Speeding up cosmological simulations with machine learning

Elif Ozlem Adiguzel

June 05, 2025

Supervised by: Dr. David Harvey, Dr. Yves Revaz

Modeling the Cosmos Through Simulations

Modeling the Cosmos Through Simulations

Model

ΛCDM

EPFL

Modeling the Cosmos Through Simulations

Model

ΛCDM

Observations

JWST, Euclid

Planck

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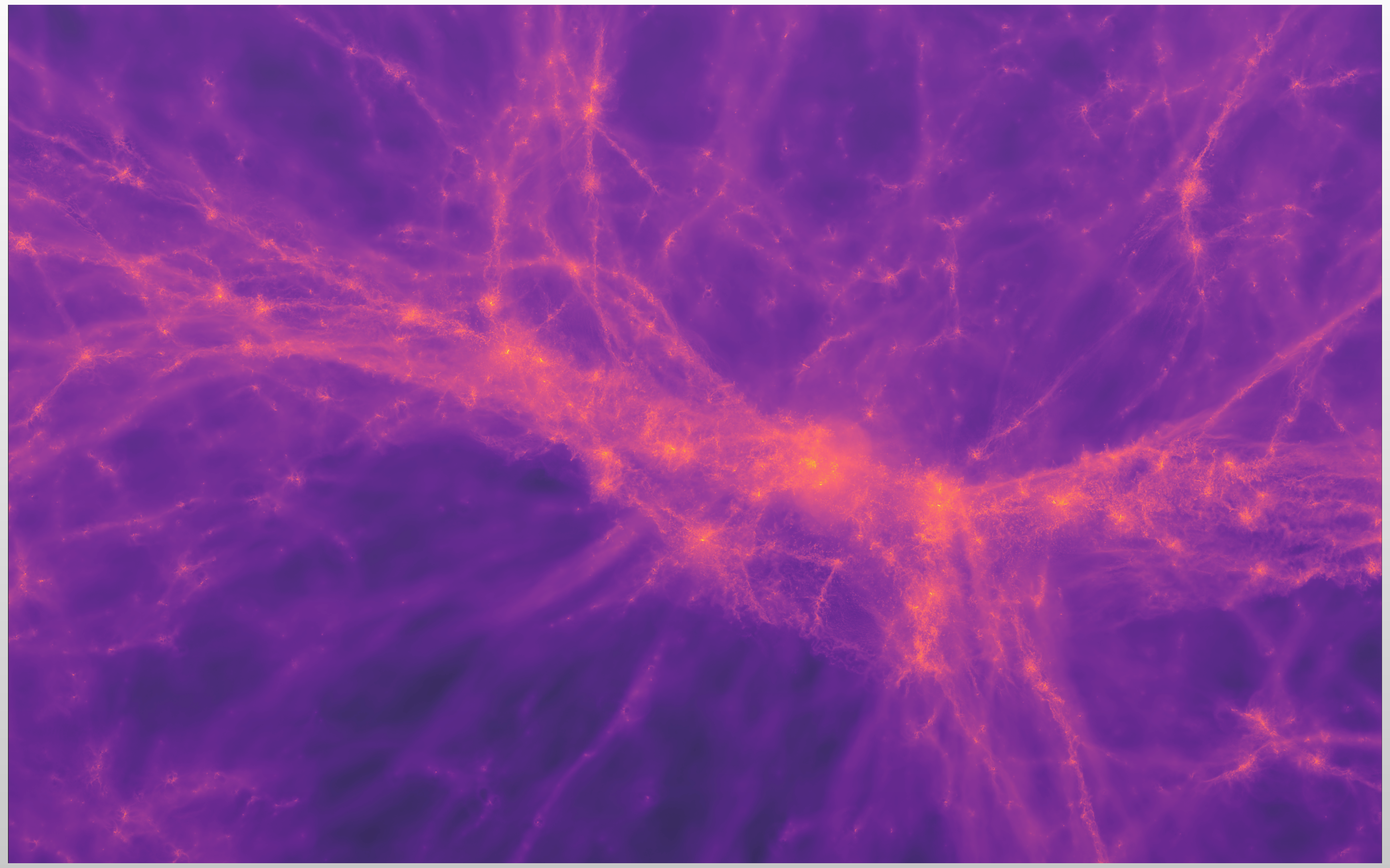

Image Credit: TNG Collaboration

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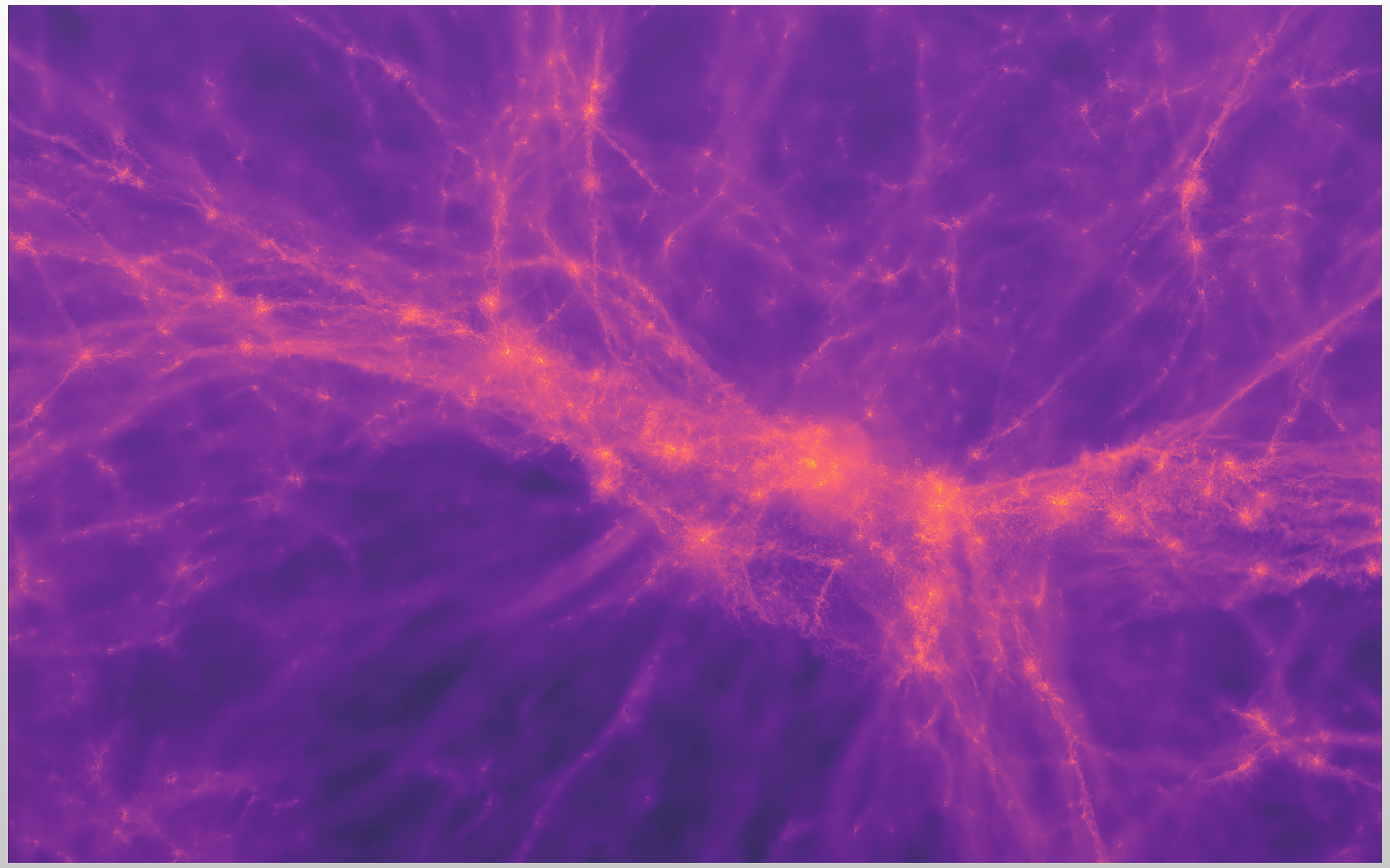

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EPFL

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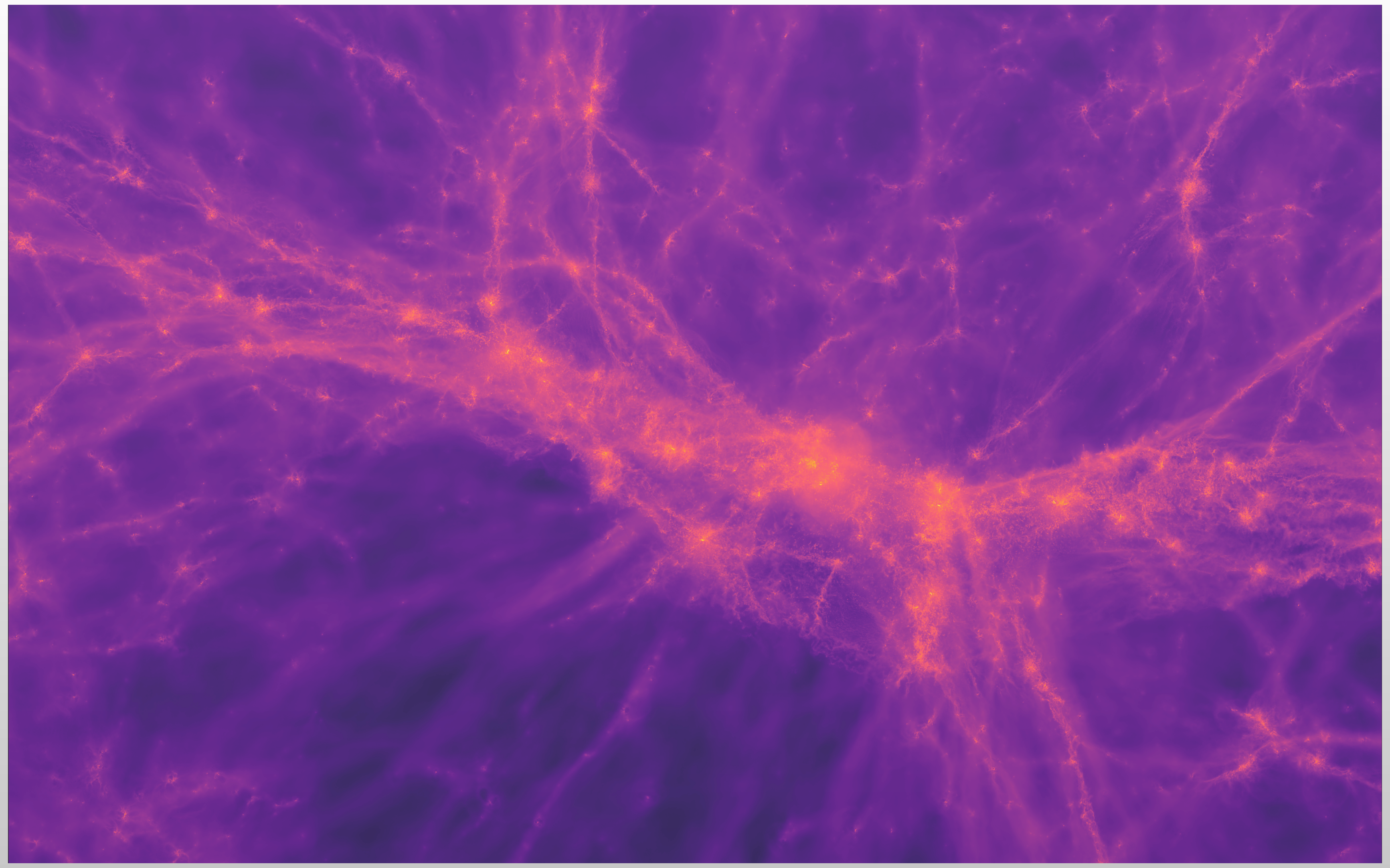

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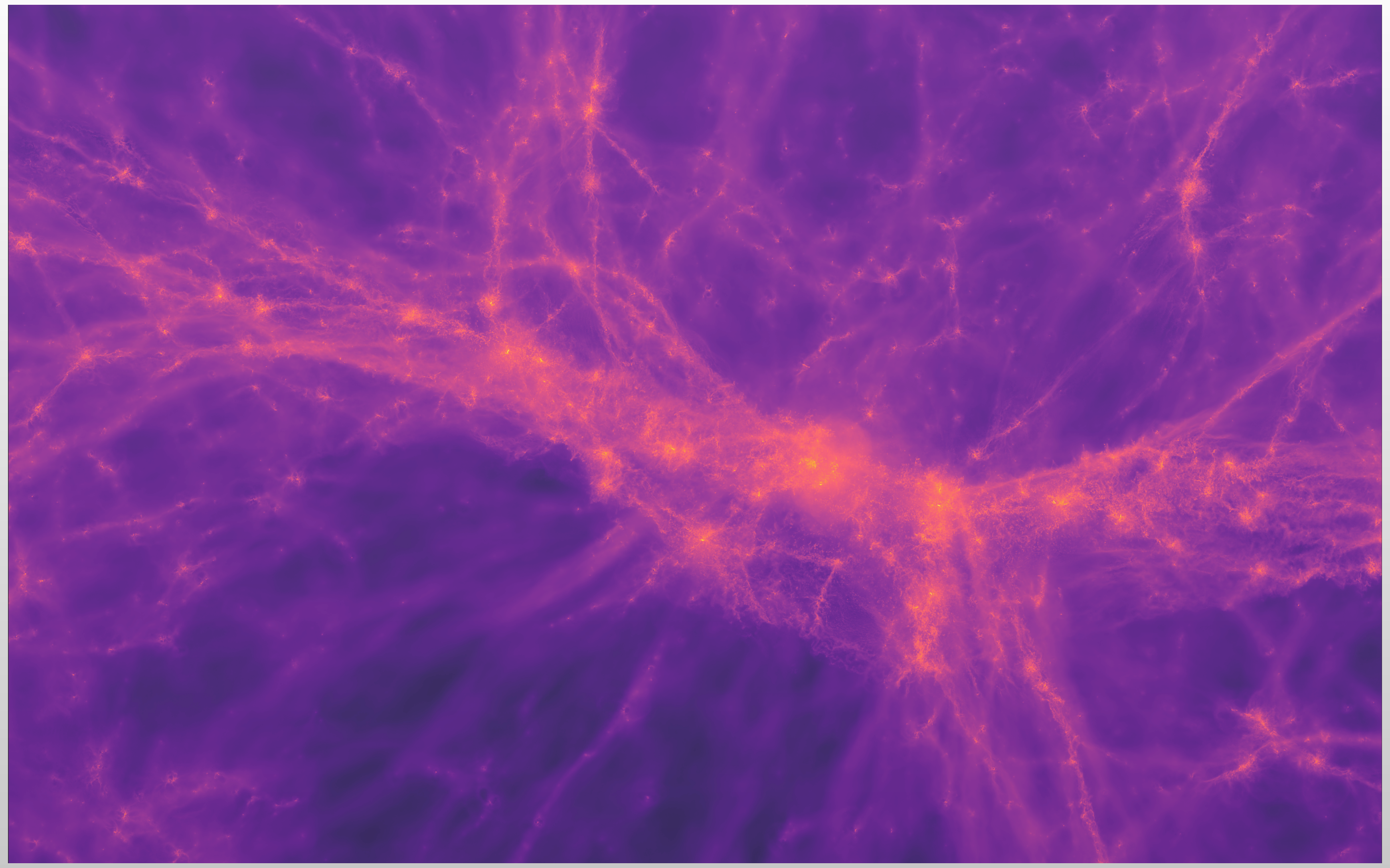

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compare

EPFL

Modeling the Cosmos Through Simulations

Model

ΛCDM

test

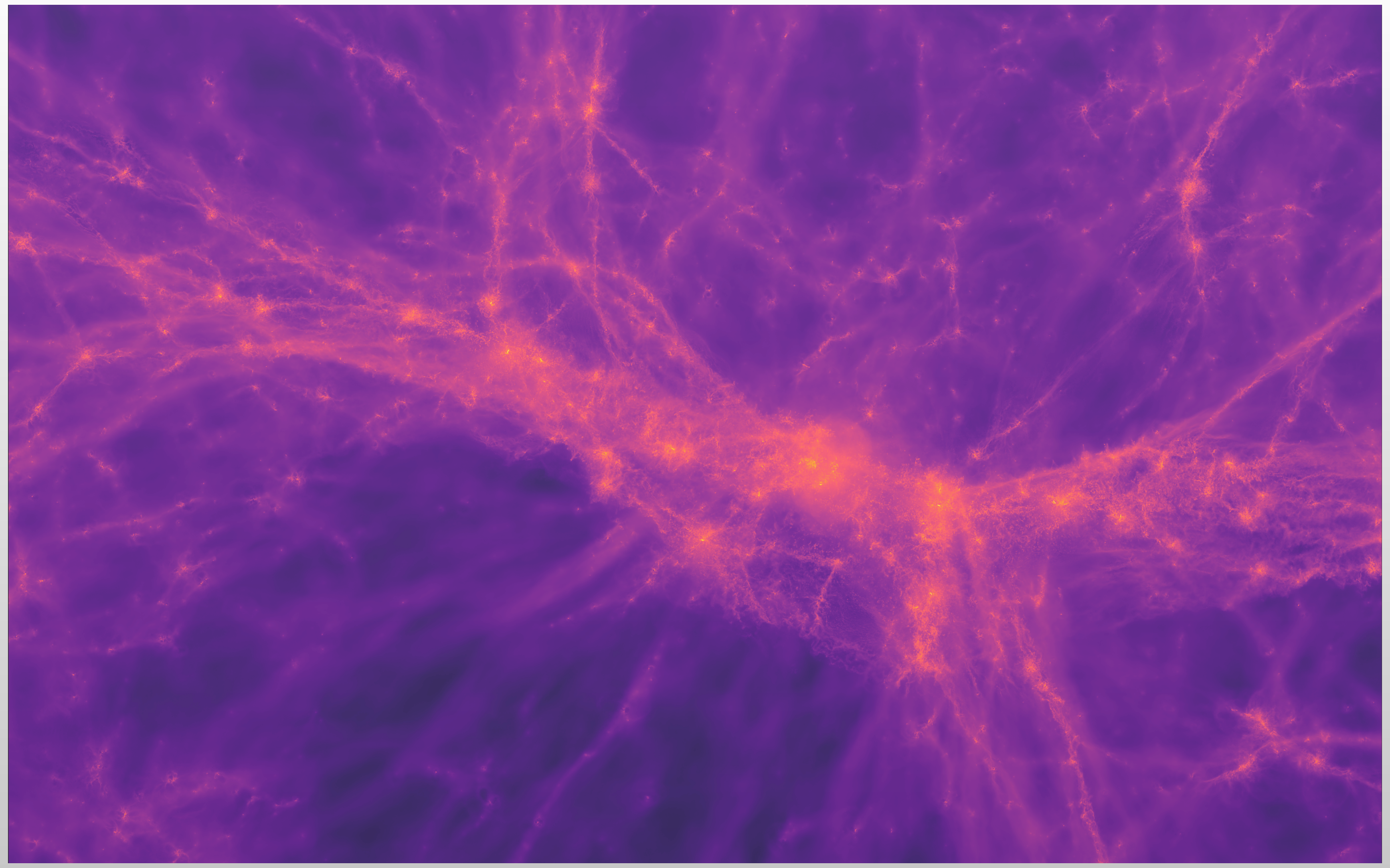
Observations

JWST, Euclid

Planck

compare

Simulations



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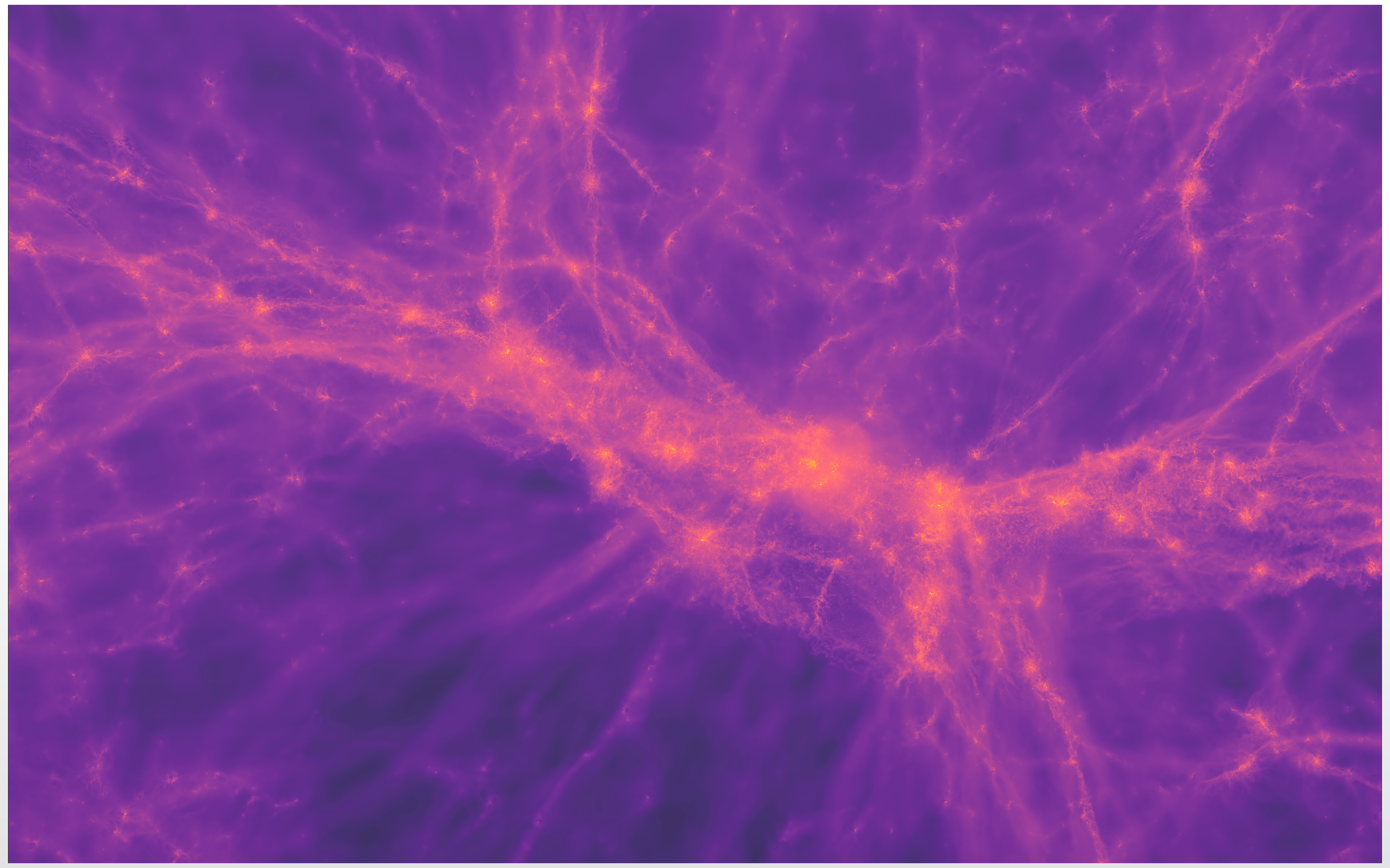
Modelling the Cosmos Through Simulations



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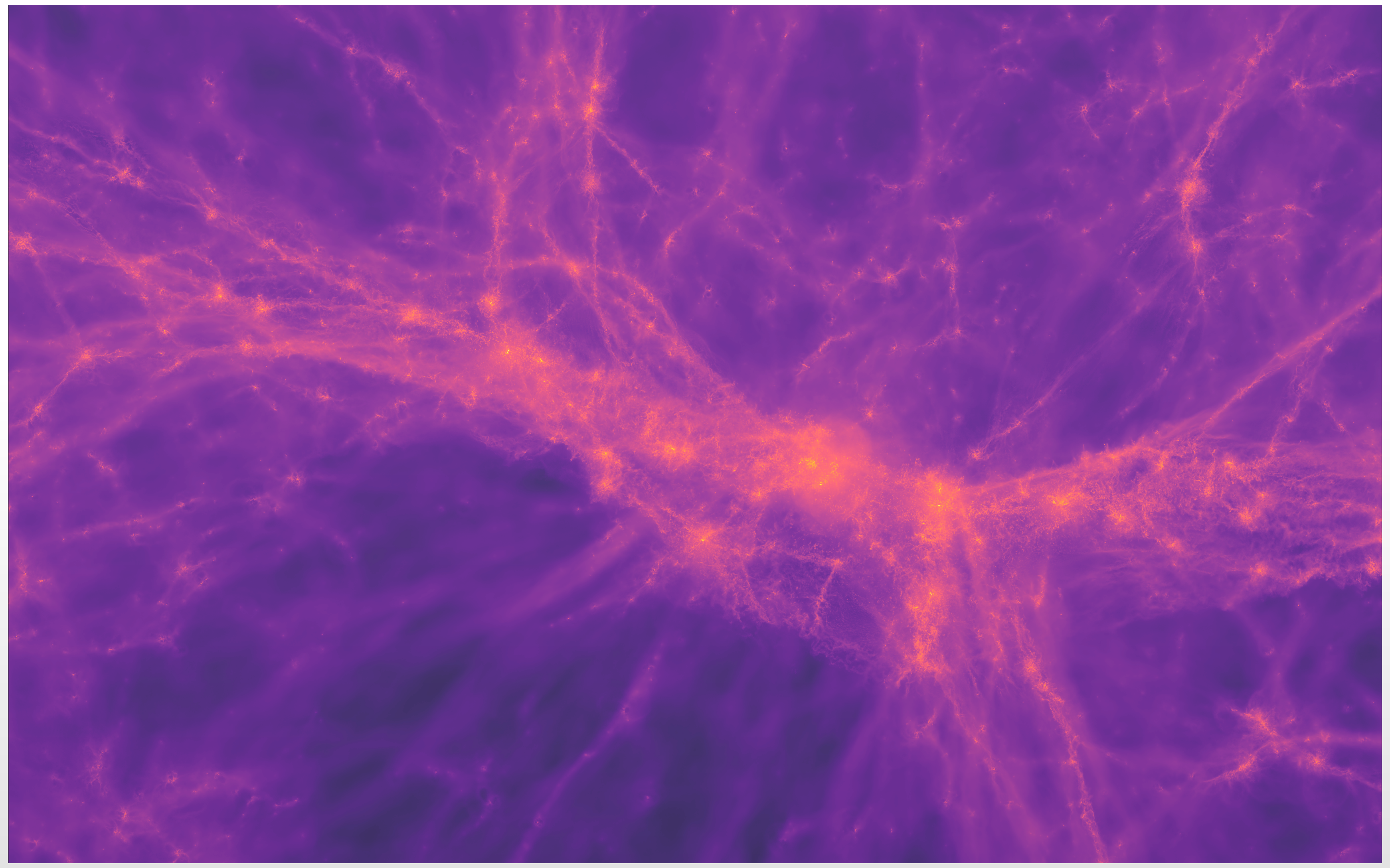

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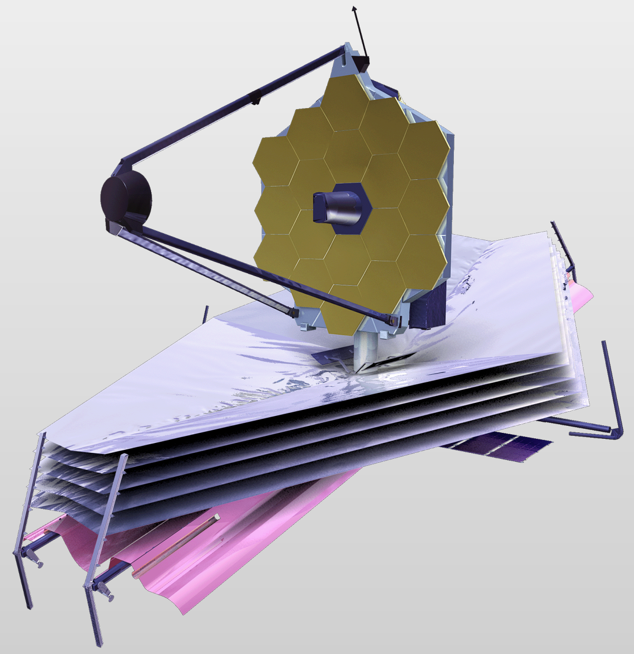
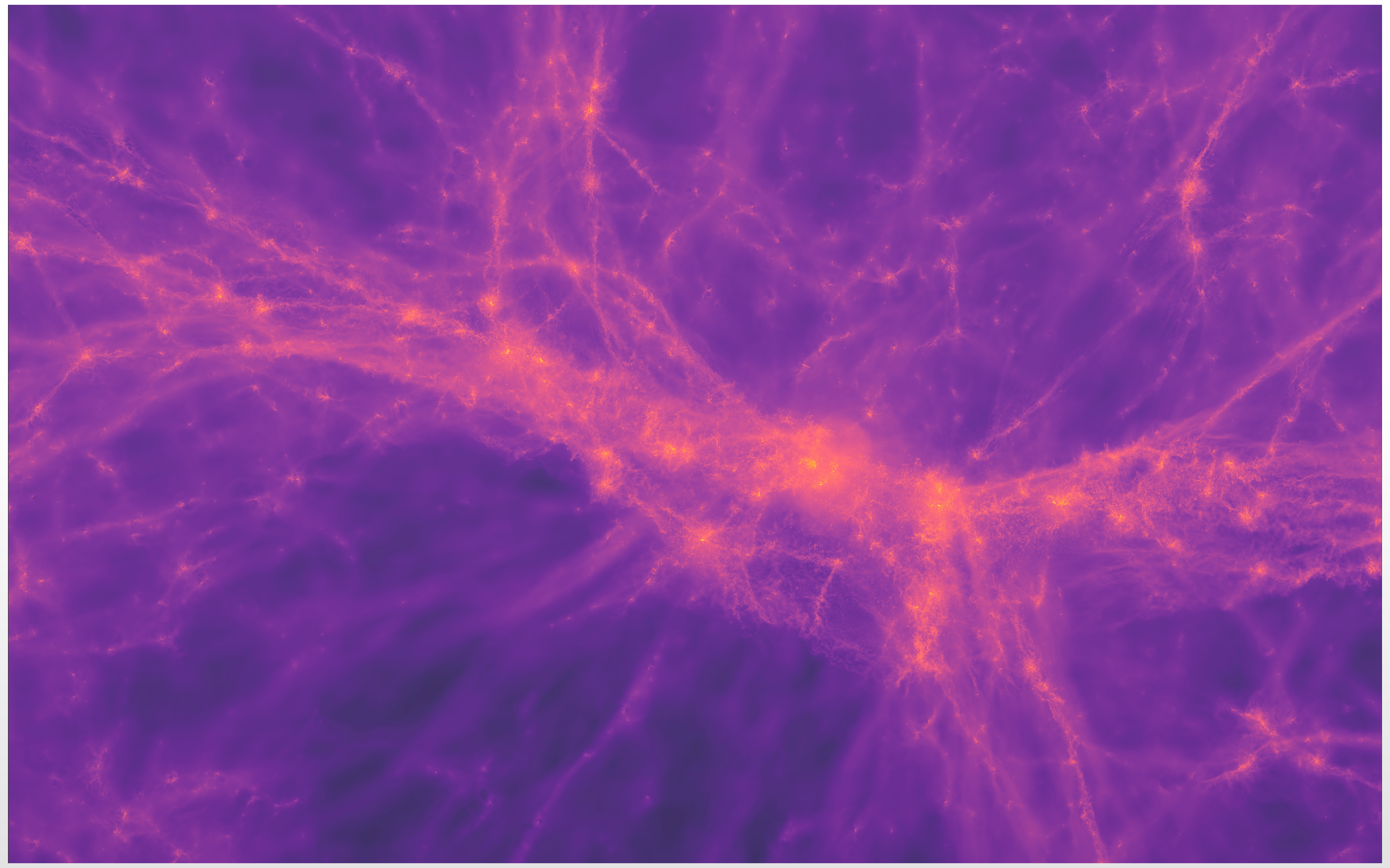
- New observations challenge current models



Modelling the Cosmos Through Simulations



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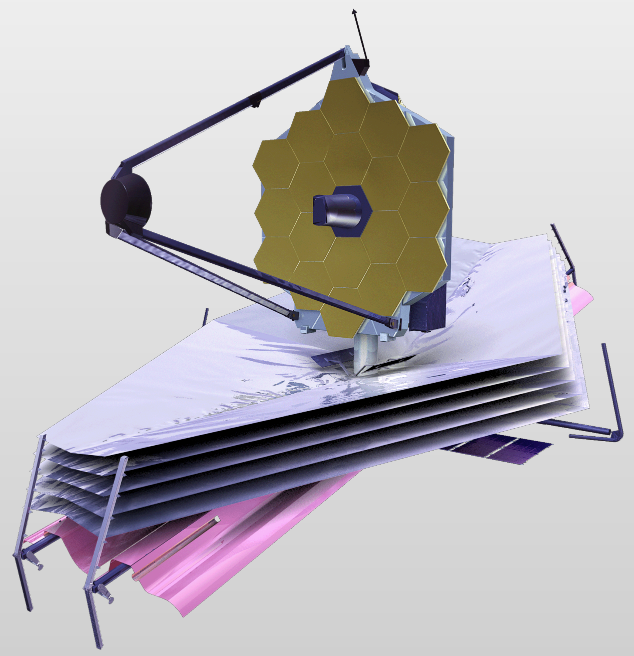
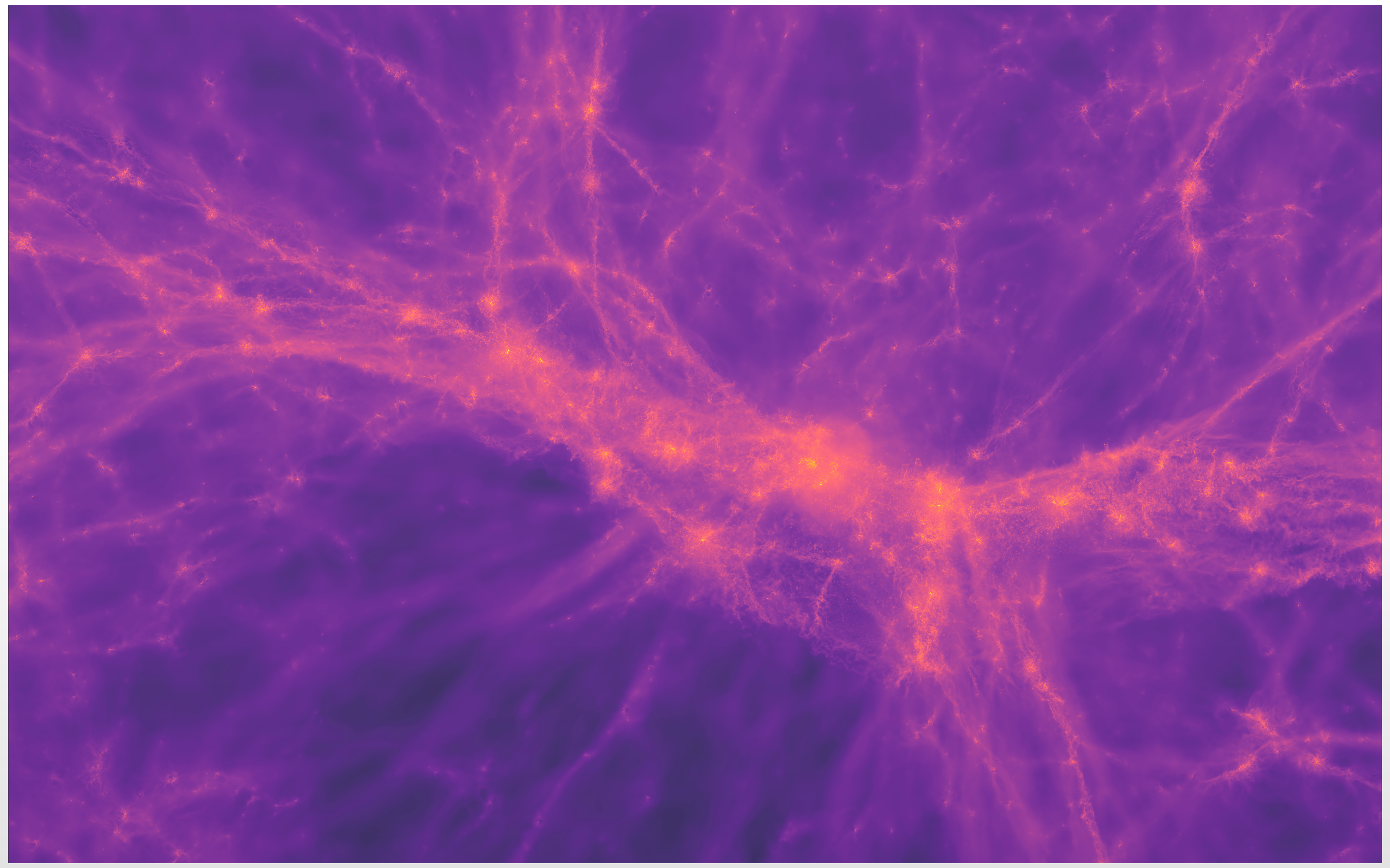
- New observations challenge current models
- Bigger, higher resolution simulations are needed



Modelling the Cosmos Through Simulations



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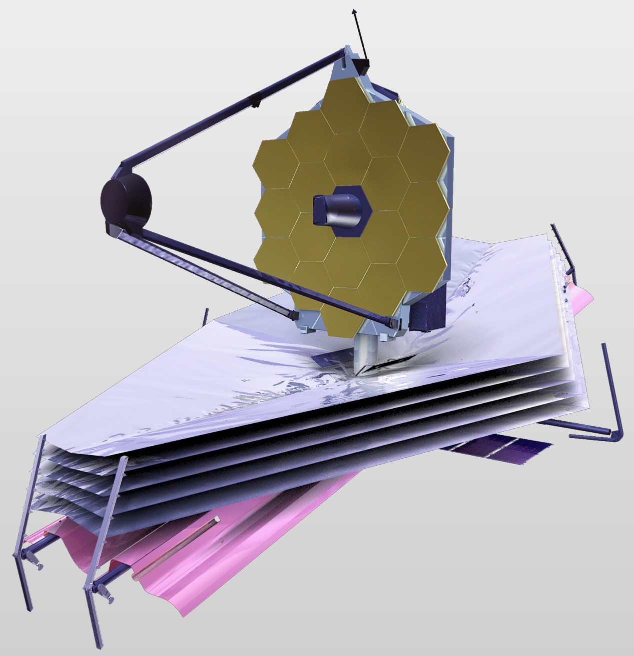
- New observations challenge current models
- Bigger, higher resolution simulations are needed

→ **Time consuming**



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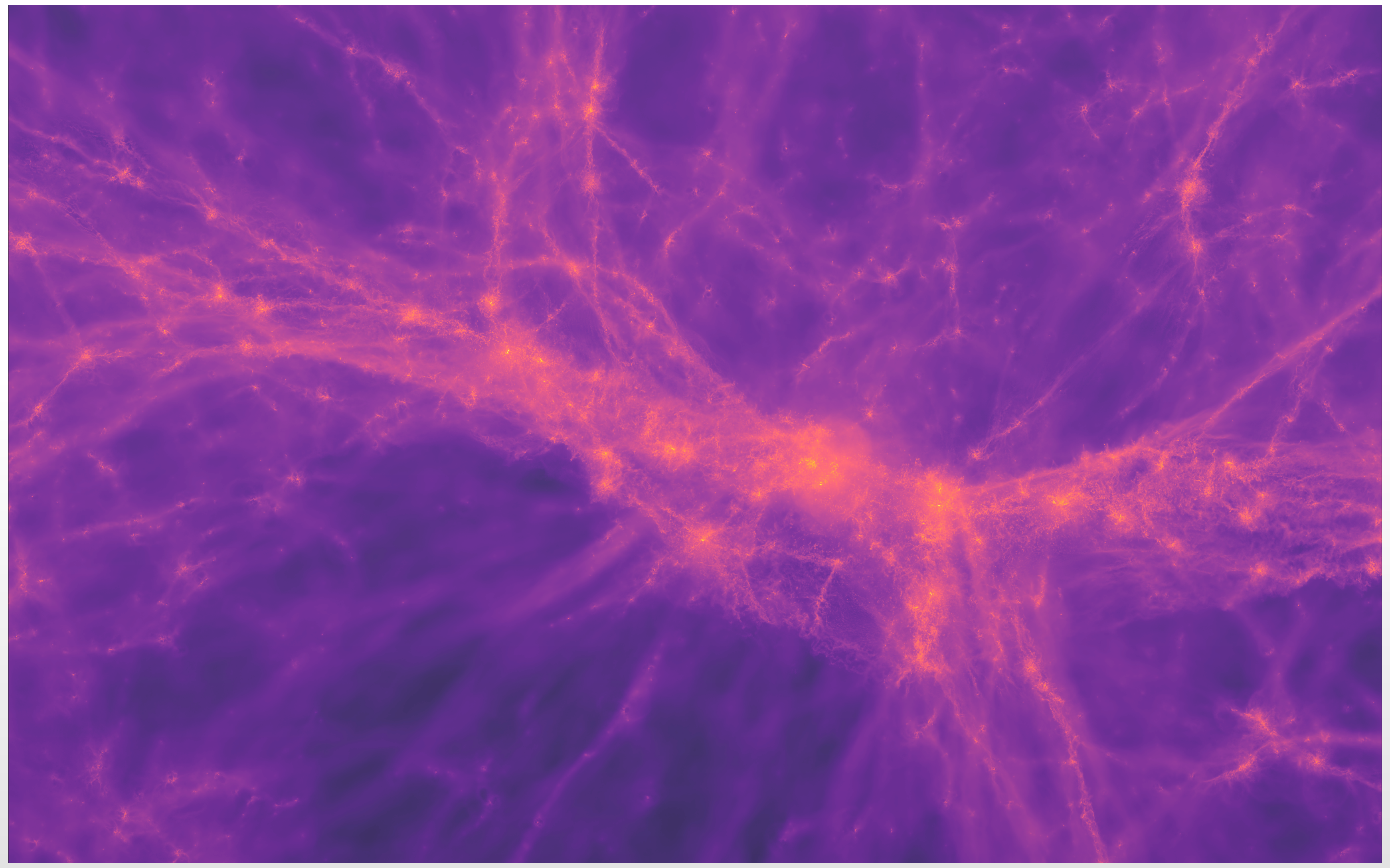

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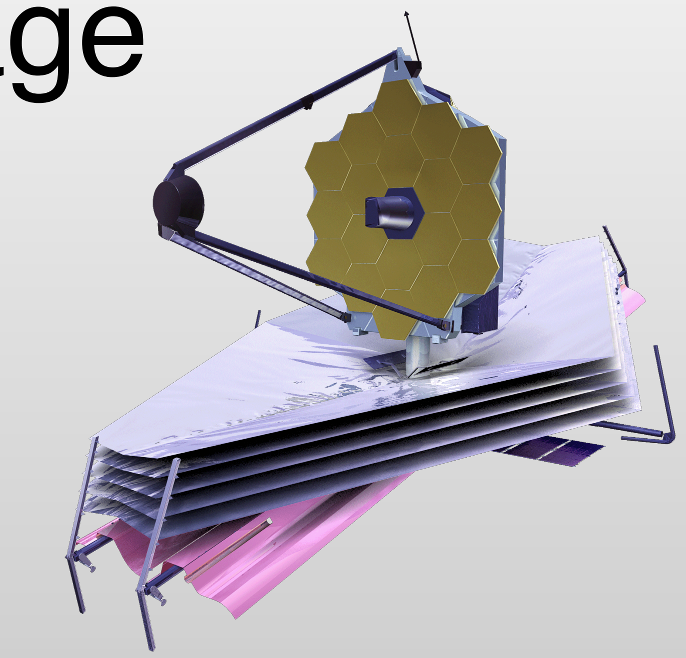
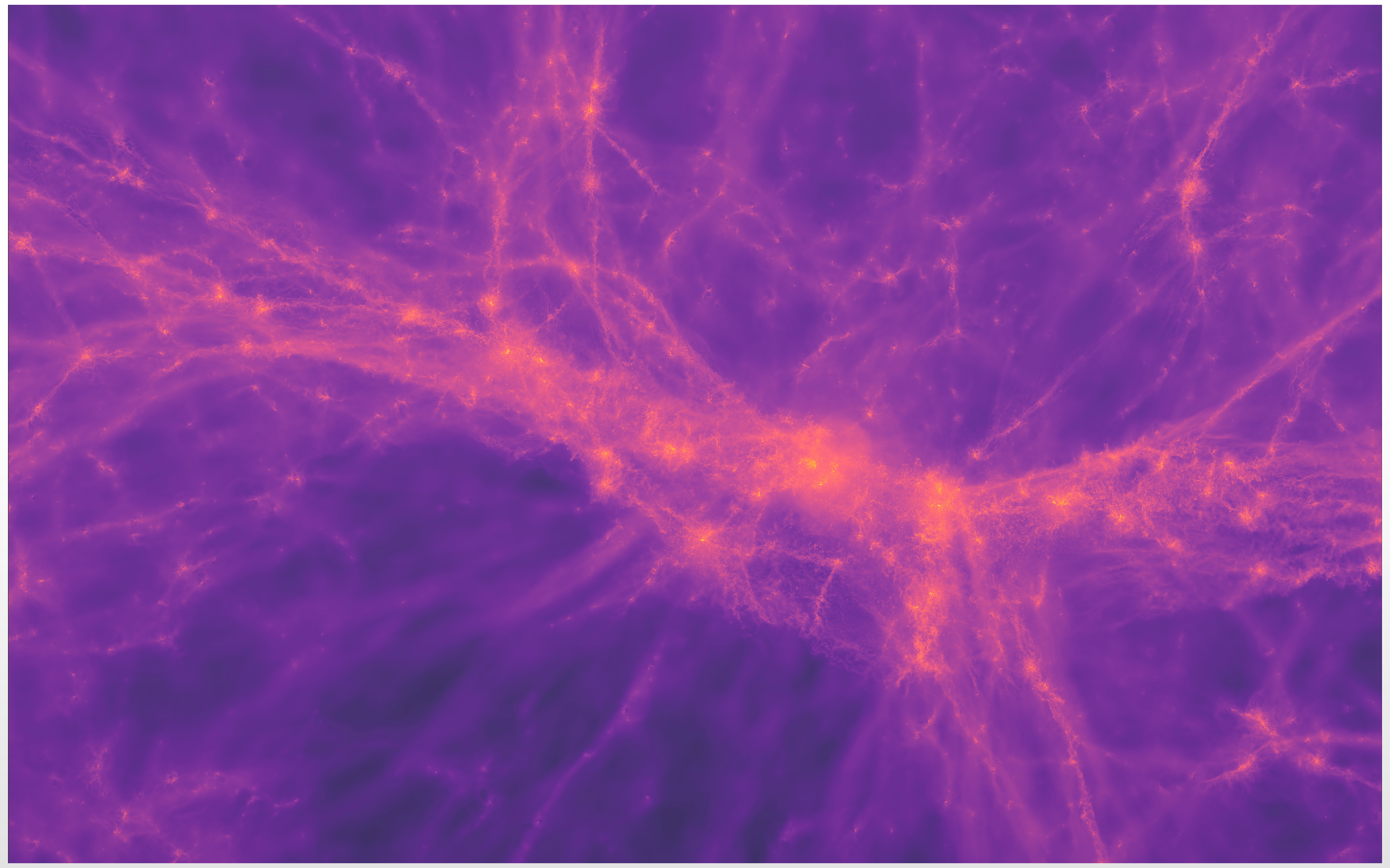
→ **Time consuming**

Different modules for each stage



EPFL

Modelling the Cosmos Through Simulations



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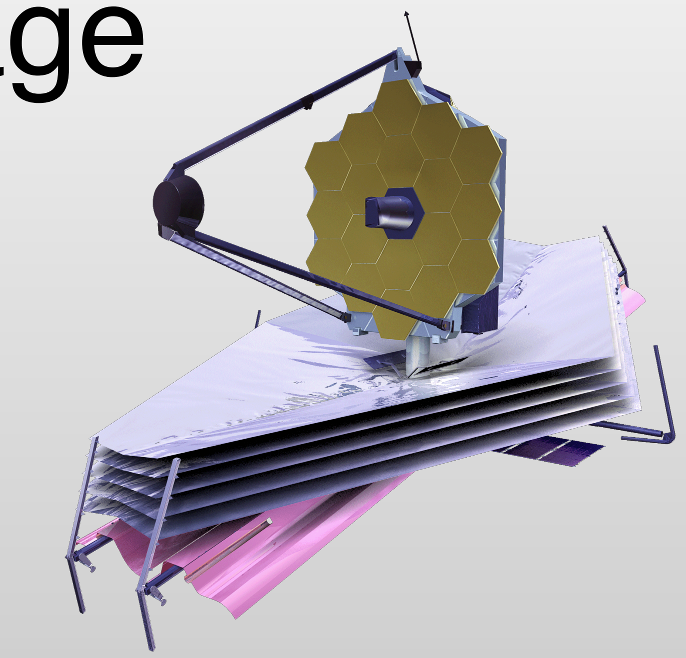
- New observations challenge current models
- Bigger, higher resolution simulations are needed

→ **Time consuming**

Different modules for each stage

Many complex equations

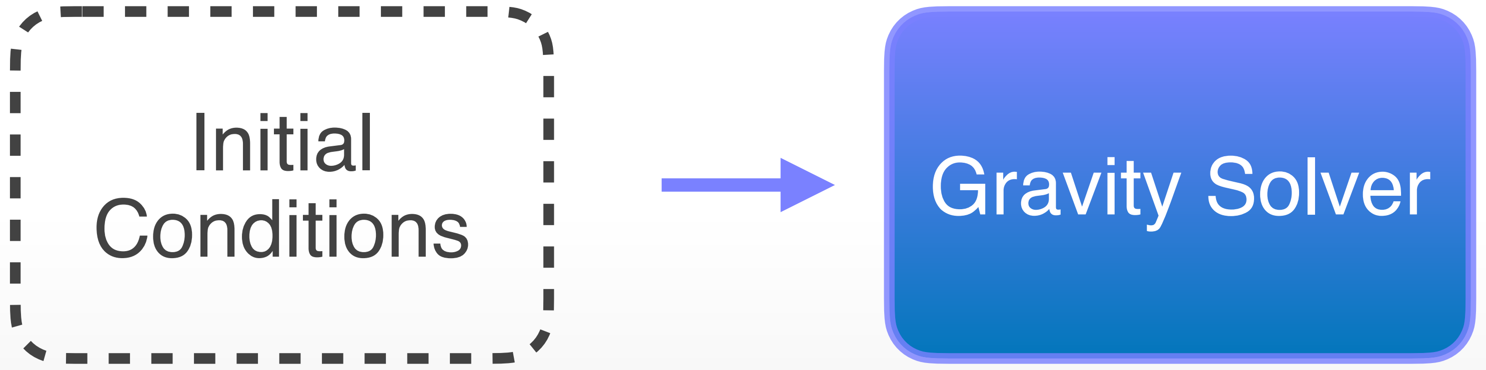


General Workflow of Simulations

General Workflow of Simulations

Gravity Solver

General Workflow of Simulations



EPFL

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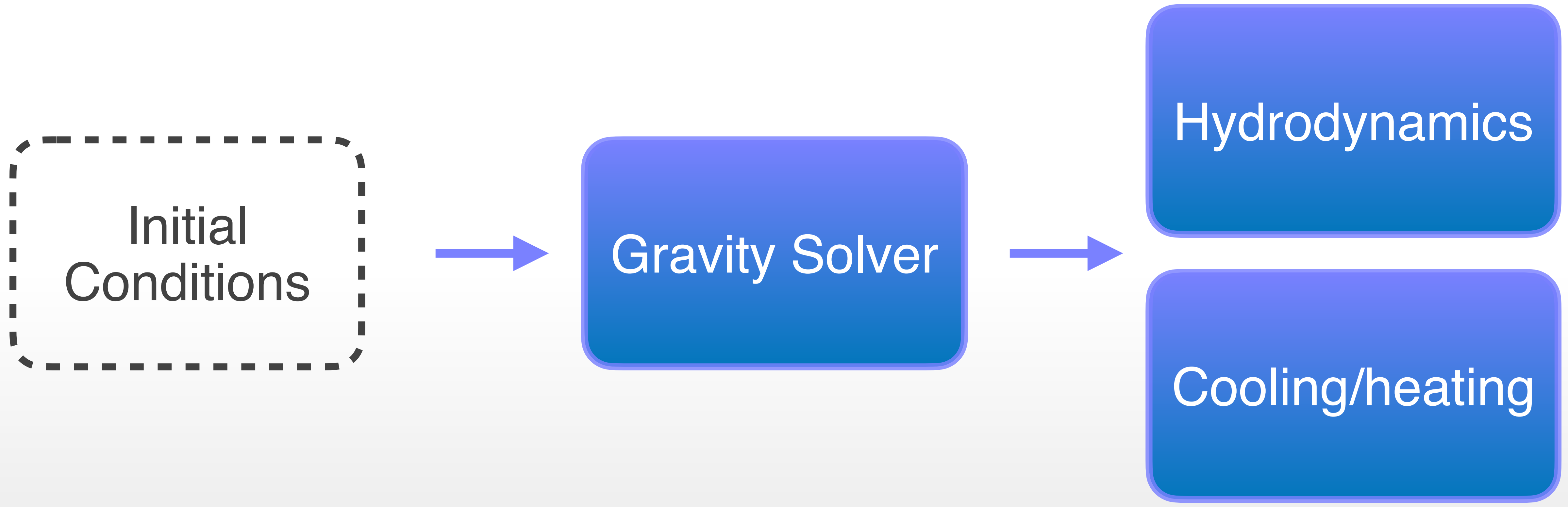

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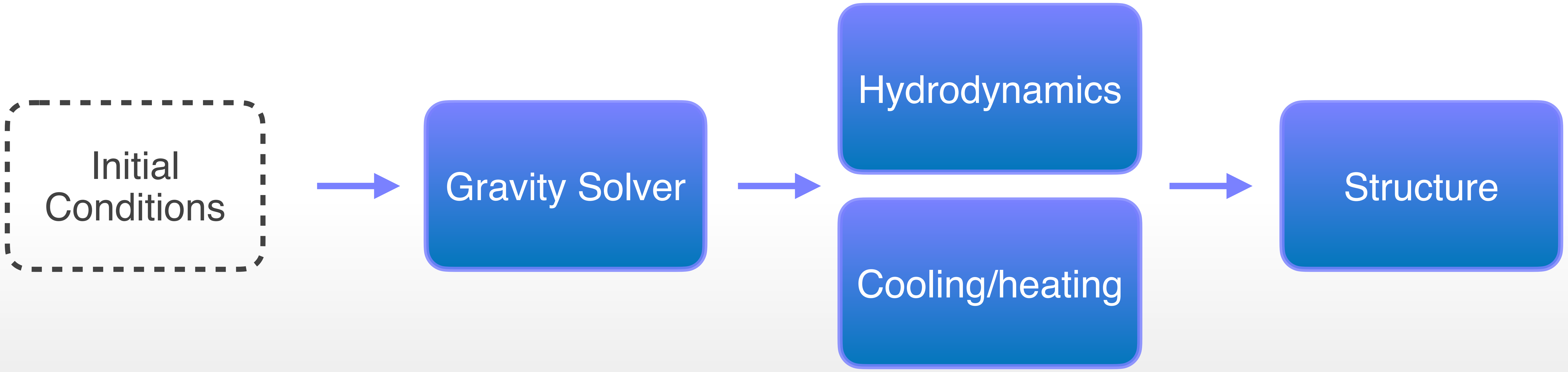

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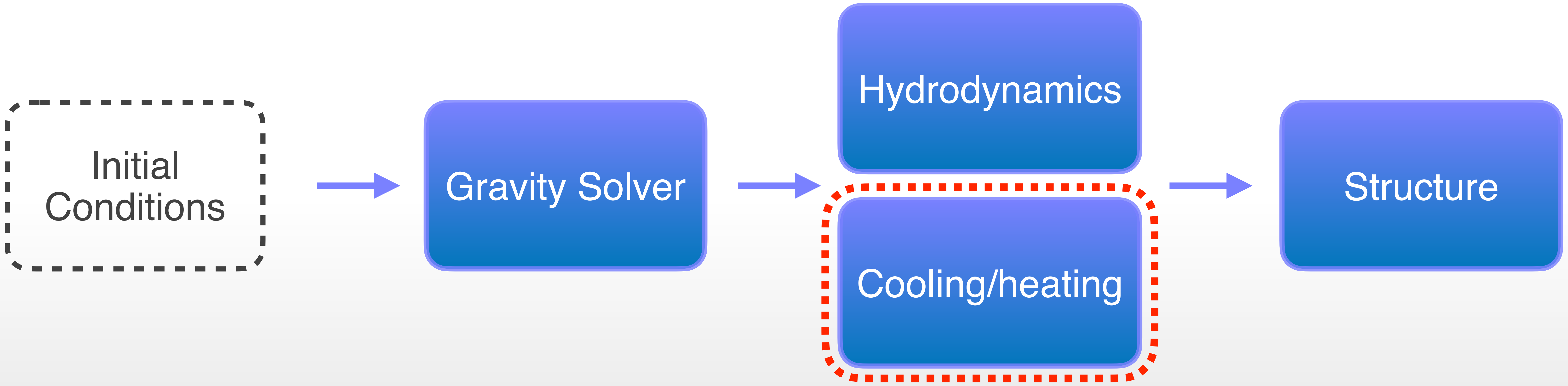

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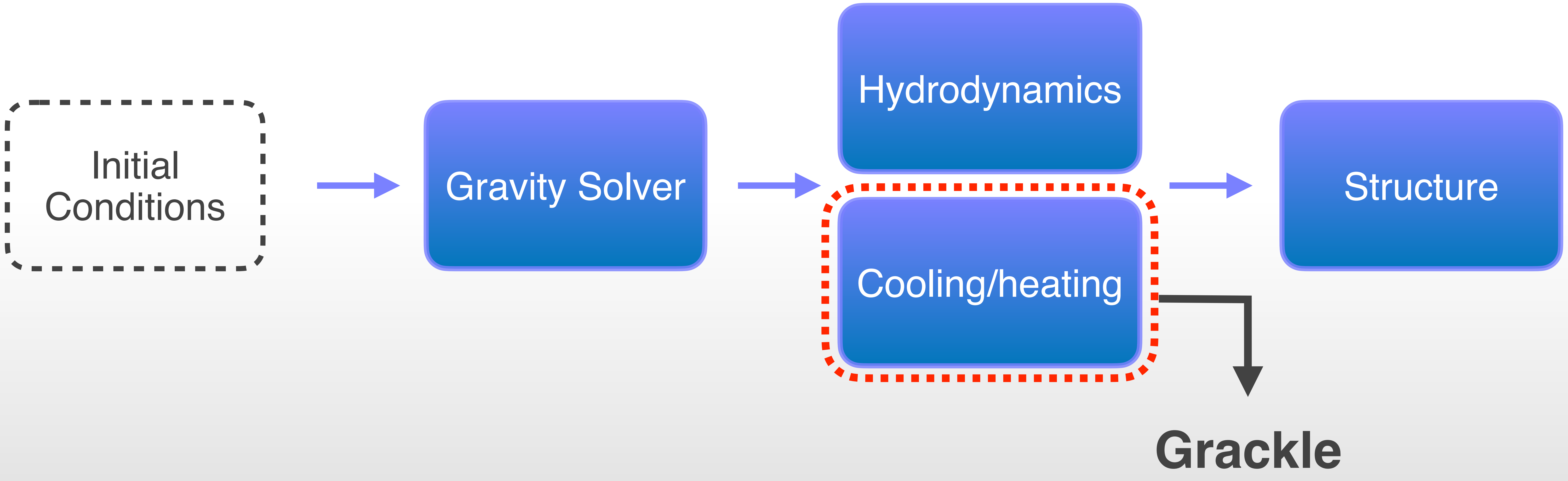

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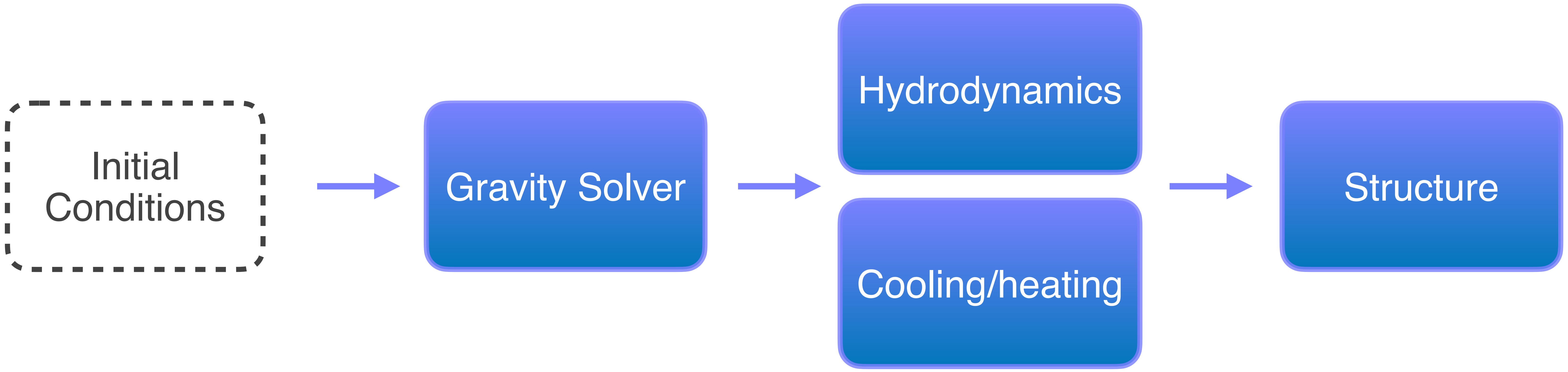
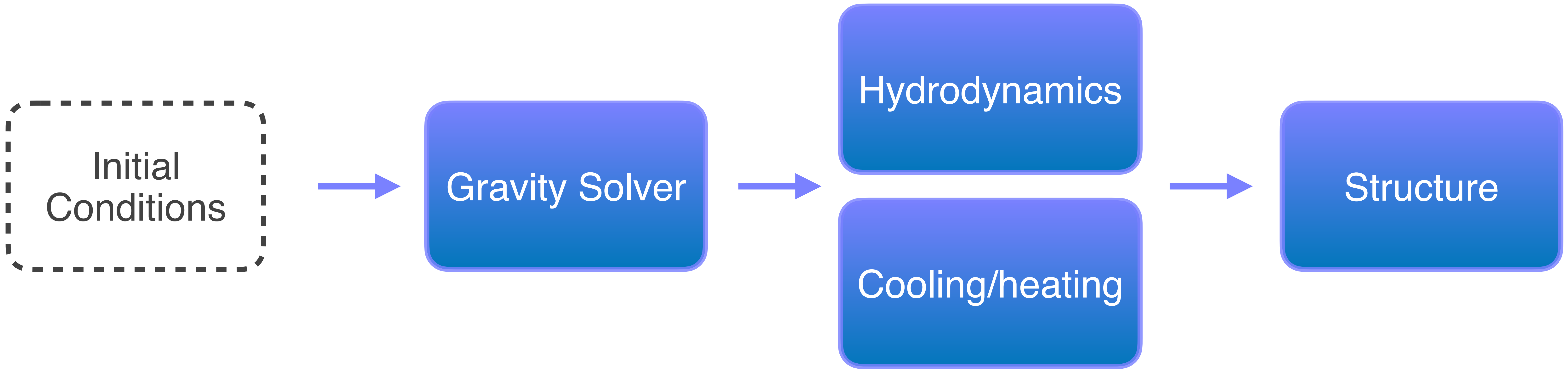

Initial Conditions
Gravity Solver
Hydrodynamics
Cooling/heating
Structure

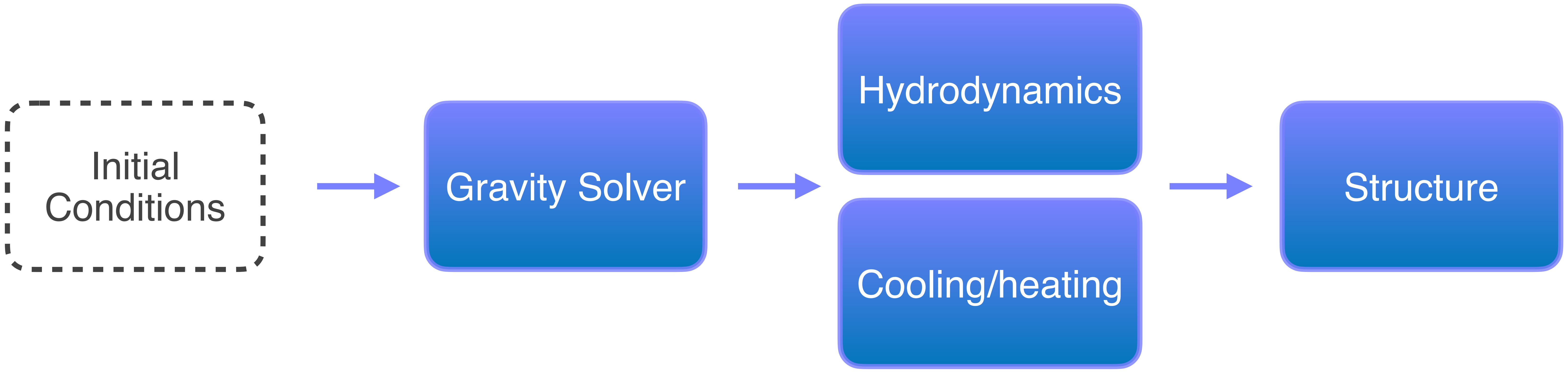
Grackle



Grackle

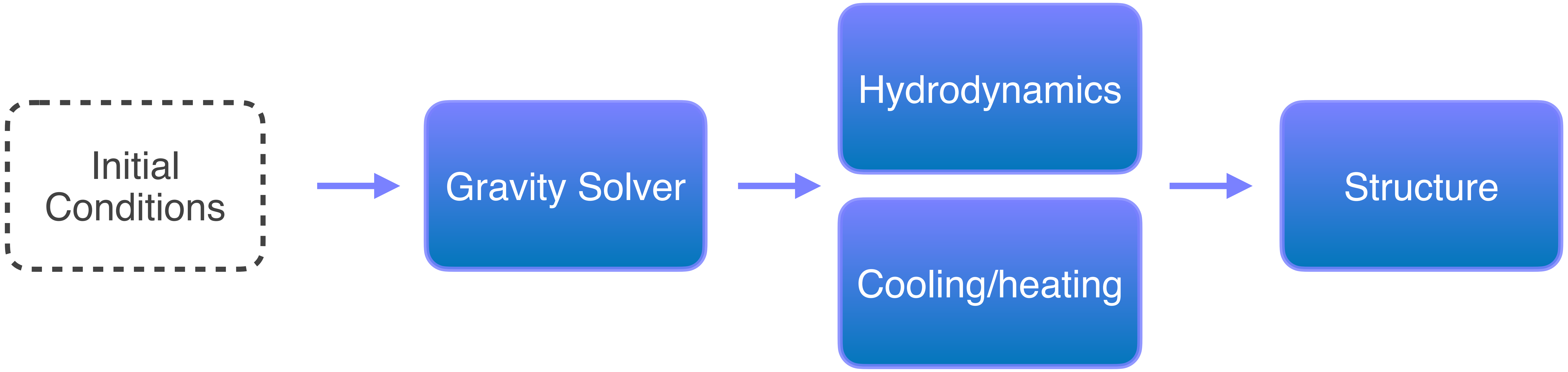
- Chemistry and cooling library

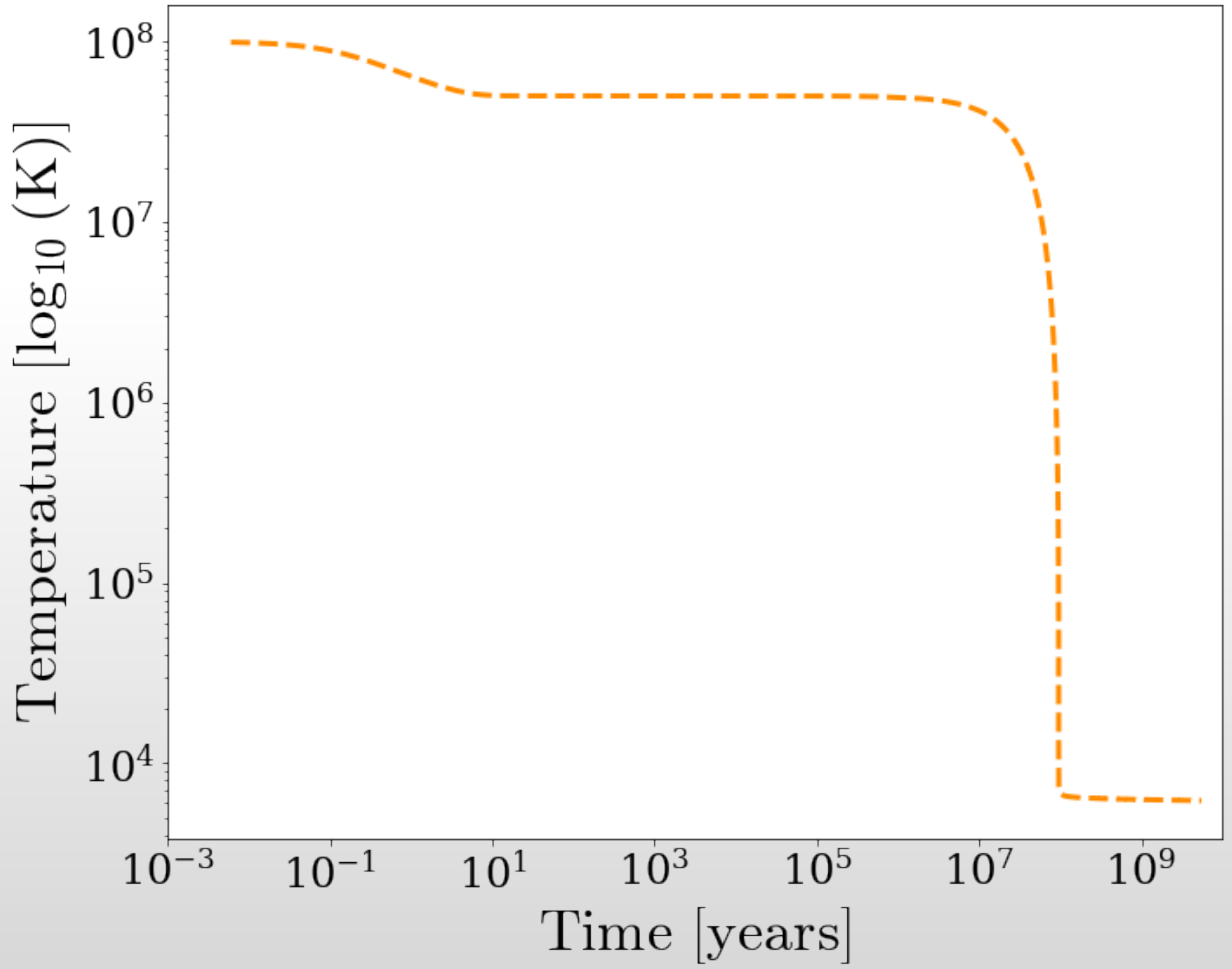
EPFL



Grackle

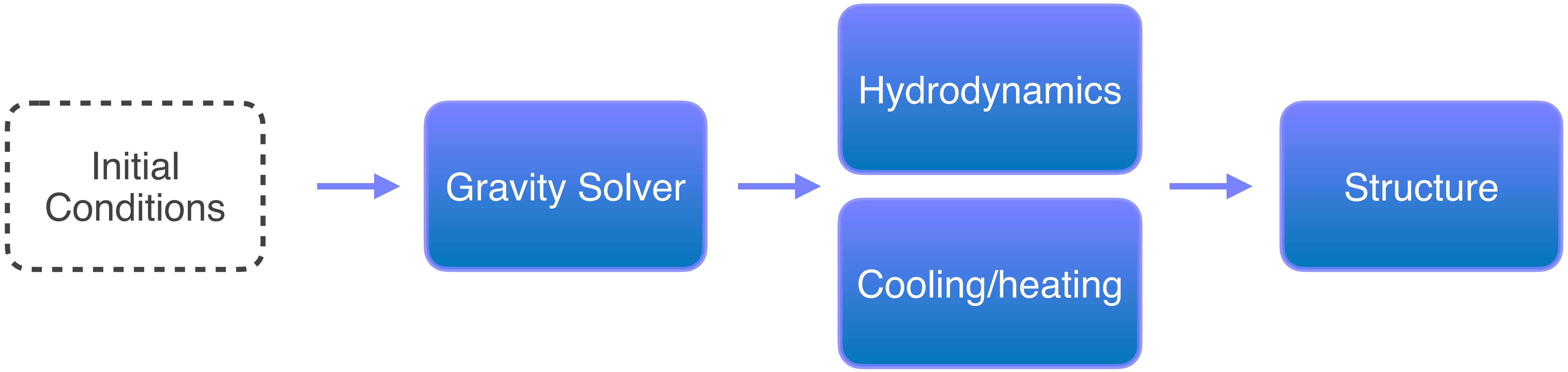
- Chemistry and cooling library
- Initial values for $T,\ \rho_i$

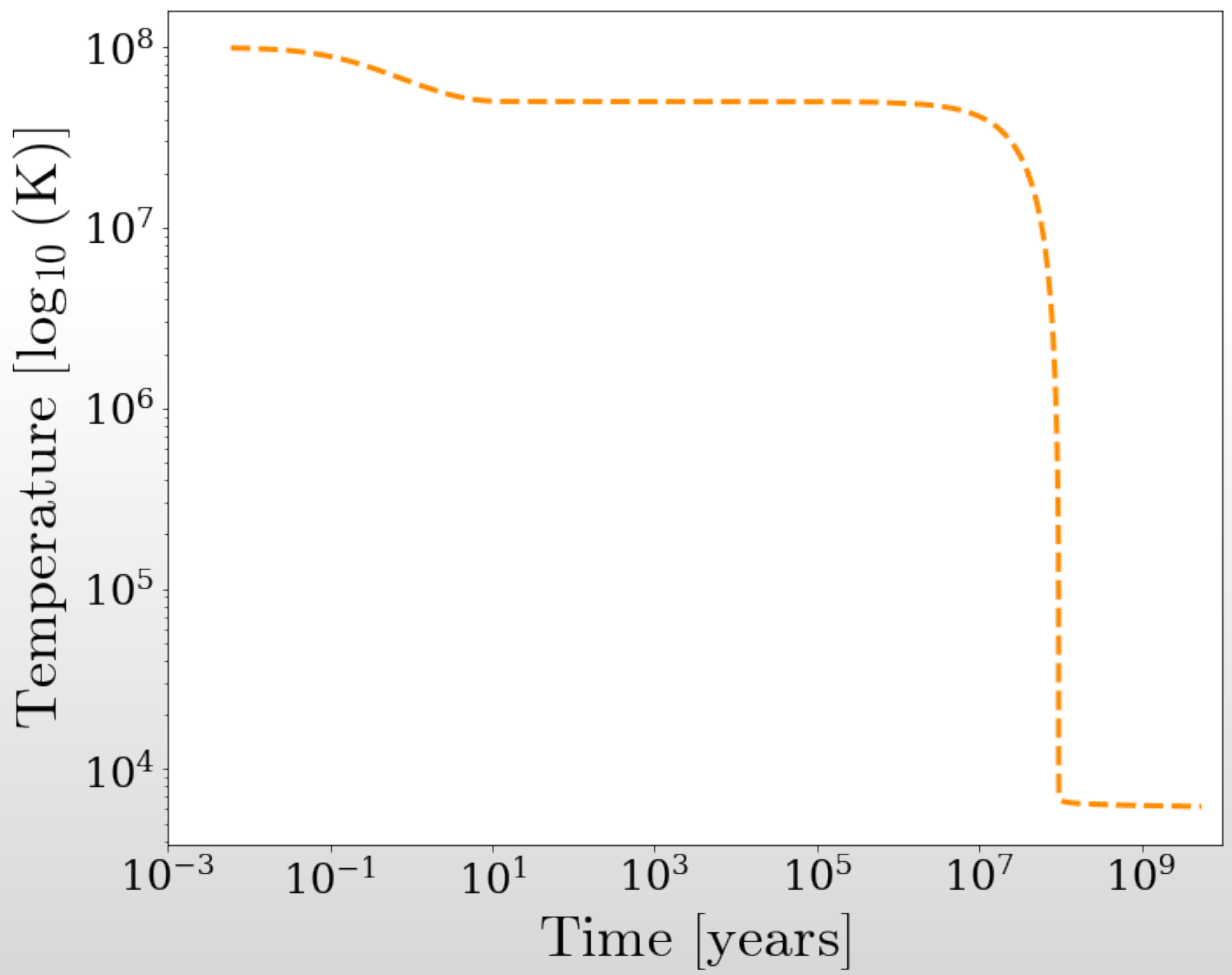


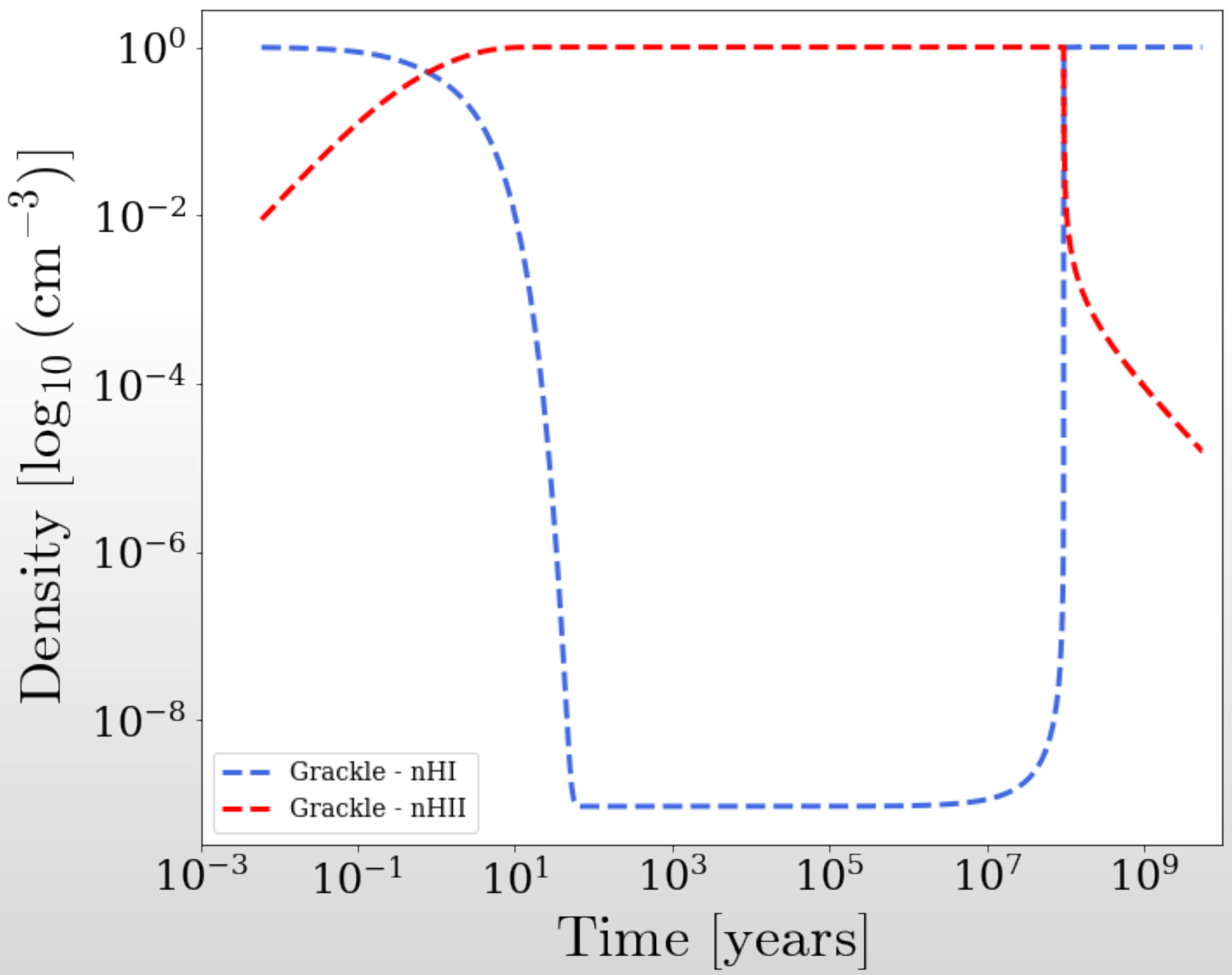


Grackle

- Chemistry and cooling library
- Initial values for $T,\ \rho_i$
- Update T at each iteration



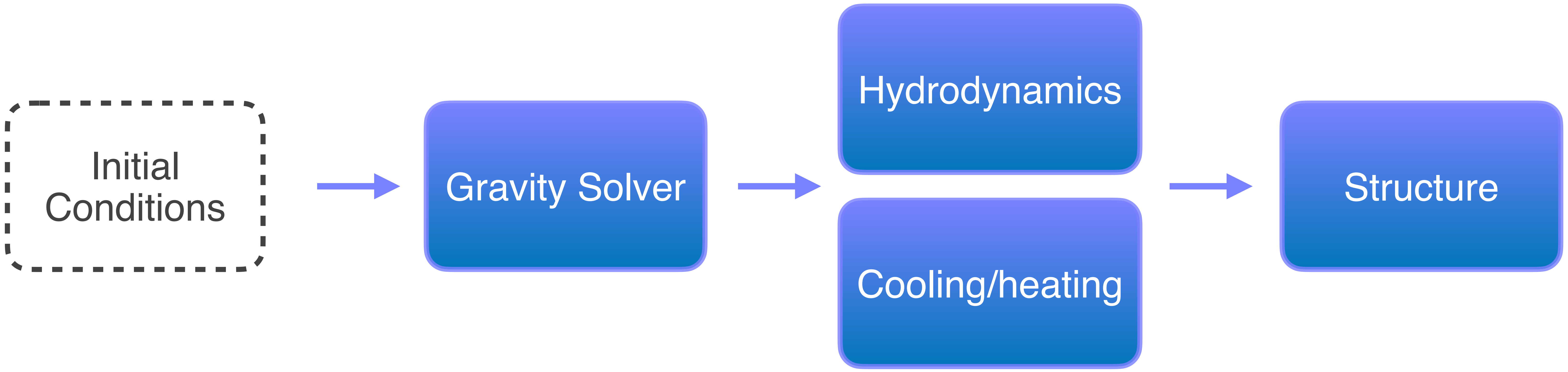


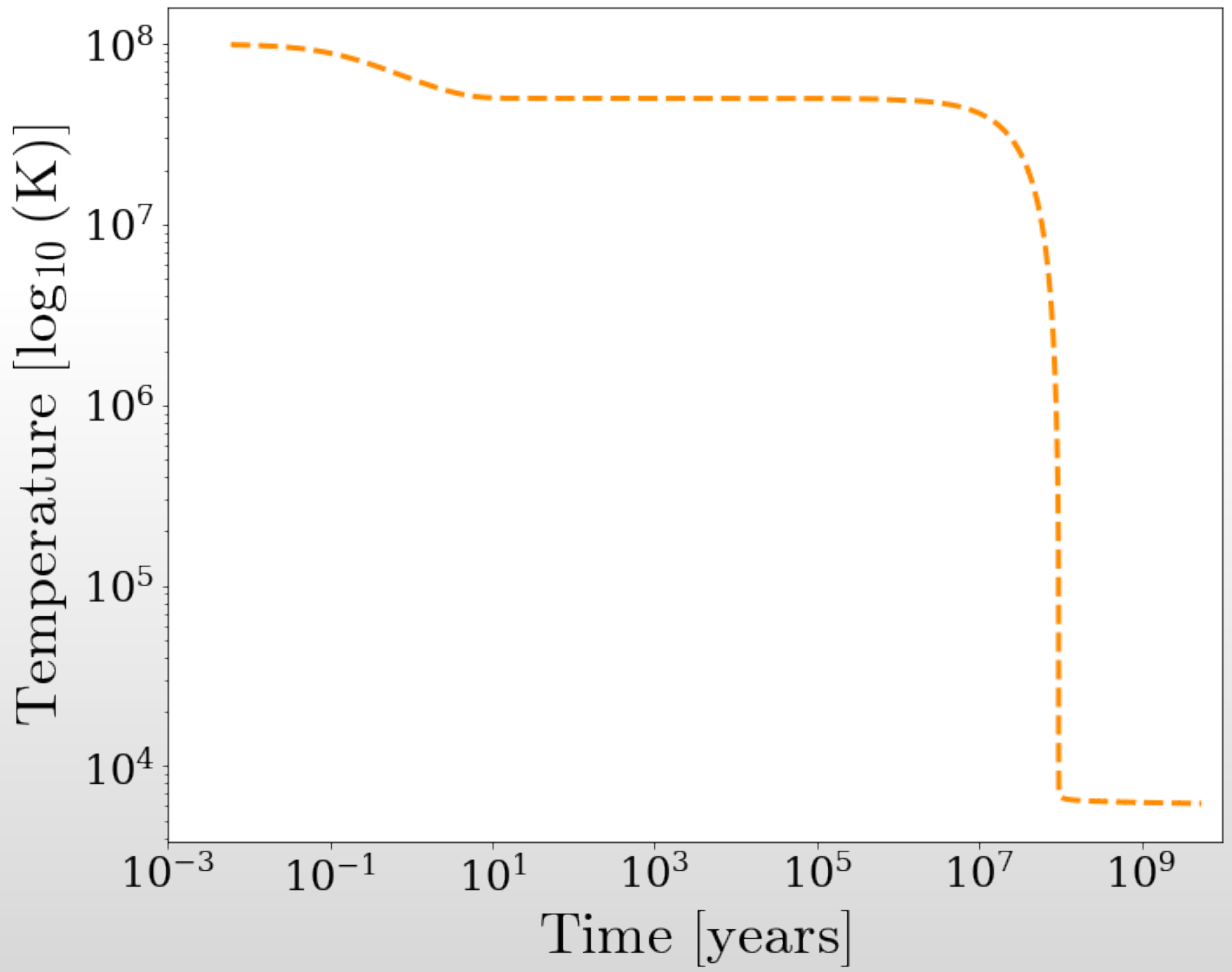


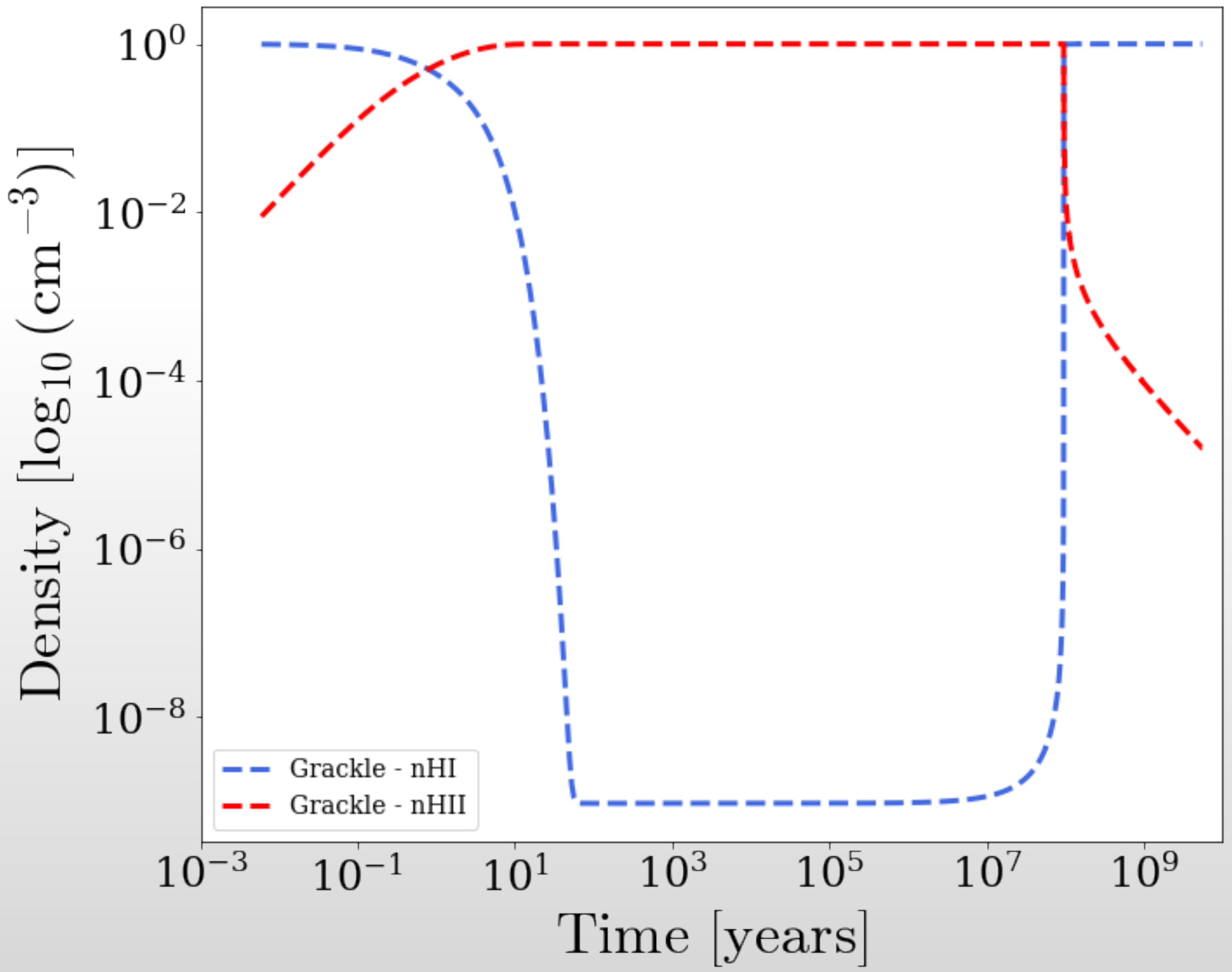
Grackle

- Chemistry and cooling library
- Initial values for $T,\ \rho_i$
- Update T at each iteration
- Update densities through rate equations:

$$\frac{\partial n_i}{\partial t} = \sum_j \sum_l k_{jl}(T) n_j n_l$$







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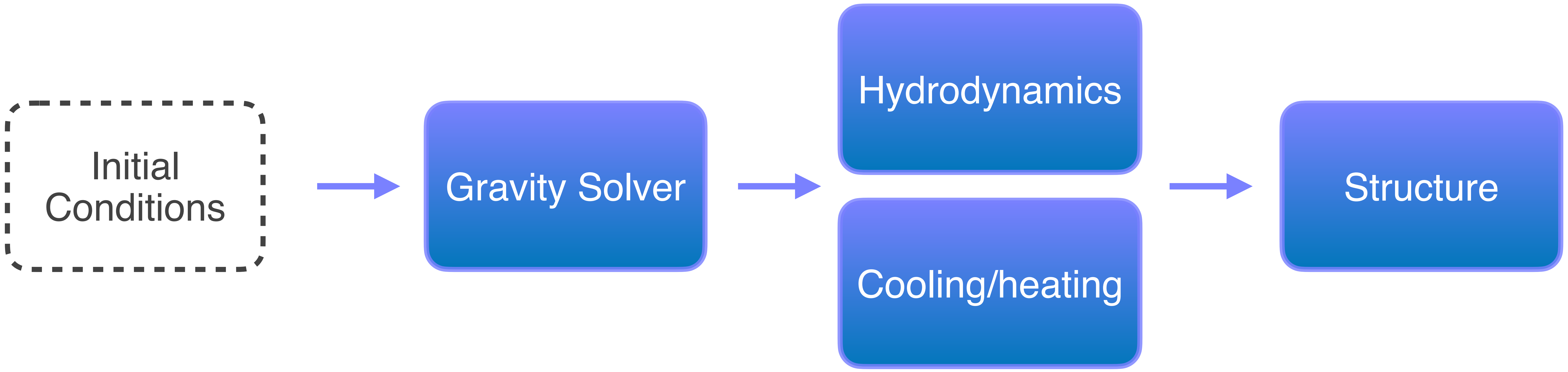
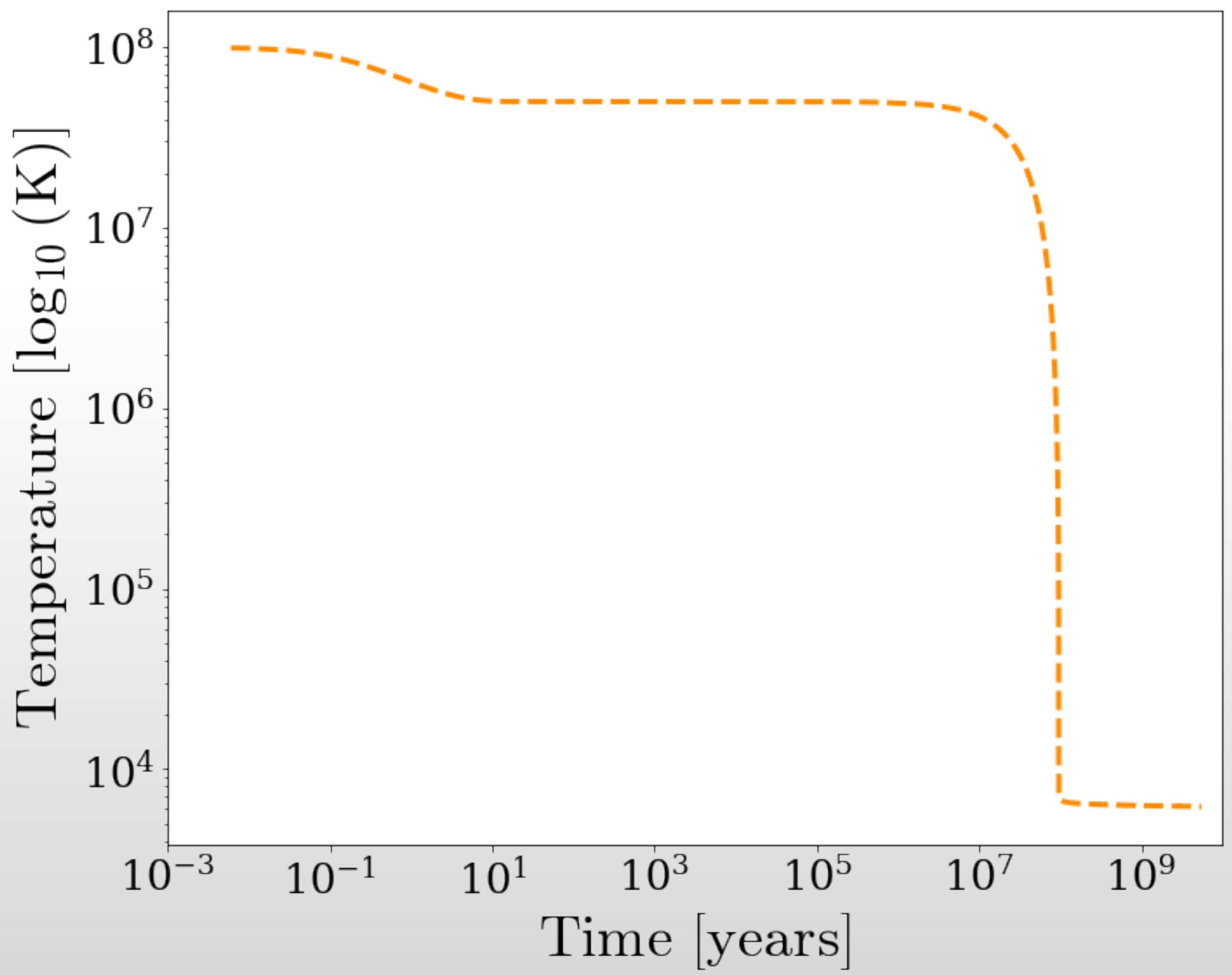
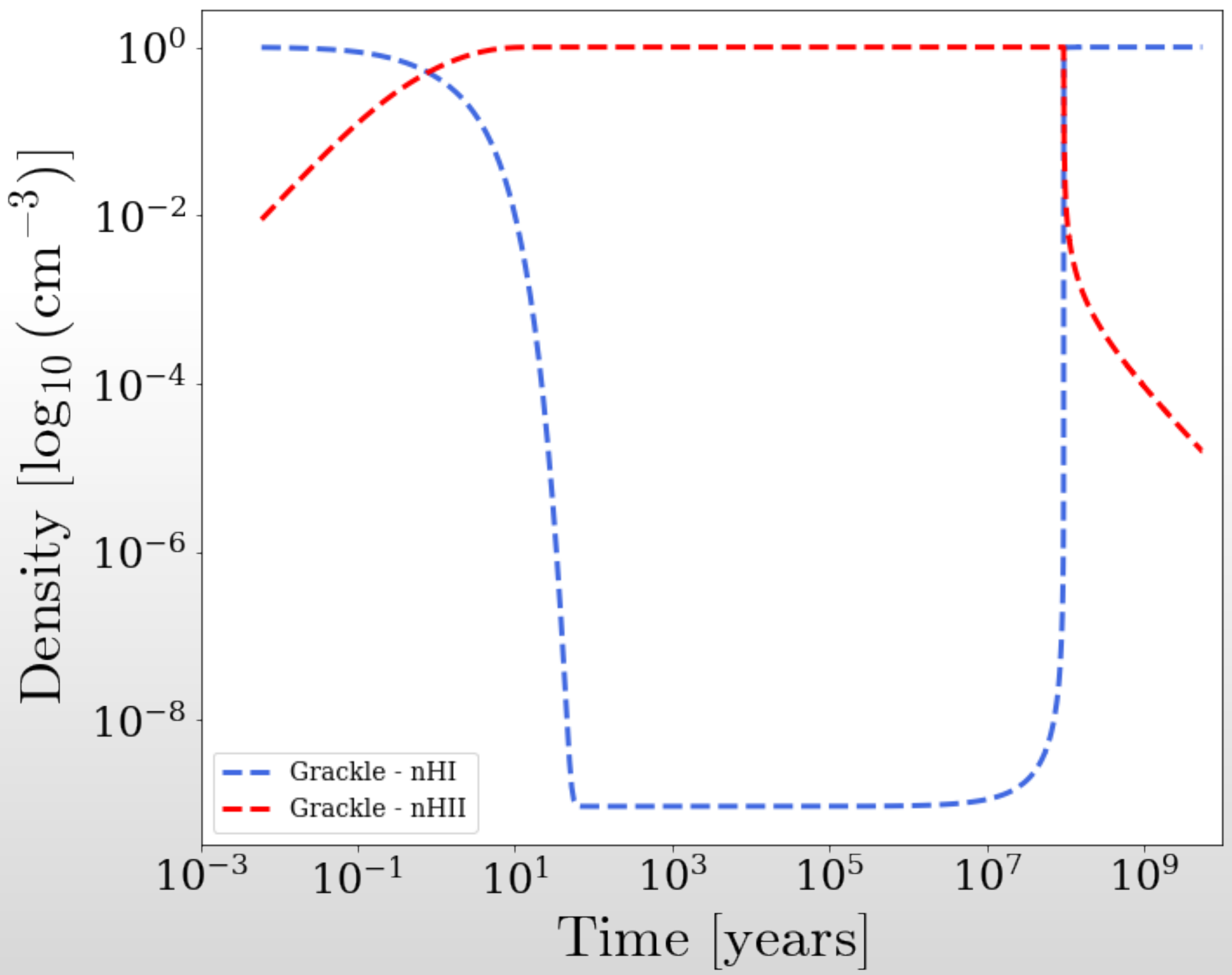
EPFL







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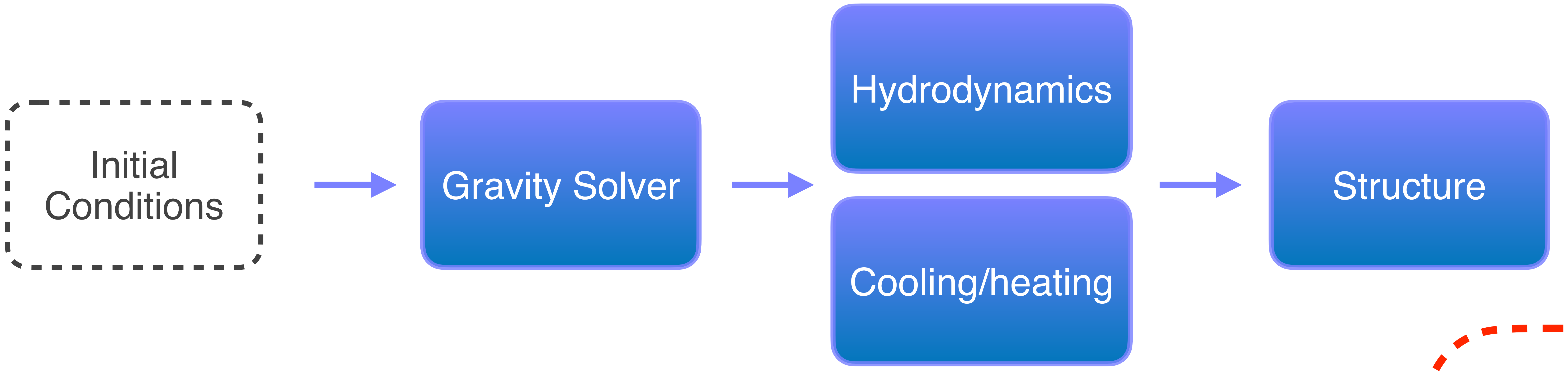

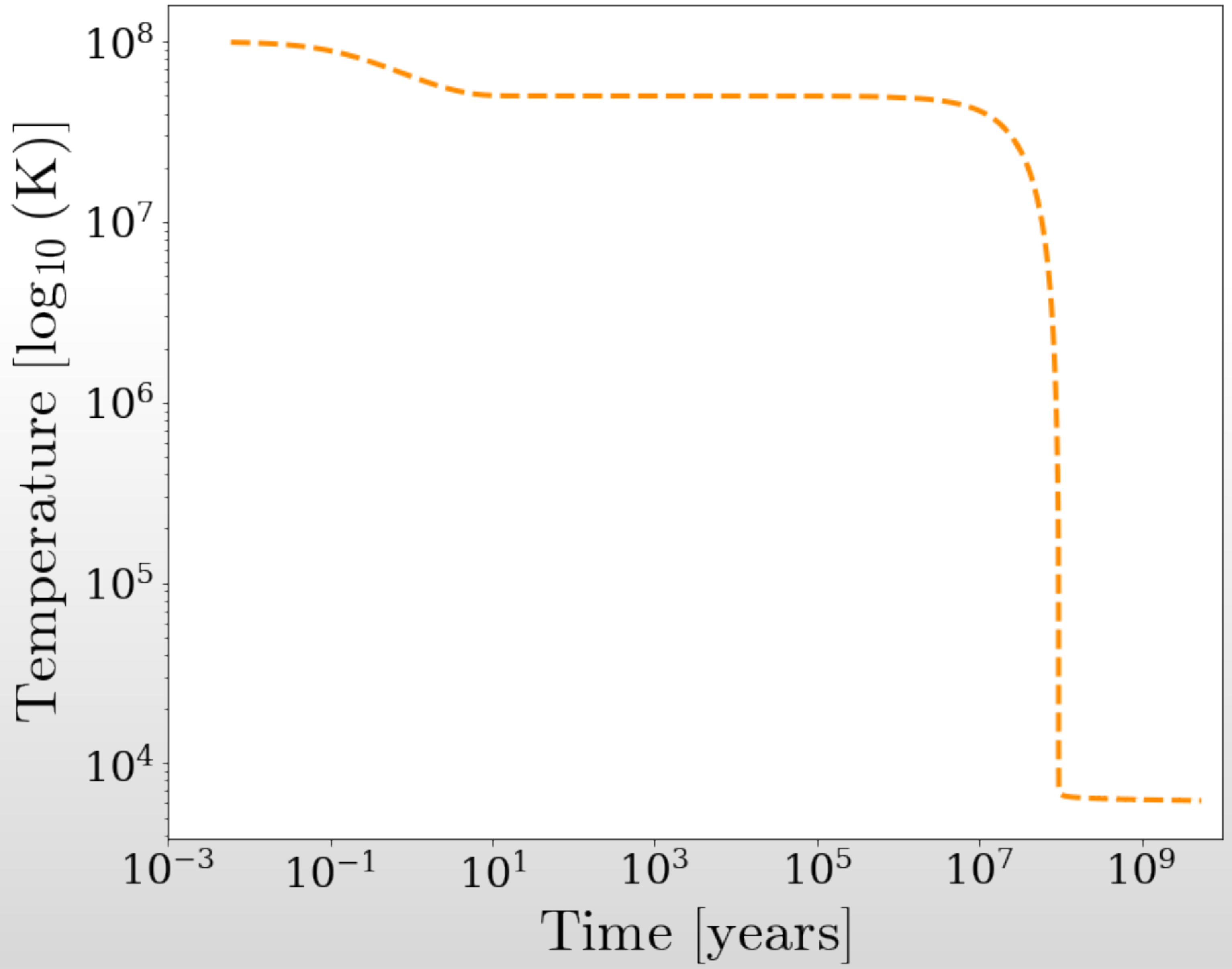

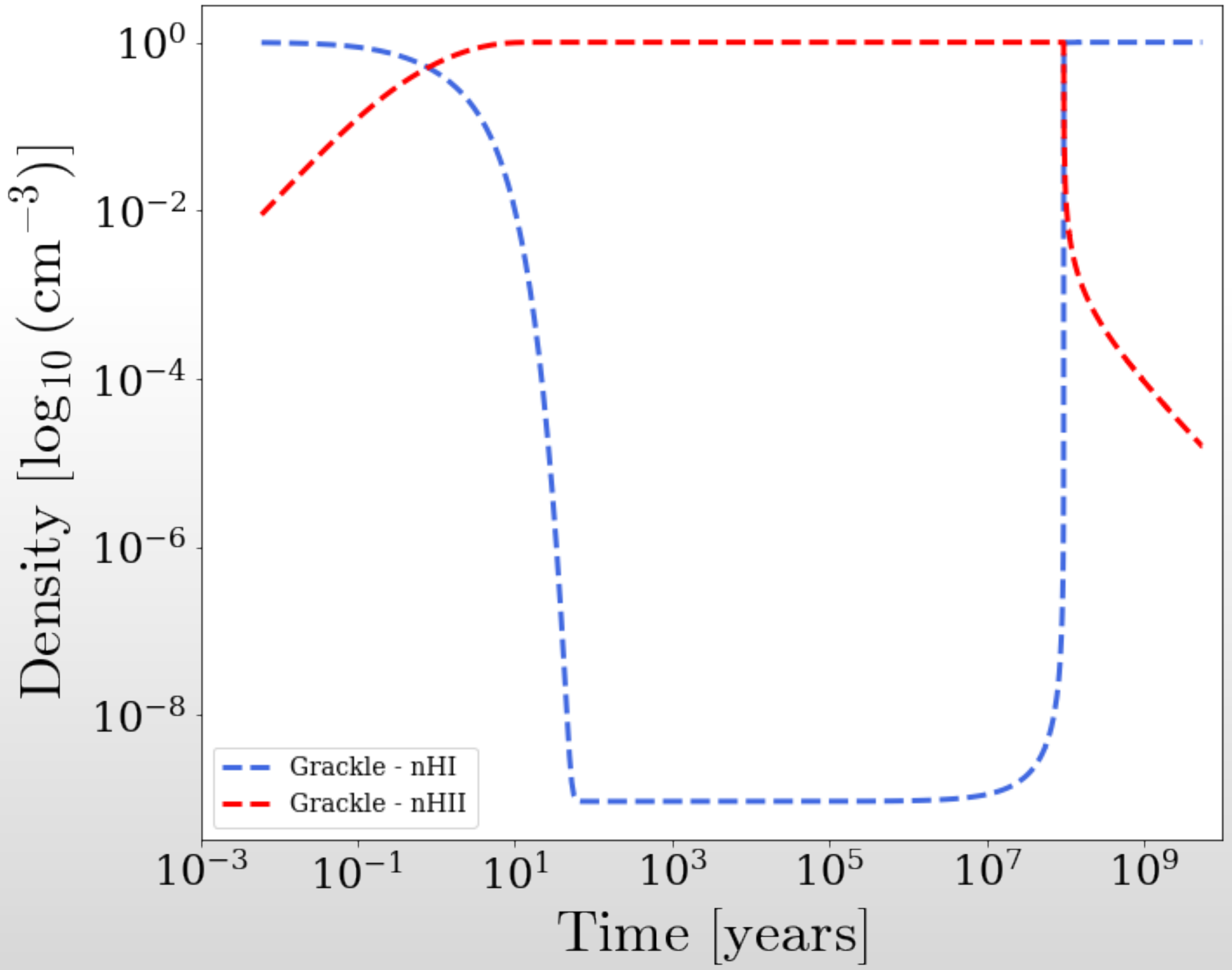

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Time Consuming!

Grackle

- Chemistry and cooling library
- Initial values for $T,\ \rho_i$
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Time Consuming!

Emulate using

Grackle

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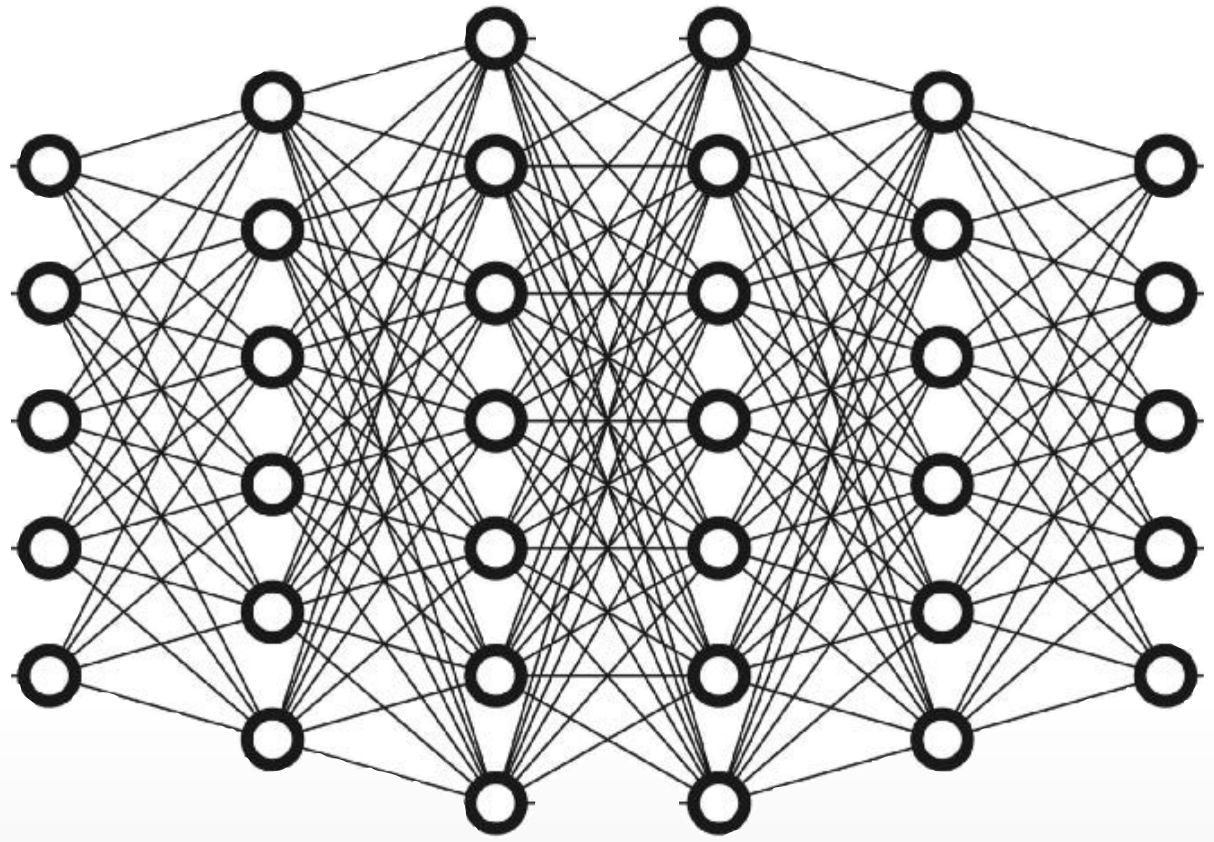
$$\frac{\partial n_i}{\partial t} = \sum_j \sum_l k_{jl}(T) n_j n_l + \cancel{\sum_j I_j n_l}$$

Time Consuming!

Emulate using

Neural Nets



EPFL

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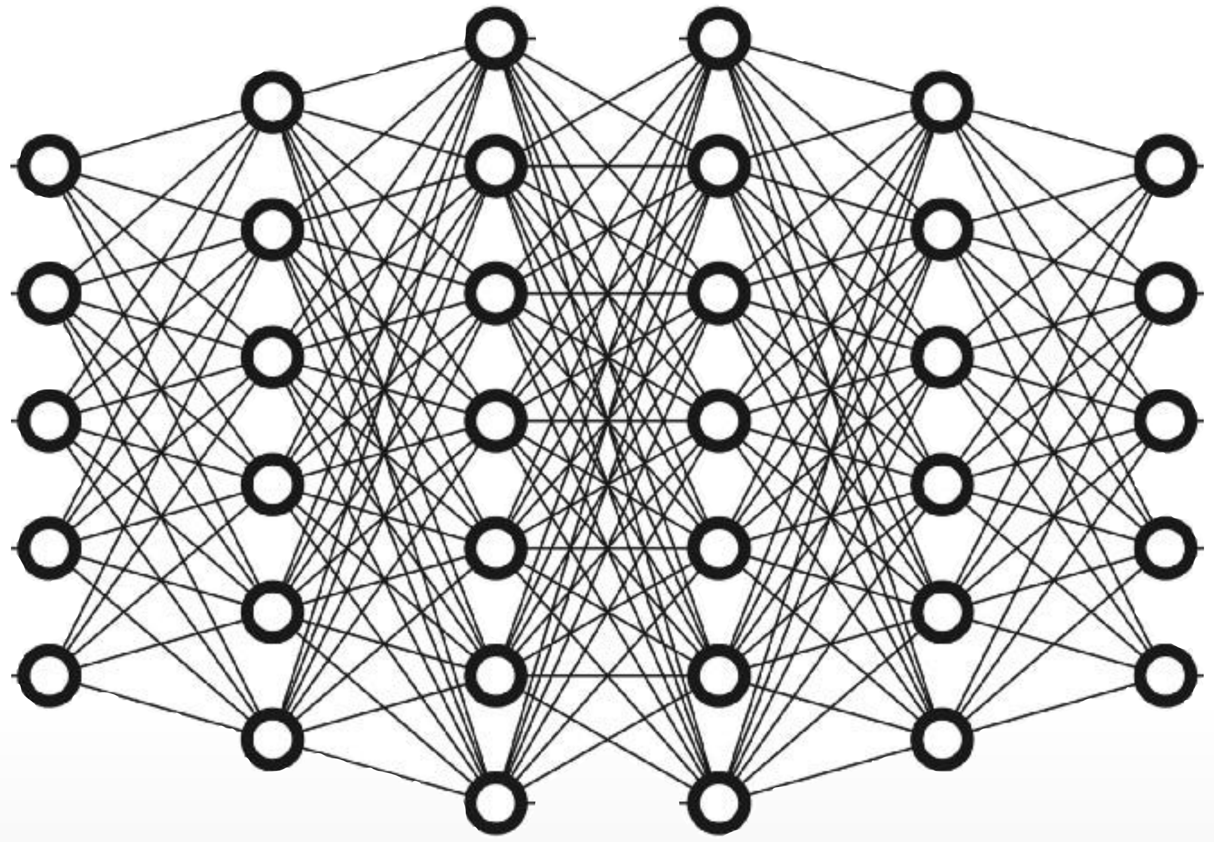
Time Consuming!

Emulate using

Neural Nets



- Simple architecture

Grackle

- Chemistry and cooling library
- Initial values for $T,\ \rho_i$
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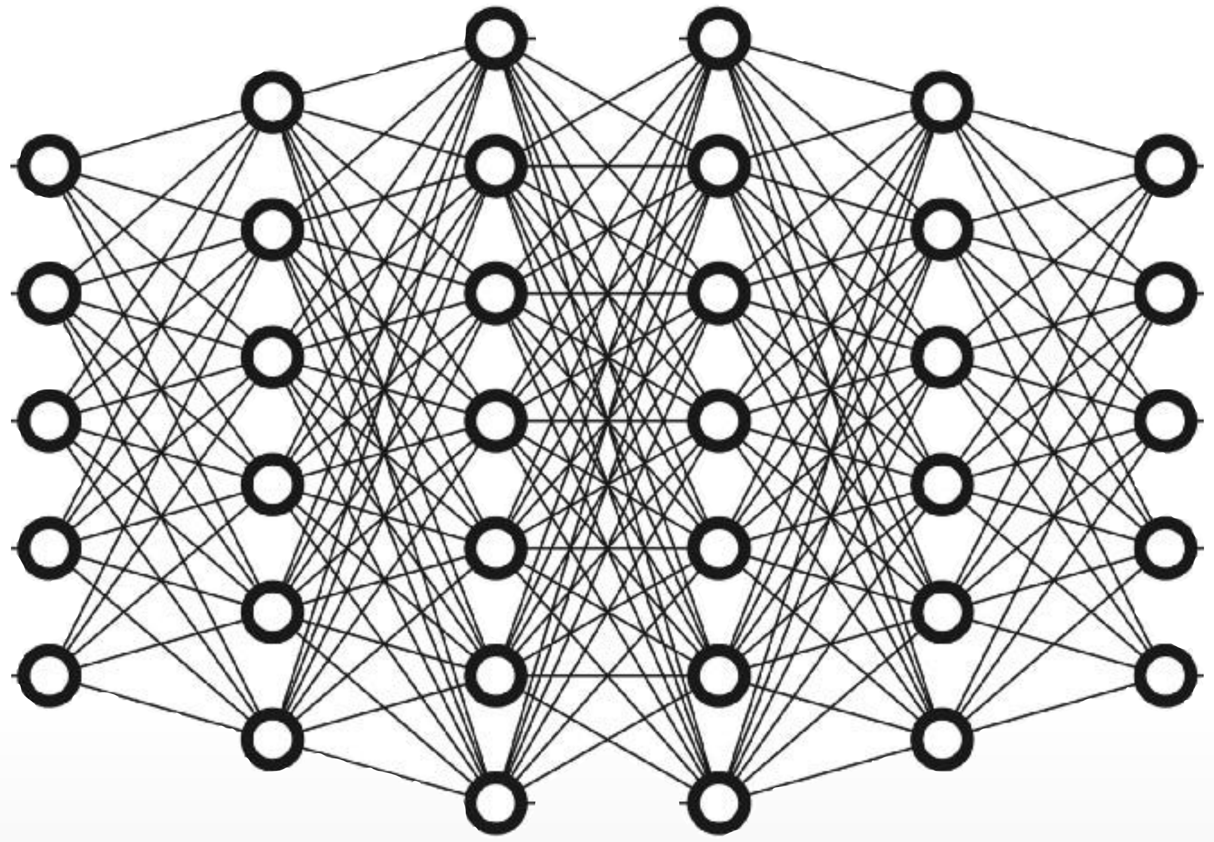
Time Consuming!

Emulate using

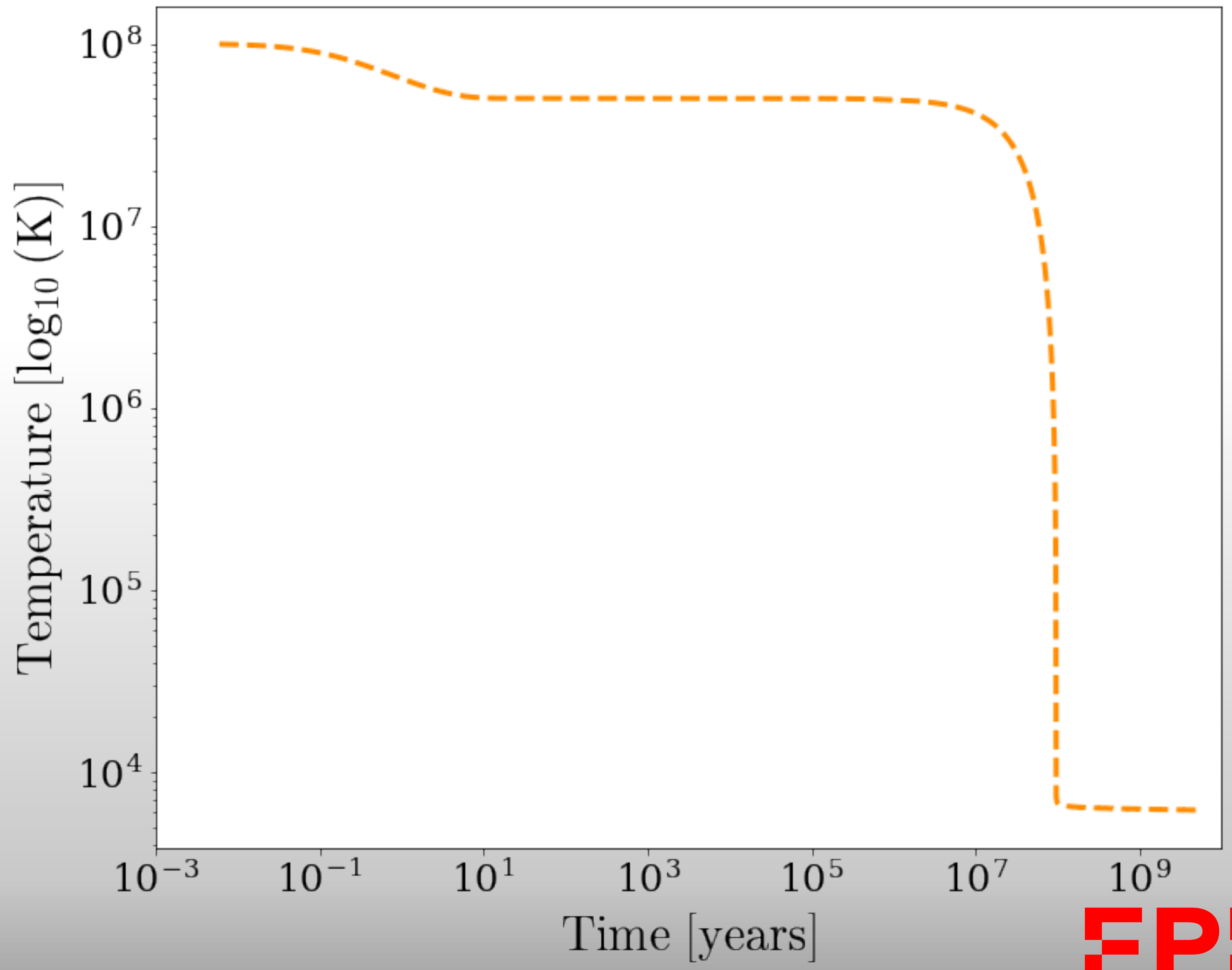
Neural Nets



- Simple architecture
- Train with data from Grackle

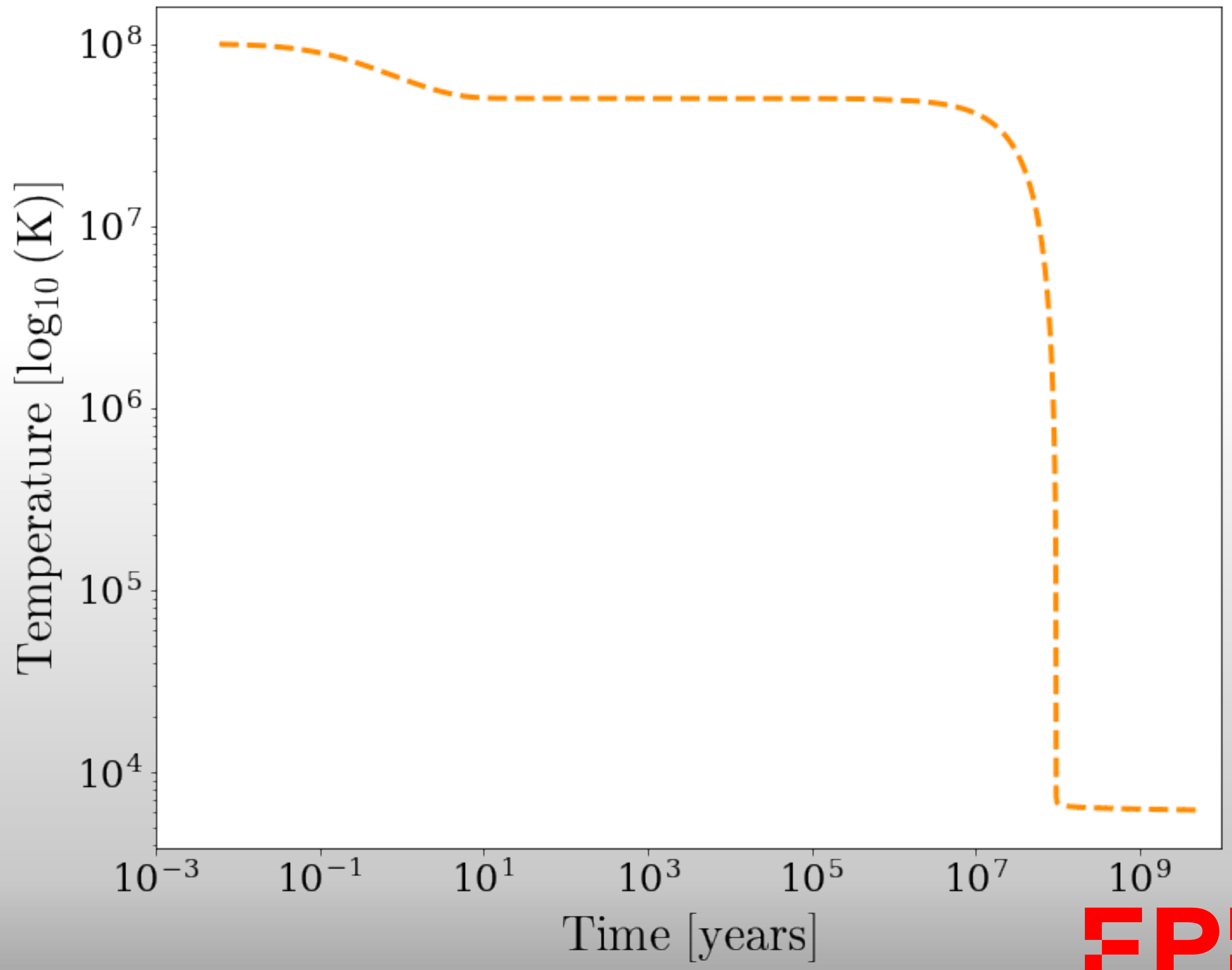
Data Generation & Training

Data Generation & Training



Data Generation & Training

Sample:
T_i
$\rho_{HI,i}$
$\rho_{HII,i}$
dt_i



EPFL

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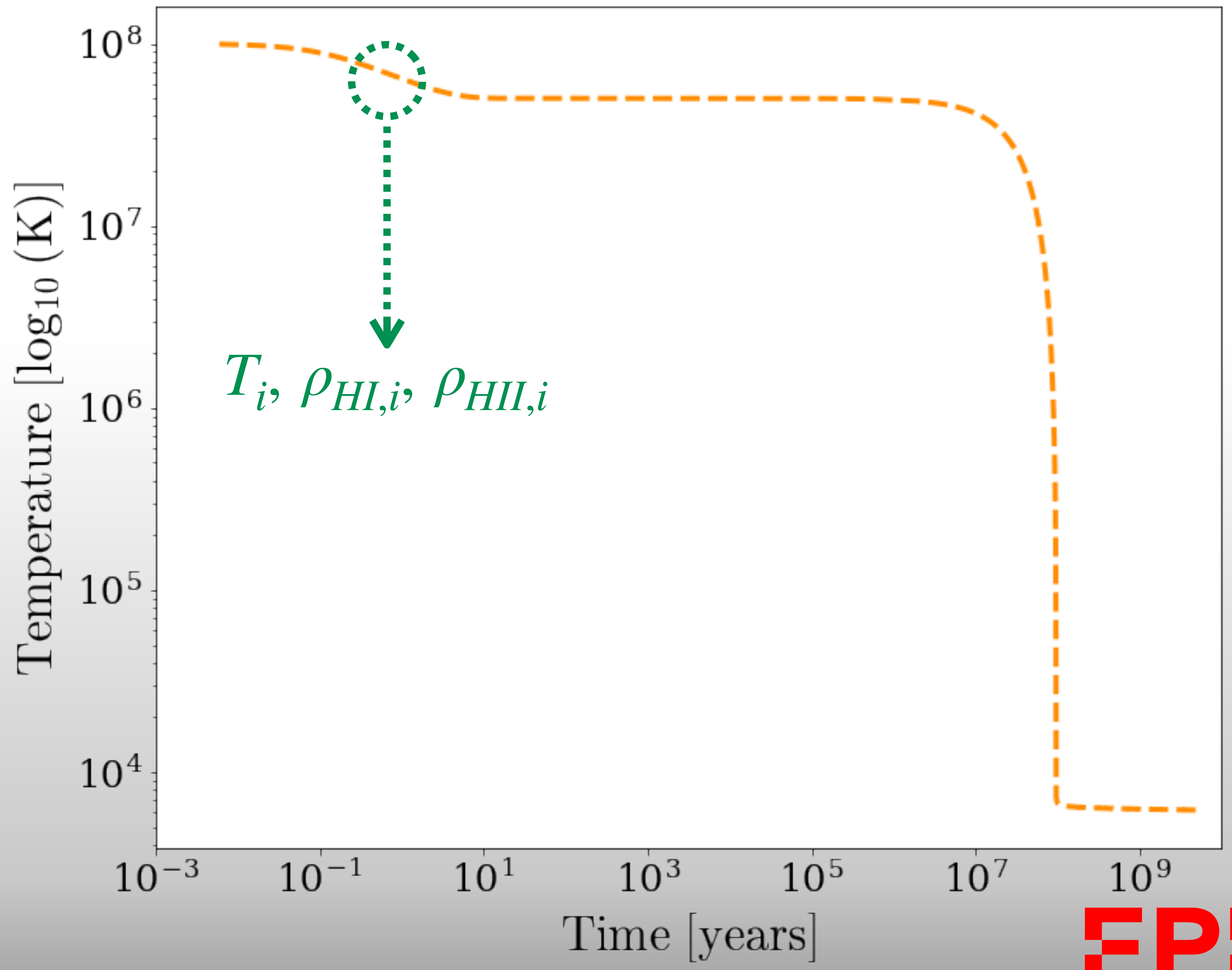

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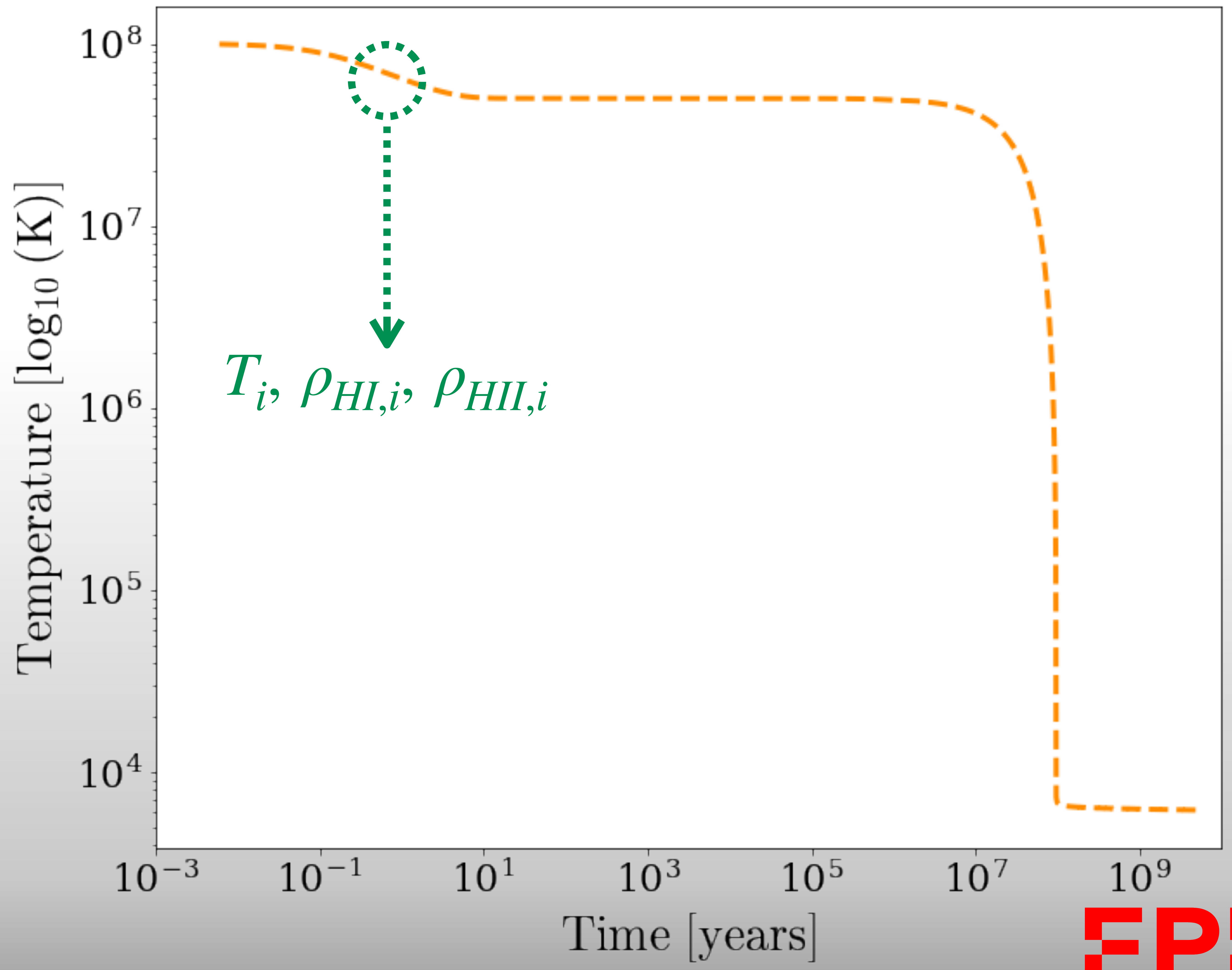
Grackle



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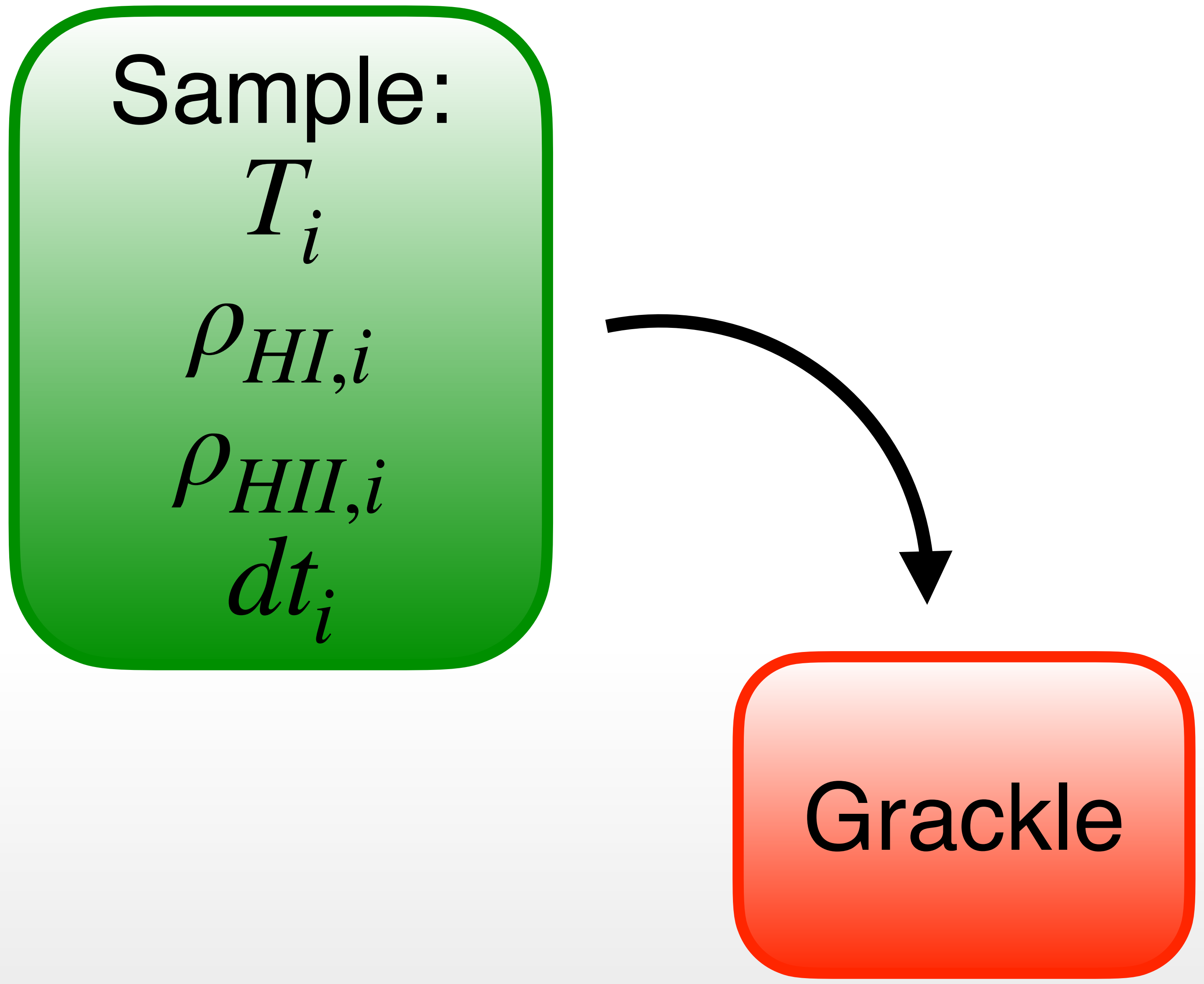
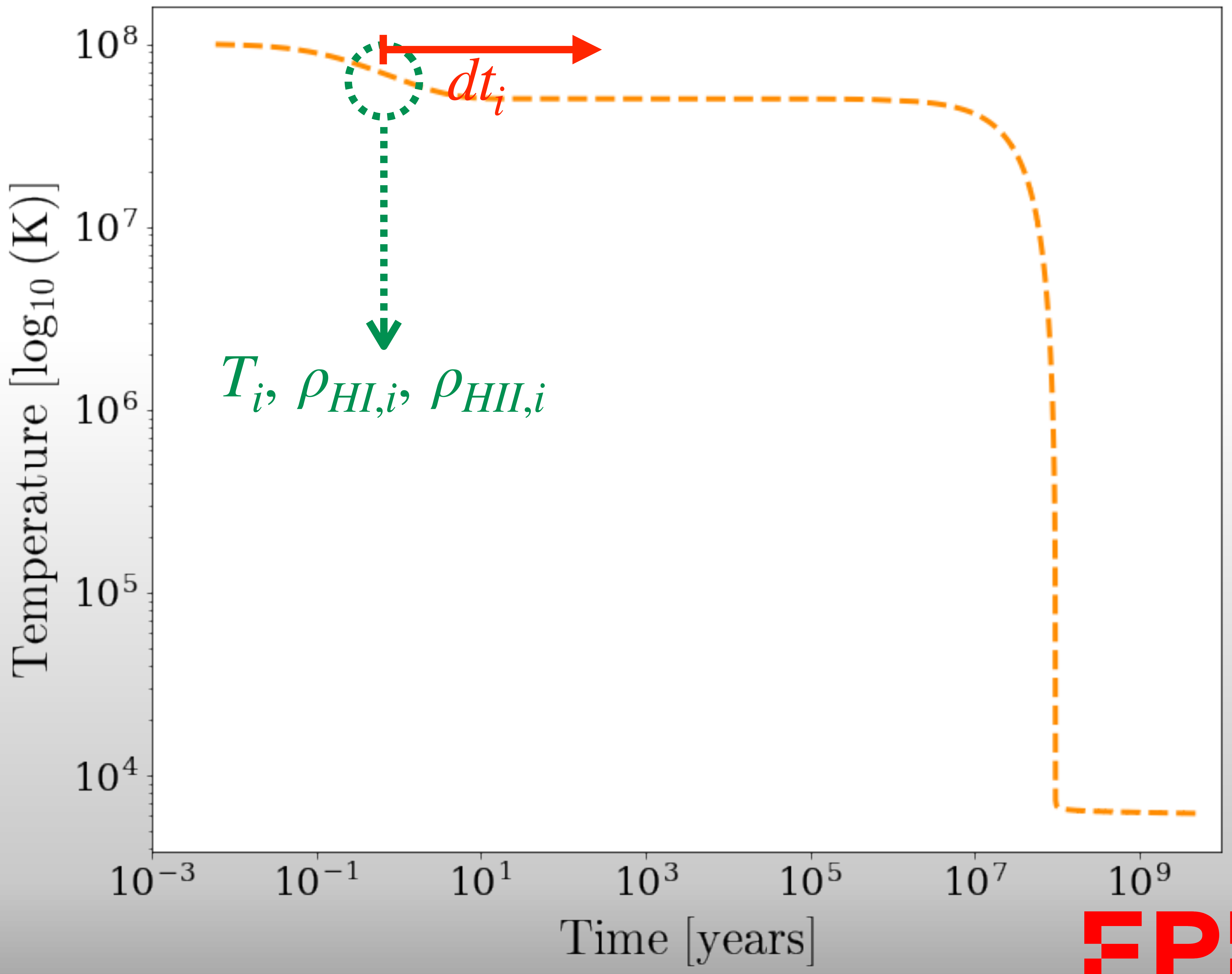




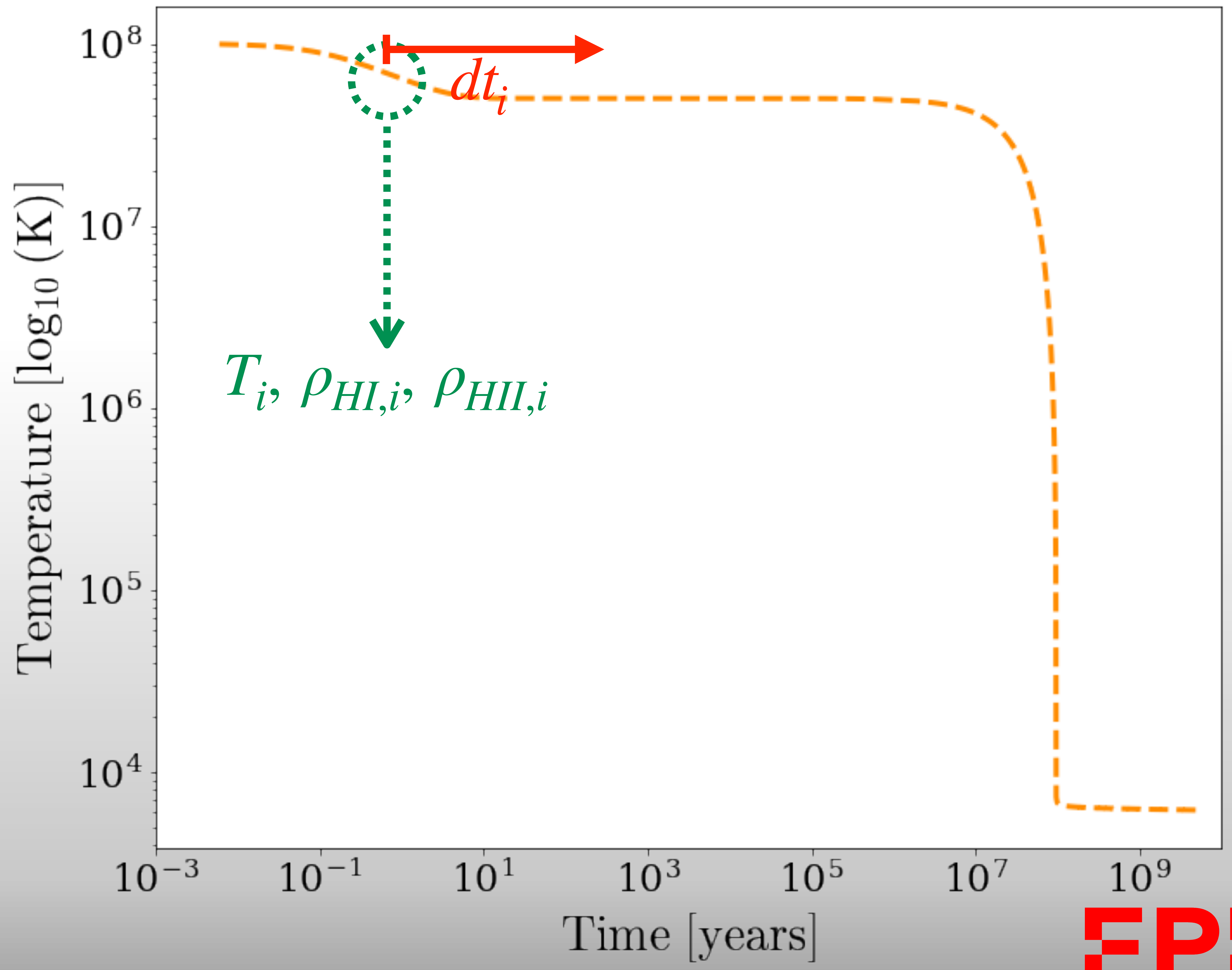
EPFL

Data Generation & Training

Sample:
T_i
$\rho_{HI,i}$
$\rho_{HII,i}$
dt_i

Grackle

Output:
T'_i
$\rho'_{HI,i}$
$\rho'_{HII,i}$
dt_i



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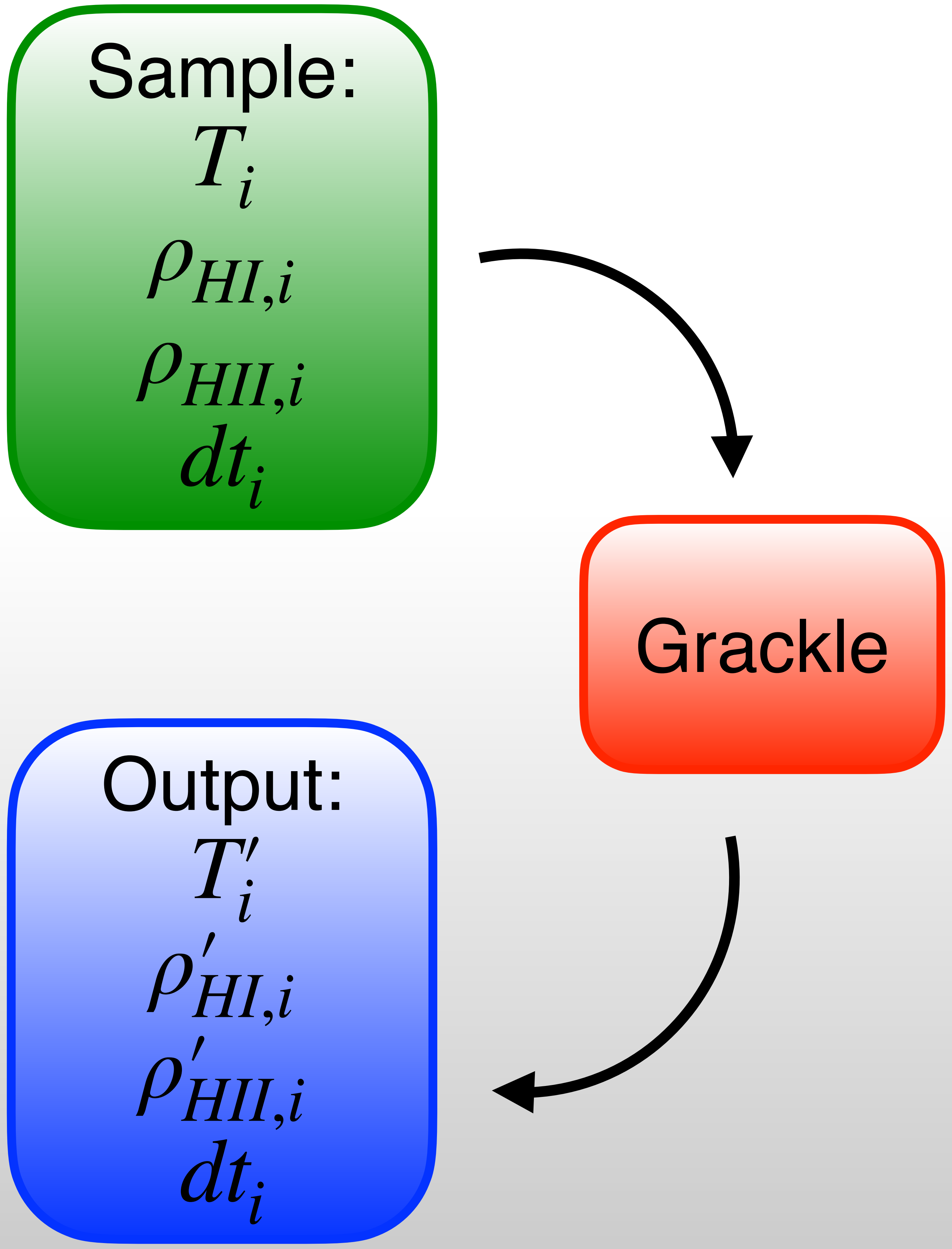

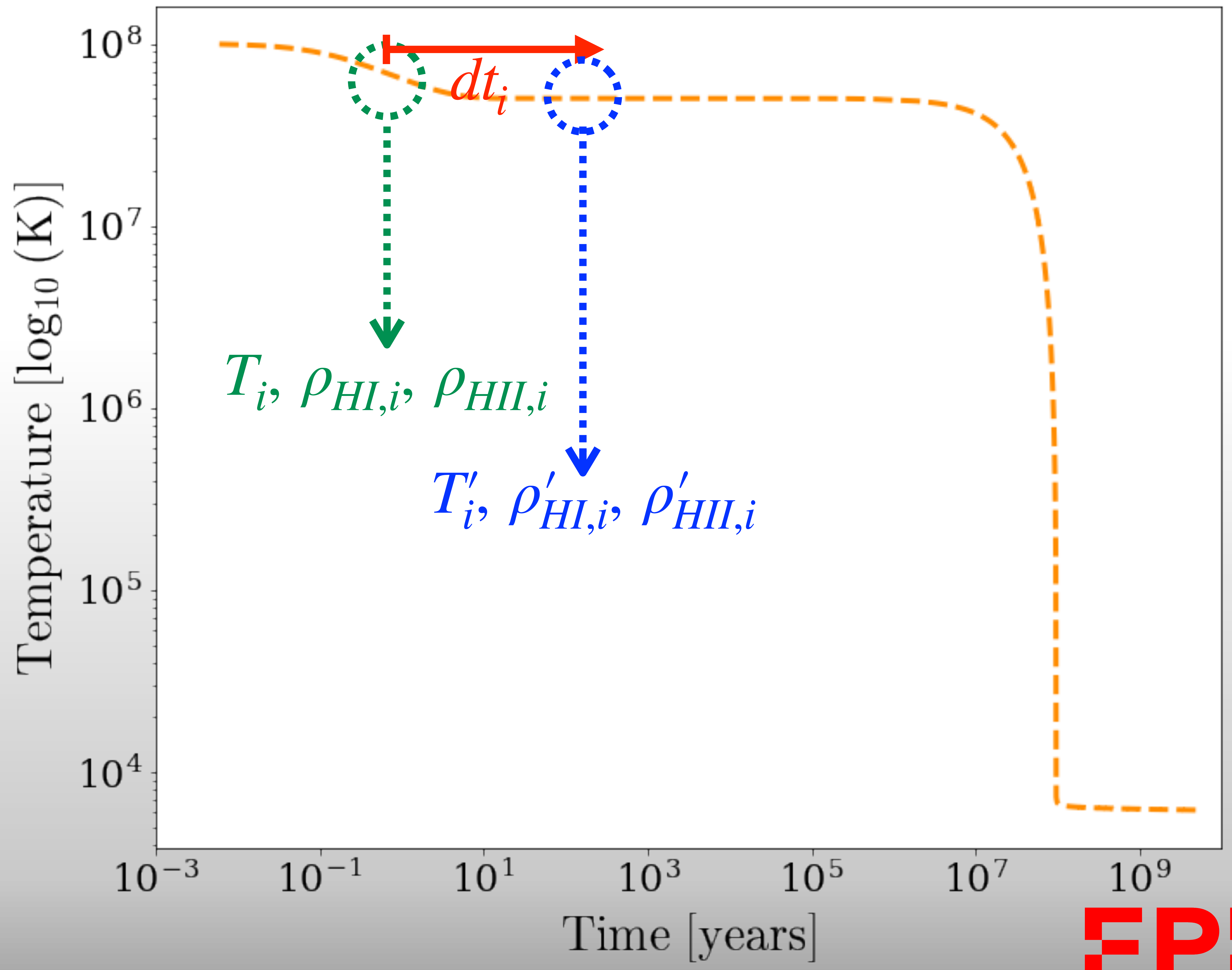

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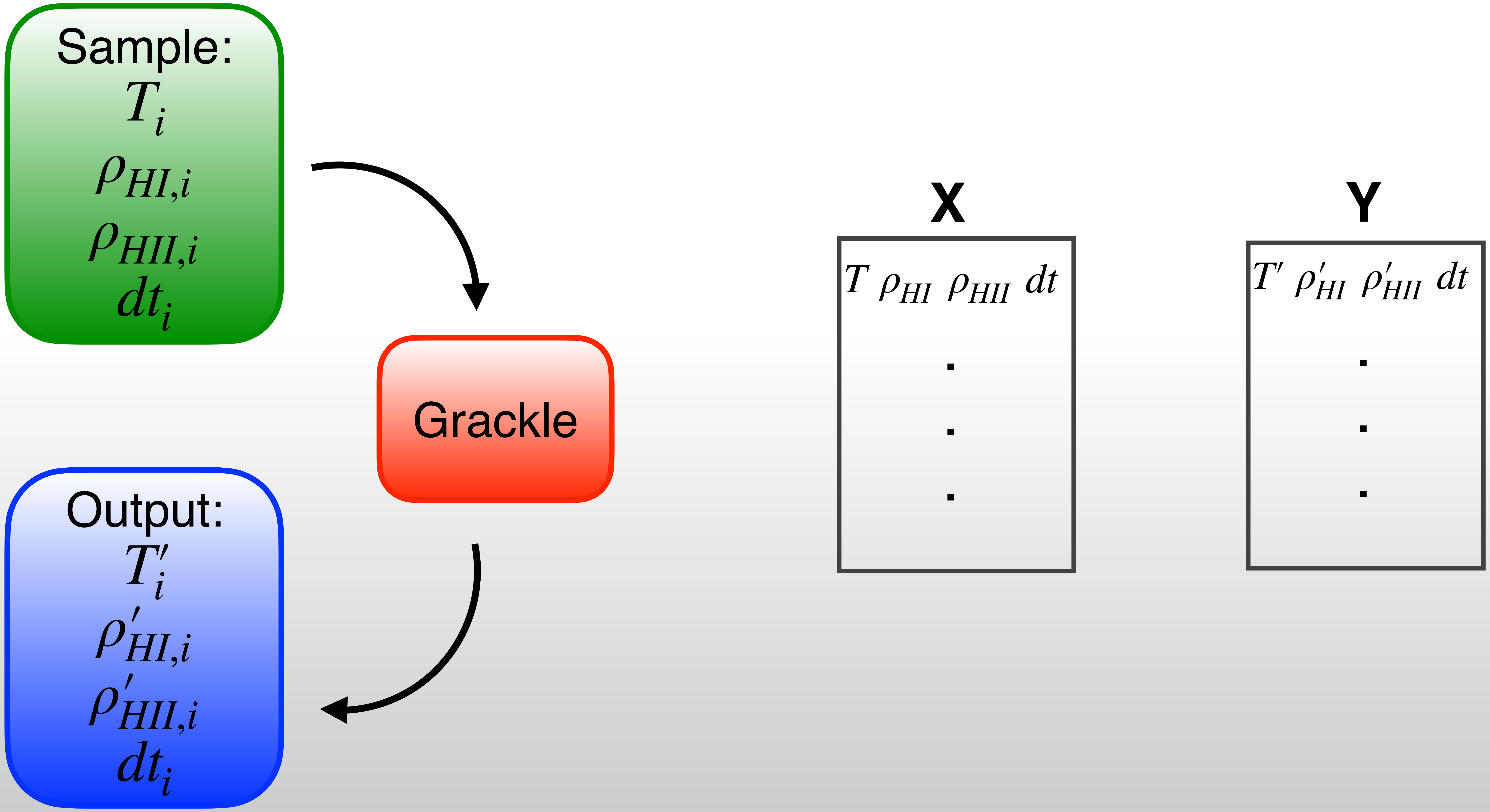

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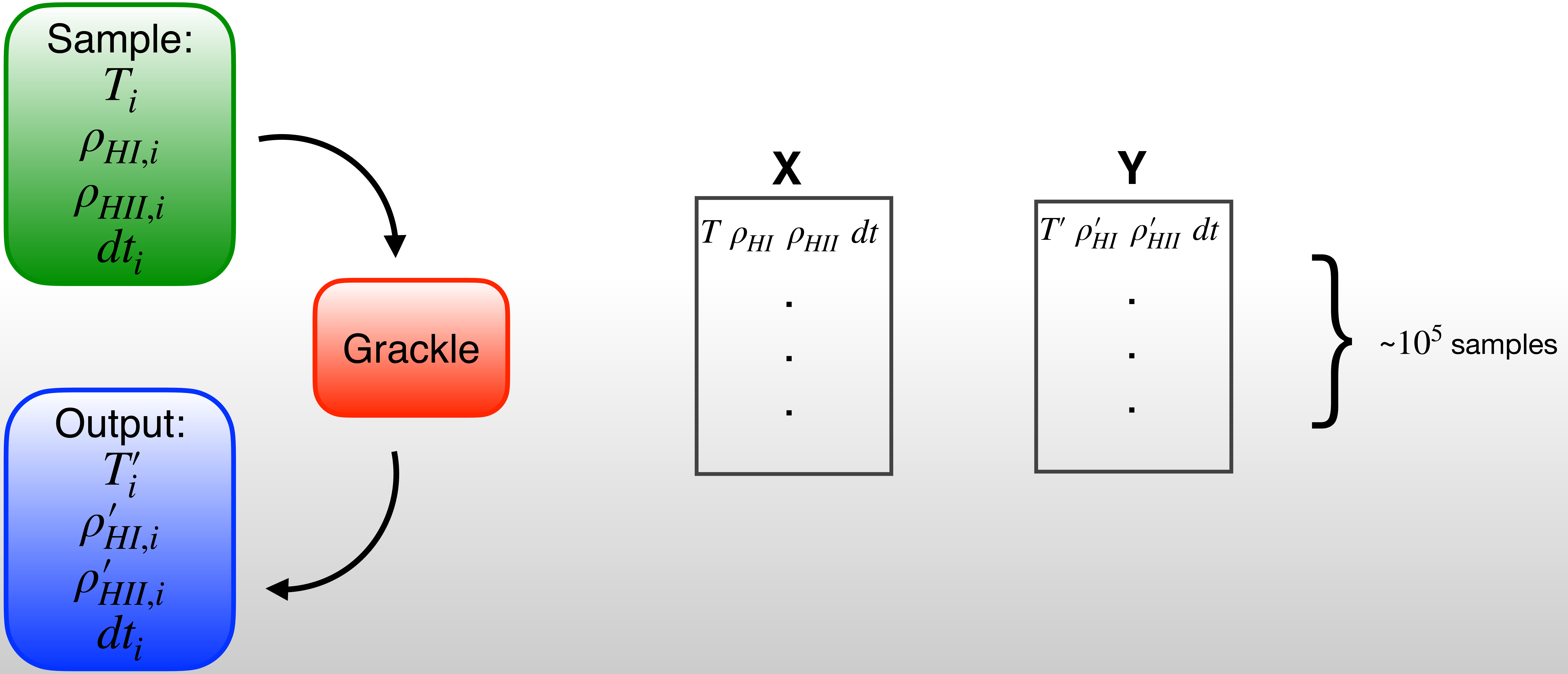


EPFL

Data Generation & Training

X

$T \; \rho_{HI} \; \rho_{HII} \; dt$

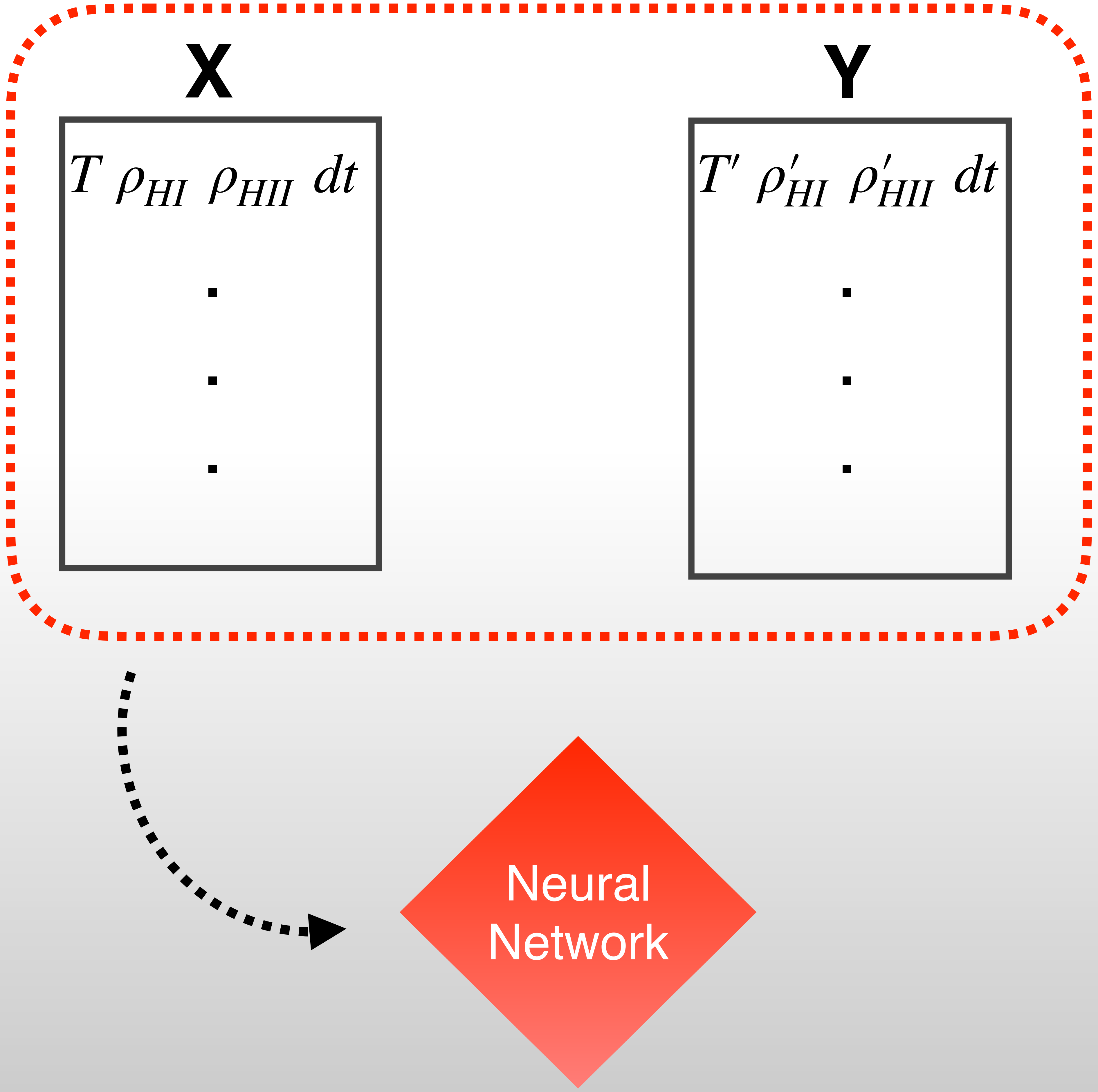
.
.
.

Y

$T' \; \rho'_{HI} \; \rho'_{HII} \; dt$

.
.
.

Data Generation & Training



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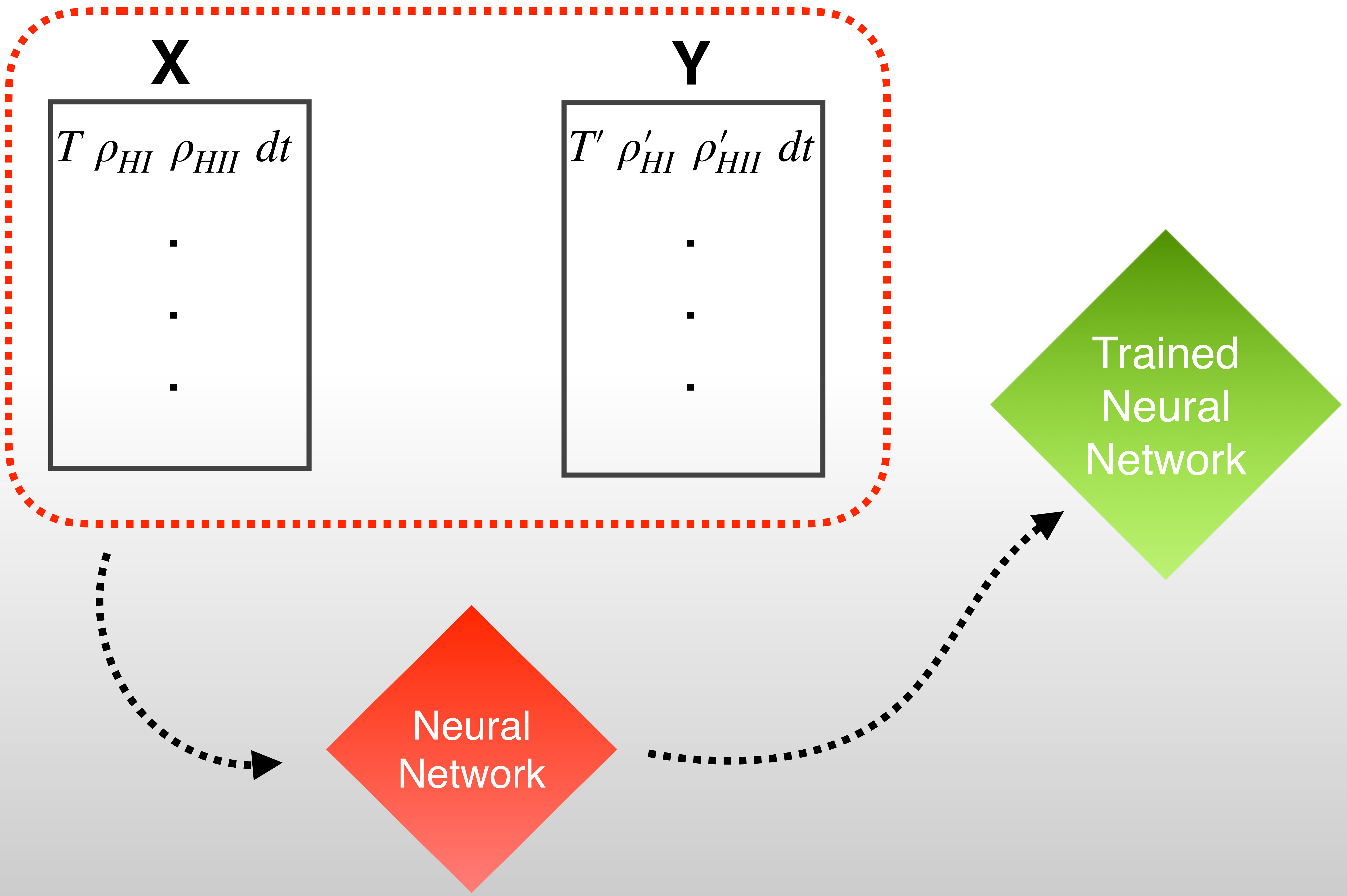

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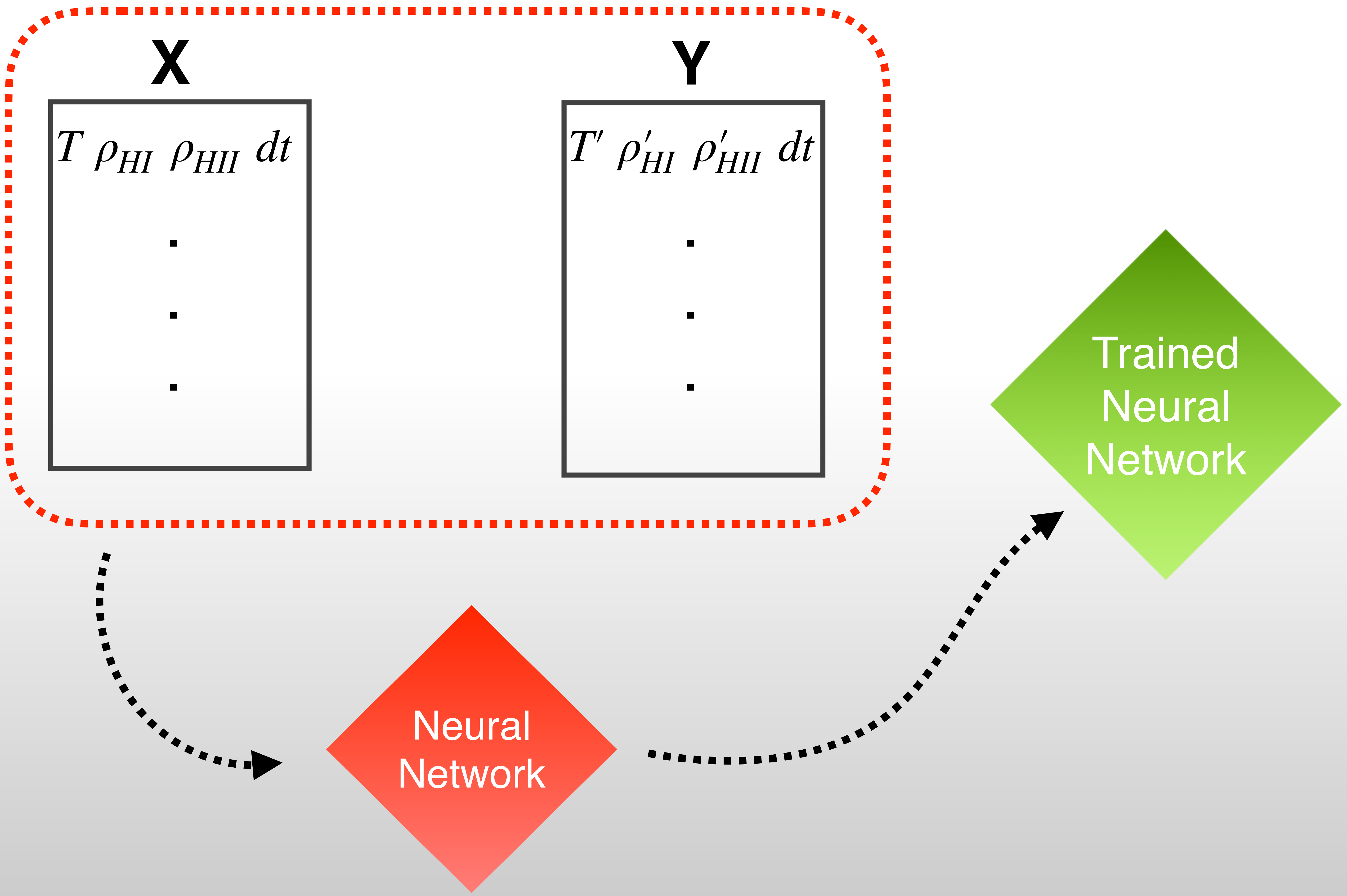
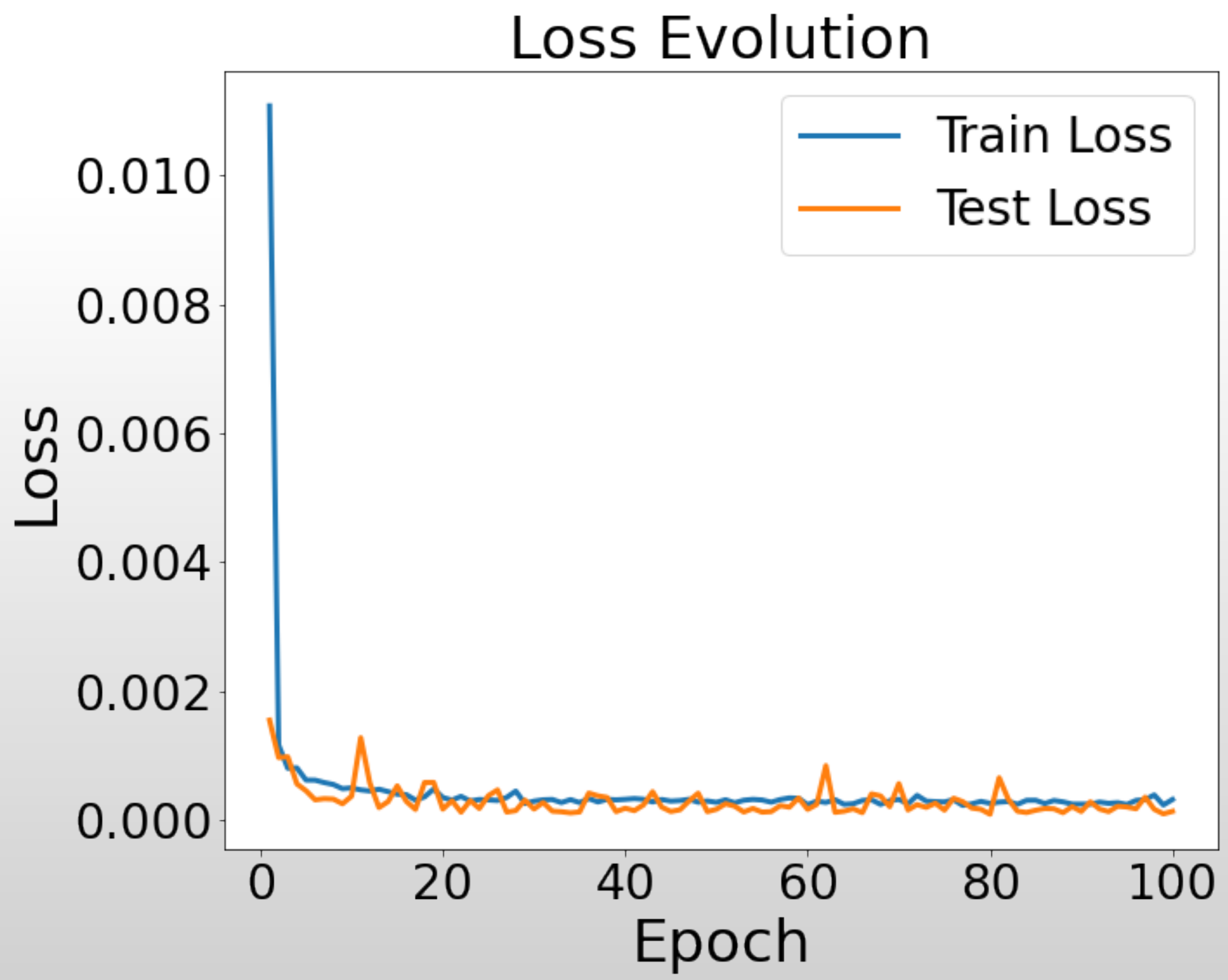
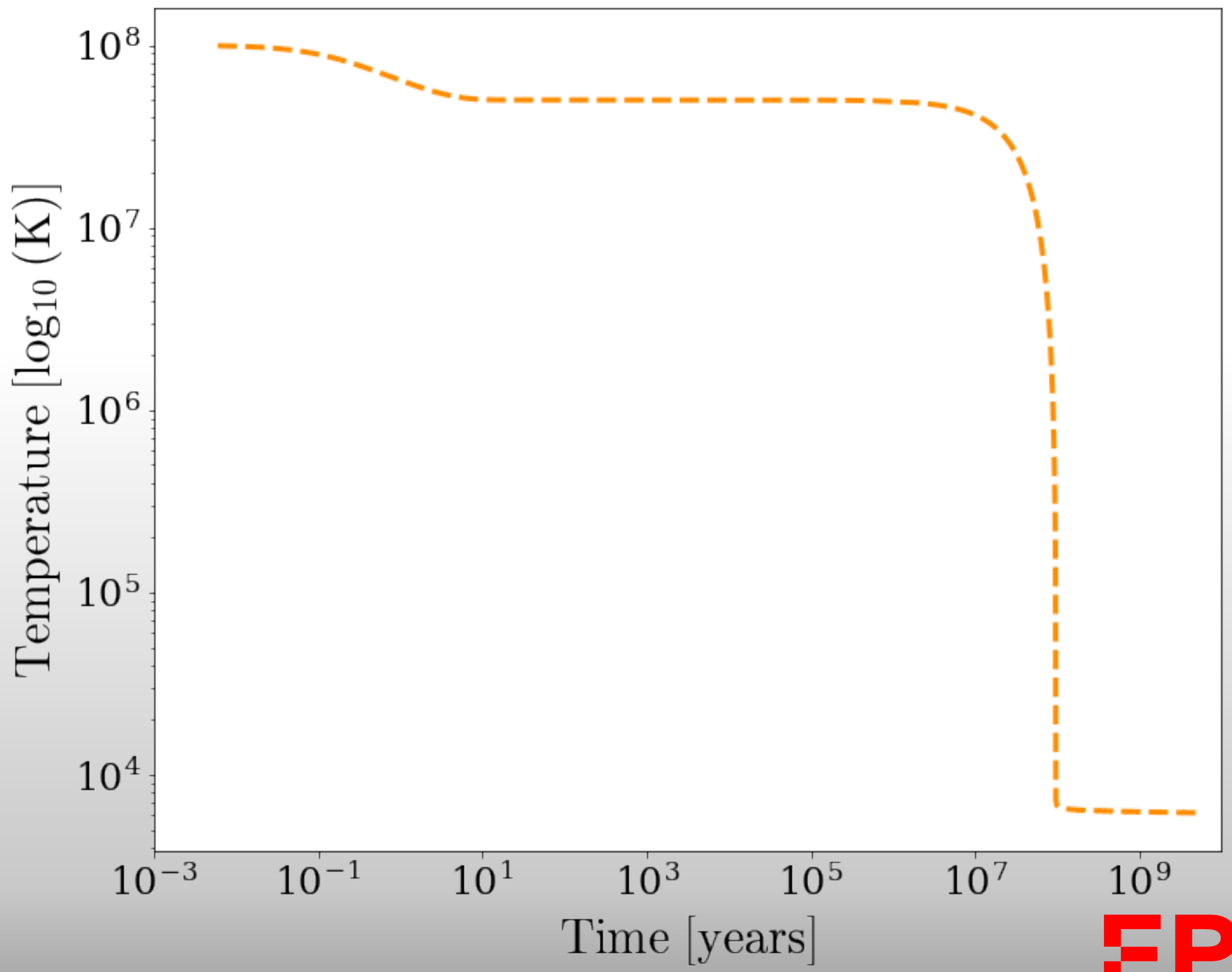




Predicting the Time Evolution of a Cell

Predicting the Time Evolution of a Cell

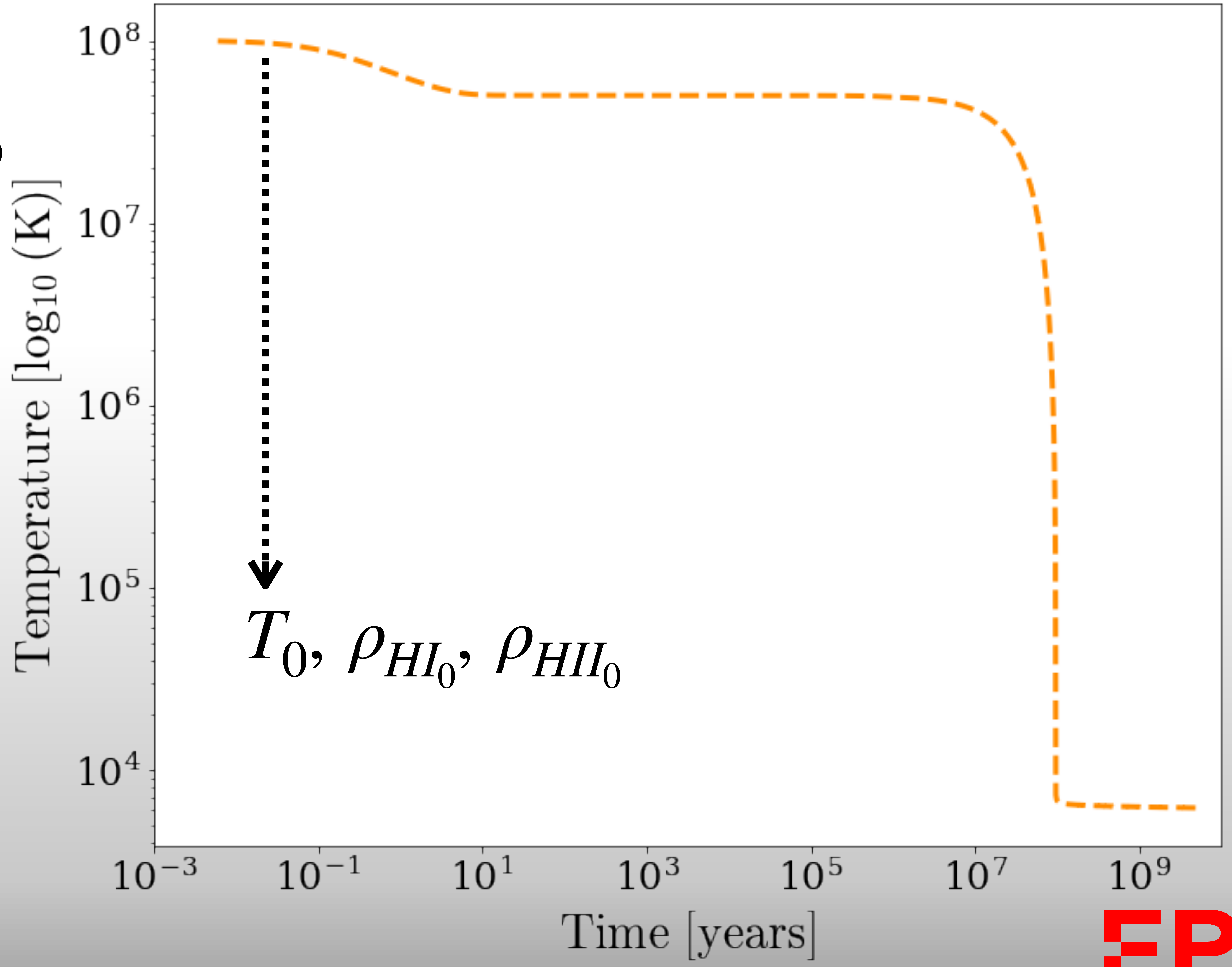


EPFL

Predicting the Time Evolution of a Cell

- Initial values: $T_0, \rho_{HI_0}, \rho_{HII_0}$

T_0 ρ_{HI_0} ρ_{HII_0} T_0 ρ_{HI_0} ρ_{HII_0} $\cdots$ T_0 ρ_{HI_0} ρ_{HII_0}



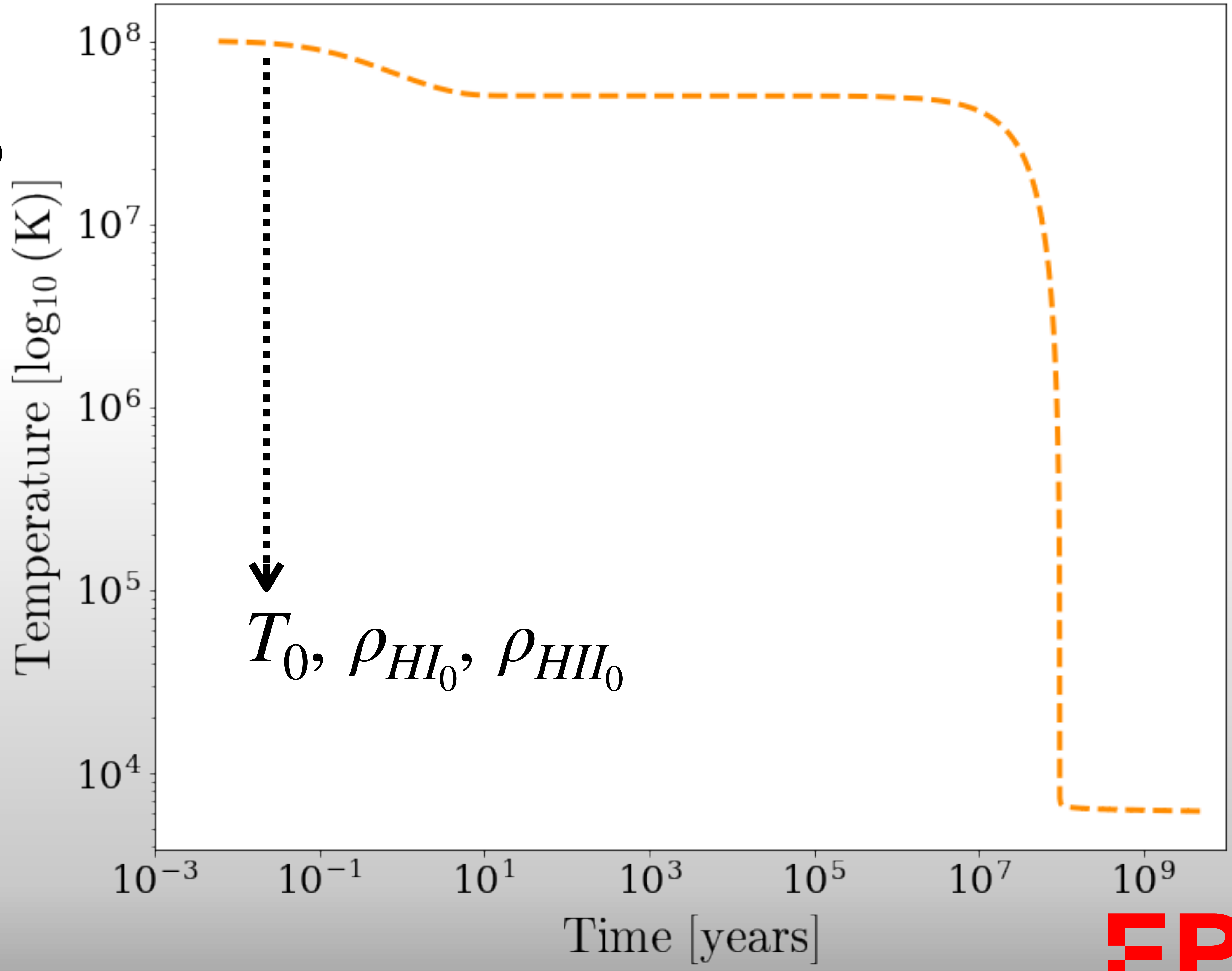
EPFL

Predicting the Time Evolution of a Cell

- Initial values: T_0, ρ_{HI_0}, ρ_{HII_0}
- $dt \in \left[10^{-2}, 10^{9}\right]$ yr

$$dt_i$$

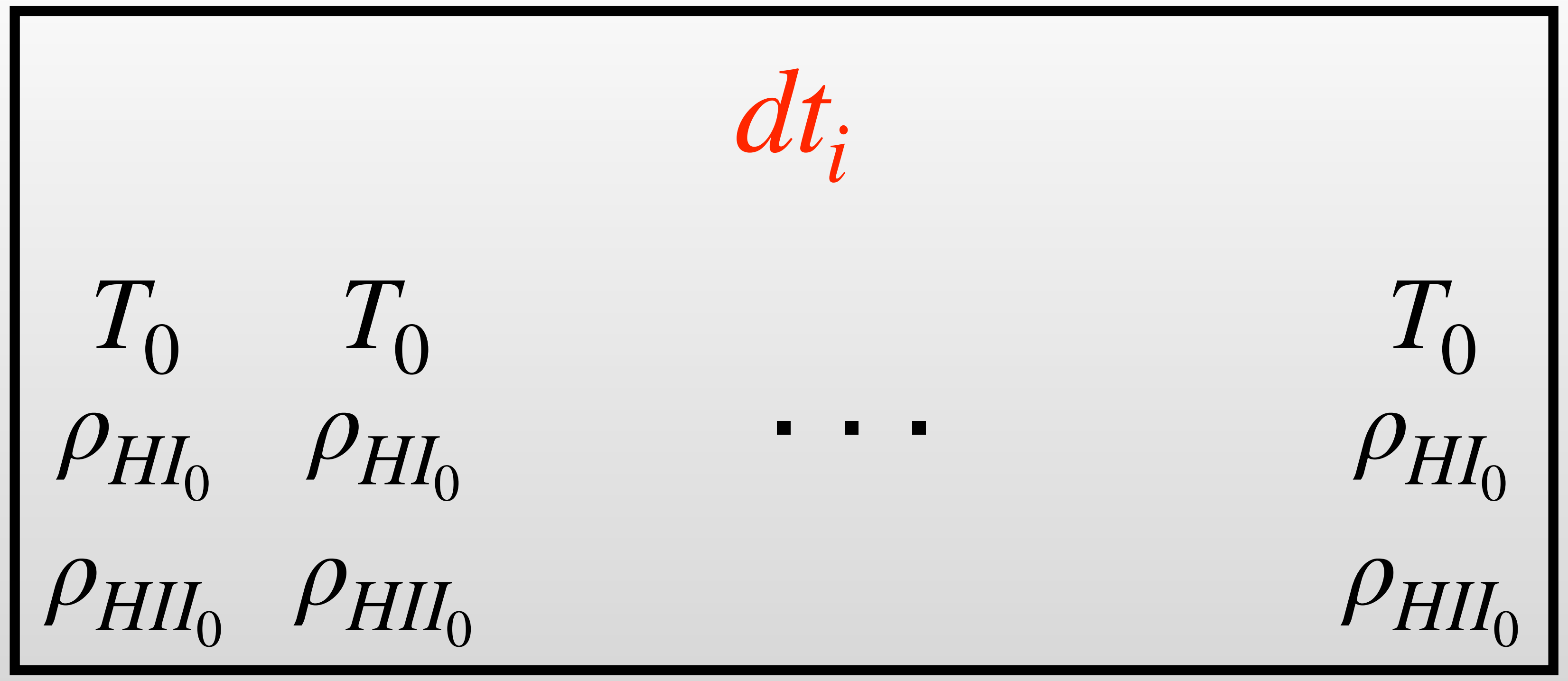
T_0	T_0		T_0
ρ_{HI_0}	ρ_{HI_0}	$\cdots$	ρ_{HI_0}
ρ_{HII_0}	ρ_{HII_0}		ρ_{HII_0}

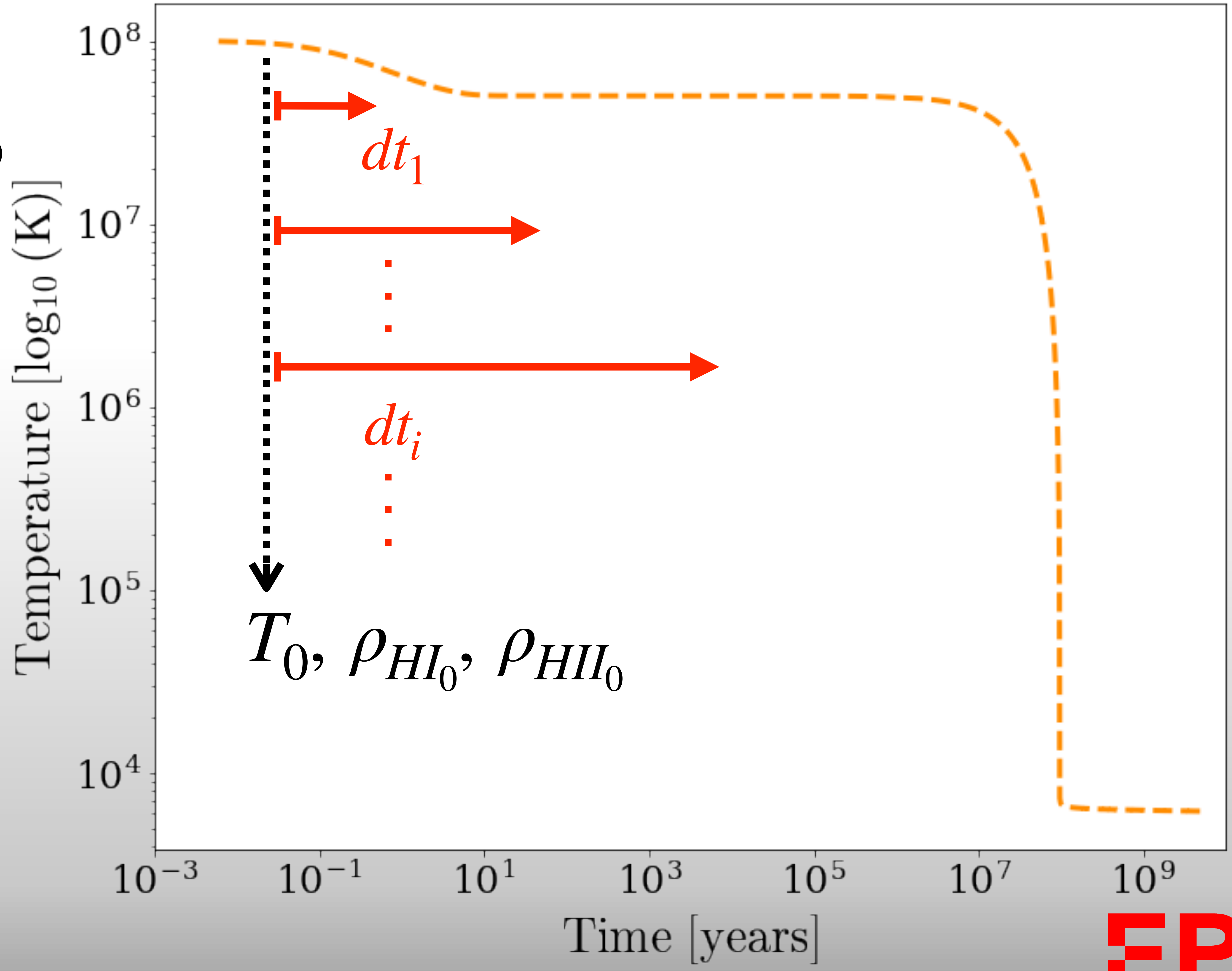


EPFL

Predicting the Time Evolution of a Cell

- Initial values: $T_0,\ \rho_{HI_0},\ \rho_{HII_0}$
- $dt \in \left[10^{-2}, 10^{9}\right]$ yr



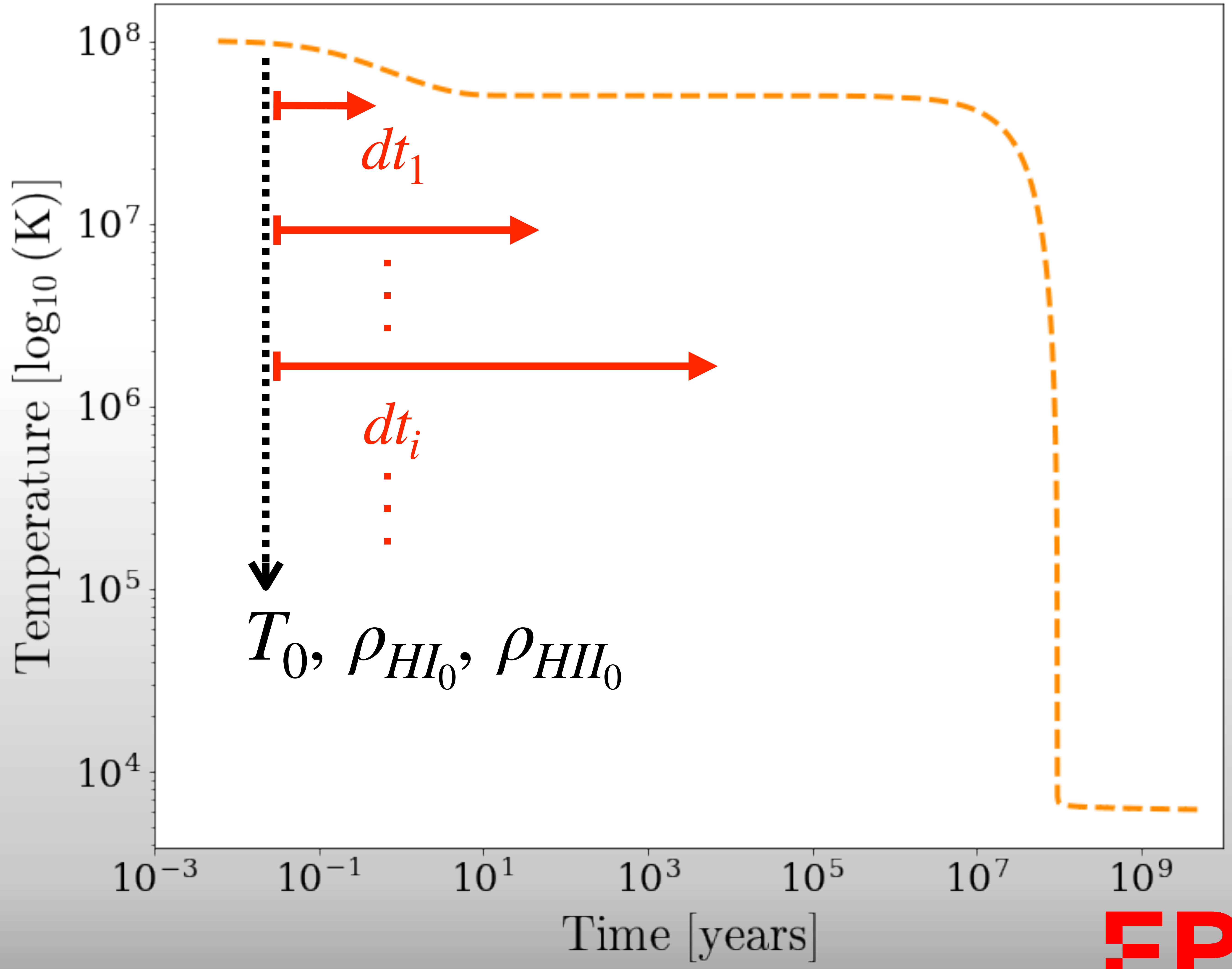


EPFL

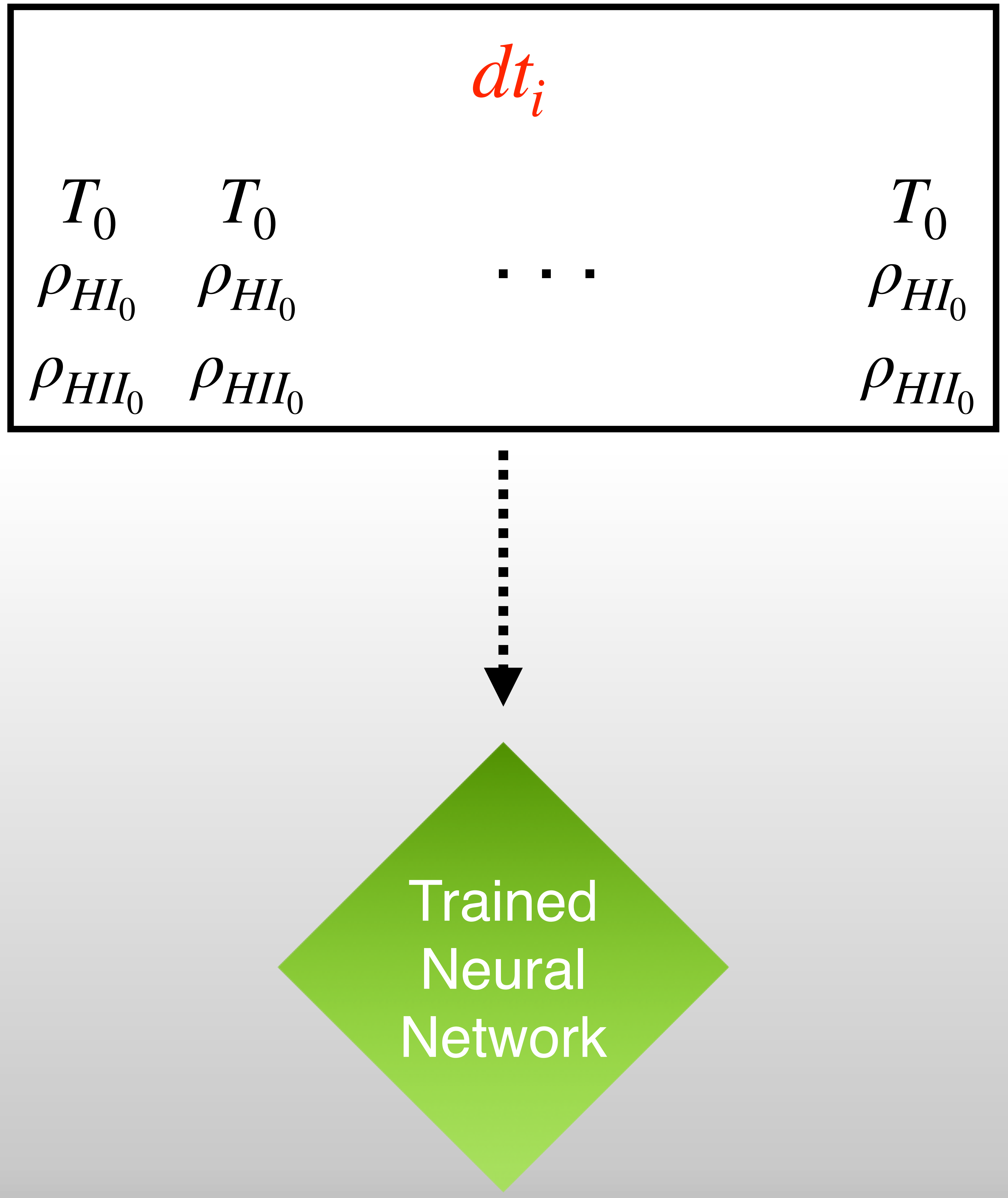
Predicting the Time Evolution of a Cell

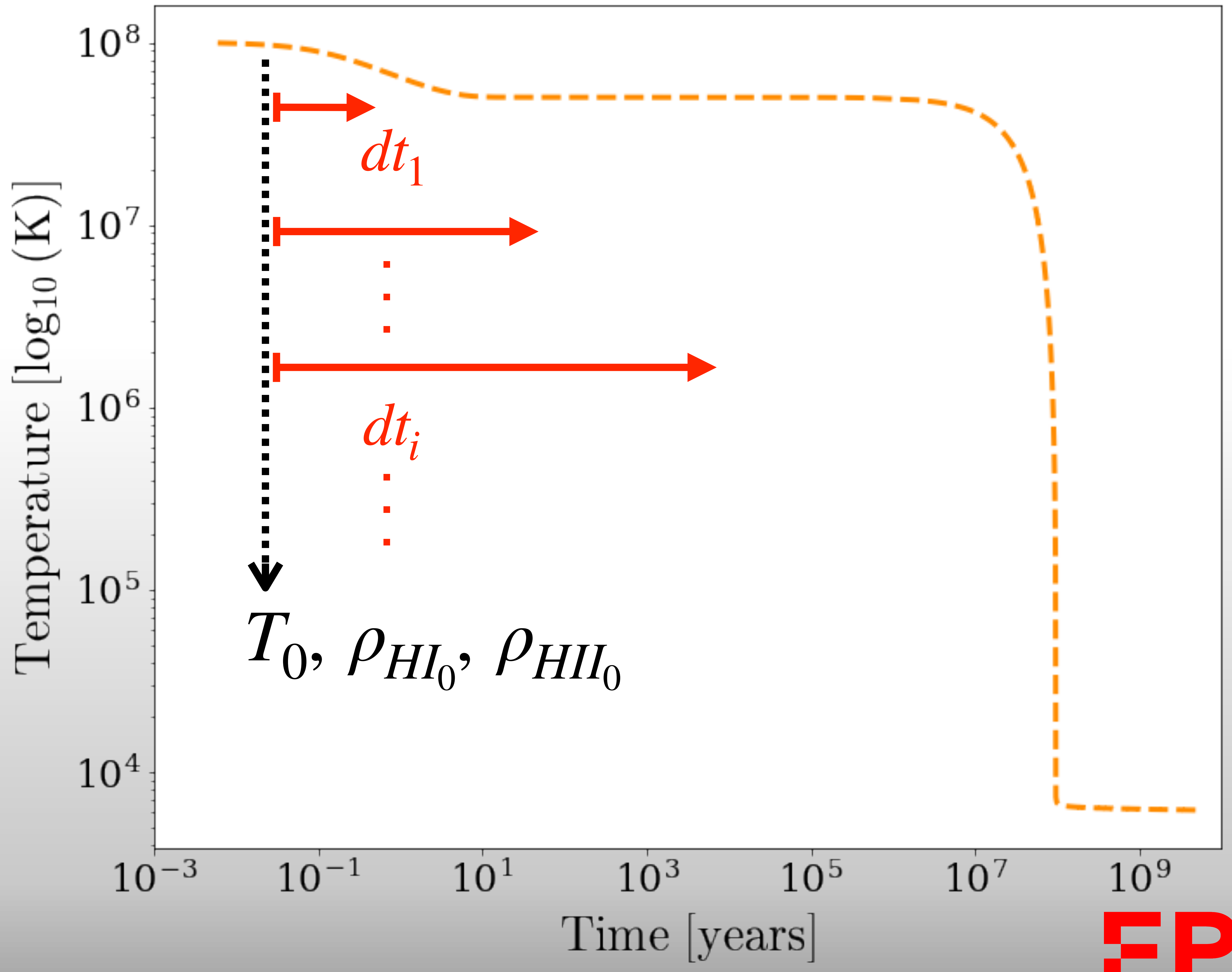
$$dt_i$$

T_0	T_0		T_0
ρ_{HI_0}	ρ_{HI_0}	$\cdots$	ρ_{HI_0}
ρ_{HII_0}	ρ_{HII_0}		ρ_{HII_0}



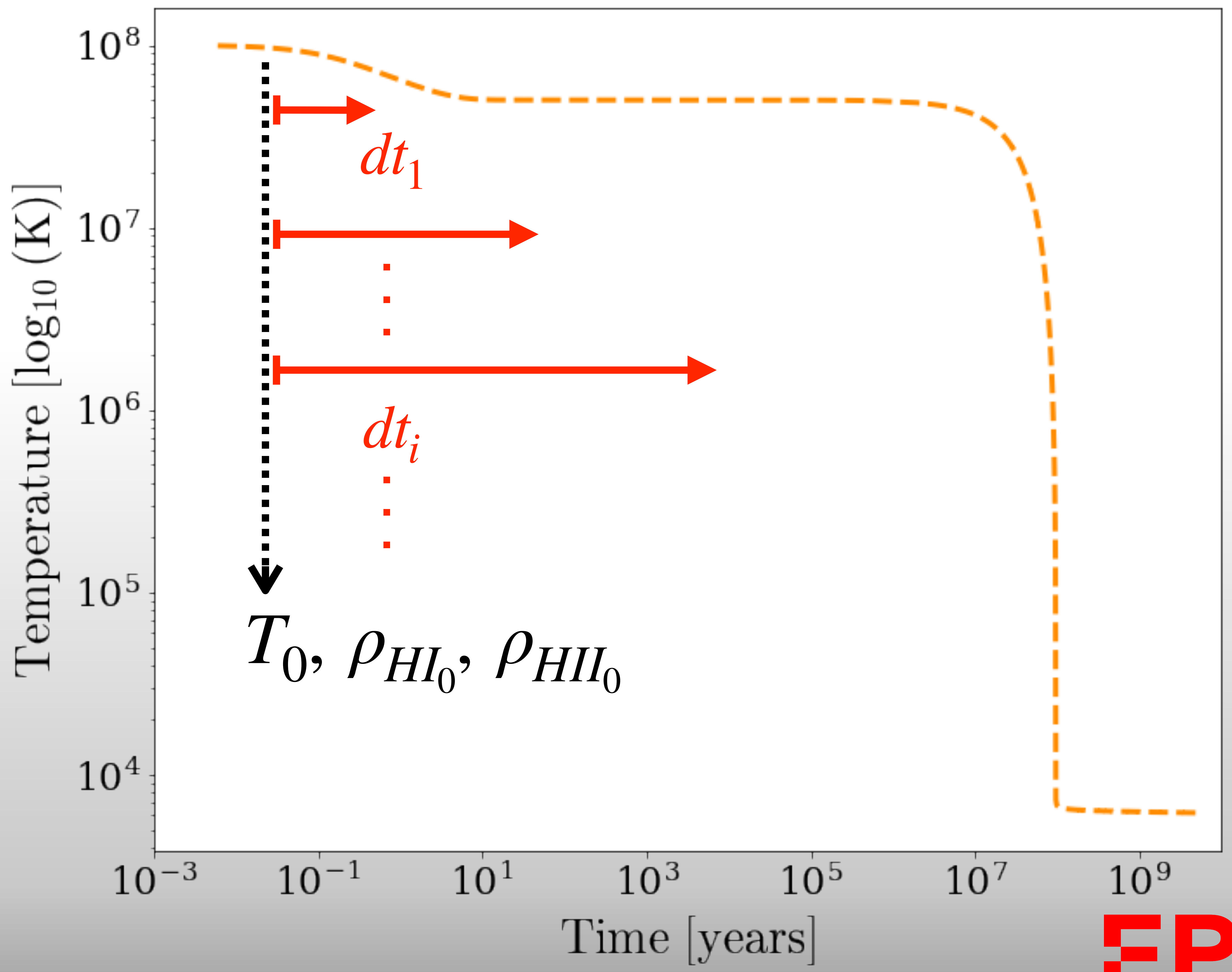
Predicting the Time Evolution of a Cell



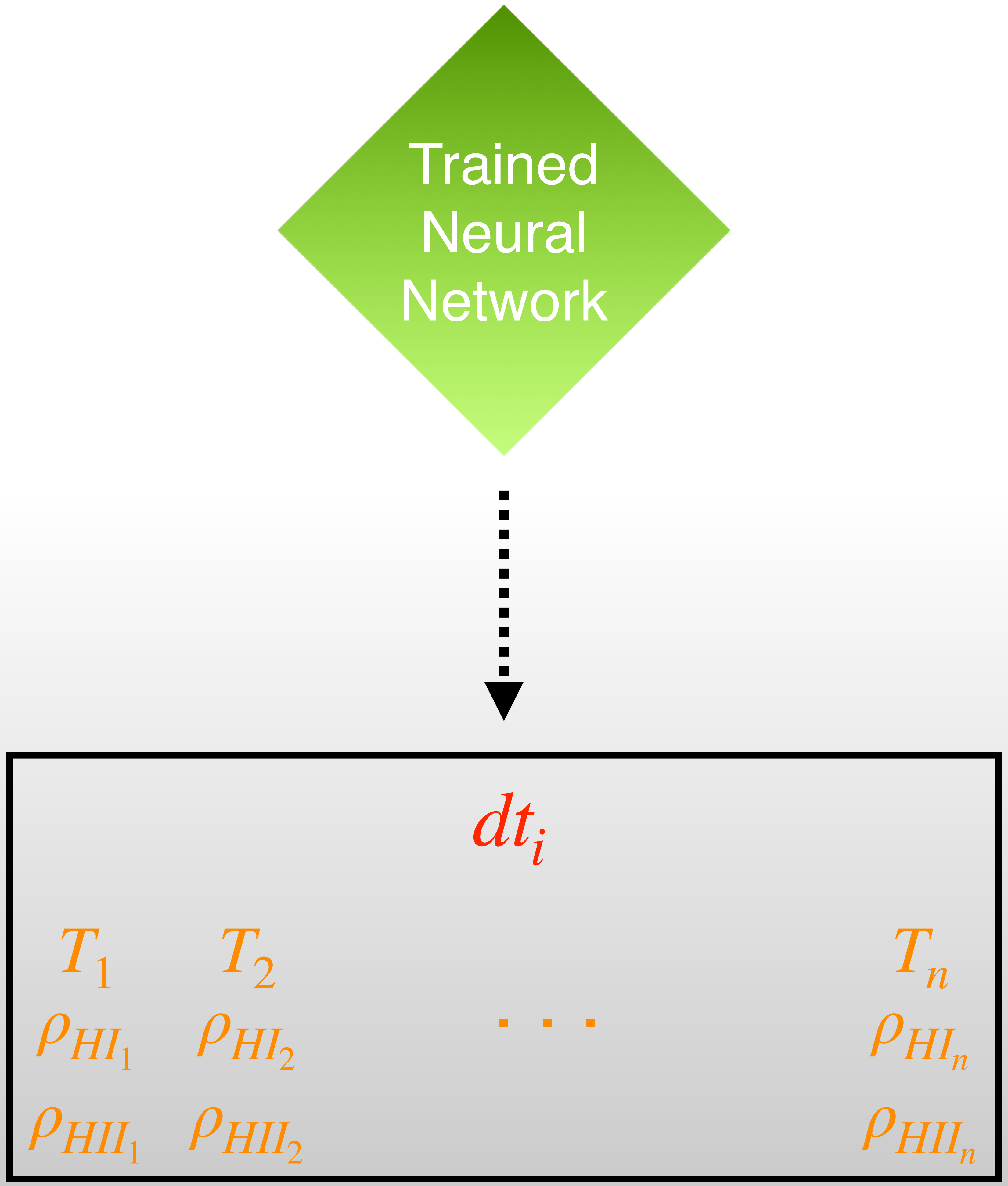


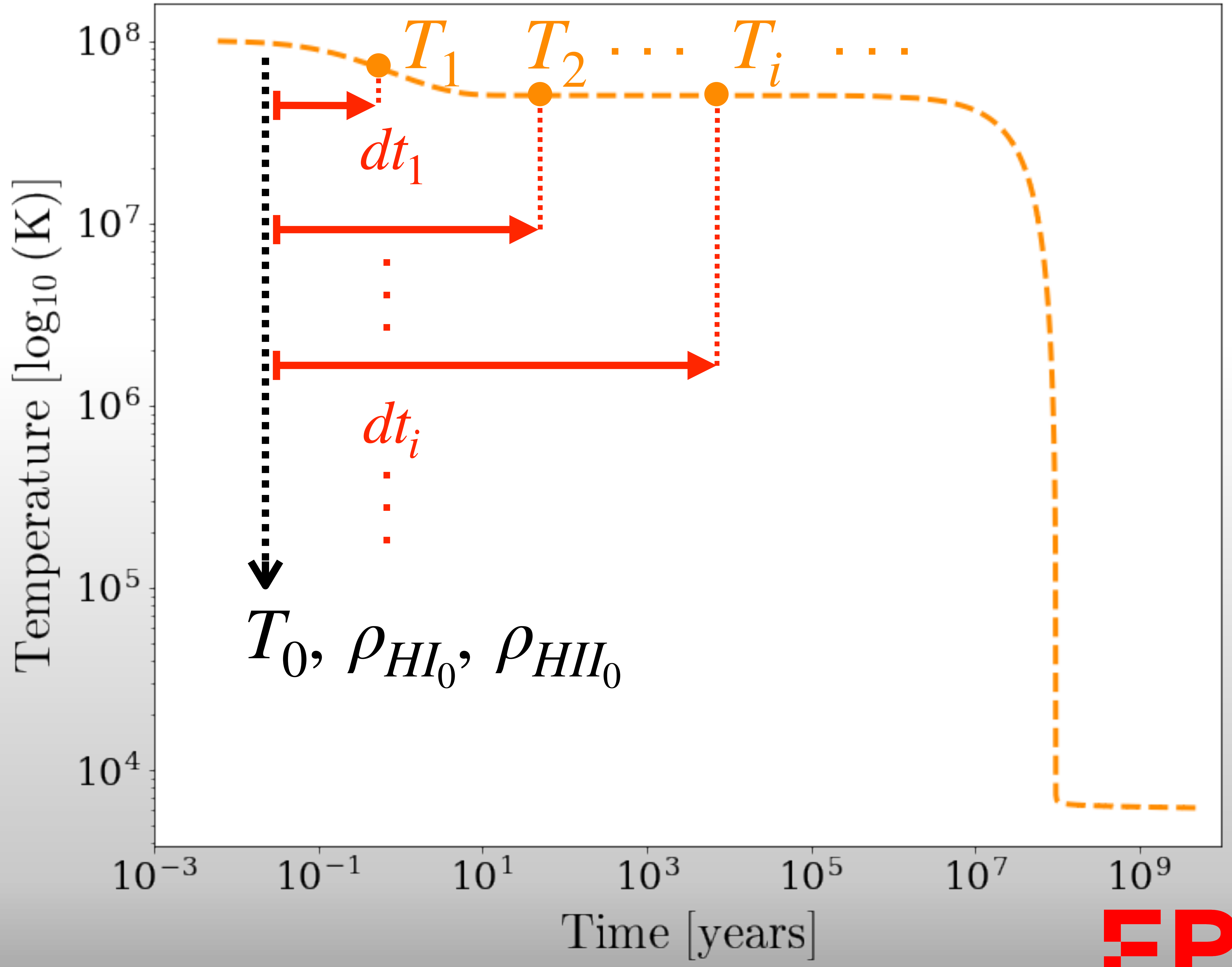
Predicting the Time Evolution of a Cell

Trained Neural Network



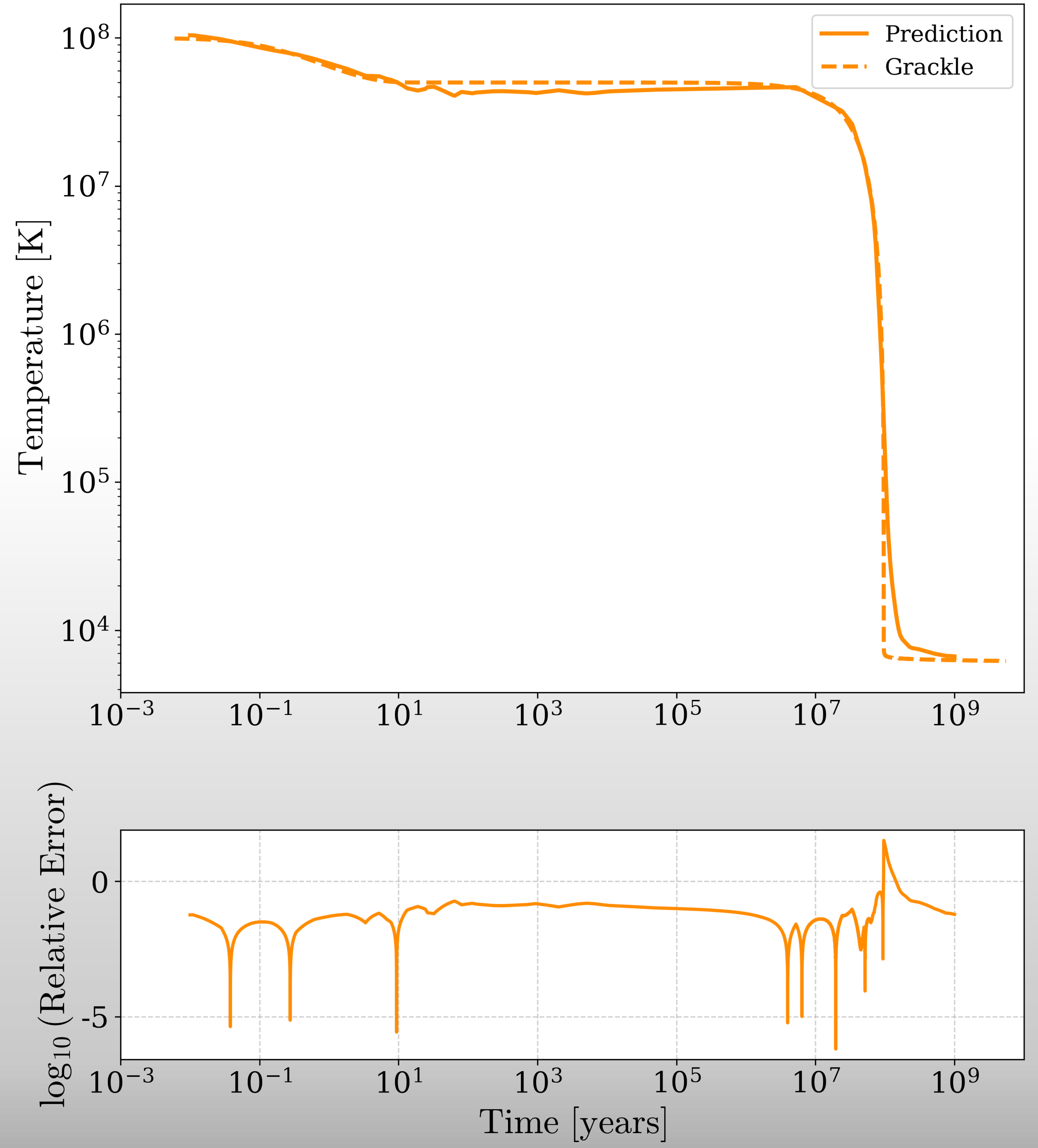
Predicting the Time Evolution of a Cell





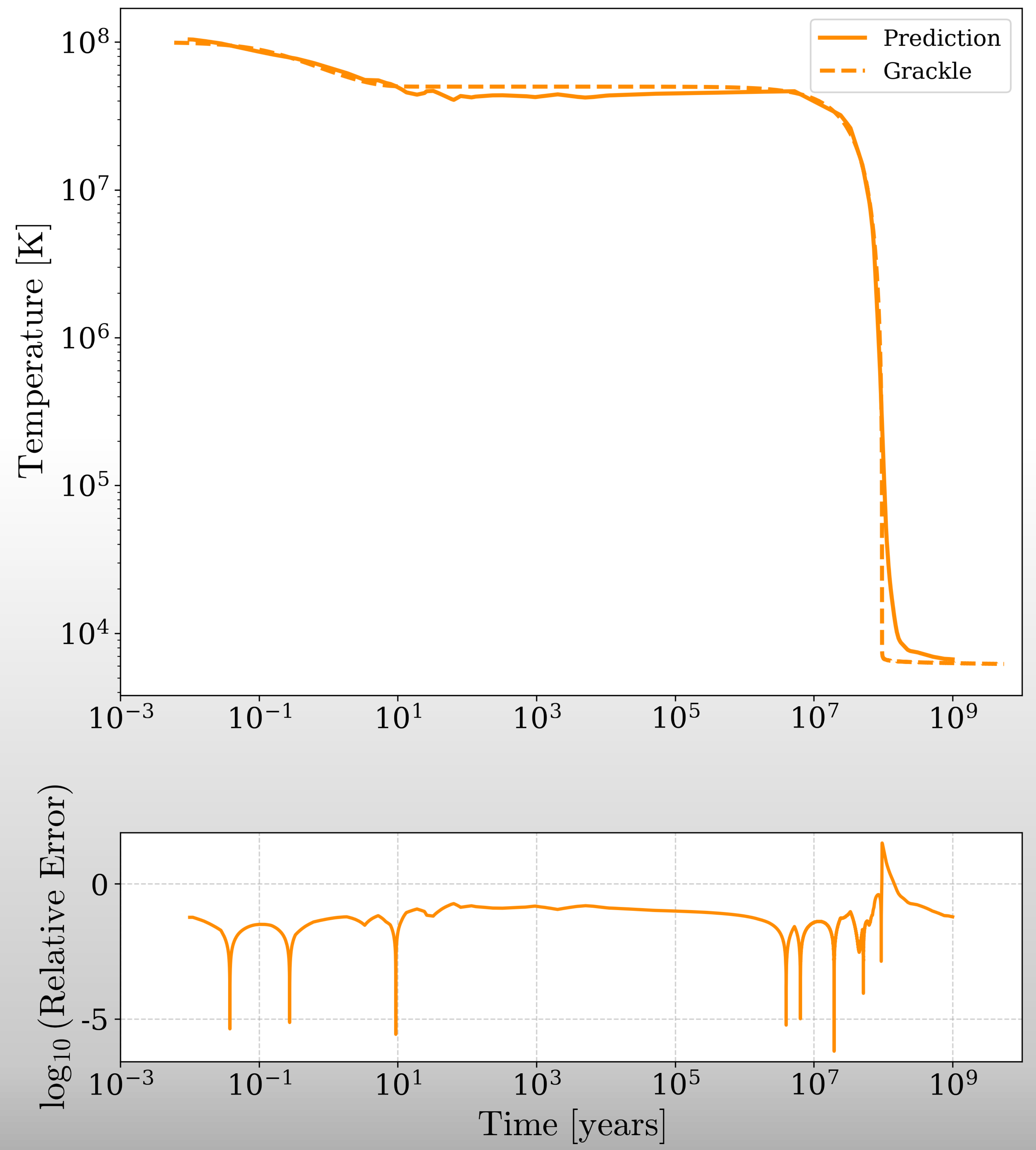
Predicting the Time Evolution of a Cell

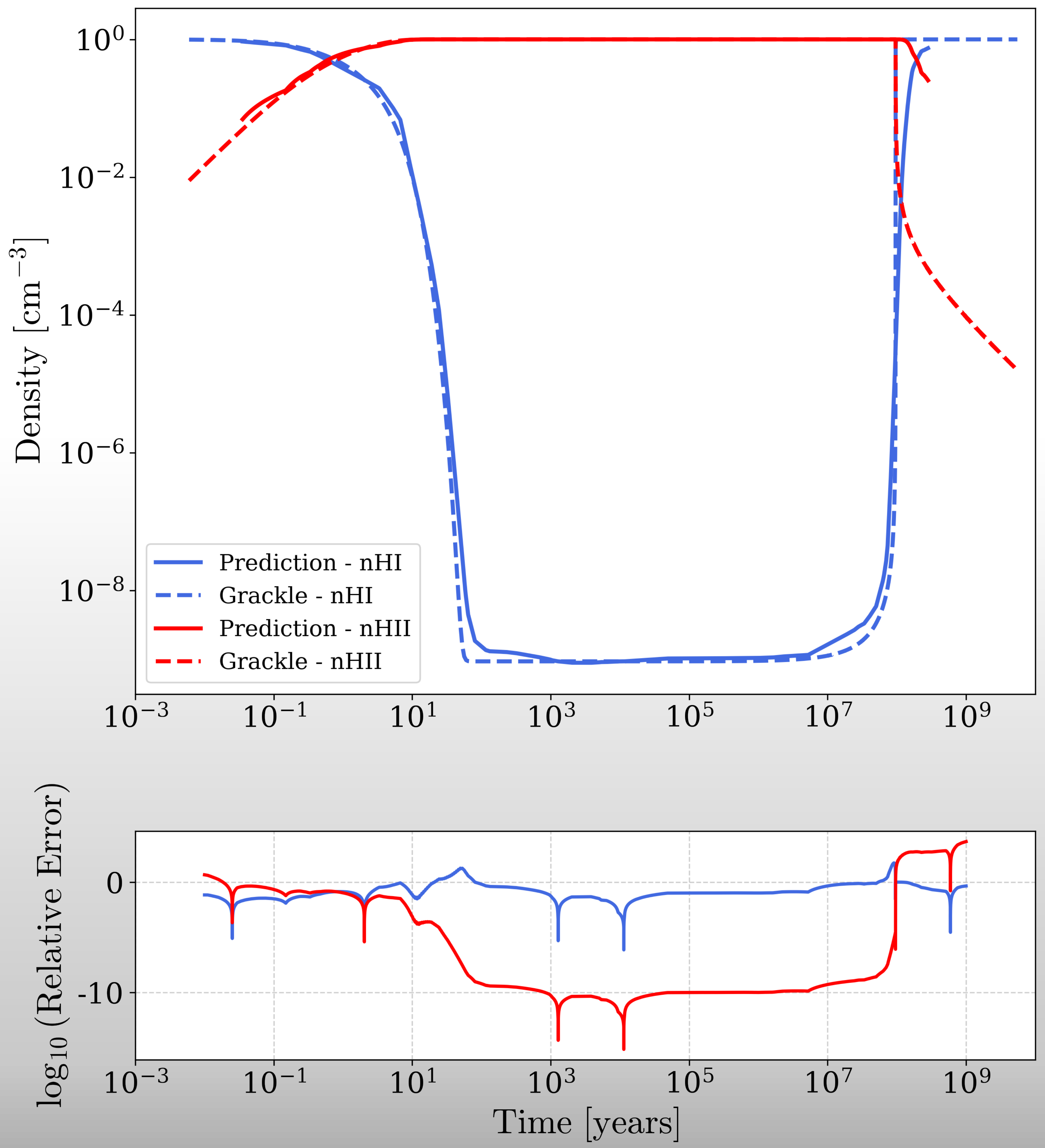
Predicting the Time Evolution of a Cell



EPFL

Predicting the Time Evolution of a Cell





Next Steps

Next Steps

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- Enforcing physical constraints at training phase

Next Steps

- Enforcing physical constraints at training phase
- Increasing the number of species: $\rho_{H_2}, \rho_{He}, \ldots$

EPFL

Next Steps

- Enforcing physical constraints at training phase
- Increasing the number of species: $\rho_{H_2}, \rho_{He}, \ldots$
- Adding radiation effects like UV background

Conclusion

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Neural networks may offer a promising approach to reducing computational bottlenecks in cosmological simulations, even with relatively simple architectures.