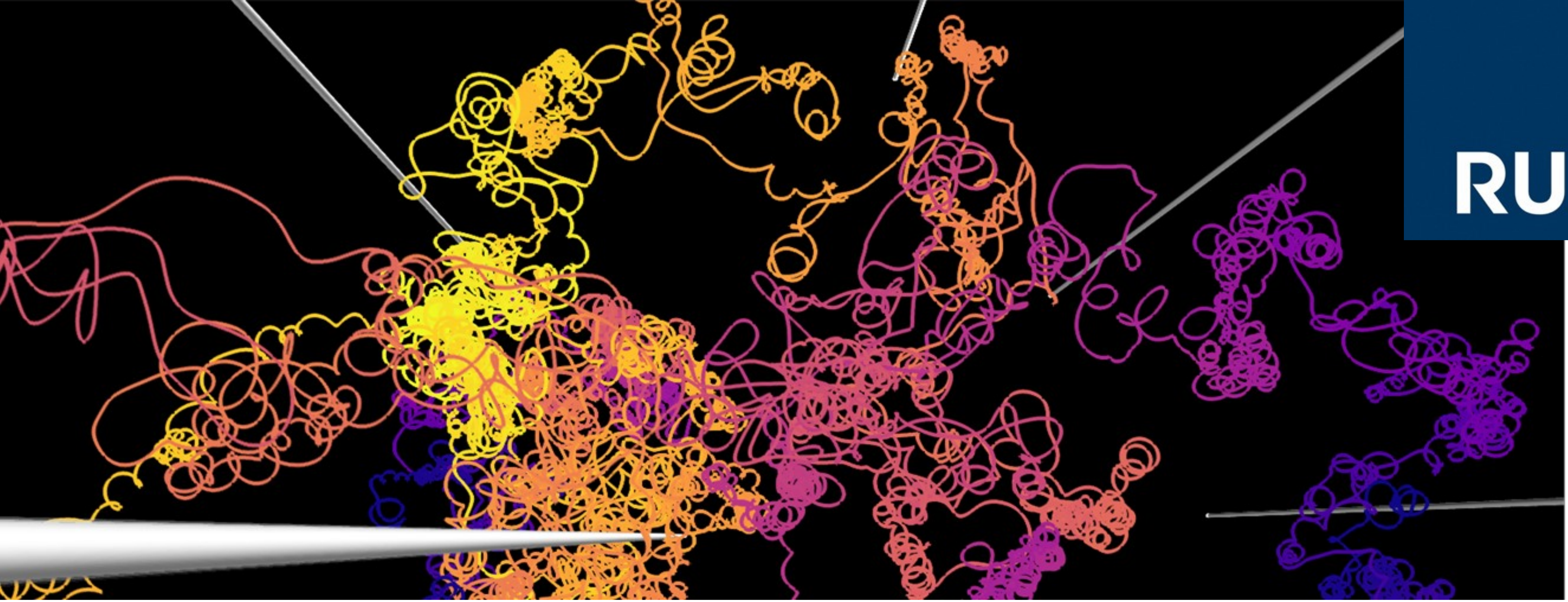

# News from CR-ENTREES – And Extensions

Leptohadronic Propagation Codes|21.02.2024

L. Merten*, A. Reimer, P. Da Vela, M. Boughelilba

# Contents

# Short INtroduction

## Basics

- Principles and Assumptions of a „Matrix-Multiplication“ Code
- CR-ENTREES – **C**osmic-**R**ay **EN**ergy **TR**ansport in tim**E**-**E**volving astrophysical **S**ettings

## Heavy Nuclei Extension

- Basic Ideas and Structure
- Modular Code in Python

## Testing and Example

- Validating indidual interactions
- First application to jet physics

## 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: $\mathrm{E} = (10^{-3} - 10^{12})\mathrm{GeV}$



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# Energy Transport Code

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

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- Resolution of 300 bins: $\mathrm{E} = (10^{-3} – 10^{12})\mathrm{GeV}$

Forward integration 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

- Cross section, target density, etc. → Interaction Probability
- MC simulations and analytical approximations → Yields


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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*** –
**C**osmic-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**

- Spectral/transition data will increase (factor $\sim 100$)
- Hardcoded transitions → unreadable and not maintainable

**Solution**

Modular object-oriented structure

- Reduces the amount of code significantly
- In general, easier to maintain and extend

**Furthermore**

- On-the-fly creation/deletion of spectra → Reduction of data


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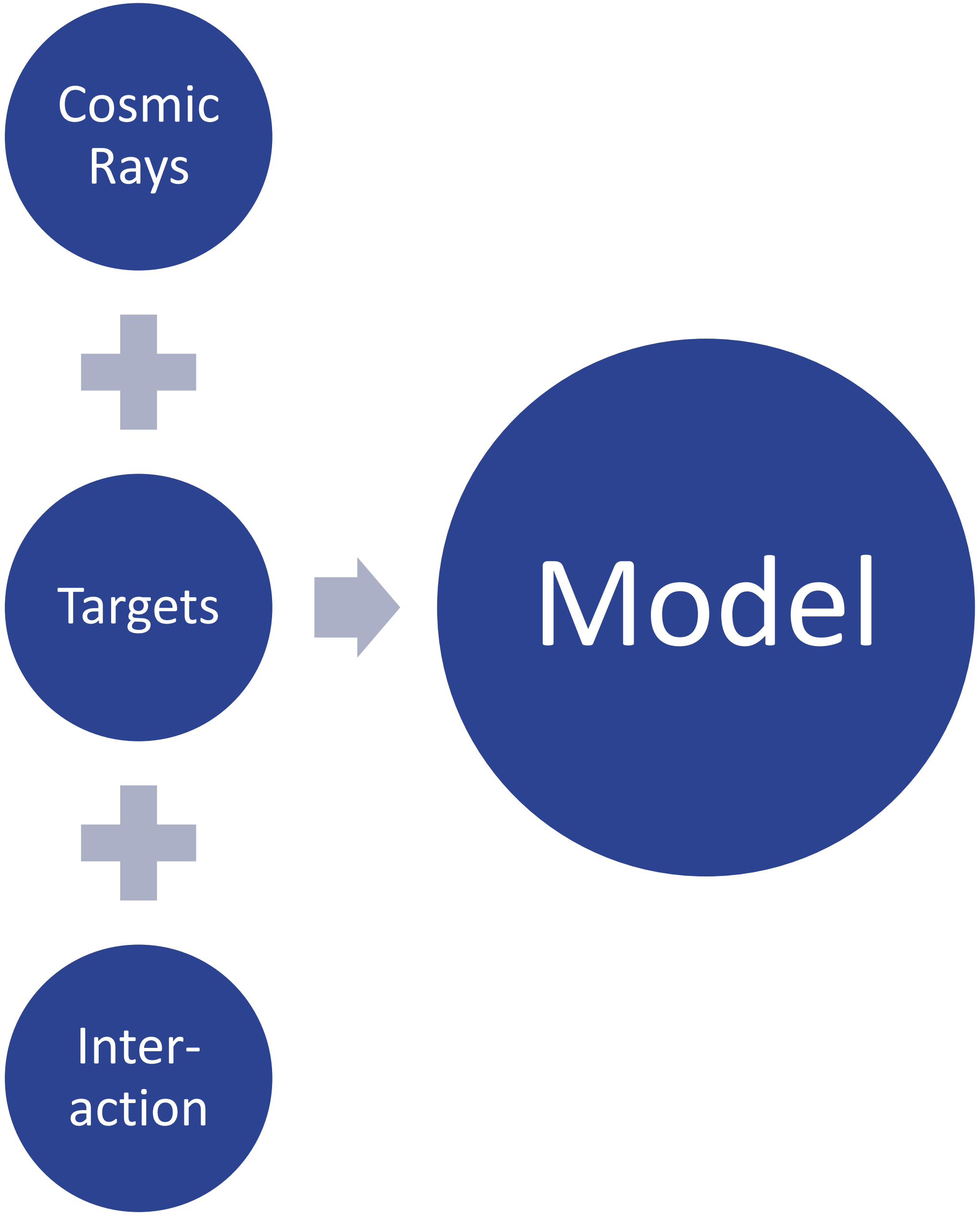
# Structure I





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# Structure II

**Species**
- Information of CR species
- One instance per species

**Targets**
- Information on photon target fields
- One instance

**Inter-action**
- Nuclear decay, photo-pion production, etc.
- One class per interaction
- One instance per active species.

**Simu-lation**
- Model that runs the simulation
- One instance per run
- Updating spectra, adds new species, etc.


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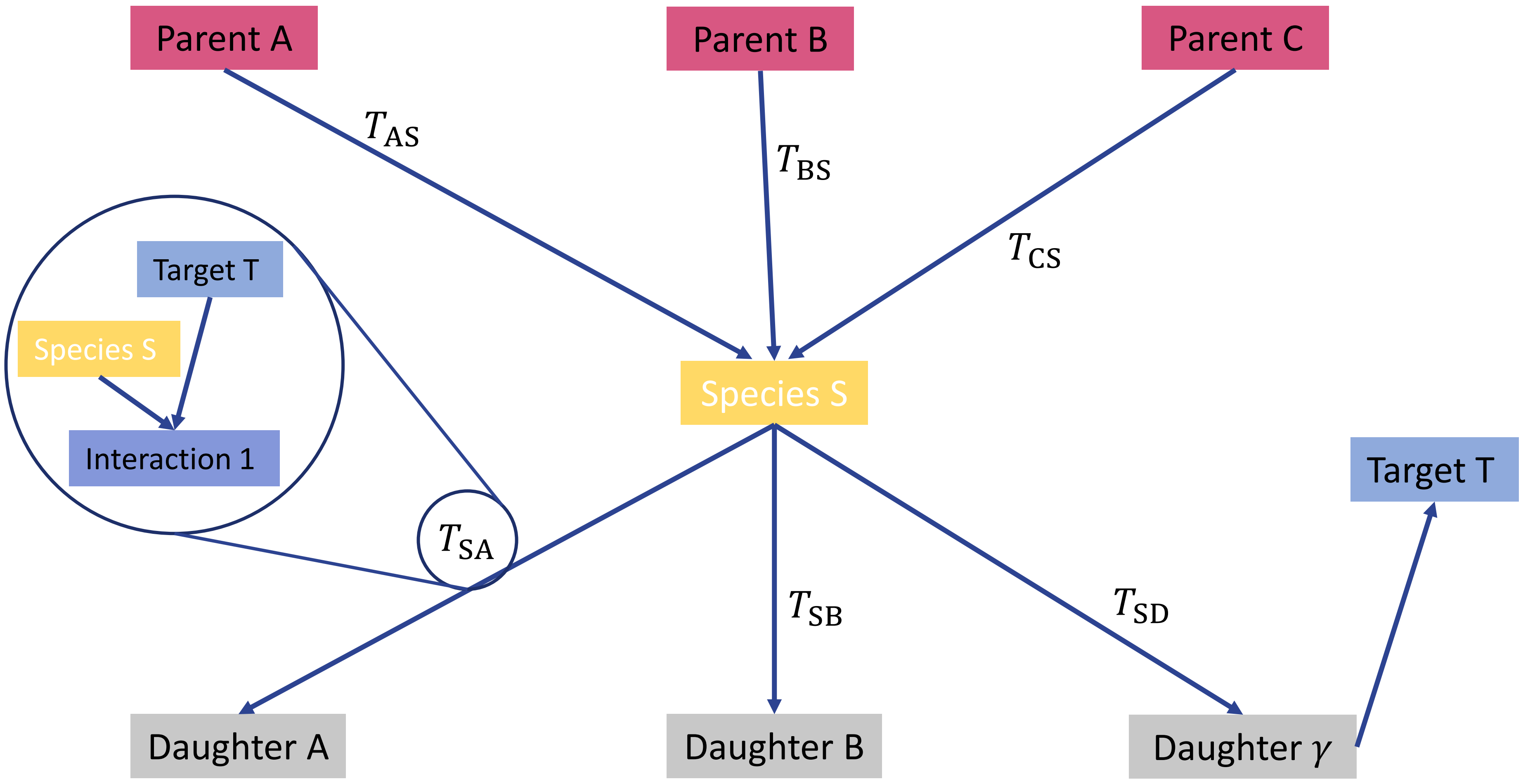
# Structure III – Transitions





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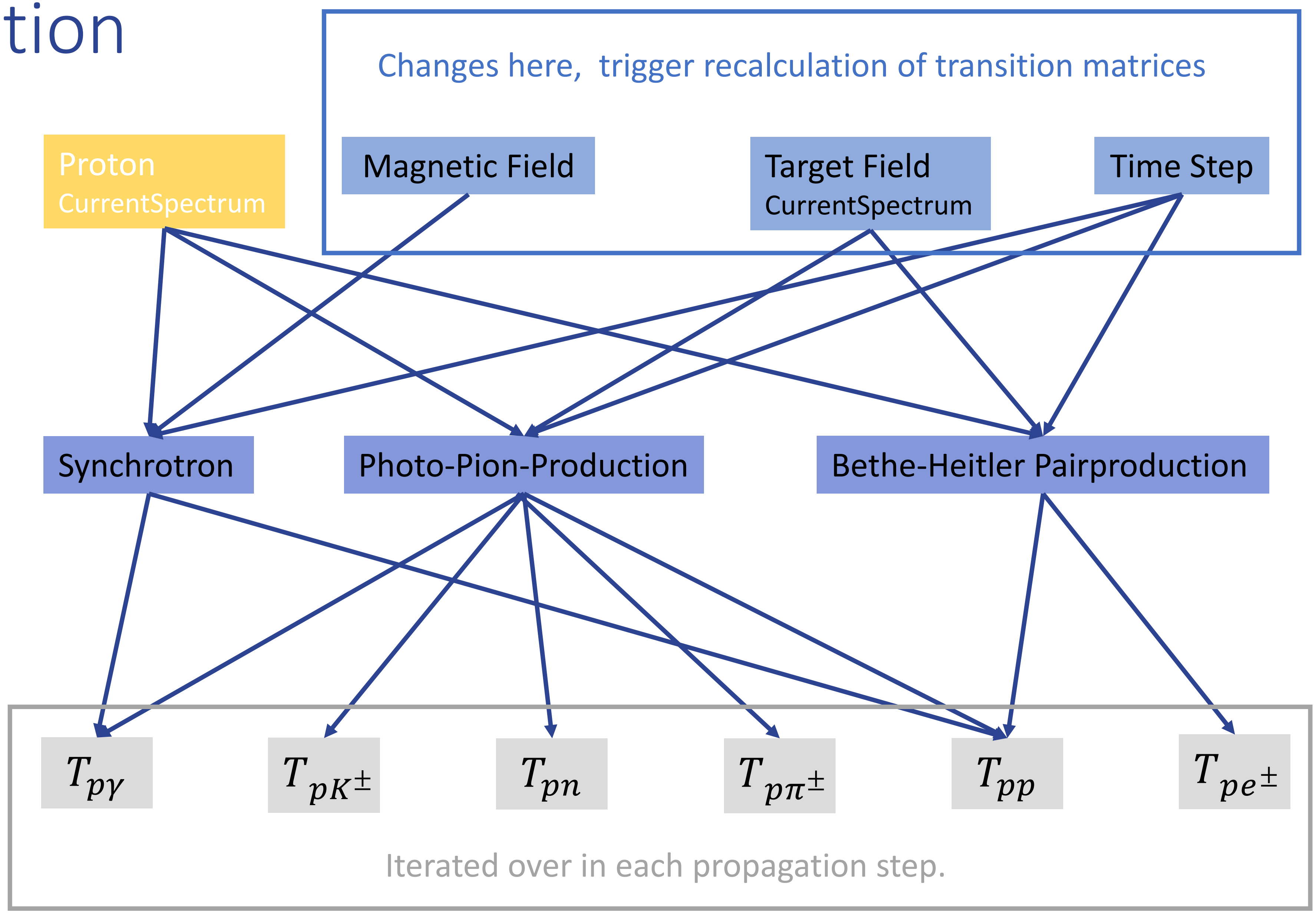
# Transition





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# Immediate Interactions

## Problem

- Very fast interacting species (e.g., nuclear decay)

→ Irrelevant species consumes memory and computing time

## Solution

Sustainably remove the species from the simulation chain

- Make sure to not produce it again
- Not neglecting the channel to (possibly stable) secondaries


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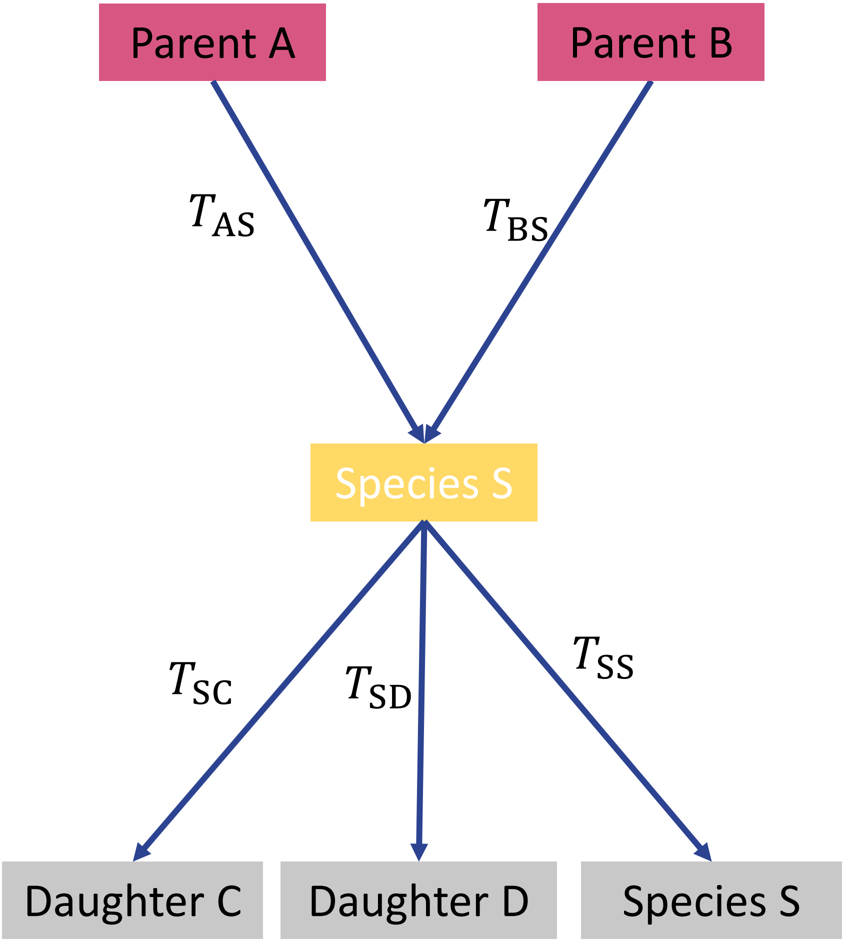
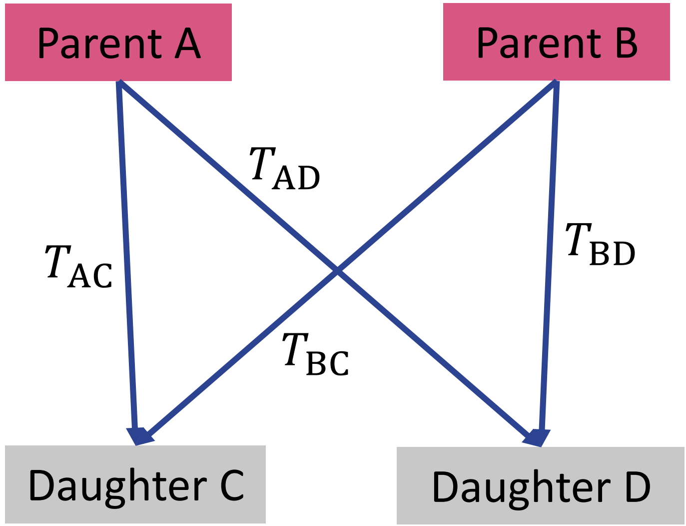
# Structure IV – Immediate Interactions




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

# 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.

## Current implementation

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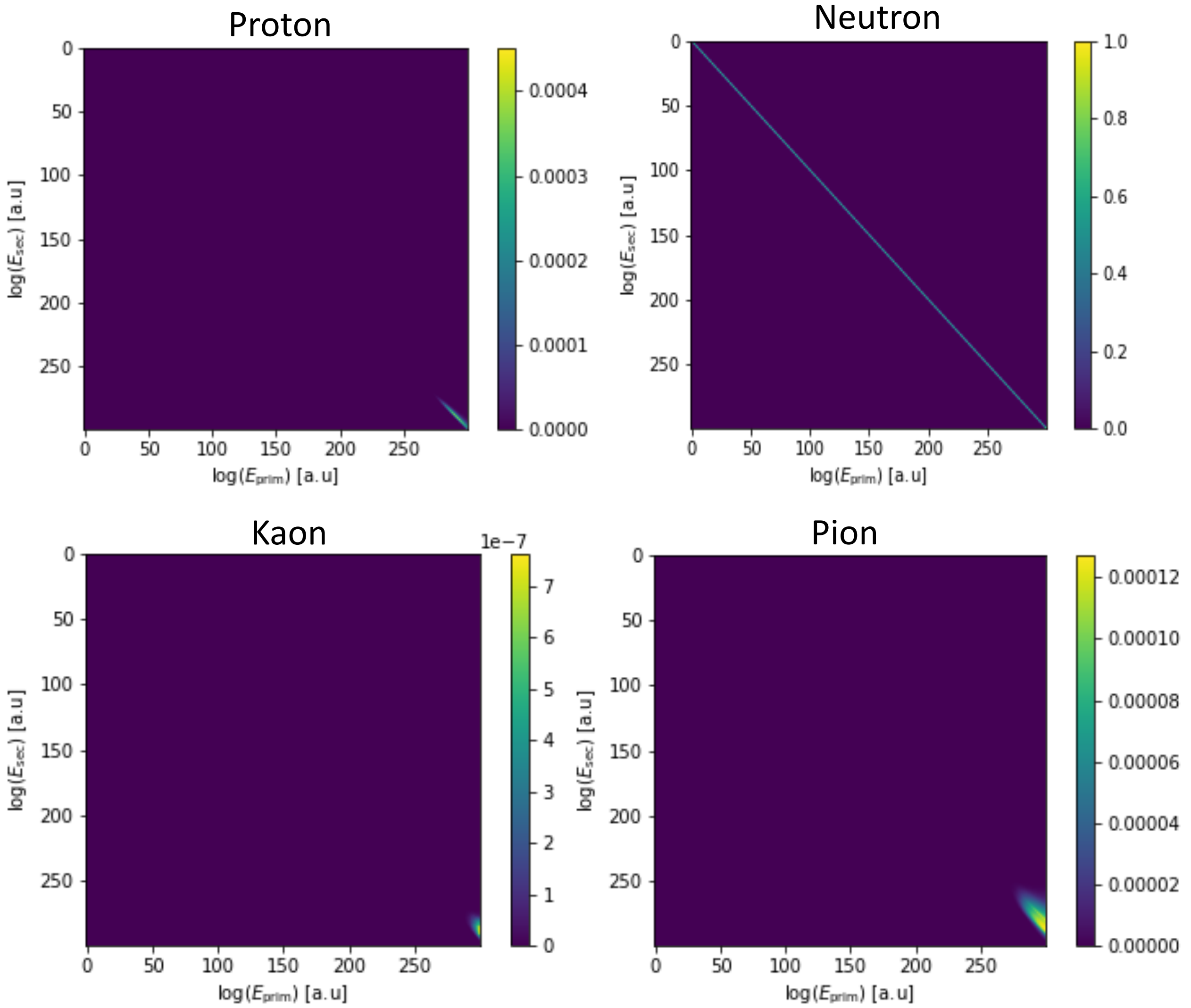
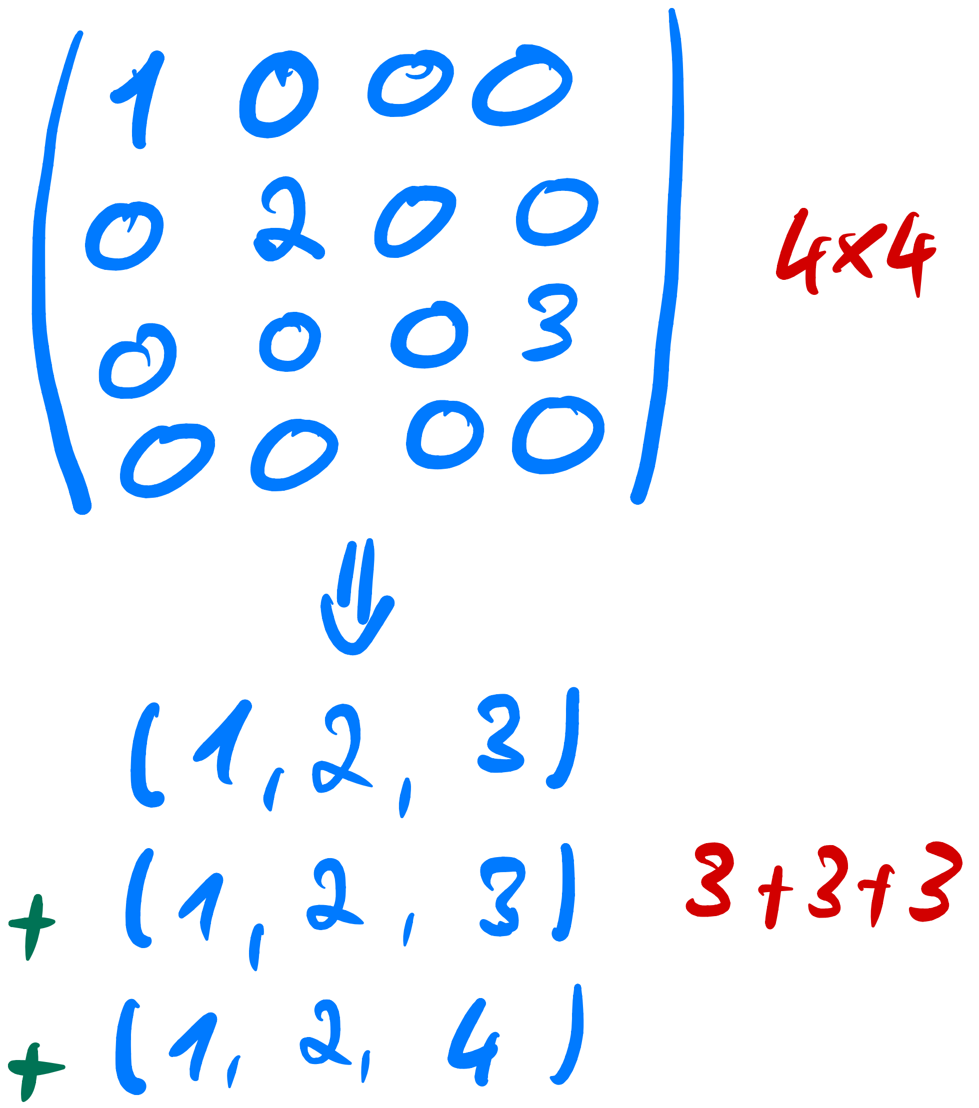
# Sparse Matrices – Yields PPP



# Sparse Matrices

## Benefits

- Reduces memory usage significanly
- Some calculations can be even faster

## Current Implementation

- Matrices are transformed at python level
  - Best format not yet decided (CSR, CSC, etc.)
- Will make PDI implementation possible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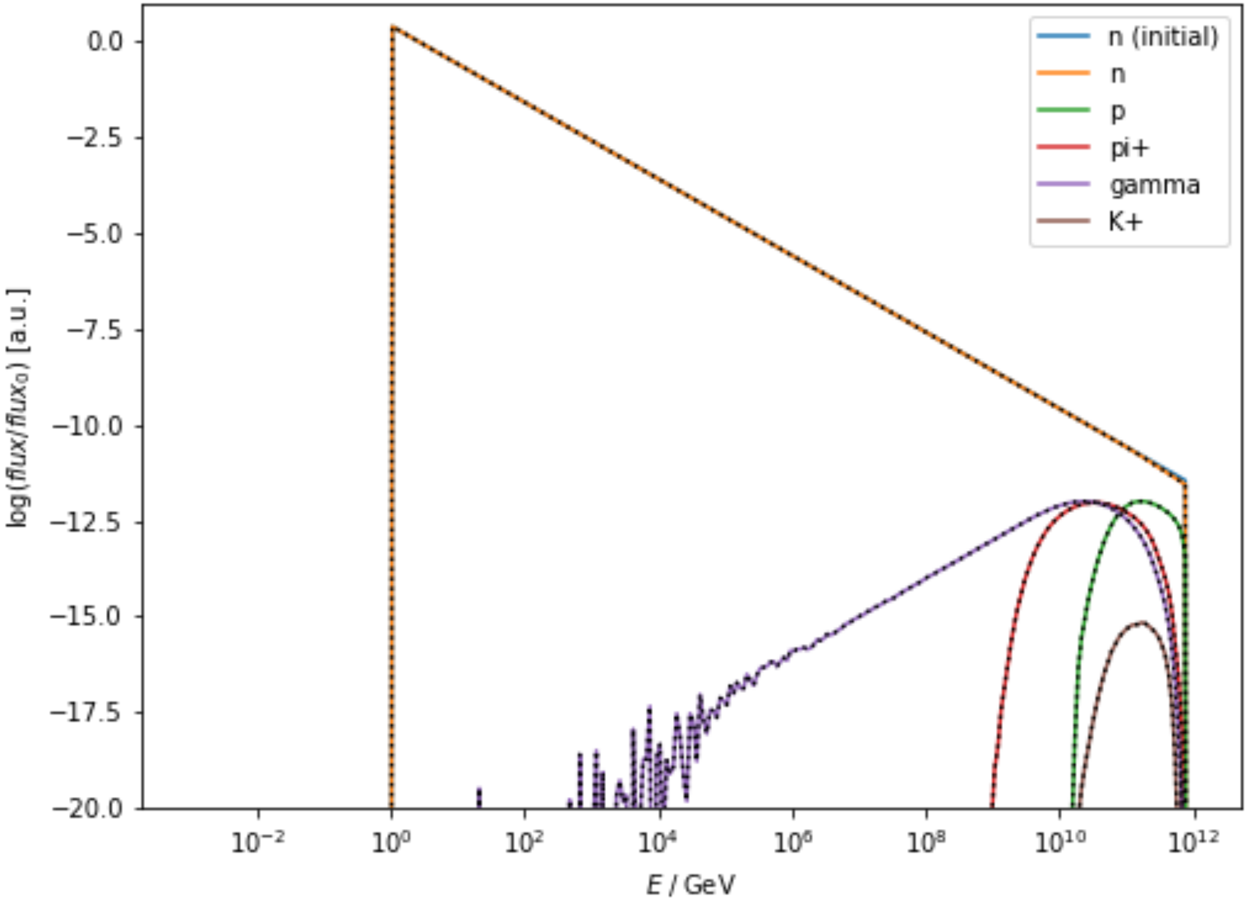
# Examples and Testing

# 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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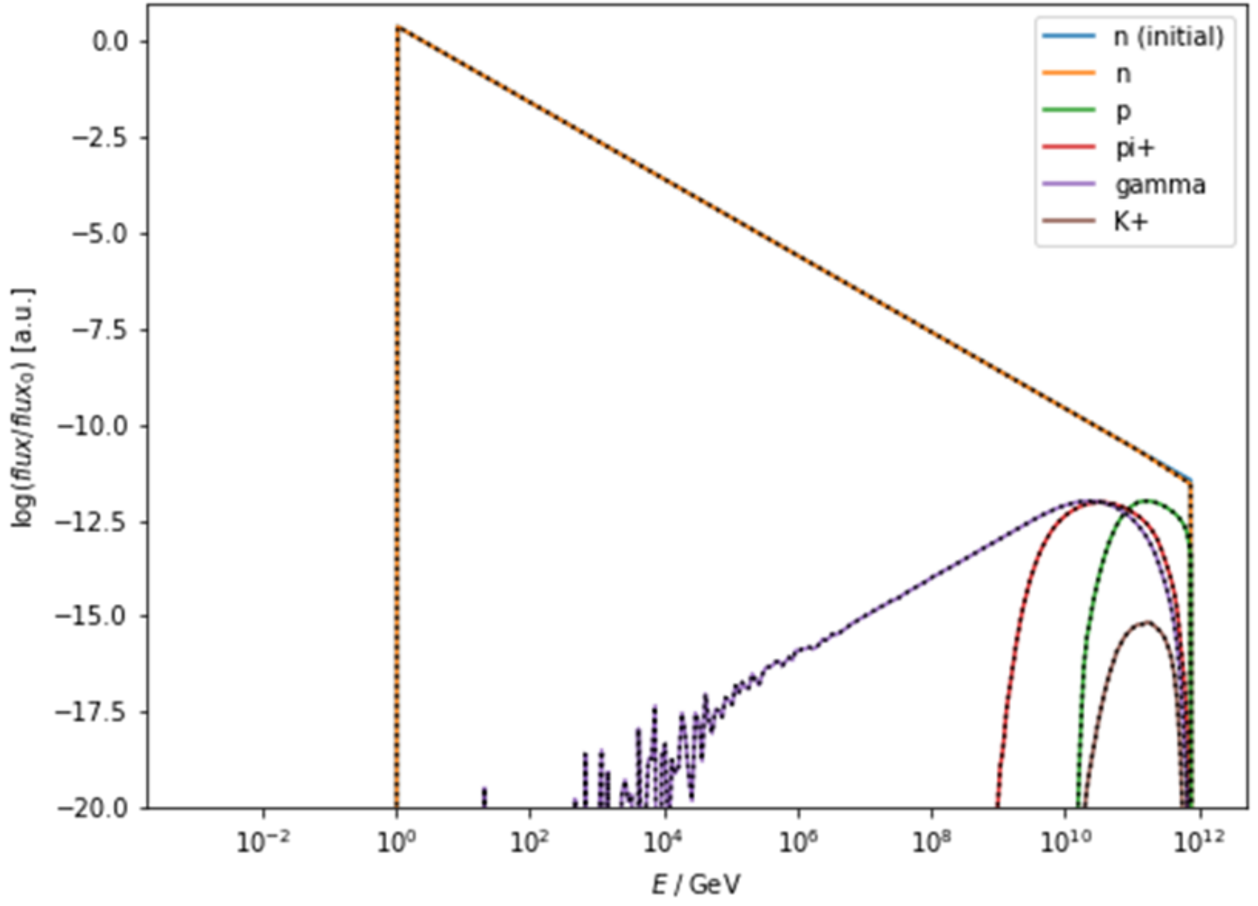
# Photo-Meson Production

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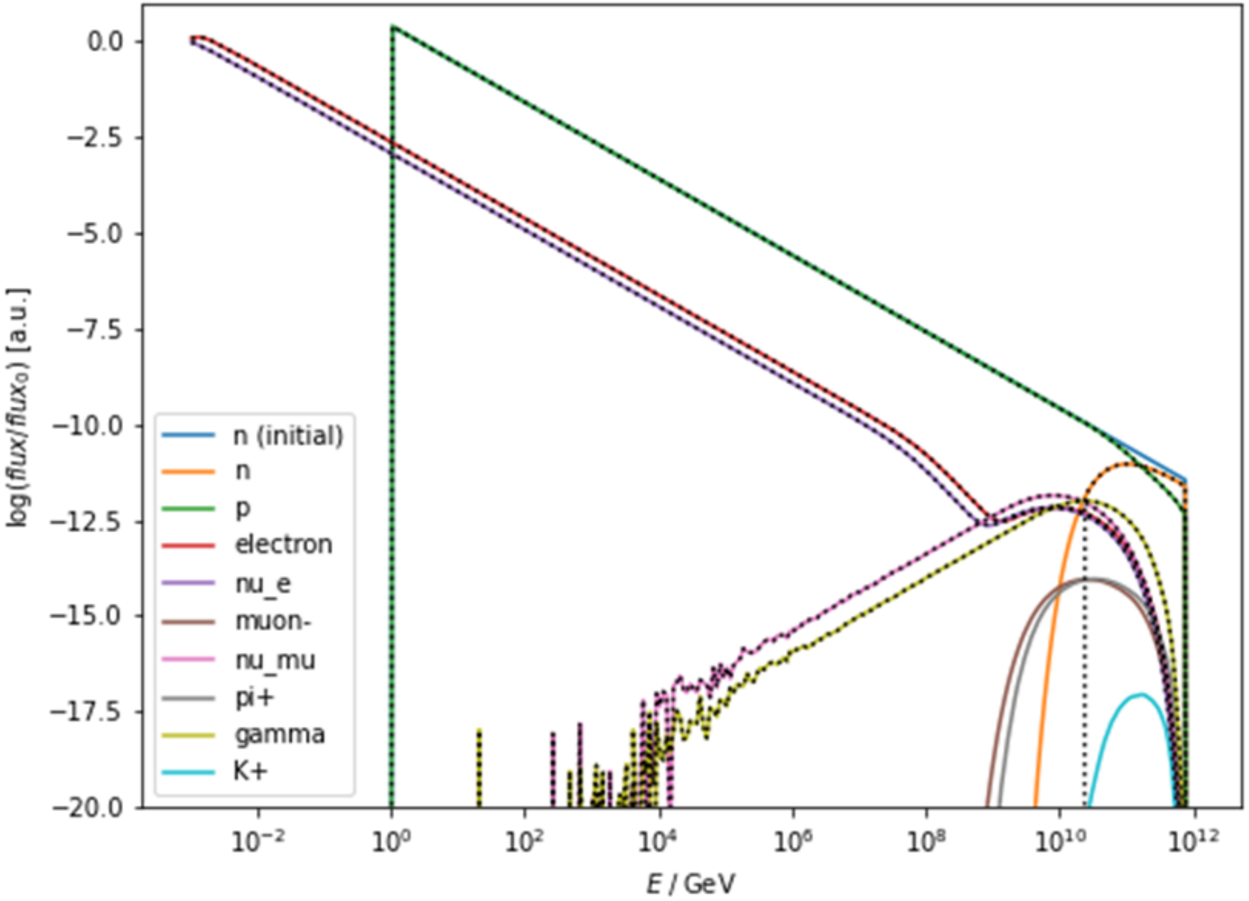


Initial condition:
$\Delta t = 10^{12}$s, $N = 100$
Target: CMB
Primary species: neutron, with $\gamma = -2$,
$E_{min} = 1$GeV, $E_{max} = 8 \times 10^{11}$GeV

Decay of unstable particles is included.


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# Simple Jet Model

- Comparison of co-moving emission features in two jets:
  - Straight jet
  - Conical jet

- Initial Parameter
  - Magnetic field, $B = 10\mathrm{G}$
  - size of emission blob, $R_{\mathrm{em}} = 3 \times 10^{16}\mathrm{cm}$ at $D = 10^{17}\mathrm{cm}$
  - Doppler Factor, $D_{\Gamma} = 22.4$
  - Electron population: Spectral Index, $\alpha = -2, \gamma_{\min} = 1, \gamma_{\max} = 100$
  - Proton population: Spectral Index, $\alpha = -2, \gamma_{\min} = 1, \gamma_{\max} = 10^{9}$


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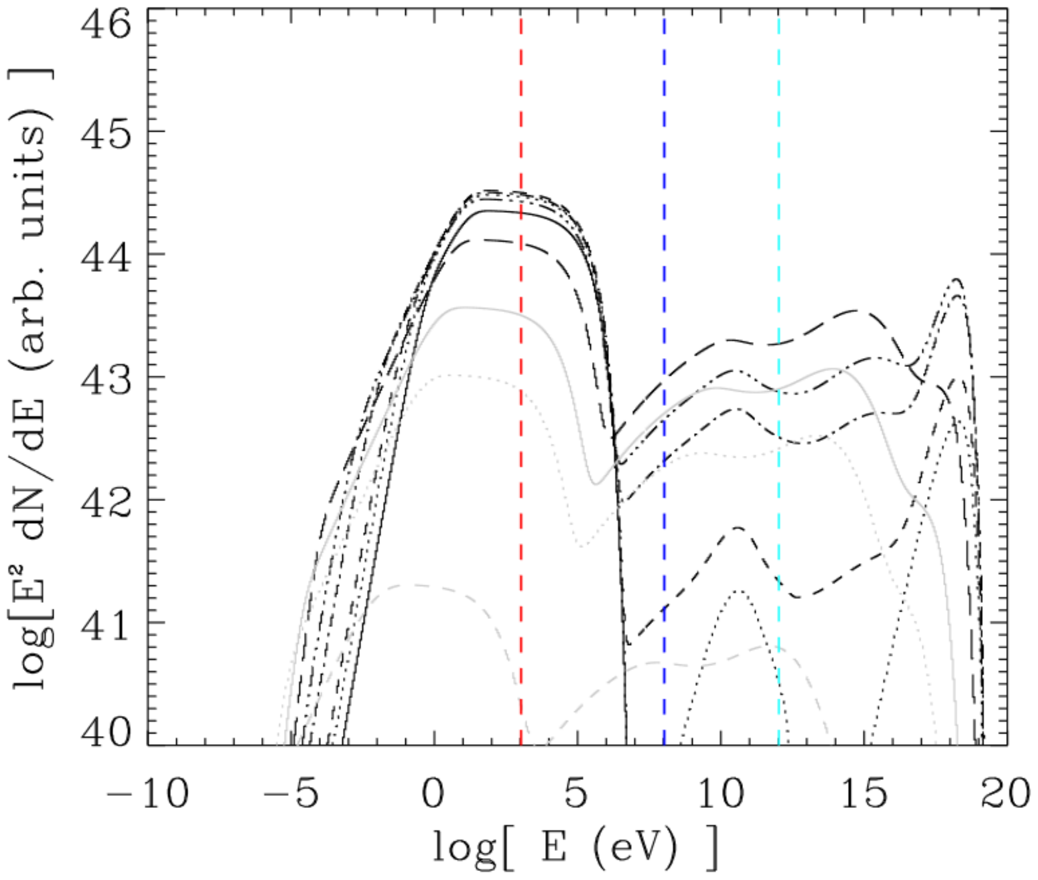
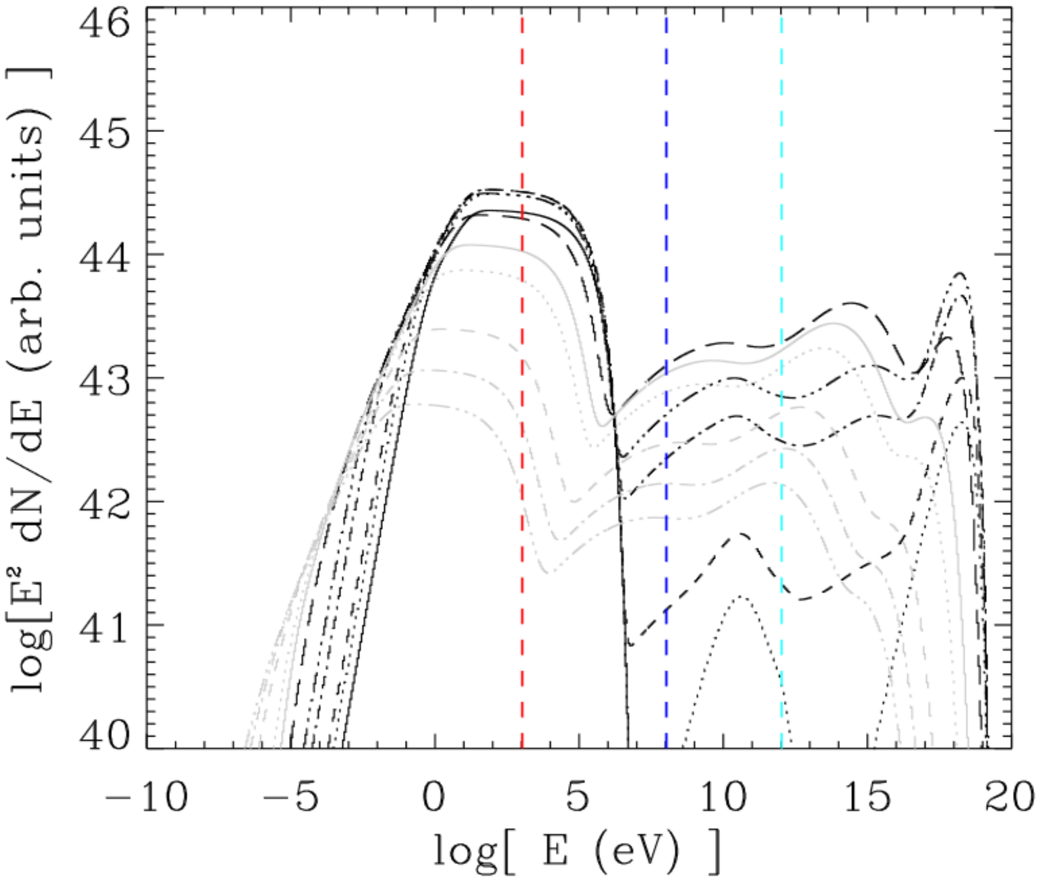
Reimer et al.PoS 444 (ICRC2023) (2023) 1481

# Simple Jet Model

## Straight Jet




## Conical Jet



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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 nuclei up to Z=26, muons, pions, and kaons

### 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

## Documentation

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



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# Outlook

- Implementation of few missing interactions
- Code cleaning (ongoing)
- Comparison with existing codes



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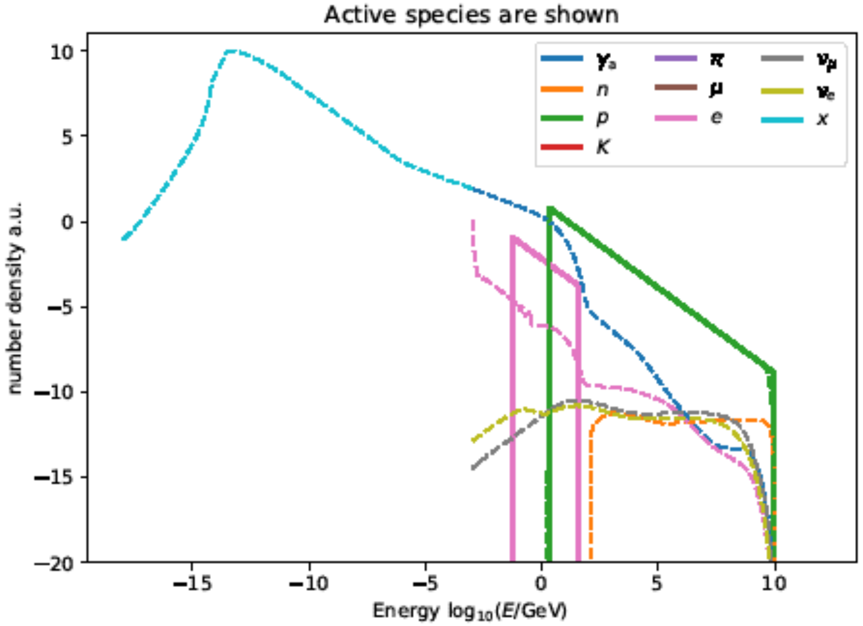
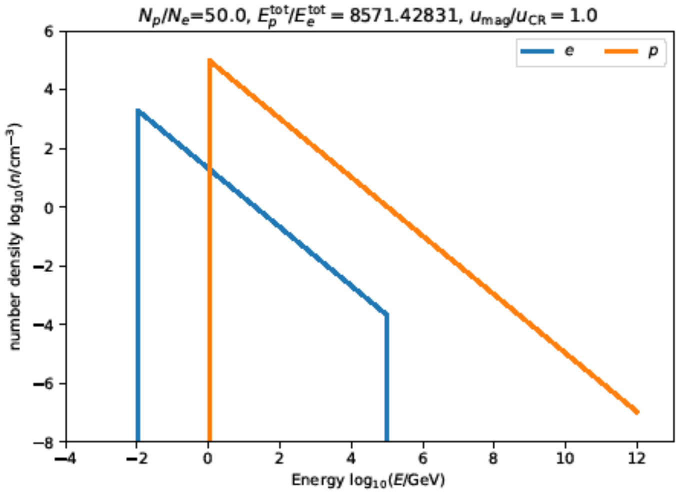
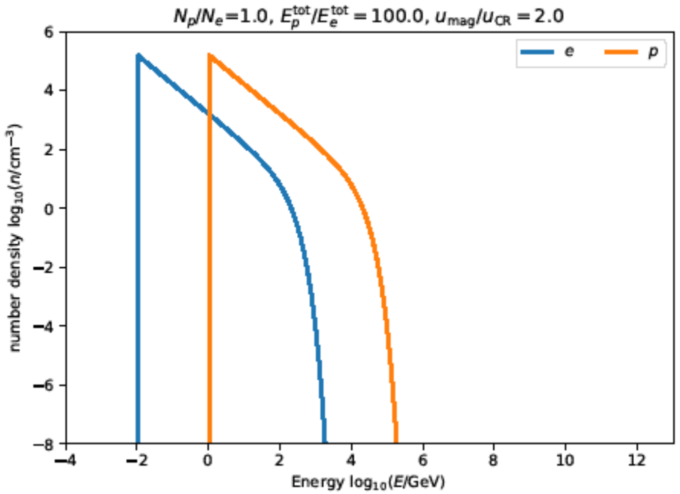
# Backup

# Tests – Basics



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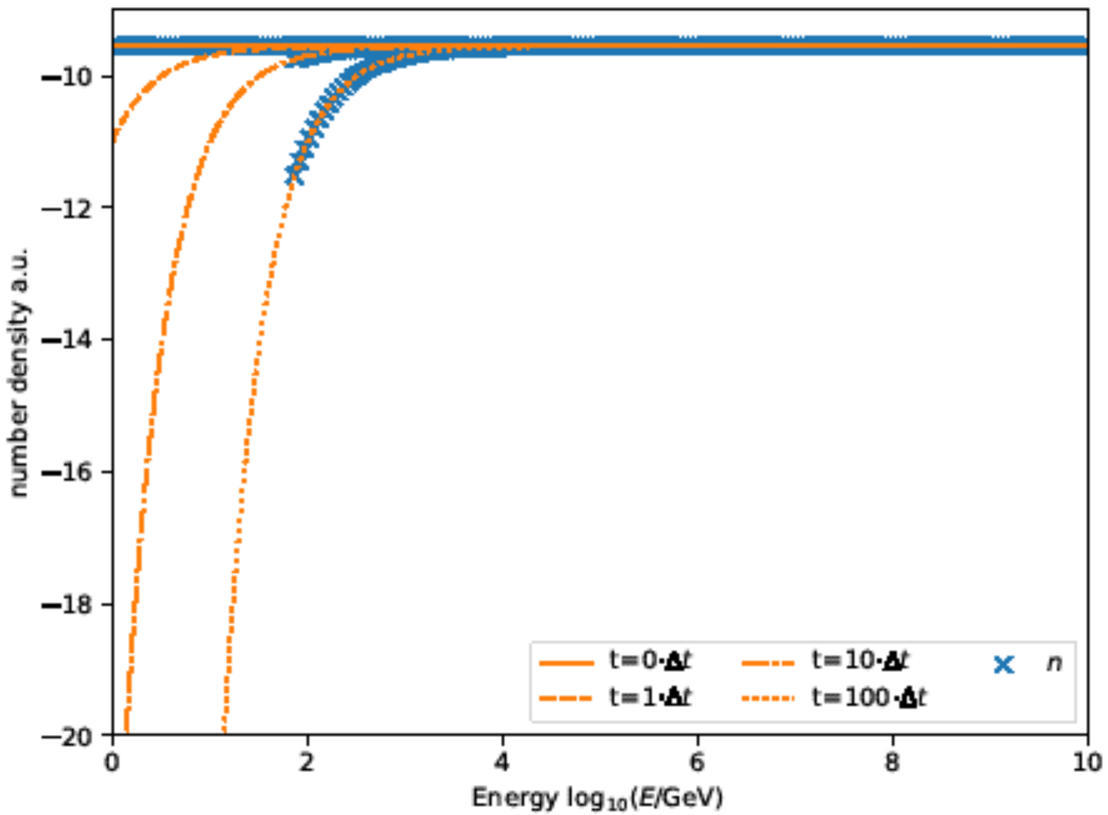
# Tests – Nuclear Decay



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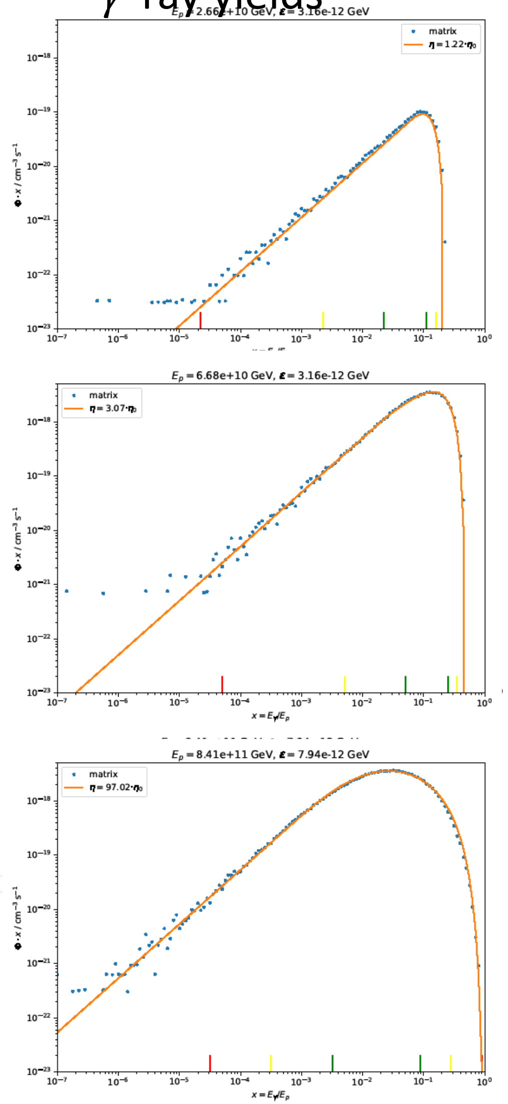
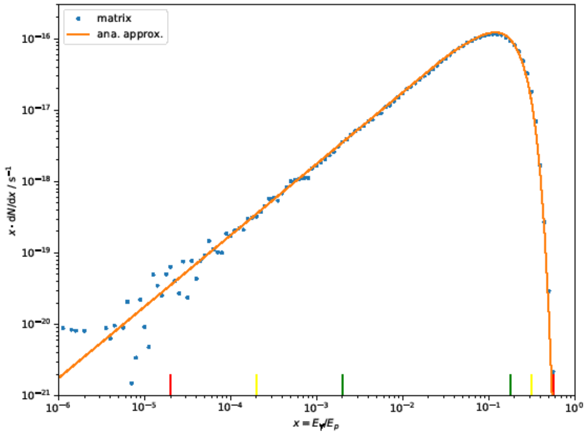
# Tests – Photo-Meson-Production

$\gamma$-ray yields

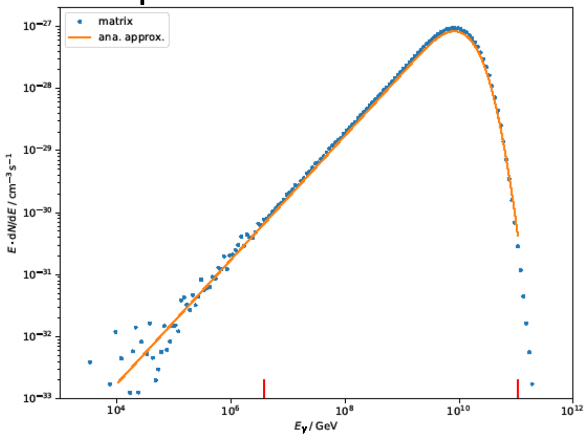



Increasing COM energy

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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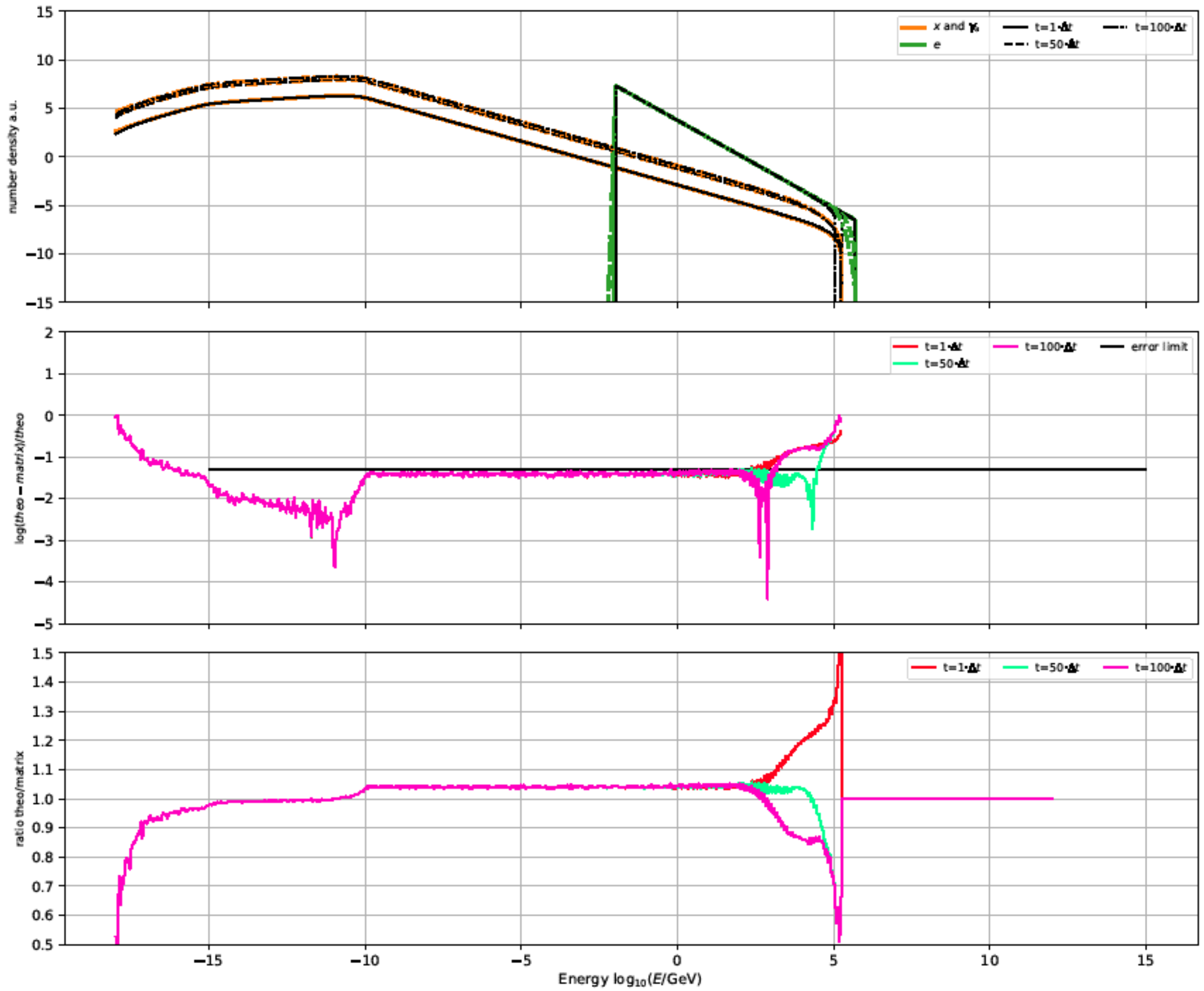
# Tests – Inverse Compton Scattering



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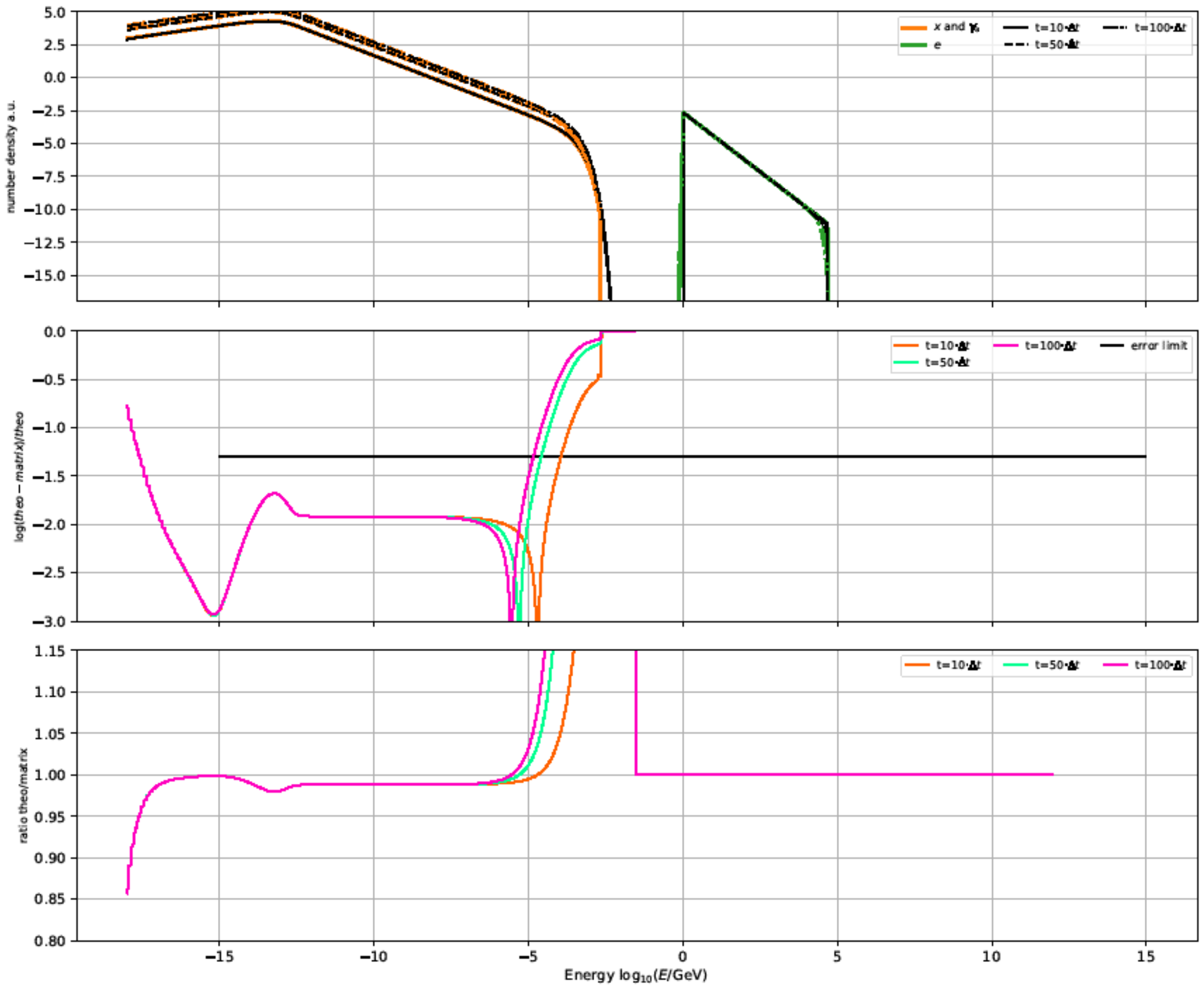
# Tests – Synchrotron Radiation



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