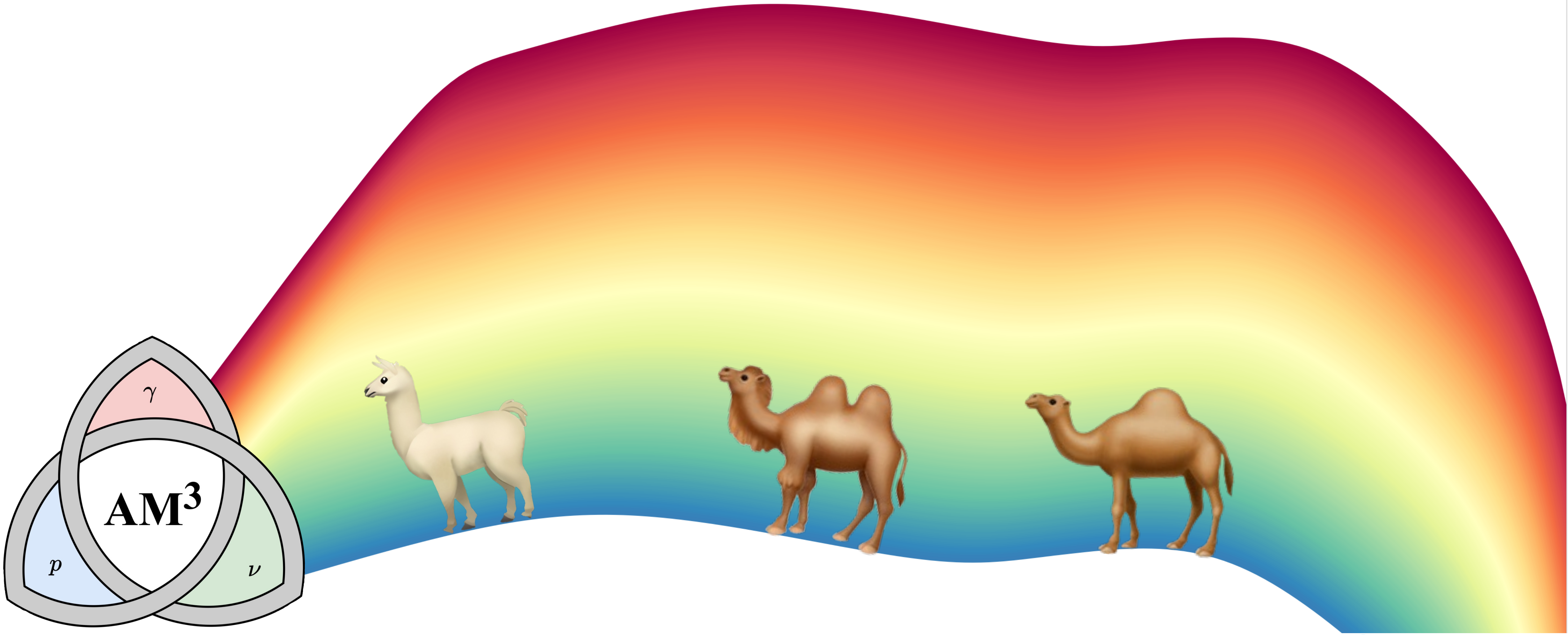


What makes gamma-ray bursts shine so bright up to very-high-energies?

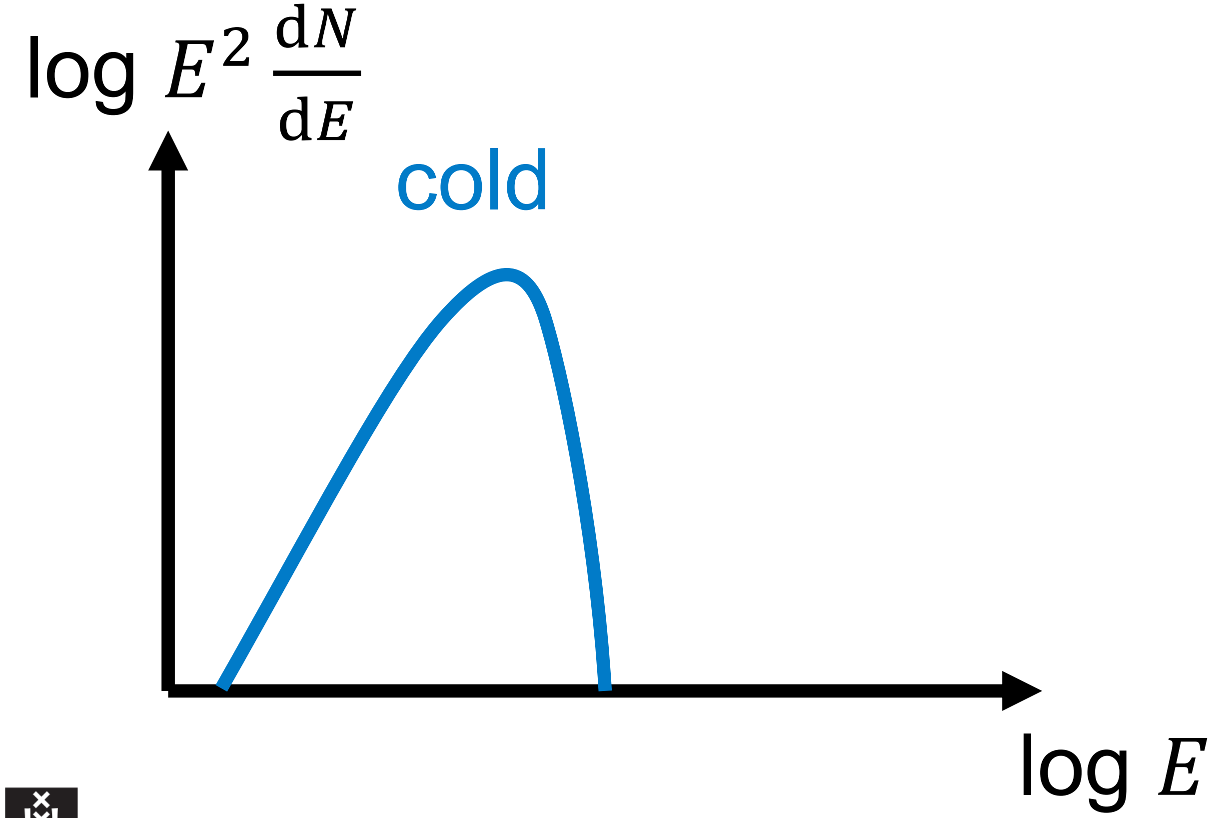
M. Klinger-Plaiser, A.M. Taylor, W. Winter, C. Yuan, S. Zhu, and friends

https://maklinger.github.io/ - m.klinger@uva.nl

DESY.
HELMHOLTZ
HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY
UNIVERSITEIT VAN AMSTERDAM
ANTON PANNEKOEK INSTITUUT

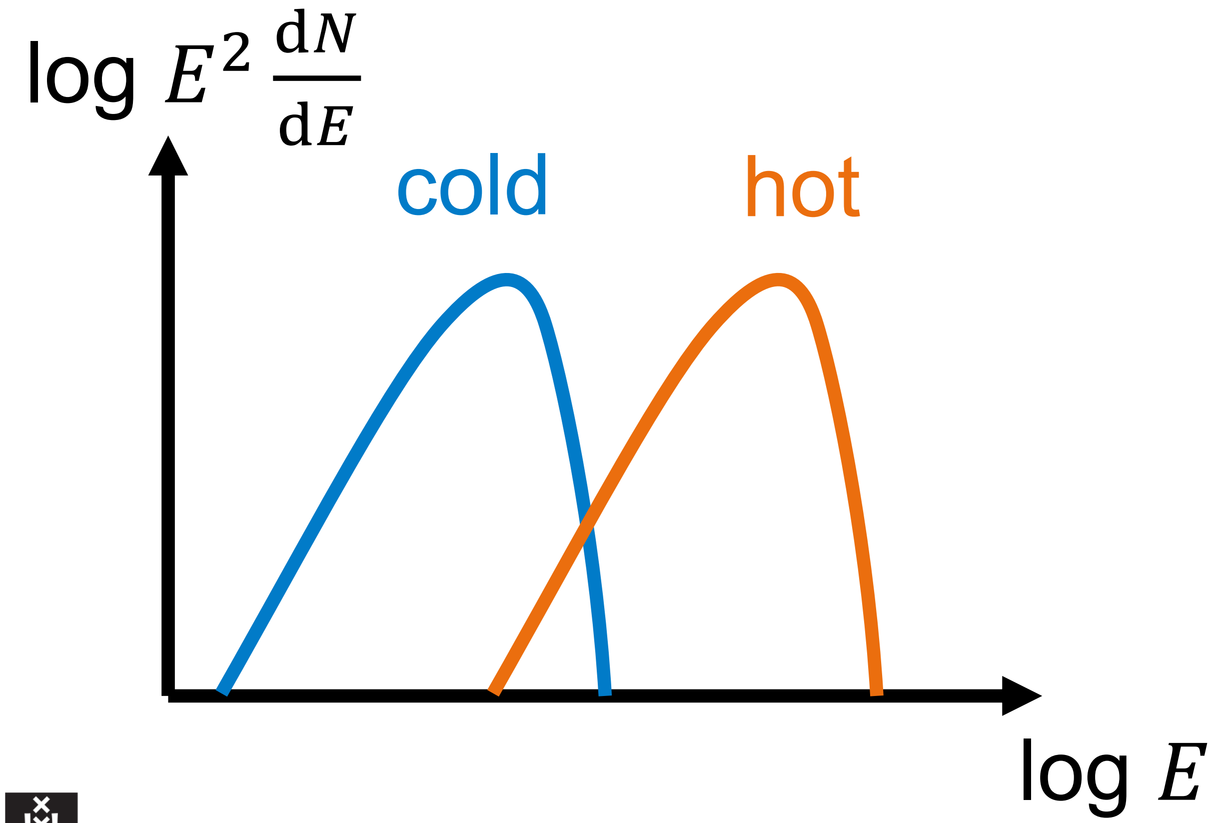
Why do we care about gamma-ray bursts at very-high energies?

Non-thermal particle acceleration

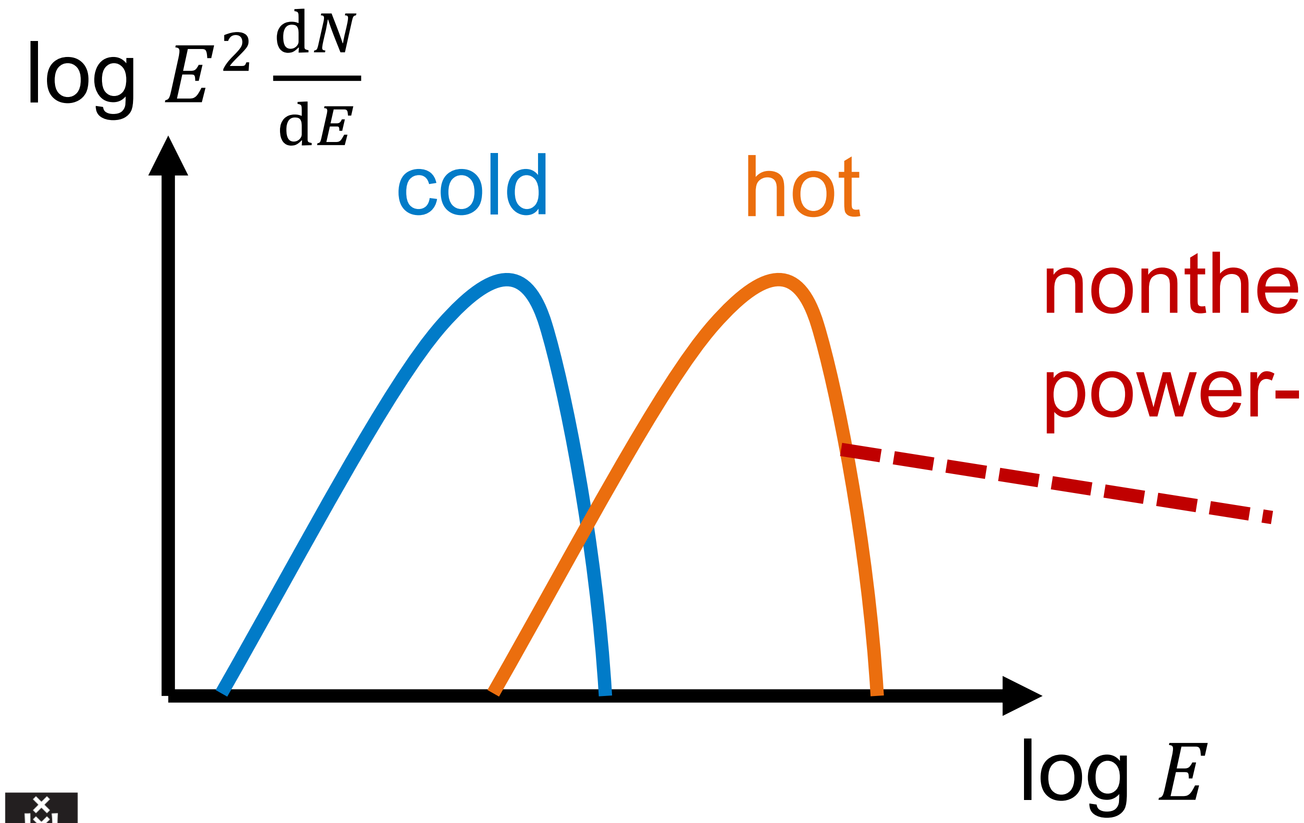


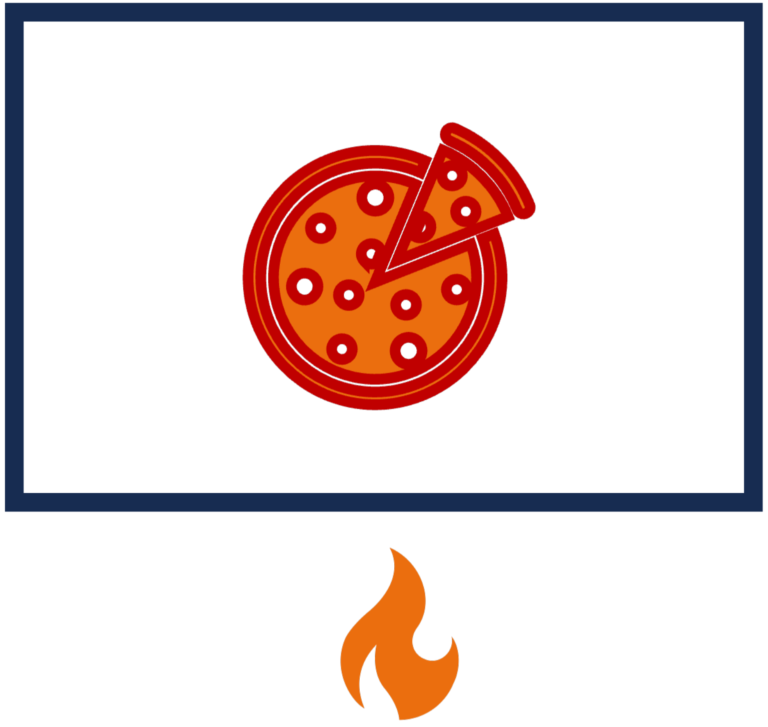
plasma

Non-thermal particle acceleration

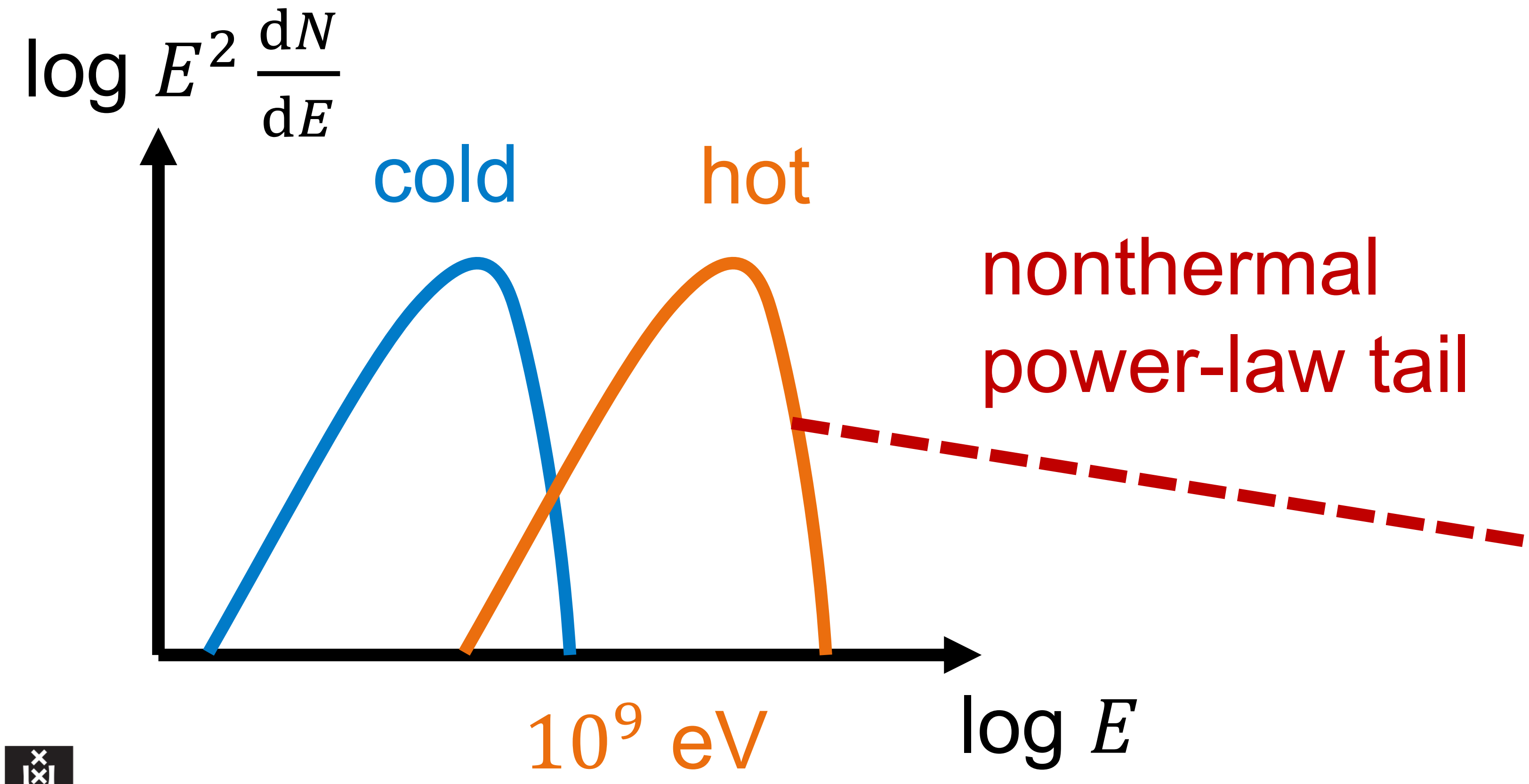


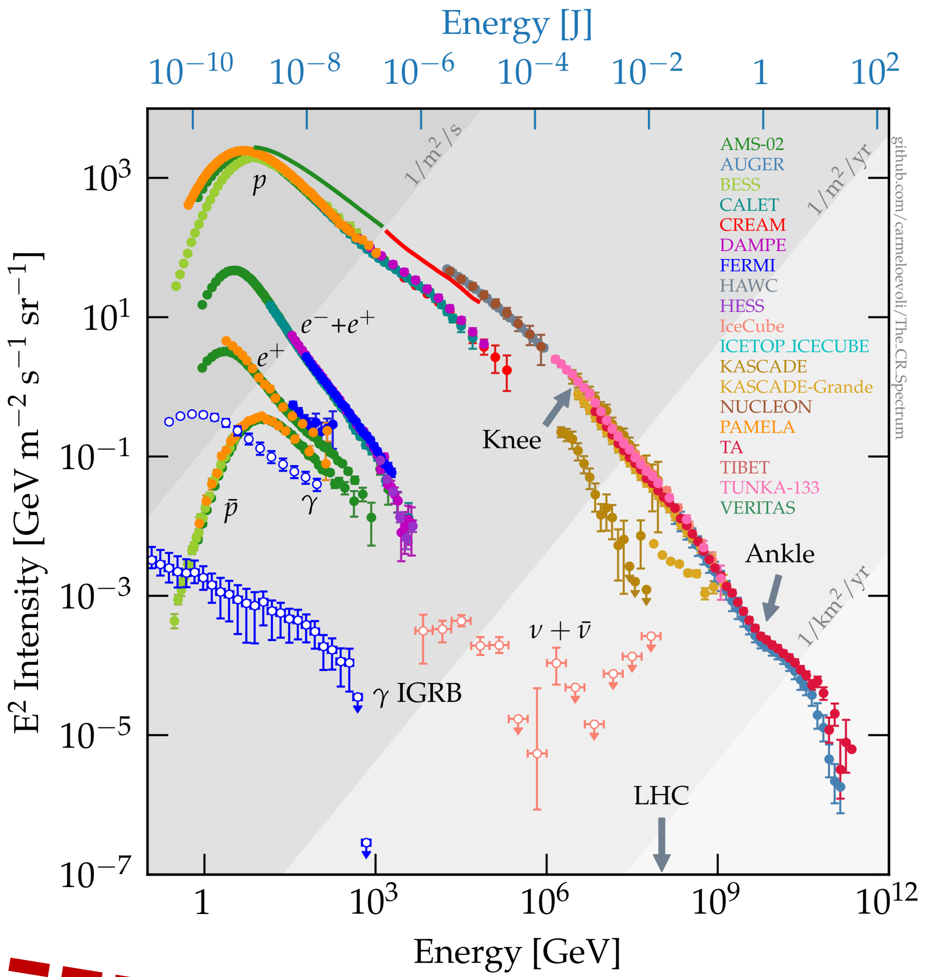
Non-thermal particle acceleration





Non-thermal particle acceleration





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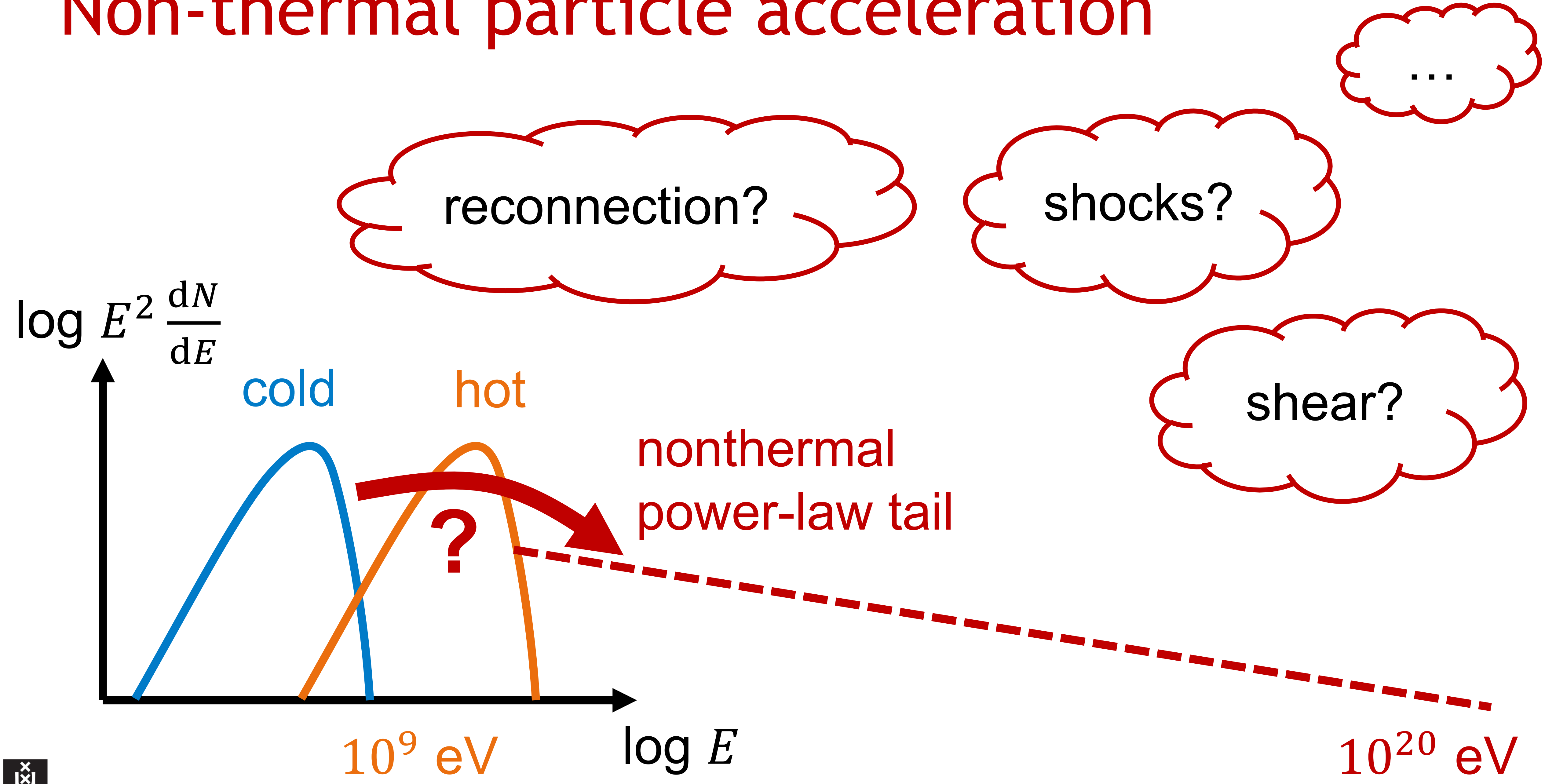
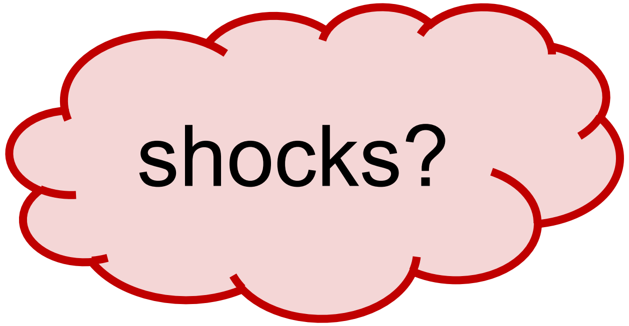
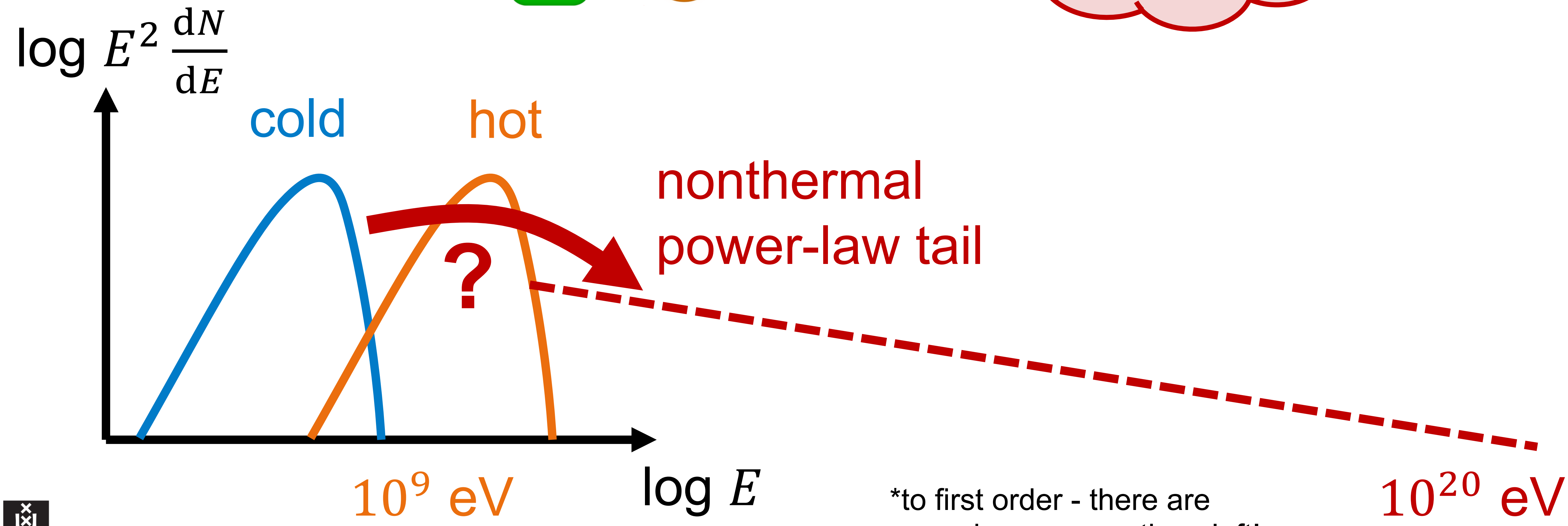


Non-thermal particle acceleration

non-relativistic
→ Fermi mechanism

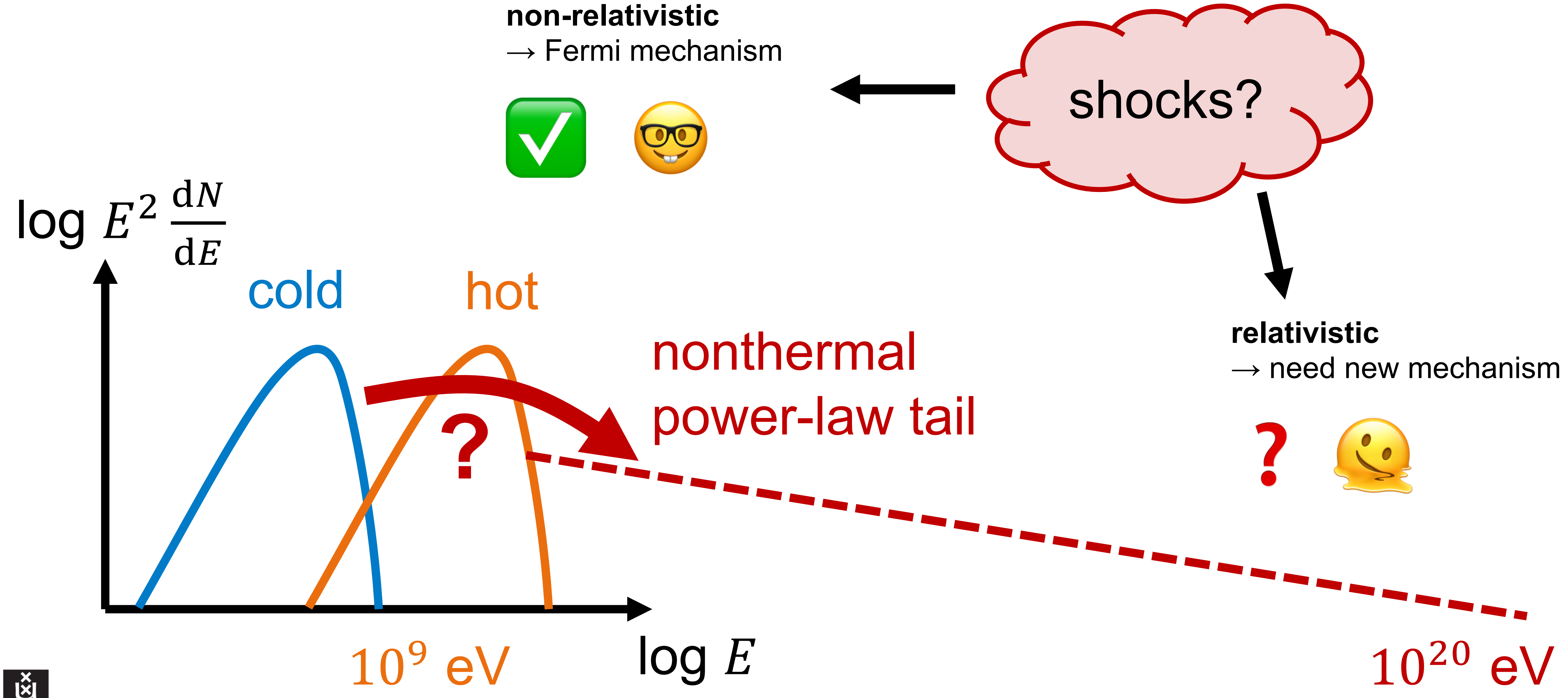
✅* 🤓





*to first order - there are enough open questions left!

Non-thermal particle acceleration

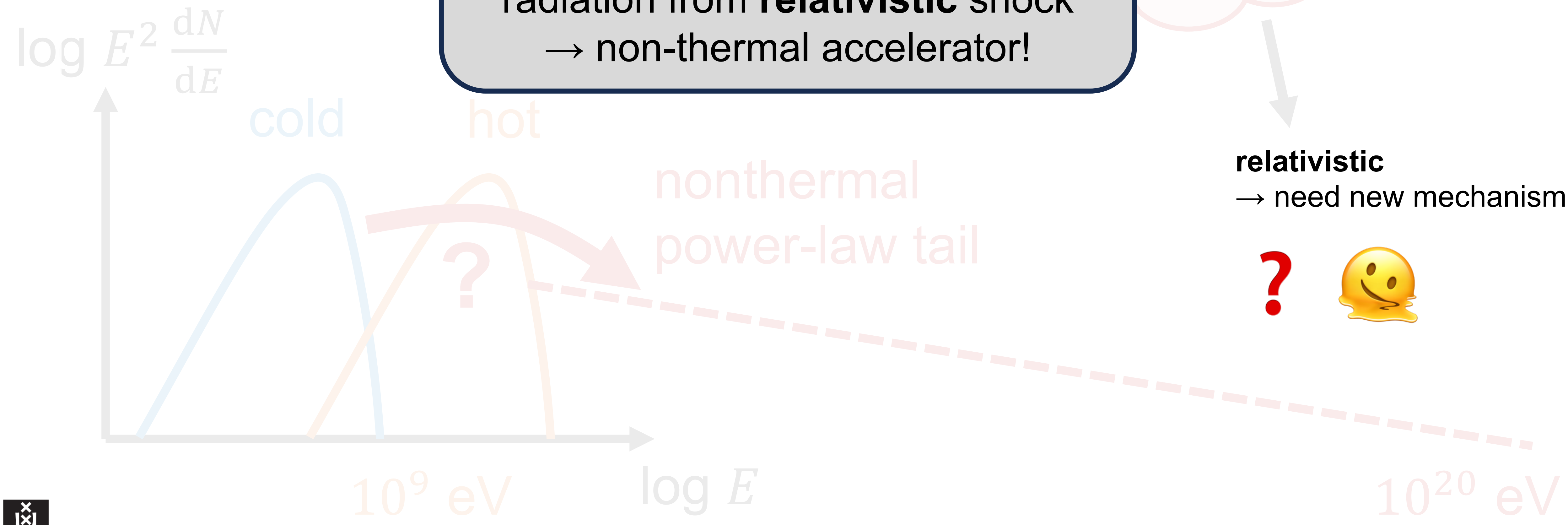


Non-thermal particle acceleration

Gamma-ray burst (GRB) afterglow

=

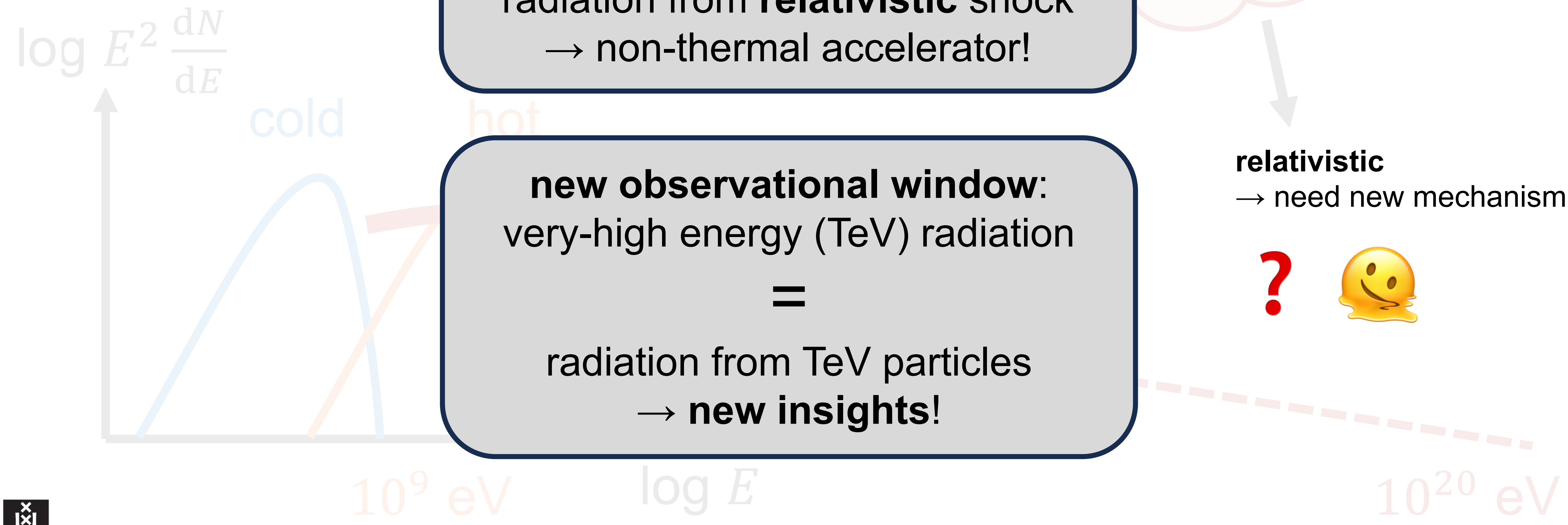
radiation from **relativistic** shock
→ non-thermal accelerator!



relativistic
→ need new mechanism

?

Non-thermal particle acceleration



Gamma-ray burst (GRB) afterglow

=

radiation from **relativistic** shock
→ non-thermal accelerator!

new observational window:
very-high energy (TeV) radiation

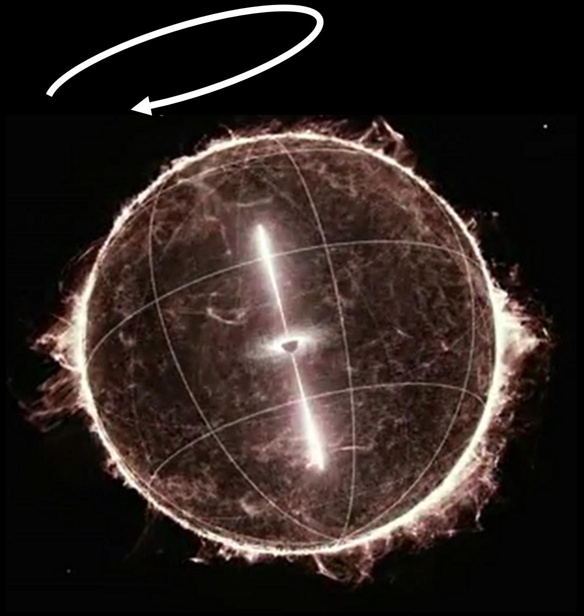
=

radiation from TeV particles
→ **new insights**!

relativistic
→ need new mechanism

?

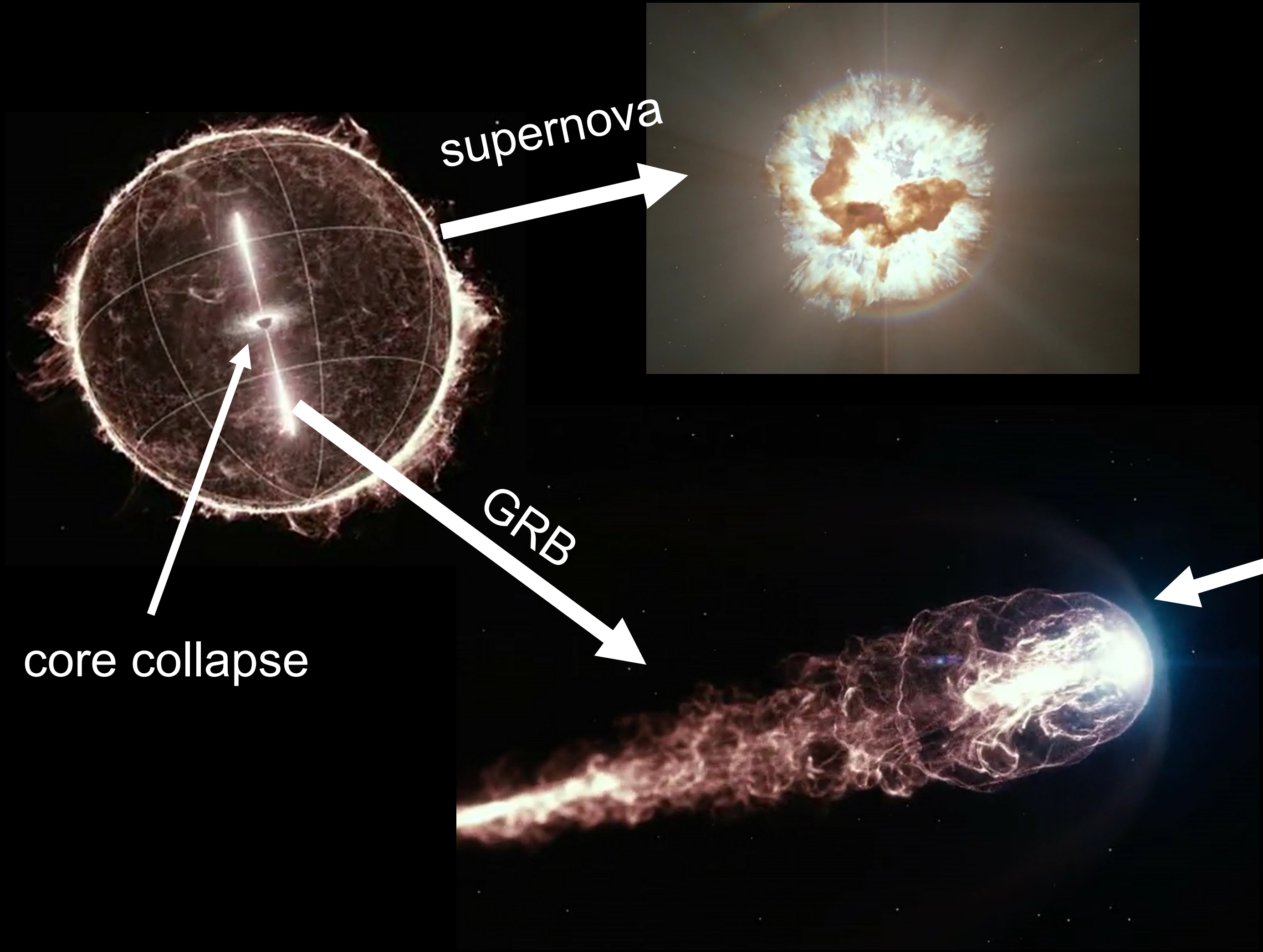
Long GRBs



massive, rotating star

images: DESY, Science Communication Lab

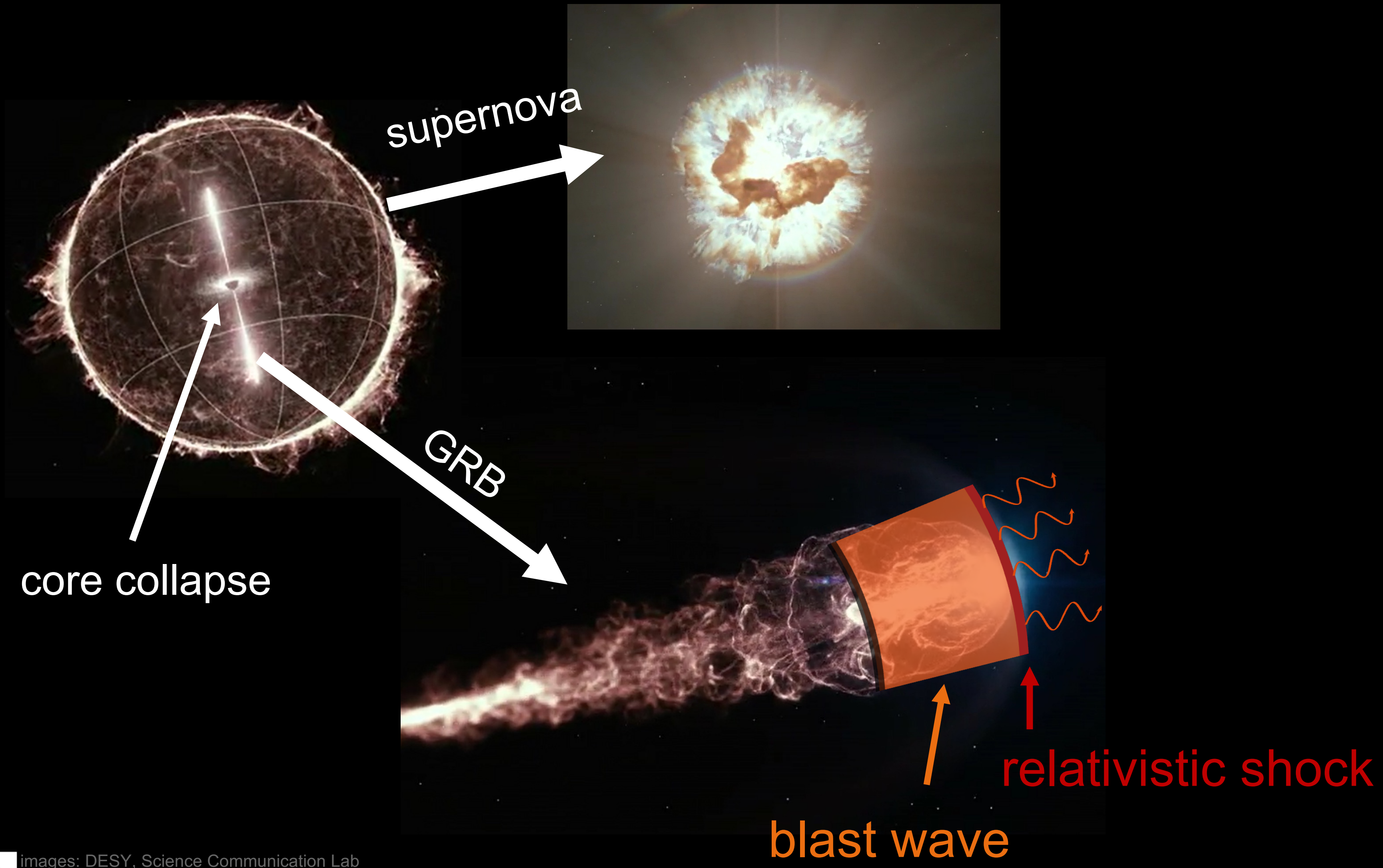
Long GRBs



Lorentz factors up to few 100

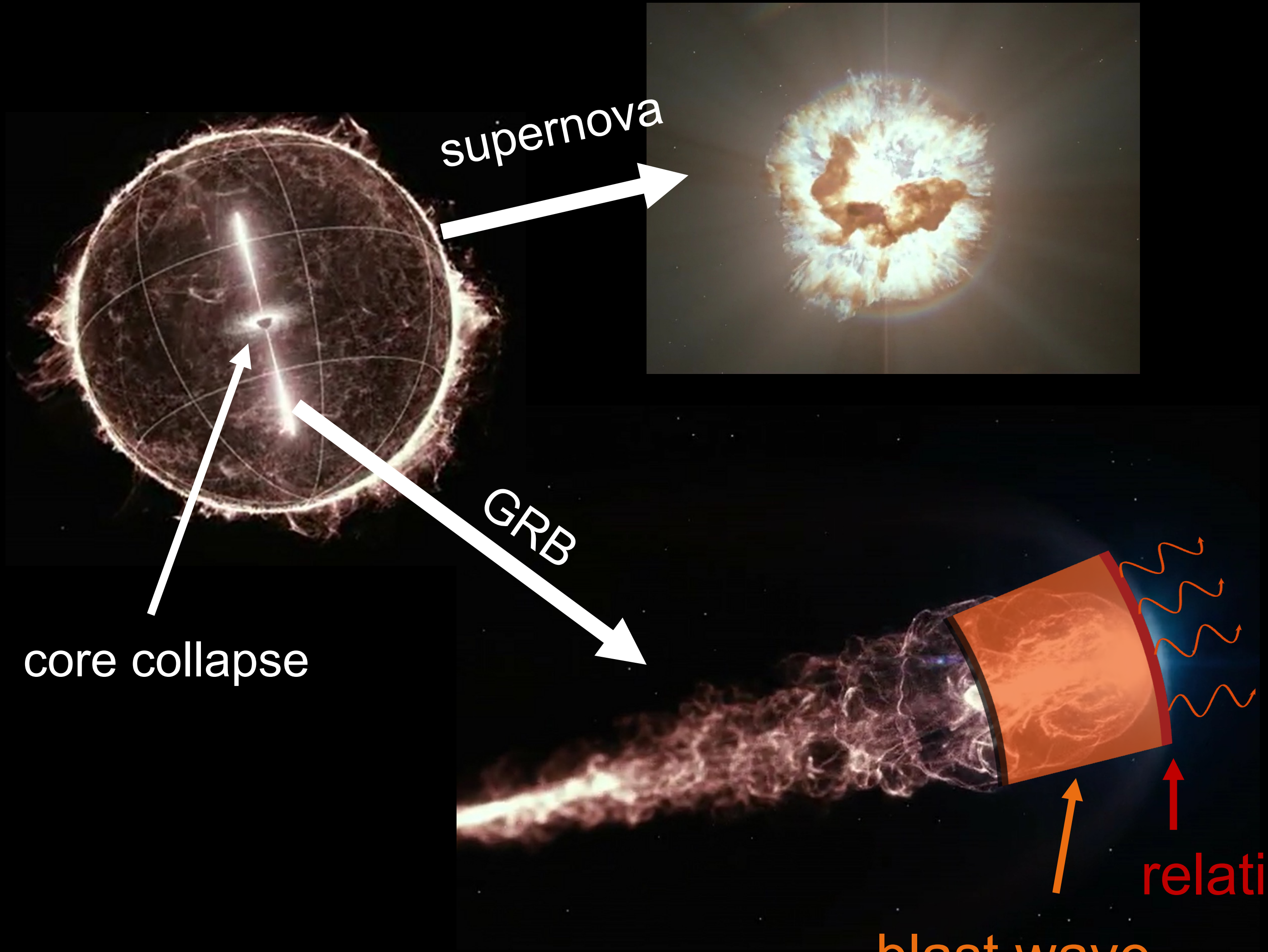
images: DESY, Science Communication Lab

Long GRBs



images: DESY, Science Communication Lab

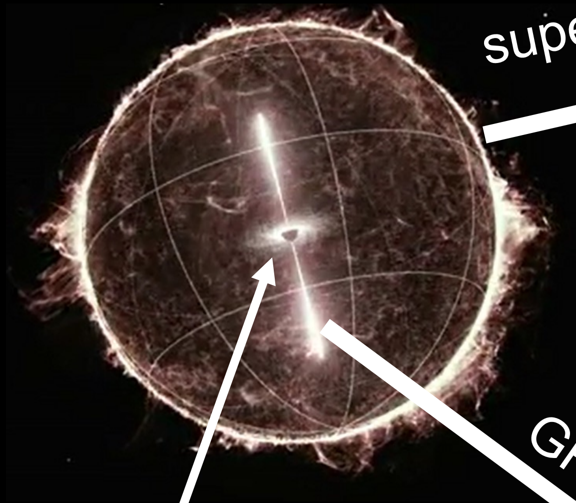
Long GRBs



afterglow = radiation from blast wave behind shock

images: DESY, Science Communication Lab

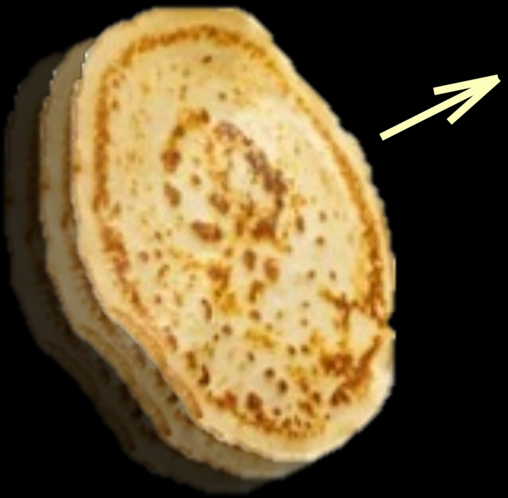
Long GRBs



supernova

GRB

core collapse



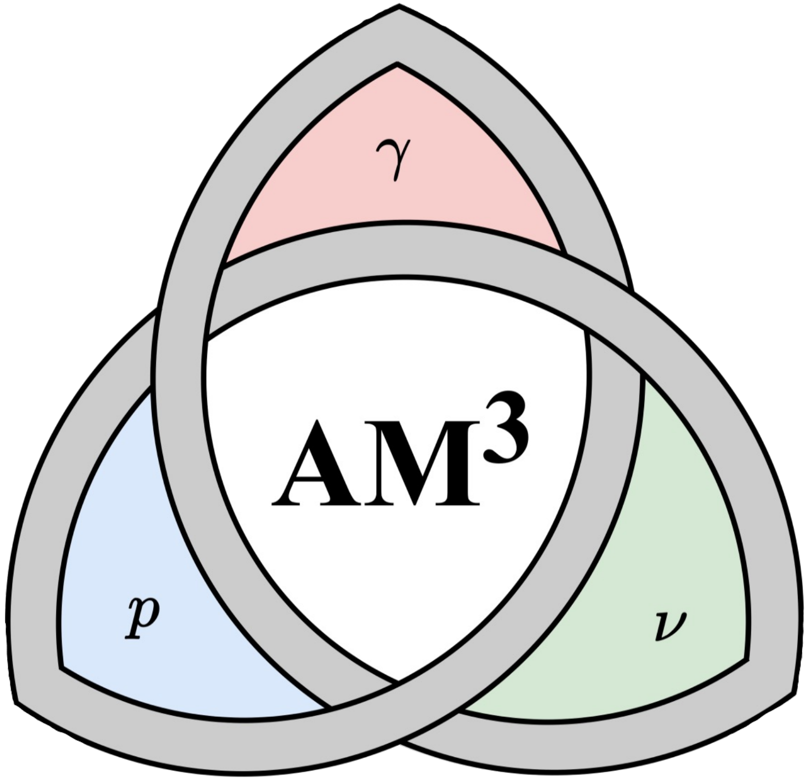
afterglow = radiation from blast wave behind shock

compressed into pancake shape

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

images: DESY, Science Communication Lab

Modelling the non-thermal particles



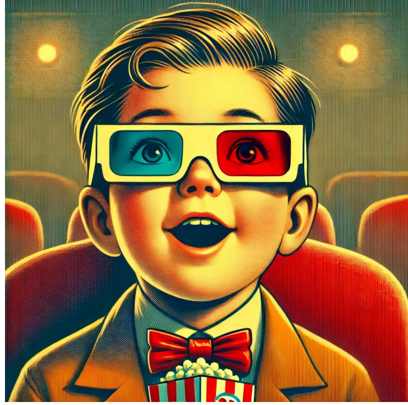
MK++ ApJS 275 4 (2024)

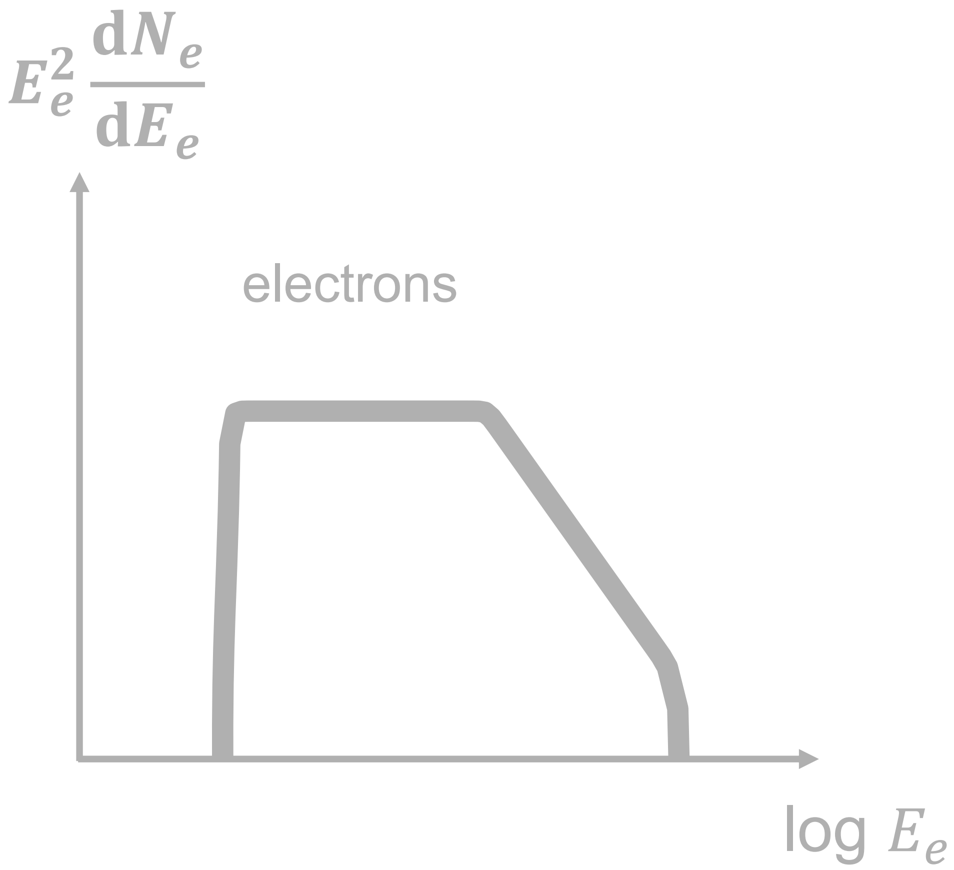
AM^3 software

→ more general 1-zone lepto-hadronic radiation modelling
→ public, fast, trackable
→ try it!

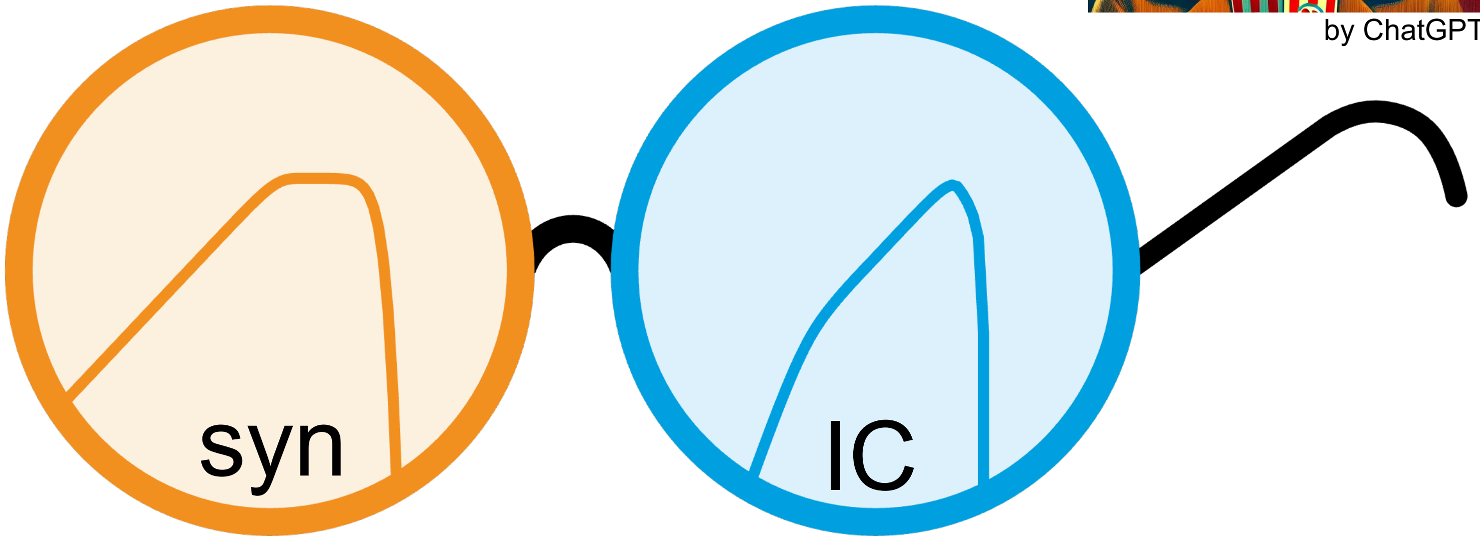
→ https://gitlab.desy.de/am3/am3

The SSC model





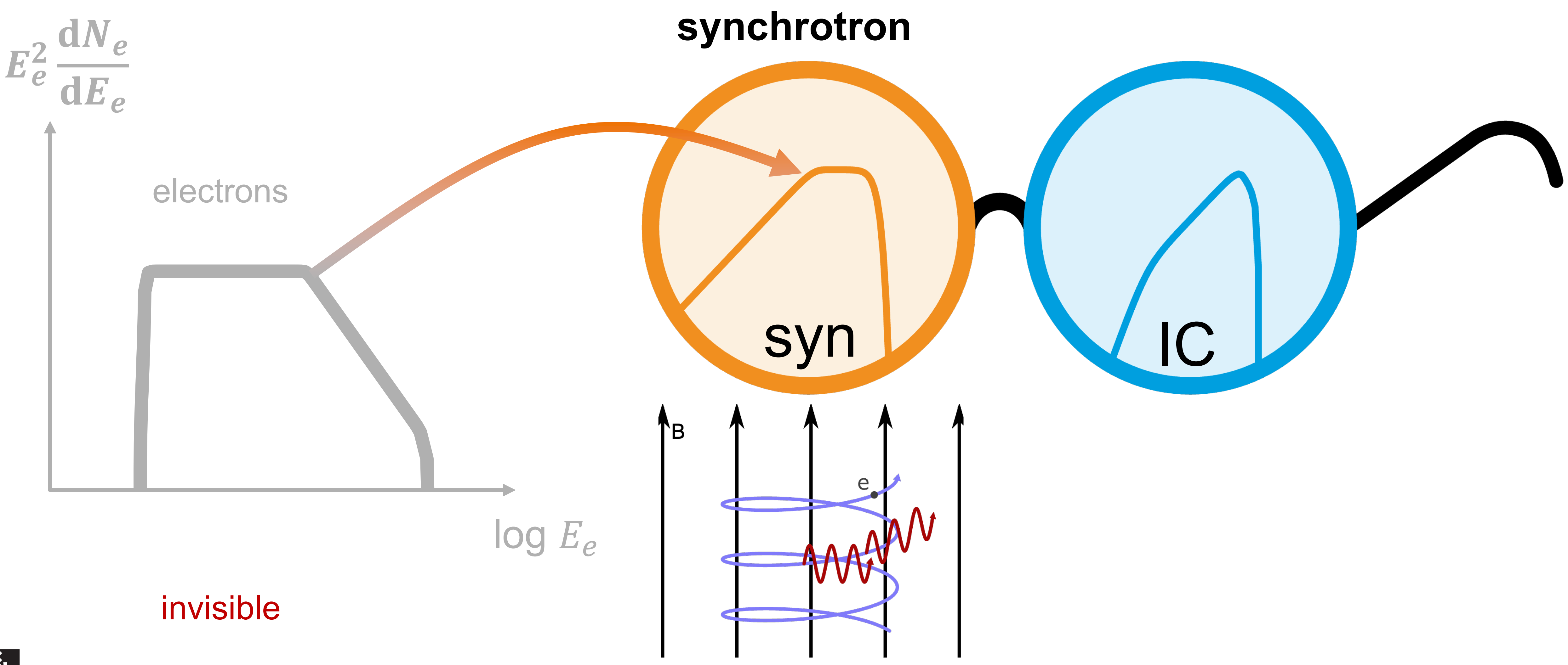
invisible



indirect observation through

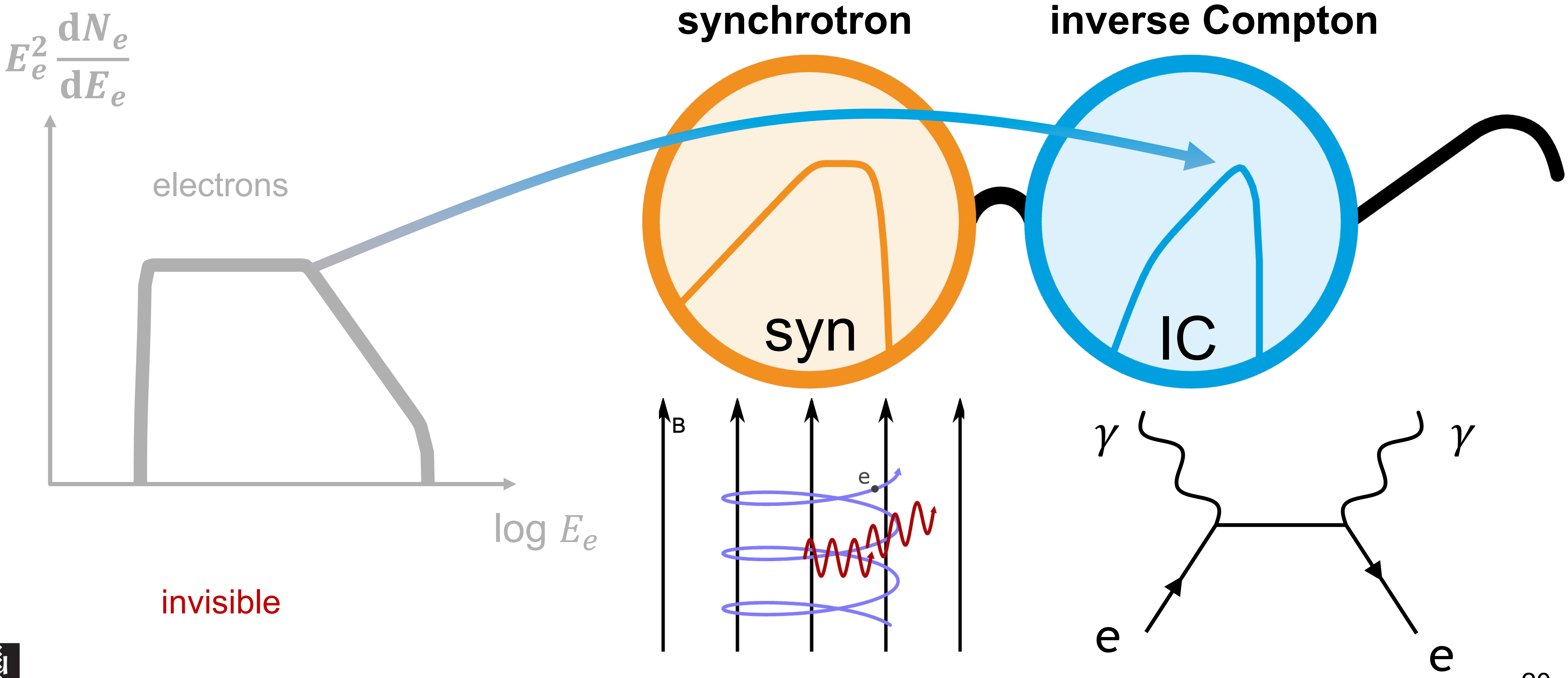
SSC goggles!

The SSC model



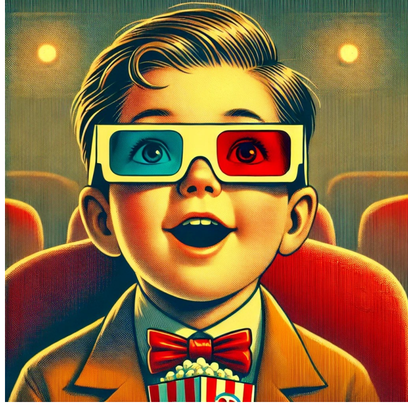
invisible

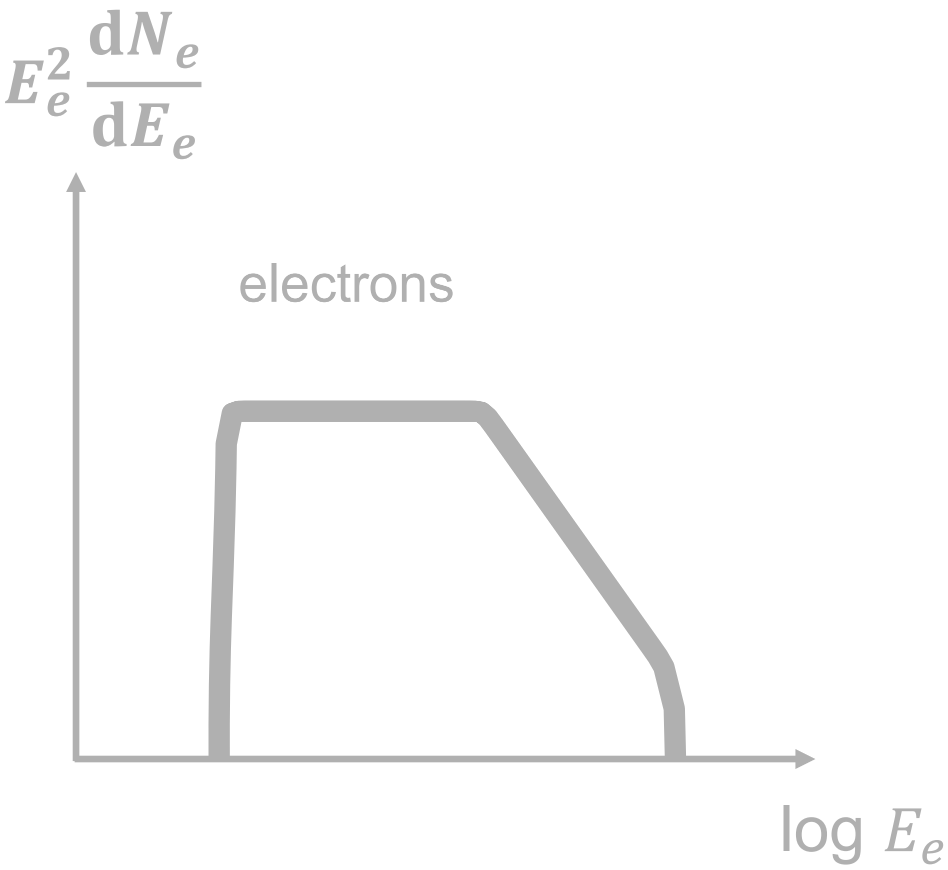
The SSC model



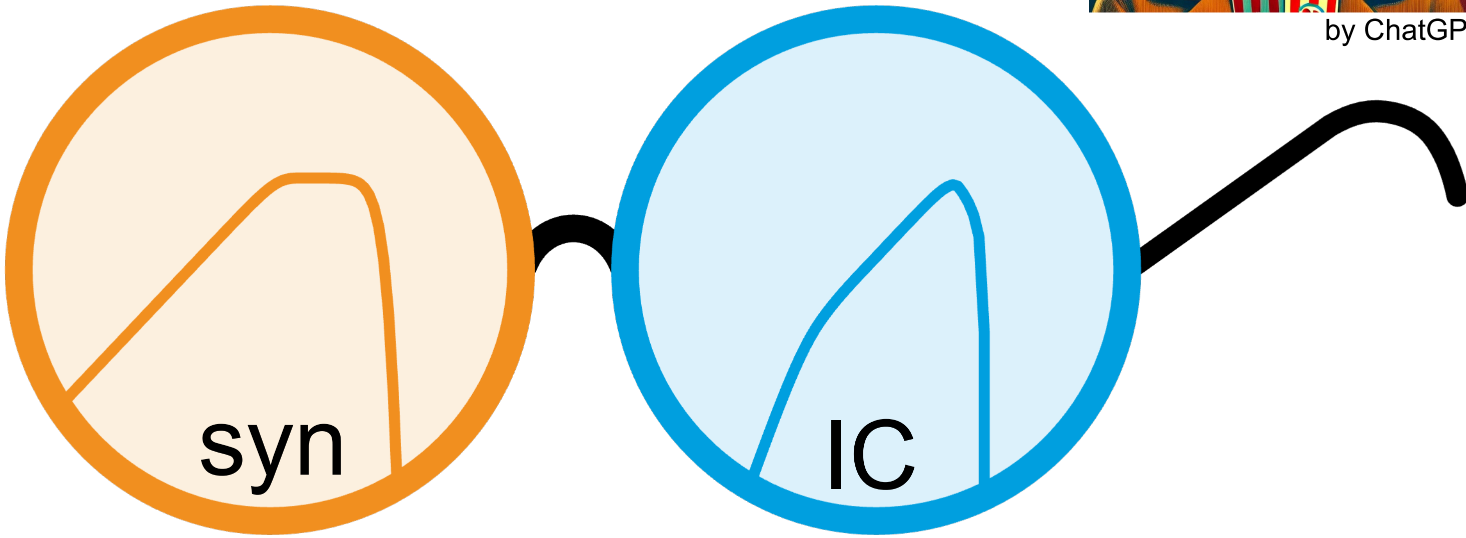
invisible

The SSC model


by ChatGPT



invisible



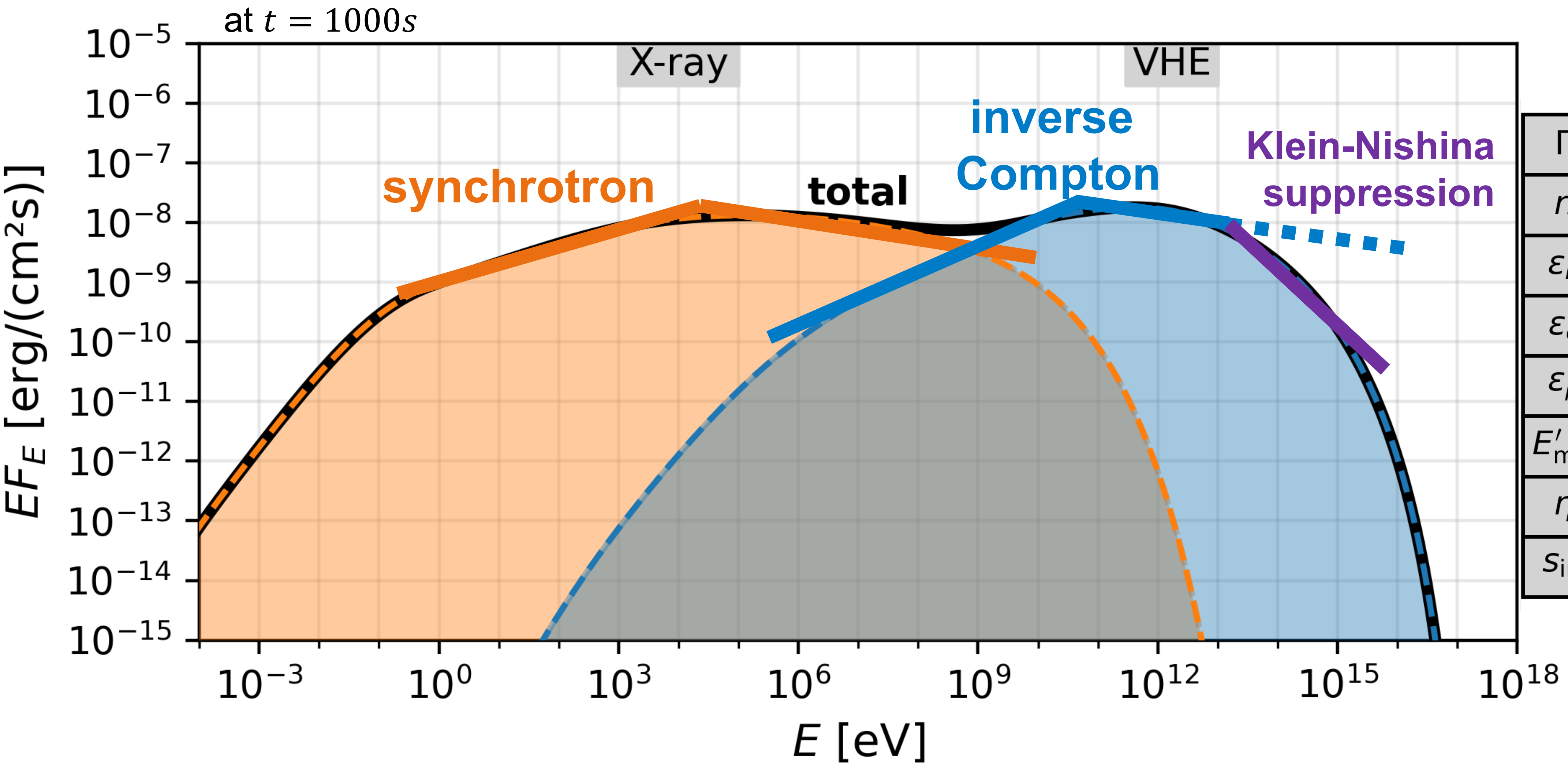
indirect observation through

SSC goggles!

↓

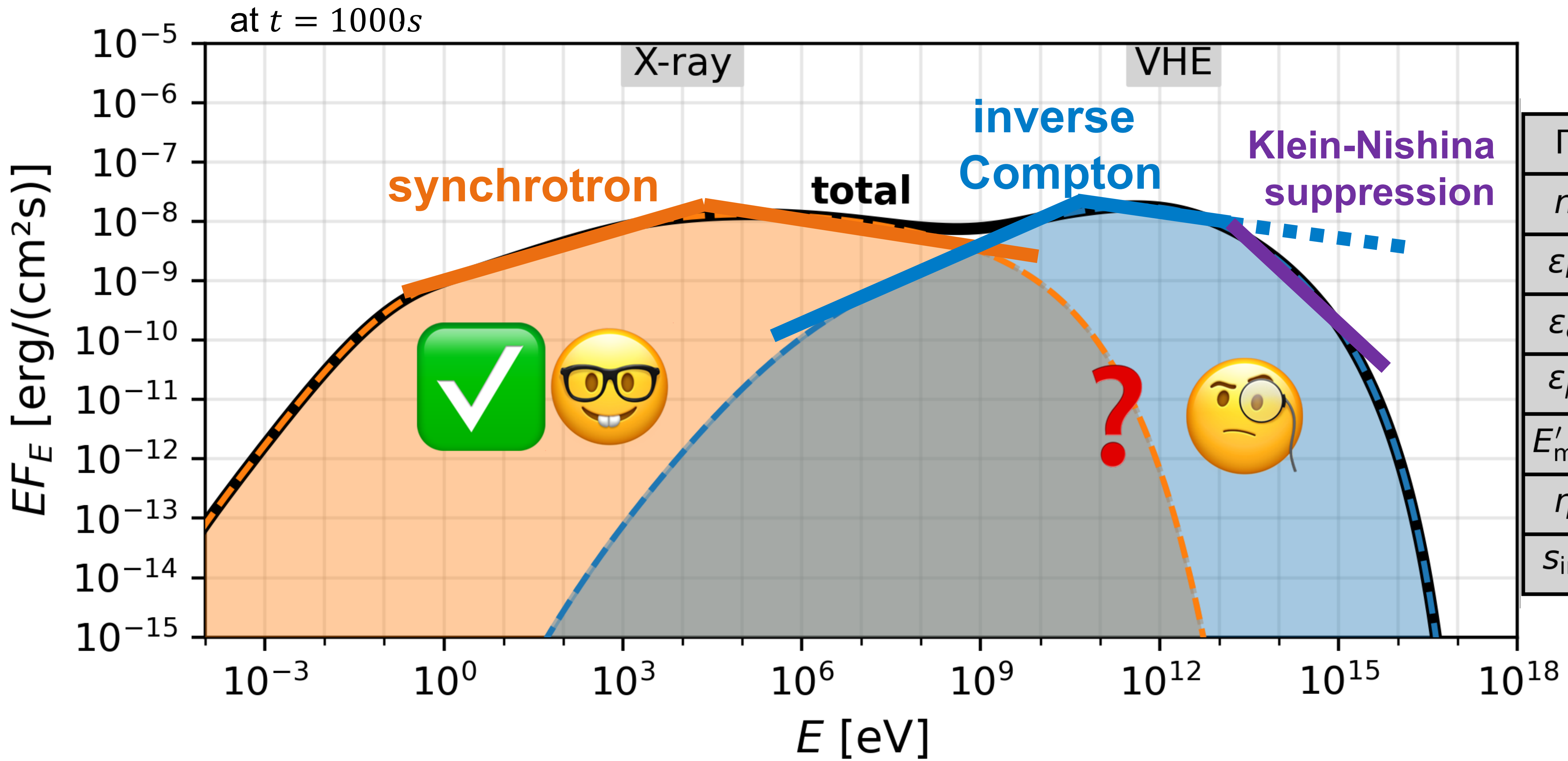
synchrotron self-Compton

The SSC model



Γ	50
n	1
ε_B	10^{-4}
ε_e	$10^{-1.5}$
ε_p	0
E'_{min}	$10^{9.0}$
η	1
s_{inj}	2.3

The SSC model



Γ	50
n	1
ε_B	10^{-4}
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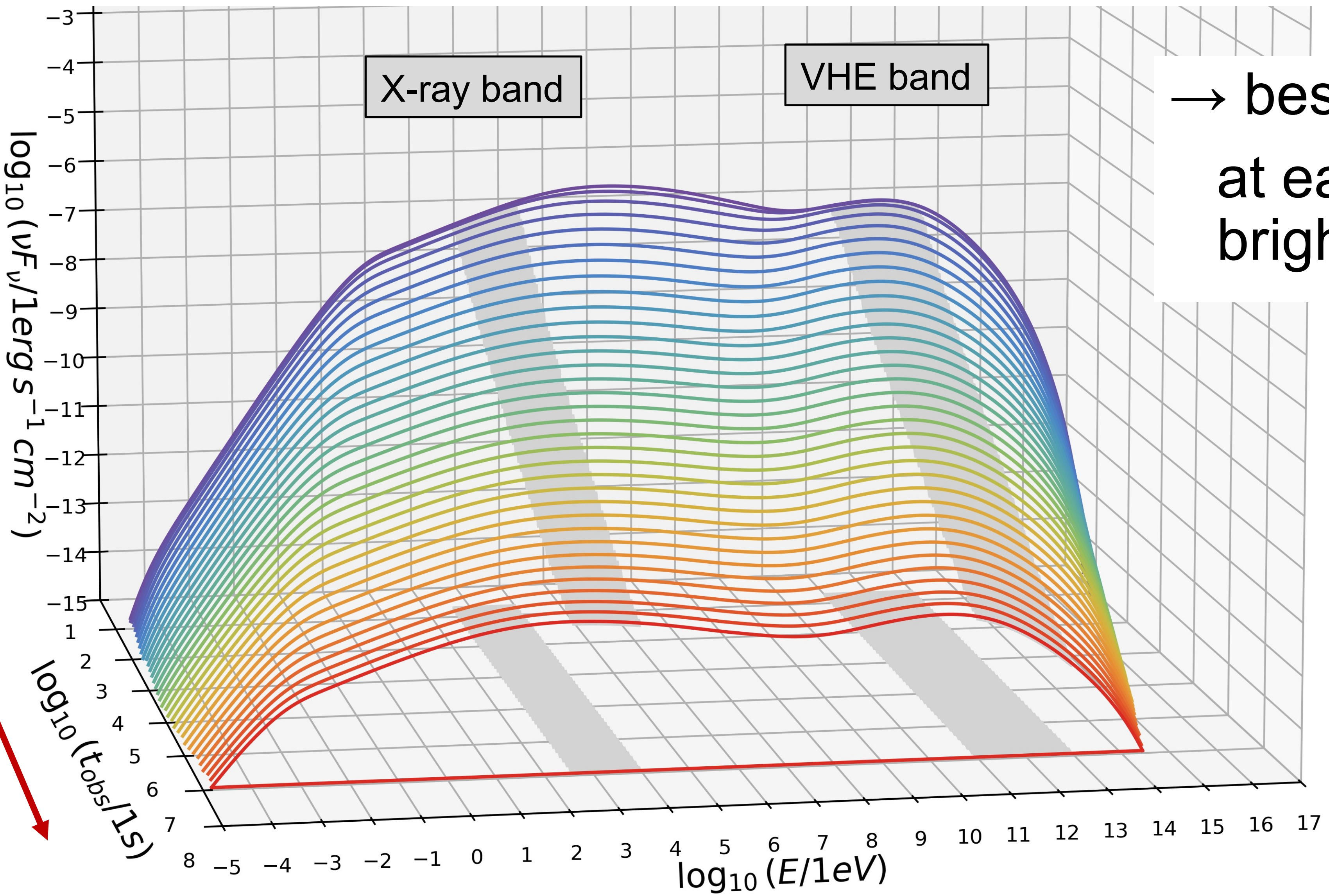
ε_p	0
E'_{min}	$10^{9.0}$
η	1
s_{inj}	2.3

?

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

A typical GRB afterglow model

observed photon energy flux νF_ν



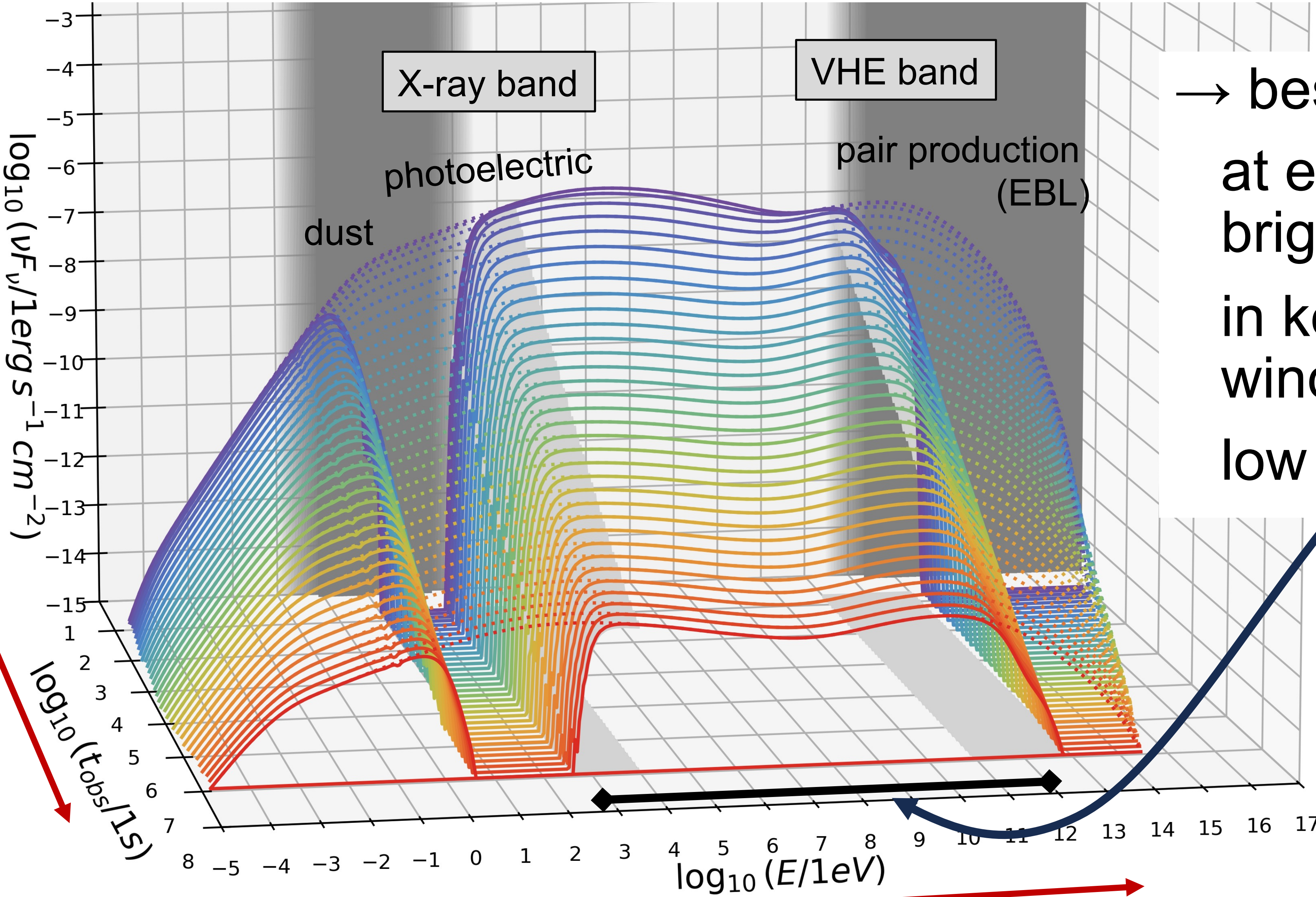
→ best statistics at early times/ bright events

observed time

observed photon energy

A typical GRB afterglow – absorption!

absorbed observed photon energy flux νF_ν



observed time

observed photon energy

→ best statistics

at early times/ bright events

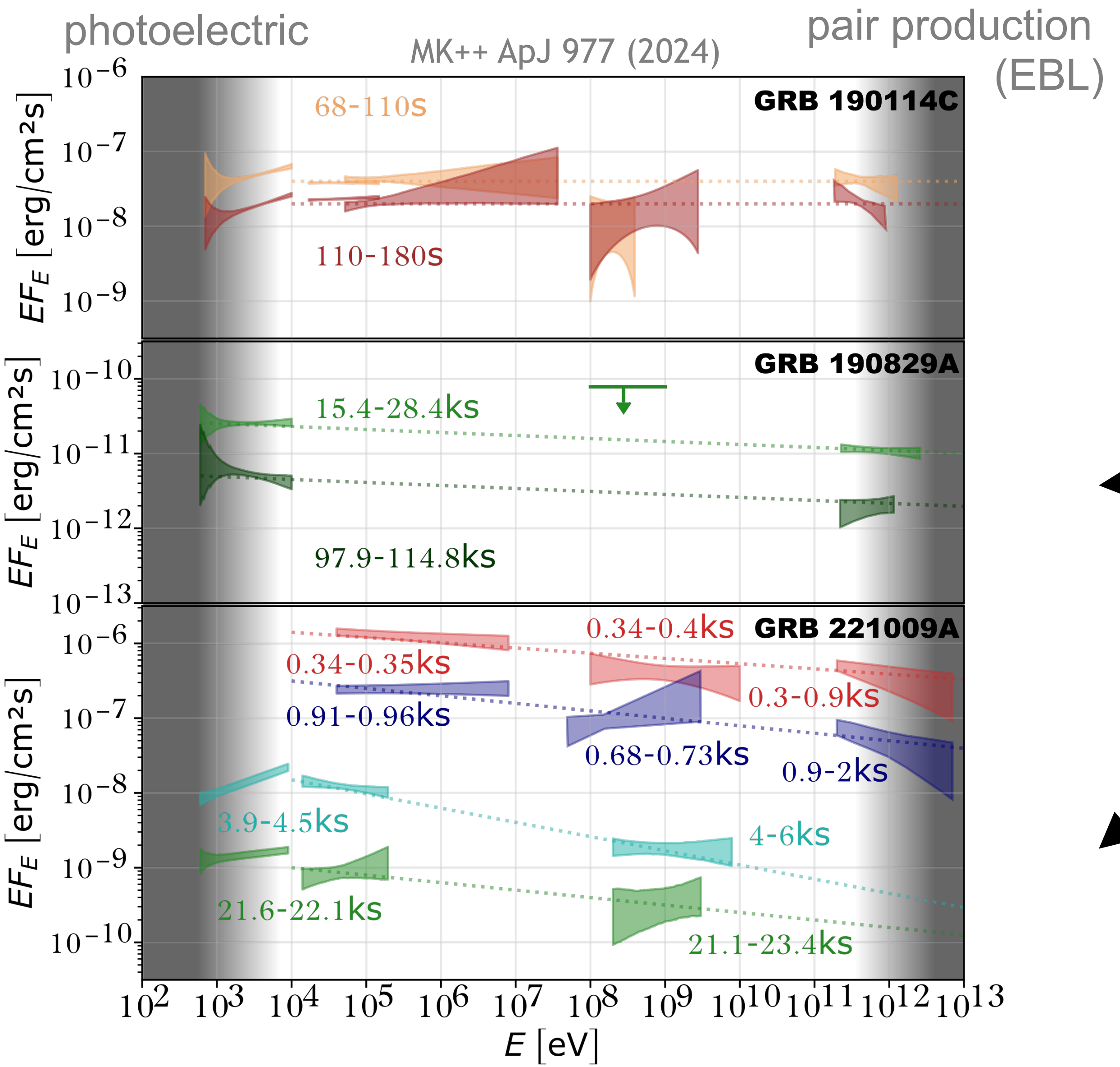
in keV-TeV window

low redshift

6 VHE detected long GRBs

GRB #	z	E_{iso} [erg]	VHE observations		comment
180720B	0.65	6×10^{53}	H.E.S.S.	10-12 hrs	sparse simultaneous data
190114C	0.42	2×10^{53}	MAGIC	**1-40 min**	early → rich MWL data set
190829A	**0.08**	3×10^{50}	H.E.S.S.	4-8 hrs, 27-32 hrs	very close → precise VHE spectrum
201015A	0.43		MAGIC	33 s – 4hrs	3.5σ
201216C	1.1	6×10^{53}	MAGIC	1 min – 2.2 hrs	6σ, EBL attenuated >150GeV
221009A	0.15	$\mathbf{10^{55}}$	LHAASO	0-2000s	brightest GRB so far

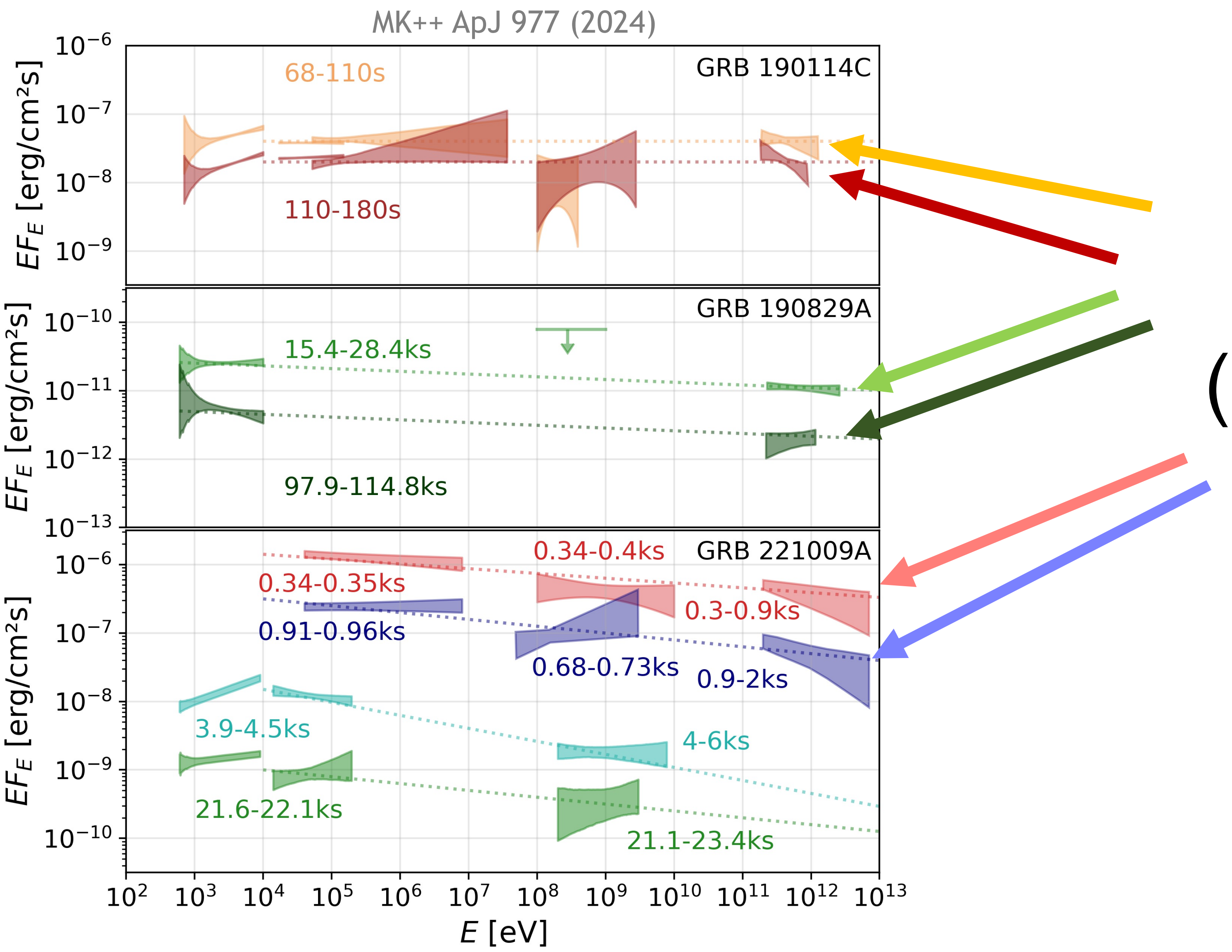
Observations



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



colors:
different times
(simultaneous data)

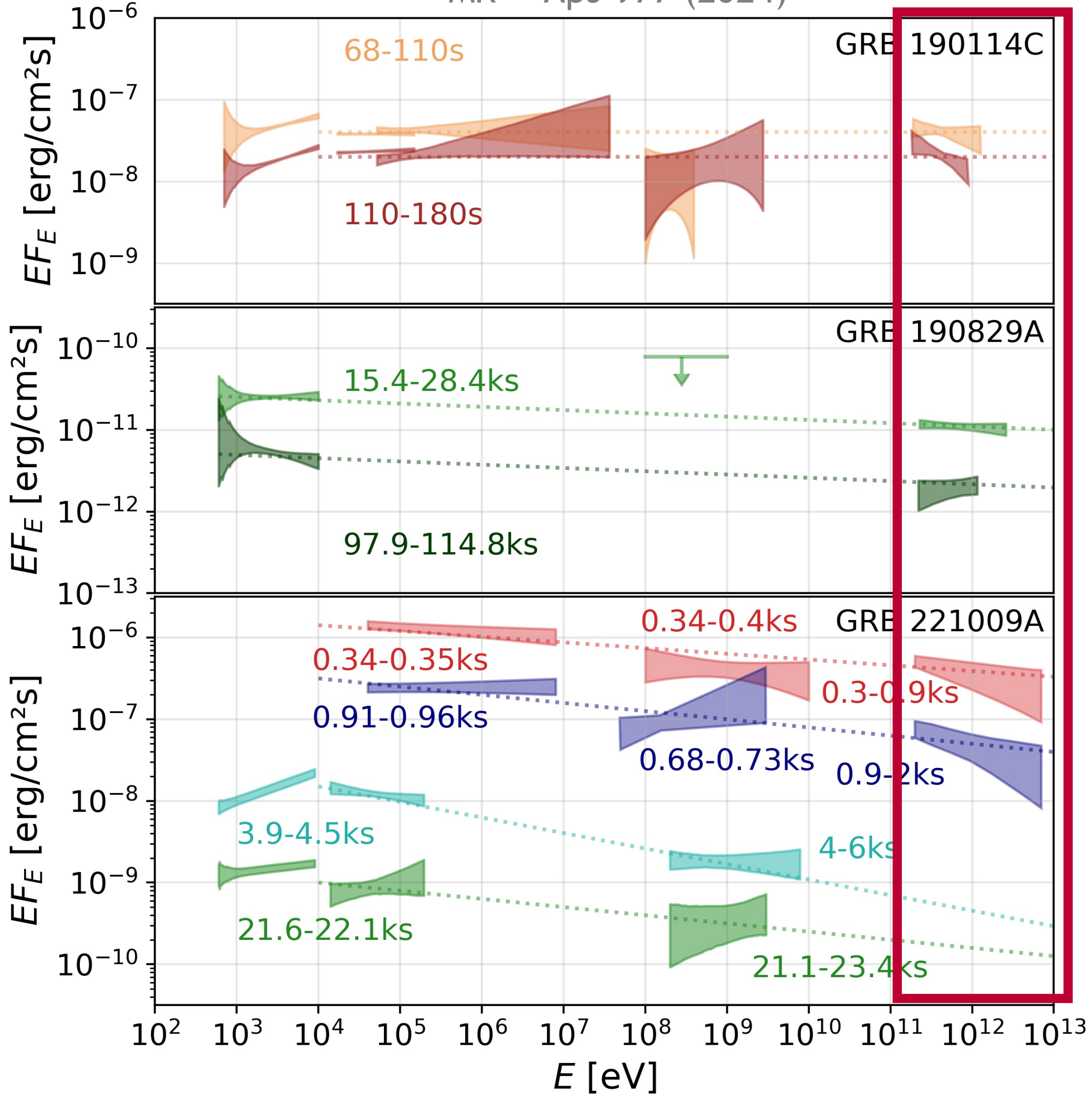
data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

Observations

very-high energy

VHE ($E_\gamma > 0.1\,TeV$)

MK++ ApJ 977 (2024)

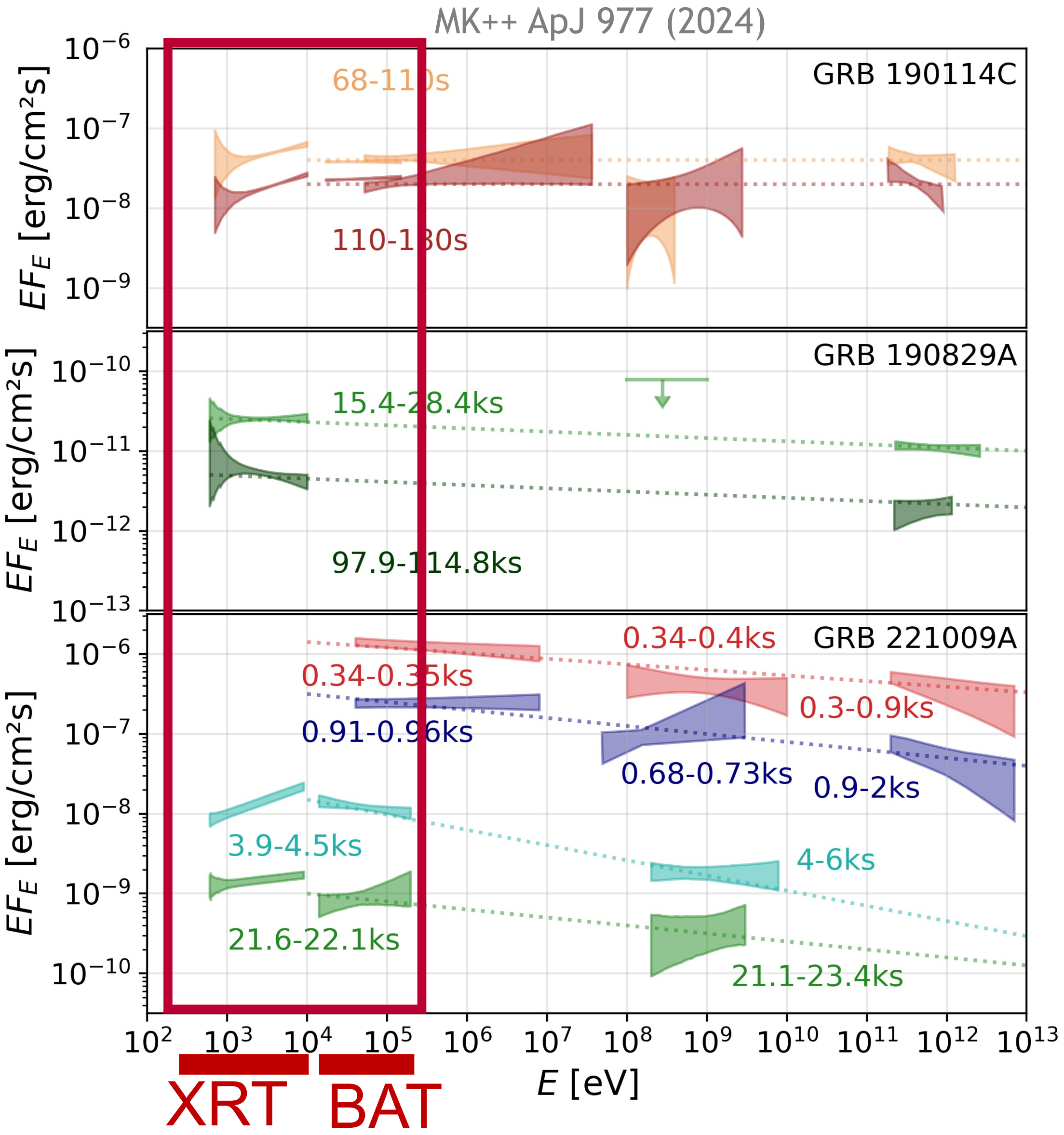


→ **MAGIC**

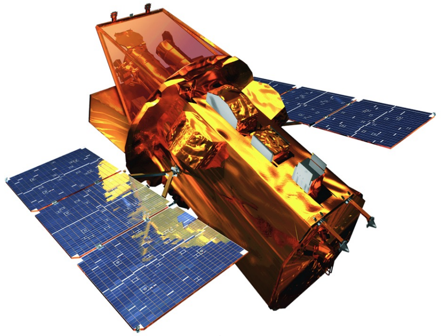
→ **H.E.S.S.**

→ **LHAASO**

Observations



Swift satellite



data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
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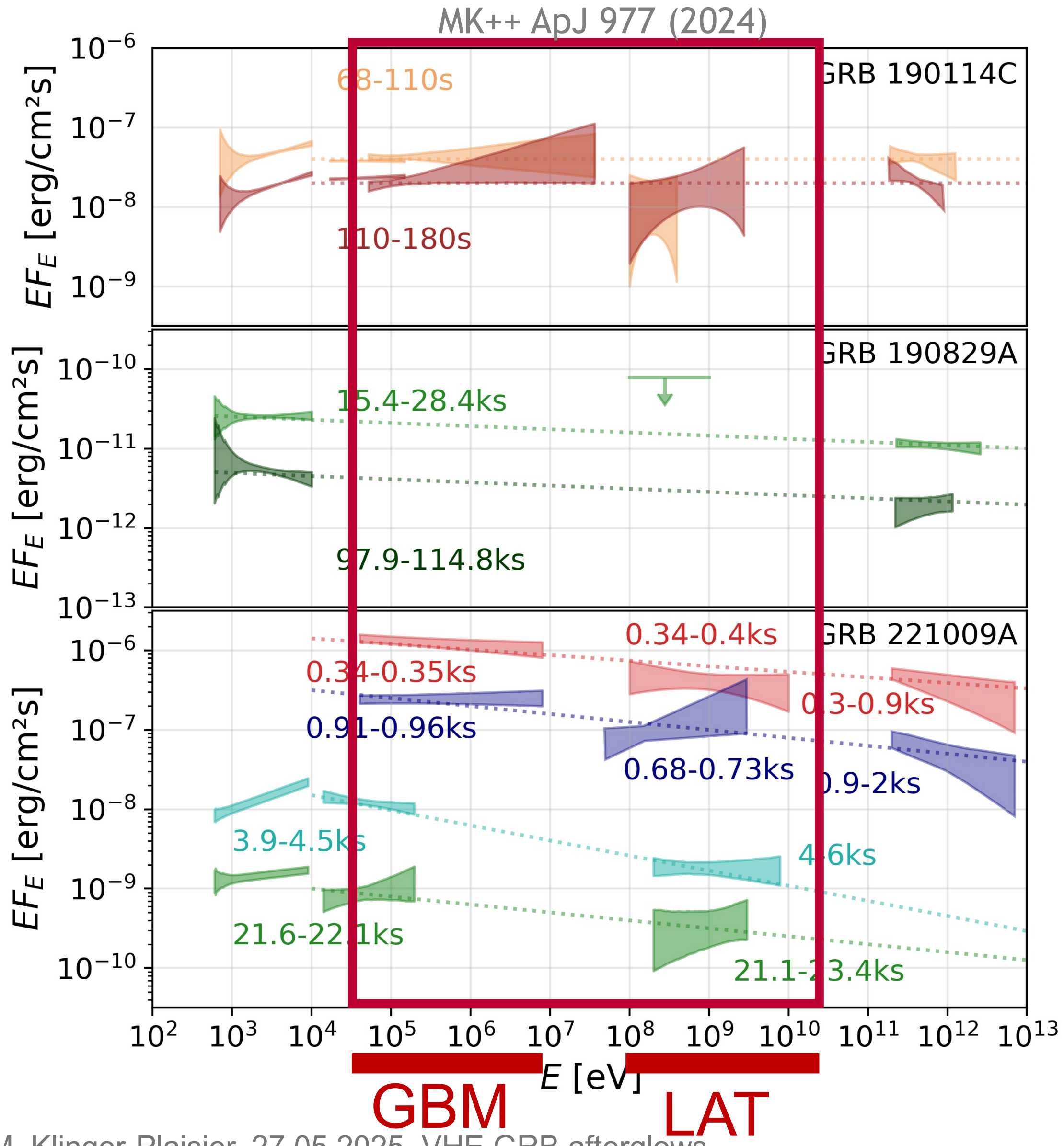
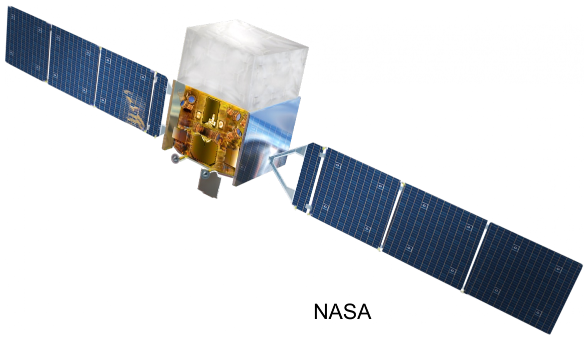
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

Observations



Fermi satellite



data from:
MAGIC Nature 575 (2019)
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MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
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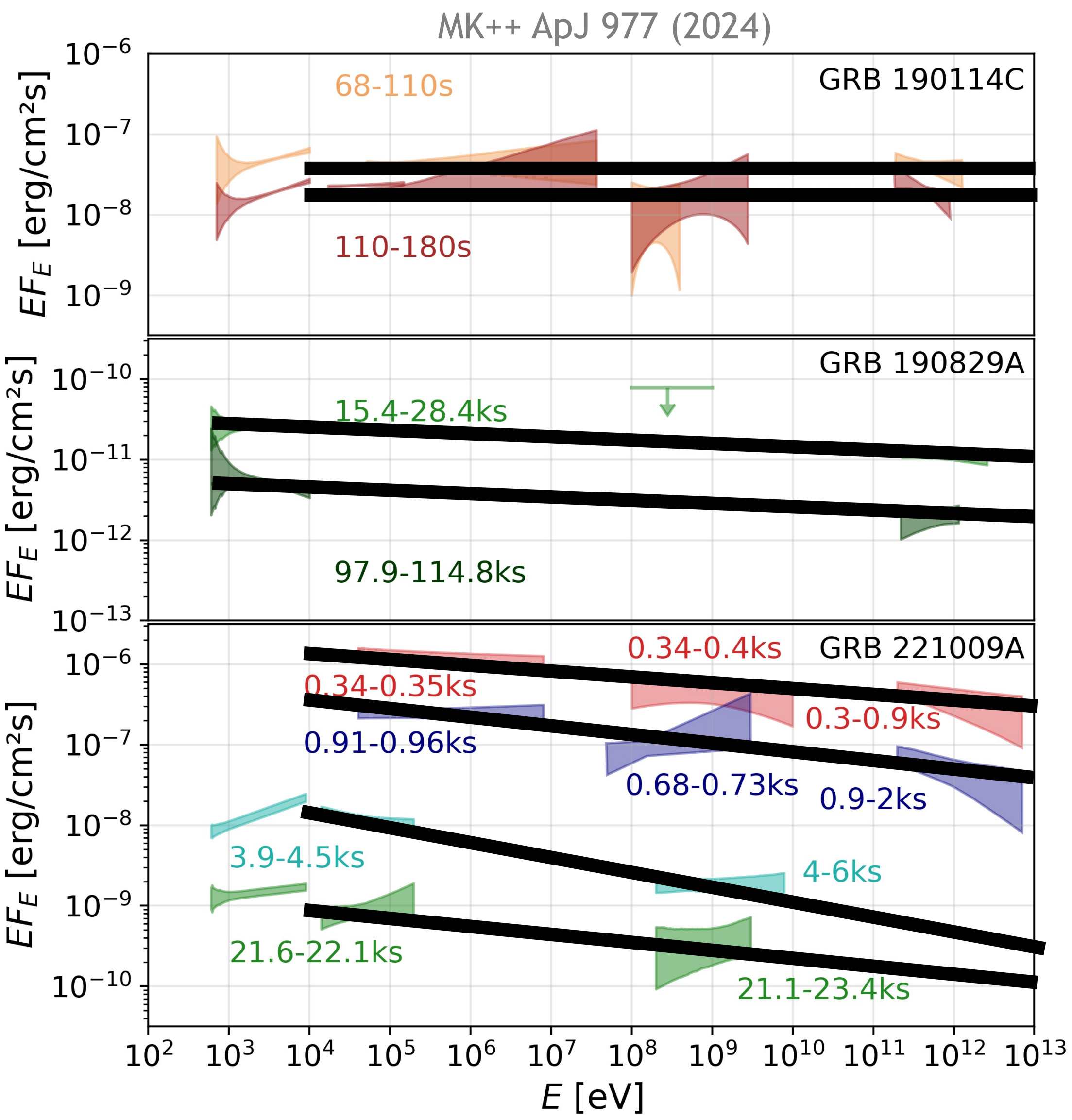
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

Observations



→ **MAGIC**

→ **H.E.S.S.**

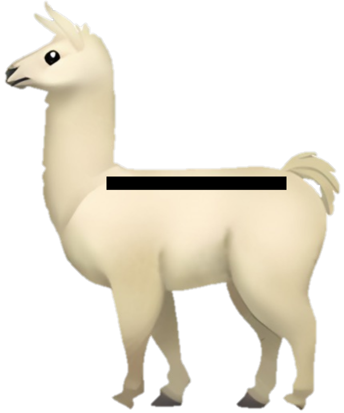
→ **LHAASO**

single power-law component up to TeV energies?

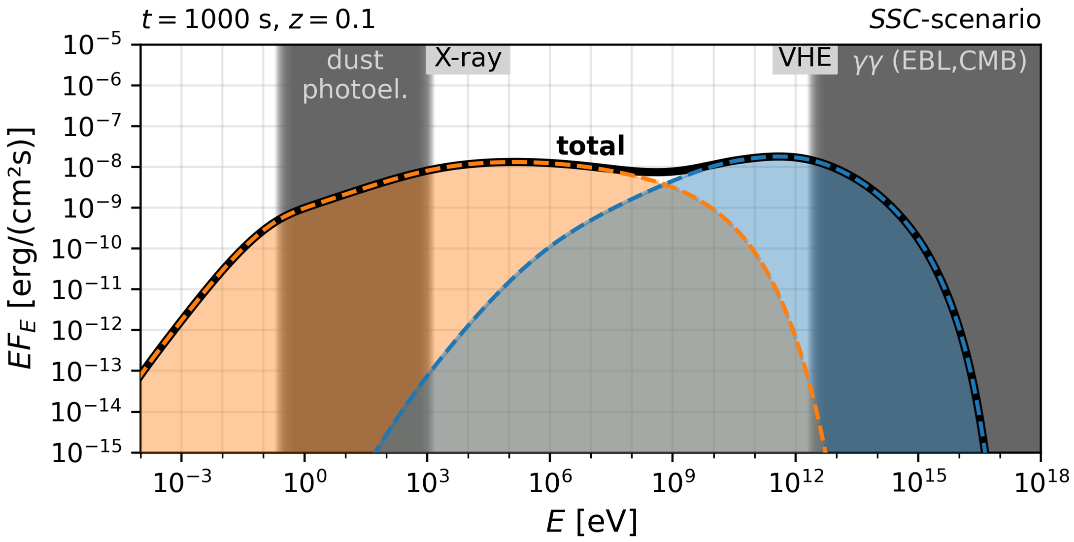
data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

SSC and ideas beyond

observations:
something
close to

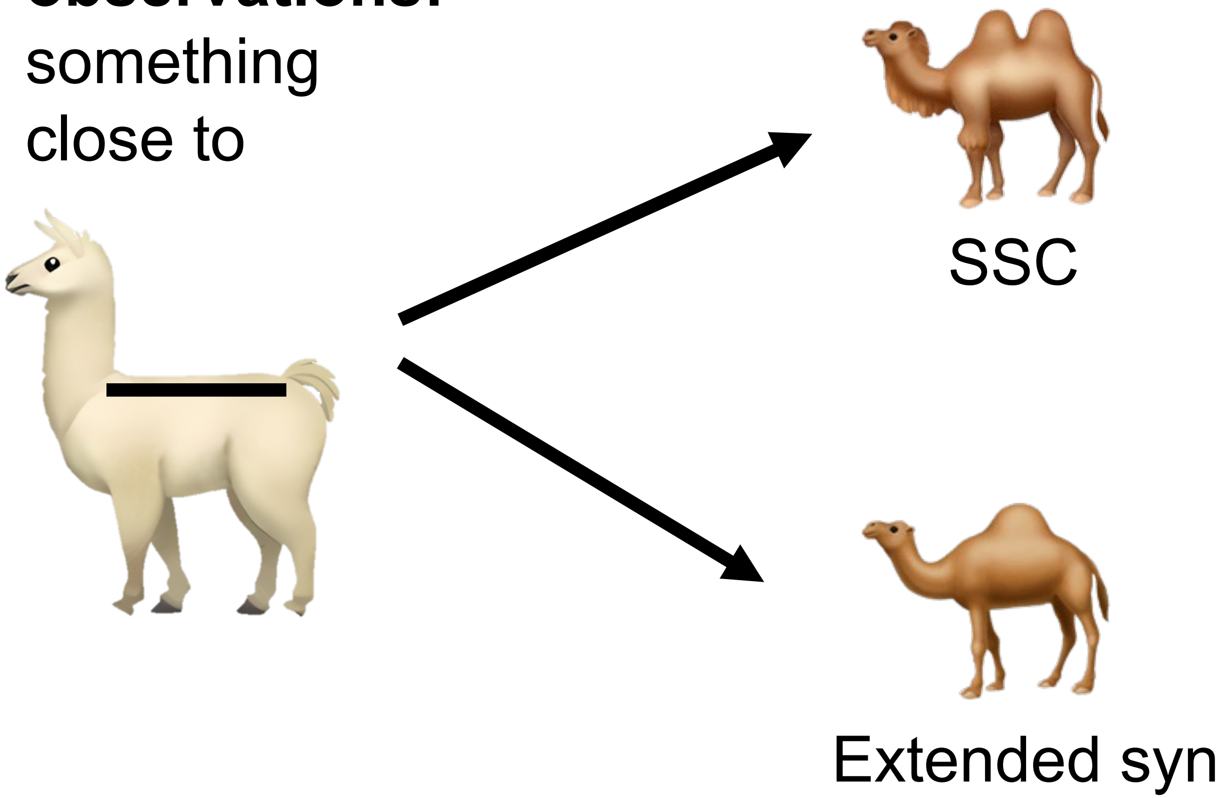


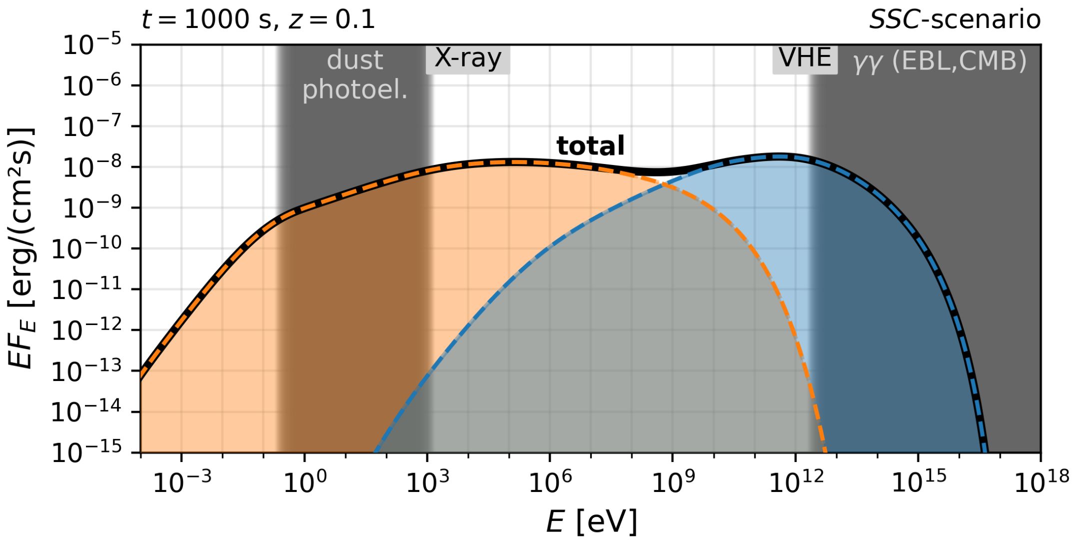
SSC

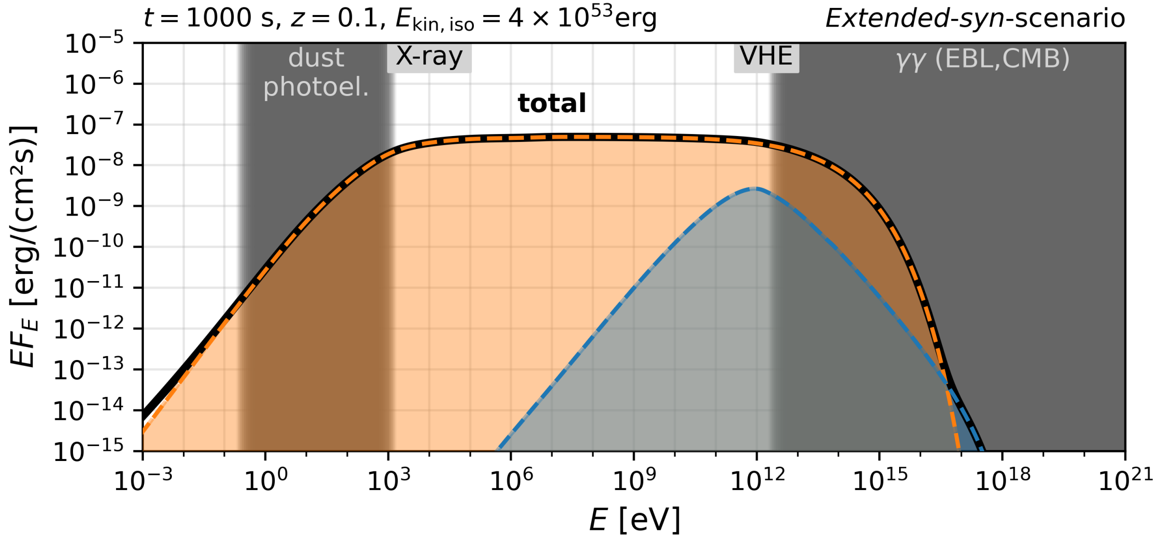


SSC and ideas beyond

observations:
something
close to



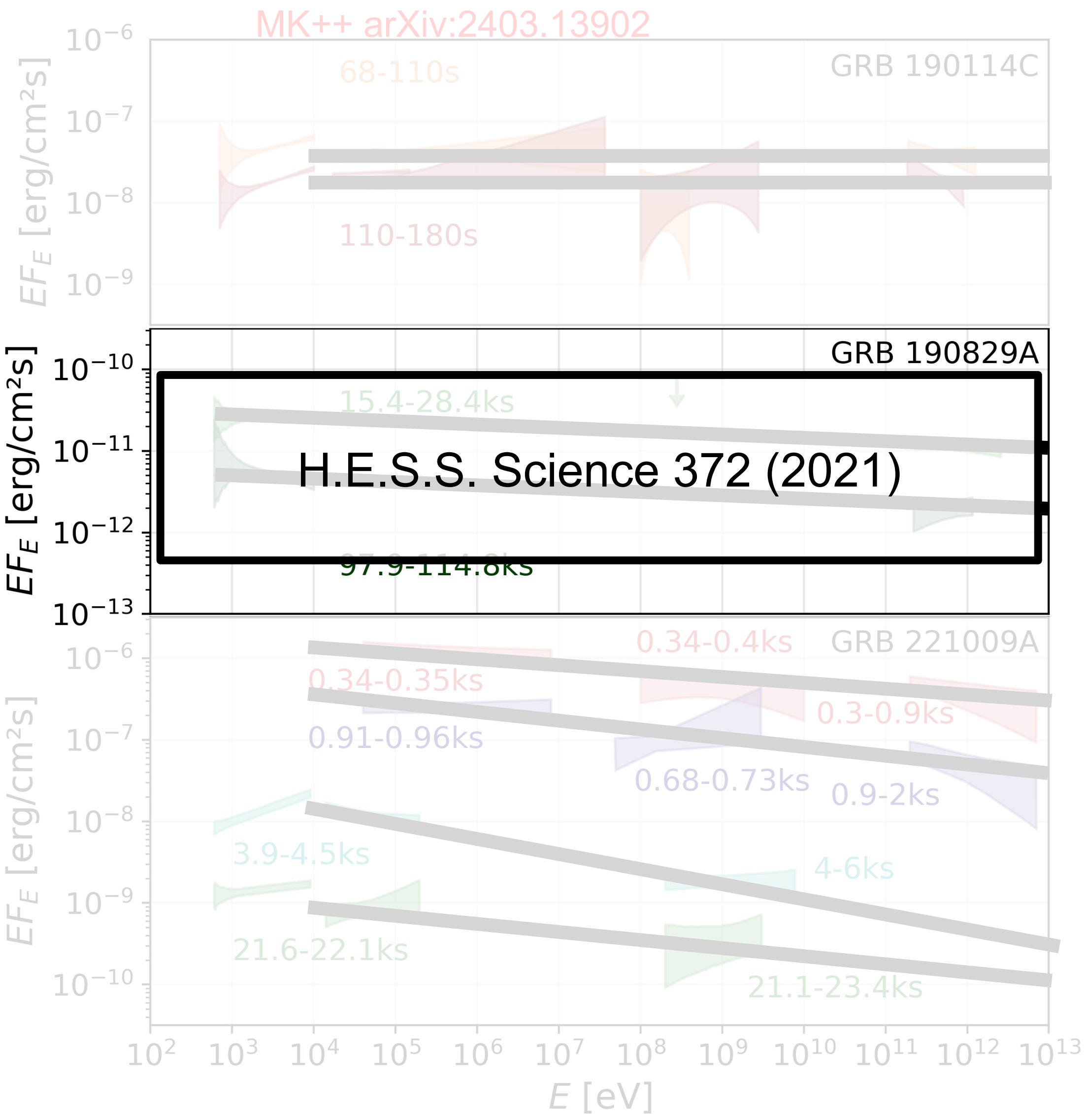




→ faster than Bohm acceleration: needs careful justification!

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

Observations

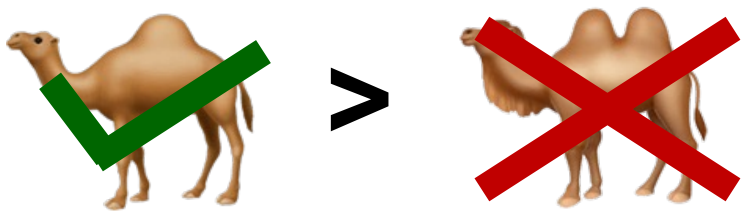


→ MAGIC

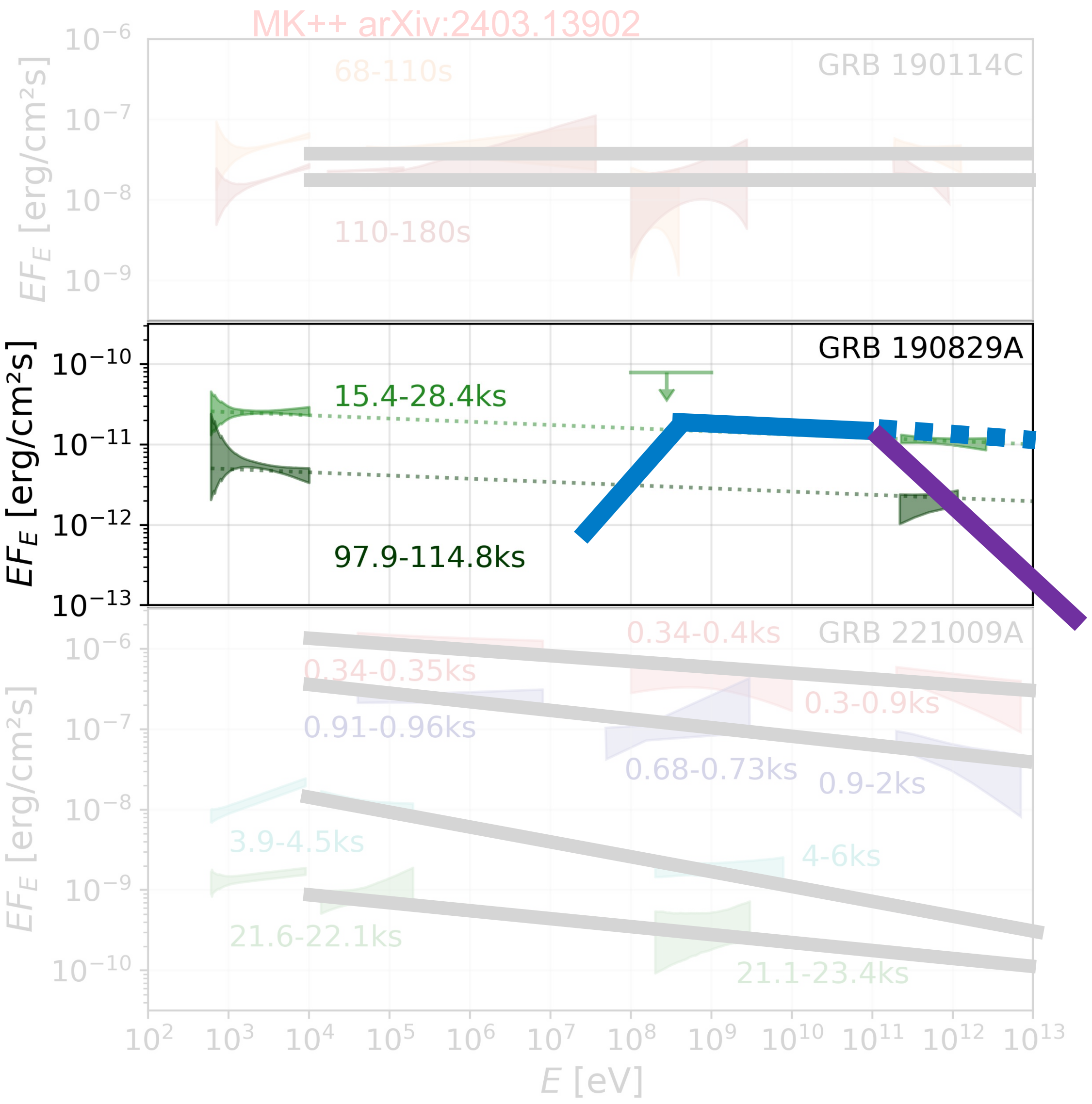
→ H.E.S.S.

→ LHAASO

statistical preference for single component!



Observations



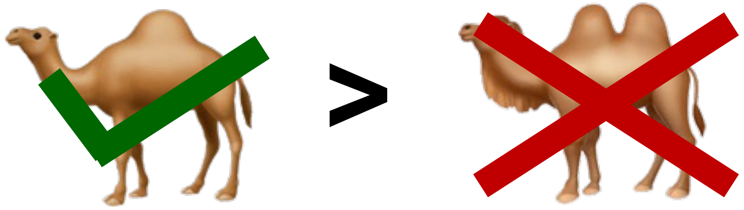
→ MAGIC

→ H.E.S.S.

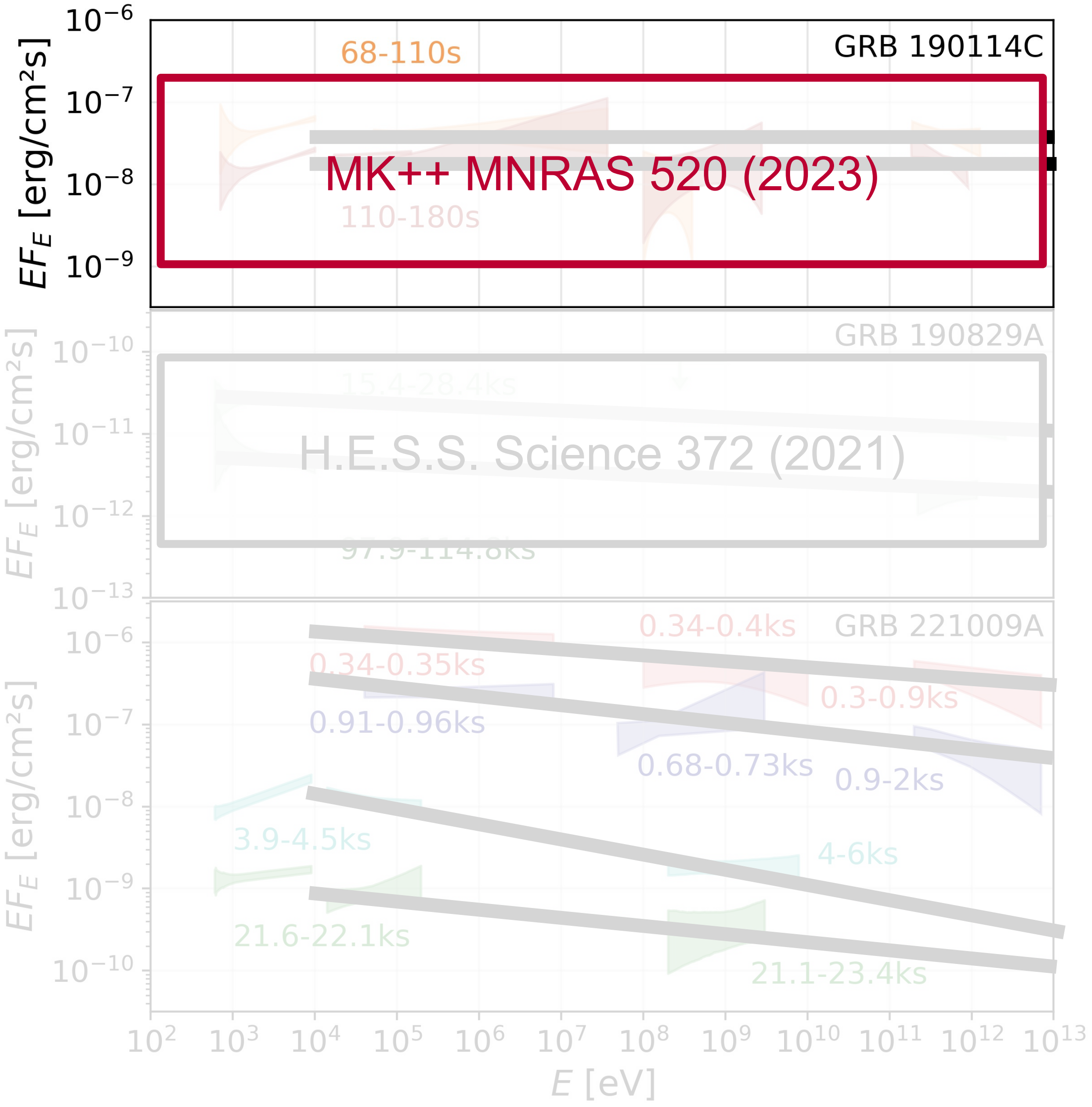
Klein-Nishina softening

→ LHAASO

statistical preference for single component!



Observations



→ **MAGIC**

?

→ **inconclusive on syn vs. SSC**

→ **H.E.S.S.**

>

→ **LHAASO**

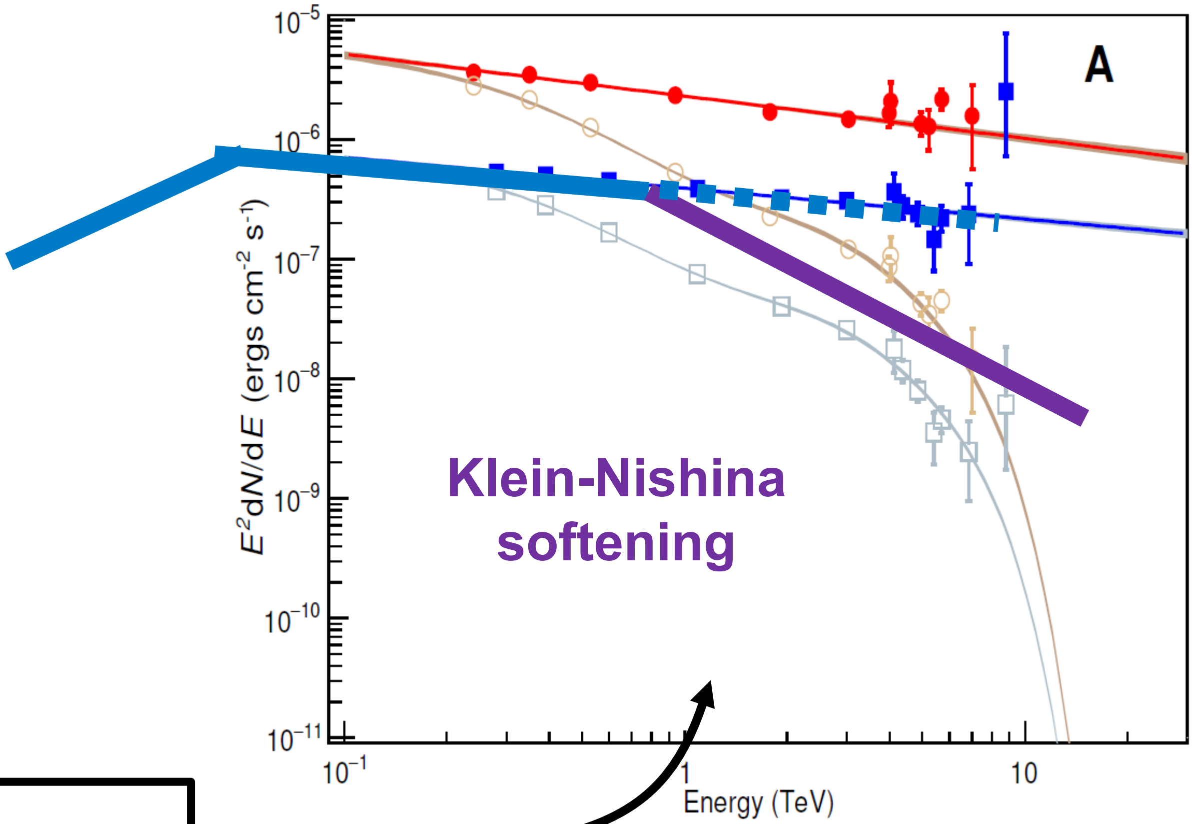
LHAASO GRB 221009A

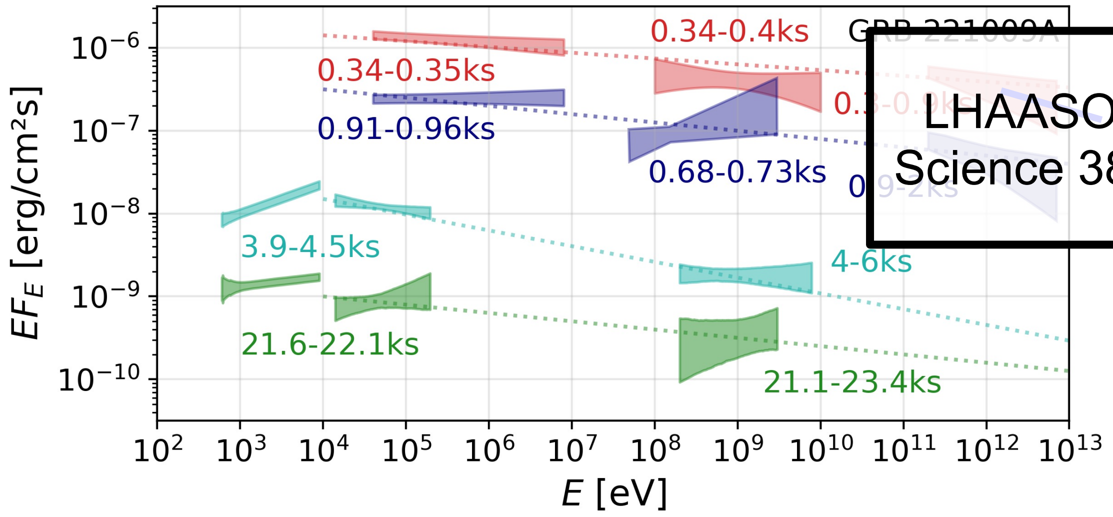
→ power law with $\gamma_{\mathrm{TeV}} \approx 2.2$

→ No softening up to at least 10 TeV

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

→ in tension with SSC





LHAASO Collab.
Science 380 (2023)

LHAASO GRB 221009A

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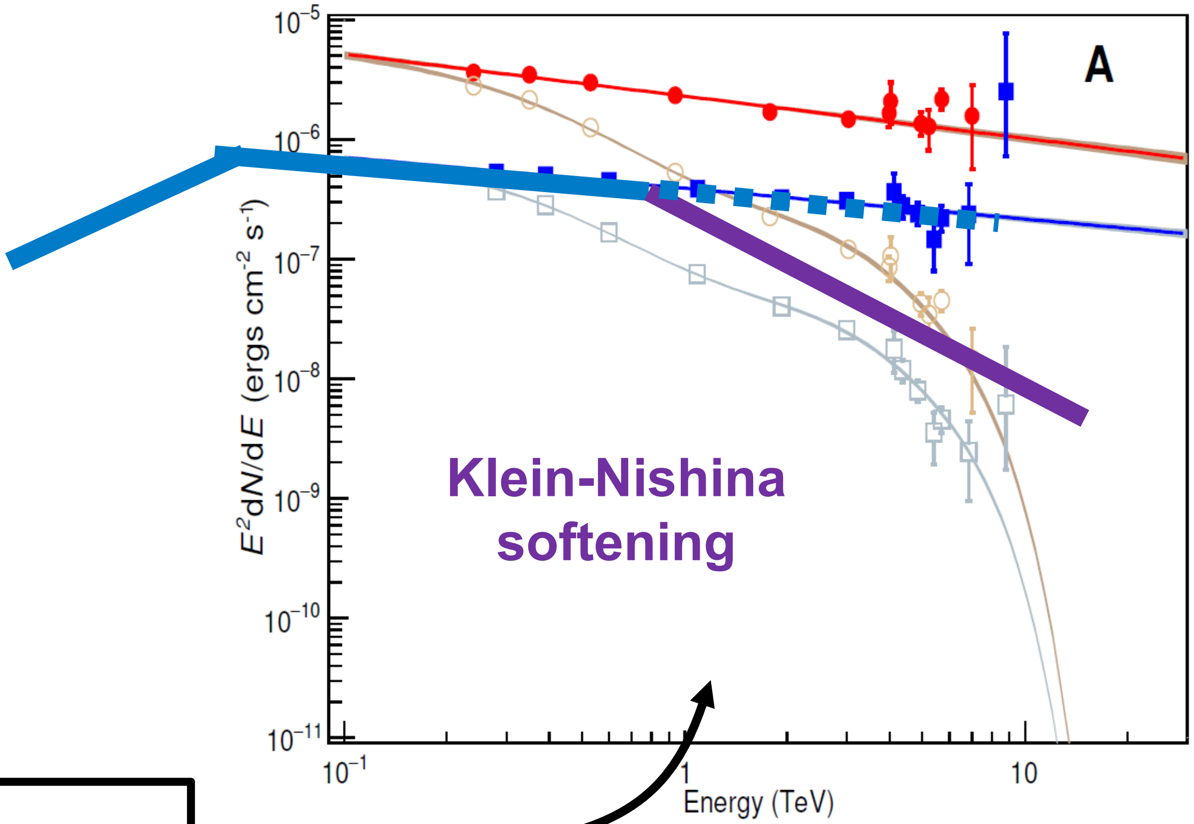
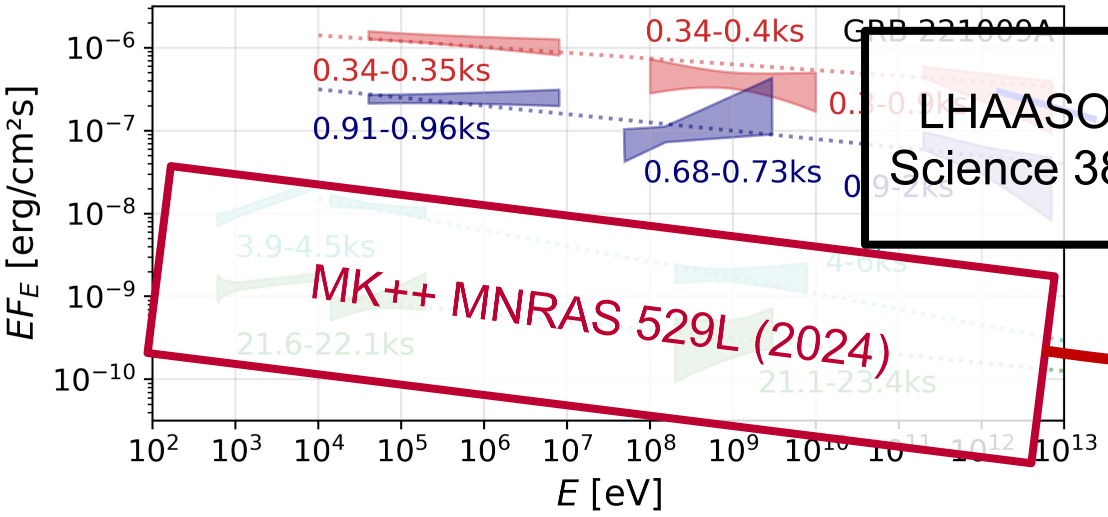
(note $z = 0.15$ → EBL abs. > few TeV)

→ **in tension with SSC**

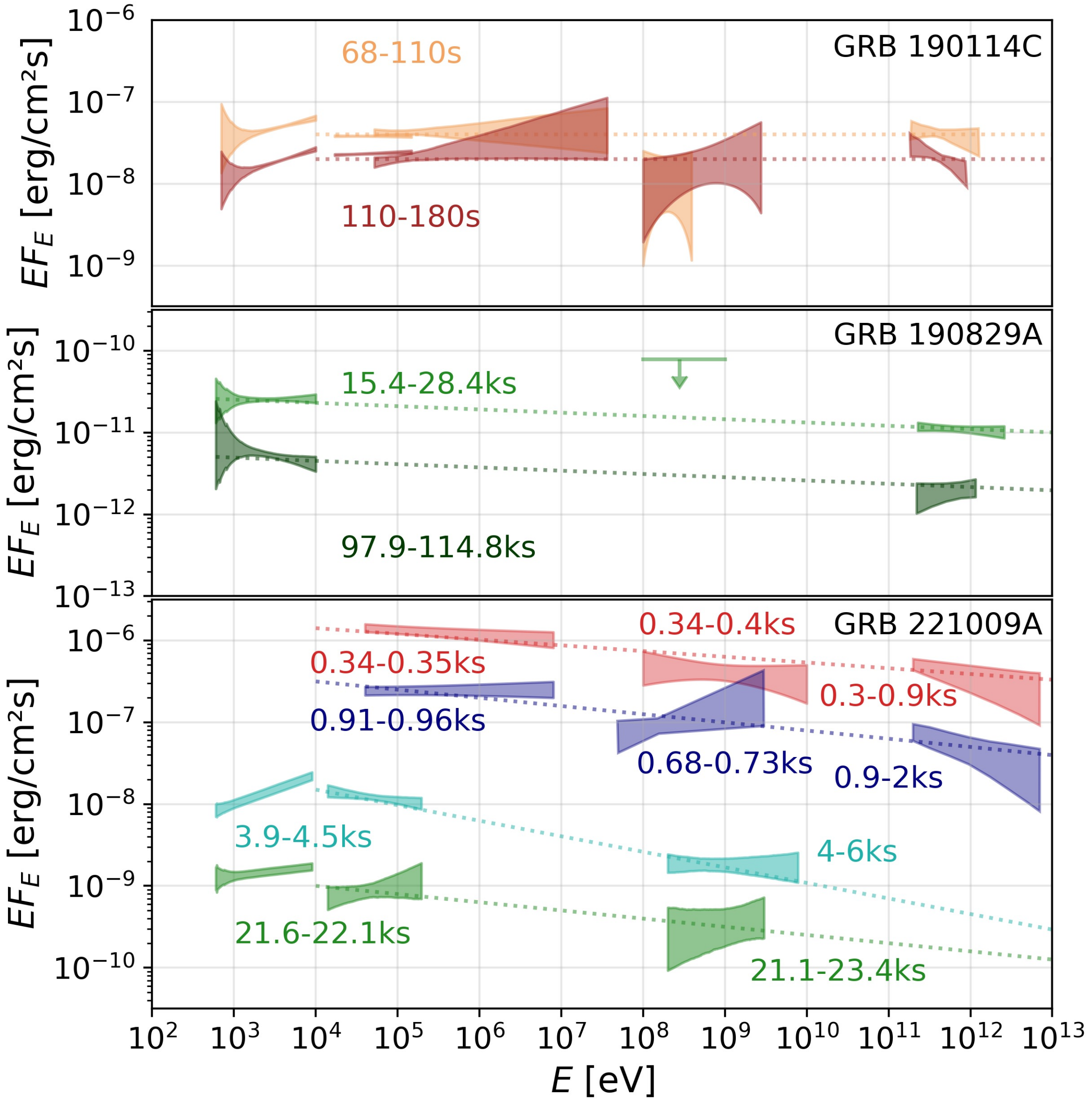




LHAASO Collab.
Science 380 (2023)

consistent with power law above few keV
→ spectral index consistent with LHAASO

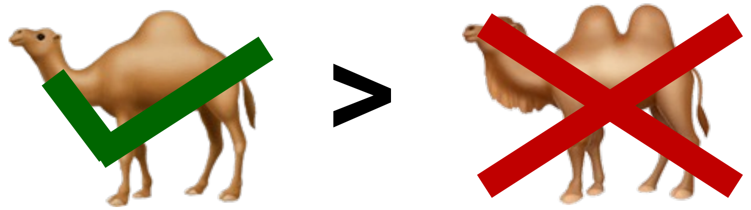
Observational summary



→ **MAGIC:**

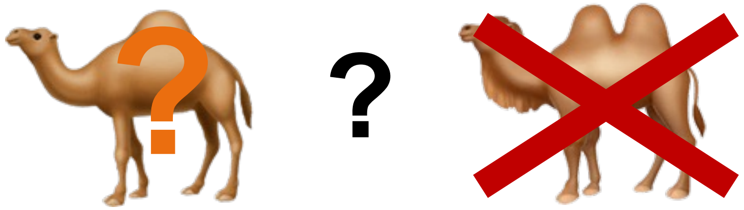
→ **inconclusive on syn vs. SSC**

→ **H.E.S.S.:**



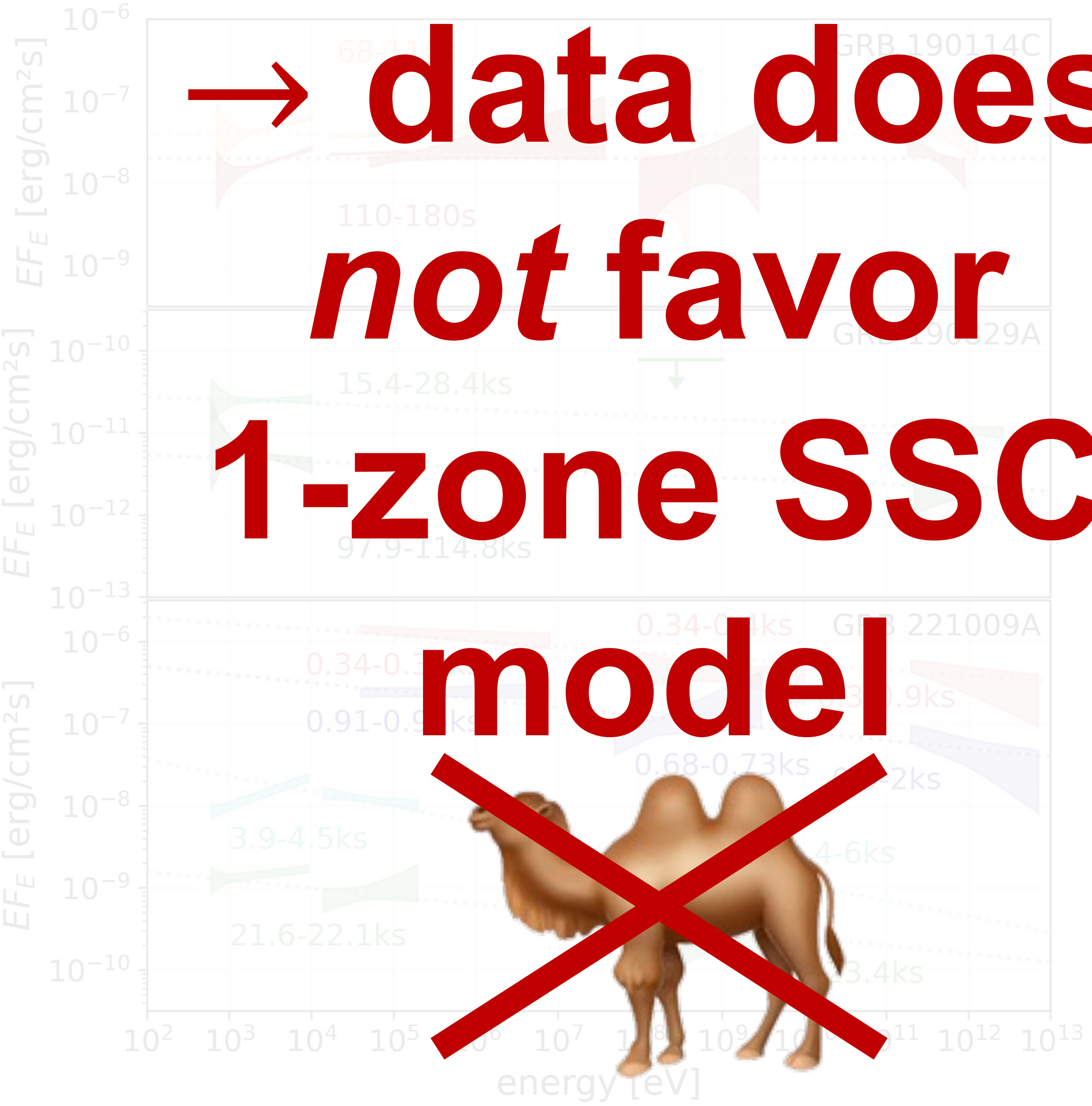
→ **preference against SSC**

→ **LHAASO:**



→ **in tension with SSC**

Observational summary:

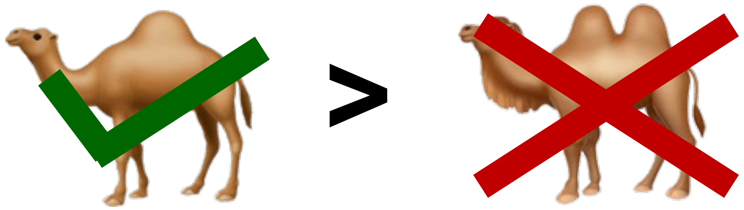


→ data does *not* favor 1-zone SSC model

→ MAGIC:

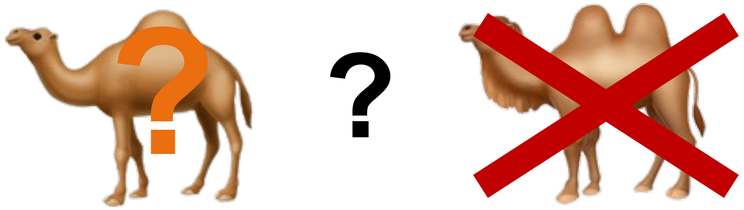
→ inconclusive on syn vs. SSC

→ H.E.S.S.:



→ preference against SSC

→ LHAASO:

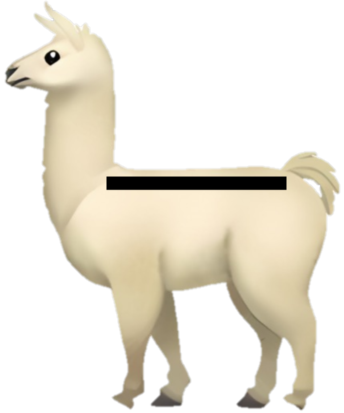


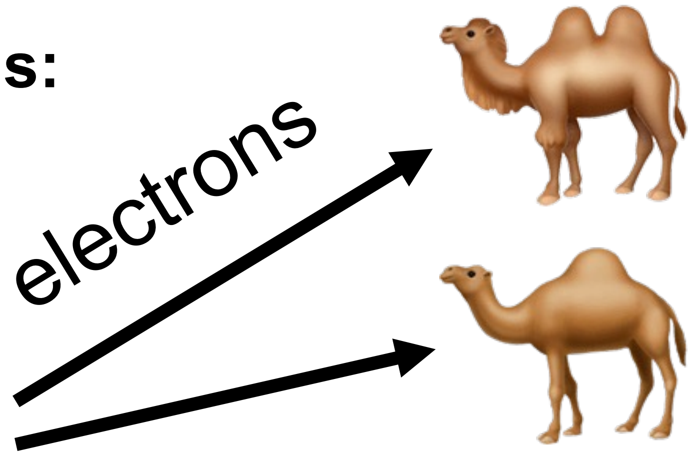
→ in tension with SSC

What makes gamma-ray bursts shine so bright up to very-high-energies?

Ways out?

observations:
something
close to



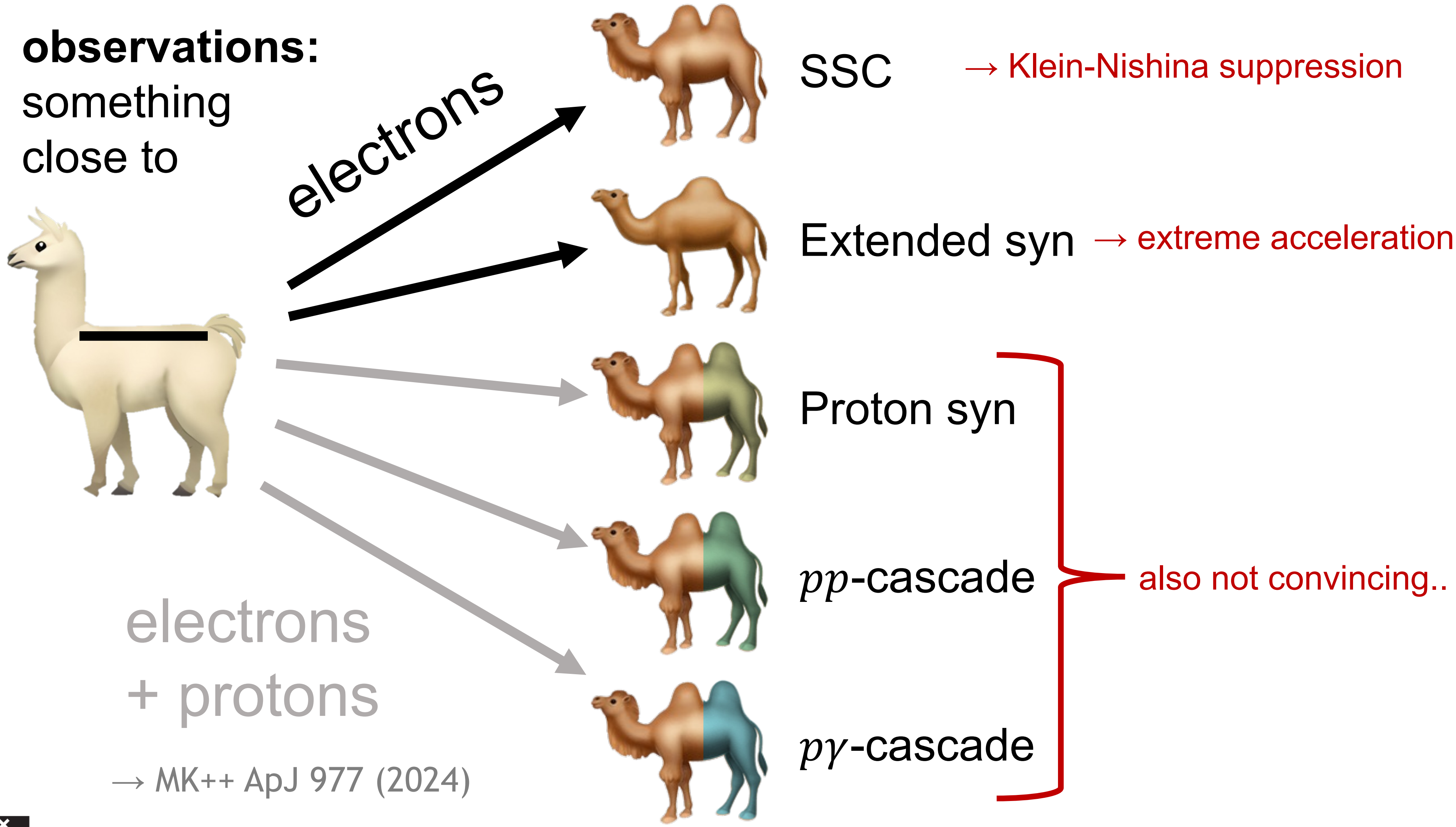


SSC → Klein-Nishina suppression

Extended syn → extreme acceleration

Ways out?

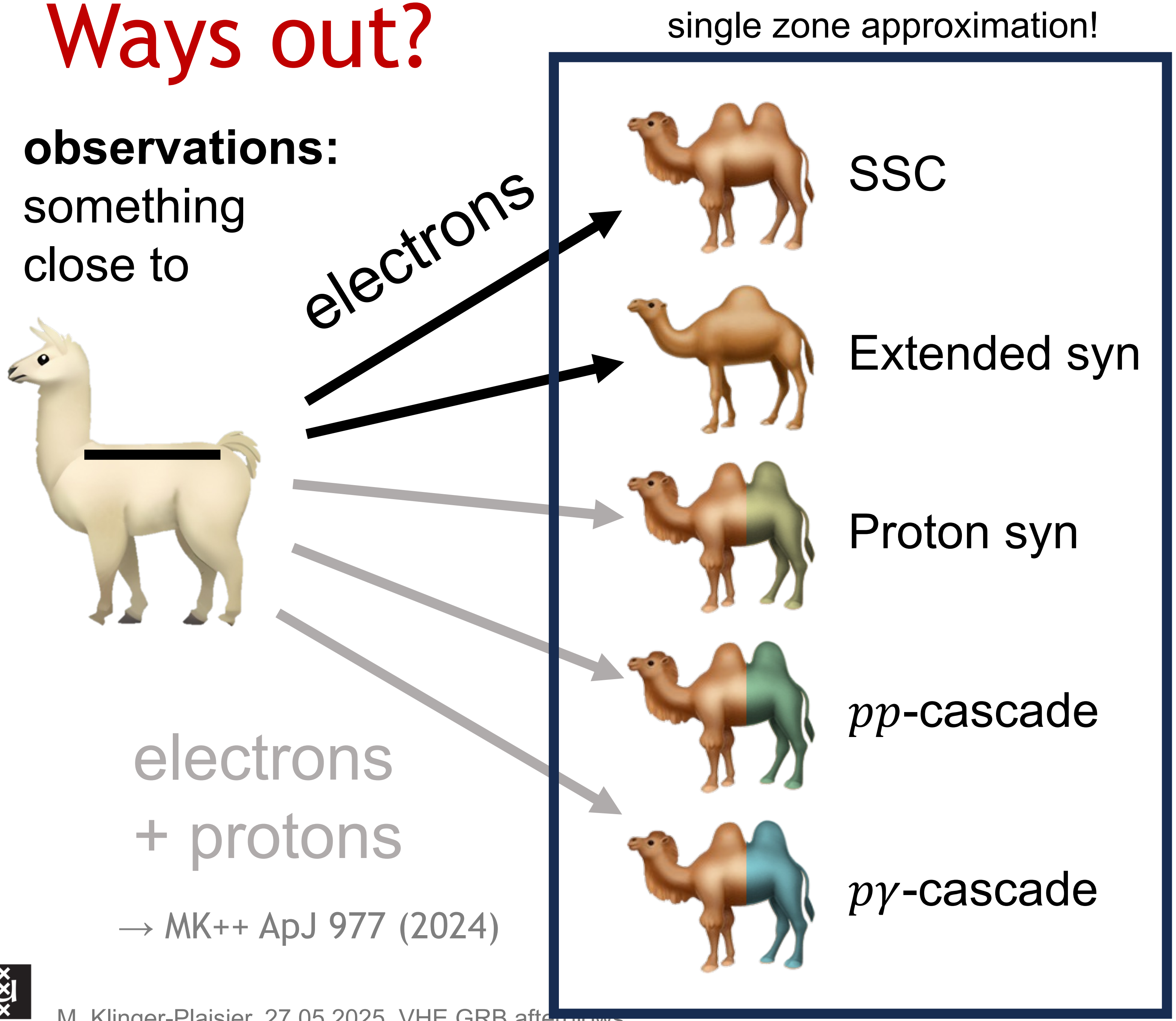
observations:
something
close to



→ MK++ ApJ 977 (2024)

Ways out?

observations:
something
close to



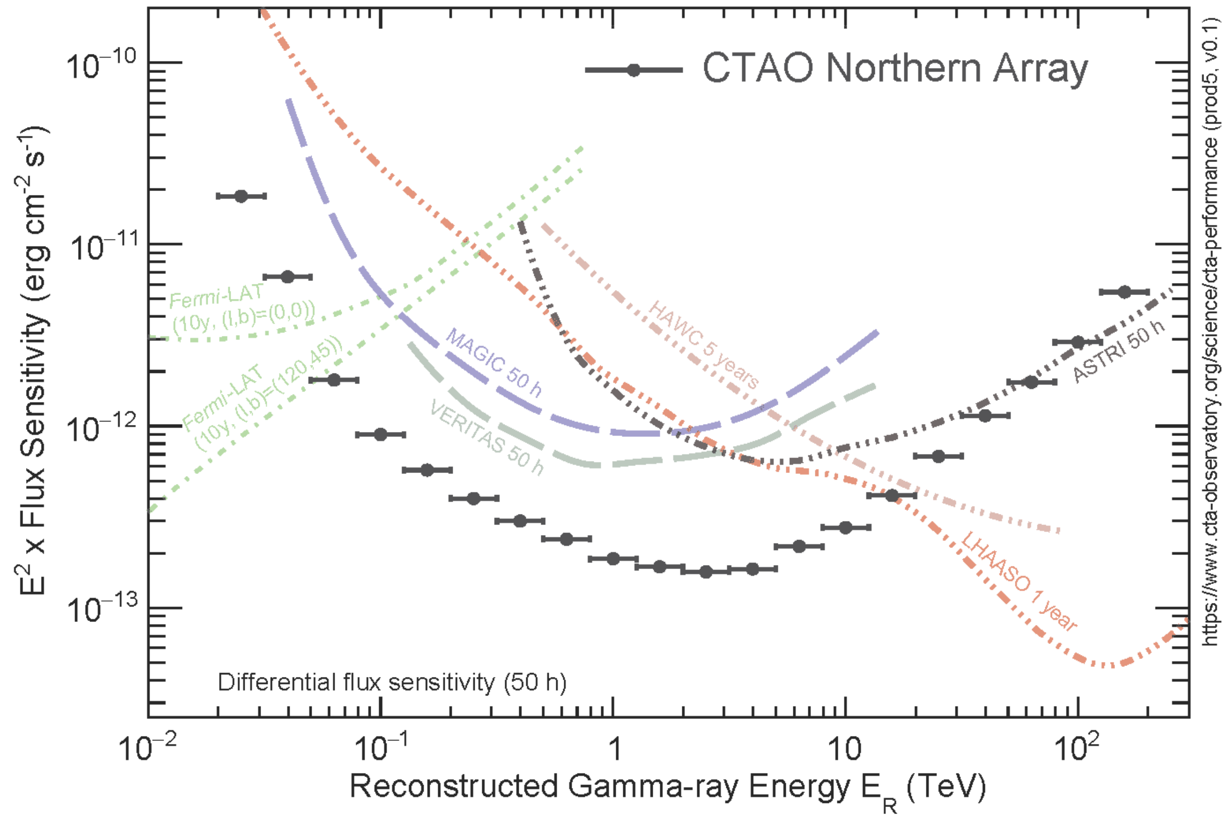
multiple coupled zones?
→ turbulence behind shock?
thermal particles?
Duffel/MacFadyen ApJ 791 (2015)
Groslj++ ApJL 963 L44 (2024)
→ decaying fields?
Lemoine/Vanthieghem/Plotnikov (2020)
→ creation of pairs upstream?
Derishev/Piran (2003, 2016, 2021),
Lemoine/Vanthieghem in prep.
→ cosmogenic origin?
Kalashev++ (2024) arXiv:2405.05402

Cherenkov Telescope Array Observatory (CTAO)

Arrays of Small/Medium/Large Sized Telescopes in La Palma and Chile

Cherenkov Telescope Array Observatory (CTAO)

- Arrays of Small/Medium/Large Sized Telescopes in La Palma and Chile
- Fast repointing (<20s)
- Low energy threshold (20 GeV)
- Increased Sensitivity (~10x)



Cherenkov Telescope Array Observatory (CTAO)

Arrays of Small/Medium/Large Sized Telescopes in La Palma and Chile

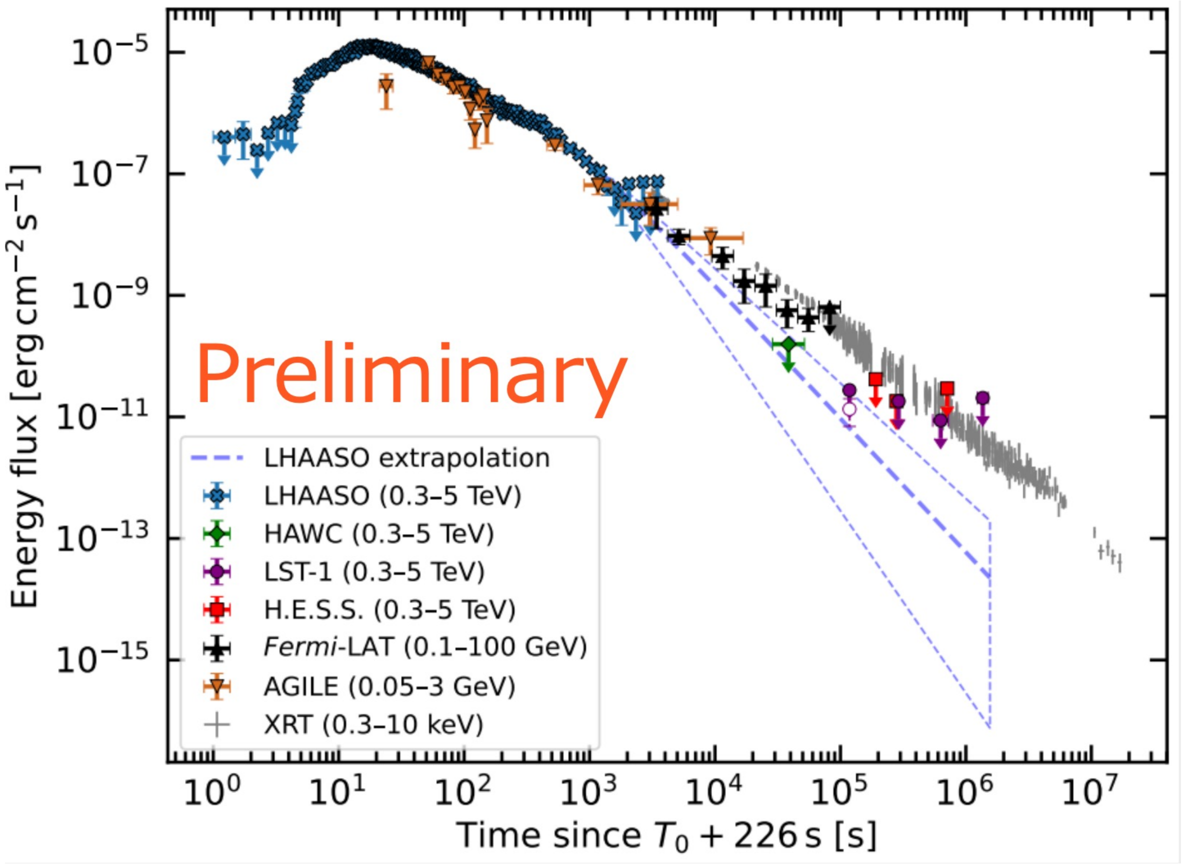
Fast repointing (<20s)

Low energy threshold (20 GeV)

Increased Sensitivity (~10x)

"around the corner"

- → LST1 already constructed and likely detected GRB 221009A (4σ)
  K. Terauchi talk at TeVPA (2024)
- → Dutch CTAO/KM3NeT synergy event at 08.09.25



Take home

Long GRB afterglows = relativistic shock radiation

→ cosmic-ray accelerator!?

VHE emission = new radiation mechanism?

observations: GRB 190114C, GRB 190829A, GRB 221009A

→ preference for single power-law!?

× 1-zone modelling?

→  synchrotron-self Compton emission? → not convincing (Klein-Nishina)!

→  extended synchrotron? → fast acceleration?

→  hadronic scenarios? → not convincing…

→ multizone!

CTA will help us tell the difference!