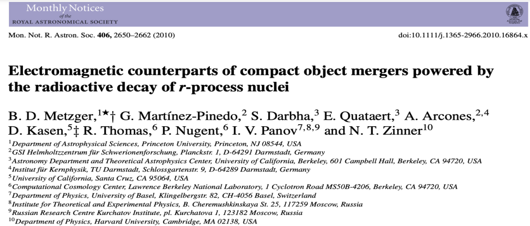
MODELLING OF KILONOVA LIGHT CURVES AND SPECTRA

Anders Jerkstrand

Stockholm University

European Research Council

A first prediction for the ages!



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **406,** 2650–2662 (2010) doi:10.1111/j.1365-2966.2010.16864.x

Electromagnetic counterparts of compact object mergers powered by the radioactive decay of *r*-process nuclei

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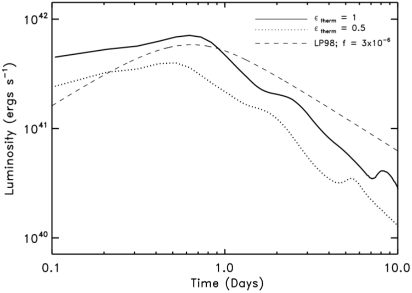
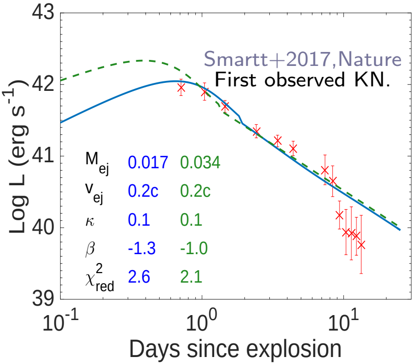
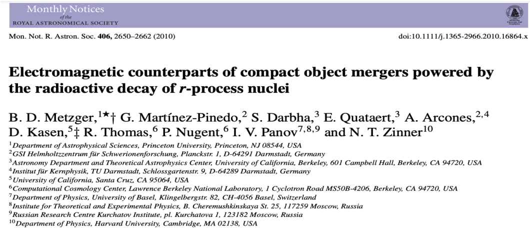




Smartt+2017,Nature
First observed KN.

A first prediction for the ages!



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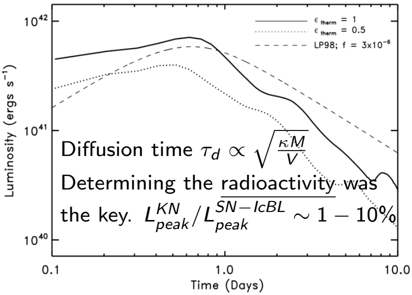
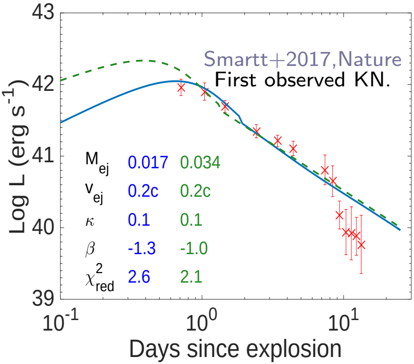


Diffusion time $\tau_d \propto \sqrt{\frac{\kappa M}{V}}$

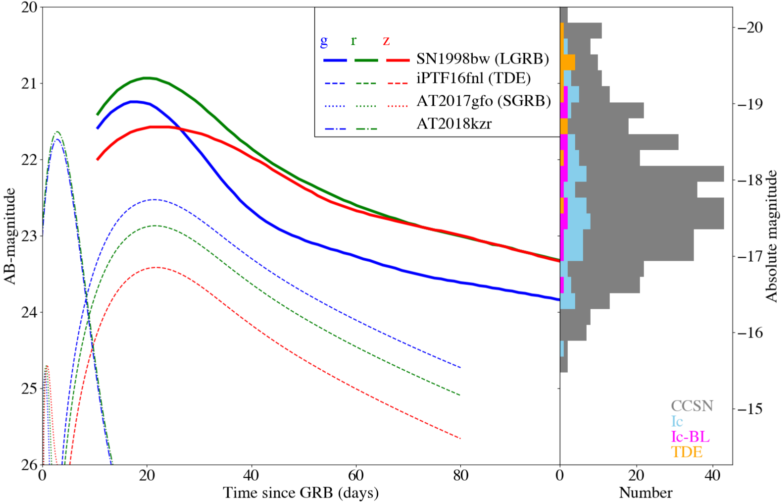
Determining the radioactivity was the key. $L^{KN}_{peak}/L^{SN-IcBL}_{peak} \sim 1-10\%$



Smartt+2017,Nature

First observed KN.

Transient light curves



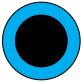
Courtesy: A Levan.

Two main phases in transient evolution

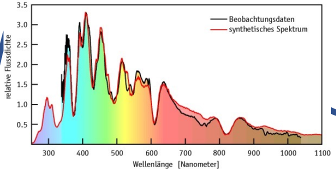
Photospheric phase

Long escape time for radiation
→ diffusion light curve

Spectra probe
<u>surface</u> layers



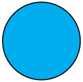
Many lines
excited and significant optical depth →
scattering spectra



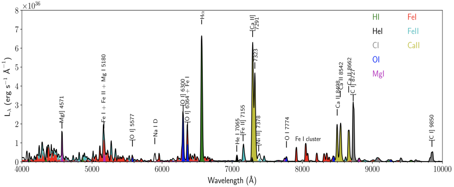
Nebular phase

Short escape time for radiation
→ a steady-state tail

Spectra probe
<u>all</u> ejecta



Few lines excited and
reduced optical depth →
emission line spectra



Time →

Simple microphysics (LTE)

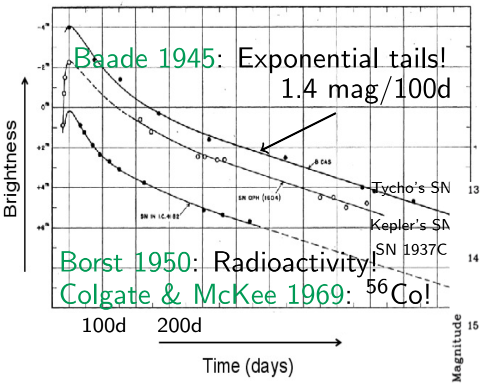
Complex michrophysics (NLTE)

Supernovae vs kilonovae

	SN	**KN**
M	$5\ M_\odot$	$0.05\ M_\odot$
V	0.01c	0.1c
t_{peak}	20d	2d
ρ_{peak}	10^{-11}	10^{-13}
$\frac{L(10t_{peak})}{L(t_{peak})}$	0.16	0.05
N_{lines}	$\sim 10^6$	$\sim 10^8$
% r.-a.	5%	100%

- Everything about KNe make them more challenging to analyse than SNe - except that all ejecta is now radioactive.
- In particular, significantly lower densities for a given evolutionary phase → expect NLTE more important.

History of late-time SN observations



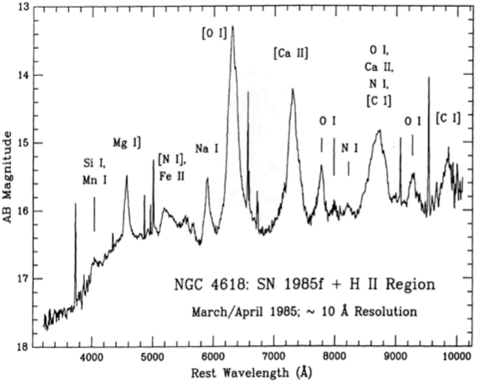
Baade 1945: Exponential tails! 1.4 mag/100d

Borst 1950: Radioactivity!

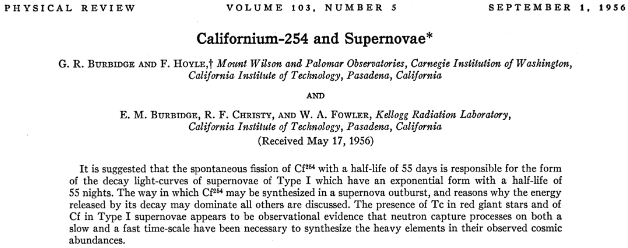
Colgate & McKee 1969: ^{56}Co!

- From $\sim 100 - 1000$d post explosion.
- Powering by $^{56}\text{Ni} \rightarrow {}^{56}\text{Co} \rightarrow {}^{56}\text{Fe}$.

Filippenko+1986: First good-quality nebular spectrum of a SN. Emission line fingerprints of the nucleosynthesis.



The Californium 254 hypothesis - and maybe a lesson for us



PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

AND

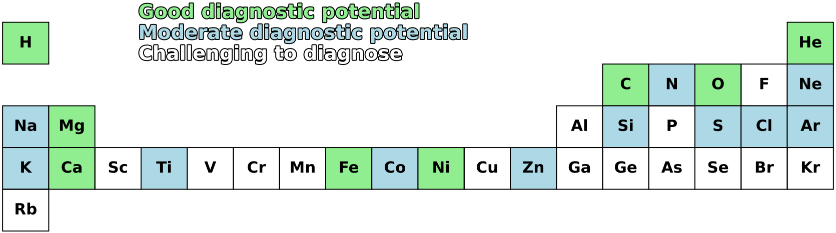
E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.

- The "red herring" that sent theorists wrong for over 20 years was that SN tails are, in Type I SNe, in fact not exponential and reflect a decay : there is time-dependent thermalization, in this case escape of gamma rays that steepen the SN LC. **Theorists took the data with insufficient amounts of salt. (but see Mihalas 1963)**
- Had Baade observed a single Type II SN, instead of three Type I, maybe history would have taken another path.

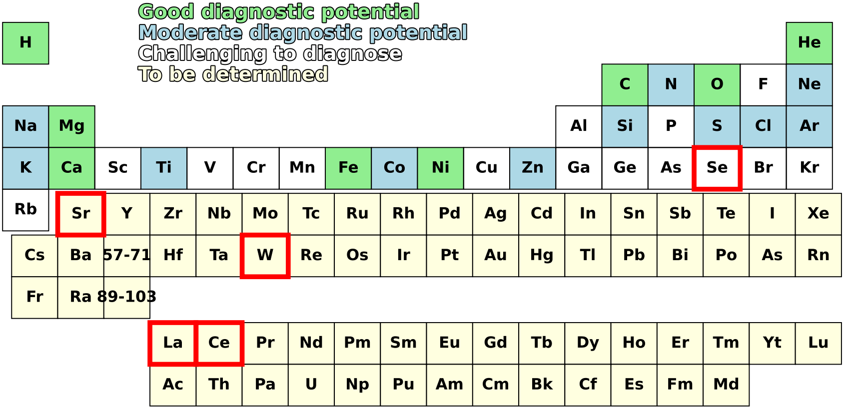
Elements we can diagnose from SN nebular phase spectra



🟩 Good diagnostic potential
🟦 Moderate diagnostic potential
⬜ Challenging to diagnose

🟩 H																	🟩 He
													🟩 C	🟦 N	🟩 O	⬜ F	🟦 Ne
🟦 Na	🟩 Mg											⬜ Al	🟦 Si	⬜ P	🟦 S	🟦 Cl	🟦 Ar
🟦 K	🟩 Ca	⬜ Sc	🟦 Ti	⬜ V	⬜ Cr	⬜ Mn	🟩 Fe	🟦 Co	🟩 Ni	⬜ Cu	🟦 Zn	⬜ Ga	⬜ Ge	⬜ As	⬜ Se	⬜ Br	⬜ Kr
⬜ Rb																	

Elements we can diagnose from SN/KN nebular phase spectra



Good diagnostic potential
Moderate diagnostic potential
Challenging to diagnose
To be determined

H																	He
													C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	As	Rn
Fr	Ra	89-103															
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yt	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md		

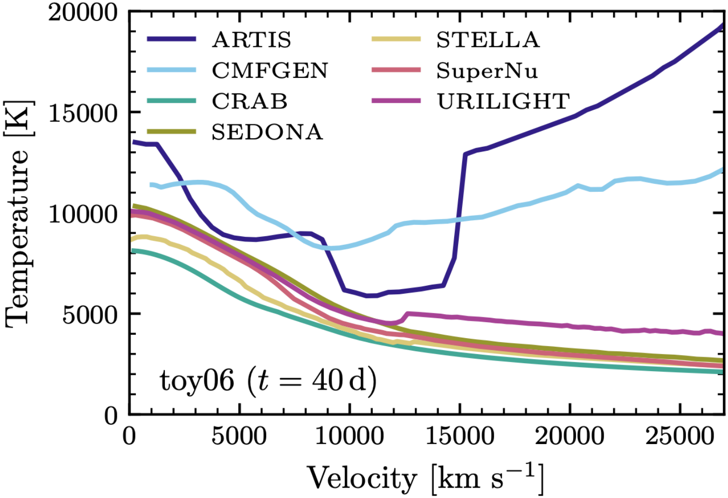
Claimed detection or potential for detection

Watson+2019,Domoto+2021,2022,Hotokezaka+2022

State of KN light curve/spectral modelling 2010-2021

- **3D, LTE codes with time-dependent transfer** : SEDONA, Tanaka-code, SuperNu. Methodologies differ mainly along two principal axes:
  1. Atomic data:
     - ...
  2. Temperature equation:
     - From thermal equilibrum with LTE source function (SEDONA, SuperNu)
     - From $T_e = T_{rad}$, with $\sigma T_{rad}^4 = \pi < J >$ (Tanaka)
- **Simpler, faster codes**: TARDIS, POSSIS, ARTIS*.
  - TARDIS was used to identify the Sr candidate line in 17gfo (Watson+2018, Nature).
  - More tomorrow from Christine Collins on ARTIS* modelling, Mattia Bulla on POSSIS modelling.

Lessons from SN code comparisons: For a simple input model, quite big differences even in LTE



Blondin+2022, A&A (StandaRT collaboration)

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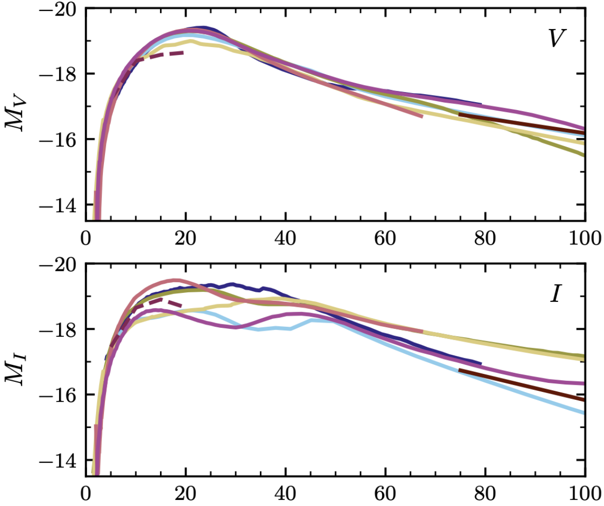


Blondin+2022, A&A (StandaRT collaboration)

When do we need to start considering NLTE?

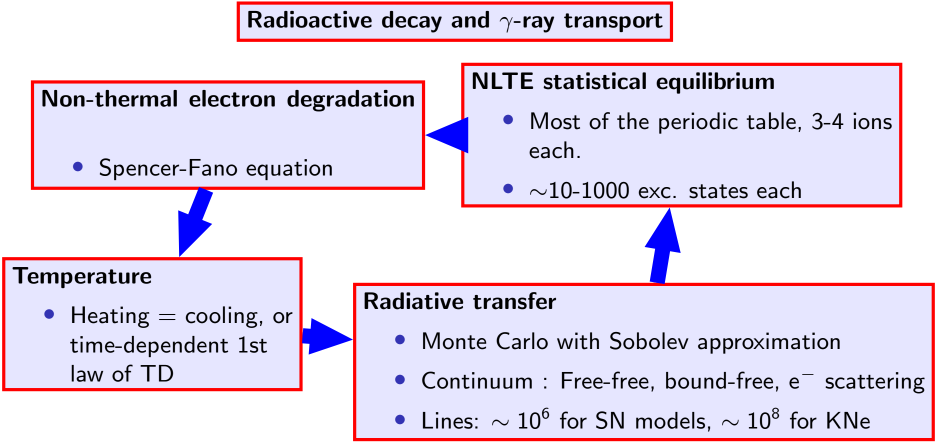
A complex question but two considerations:

1. **Spontaneous radiative decay** ($A\beta$) becomes competitive with **collisional deexcitation** (Qn_e).
   - $n_e^{crit} = \frac{A\beta}{Q(T)} \approx 10^6 \frac{A\beta}{10^{-3}} cm^{-3}$.
     Uniform sphere: $n_e = 10^9 M_{0.05} V_{0.2c}^{-3} x_e t_d^{-3}$ cm^{-3}
     $$\rightarrow t_d^{crit} = 10\text{d } M_{0.05}^{1/3} V_{0.2c}^{-1} \left(\frac{A\beta}{10^{-3}}\right)^{-1/3}$$
2. Ionization rates become governed by **non-thermal electrons** rather than **thermal ones** (or a thermal radiation field).
   - Below temperatures $kT \sim I$ and/or at low enough densities.

The SUMO code : a tool when NLTE needed

Jerkstrand 2011, PhD thesis, Jerkstrand, Fransson & Kozma 2011, Jerkstrand+2012

Adaptation to KNe : Q. Pognan (PhD thesis, ongoing)



Radioactive decay and γ-ray transport

Non-thermal electron degradation

- Spencer-Fano equation

NLTE statistical equilibrium

- Most of the periodic table, 3-4 ions each.
- $\sim$10-1000 exc. states each

Temperature

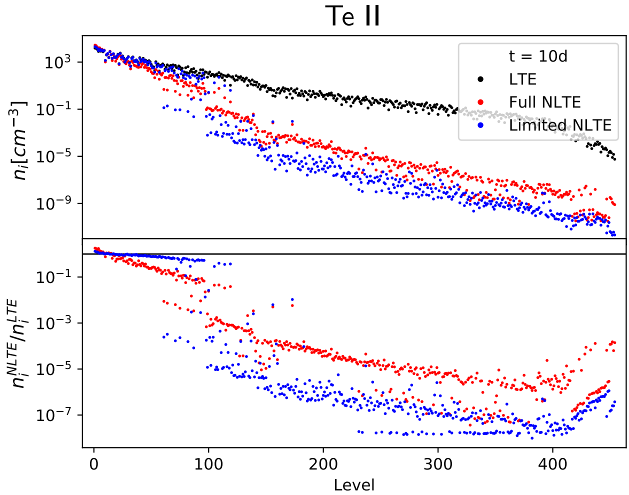
- Heating = cooling, or time-dependent 1st law of TD

Radiative transfer

- Monte Carlo with Sobolev approximation
- Continuum : Free-free, bound-free, e^- scattering
- Lines: $\sim 10^6$ for SN models, $\sim 10^8$ for KNe

- Code is 1D but allows for 3D-informed artificial mixing by **virtual grid** method.

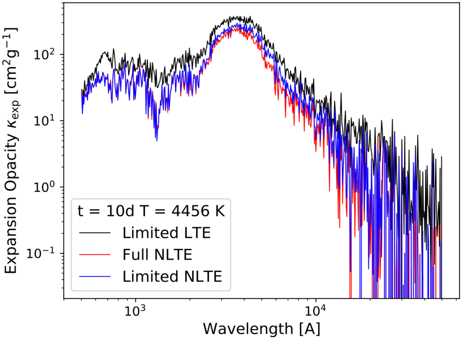
NLTE vs LTE in SUMO calculations



Pognan, AJ, Grumer 2022b

- "Radiation field keeps populations in LTE" a too sweeping statement.

NLTE vs LTE in SUMO calculations



Pognan, Jerkstrand, Grumer, MNRAS 2022b

- Validation of LTE opacities w.r.t. **excitation** for first ∼5-10d.
- Testing of LTE opacities w.r.t. **ionization** not yet feasible : need more sophisticated Spencer-Fano solver and calculation of recombination rates.

Powering

- Most power typically from β decays. Many contributors → $dN/dt \propto t^{-1}$. Average decay energy $\propto t^{-0.3} \rightarrow \boldsymbol{\dot{E}_{decay}(t) \propto t^{-1.3}}$.
- The thermalization of decay particles becomes a slow (time-dependent) process when density becomes low enough. Barnes+2016: first exploration of this physics. $f_{therm}(t, \rho_0, comp.) = \frac{\dot{E}_{dep}(t)}{\dot{E}_{decay}(t)}$.
- Kasen & Barnes 2019 (used in our first papers) :

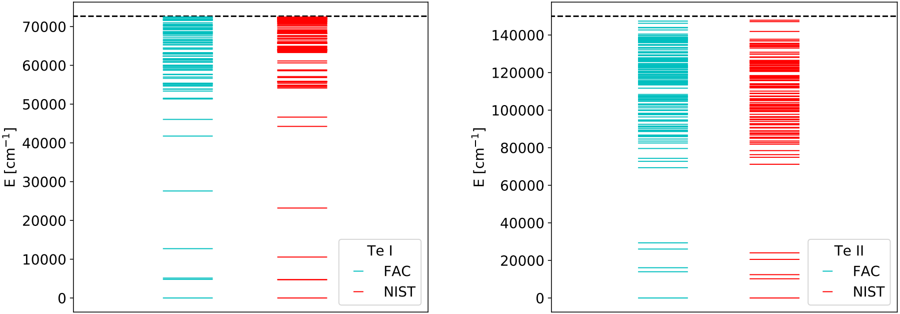
$$
\begin{aligned}
f^{e-}_{therm}(t, \rho_0) &= \left(1 + \frac{t}{13d\left(\frac{\rho_0}{\bar{\rho_0}}\right)^{2/3}}\right)^{-1} \quad , \bar{\rho_0} \text{ for } M = 0.01 \text{ and } v = 0.2c \\
f^{\alpha}_{therm}(t, \rho_0) &= \left(1 + \frac{t}{40d\left(\frac{\rho_0}{\bar{\rho_0}}\right)^{2/3}}\right)^{-1} \quad ,
\end{aligned}
$$

- Solve heating vs ionization fractions from Boltzmann equation for non-thermal electrons (see talk by Eliot Ayache tomorrow).

r-process energy levels and A-values

Calculated by J. Grumer with the **Flexible Atomic Code** (Gu 2008,open-s.)

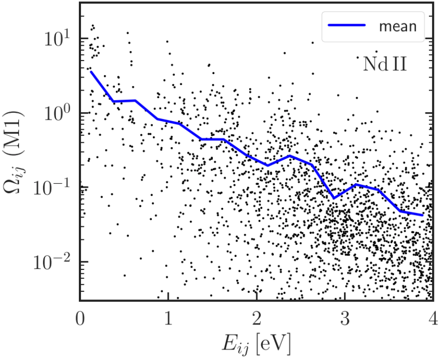
- Overall term structure captured but moderate accuracy for energies → no accurate line positions.
- Models should be able to predict SED reasonably well, but not exact line features.



Pognan, Jerkstrand & Grumer, MNRAS 2022a

Collision strengths

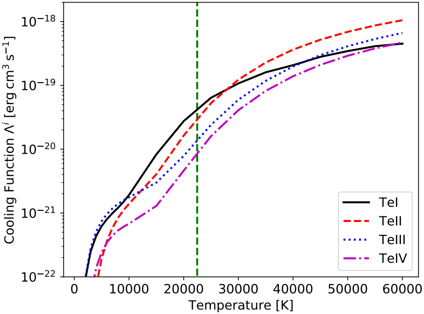
- SUMO: van Regemorter for allowed, $\Upsilon = 0.004 g_l g_u$ (Axelrod 1980, fit to iron) for forbidden.
- Other treatments in literature : HULLAC calculations (Nd only so far), $\Upsilon = 1$ others (Hotokezaka 2021)



Hotokezaka+2021

Cooling functions

- Different ions of an element have different cooling capability → coupling between ionization and temperature.
- Cooling capability typically decreases with ionization degree.



$$\Lambda = \sum_{l,u} C_{lu}(\Upsilon_{l,u}(T)) \times \Delta E_{lu} \times \left(n_l - f_{lu}(T)\frac{n_u}{n_l}\right)$$

- Level populations (and therefore Λ) in general depend on $\{T, n_{ion}, n_e, J_\nu\}$.
- Low-density limit : Λ depends on T only.

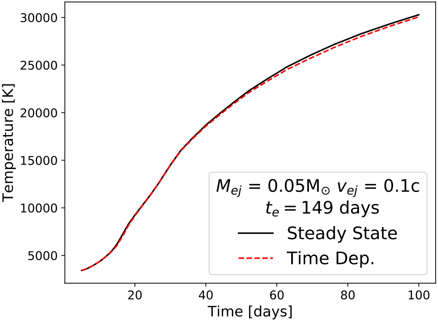
Pognan+2022a. $\Lambda(T)$ in low-density limit.
Dashed line = temperature in a SUMO model at 20d.

The temperature evolution of kilonovae

Heating: $H \propto t^{-1.3} \cdot f_{therm}(t)$
Cooling: $C \propto t^{-3} \cdot x_e(t) \cdot \Lambda(T)$

Typically $\Lambda(T) \propto T^{2\alpha}$, with $\alpha \gtrsim 1$.

For fixed x_e, Υ, equating $H = C \rightarrow$:

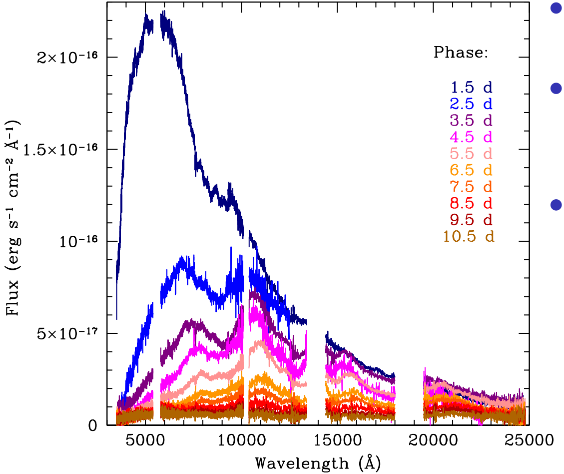


Early ($f_{therm}(t) \approx 1$) :
$\Lambda(T) \propto t^{1.7} \rightarrow \boldsymbol{T \propto t^{0.85/\alpha}}$

Late ($f_{therm}(t) \propto t^{-1.5}$):
$\Lambda(T) \propto t^{0.2} \rightarrow \boldsymbol{T \propto t^{0.1/\alpha}}$

Radiation trapping may raise T beyond radioactivity balance. We see however no strong effect of this : all models are getting hotter from ~3-5d.

Observed SED evolution of AT2017gfo : Can we infer its T_{ejecta} evolution?



Courtesy: E. Pian

- Appears to be cooling up to ~5d.
- Relatively constant SED after that, noise makes it hard to assess T evolution.
- **The T evolution of KNe as they enter their nebular phase is one of the current hot topics.**

Many interesting talks tomorrow!

From the Stockholm group : **Quentin Pognan** presents first KN spectra with SUMO, **Eliot Ayache** presents work for calculating time-dependent thermalization.

Discussion points for tomorrow:

- Atomic data : Energy levels, A-values, collision strengths, recombination
- Radioactivity and non-thermal physics : role of α decay and fission.
- Which properties of the ejecta are we most keen to determine?
- What accuracy is needed for meaningful model distinctions?
- What lessons did we learn from 25 years of studying Long GRB ejecta?

Thank you for listening!