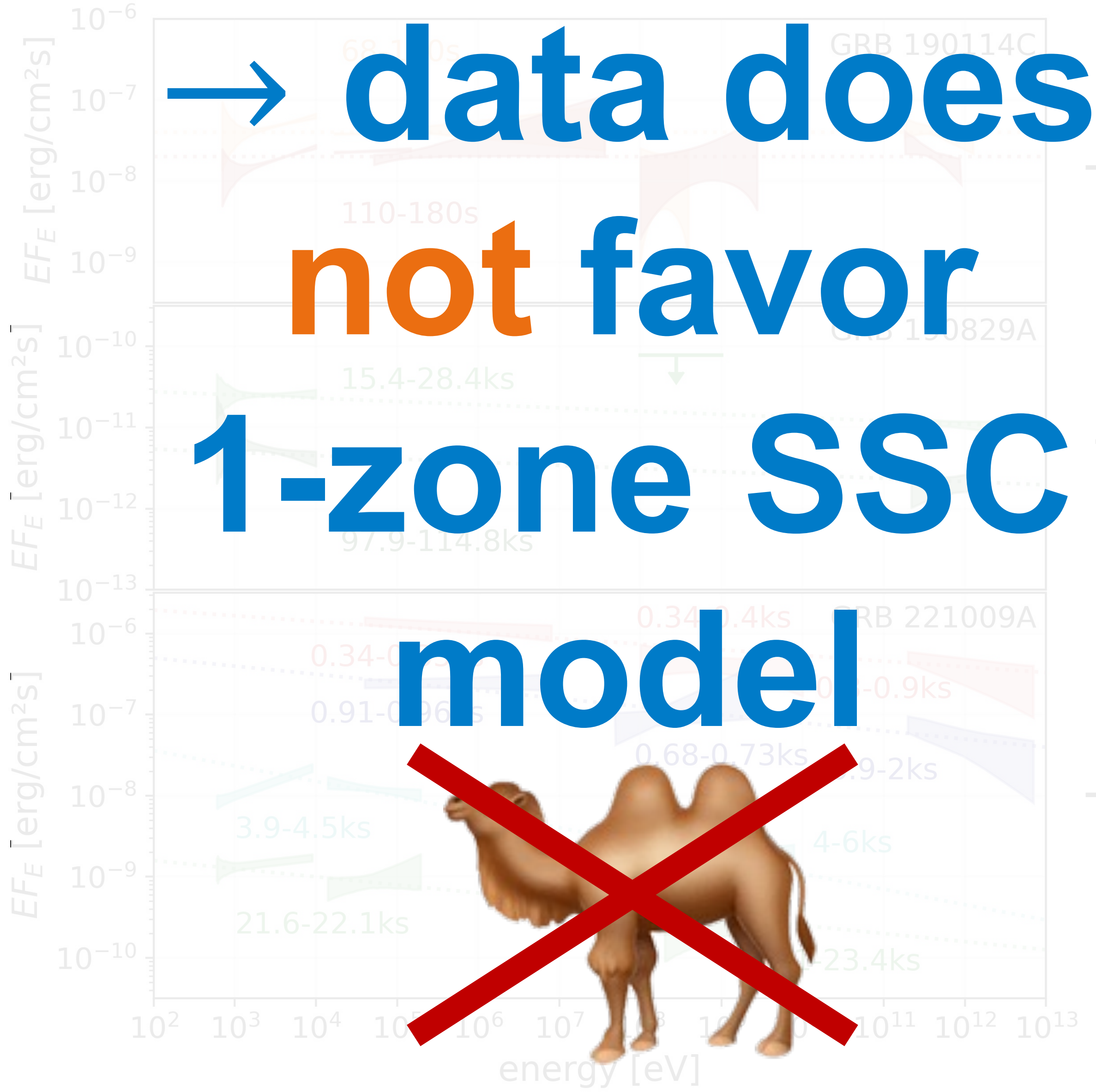
→ **LHAASO:**



→ **in tension with SSC**

Observational summary

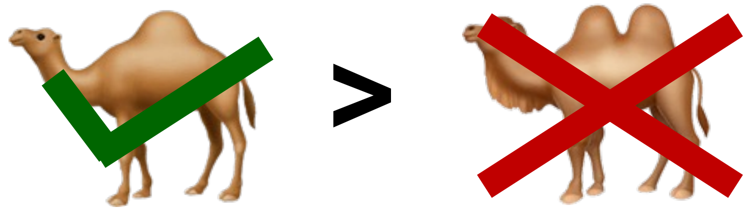
→ data does **not** favor 1-zone SSC model



→ MAGIC:

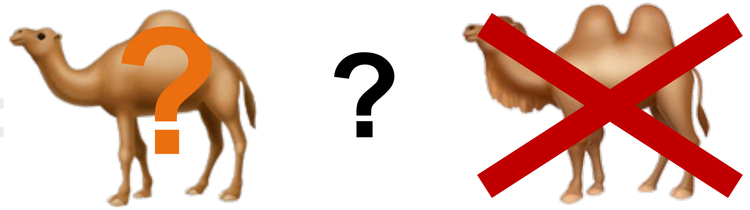
→ inconclusive on syn vs. SSC

→ H.E.S.S.:



→ preference against SSC

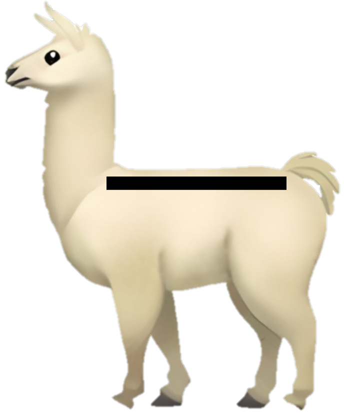
→ LHAASO:



→ in tension with SSC

SSC and ideas beyond

observations:
something
close to



SSC

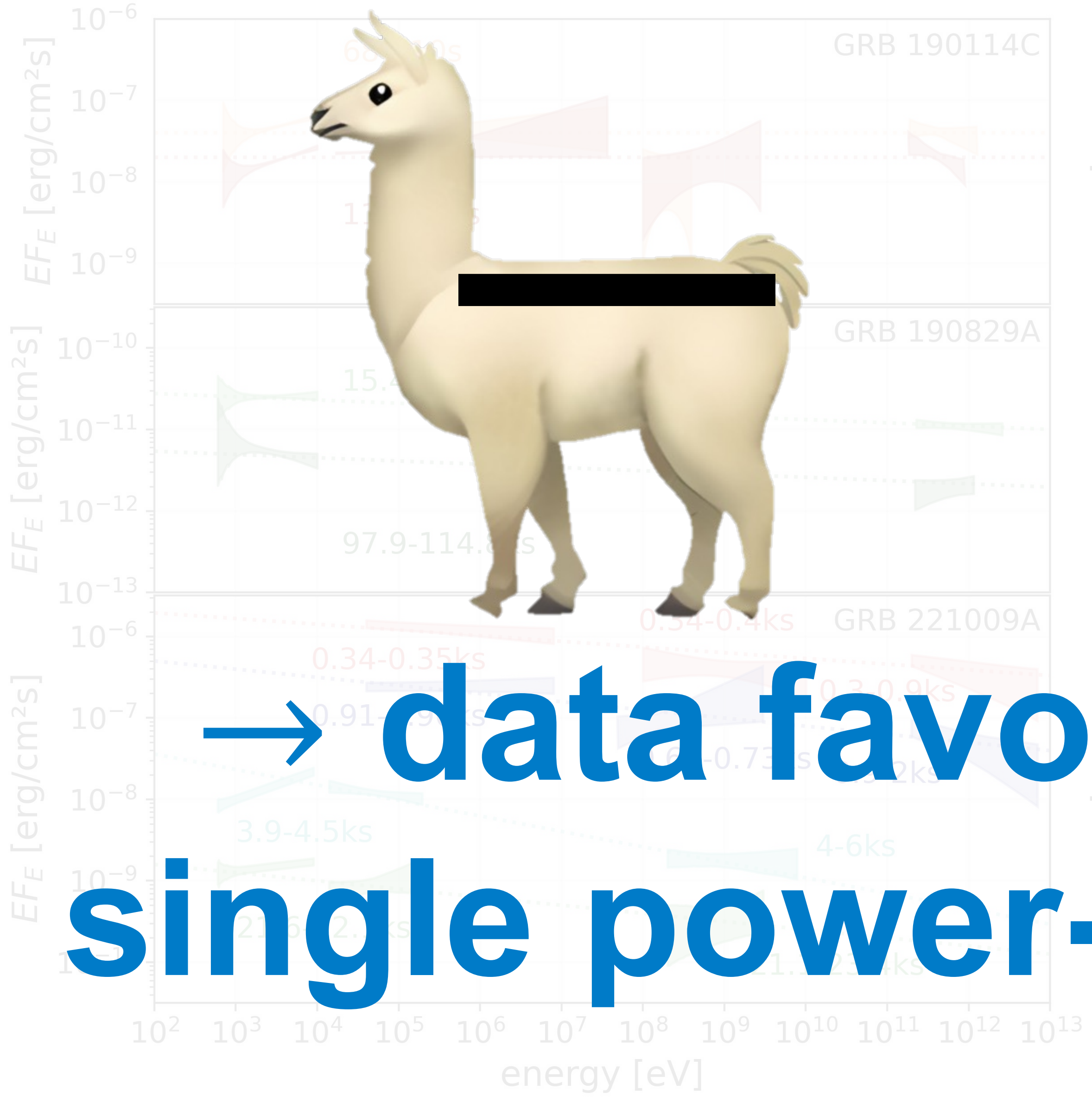
advantages:

bright

limitations:

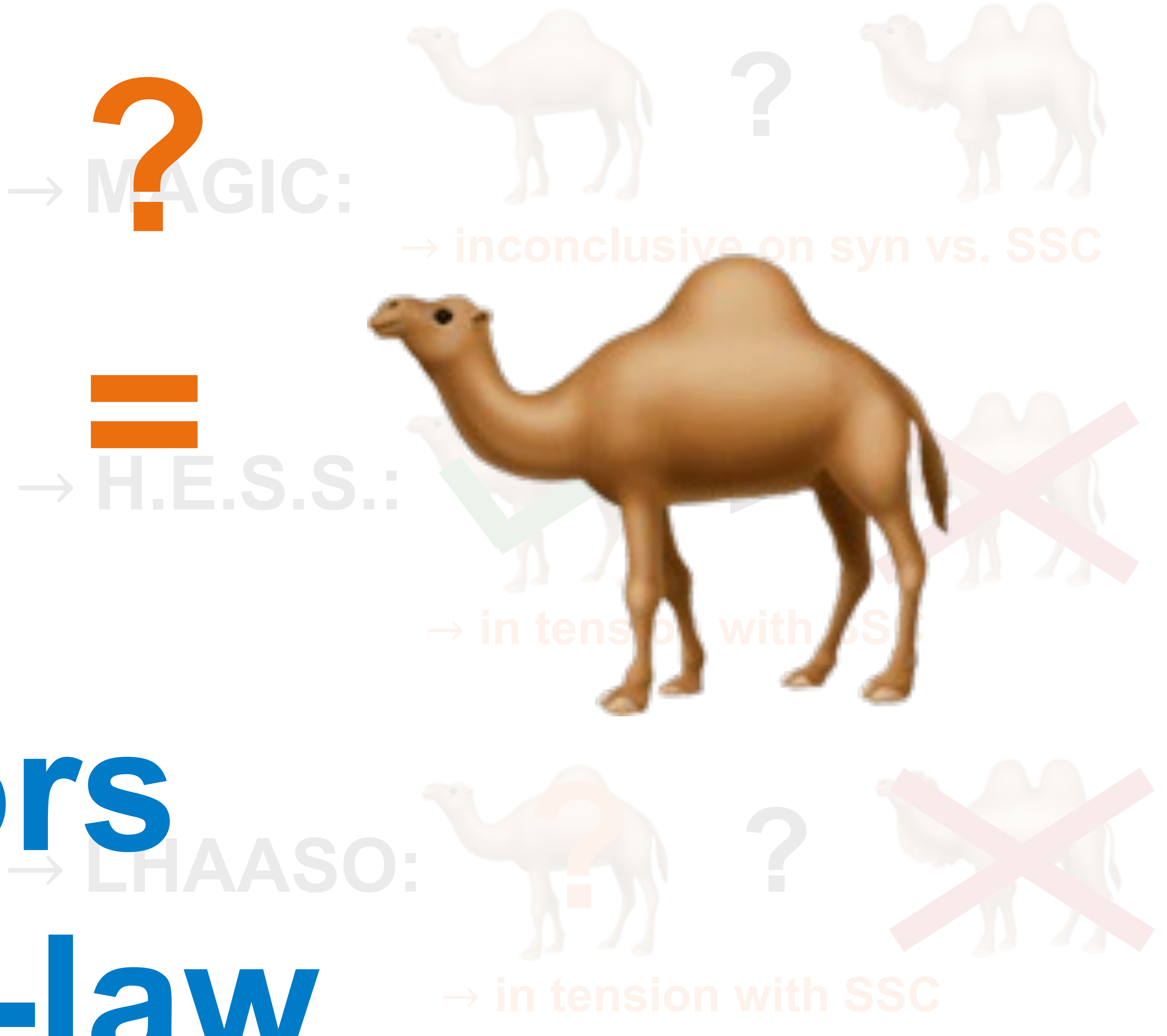
Klein-Nishina suppression

Observational summary



?

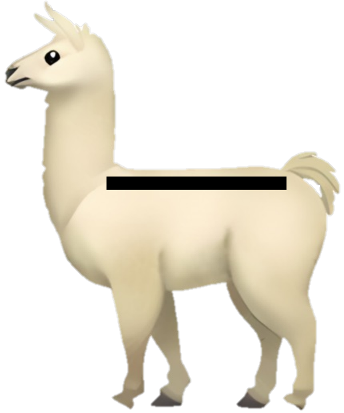
=

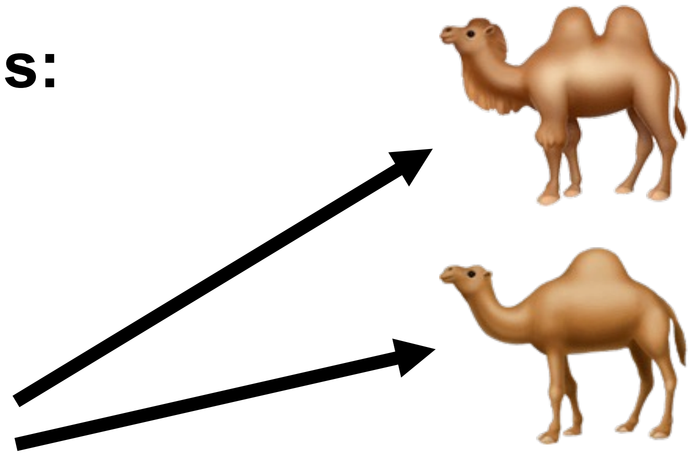


→ data favors single power-law

SSC and ideas beyond

observations:
something
close to

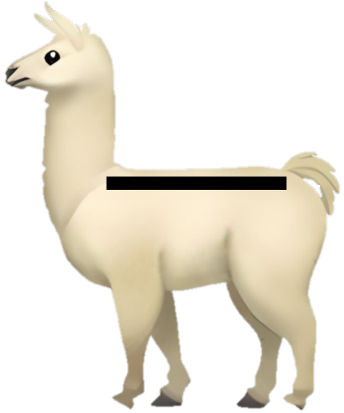




	advantages:	limitations:
SSC	bright	Klein-Nishina suppression
Extended syn	bright simple	$\eta \ll 1$ (super Bohm)

SSC and ideas beyond

observations:
something
close to



electrons

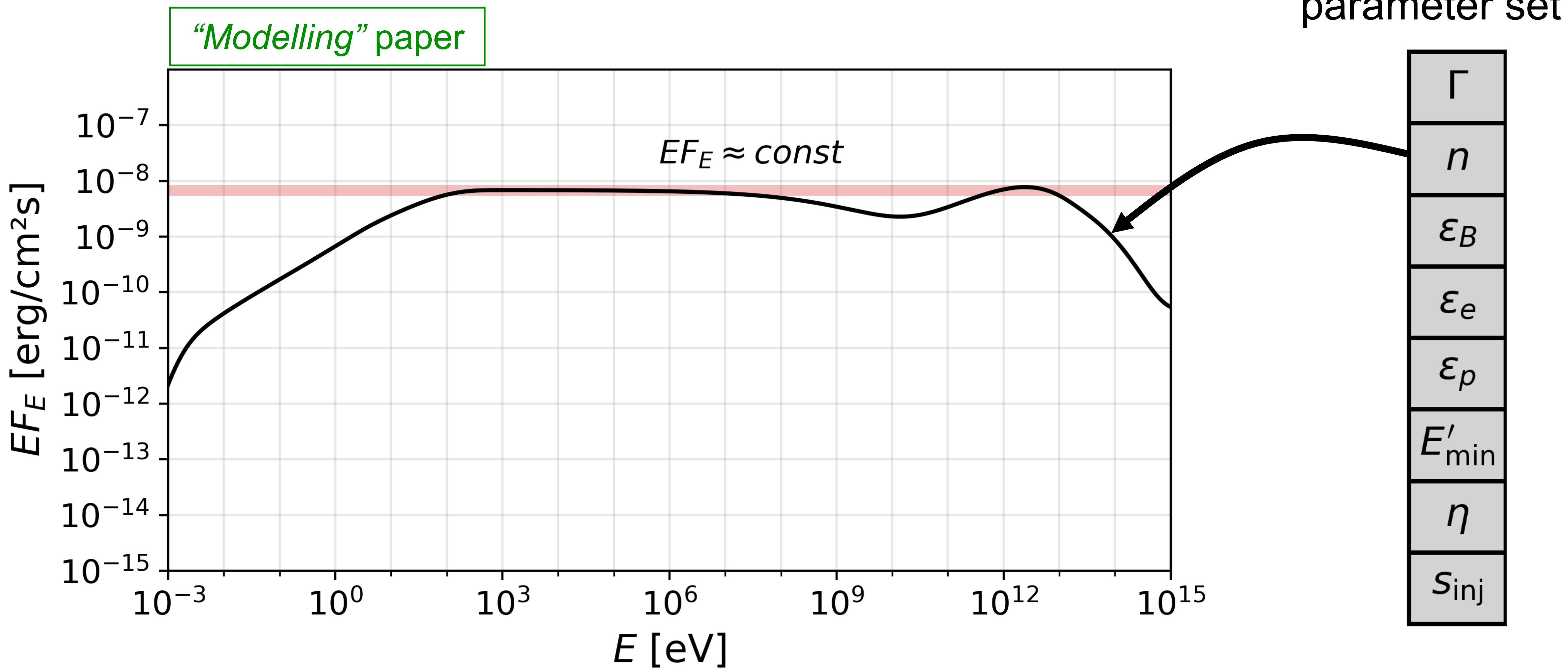
		advantages:	limitations:
	SSC	bright	Klein-Nishina suppression
	Extended syn	bright simple	$\eta \ll 1$ (super Bohm)

electrons
+ protons

→ additional radiation channels!
→ systematic exploration needed!

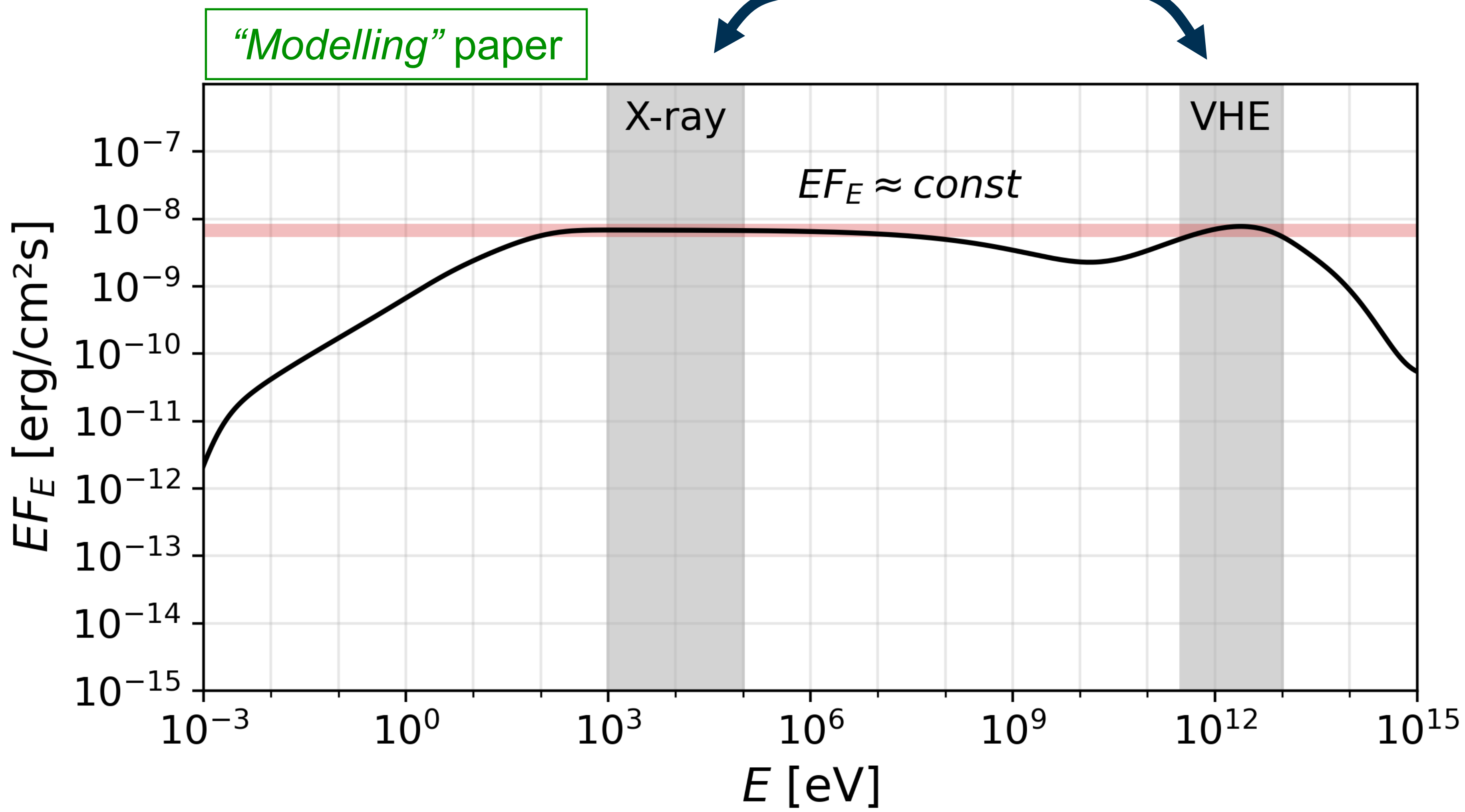
→ *"Modelling"* paper

Systematic parameter scan – selection



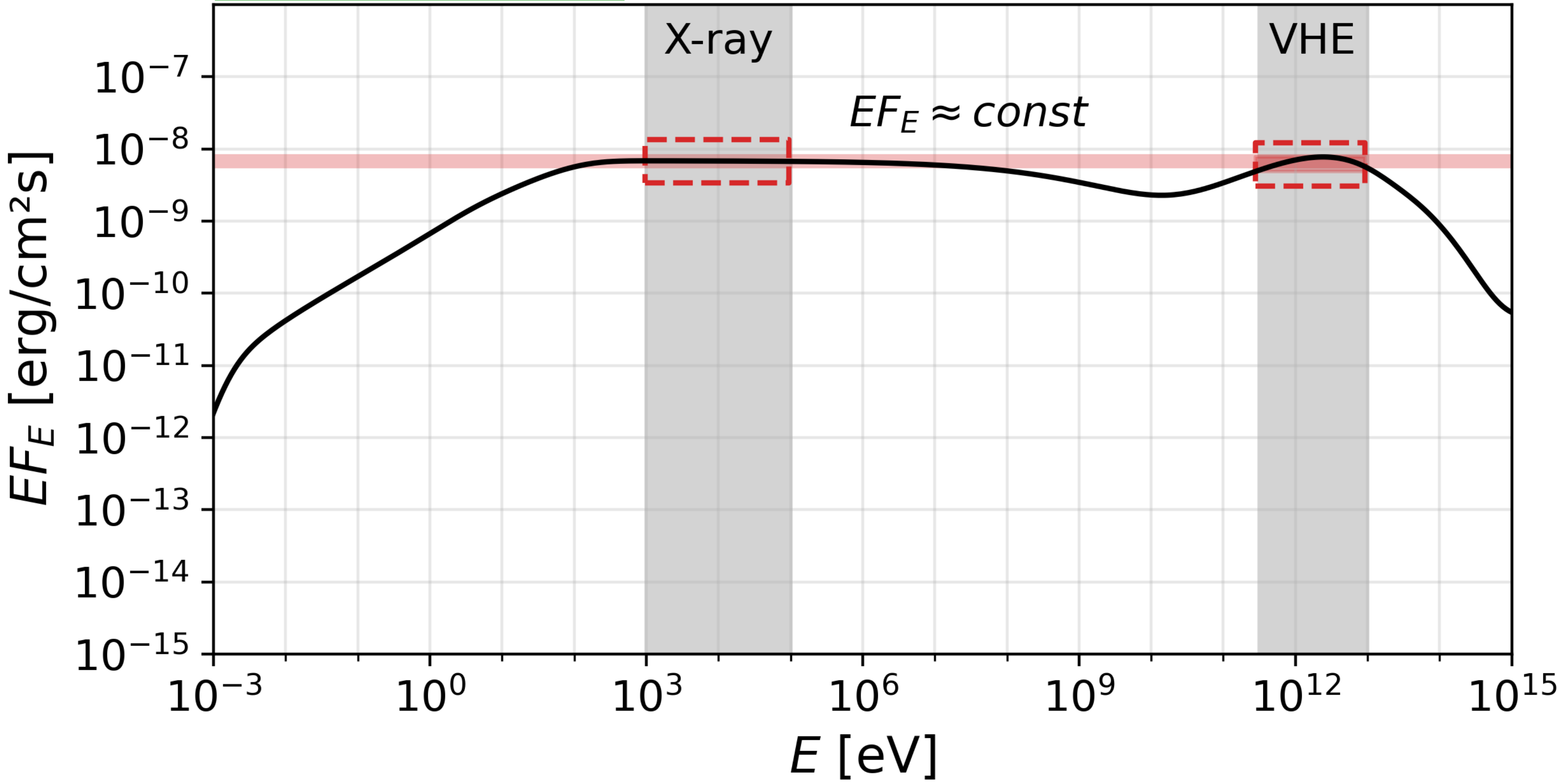
Systematic parameter scan – selection

robust data



Systematic parameter scan – selection

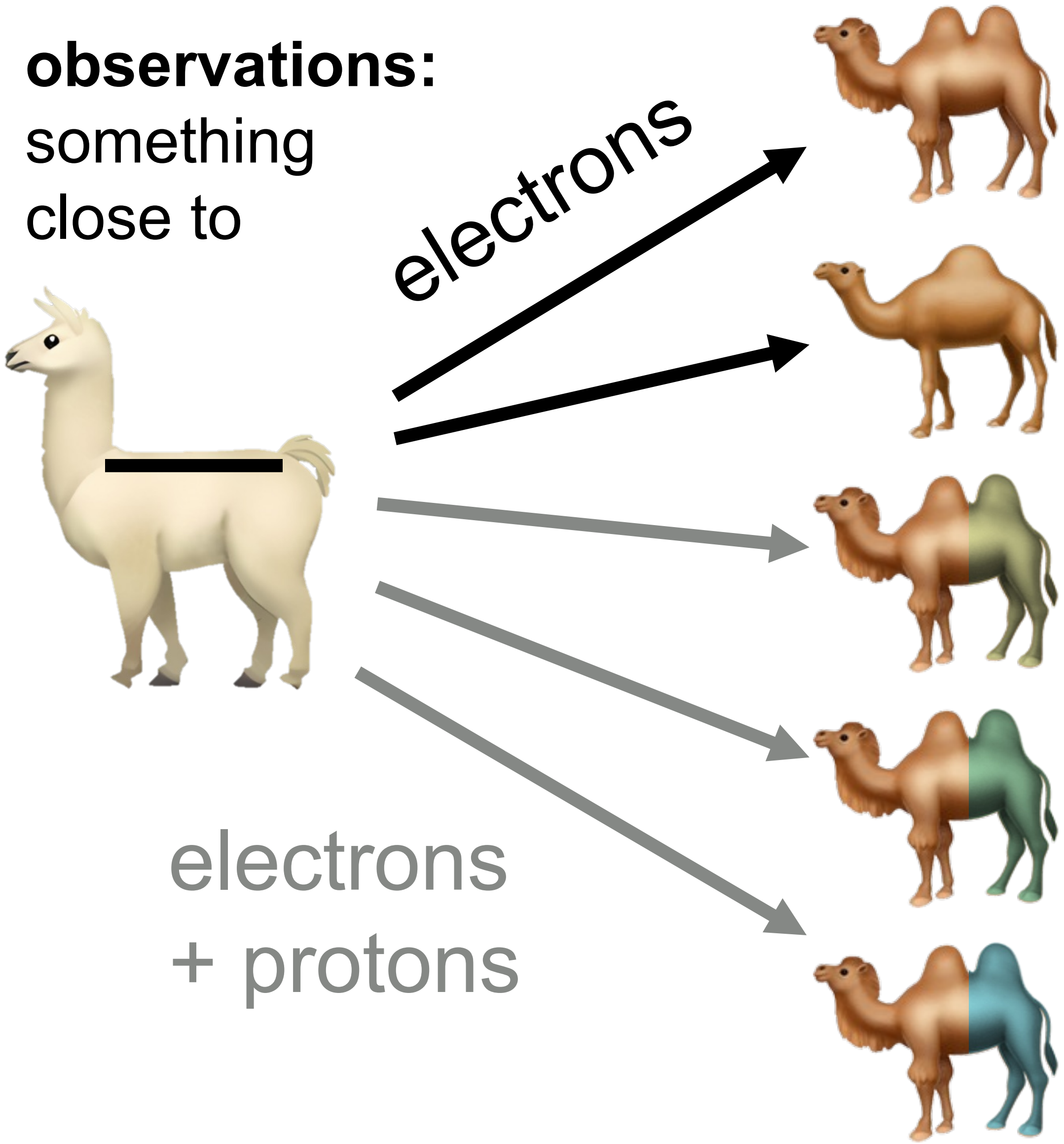
"Modelling" paper



selection criterion: contained in box

SSC and ideas beyond

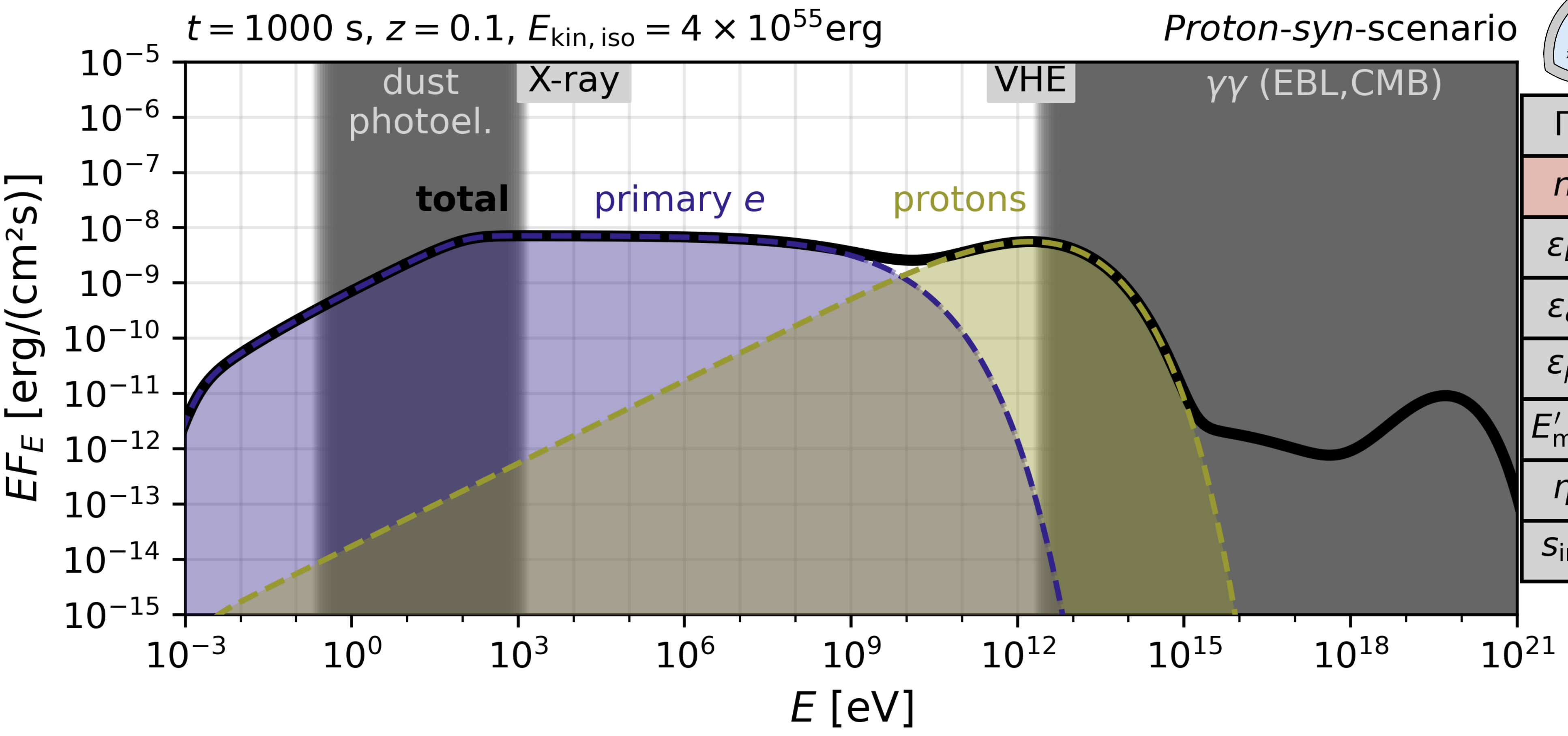
observations:
something
close to



	advantages:	**limitations:**
SSC	bright	Klein-Nishina suppression
Extended syn	bright simple	$\eta \ll 1$ (super Bohm)
Proton syn		

Proton synchrotron scenario

“Modelling” paper



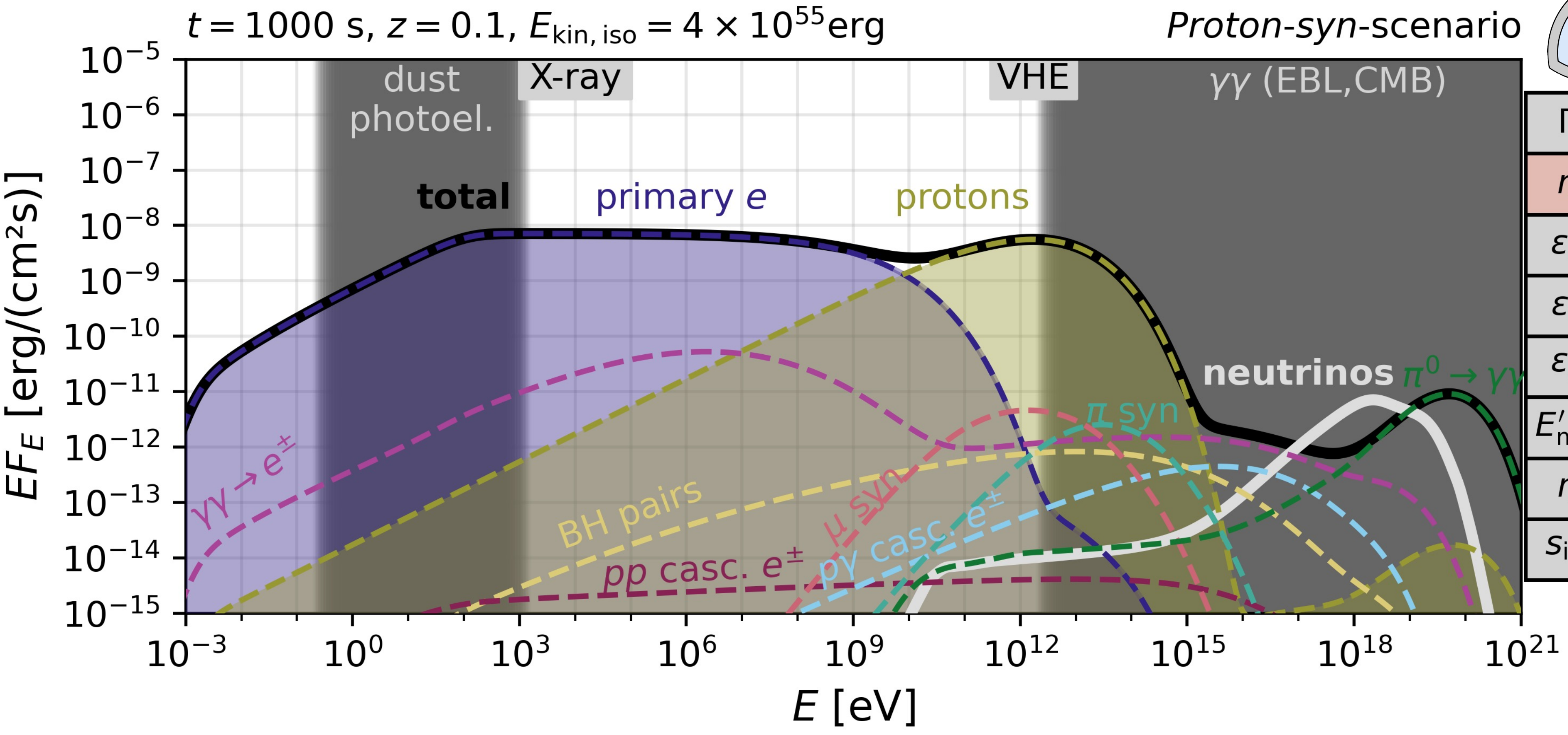
Γ	50	
n	10^2	cm^{-3}
ε_B	10^{-1}	
ε_e	$10^{-4.5}$	
ε_p	10^{-3}	
E'_{min}	$10^{9.0}$	eV
η	1	
s_{inj}	2	

→ fine-tuned exponential cut-off

see also: Isravel et al. ApJ 955 (2023), Cao et al. Sci. Adv. 9 (2023)

Proton synchrotron scenario

"Modelling" paper



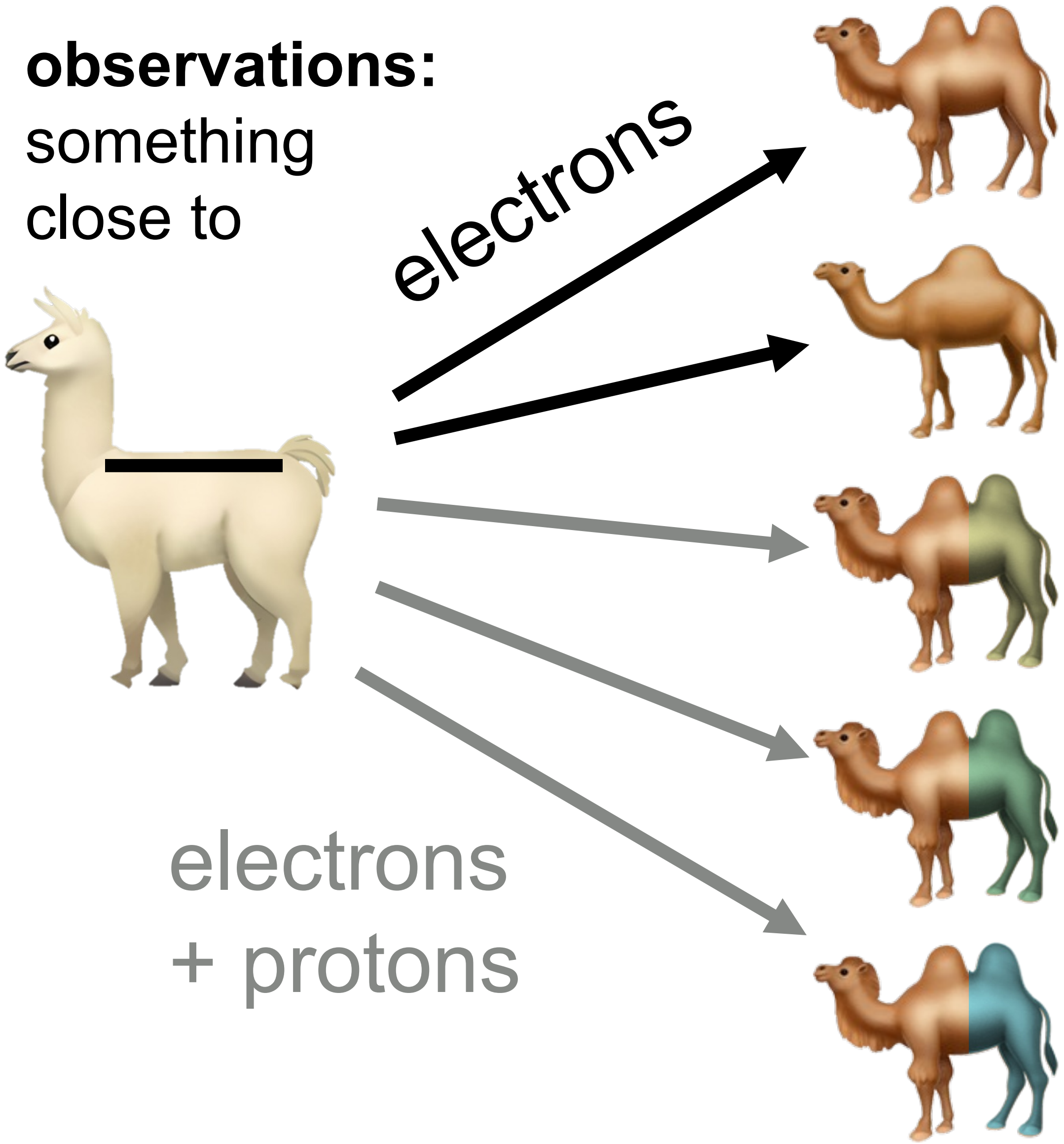
Γ	50	
n	10^2	cm^{-3}
ε_B	10^{-1}	
ε_e	$10^{-4.5}$	
ε_p	10^{-3}	
E'_{min}	$10^{9.0}$	eV
η	1	
s_{inj}	2	

→ fine-tuned exponential cut-off

see also: Isravel et al. ApJ 955 (2023), Cao et al. Sci. Adv. 9 (2023)

SSC and ideas beyond

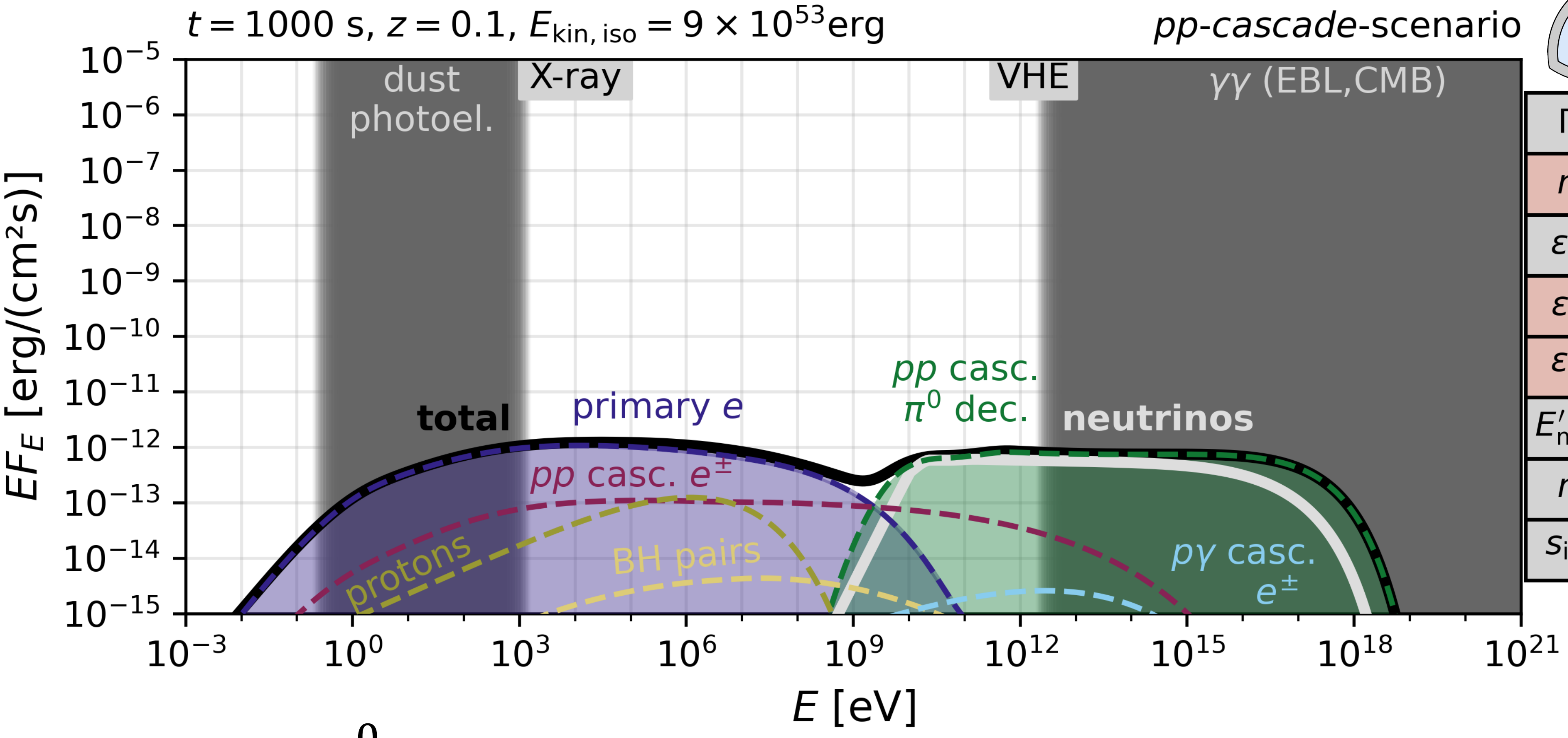
observations:
something
close to



	advantages:	**limitations:**
SSC	bright	Klein-Nishina suppression
Extended syn	bright simple	$\eta \ll 1$ (super Bohm)
Proton syn	bright	exponential cut-off
pp-cascade		

pp-cascade scenario

"Modelling" paper



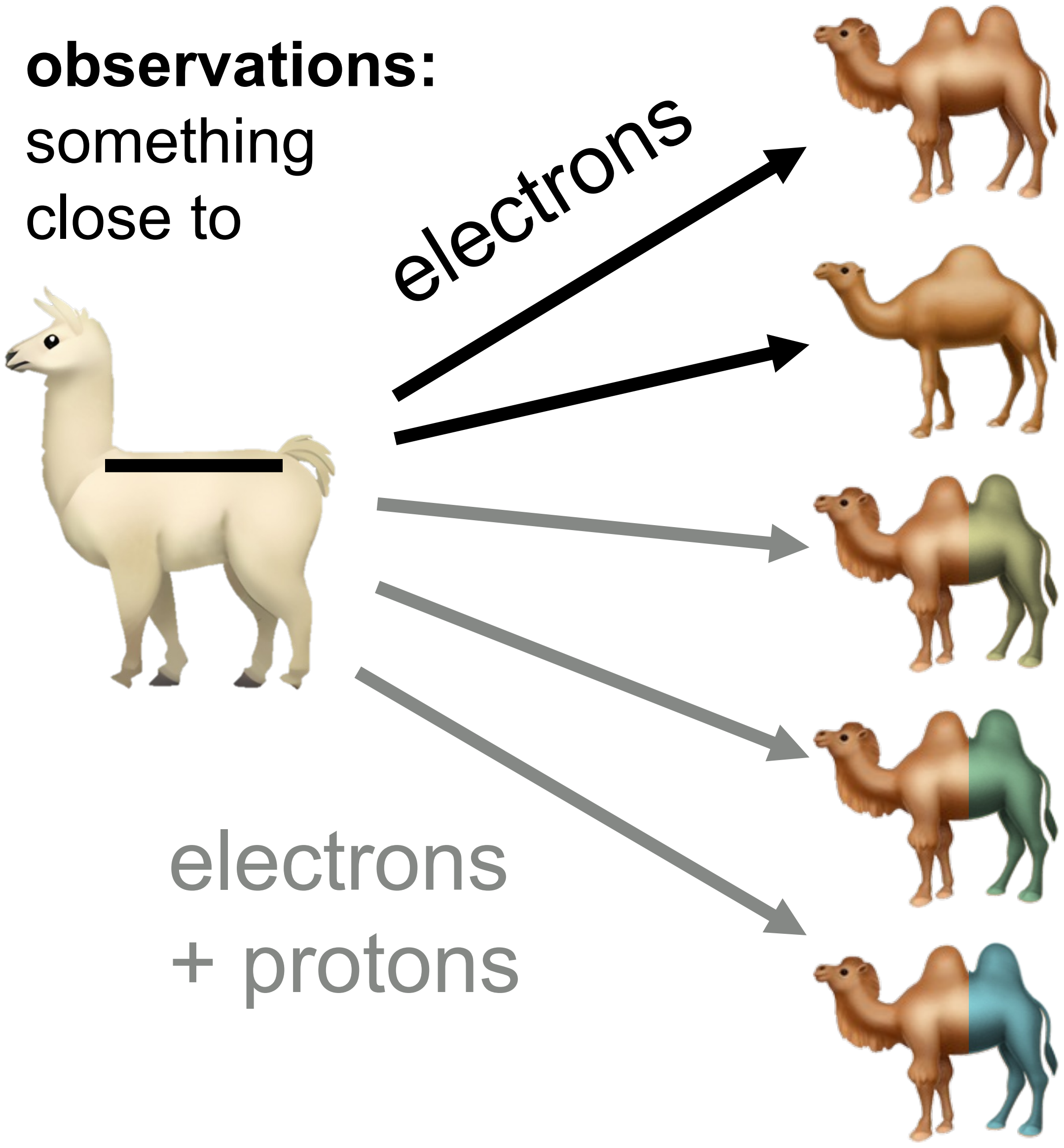
Γ	23	cm^{-3}
n	10^3	
ε_B	$10^{-4.5}$	
ε_e	$10^{-6.5}$	
ε_p	10^0	eV
E'_{min}	$10^{9.0}$	
η	3	
s_{inj}	2.1	

$\rightarrow pp \rightarrow \pi^0 \rightarrow \gamma\gamma$

$\rightarrow$ inefficient, but flat VHE component ($\gg 10TeV$)

SSC and ideas beyond

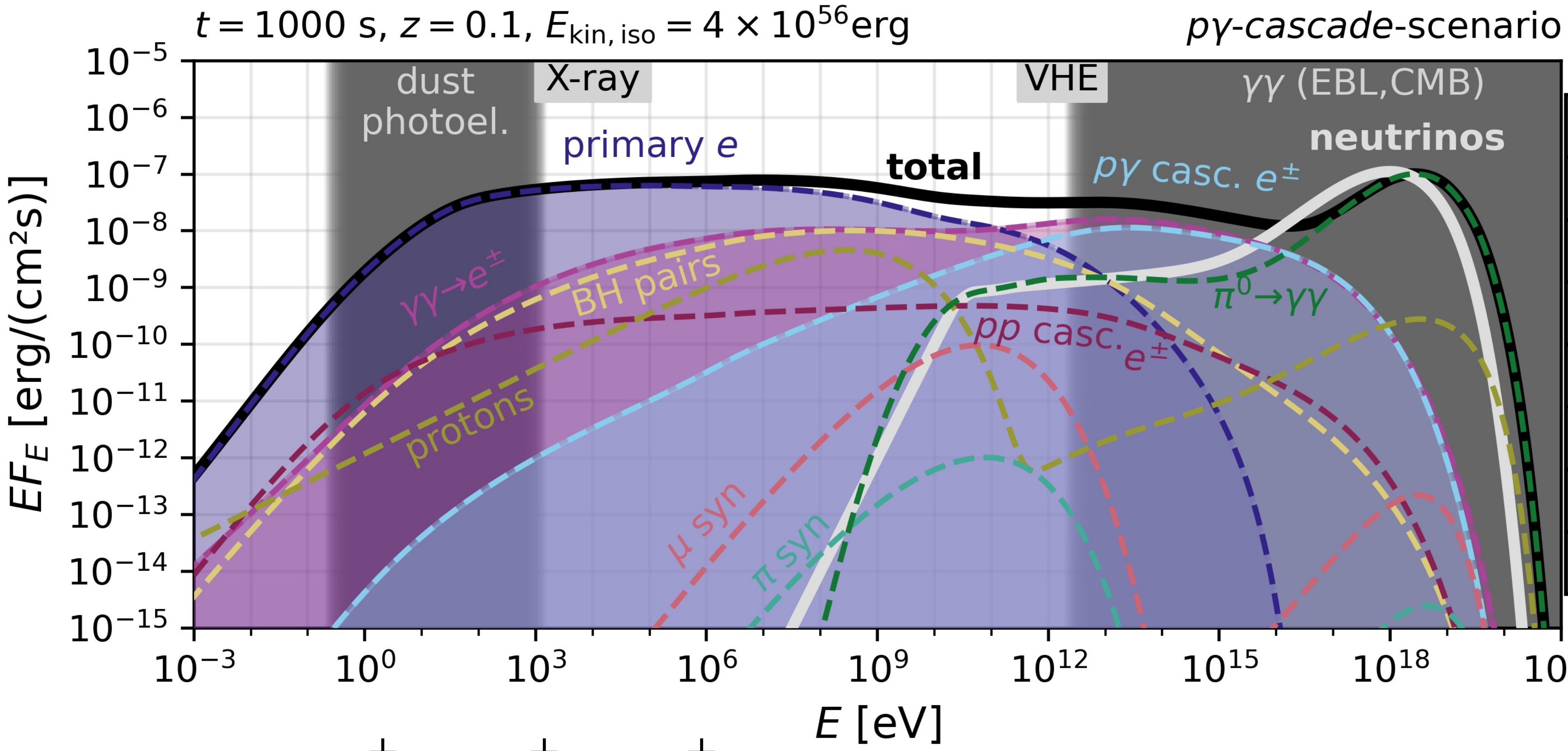
observations:
something
close to



	advantages:	**limitations:**
SSC	bright	Klein-Nishina suppression
Extended syn	bright simple	$\eta \ll 1$ (super Bohm)
Proton syn	bright	exponential cut-off
pp-cascade	extends to >10TeV	inefficient
$p\gamma$-cascade		

$p\gamma$-cascade scenario

"*Modelling*" paper



Γ	50	
n	10^3	cm^{-3}
ε_B	10^{-5}	
ε_e	$10^{-4.5}$	
ε_p	10^0	eV
E'_{min}	$10^{9.5}$	
η	1	
s_{inj}	2	

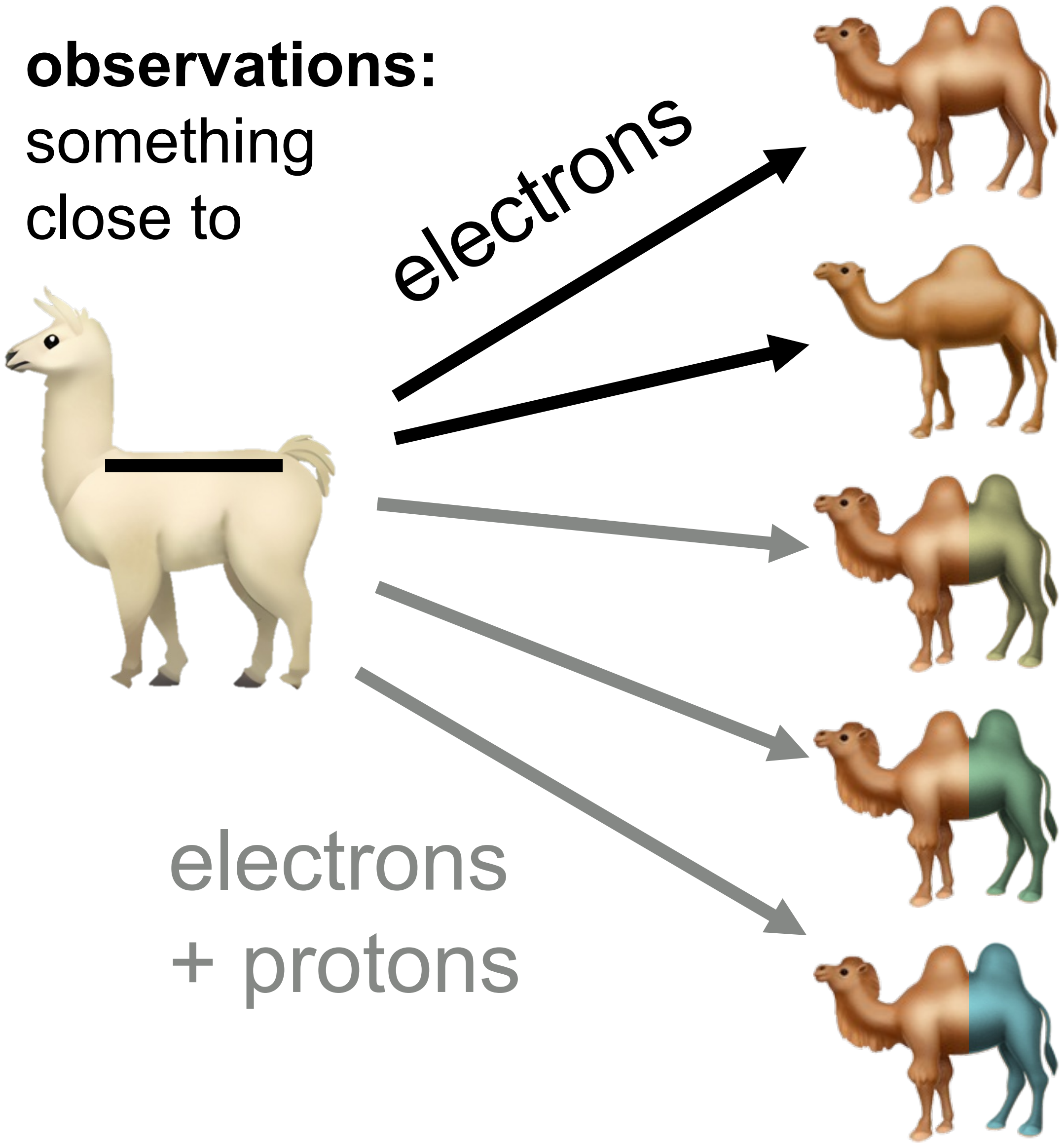
$\rightarrow p\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm} \rightarrow \gamma$

→ extreme energy + density requirements

see also: Sahu et al. ApJ 929 70 (2022)

SSC and ideas beyond

observations:
something
close to



	advantages:	limitations:
SSC	bright	Klein-Nishina suppression
Extended syn	bright simple	$\eta \ll 1$ (super Bohm)
Proton syn	bright	exponential cut-off
pp-cascade	extends to >10TeV	inefficient
$p\gamma$-cascade	bright	extreme energy + density

→ no scenario really convincing → multizone?

Summary

- Long GRB afterglows allow us to study the properties of relativistic shocks as multi-messenger fireworks
- I developed a framework for time-dependent modelling of GRB afterglows

  → publication of AM^3 → *"AM3"* paper

  → steady-state approximation is only good for intuition
- I performed model comparison at the counts-level

  → GRB 190114C: inconclusive on 🐪 vs 🐫 → *"Fitting MAGIC"* paper

  → GRB 221009A: with a single decaying component above x-rays → *"Fitting LHAASO"* paper
- I systematically explored lepto-hadronic 1-zone scenarios which reproduce extended flat power-law spectra → *"Modelling"* paper

  → SSC, Extended syn, Proton syn, pp-cascade, $p\gamma$-cascade → no convincing 1-zone scenario