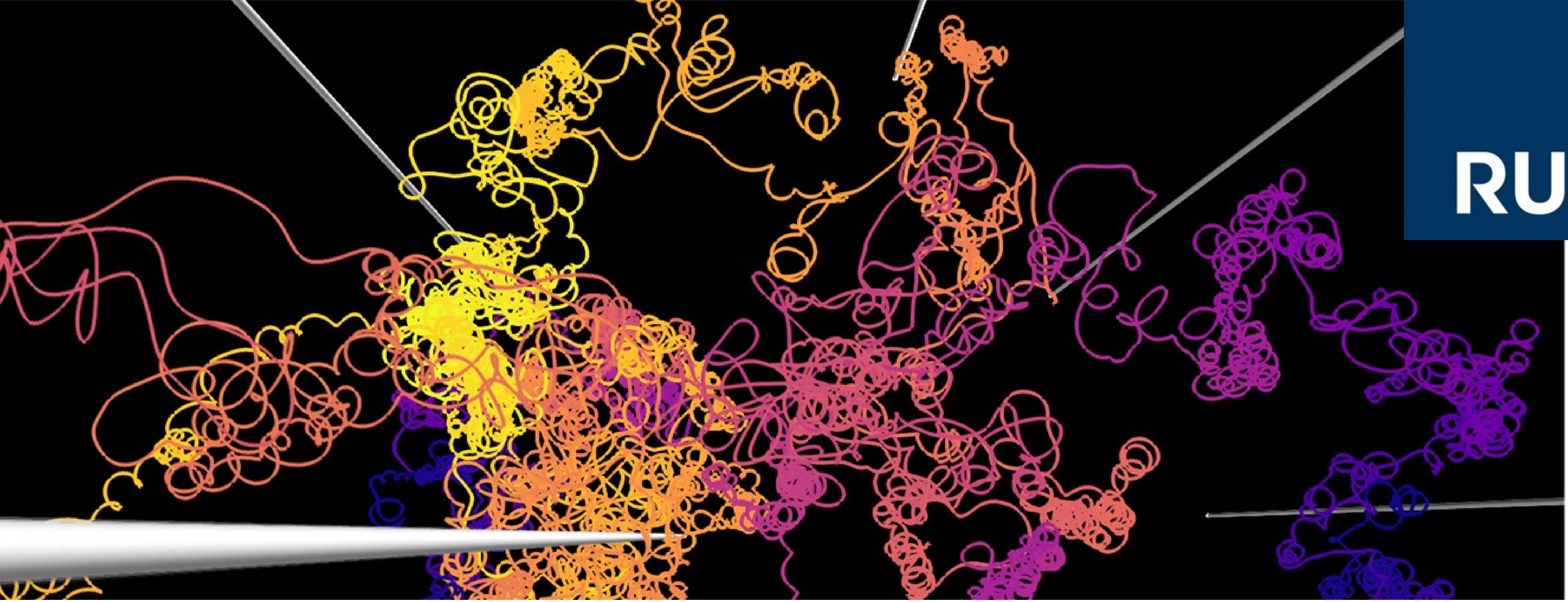

Transport of Heavy Cosmic Rays in Evolving Astrophysical Environments

Leptohadronic Propagation Codes|27.02.2023

L. Merten*, A. Reimer, P. Da Vela, M. Boughelilba, J.P. Lundquist, S. Vorobiov

Contents

Instead of an introduction…

Basics

- Principles and Assumptions of a „Matrix-Multiplication“ Code
- CR-ENTREES – first glimpse of an upcoming public version

Heavy Nuclei Extension

- Basic Ideas and Structure
- Modular Code in Python

Examples and Testing

- Plots to trigger further discussion

Summary and Outlook

- What‘s missing?
- What‘s coming next?

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Basics

Energy Transport Code

- **Main goal**: Efficient calculation of spectra → Discretization

- $f_i(t) = \int_{E_i}^{E_{i+1}} F(t,E)\,\mathrm{d}E$, vector of number density
- Resolution of 300 bins: $\mathrm{E} = (10^{-3}–10^{12})\mathrm{GeV}$

- Forward integration of energy transport equation via matrix multiplication:
- $f_j^{\beta}(t + \Delta t\,) = T_{ij}^{\alpha\beta}(\Delta t) f_i^{\alpha}(t)$, where $T^{\alpha\beta}$ is the energy transition matrix
- $T_{ij}^{\alpha\beta} = Y_{ij}^{\alpha\beta} p(\alpha, i)$, where $Y^{\alpha\beta}$ is the yield and $p(\alpha, i)$ is the interaction probability
- Energy conservation is checked and (can be) enforced

- Interaction probability is calculated based on cross section, target density, etc.
- Yields come from MC simulations and analytical approximations

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Time Scales

Problem: Time scales can be very different for involved processes, e. g. electron synchrotron radiation compared to photopion production.

- → Time step must be smaller than smallest energy loss scale

$$\Delta t < \min_{\text{all processes}} \left(\frac{\mathrm{d}E}{\mathrm{d}t} / E \right)^{-1}$$

Possible solution: Matrix doubling

- $T(2^n \Delta t) = T^{2n}(\Delta t)$, seems to work if the transition matrix does not significantly change on a time scale of $(2^n \Delta t)$.

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CR-ENTREES

CR-ENTREES –
Cosmic-Ray **EN**ergy **TR**ansport in tim**E**-**E**volving astrophysical **S**ettings

Implementation of matrix transport principle in Fortran by A. Reimer, R. Protheroe and others

- Now with restructured code, simplified installation and testing
- Will become available

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CR-ENTREES – Specifications

Species

- Protons, neutrons, electrons, muons, kaons, pions, photons, electron neutrinos, muon neutrinos, (and adiabatic energy losses)

Interactions

- Bethe-Heitler pair production, photo-pion production, nuclear decay, synchrotron radiation, inverse Compton scattering, $\gamma\gamma$-Absorption, escape, and adiabatic losses

Targets

- Black body, broken power laws, etc.: discretized on a 161-bin-array.

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CR-ENTREES – Installation and Testing

Installation with cmake

```
lmerten@lmerten-ThinkCentre-M920s: ~/Software/matrixcode/build
File  Edit  View  Search  Terminal  Help
                                                 Page 1 of 1
 CMAKE_BUILD_TYPE
 CMAKE_INSTALL_PREFIX             /usr/local
 ENABLE_PYTHON                    ON
 ENABLE_TESTING                   ON
 HDF5_Fortran_LIBRARY_dl          /usr/lib/x86_64-linux-gnu/libdl.so
 HDF5_Fortran_LIBRARY_hdf5        /usr/lib/x86_64-linux-gnu/hdf5/serial/libhdf5
 HDF5_Fortran_LIBRARY_hdf5_fort   /usr/lib/x86_64-linux-gnu/hdf5/serial/libhdf5
 HDF5_Fortran_LIBRARY_m           /usr/lib/x86_64-linux-gnu/libm.so
 HDF5_Fortran_LIBRARY_pthread     /usr/lib/x86_64-linux-gnu/libpthread.so
 HDF5_Fortran_LIBRARY_sz          /usr/lib/x86_64-linux-gnu/libsz.so
 HDF5_Fortran_LIBRARY_z           /usr/lib/x86_64-linux-gnu/libz.so

CMAKE_BUILD_TYPE: Choose the type of build, options are: None Debug Release RelW
Keys: [enter] Edit an entry [d] Delete an entry              CMake Version 3.17.0
      [l] Show log output   [c] Configure
      [h] Help              [q] Quit without generating
      [t] Toggle advanced mode (currently off)
```

Unit tests

```
lmerten@lmerten-ThinkCentre-M920s: ~/Software/matrixcode/build
File  Edit  View  Search  Terminal  Help
lmerten@lmerten-ThinkCentre-M920s:~/Software/matrixcode/build$
lmerten@lmerten-ThinkCentre-M920s:~/Software/matrixcode/build$
lmerten@lmerten-ThinkCentre-M920s:~/Software/matrixcode/build$
lmerten@lmerten-ThinkCentre-M920s:~/Software/matrixcode/build$
lmerten@lmerten-ThinkCentre-M920s:~/Software/matrixcode/build$
lmerten@lmerten-ThinkCentre-M920s:~/Software/matrixcode/build$ make test
Running tests...
Test project /home/lmerten/Software/matrixcode/build
    Start 1: baseTest
1/5 Test #1: baseTest .........................   Passed   98.07 sec
    Start 2: nuclearDecayTest
2/5 Test #2: nuclearDecayTest .................   Passed   10.31 sec
    Start 3: photoPionTest
3/5 Test #3: photoPionTest ....................   Passed   33.01 sec
    Start 4: inverseComptonTest
4/5 Test #4: inverseComptonTest ...............   Passed   48.34 sec
    Start 5: synchrotronTest
5/5 Test #5: synchrotronTest ..................   Passed   86.28 sec

100% tests passed, 0 tests failed out of 5

Total Test time (real) = 276.01 sec
lmerten@lmerten-ThinkCentre-M920s:~/Software/matrixcode/build$
```

Several predefined tests are executed included test plots.

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Heavy Nuclei

How to include heavier elements?

Problems

- Amount of spectral/transition data will increase by more than two orders in magnitude
- Hardcoded transitions would create an unreadable and unmaintainable software

Solution

- Create a modular object-oriented structure
- Reduces the amount of code significantly
- In general, easier to maintain and extend

Furthermore

- Allow for on-the-fly creation/deletion of spectra → Reduction of data

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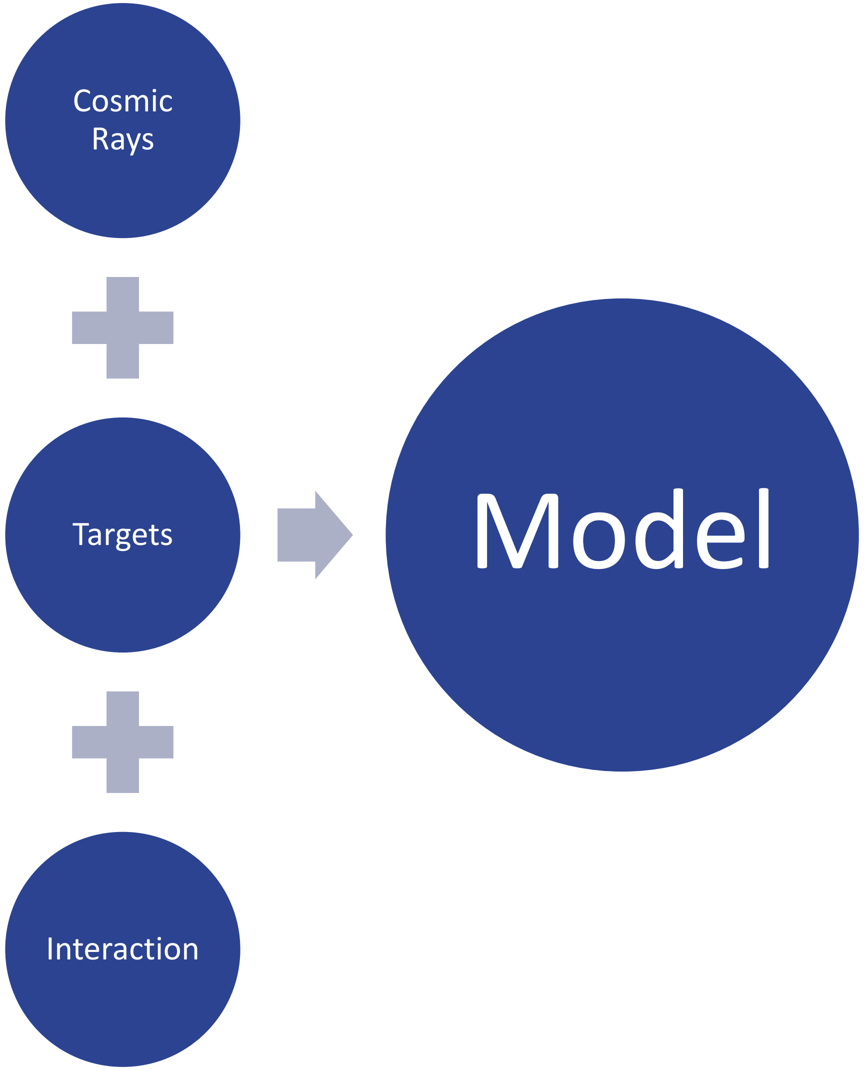
Structure I



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Structure II

Species

Contains essential information of a cosmic ray species

One instance per CR / gamma ray / neutrino etc. species is needed

Targets

Information on photon target fields, e.g., total densities, spectrum, etc.

Now, one instance Could be extended to more specific target fields.

Interaction

Base class for interaction processes, e.g., nuclear decay, photo-pion production, etc.

One class per interaction (inheritance)

One instance per active species.

Simulation

Comprises the actual model and runs the simulation

One instance per run

Updating spectra, adds new species, etc.

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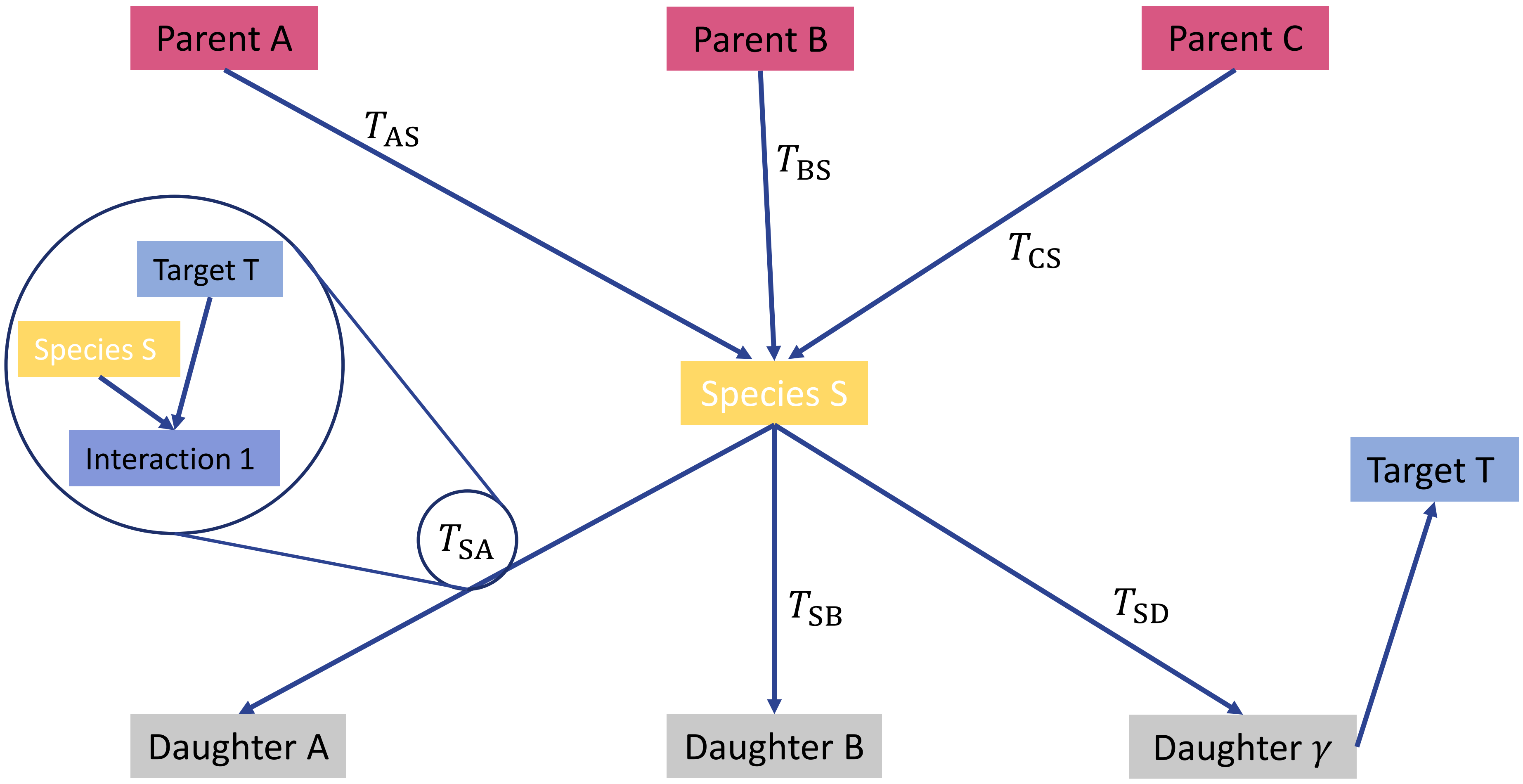
Structure III – Transitions



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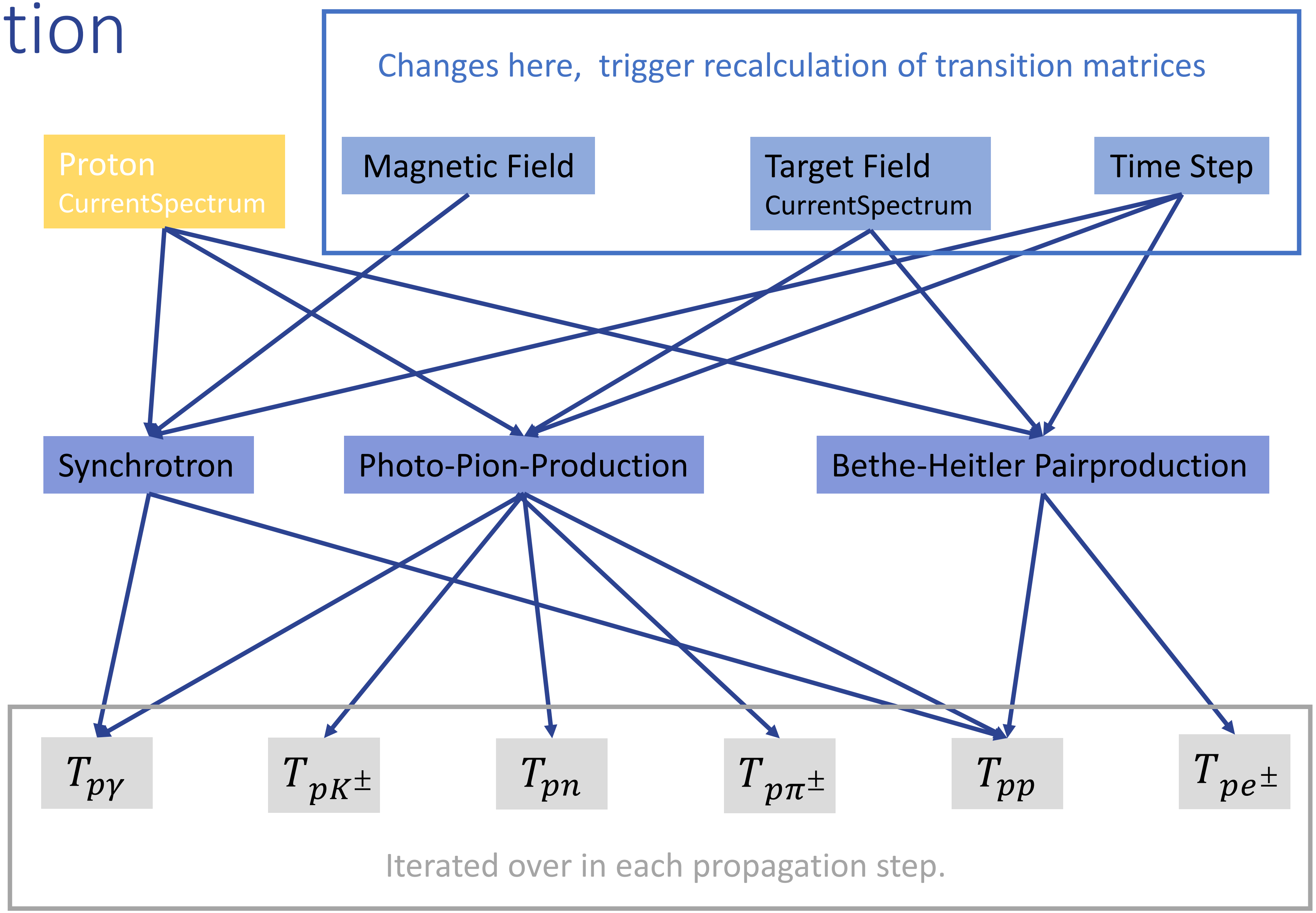
Transition



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Immediate Interactions

Problem

- Possibly very fast interacting species, e.g., a nuclear decay with very short decay time.

→Particle species becomes irrelevant after few time steps but consumes the same amount of computation time and memory.

Solution

- Sustainably remove the species from the simulation chain
- Making sure to not produce it again
- Not neglecting the channel to (possibly stable) secondaries of unstable particle

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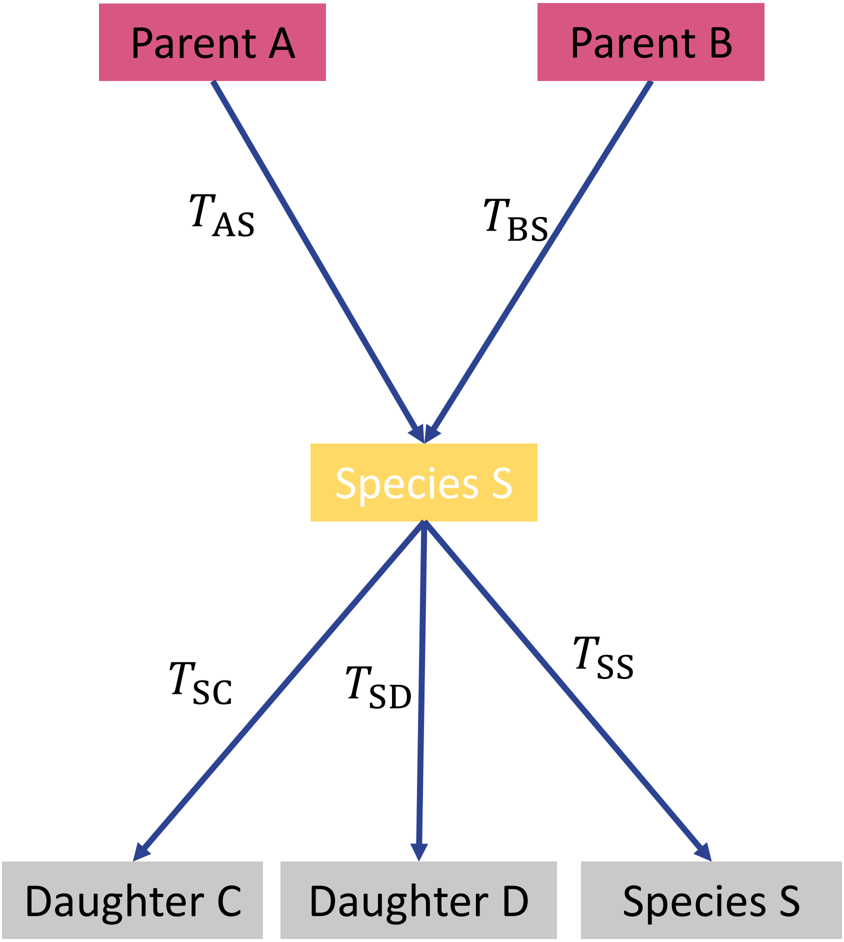
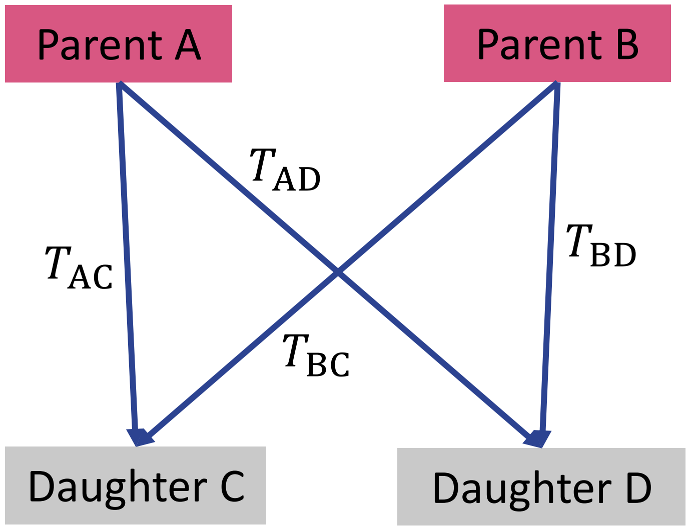
Structure IV – Immediate Interactions





$T_{\mathrm{AC}} = T^{*}_{\mathrm{SC}} T_{\mathrm{AS}}$,
with T^{*}_{SC} the transition matrix recalculated with $\Delta t = \infty$

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Immediate Interaction

Benefits

- Reduces significantly the number of simultaneously tracked species
- Reduces the memory usage
- Increases the propagation cycles per time
- Slightly reduces hard disk space of simulation results. HDF does an amazing compression, which limits the benefits on that point.

Current implementation

- Int. probability $p_{\mathrm{int}}(E) = 1 - \exp\left(-\frac{\Delta t}{\tau_{\mathrm{int}}(E)}\right) > 0.95\ \forall\ E < E_{\max}$ → unstable
- Recalculate transitions of unstable species
- If parents available: Recalculate parents’ transitions
- Remove species from simulation before next step

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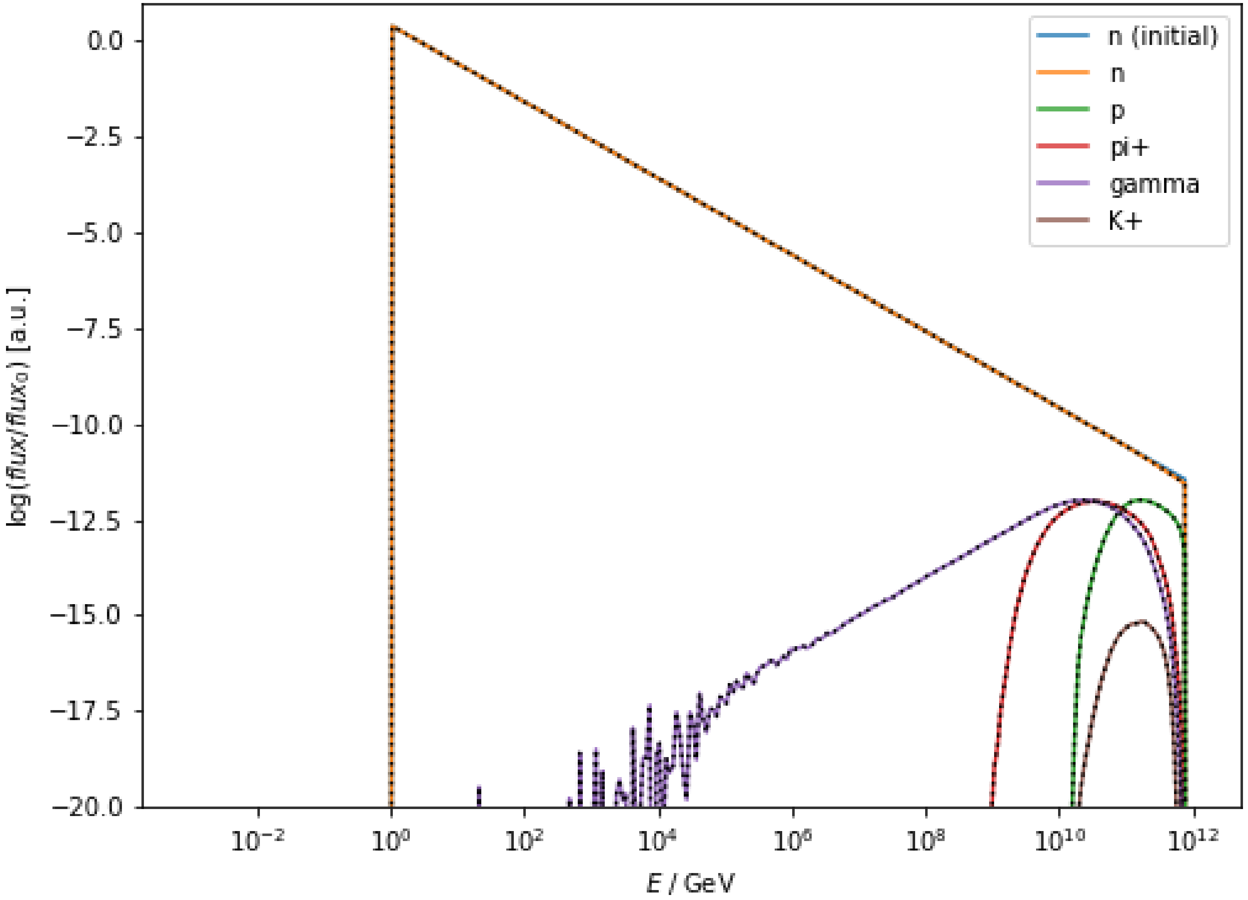
Examples and Testing

Nuclear Decay – Neutron



Initial condition:
$\Delta t = 10^{12}$s, $N = 100$
Target: CMB
Primary species: neutron, with $\gamma = -2$,
$E_{min} = 1$GeV, $E_{max} = 8 \times 10^{11}$GeV

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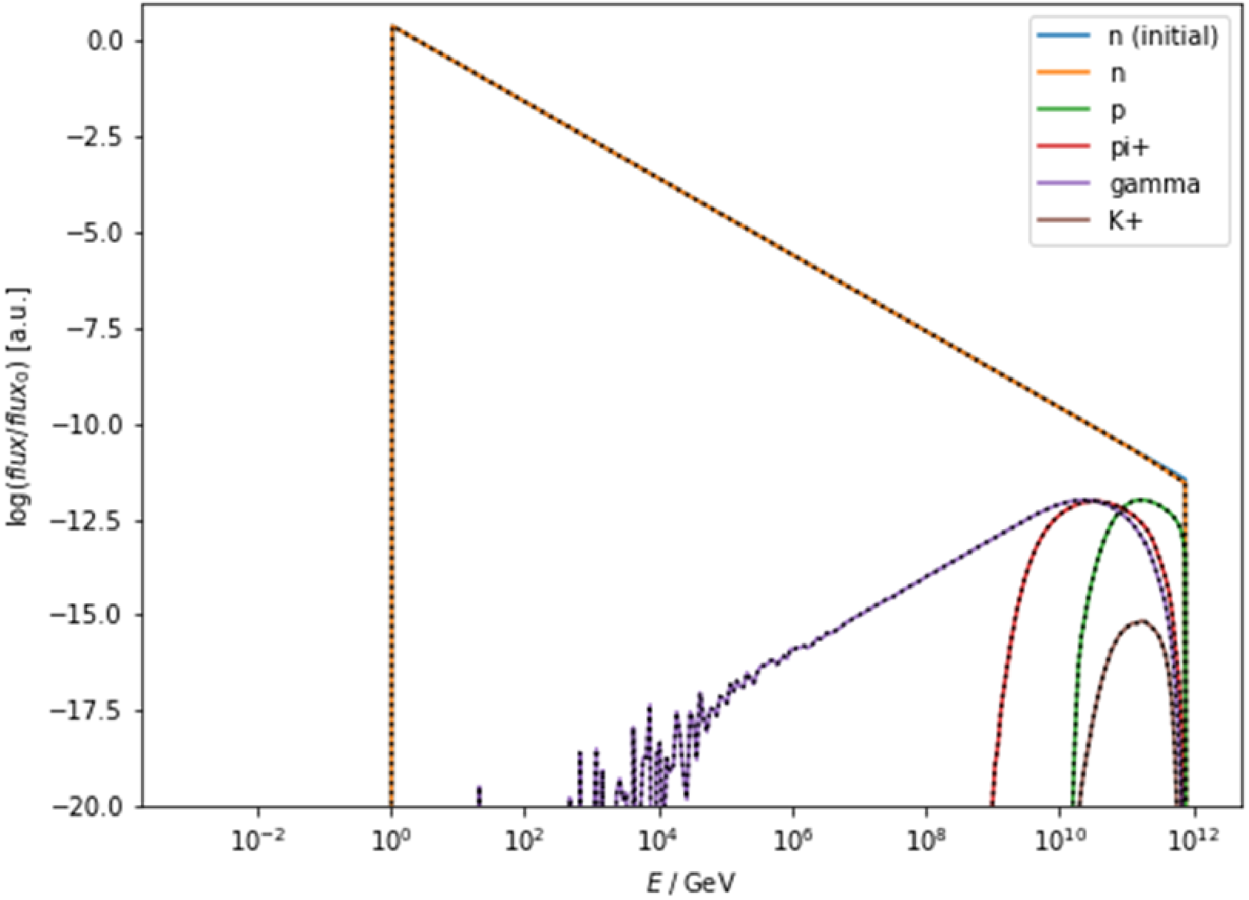
Photo-Meson Production



Initial condition:
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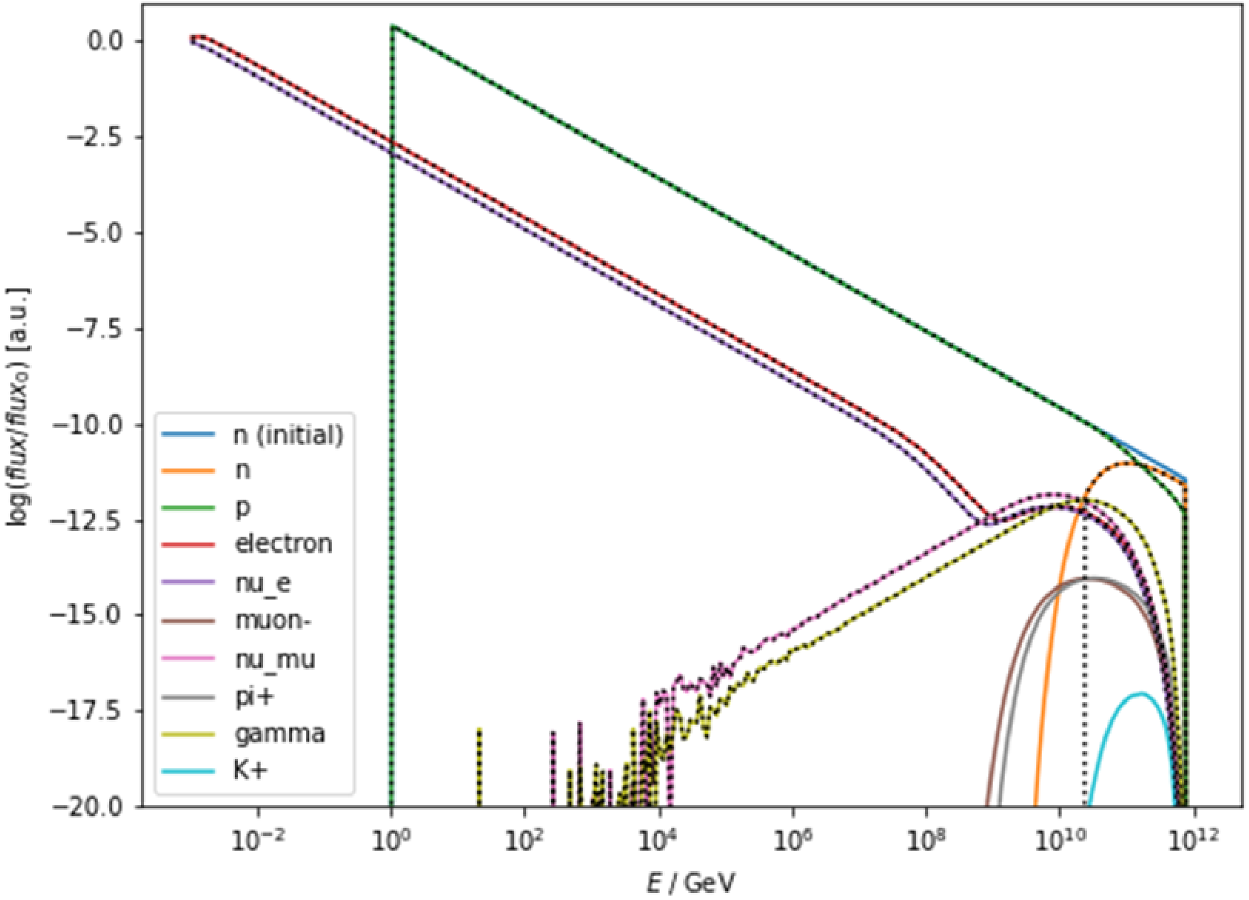

Initial condition:
$\Delta t = 10^{12}$s, $N = 100$
Target: CMB
Primary species: neutron, with $\gamma = -2$,
$E_{min} = 1$GeV, $E_{max} = 8 \times 10^{11}$GeV

Decay of unstable particles is included.

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Summary and Outlook

Summary I

- CR-ENTREES is (almost) ready for publication
  - Modular structure
- Heavy Elements will be treated in an all new python version
  - Computation intensive calculation (transition matrices) in Fortran → wrapping with f2py
- Output is in hdf format
  - Fast, good compression, allows for useful meta data storage
- Allows for an arbitrary number of species
- Species, Targets and Interaction can be „freely“ combined

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Summary II – Interactions

Nuclear Decay
- Available for nuclei up to Z=26, muons, pions, and kaons
- >97% of all decay channels are included with secondary yields

Photo Pion Production
- Available for nuclei
- Checks for (deuteron, tritium and He3) needed

Bethe-Heitler pair production
- Available for protons
- Aiming for a scaling ansatz

Inverse Compton Scattering
- Available

Synchrotron
- Available for electrons
- Generalization to other elements needed

Photo-Disintegration
- Work in progress

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Summary III

Species are added/deleted on the fly

- Reduction of computation time and storage
- Testing in progress → might be inefficient for non-linear set ups

Non-linearity

- Updates of target field based on x-ray flux
- Work in progress

Documentation

- Mainly based on docstrings in the modules, classes, function
- Example jupyter notebook

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Outlook

- Implementation of missing interactions
- Code cleaning
- Comparison with existing codes

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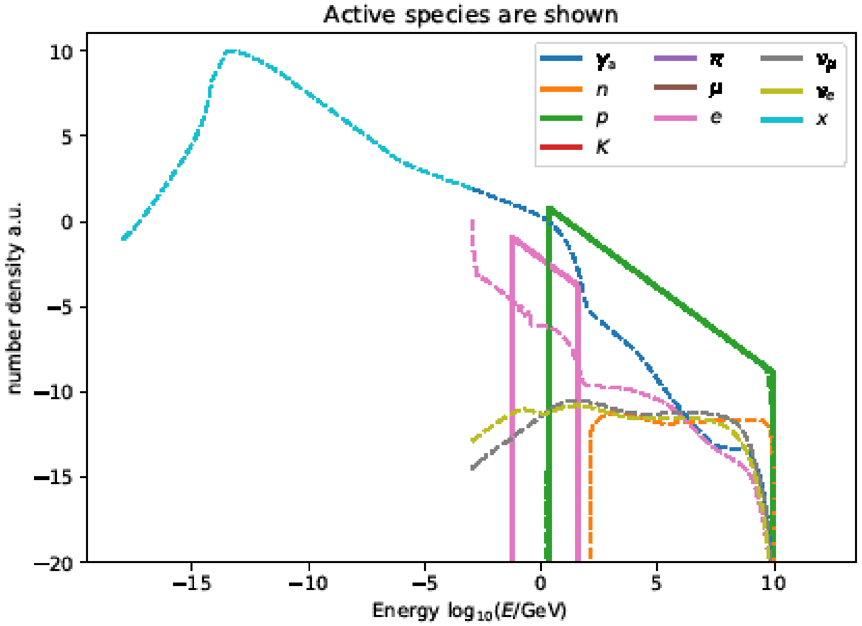
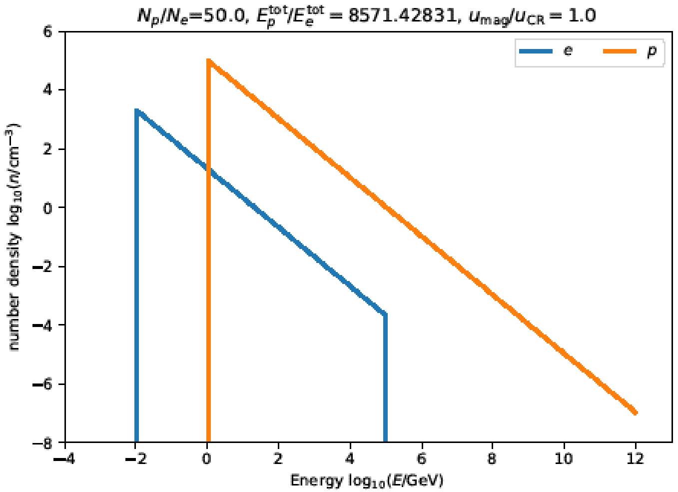
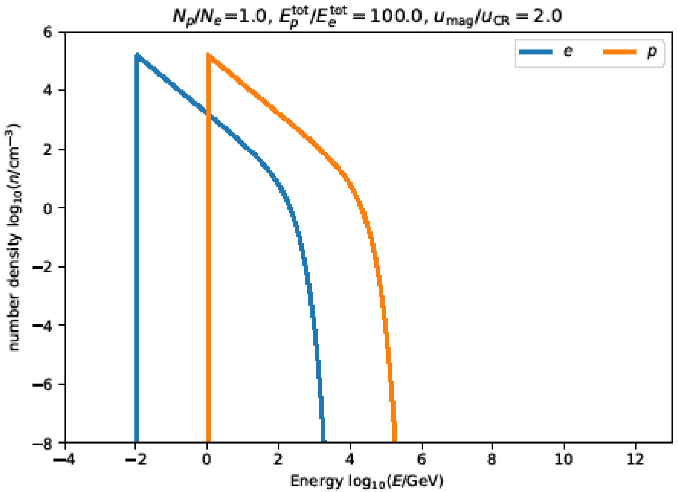
Backup

Tests – Basics







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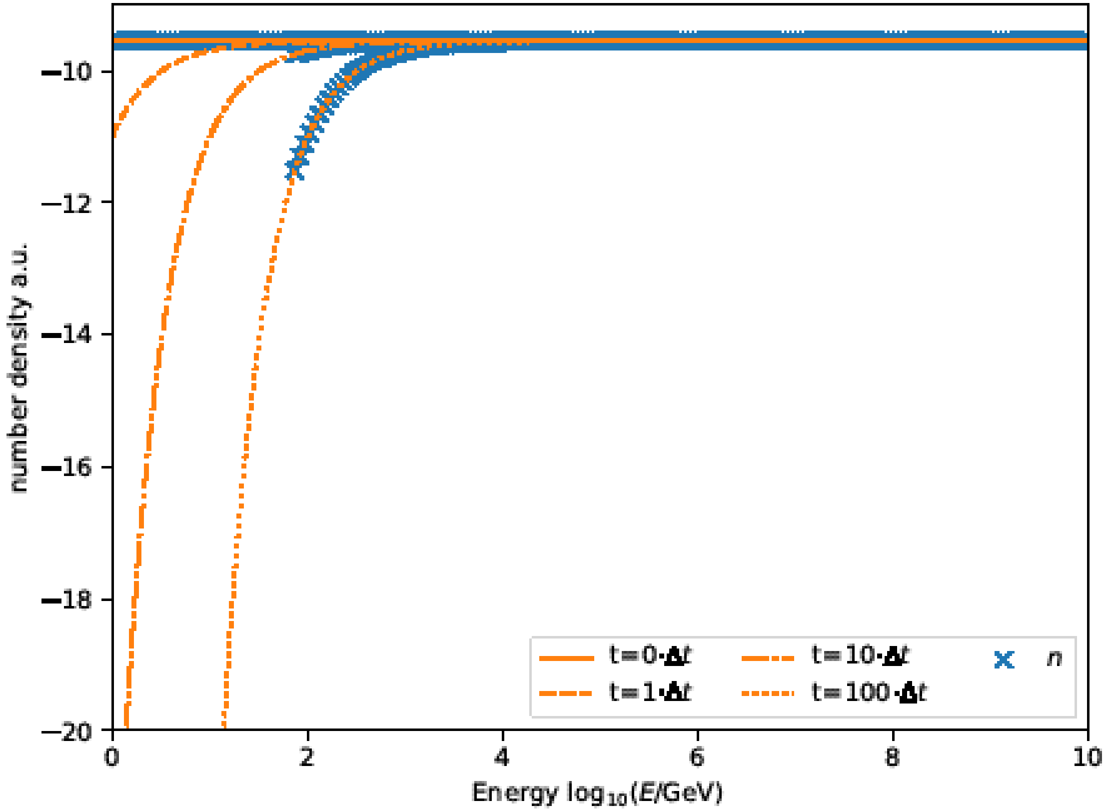
Tests – Nuclear Decay



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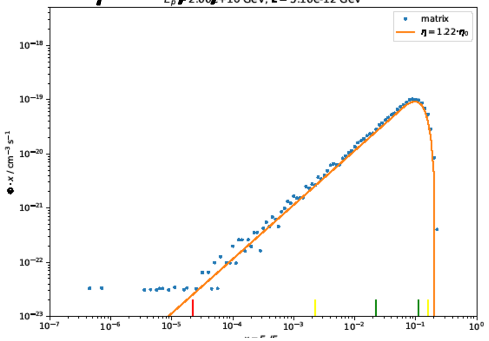
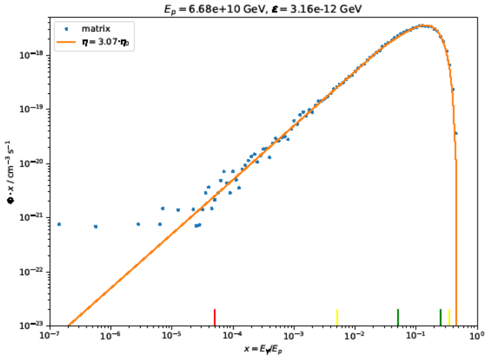
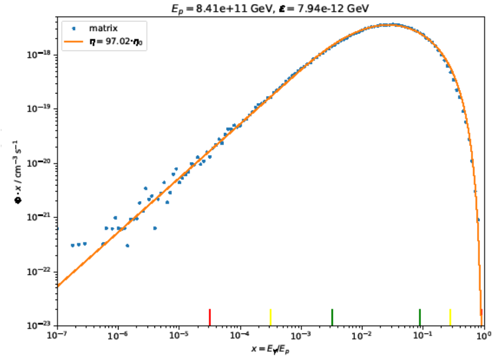
Tests – Photo-Meson-Production

γ-ray yields

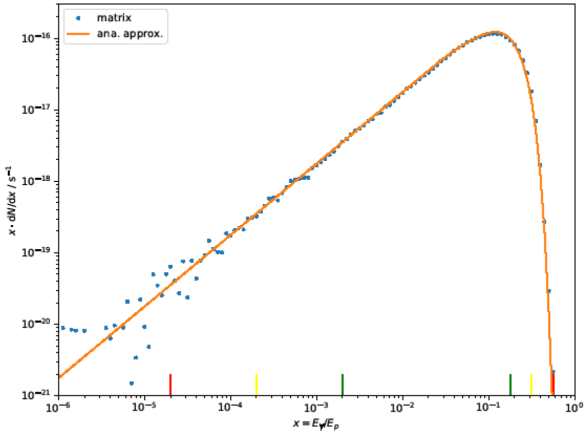




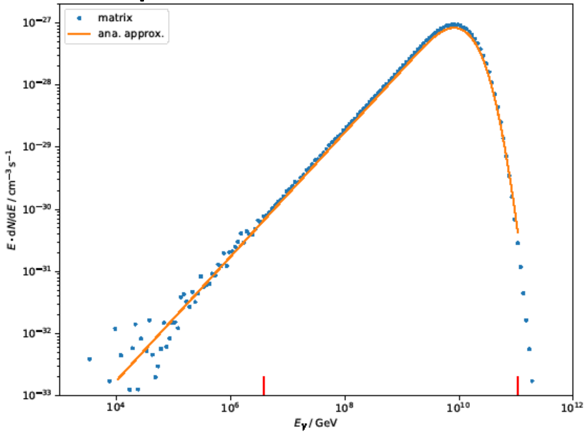


Increasing COM energy

Mono-energetic proton on CMB



Energy spectrum of protons on CMB



Comparison with semianalytic models of Kelner &Aharonian (2008)
Allows only to compare the normalization as both approaches are based on SOPHIA

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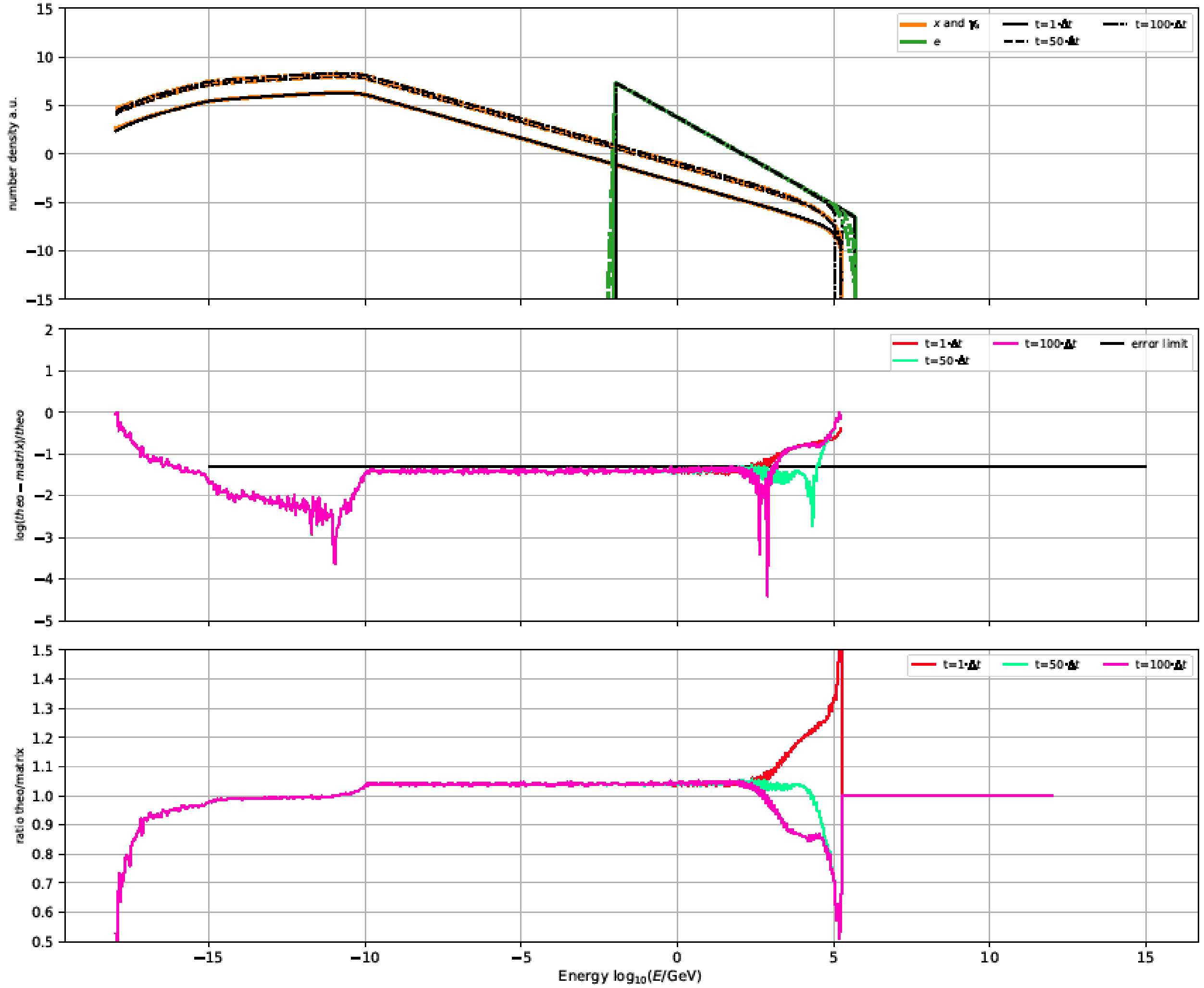
Tests – Inverse Compton Scattering



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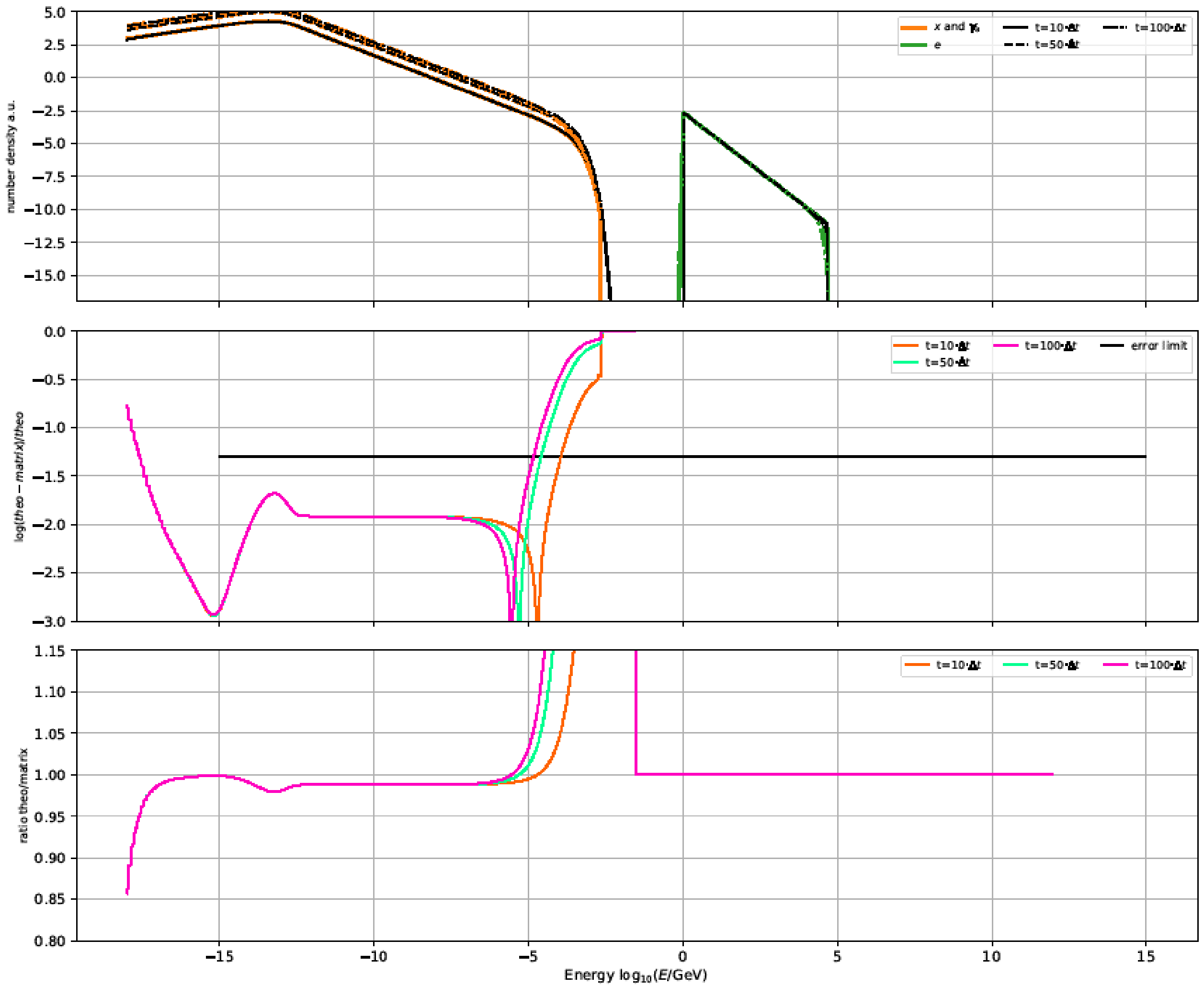
Tests – Synchrotron Radiation



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