Lepto-hadronic radiation modeling of gamma-ray burst afterglows

M.Klinger-Plaisier, 16.10.2024, NOVA Network 3 meeting

DESY.

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

HELMHOLTZ

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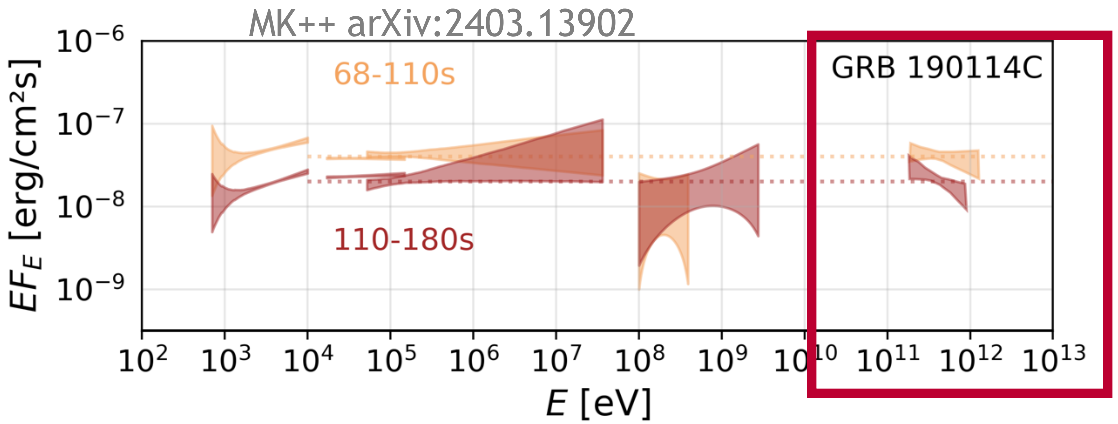
ANTON PANNEKOEK INSTITUUT

GRB afterglows detected at VHE!

Gamma-ray burst

Very high energies
> 0.1 TeV photons

GRB afterglows detected at VHE!



→ **MAGIC**

very early (~100s)

data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ arXiv:2309.10515
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

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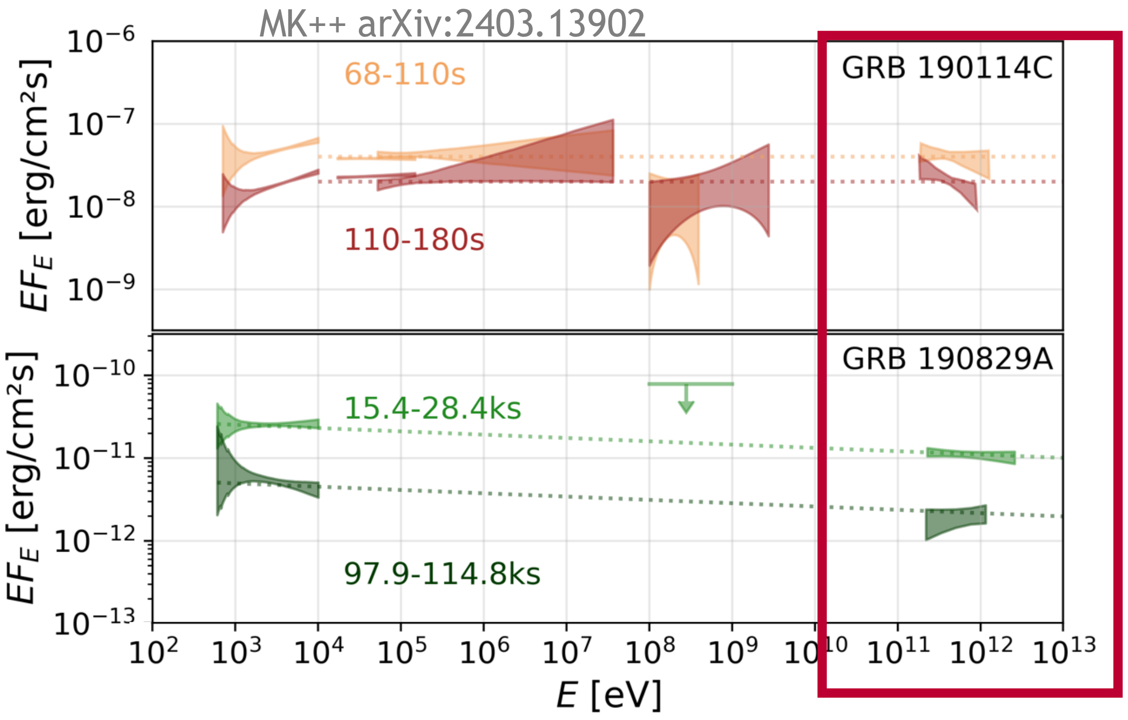

→ **MAGIC** very early (~100s)

→ **H.E.S.S.** very close (z~0.08)

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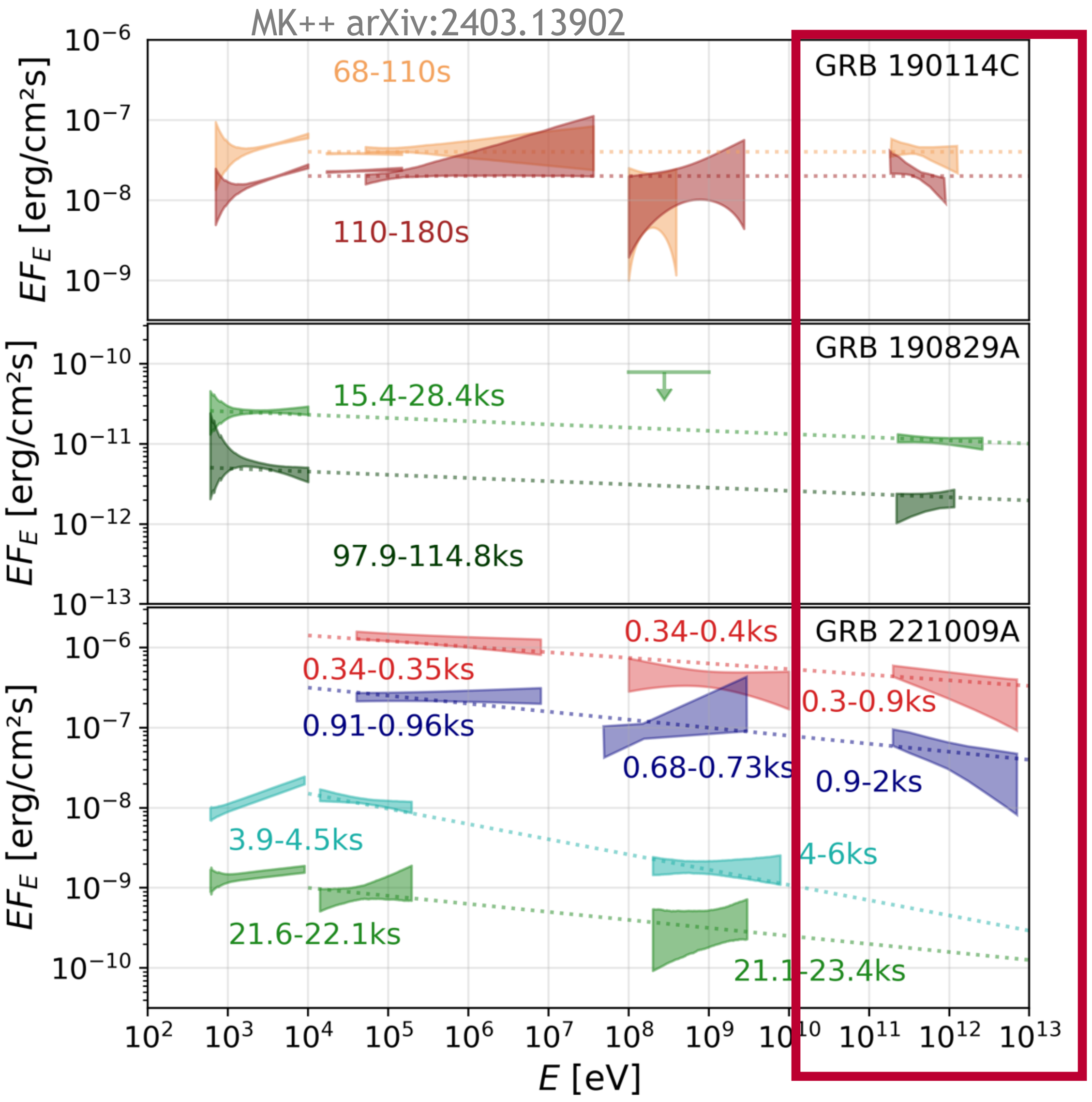

→ **MAGIC** very early (~100s)

→ **H.E.S.S.** very close (z~0.08)

→ **LHAASO** very bright (BOAT)

data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
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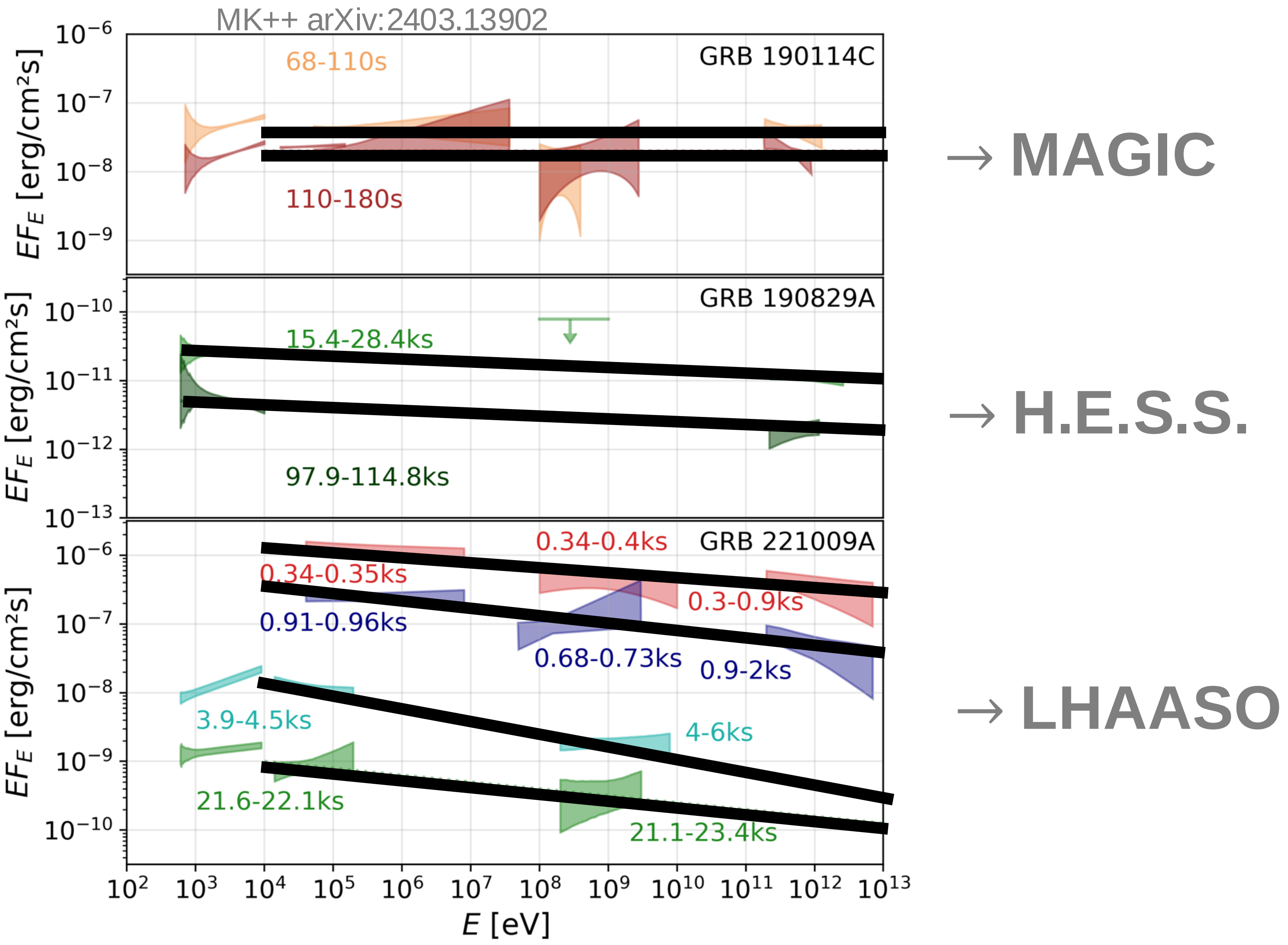

- Single component?
- Flat power-law spectra extending up to >TeV

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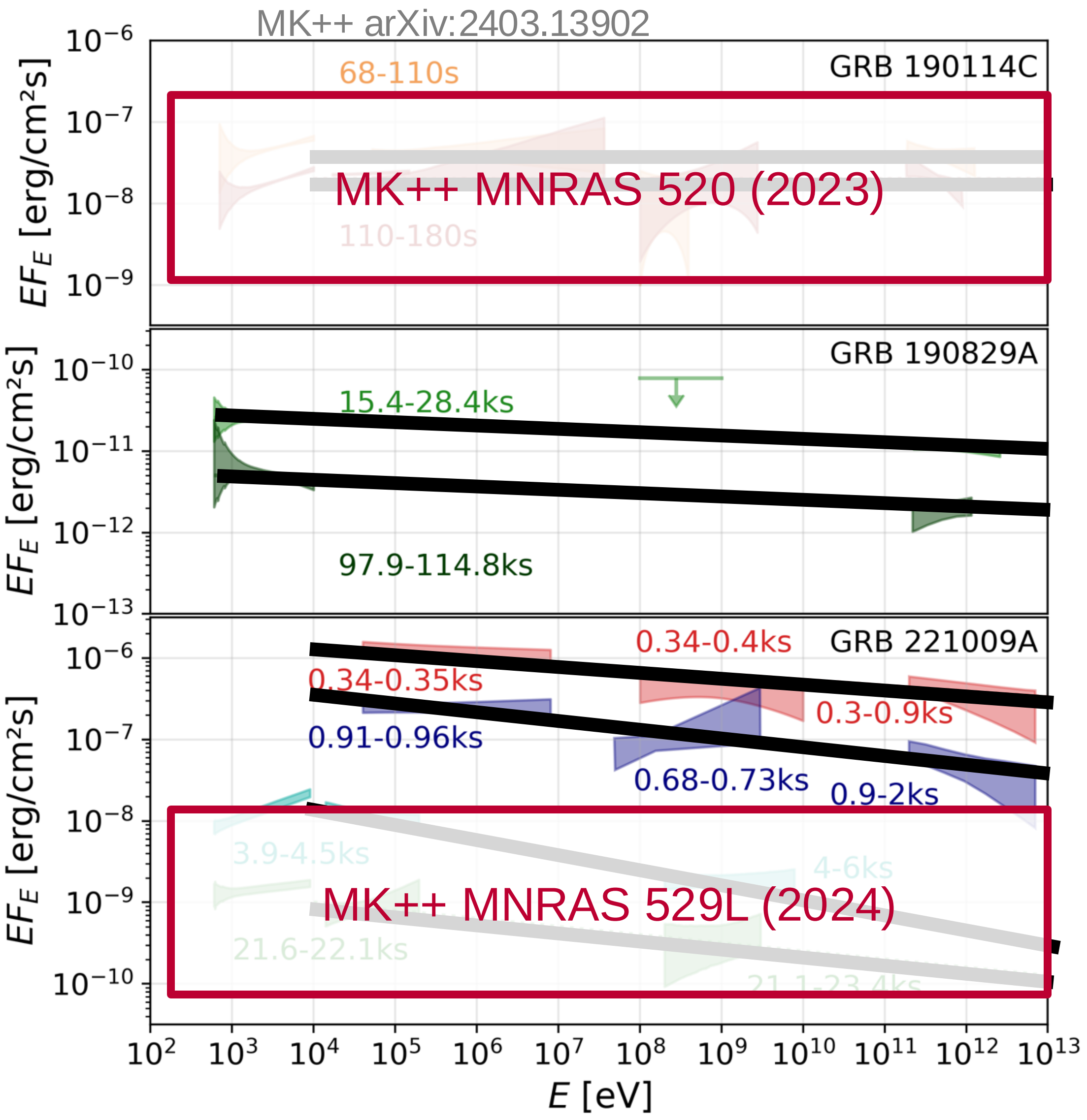

→ **MAGIC**

→ **H.E.S.S.**

→ **LHAASO**

- Single component?
- Flat power-law spectra extending up to >TeV
- **No preference at counts-level**

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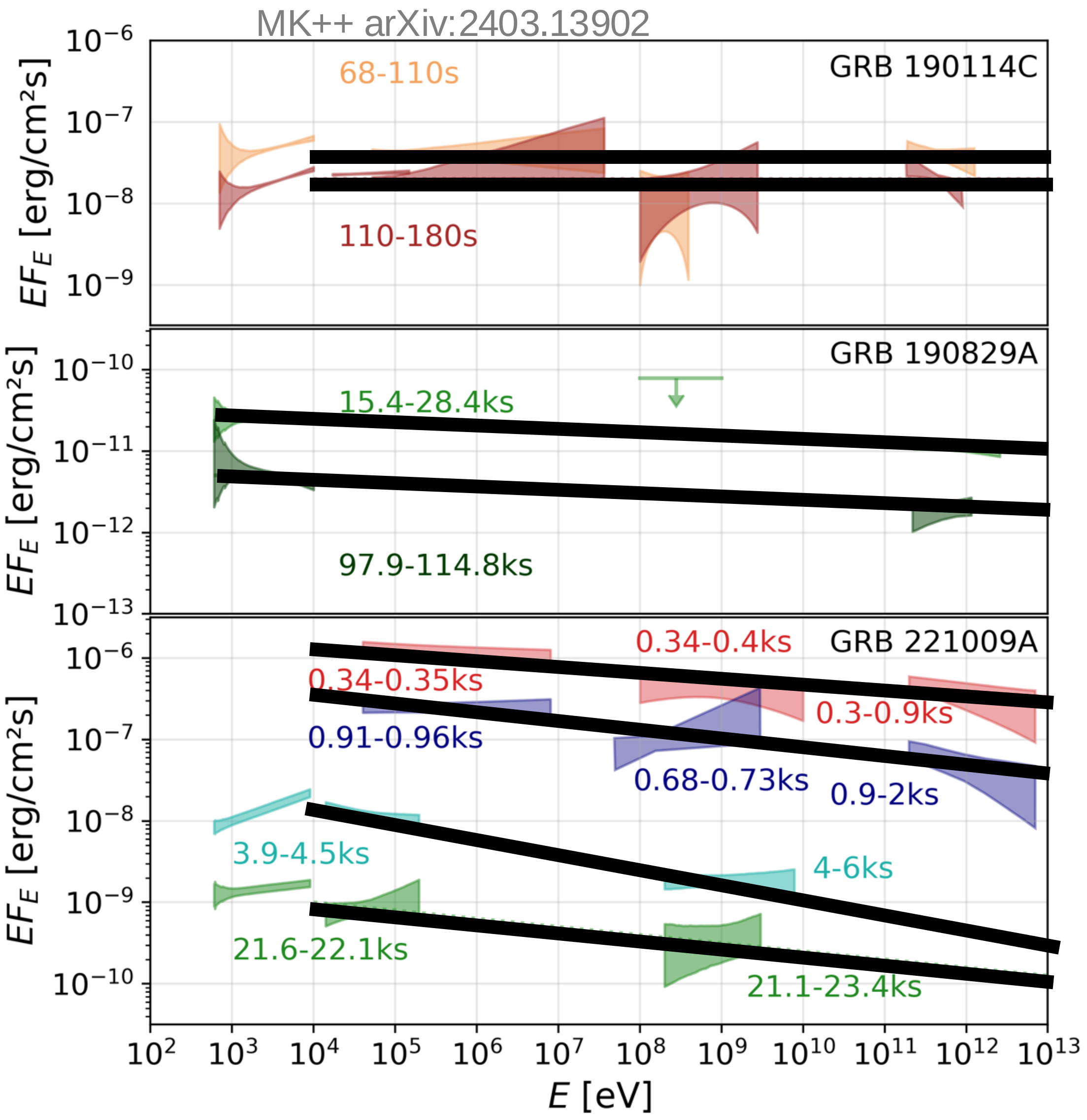

→ **MAGIC**

→ **H.E.S.S.**

→ **LHAASO**

- Single component?
- Flat power-law spectra extending up to >TeV
- No preference at counts-level

→ How to interpret this?

data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
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Tavani++ arXiv:2309.10515
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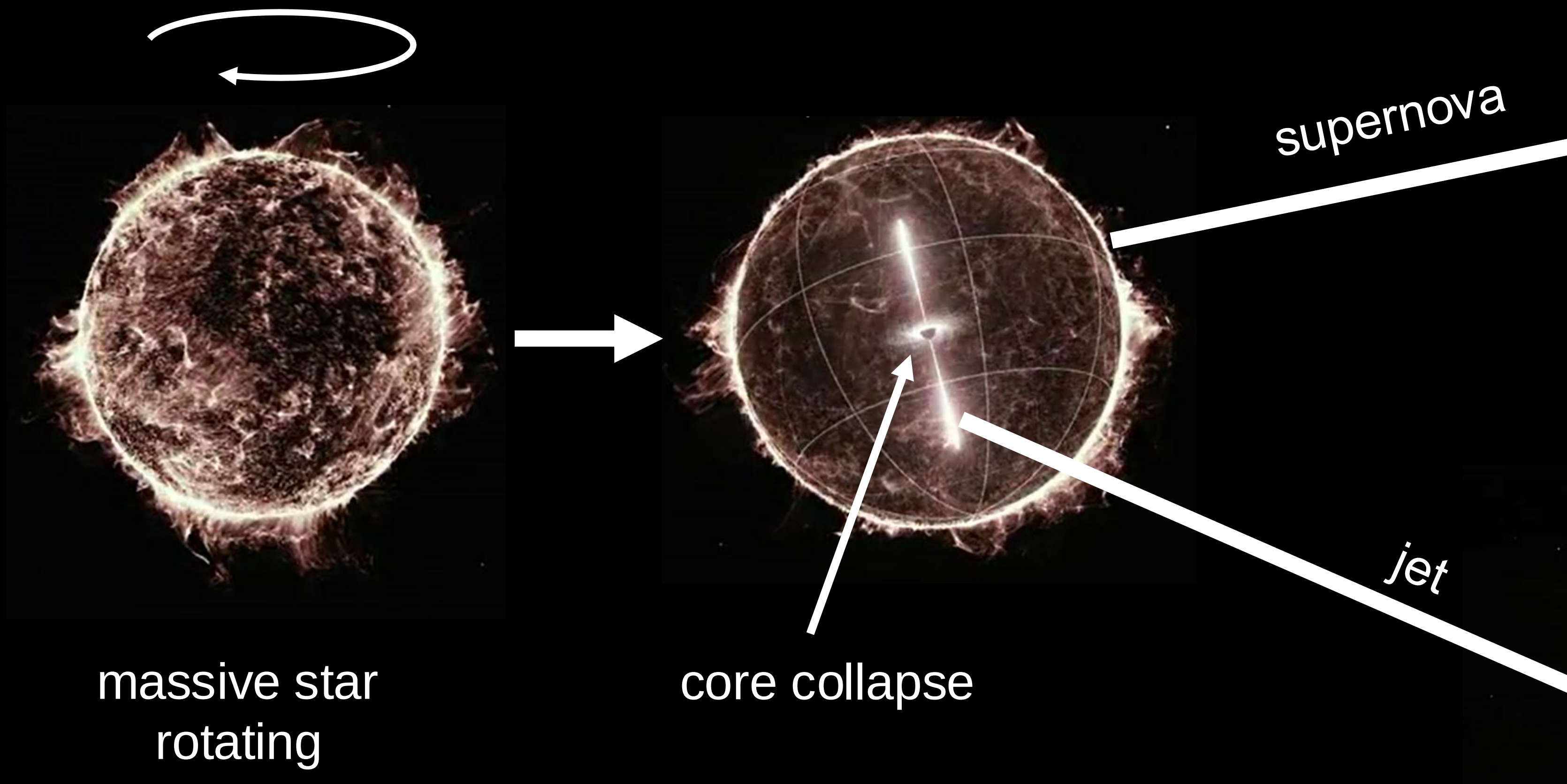
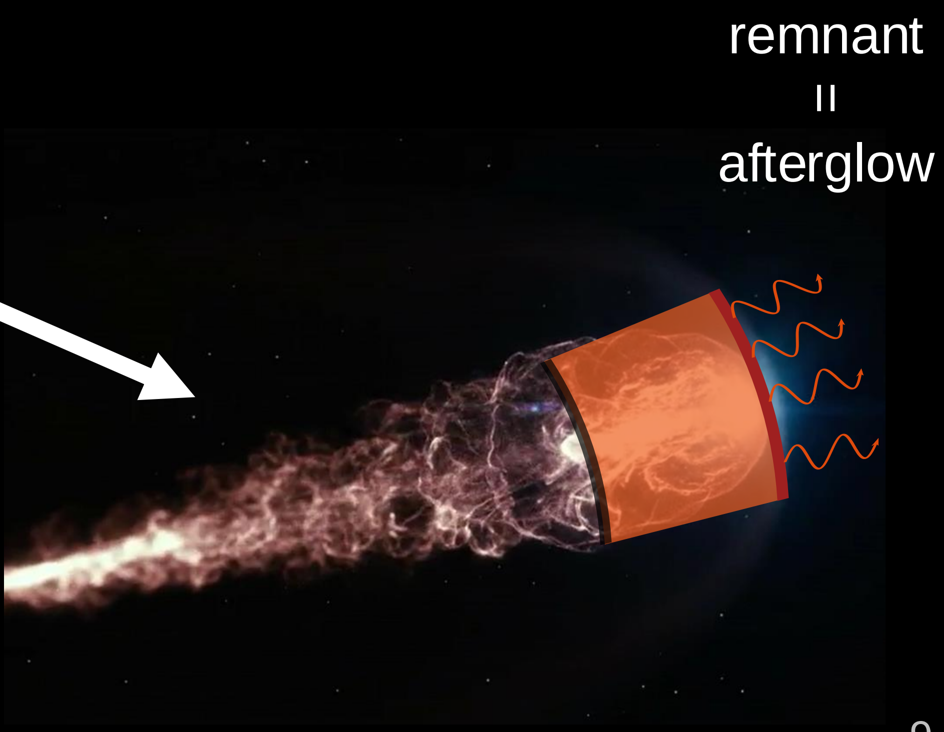
What are GRB afterglows?

Long GRB afterglows





images: DESY, Science Communication Lab

Why to care about GRB afterglows at VHE?

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Main observations:
photon spectra
→ **non-thermal**

Interpretation:
relativistic outflow
→ **relativistic shock**

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many assumptions

Non-thermal particle acceleration
at relativistic shocks

Why to care about GRB afterglows at VHE?

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Interpretation:
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New observations at VHE

Can test
many assumptions

Non-thermal particle acceleration
at relativistic shocks

Why to care about GRB afterglows at VHE?

Main observations:
photon spectra
→ non-thermal

Interpretation:
relativistic outflow
→ relativistic shock

New observations at VHE

Can test
many assumptions

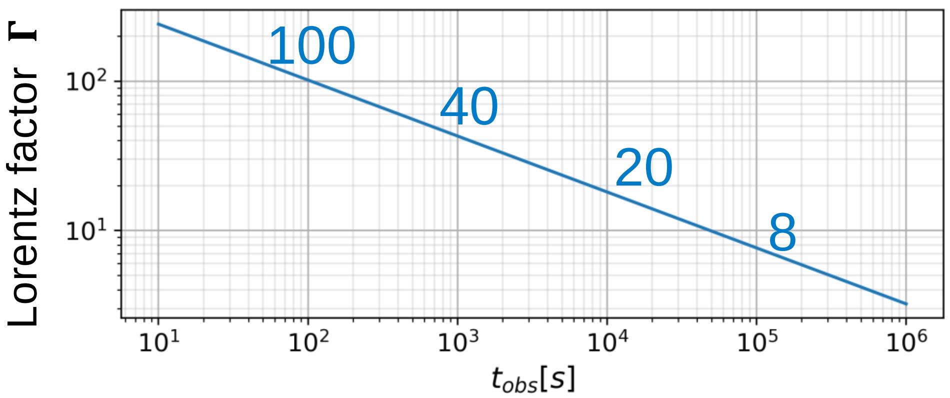
Non-thermal particle acceleration
at relativistic shocks

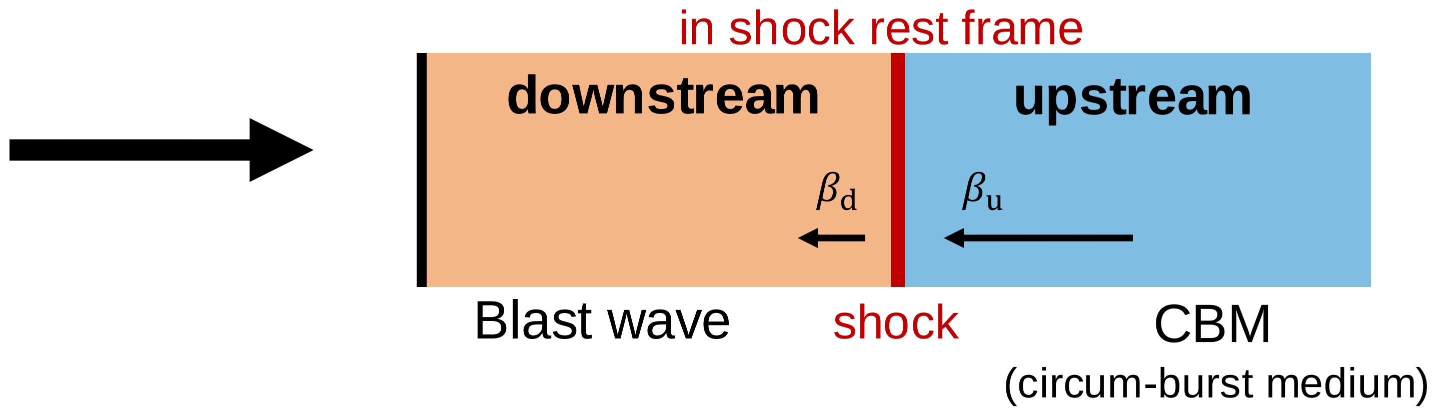
→ “*standard*” model does not perform well
→ we can learn something new!

The “*standard*” model: SSC radiation from a relativistic shock

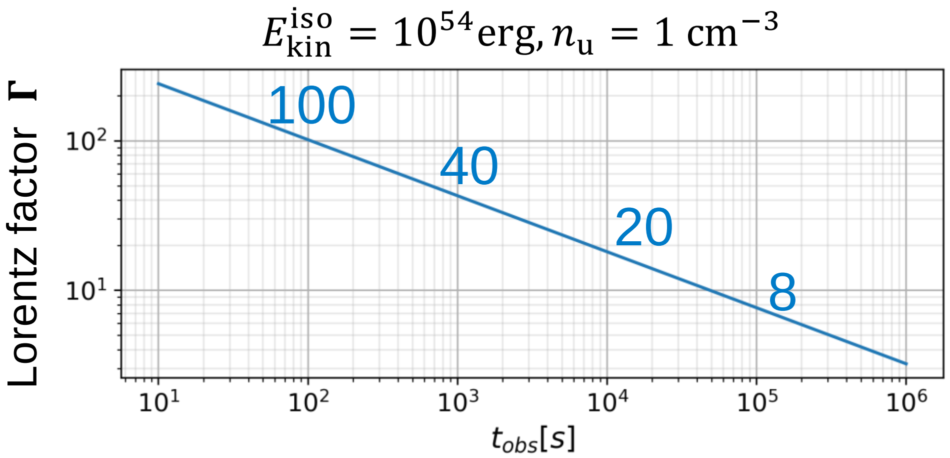
Radiation from a relativistic shock

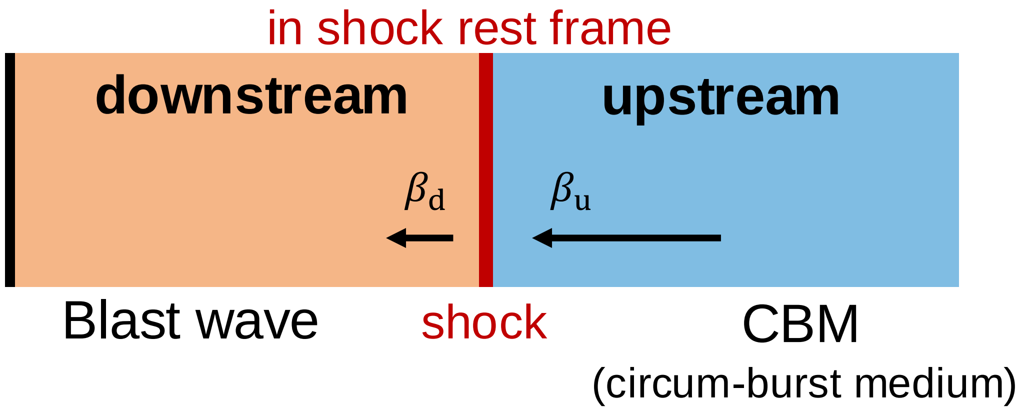
$E_{\rm kin}^{\rm iso} = 10^{54}\,{\rm erg}, n_{\rm u} = 1\ {\rm cm}^{-3}$

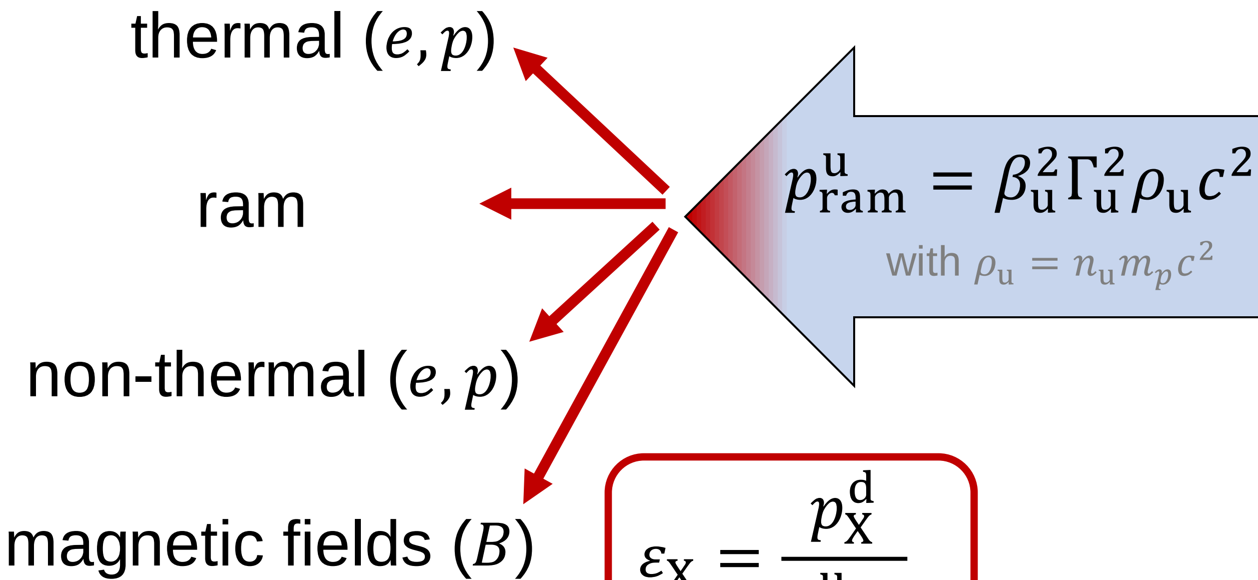




Radiation from a relativistic shock

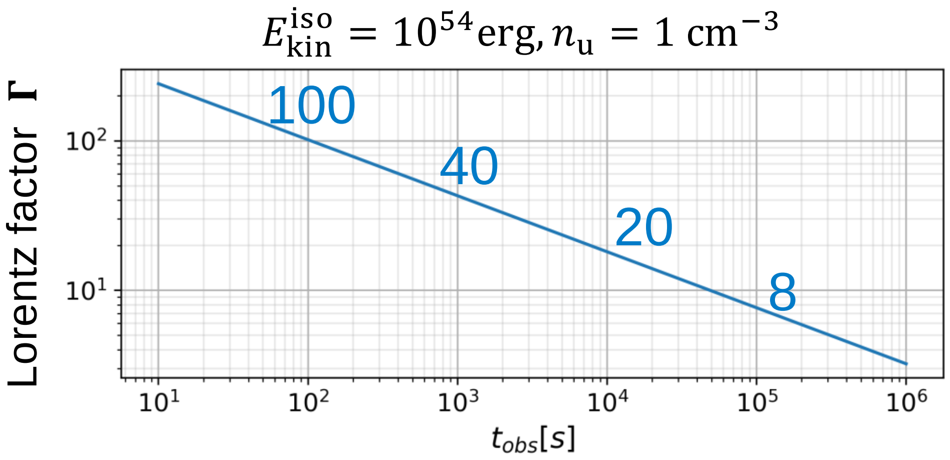


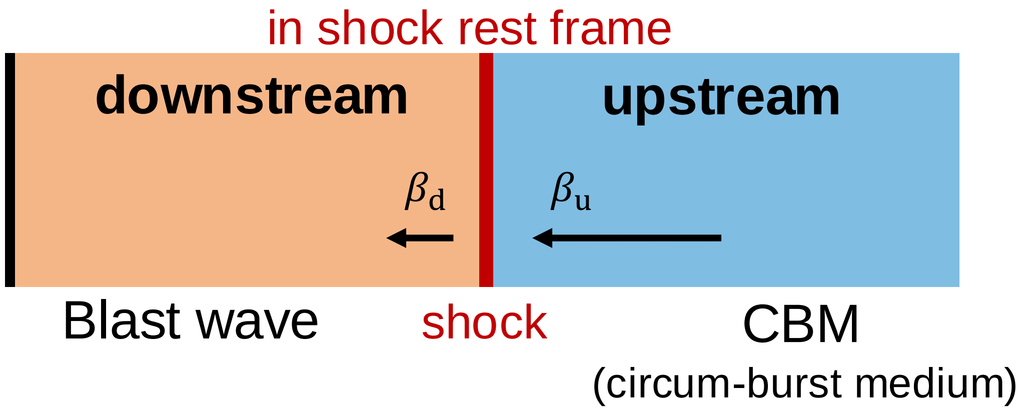


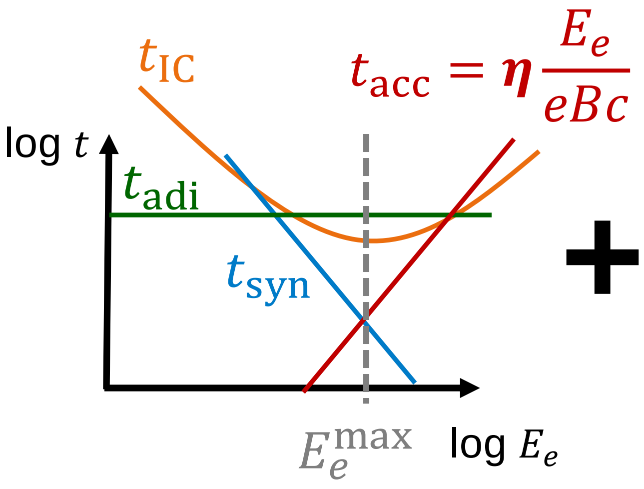


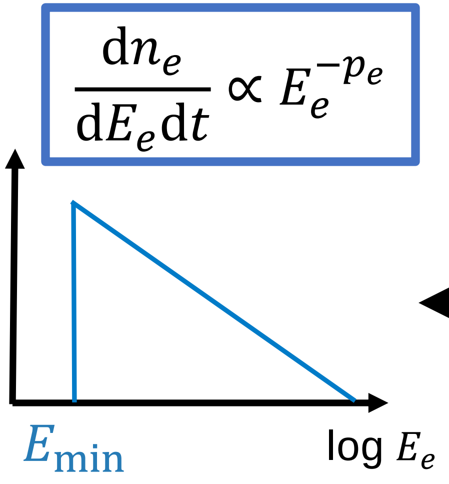
$$\varepsilon_{\mathrm{X}} = \frac{p_{\mathrm{X}}^{\mathrm{d}}}{p_{\mathrm{ram}}^{\mathrm{u}}}$$

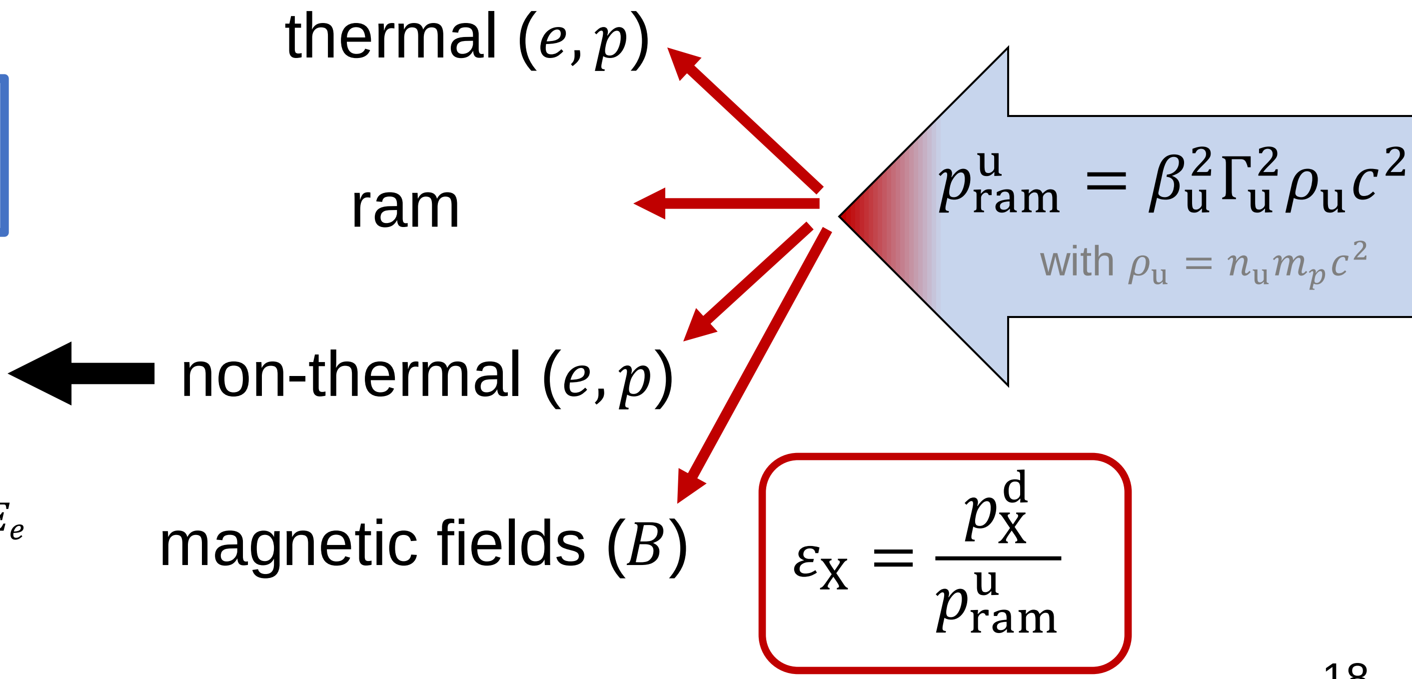
Radiation from a relativistic shock







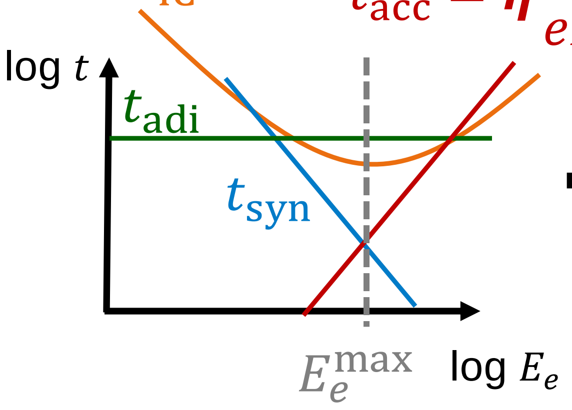




Radiation from a relativistic shock

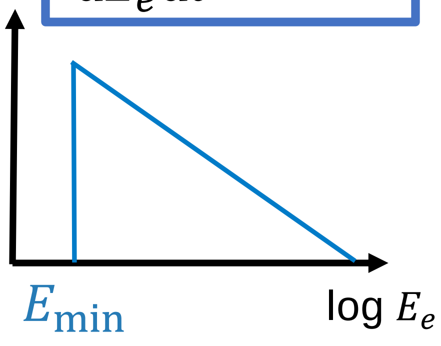
→ quasi-steady state

$$\frac{\mathrm{d}\boldsymbol{N}}{\mathrm{d}\boldsymbol{E}} \sim \boldsymbol{\tau} \quad \times \frac{\mathrm{d}N_e}{\mathrm{d}E_e \mathrm{d}t}$$



+

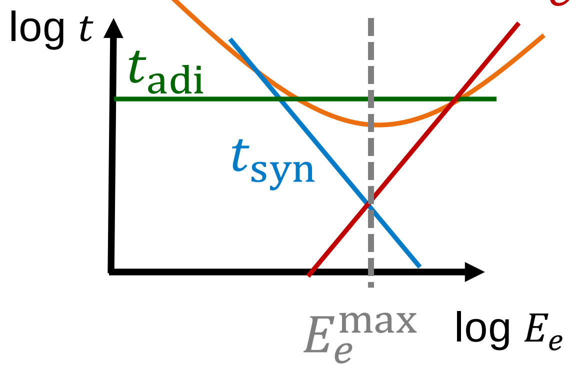
$$\frac{\mathrm{d}n_e}{\mathrm{d}E_e \mathrm{d}t} \propto E_e^{-p_e}$$



Radiation from a relativistic shock

→ quasi-steady state

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



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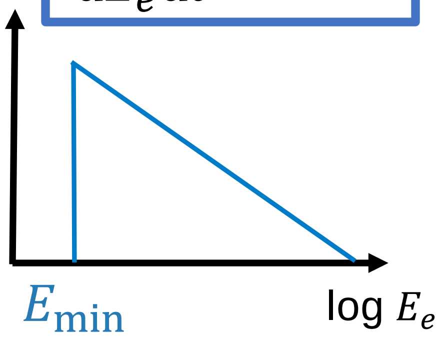
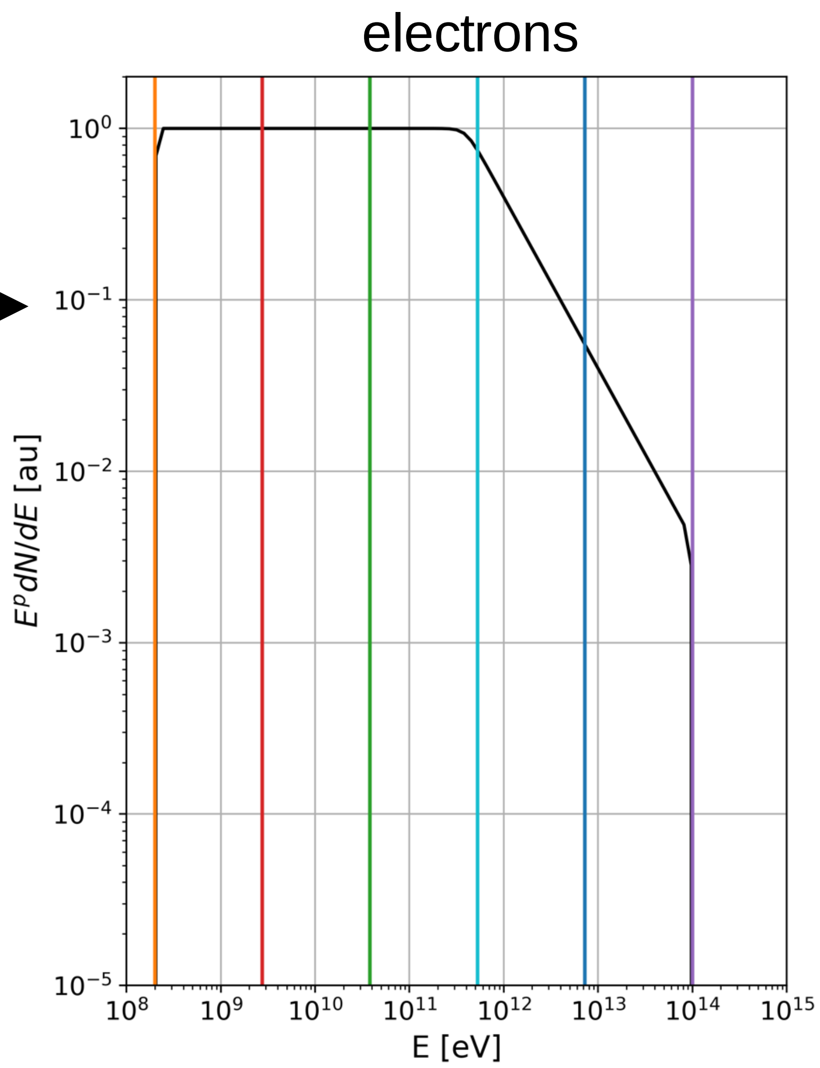
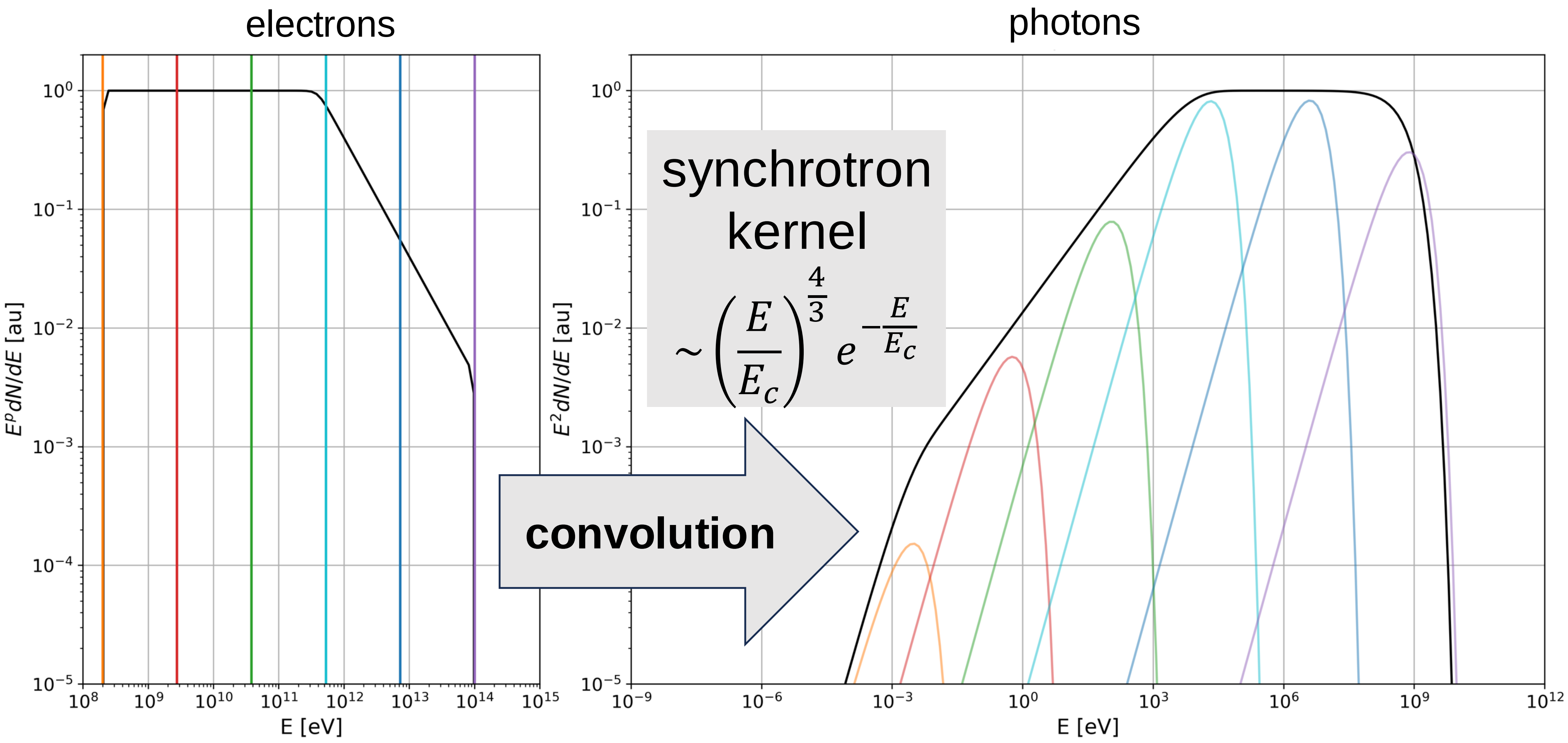
$$\frac{\mathrm{d}n_e}{\mathrm{d}E_e \mathrm{d}t} \propto E_e^{-p_e}$$



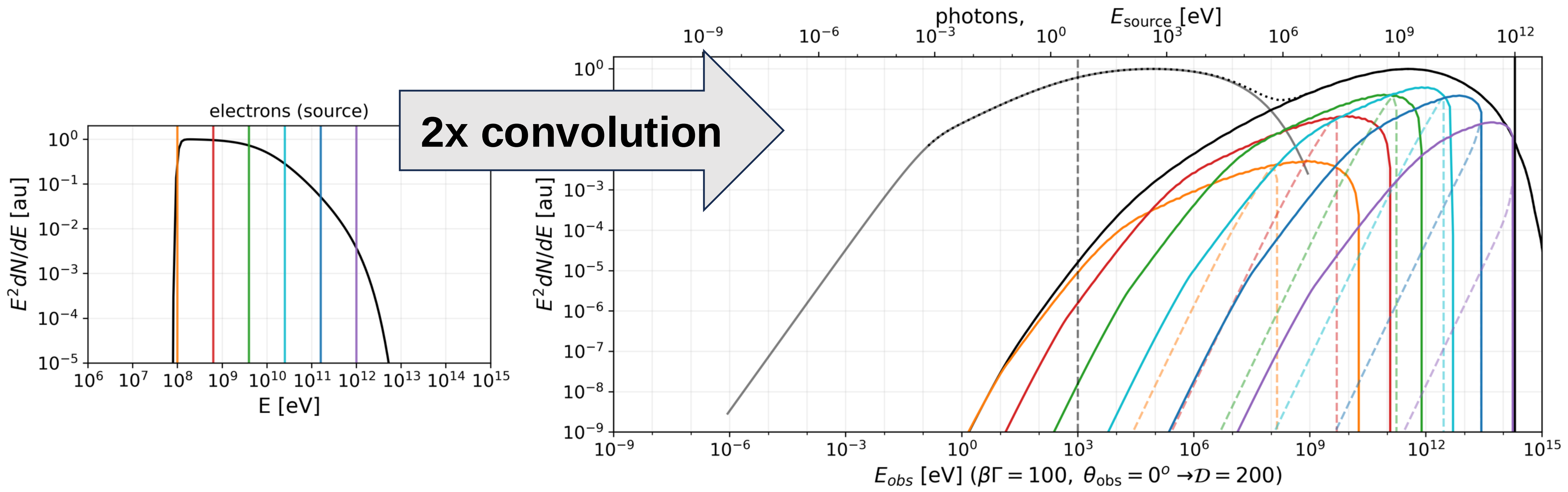


Radiation from a relativistic shock

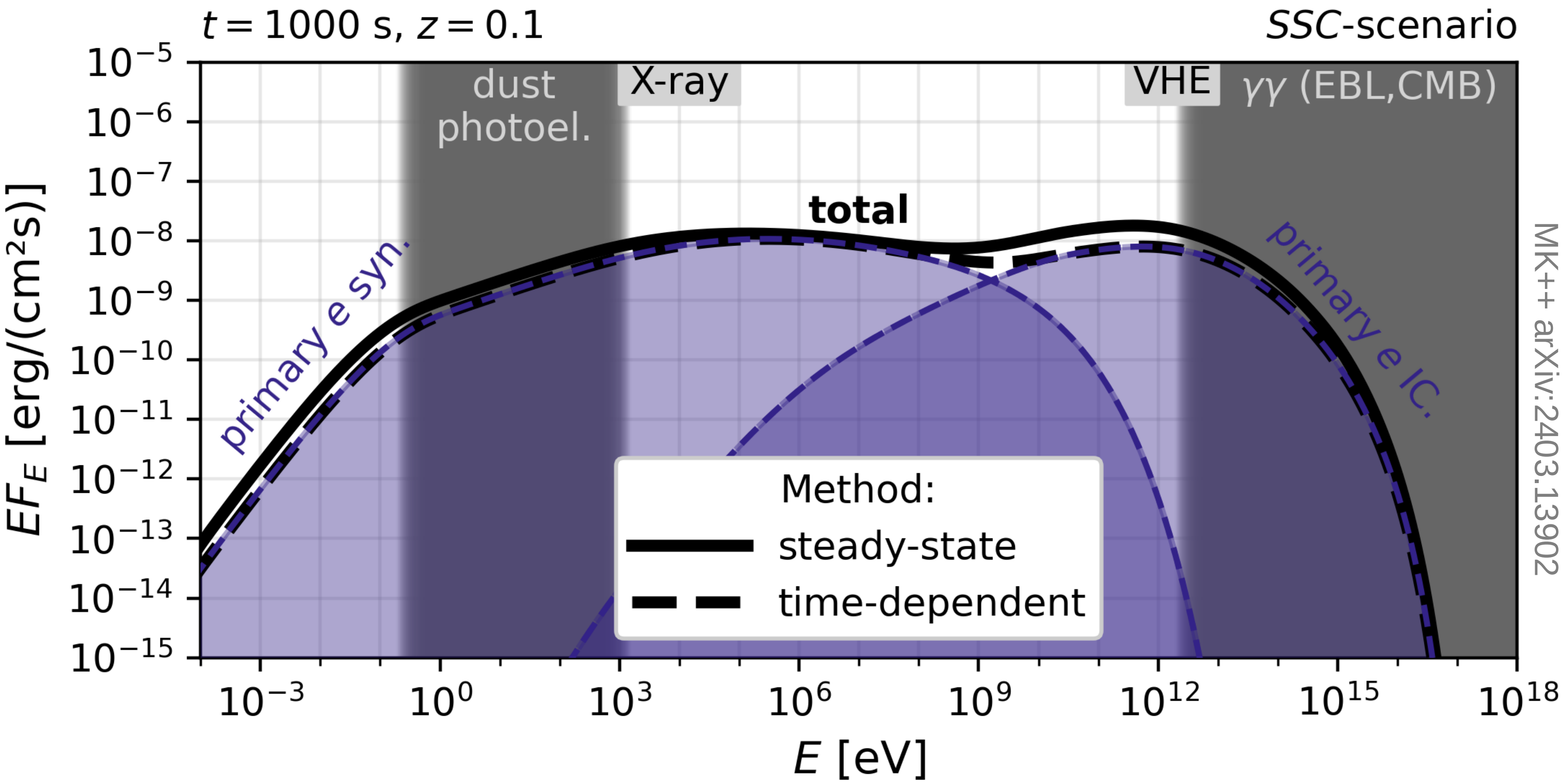


Radiation from a relativistic shock

- Synchrotron self-Compton (SSC)

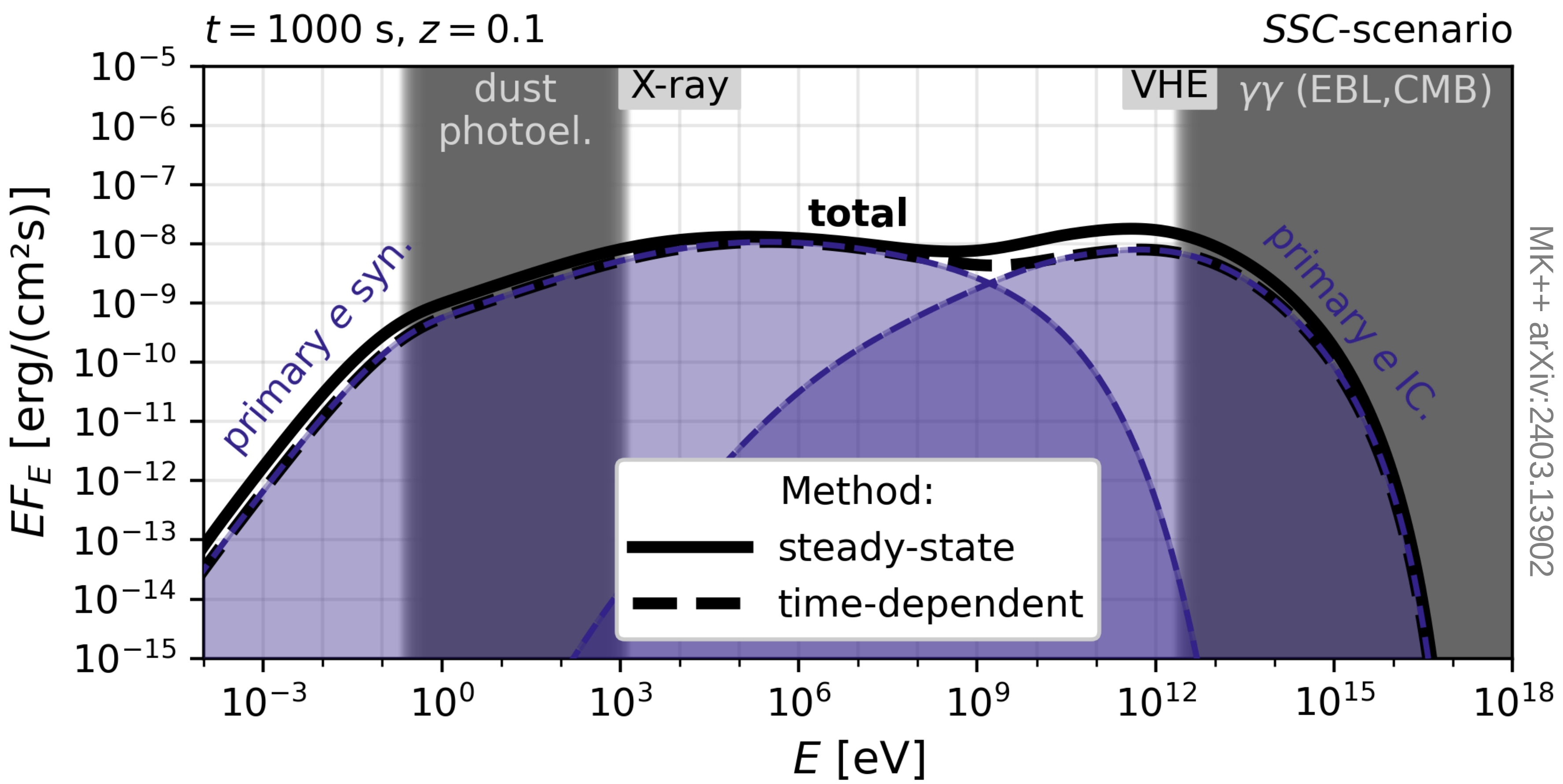


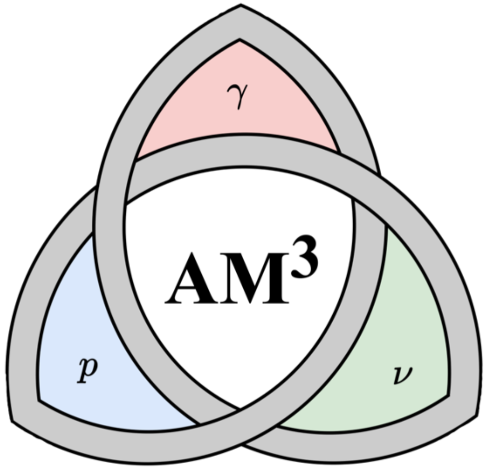
Time-dependent modelling:



→ show time-dependent results

Time-dependent modelling: AM^3





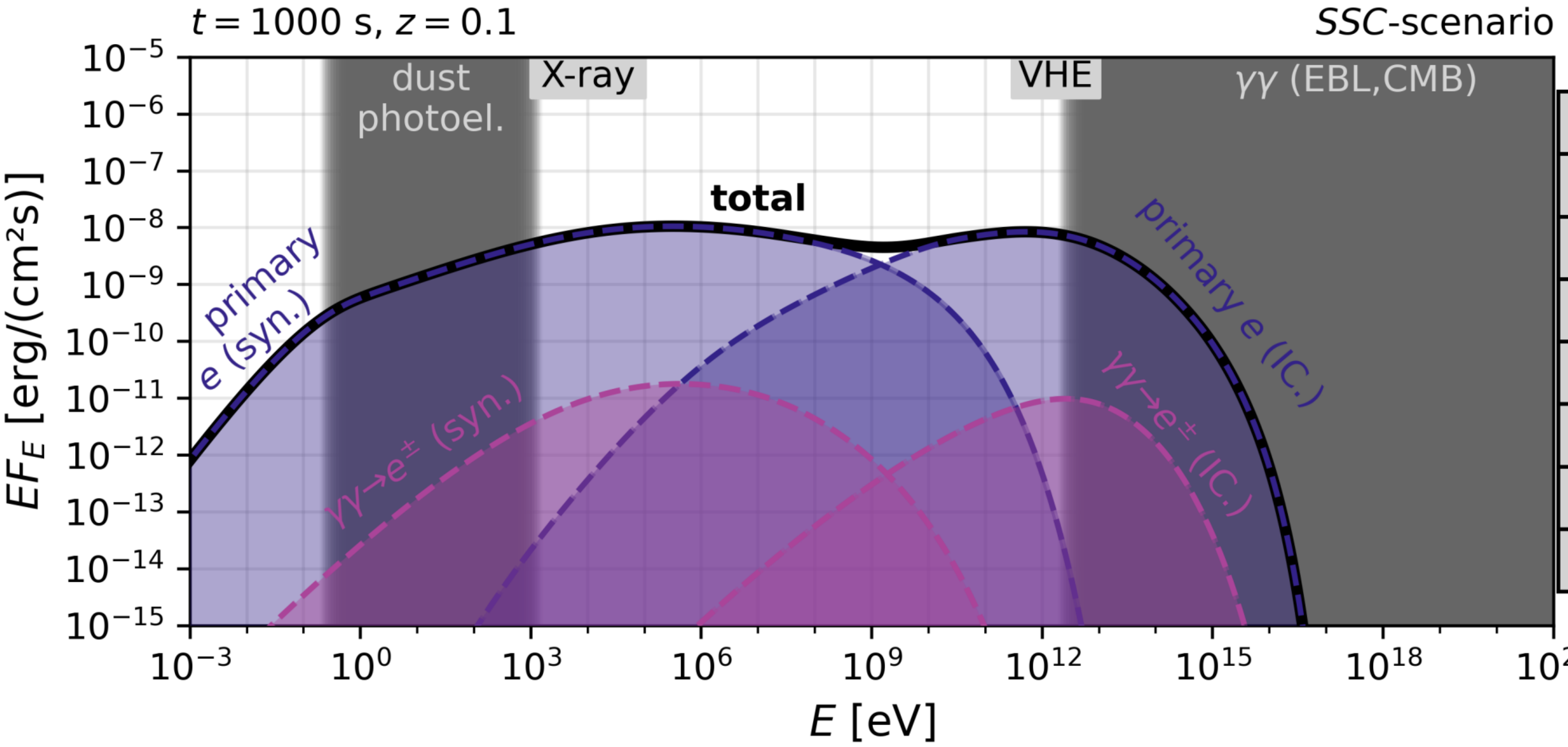
arXiv:2312.13371

- solve transport eq.
- publicly available
- documented
- fast
- trackable
- C++ and python3

→ talk to me

→ show time-dependent results

The SSC scenario



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

MK++ arXiv:2403.13902

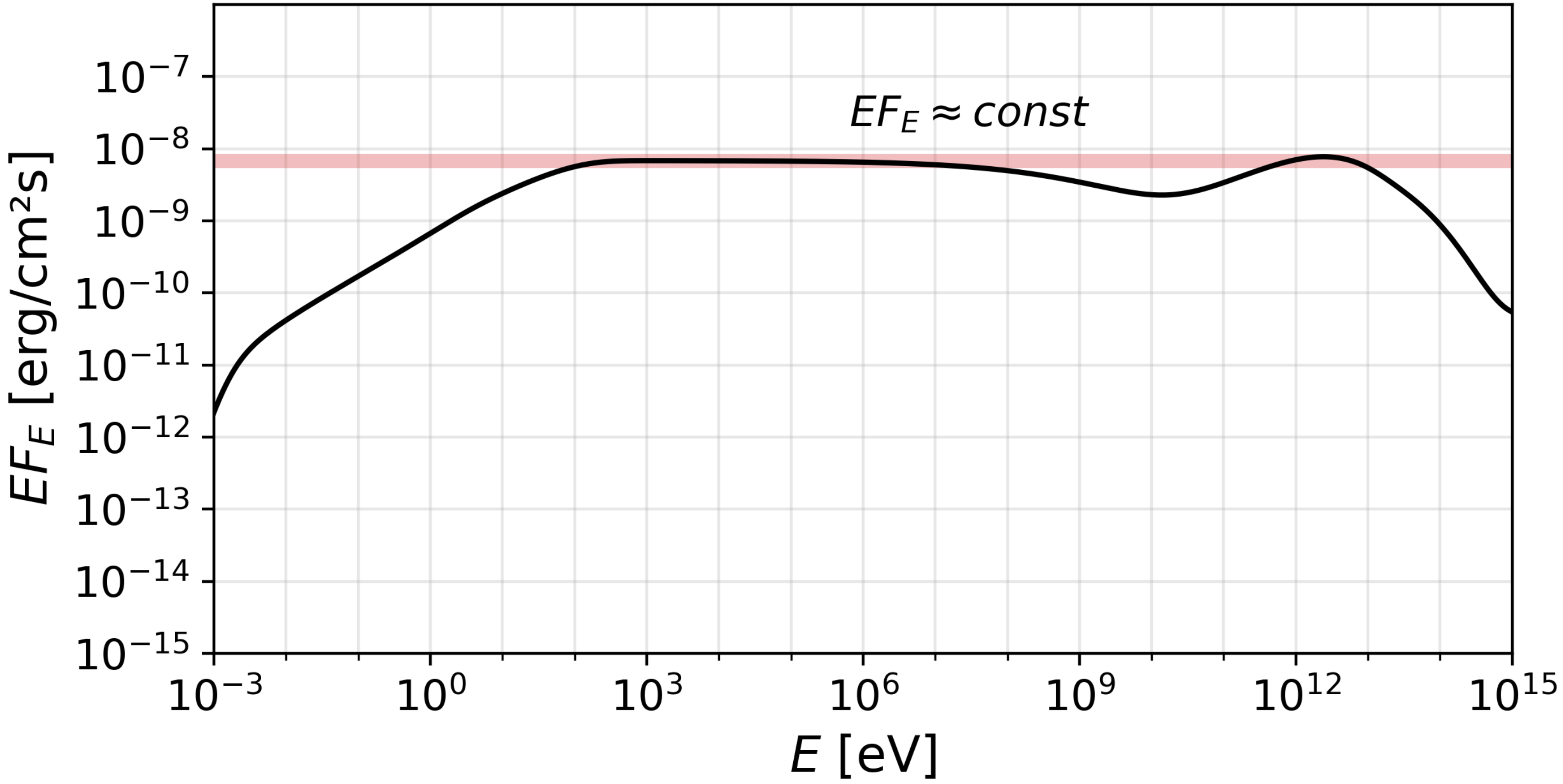
advantages	**limitations**

- bright	- Klein-Nishina suppression
	  - VHE slope soft
	  - fine-tuned height ratio

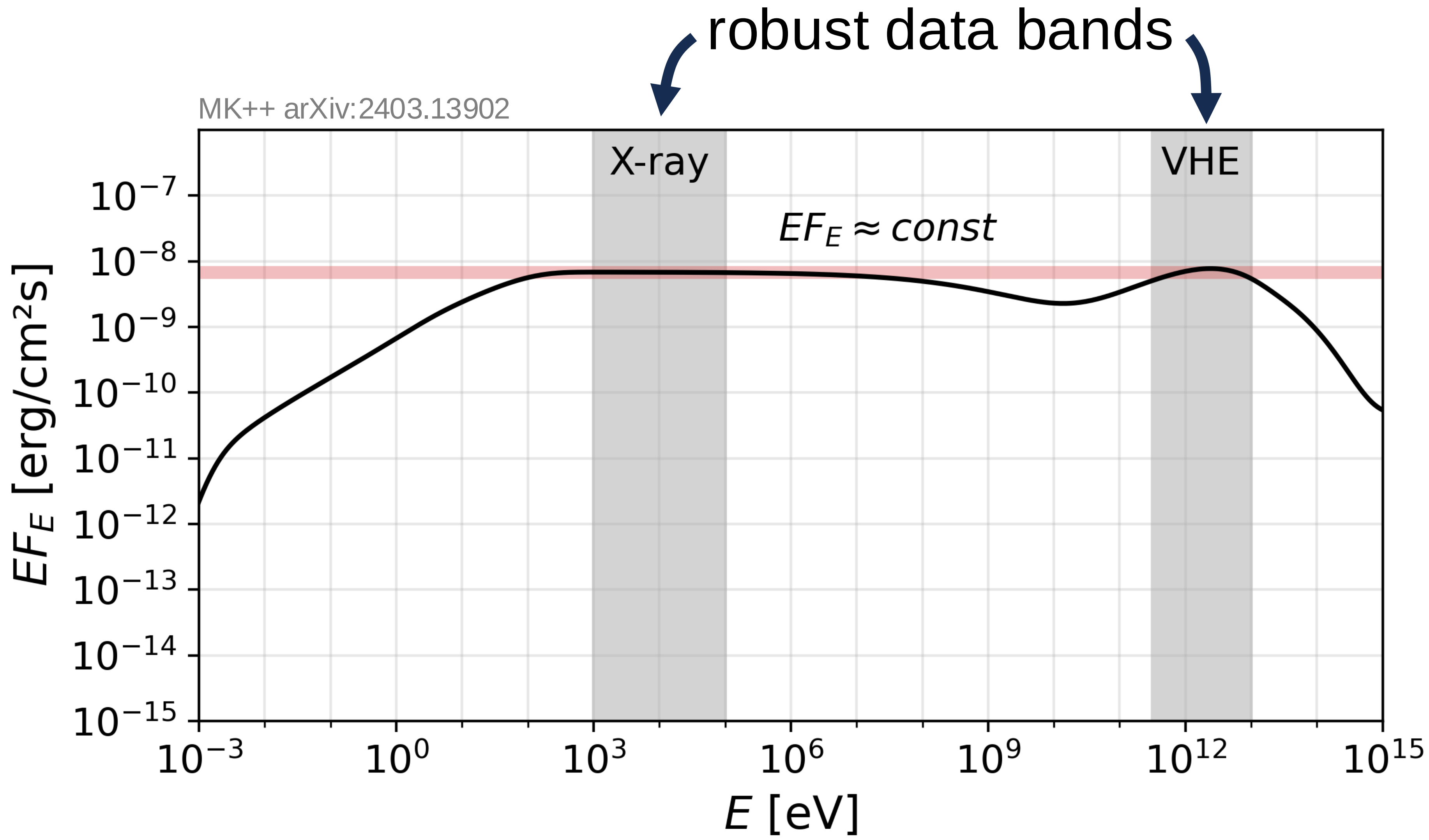
Alternatives?

Systematic parameter scan

MK++ arXiv:2403.13902

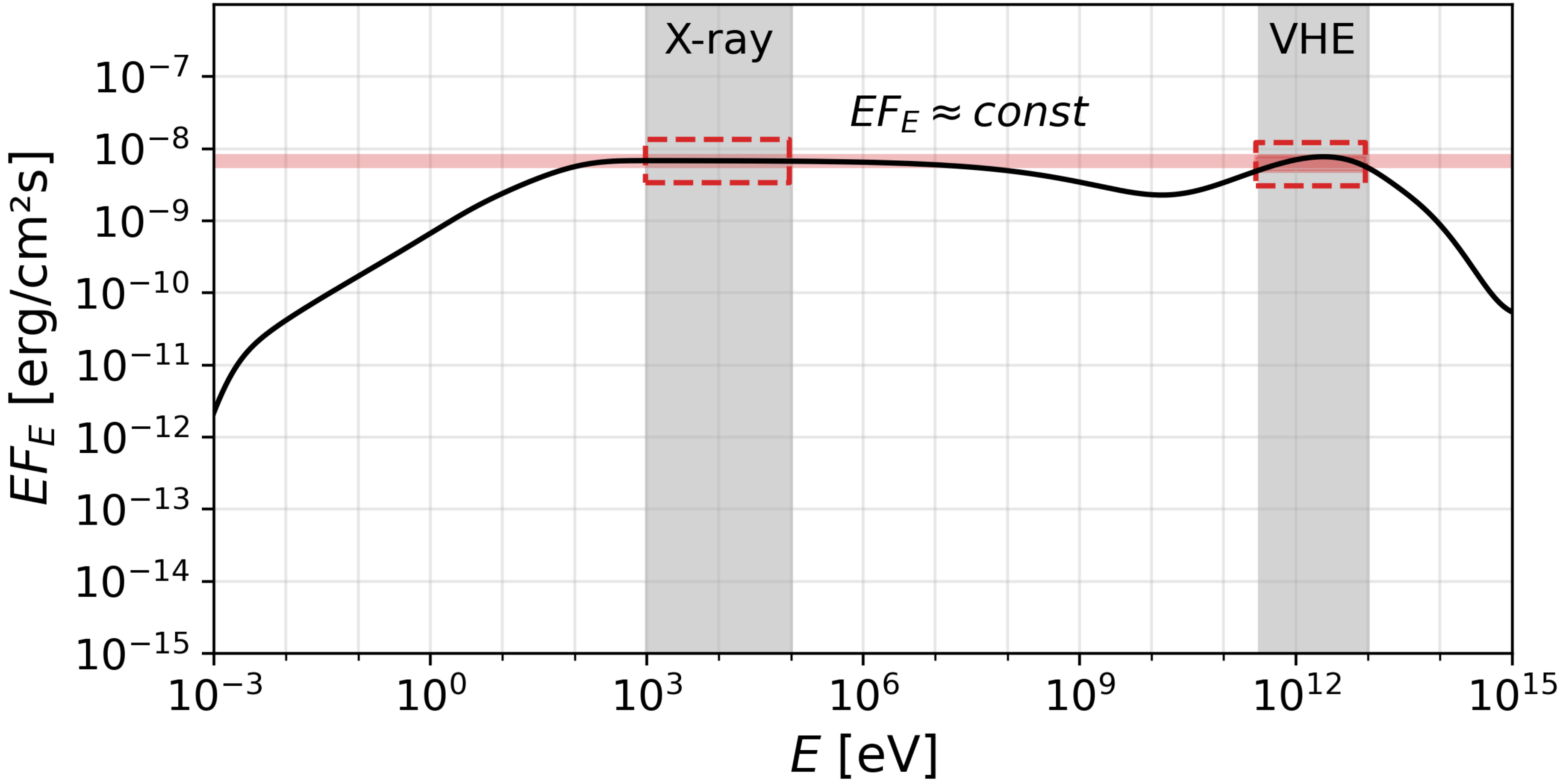


Systematic parameter scan



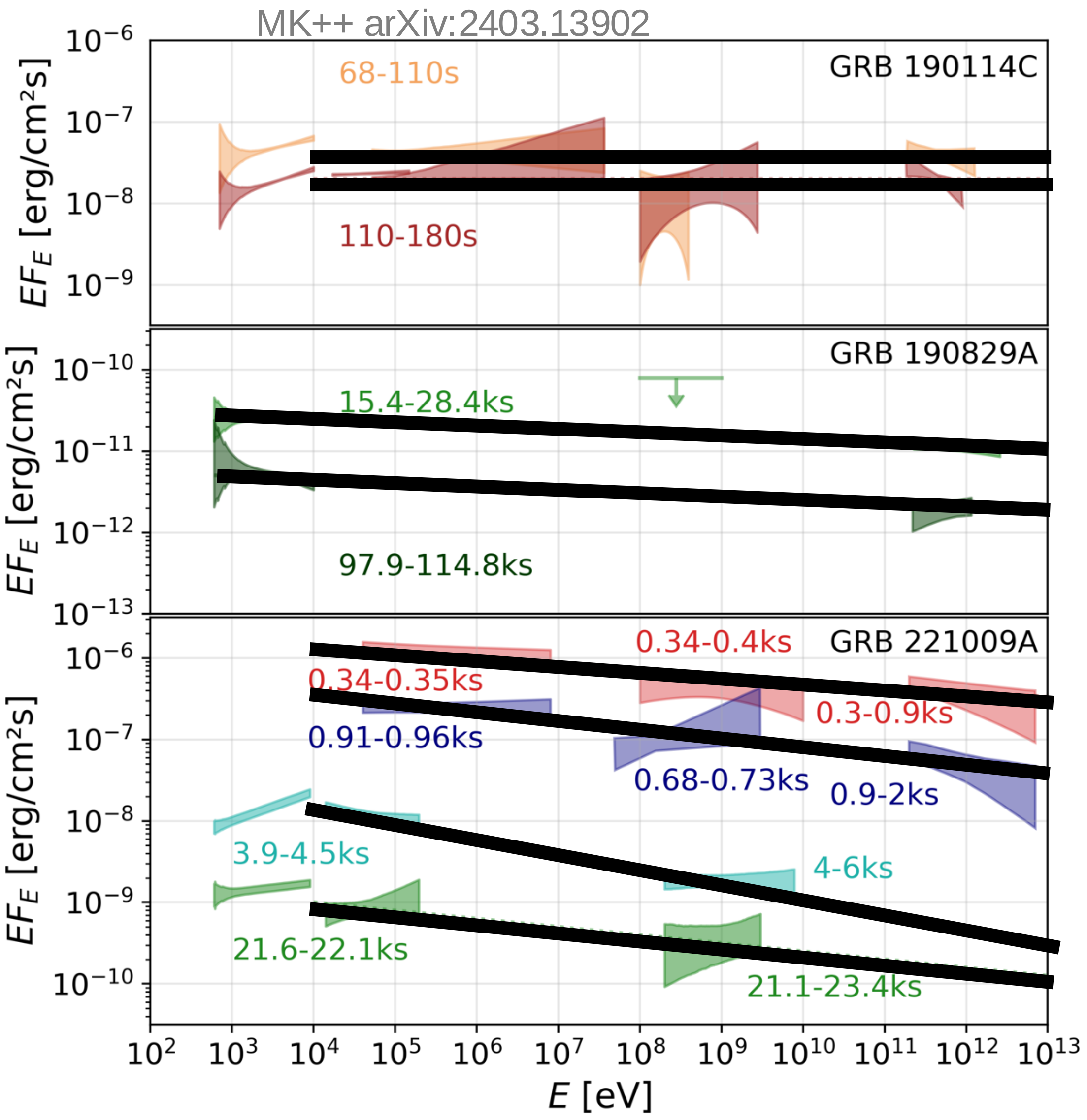
Systematic parameter scan

MK++ arXiv:2403.13902



selection criterion: contained in box

Systematic parameter scan



→ **MAGIC**

→ **H.E.S.S.**

→ **LHAASO**

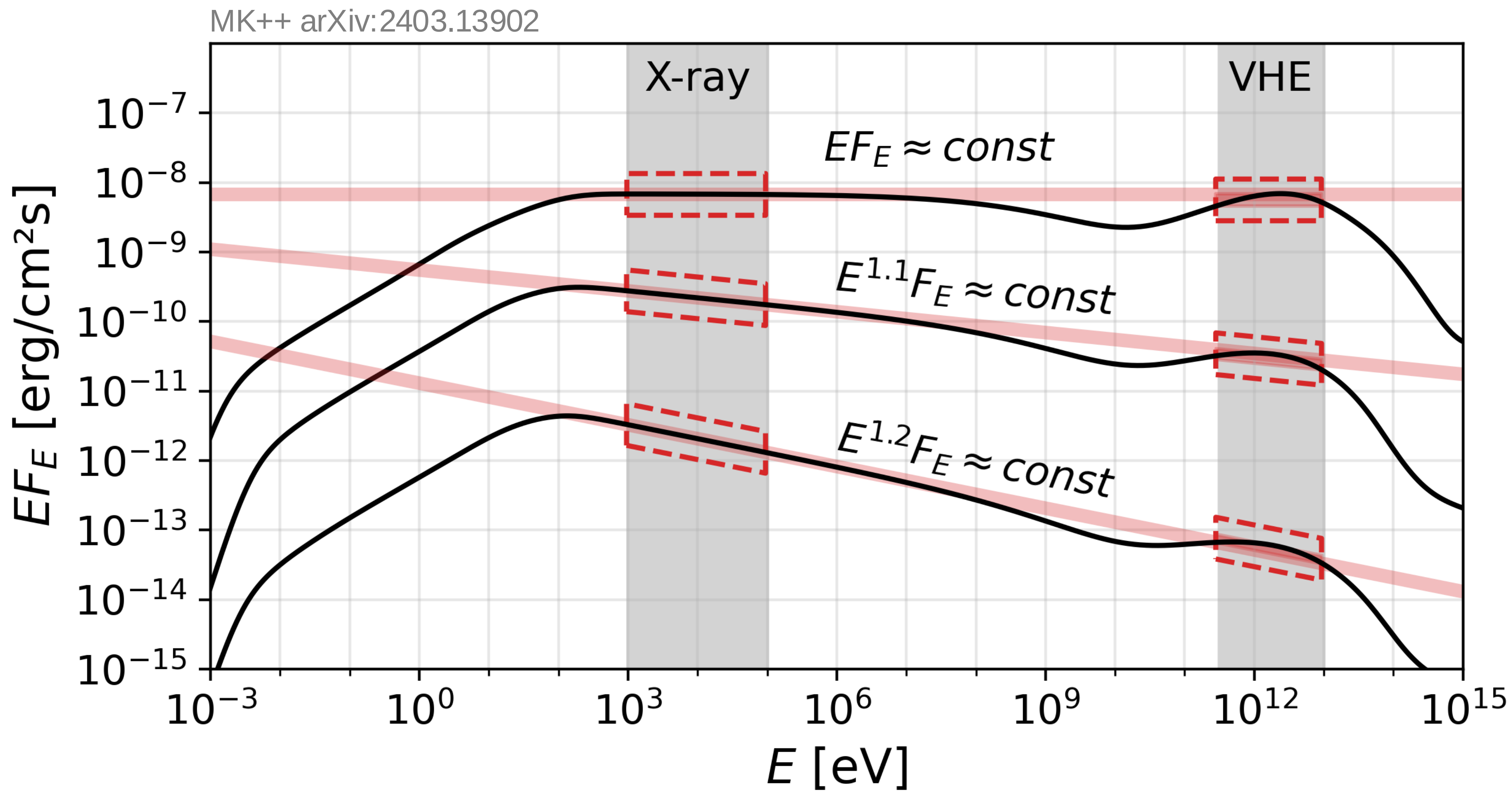
spectral index

$\gamma \approx 2$

$\gamma \approx 2.1$

$\gamma \approx 2.2$

Systematic parameter scan



spectral index

$\gamma \approx 2$

$\gamma \approx 2.1$

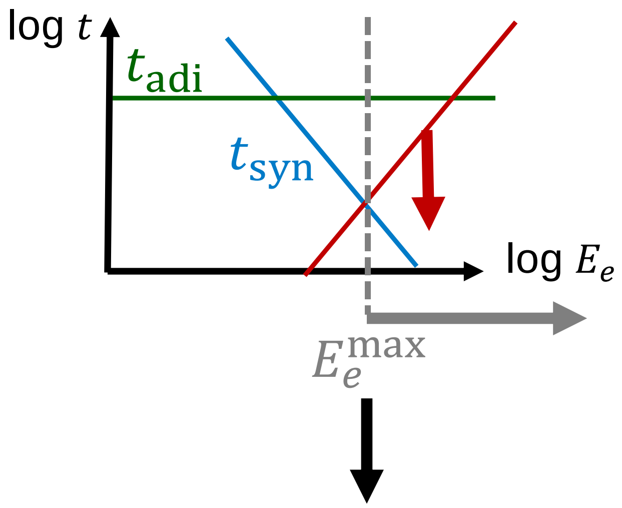
$\gamma \approx 2.2$

Beyond the SSC model?

Beyond the SSC model?

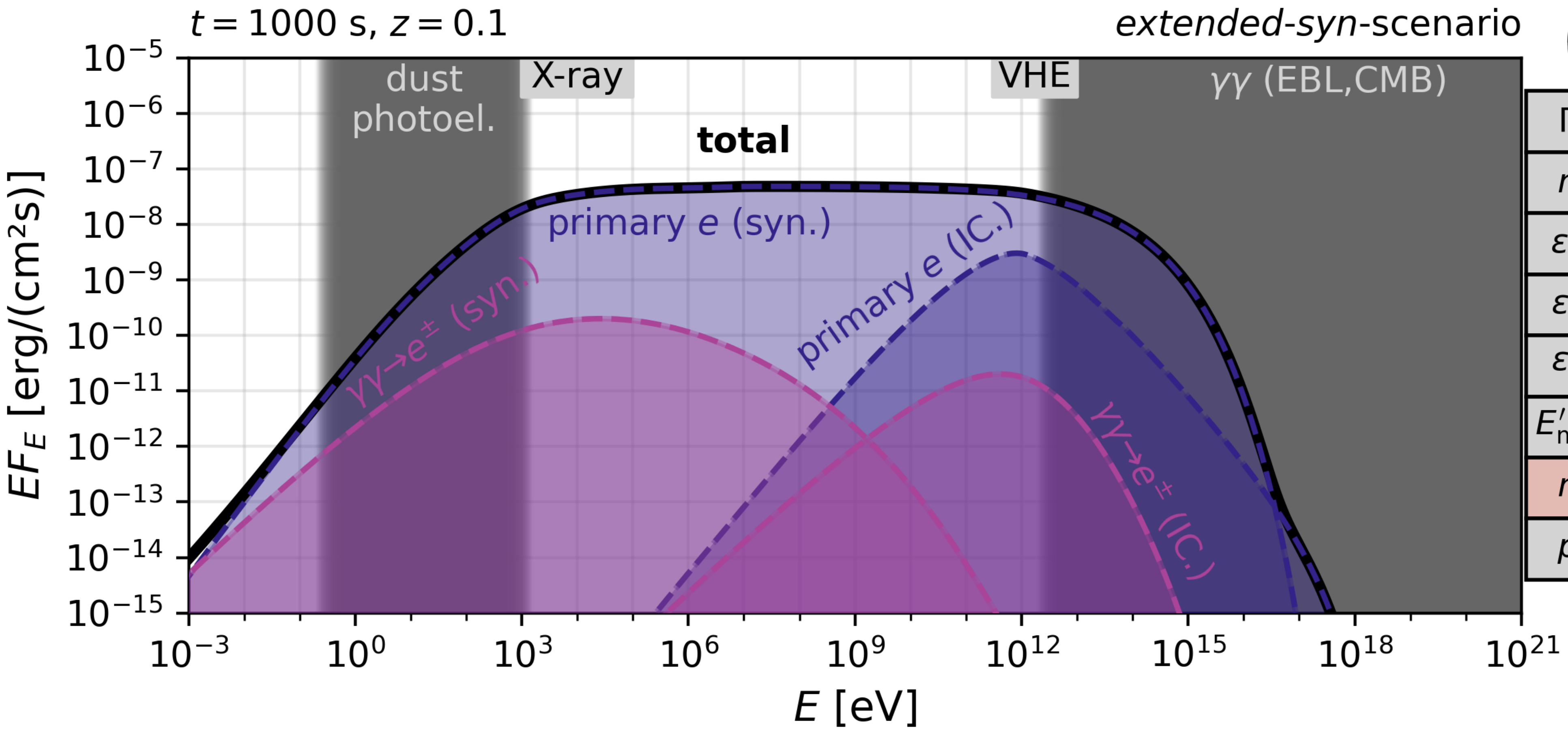
- faster than Bohm acceleration: $\eta \ll 1$
  - → 1 zone: violation of MHD conditions
    Kumar++ MNRAS 427 (2012), Huang++ APJ 925 (2022)
  - → 2 zone: decouple acceleration zone from radiation zone
    Khangulyan++ APJ 947 (2021)
  - → **extended electron synchrotron component**

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



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

Extended Synchrotron Scenario



Γ	50
n	1
ε_B	10^{-3}
ε_e	$10^{-1.5}$
ε_p	0
$E'_{\min}$	$10^{10.5}$
η	10^{-4}
p	2

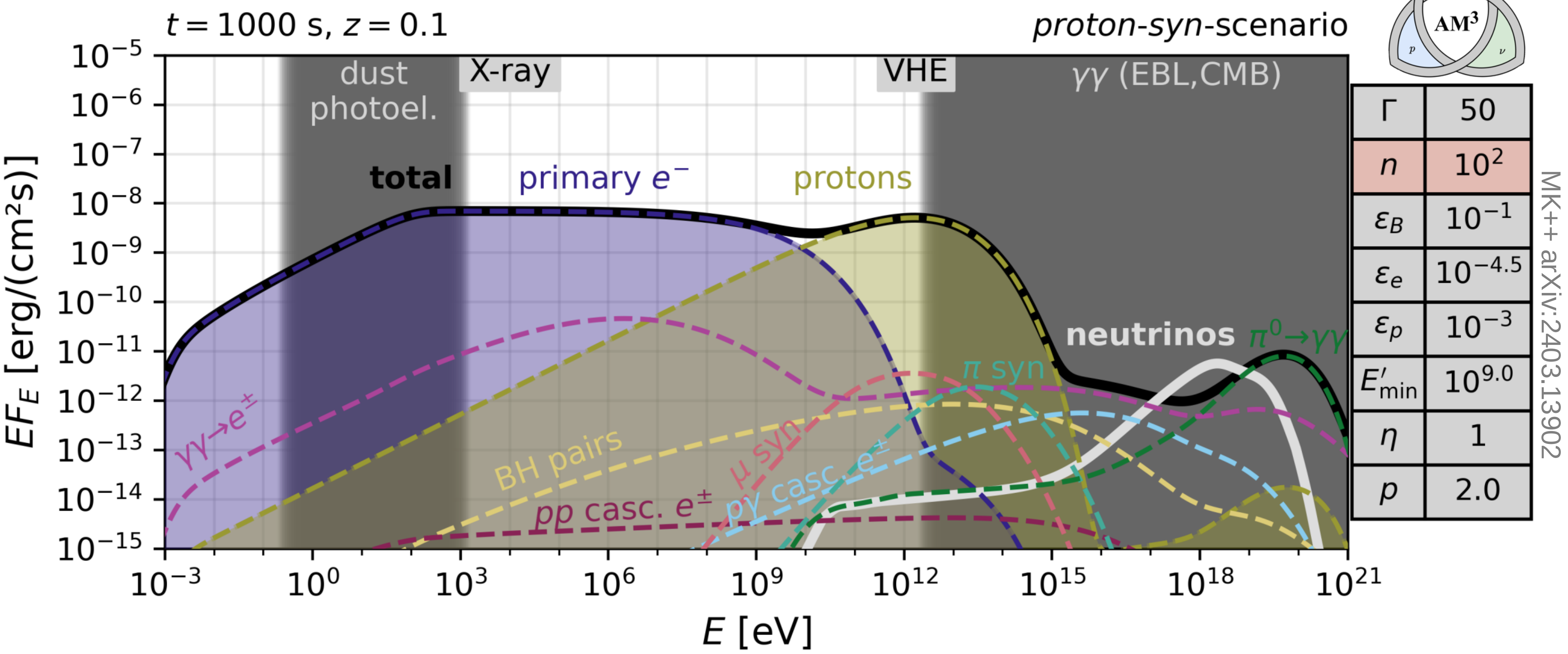
MK++ arXiv:2403.13902

advantages	**limitations**
- bright - directly yields single power law	- requires $\eta \ll 1$ (challenging in 1 zone)

Beyond the SSC model?

- faster than Bohm acceleration: $\eta \ll 1$
  - → 1 zone: violation of MHD conditions
    Kumar++ MNRAS 427 (2012), Huang++ APJ 925 (2022)
  - → 2 zone: decouple acceleration zone from radiation zone
    Khangulyan++ APJ 947 (2021)
  - → extended electron synchrotron component
- involve hadrons
  - → **proton synchrotron** as VHE (Isravel++ ApJ 955 (2023), Cao++ arXiv:2310.08845)

Proton synchrotron scenario



Γ	50
n	10^2
ε_B	10^{-1}
ε_e	$10^{-4.5}$
ε_p	10^{-3}
$E'_{\min}$	$10^{9.0}$
η	1
p	2.0

advantages	limitations
- bright	- fine-tuned exponential cut-off → peak flux, peak energy, cut-off shape

Beyond the SSC model?

- faster than Bohm acceleration: $\eta \ll 1$
  - → 1 zone: violation of MHD conditions
    Kumar++ MNRAS 427 (2012), Huang++ APJ 925 (2022)
  - → 2 zone: decouple acceleration zone from radiation zone
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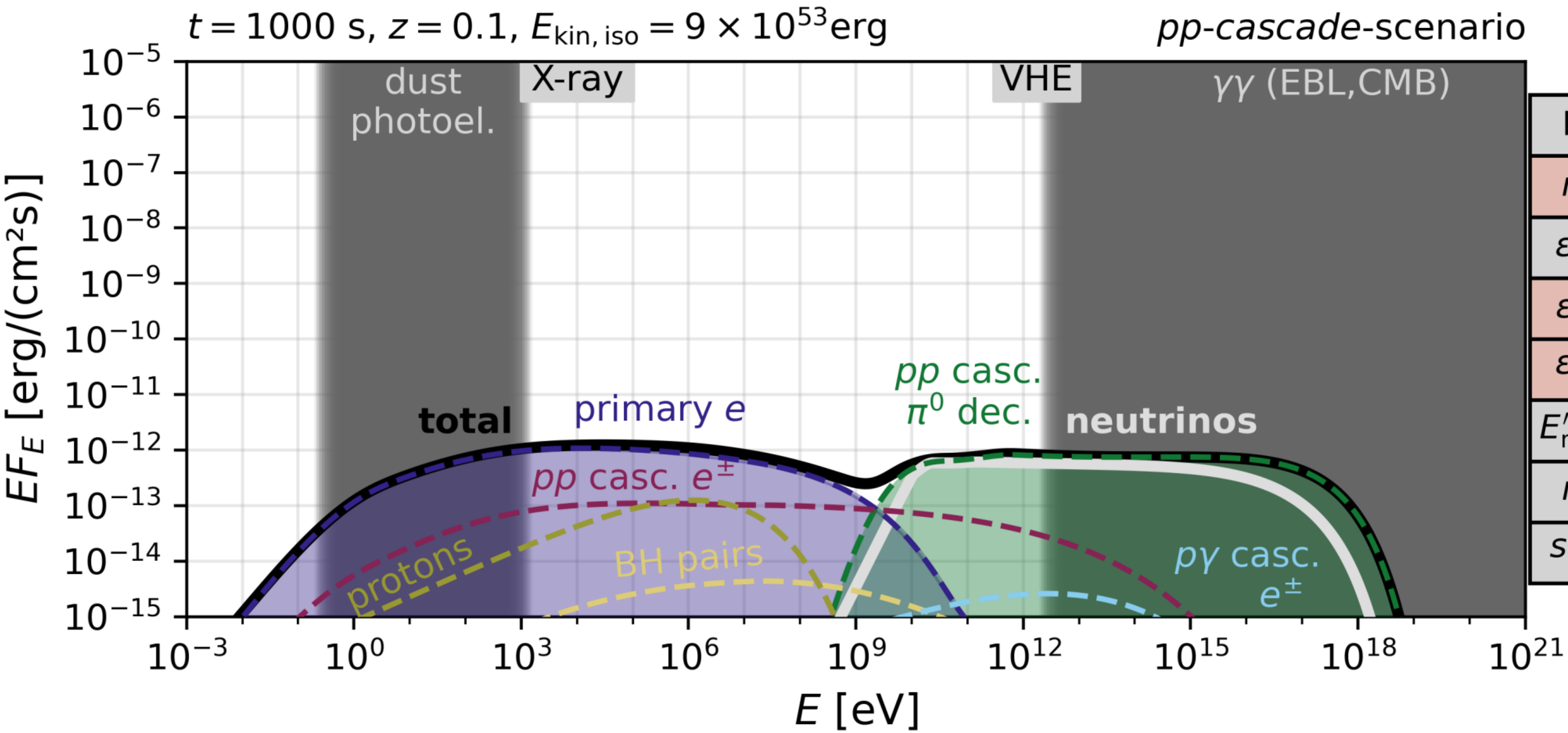
  - → extended electron synchrotron component
- involve hadrons
  - → proton synchrotron as VHE (Isravel++ ApJ 955 (2023), Cao++ arXiv:2310.08845)
  - → **pp-cascade**: larger densities such as in molecular clouds

pp-cascade scenario



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

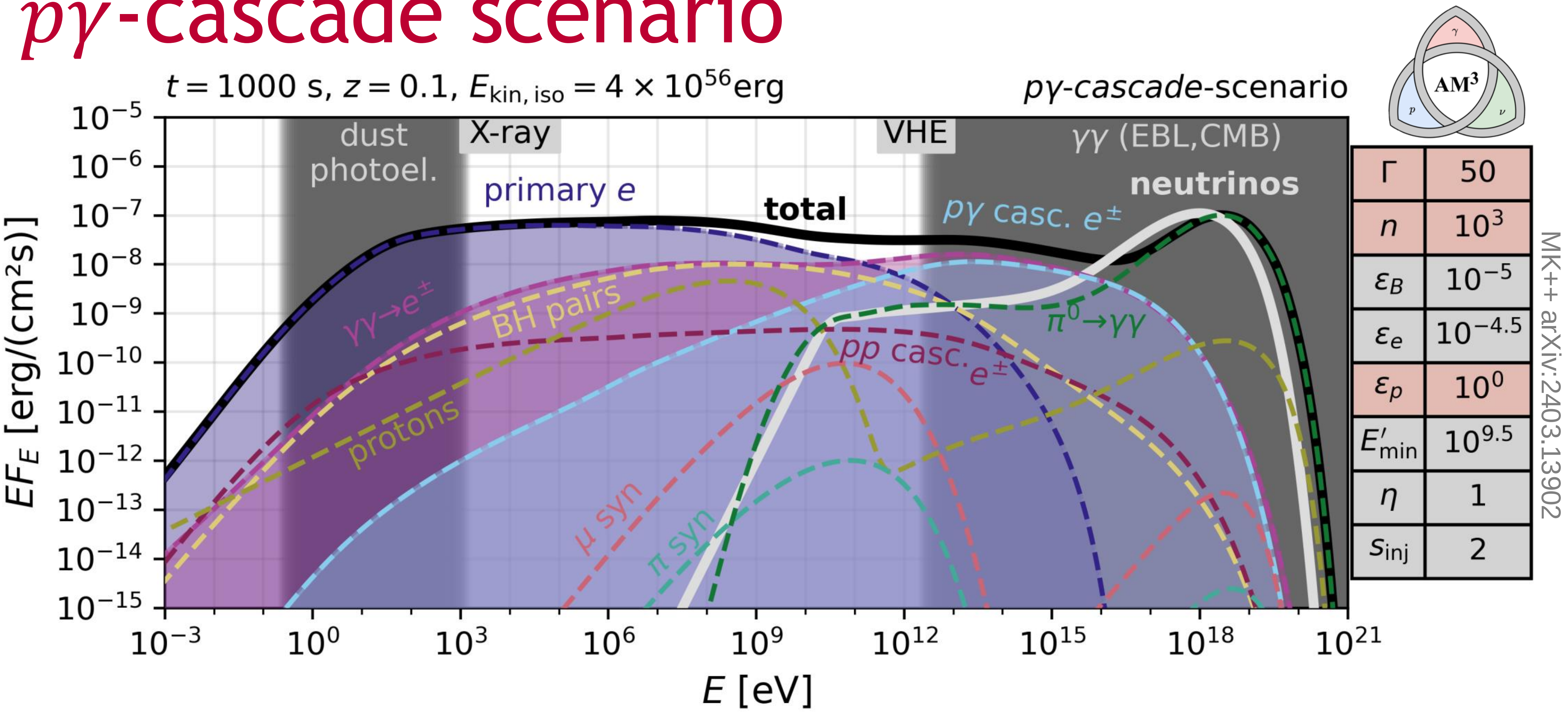
MK++ arXiv:2403.13902

advantages	**limitations**
- flat VHE component ($\gg 10$ TeV)	- inefficient - fine-tuned baryonic loading ($\varepsilon_e/\varepsilon_p \ll 1$)

Beyond the SSC model?

- faster than Bohm acceleration: $\eta \ll 1$
  - → 1 zone: violation of MHD conditions
    Kumar++ MNRAS 427 (2012), Huang++ APJ 925 (2022)
  - → 2 zone: decouple acceleration zone from radiation zone
    Khangulyan++ APJ 947 (2021)
  - → extended electron synchrotron component
- involve hadrons
  - → proton synchrotron as VHE (Isravel++ ApJ 955 (2023), Cao++ arXiv:2310.08845)
  - → pp-cascade: larger densities such as in molecular clouds
  - → **$p\gamma$-cascade**: increase injected power

$p\gamma$-cascade scenario



advantages	**limitations**
- bright	- extreme density + energy requirements - fine-tuned baryonic loading ($\varepsilon_e/\varepsilon_p \ll 1$)

Summary

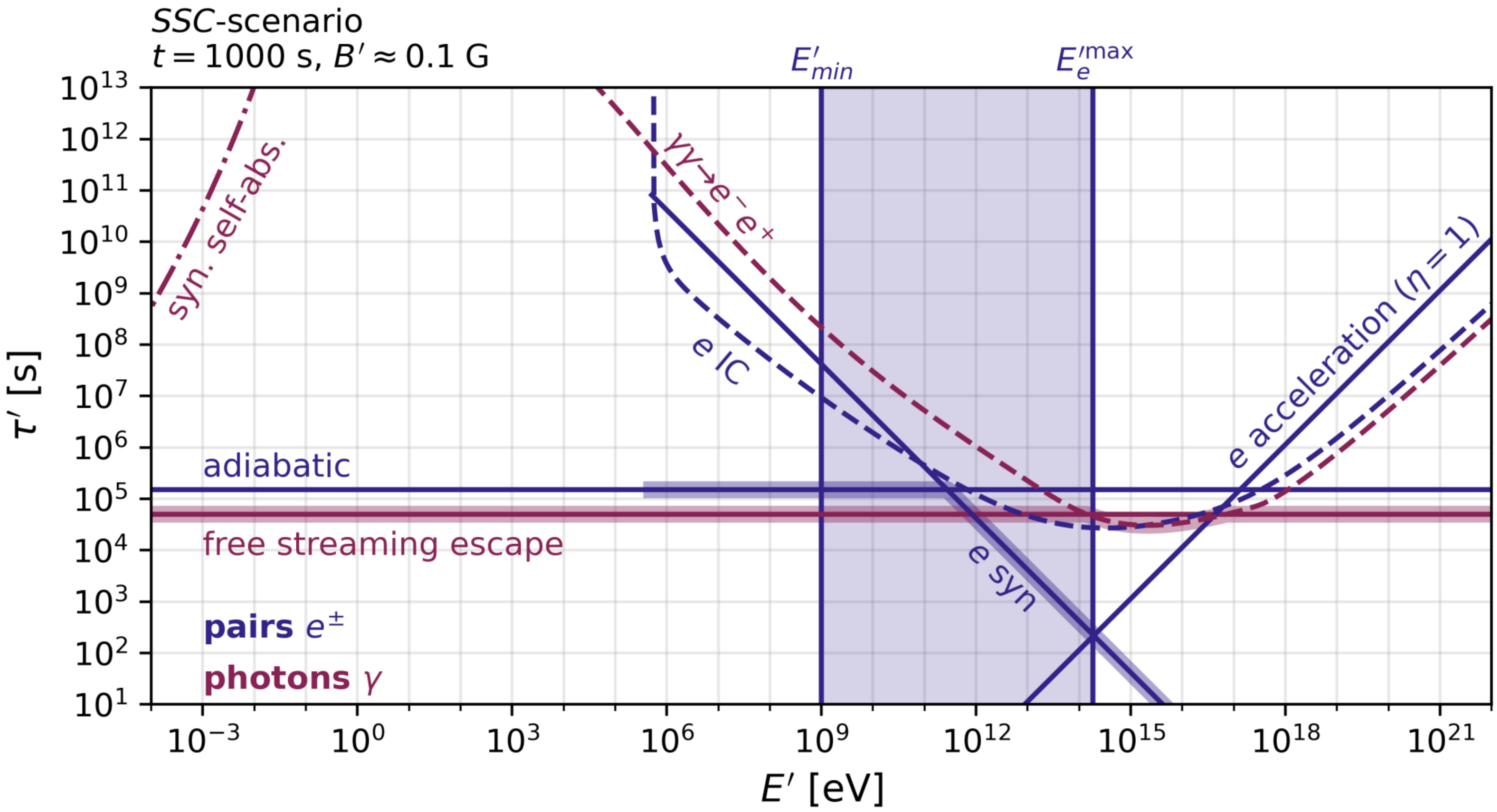
- GRB afterglows are an excellent opportunity to observe relativistic shocks
- now observed at VHE
- systematic scan of lepto-hadronic scenarios
  - → SSC: KN suppression
  - → extended syn: $\eta \ll 1$
  - → proton-syn: exponential cut-off
  - → *pp*-cascade: flat but inefficient
  - → $p\gamma$-cascade: extreme energy/density requirements
  - → **no perfect fit yet!** Multi-zone?

Backup

Large energy requirements?

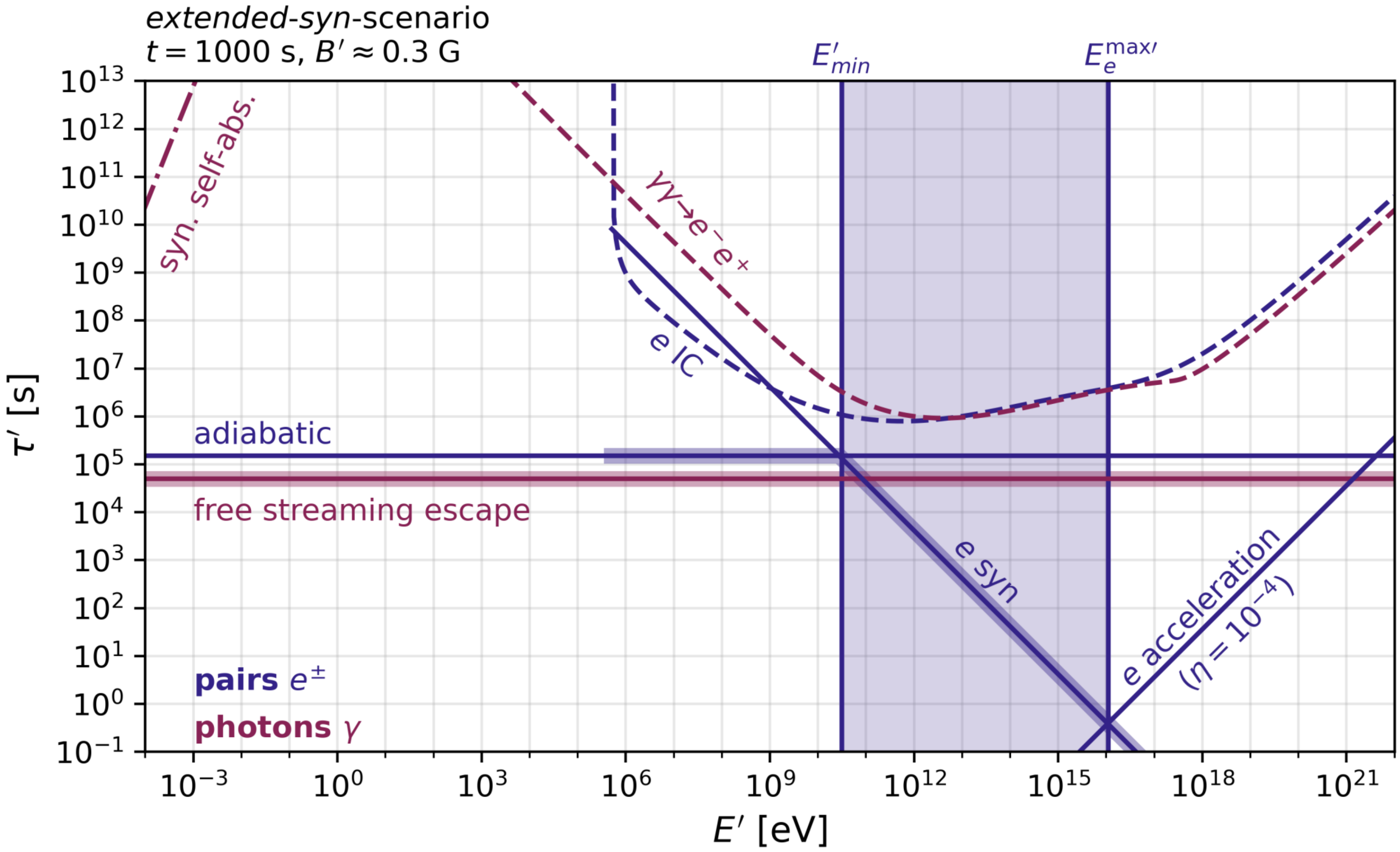
- massive star collapse
  - → accreted mass $\mathrm{M} \approx 10M_{\odot}$
  - → $\varepsilon_{kin} \approx 10\%$ converted to kinetic energy of outflow
  - → into cone with opening angle $\theta = 3°$
  - → $E_{kin,iso} \approx 10^{57} erg \left(\frac{M}{10M_{\odot}}\right)\left(\frac{\varepsilon_{kin}}{0.1}\right)\left(\frac{3°}{\theta}\right)^2$

Time scales



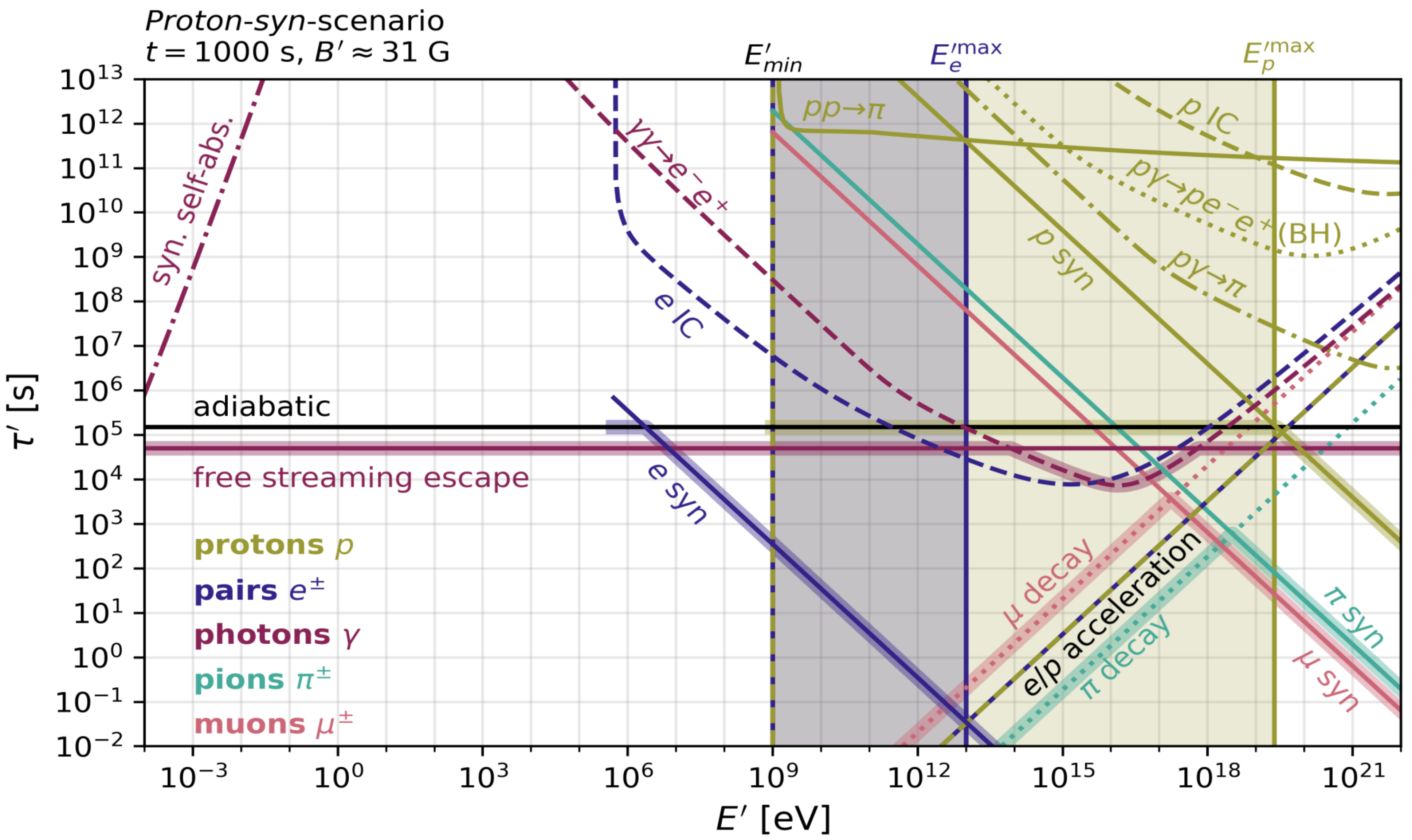
SSC-scenario
$t = 1000$ s, $B' \approx 0.1$ G
E'_{min}
E'^{max}_{e}
syn. self-abs.
$\gamma\gamma \to e^- e^+$
e IC
e acceleration ($\eta = 1$)
adiabatic
free streaming escape
e syn
pairs $e^\pm$
photons γ
τ' [s]
E' [eV]

Time scales



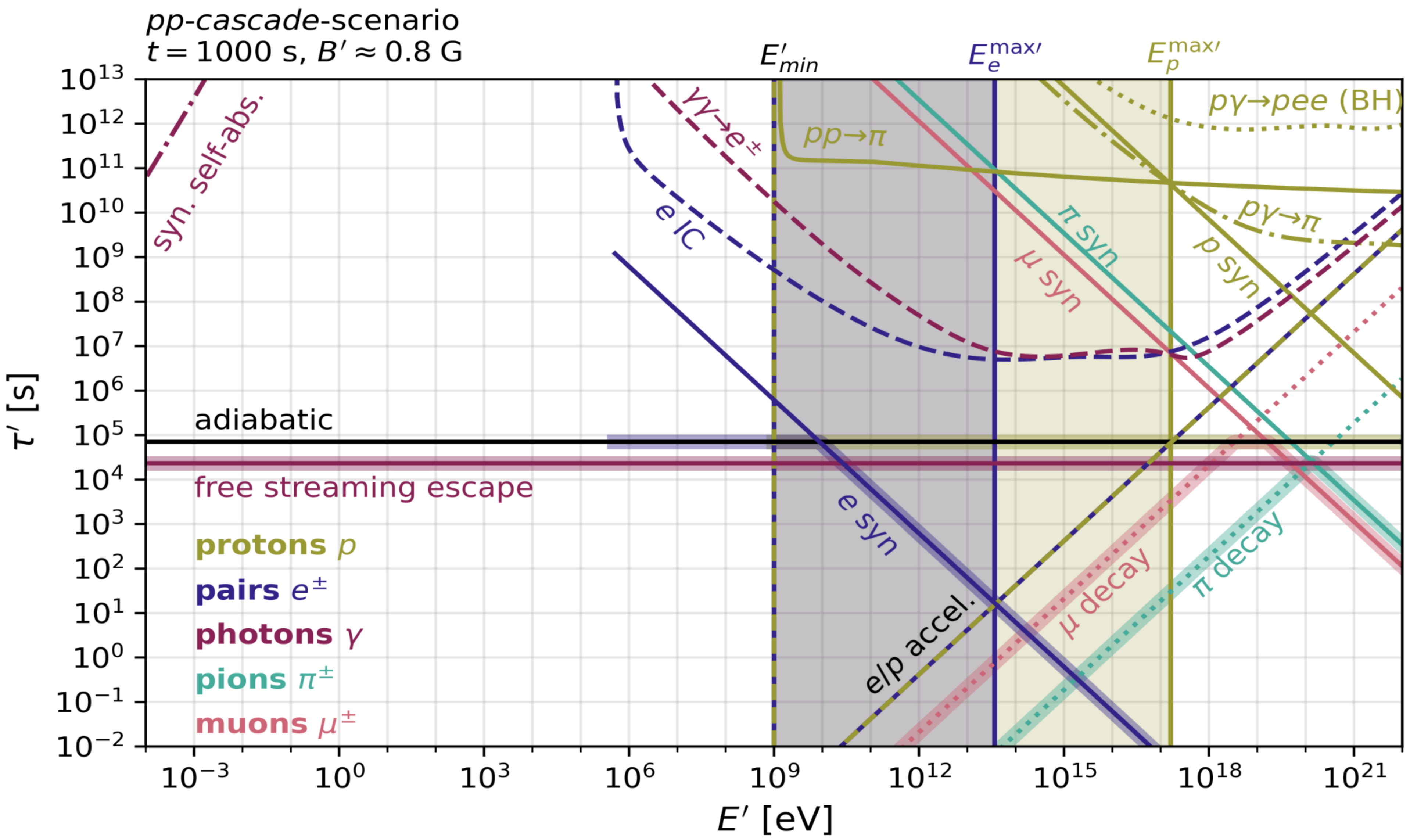
extended-syn-scenario
t = 1000 s, B′ ≈ 0.3 G
E′min
Ee max′
syn. self-abs.
γγ→e−e+
e IC
adiabatic
free streaming escape
e syn
e acceleration
(η = 10−4)
pairs e±
photons γ
τ′ [s]
E′ [eV]

Time scales



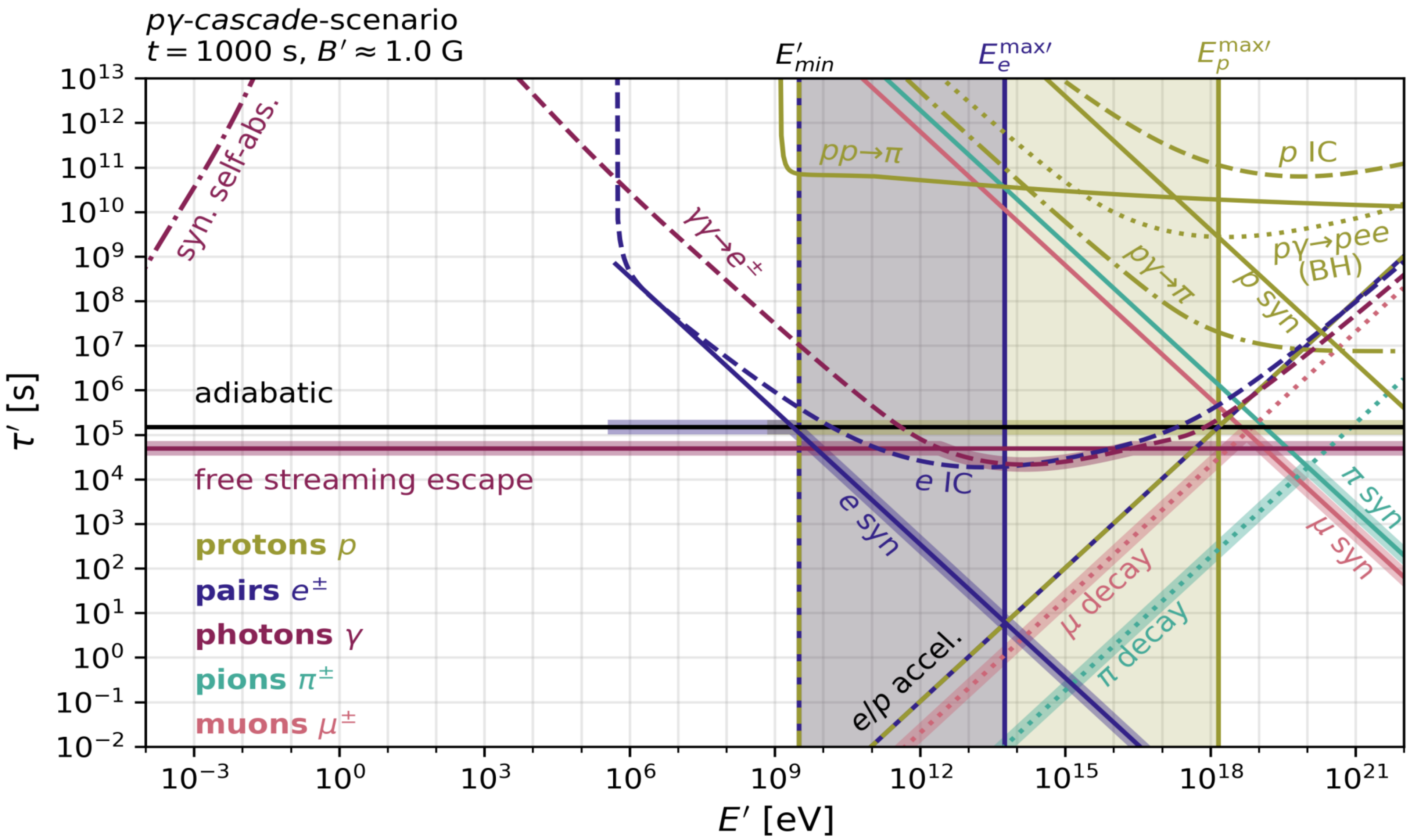
Proton-syn-scenario
t = 1000 s, B′ ≈ 31 G
E′min
E′e max
E′p max
pp→π
p IC
pγ→pe⁻e⁺(BH)
p syn
pγ→π
γγ→e⁻e⁺
e IC
syn. self-abs.
adiabatic
free streaming escape
e syn
μ decay
e/p acceleration
π decay
π syn
μ syn
protons p
pairs e±
photons γ
pions π±
muons μ±
τ′ [s]
E′ [eV]

Time scales



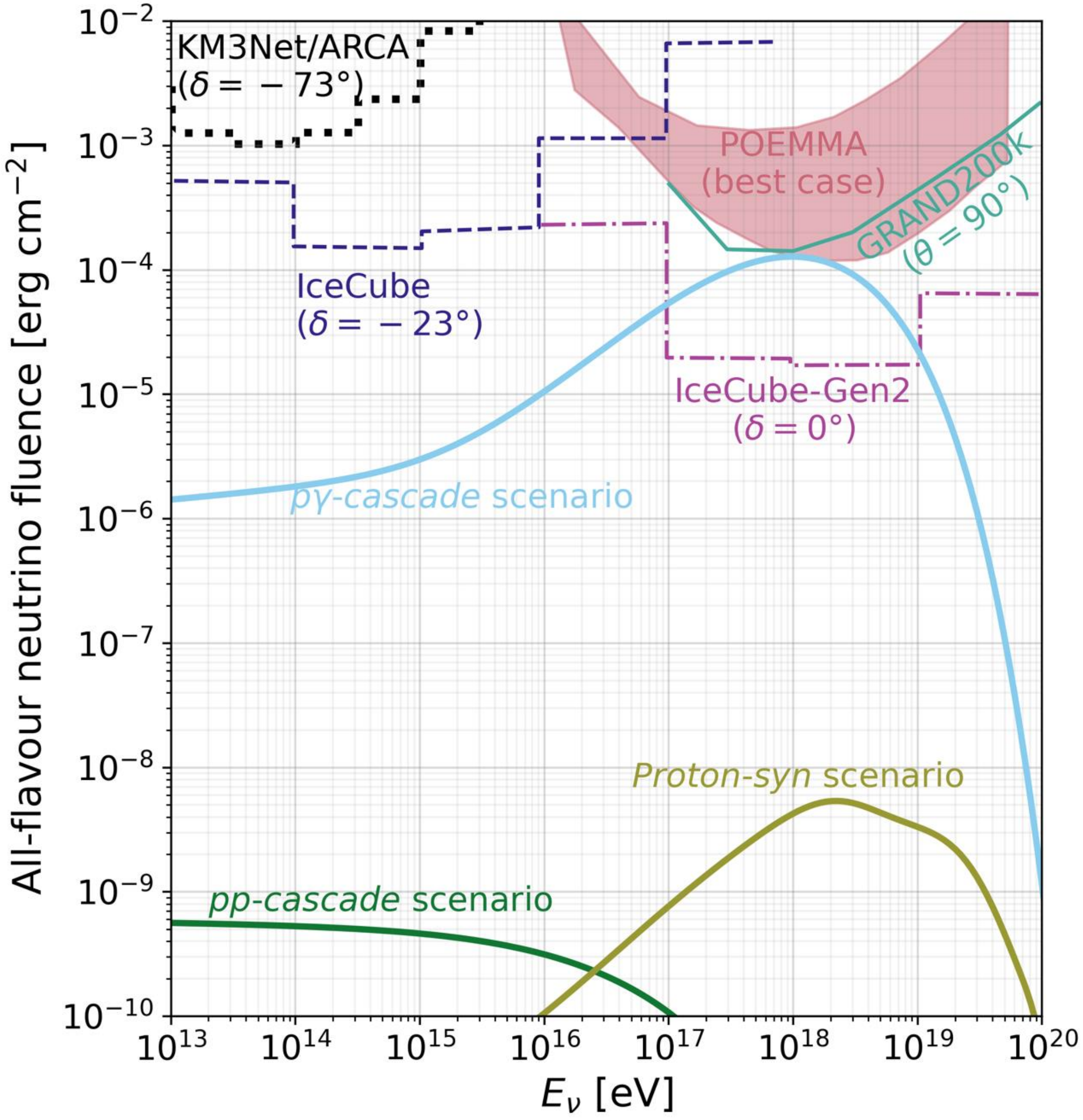
pp-cascade-scenario
t = 1000 s, B′ ≈ 0.8 G
E′min
Ee max′
Ep max′
syn. self-abs.
γγ→e±
pp→π
pγ→pee (BH)
e IC
π syn
μ syn
pγ→π
p syn
adiabatic
free streaming escape
e syn
e/p accel.
μ decay
π decay
protons p
pairs e±
photons γ
pions π±
muons μ±
τ′ [s]
E′ [eV]

Time scales



$p\gamma$-cascade-scenario
$t = 1000$ s, $B' \approx 1.0$ G
E'_{min}
$E_e^{max\prime}$
$E_p^{max\prime}$
syn. self-abs.
$\gamma\gamma \to e^\pm$
$pp \to \pi$
p IC
$p\gamma \to pee$ (BH)
$p\gamma \to \pi$
p syn
adiabatic
free streaming escape
e IC
e syn
π syn
μ syn
μ decay
π decay
e/p accel.
protons p
pairs $e^\pm$
photons γ
pions $\pi^\pm$
muons $\mu^\pm$
τ' [s]
E' [eV]

Neutrinos



KM3Net/ARCA
($\delta = -73°$)
POEMMA
(best case)
GRAND200k
($\theta = 90°$)
IceCube
($\delta = -23°$)
IceCube-Gen2
($\delta = 0°$)
$p\gamma$-cascade scenario
Proton-syn scenario
pp-cascade scenario
All-flavour neutrino fluence [erg cm^{-2}]
E_ν [eV]