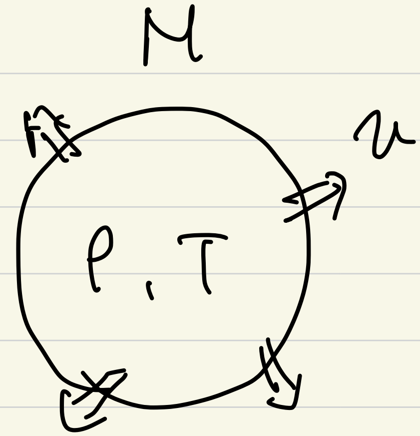
kilonova



properties of the ejecta

$$\begin{cases} M \sim 0.01\,M_\odot & (10^{-3} - 10^{-1}\,M_\odot) \\ v \sim 0.1\,c & (0.05 - 0.3\,c) \\ t \sim 1\,\text{day} & (0.1 - 100\,\text{days}) \end{cases}$$

$$\left(\begin{aligned} M_{0.01} &= \frac{M}{0.01\,M_\odot} \\ v_{0.1} &= \frac{v}{0.1\,c} \\ t_d &= \frac{t}{1\,d} \end{aligned} \right)$$

· Radius

$$R \sim vt \sim (0.1 \times 3 \times 10^{10}) \cdot 10^5$$

$$\sim 3 \times 10^{14}\,\text{cm}\; v_{0.1}\, \underline{t_d}$$

$$1\,\text{AU} \sim 1.5 \times 10^{13}\,\text{cm}$$

(sun - earth)

· Density $\quad M = \frac{4}{3}\pi R^3 \rho$ (homogeneous)

$$\rho \sim \frac{3M}{4\pi} R^{-3}$$

$$\sim \frac{3}{4\pi}\left(10^{-2} \cdot 2\times 10^{33}\right) \frac{1}{(3\times 10^{14})^3}$$

$$\sim 2\times 10^{-13}\ \mathrm{g\ cm^{-3}}\ M_{0.01}\, v_{0.1}^{-3}\, t_d^{-3}$$

$$\rho_{NS} \sim 10^{14}\ \mathrm{g\ cm^{-3}}$$

$$n \sim \frac{\rho}{A m_p} \sim \frac{10^{-13}}{100\ 10^{-24}} \sim 10^{9}\ \mathrm{cm^{-3}}\ @\ 1\,d$$

A ↑ mass number

· Radioactive luminosity

$$L \sim M \dot{q} \leftarrow \mathrm{erg\,s^{-1}\,g^{-1}}$$

$$\sim 10^{-2} \cdot 2\times10^{33} \cdot 2\times10^{10}$$

$$\sim 4\times10^{41}\,\mathrm{erg\,s^{-1}}\, M_{0.01}\, t_d^{-1.3}$$

$\dot{q} \sim 2\times10^{10}\, t_d^{-1.3}$ $\mathrm{erg\,s^{-1}\,g^{-1}}$

(γ, β, ν)

· Effective temperature $L \sim 4\pi R^2 \sigma T^4$

$\uparrow$ Stefan-Boltzmann $\sim 6\times10^{-5}$ $\mathrm{erg\,s^{-1}\,cm^{-2}\,K^{-4}}$

$$T^4 \sim \frac{L}{4\pi R^2 \sigma}$$

$$\sim \frac{4\times10^{41}}{4\pi(3\times10^{14})^2\ 6\times10^{-5}} \sim 10^{16}$$

$T \sim 10^4\,K$ $\leftarrow$ gas is partially ionized

NS merger ejecta : rapidly expanding, metal-dominant and partially ionized gas

γ- rays (~MeV)

γ-rays will escape

when $\tau \sim \kappa \rho R < 1$

$$\kappa \frac{3}{4\pi} \frac{M}{(ut)^3} ut < 1$$

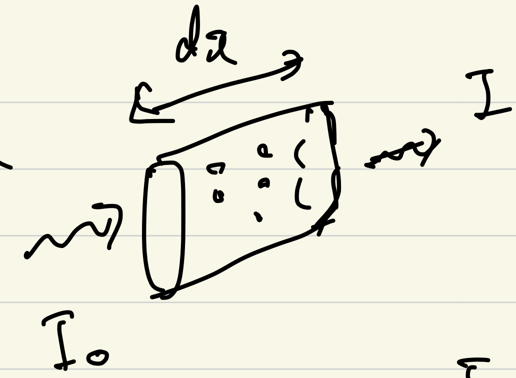
$$\rightarrow t > \left(\frac{3\kappa}{4\pi}\right)^{1/2} M^{1/2} u^{-1}$$

$$\sim \left(\frac{0.1}{4}\right)^{1/2} (2\times 10^{31})^{1/2} \frac{1}{3\times 10^{9}}$$

$$\sim 2\times 10^{5}\, s \sim 3\, \text{days}\, M_{0.01}^{1/2}\, u_{0.1}^{-1}$$

"heating" by γ-rays becomes inefficient at 3 days.

$$\tau = \int \underbrace{n}_{cm^{-3}} \underbrace{\sigma}_{cm^{2}} dx$$

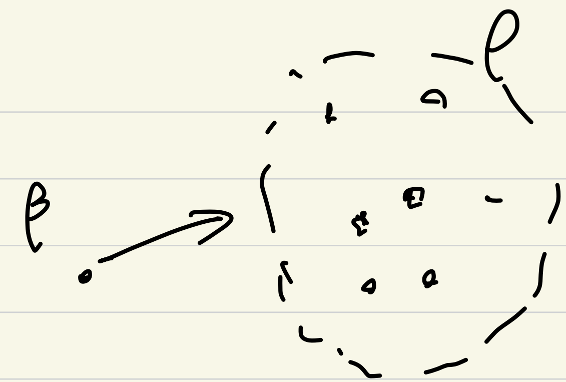


$$I = I_0 e^{-\tau}$$

$$\tau = \int \underbrace{\rho}_{g\,cm^{-3}} \underbrace{\kappa}_{cm^{2} g^{-1}} dx$$

$$\kappa_\gamma \sim 0.1\, cm^2 g^{-1}$$

β-particles (~MeV)



energy loss by ionization/excitation

$$\frac{\dot{E}}{\rho} \sim 4\times10^{10}\ \mathrm{MeV\ s^{-1}\ cm^{3}\ g^{-1}}$$

$$\rho \sim 2\times10^{-13}\ \mathrm{g\ cm^{-3}}\ M_{0.01}\, v_{0.1}^{-3}\, t_d^{-3}$$

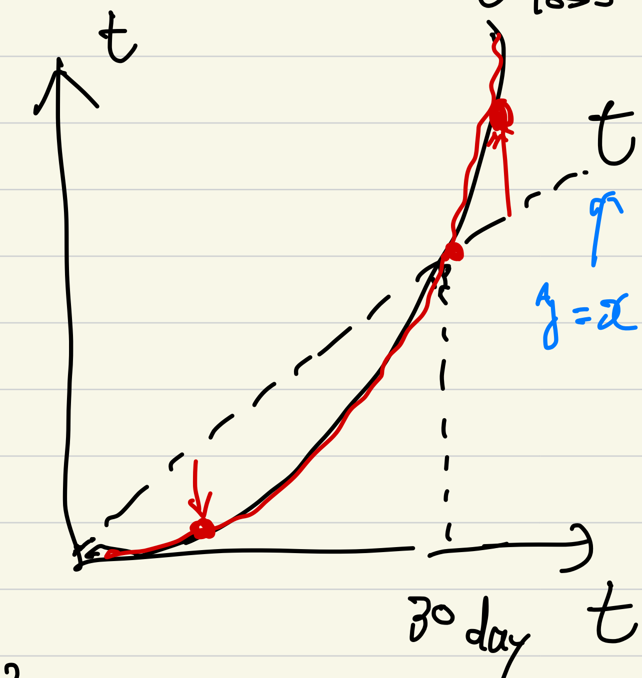
time to lose the energy

$$t_{loss} = \frac{E}{\dot{E}} \simeq \frac{1\ \mathrm{MeV}}{4\times10^{10}\,\rho\ \mathrm{MeV\ s^{-1}}}$$

$$\simeq \frac{1}{4\times10^{10}\cdot 2\times10^{-13}}$$

$$\simeq 10^{2}\ \mathrm{s} = 10^{-3}\ \mathrm{days}\ M_{0.01}^{-1}\, v_{0.1}^{3}\, t_d^{3}$$

$$t_{loss} \simeq 10^{-3}\,\text{days}\; M_{0.01}^{-1}\, u_{0.1}^{-3}\, t_d^{3}$$



e-particles cannot lose energy when $t_{loss} > t$

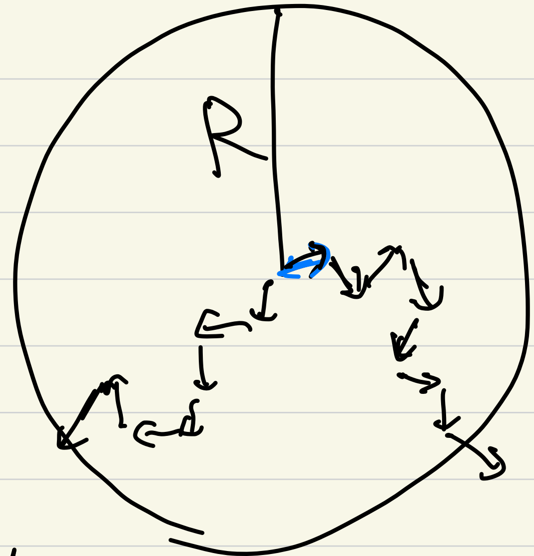
$$10^{-3} M_{0.01}^{-1} u_{0.1}^{3} t_d^{3} > t_d$$

$$\rightarrow t_d^{2} > \underset{\text{days}}{10^{3}} M_{0.01} u_{0.1}^{-3}$$

$$t_d \gtrsim 30\,\text{days}\; M_{0.01}^{1/2} u_{0.1}^{-3/2}$$

more efficient "heating" source

photon transfer



- Optical depth

$$\tau = \int \kappa\rho\, dx$$

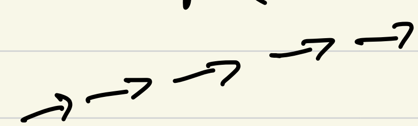
- mean free path ℓ (typical distance for interaction)

$$\tau = \kappa\rho\ell = 1$$

$$\rightarrow \ell = \frac{1}{\kappa\rho} \cdot [cm]$$

$cm^2\, g^{-1}$ $g\, cm^{-3}$

$N\ell$



- Random walk N interaction

$R = \sqrt{N}\,\ell$ $\leftarrow$ shorter than $N\ell$

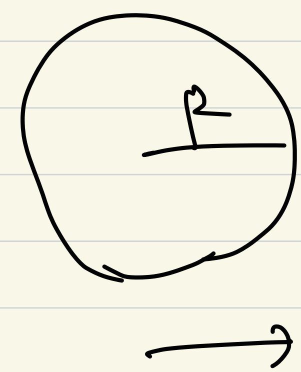
$$t_{esc} = \underbrace{\frac{\ell}{c}}_{\leftarrow \text{ time for 1 step}} N \simeq \frac{\ell}{c}\left(\frac{R}{\ell}\right)^2$$

$$= \frac{R}{c}\,\frac{R}{\ell} = \frac{R}{c}\,\underbrace{\kappa\rho R}_{\tau \text{ optical depth}}$$

$$\simeq \underbrace{\frac{R}{c}}_{\text{light crossing time}}\,\underline{\tau}$$

$$R = \sqrt{N}\,\ell$$

$$\ell = \frac{1}{\kappa\rho}$$



Escape time for NS merger ejecta

$$t_{esc} = \frac{R}{c}\kappa\rho R \qquad \rho \propto R^{-3}$$

$$= \frac{\kappa}{c}\frac{3M}{4\pi}R^{-1} = \frac{3\kappa}{4\pi c} M u^{-1} t^{-1}$$

$M = \frac{4}{3}\pi R^3 \rho$

$R = ut$

① $t_{esc} > t \Rightarrow$ no escape

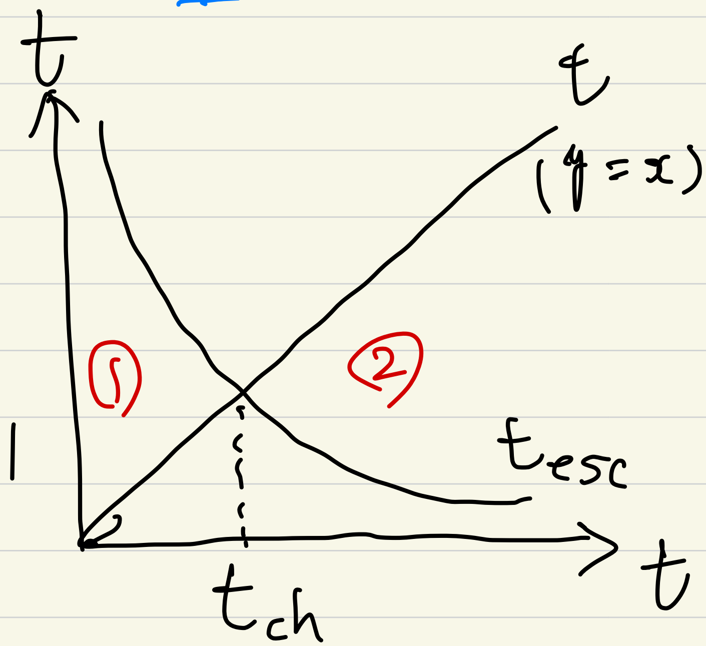
② $t_{esc} < t \Rightarrow$ escape

optical depth

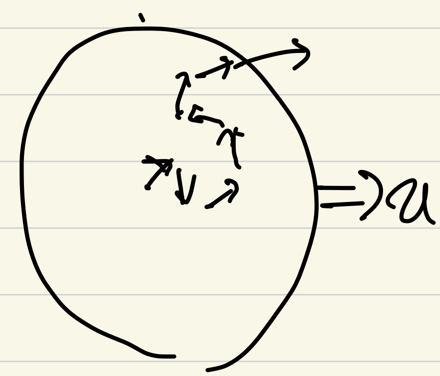
$\tau = \kappa\rho R$

$\propto \kappa R^{-3} R \propto R^{-2}$

different from $\tau < 1$



homologous expansion



κ : opacity

$cm^2\, g^{-1}$

$$t_{esc} = \frac{3\kappa}{4\pi c} M v^{-1} t^{-1}$$

Characteristic time

$$t_{esc} = t$$

$$\rightarrow \quad t_{ch}^2 = \frac{3\kappa}{4\pi c} M v^{-1}$$

$\kappa = 1\ cm^2 g^{-1}$

bound-bound transition

$$t_{ch} = \left(\frac{3}{4\pi c}\right)^{1/2} \kappa^{1/2} M^{1/2} v^{-1/2}$$

$\begin{cases} M = 10^{-2} M_{\odot} \\ v = 0.1c \end{cases}$

$$\sim \left(\frac{1}{4\ 3\times10^{10}}\right)^{1/2} \left(\frac{2\times10^{31}}{3\times10^{9}}\right)^{1/2}$$

longer for

$$\sim 3\times10^{5}\ s$$

$\left(\begin{array}{l} \text{higher } \kappa \\ \text{higher } M \\ \text{lower } v \end{array} \right.$

$$\sim 4\ \text{days}\ \kappa_1^{1/2} M_{0.01}^{1/2} v_{0.1}^{-1/2}$$

$\dot{q} \propto t^{-1.3}$

luminosity at $t = t_{ch}$

fraction of energy deposition

$$L_{ch} = M \, \dot{q}(t_{ch}) \underbrace{f_{dep}}_{0.5}$$

$f_{dep} < 1$

$$\simeq 3 \times 10^{40} \, \mathrm{erg\,s^{-1}} \, M_{0.01}^{0.35} \, u_{0.1}^{0.65} \, \kappa_1^{-0.65}$$

brighter for smaller κ $\leftrightarrow$ smaller t_{ch}

higher u $\leftrightarrow$

higher M $\leftrightarrow$ ~~longer t_{ch}~~

$L \propto \underbrace{M}_{\text{wins}} \dot{q}$