The Thermalization of γ-rays in Kilonovae

Or Guttman, Ben Shenhar, Arnab Sarkar and Eli Waxman

Weizmann Institute of Science

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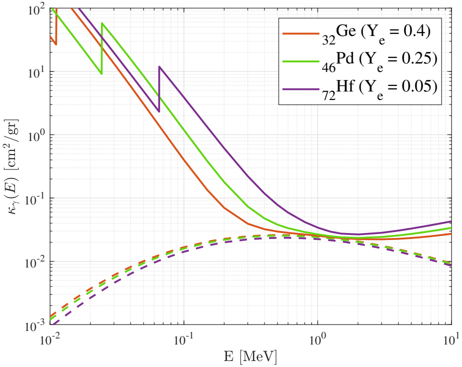
Introduction

- Neutron star mergers are a potential site for the R-process, however observational constrains are still lacking.
- UVOIR Observations of Kilonovae could reveal information on the nucleosynthesis.
- As the light curve is powered by deposition of radioactive decay products (mainly γ, e^-), understanding the energy deposition process is essential for modeling.
- In Ia SNe, t_0 the time at which γ-ray energy start to escape deposition is a useful probe of the ejecta.
- Overall, we aim toward a simple model of the γ-ray heating, which would enable future observers to derive constrains from the light curve.

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$1MeV), roughly Z-independent.
- Pair-production (PP): high energies ($>$ few MeV) and high Z.



t_0 in Ia SNe and KNe

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

  PE is weak, Compton is dominant over a wide energy range.

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

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

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

  $t_0 = \sqrt{\kappa_{\gamma,\mathrm{eff}}\underbrace{\langle\Sigma\rangle t^2}_{\text{constant}}} \rightarrow$ probes the column density of the ejecta ($\sim M/v^2$).

(e.g. Wygoda et al 2019)

t_0 in Ia SNe and 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.

→ PE can cause $\kappa_{\gamma,\text{eff}}$ to be larger and Y_e-dependent - *potential probe of the R-process*.

(Hotokezaka & Nakar 2020, Barnes et al 2021)

Hotokezaka & Nakar 2020 used $\langle \kappa_\gamma(E) \rangle$ to find t_0,

found $\kappa_{\gamma,\text{eff}} \approx 0.07\text{cm}^2\,\text{gr}^{-1}$for weak R-process, $\approx 0.4\text{cm}^2\,\text{gr}^{-1}$ for strong R-process.

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

The γ-ray deposition in Kilonovae: Goals & Methods

Our aim: (i) Estimate the γ-ray energy deposition fraction $f_\gamma(t)$,

(ii) Provide an analytical approximation, $f_{\gamma,\mathrm{eff}}(t)$.

$f_{\gamma,\mathrm{eff}}$ should have a simple form of:

$$f_{\gamma,\mathrm{eff}} \approx \begin{cases} 1 & t \ll t_0 \\ \left(\frac{t}{t_0}\right)^{-2} & t \gg t_0. \end{cases}$$

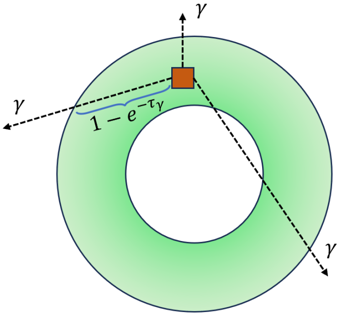
To estimate t_0:

(i) We use a semi-analytical solution to find f_γ.

(ii) We set t_0 such that it is at the "knee" of f_γ ($f_\gamma = 1 - e^{-1}$).

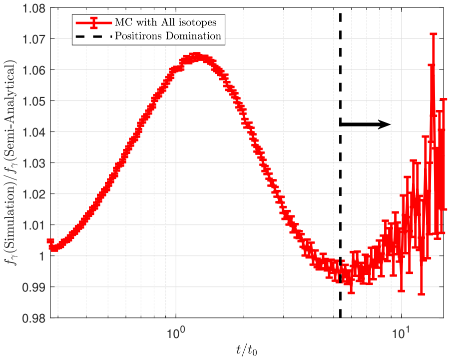
A Semi-Analytical solution to γ-ray deposition

Illustration of the method



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

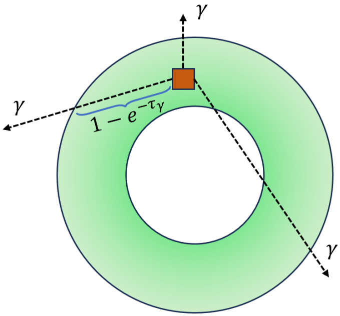
Ia SN toy model, toy06 (Blondin et al 2022)



The method agrees with Monte-Carlo simulations up to ∼10% error.
→ $<$ 10% error in the total (γ-rays + charged particles) energy deposition rate.

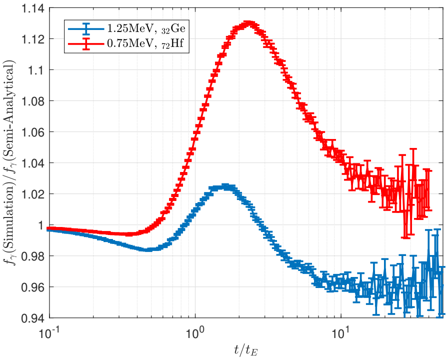
A Semi-Analytical solution to γ-ray deposition

Illustration of the method



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

KN toy model (Barnes & Kasen 2013)



The method agrees with Monte-Carlo simulations up to $\sim$10% error.

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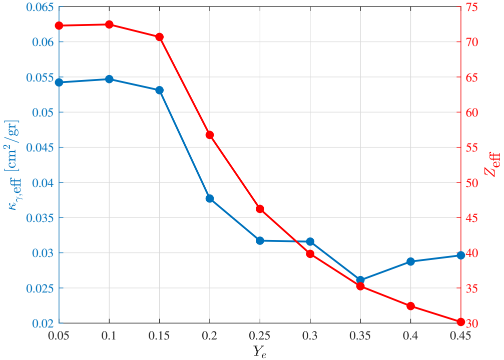
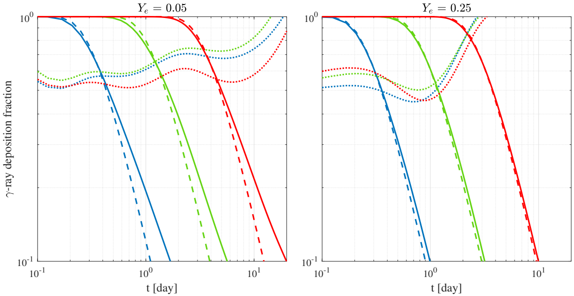
The γ-ray deposition in Kilonovae: Results



The Y_e-dependence of $\kappa_{\gamma,\mathrm{eff}}$, mainly due to the change in Z



γ-ray deposition fractions:
Semi-Analytical (solid) and Analytical (dashed)

$\kappa_{\gamma,\mathrm{eff}}$ changes only by a factor $\sim$2 between low and high-Y_e conditions.

The γ-ray deposition in Kilonovae: Results

The thermalization of the γ-rays can be calculated using Y_e-independent approximation,

$$\kappa_{\gamma,\mathrm{eff}} \approx 0.034\mathrm{cm}^2\,\mathrm{gr}^{-1}, \quad t_0 \approx 1\mathrm{day}\ f_{\Sigma}^{\frac{1}{2}} \left(\frac{M}{0.05M_\odot}\right)^{\frac{1}{2}} \left(\frac{v}{0.2c}\right)^{-1},$$

where f_Σ is a factor of order unity,

using interpolation found by the semi-analytical solution & motivated by earlier works in SNe:

$$f_{\gamma,\mathrm{eff}}(t) = \frac{1}{1+(t/t_0)^2}.$$

(Sharon & Kushnir 2020)

This gives the total (γ-rays + charged particles) energy deposition rate with up to $\lesssim 20\%$ error.

Summary

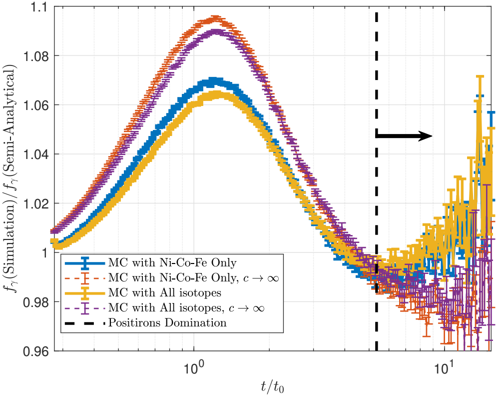
- A simple Y_e-independent analytical tool is given for estimating the γ-ray thermalization.
- The γ-ray spectrum in KNe is dominated by $\sim$1 MeV photons.
  Thus, $\kappa_{\gamma,\mathrm{eff}}$ is never much larger than the effective opacity due to Compton scattering.
- Earlier estimations greatly overestimated $\kappa_{\gamma,\mathrm{eff}}$, since $\langle\kappa_\gamma(E)\rangle$ is a bad measure of $\kappa_{\gamma,\mathrm{eff}}$.
- $\kappa_{\gamma,\mathrm{eff}}$ is largely insensitive to ejecta conditions, but t_0 can probe M/v^2 (*if measured*).
- The Semi-Analytical solution to the γ-ray deposition can replace expansive Monte-Carlo simulations.

Backup Slides

A Semi-Analytical solution to γ-ray deposition

The method agrees with Monte-Carlo simulations up to $\sim$10% error.

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



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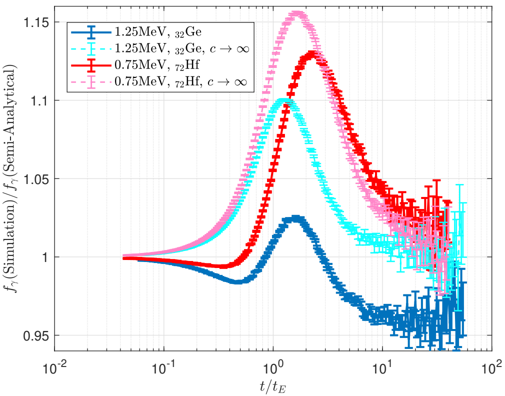

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The γ-ray deposition in Kilonovae: Results