RUHR UNIVERSITÄT BOCHUM

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Synchrotron Module CRPropa 3.2

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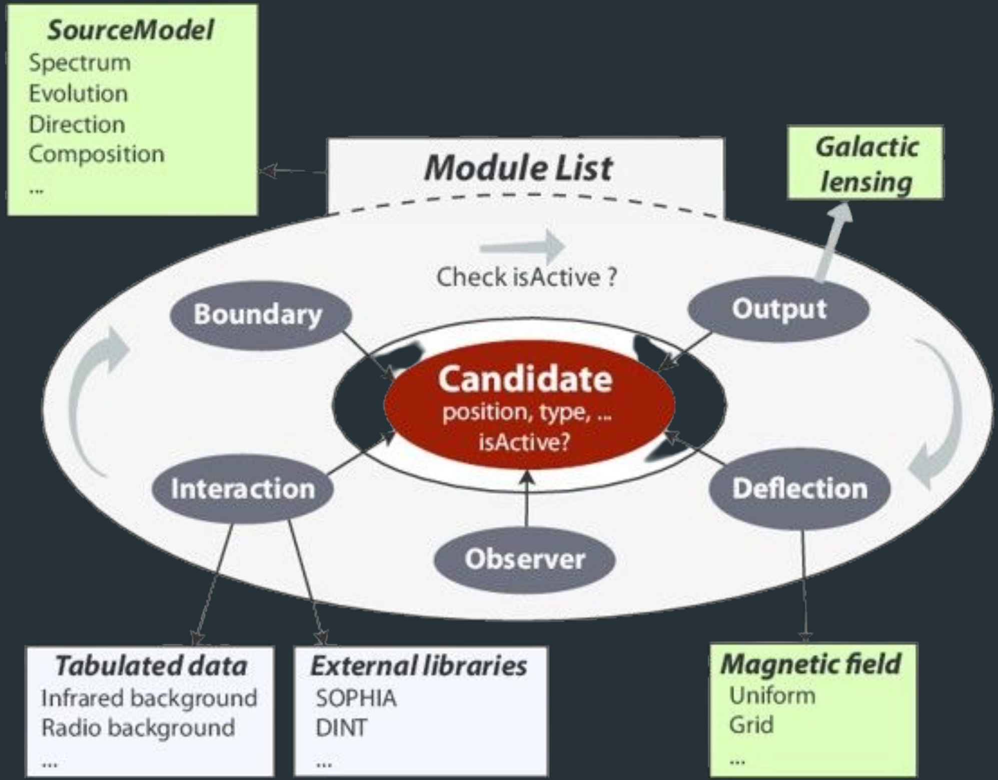
CRPropa 3.2

- High and ultra-high energy particle propagation
  - Modular design with separate modules focusing on cosmic ray propagation and interactions
  - Modules can be customized and extended
  - **Synchrotron Module**



Synchrotron Module - CRPropa 3.2

- Synchrotron radiation is implemented as continuous energy losses from magnetic field interactions

$$\frac{dE}{dx} = \frac{2}{3}\frac{e^2 c}{r^2}\beta^2\gamma^2$$

(Jackson, 1999)

Works Well	Not So Well
- Primary electron energy distributions	- No synchrotron self-absorption - High volume of secondaries

How Secondaries Are Produced

- Random energy values are selected based on probabilities from a distribution function
- Values are selected until a condition is met:

nsamples	defines total number of photon secondaries per step to be accepted
break condition	when photon's energy > primary electron's energy, randomly accepted or rejected
secondary threshold	only photons with energy greater than the threshold will be accepted

- **Problem**: high volume of secondaries are produced

Mitigation Methods

nsamples: the max number of secondary particles that will be accepted

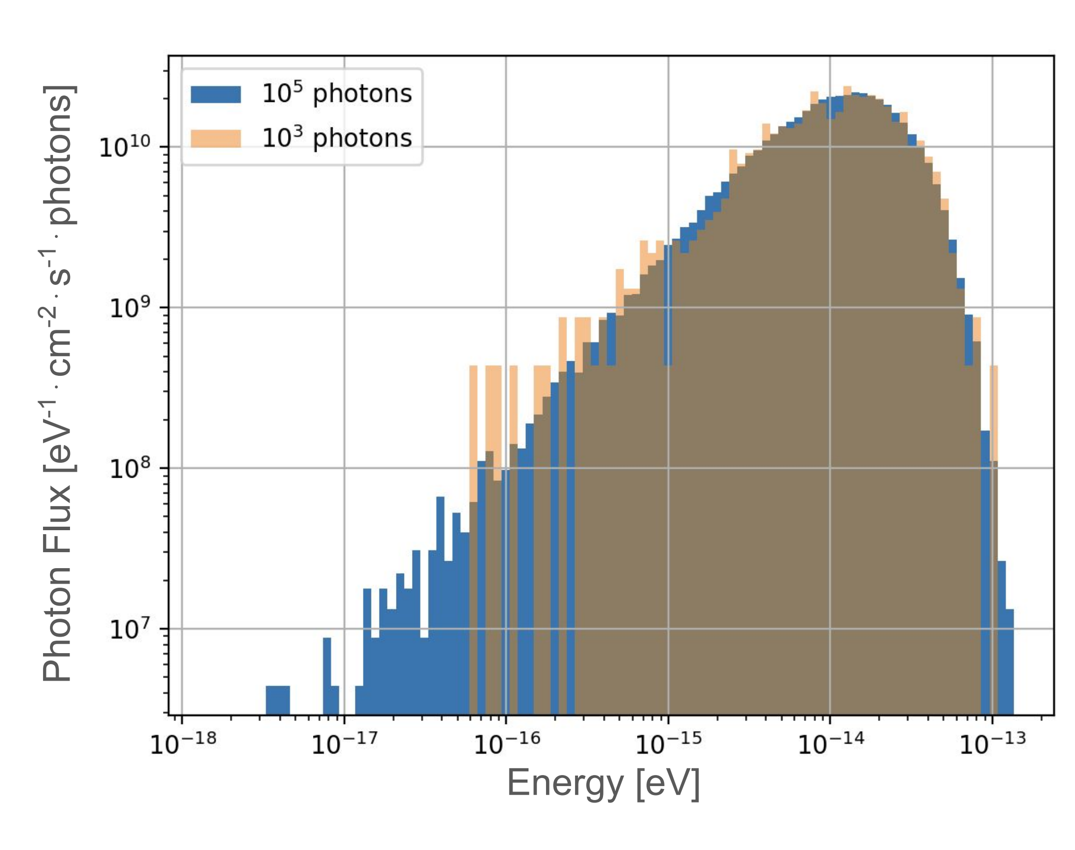
thinning: secondary particles are randomly accepted based on their energy relative to that of the primary particle

critical energy condition: if 14 times the critical energy < secondary threshold, photons will no longer be considered

Problem persists…

Synchrotron Secondary Spectra

- Two outputs where 10^3 and 10^6 photons are accepted
- The secondaries persist to be a problem, prompting the need for alternatives



Synchrotron SED Approach

Produce expected primary energy distribution by directly solving synchrotron radiation via numerical integration:

Electron distribution line of sight integral:

$$I(v,\ \theta,\ l,\ b)\ =\ \int_0^\infty dr\ \epsilon_1(v,\ \theta,\ l,\ b)$$

(Schlikeiser, 2003)

Emission coefficient: $$\epsilon_1(v,\ \theta,\ l,\ b)\ =\ c_1(s)\ m^{(3-s)/4} c\ r_0^{(s+5)/4} \times N_0(r)\ B_\perp^{(s+1)/2}(r)\ v^{(1-s)/2}$$

$$c_1(s)\ =\ \frac{4}{3}\left(\frac{2\pi}{3}\right)^{(s+1)/2}\frac{s+(7/3)}{s+1}\Gamma\left[\frac{3s+7}{12}\right]\Gamma\left[\frac{3s-1}{12}\right]$$

Synchrotron SED Approach

Produce expected primary energy distribution by directly solving synchrotron radiation via numerical integration:

Advantages	Disadvantages
High precision	Computationally expensive for large volume of particles

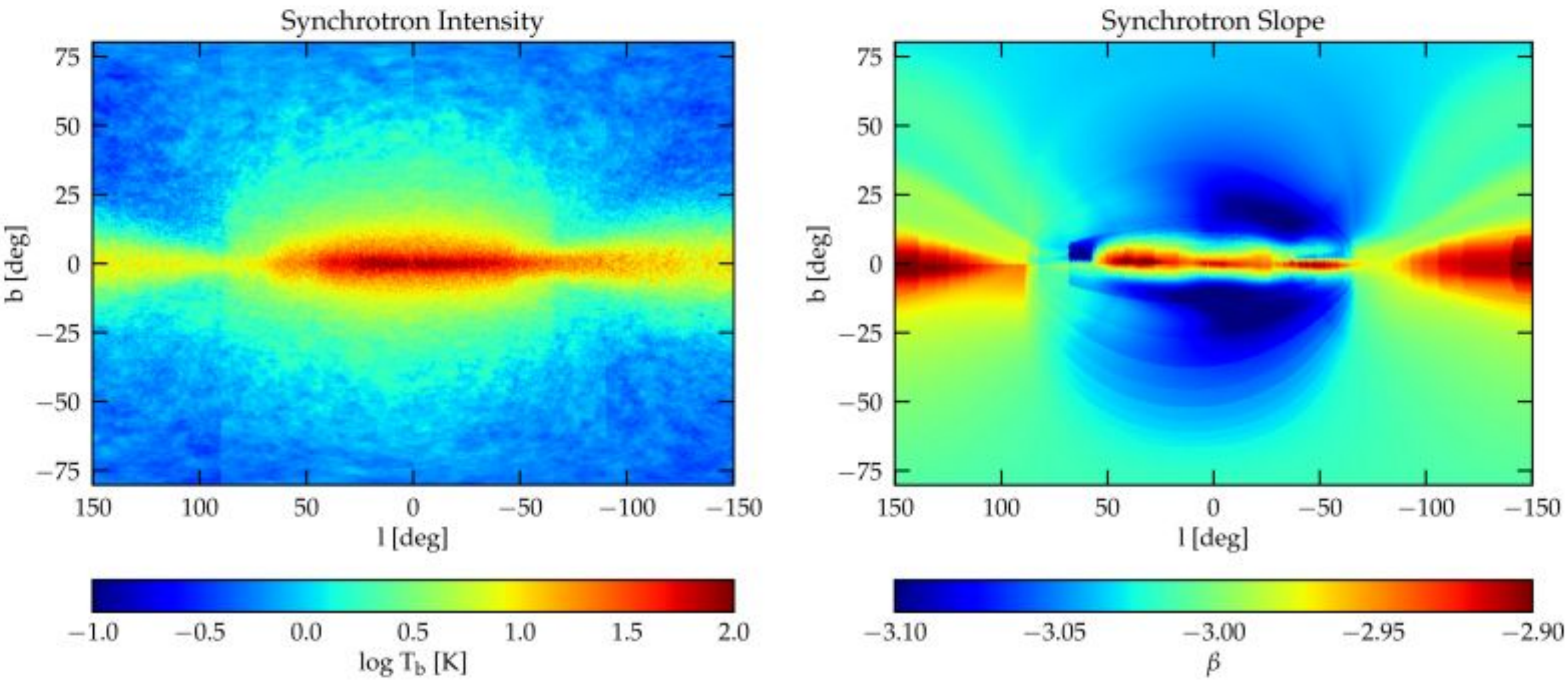
HERMES Framework

- HERMES is a public code that generates skymaps of radiative Galactic processes through line of sight integration
  - Written in C++ with Python binding via pybind11
  - Parts of the Infrastructure adapted from CRPropa

Define Line of Sight	Spatial Grid of Target Region	Define Integration Path	Interactions	Sky Map
within the Milky Way	Discretize the target region into grid cells	from observer's line of sight through grid cells	Simulate interactions of particles within each grid cell along line of sight	Generate a sky map for the simulated process (i.e. synchrotron)

Open-Ended Questions

- Alternate approaches to synchrotron radiation?
- HERMES to supplement CRPropa?
- HERMES for extragalactic galaxies as point sources?
- Are secondaries relevant? Synchrotron loss modelling?
- User-defined magnetic field in synchrotron module?



Cartesian projection in Galactic coordinates of the synchrotron intensity (left panel) and of the synchrotron slope (right panel). Both plots are computed at the frequency of 408 MHz (Dundovic et al., 2021).

Plan: Feed cosmic ray density from CRPropa into HERMES' synchrotron integrator to produce synchrotron skymaps and recreate synchrotron spectra