Modelling kilonovae with SUMO

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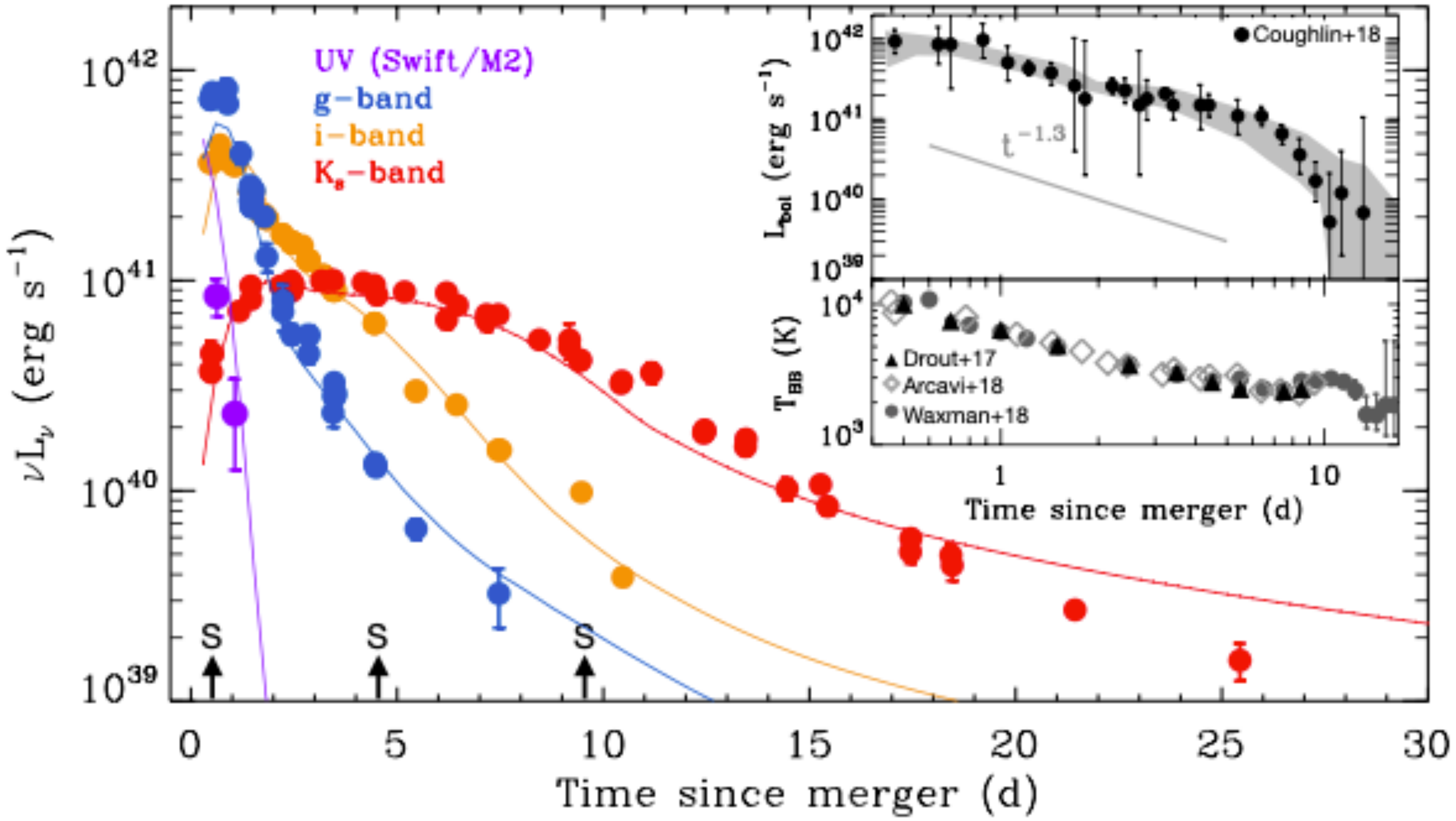
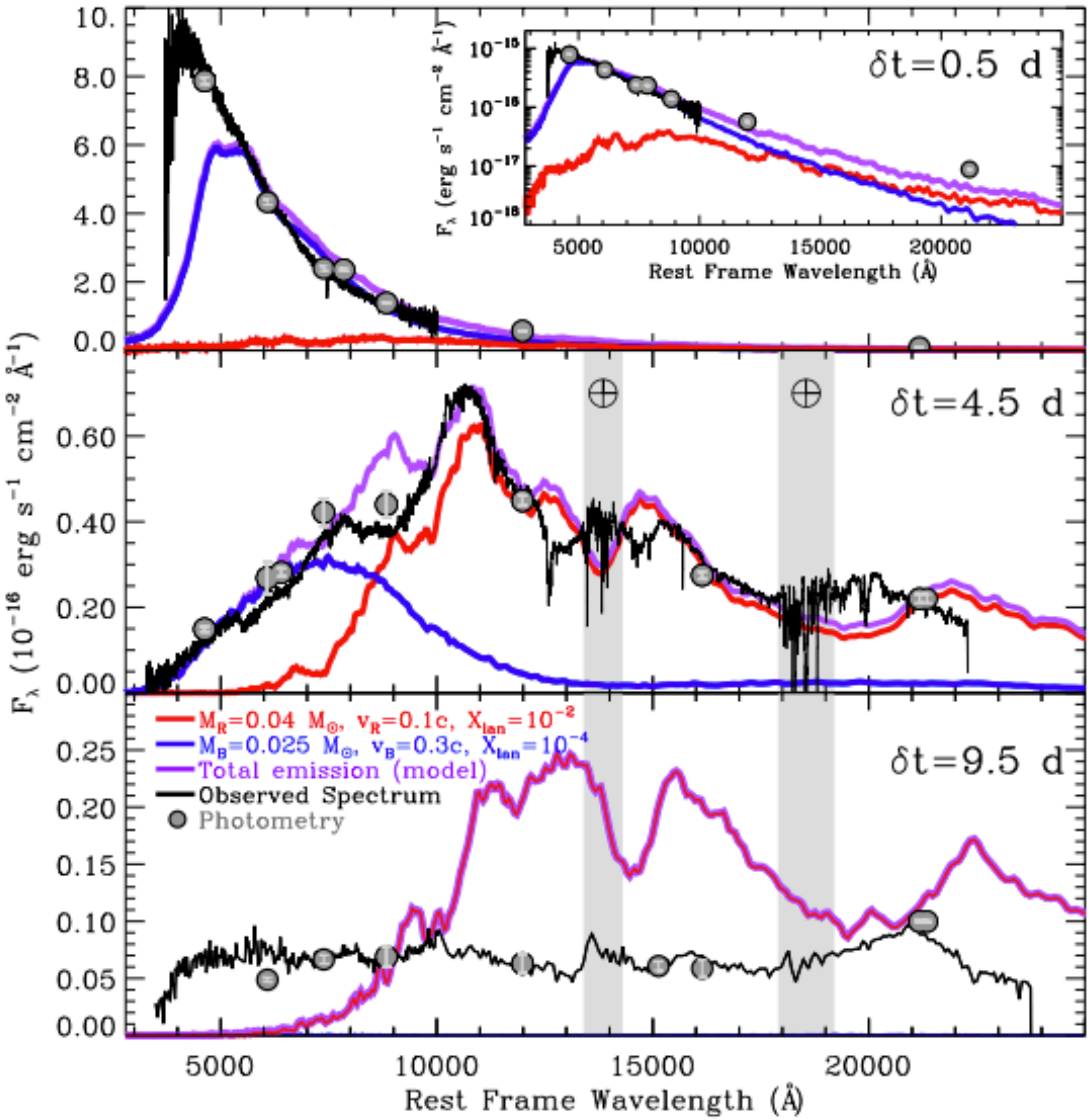
AT 2017gfo





$$n_e \sim 10^6 M_{0.05} V_{0.1c}^{-3} \left(\frac{t}{10d}\right)^{-3} \ cm^{-3}$$

$$n_e^{crit} = \frac{A}{Q} \sim \frac{10^{-3}}{10^{-7}} \sim 10^4 \ cm^{-3}$$

Margutti & Chornock 2021

The SUMO code

Jerkstrand+2011, 2012
Thesis 2011

Mixing treatment

Macroscopic vs microscopic.
Clumping.

Temperature

First law of thermodynamics.

Radioactive deposition

Gamma rays, leptons, alphas, spontaneous fission products.
Time-dependent thermalization.

NLTE ionization and excitation

H-Ni plus so far 4 r-process elements.

High-energy electron degradation

Spencer-Fano equation.
Heating - ionisation - excitation.
r-process element x-sections.

Radiative transfer

Scattering/fluorescence in ~300,000 H-Zn lines, ~100,000 r-process lines.
Special relativity.

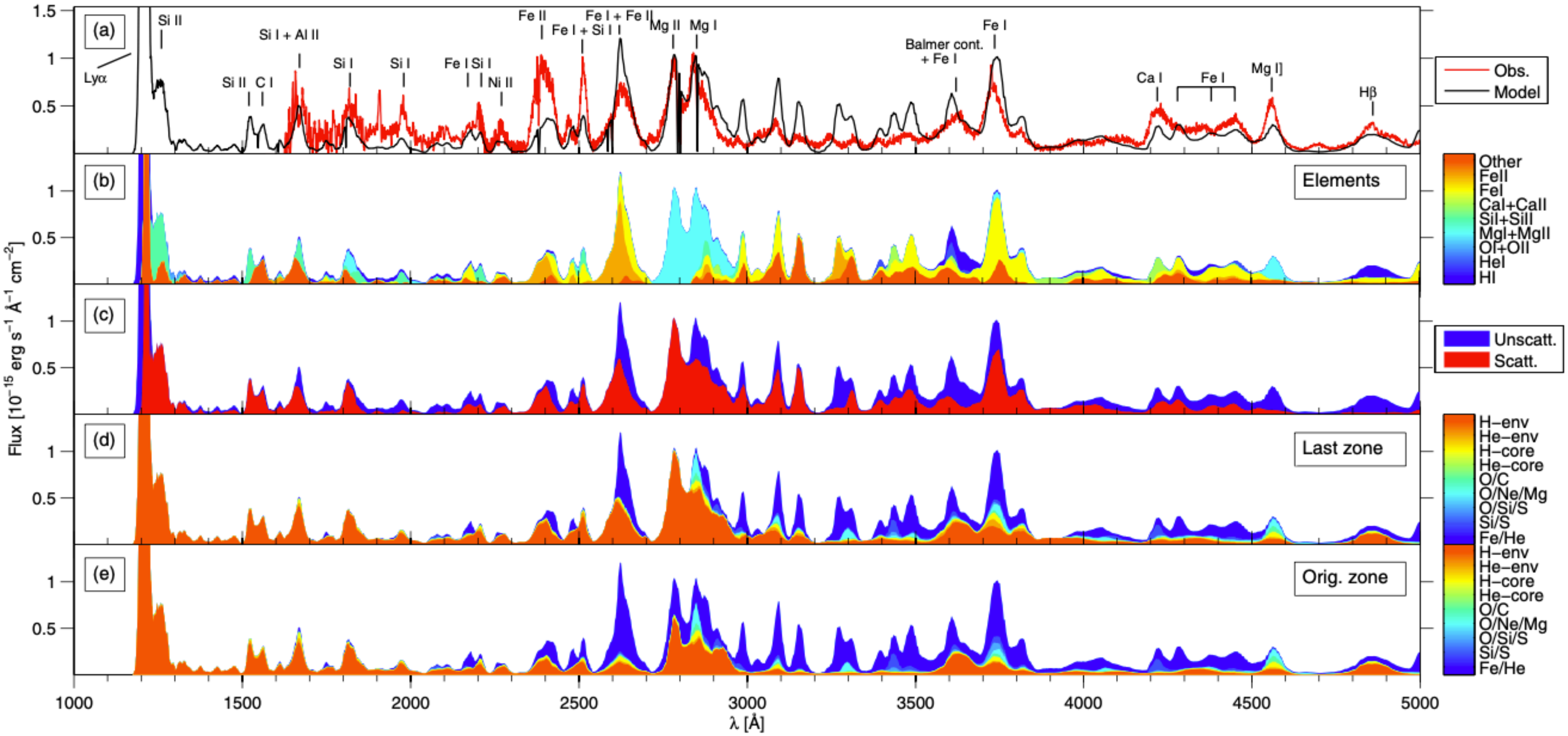
Supernovae Kilonovae

- A **spectral code** (no time-dependent radiation transport, c = ∞). No hydrodynamics.
- Specialized in the **post-peak, NLTE phase**.
- **1D** (but foundation of new 3D variant in place, PhD project launched to further develop (Bart van Baal)).
- **Fortran 90, pure MPI parallelisation.**

So far used to model **IIP SNe, IIb SNe, Ic-BL SNe, Ia SNe, pair-instability SNe.**

A SN model example

A. Jerkstrand et al.: The ^{44}Ti-powered spectrum of SN 1987A



A closer look at determining ejecta temperatures

Three main methodologies so far in use for KNe:

SEDONA (Kasen+2006)

ARTIS (Lucy+2005,Kromer+2009)

SUPERNU (Woallager+2013,2014)

SEDONA (Kasen+2006)

Energy equation in steady state (radiative equilibrium):

γ dep + "thermal absorption" = "thermal emission"

Lucy 1999 - how to calculate these in Monte Carlo codes:

$$\gamma \text{ dep} + \frac{1}{V_c \Delta t} \sum_i \alpha_{abs,\lambda} ds_i E_i = \int_0^\infty B_\lambda(T) \times \alpha_{abs,\lambda} d\lambda$$

cell volume

time step

thermalising absorption coefficient

path length traversed

packet energy

Assumes **LTE** ($S = j/\alpha = B$, ok at early times)

$$= \frac{1}{ct_{exp}} \sum_{\lambda \pm \Delta\lambda} \frac{\lambda_i}{\Delta\lambda} (1 - e^{-\tau_i})\, \epsilon$$

ϵ = fixed, constant thermalization probability

$$\frac{1}{ct_{exp}} \sum_{\lambda \pm \Delta\lambda} \frac{\lambda_i}{\Delta\lambda} (1 - e^{-\tau_i})\, p_{abs}$$

p_{abs} = calculated thermalization probability, $\ll 1$

In this formalism, $\epsilon/\mathrm{p_{abs}}$ can be put outside the sum (LHS) and integral (RHS) and therefore **cancels out** (assuming radiation field dominates heating and only lines contribute to $\alpha_{abs,\lambda}$).

In this limit, the temperature solution therefore does not depend on $\epsilon/\mathrm{p_{abs}}$.

ARTIS method (used by Tanaka group)

Kromer+2009 (ARTIS):

Same Monte Carlo estimator for the radiation field:

$$J = \frac{1}{4\pi \Delta t V_c} \sum_i E_i ds_i$$

Then

$$T_{rad} \equiv \left(\frac{\pi J}{\sigma} \right)^{1/4}$$

$$T_{gas} = T_{rad}$$

T_{rad} is defined as the temperature at which $B(T_{rad}) = \sigma T^4/\pi$ equals J.

.

Is T_{gas} equal to T_{rad}?
Define

$$\alpha_P = \frac{\int B\alpha d\lambda}{\int B d\lambda} = \frac{\int B\alpha d\lambda}{B(T_{gas})} = \frac{\int B\alpha d\lambda}{\sigma T^4/\pi}$$

The Lucy formula can then be written

$$\frac{1}{V_c \Delta t} \alpha_P \sum_i \frac{\alpha_{abs}}{\alpha_P} E_i ds_i = \alpha_P \times B(T_{gas})$$

If

$$\sum \frac{\alpha_{abs}}{\alpha_P} E_i ds_i = \sum E_i ds_i$$

i.e. if $\bar{\alpha} = \alpha_P$, then $J = B(T_{gas})$.

This holds if the radiation field is exactly Planckian.

In this way, don't need to specify the $\alpha_{abs,\lambda}$ function at all.

Gray tests of LTE codes

Kasen+2006, compares to Lucy 2005 (ARTIS method).

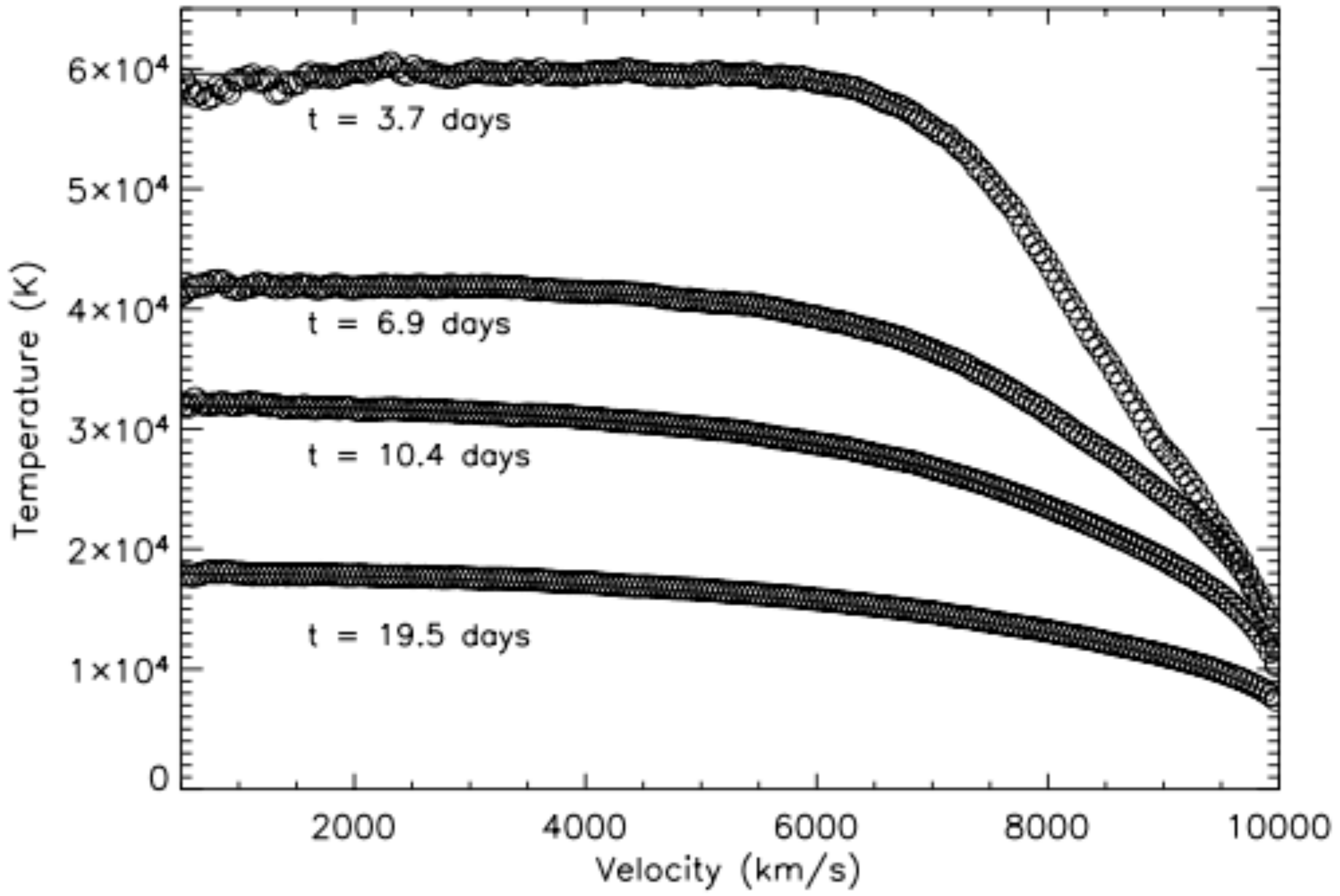
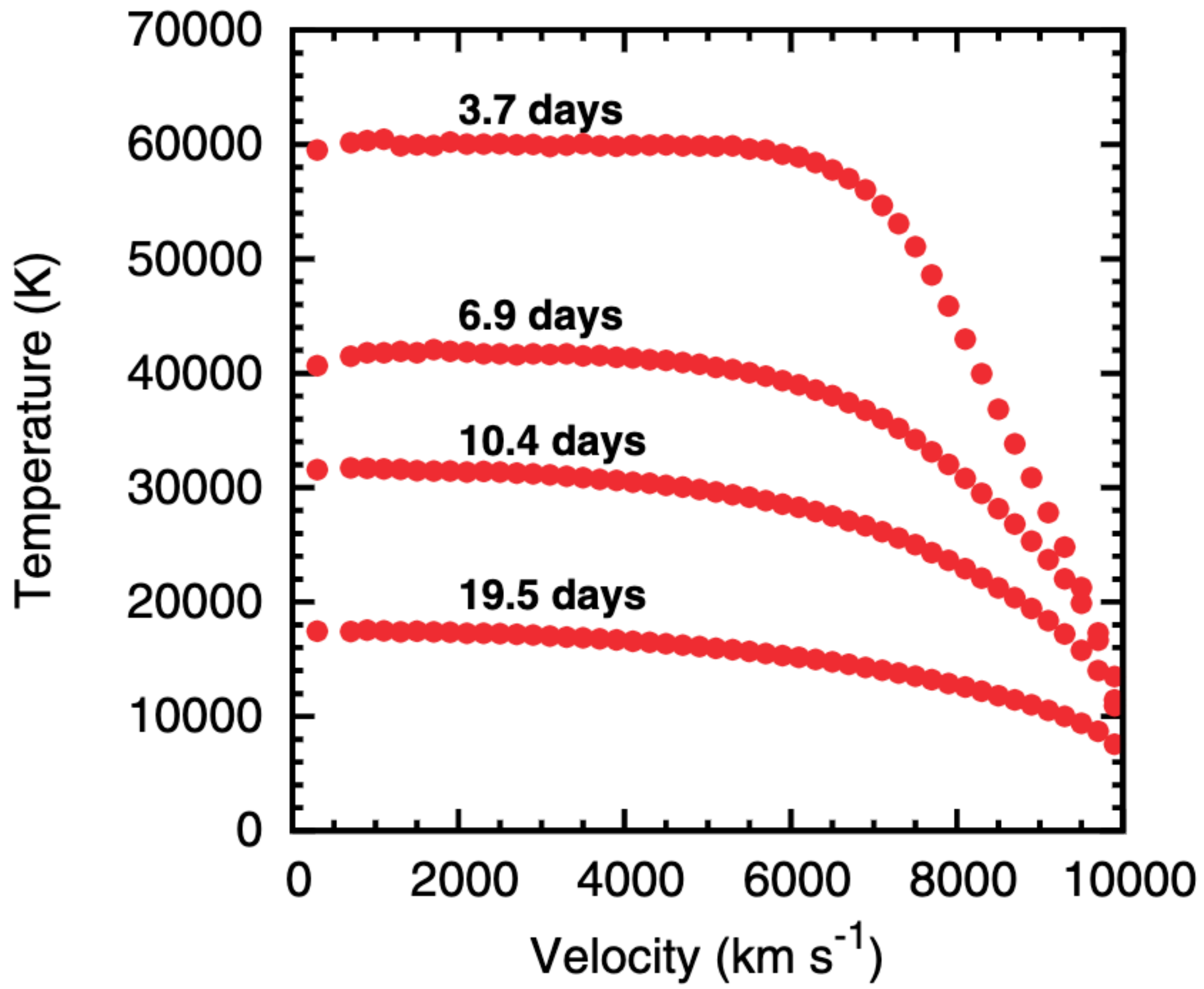


FIG. 2.—SEDONA calculation of the temperature structure (*open circles*) at a few select times for the test SN Ia model, compared to the numerical results presented in Lucy (2005a) (*solid lines*).

Tanaka+2013 : same test (they use same method as Lucy)

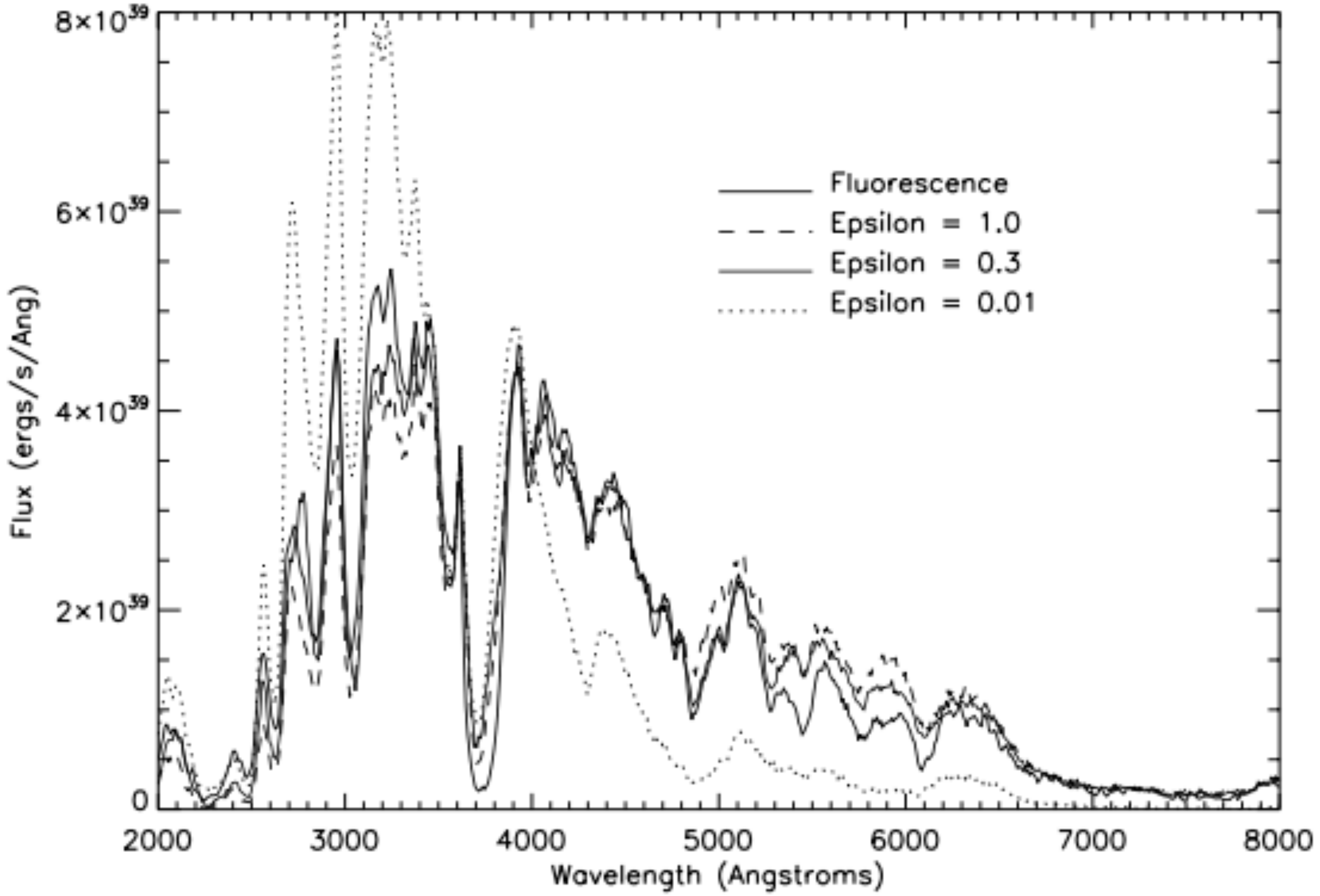


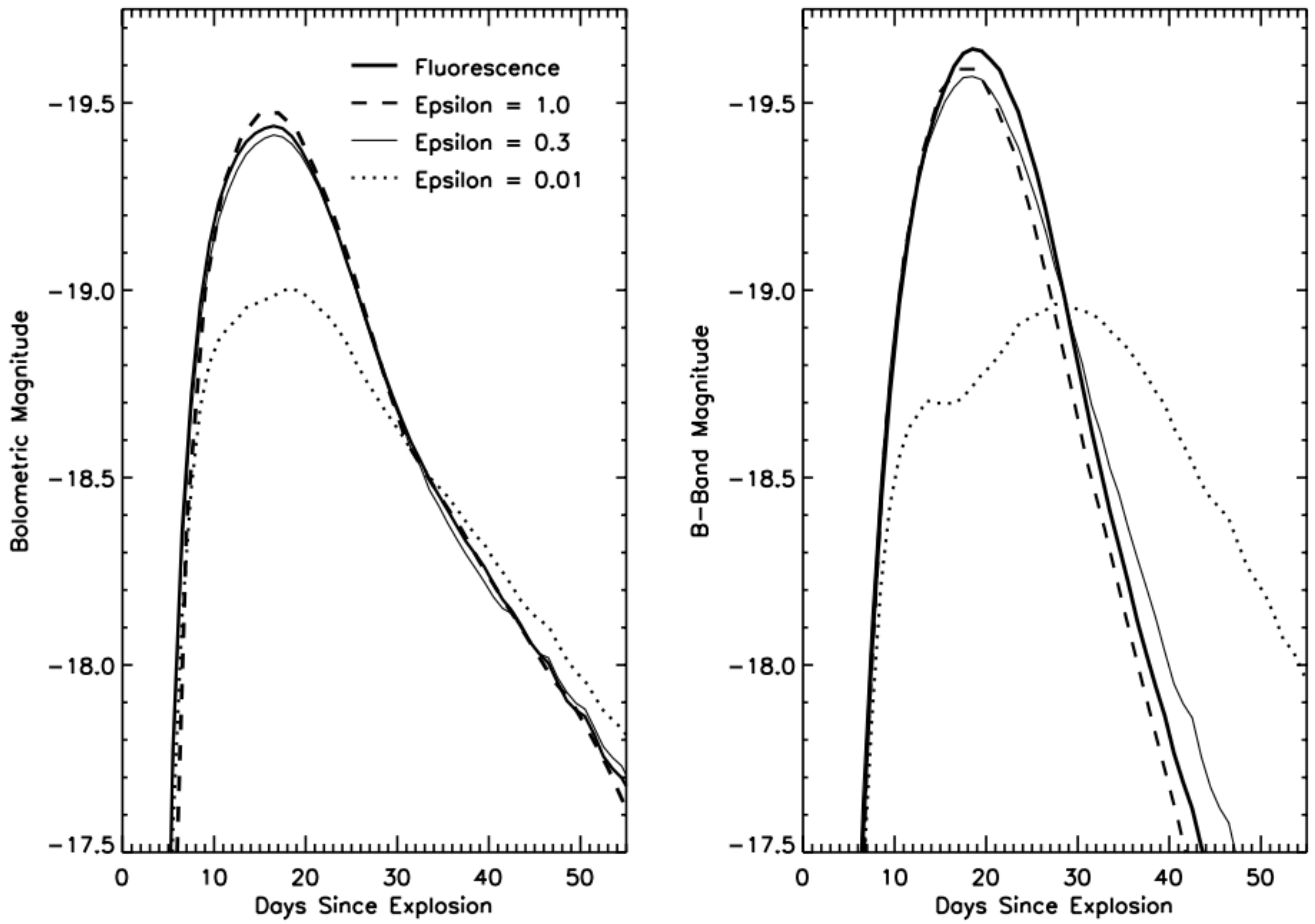
Kasen's test shows that the radiation field computed with his method is close to Planckian, so no significant differences to ARTIS method for $t \lesssim t_{peak}$.

These tests do not demonstrate, however, that an accurate temperature is estimated for non-gray opacities.

Non-gray tests

Kasen+2006 : Fluorescence vs thermalization/resonance scattering, W7 at peak.

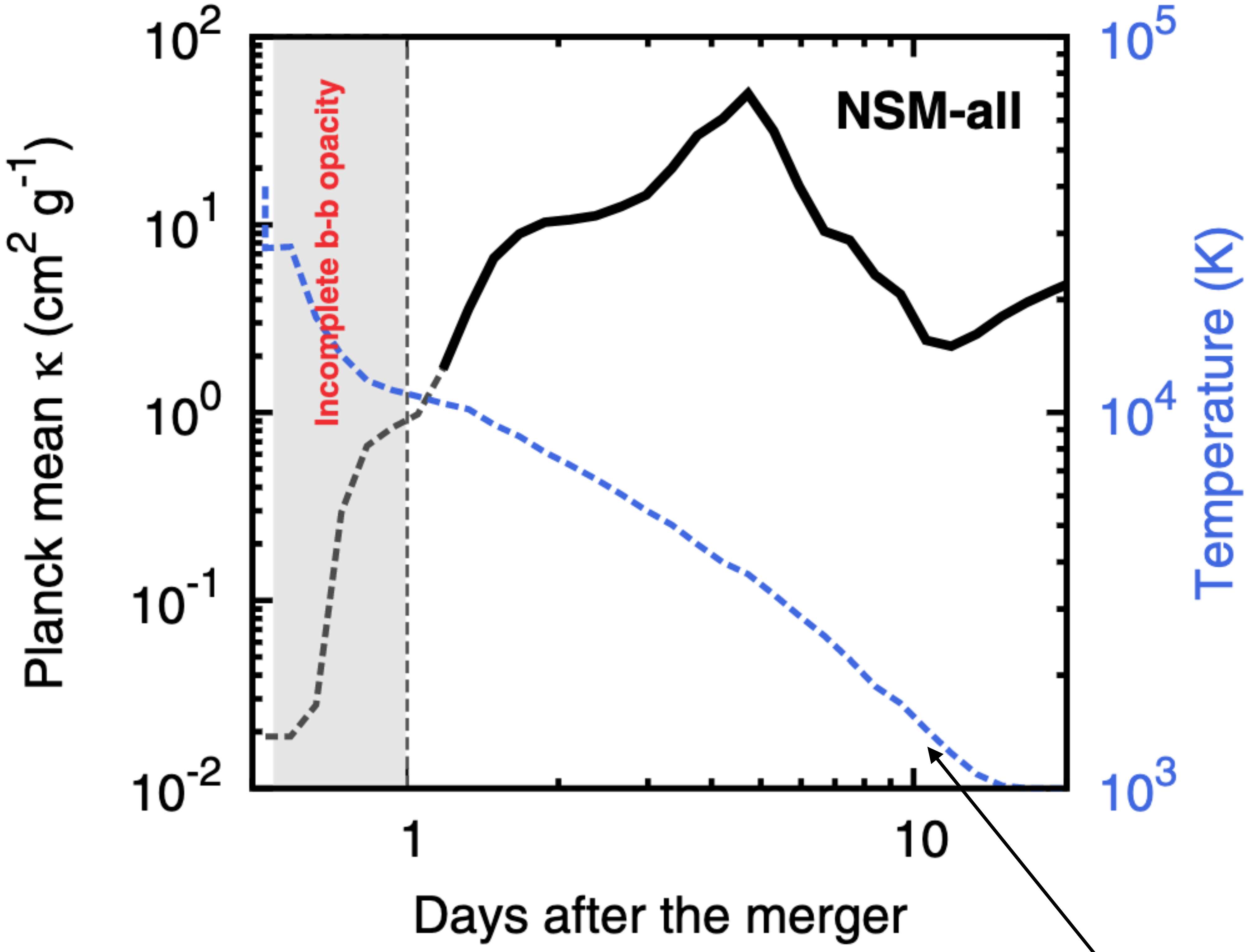




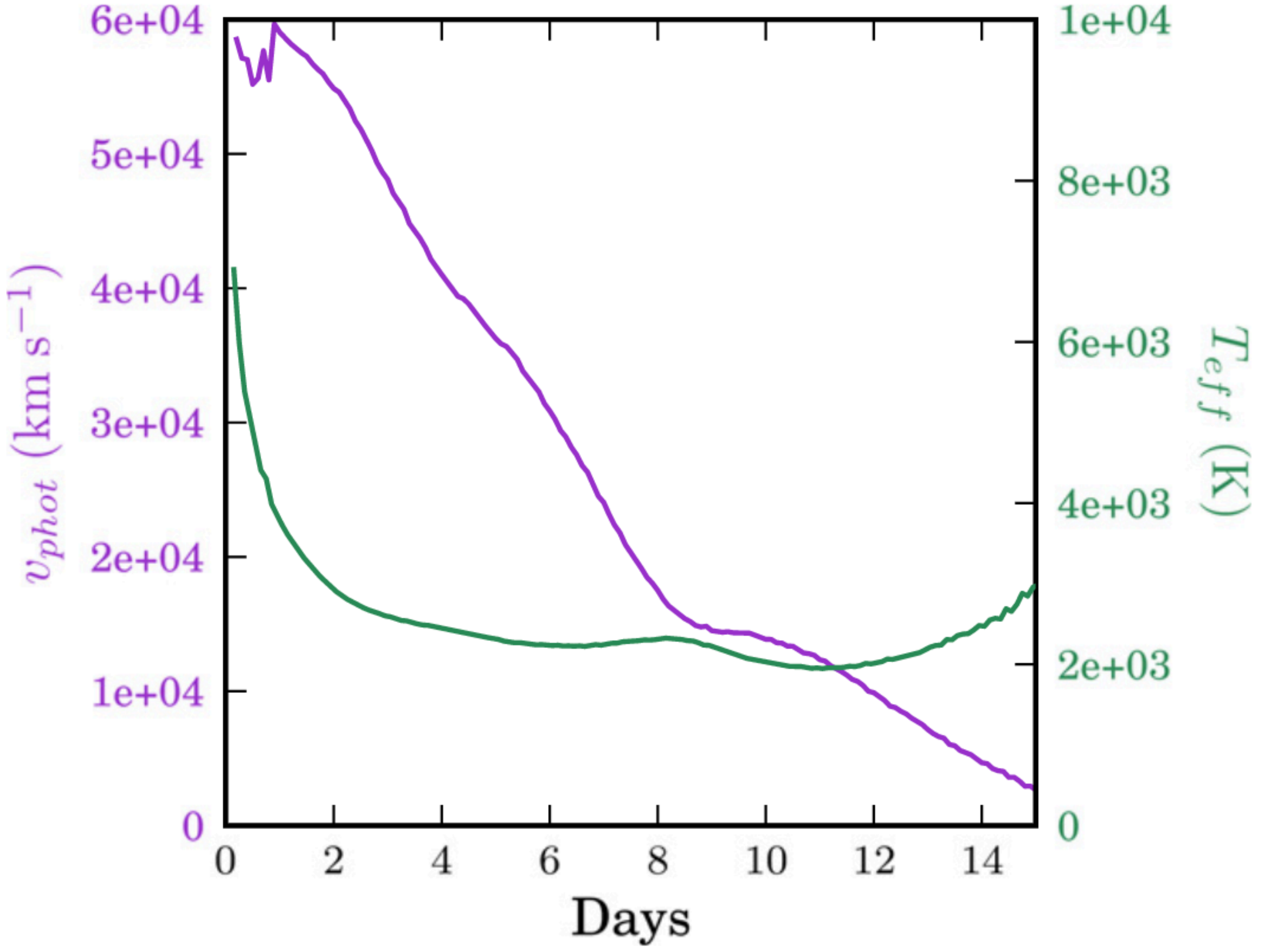
Initially surprising, a large destruction probability ϵ is needed to well reproduce the more detailed simulations, despite probability of collisional deexcitations (p_{abs}) being very small. *Thermalization mimics fluorescence.*

Predicted temperature evolution of KNe with LTE codes

Tanaka+2013. At 0.1c



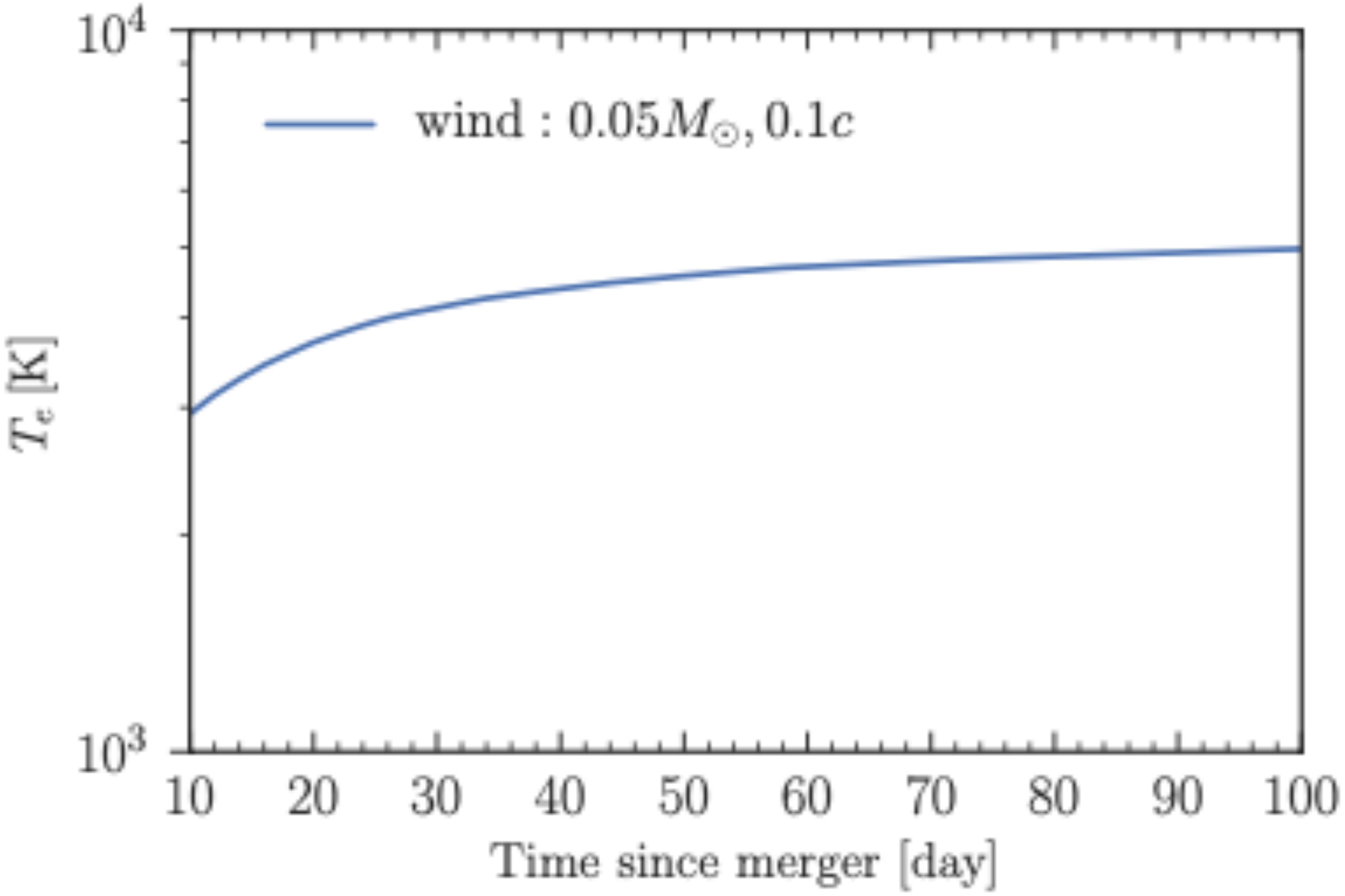
Barnes+2013 (SEDONA).



Temperature drops below 2000 K after 10 days

Hotokezaka+2021

First published results using NLTE-calculated temperatures. Temperature slowly increases with time.



Heating: $P(t) \times f_{therm}(t) = t^{-1.3} \times t^{-1.5} = t^{-2.8}$

erg cm3 s-1

Cooling: $V(t) \times n_{ion} \times n_e \times \Lambda(T, n_e) \approx t^{-3}\Lambda(T)$

so $\Lambda(T)$ slowly increases with t.

As $\Lambda(T)$ always increases with T, T slowly increases with t.

SUMO

Energy equation in steady state (radiative equilibrium):

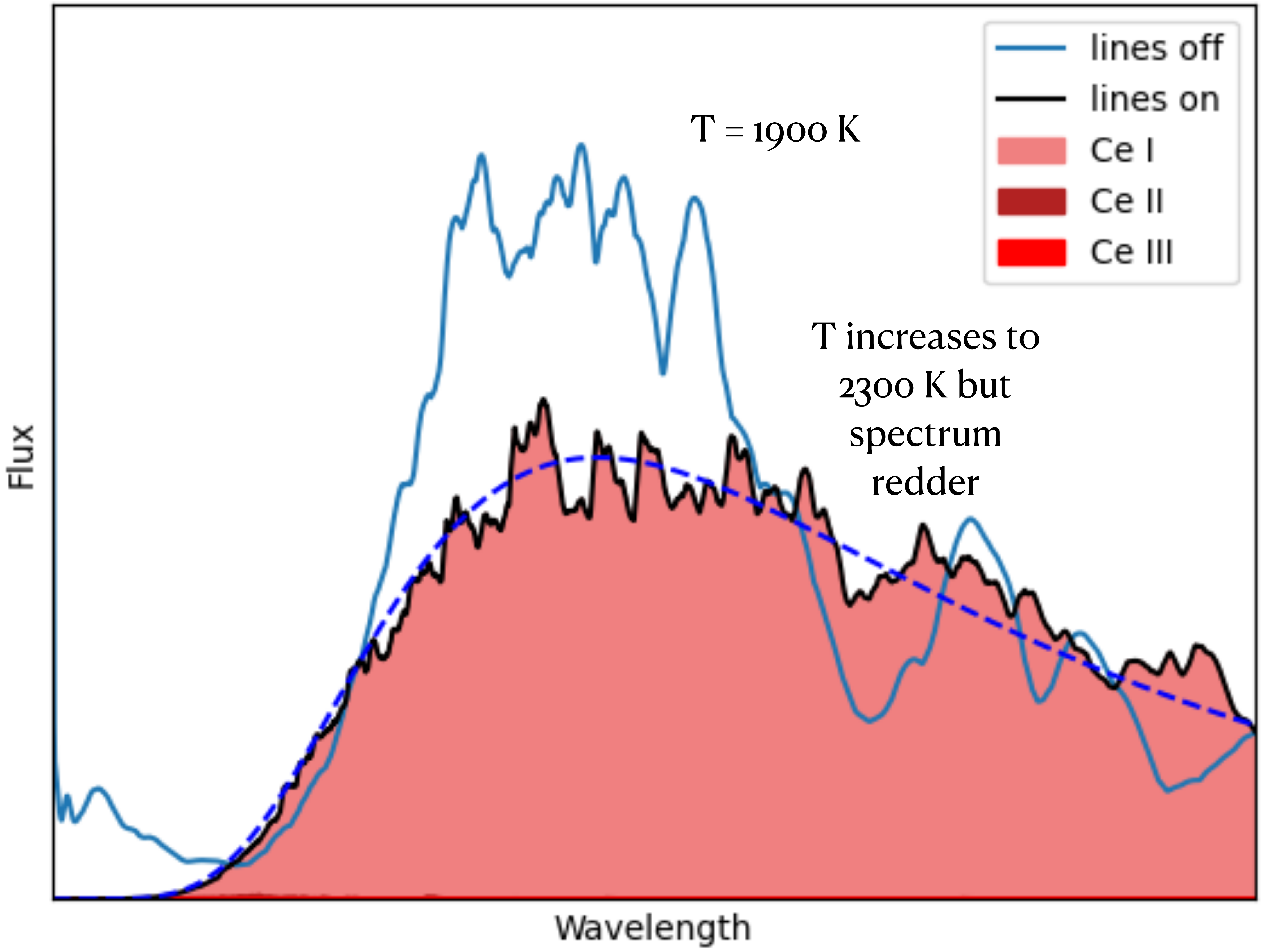
$$\gamma\ \text{dep} \times f_{heat} + \text{"thermal absorption"} = \text{"NLTE thermal emission"}$$

From Spencer-Fano solver

Calculated by solving NLTE level populations and how thermal electrons cool off each transition. Remove assumptions of 1) LTE 2a) Planckian field 2b) Parameterized thermalization.

One would expect a higher temperature because an NLTE gas at low densities emits less efficiently than an LTE one.

A Cerium kilonova



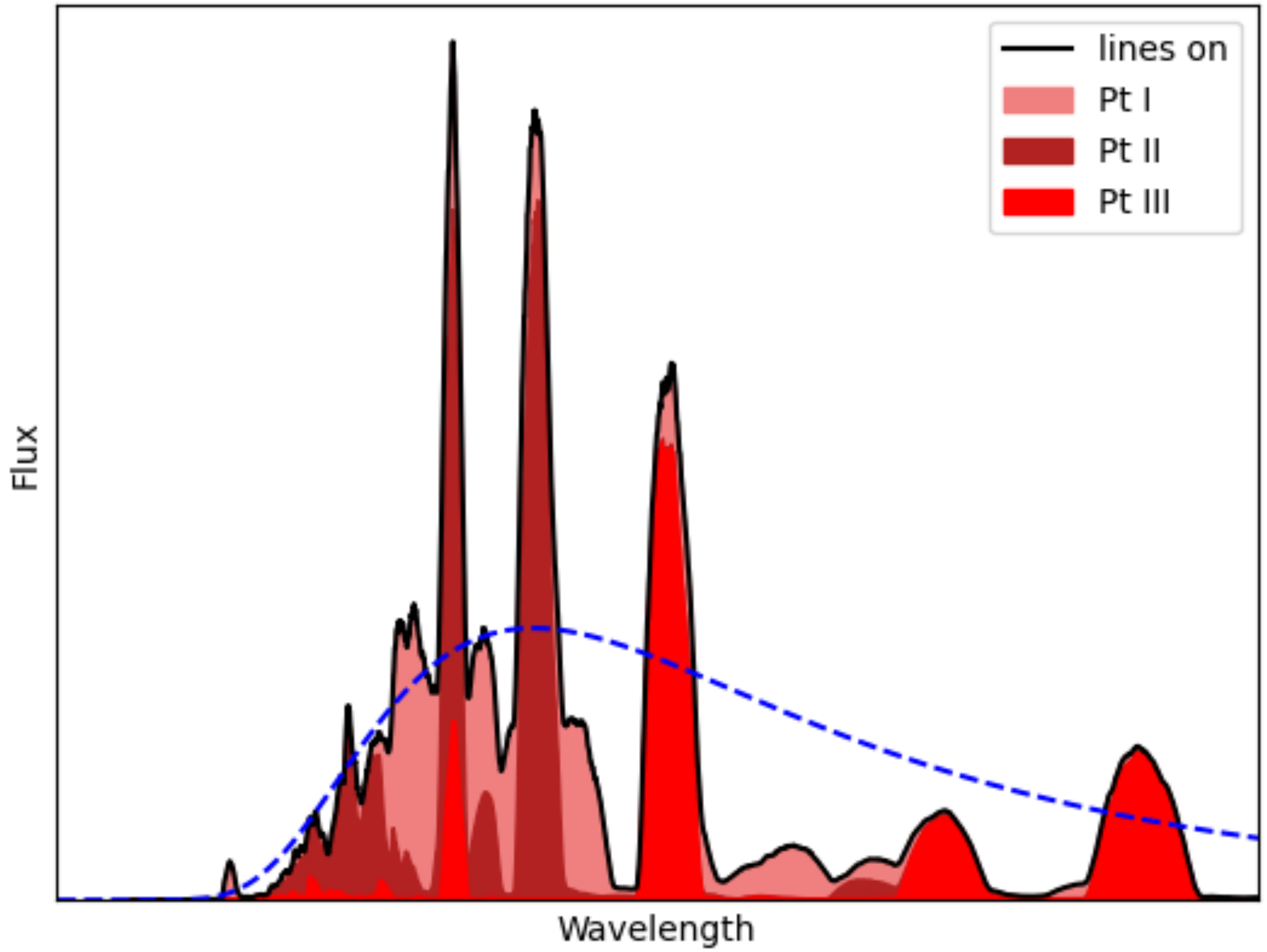
T = 1900 K

T increases to
2300 K but
spectrum
redder

$\sim 10^5$ lines
$\sim 10^4$ lines
$\sim 10^3$ lines

Optical
NIR

A Platinum kilonova



~10^3 lines
~10^3 lines
~10^4 lines

← Optical →

Summary

- Kilonovae transition, as supernovae, into a NLTE phase after peak. SUMO currently being developed to model this phase.

- Currently available models are based on LTE codes, but one should be aware methodologies differ significantly also between these.

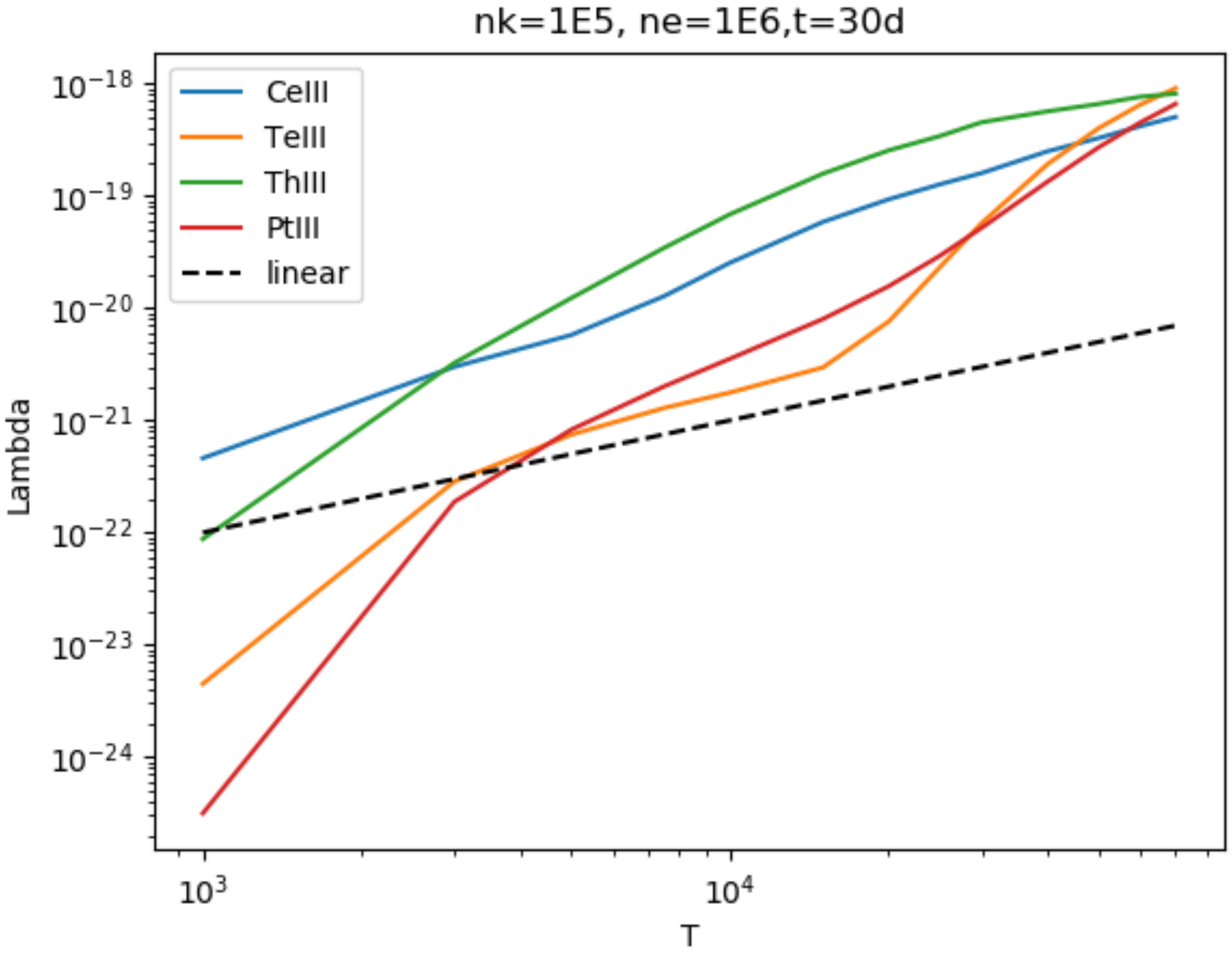
- The single published NLTE paper so far (Hotokezaka+2021) obtains a rising temperature at late times.

- Understanding temperature evolution will help us interpret the late-time light curve decline rates in different bands, and hopefully be able to identify elements and estimate masses.

RESERVES

Cooling functions Λ

SUMO calculations with FAC atomic data from Uppsala group



Compare e.g. Fe III