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Hydrogen-rich Supernovae under energy injection by central heating source

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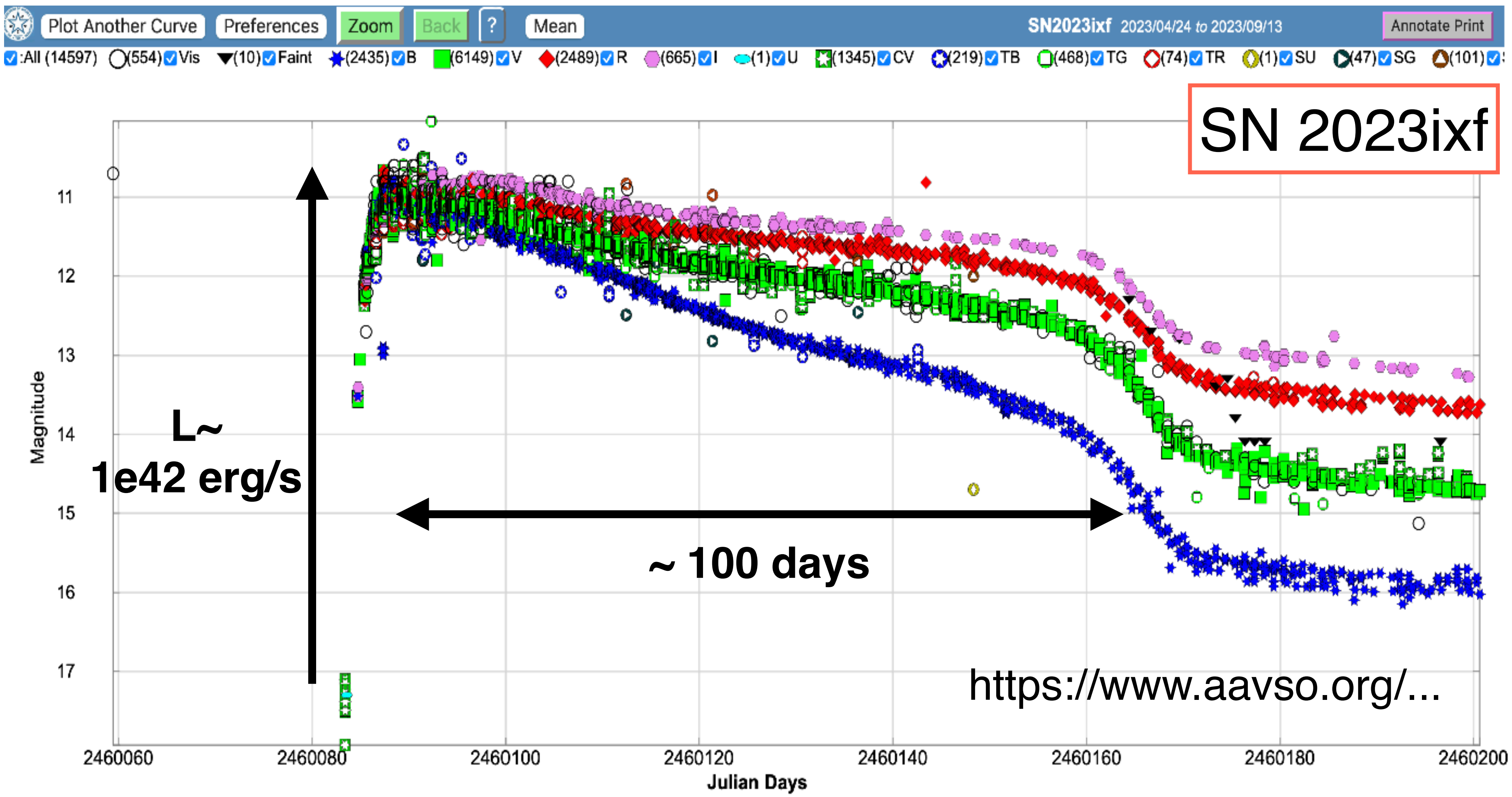
arXiv2401.13731

Hydrogen-rich Supernovae

Hydrogen in spectrum & Plateau in light curve

=> Type IIP supernovae



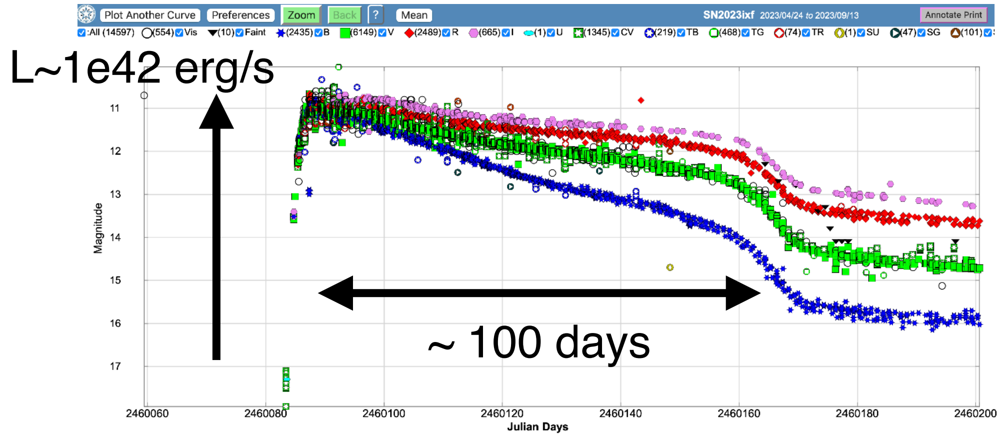
Explosion of red supergiants

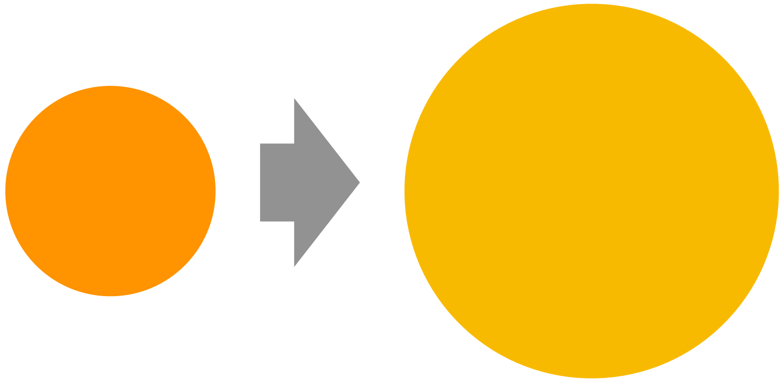
Basics of SN

1st law of thermodynamics

$$\frac{dE}{dt} = -P\frac{dV}{dt} - L$$

- $P \sim P_{\rm rad} = E/3V,\ V \sim (vt)^3$
- $L \simeq \frac{tE}{t_{\rm diff}^2}$
- $t_{\rm diff} = \left(\frac{3\kappa M}{4\pi c v}\right)^{1/2}$





Basics of SN

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$$\frac{dE}{dt} = -\frac{E}{t} - \frac{tE}{t_{\rm diff}^2}$$

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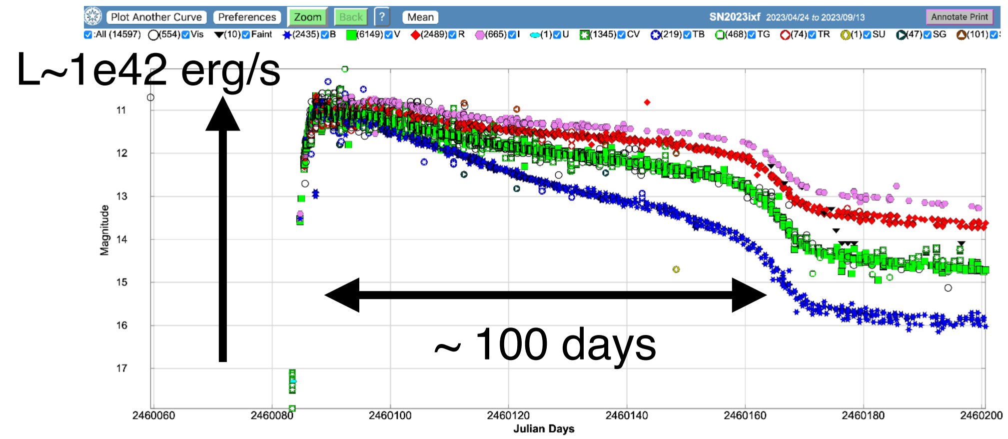

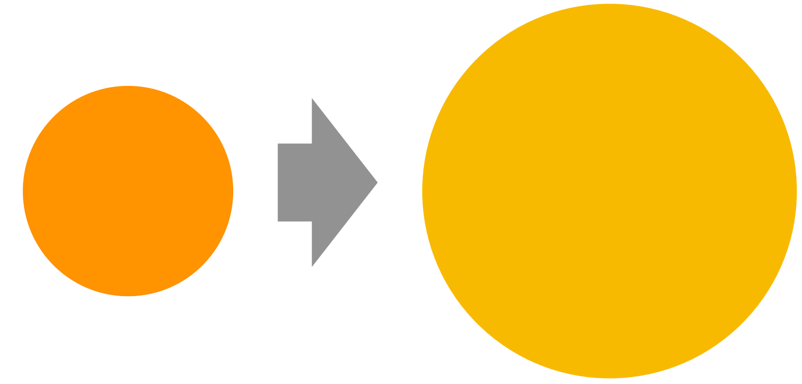

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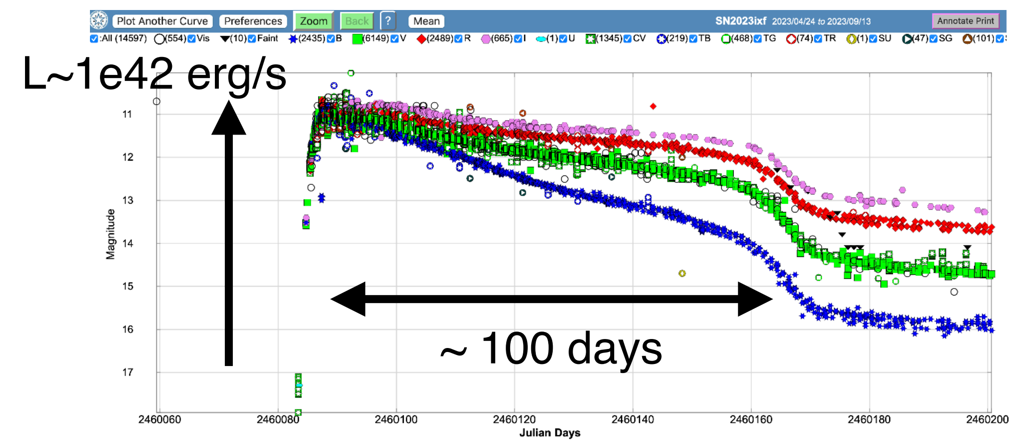
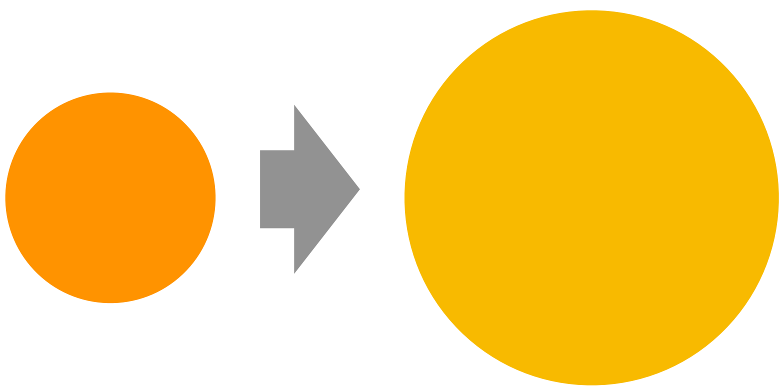
- ✦ $t_{\rm diff} = \left(\frac{3\kappa M}{4\pi c v}\right)^{1/2} \simeq 100\,{\rm day}$

$$L \simeq \frac{t_0 E_{\rm SN}}{t_{\rm diff}^2} e^{-t^2/t_{\rm diff}^2} \sim 10^{42}\,{\rm erg\,s^{-1}}$$

$$t_{\rm pl} \propto E_{\rm SN}^{-1/4} M^{3/4}$$

$$L_{\rm pl} \propto R_0 E_{\rm SN} M^{-1}$$





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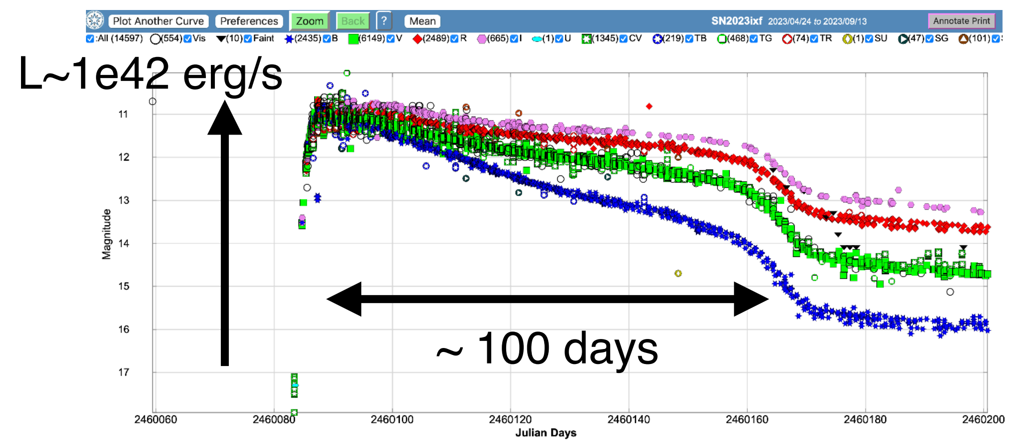
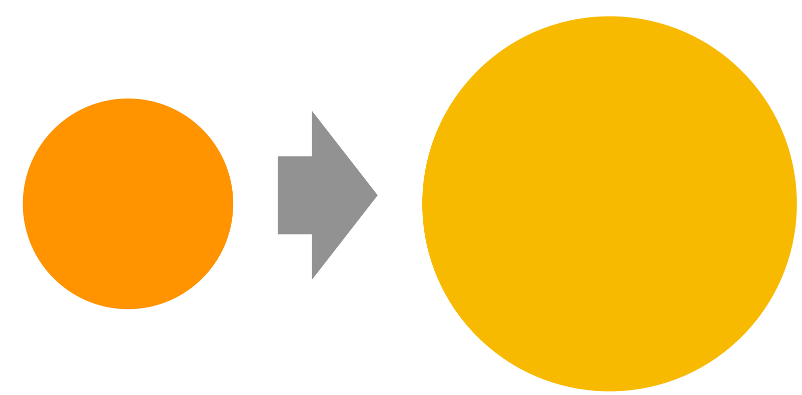
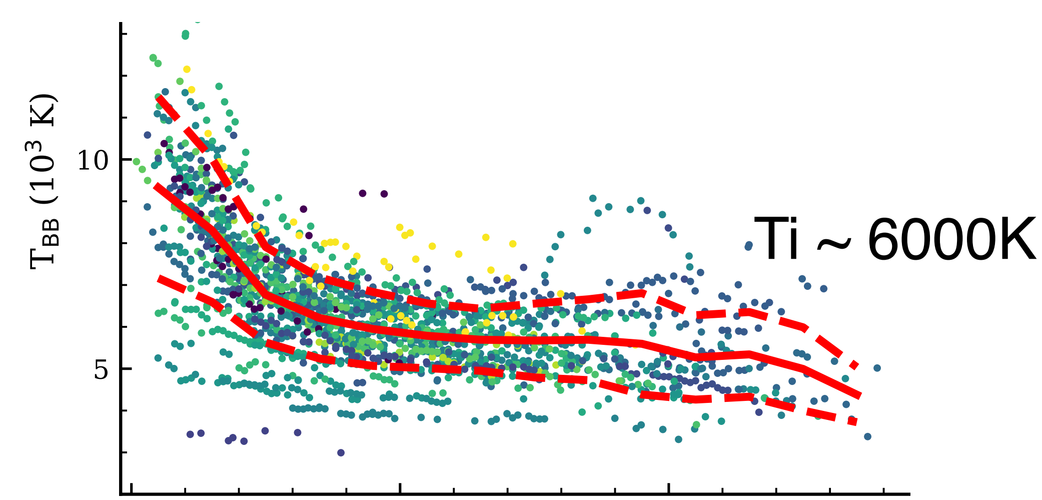
$$t_{\rm pl} \propto E_{\rm SN}^{-1/4} M^{3/4}$$
$$L_{\rm pl} \propto R_0 E_{\rm SN} M^{-1}$$

$T_{\rm eff} \sim (L/R^2)^{1/4} \propto t^{-1/2}$ is inconsistent with observations

=> H recombination plays a role





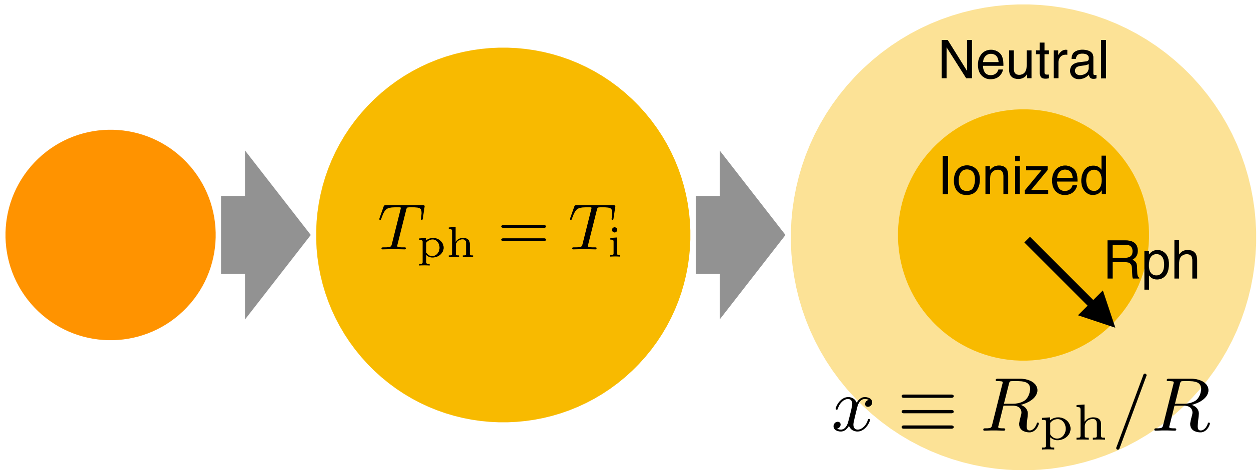


Martinez+22

Basics of IIP SN

1st law of thermodynamics

$$\frac{dE}{dt} = -\frac{E}{t} - \frac{tE}{t_{\mathrm{diff}}^2}$$



Basics of IIP SN

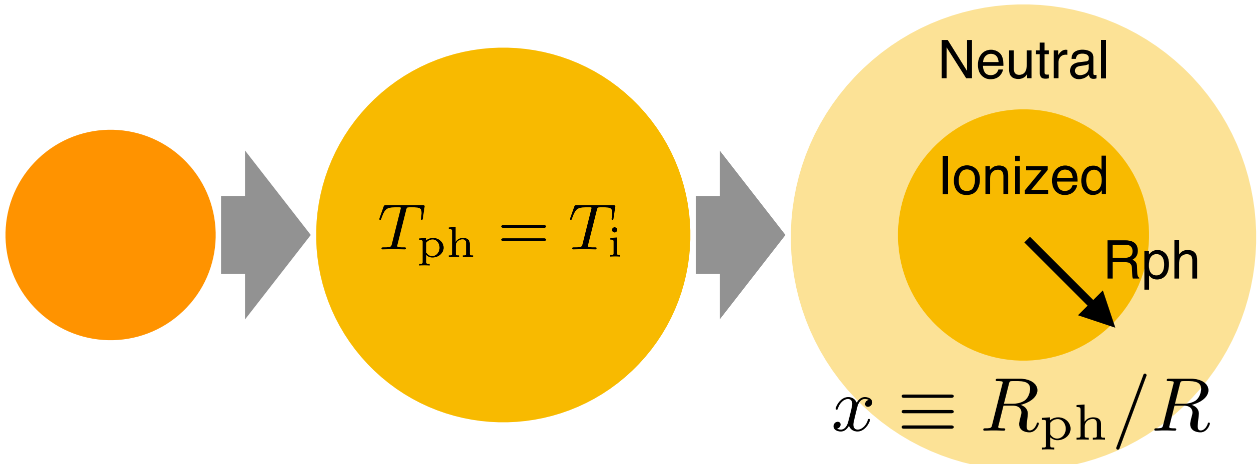
1st law of thermodynamics

$$\frac{dE}{dt} = -\frac{E}{t} - \frac{tE}{t_{\rm diff}^2}$$

$T_{\rm ph} = T_{\rm i}$

✦ $V \sim (xR)^3$

✦ $L \simeq \frac{tE}{t_{\rm diff}^2} \propto (xR)^2 T_{\rm i}^4$



Basics of IIP SN

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$$\frac{dE}{dt} = -\frac{E}{t} - \frac{tE}{t_{\rm diff}^2}$$

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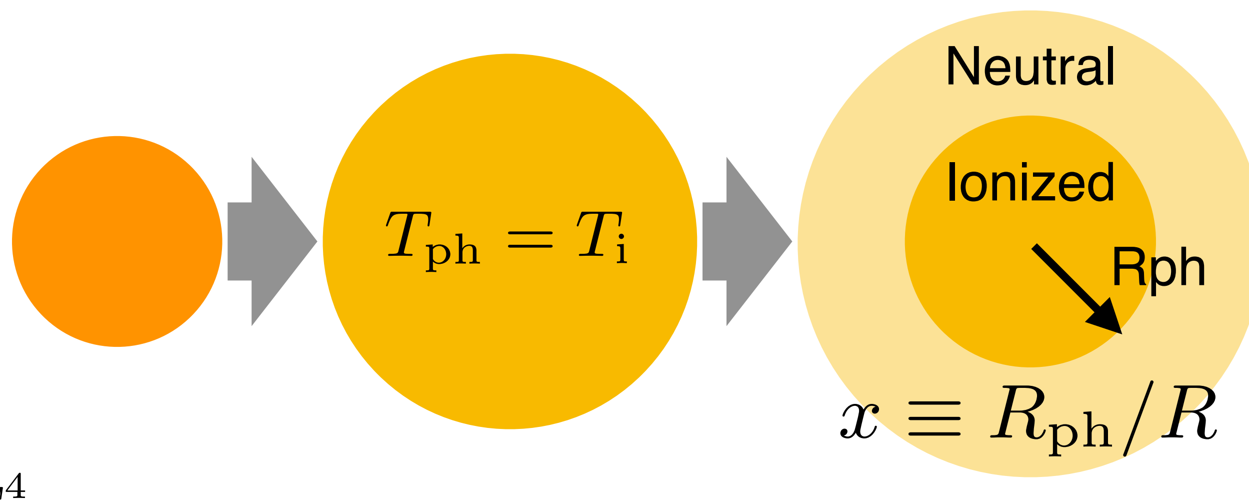
- ✦ $V \sim (xR)^3$
- ✦ $L \simeq \frac{tE}{t_{\rm diff}^2} \propto (xR)^2 T_{\rm i}^4$

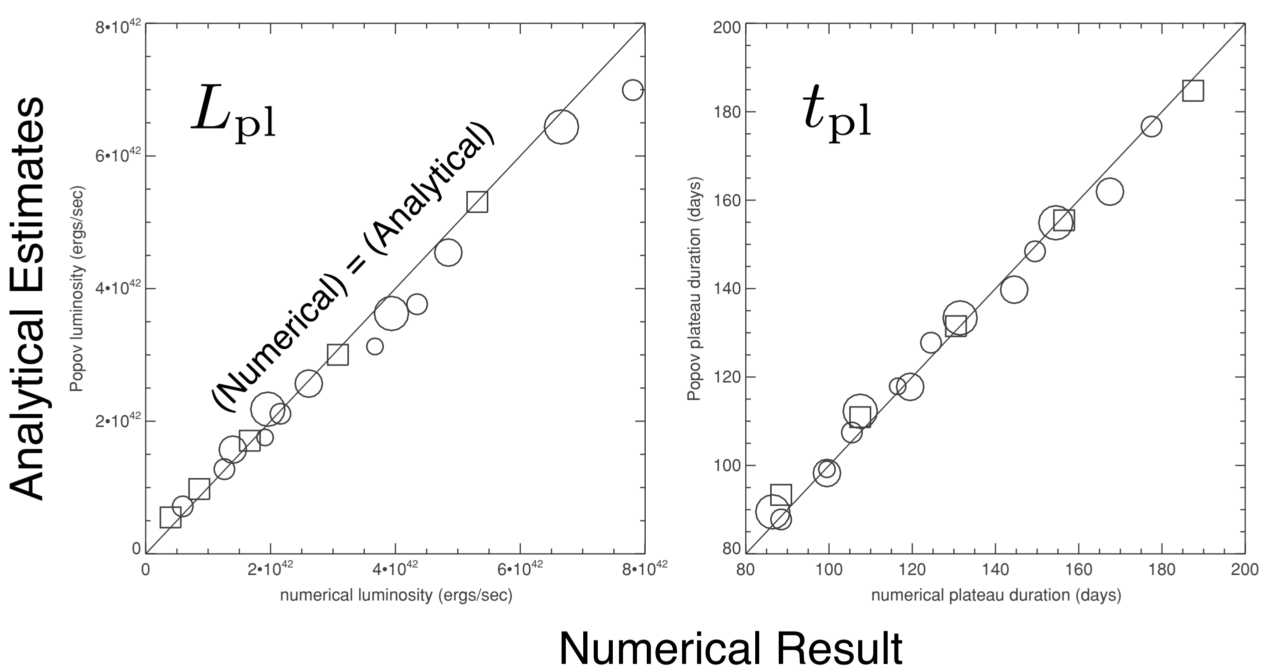
$$\frac{dx}{dt} = -\frac{2x}{5t} - \frac{t}{5t_{\rm diff}^2 x}$$

$$t_{\rm pl} \propto R_0^{1/7} E_{\rm SN}^{-5/28} M^{15/28}$$

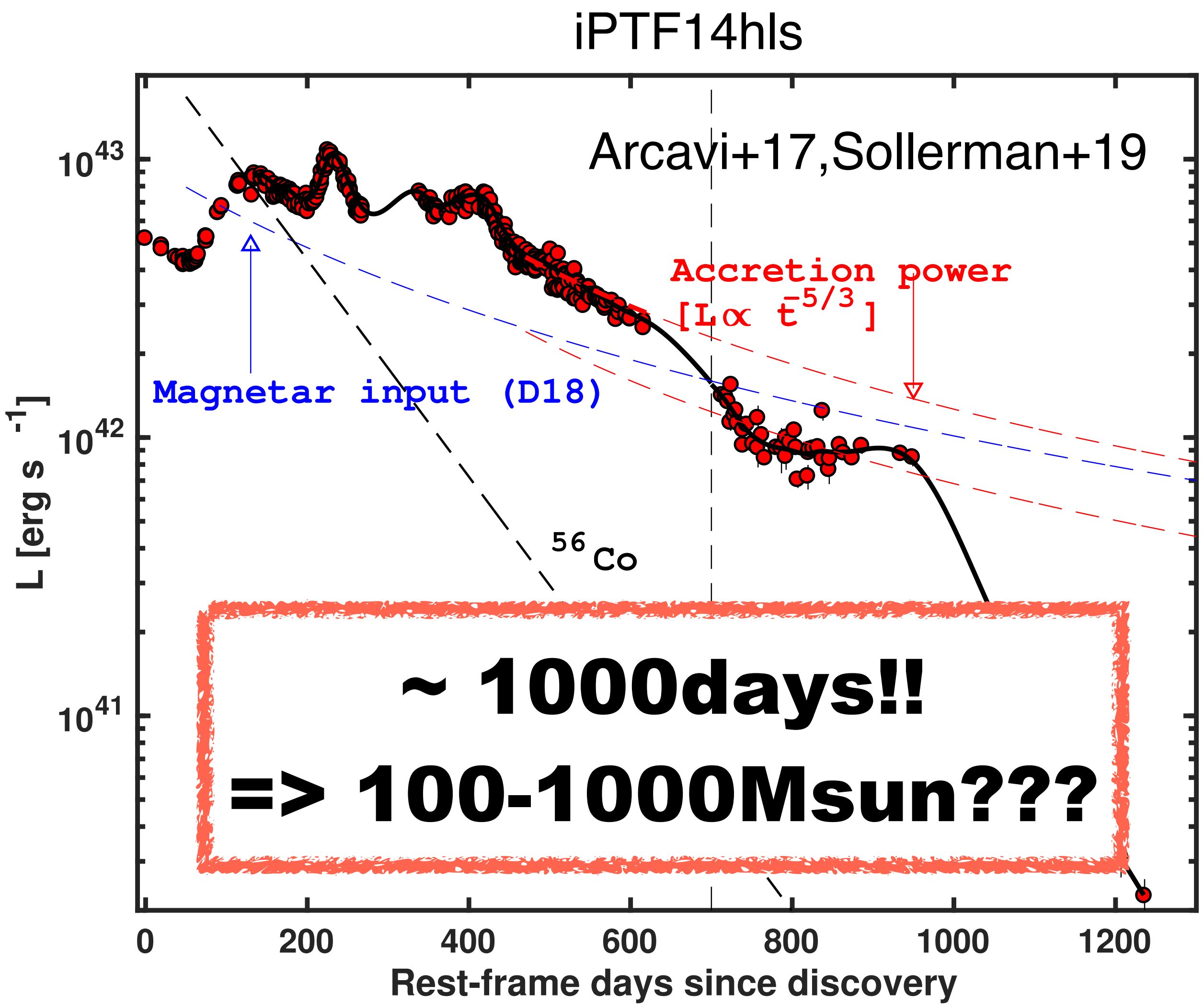
$$L_{\rm pl} \propto R_0^{4/7} E_{\rm SN}^{11/14} M^{-5/14}$$

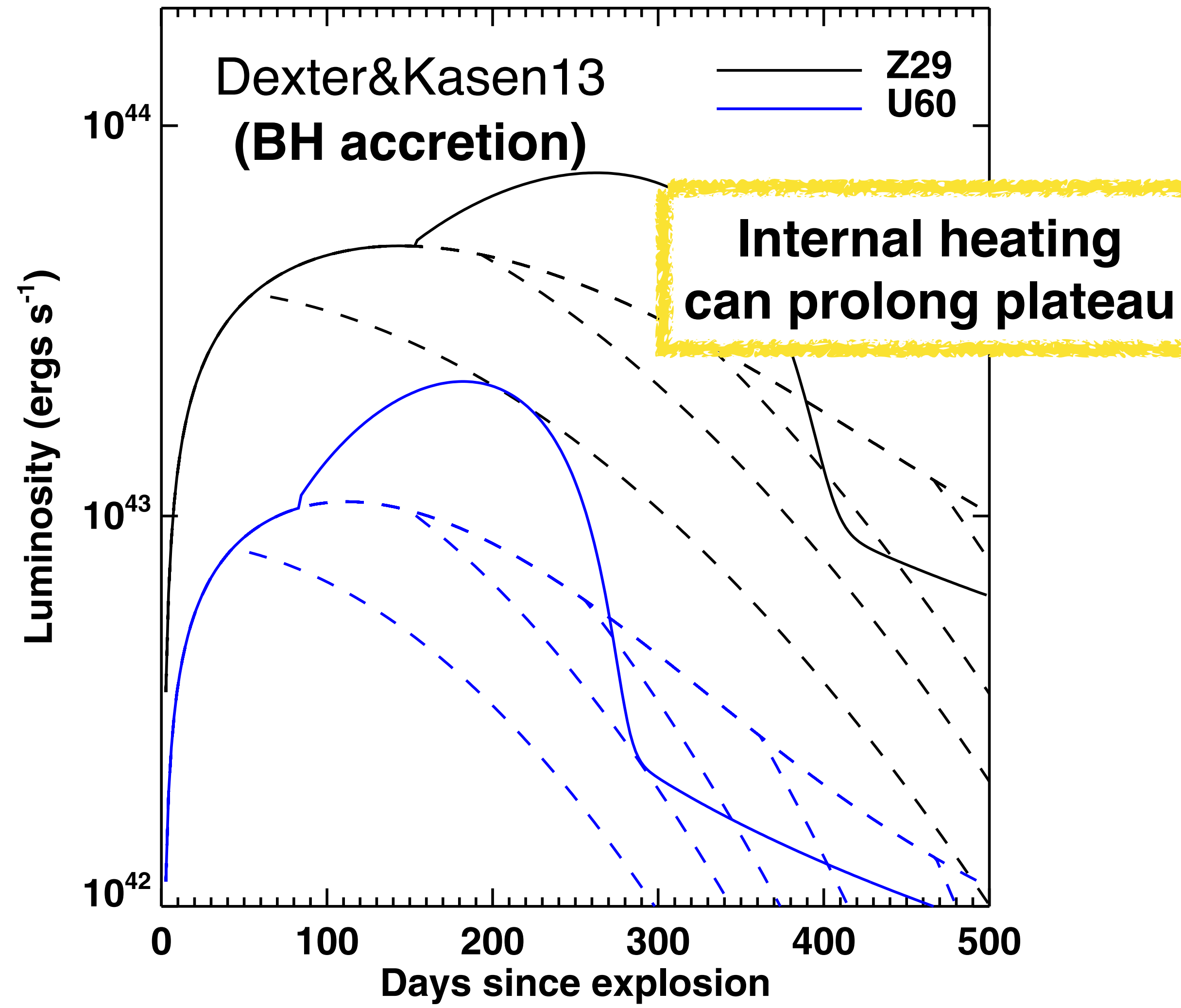


Kasen&Woosley09



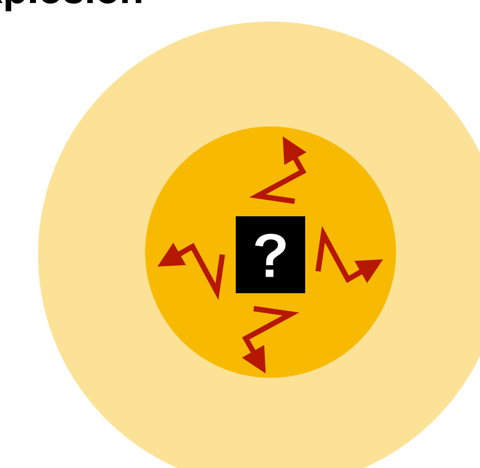
Very long Plateau = Very massive star?



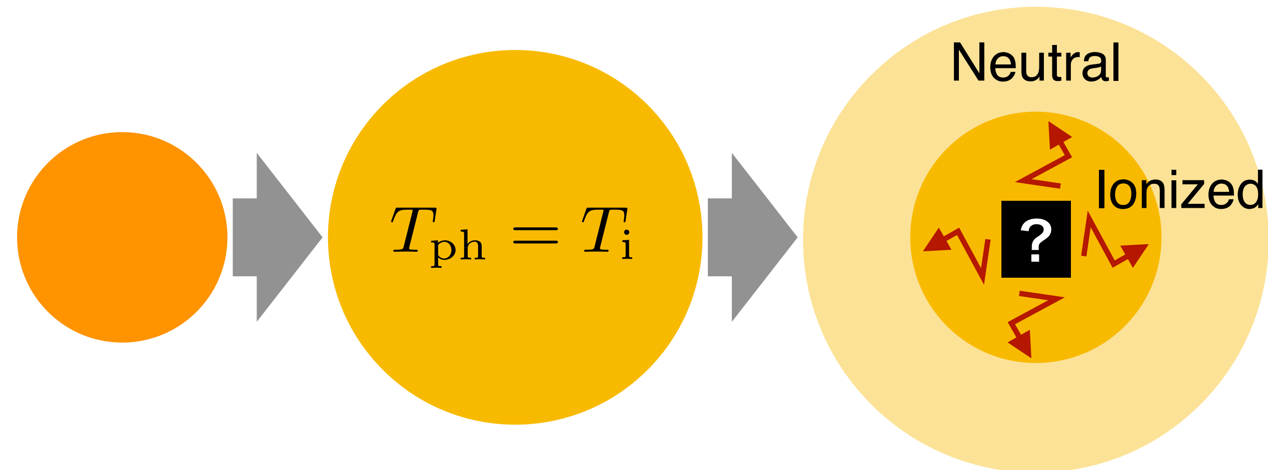


$$t_{\rm pl} \propto R_0^{1/7} E_{\rm SN}^{-5/28} M^{15/28}$$

We study internal heating effects on plateau duration



Method



1st law of thermodynamics

$$\frac{dE}{dt} = -\frac{E}{t} - \frac{tE}{t_{\rm diff}^2} + H$$

$T_{\rm ph} = T_{\rm i}$

$$\frac{dx}{dt} = -\frac{2x}{5t} - \frac{t}{5t_{\rm diff}^2 x} + \frac{H}{5H_{\rm cr}}\frac{1}{tx^3}$$

EoM

$$M\frac{dv}{dt} \simeq 4\pi R^2 P$$

$$H_{\rm cr} = 4\pi (v t_{\rm diff})^2 \sigma T_{\rm i}^4 \simeq 3.00 \times 10^{43}\,{\rm erg\,s^{-1}}\, M_{10} v_{6000} T_{\rm i,6000}^4$$

Heating source

i) H= const (Toy model)

ii) Nickel (ordinary type IIP) $H(t) = M_{\rm Ni}\left[(\varepsilon_{\rm Ni} - \varepsilon_{\rm Co})\, e^{-t/t_{\rm Ni}} + \varepsilon_{\rm Co} e^{-t/t_{\rm Co}}\right] f_\gamma(t)$

$$f_\gamma(t) \equiv (1 - e^{-x\tau_\gamma})\ ,$$

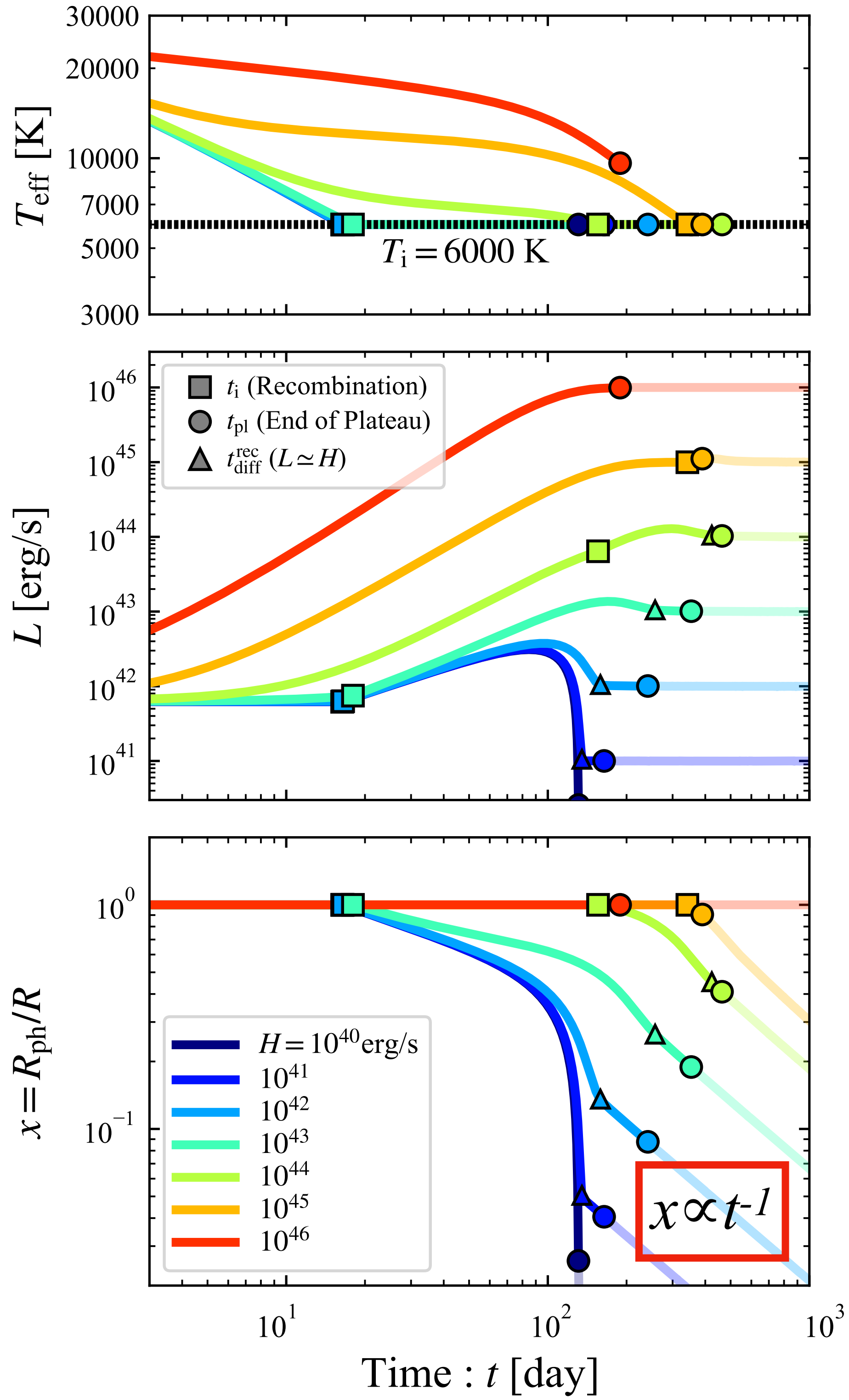
$$\tau_\gamma = \kappa_\gamma \rho R \simeq 5.33\, M_{10} v_{6000}^{-2} \left(\frac{t}{100\,{\rm day}}\right)^{-2}$$

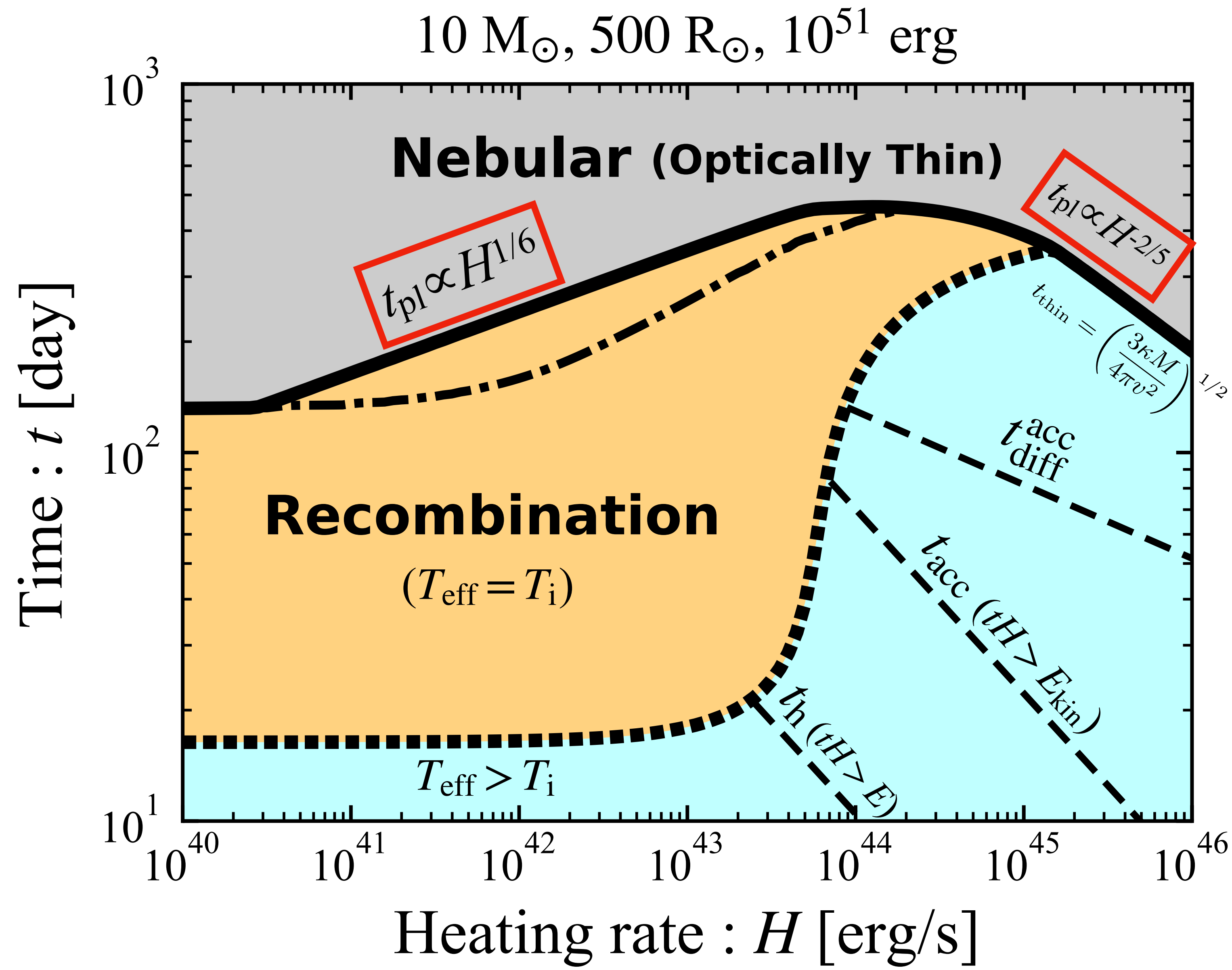
iii) Magnetar $H(t) \simeq L_{\rm sd} \simeq \frac{E_{\rm rot}}{t_{\rm sd}}\left(1 + \frac{t}{t_{\rm sd}}\right)^{-2}$

iv) Shock Interaction

Results

H=const (Toy model)





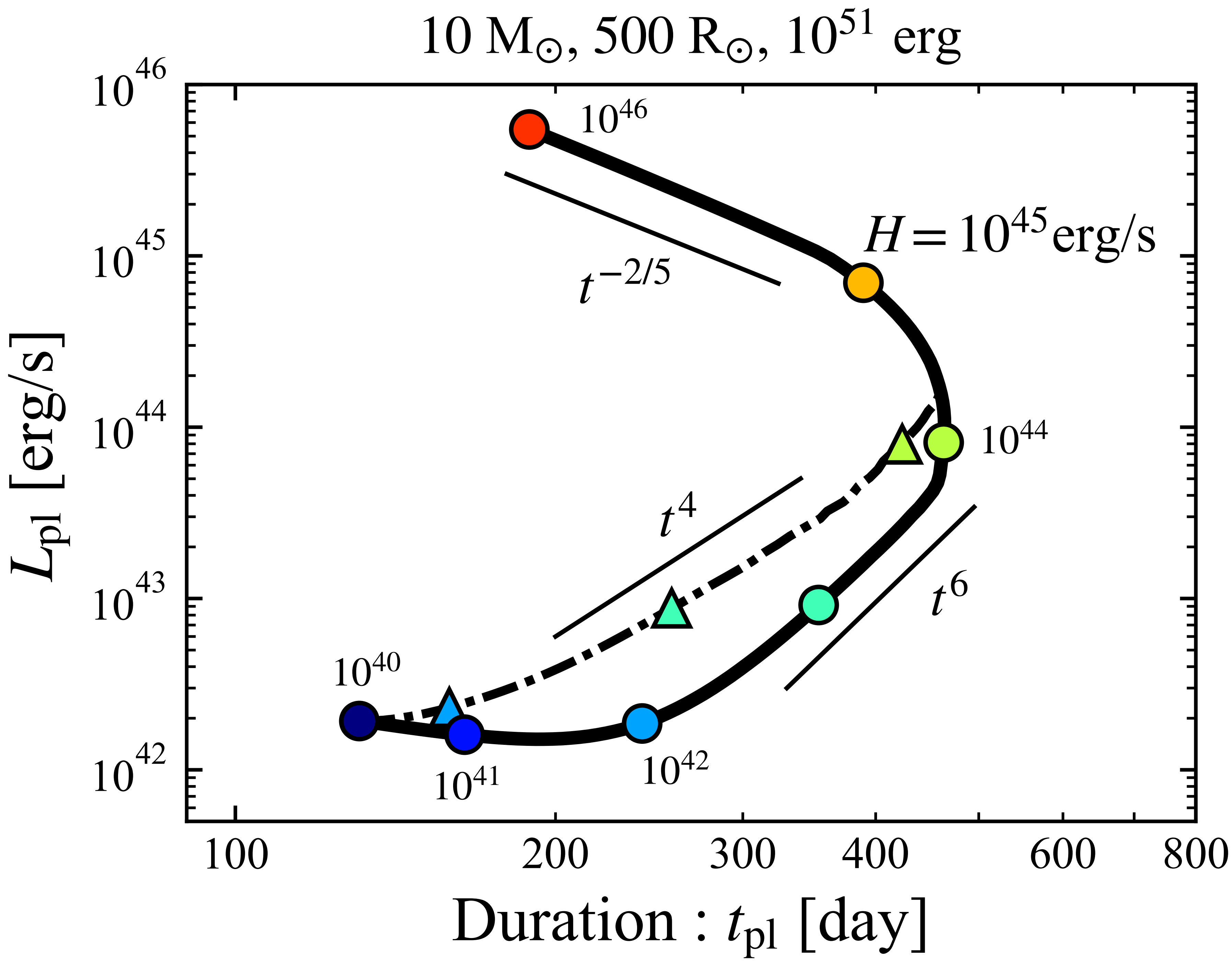
Longest plateau for maximal heating rate which **does not accelerate** ejecta

$$H_{\rm max} = \left(\frac{3\pi c v^5 M}{5^2 \kappa}\right)^{1/2} \simeq 2.27 \times 10^{44}\,{\rm erg\,s^{-1}}\, M_{10}^{1/2} v_{6000}^{5/2}$$

$$t_{\rm pl,max} = \left(\frac{3^5 \kappa^3 c M^5}{2^{12} 5^2 \pi^5 (\sigma_{\rm SB} T_{\rm i}^4)^2 v^7}\right)^{1/12} \simeq 568\,{\rm day}\, T_{\rm i,6k}^{-2/3} M_{10}^{5/12} v_{6000}^{-7/12},$$

Results

H=const (Toy model)



$$L_{\rm pl} \equiv \frac{\int^{t_{\rm pl}} L dt}{t_{\rm pl}}$$

Results

Ni heating (=Normal SNe)

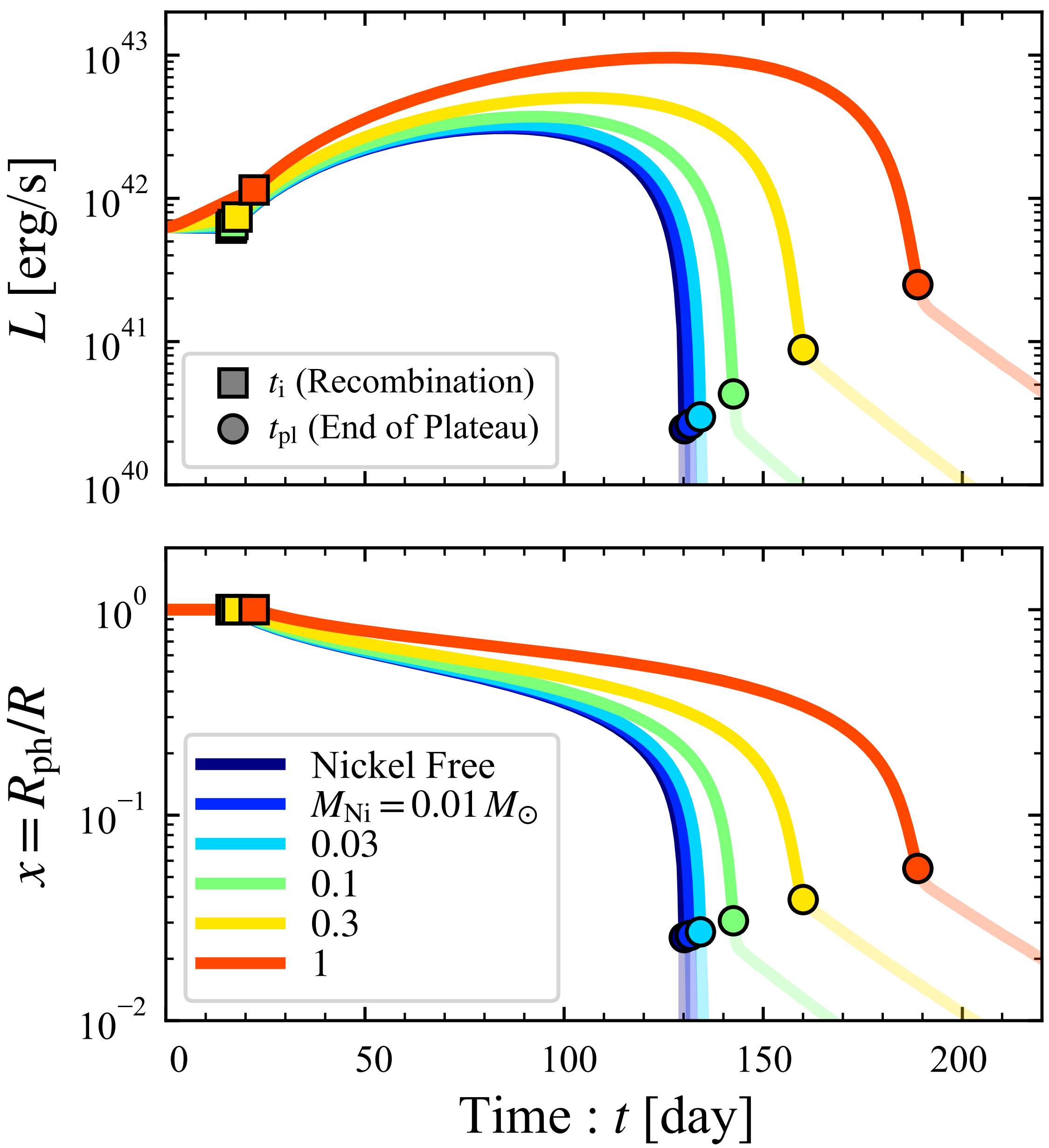
$$H(t) = M_{\rm Ni}\left[(\varepsilon_{\rm Ni}-\varepsilon_{\rm Co})\,e^{-t/t_{\rm Ni}}+\varepsilon_{\rm Co}e^{-t/t_{\rm Co}}\right]f_\gamma(t)$$

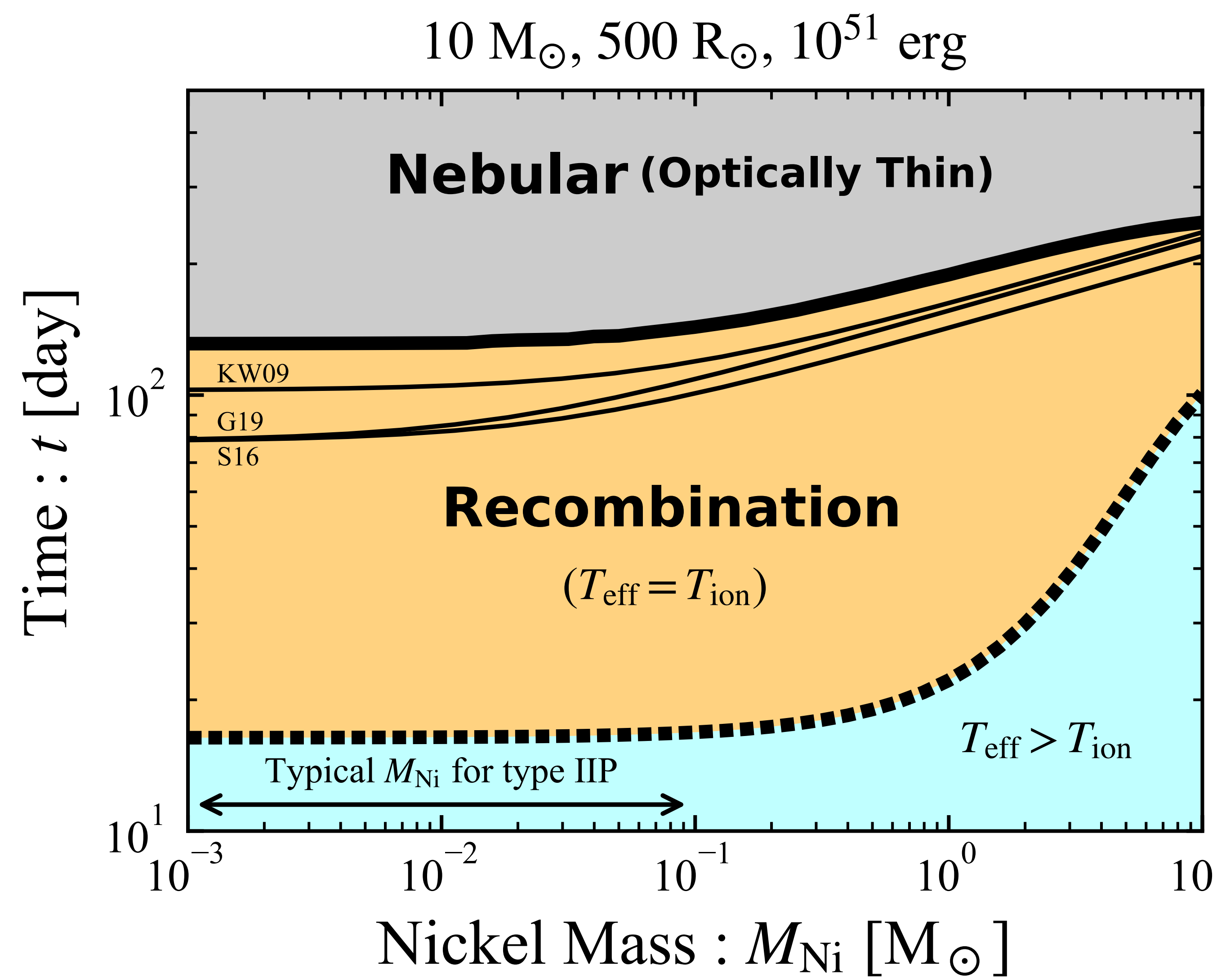
$$f_\gamma(t) \equiv (1-e^{-x\tau_\gamma})\,,$$

$$\tau_\gamma = \kappa_\gamma \rho R \simeq 5.33\,M_{10} v_{6000}^{-2}\left(\frac{t}{100\,\rm day}\right)^{-2}$$

No acceleration

$$E_{\rm Ni} \equiv \int_{t_0}^{\infty} H(t, M_{\rm Ni})dt \simeq 1.80\times10^{50}\,{\rm erg}\,M_{\rm Ni,1}$$

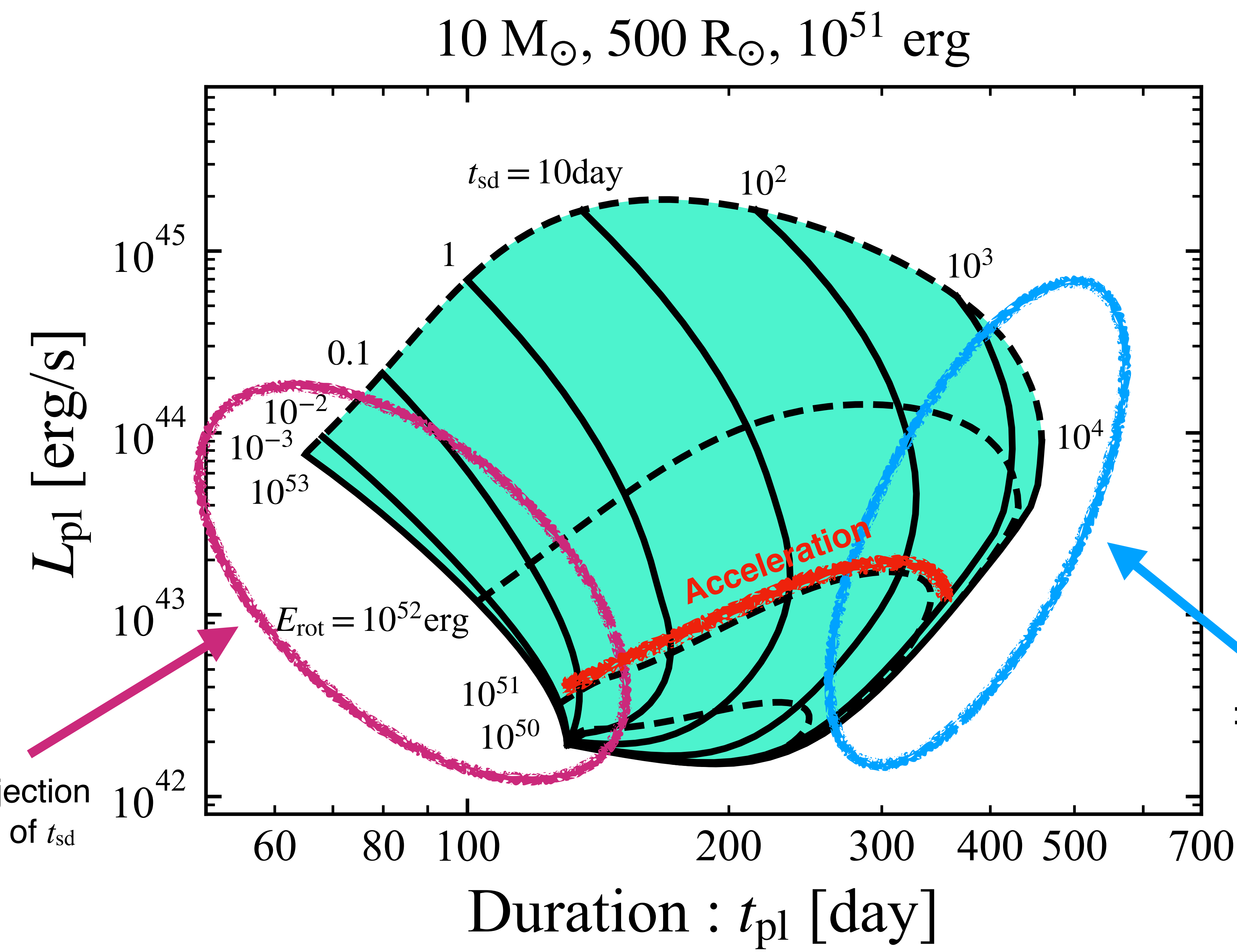




Results

Magnetar

$$H(t) \simeq L_{\rm sd} \simeq \frac{E_{\rm rot}}{t_{\rm sd}}\left(1+\frac{t}{t_{\rm sd}}\right)^{-2} \qquad \int_0^\infty H(t)dt = E_{\rm rot}$$



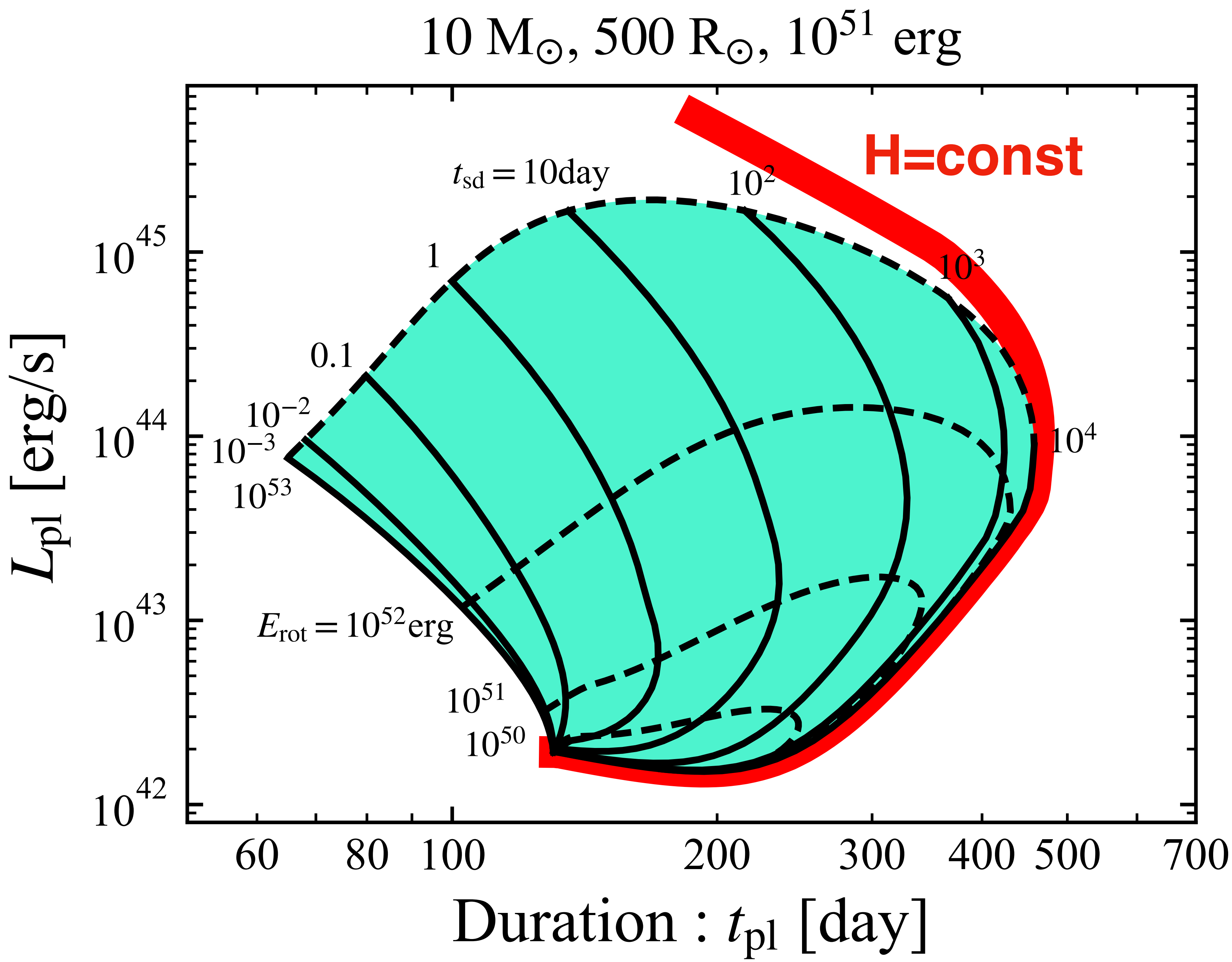
Instantaneous injection
=> Independent of $t_{\rm sd}$

$t_{\rm sd} >> t_{\rm pl}$
:Practically H=const

Results

Magnetar

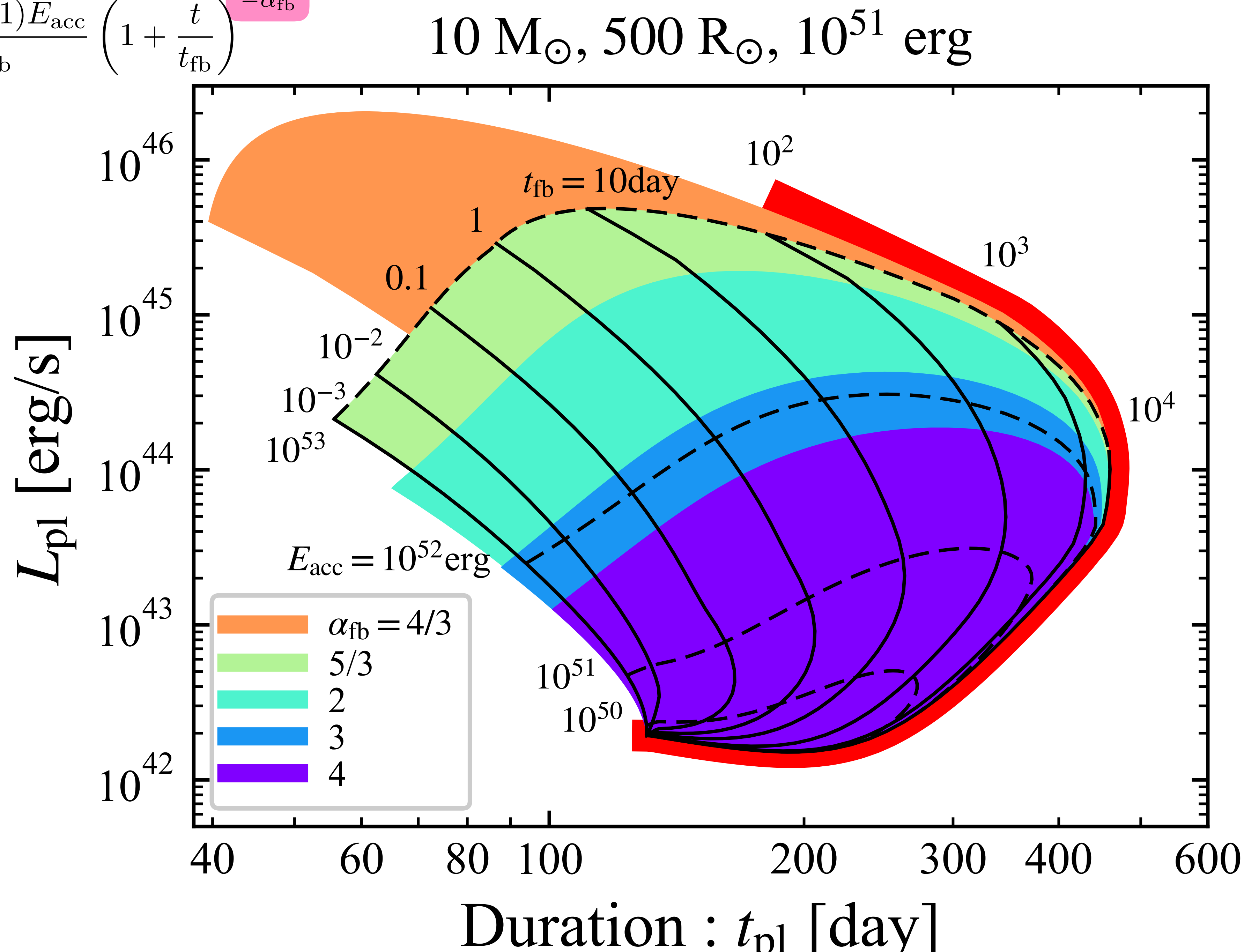
$$H(t) \simeq L_{\rm sd} \simeq \frac{E_{\rm rot}}{t_{\rm sd}}\left(1+\frac{t}{t_{\rm sd}}\right)^{-2} \qquad \int_0^\infty H(t)dt = E_{\rm rot}$$



Results

Magnetar => General Engine

$$H(t) = \frac{(\alpha_{\rm fb}-1)E_{\rm acc}}{t_{\rm fb}}\left(1+\frac{t}{t_{\rm fb}}\right)^{-\alpha_{\rm fb}}$$

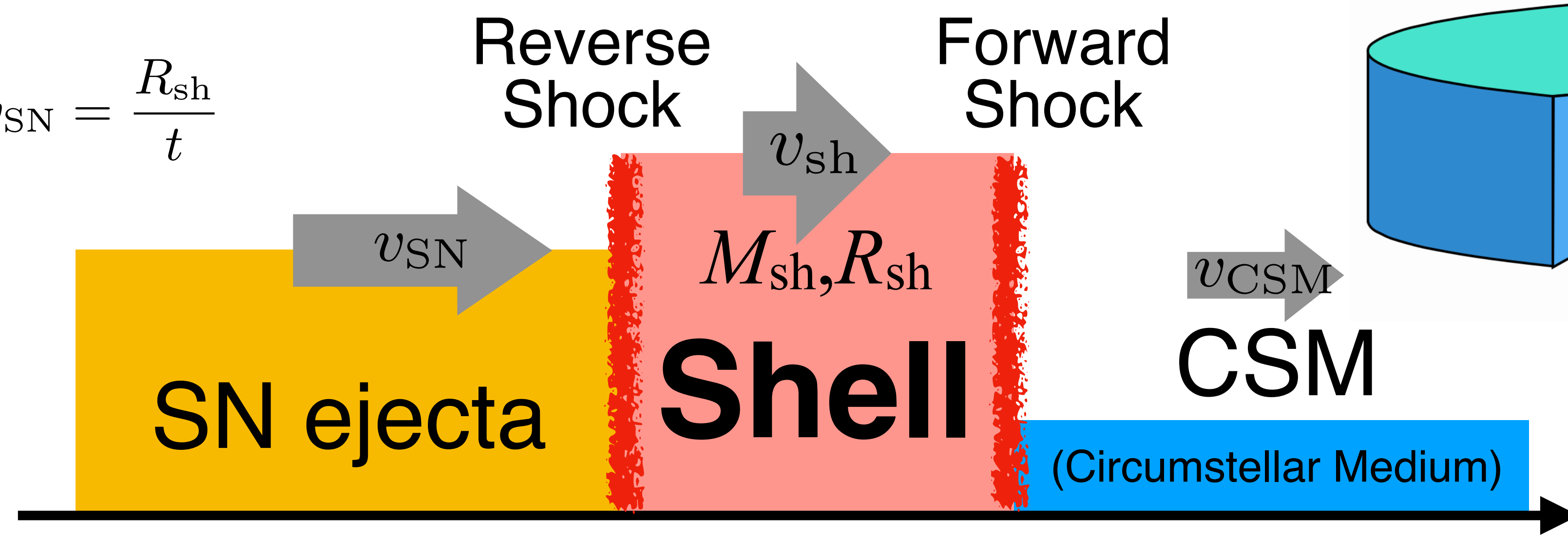


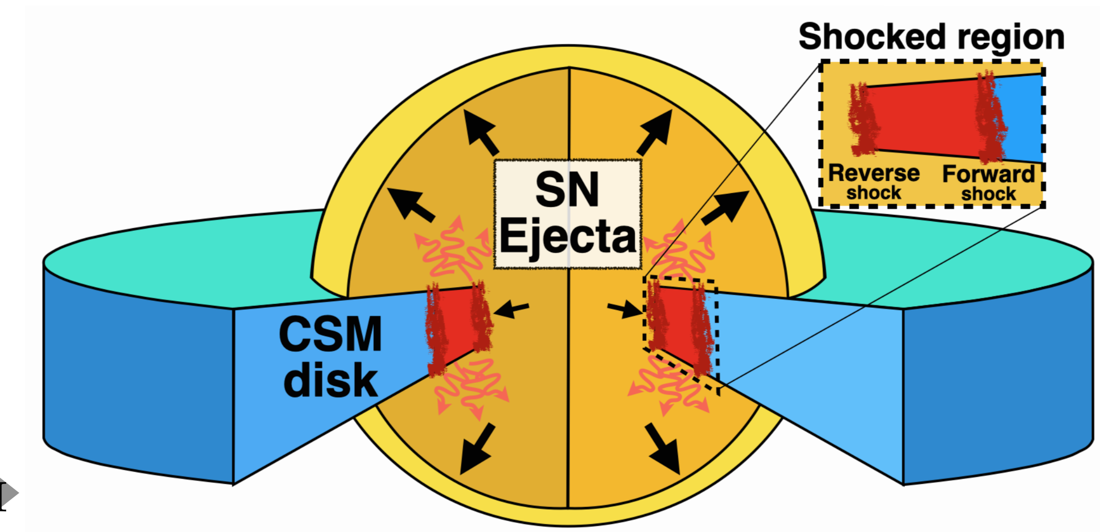
Temporally-constant heating model gives an absolute boundary of attainable plateau duration

Shock Interaction

$$\rho_{\rm CSM} = Ar^{-q}$$

$$v_{\rm SN} = \frac{R_{\rm sh}}{t}$$





$$M_{\rm sh}\frac{dv_{\rm sh}}{dt} = 4\pi R_{\rm sh}^2 \rho_{\rm SN}(v_{\rm SN} - v_{\rm sh})^2 - 4\pi R_{\rm sh}^2 \rho_{\rm CSM}(v_{\rm sh} - v_{\rm CSM})^2$$

$$\frac{dM_{\rm sh}}{dt} = 4\pi R_{\rm sh}^2 \rho_{\rm SN}(v_{\rm SN} - v_{\rm sh}) + 4\pi R_{\rm sh}^2 \rho_{\rm CSM}(v_{\rm sh} - v_{\rm CSM})$$

$$L_{\rm FS} \sim 4\pi R_{\rm sh}^2 \rho_{\rm CSM}(v_{\rm sh} - v_{\rm CSM})^3$$

$$L_{\rm RS} \sim 4\pi R_{\rm sh}^2 \rho_{\rm SN}(v_{\rm SN} - v_{\rm sh})^3$$

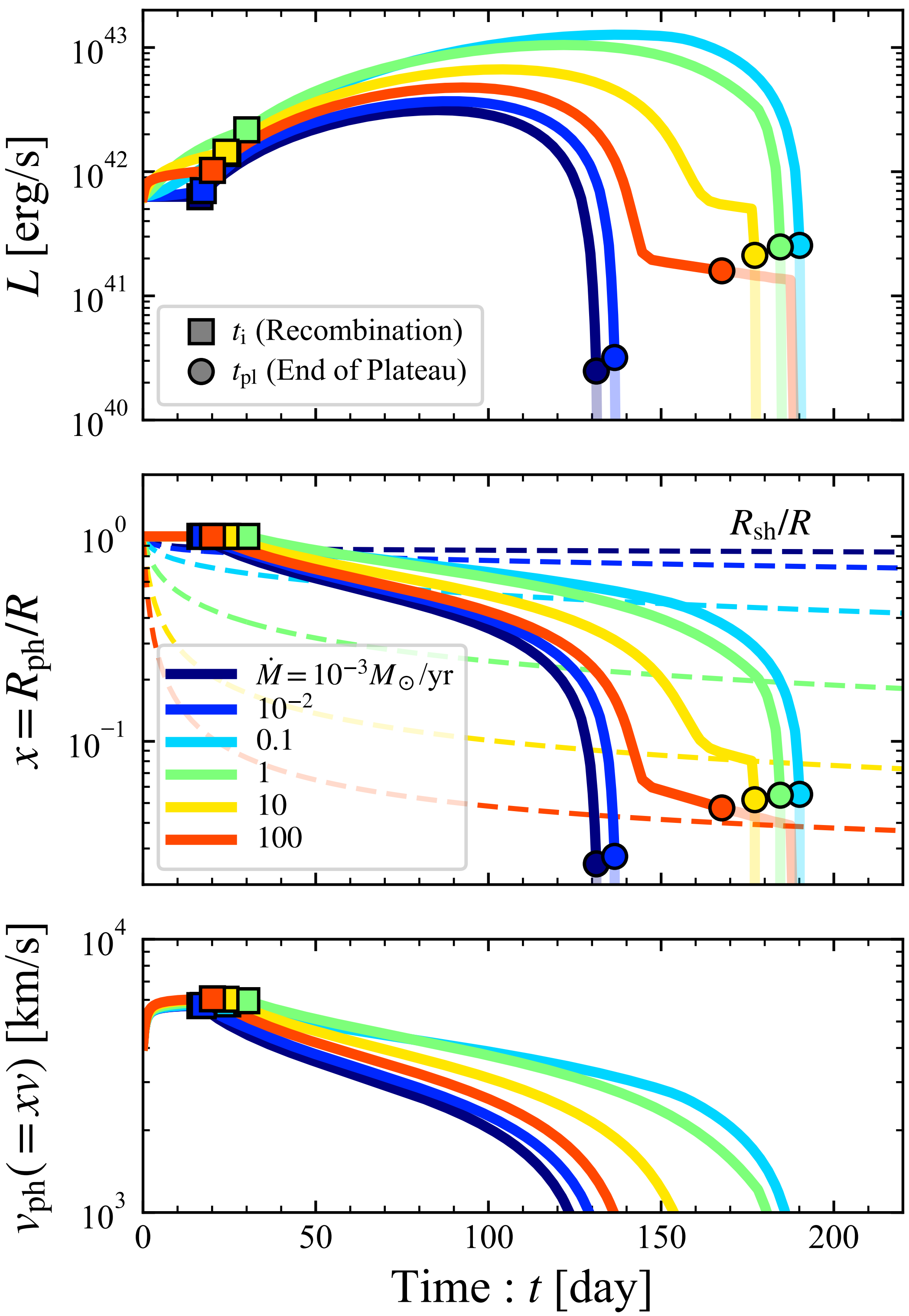
$$H = L_{\rm FS} + L_{\rm RS}$$

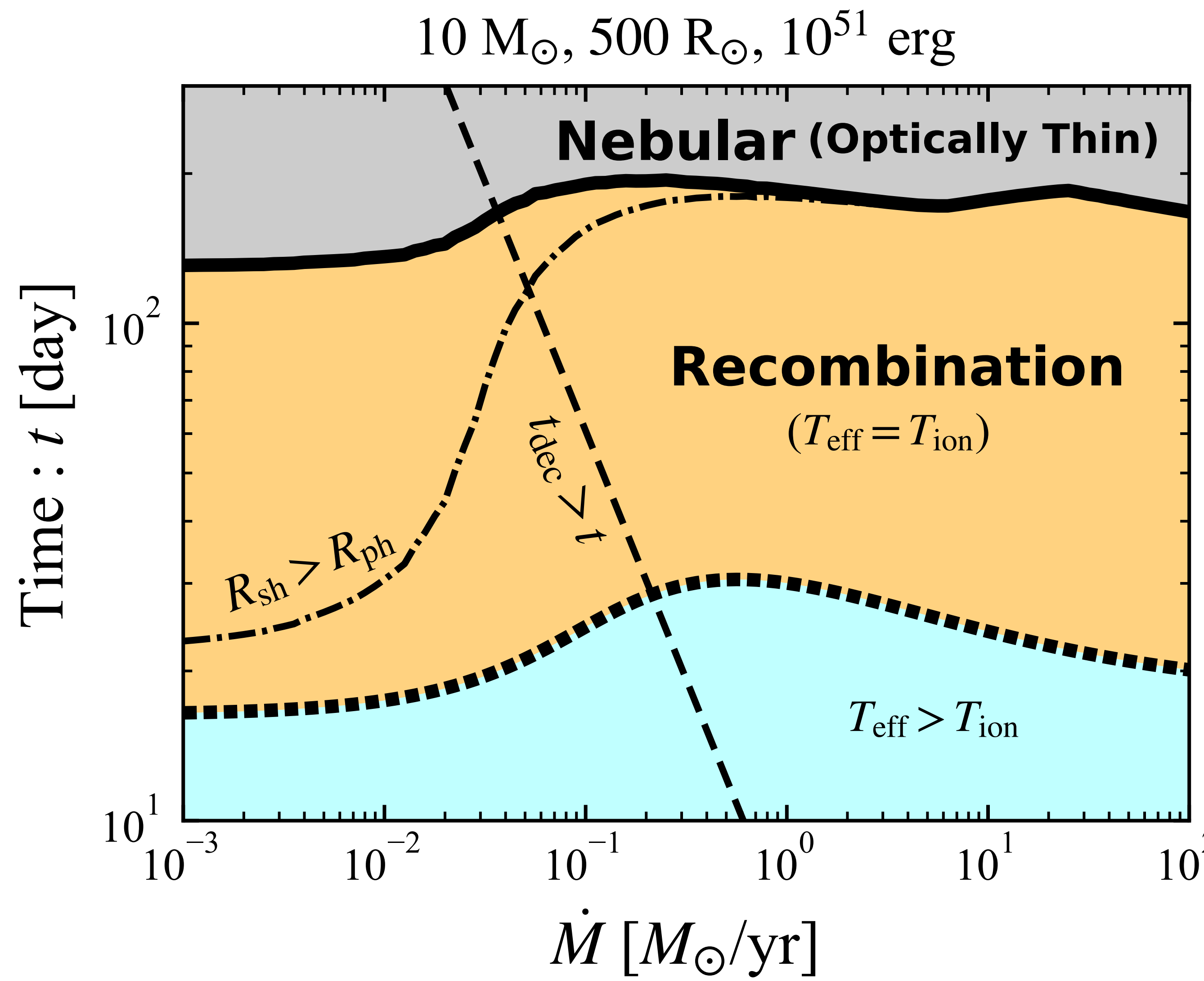
Shock should be embedded in ejecta

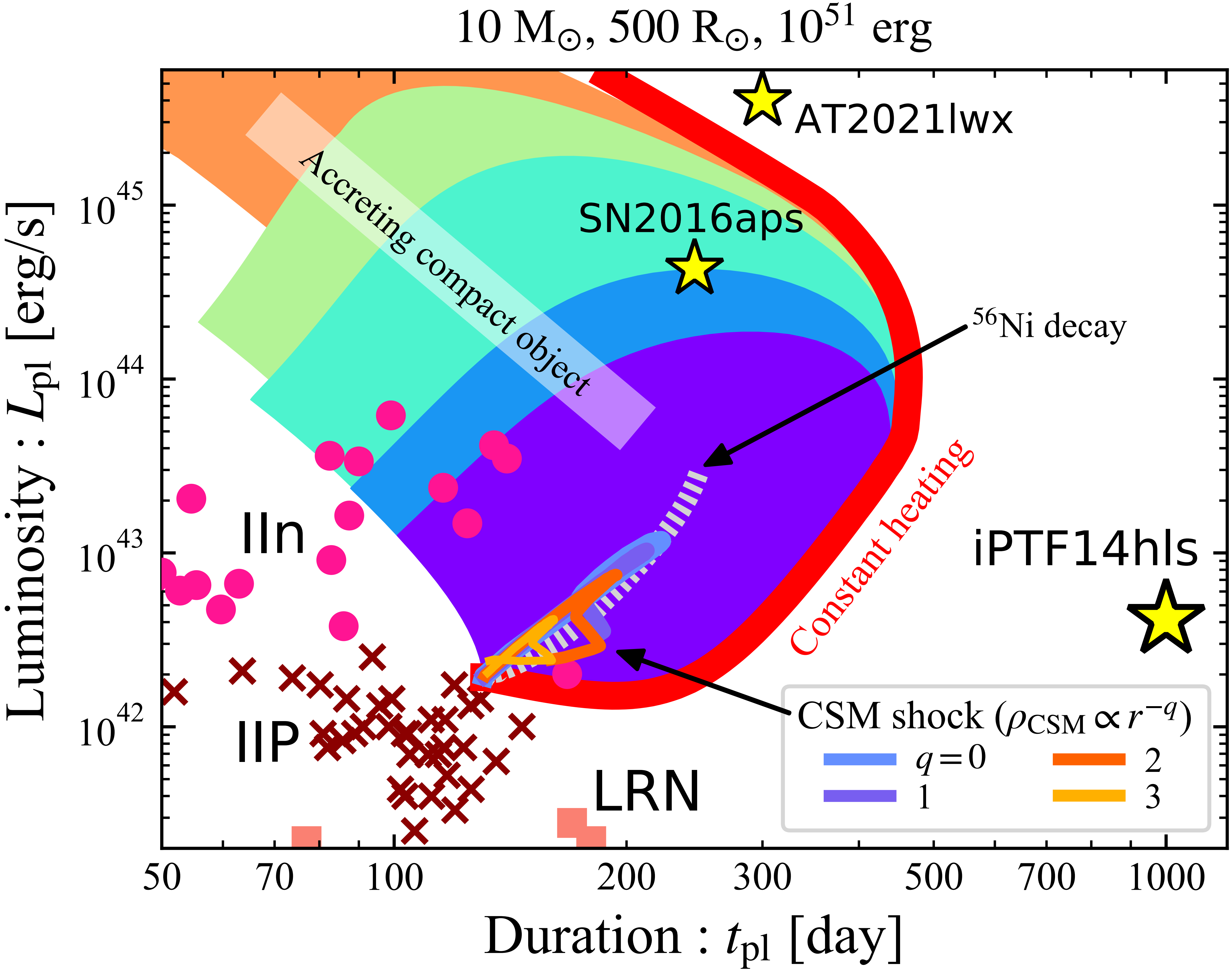
$$R_{\rm sh} \leq R_{\rm ph} (= xR)$$

Results

Shock Interaction







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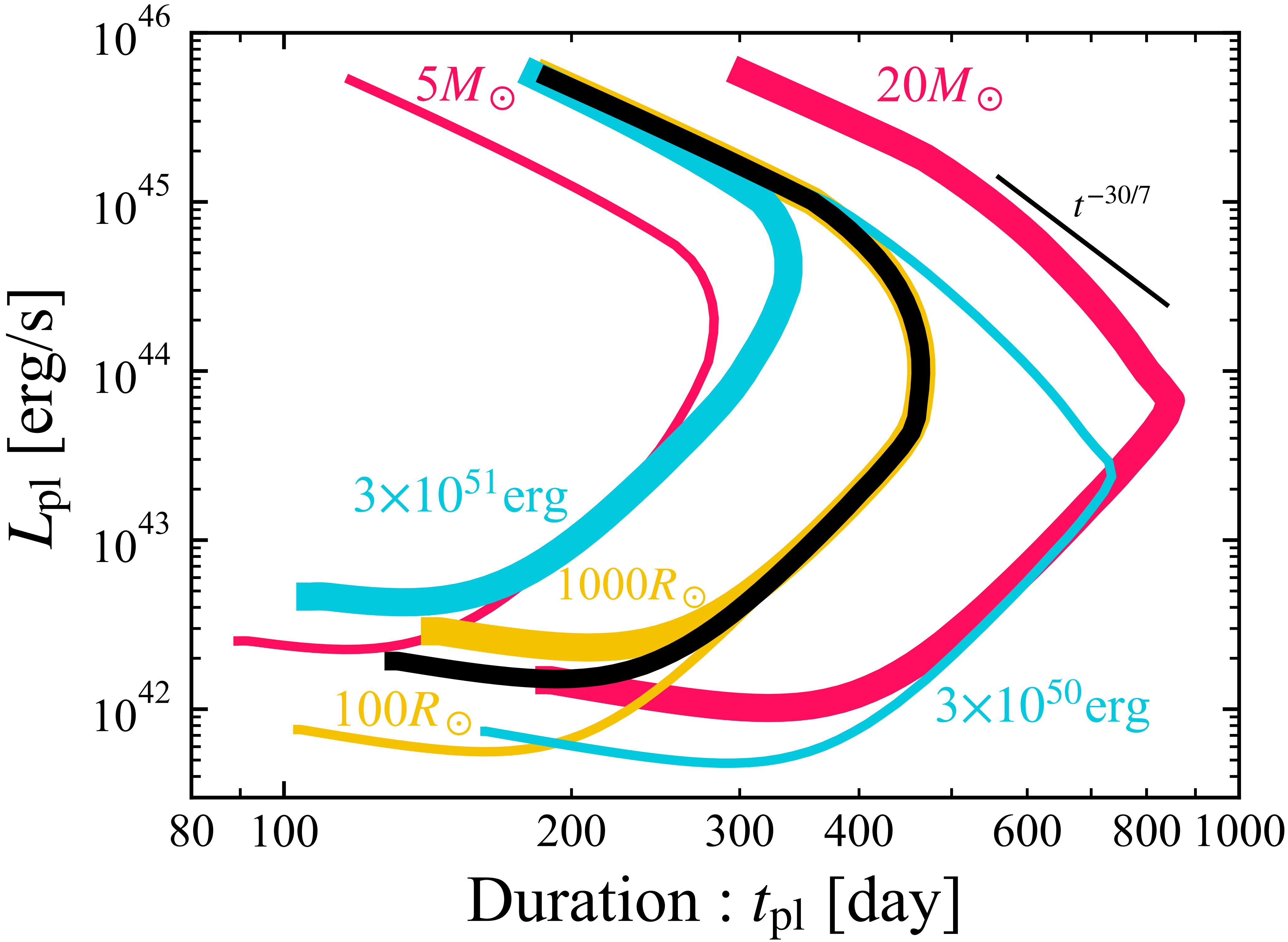
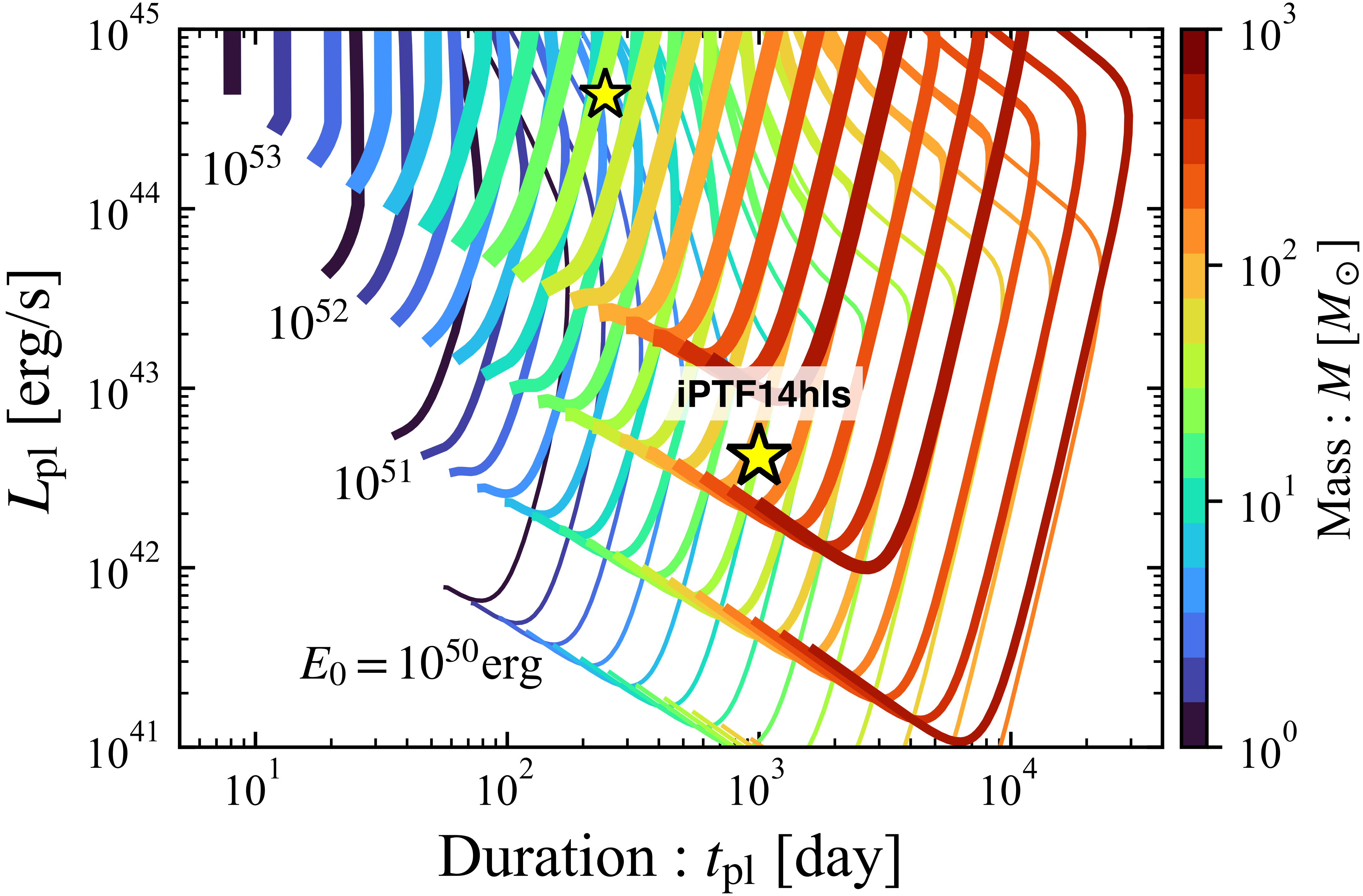


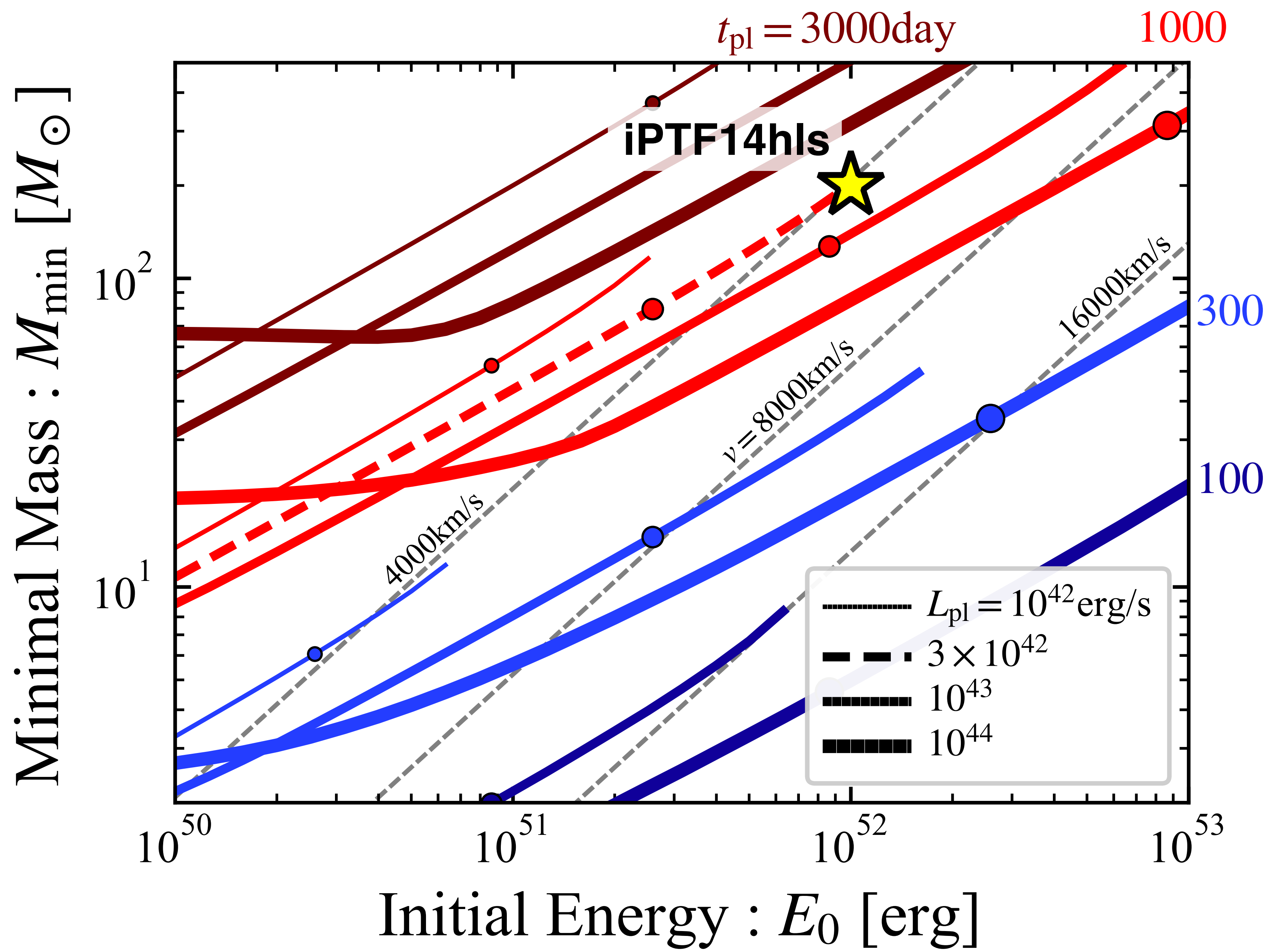
10^{46}
10^{45}
10^{44}
10^{43}
10^{42}
$L_{\rm pl}$ [erg/s]
80
100
200
300
400
600
800
1000
Duration : $t_{\rm pl}$ [day]
$5M_\odot$
$20M_\odot$
$t^{-30/7}$
3×10^{51}erg
$1000R_\odot$
$100R_\odot$
3×10^{50}erg

Boundaries for different M,E0

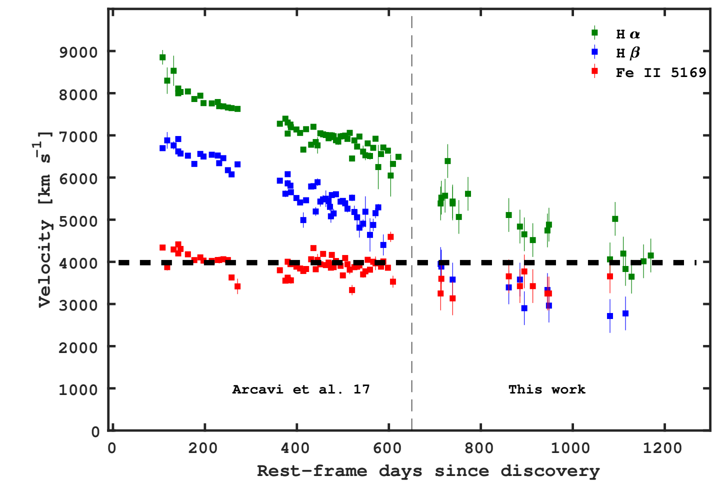


Minimal mass to produce iPTF14hls(L=3e+42erg/s,t=1000day)?

Minimal mass for iPTF14hls



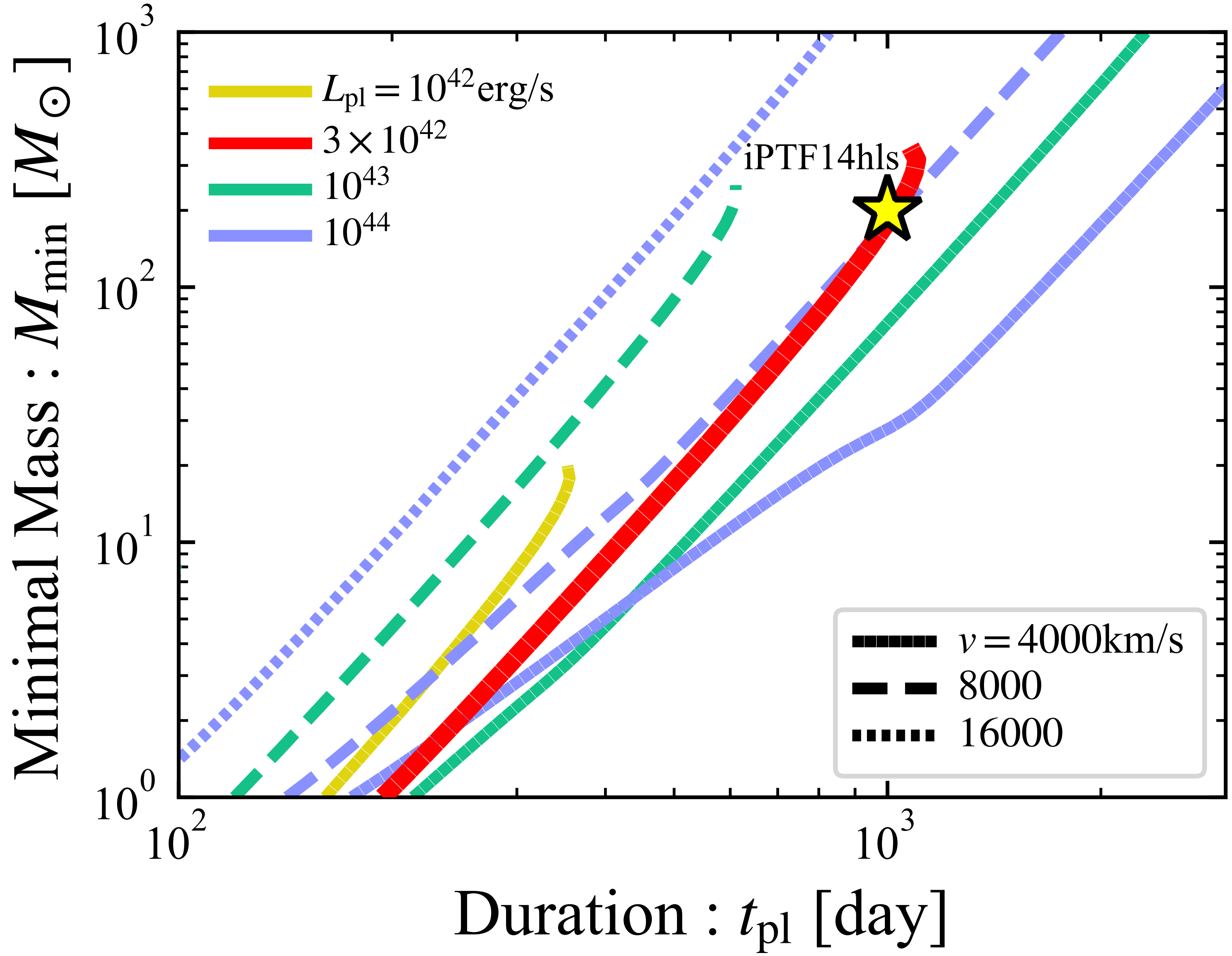
Sollerman+19

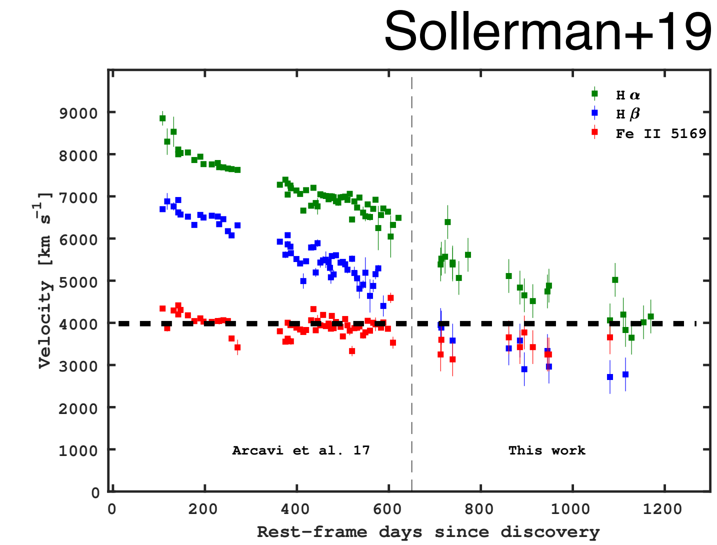


Minimal mass:
~200Msun

$$M_{\rm min} \simeq 150\,{\rm M}_\odot\, E_{0,52}^{3/5} \left(\frac{L_{\rm pl}}{3\times10^{42}\,{\rm erg/s}}\right)^{-1/5} \left(\frac{t_{\rm pl}}{10^3\,{\rm day}}\right)^{6/5}$$

Minimal mass for iPTF14hls





Minimal mass:
~200Msun

$$M_{\rm min} \simeq 100\,{\rm M_\odot} \left(\frac{L_{\rm pl}}{3\times10^{42}\,{\rm erg/s}}\right)^{-\frac{1}{2}} \left(\frac{v}{4000\,{\rm km/s}}\right)^{3} \left(\frac{t_{\rm pl}}{10^{3}\,{\rm day}}\right)^{3}$$

Summary

- H-rich SNe have plateau phase = Recombination goes on
- Very-long plateau: Massive star or ***engine-powered explosion***
- Extending one-zone (Popov) model for general heating source
- *H*=const model gives ***an absolute boundary*** of attainable plateau duration
- Minimal mass is obtained for given events with (v,L,t)

  => iPTF14hls: Mmin >~ 200Msun