The Thermalization of γ-rays in Kilonovae

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The Radiative Transfer and Atomic Physics of Kilonovae
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Introduction

- UVOIR observations of Kilonovae will be key for constraining the properties of matter ejected from NSMs.

- To this end, robust light curve modeling is essential.
  A key component is the energy deposition process of radioactive decay products (mainly γ, e^{-}) which powers the transient.

- In Ia SNe t_0 (hereafter $t_{\gamma,\mathrm{eff}}$), the time at which γ-ray energy start to escape deposition, is an observable feature and a useful probe of the ejecta.

Our work

In this work we focus on the γ-ray heating in KNe, and:

- Find $t_{\gamma,\mathrm{eff}}$ for a wide range of ejecta properties (Y_e, s_0 and M, v) and test its sensitivity to nuclear physics uncertainties.
- Give a semi-analytic method for calculating the γ-ray heating for any density profile $\rho(\mathbf{v})$.
- Present a simple analytic approximation method, and apply it for spherical KNe.

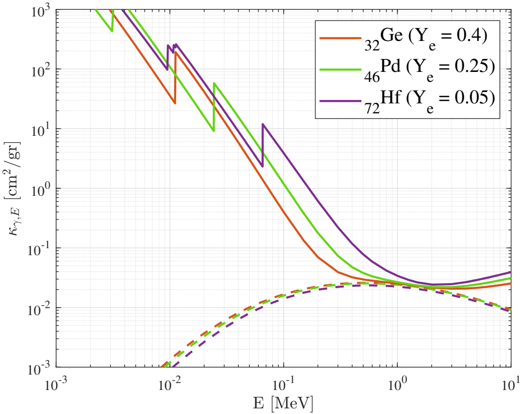
Our method assume uniform composition, but can be extended to non-uniform composition.

Modeling of the $e^{\pm}$ heating - in Ben Shenhar's talk tomorrow.

γ-ray thermalization in a nutshell

γ-rays lose energy by:

- Photo-electric effect (PE): low energies (<few 100keV) and high Z.
- Compton scattering: intermediate energies ($\sim$1MeV), roughly Z-independent ($\propto \frac{Z}{A}$).
- Pair-production (PP): high energies ($>$ few MeV) and high Z.



γ-ray thermalization in Ia SNe

- In Ia SNe, the Z of the ejecta is relatively low ($Z \lesssim 30$):

  PE is weak, Compton scattering is dominant over a wide energy range around 1MeV.

- The γ-rays from ^{56}Ni and ^{56}Co "see" energy deposition opacity due to Compton:

  $\kappa_{\gamma,\text{eff}} \approx \langle \kappa_{\gamma,E} \rangle \approx 0.025\text{cm}^2\,\text{gr}^{-1}$ (Swartz et al 1995, Jeffery 1999)

- For an ejecta with column density $\langle \Sigma \rangle \sim \frac{M}{4\pi v^2 t^2}$,

  $t_{\gamma,\text{eff}} = \sqrt{\kappa_{\gamma,\text{eff}} \underbrace{\langle \Sigma \rangle t^2}_{\text{constant}}} \rightarrow$ probes the column density of the ejecta ($\sim M/v^2$).

  (e.g. Wygoda et al 2019)

γ-ray thermalization in KNe

In KNe, depending on initial conditions (mainly Y_e), Z of the ejecta changes & reaches $\sim$70.

PE dominates and increases the opacity at $\lesssim$ 1MeV.

Also, heavier elements tend to emit softer γ-rays.

(Hotokezaka & Nakar 2020)

$\rightarrow$ PE may cause $\kappa_{\gamma,\text{eff}}$ to be larger and Y_e-dependent - *a potential probe of the R-process?*

Some past works took $\kappa_{\gamma,\text{eff}} \approx 0.025\text{cm}^2\,\text{gr}^{-1}$for all Y_e as in Ia SNe (Hotokezaka et al 2016, Kasen & Barnes 2019).

Other works used $\kappa_{\gamma,\text{eff}} = \langle \kappa_{\gamma,E} \rangle$:

Barnes et al 2016 - $0.1\text{cm}^2\,\text{gr}^{-1}$ for low-Y_e (used by Rosswog et al 2017, Bulla 2023),

Hotokezaka & Nakar 2020 - $0.4\text{cm}^2\,\text{gr}^{-1}$for strong R-process, $0.07\text{cm}^2\,\text{gr}^{-1}$ for weak.

Barnes et al 2021 saw $\langle \kappa_{\gamma,E} \rangle$ up to $\sim 3\text{cm}^2\,\text{gr}^{-1}$in low-$Y_e$.

A model for γ-ray deposition in a radioactive expanding ejecta

Our aim: calculate the γ-ray energy deposition fraction $f_\gamma(t) = \dot{Q}_{\gamma,\text{ dep}}/\dot{Q}_\gamma$, with good accuracy at least until $\dot{Q}_{\gamma,\text{ dep}} \approx \dot{Q}_{\text{charged, dep}}(\approx \dot{Q}_{\text{charged}})$.

$$\begin{cases} f_\gamma \approx 1 & \text{early times} \\ f_\gamma \propto t^{-2} & \text{late times} \end{cases}$$

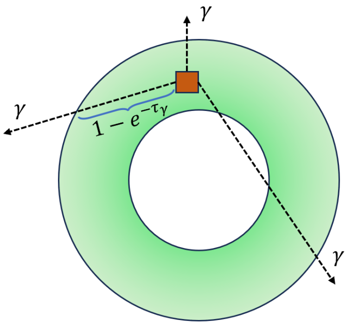
(i) We use a semi-analytic method to find $f_\gamma(t)$.

(ii) We approximate f_γ using an analytic approximation $f_{\gamma,\text{eff}}$ by:

- (a) Finding the shape of f_γ for a single γ-ray line,
- (b) "Stretching" the shape function according to $t_{\gamma,\text{eff}}$ which is the time of "knee" $f_\gamma \approx 1 - e^{-1}$,

This give $\kappa_{\gamma,\text{eff}}$, as $t_{\gamma,\text{eff}} = \sqrt{\kappa_{\gamma,\text{eff}}\langle\Sigma\rangle t^2}$.

The semi-analytic method

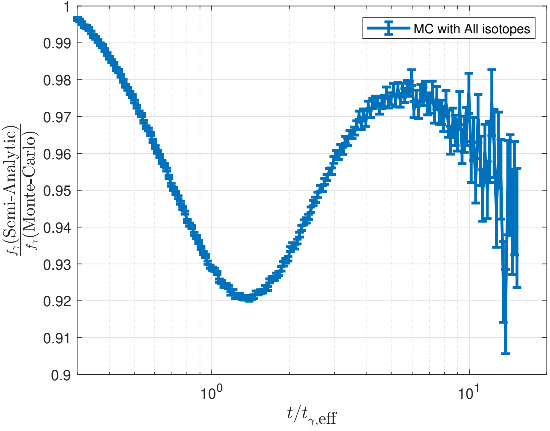


$\int dE \int d^3r \int d\hat{\boldsymbol{\Omega}}$

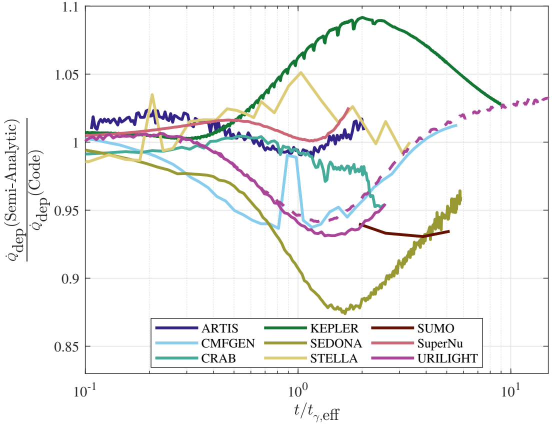
Ia SNe as a test case

(i) The semi-analytic method agrees with Monte-Carlo simulation to $\lesssim$10% error.

(ii) We reproduce $\kappa_{\gamma,\text{eff}} \approx 0.025\text{cm}^2\,\text{gr}^{-1}$.



Comparison to URILIGHT MC code



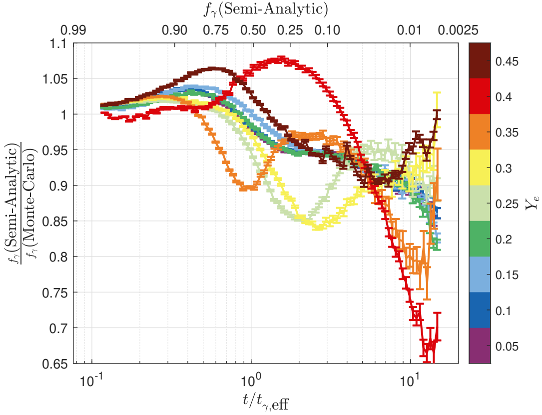
$\sim$ 10% deviations between numeric codes

Survey of Blondin et al 2022 (toy06 model)

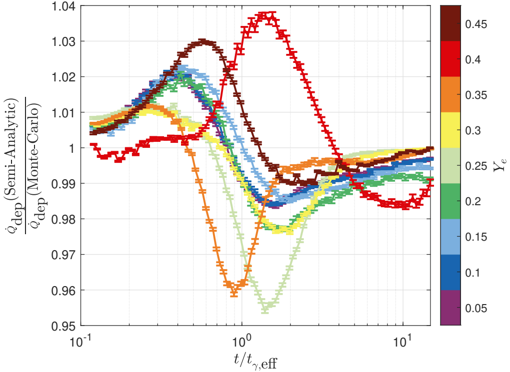
The application for Kilonovae

Spherical, $v \sim 0.2c$ ejecta models (Kasen & Barnes 2013, Waxman et al 2017, uniform density)
The semi-analytic method agrees with Monte-Carlo simulation to ∼10% error near the "knee".

→ $\lesssim$10% error in the total (γ-rays + charged particles) energy deposition rate.



γ-ray deposition fraction



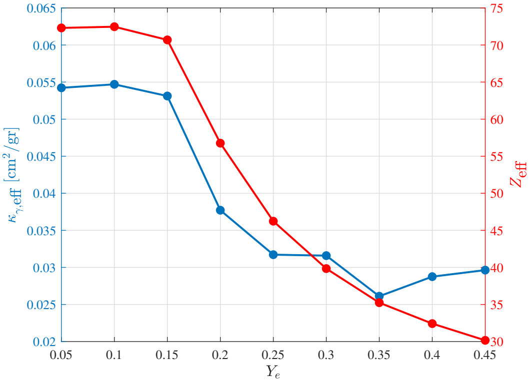
Total energy deposition rate

The $\kappa_{\gamma,\text{eff}}$ of Kilonovae

We develop an analytic approximation, using the semi-analytic method, by:

(i) Setting $f_{\gamma,\text{eff}}(t) = \frac{1}{1+(t/t_{\gamma,\text{eff}})^2}$,
(motivated by Sharon & Kushnir 2020)

(ii) Finding $t_{\gamma,\text{eff}}$ (and $\kappa_{\gamma,\text{eff}}$).

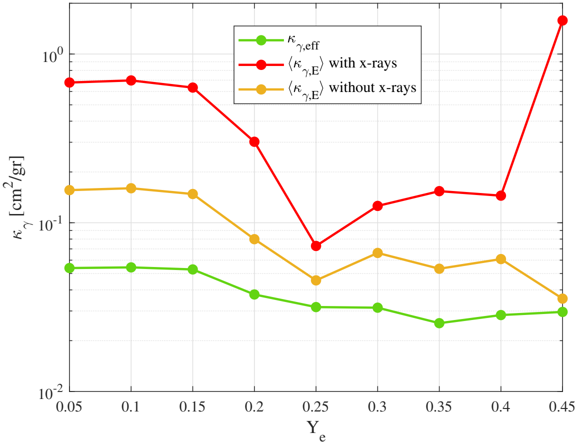


The Y_e-dependence of $\kappa_{\gamma,\text{eff}}$

$\kappa_{\gamma,\text{eff}}$ changes only by a factor $\sim$2 between low and high-Y_e conditions, as in any case most of the energy is carried by $\sim$1MeV γ-rays.

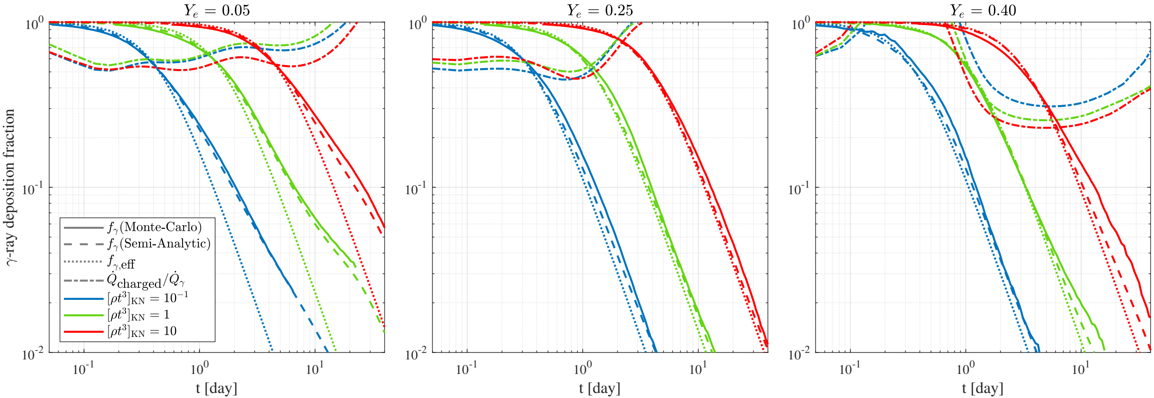
Why $\kappa_{\gamma,\mathrm{eff}}$ was overestimated in the past?

The mean opacity $\langle \kappa_{\gamma,E} \rangle$ overestimates the true $\kappa_{\gamma,\mathrm{eff}}$:
It is the correct opacity only when the ejecta is transparent for **all** γ-rays: $f_\gamma \approx \langle \kappa_{\gamma,E} \rangle \langle \Sigma \rangle$.
At times near the "knee", due to PE at low energies, there are still γ-rays with $\kappa_{\gamma,E} \langle \Sigma \rangle \gg 1$.



γ-ray deposition functions

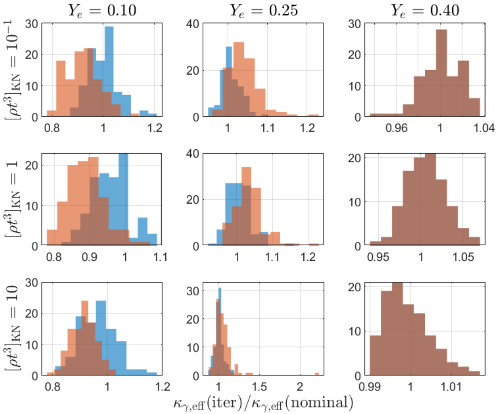
$f_{\gamma,\text{eff}}(t)$ is a good approximation to f_γ, at least until $\dot{Q}_{\gamma,\text{ dep}} \approx \dot{Q}_{\text{charged, dep}}$:



Nuclear physics uncertainties

We find $\kappa_{\gamma,\mathrm{eff}}$ to be robust to nuclear physics uncertainties (typically $\lesssim 10\%$):

By modifying theoretical nuclear reactions rates by a random factor of $C \in [10^{-2}, 10^{2}]$, and changing the nuclear mass model: FRDM (blue), UNEDF1 (orange).



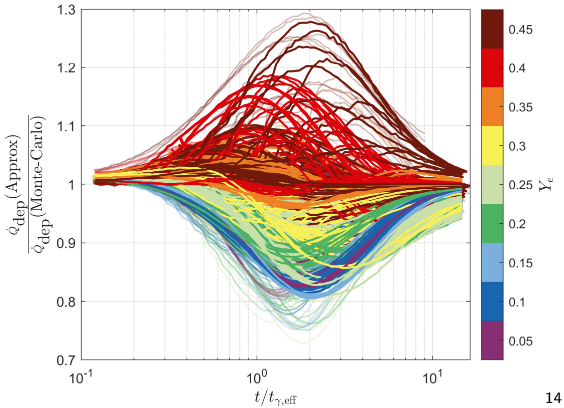
A Y_e-independent analytic approximation

As the Y_e-dependence is weak, a simple approximation can be applied to all Y_e's:

$$\kappa_{\gamma,\mathrm{eff}} \approx 0.034\mathrm{cm}^2\,\mathrm{gr}^{-1}, \quad t_{\gamma,\mathrm{eff}} \approx 1\mathrm{day}\, f_\Sigma^{\frac{1}{2}} \left(\frac{M}{0.05M_\odot}\right)^{\frac{1}{2}} \left(\frac{v}{0.2c}\right)^{-1}, \quad f_{\gamma,\mathrm{eff}}(t) = \frac{1}{1+(t/t_{\gamma,\mathrm{eff}})^2},$$

where f_Σ is a factor of order unity.

This gives the total energy deposition rate (γ-rays + charged particles) with $\lesssim 20\%$ error for $v \sim 0.2c$ ejecta



Key Takeaways

- The semi-analytic method can replace expensive MC simulations for a general ejecta.
- For spherical KNe of uniform composition:
  $\kappa_{\gamma,\text{eff}} \approx 0.034 \text{cm}^2\,\text{gr}^{-1}$, $t_{\gamma,\text{eff}} \approx \ 1\text{day} \ \left(\frac{M}{0.05M_\odot}\right)^{\frac{1}{2}} \left(\frac{v}{0.2c}\right)^{-1}$, $f_{\gamma,\text{eff}}(t) = \frac{1}{1+(t/t_{\gamma,\text{eff}})^2}$,
  gives the total energy deposition rate with $\lesssim 20\%$ error.
- $\kappa_{\gamma,\text{eff}} \approx 0.03(0.05)\ \text{cm}^2\,\text{gr}^{-1}$for $Y_e \gtrsim (\lesssim) 0.25$ and insensitive to large uncertainties in the nuclear physics model, as the γ-ray spectrum in KNe is dominated by $\sim$1 MeV photons.
- $\kappa_{\gamma,\text{eff}}$ was overestimated in the past (0.07 to $3\text{cm}^2\,\text{gr}^{-1}$), as $\langle \kappa_\gamma(E) \rangle$ is not the appropiate definition for it.
- $t_{\gamma,\text{eff}}$ is nearly insensitive to Y_e and s_0, it depends mostly on the column density: (probably) not a probe of the r-process, but a potential probe of M/v^2.