AM³ and Lepto-Hadronic Gamma-ray Burst Afterglow Spectra up to TeV Energies

M. Klinger-Plaisier, 26.02.2025

Workshop on Numerical Multi Messenger Modelling

in collaboration with A. M. Taylor, W. Winter, C. Yuan, X. Rodrigues, A. Rudolph, S. Gao, G. Fichet de Clairfontaine, A. Fedynitch, M.Pohl

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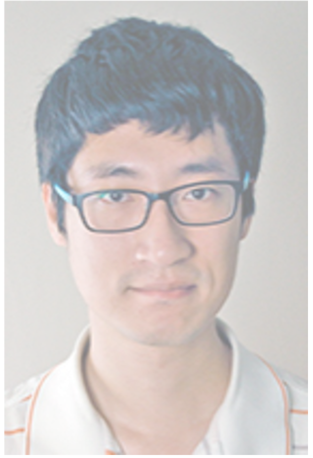
HELMHOLTZ
HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY
DESY.
Universiteit van Amsterdam
Anton Pannekoek Instituut

The AM^3 Team

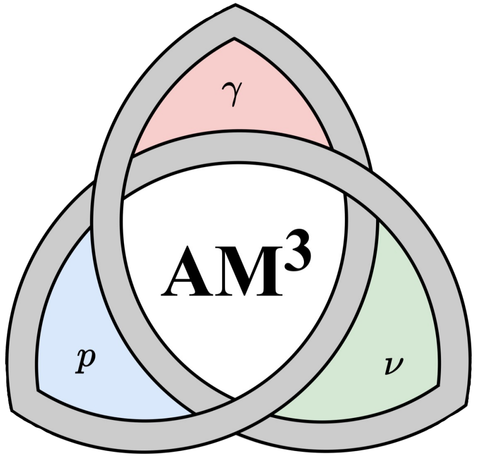


Gao

Klinger-Plaisier

Rudolph

Rodrigues



Yuan

Fichet De Clairfontaine

Fedynitch

Winter

Pohl

AM³ and Lepto-Hadronic Gamma-ray Burst Afterglow Spectra up to TeV Energies

AM^3 and Lepto-Hadronic **Gamma-ray Burst Afterglow** Spectra up to TeV Energies

acceleration

particle & energy reservoir → non-thermal ions & electrons (cosmic rays)

AM³ and Lepto-Hadronic **Gamma-ray Burst Afterglow** Spectra up to TeV Energies

where? → GRB afterglow

how? → relativistic shock,
but how exactly?

acceleration

particle & energy reservoir → **non-thermal ions & electrons (cosmic rays)**

AM^3 and Lepto-Hadronic Gamma-ray Burst Afterglow Spectra up to TeV Energies

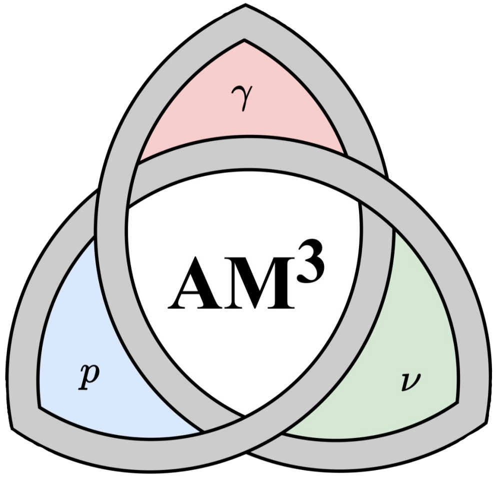
mechanism?

→ focus of this talk

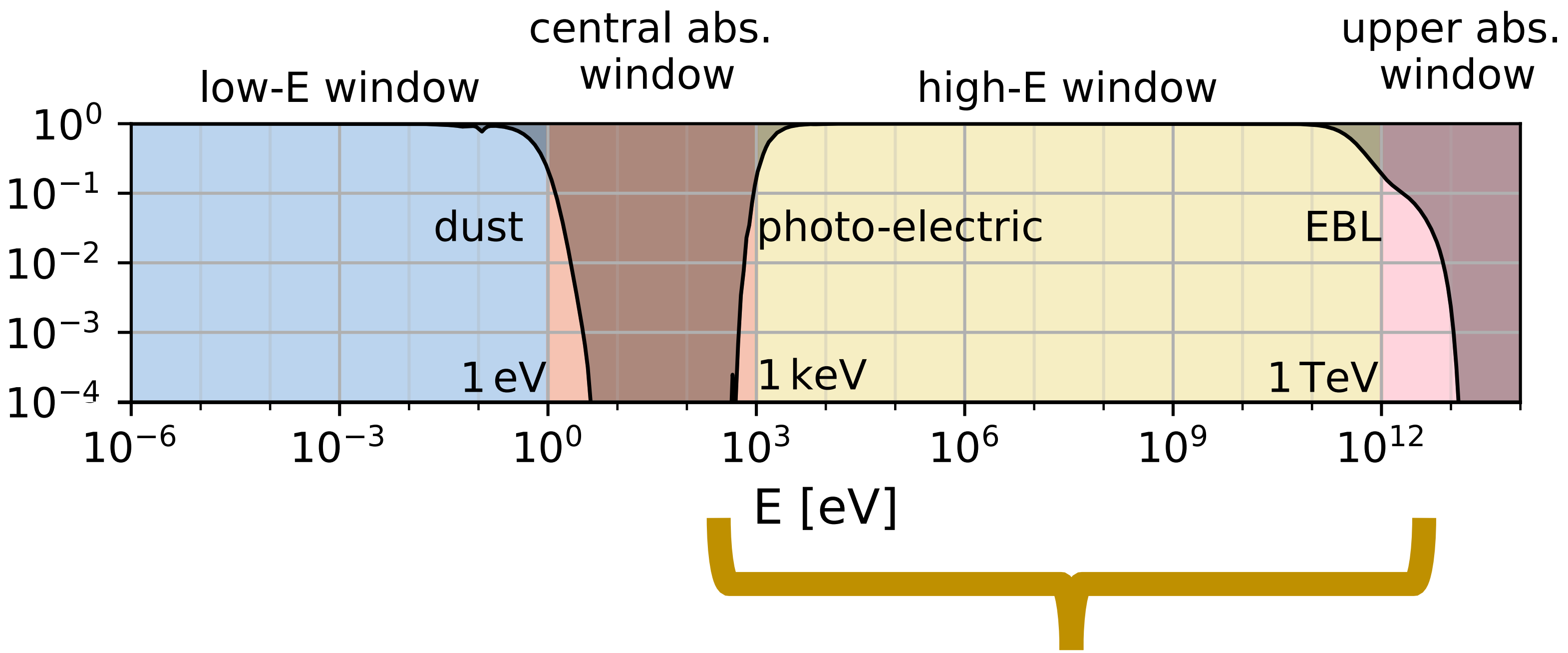
acceleration

radiation

particle & energy reservoir → non-thermal ions & electrons (cosmic rays) → photons neutrinos cosmic rays



photons:
absorption factor $e^{-\tau(E)}$



→ keV–TeV window

acceleration radiation propagation

particle & energy reservoir → non-thermal ions & electrons (cosmic rays) → photons neutrinos cosmic rays → flux at Earth

AM³ and Lepto-Hadronic Gamma-ray Burst Afterglow Spectra up to TeV Energies

new constraining TeV spectra!

instrument response (→ GeV)

acceleration — radiation — propagation — **detection**

particle & energy reservoir → non-thermal ions & electrons (cosmic rays) → photons neutrinos cosmic rays → **flux at Earth** → **observation**

AM³ and Lepto-Hadronic Gamma-ray Burst Afterglow Spectra up to TeV Energies

new tests of

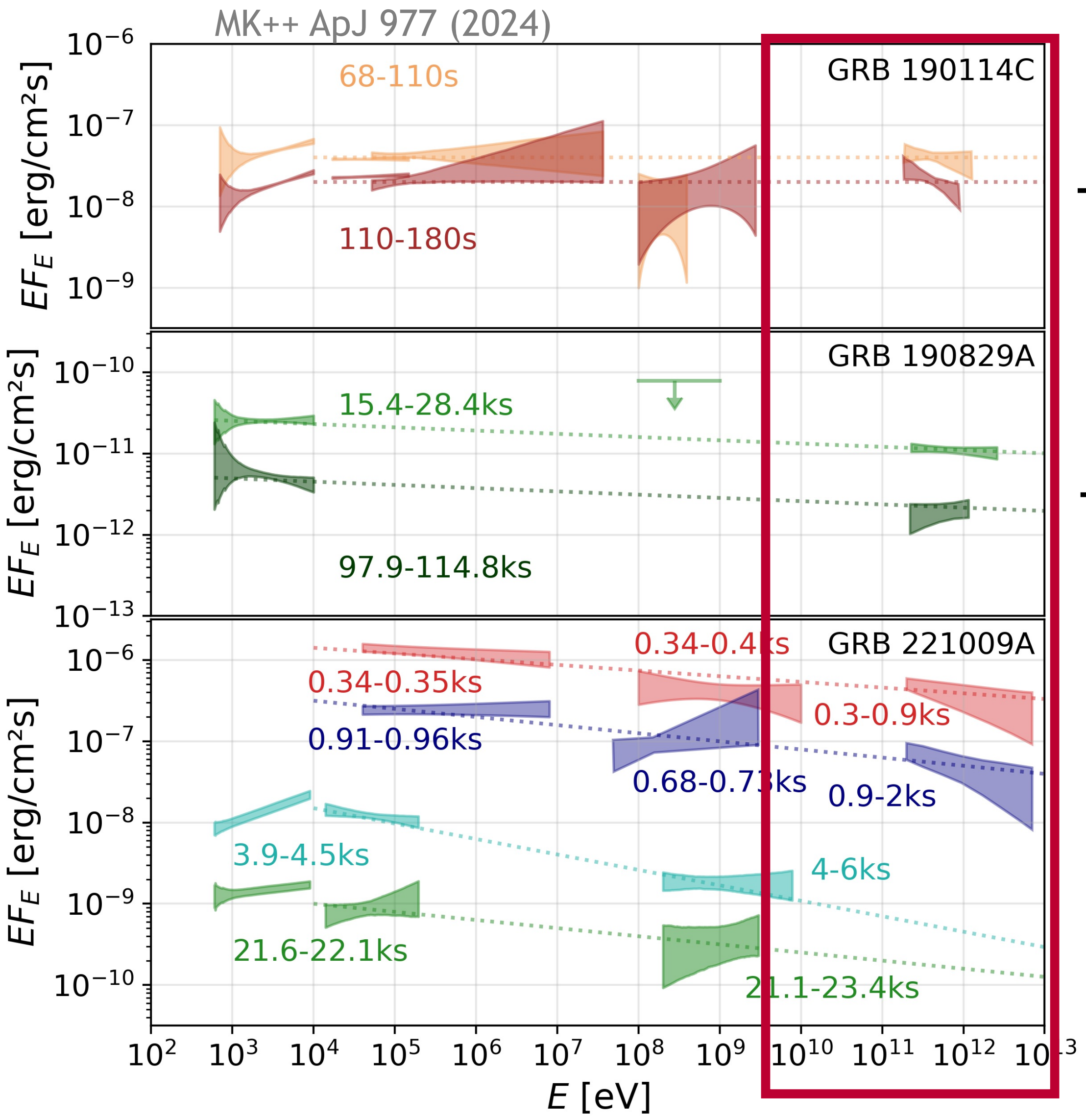
new constraining TeV spectra!

instrument response (→ GeV)

acceleration **radiation** **propagation** **detection**

particle & energy reservoir → **non-thermal ions & electrons (cosmic rays)** → **photons neutrinos cosmic rays** → **flux at Earth** → **observation**

GRB afterglows detected at VHE!



→ **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)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
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MK++ MNRAS 529L (2024)

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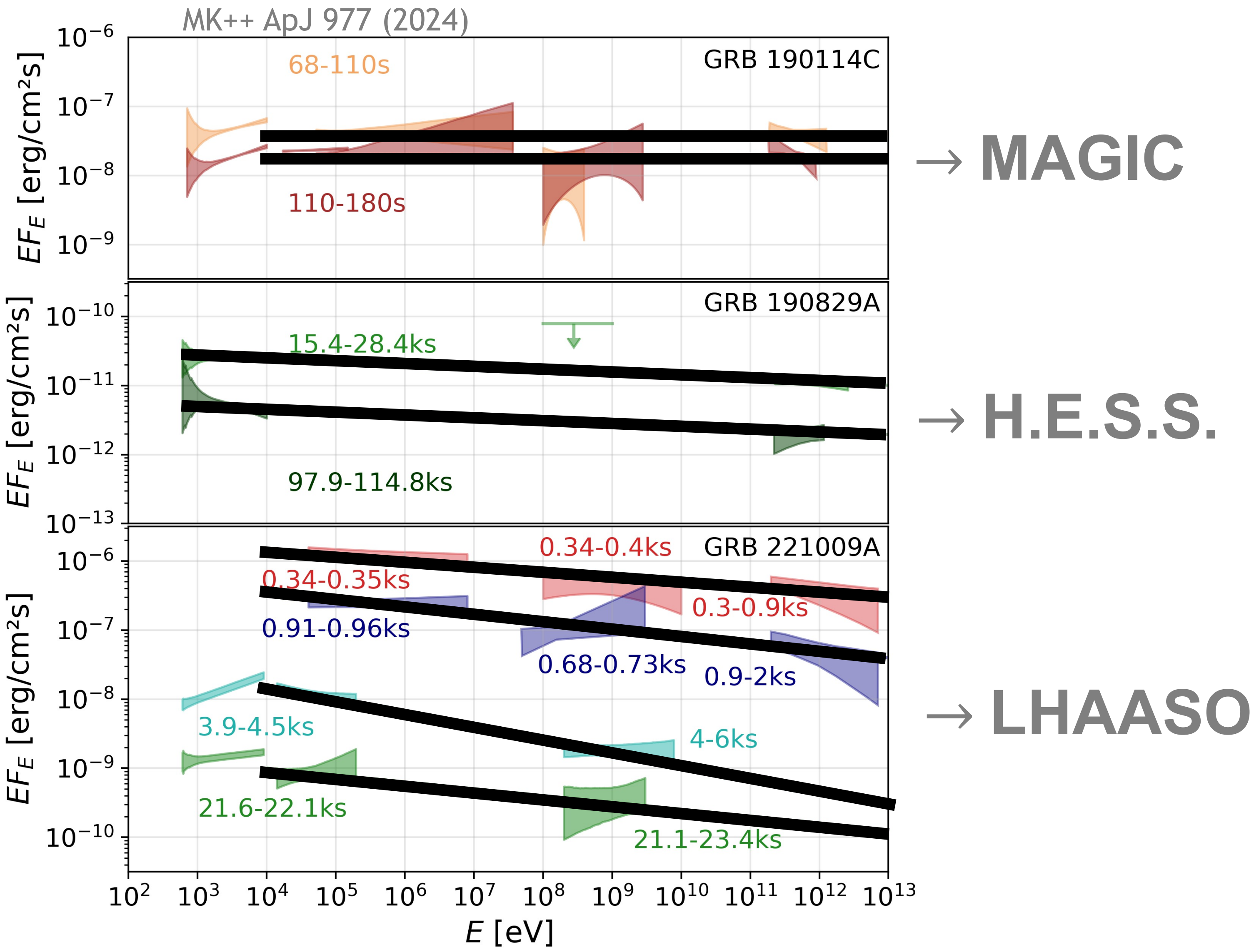

- Flat power-law spectra extending up to >TeV
- Single component?

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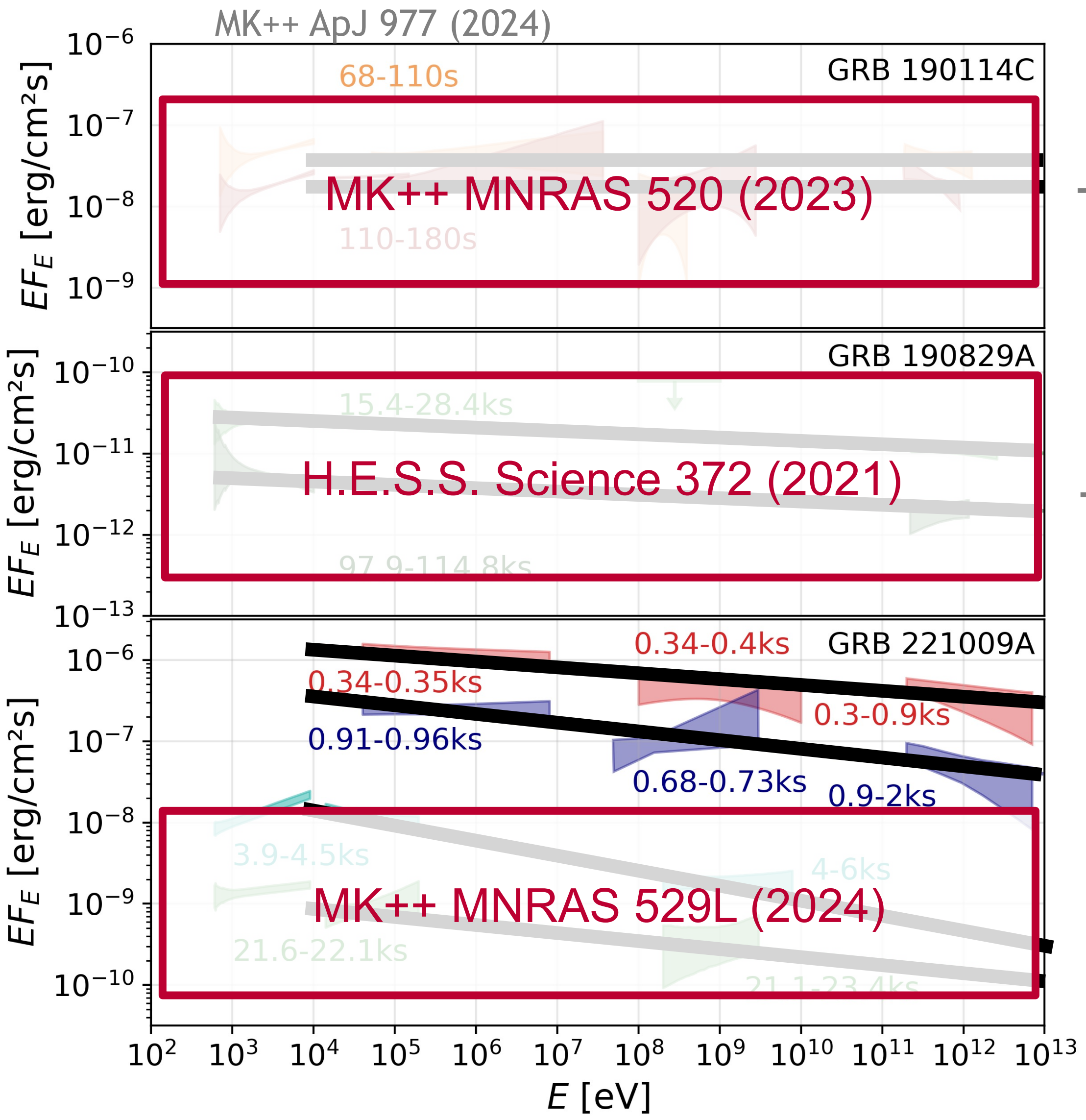

→ MAGIC

→ H.E.S.S.

→ LHAASO

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

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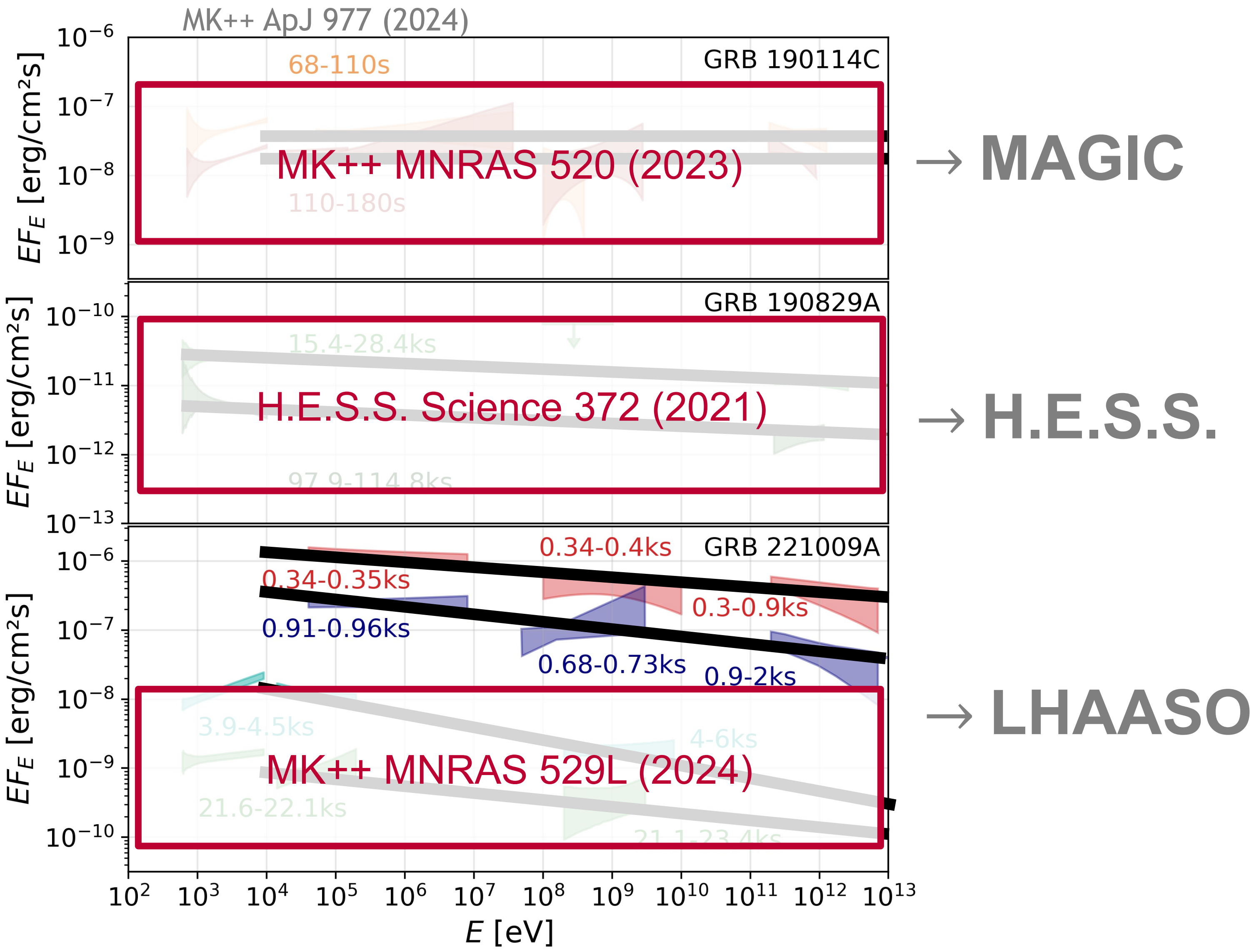

- Flat power-law spectra extending up to >TeV
- Single component?
- No preference at counts-level
- **How to interpret this?**

data from:
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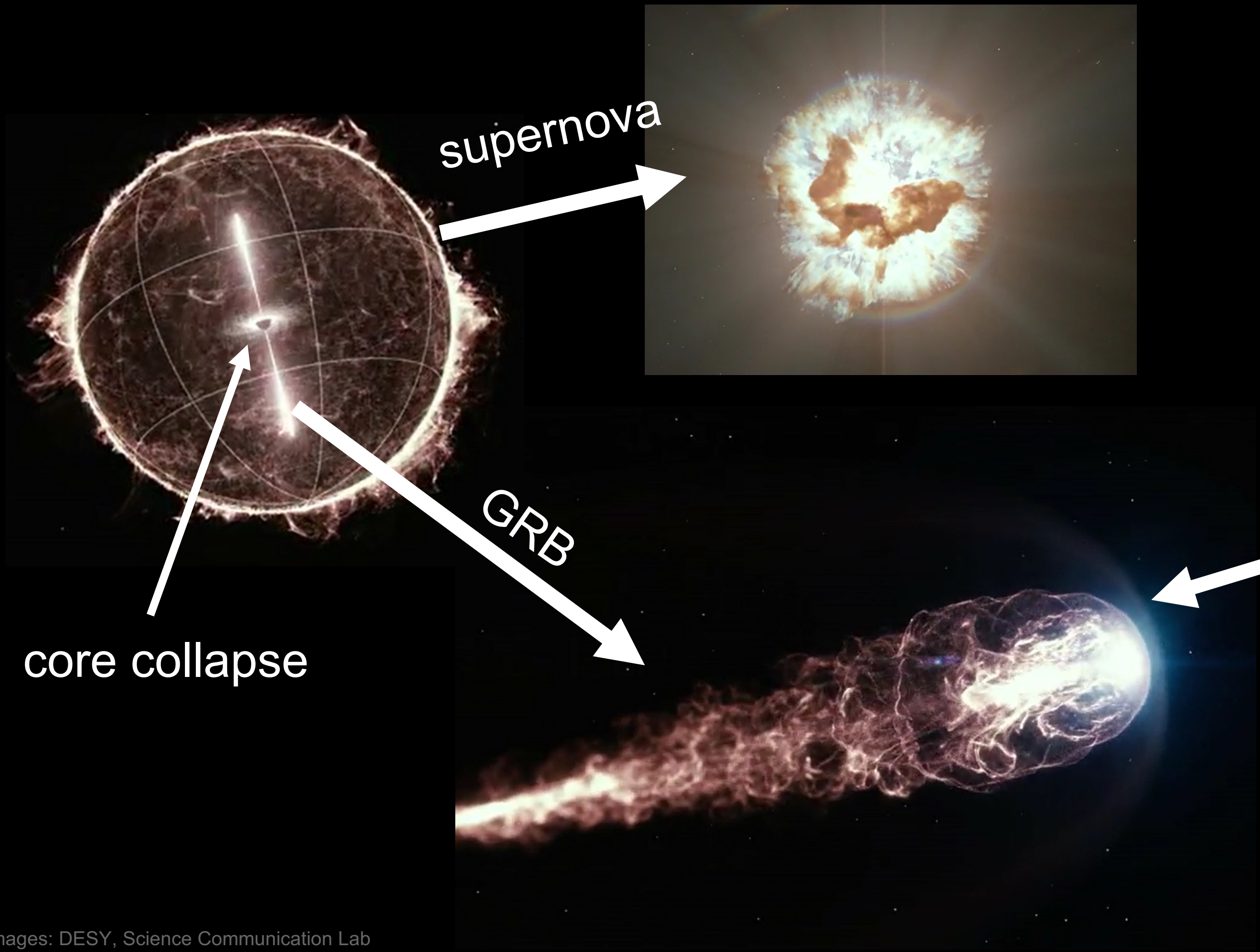
Long GRBs

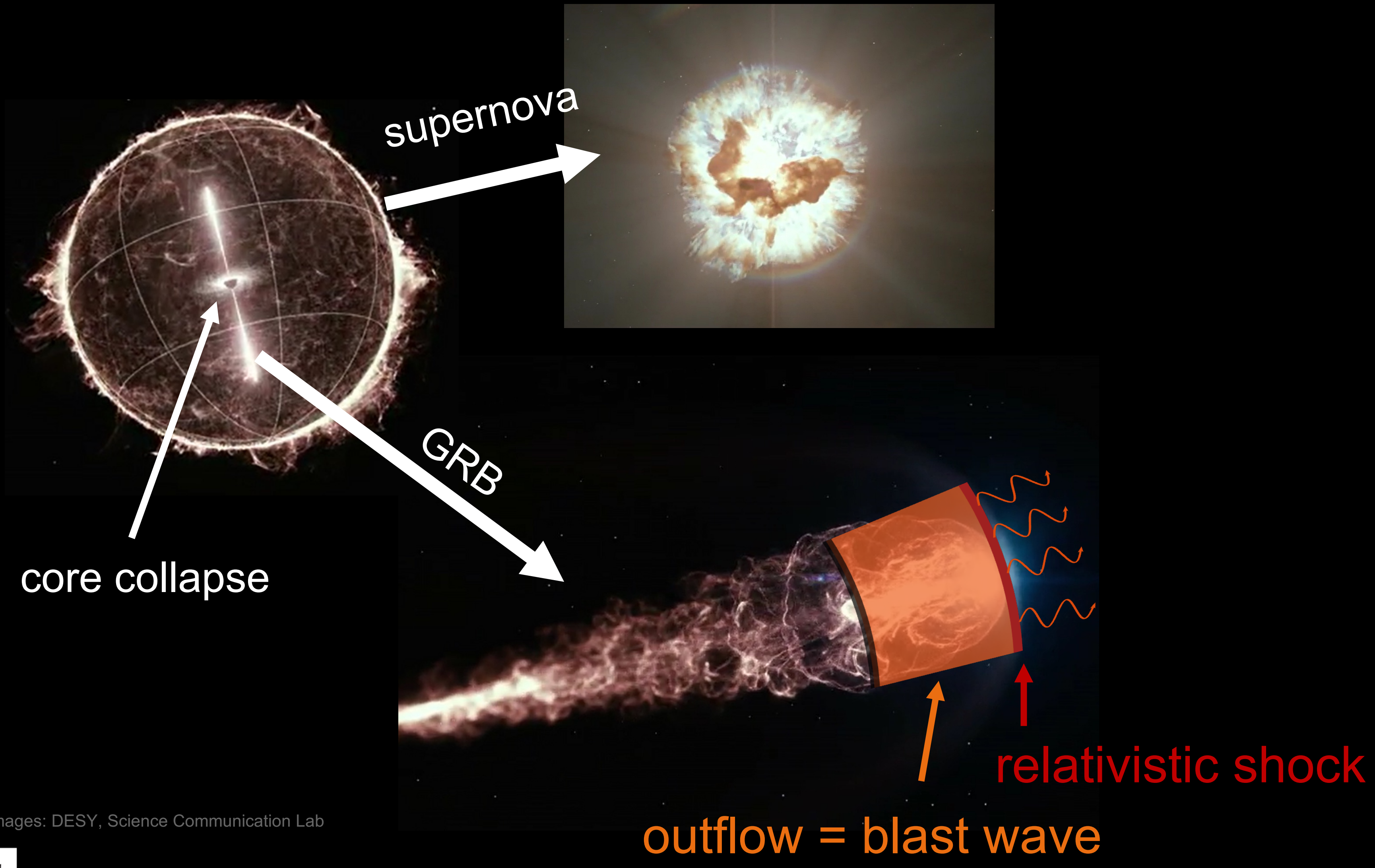


Lorentz factors up to few 100

→ quasi-isotropic outflow

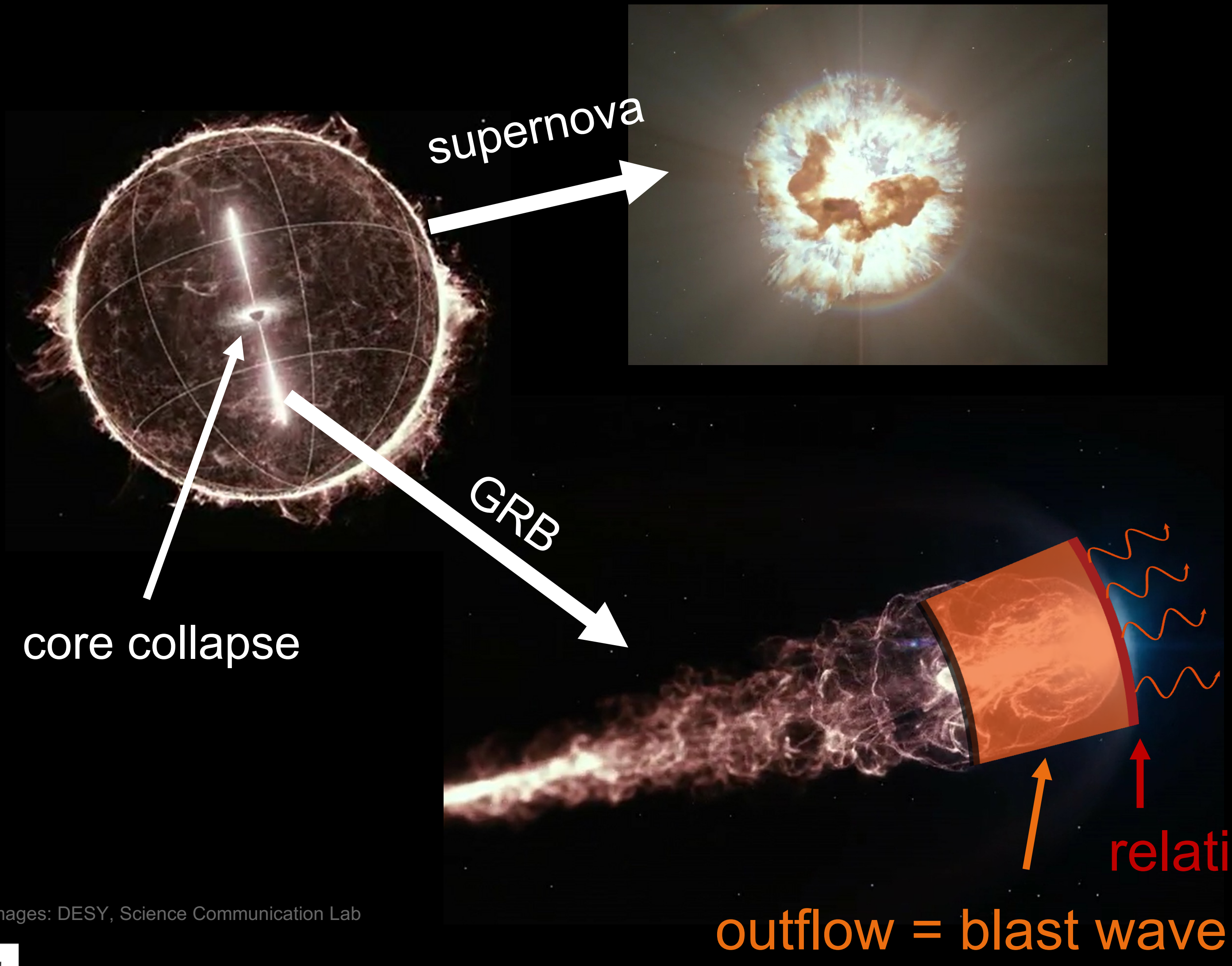
images: DESY, Science Communication Lab

Long GRBs



images: DESY, Science Communication Lab

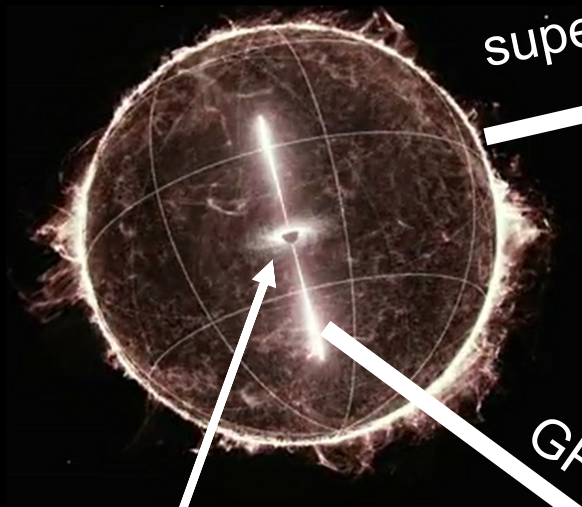
Long GRBs



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)

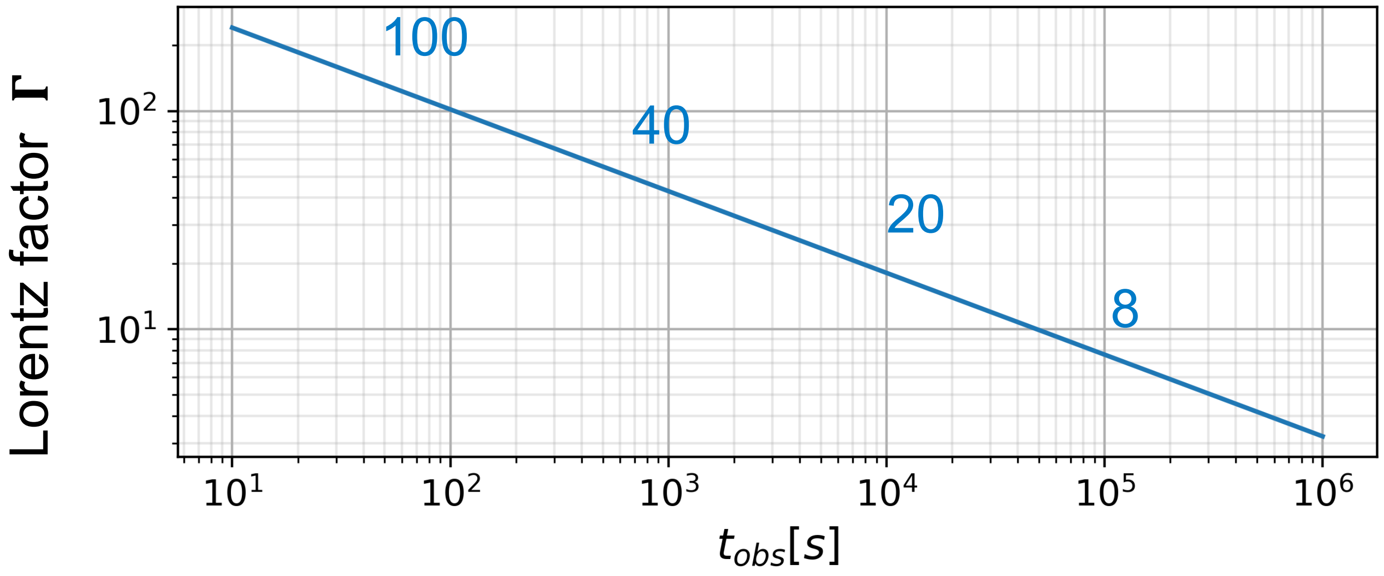
images: DESY, Science Communication Lab

Pancake dynamics

energy conservation:
- → sweeping up
- → slowing down

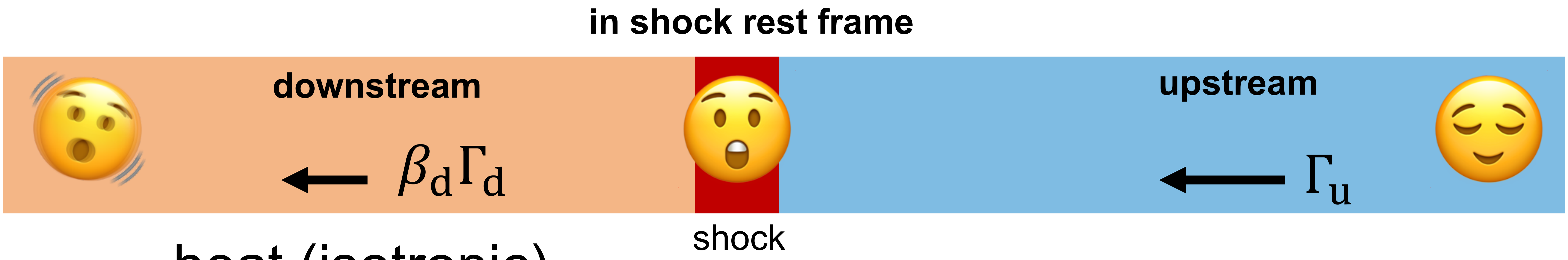
power-law deceleration (Blandford&McKee 1976)

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



$$\rightarrow \Gamma(t_{\mathrm{obs}}) \propto 100 \left(\frac{E_{\mathrm{kin,iso}}}{10^{54} erg}\right)^{\frac{1}{8}} \left(\frac{1cm^{-3}}{n_{\mathrm{u}}}\right)^{\frac{1}{8}} \left(\frac{100s}{t_{\mathrm{obs}}}\right)^{\frac{3}{8}}$$

Energy conversion at the shock



heat (isotropic)

slower outflow (anisotropic)

turbulent magnetic fields (ε_B)

non-thermal particles
(power law: $s_\mathrm{inj}, E_\mathrm{min}, E_\mathrm{max}, \varepsilon_{e/p}$)

kinetic energy/
ram pressure

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

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

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

Astrophysical Multi-Messenger Modeling (AM^3)

→ 1 homogeneous, isotropic fluid cell
→ **solve comoving transport equations**

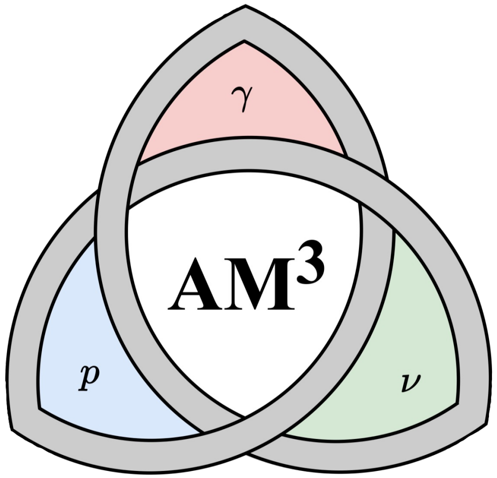
for species $i \in [p, n, e, \pi, \mu, \nu, \gamma]$

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

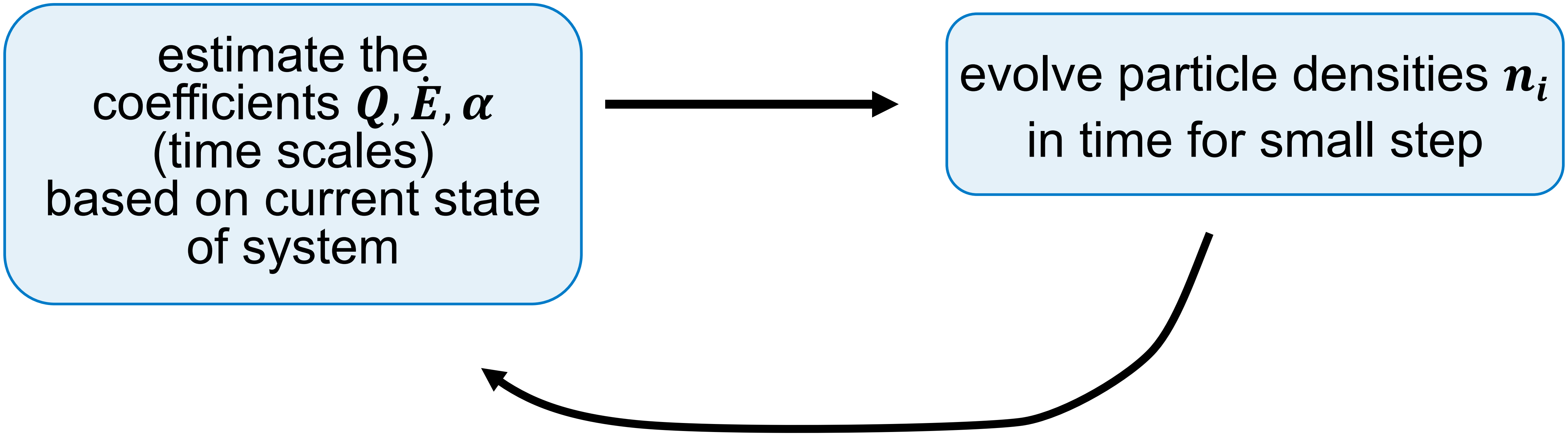
depend in general on E, t, n_j

particle number density

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



AM³ workflow



AM³ workflow

estimate the coefficients $\boldsymbol{Q}, \dot{\boldsymbol{E}}, \boldsymbol{\alpha}$ (time scales) based on current state of system

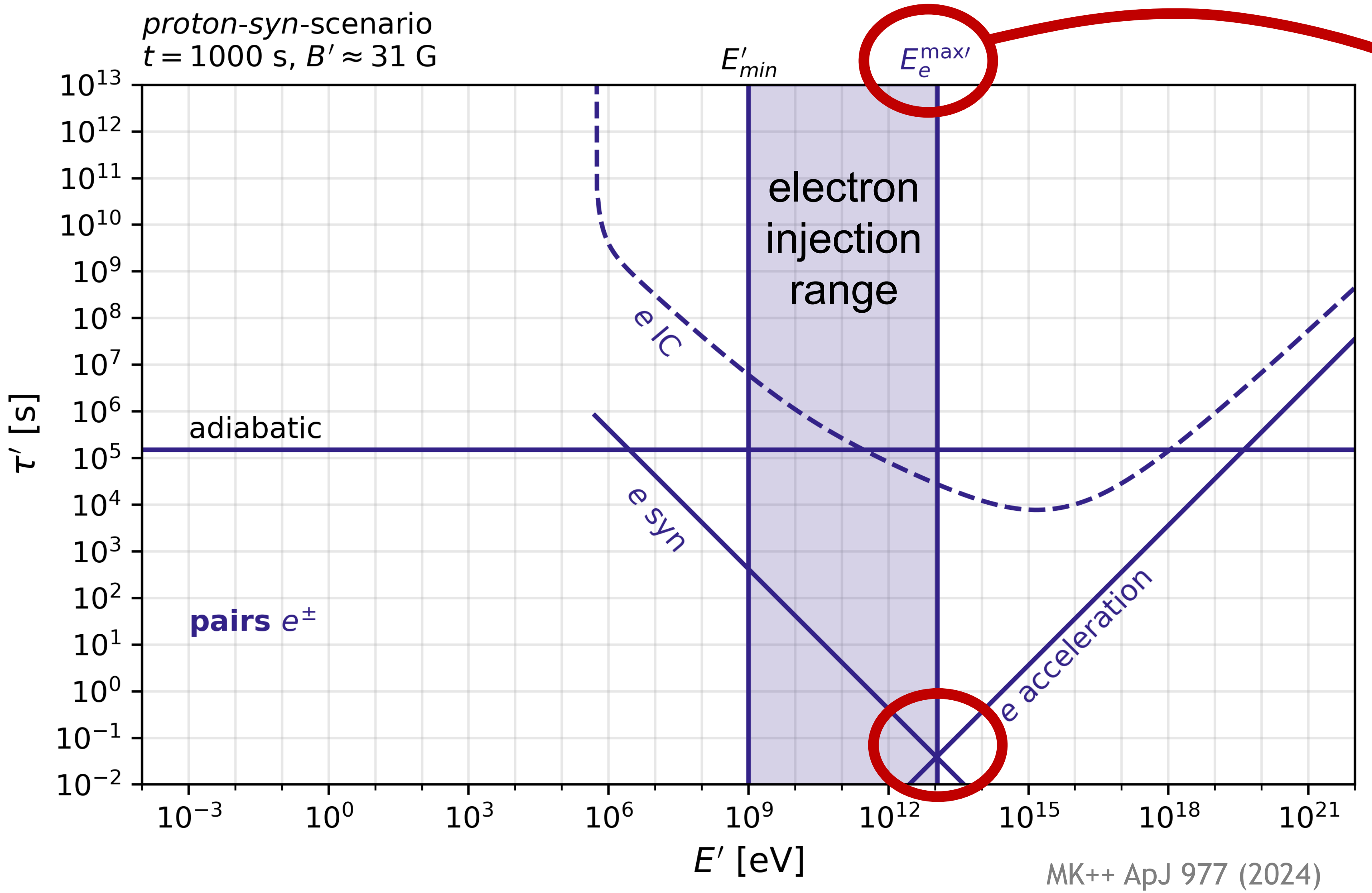
evolve particle densities $\boldsymbol{n}_{\boldsymbol{i}}$ in time for small step

Estimate the coefficients

	e^-	e^+	γ	n	p	ν	$\mu^\pm$	$\pi^\pm$
Injection	$Q_{e^-,\mathrm{inj}}$	–	$Q_{\gamma,\mathrm{inj}}$	–	$Q_{p,\mathrm{inj}}$	–	–	–
Escape	$\alpha_{e^-,\mathrm{esc}}$	$\alpha_{e^+,\mathrm{esc}}$	$\alpha_{\gamma,\mathrm{esc}}$	$\alpha_{n,\mathrm{esc}}$	$\alpha_{p,\mathrm{esc}}$	$\alpha_{\nu,\mathrm{esc}}$	$\alpha_{\mu,\mathrm{esc}}$	$\alpha_{\pi,\mathrm{esc}}$
Synchrotron	$\dot{E}_{e^-,\mathrm{SY}}$	$\dot{E}_{e^+,\mathrm{SY}}$	$\alpha_{\gamma,\mathrm{SY}}$, $Q_{\gamma,\mathrm{SY}}$	–	$\dot{E}_{p,\mathrm{SY}}$	–	$\dot{E}_{\mu,\mathrm{SY}}$	$\dot{E}_{\pi,\mathrm{SY}}$
Inverse Compton	$\dot{E}_{e^-,\mathrm{IC}}$	$\dot{E}_{e^+,\mathrm{IC}}$	$\alpha_{\gamma,\mathrm{IC}}$, $Q_{\gamma,\mathrm{IC}}$	–	$\dot{E}_{p,\mathrm{IC}}$	–	$\dot{E}_{\mu,\mathrm{IC}}$	$\dot{E}_{\pi,\mathrm{IC}}$
Pair annihilation	$Q_{e^-,\mathrm{pair}}$	$Q_{e^+,\mathrm{pair}}$	$\alpha_{\gamma,\mathrm{pair}}$	–	–	–	–	–
Bethe-Heitler	$Q_{e^-,\mathrm{BH}}$	$Q_{e^+,\mathrm{BH}}$	–	–	$\dot{E}_{p,\mathrm{BH}}$	–	–	–
Photo-pion	–	–	$\alpha_{\gamma,\mathrm{p}\gamma}$, $Q_{\gamma,\mathrm{p}\gamma}$	$\alpha_{n,\mathrm{p}\gamma}$, $Q_{n,\mathrm{p}\gamma}$	$\alpha_{p,\mathrm{p}\gamma}$, $Q_{p,\mathrm{p}\gamma}$	–	–	$Q_{\pi,\mathrm{p}\gamma}$
Proton-proton	–	–	$Q_{\gamma,\mathrm{pp}}$	–	$\dot{E}_{p,\mathrm{pp}}$	–	–	$Q_{\pi,\mathrm{pp}}$
Adiabatic/Expansion	$\dot{E}_{e^-,\mathrm{ad}}$, $\alpha_{e^-,\mathrm{exp}}$	$\dot{E}_{e^+,\mathrm{ad}}$, $\alpha_{e^+,\mathrm{exp}}$	$\alpha_{\gamma,\mathrm{exp}}$	$\dot{E}_{p,\mathrm{ad}}$, $\alpha_{p,\mathrm{exp}}$	$\alpha_{n,\mathrm{exp}}$	$\alpha_{\nu,\mathrm{exp}}$	$\dot{E}_{\mu,\mathrm{ad}}$, $\alpha_{\mu,\mathrm{exp}}$	$\dot{E}_{\pi,\mathrm{ad}}$, $\alpha_{\pi,\mathrm{exp}}$
Pion Decay	–	–	–	–	–	$Q_{\nu,\pi-\mathrm{dec}}$	$Q_{\mu,\pi-\mathrm{dec}}$	$\alpha_{\pi,\pi-\mathrm{dec}}$
Muon Decay	$Q_{e^-,\mu-\mathrm{dec}}$	$Q_{e+,\mu-\mathrm{dec}}$	–	–	–	$Q_{\nu,\mu-\mathrm{dec}}$	$\alpha_{\mu,\mu-\mathrm{dec}}$	–

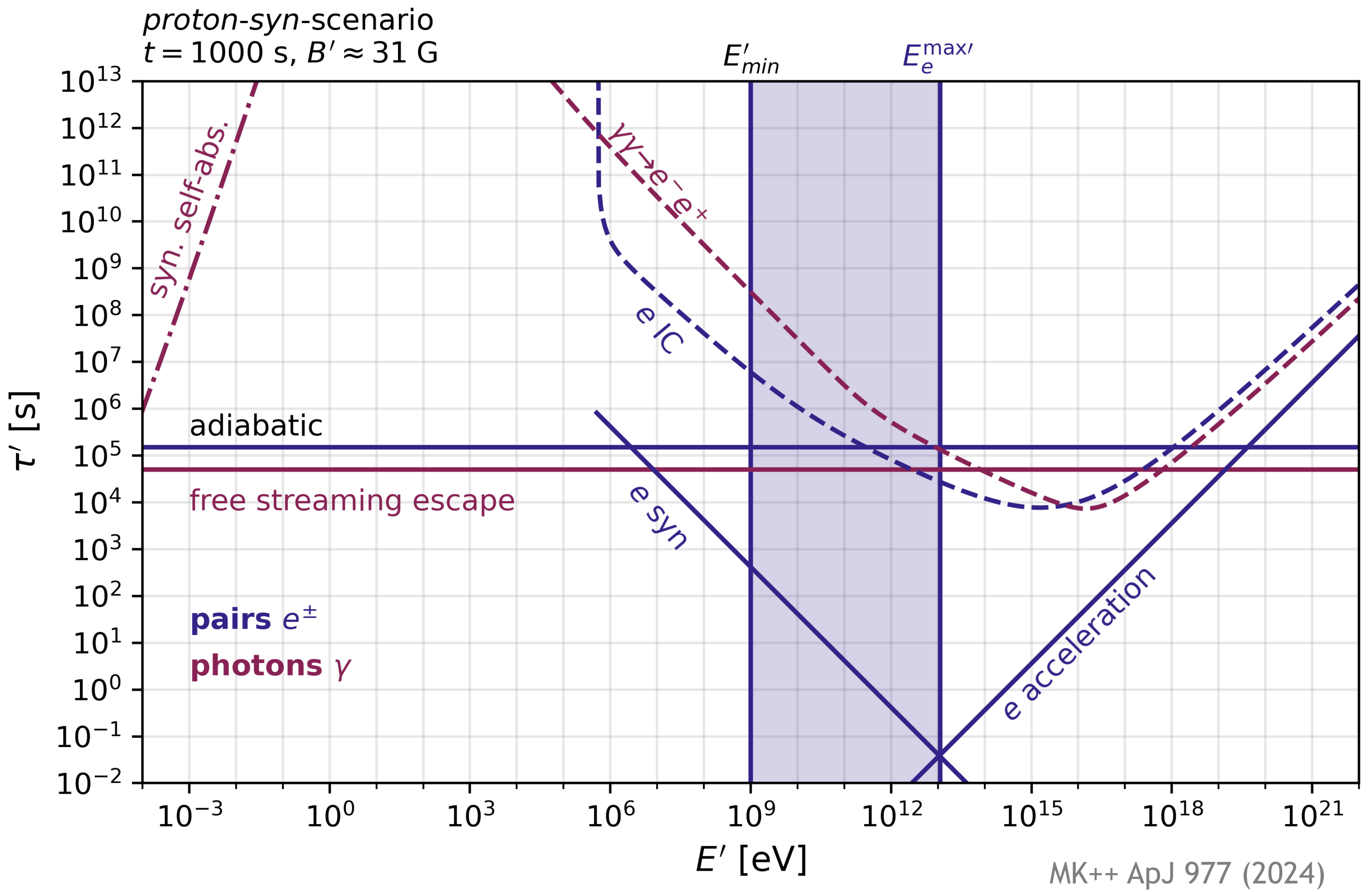
→ see appendix of Klinger et al. 2024 ApJS 275 4 for details

GRB afterglow example



reparameterise $E_{e/p}^{\mathrm{max}\prime}$ via (inverse) efficiency η → acceleration vs. cooling

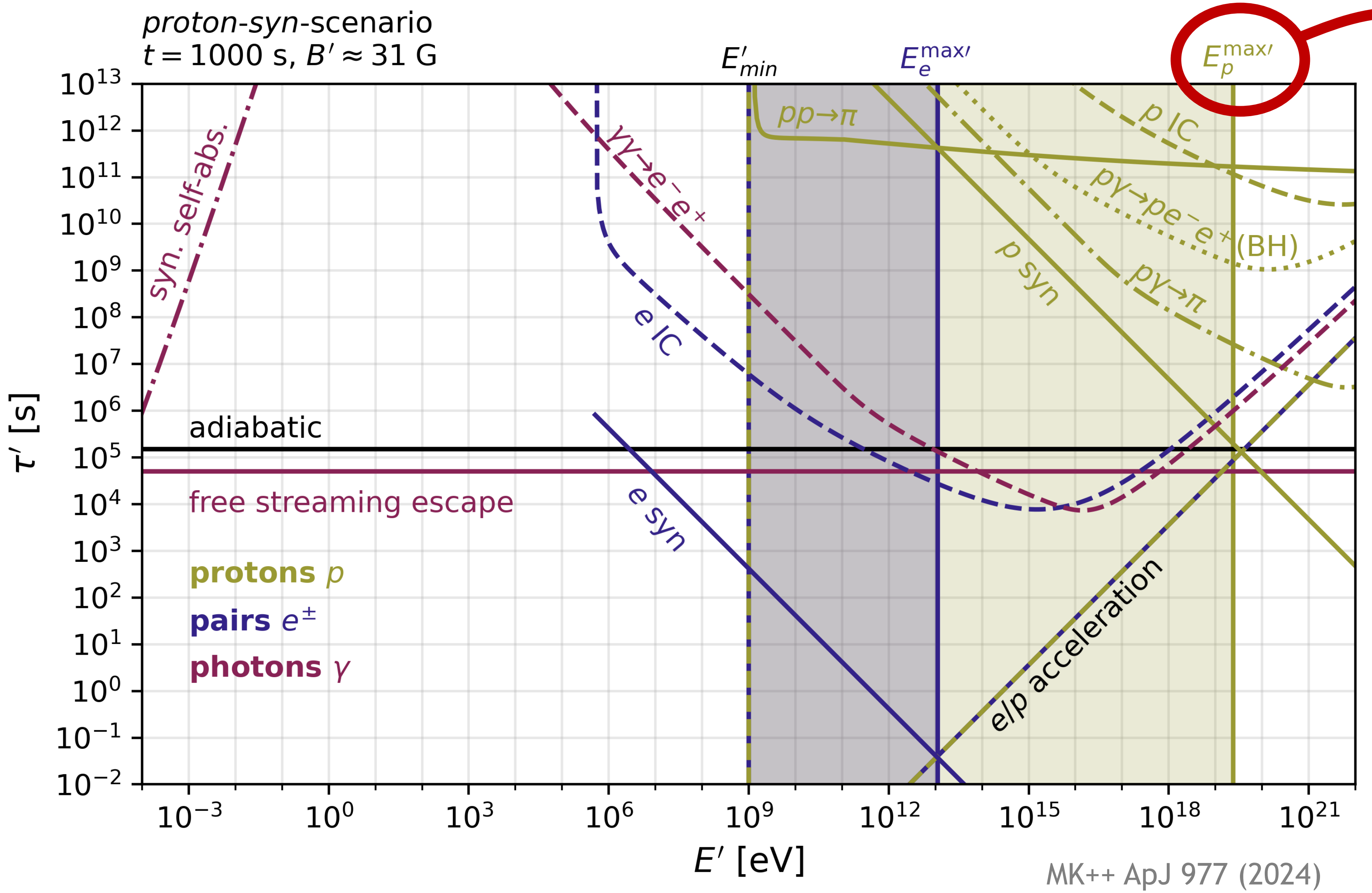
GRB afterglow example



MK++ ApJ 977 (2024)

→ including photons

GRB afterglow example

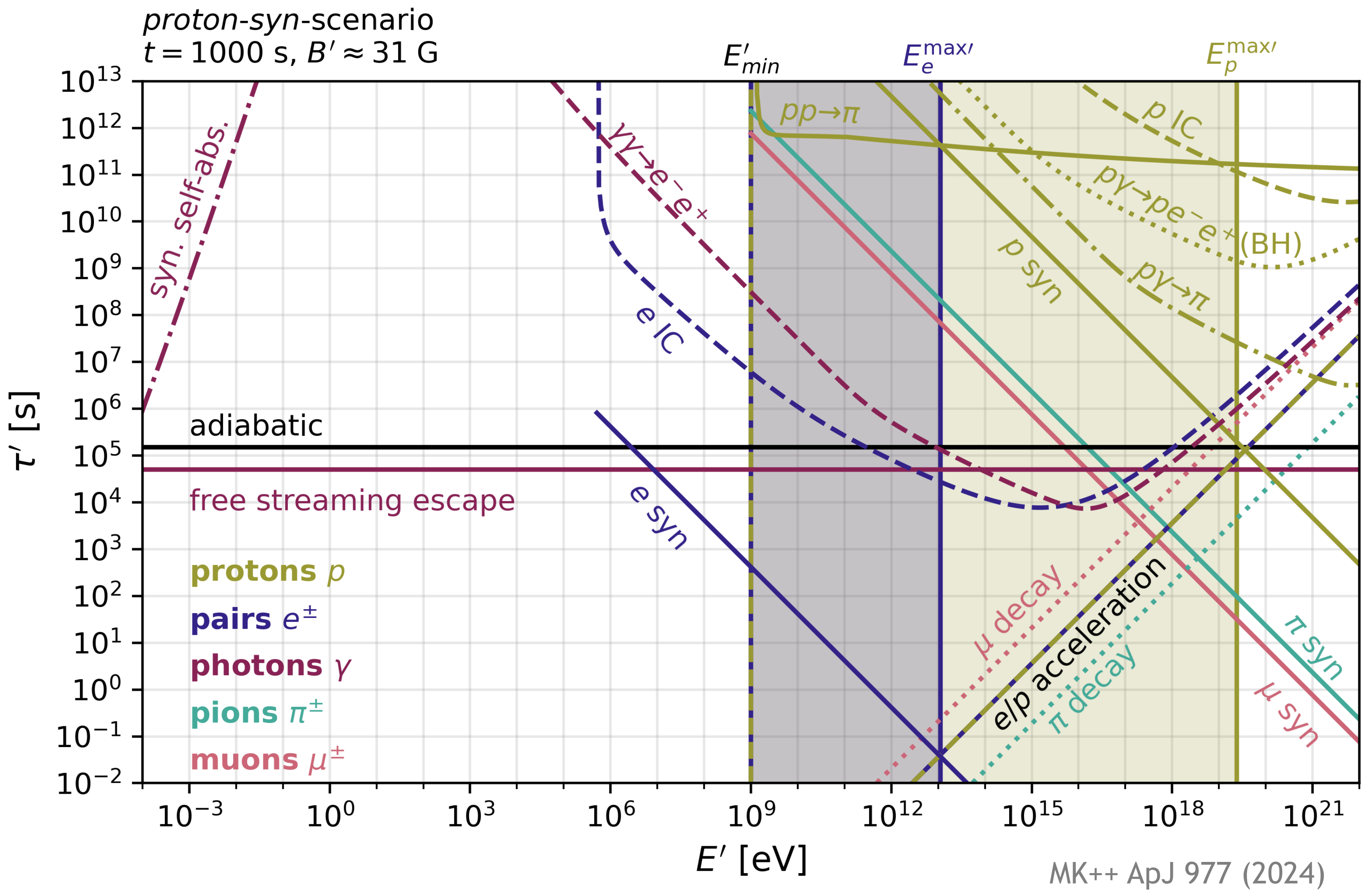


MK++ ApJ 977 (2024)

same η

→ including protons

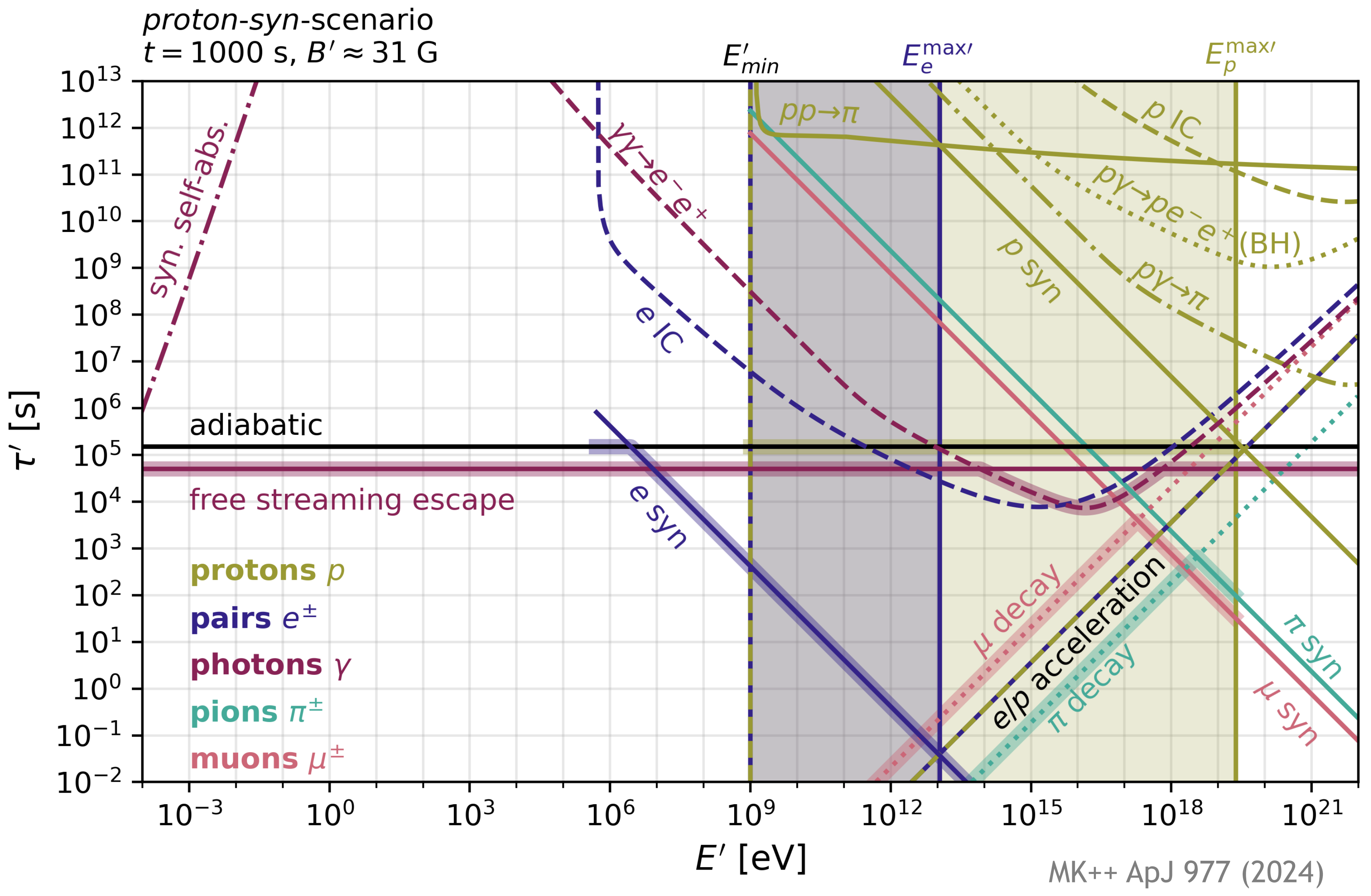
GRB afterglow example



MK++ ApJ 977 (2024)

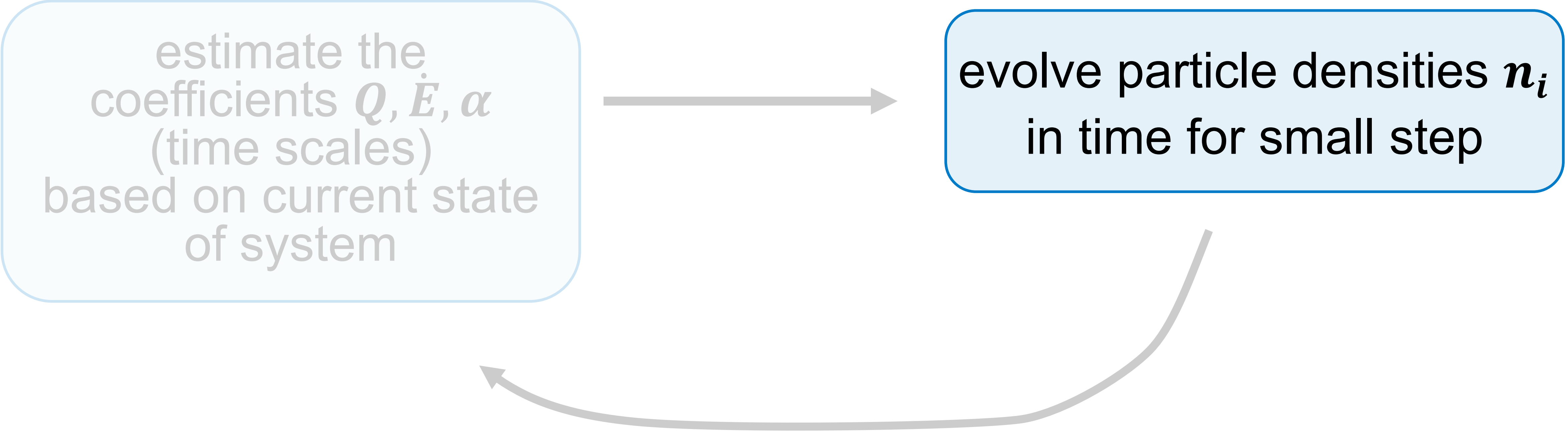
→ including muons and pions from cascade

GRB afterglow example



→ effect on (quasi) steady state $\propto Q \times \tau_{\min}$

AM³ workflow



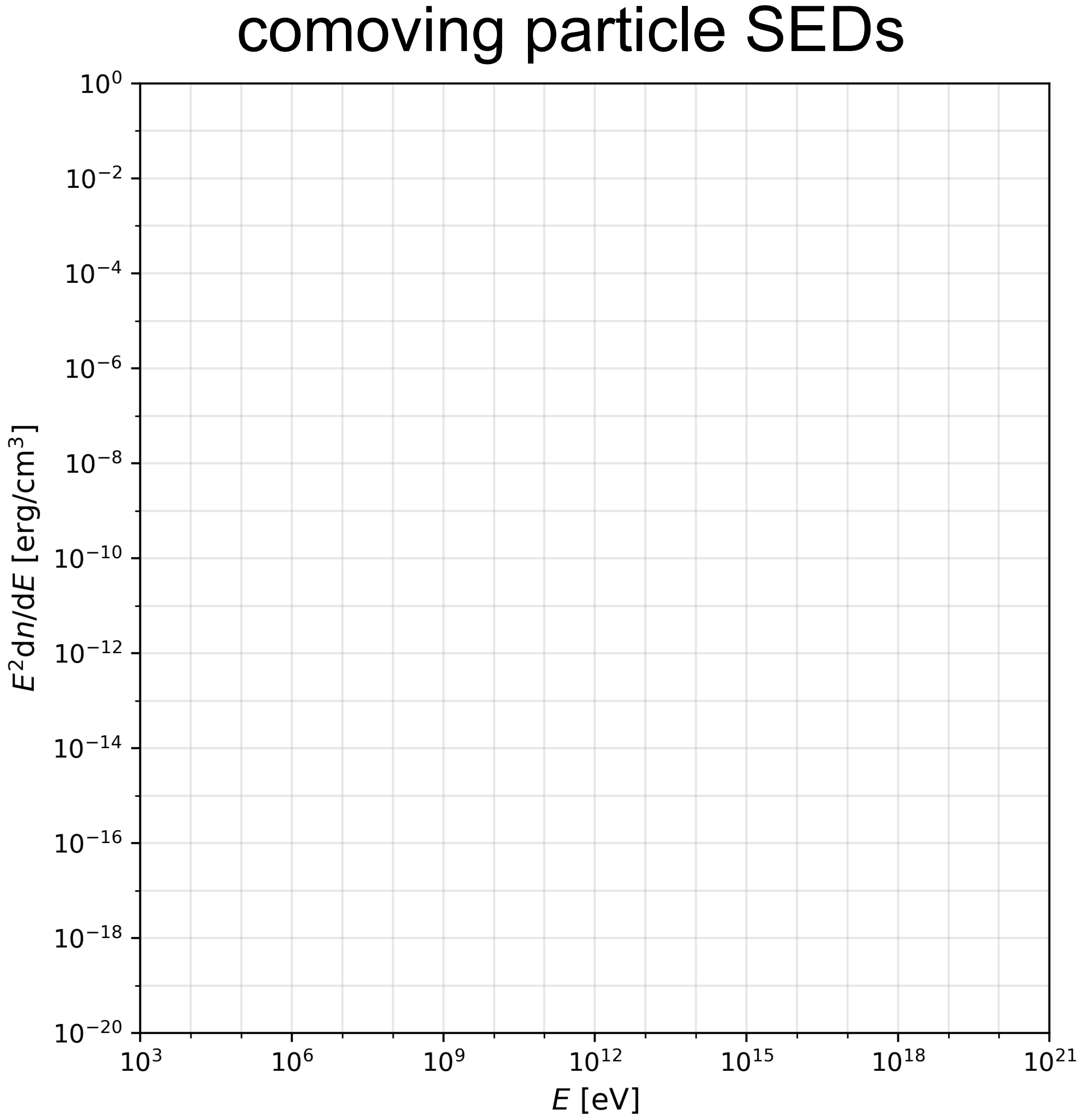
fast solver combining

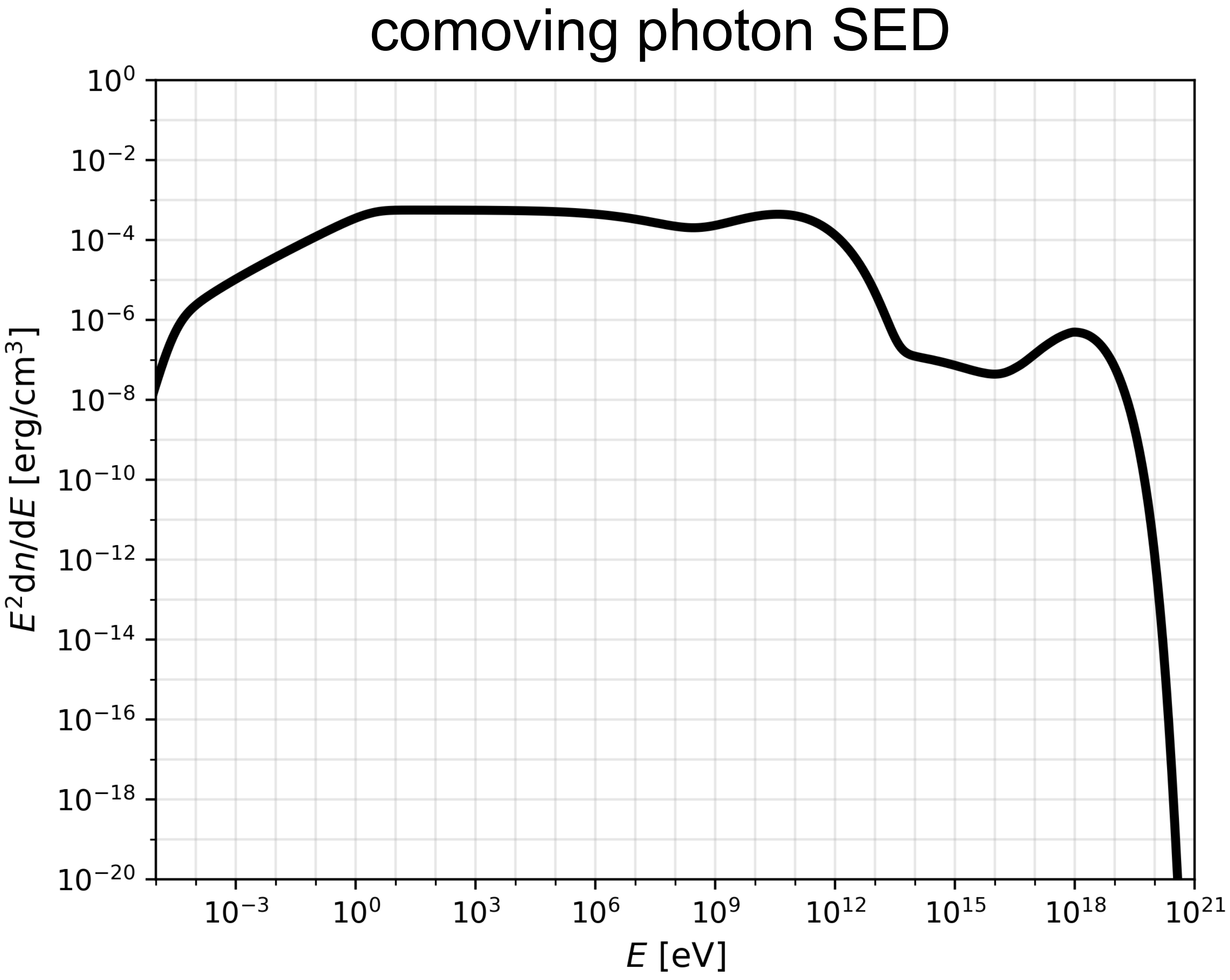
→ tridiagonal matrix method

→ semi-analytical approximations

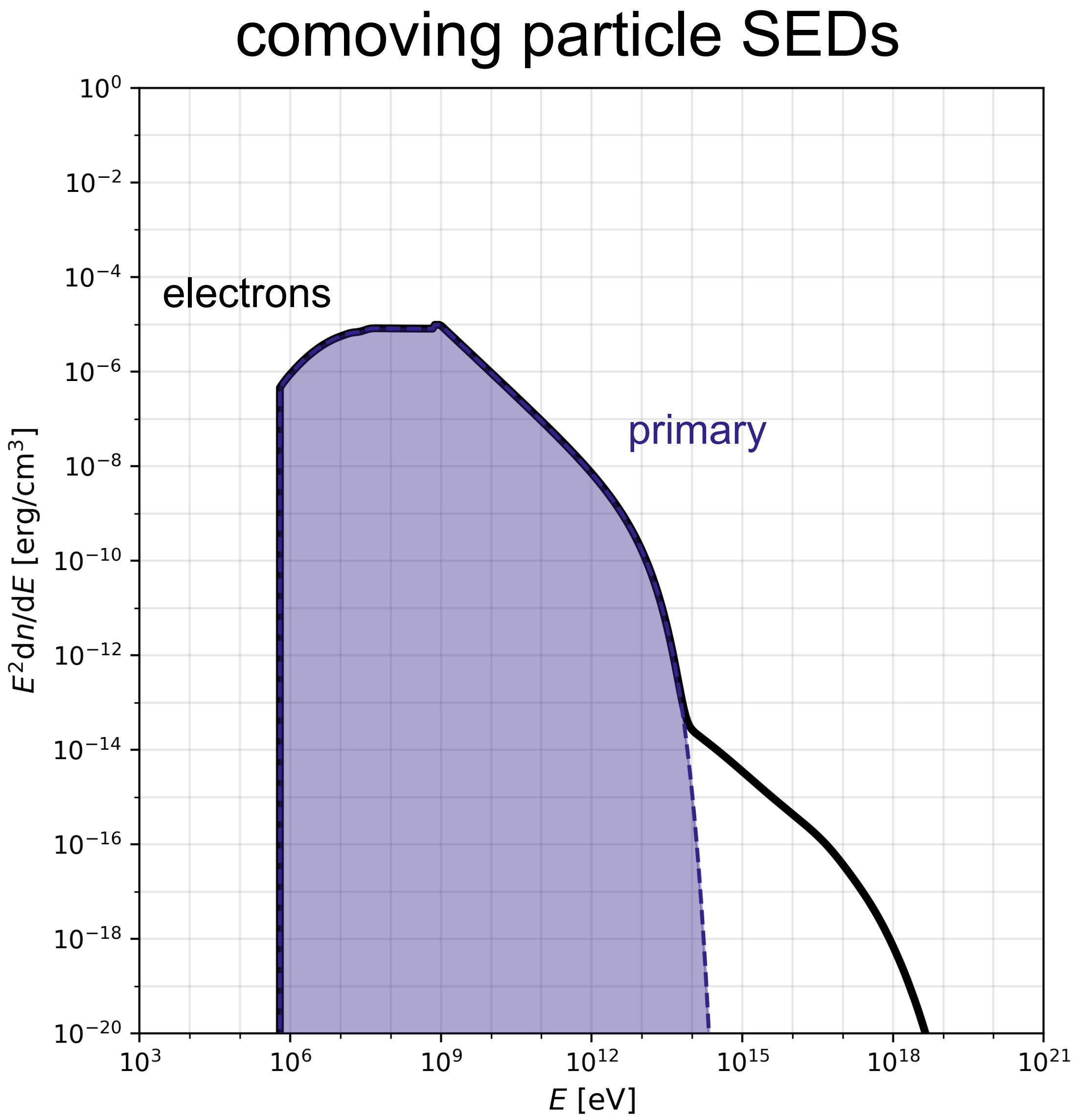
→ see Klinger et al. 2024 ApJS 275 4 for details (or my talk from last year)

Particle Densities → AM³ is trackable

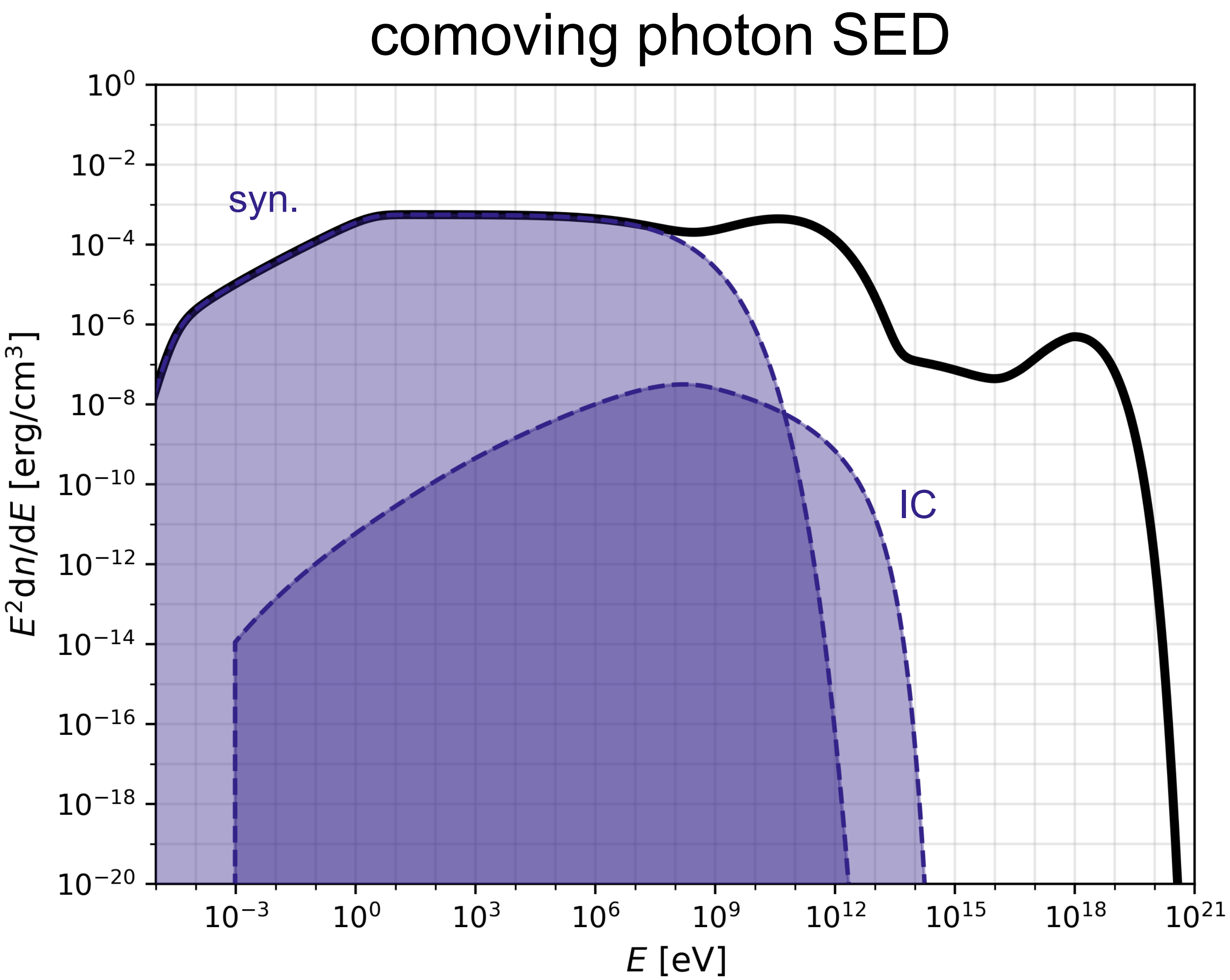




Trackable

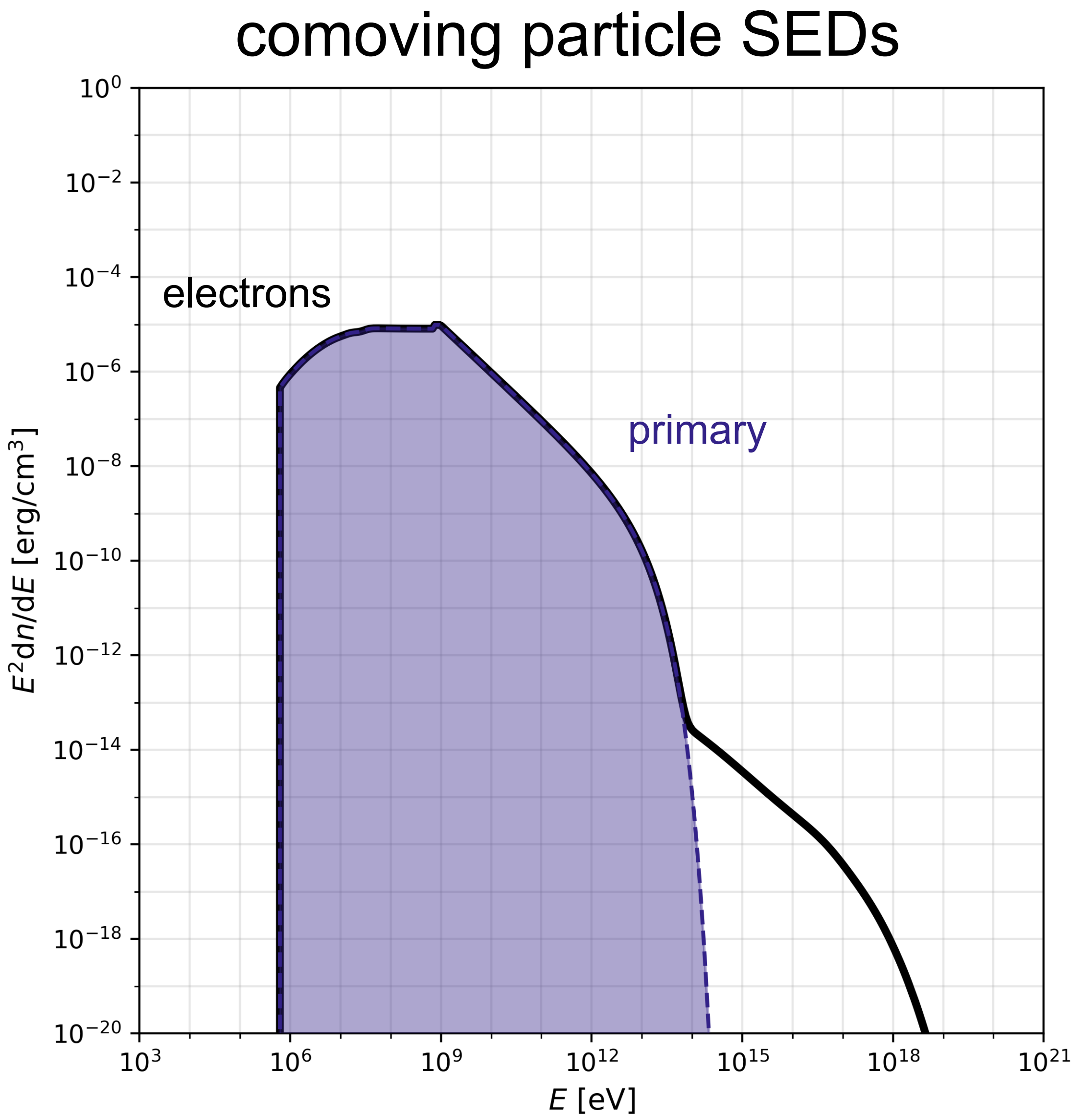


comoving particle SEDs
electrons
primary
$E^2 dn/dE$ [erg/cm^3]
E [eV]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}



comoving photon SED
syn.
IC
$E^2 dn/dE$ [erg/cm^3]
E [eV]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-3}
10^0
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}

Trackable


comoving particle SEDs
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10^0
10^−2
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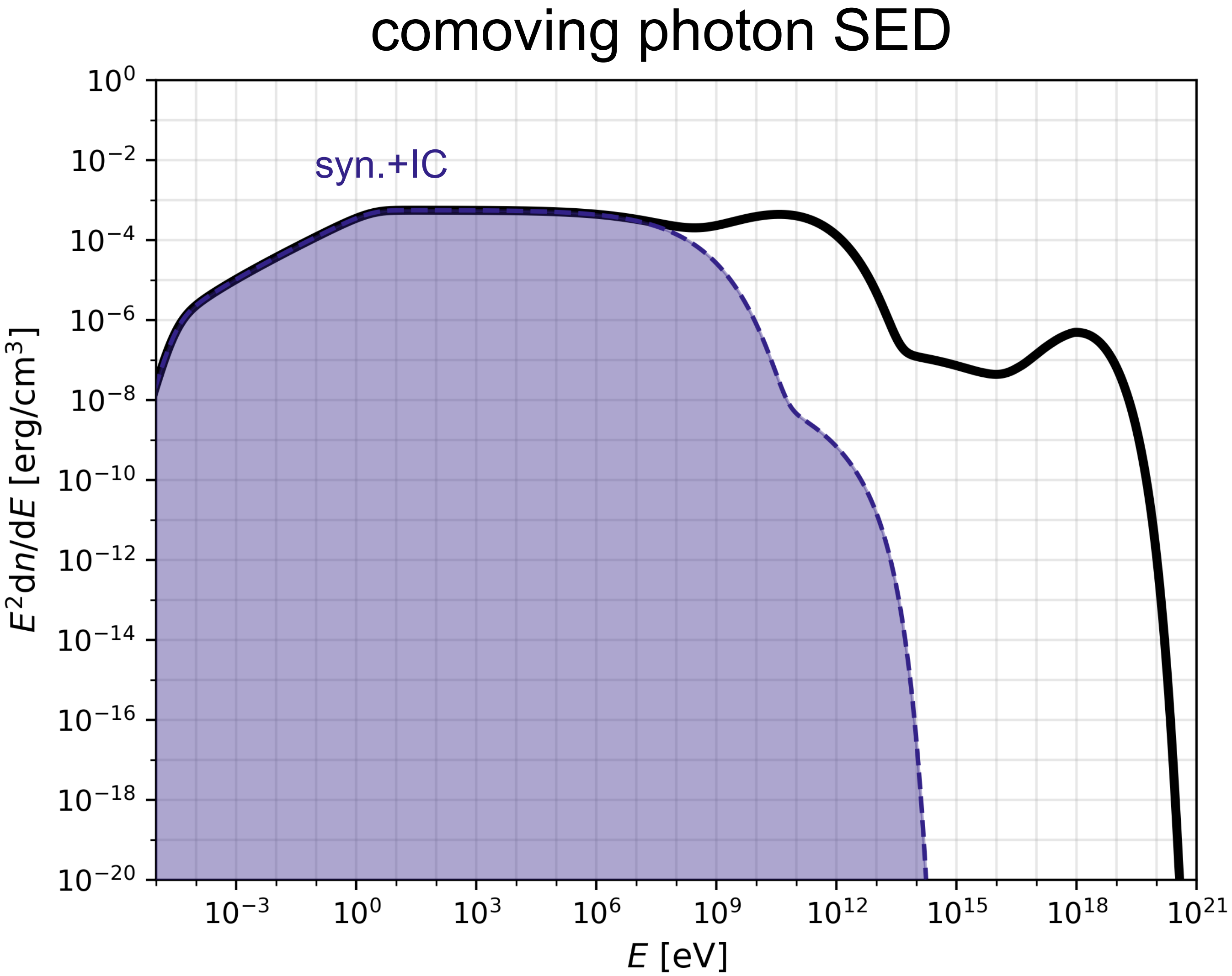
10^15
10^18
10^21


comoving photon SED
syn.+IC
$E^2 dn/dE$ [erg/cm^3]
E [eV]
10^0
10^−2
10^−4
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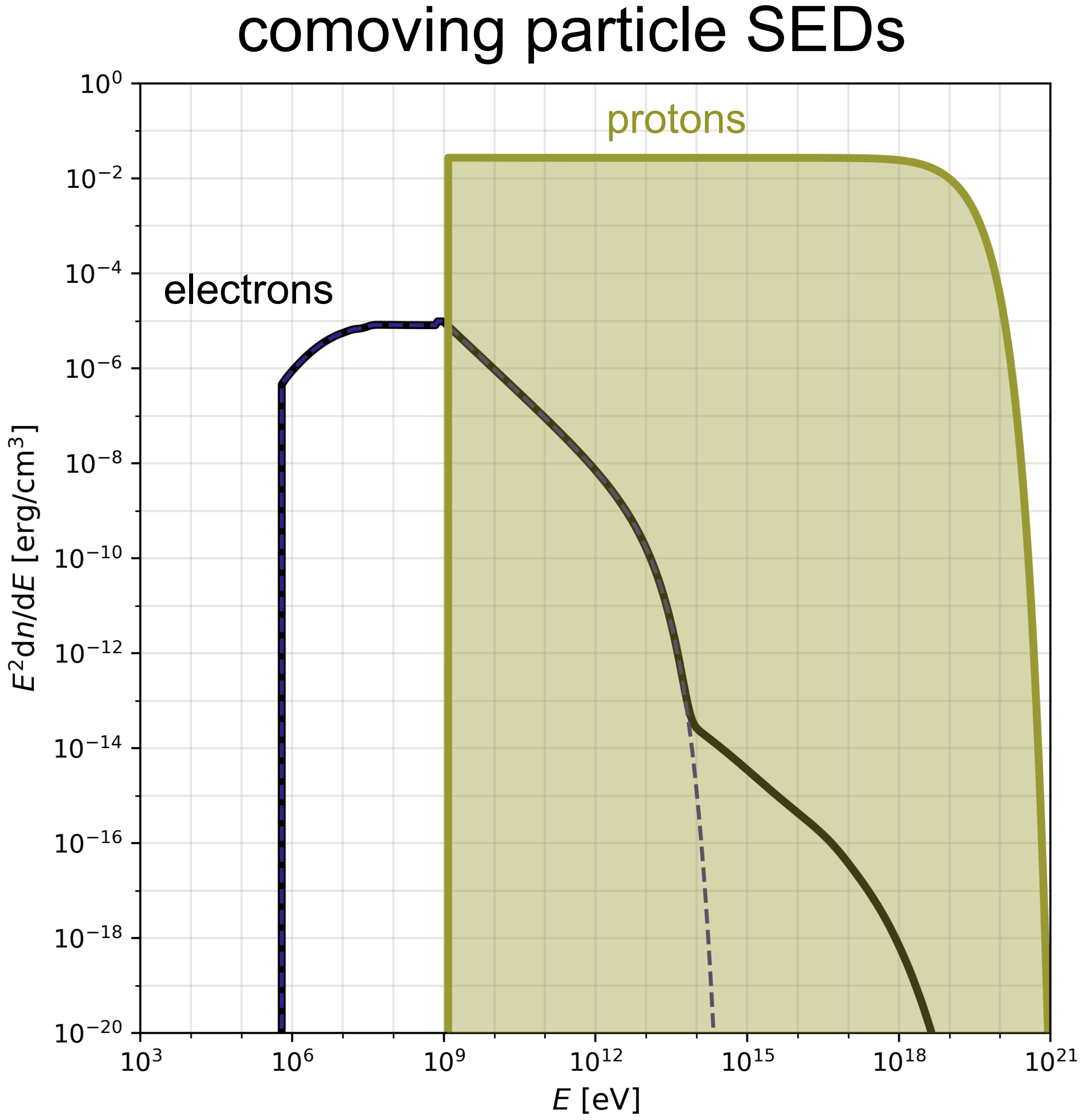
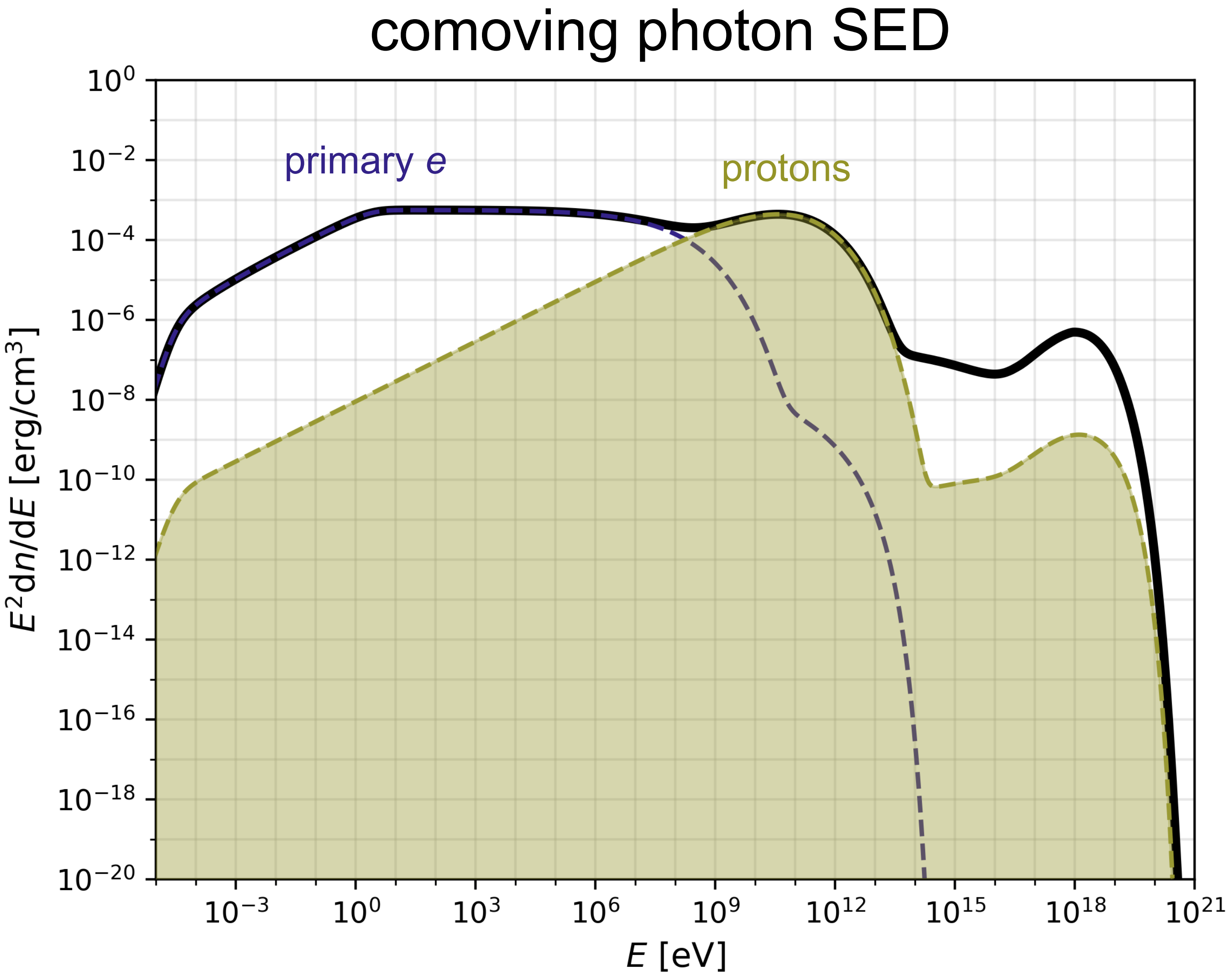
10^−3
10^0
10^3
10^6
10^9
10^12
10^15
10^18
10^21

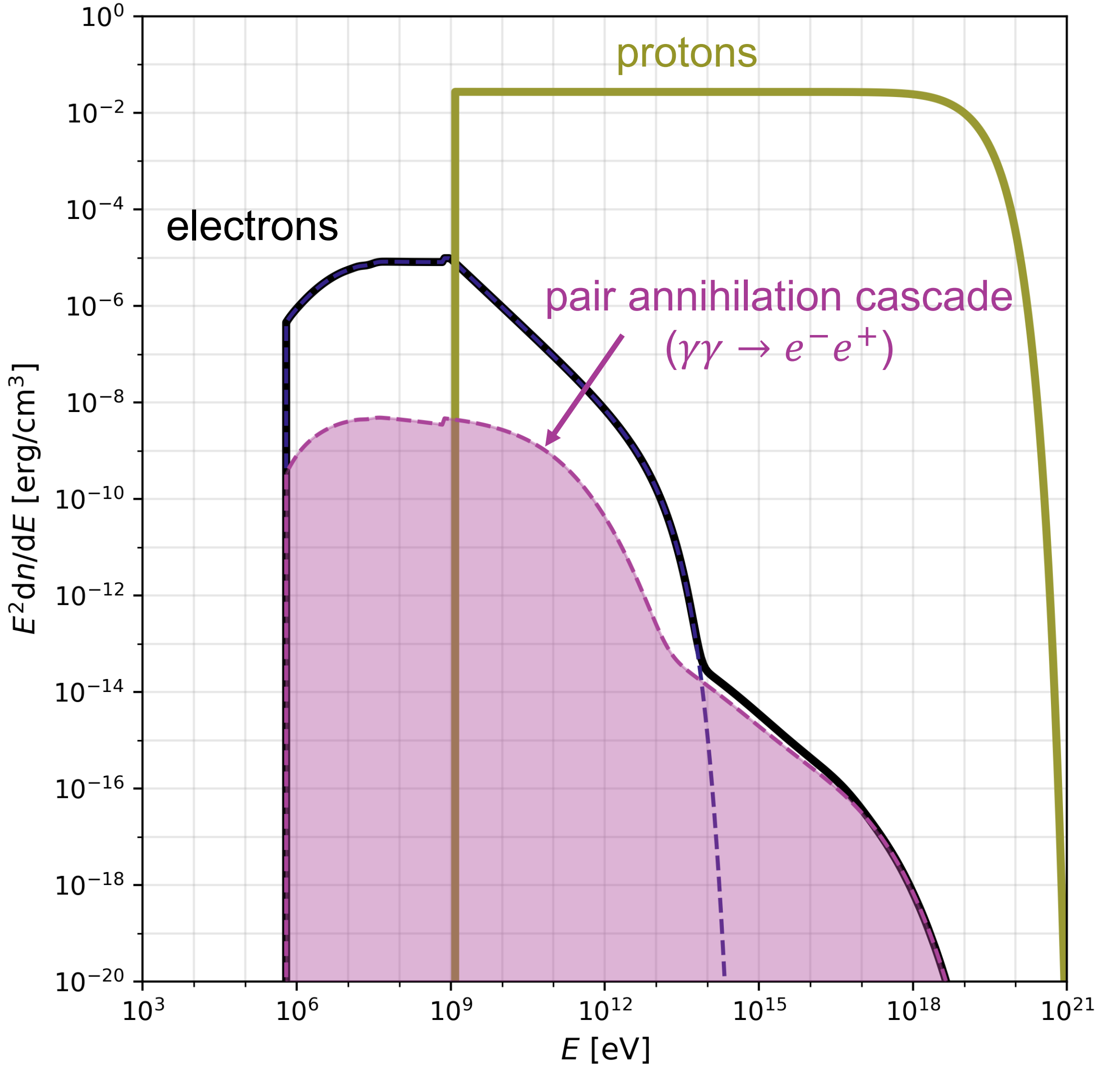
Trackable


comoving particle SEDs
protons
electrons
$E^2 dn/dE$ [erg/cm^3]
E [eV]

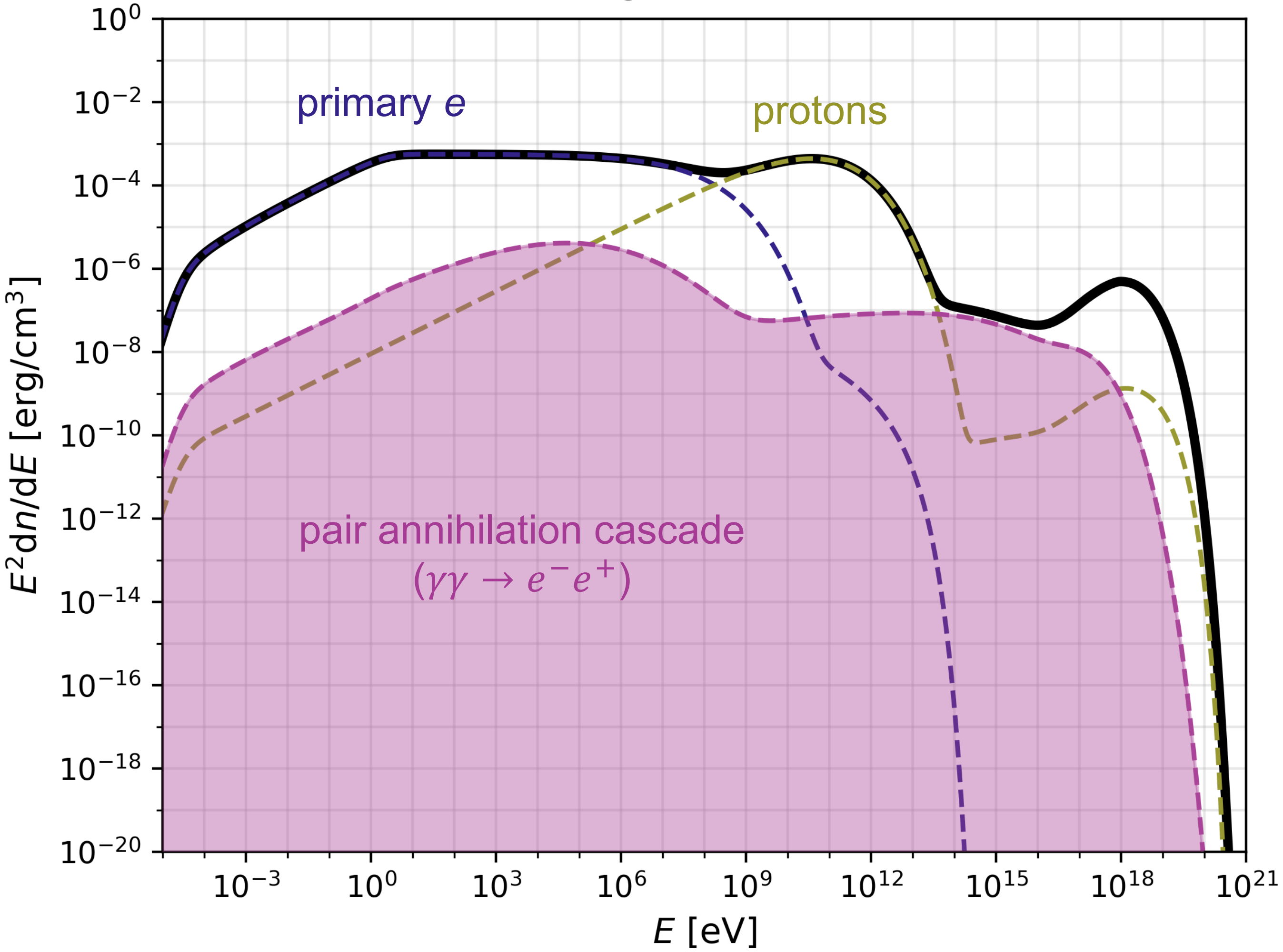

comoving photon SED
primary e
protons
$E^2 dn/dE$ [erg/cm^3]
E [eV]

Trackable – pair annihilation

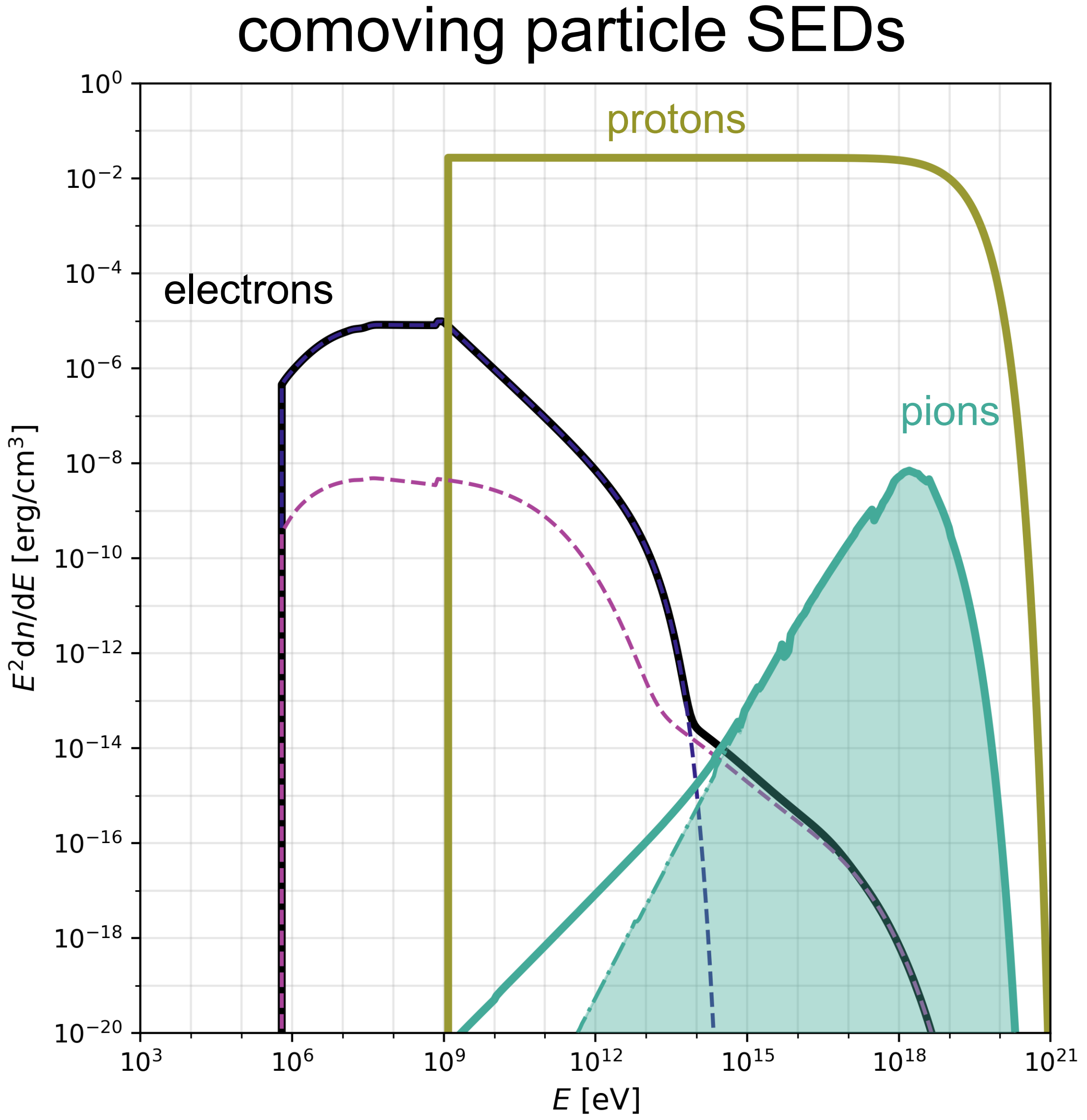
comoving particle SEDs

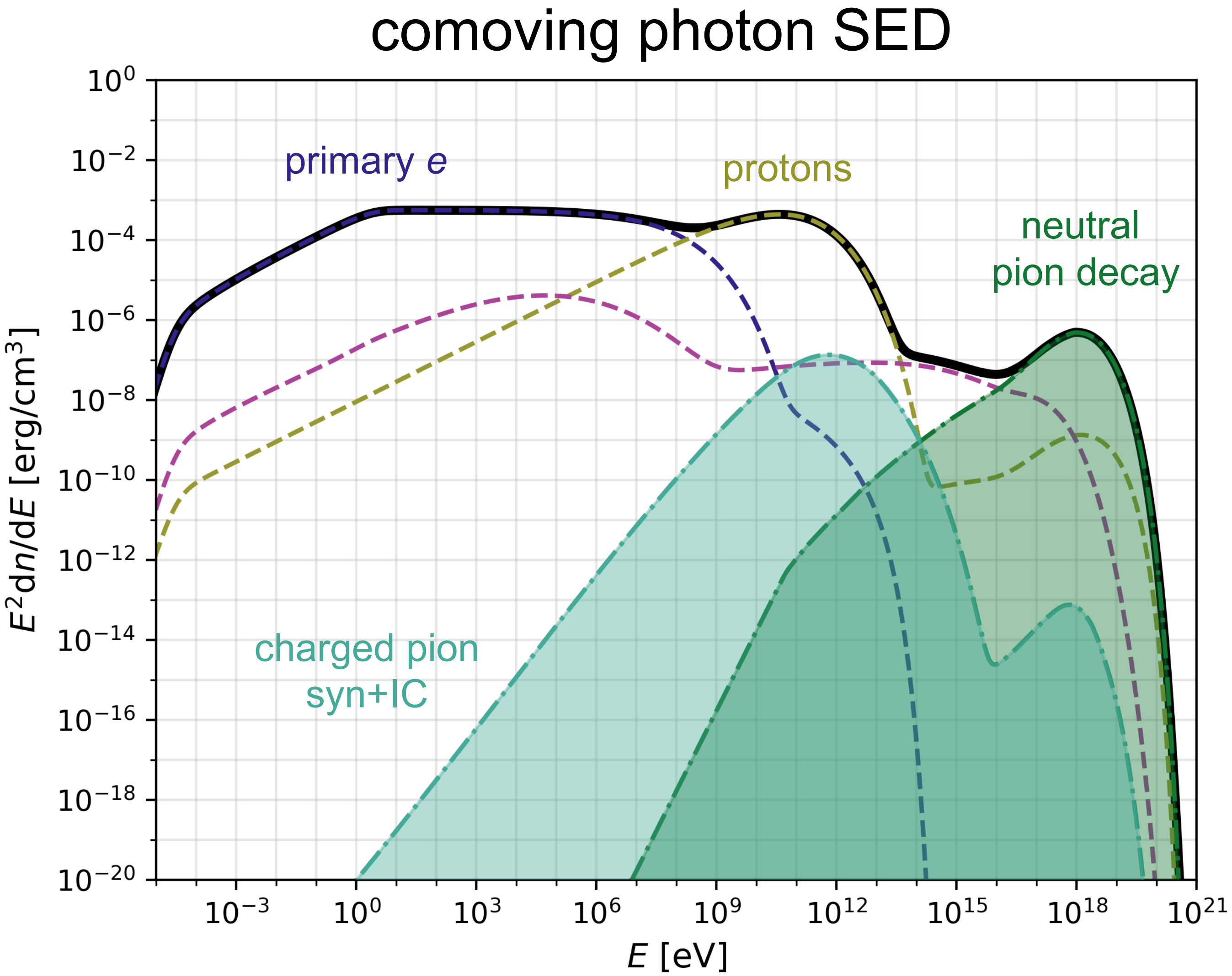


comoving photon SED

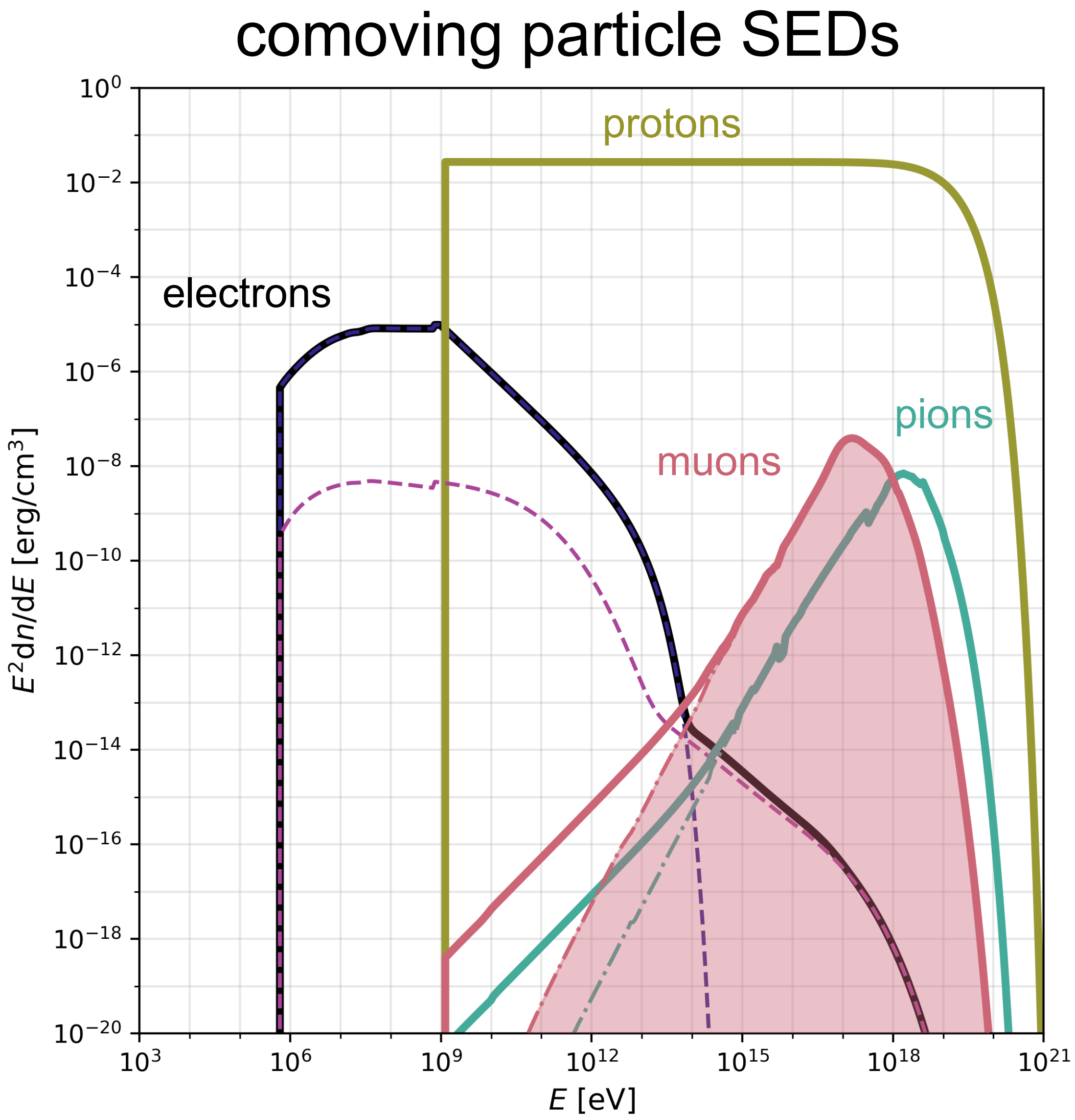


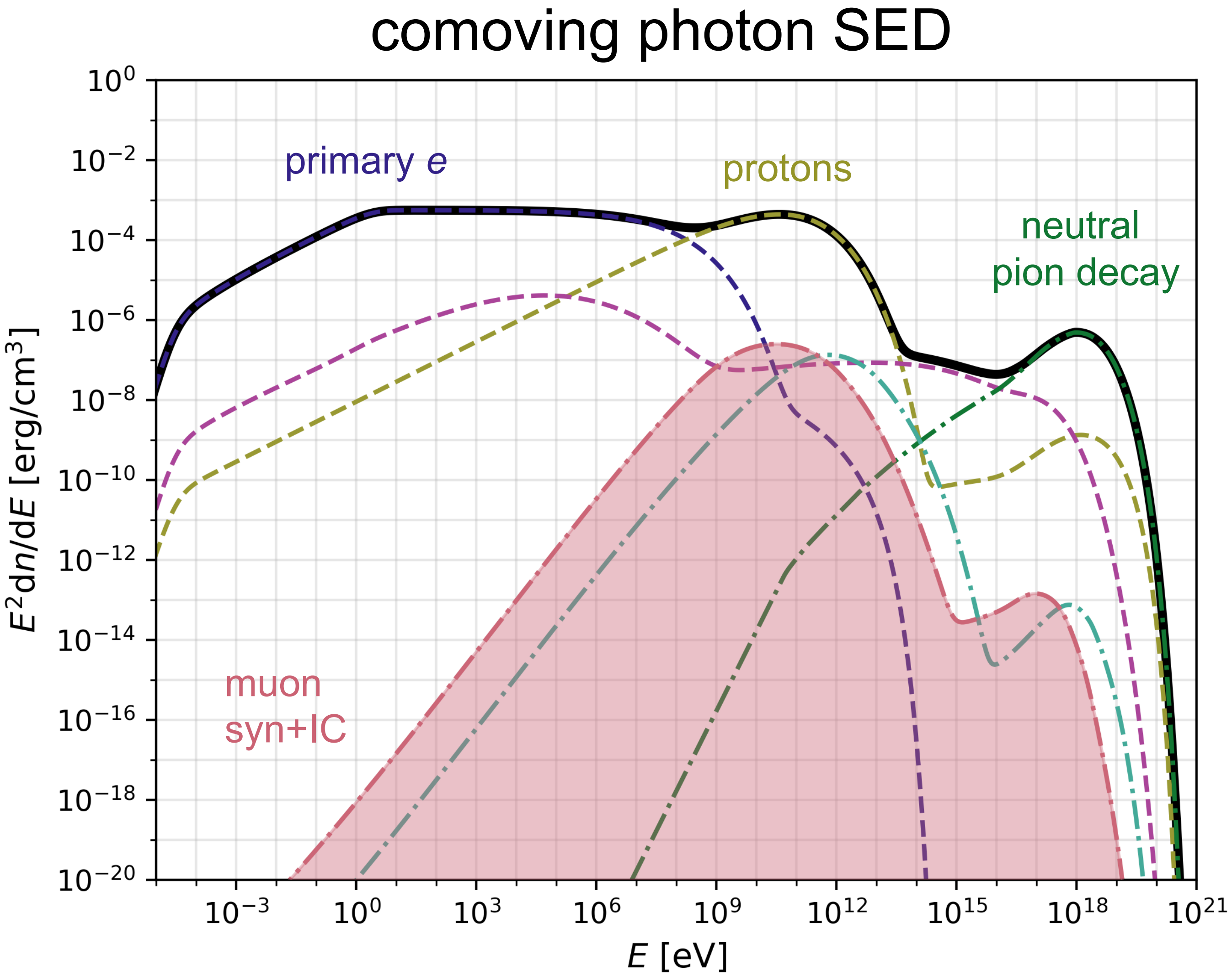
Trackable – photo-pion cascade: $p\gamma \rightarrow \pi$





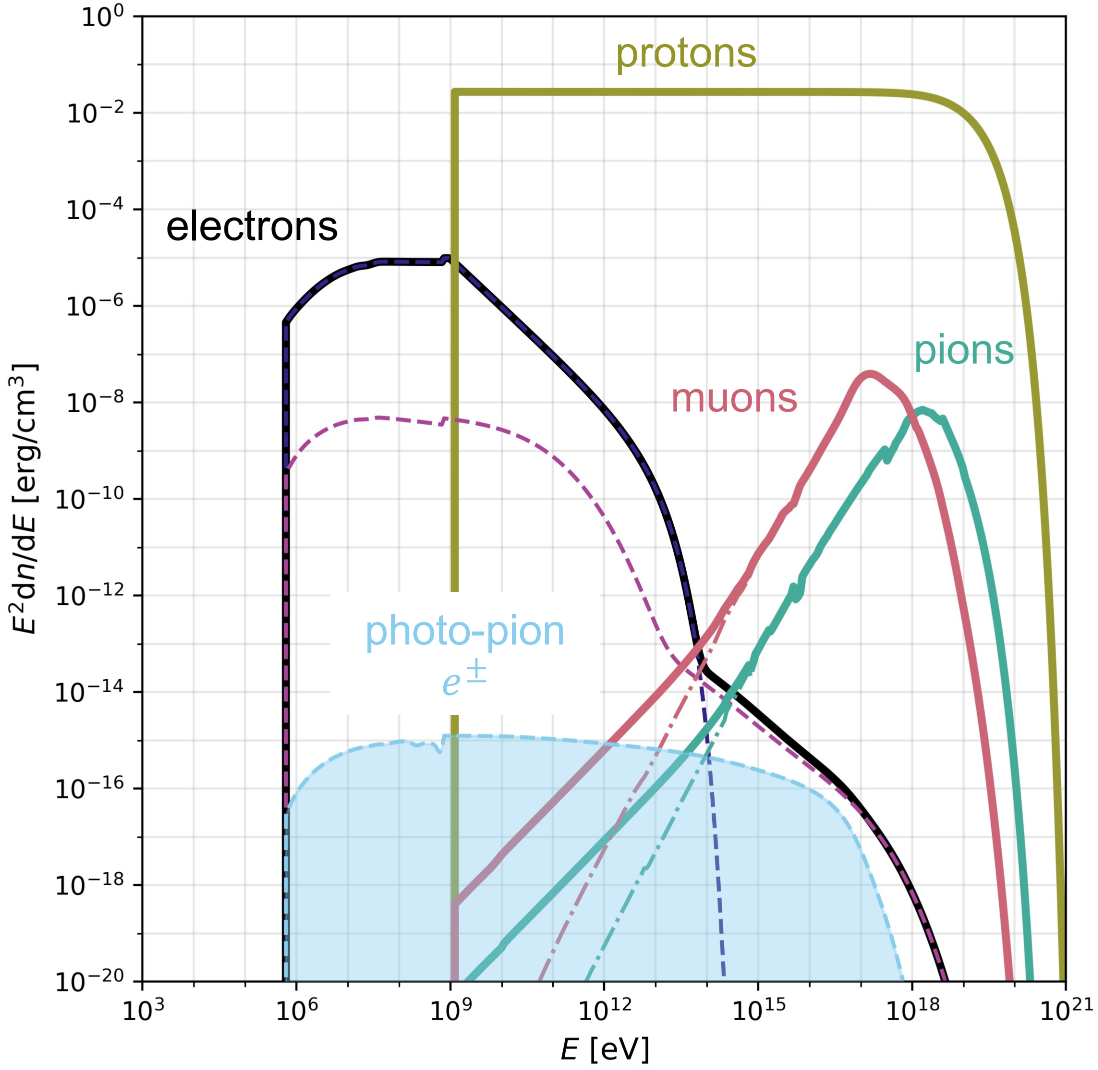
Trackable – photo-pion cascade: $p\gamma \rightarrow \pi \rightarrow \mu$



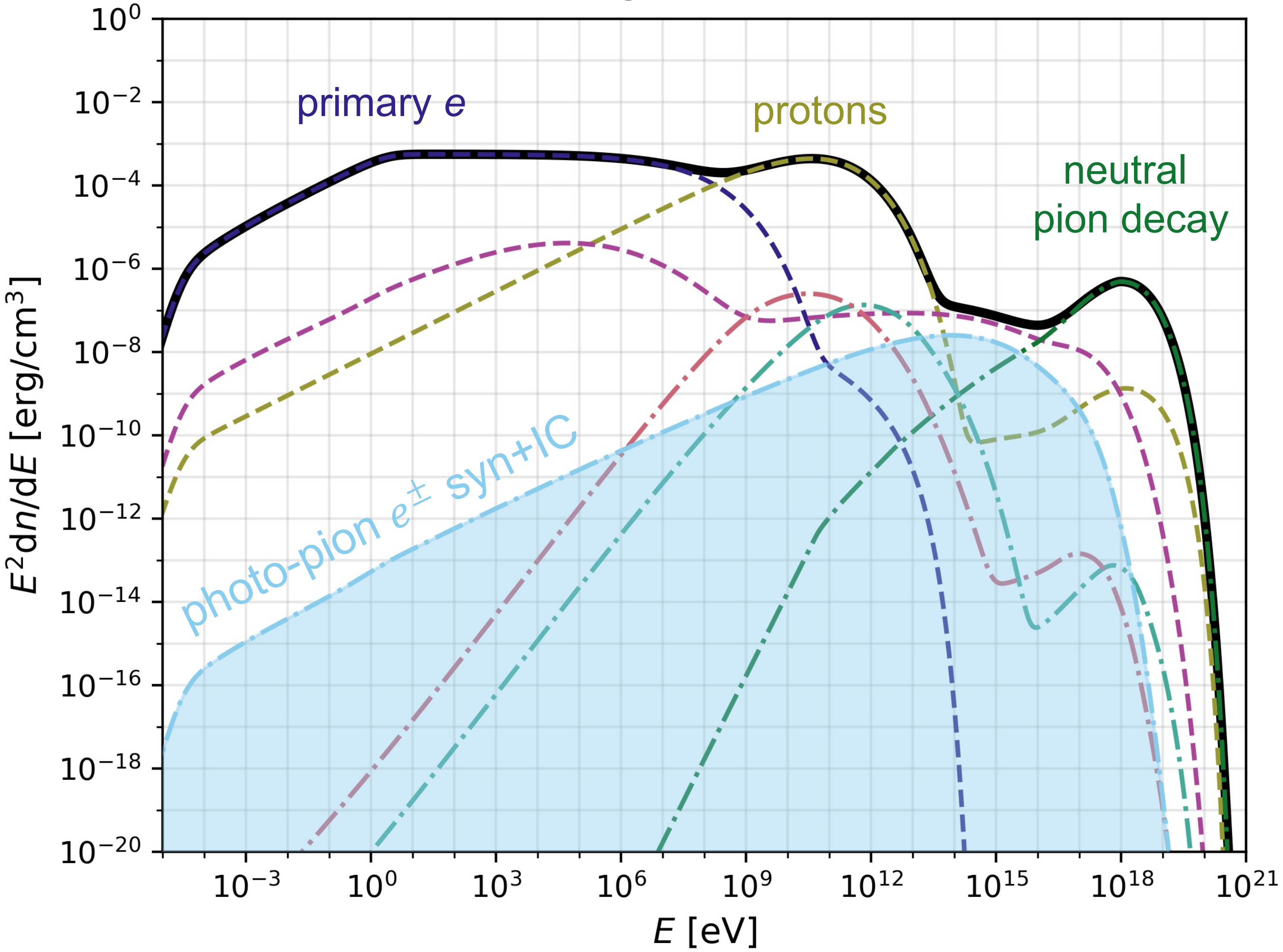


Trackable - photo-pion cascade: $p\gamma \rightarrow \pi \rightarrow \mu \rightarrow e^{\pm}$

comoving particle SEDs

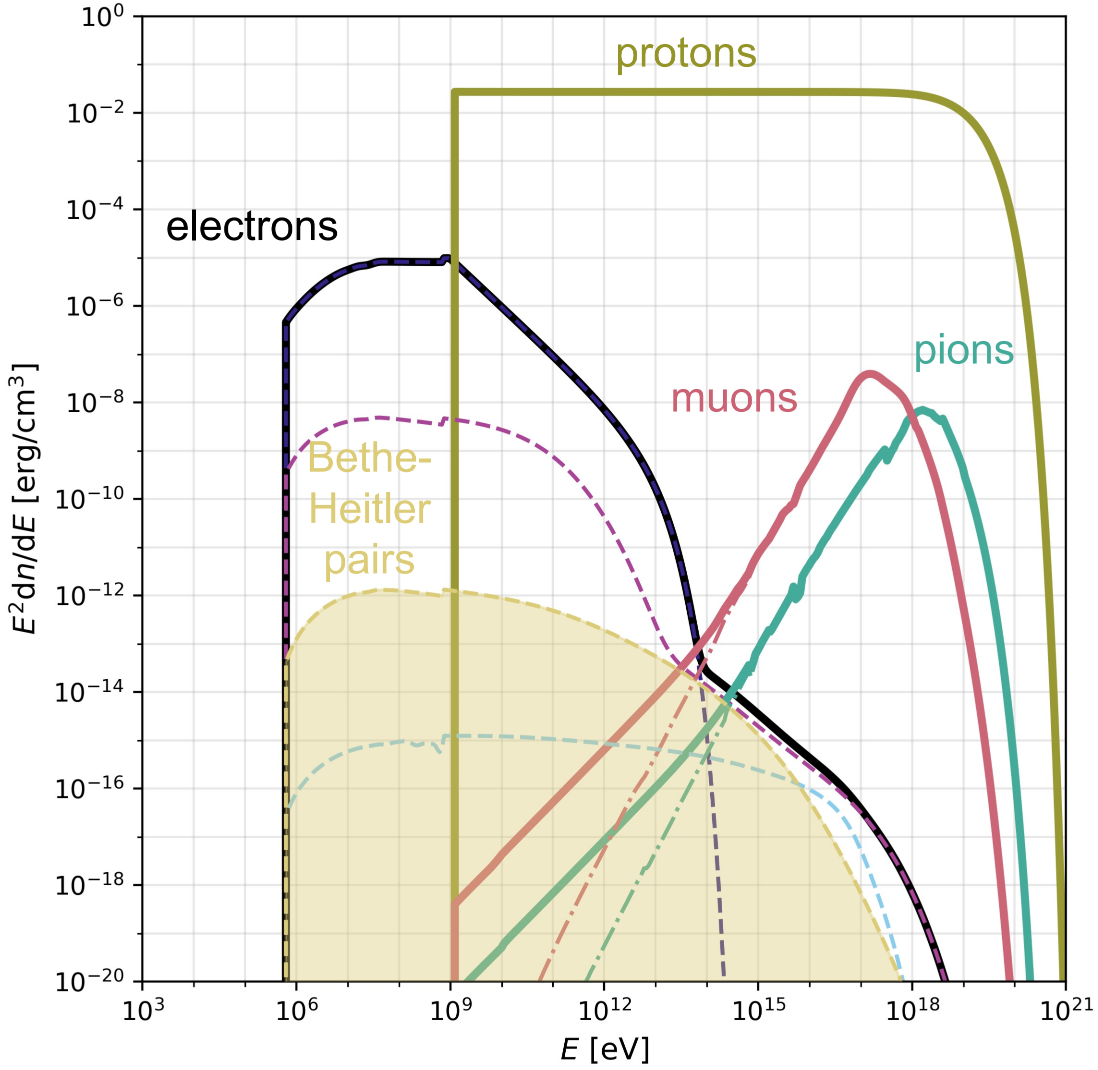


comoving photon SED

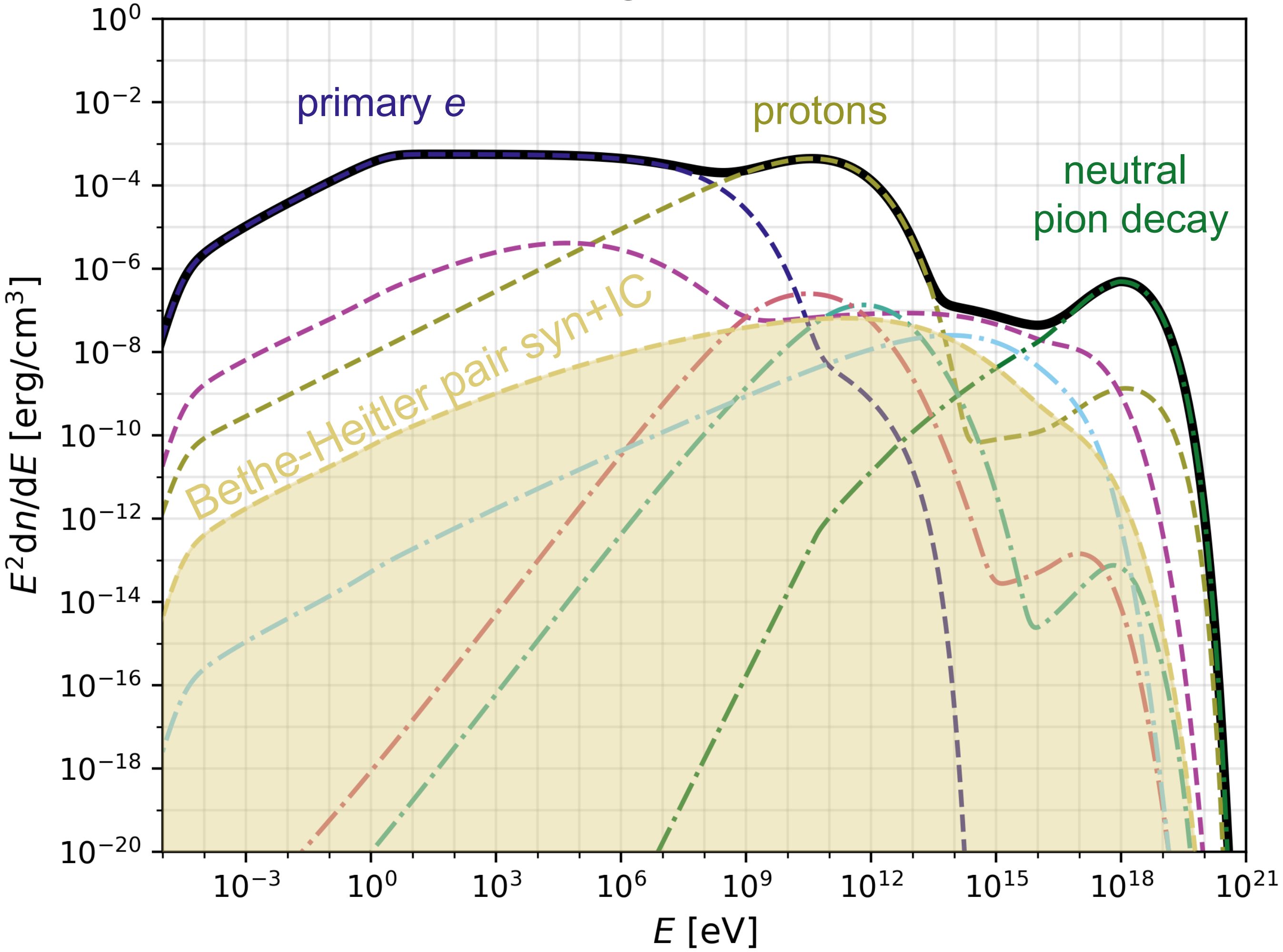


Trackable – Bethe-Heitler : $p\gamma \rightarrow p e^{+} e^{-}$

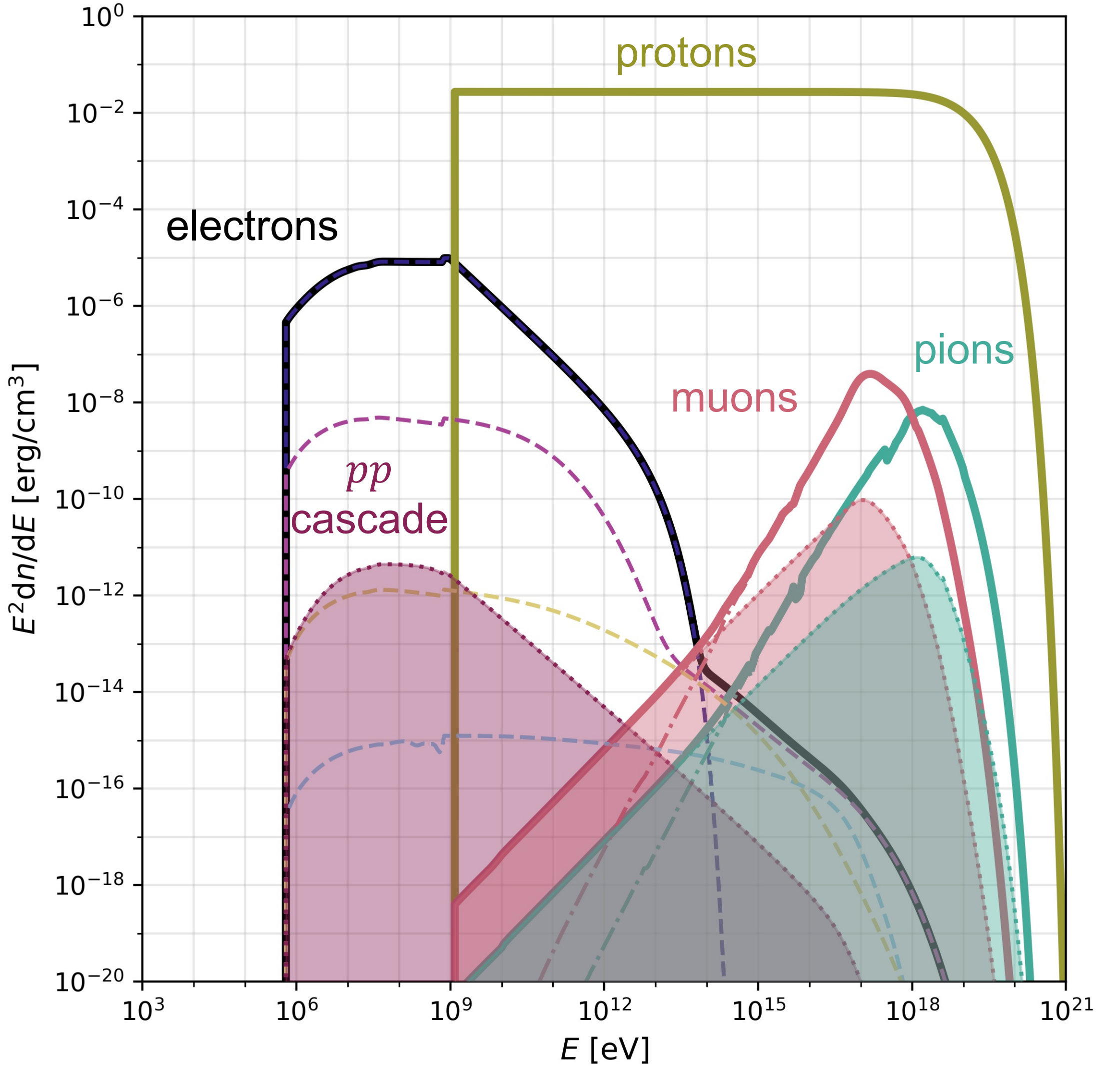
comoving particle SEDs

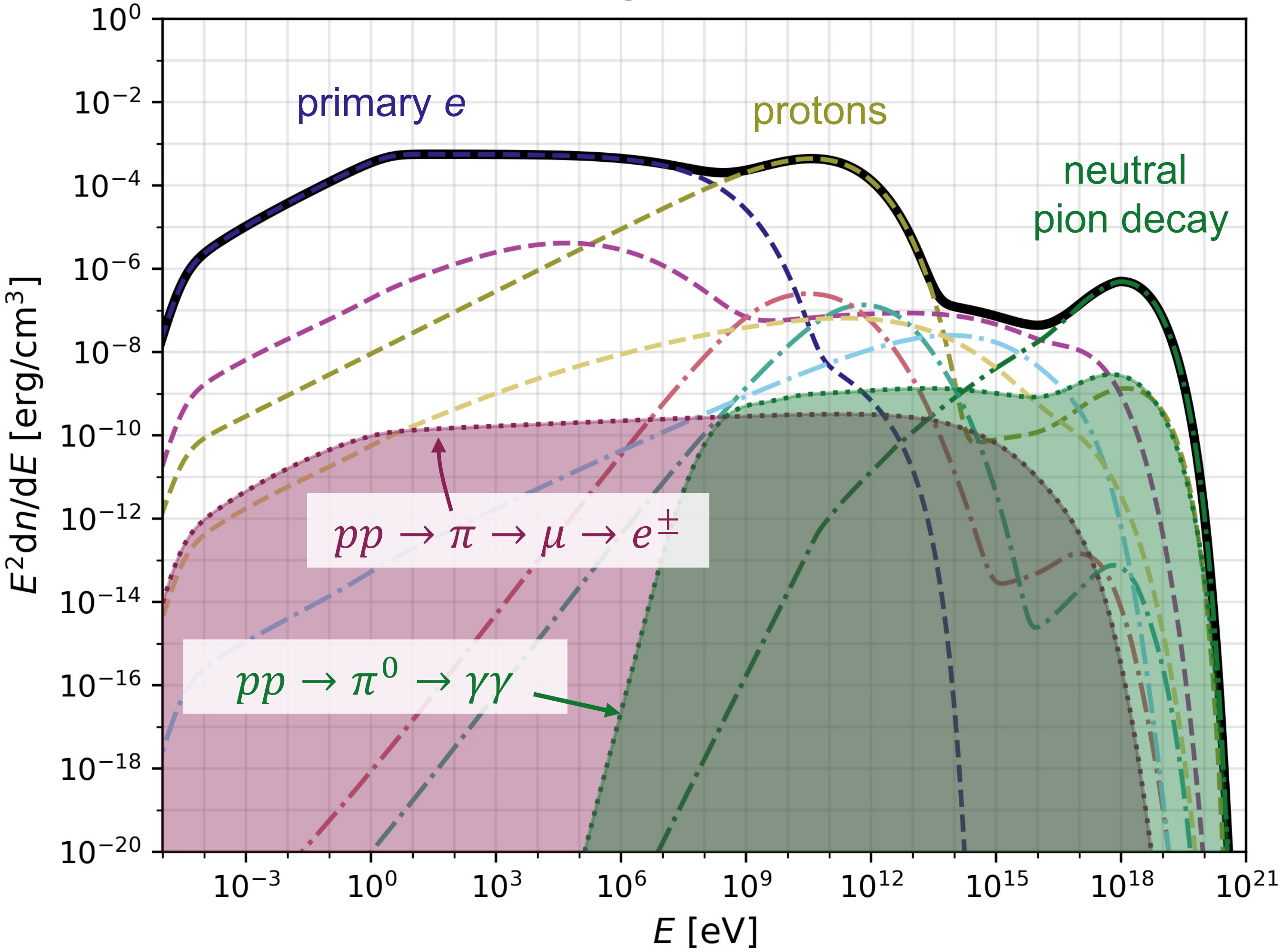


comoving photon SED

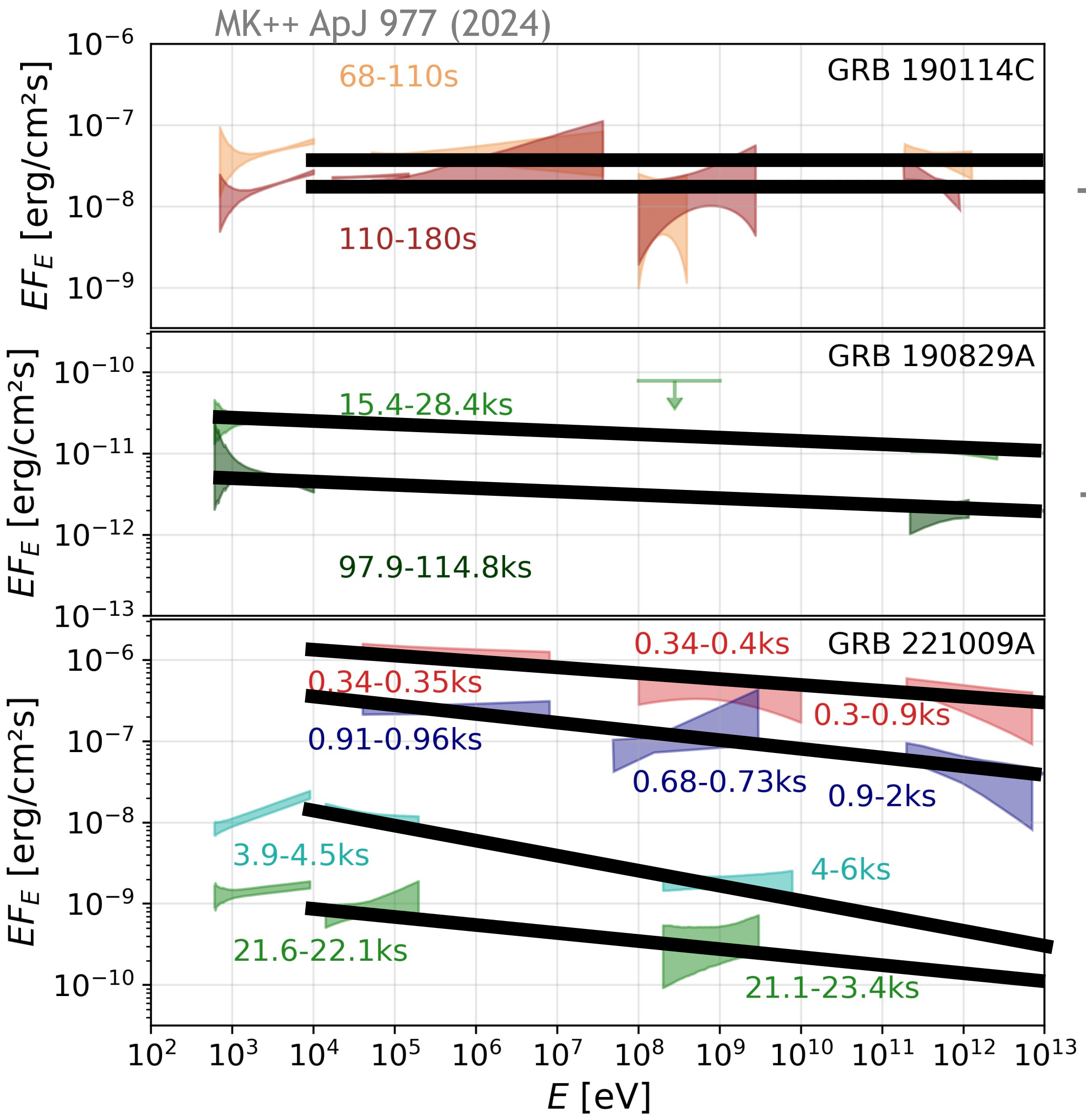


Trackable - proton-proton : $pp \rightarrow \pi \rightarrow \mu \rightarrow e^{\pm}$





Which scenarios fit GRB afterglow observations?



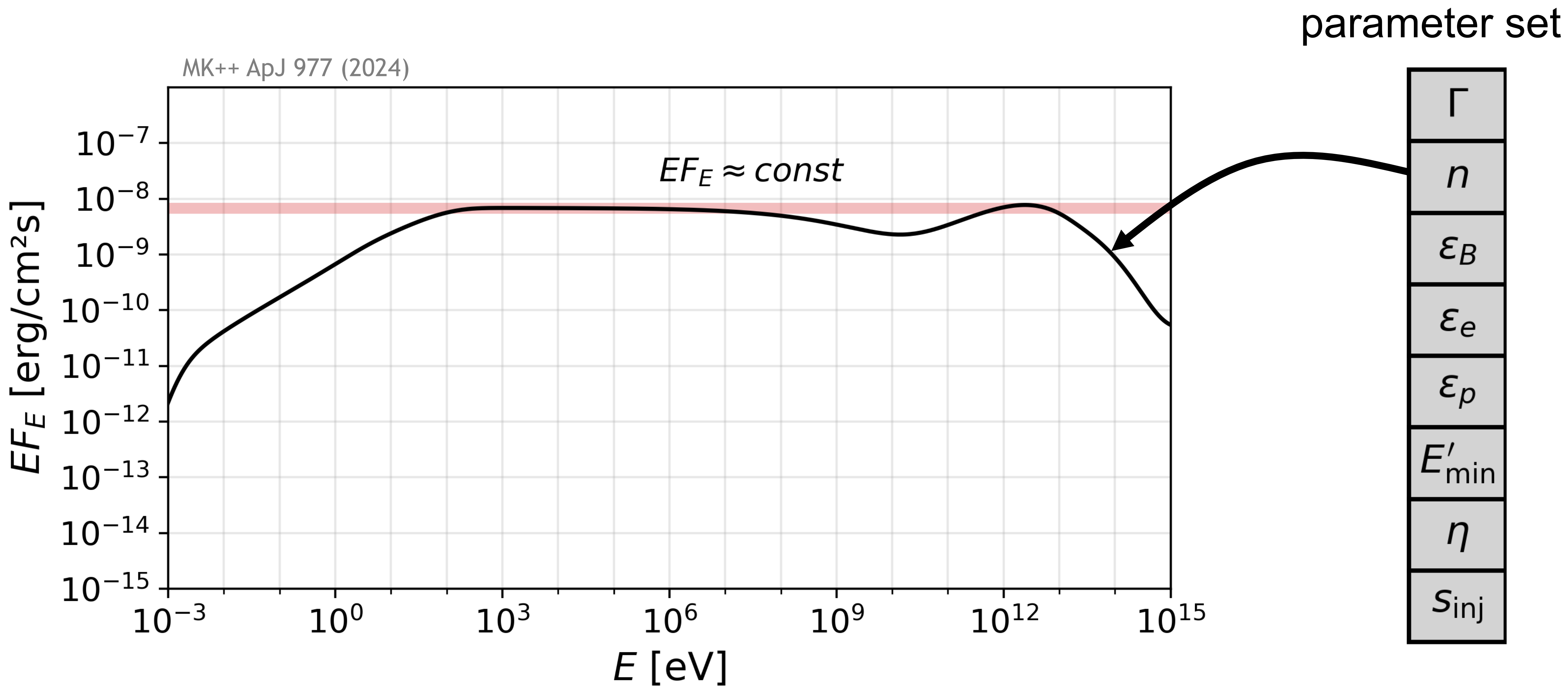
→ **MAGIC**

→ **H.E.S.S.**

→ **LHAASO**

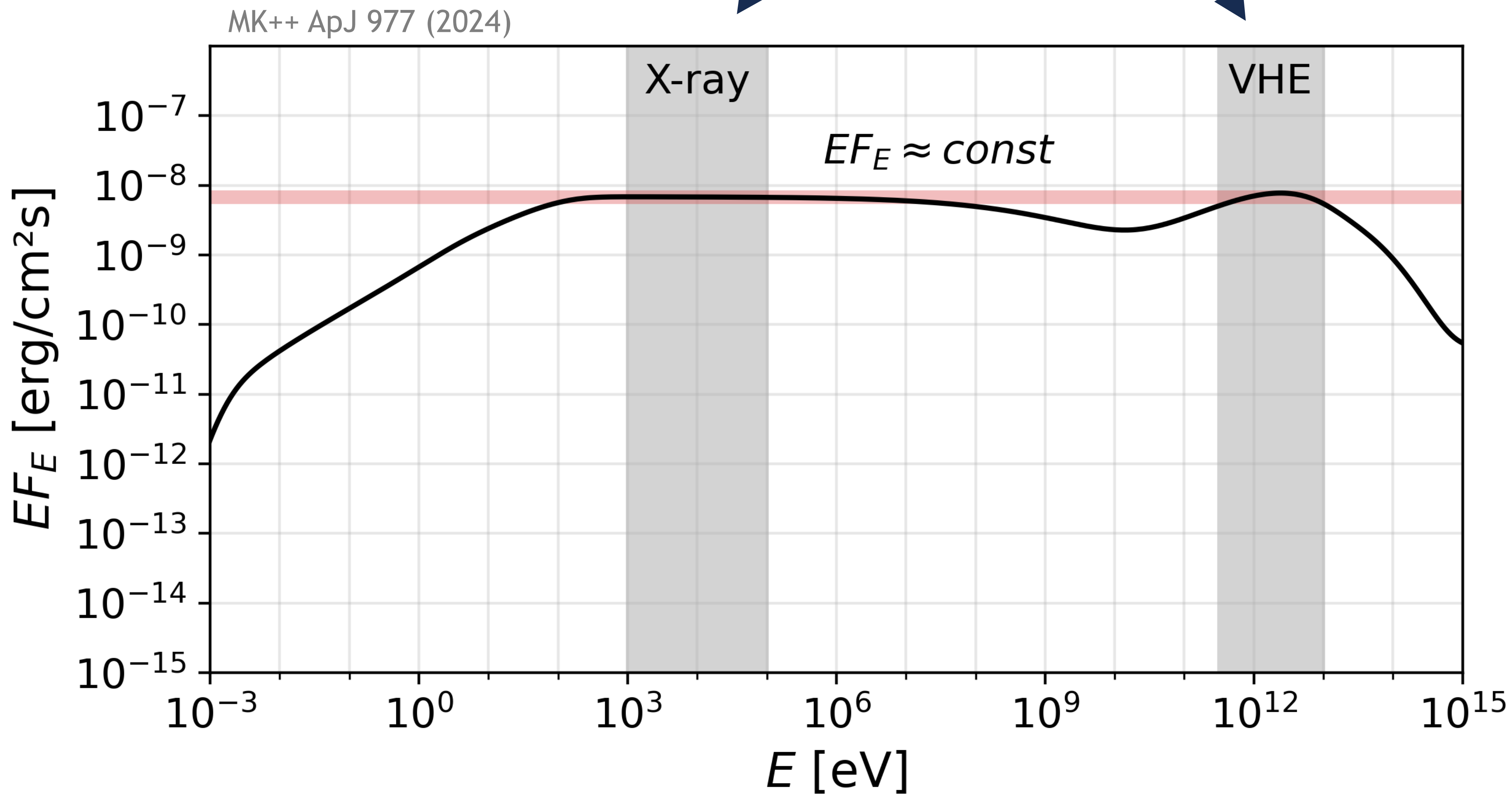
data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

Systematic parameter scan – selection

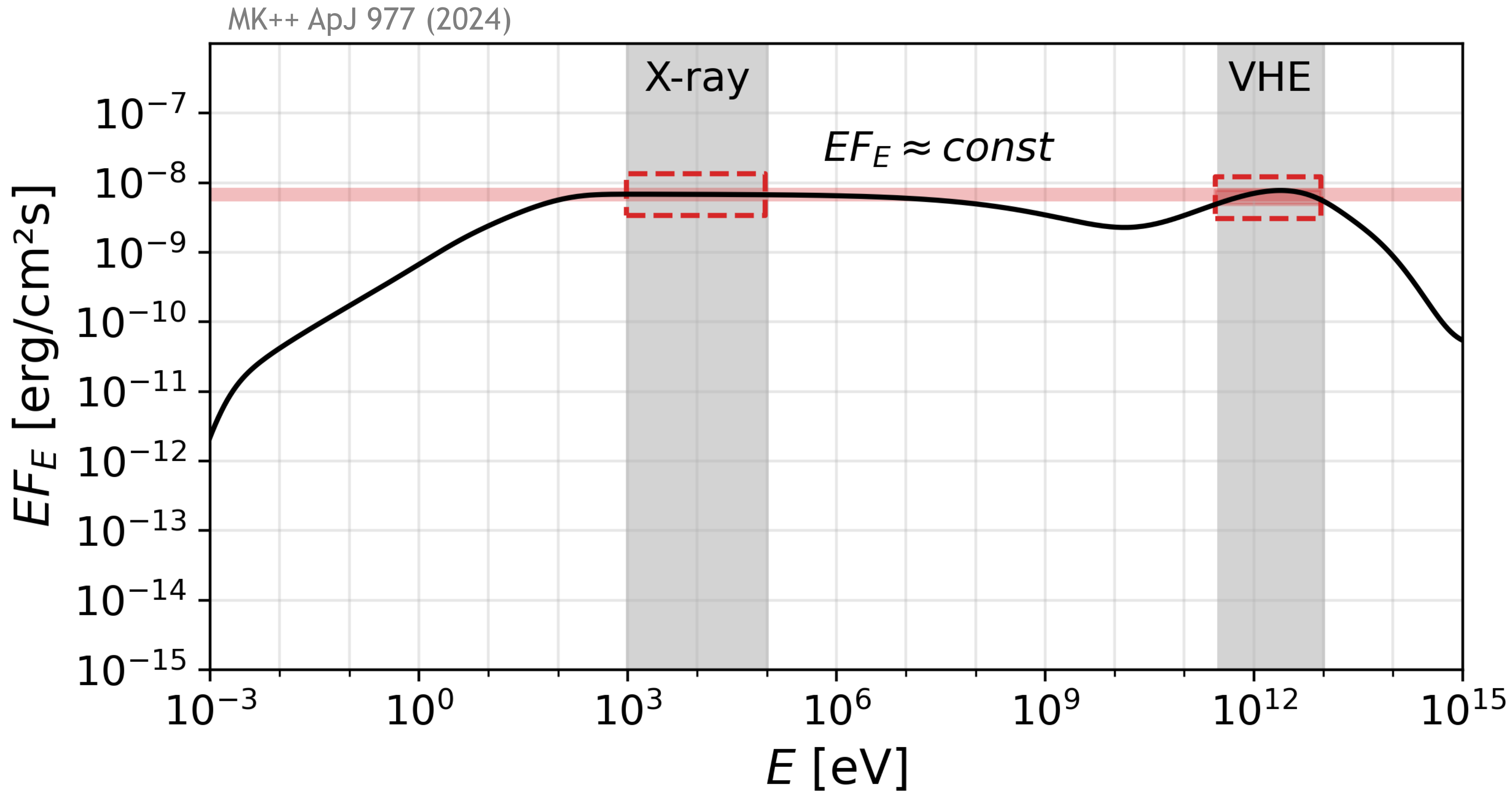


Systematic parameter scan – selection

robust data



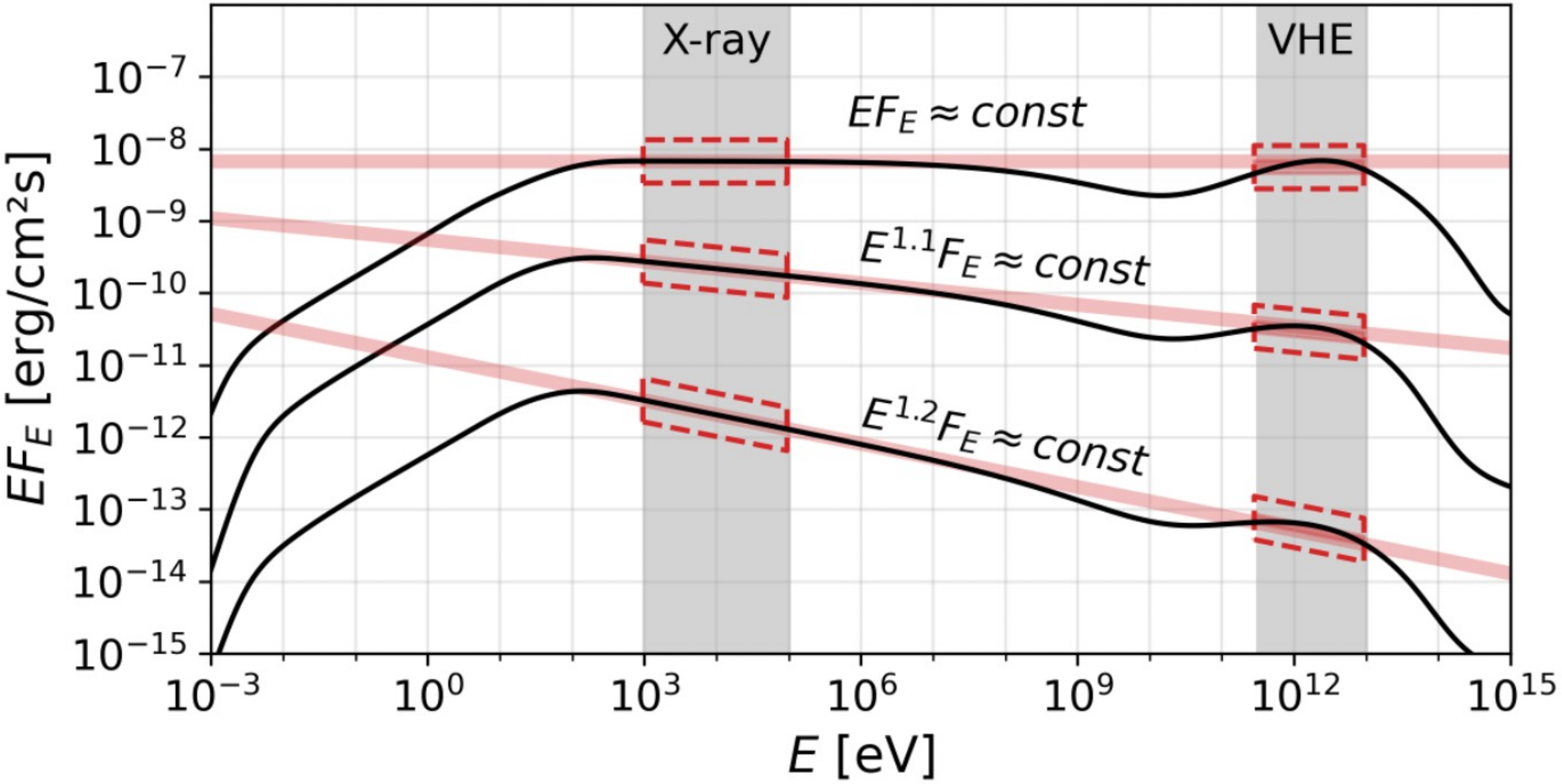
Systematic parameter scan – selection



selection criterion: contained in box

Systematic parameter scan

MK++ ApJ 977 (2024)



spectral index

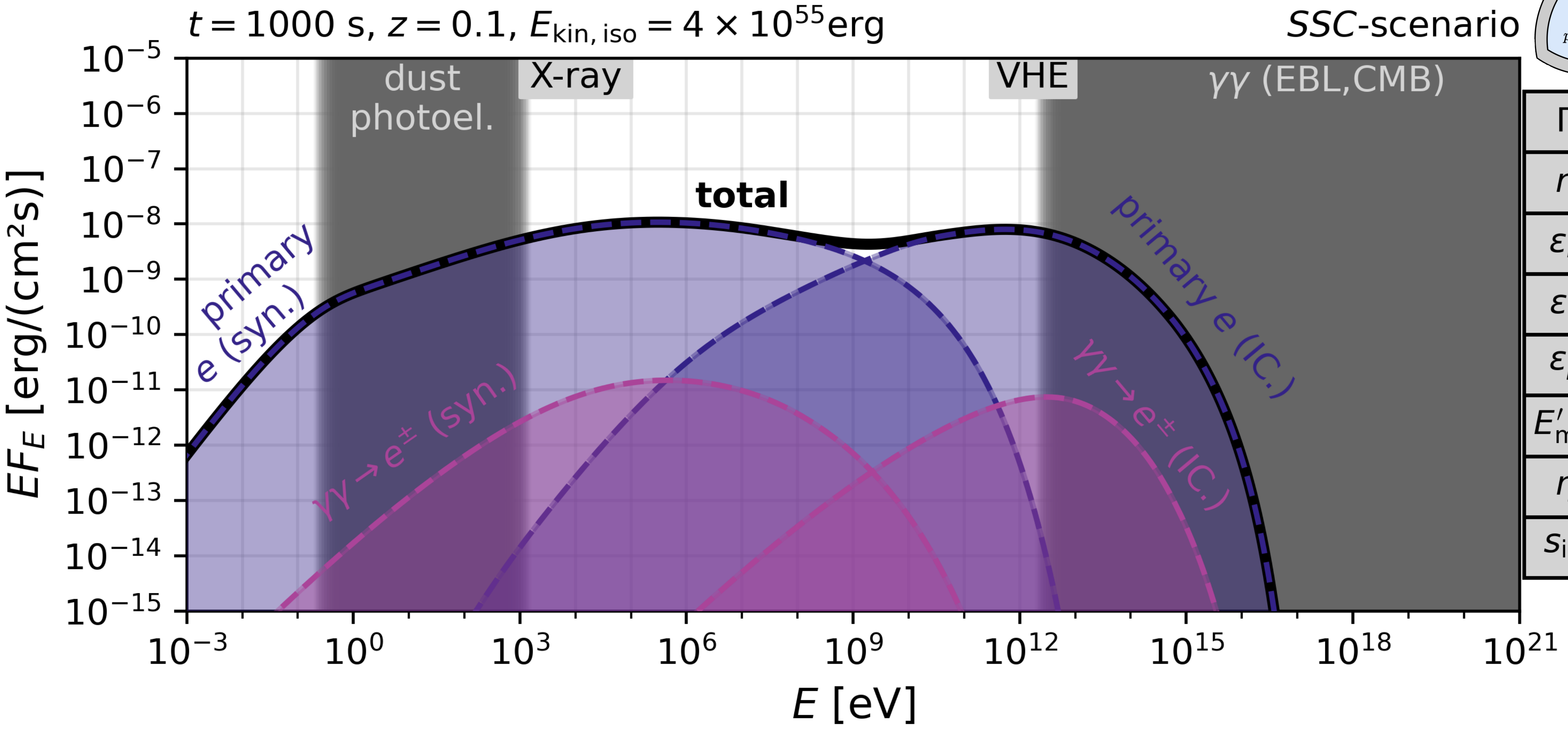
$\gamma \approx 2$

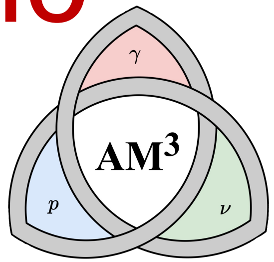
$\gamma \approx 2.1$

$\gamma \approx 2.2$

Synchrotron-Self Compton (SSC) Scenario

MK++ ApJ 977 (2024)



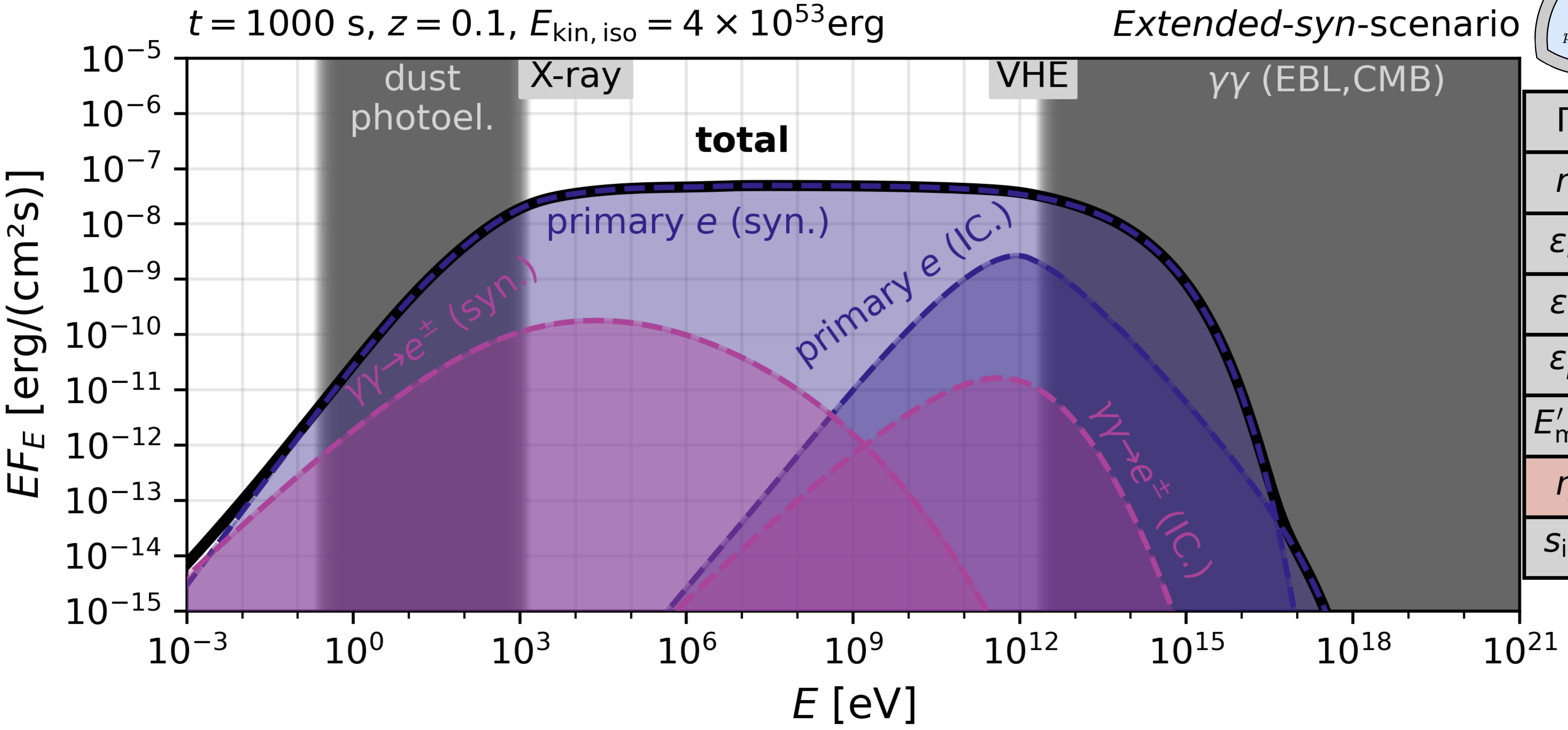


Γ	50	
n	1	cm^{-3}
ε_B	10^{-4}	
ε_e	$10^{-1.5}$	
ε_p	0	
E'_{min}	$10^{9.0}$	eV
η	1	
s_{inj}	2.3	

→ Klein-Nishina suppression at VHE: 1) softening, 2) fine-tuned energy density

Extended Synchrotron Scenario

MK++ ApJ 977 (2024)

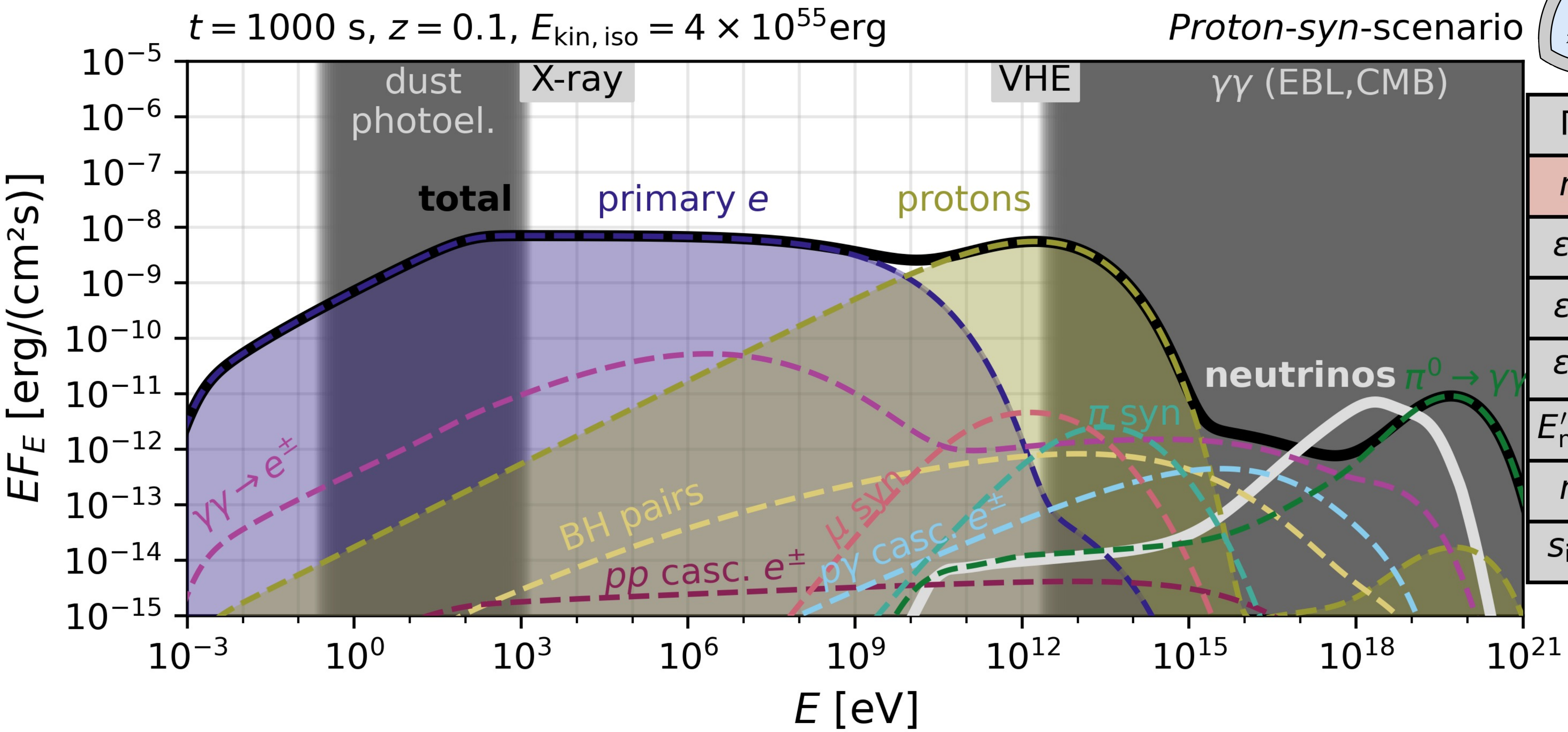


Γ	50	
n	1	cm^{-3}
ε_B	10^{-3}	
ε_e	$10^{-1.5}$	
ε_p	0	
E'_{min}	$10^{10.5}$	eV
η	10^{-4}	
s_{inj}	2	

$\eta \ll 1$ (extremely fast acceleration) $\rightarrow$ effective multi-zone parameter?

$\rightarrow$ e.g., Khangulyan++ APJ 947 (2021)

Proton Synchrotron Scenario



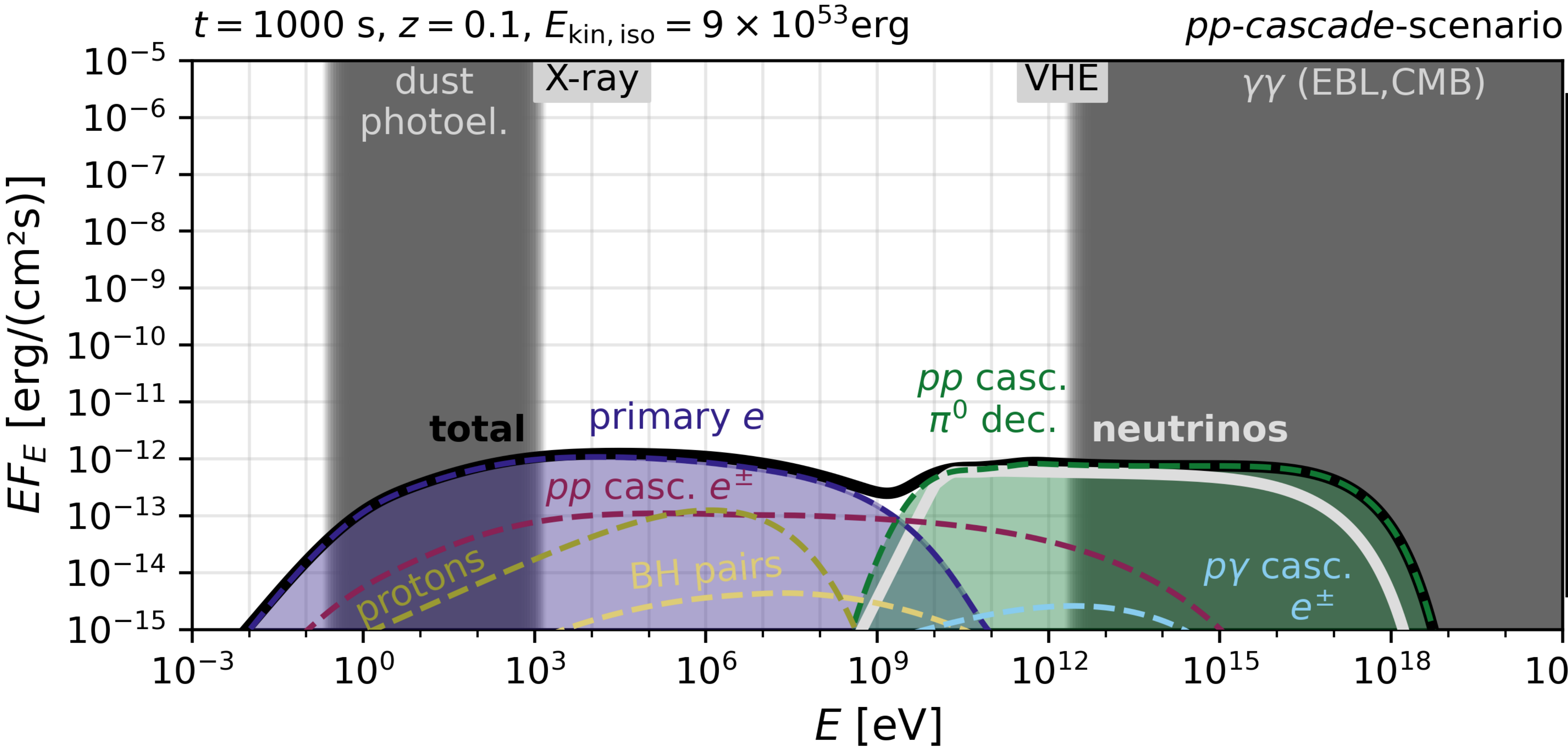
Γ	50	
n	10^2	cm^{-3}
ε_B	10^{-1}	
ε_e	$10^{-4.5}$	
ε_p	10^{-3}	
$E'_{\min}$	$10^{9.0}$	eV
η	1	
s_{inj}	2	

→ fine-tuned exponential cut-off

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

Proton-Proton Cascade Scenario

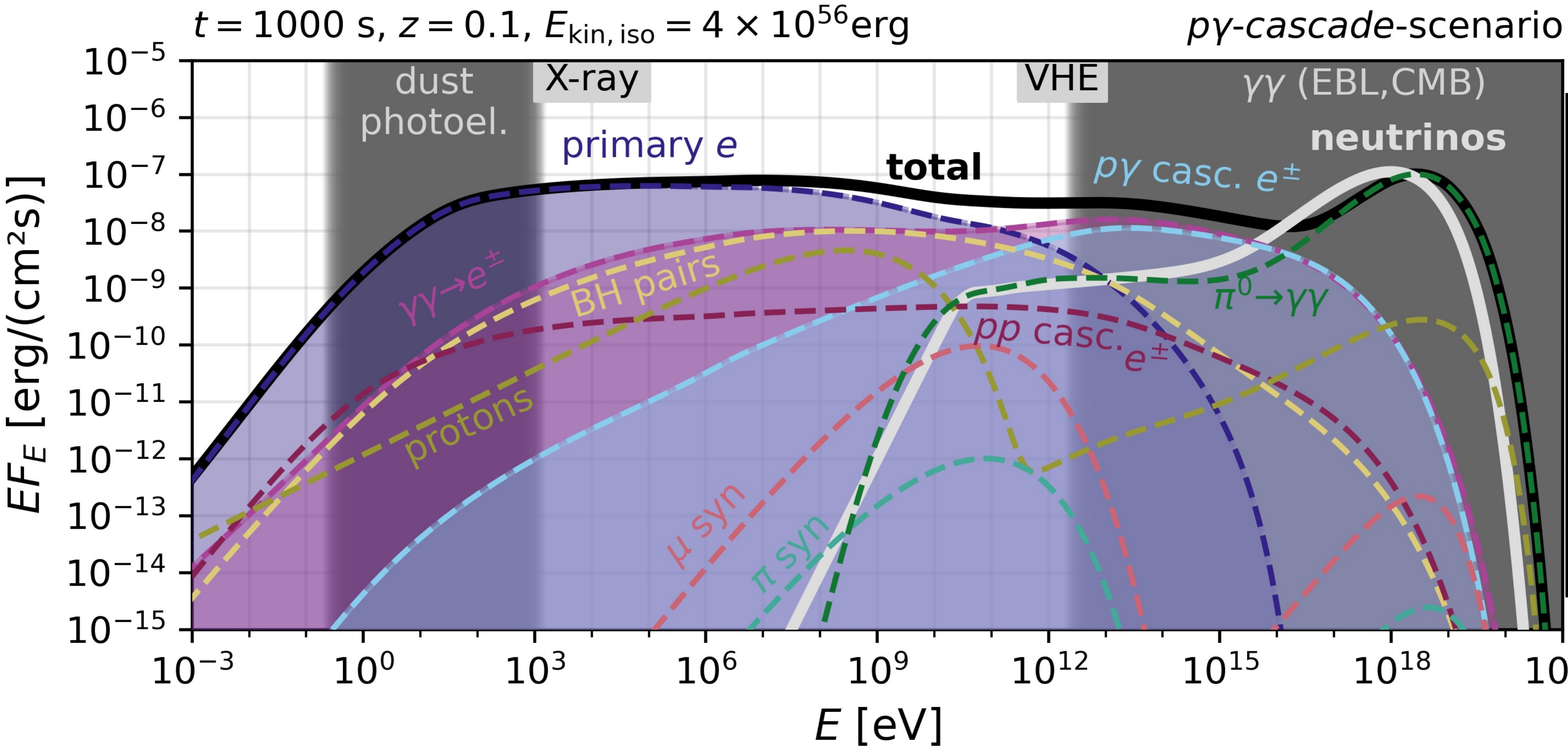
MK++ ApJ 977 (2024)



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

→ pp-interactions inefficient!

Proton-Photon Cascade Scenario



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

→ extreme energy + density requirements

Large energy requirements of $10^{57} erg$?

massive star collapse

→ accreted mass $M \approx 10 M_{\odot}$

→ $\varepsilon_{\mathrm{kin}} \approx 10\%$ converted to kinetic energy of outflow

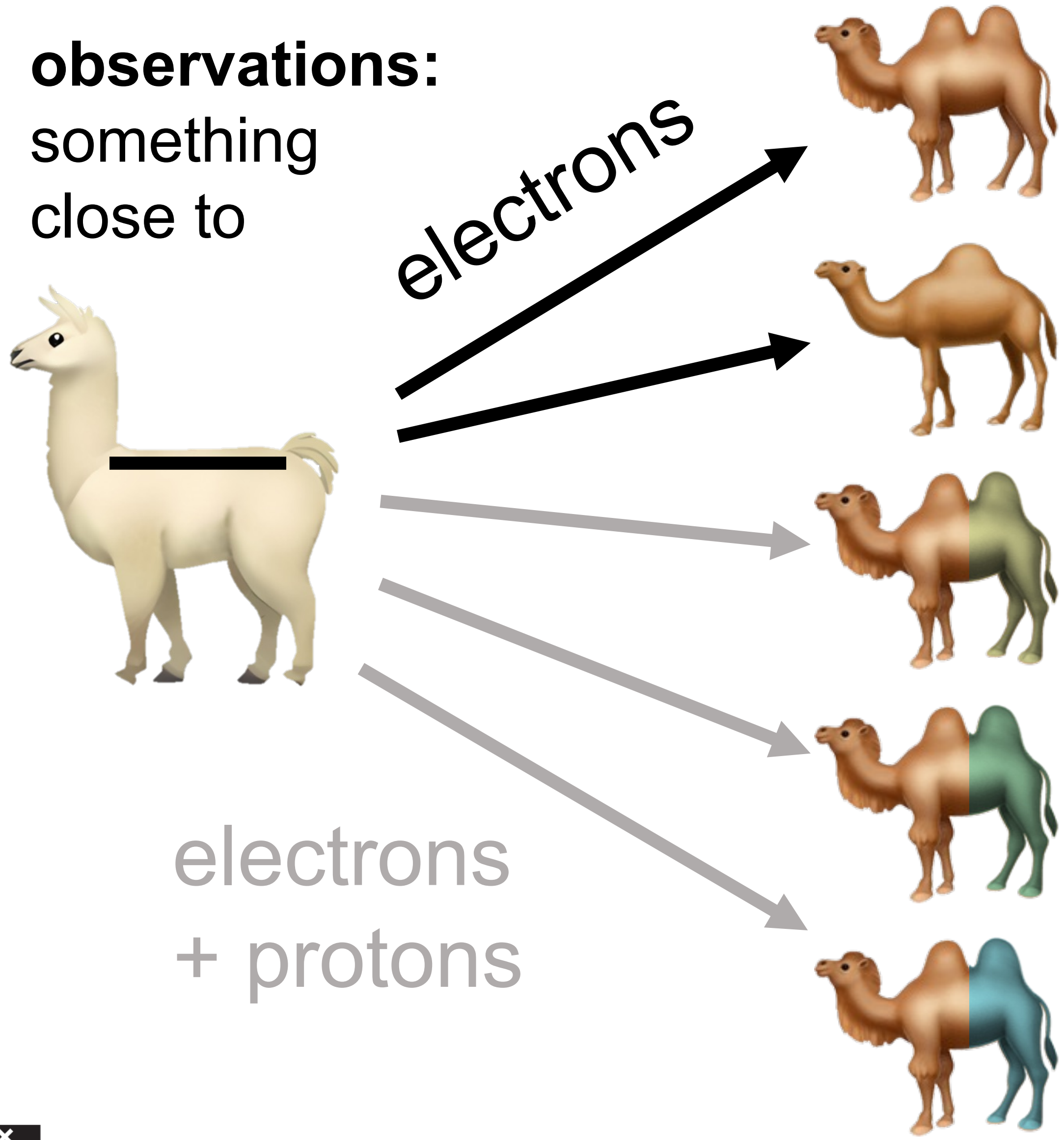
→ into cone with opening angle $\theta = 3°$

→ $E_{\mathrm{kin,iso}} \approx 10^{57} erg \left(\frac{M}{10 M_{\odot}}\right) \left(\frac{\varepsilon_{\mathrm{kin}}}{0.1}\right) \left(\frac{3°}{\theta}\right)^2$

→ **extreme, but not crazy!**

Scenarios

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

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observations:
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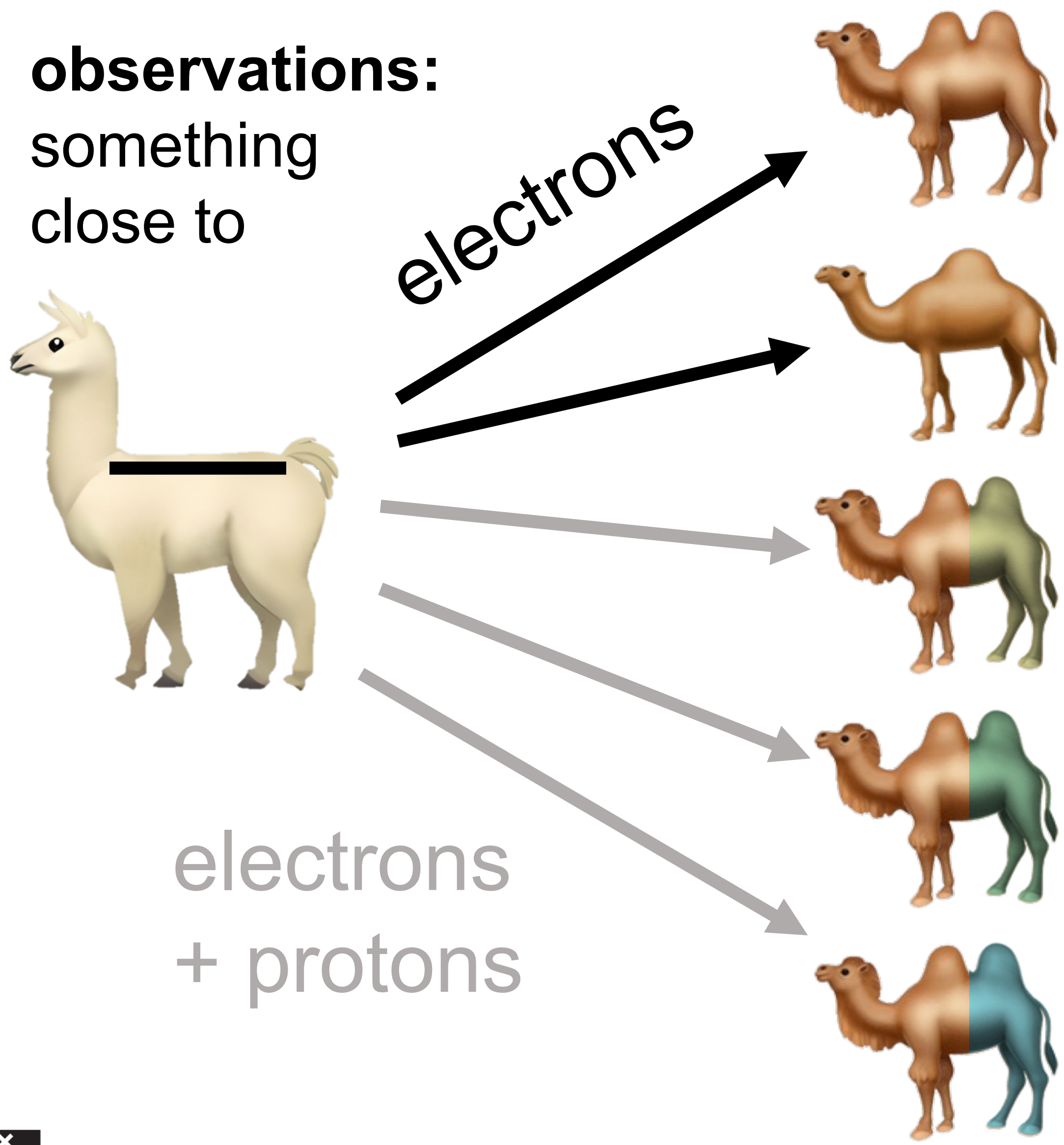

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SSC	bright	Klein-Nishina suppression
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$p\gamma$-cascade	bright	extreme energy + density

→ no scenario really convincing

→ multi-zone?

GRB afterglows to power UHECRs?

UHECRs: $E_p > 10^{18} eV$

→ p-syn, $p\gamma$-cascade

total energy?

→ assume all UHECRs powered by GRB afterglows of same type

→ at rate $\sim 1\ Gpc^{-3}\ yr^{-1}$

→ total required power: $\sim 10^{53} \frac{erg}{Gpc^3 yr}$

→ required energy per GRB:

$$E_{\mathrm{UHECR,iso}} \approx 10^{53} erg \approx \varepsilon_{\mathrm{esc}} f_{\mathrm{bol}} \varepsilon_p E_{\mathrm{kin,iso}}$$

→ **compatible with powering the UHECRs**

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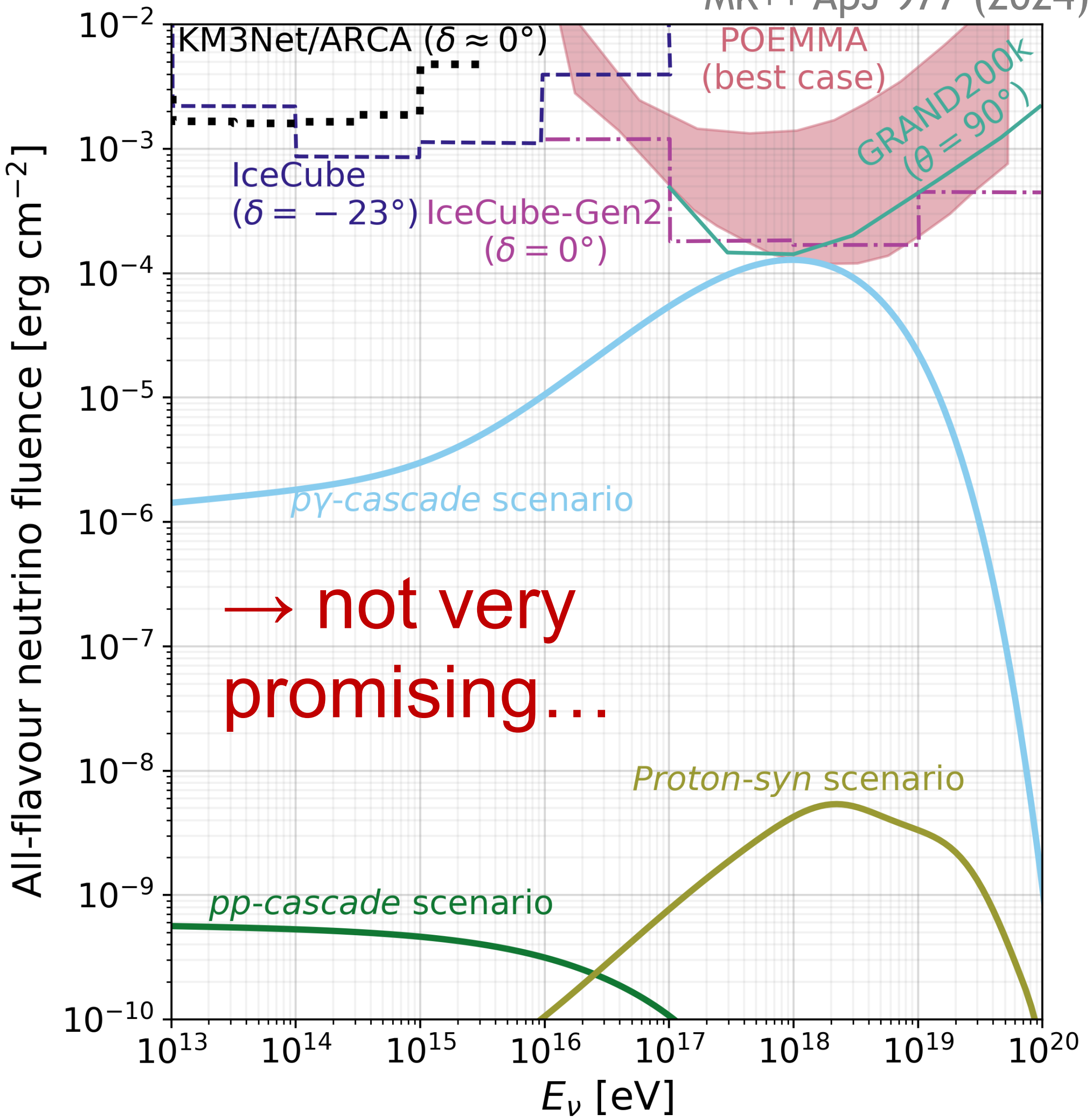
→ **compatible with powering the UHECRs**

Neutrinos?

MK++ ApJ 977 (2024)



rough estimate ($t \times EF_E$) against optimistic scenarios

Take Home

https://am3.readthedocs.io/en/latest/
contact-am3@desy.de

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

AM³: astrophysical multi-messenger modelling

→ fast, modular, C++/Python, documented

→ public: Klinger et al. ApJS 275 4 (2024)

New **GRB afterglow** MWL spectra up to TeV energies

→ challenge single zone models

→ even when including lepto-hadronic scenarios

- consistent with UHECR limits, low neutrino fluences

→ time to depart towards multizone

→ Klinger et al. ApJ 977 2 (2024)

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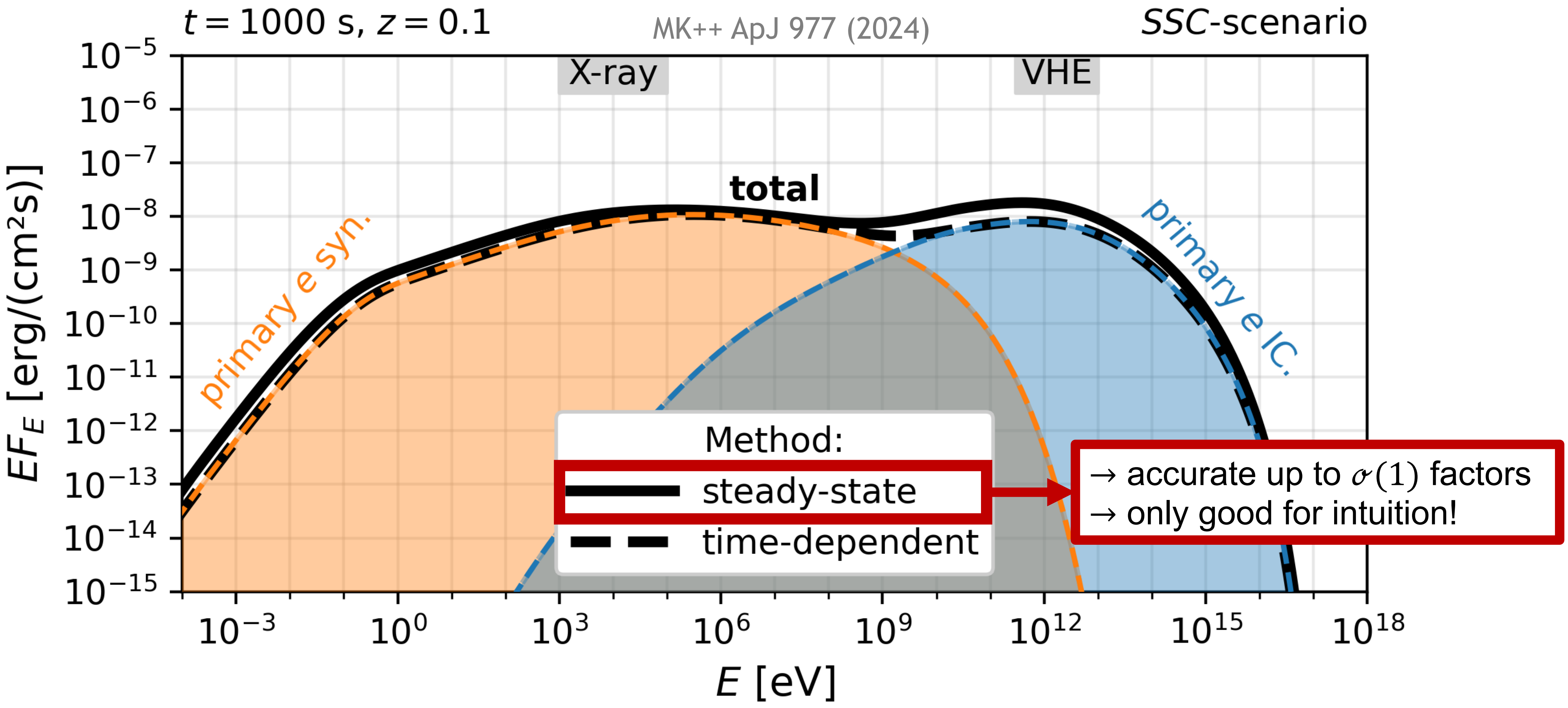
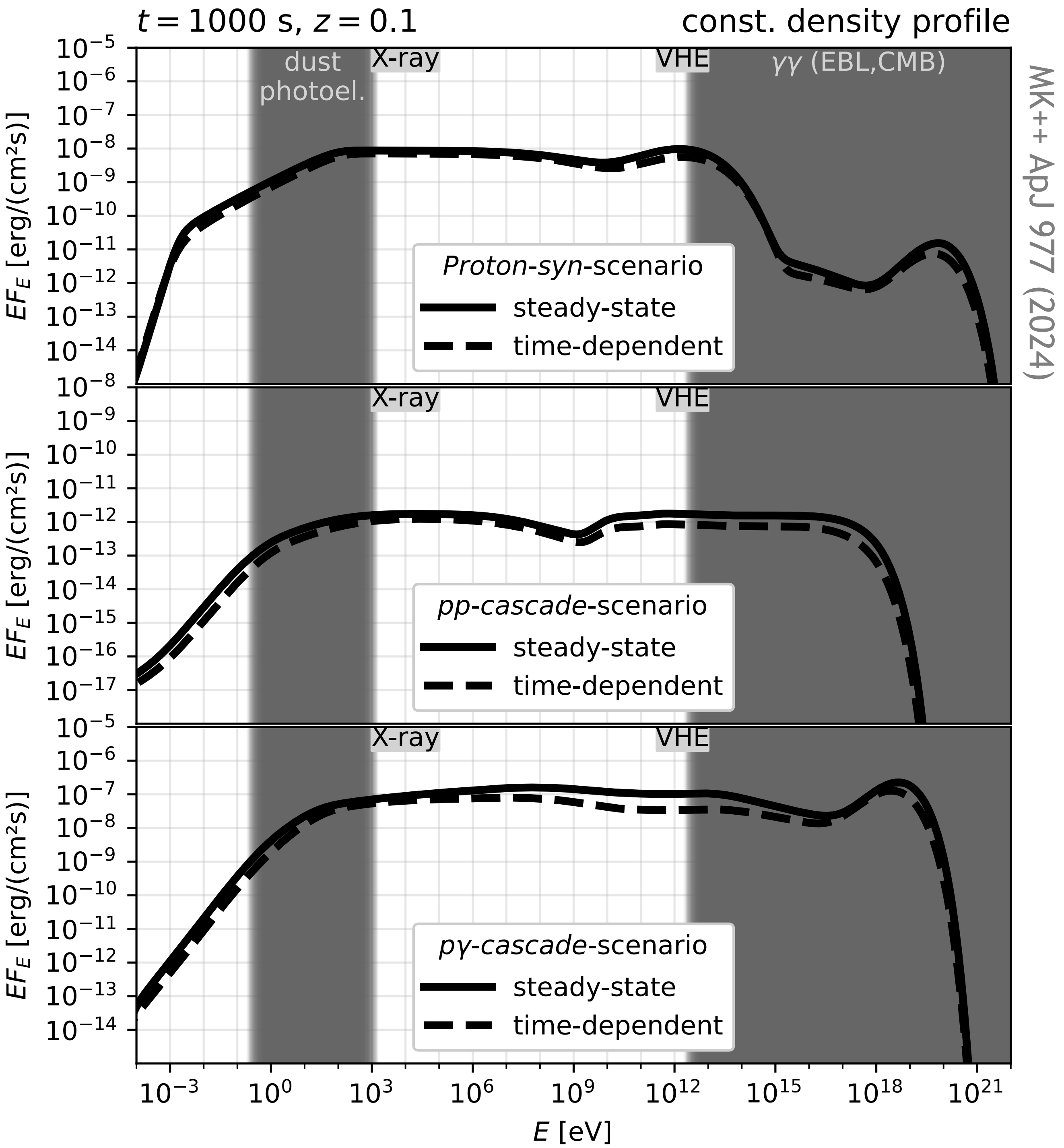
Thank you for your attention!

BACKUP

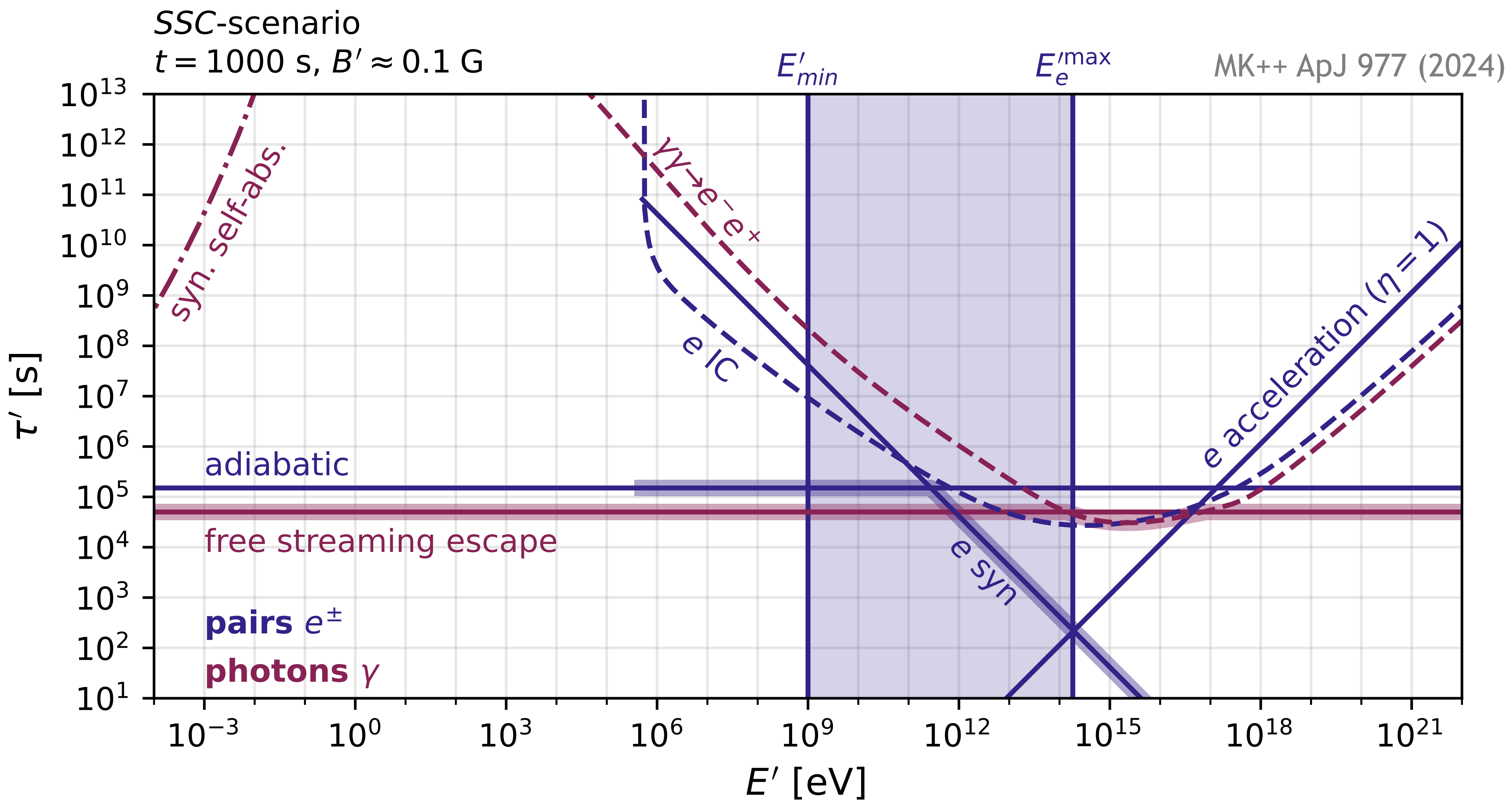
Time-dependent ≈ quasi-steady state



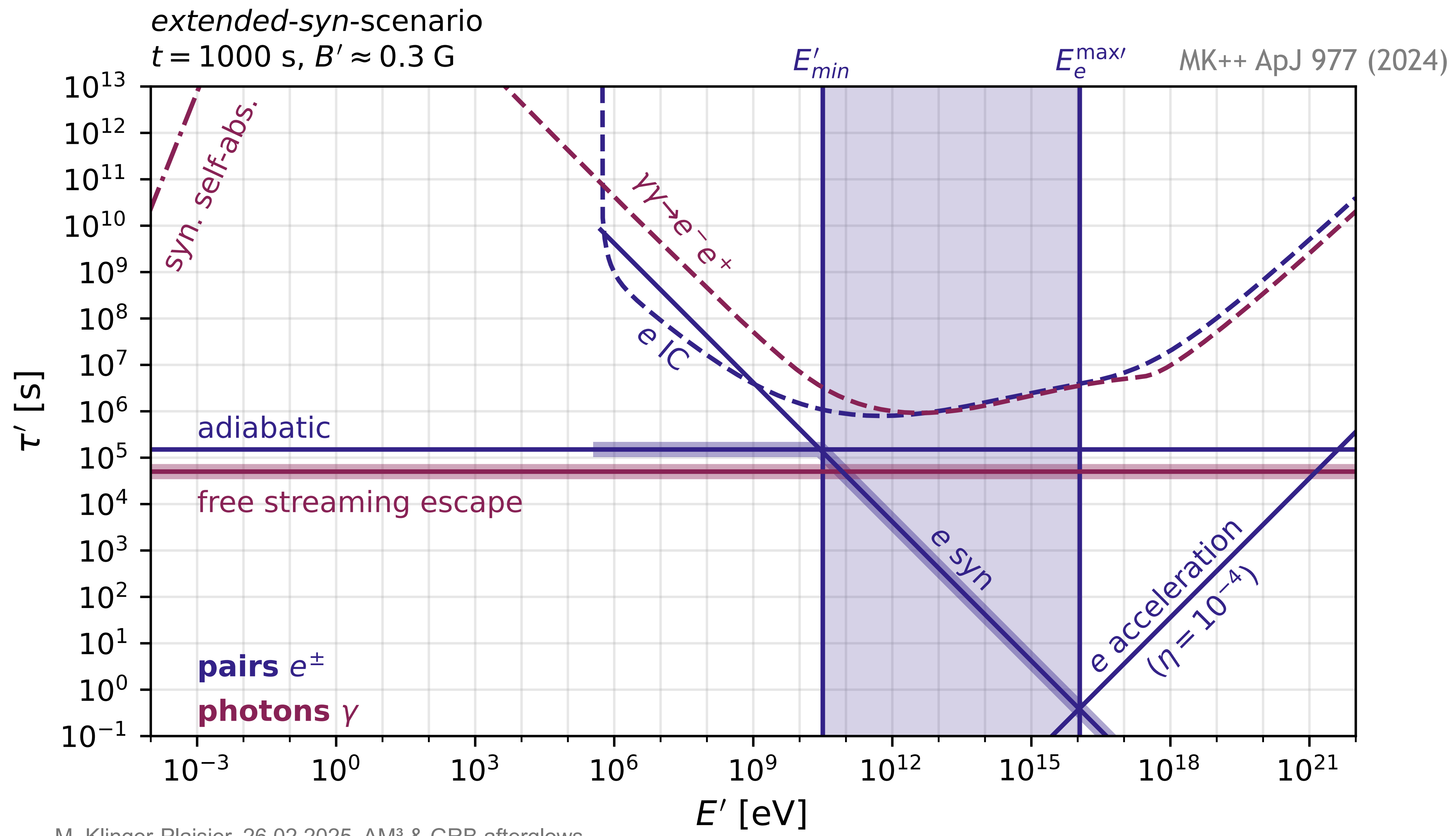


$t = 1000$ s, $z = 0.1$
const. density profile
dust photoel.
X-ray
VHE
$\gamma\gamma$ (EBL,CMB)
Proton-syn-scenario
steady-state
time-dependent
pp-cascade-scenario
steady-state
time-dependent
pγ-cascade-scenario
steady-state
time-dependent
EF_E [erg/(cm²s)]
E [eV]
MK++ ApJ 977 (2024)

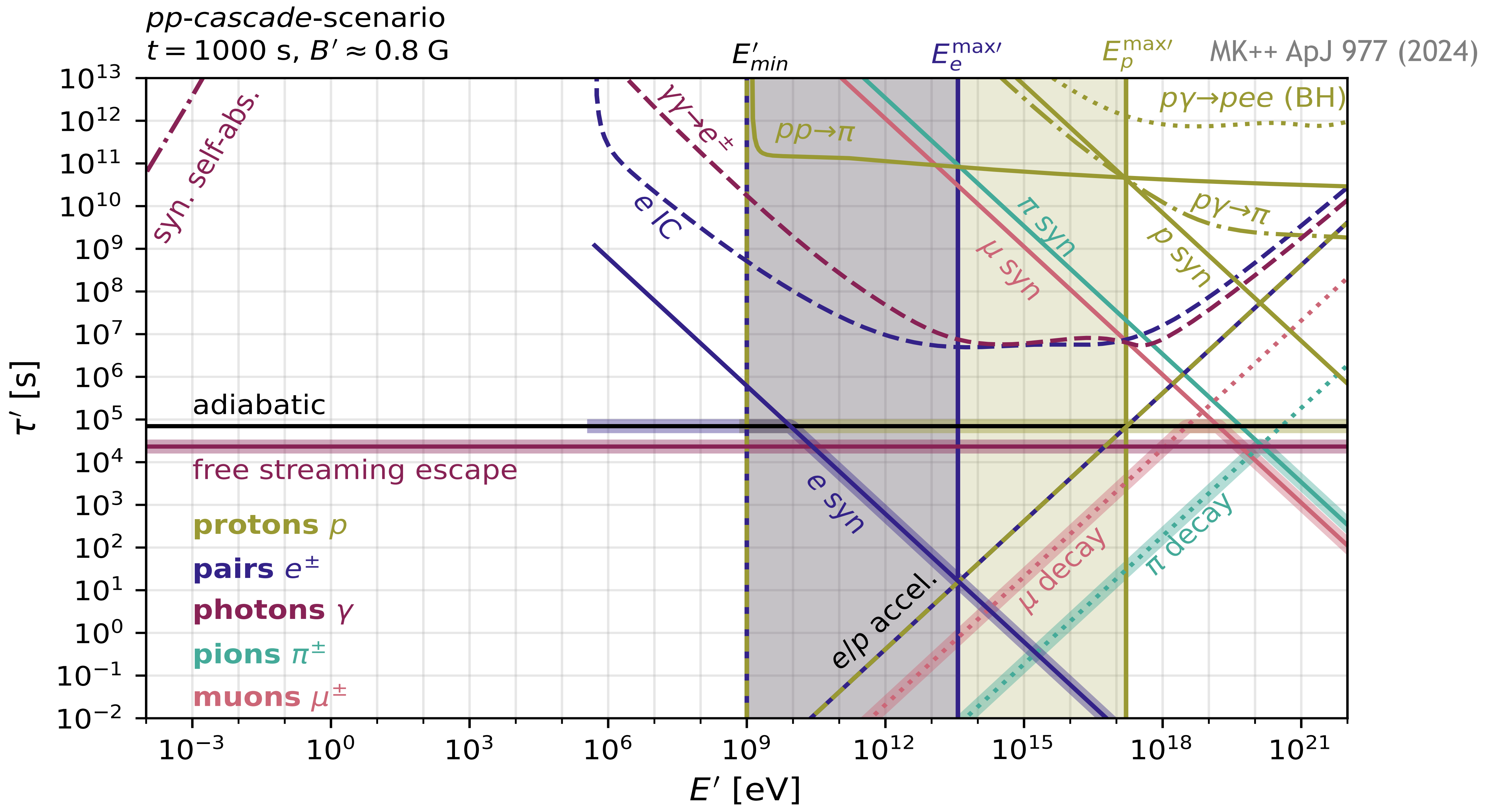
Time scales – SSC scenario



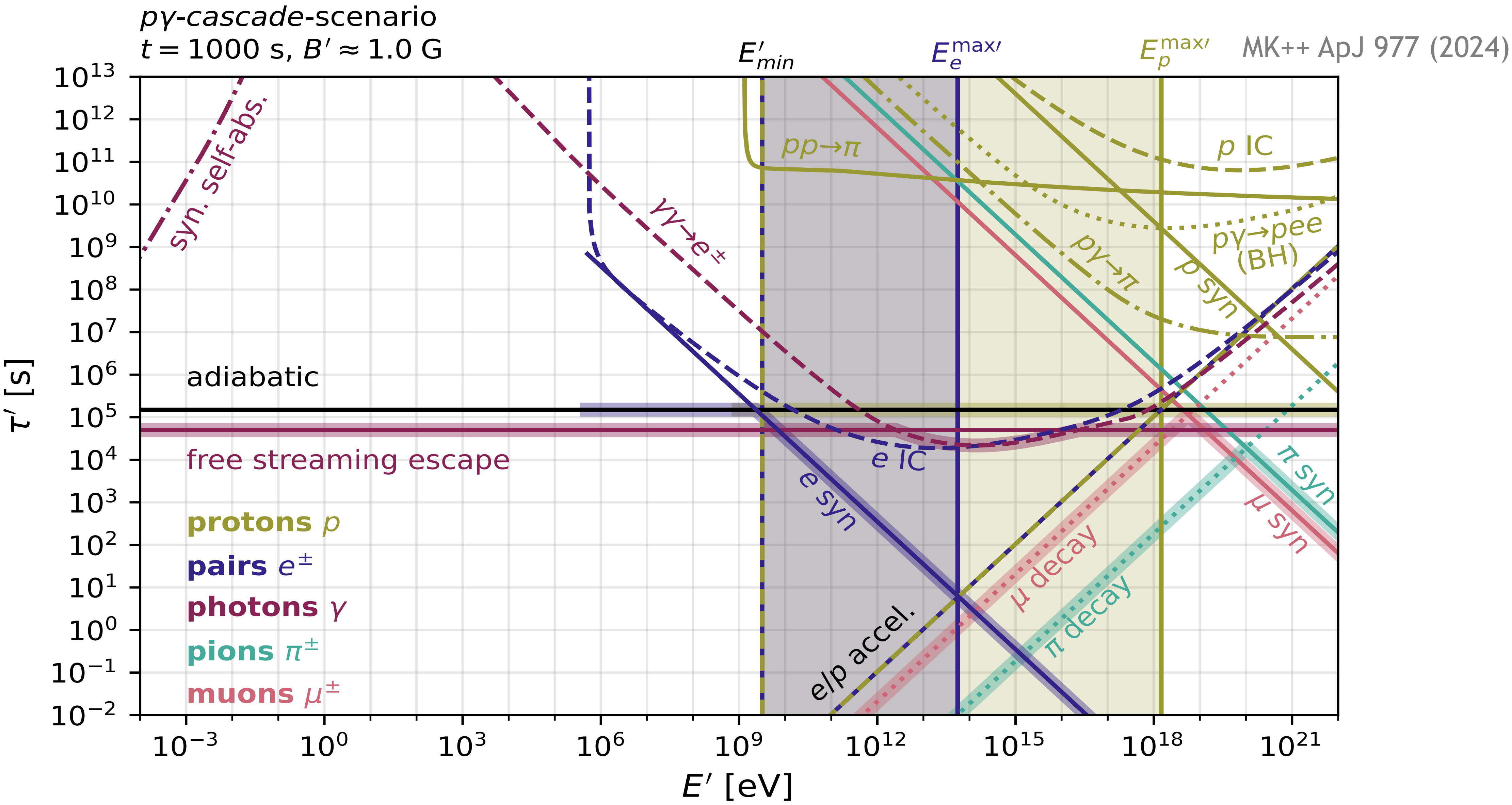
Time scales – extended syn scenario



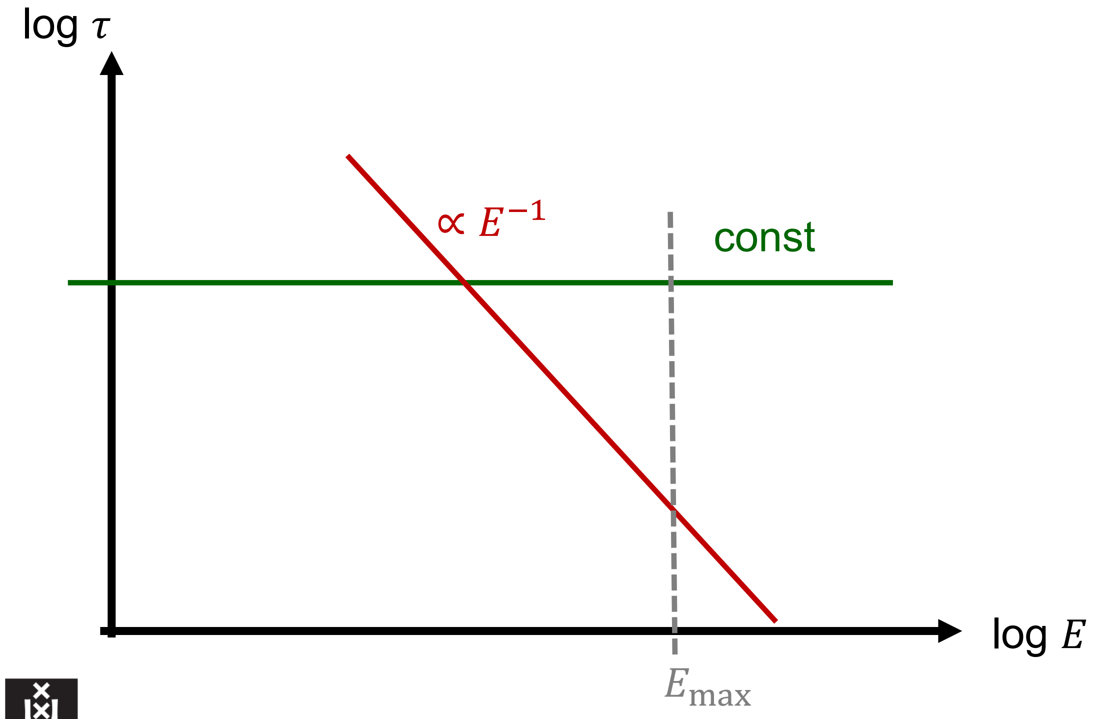
Time scales – pp-cascade scenario



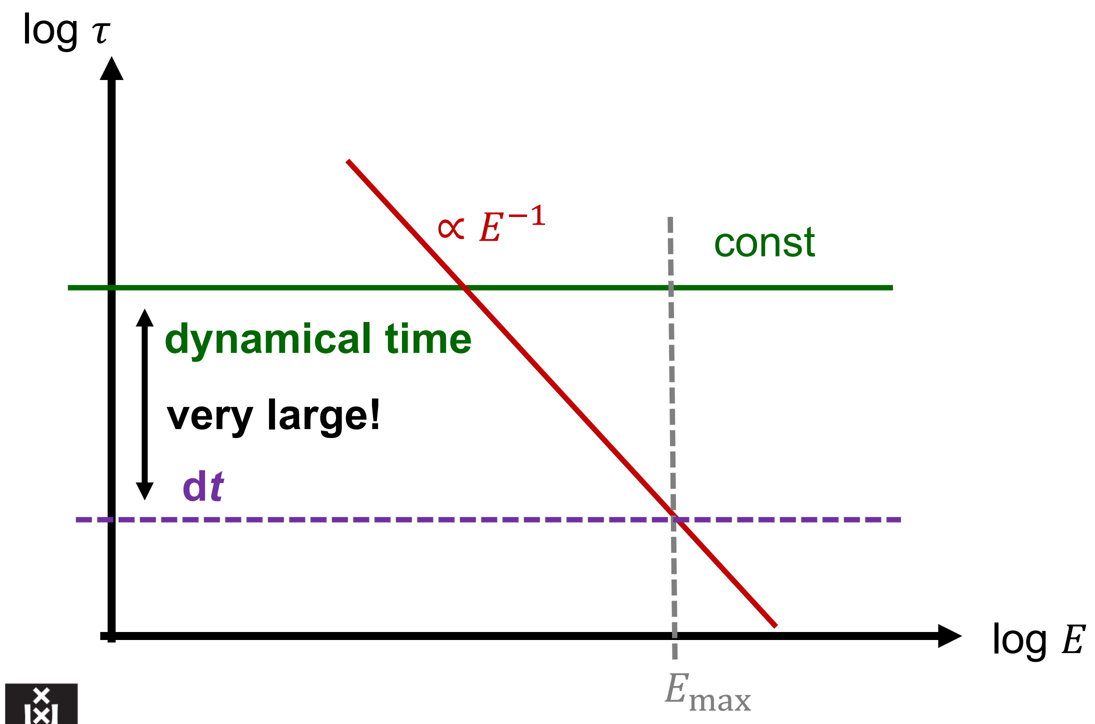
Time scales – $p\gamma$-cascade scenario



Evolve the particle densities



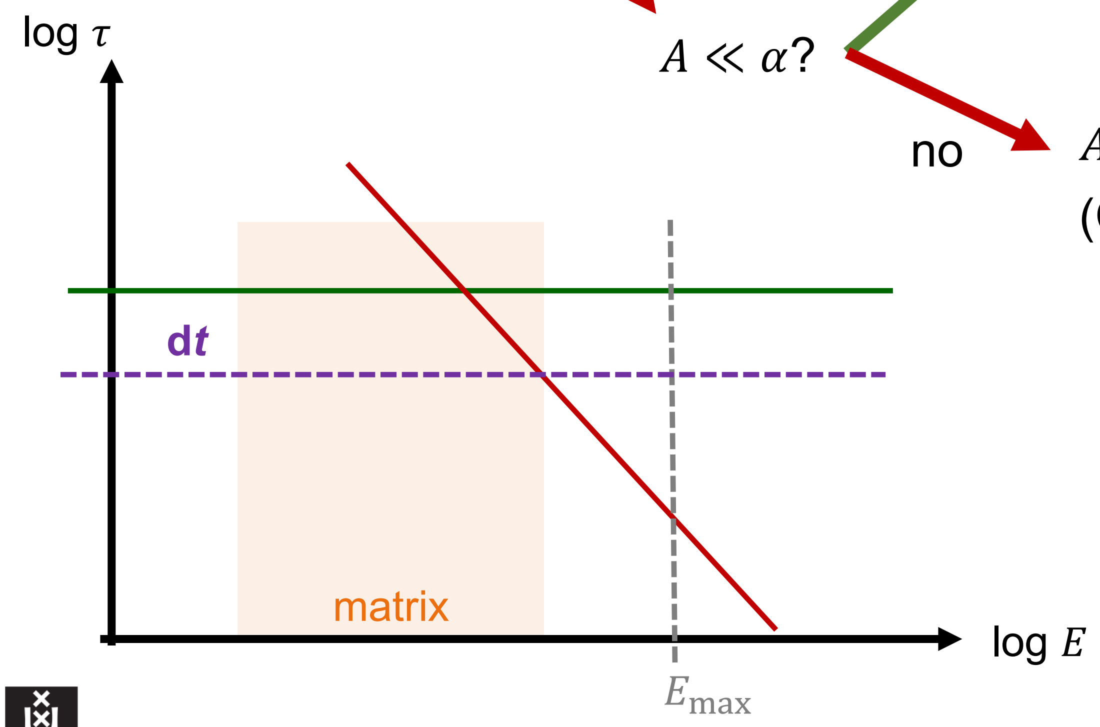
Evolve the particle densities



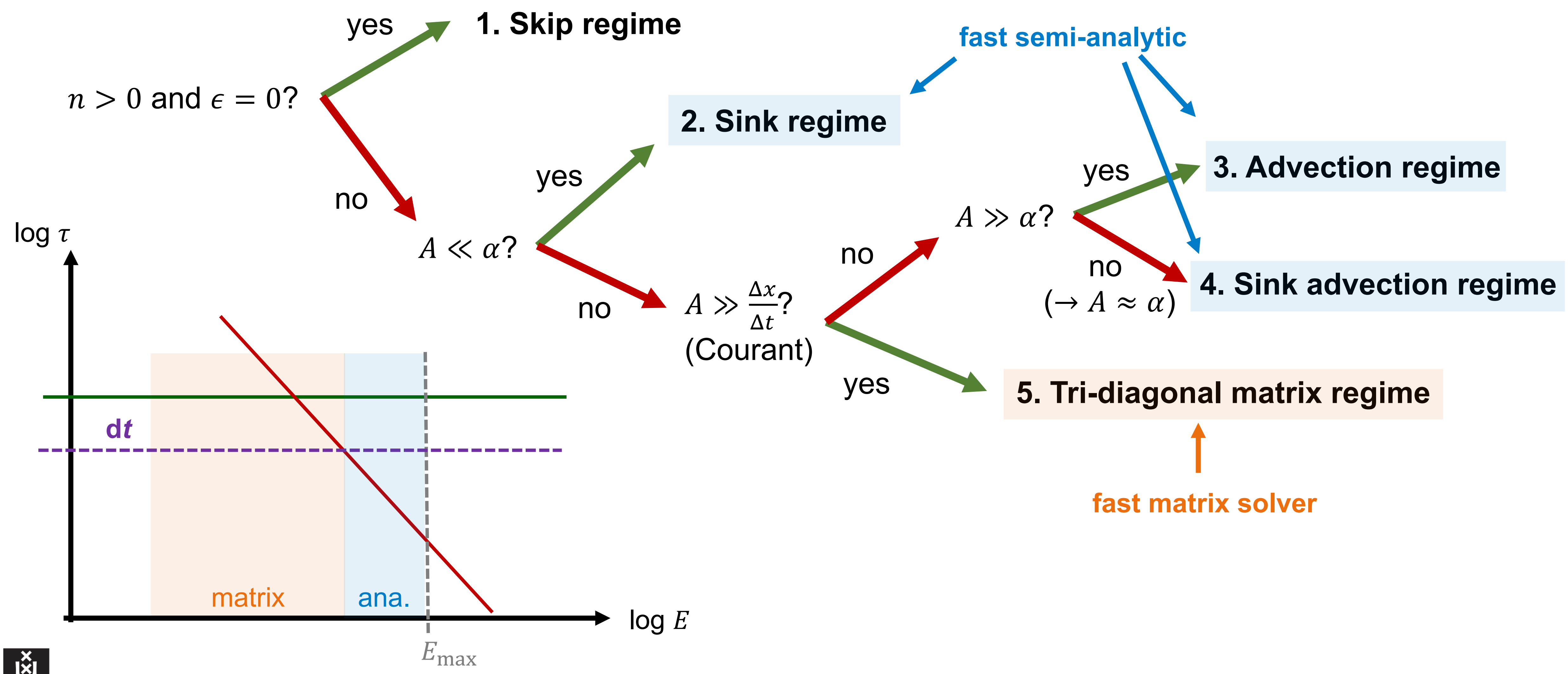
Evolve the particle densities

$n > 0$ and $\epsilon = 0$?
- yes → **1. Skip regime**
- no → $A \ll \alpha$?
  - yes → **2. Sink regime**
  - no → $A \gg \frac{\Delta x}{\Delta t}$? (Courant)
    - no → $A \gg \alpha$?
      - yes → **3. Advection regime**
      - no ($\rightarrow A \approx \alpha$) → **4. Sink advection regime**
    - yes → **5. Tri-diagonal matrix regime**

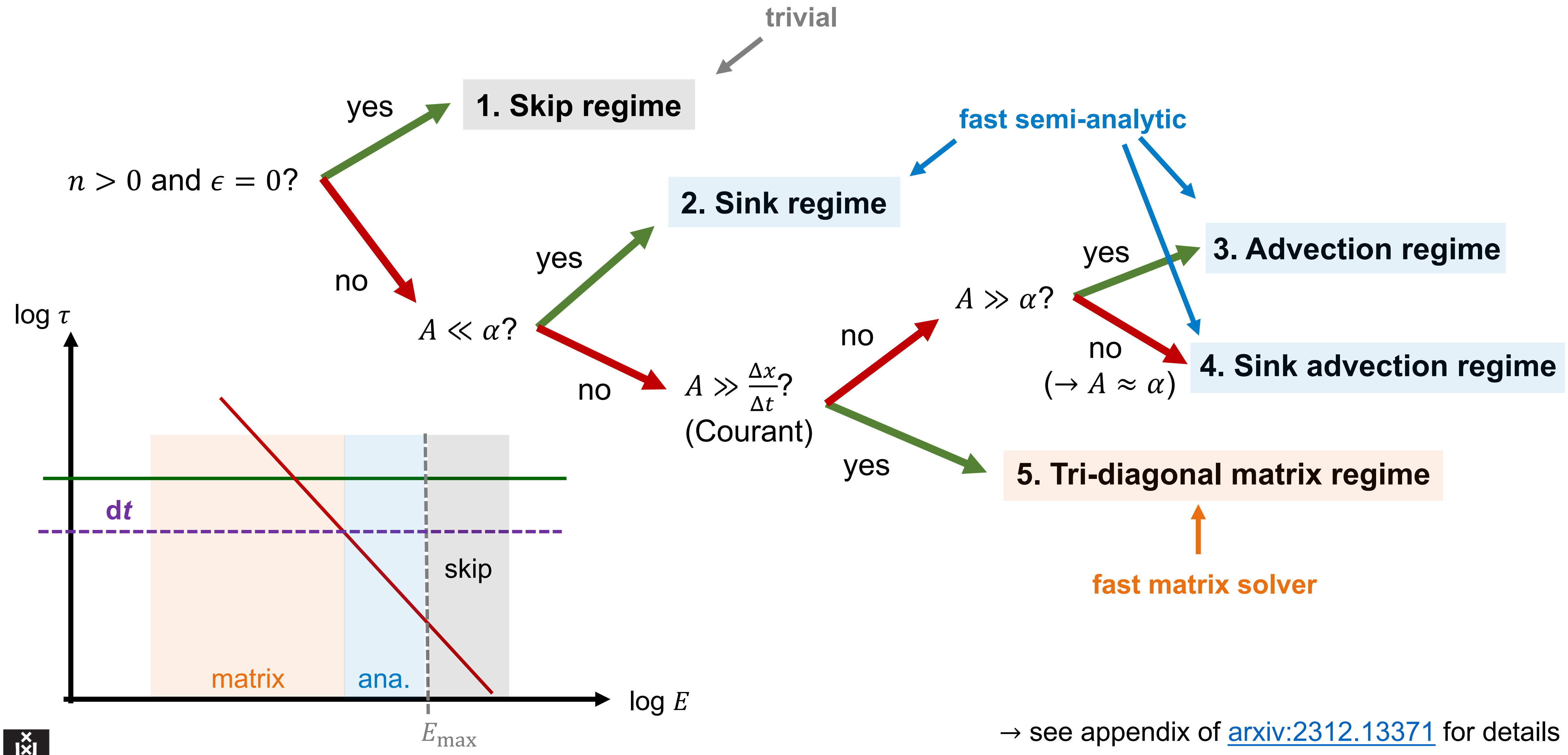
fast matrix solver ↑ (5. Tri-diagonal matrix regime)



Evolve the particle densities

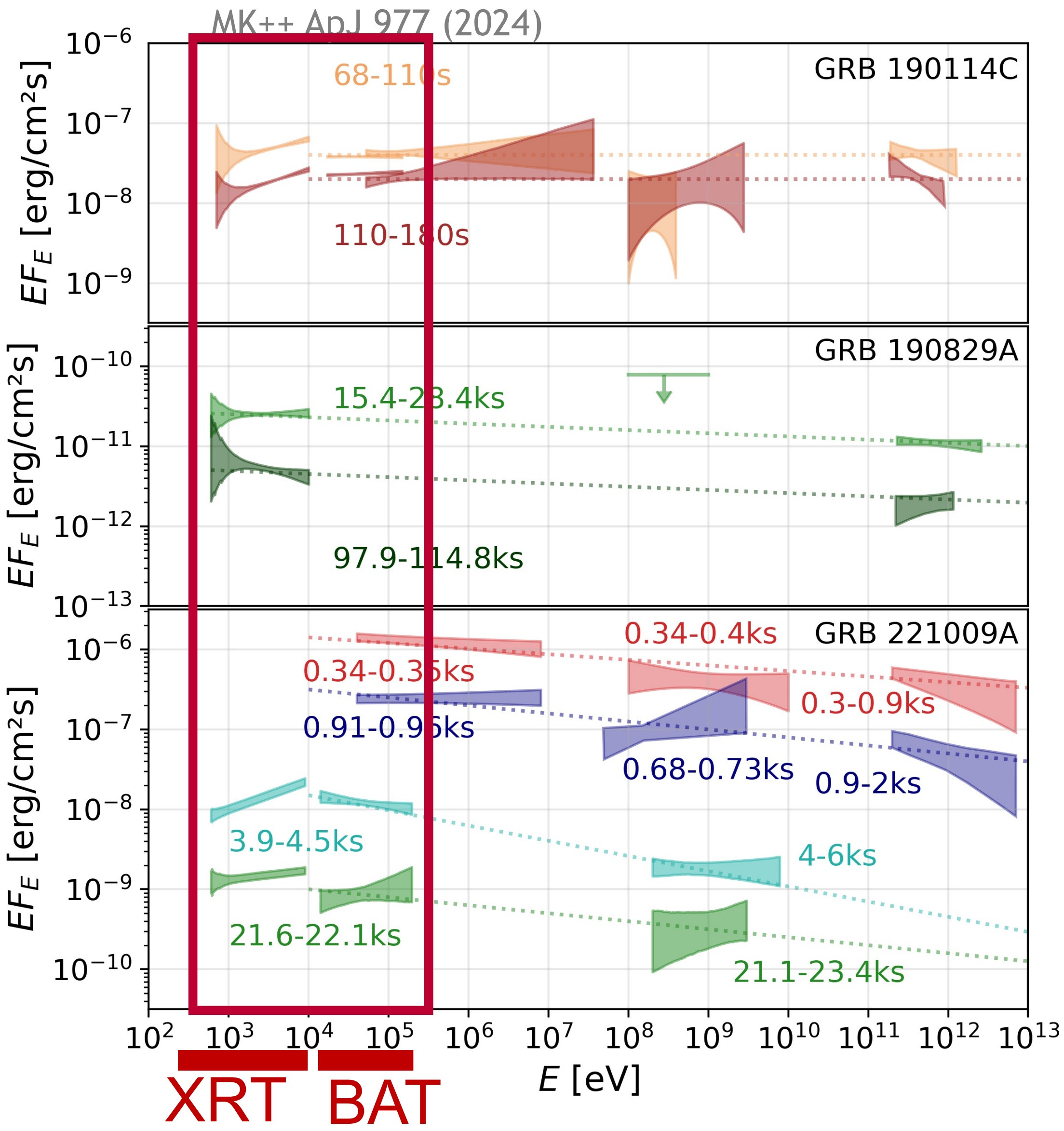


Evolve the particle densities

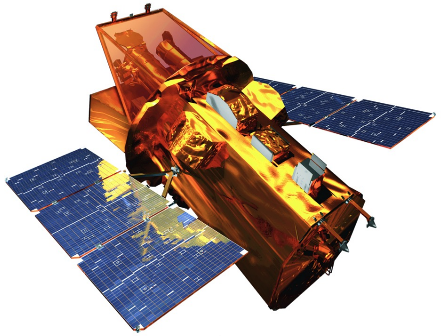


→ see appendix of arxiv:2312.13371 for details

GRB afterglows detected at X-rays!



Swift satellite



NASA

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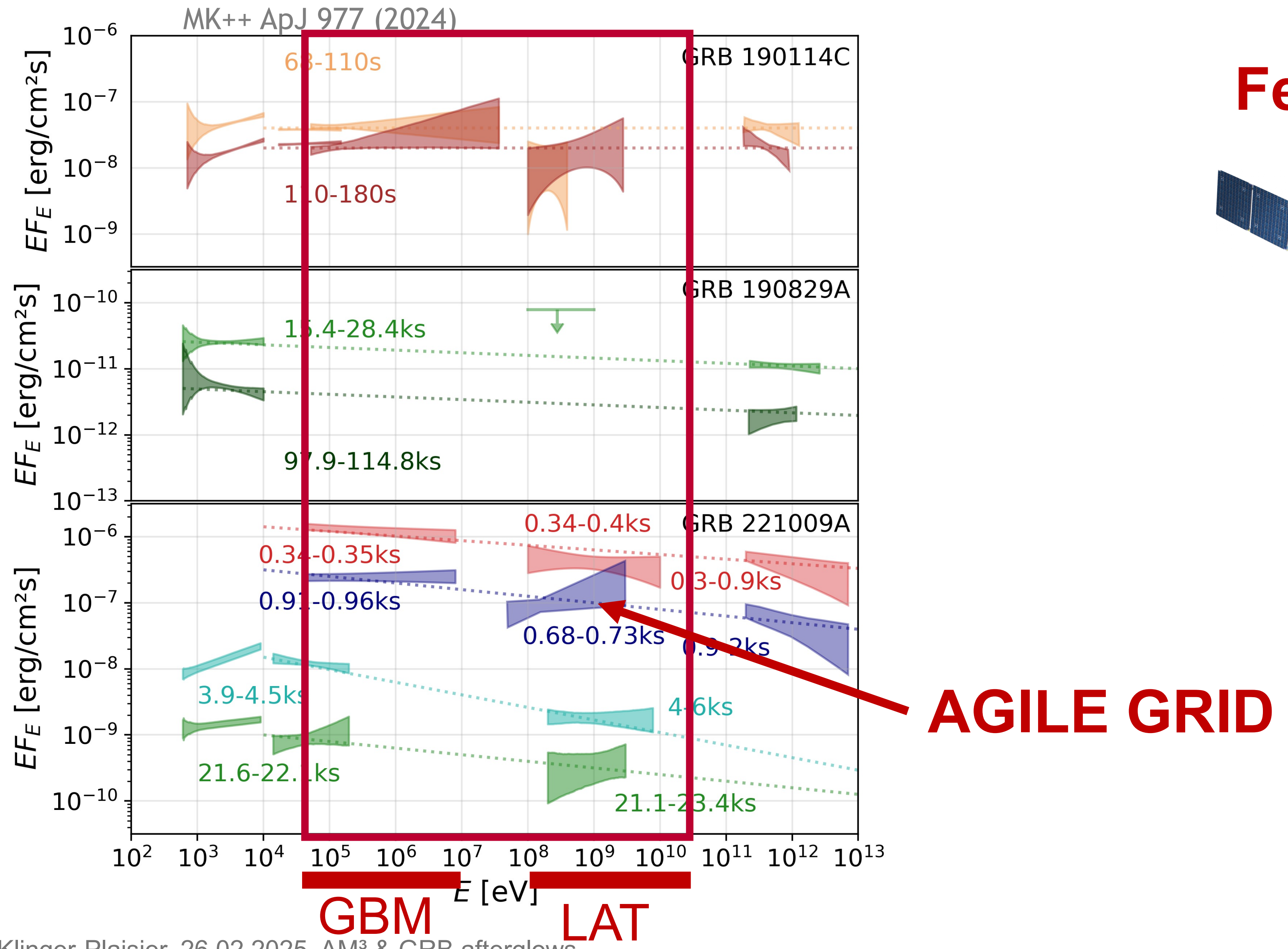
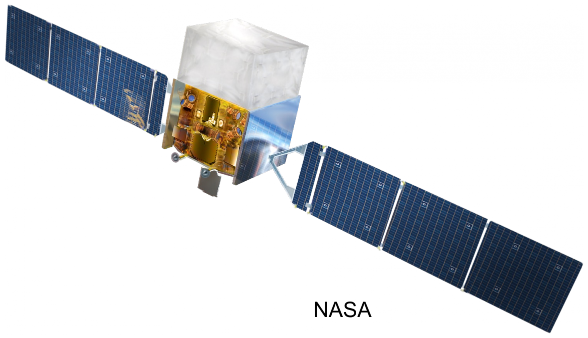
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

GRB afterglows detected at HE!



Fermi satellite



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