Numerical Electron Degradation in Kilonovae

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EMI + IReNA workshop, October 20th 2022

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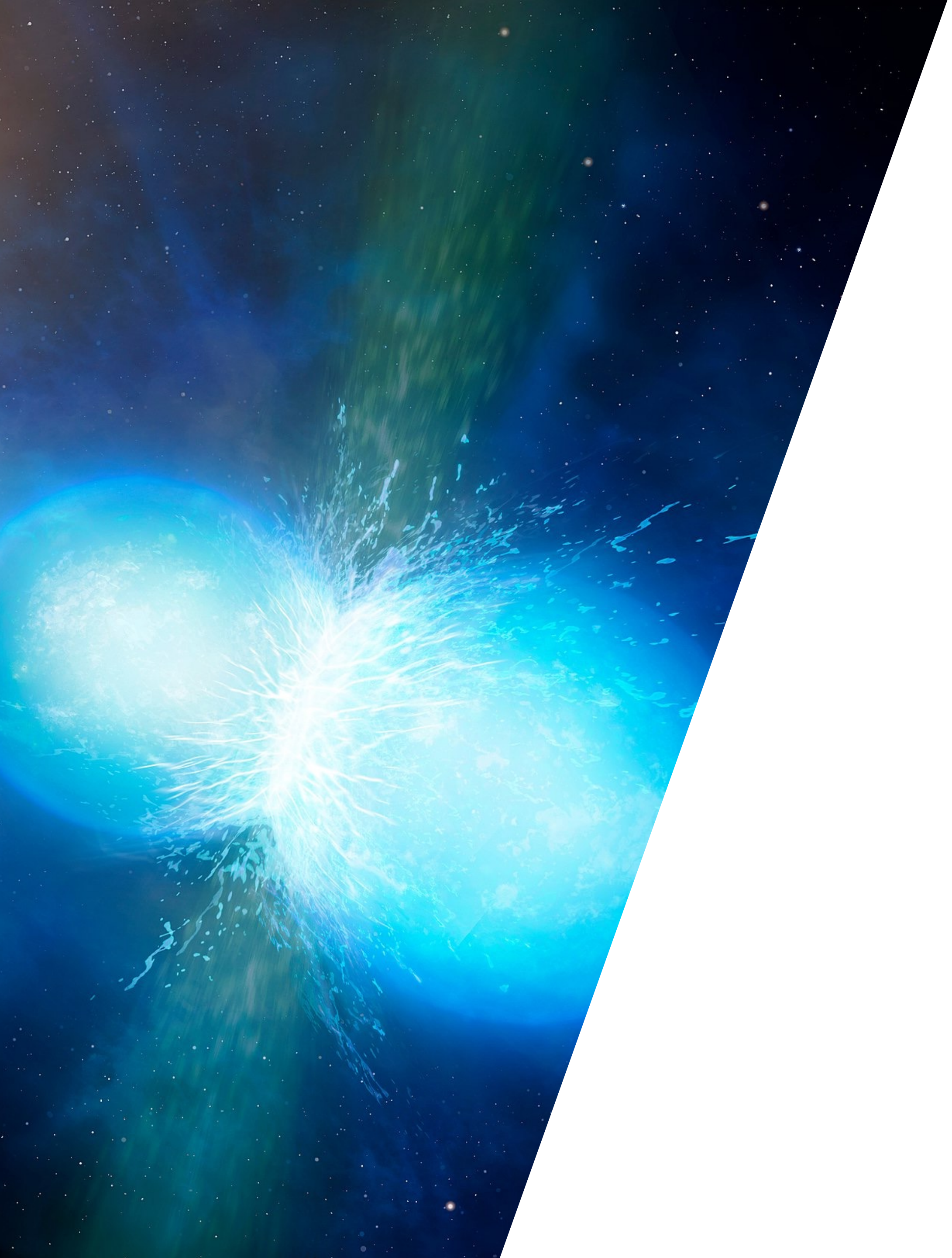

Outline

- Time dependent nebular phase
  and the non-thermal electrons
- Ionization cross-sections
- Numerical non-thermal electron degradation

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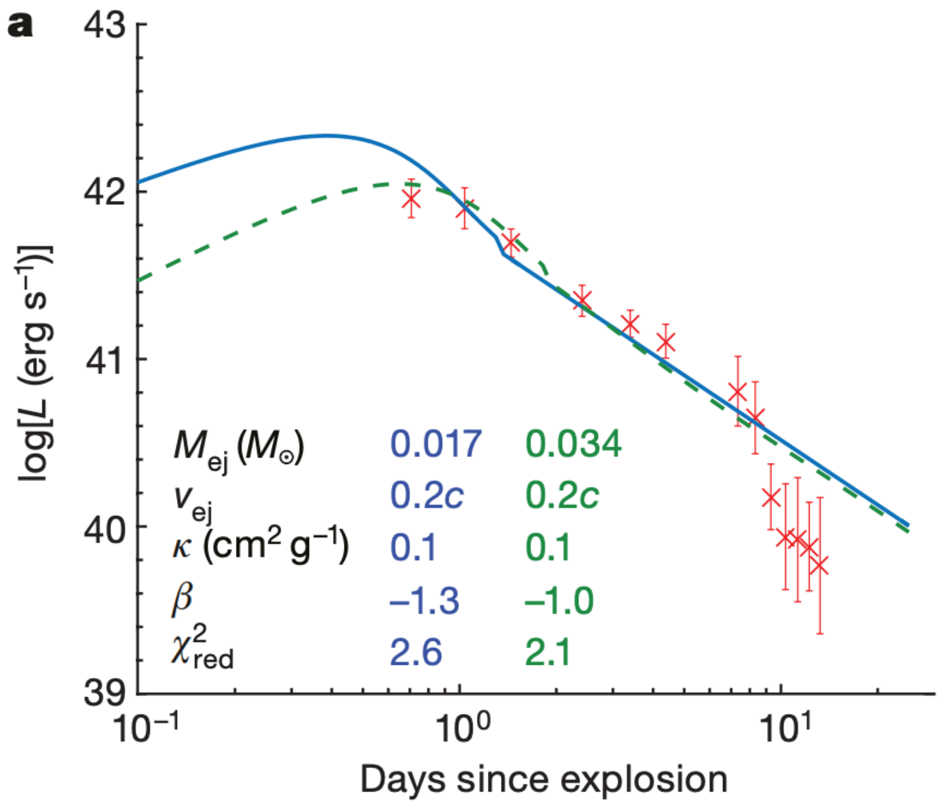
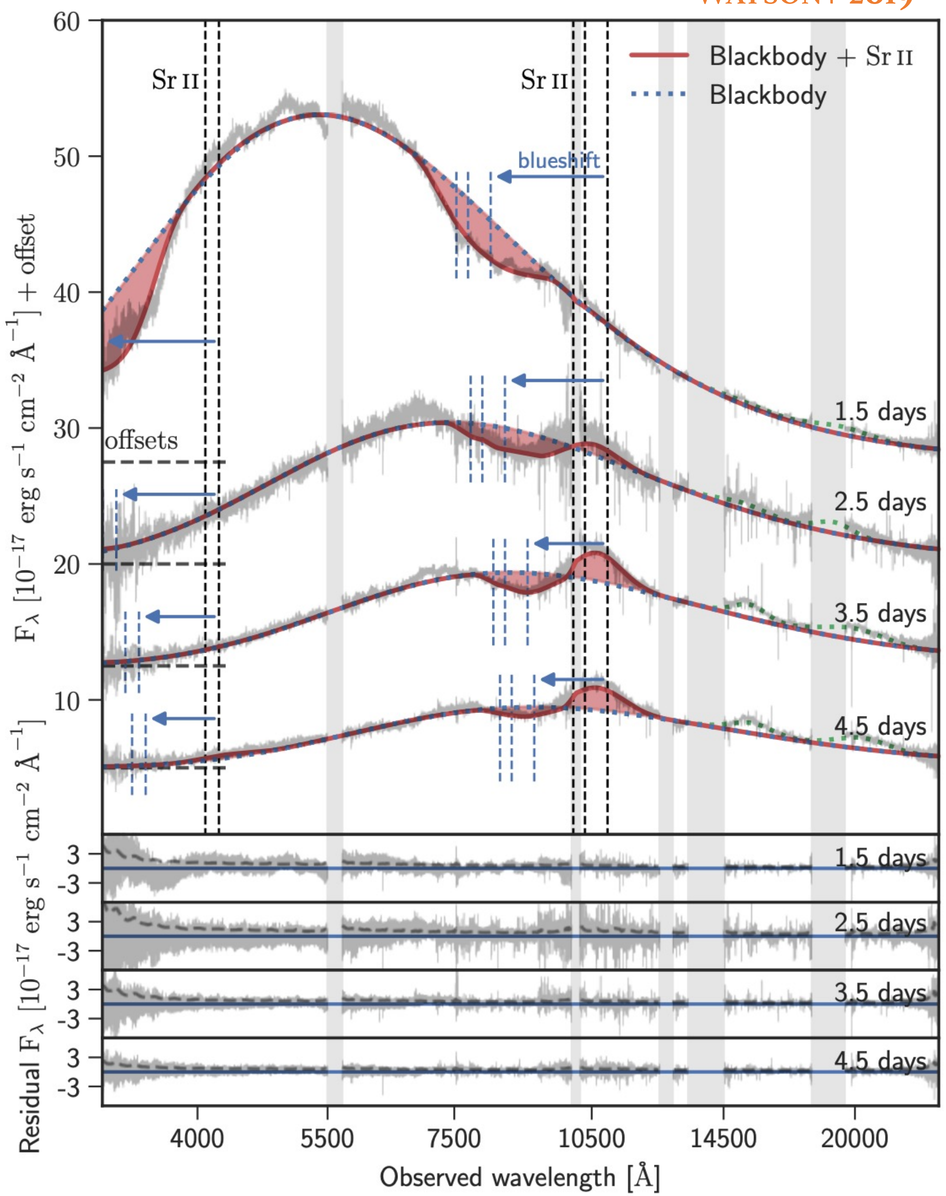
The nebular phase

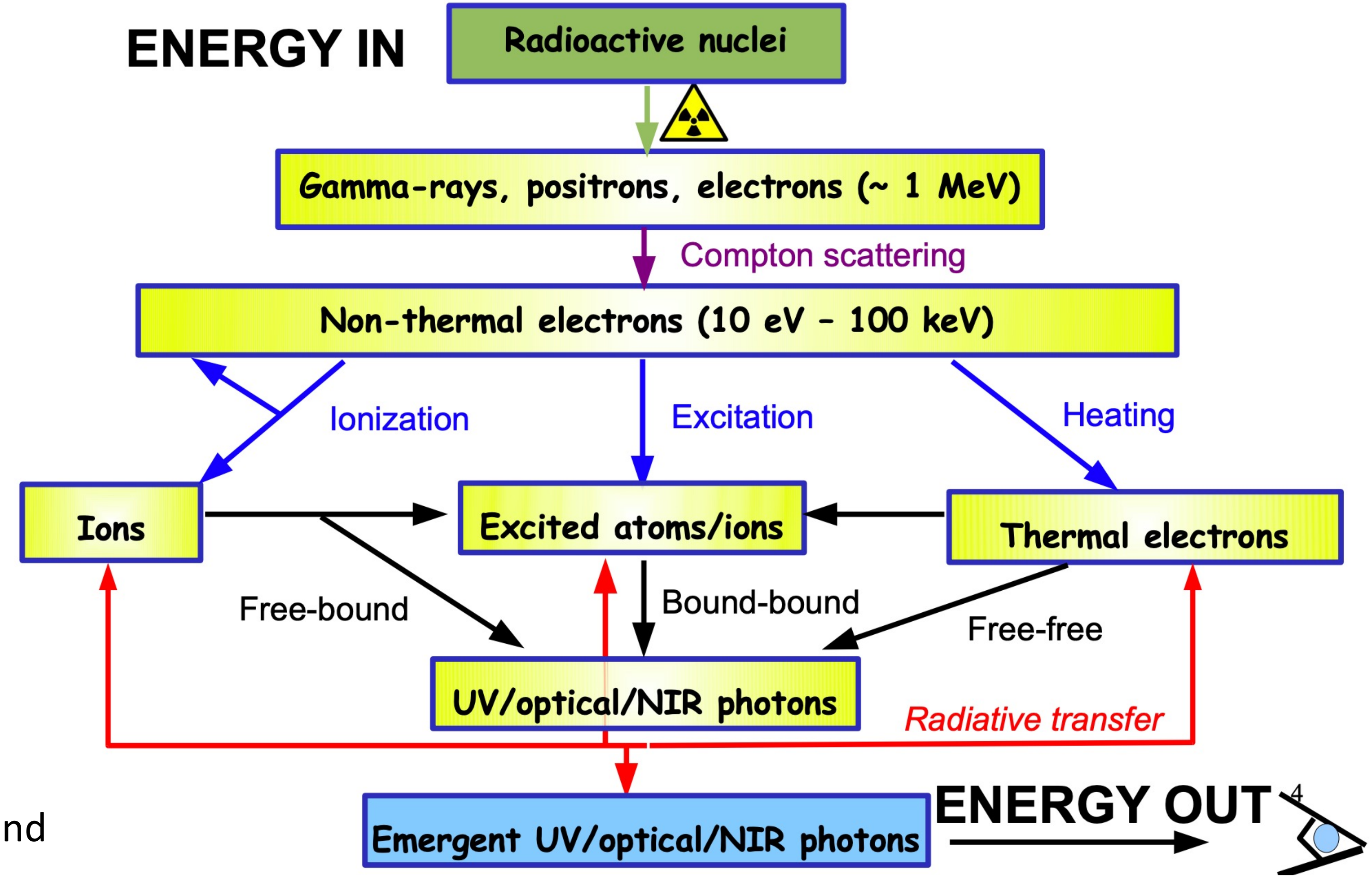


SMARTT+ 2017

WATSON+ 2019



The nebular phase



Credits: A. Jerkstrand

Time-dependence

Barnes & Kasen 2016, Kasen & Kasen 2019, Barnes+2021

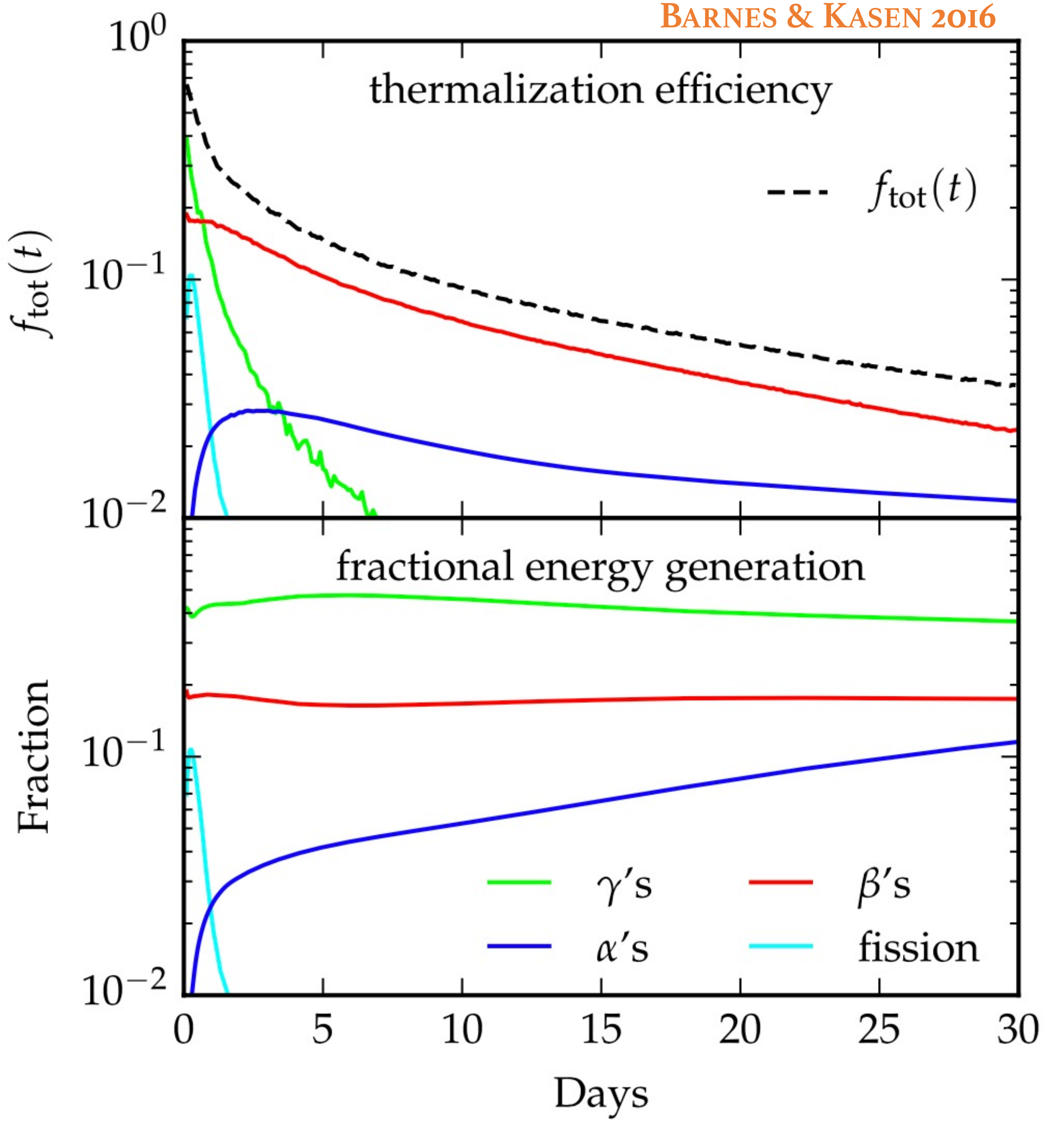
Time-dependent thermalisation efficiency

$$f_p(t) = \frac{\dot{E}_{th}}{\dot{E}_{rad}} = \frac{\ln\left[1 + 2\left(\frac{t}{t_{ineff,p}}\right)^2\right]}{2\left(\frac{t}{t_{ineff,p}}\right)^2}.$$

$$f_{tot}(t) = 0.36\left[\exp(-at) + \frac{\ln(1 + 2bt^d)}{2bt^d}\right],$$

LTE: total heating fraction + Saha-Boltzmann

Barnes & Kasen 2016



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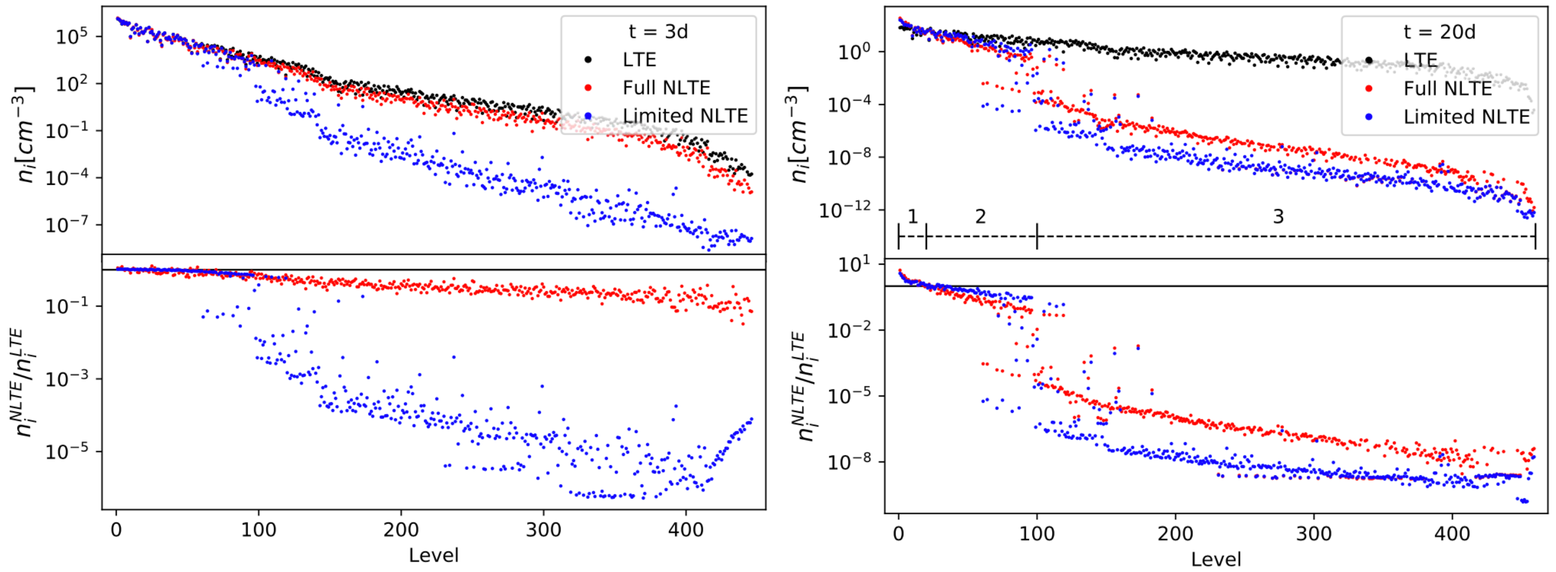
Local vs Non-local Thermodynamical Equilibrium

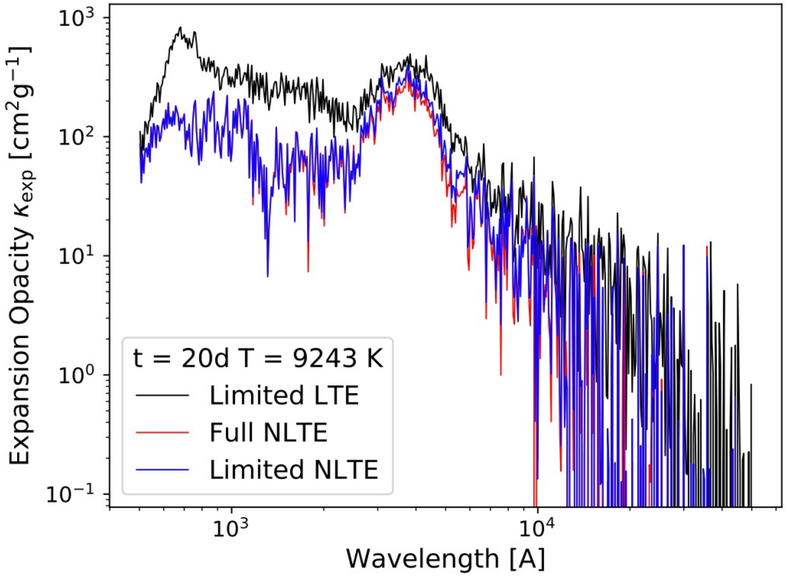
LTE is insufficient after 10 days

Pognan+ 2022



Level populations for CeII

Pognan+ 2022



Expansion opacities

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Time-dependence

Barnes & Kasen 2016, Kasen & Barnes 2019, Barnes+2021

Time-dependent thermalisation efficiency

$$f_{\mathrm{p}}(t) = \frac{\dot{E}_{\mathrm{th}}}{\dot{E}_{\mathrm{rad}}} = \frac{\ln\left[1 + 2\left(\frac{t}{t_{\mathrm{ineff,p}}}\right)^2\right]}{2\left(\frac{t}{t_{\mathrm{ineff,p}}}\right)^2}.$$

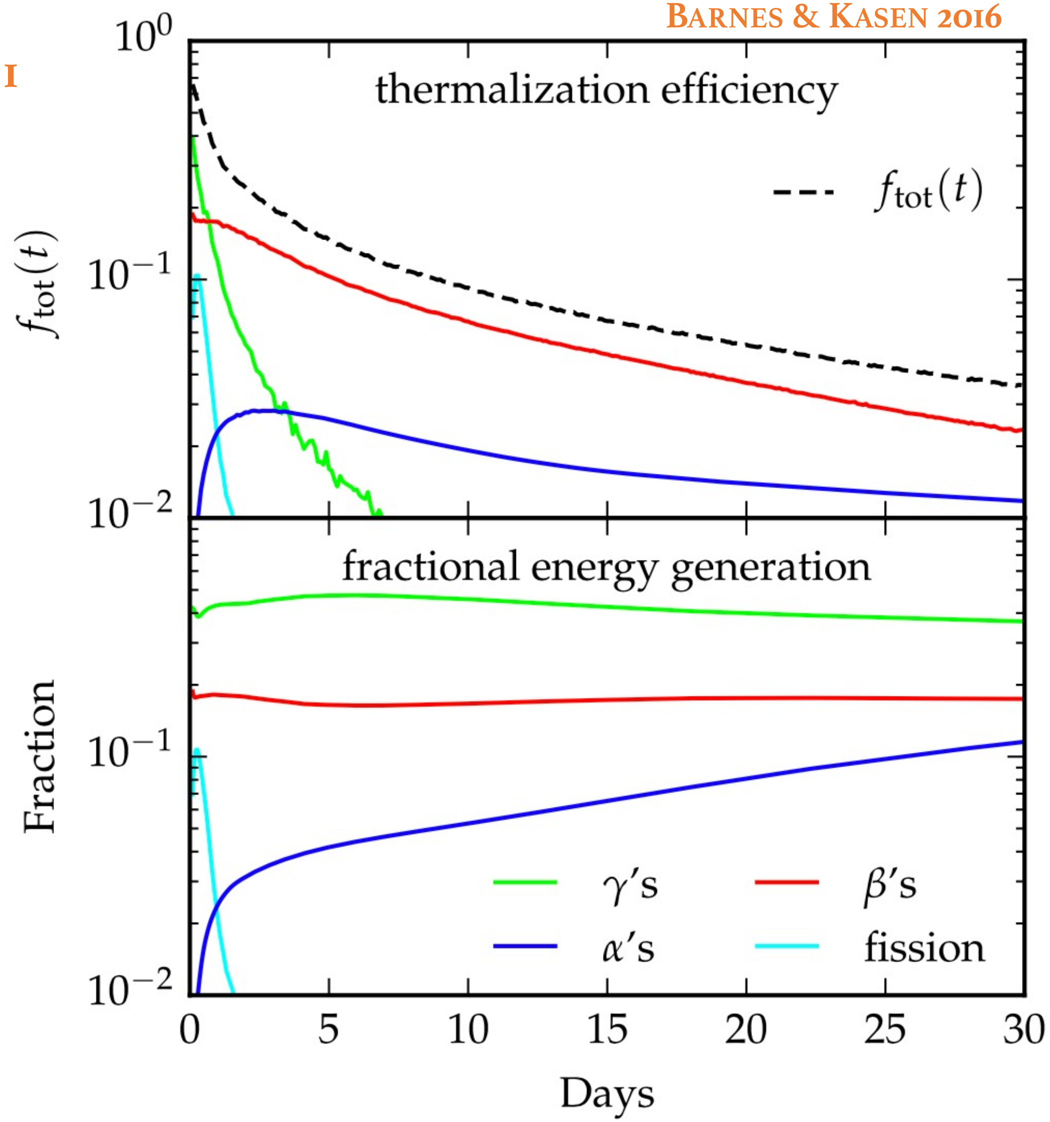
$$f_{\mathrm{tot}}(t) = 0.36\left[\exp(-at) + \frac{\ln(1 + 2bt^d)}{2bt^d}\right],$$

LTE: total heating fraction + Saha-Boltzmann

NLTE: Every energy deposition channel fraction:

- Heating
- Ionization
- Excitation

Barnes & Kasen 2016



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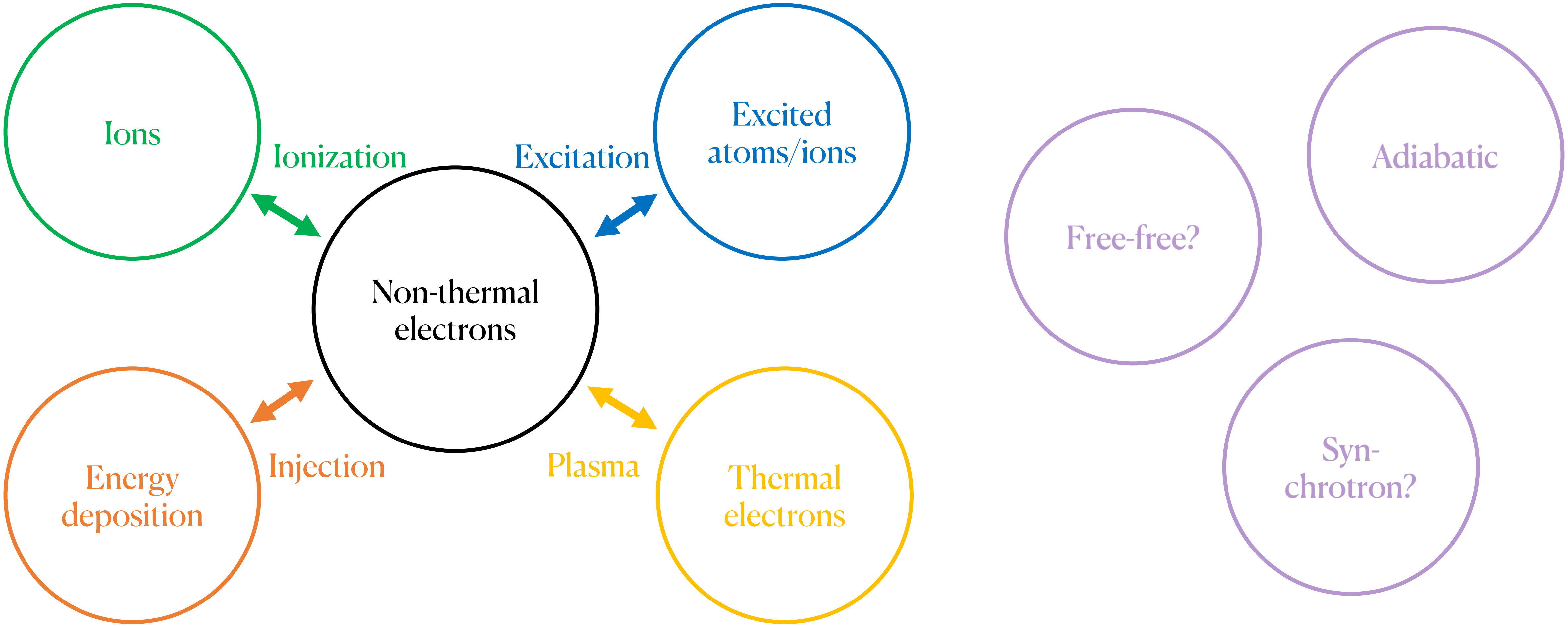
Non-thermal electron degradation

Competition between processes



Non-thermal electron degradation

COMPETITION BETWEEN PROCESSES

https://github.com/eliotayache/elec_degrad

Plasma losses: Huba+2013

Bremsstrahlung:

Barnes&Kasen2016: Includes tabulated cross-sections from Seltzer&Berger for various compositions. Includes screening at low energies.

Bethe1934: Does not include screening at low energies.

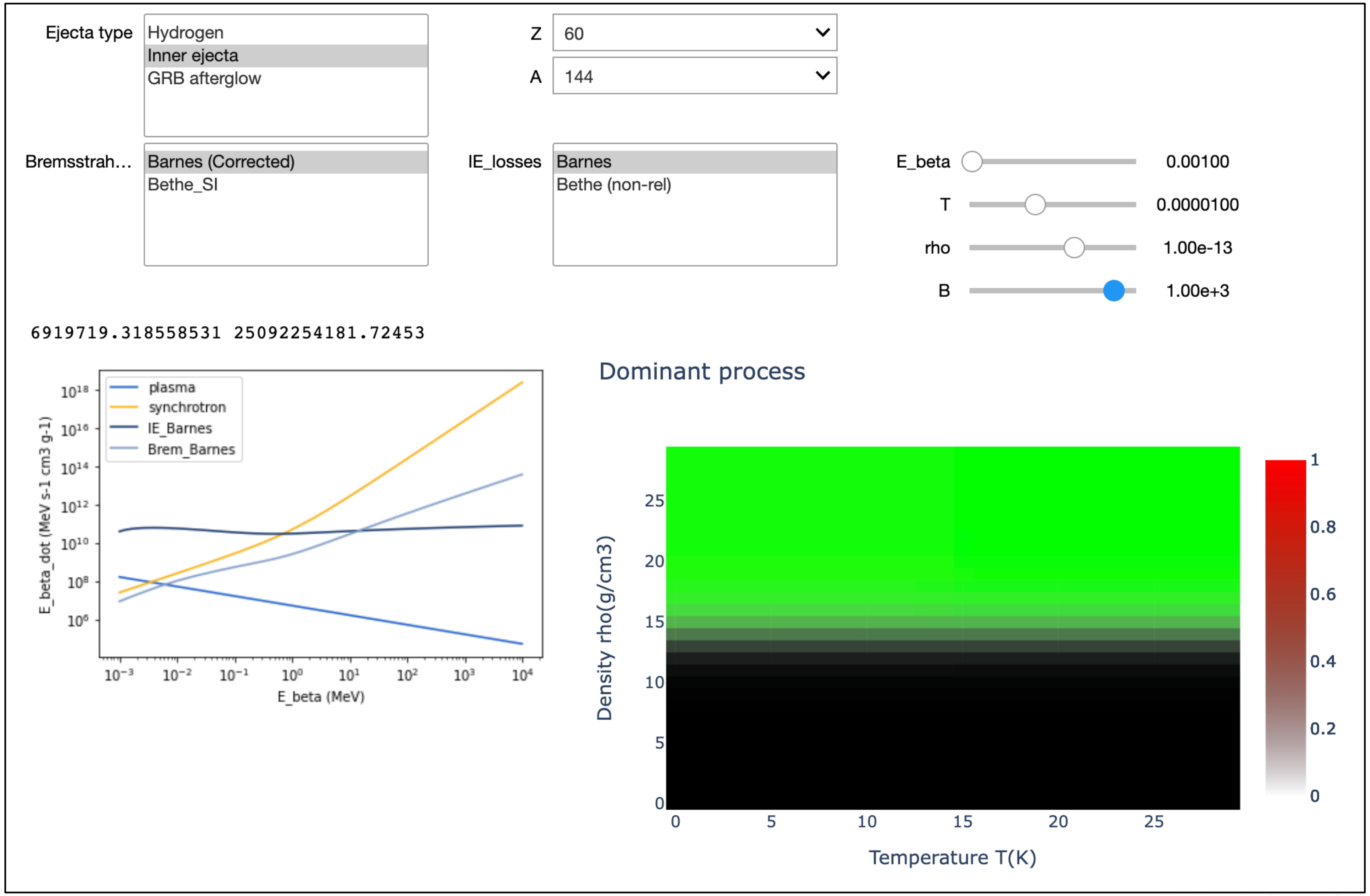
Ionization/Excitation:

Barnes&Kasen2016: includes excitation and ionization for averaged composition

Bethe formulation: non-relativistic. Only includes ionization.

Synchrotron

total synchrotron radiated energy for a single electron.



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Non-thermal electron degradation

Assumptions and Challenges

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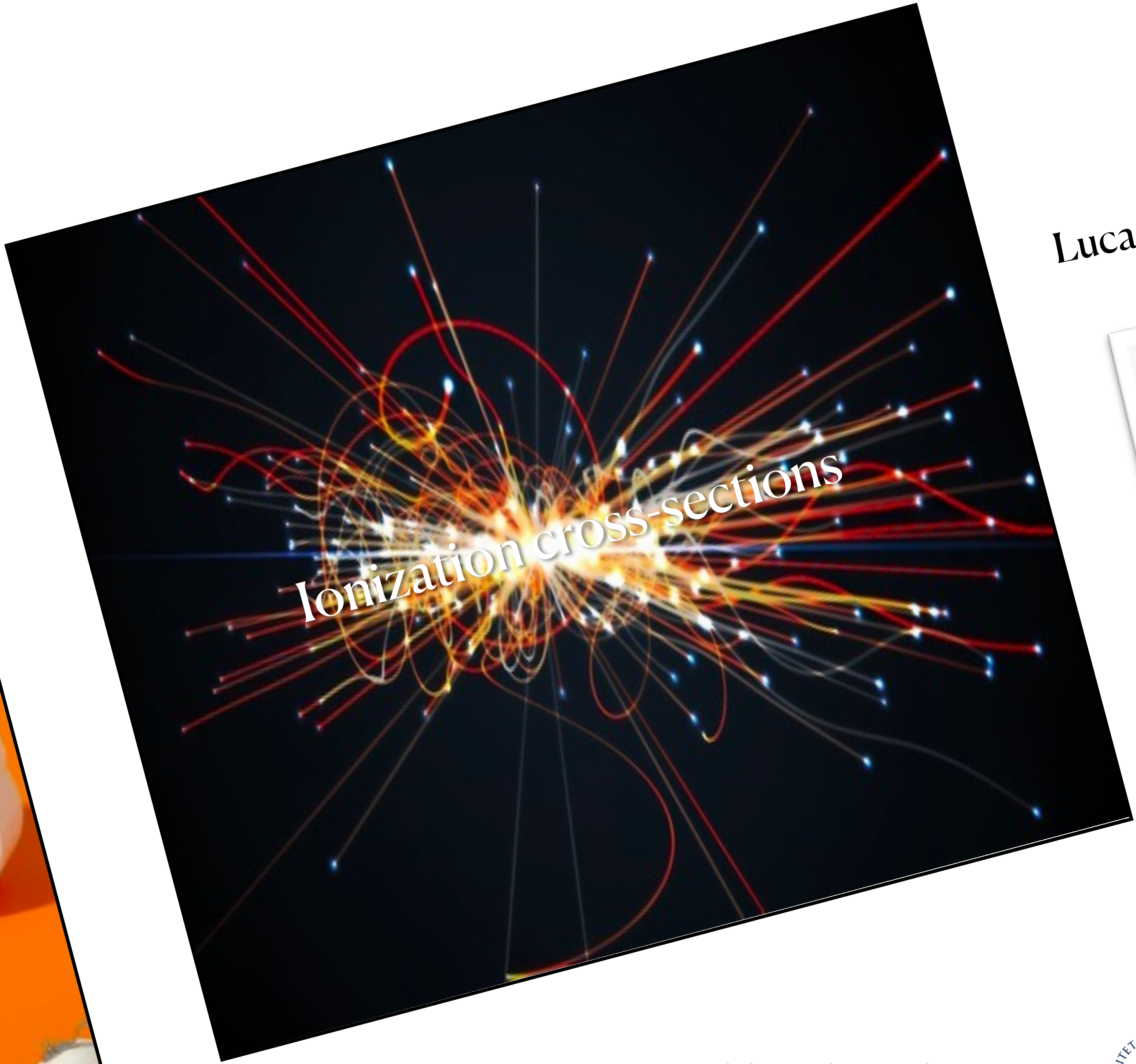
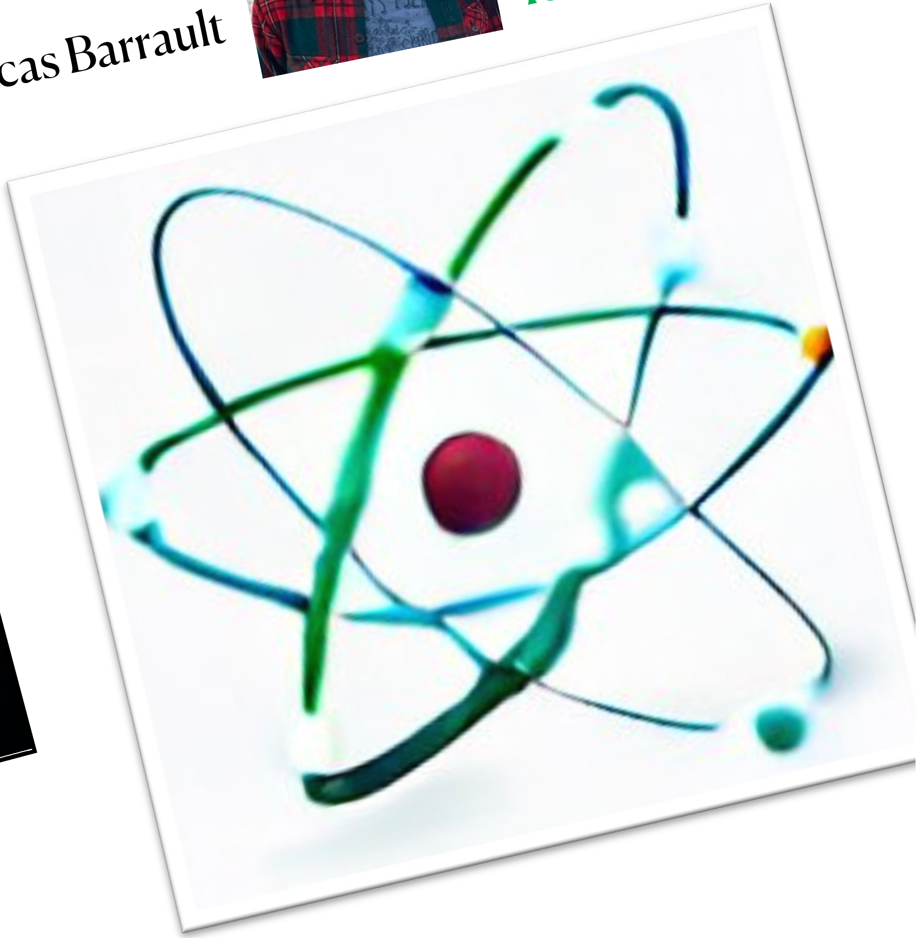


Lucas Barrault

Ions

Ionization



Ionization cross-sections

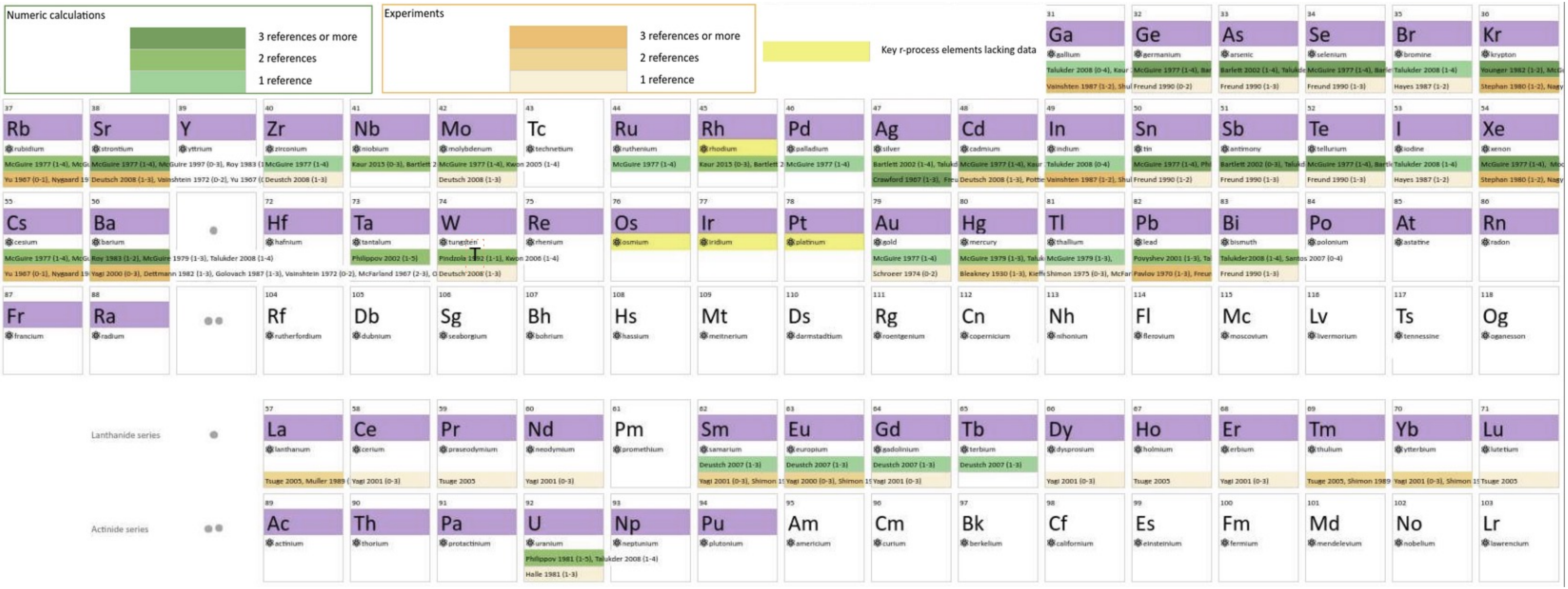
Data Dimensionality

For each element the cross section value will depend on:

- Ionization level -> How many electrons does the initial ion have?
- Subshell -> Which subshell is loosing its electron? "partial" CS / "total" CS
- Ion excitation state -> What is the excitation structure of the resulting ion?
- Incoming electron energy -> How much energy is available? "total" CS
- Secondary electron energy -> "differential" CS

Ionization cross-sections

DATA AVAILABILITY



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Ionization cross-sections

DATABASES

Experimental data

NIFS DATABASE.

<National Institute for Fusion Science>

Atomic and Molecular Numerical Databases

Cross Sections and Rate Coefficients for Ionization, Excitation, and Recombination by Electron Impact
Charge Transfer by Heavy Particle Collision, and Collision Processes of Molecules,
Sputtering Yields of Solids, and Back Scattering Coefficients from Solids

Bibliographic Databases

Fusion and Plasma Sciences, Atomic and Molecular Physics, and Atomic Collision Processes

Made by A&M Data Research Section

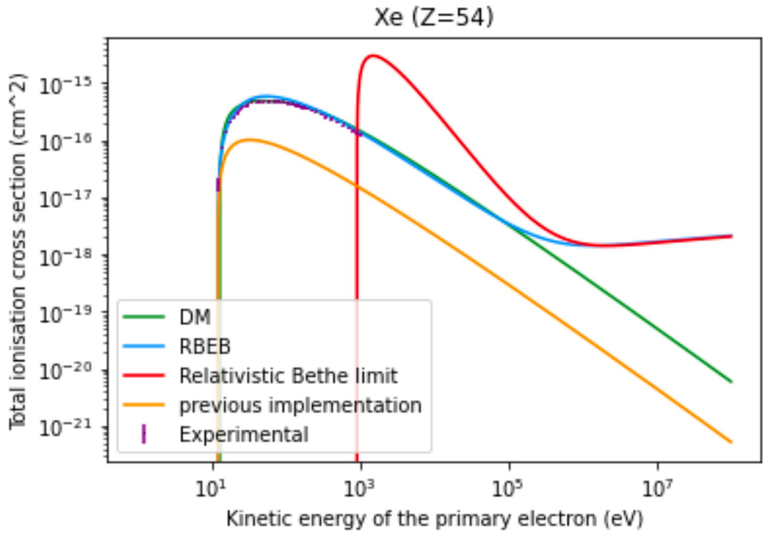
https://dbshino.nifs.ac.jp/

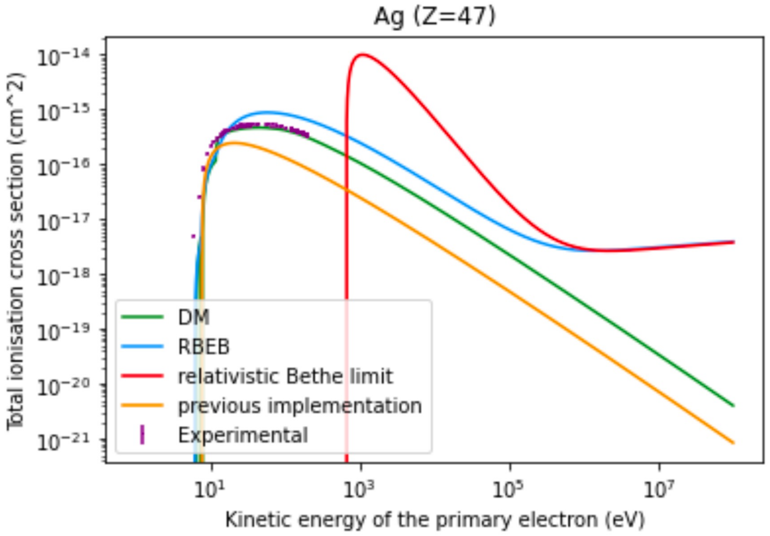
Model parameters

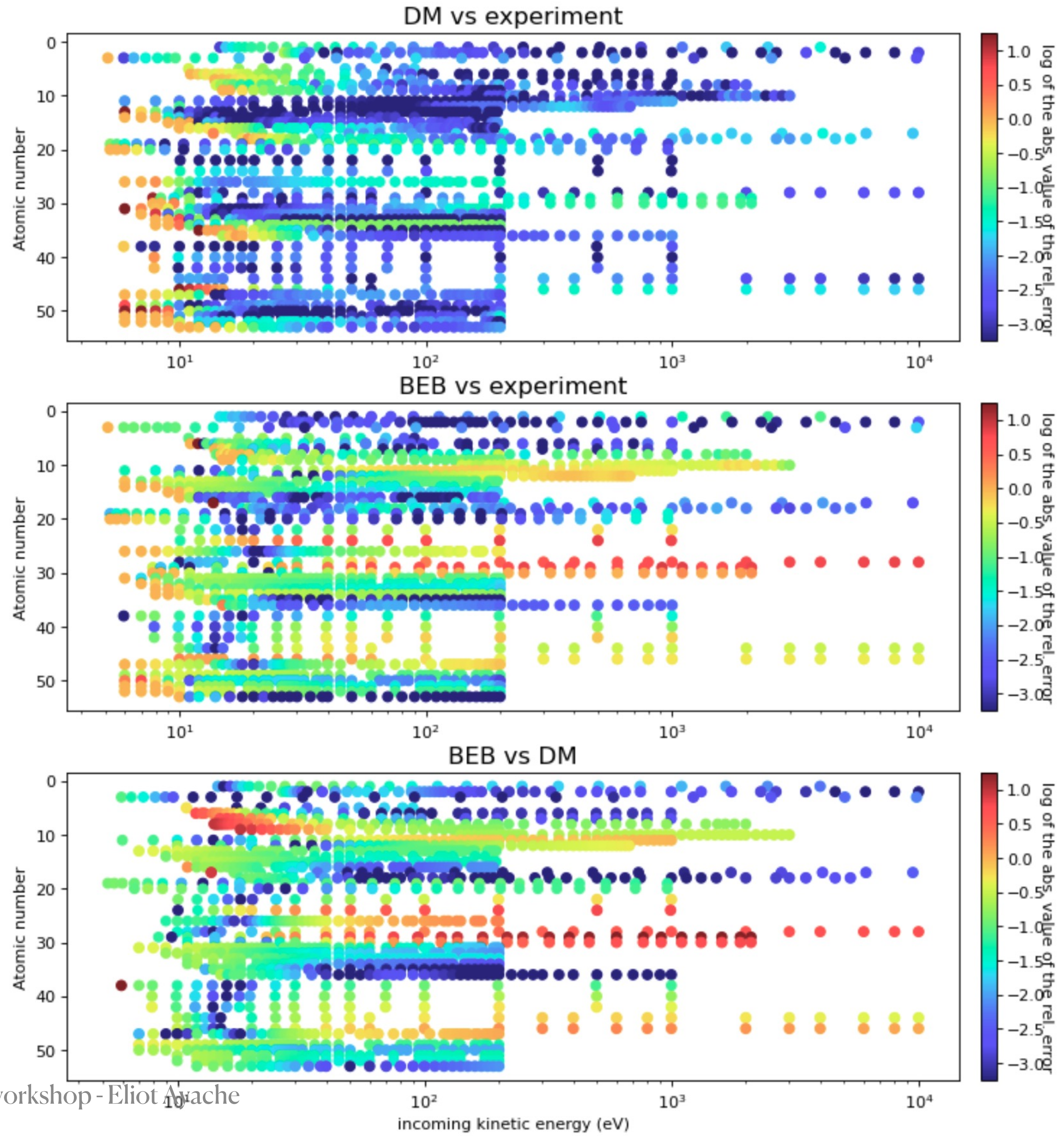
- Deutsch-Mark
- Binary Encounter

EADL -> Binding energies, kinetic energies for the subshells
NIST -> Ionization energy thresholds

Model comparison

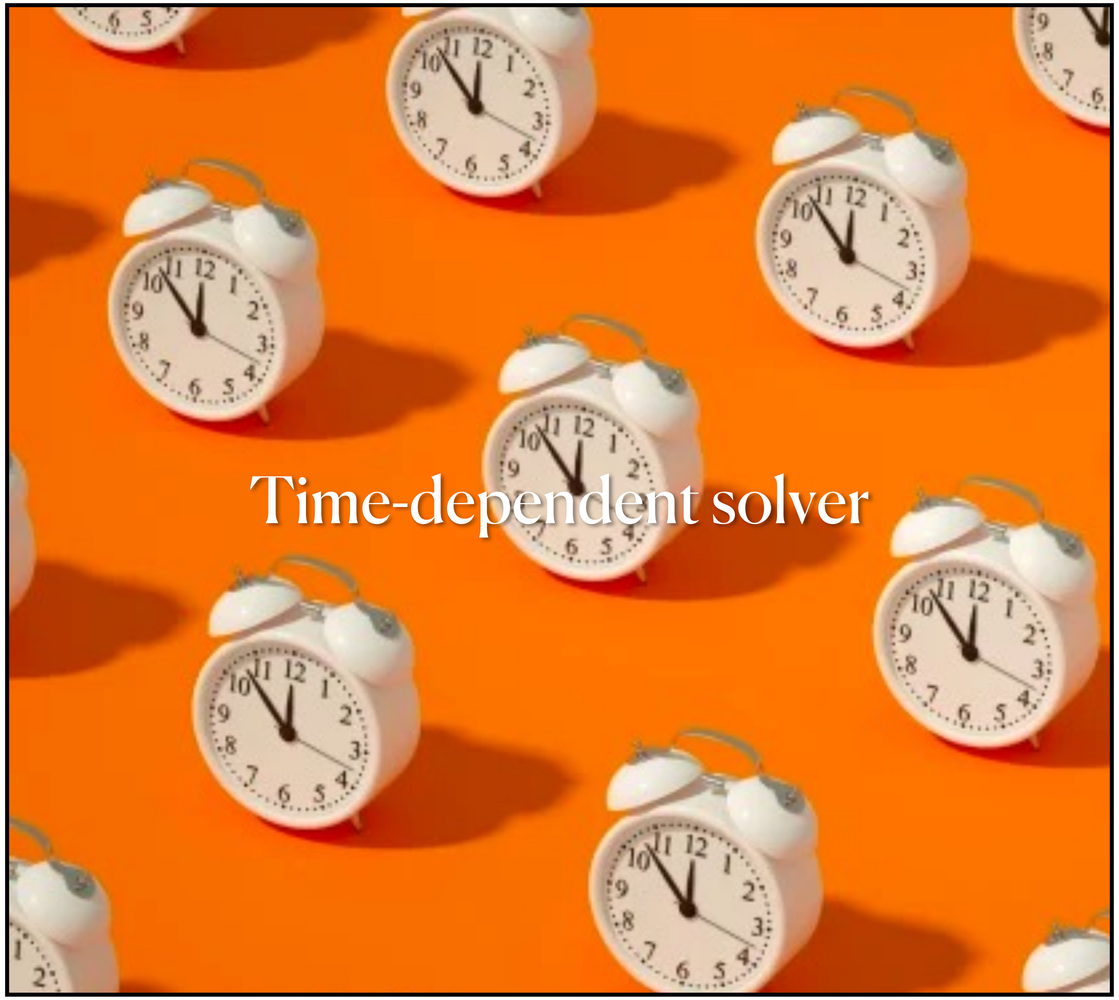






Non-thermal electron degradation

Assumptions and Challenges




Time-dependent solver

Time-dependent formulation

Mathematical formulation

$$\frac{\partial F(E;t)}{\partial t} = n\left[\int F(E')R(E' \to E)\mathrm{d}E' - \int F(E)R(E \to E'')\mathrm{d}E''\right]$$

Vanilla Boltzmann equation

$$\frac{1}{v_E}\frac{\partial z(E,t)}{\partial t} = nKz(E,t) + \frac{1}{v_E}\left[\frac{\partial z\mathcal{L}_e}{\partial E} - \frac{z\mathcal{L}_e}{v_E}\frac{\partial v_E}{\partial E}\right] + \frac{S(E,t)}{v_E}$$

+ Excitation
+ Adiabatic expansion
+ ...

Ionization

Thermal losses

Energy deposition

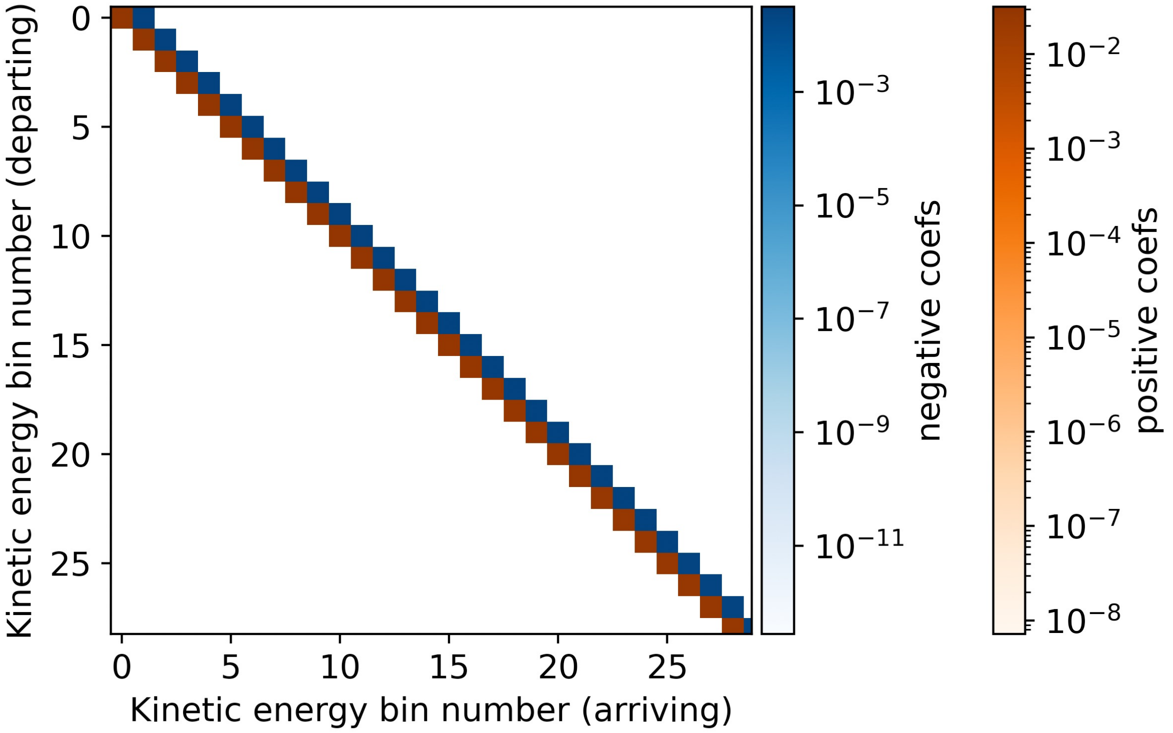
Time-dependent formulation

Discretization

$$z_m^n \left[\frac{1}{v_m(t_n - t_{n-1})} - \frac{L_m}{v_m(E_m - E_{m-1})} + \frac{L_m}{v_m^2}\frac{dv}{dE}\Big|_m + n\sum_{m'} \sigma_{m\to m'} \mathrm{d}E_{m'} \right]$$

$$-n\sum_{m'} z_{m'}^n \sigma_{m'\to m} \mathrm{d}E_{m'} + z_{m-1}^n \frac{L_{m-1}}{v_m(E_m - E_{m-1})}$$

$$= \frac{z_m^{n-1}}{v_m(t_n - t_{n-1})}$$



"Upwinding" -> stability

Upper triangular -> energy resolution

Thermal losses: Barnes & Kasen 2016

$$\dot{E}_\beta^{\mathrm{pl}} = 7.7\times 10^{-15} E_\beta^{-1/2} \times \frac{n_e}{1\mathrm{cm}^{-3}} \lambda_{ee} \left(1.0 - \frac{3.9}{7.7}\frac{T}{E_\beta}\right) \mathrm{MeV s^{-1}}$$

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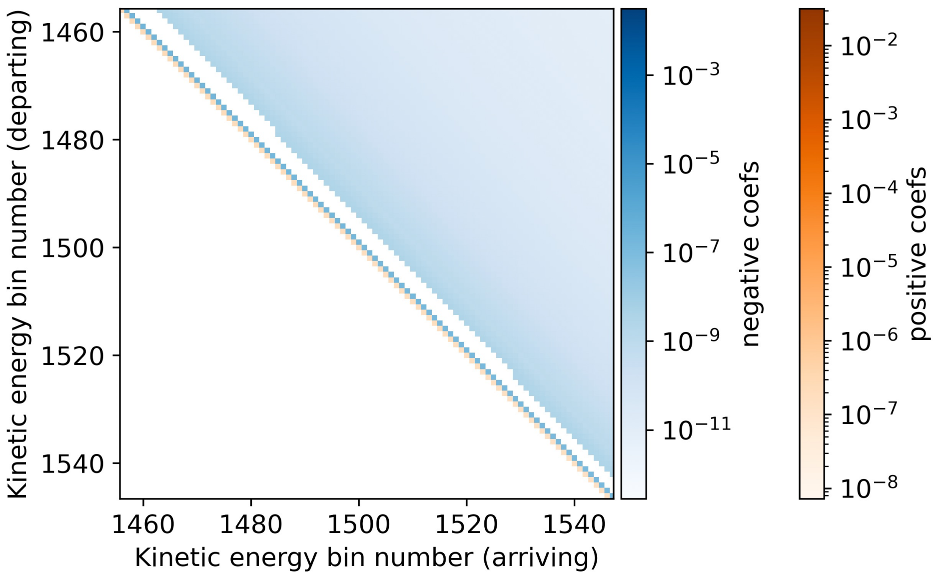
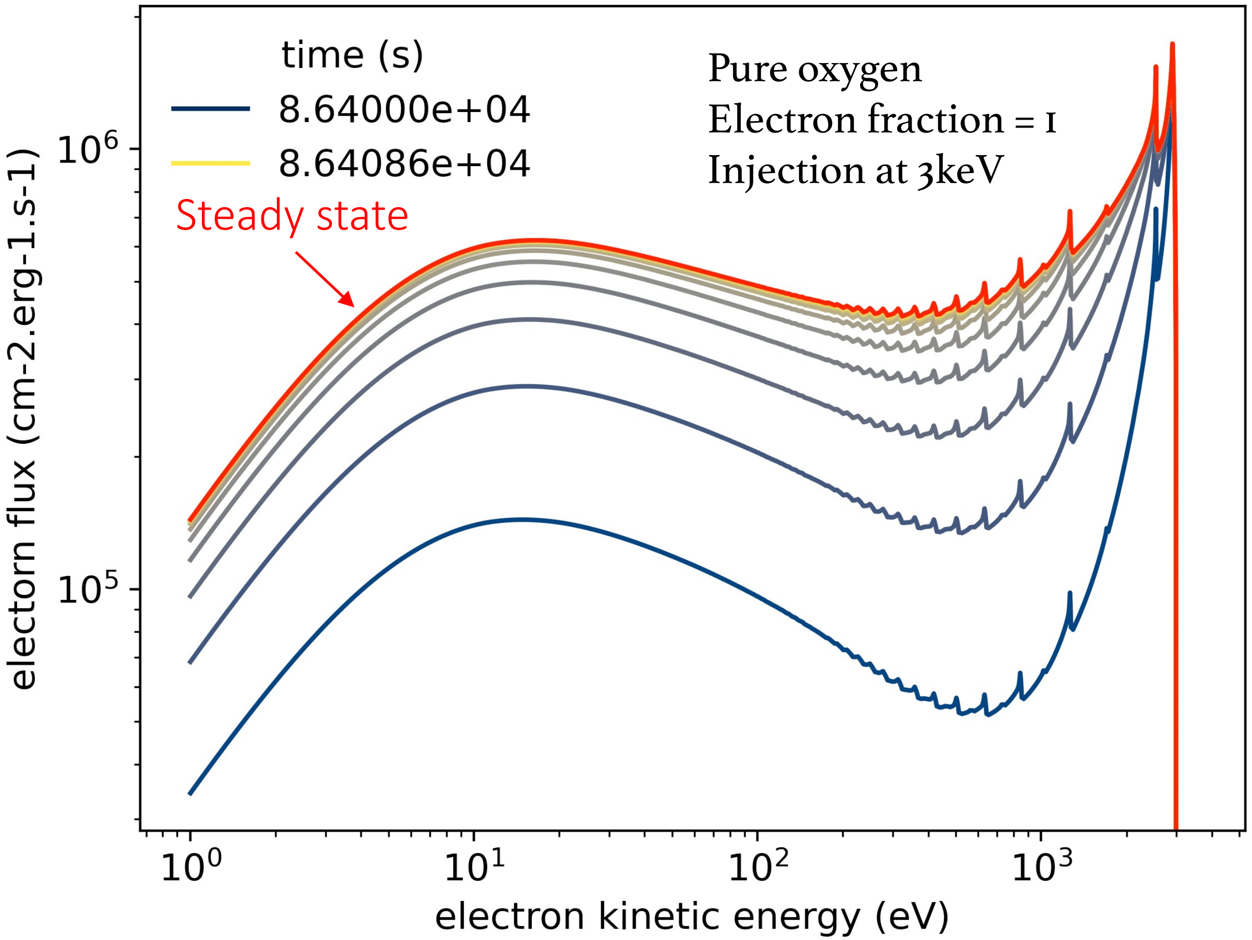
Preliminary results

Time-dependent evolution

Converges onto steady state solution
Numerical artefacts: resolution dependent

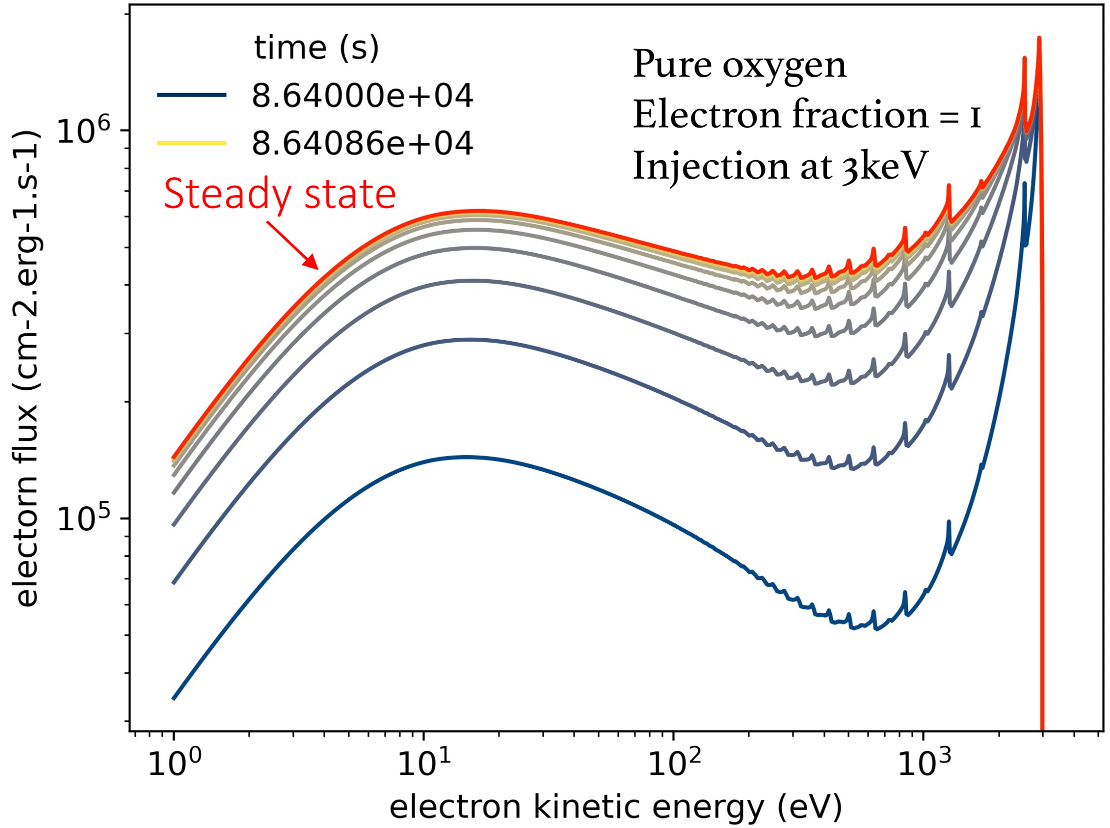




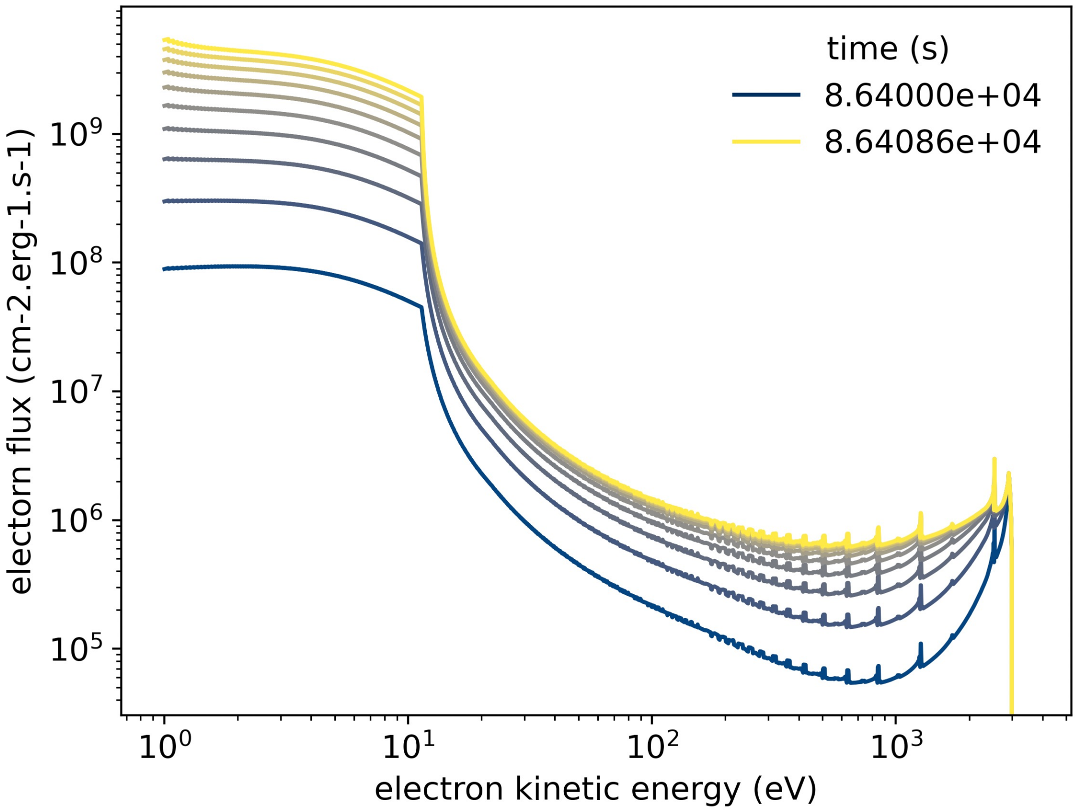
Preliminary results

TIME-DEPENDENT EVOLUTION

With thermal losses



Without thermal losses



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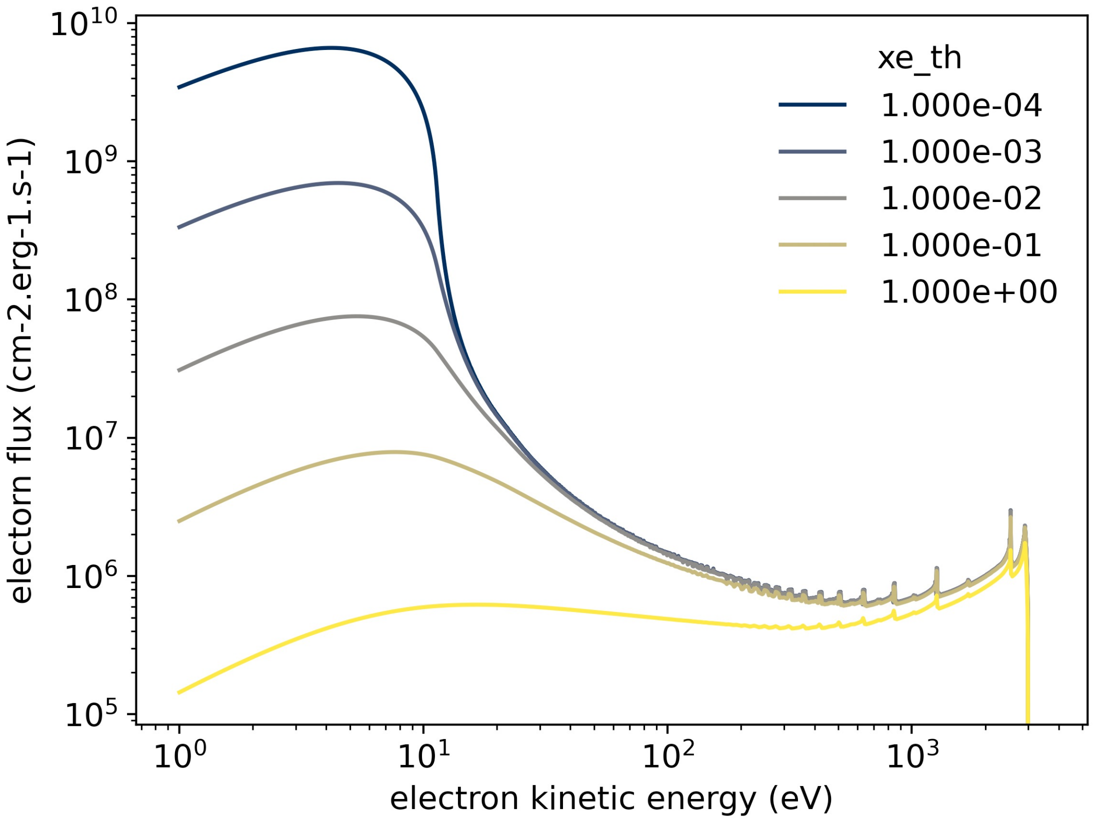
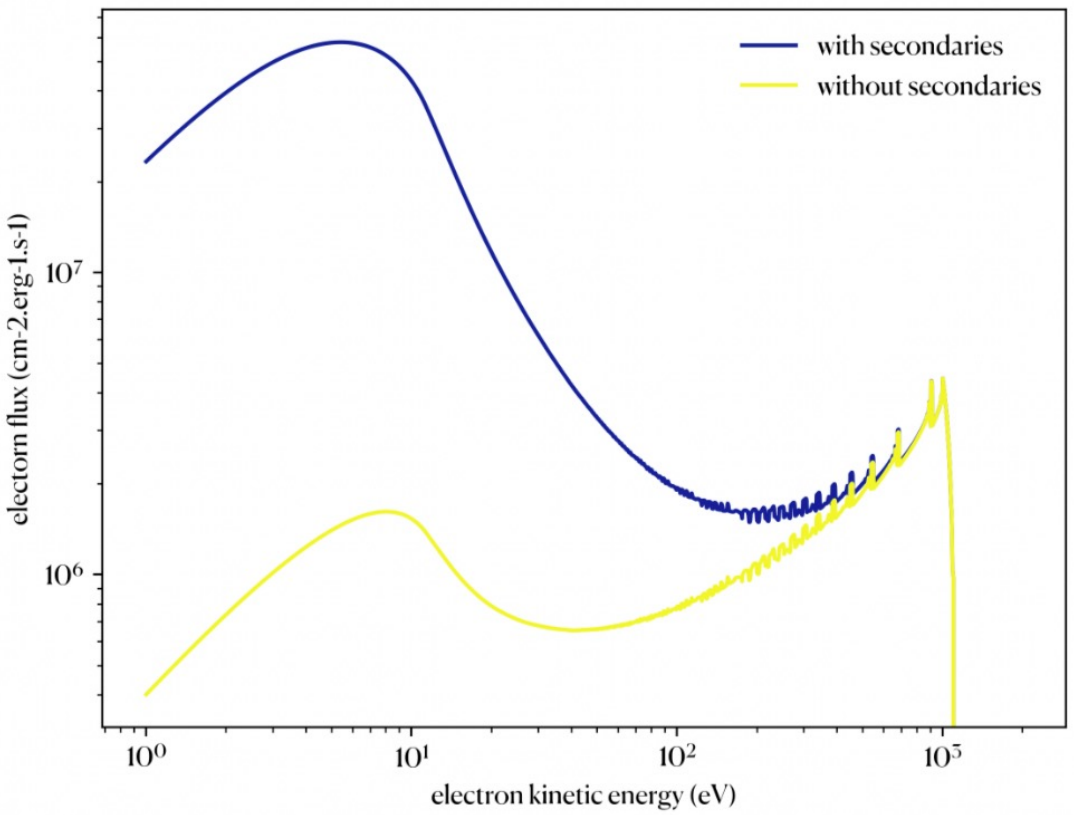
Preliminary results

Pure Oxygen

Effect of electron fraction



Effect of secondaries



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Conclusions

- Time-dependence needs implementing AT ALL STAGES of the NTLE processes

- More work is needed on measuring and modelling r-process cross-sections.

- Numerical non-thermal electron degradation is data heavy and computationally expensive, but can be carried out in a self-consistent way.

- Future work:
  - Adiabatic processes
  - Target excited states
  - Auger processes