News from

Astrophysical Multi-Messenger Modeling

arXiv:2312.13371

Marc Klinger*, **21.02.2024,**
Workshop on Numerical Multi-messenger Modeling, Paris

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

HELMHOLTZ

DESY.

***marc.klinger@desy.de**

https://maklinger.github.io/

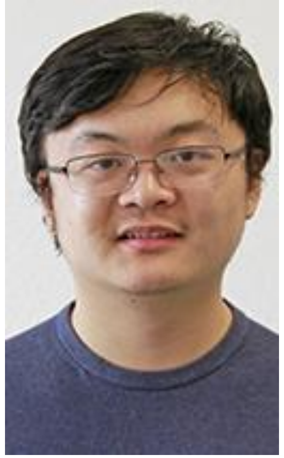
The AM^3 team


Gao


Klinger


Rudolph


Rodrigues


Yuan


Fichet De Clairfontaine

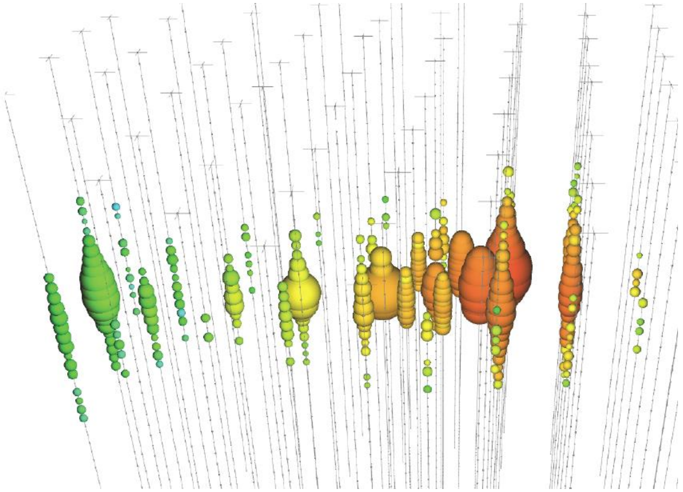

Fedynitch


Winter


Pohl

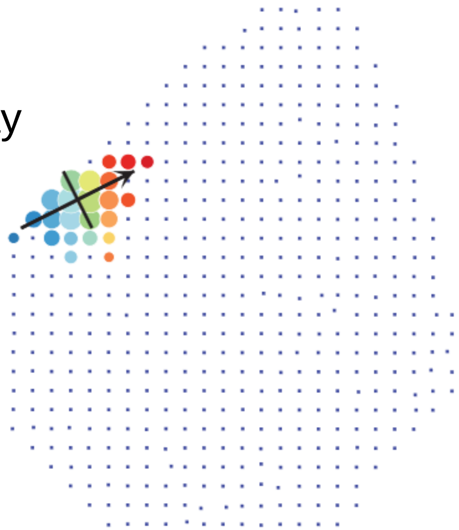
Typical multi-messenger astrophysics challenge

neutrino

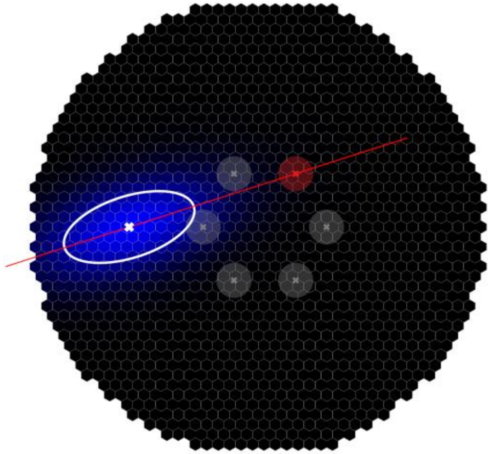


IceCube Masterclass

cosmic ray



TA collaboration 2023



γ-ray

observation

secondary particle
counts (/rate)

Typical multi-messenger astrophysics challenge

flux at Earth

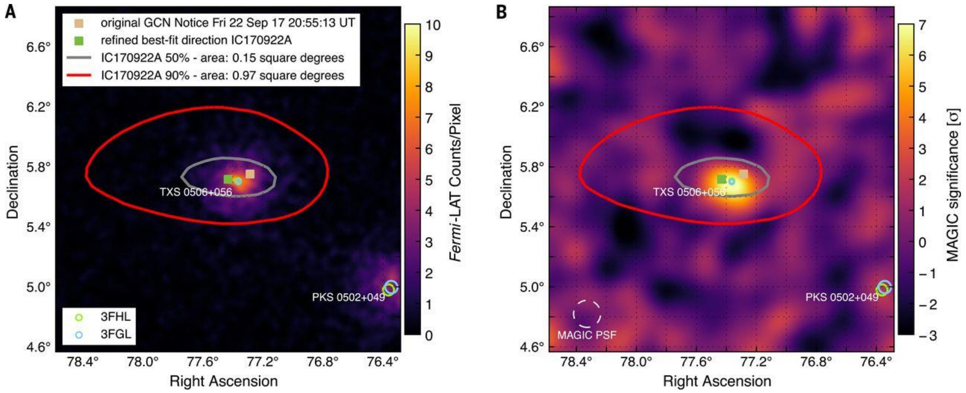
detection

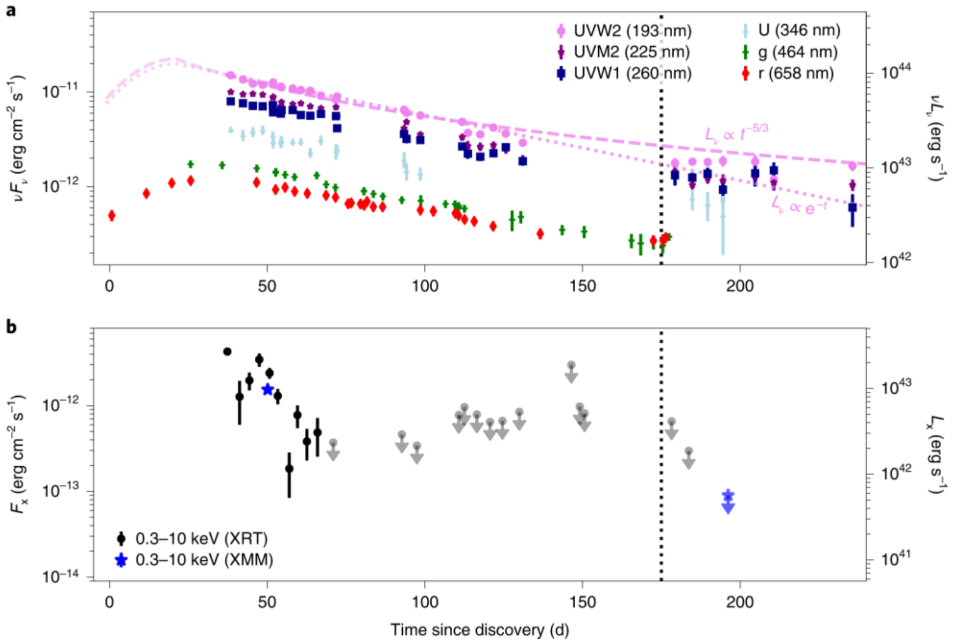
observation

secondary particle counts (/rate)

Typical multi-messenger astrophysics challenge

IceCube et al., Science, 361,146 (2018)





Stein et al., Nature Astronomy, 5, 510-518 (2021)

spatial/temporal coincidences

e.g. blazars, tidal disruption events (TDE)

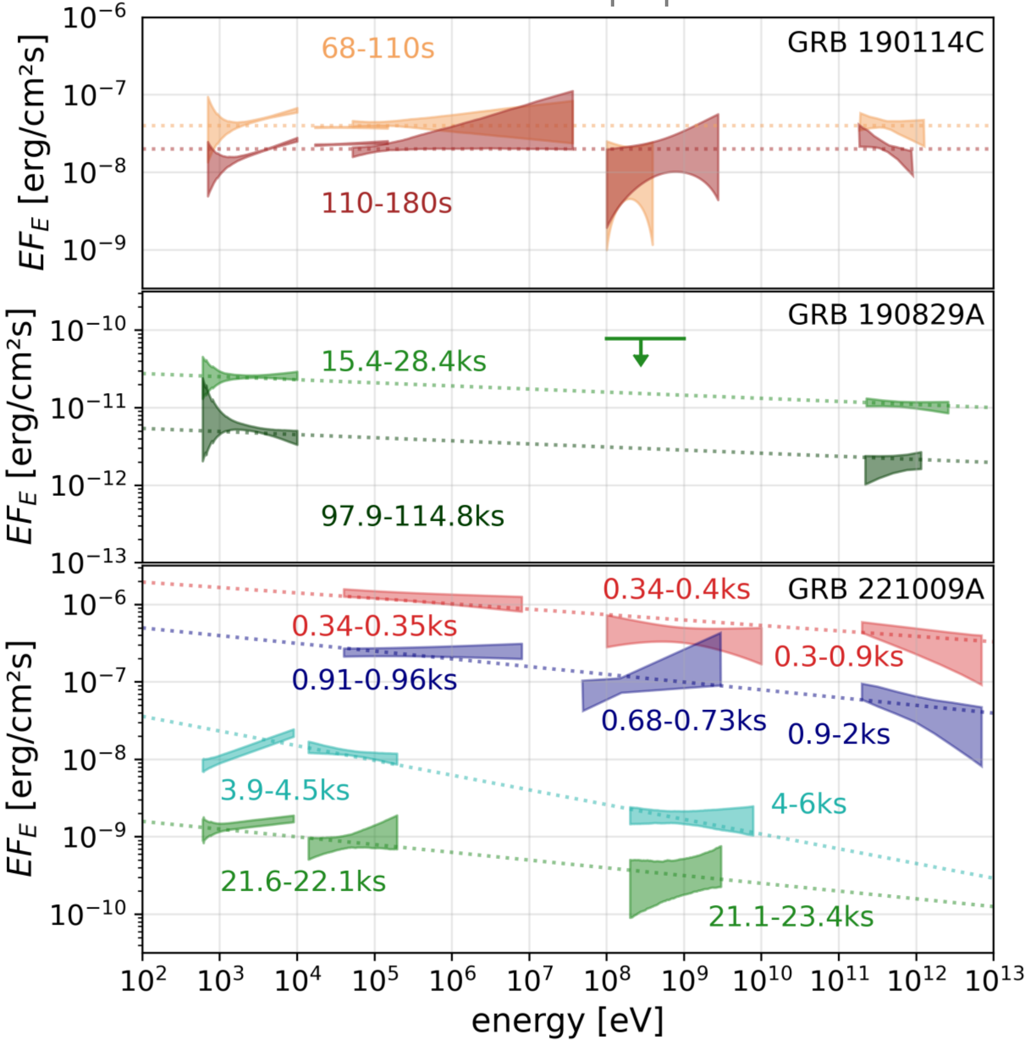
flux at Earth

detection

observation

Typical multi-messenger astrophysics challenge

MK++ in prep.



spatial/temporal coincidences

e.g. blazars, tidal disruption events (TDEs)

multi-wavelength spectra

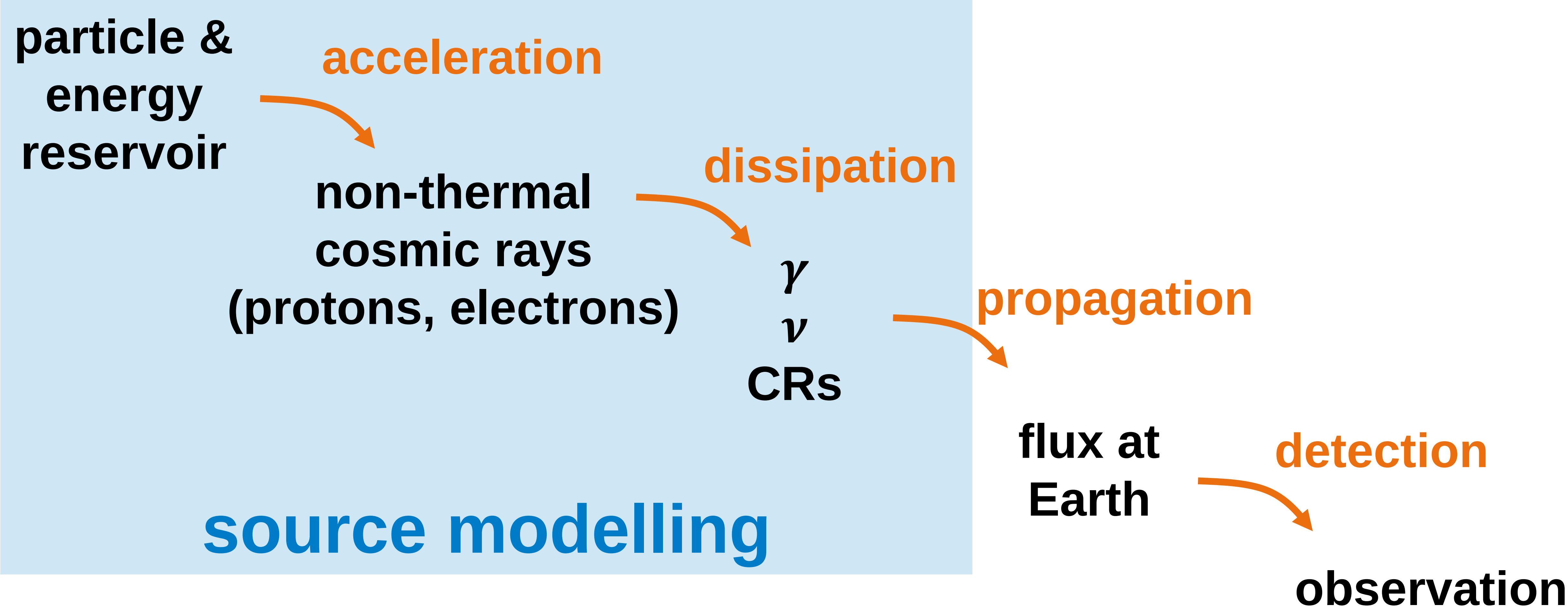
e.g. blazars, gamma-ray bursts (GRBs),…

flux at Earth

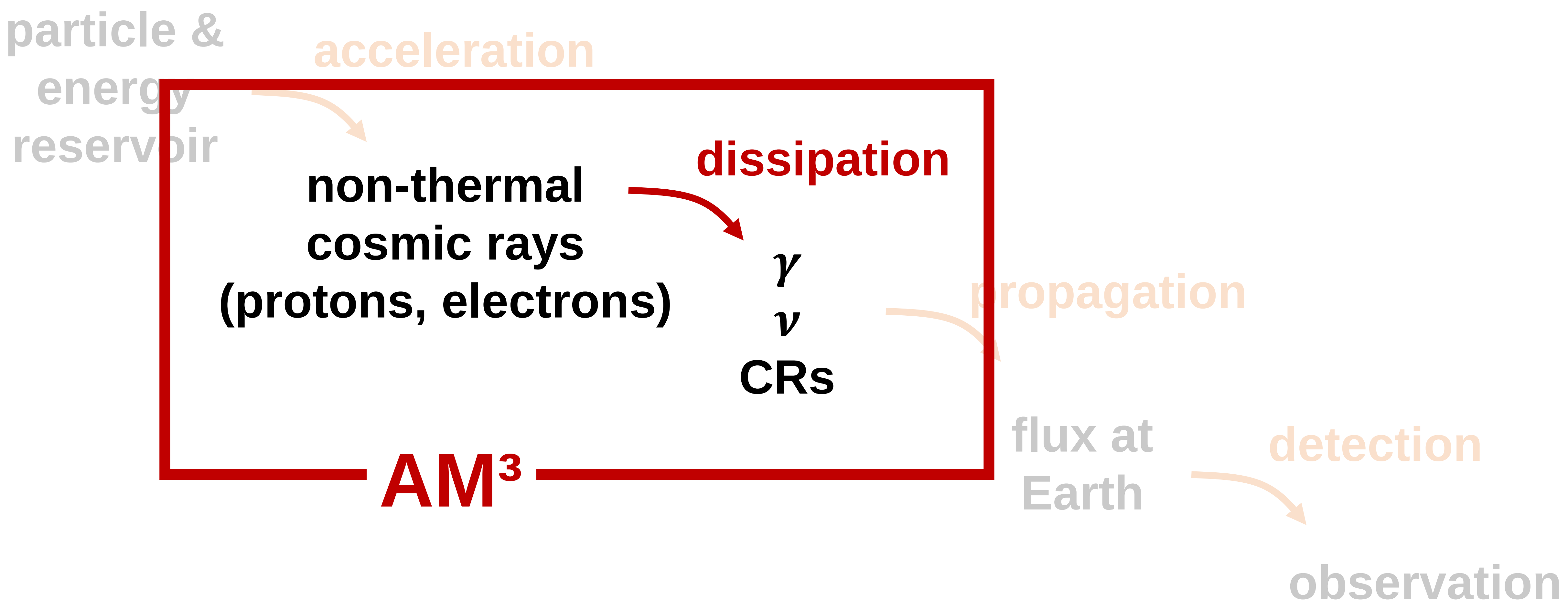
detection

observation

Typical multi-messenger astrophysics challenge



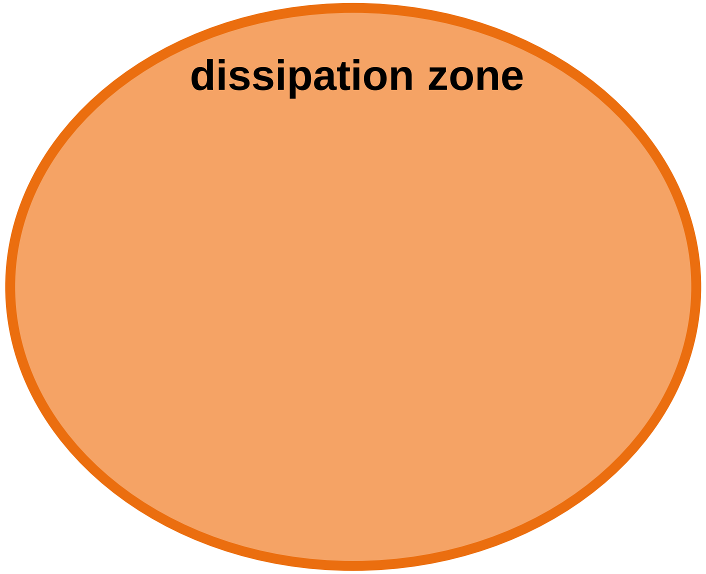
Typical multi-messenger astrophysics challenge



Astrophysical Multi-Messenger Modeling

The task

→ in the comoving frame
→ homogeneous/isotropic



The task

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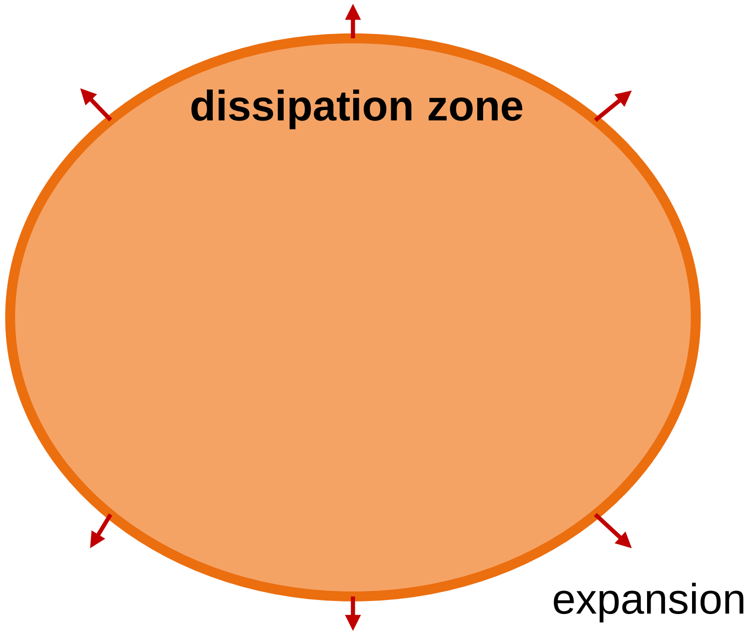

The task

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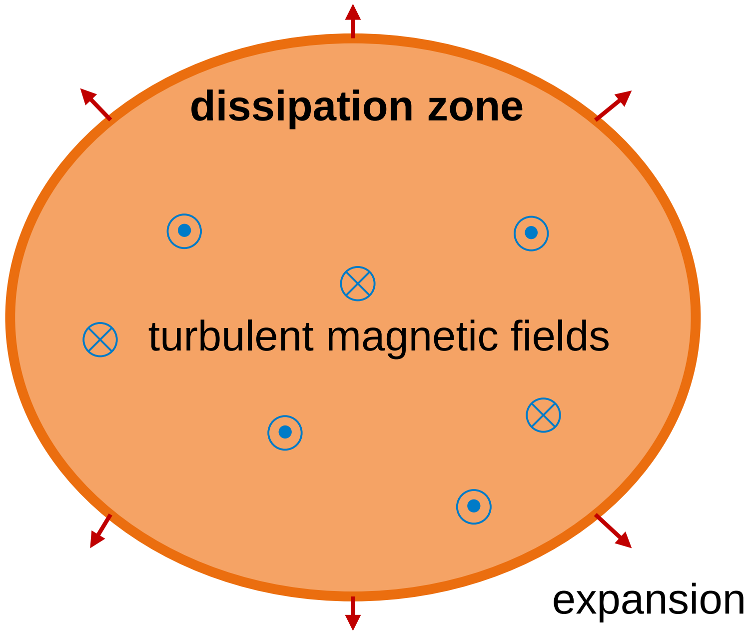
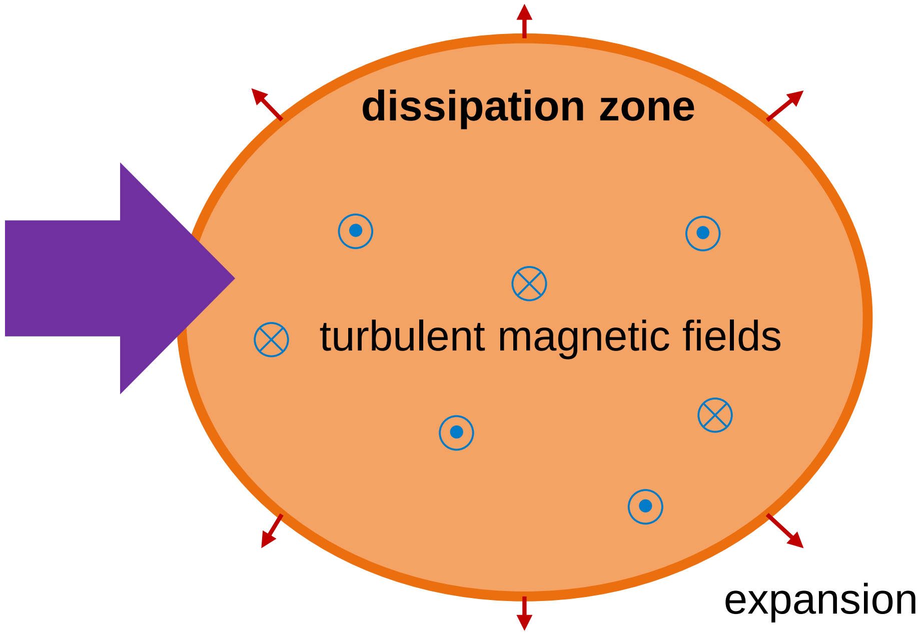


The task

→ in the comoving frame
→ homogeneous/isotropic

injection of
relativistic particles/
target photon fields



The task

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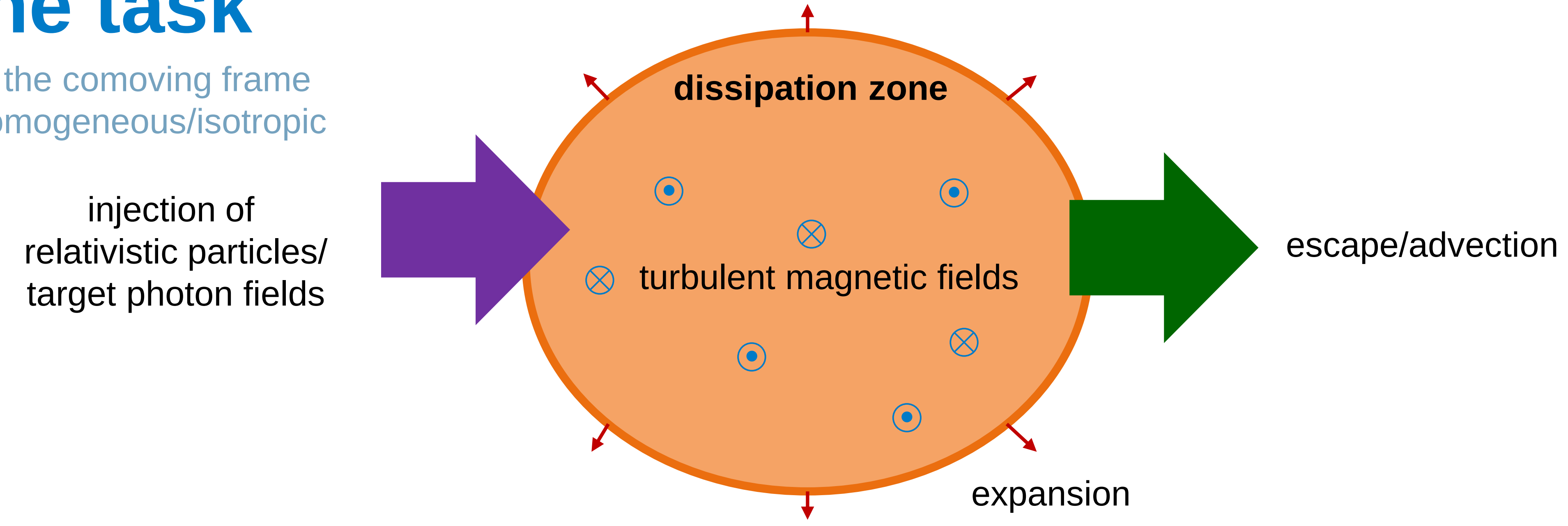
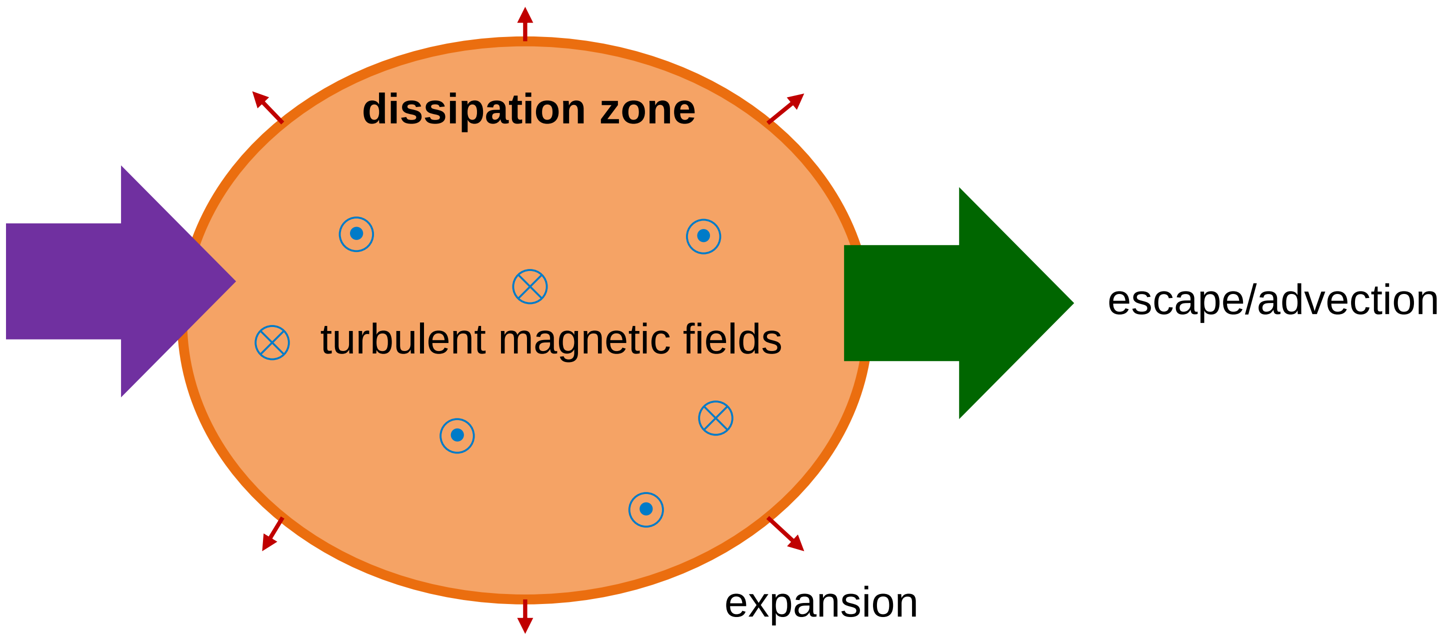
→ homogeneous/isotropic



The task

→ in the comoving frame
→ homogeneous/isotropic



→ solve transport eqs.

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

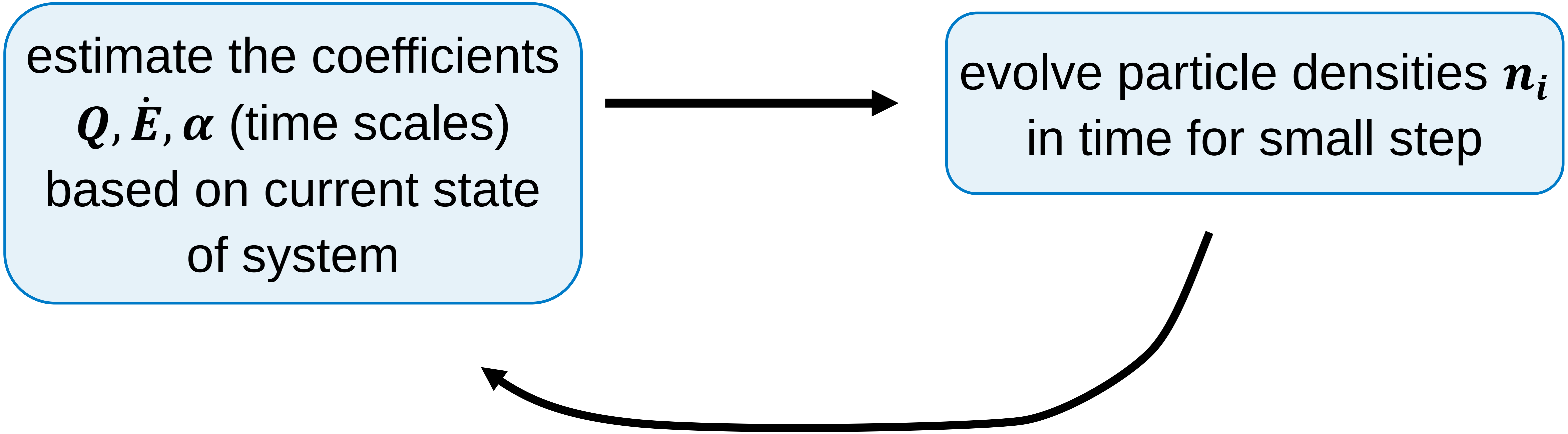
for species $i \in [p, n, e, \pi, \mu, \nu, \gamma]$

particle number density

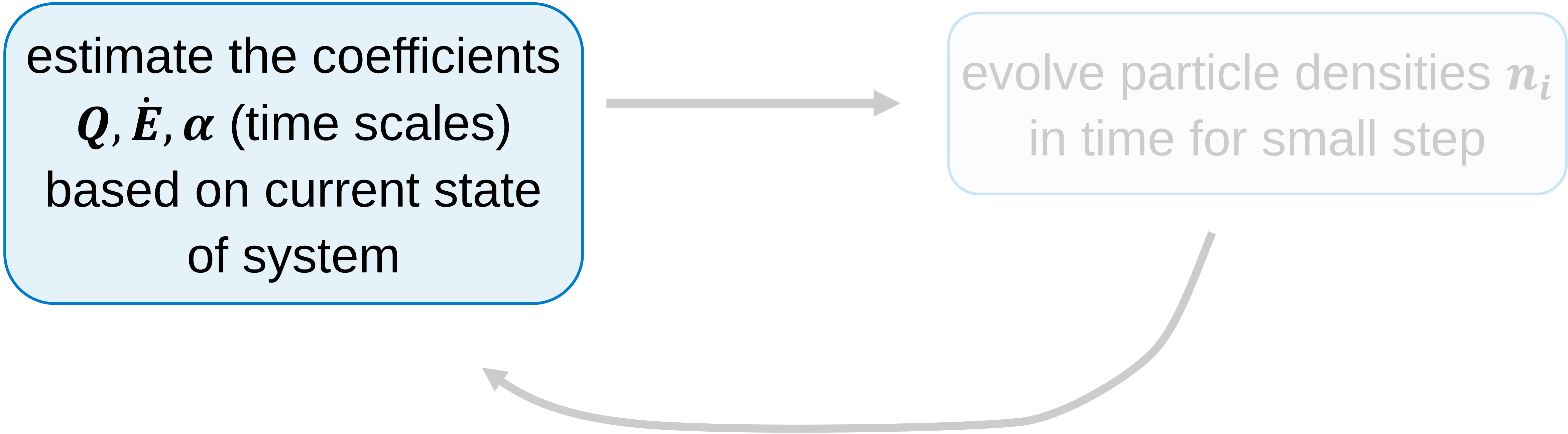
$$n_i(E,t) = \frac{\partial^2 N_i}{\partial E \, \partial V}$$

depend in general on E, t, n_j

The workflow



The workflow

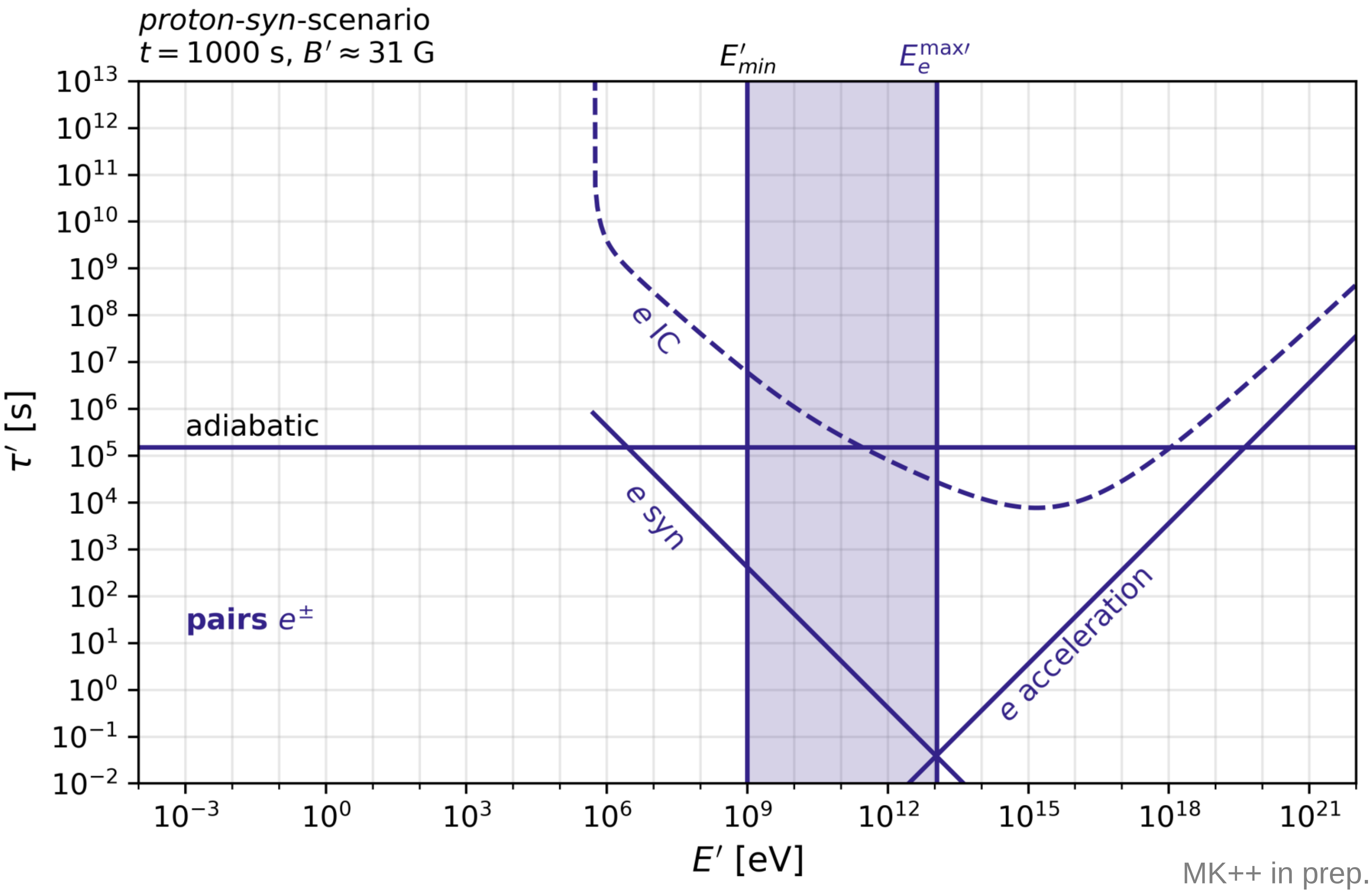


Estimate the coefficients

	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	$Q_{e^-,\mu-\mathrm{dec}}$	$Q_{e^+,\mu-\mathrm{dec}}$	–	–	–	$Q_{\nu,\mu-\mathrm{dec}}$	$\alpha_{\mu,\mu-\mathrm{dec}}$	–

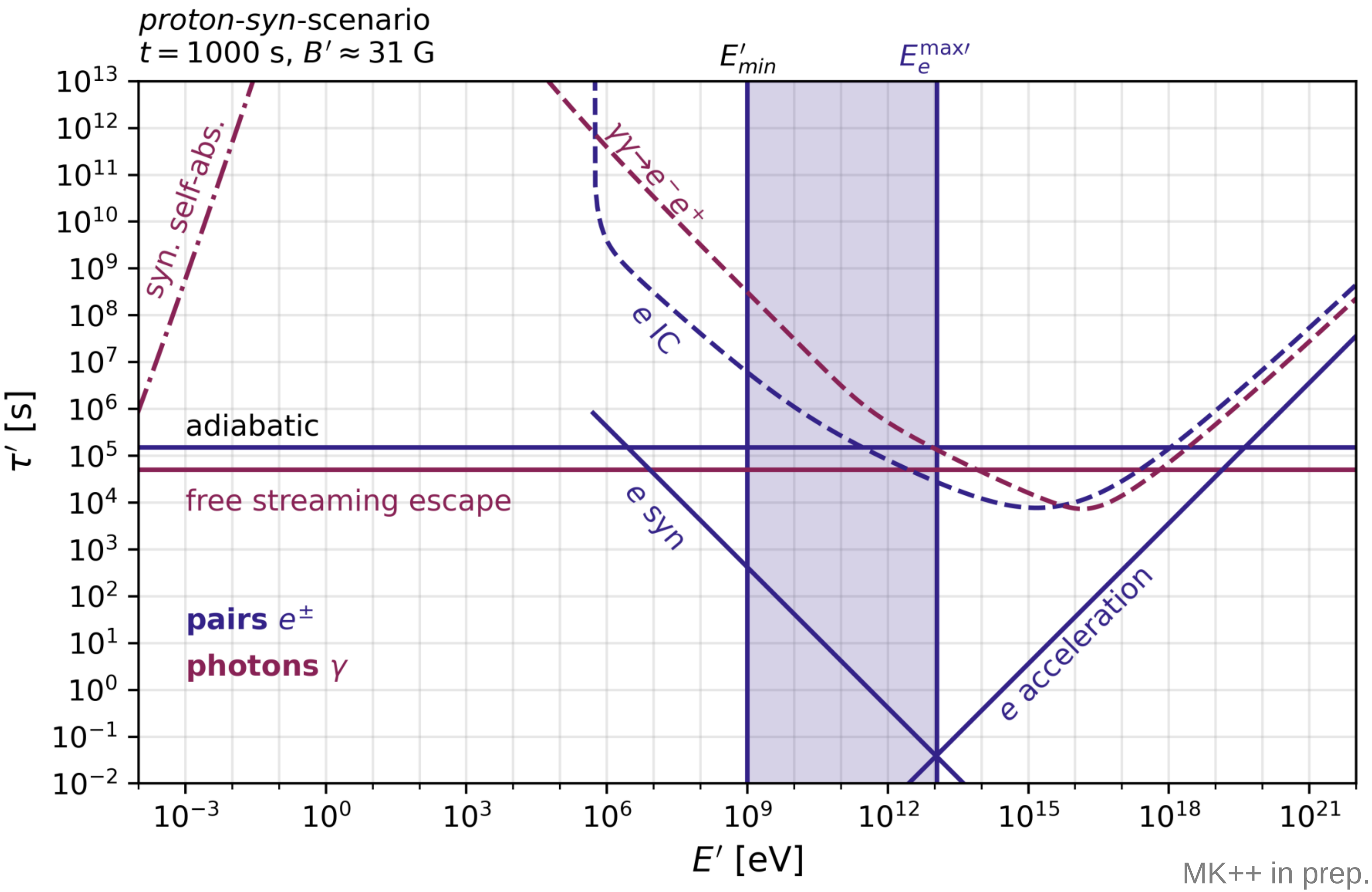
→ see appendix of arxiv:2312.13371 for details

Estimate the coefficients: GRB example



MK++ in prep.

Estimate the coefficients: GRB example



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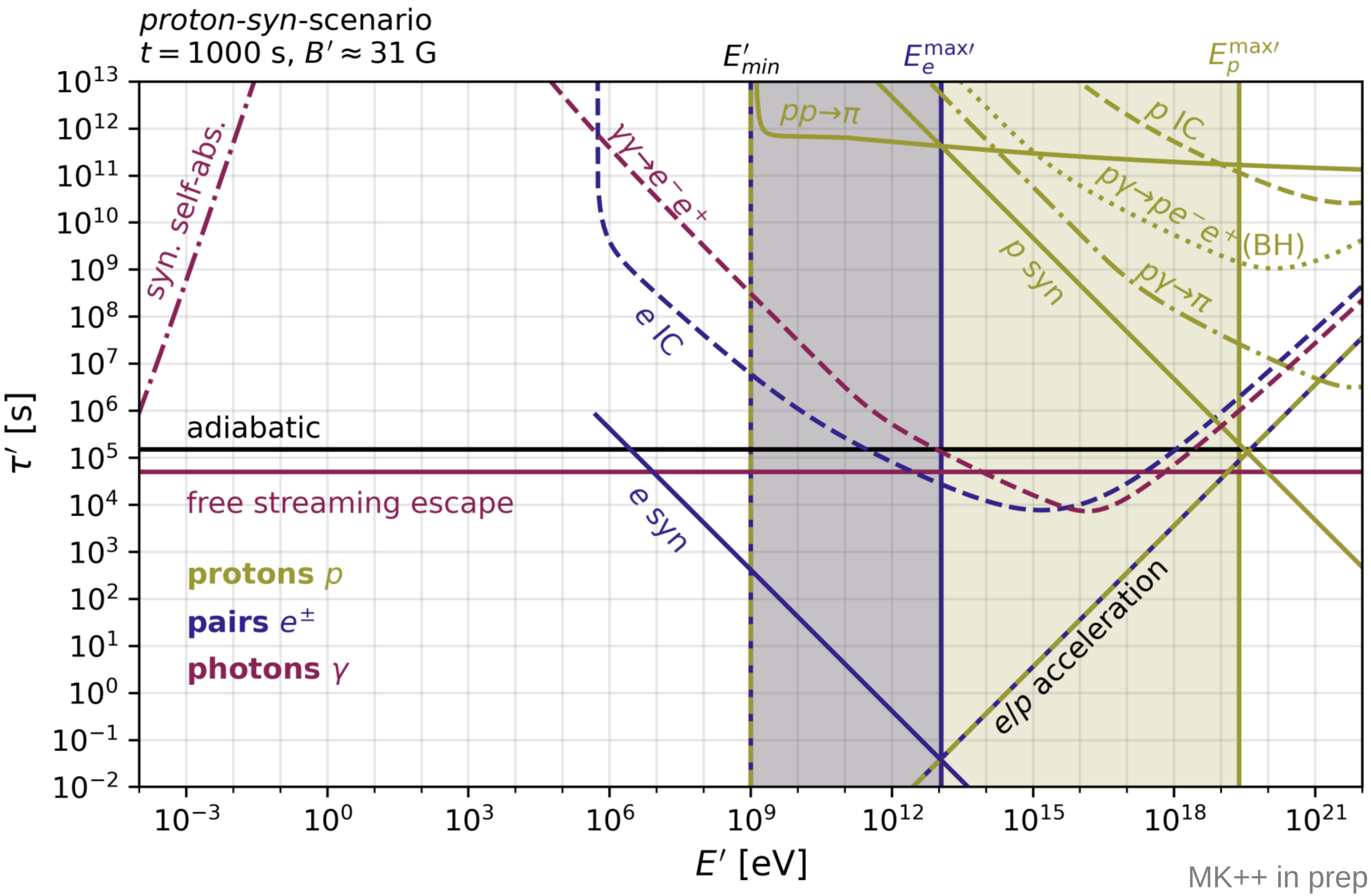
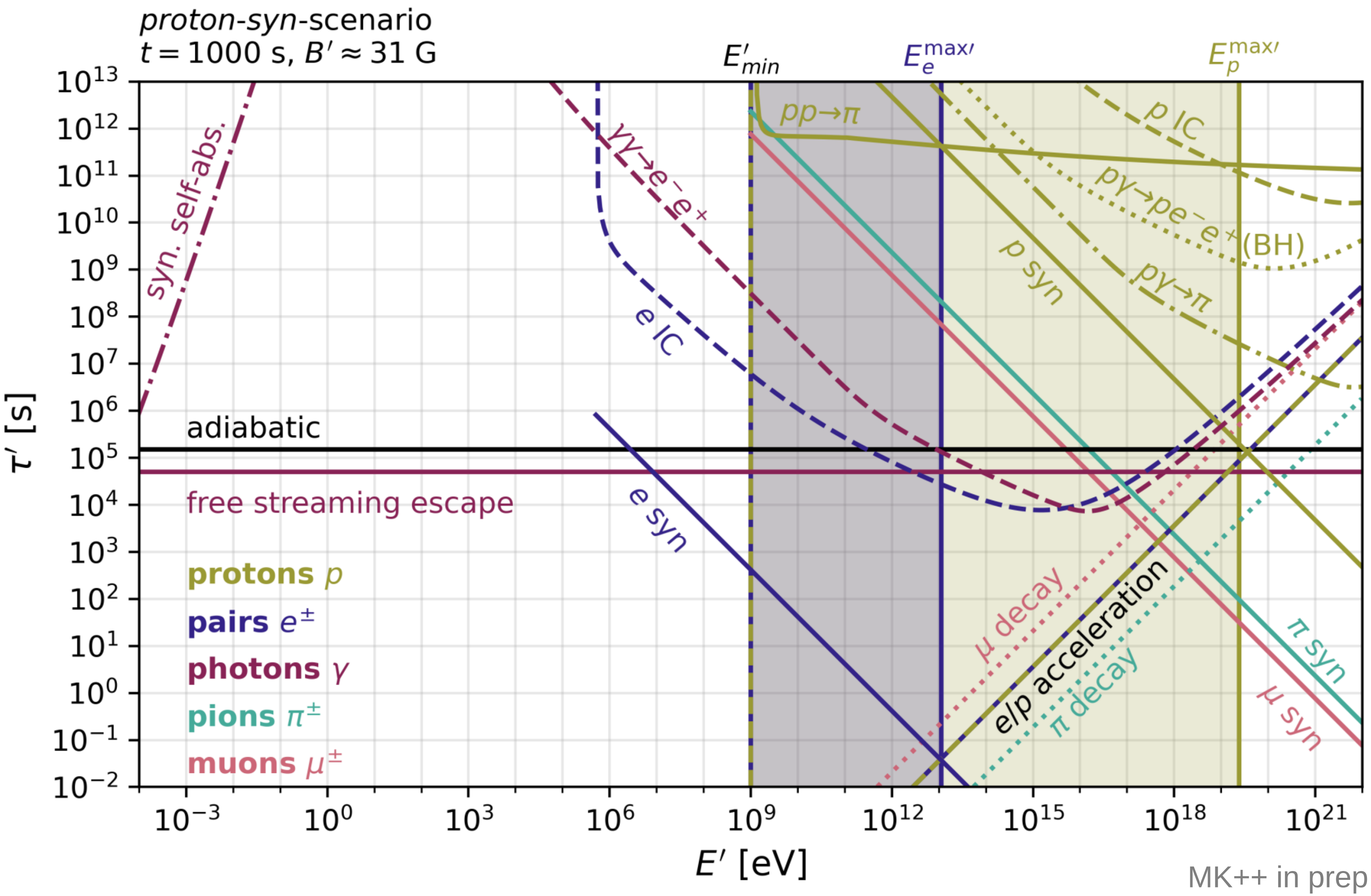


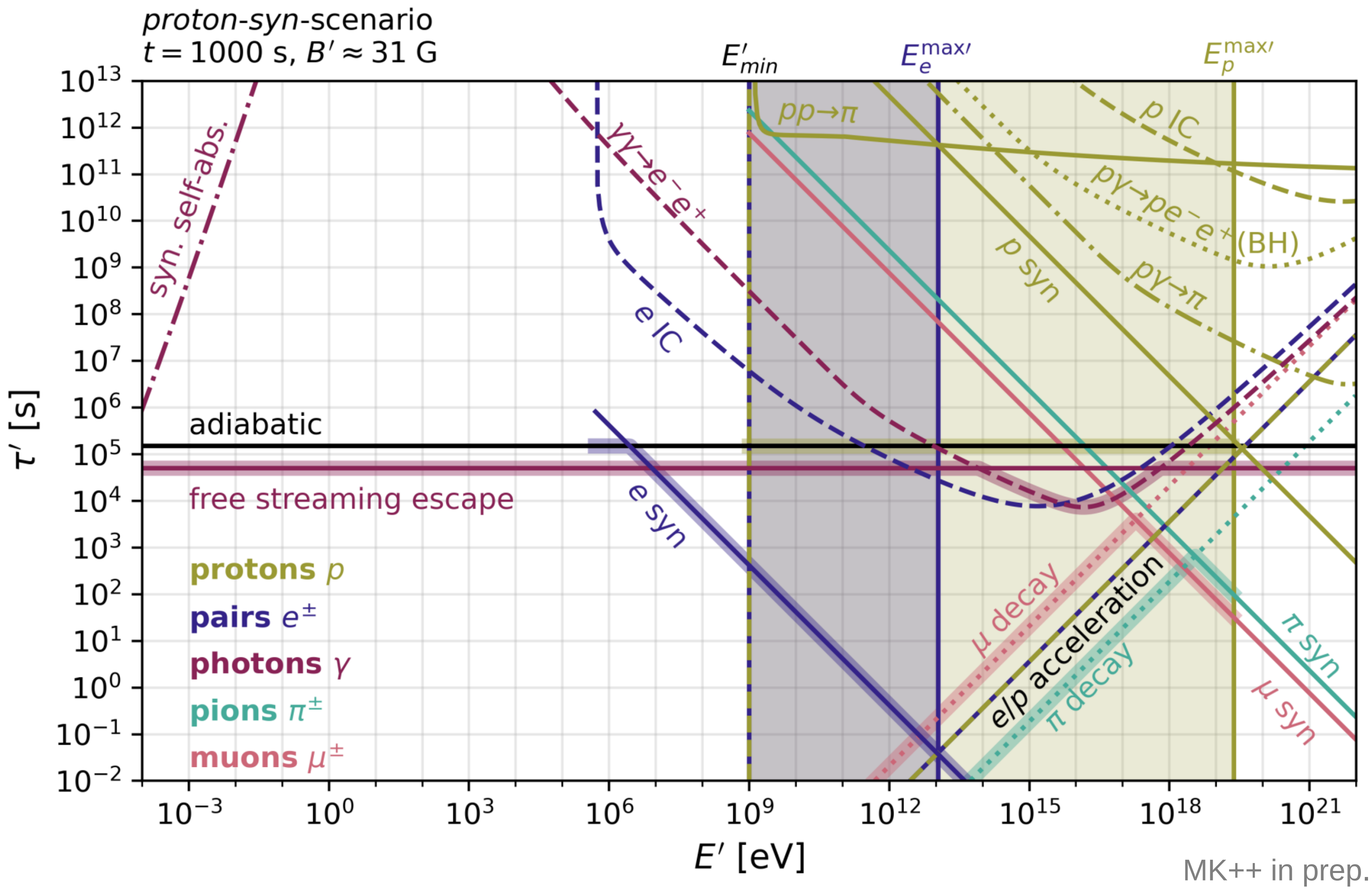
MK++ in prep.

Estimate the coefficients: GRB example



MK++ in prep.

Estimate the coefficients: GRB example



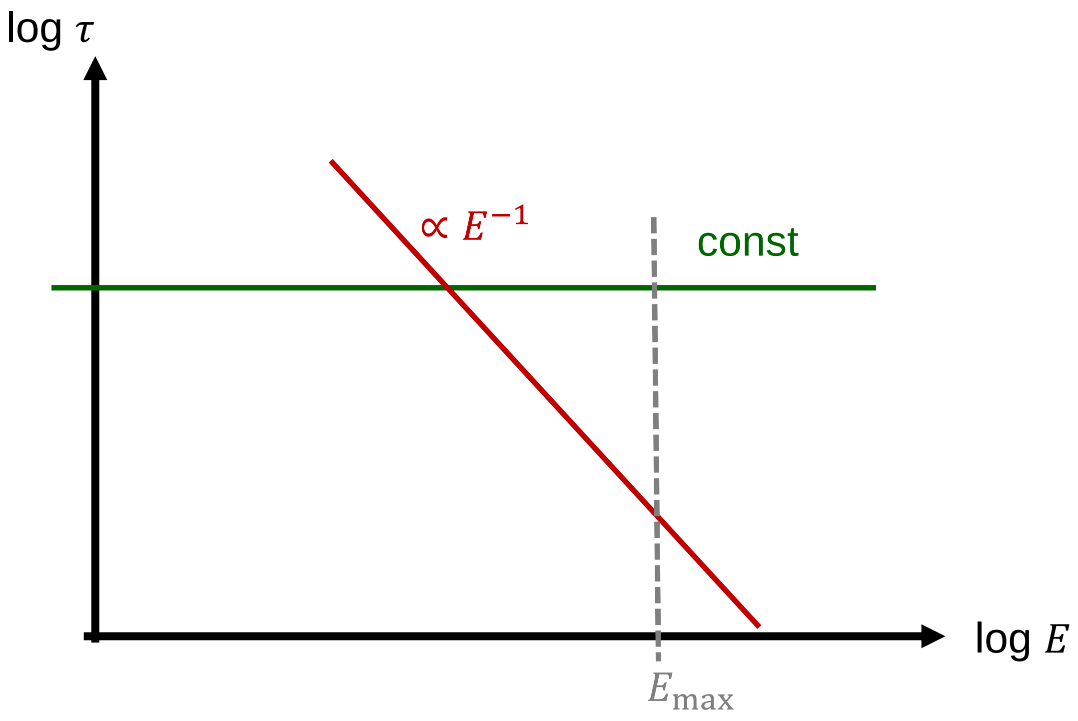
MK++ in prep.

The workflow

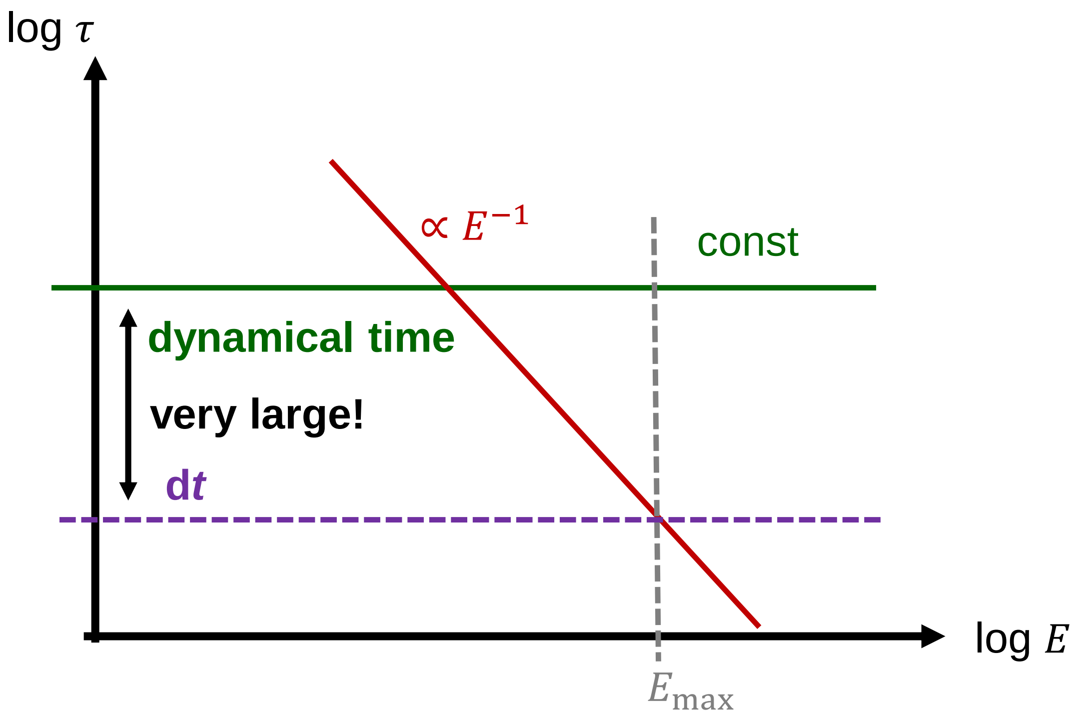
estimate the coefficients $Q, \dot{E}, \alpha$ (time scales) based on current state of system

evolve particle densities n_i in time for small step

Evolve the particle densities



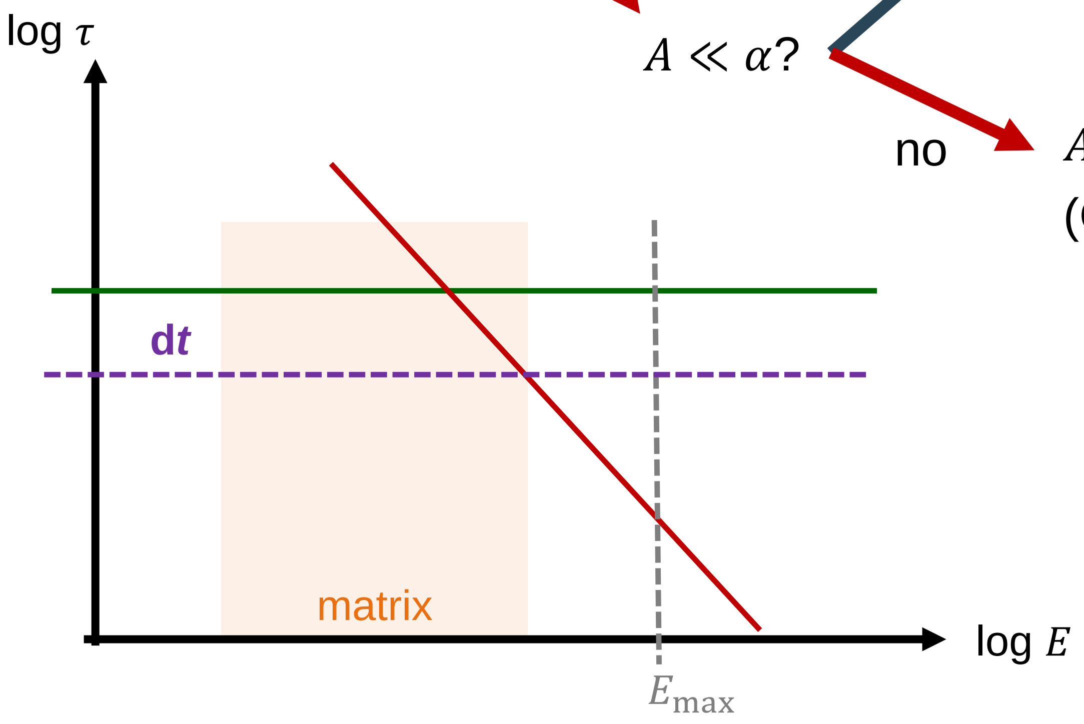
Evolve the particle densities



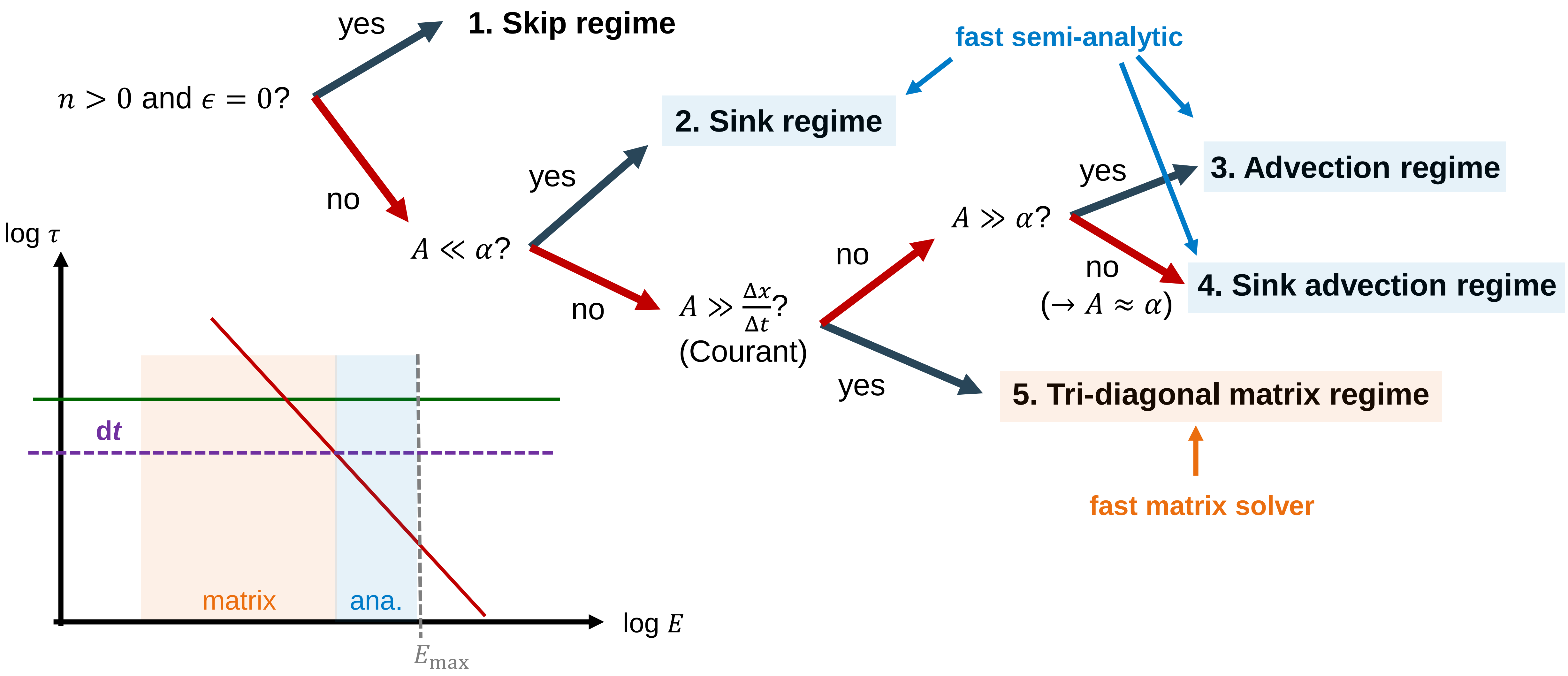
Evolve the particle densities

$n > 0$ 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**

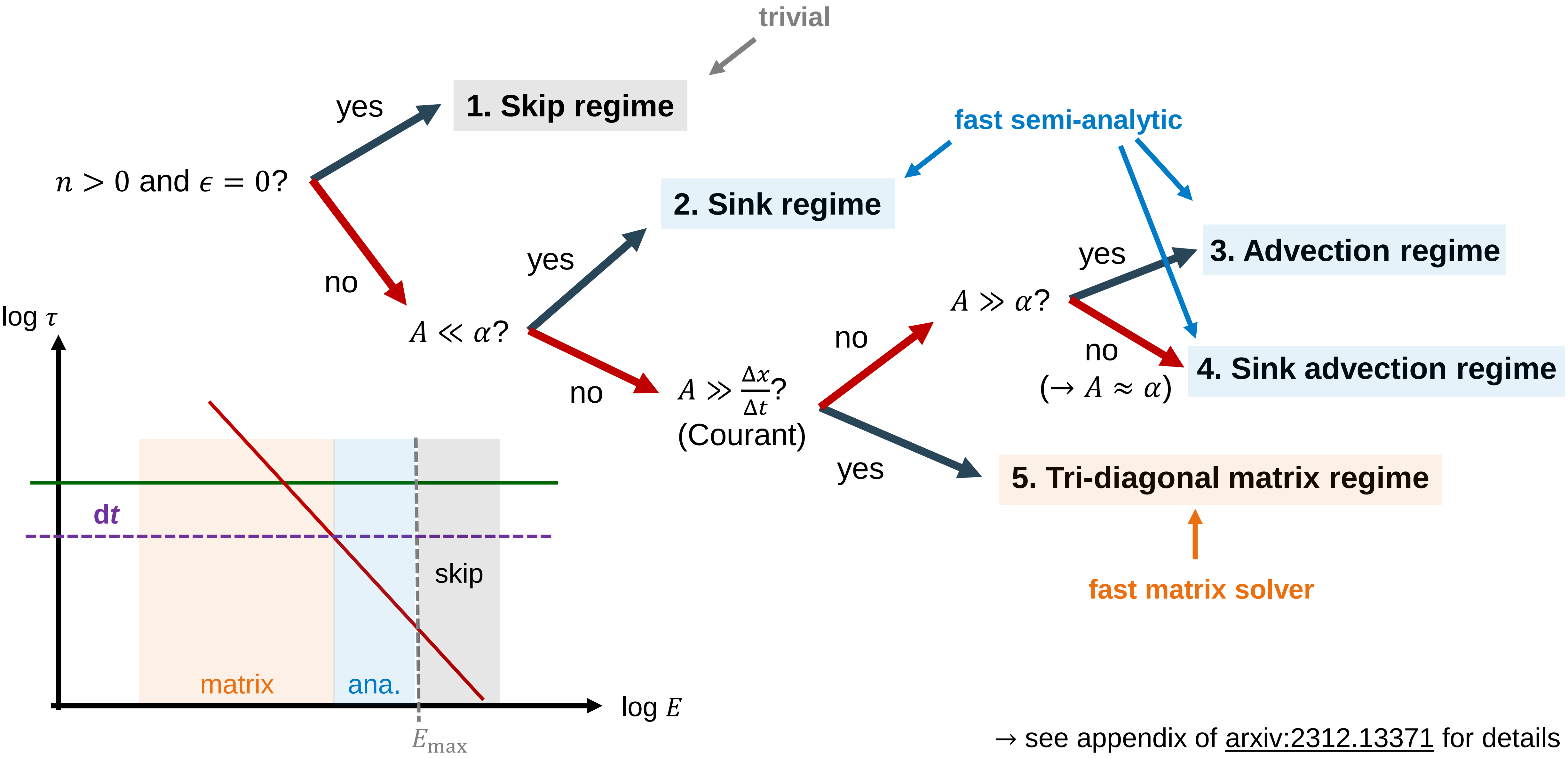
fast matrix solver



Evolve the particle densities



Evolve the particle densities



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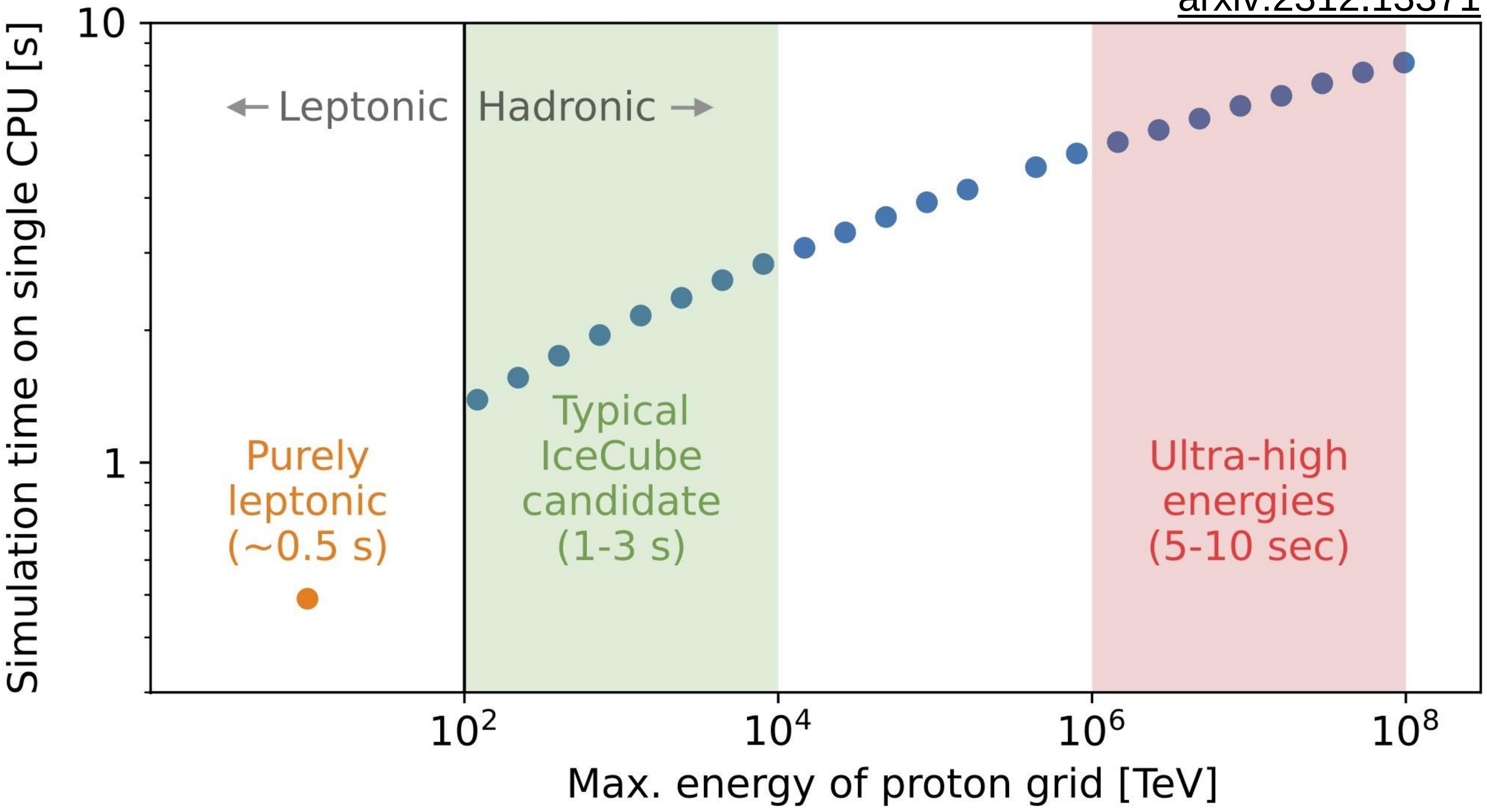
Fast

- steady state in 1-10 seconds

arxiv:2312.13371



Fast

- steady state in 1-10 seconds
- speed optimizations:

→ pre-calculated/tabulated/simplified kernels
(cut to relevant energy ranges)

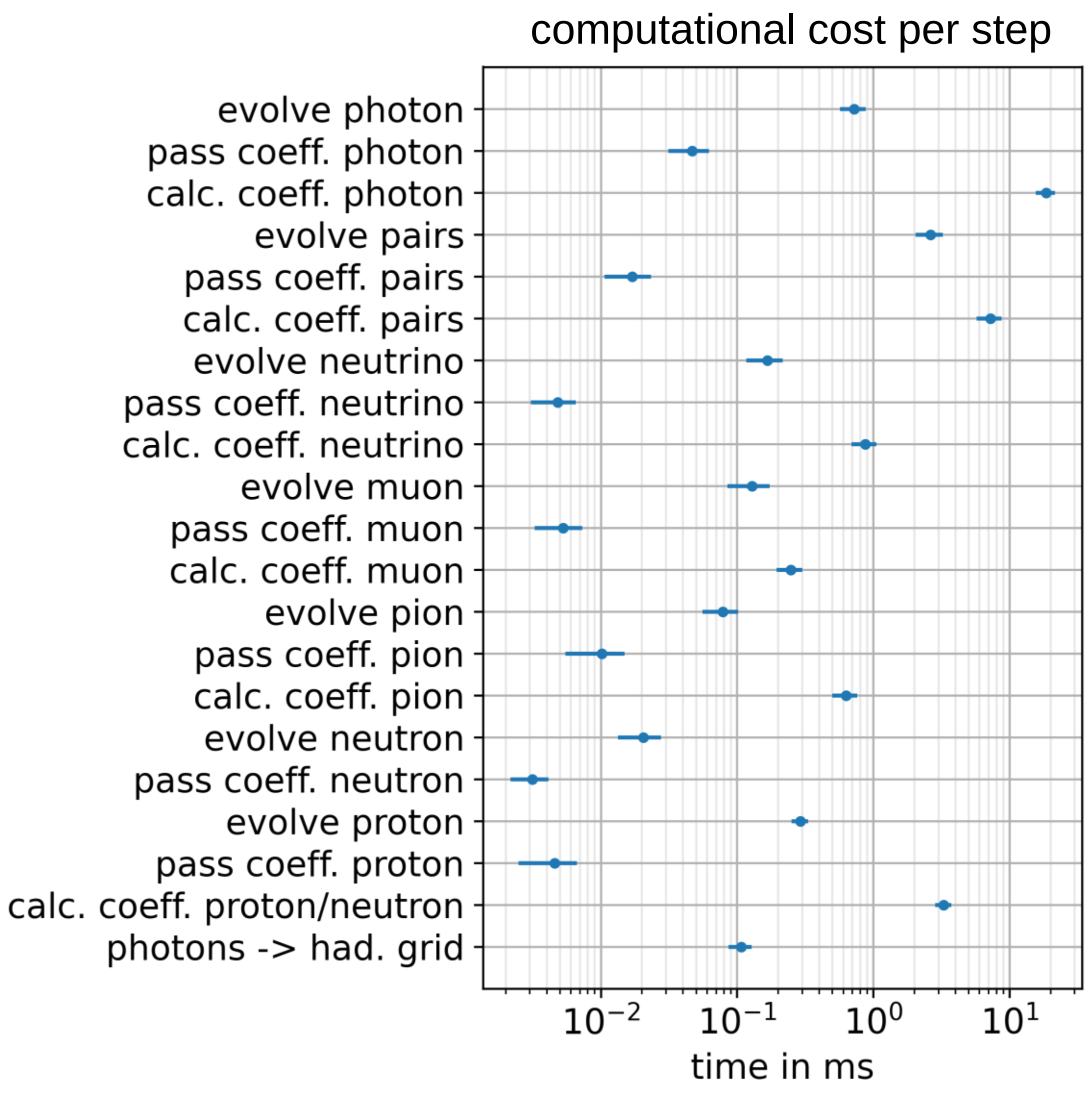
→ ~40 switches allow to select for relevant processes

→ monitor computational cost

→ speed optimized solver

→ compiled (C++)

→ adjustable energy grid



Trackable

- possibility to co-evolve components to track contribution

  → which neutrinos come from $pp/p\gamma$?

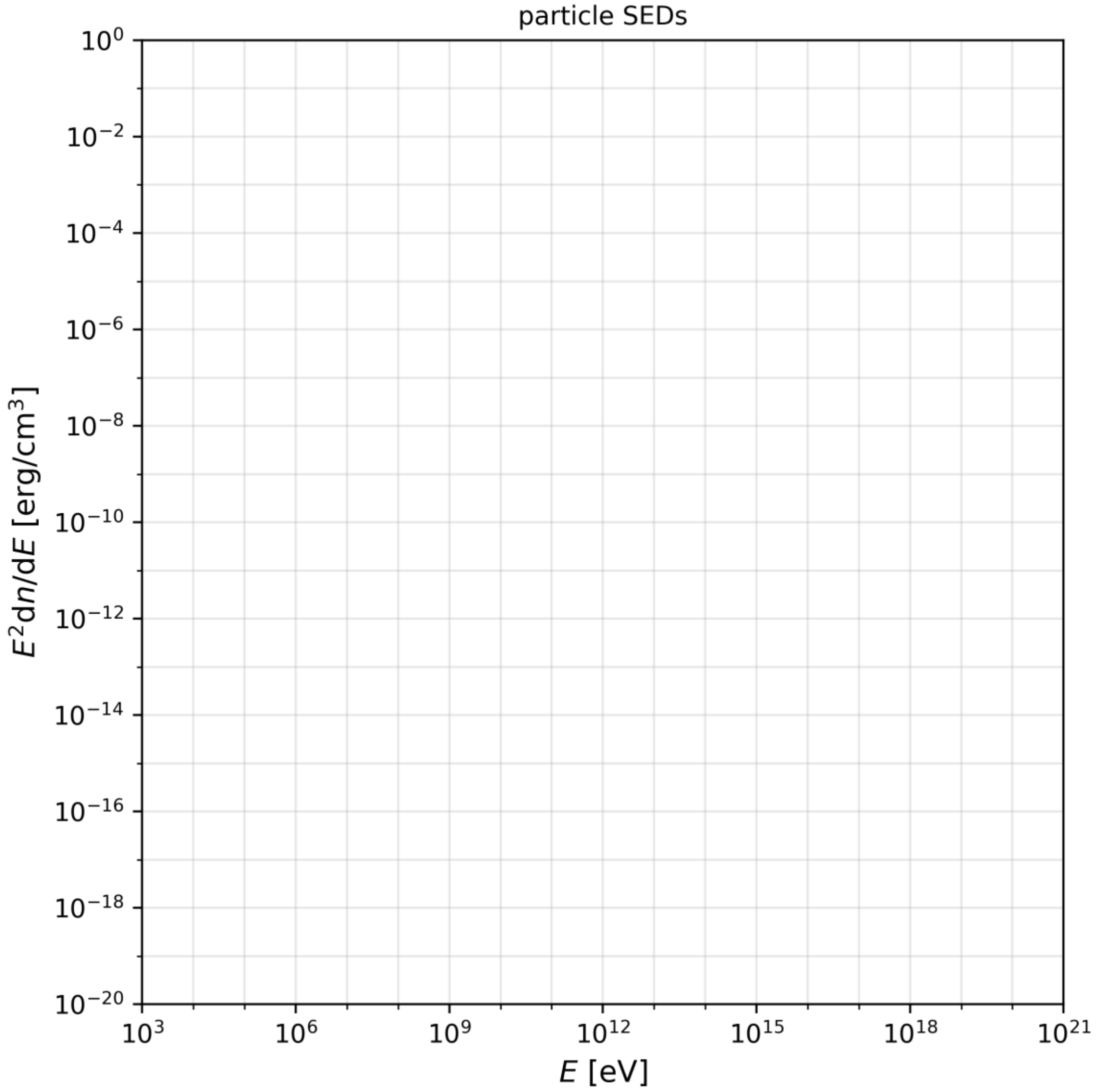
  → which processes contribute how much to electrons/positrons?

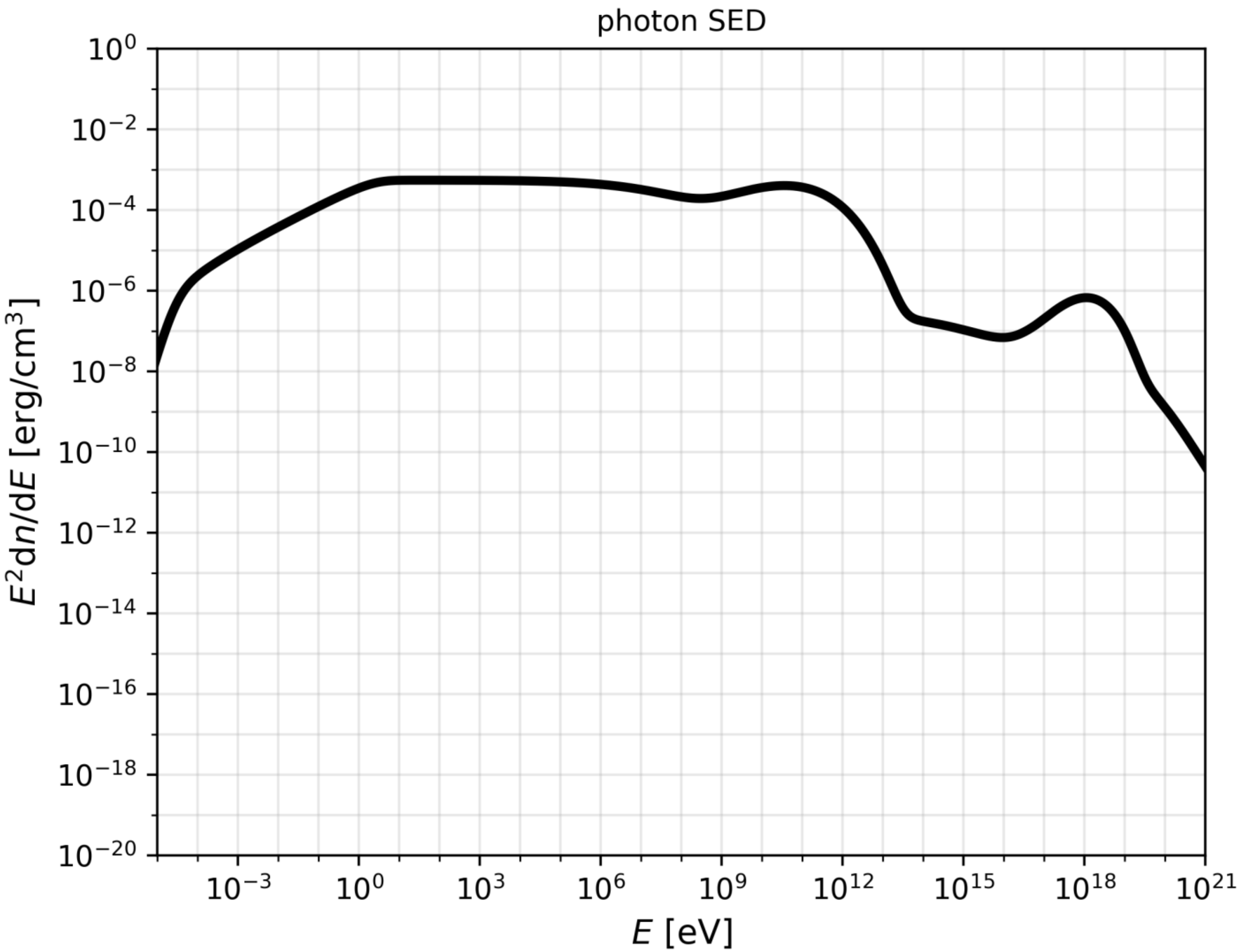
  → which components dominate photon spectra at which energies?

- no real slow down

- great intutition!

Trackable


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


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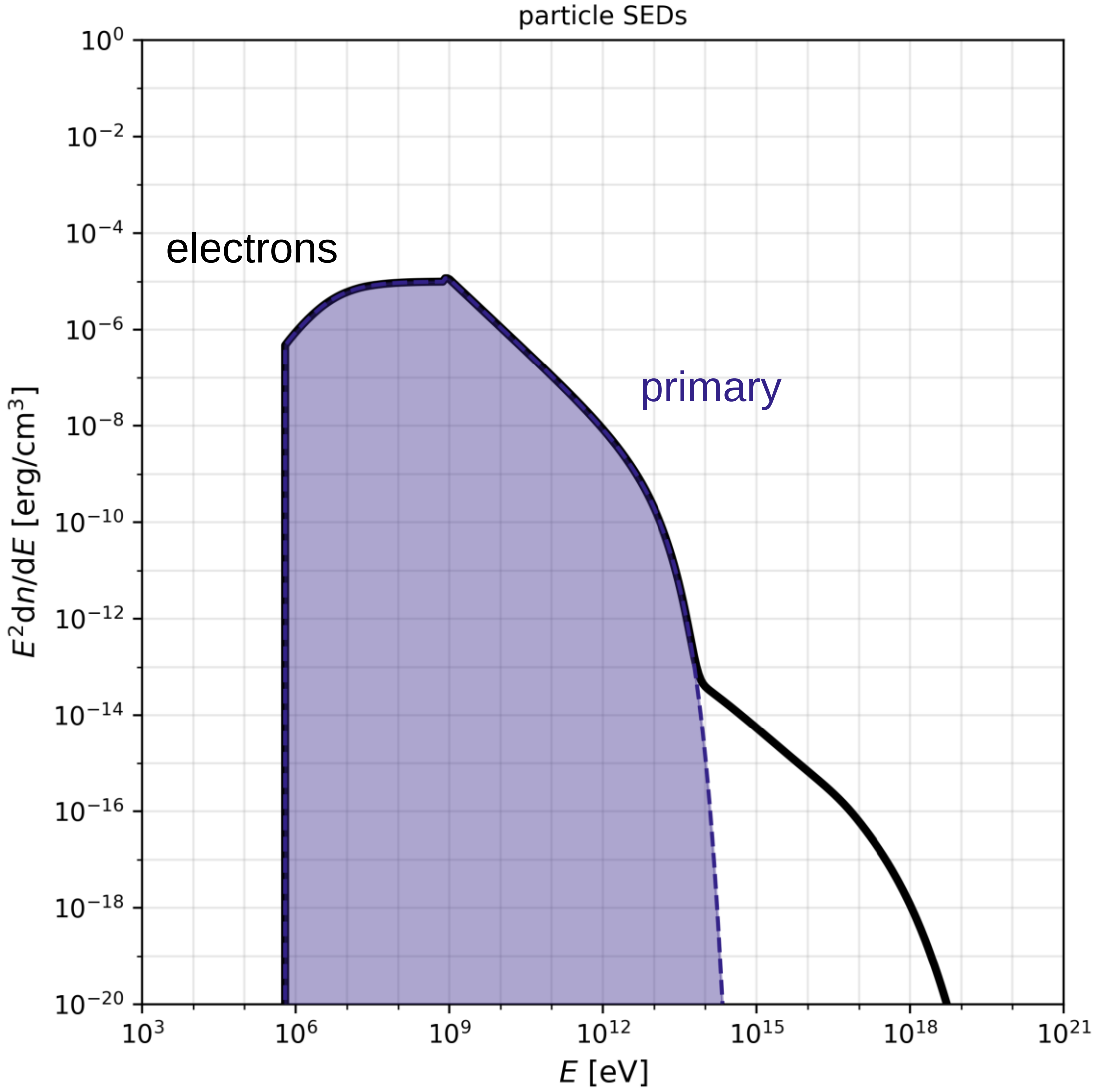
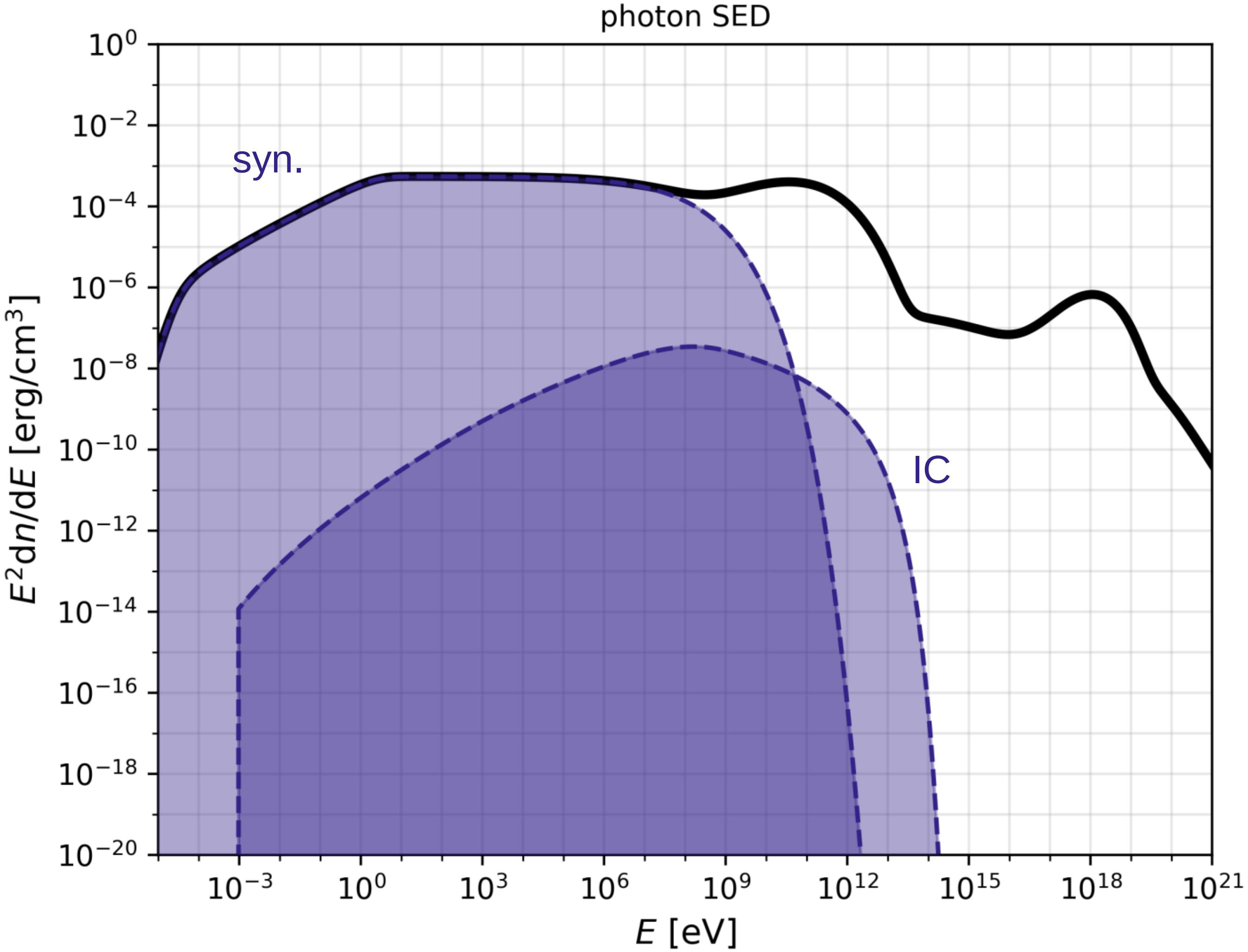
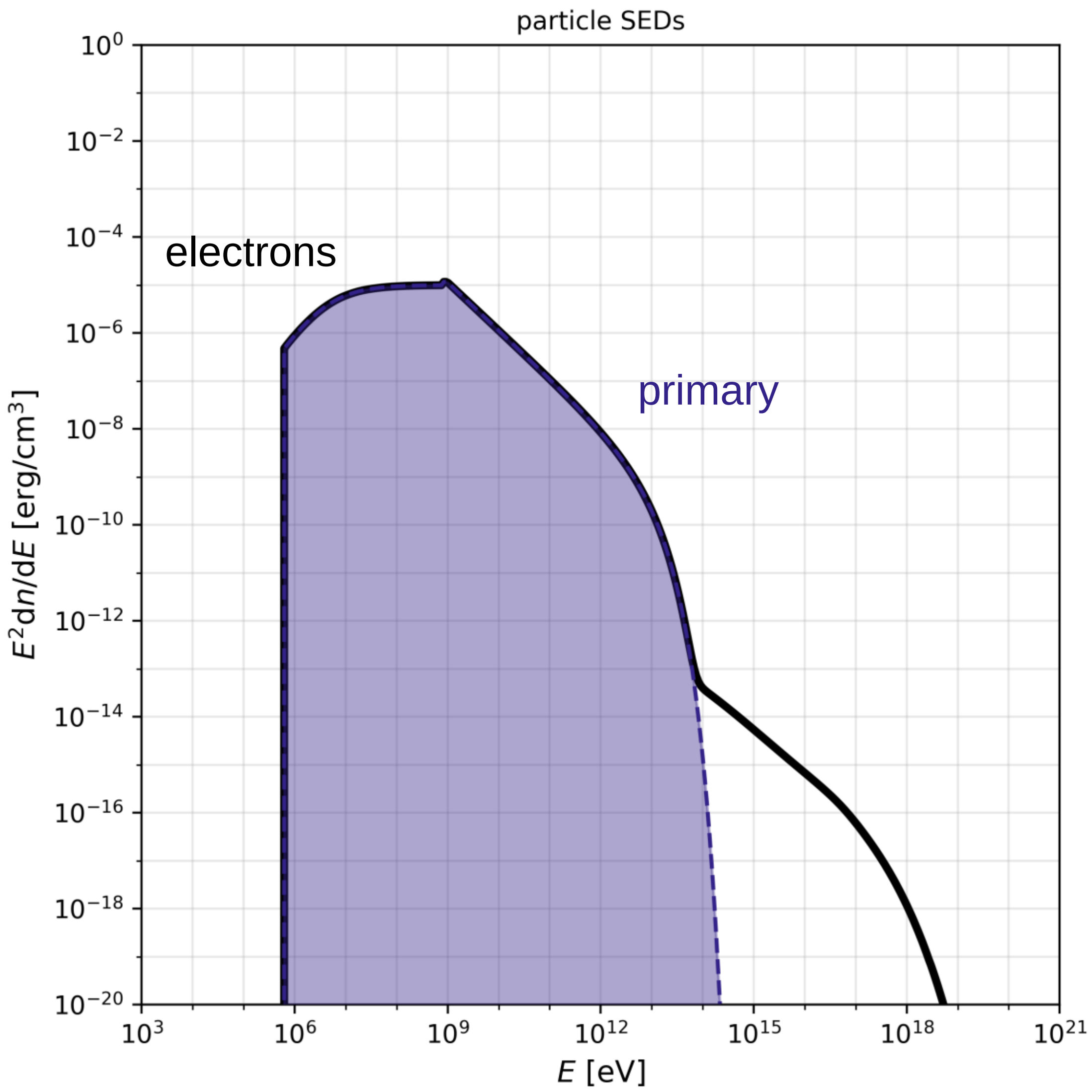
$E^2 dn/dE$ [erg/cm^3]
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
10^{18}
10^{21}
E [eV]

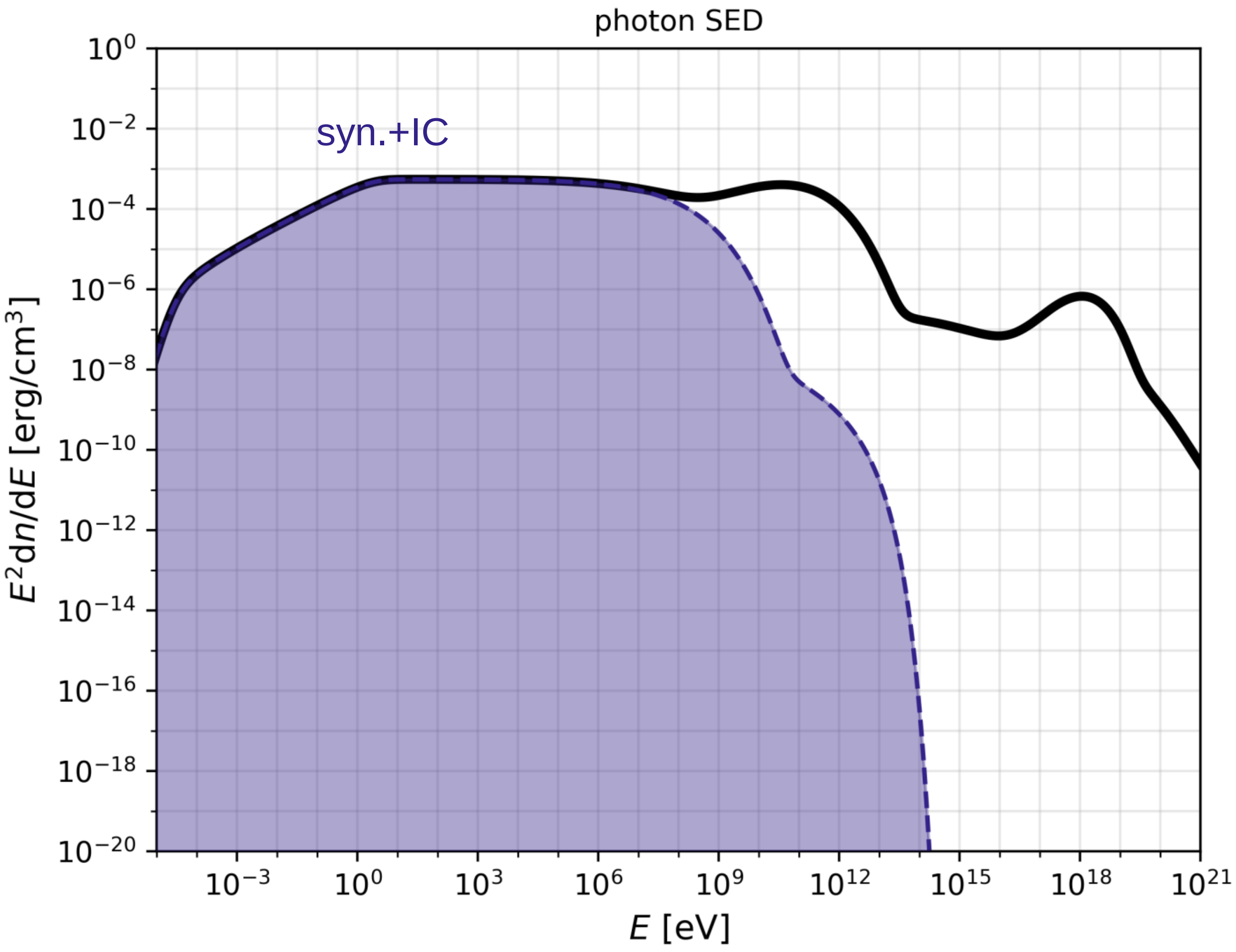
Trackable


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

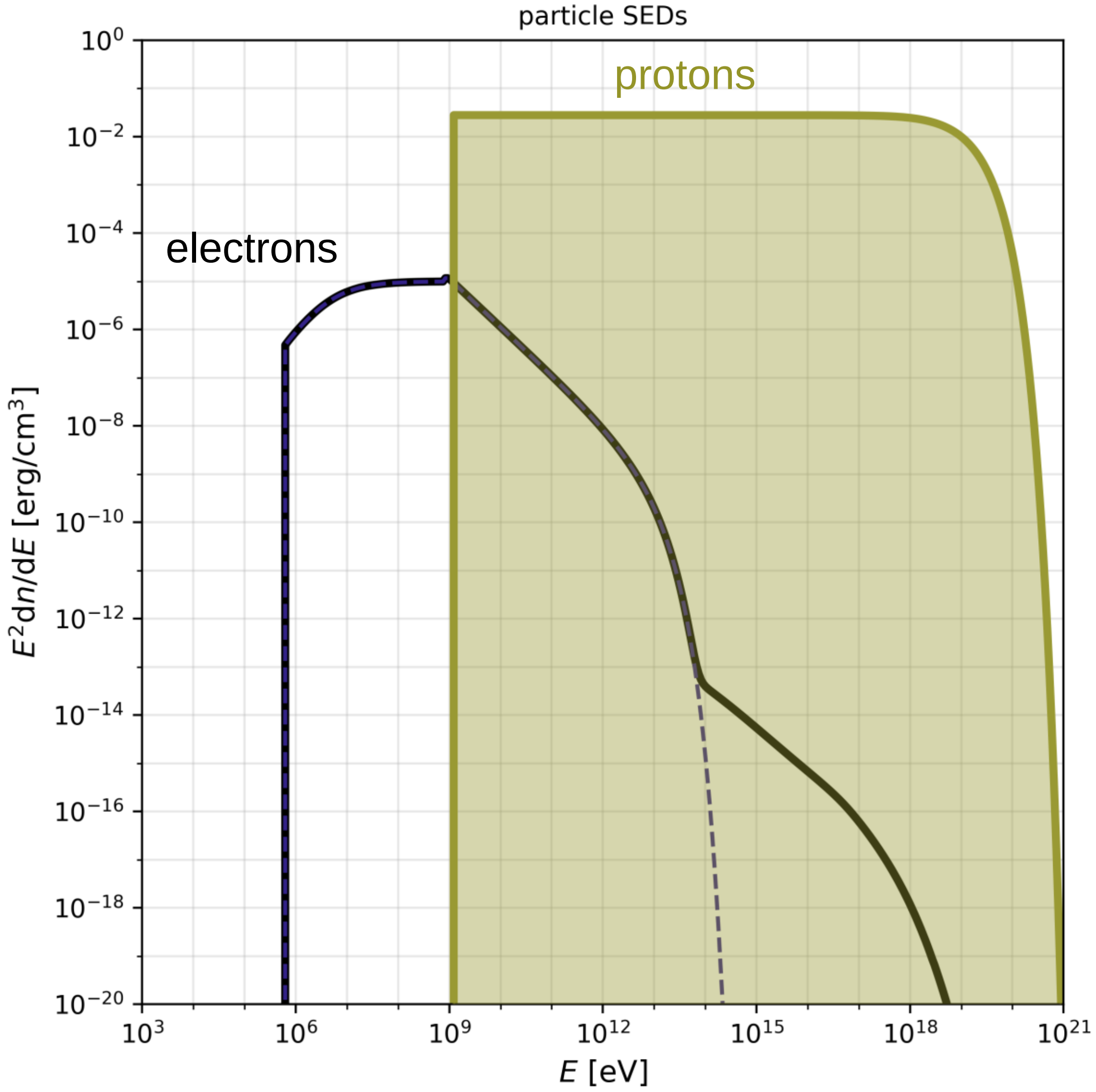

photon SED
syn.
IC
$E^2 dn/dE$ [erg/cm^3]
E [eV]

Trackable


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


photon SED
syn.+IC
$E^2 dn/dE$ [erg/cm^3]
E [eV]

Trackable


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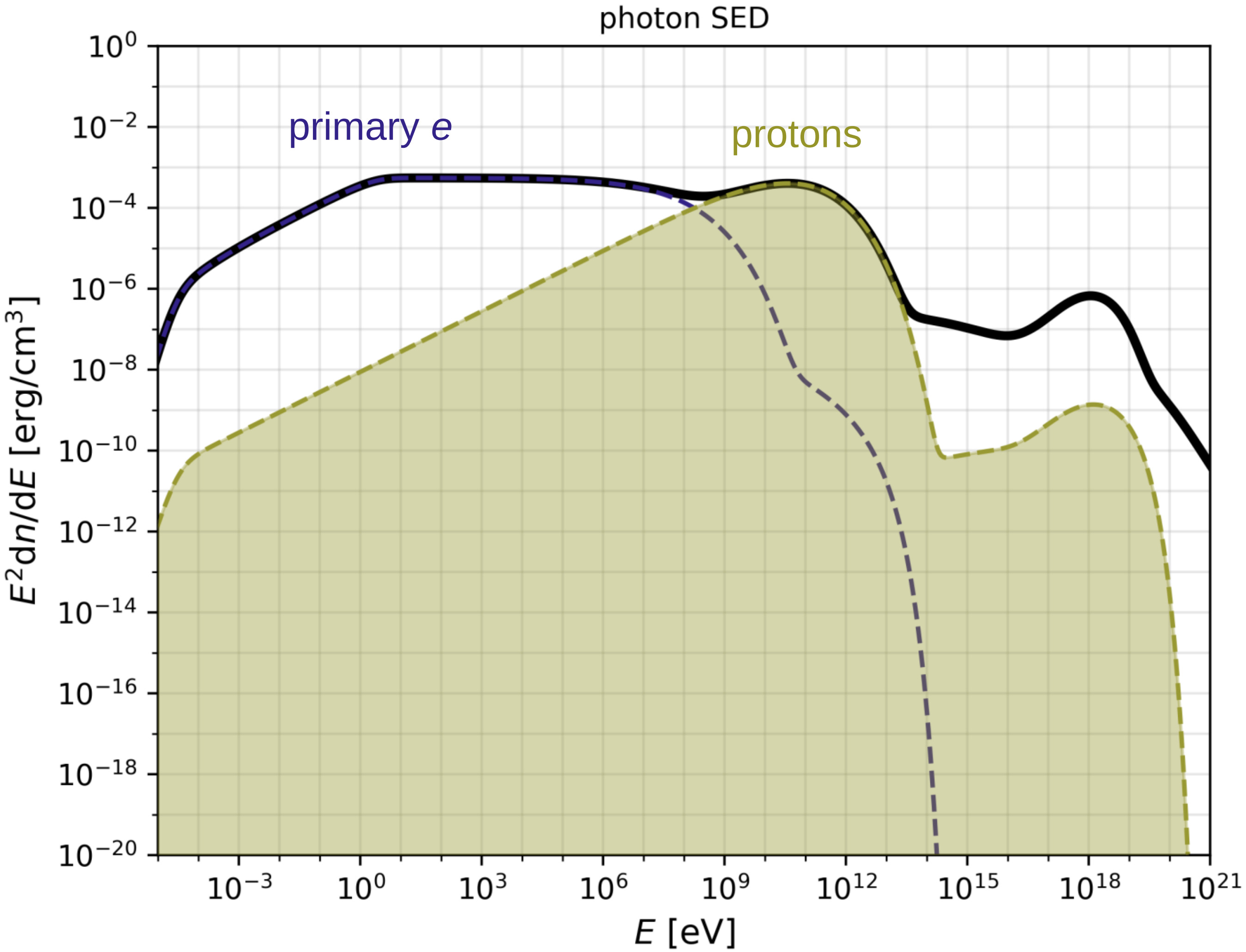
10^{-20}
10^3
10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}


photon SED
primary e
protons
$E^2 dn/dE$ [erg/cm^3]
E [eV]
10^0
10^{-2}
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10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
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10^0
10^3
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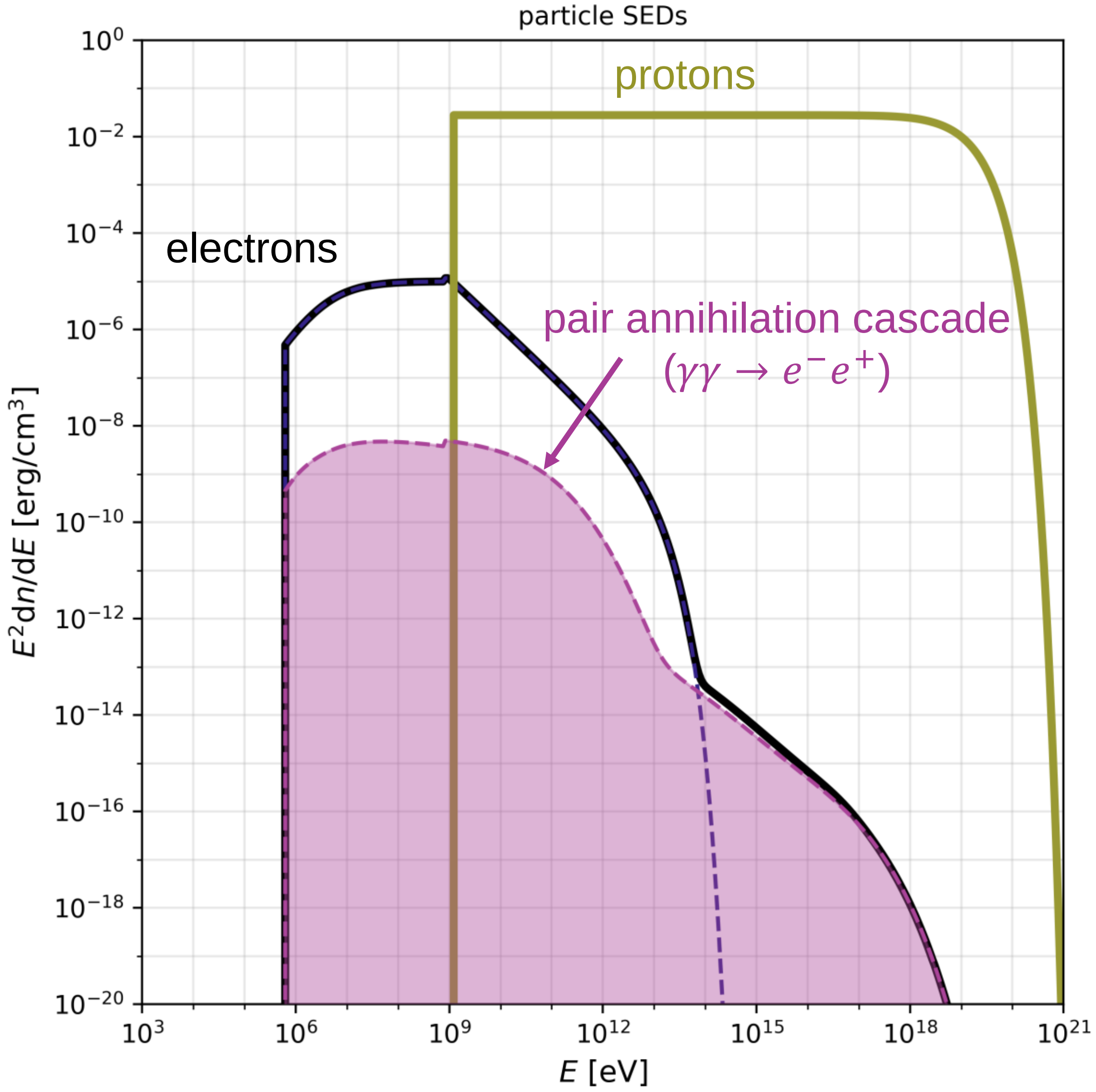
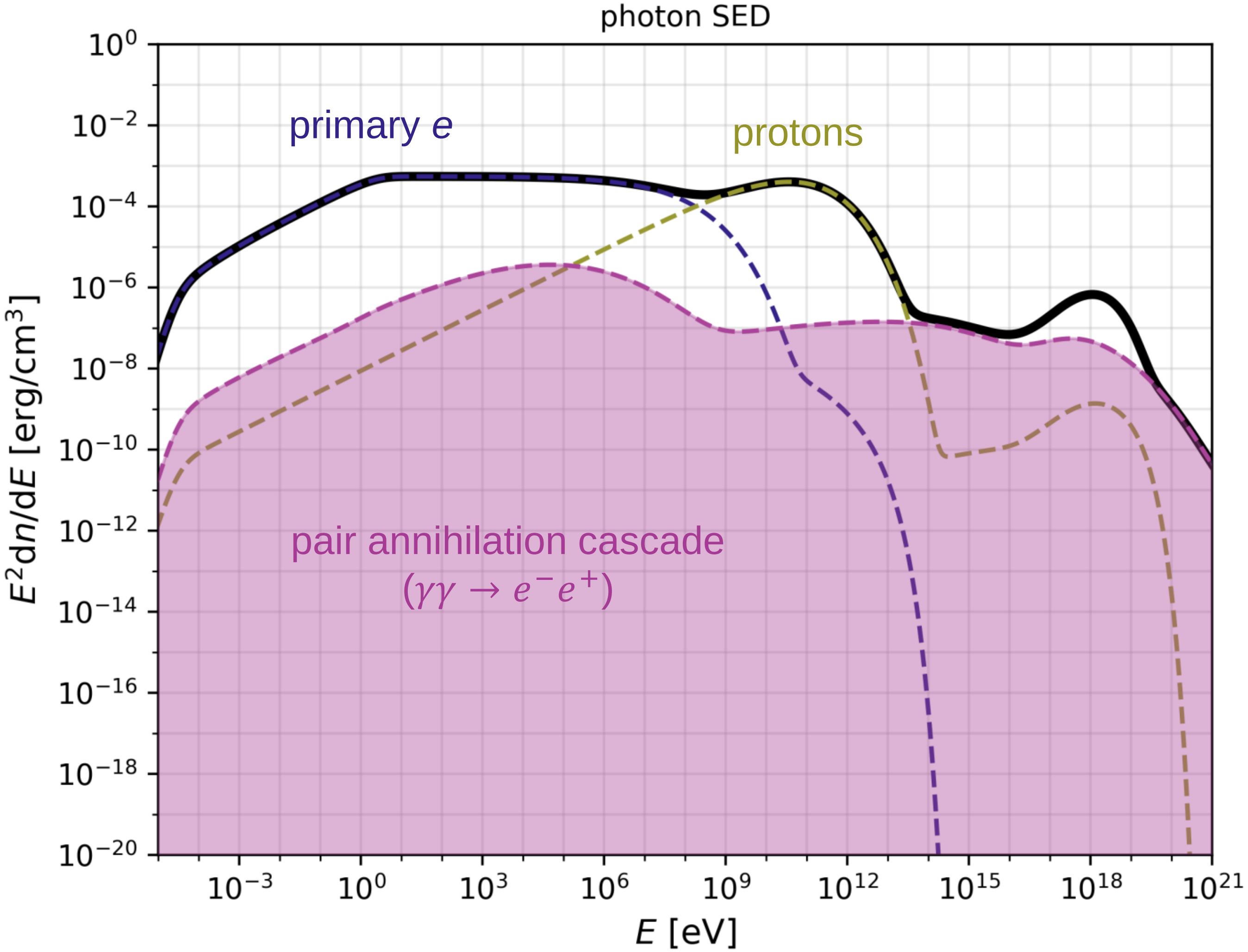
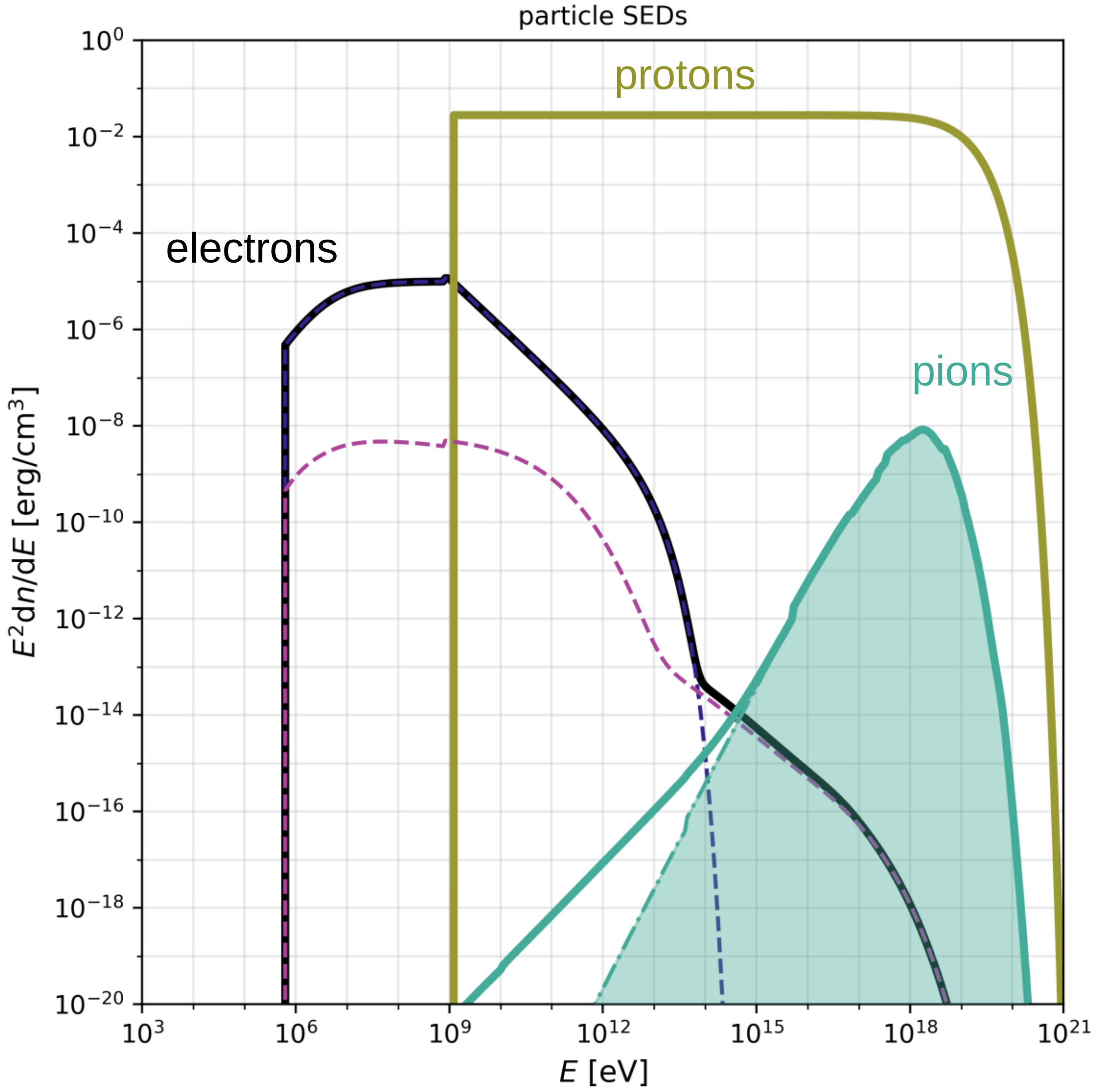
10^{15}
10^{18}
10^{21}

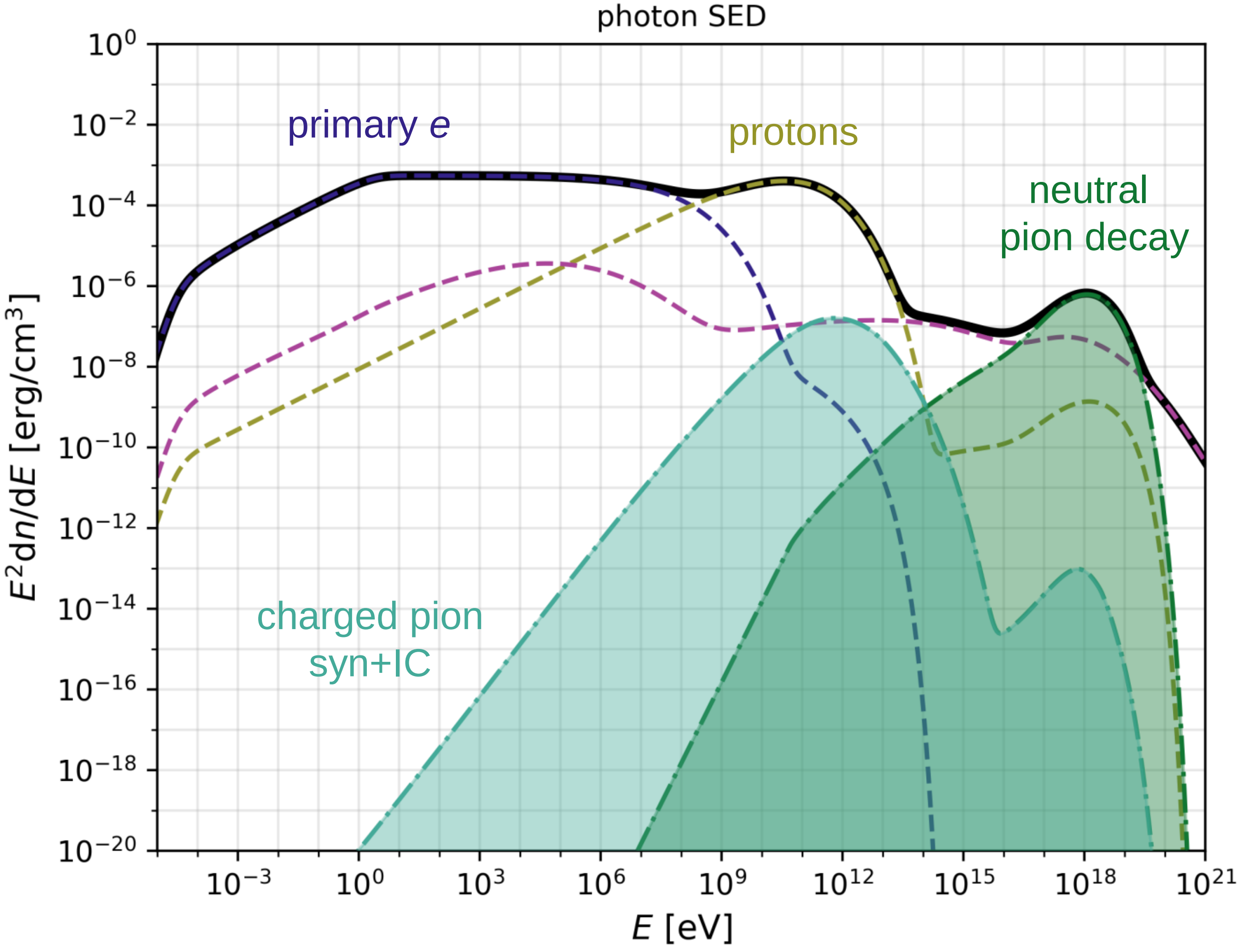
Trackable – pair annihilation



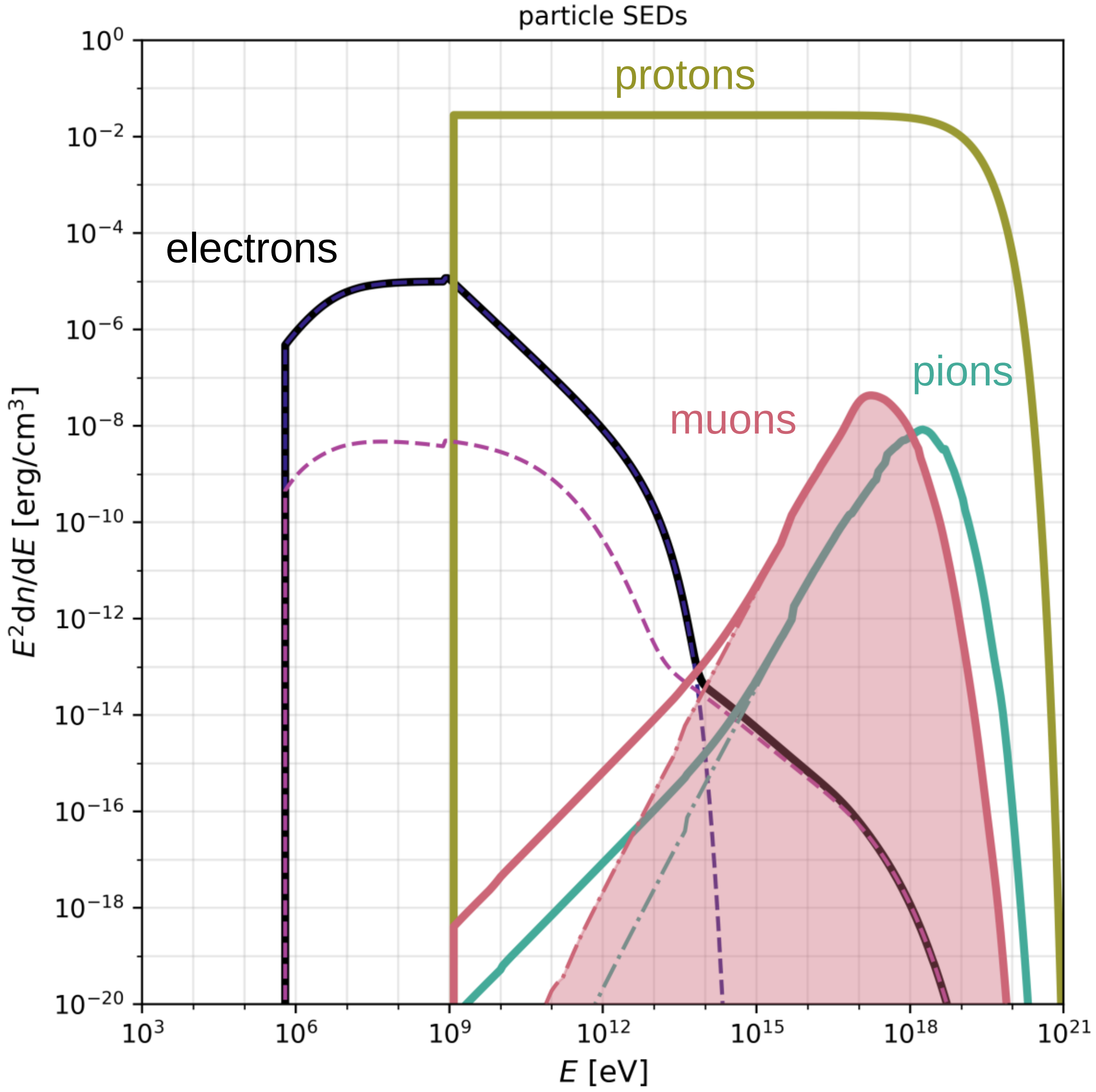


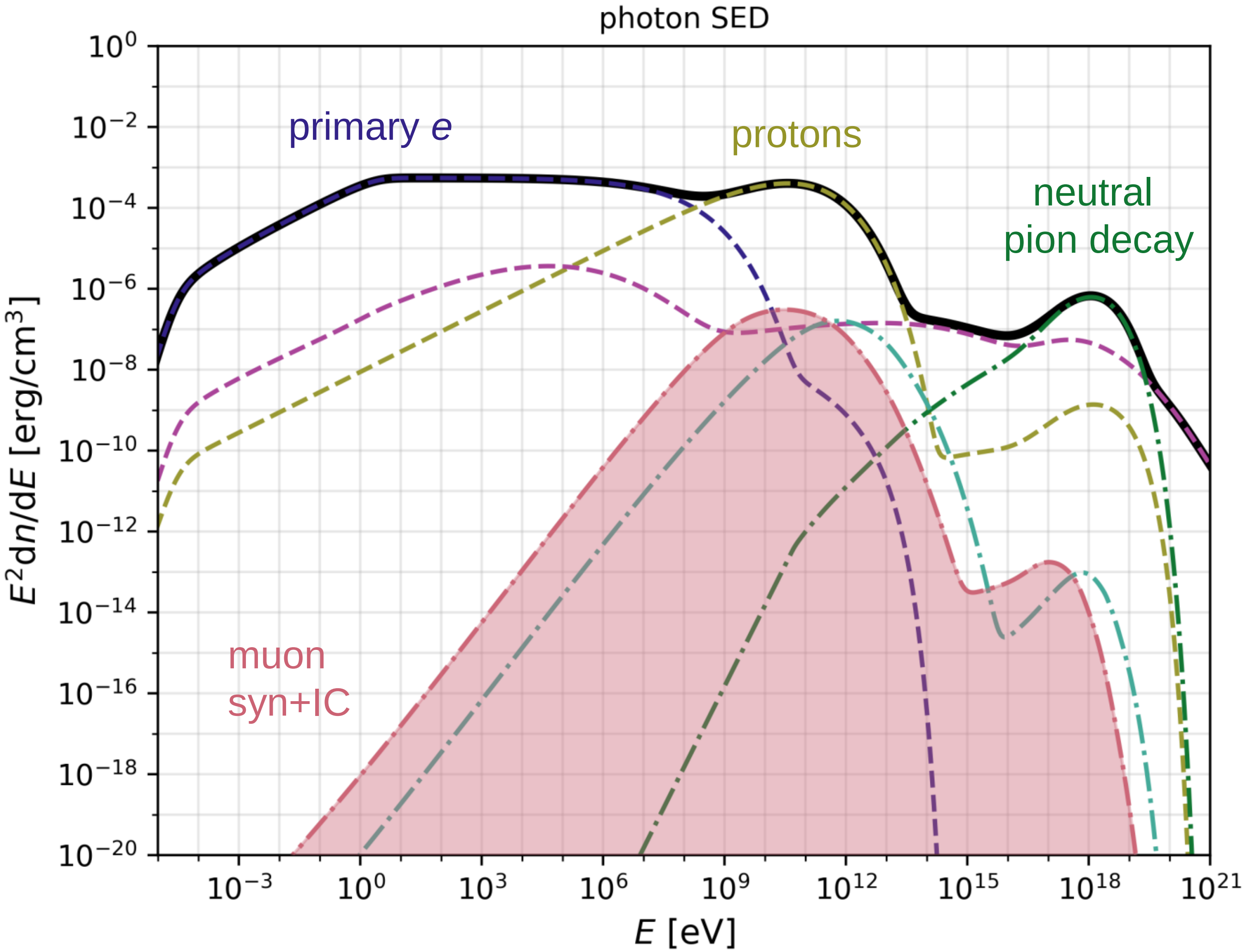
Trackable – photo-pion cascade: $p\gamma \rightarrow \pi$



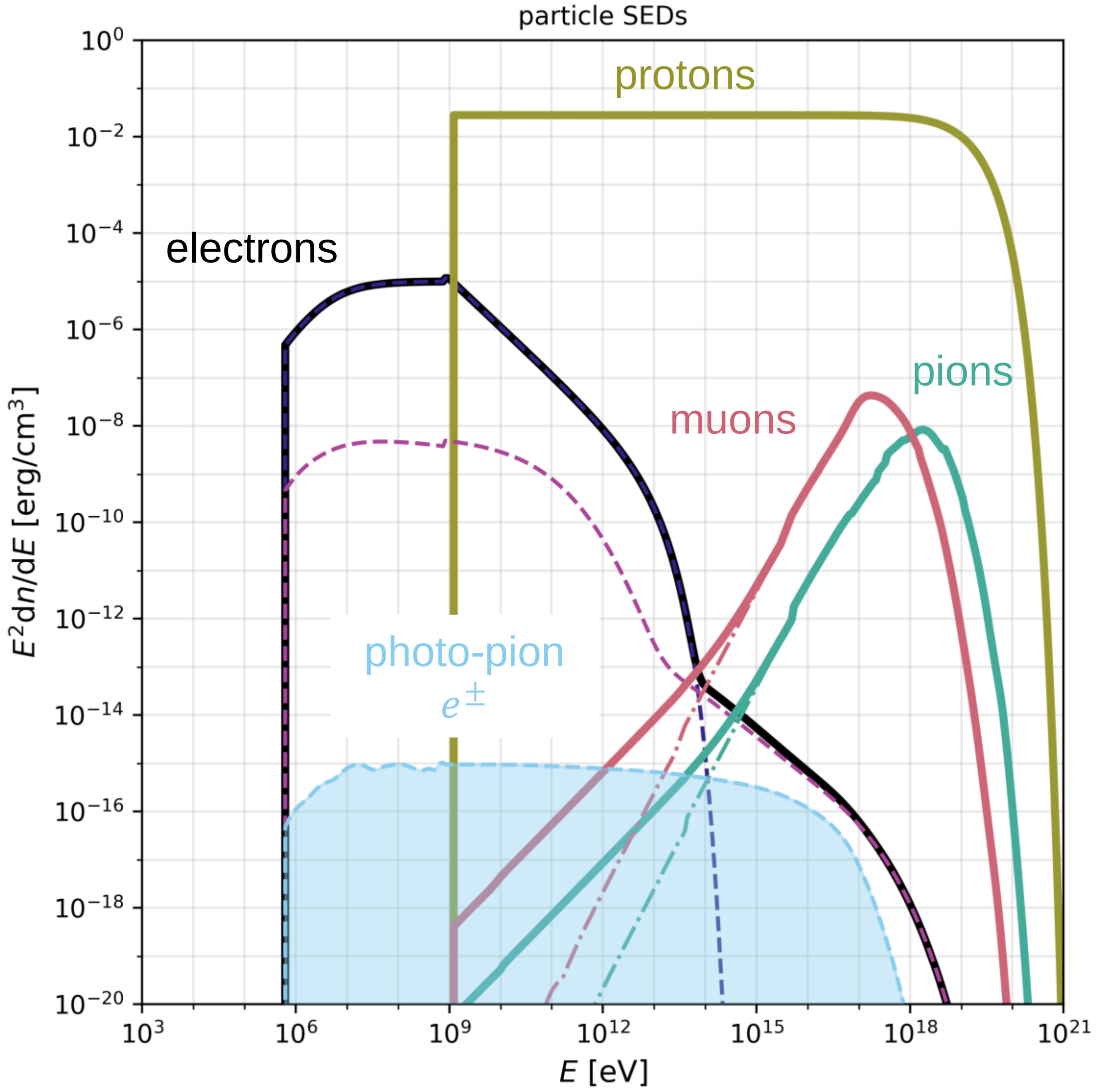


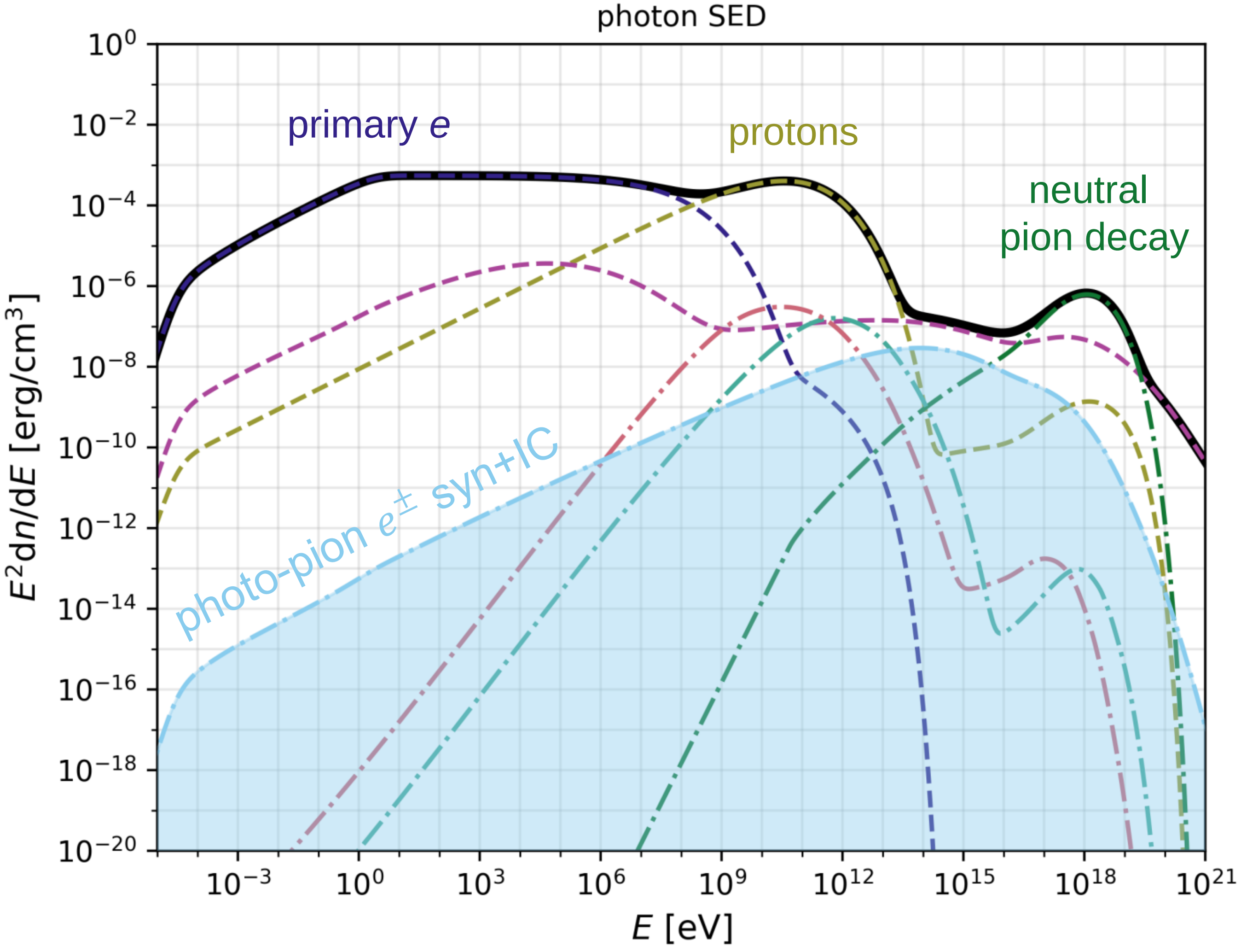
Trackable – photo-pion cascade: $p\gamma \to \pi \to \mu$



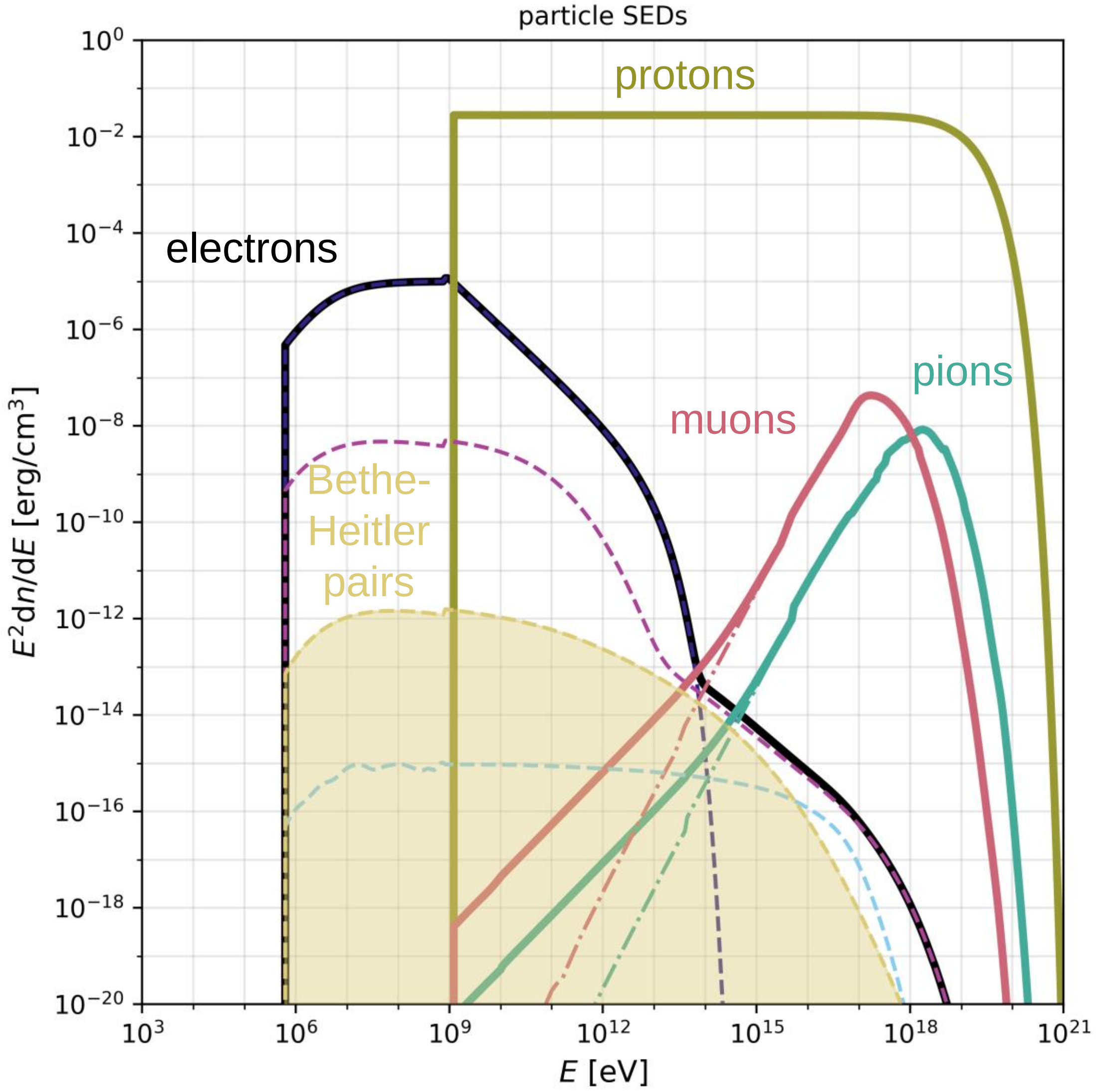


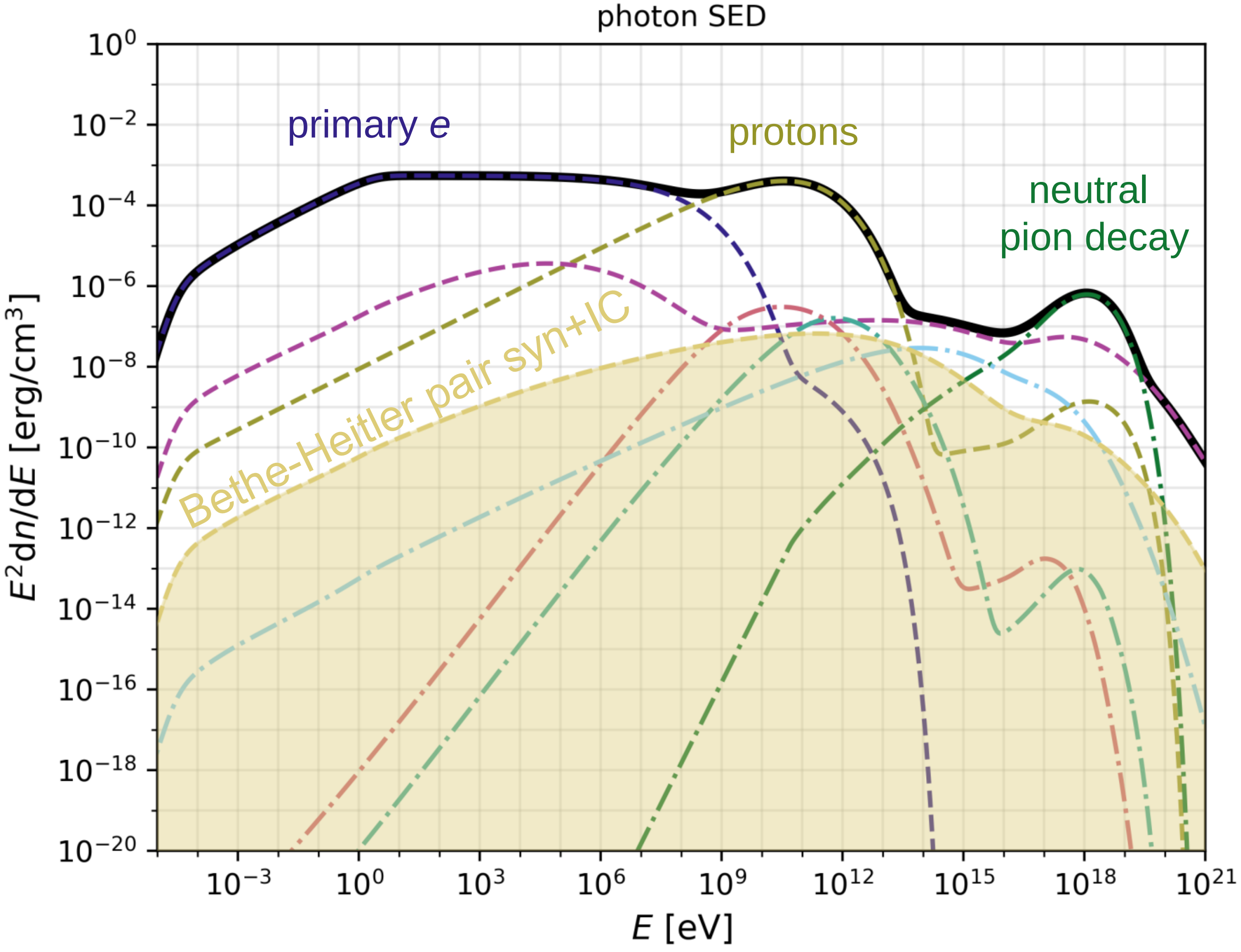
Trackable – photo-pion cascade: $p\gamma \rightarrow \pi \rightarrow \mu \rightarrow e^{\pm}$



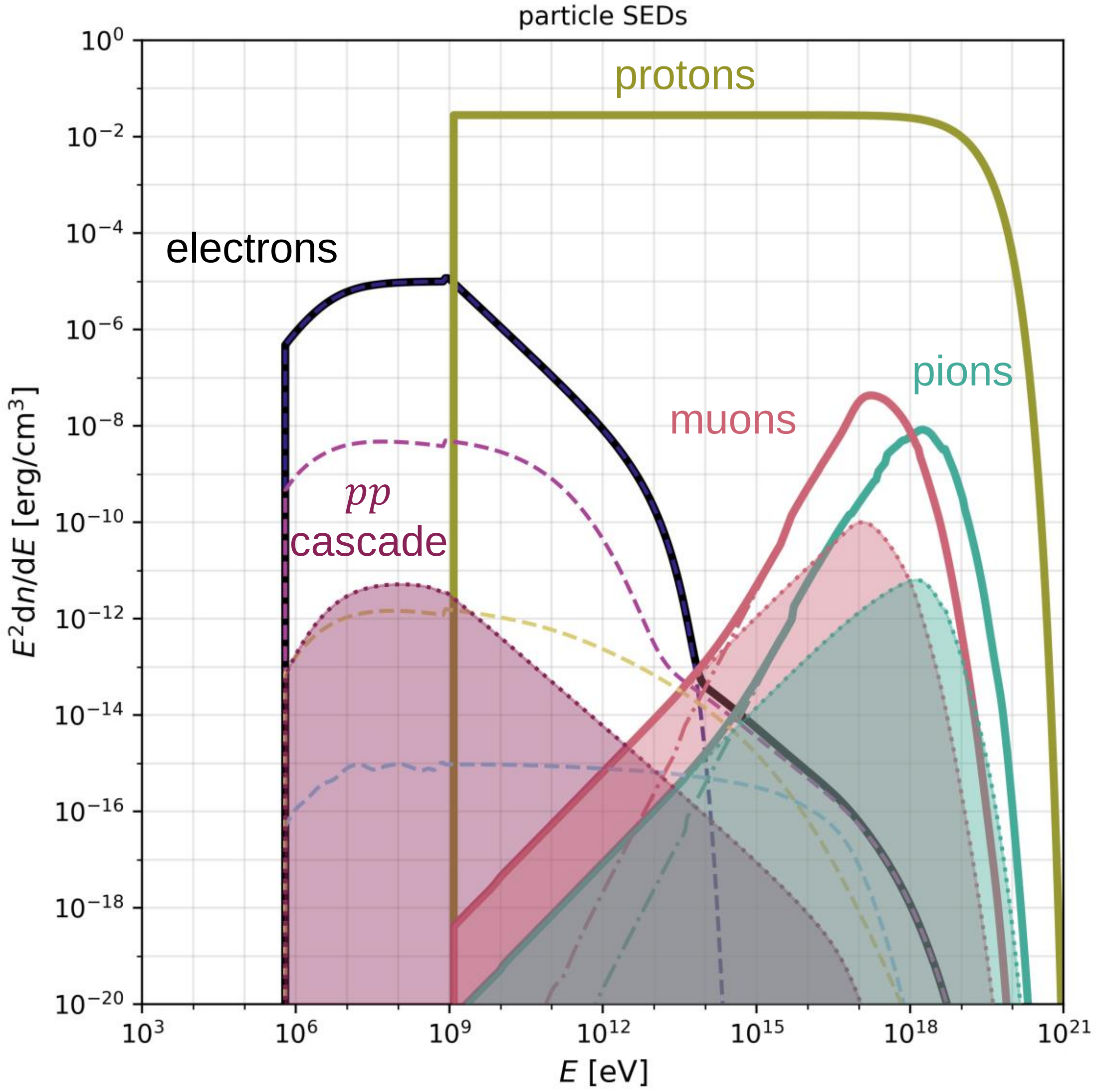


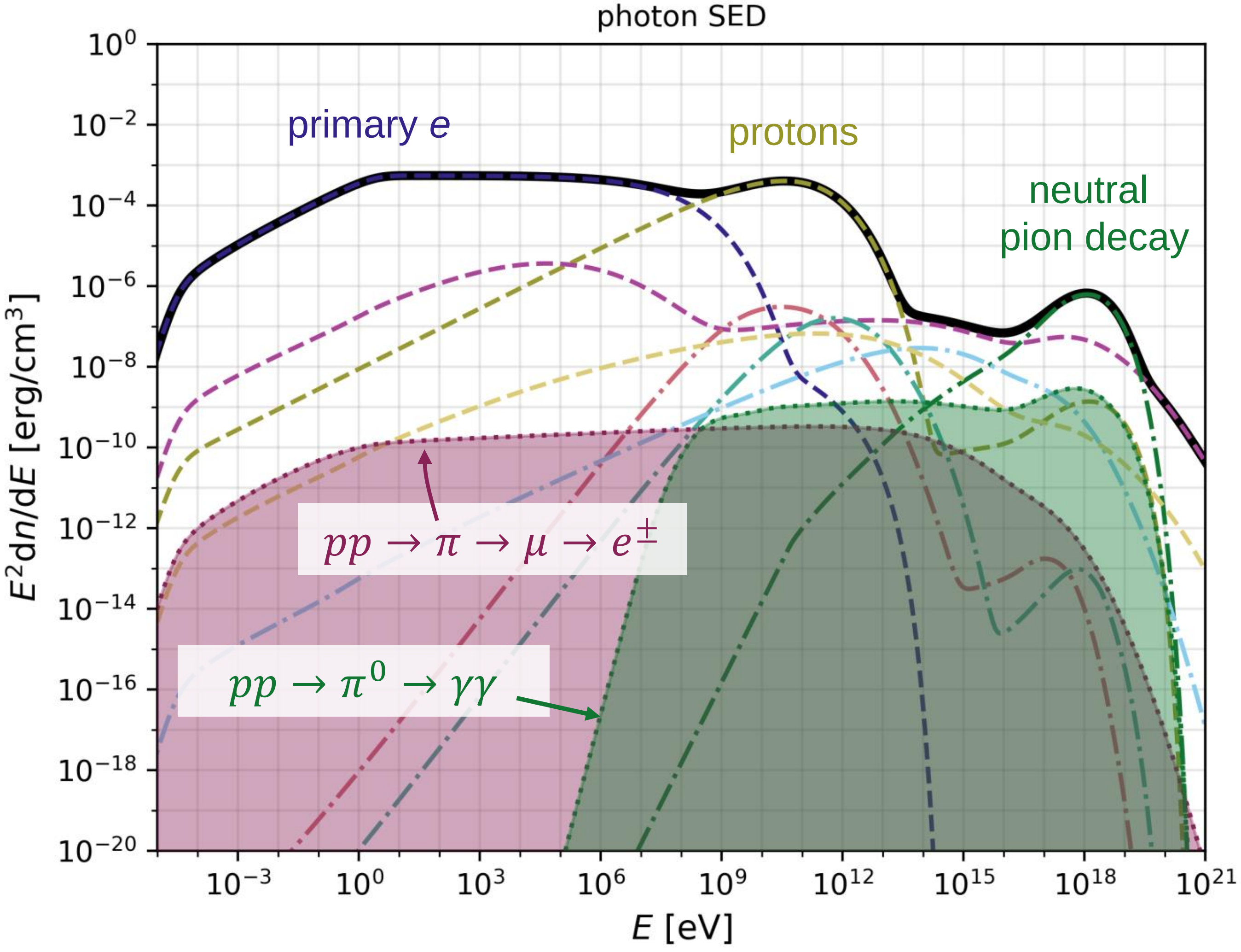
Trackable – Bethe-Heitler : $p\gamma \rightarrow pe^{+}e^{-}$



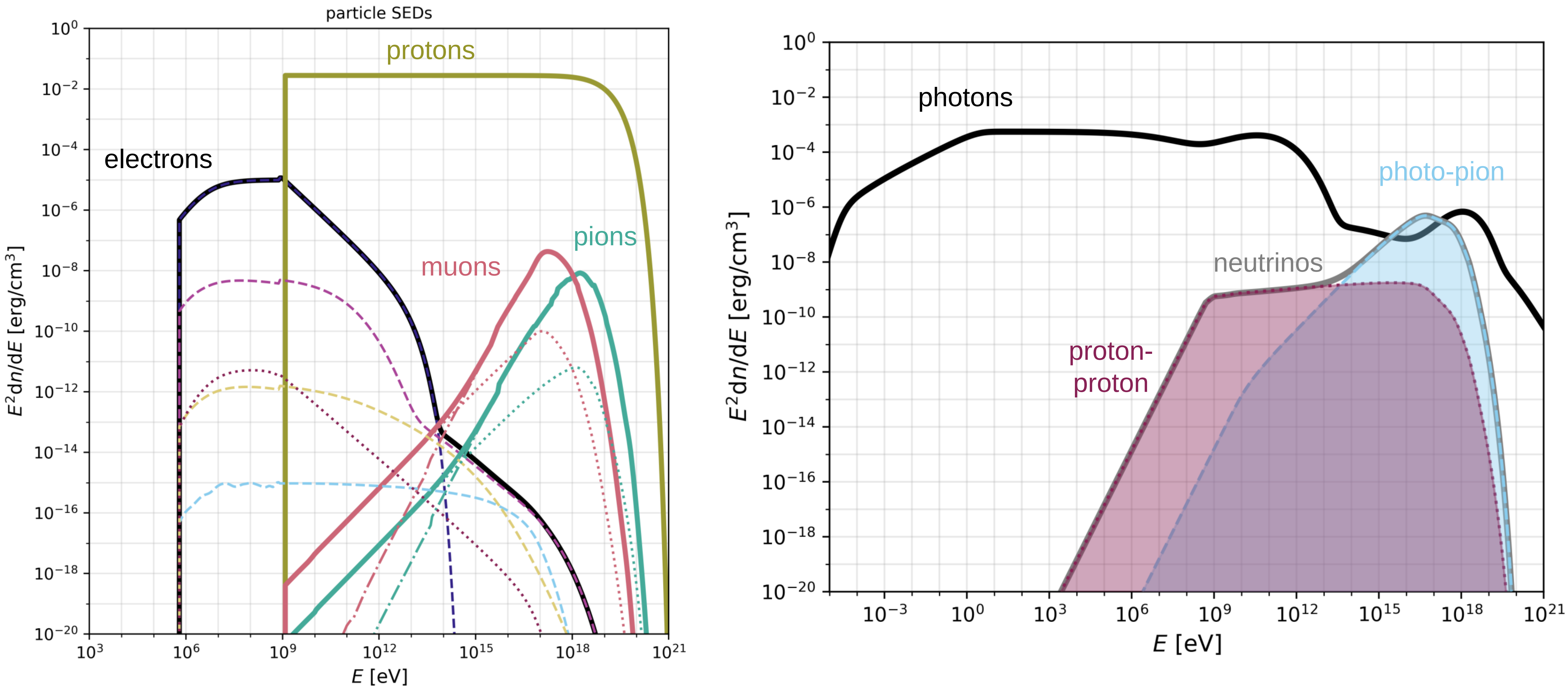


Trackable – proton-proton : $pp \rightarrow \pi \rightarrow \mu \rightarrow e^{\pm}$

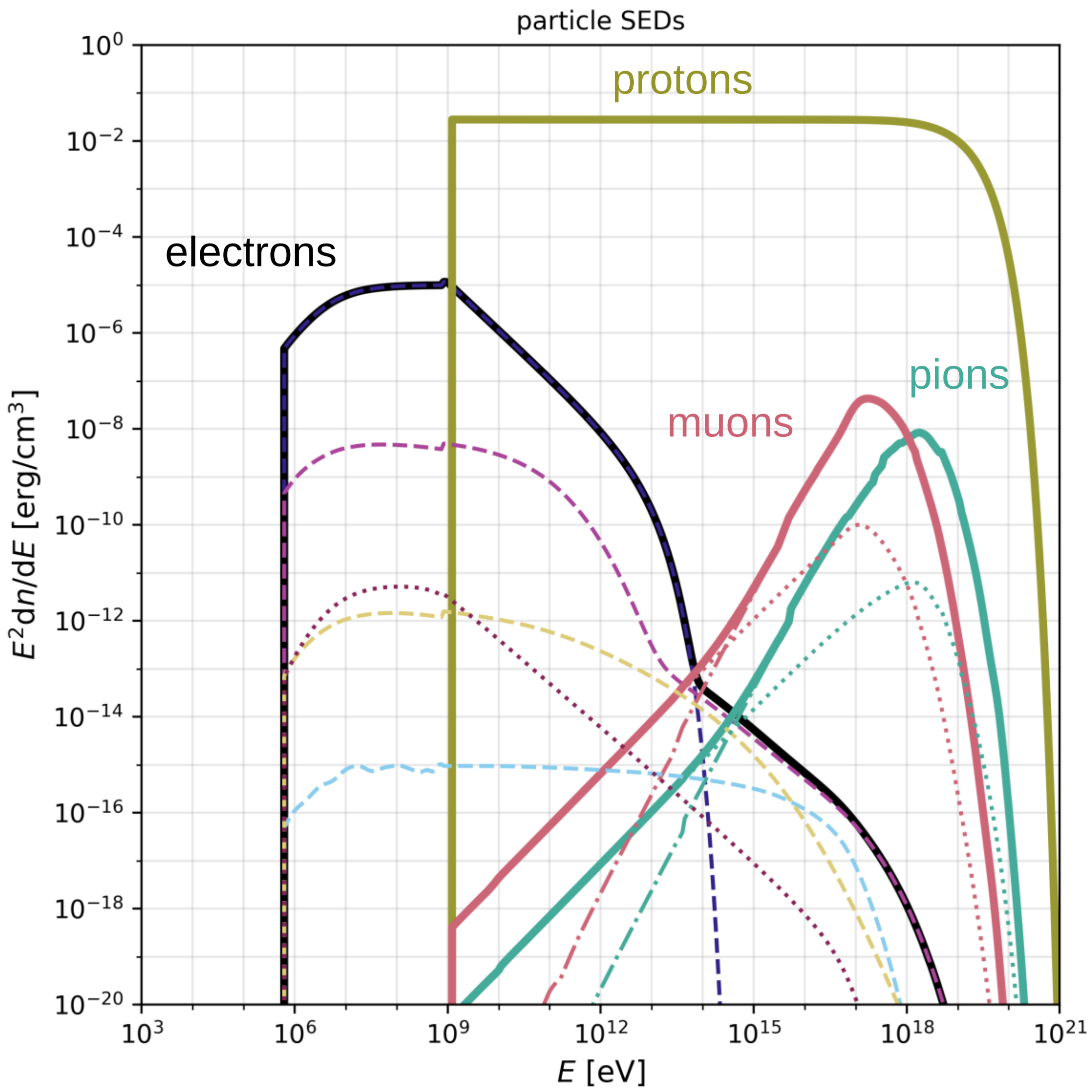


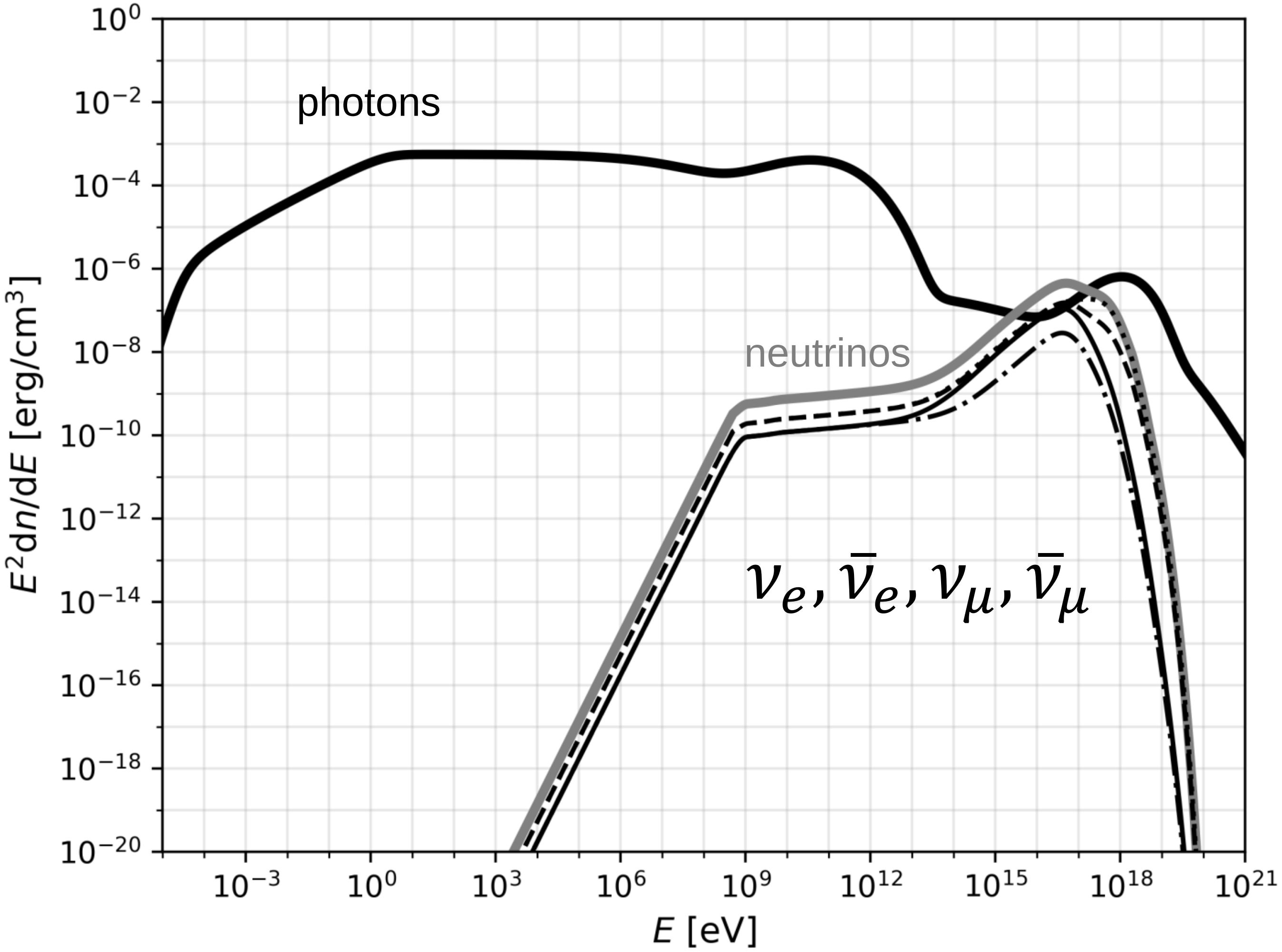


Trackable – neutrinos



Trackable – neutrino flavours





Now public!

arxiv:2312.13371

- paper with detailed summary of processes, solver, etc…

AM³: An Open-Source Tool for Time-Dependent Lepto-Hadronic Modeling of Astrophysical Sources

Marc Klinger,[1] Annika Rudolph,[2] Xavier Rodrigues,[3] Chengchao Yuan (袁成超),[1]
Gaëtan Fichet de Clairfontaine,[4] Anatoli Fedynitch,[5,6] Walter Winter,[1] Martin Pohl,[1,7] and Shan Gao[1,8]

[1] *Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*
[2] *Niels Bohr International Academy and DARK, Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100, Copenhagen, Denmark*
[3] *European Southern Observatory, Karl-Schwarzschild-Strae 2, 85748 Garching bei M ü nchen, Germany*
[4] *Julius-Maximilians-Universität Würzburg, Fakultät für Physik und Astronomie, Emil-Fischer-Str. 31, D-97074 Würzburg, Germany*
[5] *Institute of Physics, Academia Sinica, Taipei City, 11529, Taiwan*
[6] *Institute for Cosmic Ray Research, the University of Tokyo, 5-1-5 Kashiwa-no-ha, Kashiwa, Chiba, 277-8582, Japan*
[7] *Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam, Germany*
[8] *Sartorius Corporate Administration GmbH, Otto-Brenner-Strasse 20, 30379, Göttingen, Germany*

(Received; Revised; Accepted)

ABSTRACT

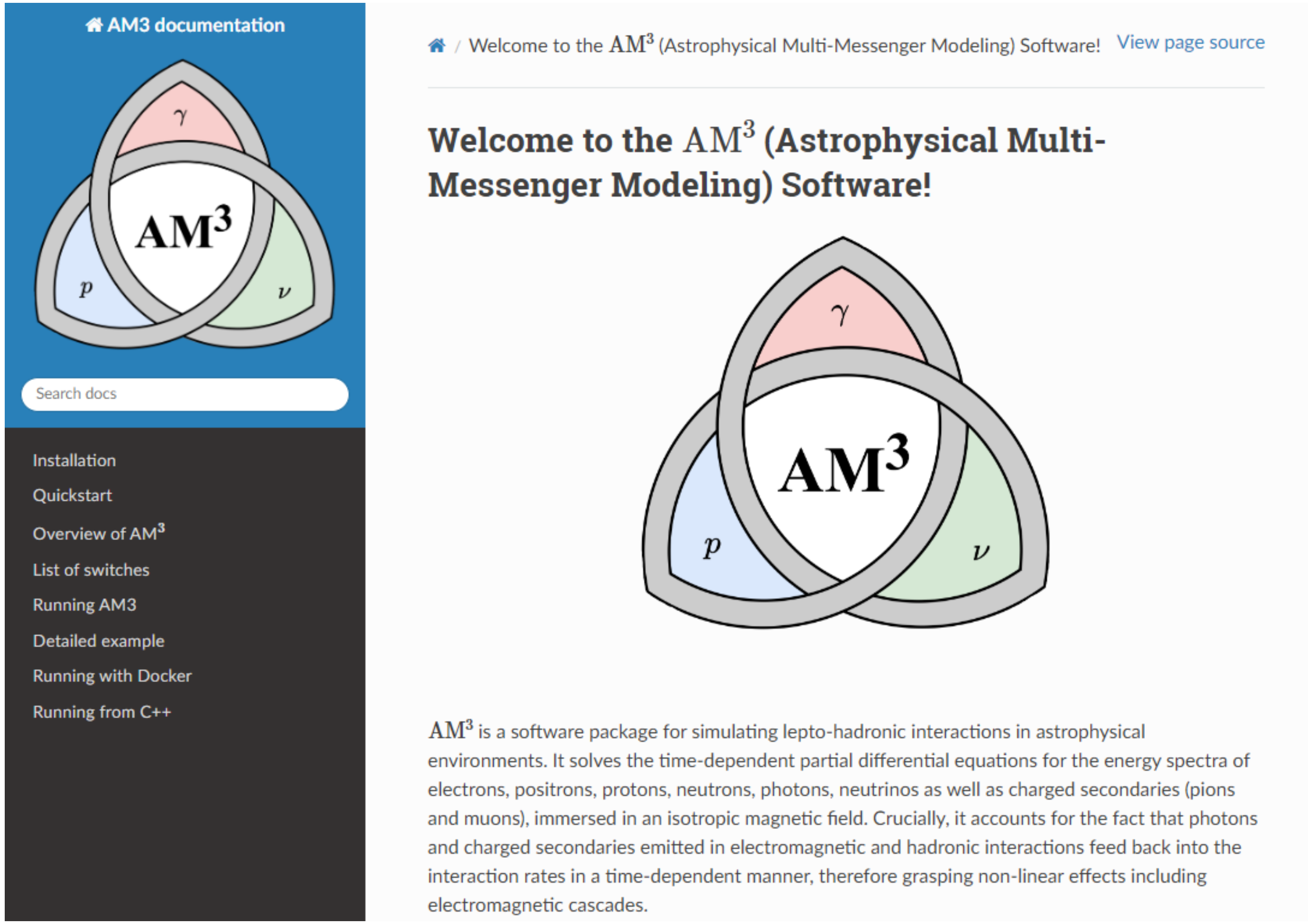
We present the AM³ ("Astrophysical Multi-Messenger Modeling") software, which has been successfully used in the past to simulate the multi-messenger emission, including neutrinos, from active galactic nuclei, including the blazar sub-class, gamma-ray bursts, and tidal disruption events. AM³ is a documented state-of-the-art open source software [a] that efficiently solves the coupled integro-differential equations for the spectral and temporal evolution of the relevant particle densities (photons, electrons, positrons, protons, neutrons, pions, muons, and neutrinos). AM³ includes all relevant non-thermal processes (synchrotron, inverse Compton scattering, photon-photon annihilation, proton-proton and proton-photon pion production, and photo-pair production). The software self-consistently calculates the full cascade of primary and secondary particles, outperforming simple test-particle approaches, and allows for non-linear feedback and predictions in the time domain. It also allows to track separately the contributions of different radiative processes to the overall photon and neutrino spectra, including the different hadronic interaction channels. With its efficient hybrid solver combining analytical and numerical techniques, AM³ combines efficiency and accuracy at a user-adjustable level. We describe the technical details of the numerical framework and present examples of applications to various astrophysical environments.

Keywords: numerical methods — neutrino astronomy — gamma-ray astronomy — radiative processes

Now public!

https://am3.readthedocs.io/en/latest/

- paper with detailed summary of processes, solver, etc…
- documentation with examples in C++ and python



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contact-am3@desy.de

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- source code public on GitLab and maintained by AM³ team

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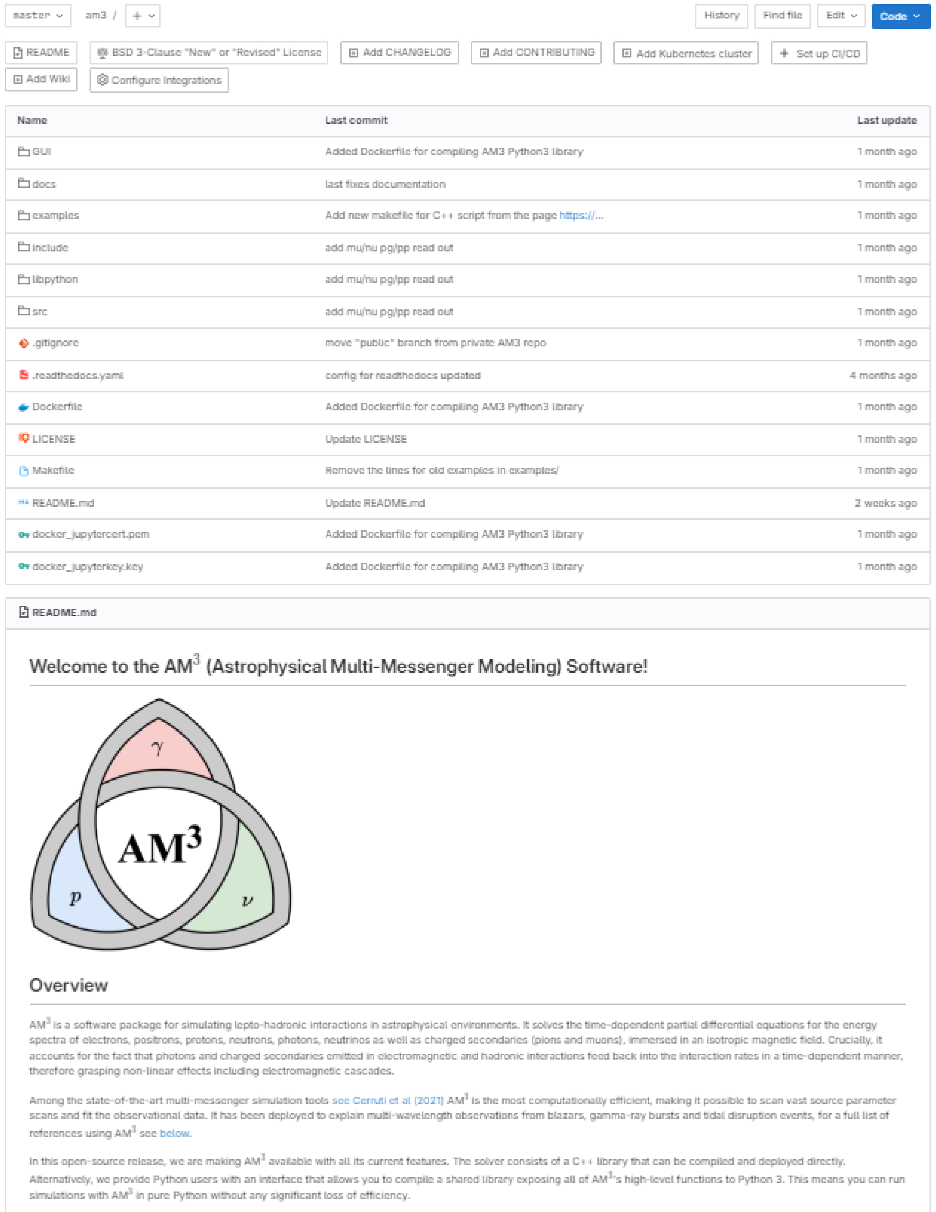

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- collaborators welcome!
- C++ AND python3 (same user interface names)
- Docker

Tested

- Blazars → see talks by Anastasiia, Sara and Xavier
- TDEs → see Chengchao's talk
- GRB prompt emission → see Željka's talk
- GRB afterglows → now


DESY, Science Communication Lab

Gamma-Ray Burst Afterglows

with Chengchao Yuan, Andrew Taylor, Walter Winter

and AM³

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

HELMHOLTZ

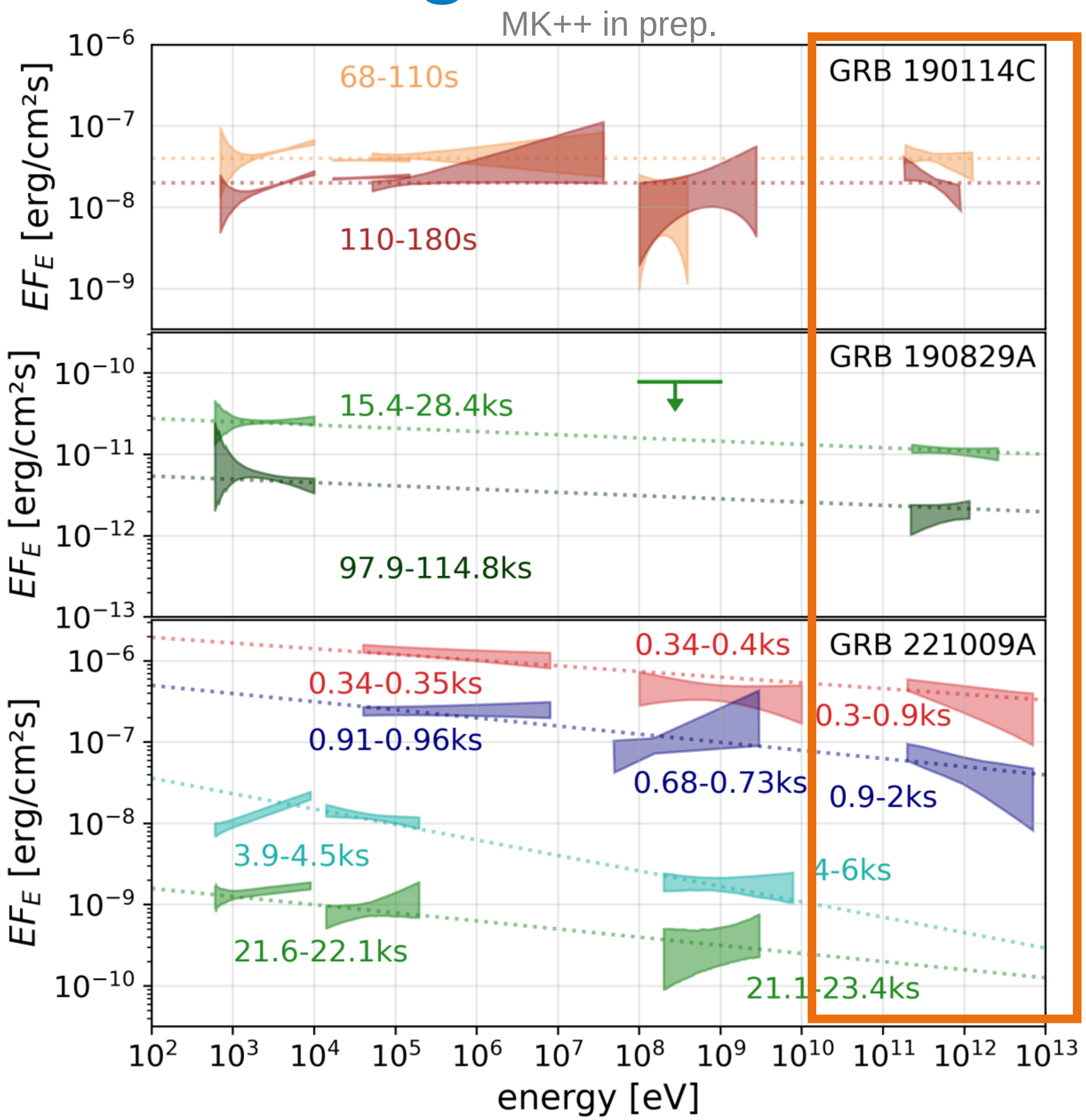
DESY.

Why to care about GRBs?

- **non-thermal particle acceleration** at **shocks**
- **relativistic** realisation: afterglow of a gamma-ray burst
- **observational handle: mainly photon spectra**
- connection of observed photon spectra to underlying physics based on **many assumptions** → room for improvement
- new observational window at VHE

→ crisis (= we can learn something new!)

GRB afterglows detected at VHE!



→ **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)
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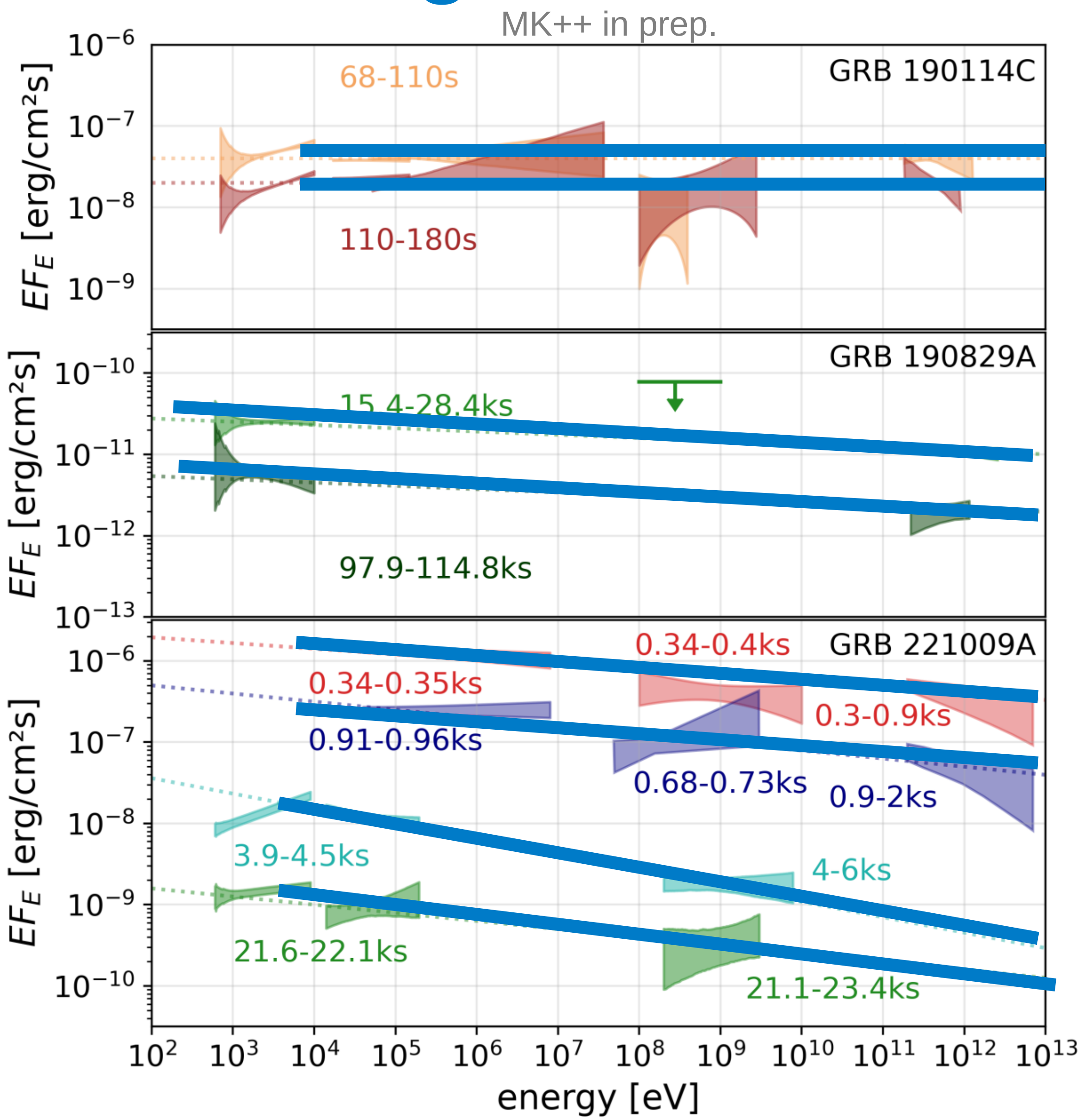

→ MAGIC

→ H.E.S.S.

→ LHAASO

- **single component?**
- **flat power-law spectra extending up to >TeV**

data from:
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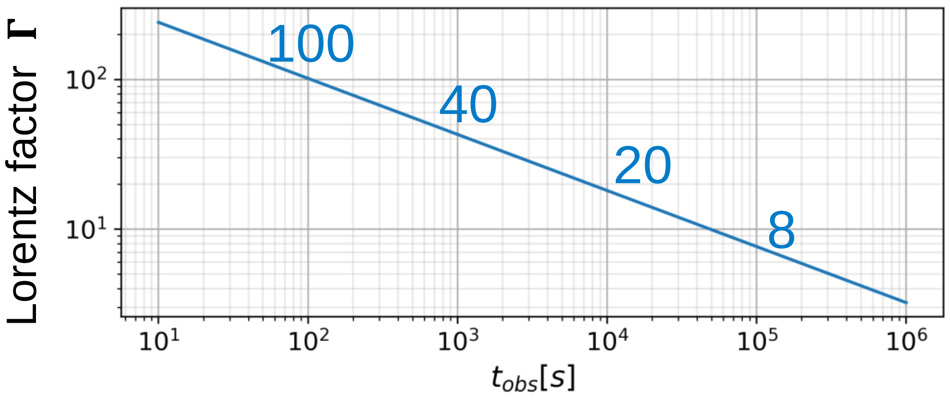
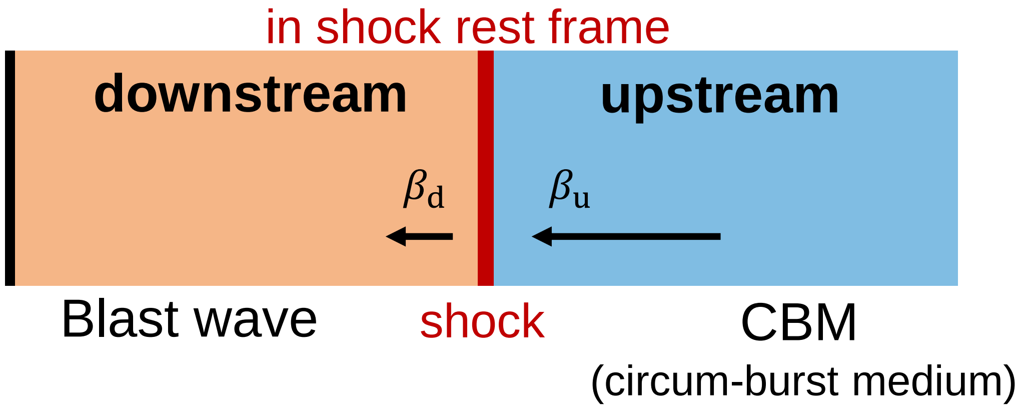
Afterglows: Radiation from a relativistic shock

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



Blandford & McKee 1976



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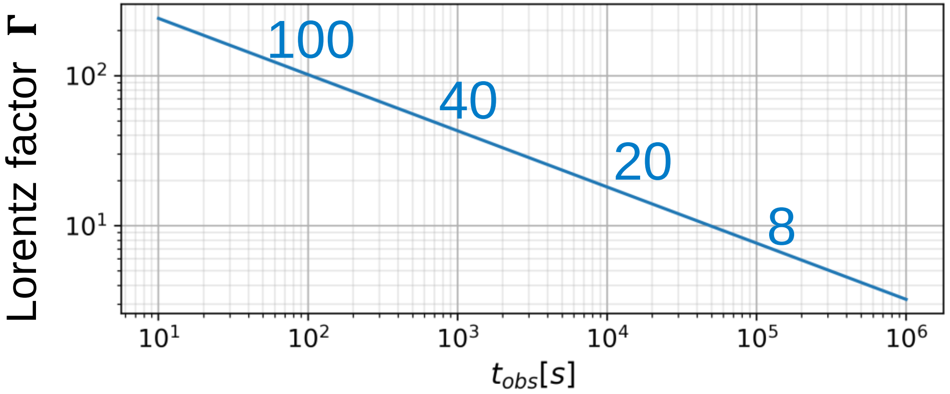

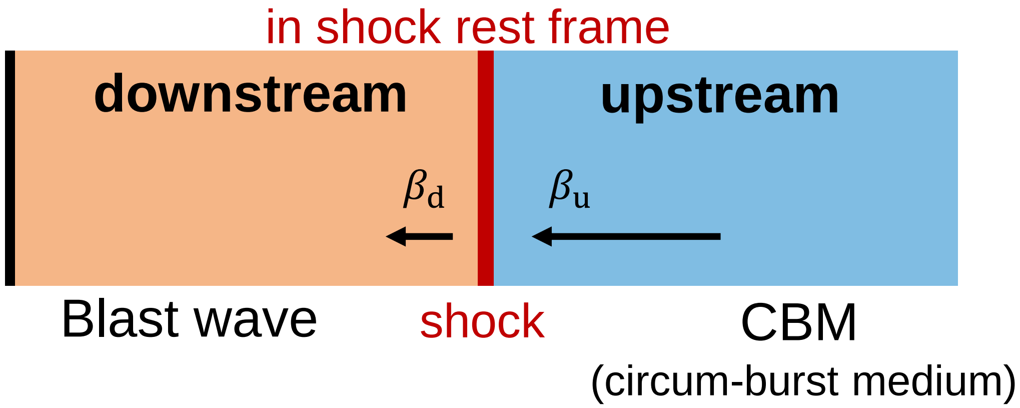

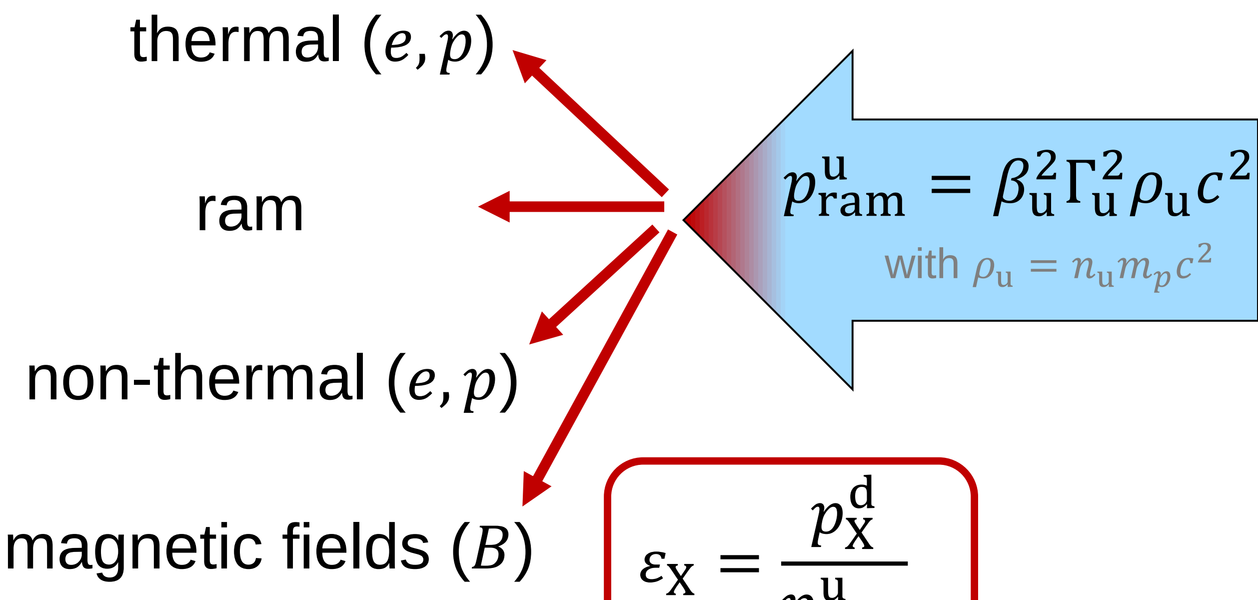

$$\varepsilon_{\mathrm{X}} = \frac{p_{\mathrm{X}}^{\mathrm{d}}}{p_{\mathrm{ram}}^{\mathrm{u}}}$$

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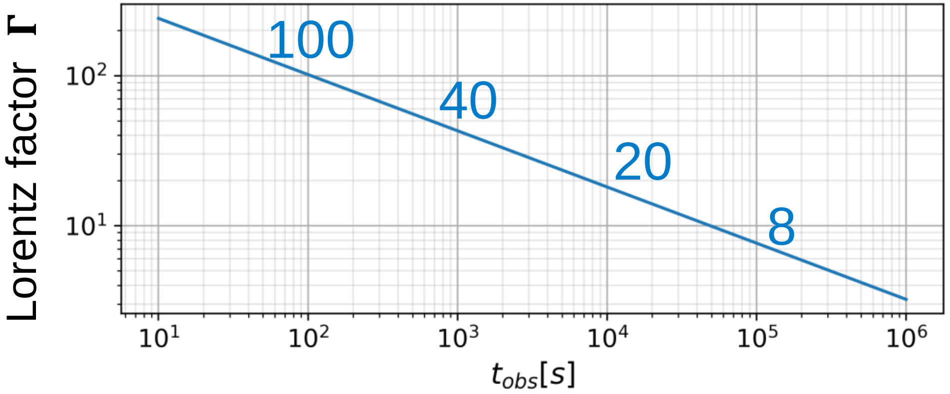
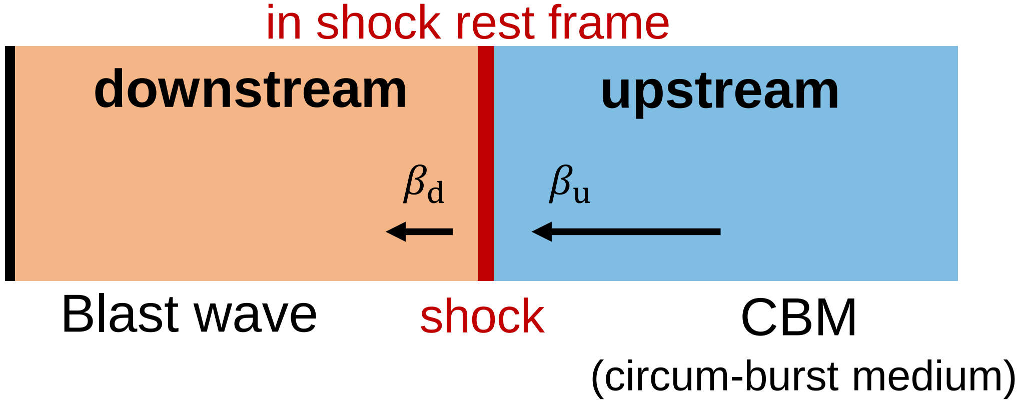
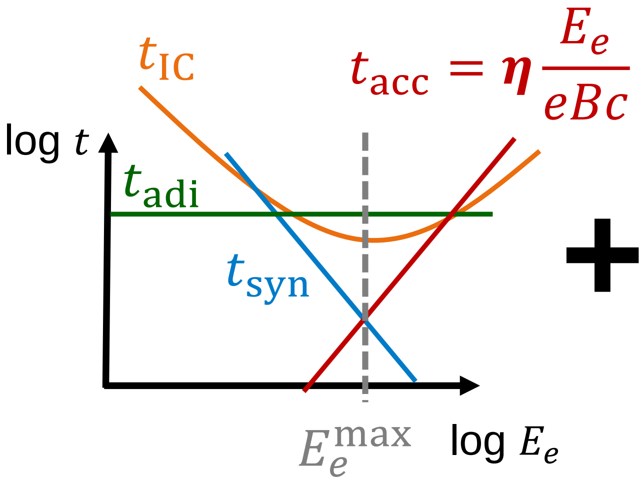
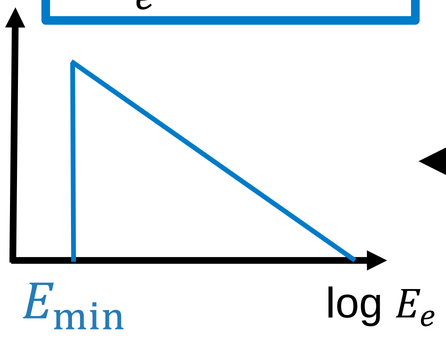


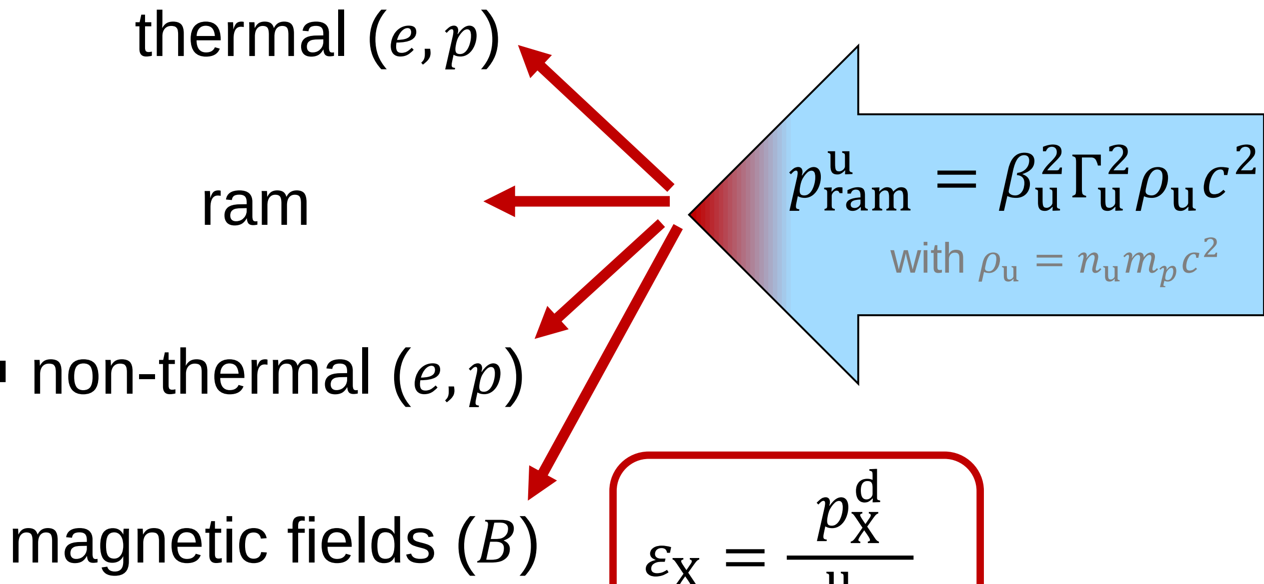




+

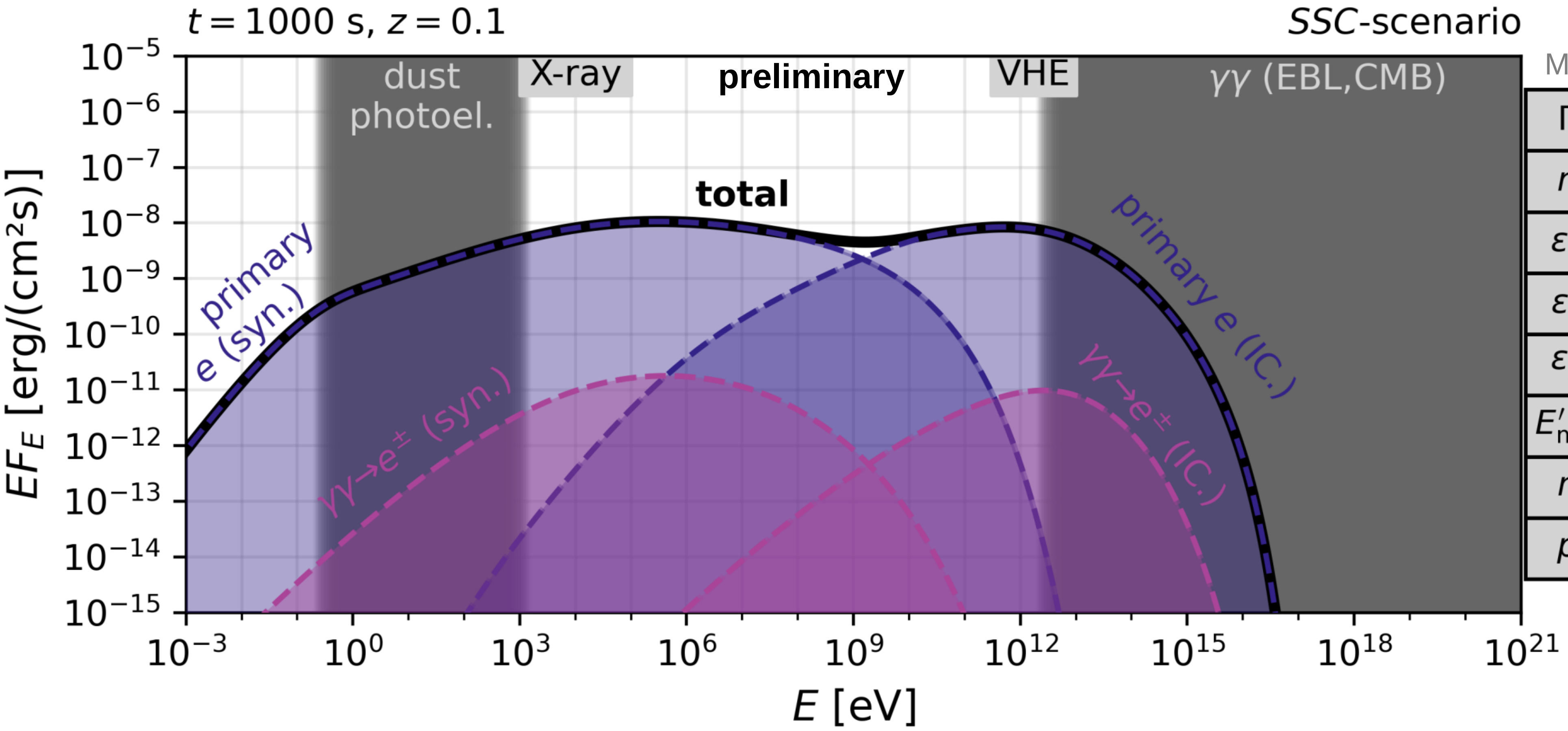
$$\frac{{\rm d}n_e}{{\rm d}E_e{\rm d}t} \propto E_e^{-p_e}$$





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

Synchrotron Self-Compton (SSC) scenario



MK++ in prep.

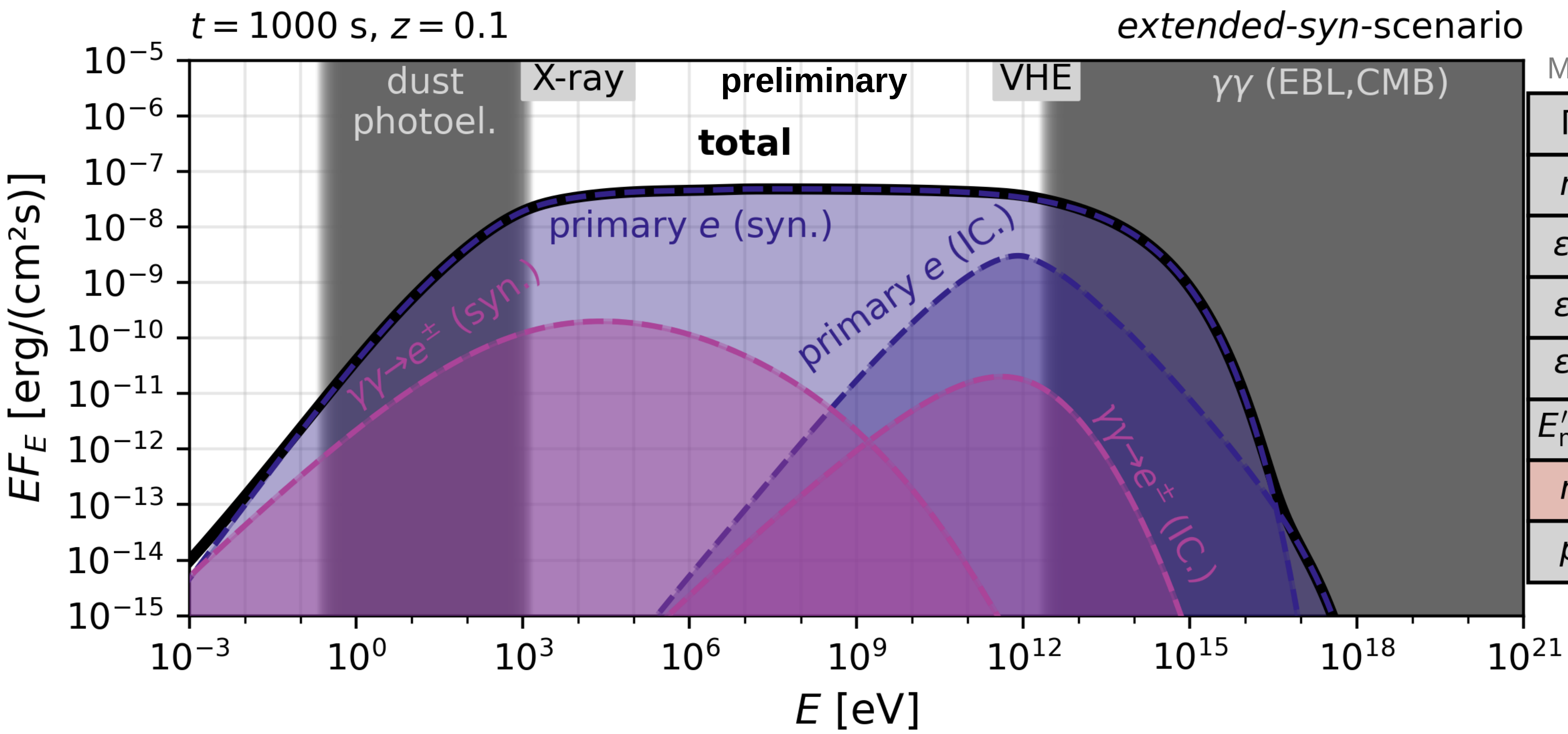
Γ	50
n	1
ε_B	10^{-4}
ε_e	$10^{-1.5}$
ε_p	0
E'_{min}	$10^{9.0}$
η	1
p	2.3

time dependent modeling with AM³!

Problem: Klein-Nishina suppression tricky!

(1) slope at VHE very soft (2) parameter fine tuning to get peaks at ~ same height

Extended synchrotron scenario



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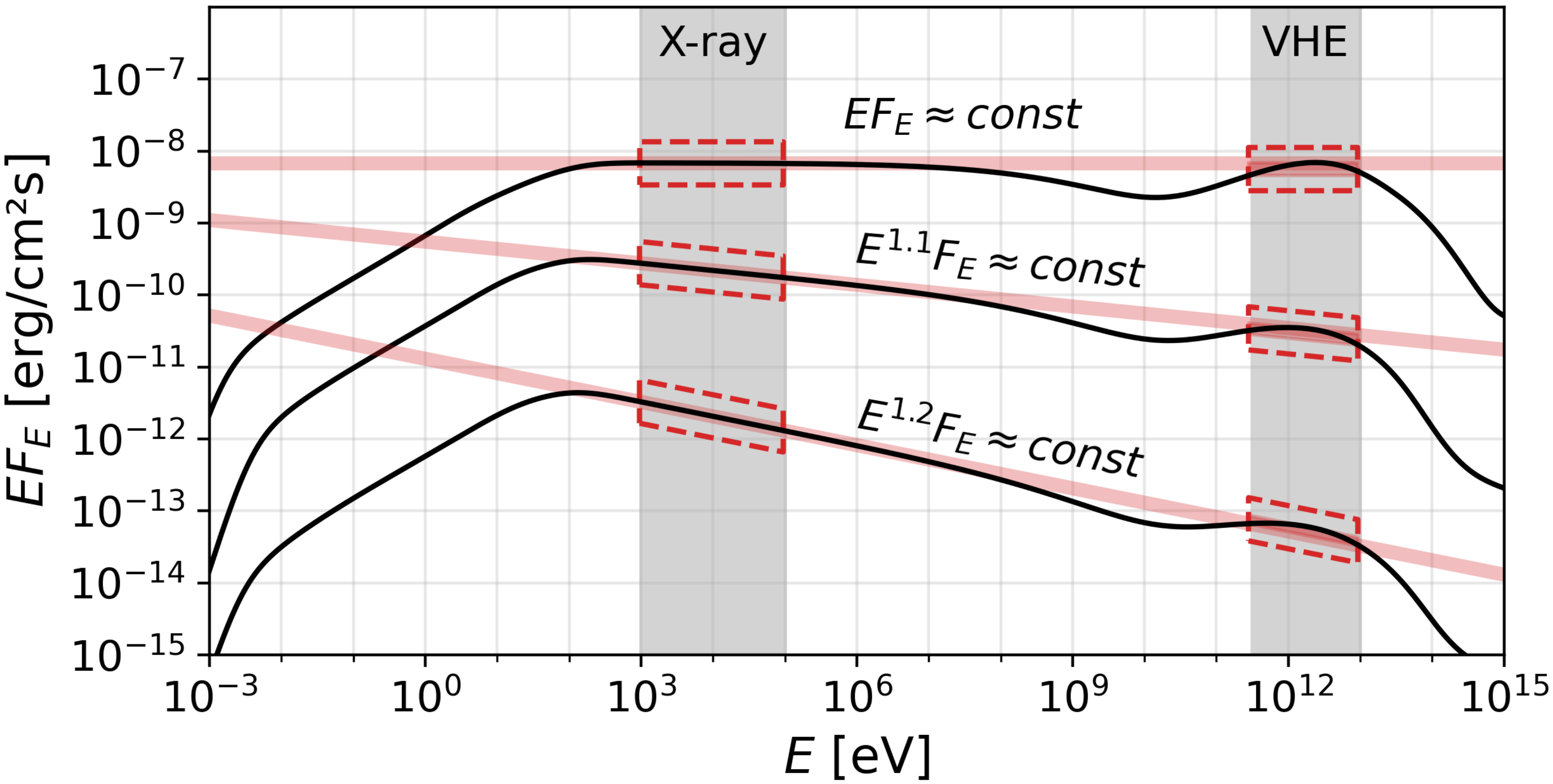
ε_e	$10^{-1.5}$
ε_p	0
E'_{min}	$10^{10.5}$
η	10^{-4}
p	2

Problem: how to explain $\eta \ll 1$?

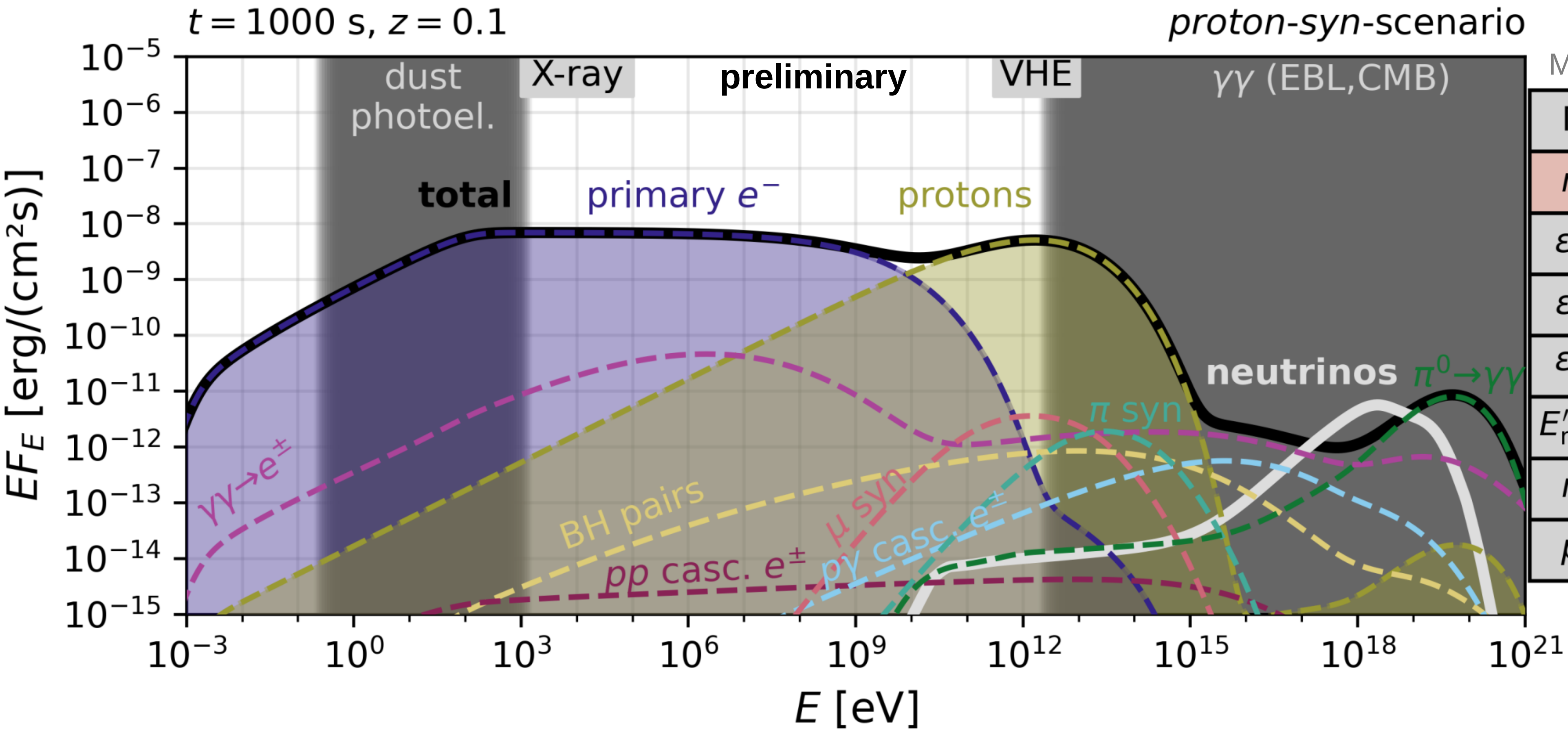
time dependent modeling with AM³!

Scan for flat scenarios

MK++ in prep.



Proton synchrotron scenario



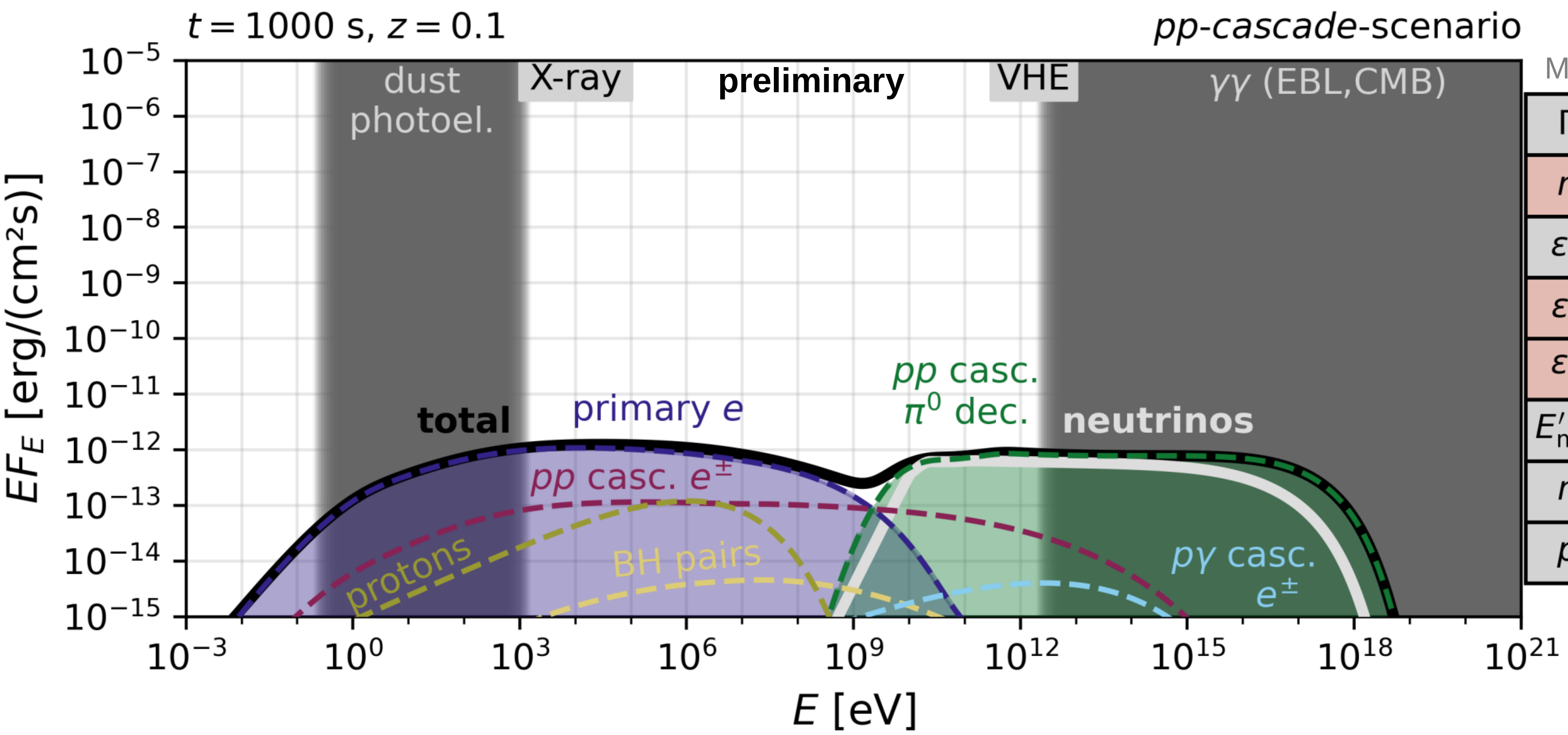
MK++ in prep.

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

Problem: proton synchrotron component at exponential cut-off!

time dependent modeling with AM³!

pp-cascade scenario



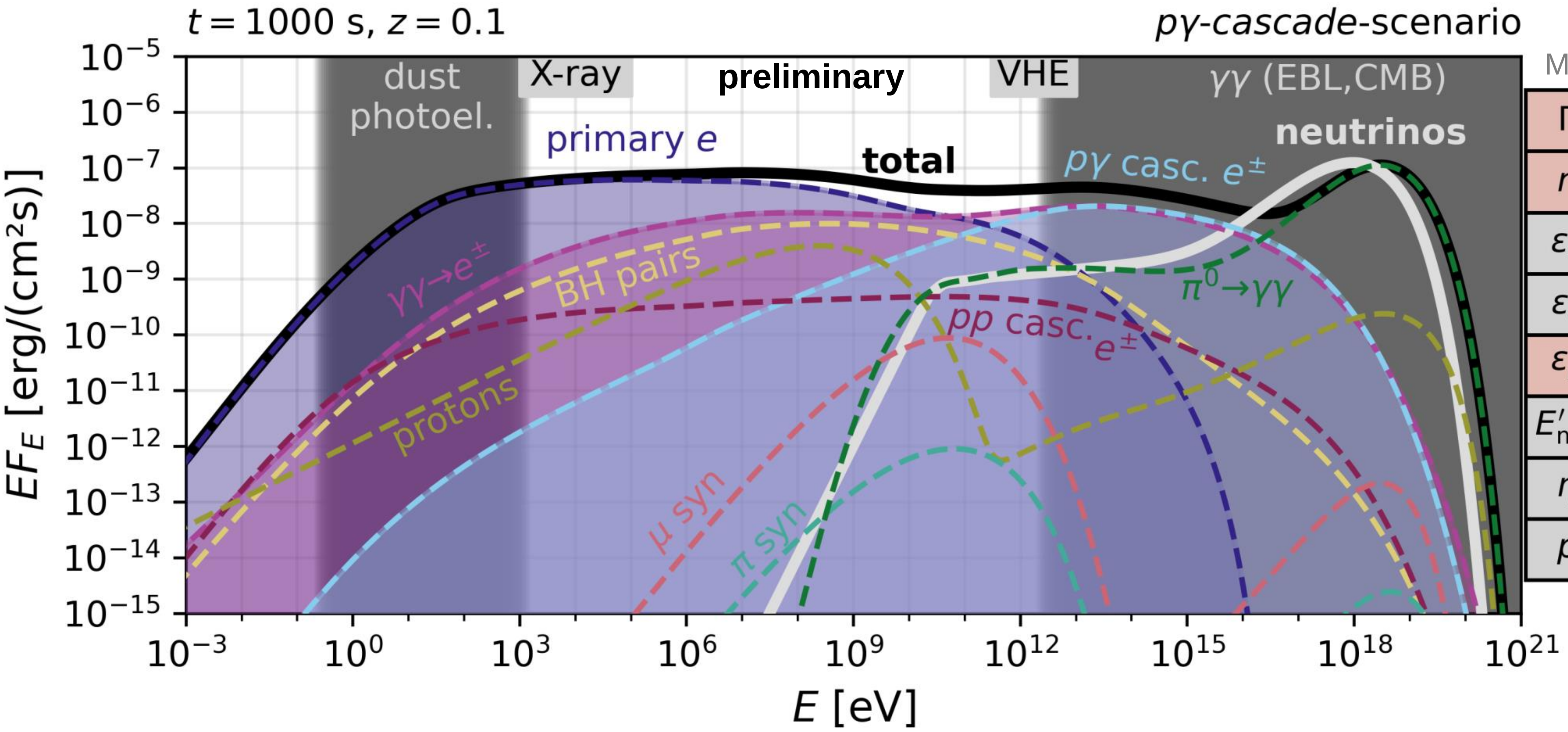
MK++ in prep.

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
p	2.1

time dependent modeling with AM³!

Not very bright, high densities, extreme baryonic loading, **but flat!**

$p\gamma$-cascade scenario



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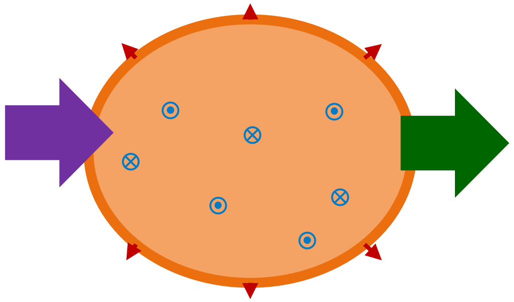
time dependent modeling with AM³!

Extreme energy requirements!

Summary

AM^3 - public!



- solve transport equations - time dependent!
- for protons, electrons, photons
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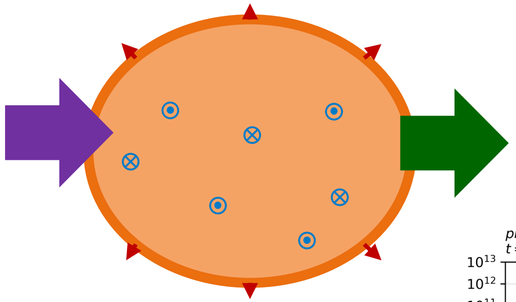

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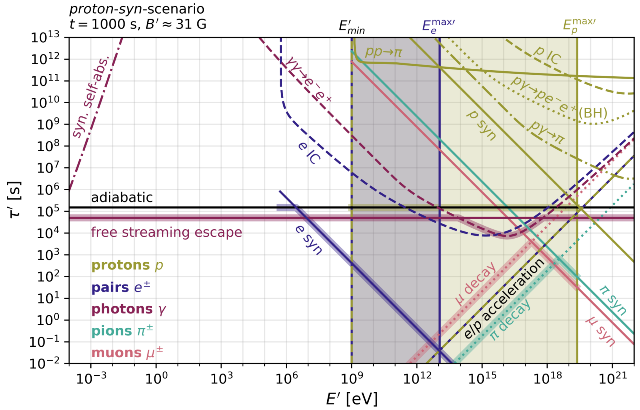

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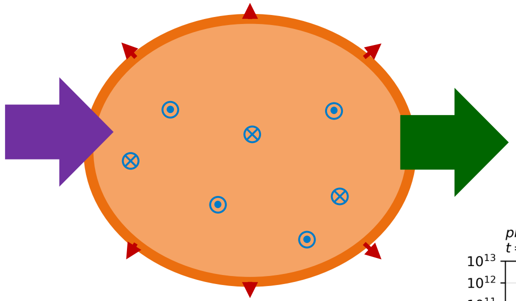

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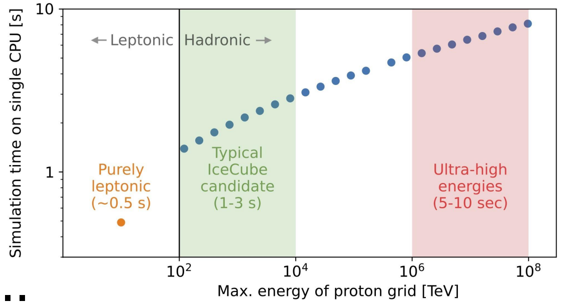

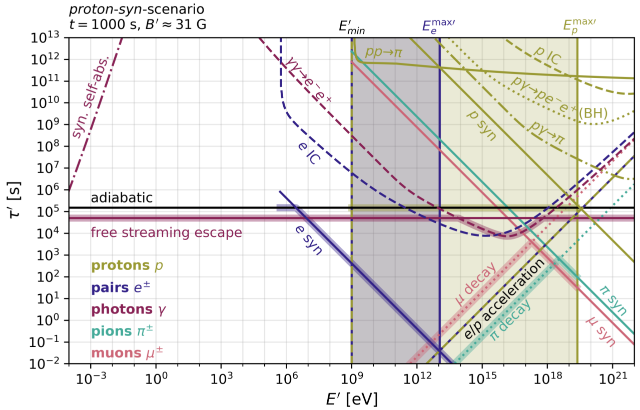

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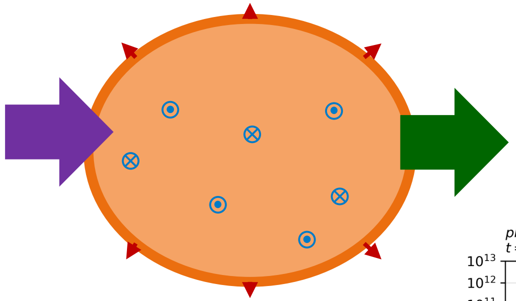

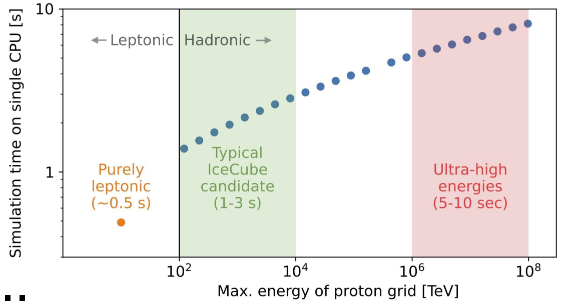

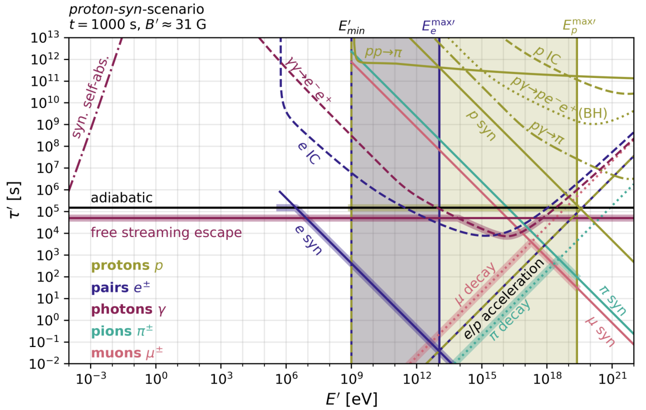

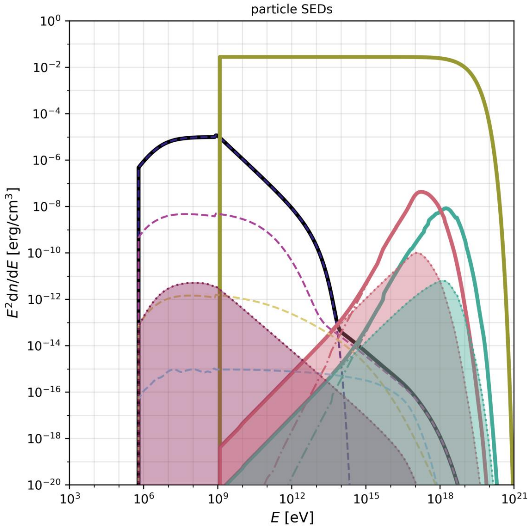

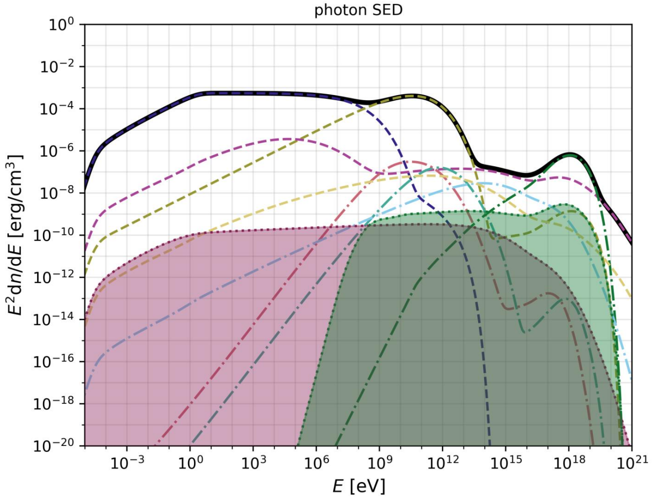

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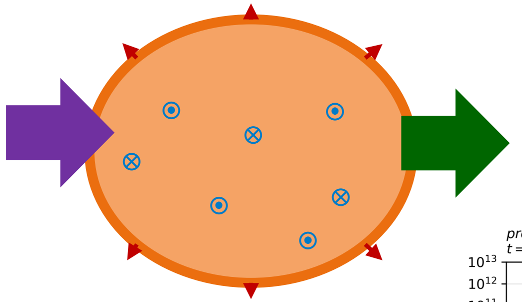

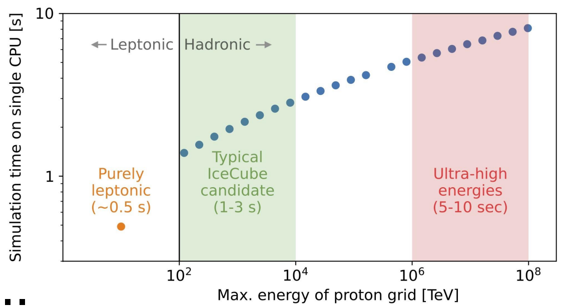

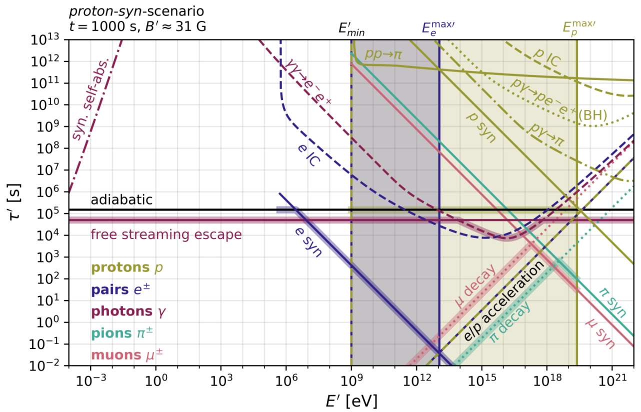

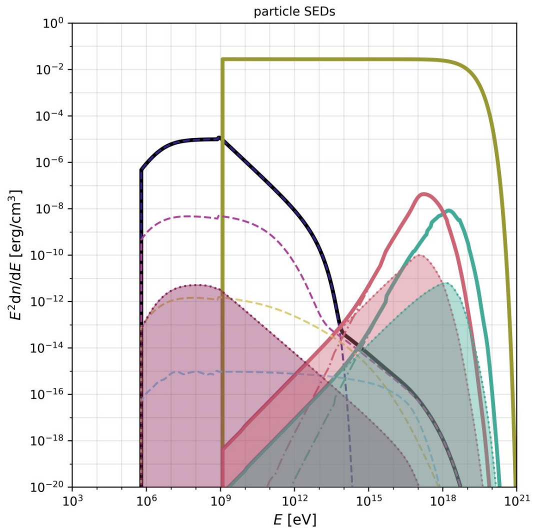

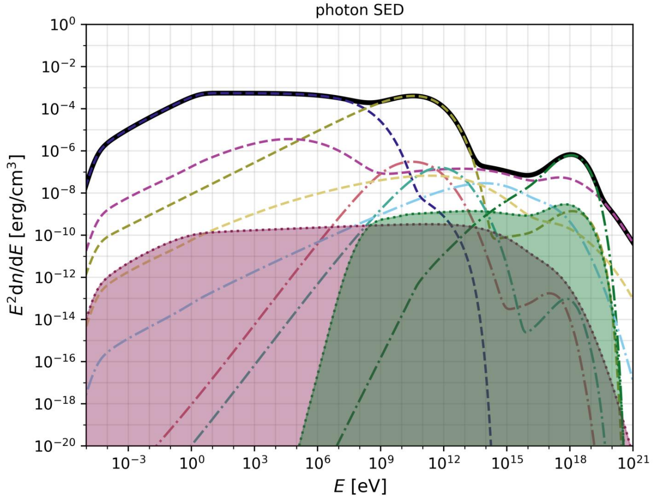

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GRB afterglows

- VHE detection of GRB afterglows creates crisis for *standard* SSC model

  → chance to learn something new!
- alternative single zone scenarios:

  → extended synchrotron (probably rather multi-zone)

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- no perfect fit found yet!

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Thank you!

Backup

Estimating the time scales / source terms

process: $a \to b$ (e.g. synchrotron)

convolution | radiation kernel

$$Q_{a\to b}(E_b,t) = \int \mathrm{dln}E_a n_a(E_a)\, R_{a\to b}(E_a,E_b)$$

convolution | radiation kernel

$$\alpha_{a\to b}(E_a,t) = \int \mathrm{dln}E_b n_b(E_b)\, R_{a\to b}(E_a,E_b)$$

process: $a + b \to c + d$ (e.g. inverse Compton)

convolution | convolution

$$Q_{a,b\to c}(E_c,t) = \int \mathrm{dln}E_a n_a(E_a) \int \mathrm{dln}E_b n_b(E_b)\, R_{a,b\to c}(E_a,E_b,E_c)$$

$$R_{a,b\to c}(E_a,E_b,E_c) = \frac{c}{2}\int \mathrm{d}\mu\,(1-\mu)\,\frac{\mathrm{d}\sigma_{a,b\to c}}{\mathrm{d}E_c\mathrm{d}\mu}(E_a,E_b,E_c,\mu)$$

radiation kernel | angle average | cross section

convolution | convolution

$$\alpha_{a,b\to c}(E_a,t) = \int \mathrm{dln}E_c n_c(E_c) \int \mathrm{dln}E_b n_b(E_b)\, R_{a,b\to c}(E_a,E_b,E_c)$$

Fireball model: Long GRB

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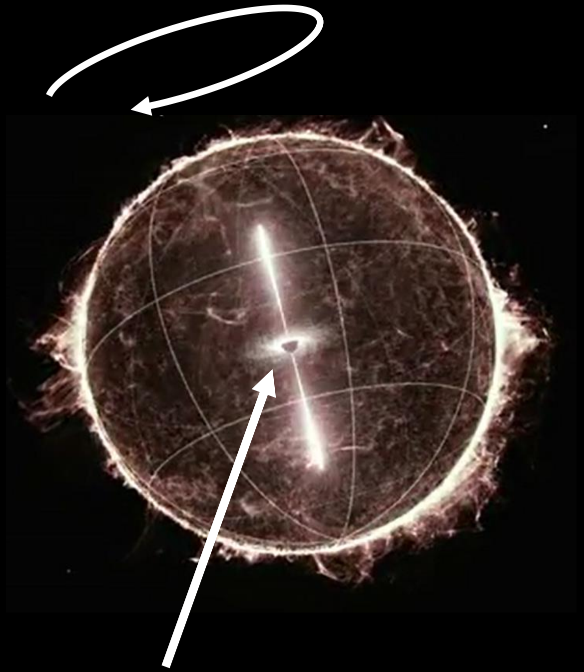
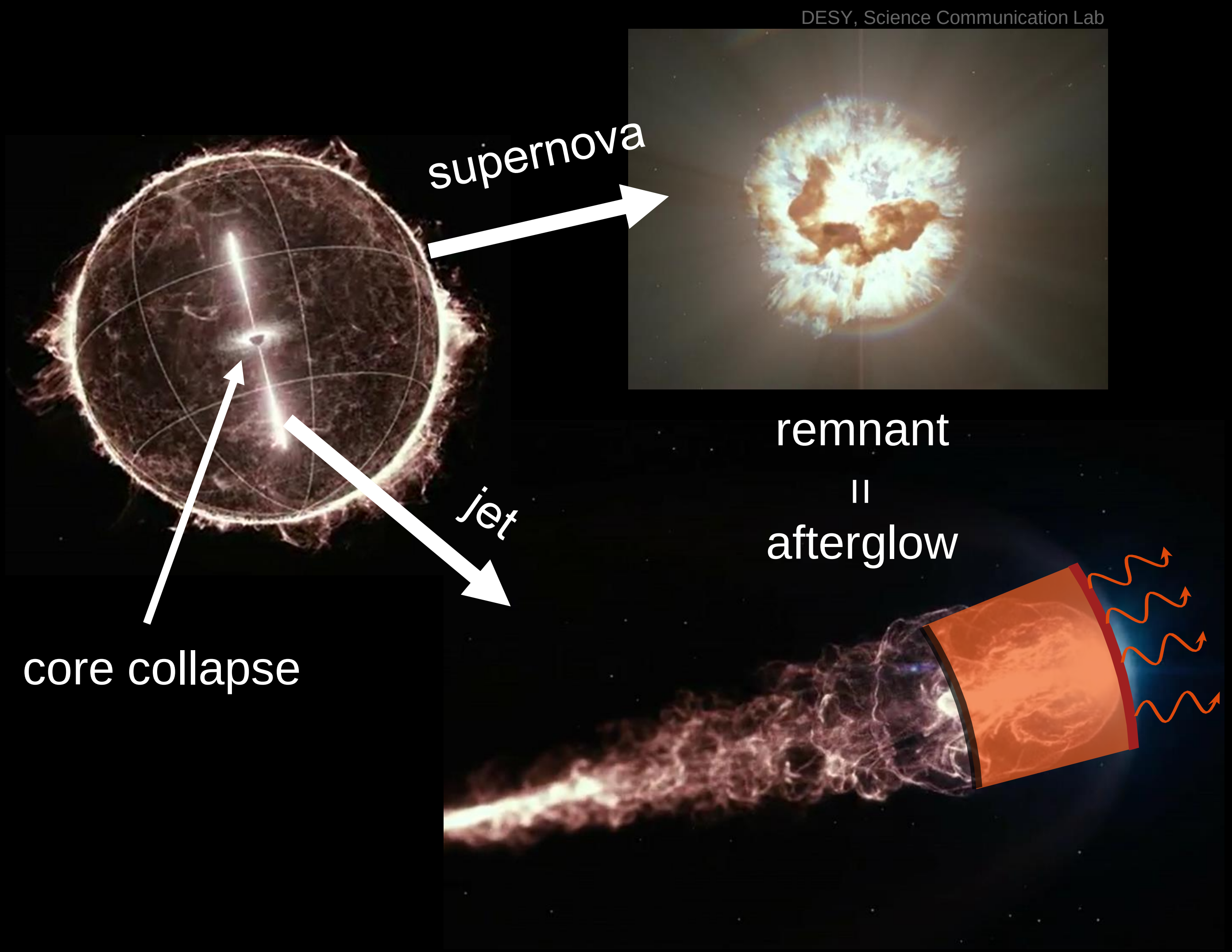
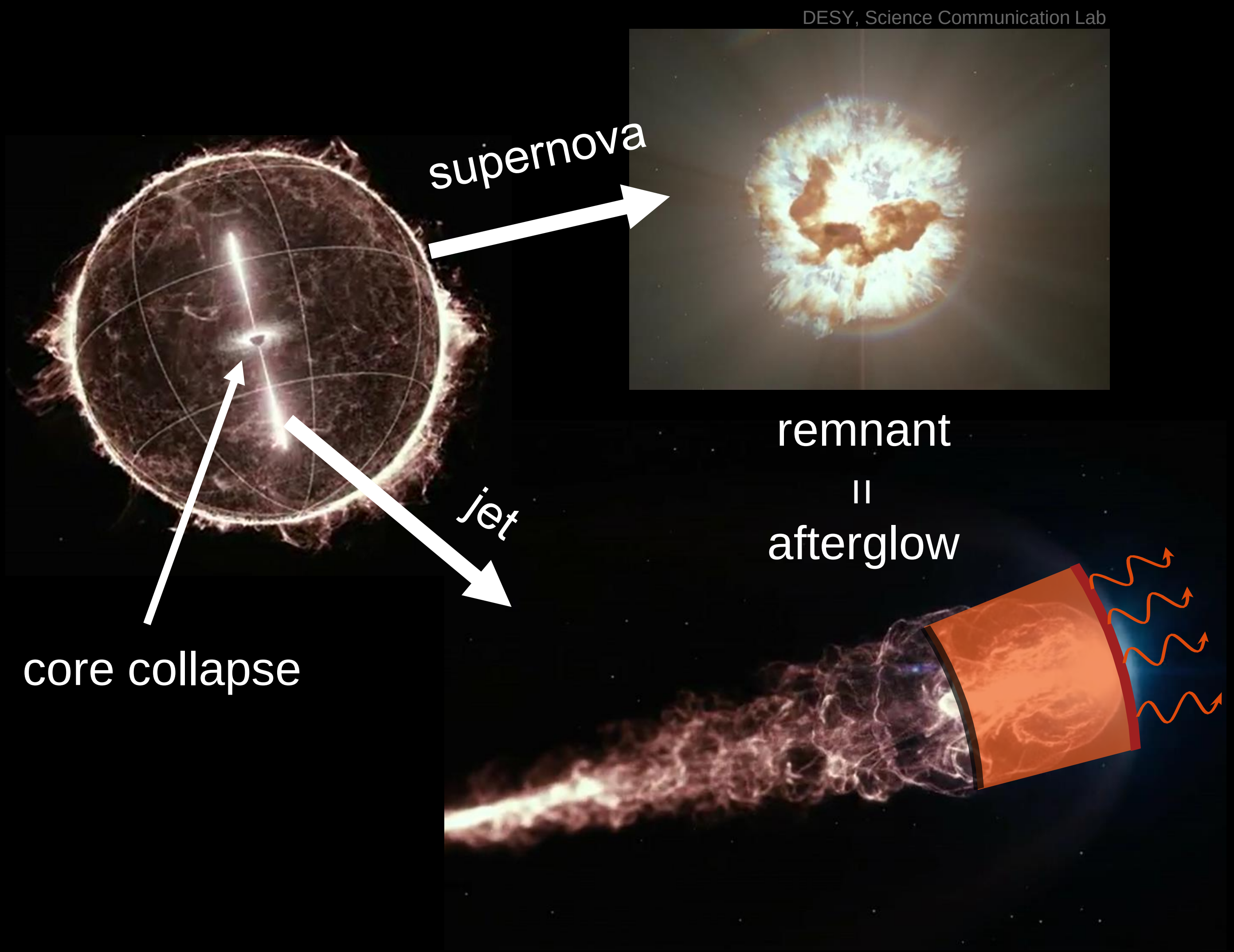


core collapse

Fireball model: Long GRB

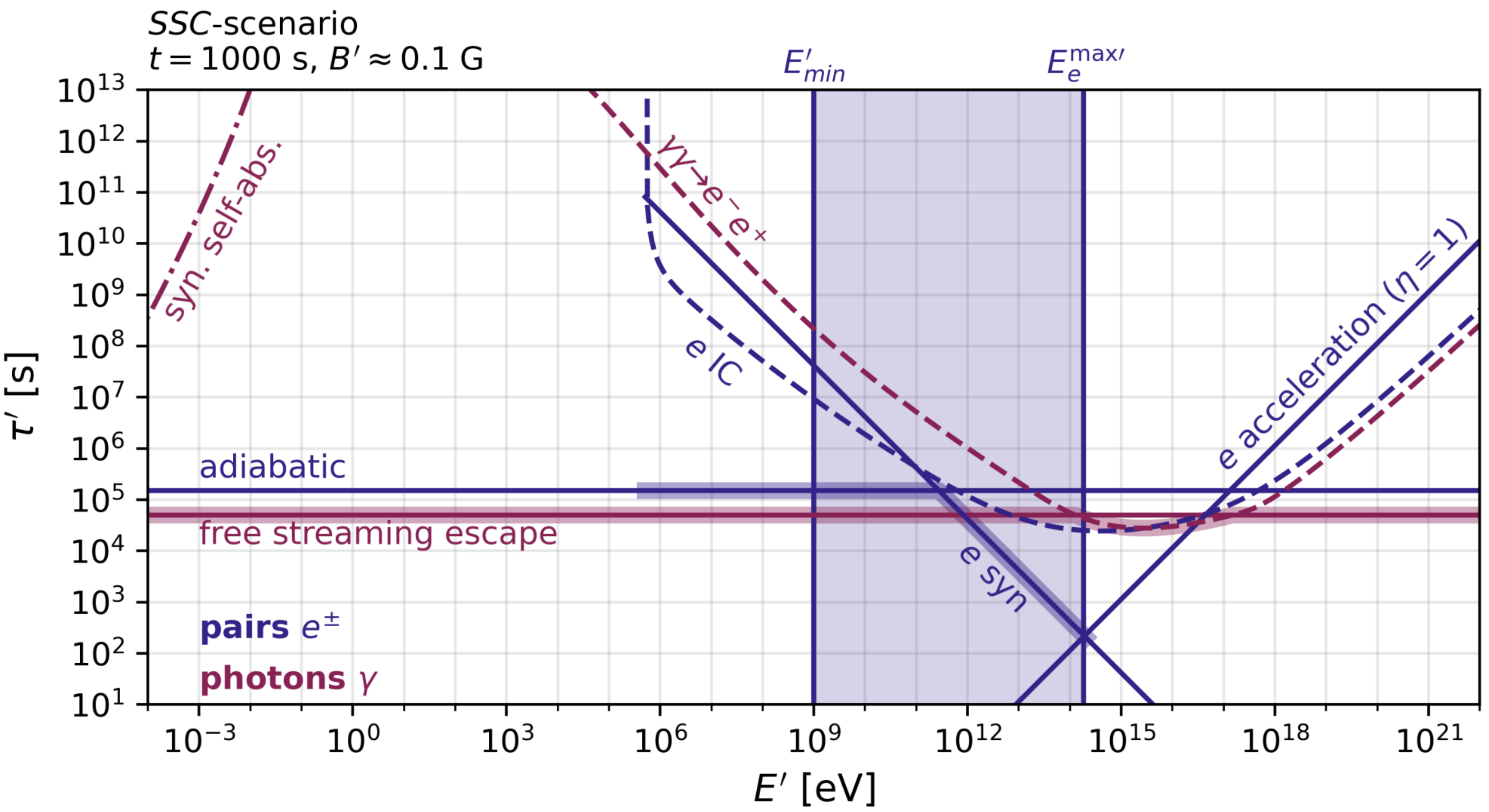


Fireball model: Long GRB

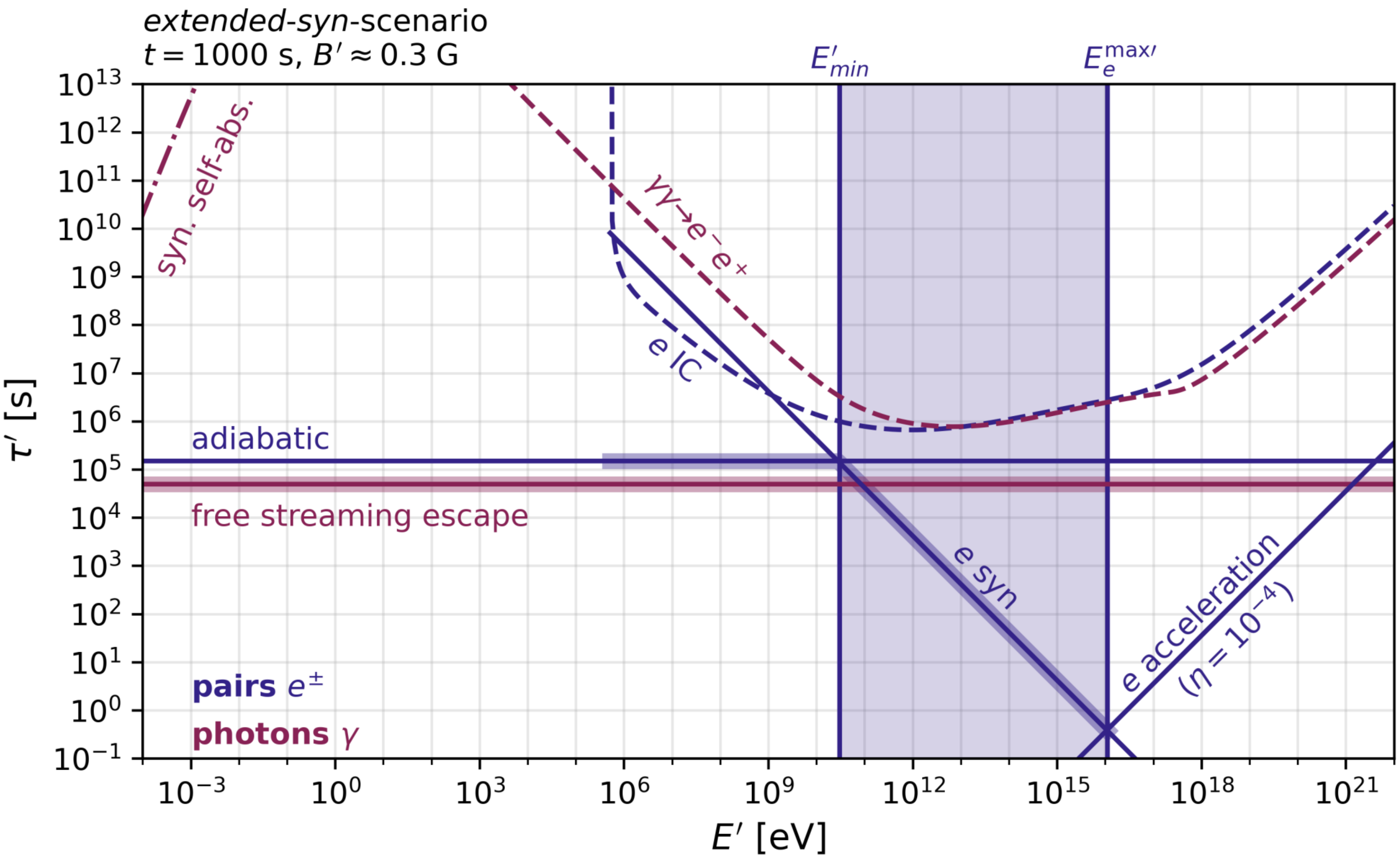


- Lorentz factors up to few 100
  → relativistic compression
- Quasi isotropic outflow
- Energetics:
  → observed up to: $E_{\mathrm{iso}} \sim 10^{55}\,\mathrm{erg}$
  → $E_{\mathrm{tot}} = \frac{\Omega}{4\pi} E_{\mathrm{iso}} \sim 10^{51}\,\mathrm{erg}$
  → comparable to SN !
- efficient converters of kinetic energy to radiation

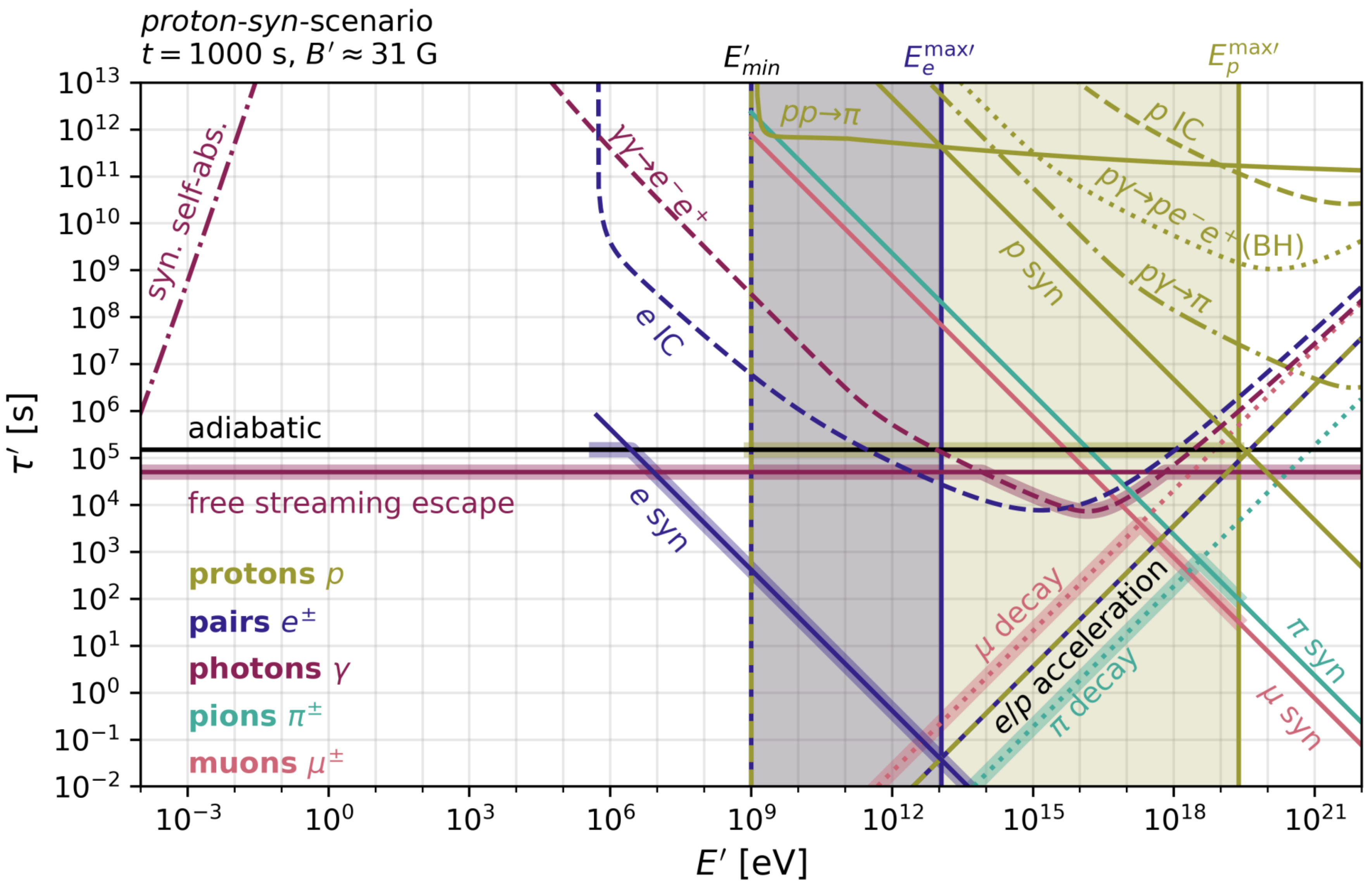
Time scales: SSC



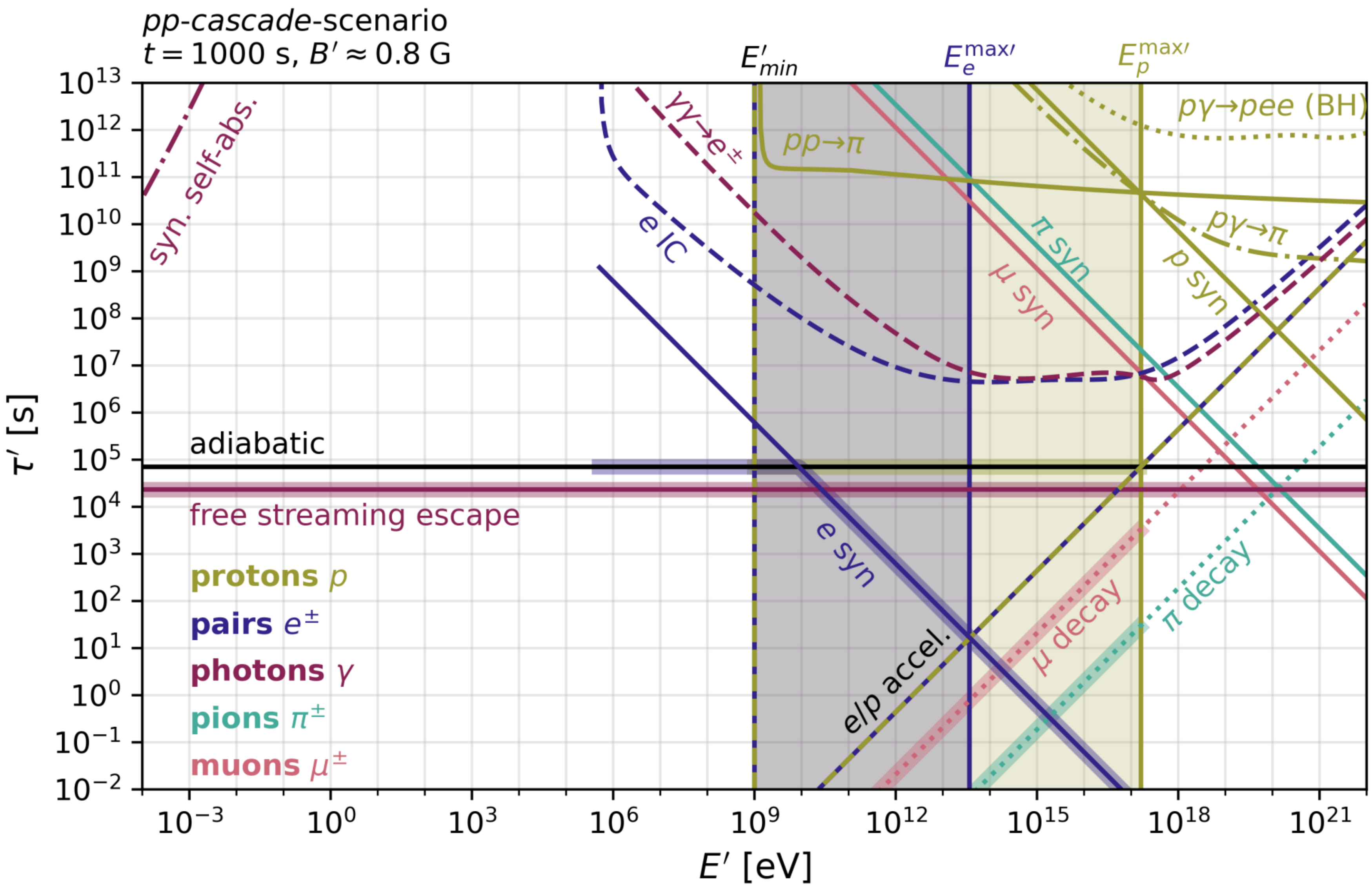
Time scales: extended synchrotron



Time scales: proton synchrotron



Time scales: pp-cascade



Time scales: $p\gamma$-cascade