ACROPOLIS: A generiC fRamework fOr Photodisintegration Of LIght elementS

Based on 2011.XXXXX

Available on GitHub

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TOOLS 2020, Tools for High Energy Physics and Cosmology

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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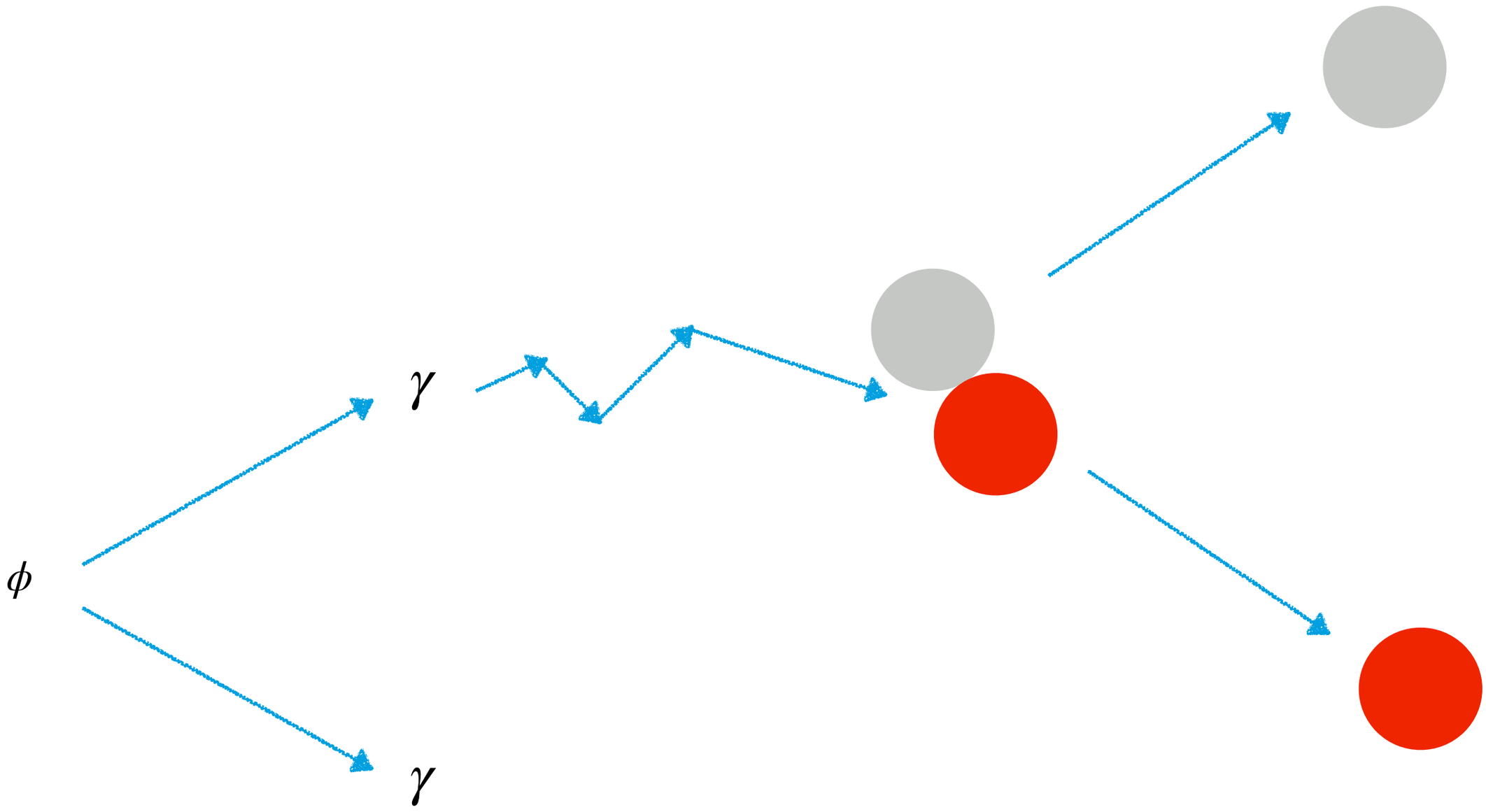
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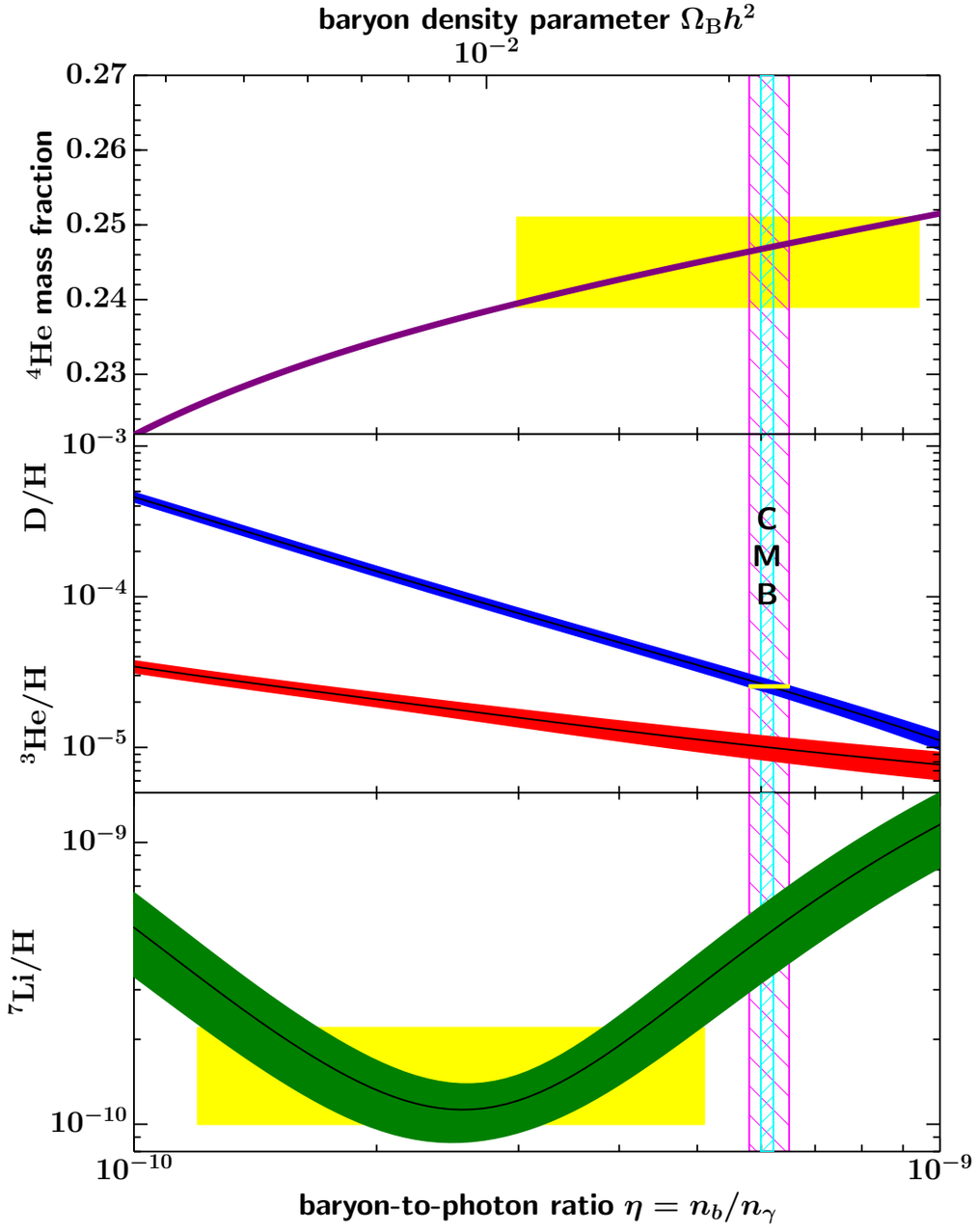
Outline

- BBN vs. Photodisintegration
- Non-thermal photon spectrum
- Non-thermal nucleosynthesis
- ACROPOLIS
  - Overview
  - Example: Decay of decoupled MeV-scale BSM particle
  - Implementing your own model
- Summary

BBN vs. Photodisintegration

BBN

- BBN: formation of light nuclei via nuclear reactions in the early Universe
  $t \sim 1 - 10^3\,\mathrm{s},\ T \sim \mathrm{MeV} - \mathrm{keV}$
- Description of reactions via Boltzmann equations
- Good agreement between SM prediction and observations
- Publicly available codes (e.g. AlterBBN [arXiv: 1806.11095], PArthENoPE [arXiv: 1712.04378], PRIMAT [arXiv: 1801.08023])

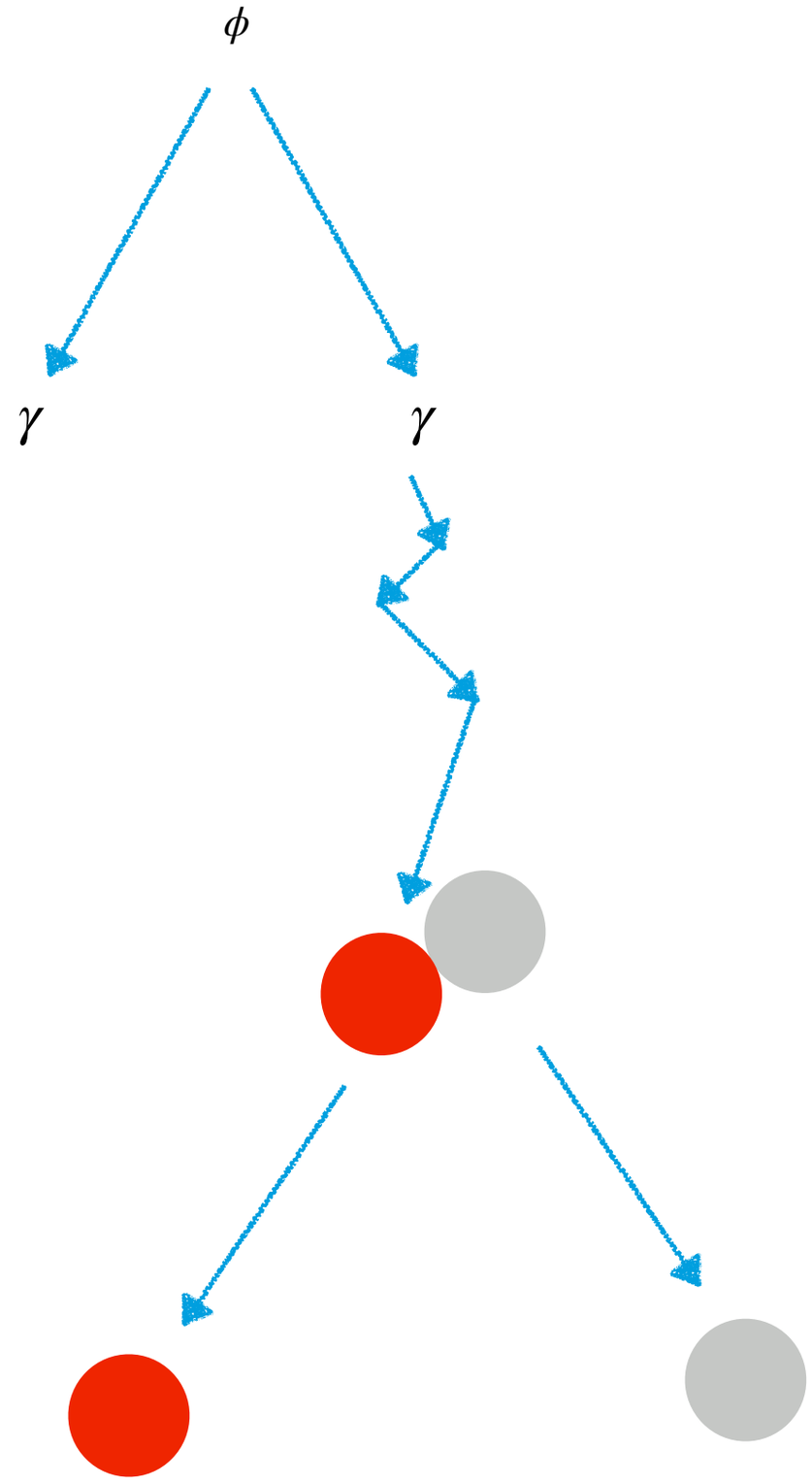


PDG 2019, http://pdg.lbl.gov/2019/reviews/rpp2019-rev-bbang-nucleosynthesis.pdf

BBN vs. Photodisintegration

Photodisintegration

- What happens if there are late-time ($t \gtrsim 10^4\,\mathrm{s}$) high-energy ($E \gtrsim 1.5\,\mathrm{MeV}$) electromagnetic injections into the SM (after BBN)?
  - Resulting electromagnetic cascade leads to high-energetic non-thermal part of photon spectrum
  - Photodisintegration of primordial light nuclei
- ACROPOLIS first publicly available code for photodisintegration



Non-thermal photon spectrum

Boltzmann equation

- Spectra differential in energy $\mathrm{f}_x(t,E) = g_x f_x(t,p) Ep/(2\pi^2)$
- Boltzmann equation with quasi-static equilibrium, $\Gamma_x \gg H$ [arXiv: astro-ph/9412055, hep-ph/0604251], $x \in \{e^{\pm}, \gamma\}$

$$\frac{\partial \mathrm{f}_x(E)}{\partial t} \simeq S_x(E) - \Gamma_x(E)\mathrm{f}_x(E) + \sum_{x'} \int_E^\infty \mathrm{d}E'\, K_{x'\to x}(E,E')\mathrm{f}_{x'}(E') \simeq 0$$

$$\mathrm{f}_x(E) = \frac{1}{\Gamma_x(E)} \left(S_x(E) + \sum_{x'} \int_E^\infty \mathrm{d}E'\, K_{x'\to x}(E,E')\mathrm{f}_{x'}(E') \right)$$

- $S_x(E) = S_x^{(0)}\delta(E-E_0) + S_x^{(\mathrm{FSR})}(E)$ source term
- Γ_x total interaction rate
- $K_{x'\to x}$ differential interaction rate
- After $\mathrm{F}_x(E) = \mathrm{f}_x(E) - S_x^{(0)}\delta(E-E_0)/\Gamma_x(E)$ solution via discretization method

Non-thermal photon spectrum

Reactions

- Most important reactions are
  - Double photon pair creation $\gamma\gamma_{\mathrm{th}} \rightarrow e^{+}e^{-}$
  - Photon-photon scattering $\gamma\gamma_{\mathrm{th}} \rightarrow \gamma\gamma$
  - Bethe-Heitler pair creation $\gamma N \rightarrow e^{+}e^{-}N$
  - Compton scattering $\gamma e^{-}_{\mathrm{th}} \rightarrow \gamma e^{-}$
  - Inverse Compton scattering $e^{\pm}\gamma_{\mathrm{th}} \rightarrow e^{\pm}\gamma$
- Non-thermal photon spectrum close to universal spectrum [arXiv: astro-ph/0211258] if injection energy is above threshold for double photon pair creation,
  $E_0 > E^{\mathrm{th}}_{e^{+}e^{-}} = m_e^2/(22T)$
- Photodisintegration only possible if $E^{\mathrm{th}}_{e^{+}e^{-}}$ is above disintegration thresholds,
  $T \lesssim 7.5\,\mathrm{keV}$

Non-thermal nucleosynthesis

- Boltzmann equation $\dot{Y}_X(t) = \Sigma_j\, Y_j(t)\Gamma_{j\gamma\to X}(t) - Y_X(t)\Sigma_{j'}\,\Gamma_{X\gamma\to j'}(t)$
- $Y_X = n_X/n_b$
- $\Gamma_r(t) = \int_0^\infty \mathrm{d}E\, \mathrm{f}_\gamma(t,E)\sigma_r(E)$ reaction rates
- σ_r cross-section

- ODE with previously calculated photon spectrum, solution for $\bar{Y} = [Y_n, Y_p, Y_D, \ldots]^T$
- $\bar{Y}(T) = \exp\left(\int_{T_0}^{T} \mathrm{d}T'\, R(T')\right)\bar{Y}(T_0)$
- $[R(T)]_{XX'} = \frac{\mathrm{d}t}{\mathrm{d}T} \times [\Gamma_{X'\gamma\to X}(T) - \delta_{XX'}\Sigma_{j'}\,\Gamma_{X\gamma\to j'}(T)]$ rate matrix

ACROPOLIS

A generiC fRamework fOr Photodisintegration Of LIght elementS

- First publicly available code for photodisintegration of primordial light elements
- Open-source, GPL3
- Written in Python (version ≥ 3.8), dependencies NumPy (≥ 1.19.1), SciPy (≥ 1.5.2), Numba (≥ 0.51.2)
- Available via GitHub
- Optional database files (~500 MB, use wget) of electromagnetic cascade reaction rates for speed-up (~10 min without, ~1 min with database files), place in data/
- Includes example programs for
  - Decay of decoupled MeV-scale BSM particle
  - Residual annihilations of MeV-scale DM
- Modular framework can easily be adapted for a given BSM model
- Scanning framework

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Overview

Model

- Source terms
- Temperature range
- Injection energy E_0
- Anything else that is needed
- ex. DecayModel, AnnihilationModel

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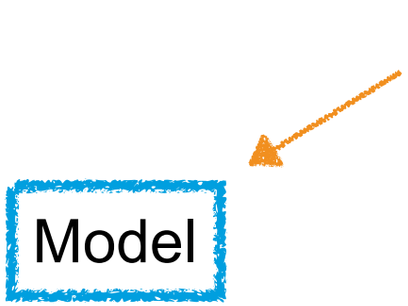
Overview



- Reads in input data
- abundance_file
- cosmo_file
- param_file
- Supplies methods for interpolation of

$T, \mathrm{d}T/\mathrm{d}t, H, \ldots$

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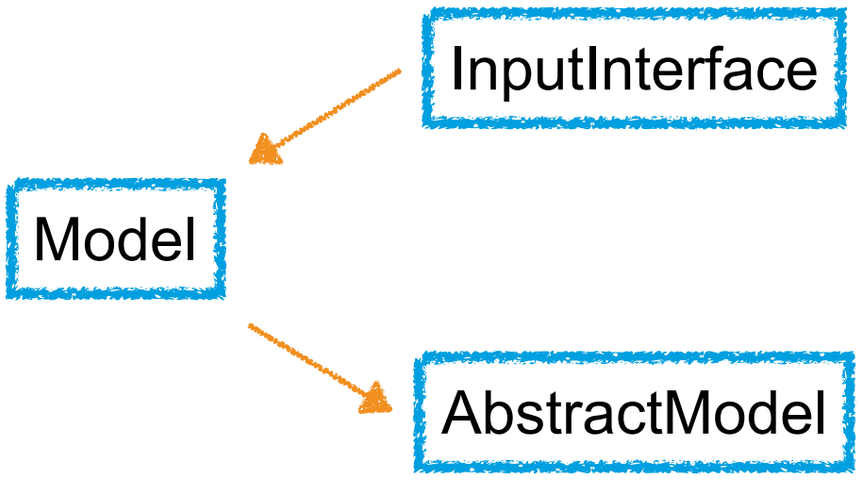
Overview



- Abstract class for models
- Passes source terms & temperature range to model
- Needs InputInterface & injection energy E_0 in constructor
- Provides method run_disintegration

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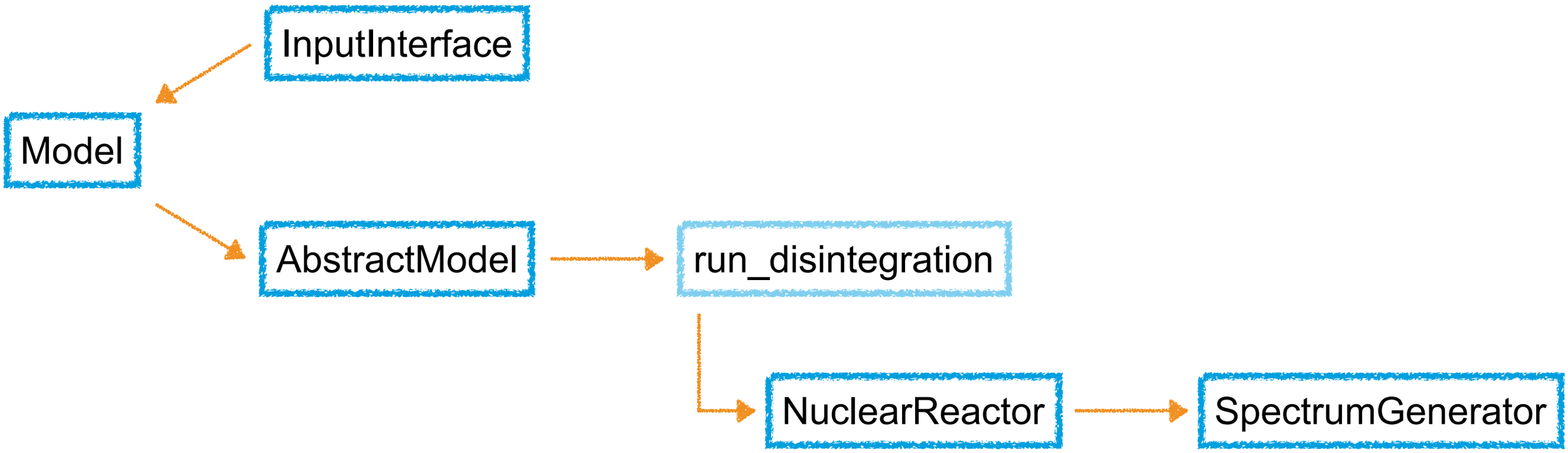
Overview



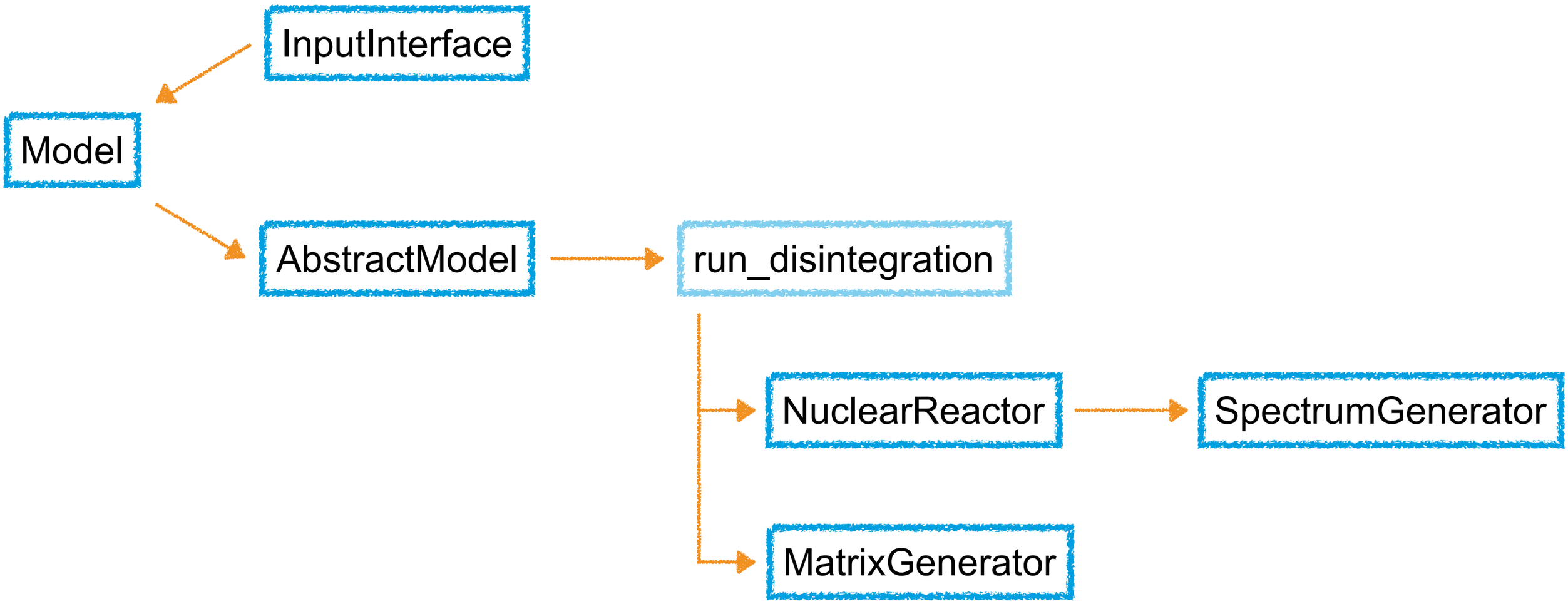
- Calculates reaction rates

$$\Gamma_r(t) = \int_0^\infty \mathrm{d}E\, \mathrm{f}_\gamma(t, E)\sigma_r(E)$$

- Calculates f_γ

ACROPOLIS

Overview



- Calculates rate matrix $R(T)$
- Integrates $\int_{T_0}^{T_f} \mathrm{d}T\, R(T)$

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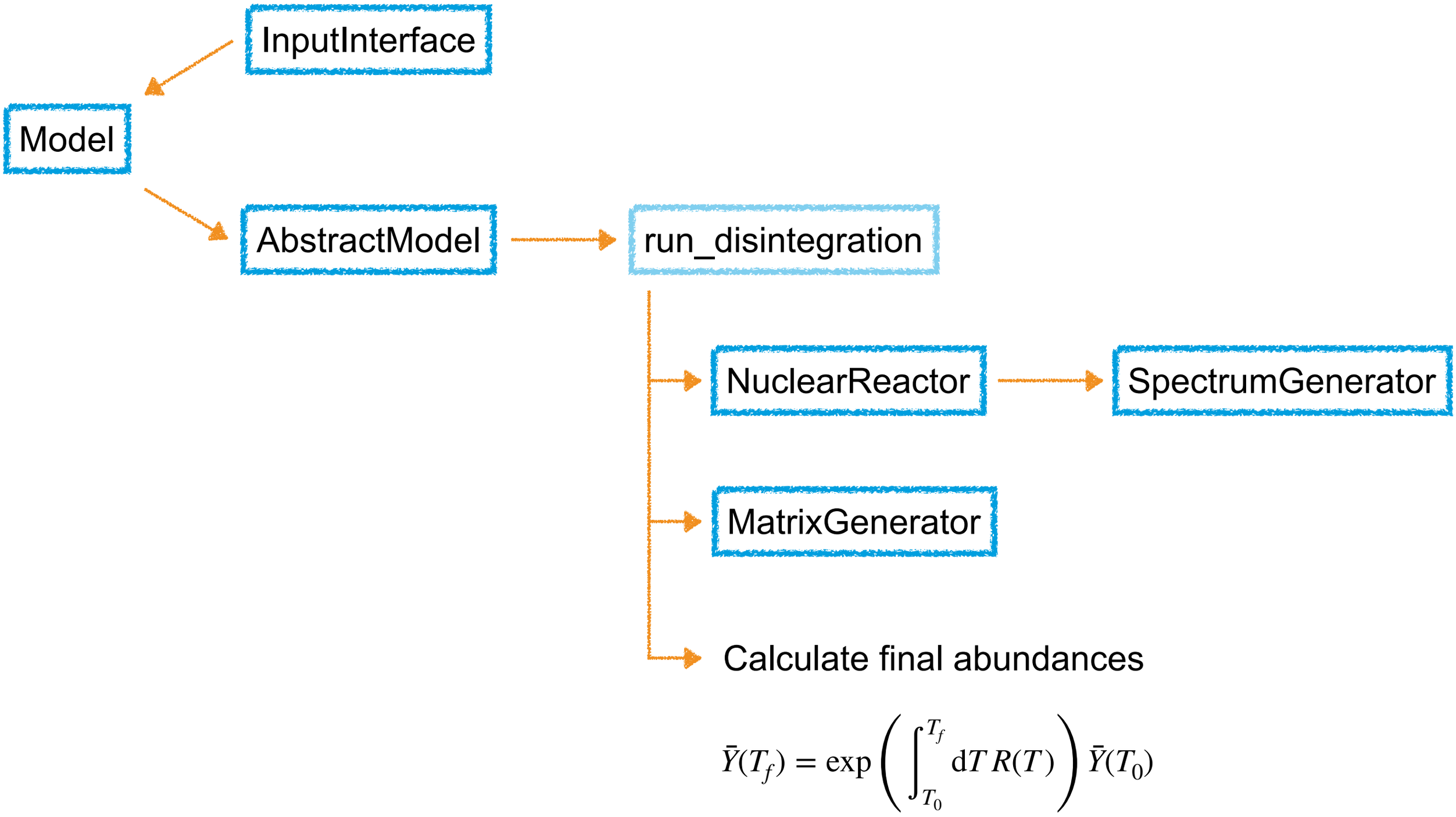
Overview



$$\bar{Y}(T_f) = \exp\left(\int_{T_0}^{T_f} \mathrm{d}T\, R(T)\right) \bar{Y}(T_0)$$

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Example: Decay of decoupled MeV-scale BSM particle

- Implemented in DecayModel
- Particle ϕ, mass m_ϕ, lifetime τ_ϕ, branching ratios $\mathrm{BR}_{e^+e^-}$, $\mathrm{BR}_{\gamma\gamma}$
- Injection energy $E_0 = m_\phi/2$
- Source terms $S_x(E) = S_x^{(0)}\delta(E - E_0) + S_x^{(\mathrm{FSR})}(E)$,
  - $S_\gamma^{(0)} = \mathrm{BR}_{\gamma\gamma} \times 2n_\phi/\tau_\phi$
  - $S_{e^-}^{(0)} = S_{e^+}^{(0)} = \mathrm{BR}_{e^+e^-} \times n_\phi/\tau_\phi$
  - $S_\gamma^{(\mathrm{FSR})}(E) = \mathrm{BR}_{e^+e^-} \times \frac{n_\phi}{\tau_\phi E_0} \times \frac{\alpha}{\pi} \frac{1 + (1-x)^2}{x} \ln\left(\frac{4E_0^2(1-x)}{m_e^2}\right) \times \Theta\left(1 - \frac{m_e^2}{4E_0^2} - x\right)$
- Number density $n_\phi(t) \simeq n_\phi(T_0) \times \left(a(t_0)/a(t)\right)^3 \exp(-t/\tau_\phi)$
- SM cosmo_file and abundance_file
- Callable via ./decay m_ϕ/MeV τ_ϕ/s T_0/MeV $n_\phi(T_0)/n_\gamma(T_0)$ $\mathrm{BR}_{e^+e^-}$ $\mathrm{BR}_{\gamma\gamma}$
- Similar interface for residual annihilations of DM particle

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Example: Decay of decoupled MeV-scale BSM particle

acropolis — -zsh — 68×19

```
[depta@Frederiks-MacBook-Pro acropolis % ./decay 10 1e5 10 1e-10 0 1 ]
INFO    : Extracting/Reading data files.
INFO    : Finished after 4.5s.
INFO    : Calculating non-thermal spectra and reaction rates.
INFO    : Finished after 21.8s.
INFO    : Running non-thermal nucleosynthesis.
INFO    : Finished after 18.9s.
      |      mean      |      high      |       low
-----------------------------------------------------------
    n | 1.27835e-08 | 1.24894e-08 | 1.31176e-08
    p | 7.53096e-01 | 7.53161e-01 | 7.53036e-01
   H2 | 1.92535e-05 | 1.88105e-05 | 1.97567e-05
   H3 | 5.53065e-08 | 2.28921e-08 | 3.76285e-07
  He3 | 7.63949e-06 | 3.27977e-06 | 7.82619e-06
  He4 | 6.17092e-02 | 6.16965e-02 | 6.17237e-02
  Li6 | 8.39044e-15 | 2.70471e-14 | 1.30028e-15
  Li7 | 1.98144e-11 | 7.64333e-12 | 6.47316e-11
  Be7 | 3.24951e-10 | 1.29786e-10 | 3.05213e-10
depta@Frederiks-MacBook-Pro acropolis %
```

ACROPOLIS

Implementing your own model

- Needed methods:
  - Source terms for monochromatic energy in photons and electrons
  - Final state radiation source term (only photons)
  - Temperature range, where to perform calculation
- Needed information for InputInterface:
  - cosmo_file: at least containing $t, T, \mathrm{d}T/\mathrm{d}t, T_\nu, H$; possible to extend
  - param_file: at least containing baryon-to-photon ratio η; possible to extend
  - abundance_file: calculated abundances from BBN, rows for nuclei (ordered by mass and charge number), columns for different values (e.g. mean, low, high from AlterBBN)

Summary

- ACROPOLIS is first public code for photodisintegration of light elements
- Calculates non-thermal photon spectrum and effect on light elements via photodisintegration
- Includes example programs for
  - Decay of decoupled MeV-scale BSM particle
  - Residual annihilations of MeV-scale DM
- Modular framework can easily be adapted for a given BSM model
- Available via GitHub
- Manual soon to appear on arXiv

Thank you