Neutrino and EM signatures from superluminous supernovae (SLSNe)

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Fermilab

Optical transients: SLSNe

Class of supernovae (SNe) that are more luminous (hence superluminous) than ordinary SNe

Ho et al. 2201.12366
Moriya 2407.12302

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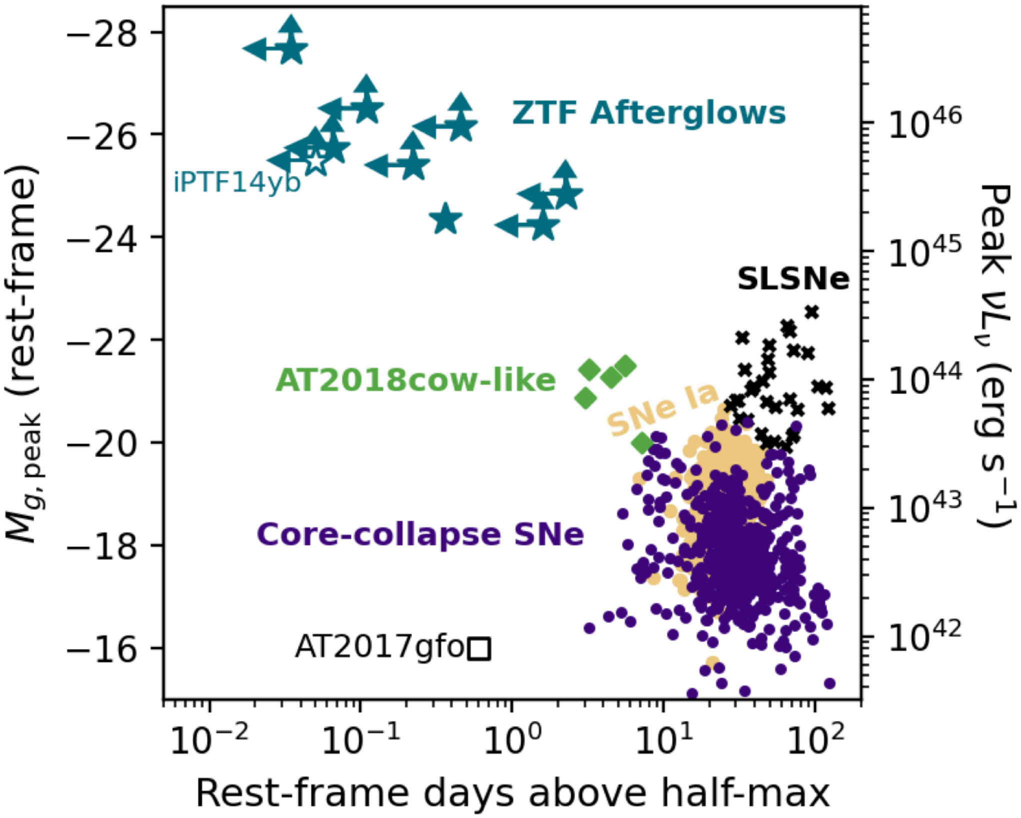

Bright optical transients with peak $M_{\mathrm{AB}} \sim -21$ or brighter

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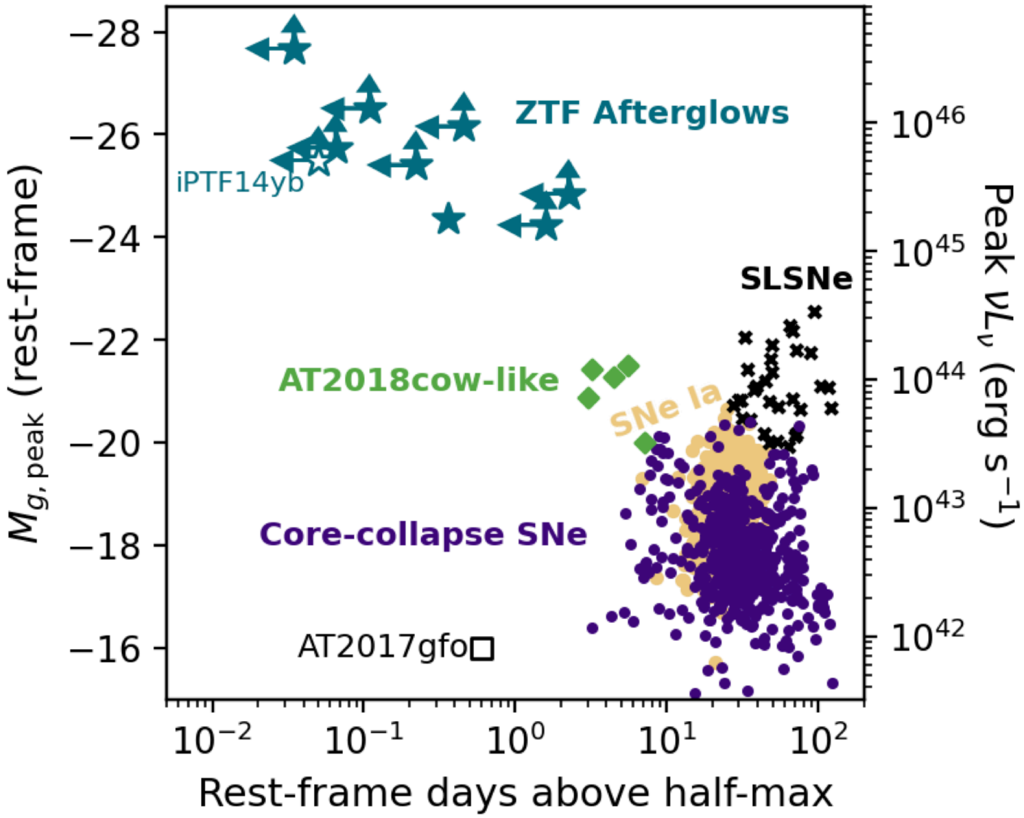

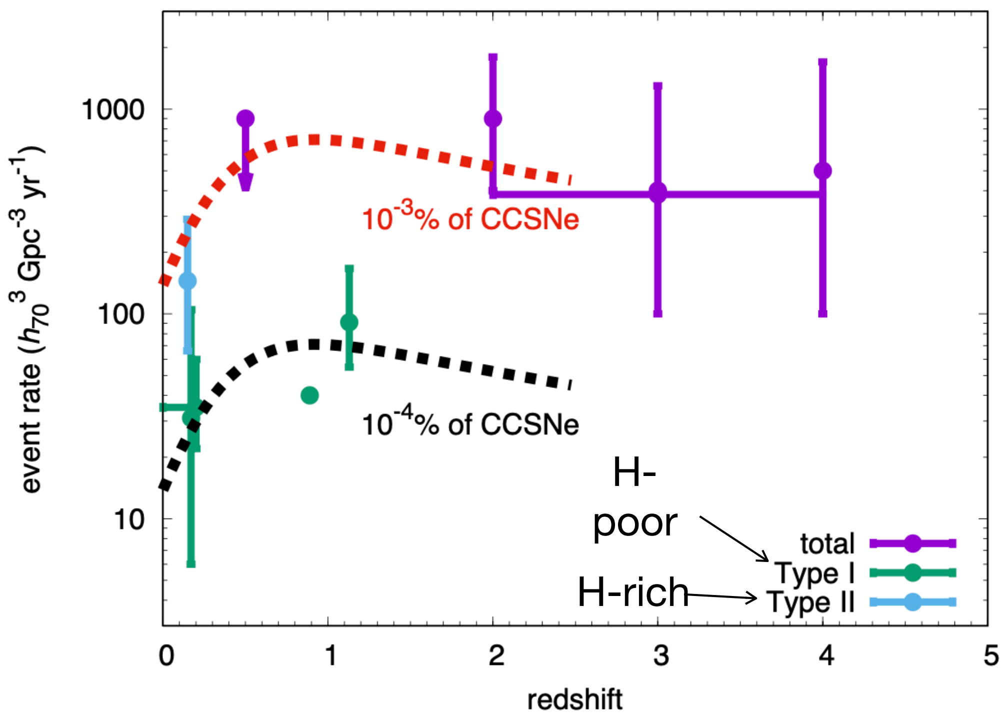

Bright optical transients with peak $M_{\rm AB} \sim -21$ or brighter

But rare, fiducial rate $\sim 10^{-8} - 10^{-7}\ {\rm Mpc^{-3}yr^{-1}}$

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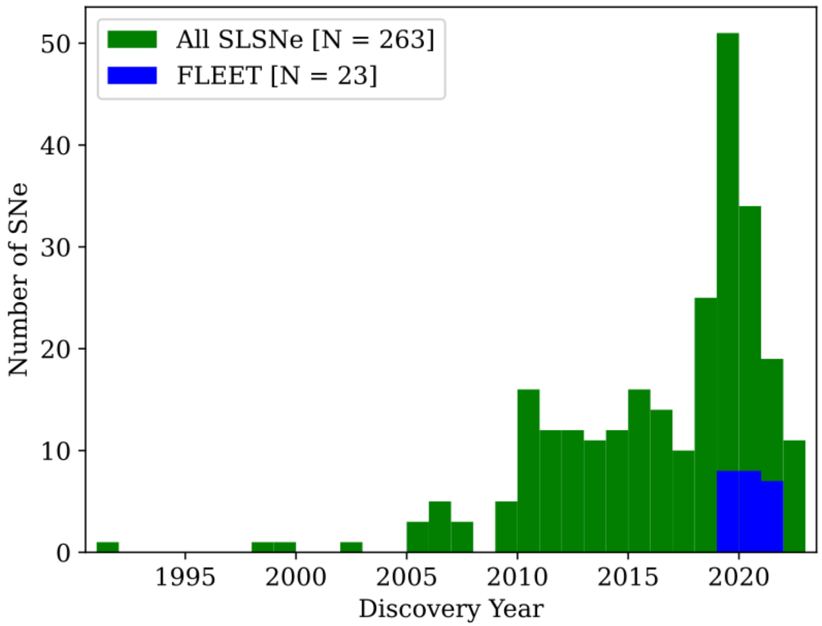
SLSNe: Why are they interesting?



A large number of them have been discovered

Rubin LSST can see $\mathcal{O}(10^4)$ SLSNe/yr

Gomez et al. 2407.07946
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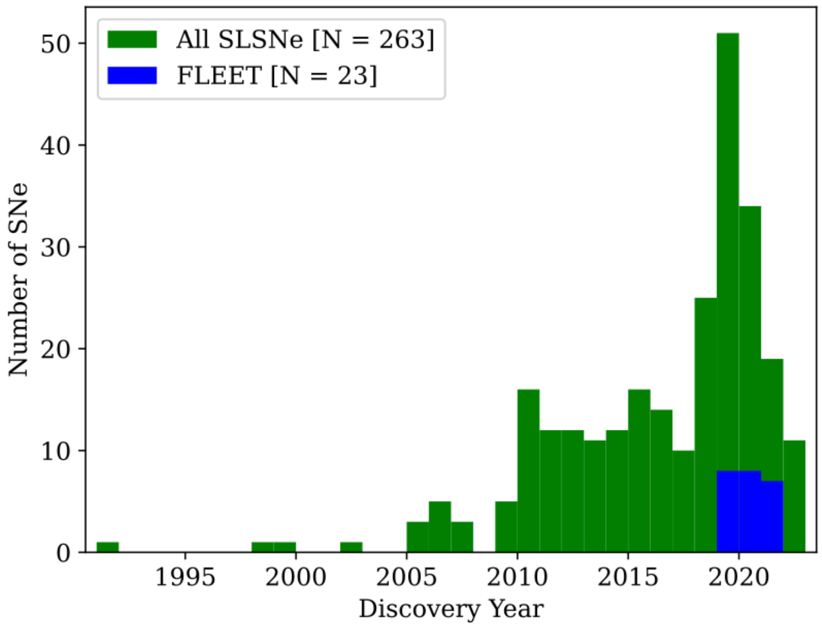

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What powers them is unclear

- Shock interaction between SN ejecta and dense (optically thick) CSM
- Pair instability SNe and large Ni-56 yields
- **Magnetar-powered**
  Particularly relevant for Type - I SLSNe (lacking obvious evidence of CSM interactions)

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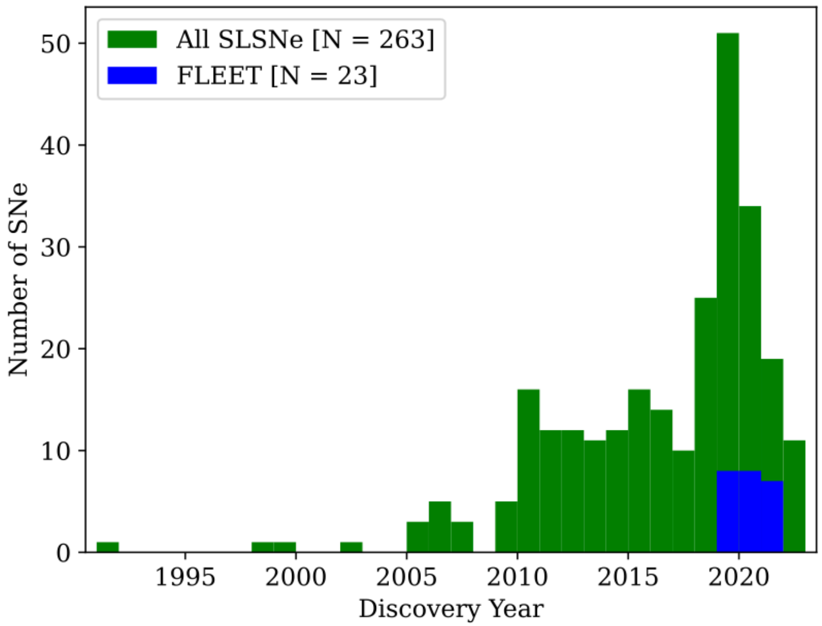
SLSNe: Why are they interesting?



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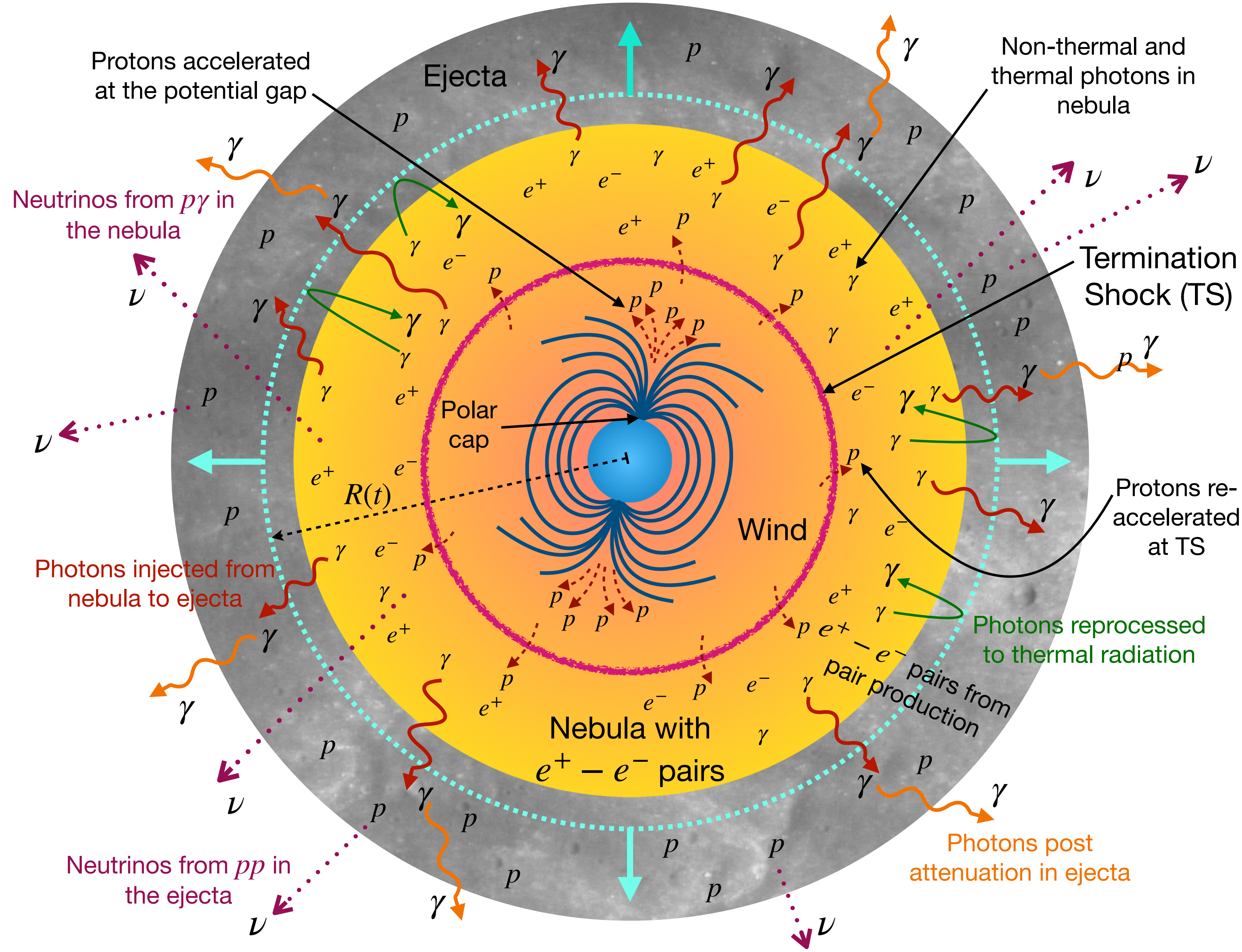
Excellent detection prospects + unclear power source: multimessenger signatures → complementary probes

Gomez et al. 2407.07946
Moriya 2407.12302

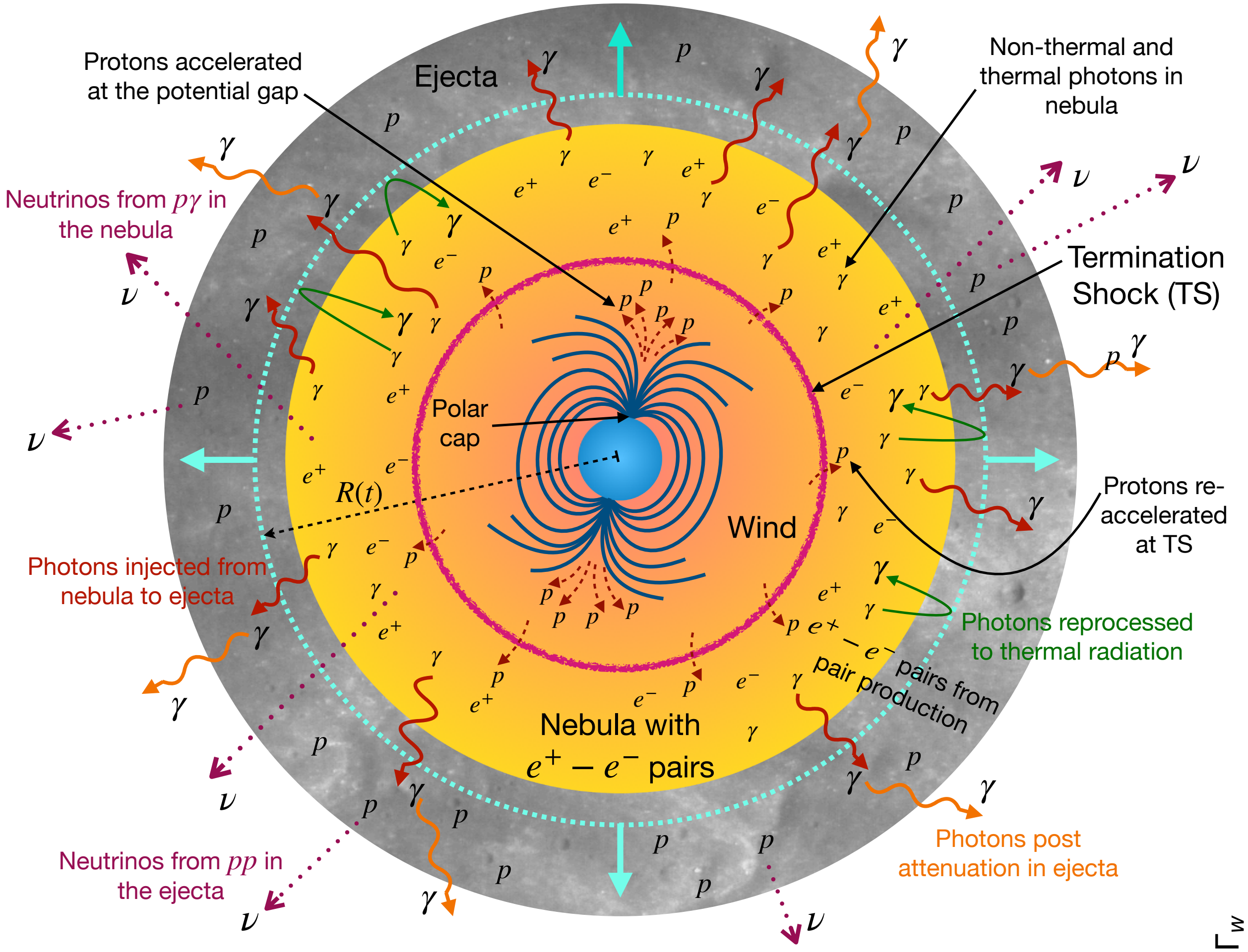
Magnetar-powered SLSNe: Model



Mukhopadhyay et al. 2026
Mukhopadhyay et al. 2025
Mukhopadhyay & Kimura 2025
Mukhopadhyay & Kimura 2026

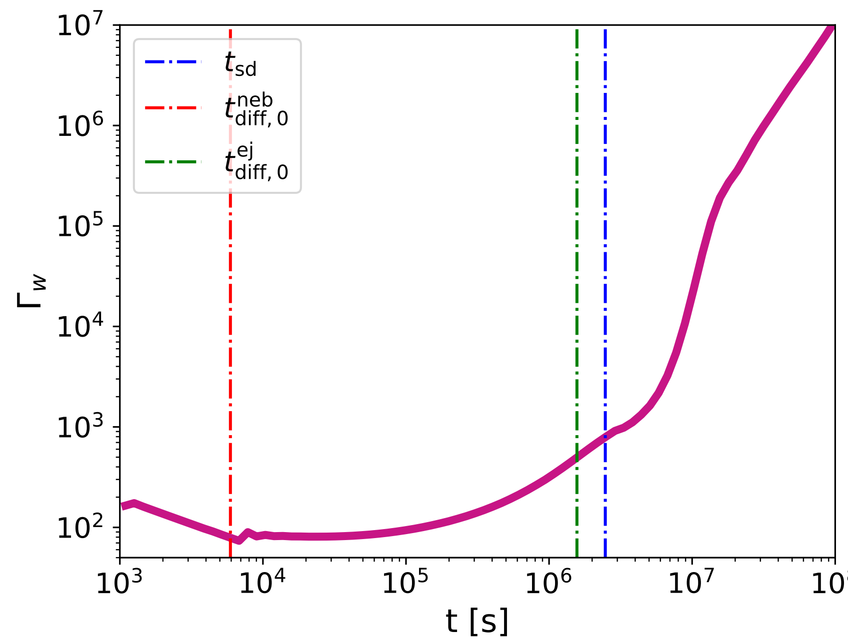
Magnetar: Loses rotational energy through spindown

Magnetar-powered SLSNe: Model



$$\Gamma_w \approx \frac{L_{\rm sd}}{4\pi m_e c^2 n^w_{e^\pm} R_s^2 c}$$

Pair multiplicity and wind Lorentz factor evaluated consistently



Mukhopadhyay et al. 2026
Mukhopadhyay et al. 2025
Mukhopadhyay & Kimura 2025
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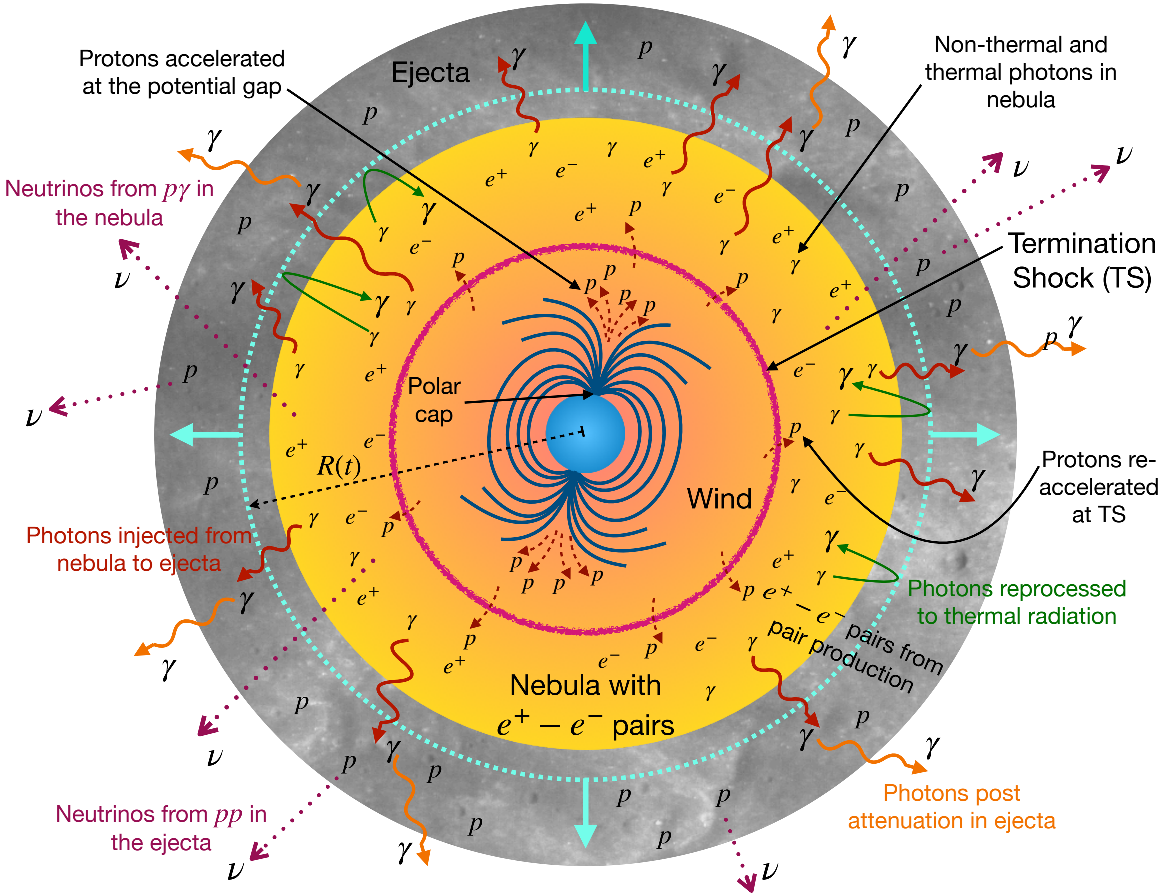
Wind: carries pairs, magnetic energy, and accelerated ions outwards

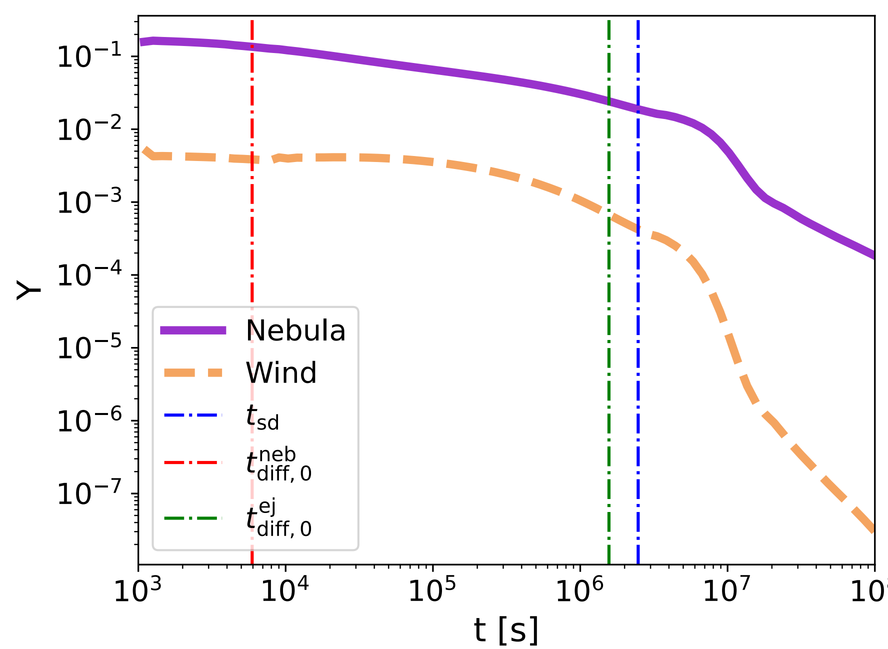
Magnetar-powered SLSNe: Model



Pair creation rate computed from primary and secondary photons

$$Y = \frac{\dot{N}^{c}_{e^\pm} m_e c^2}{L_{sd}}$$

Pair multiplicity and wind Lorentz factor evaluated consistently



Termination shock/nebula: wind dissipates; relativistic pairs produce synchrotron + inverse Compton radiation.
CR protons interact predominantly with the intense photon field through $p\gamma$, producing neutrinos.

Mukhopadhyay et al. 2026
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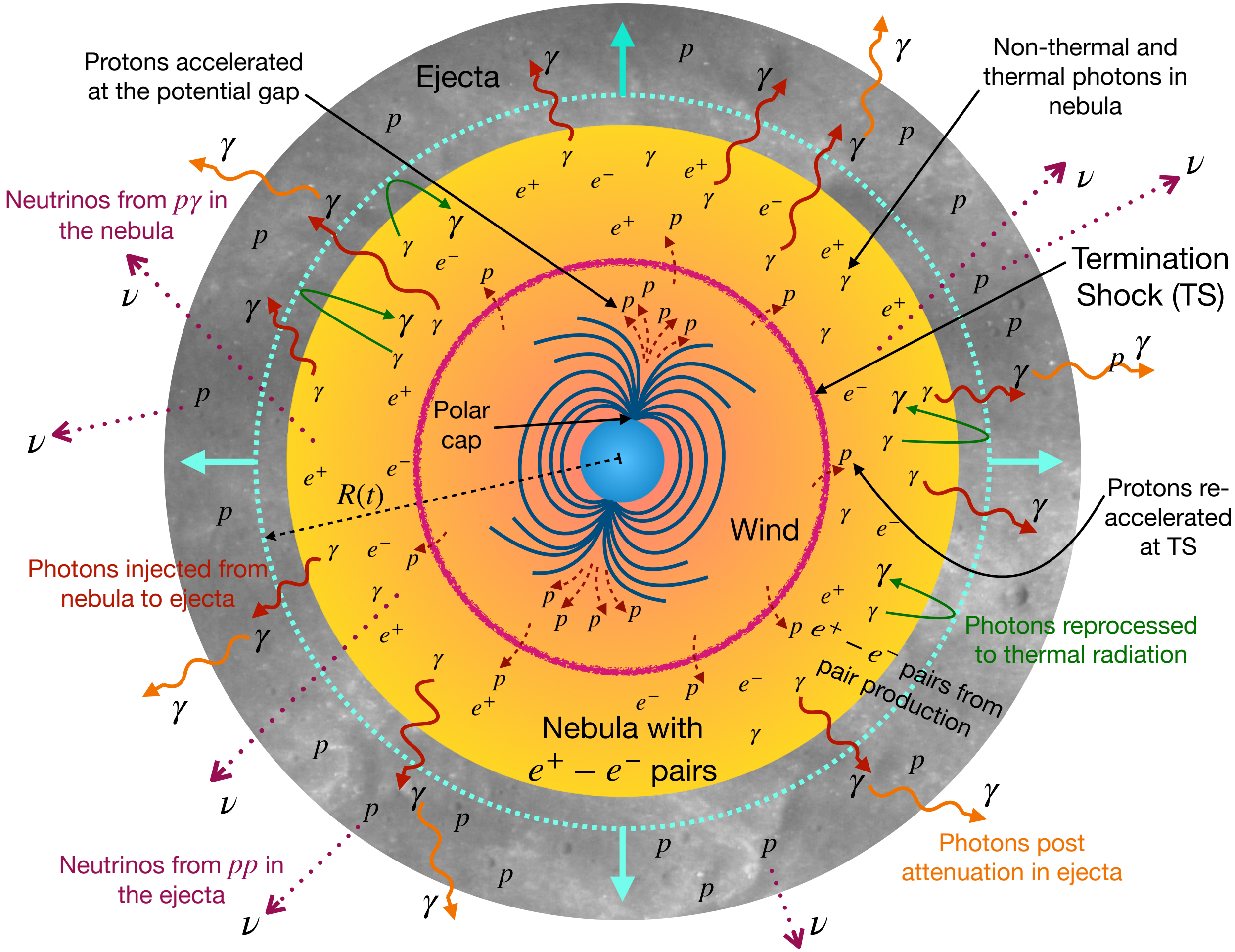

Ejecta composition determines the wavelength-dependent opacity

Composition: Mostly He-dominated with some O and Ni-56

Ejecta: absorbs/reprocesses much of the nebular radiation into the optical SLSN.

Escaping CRs interact through pp, giving a second neutrino component.

Photons escaping the system are strongly energy- and time-dependent because the ejecta becomes progressively transparent.

Mukhopadhyay et al. 2026
Mukhopadhyay et al. 2025
Mukhopadhyay & Kimura 2025
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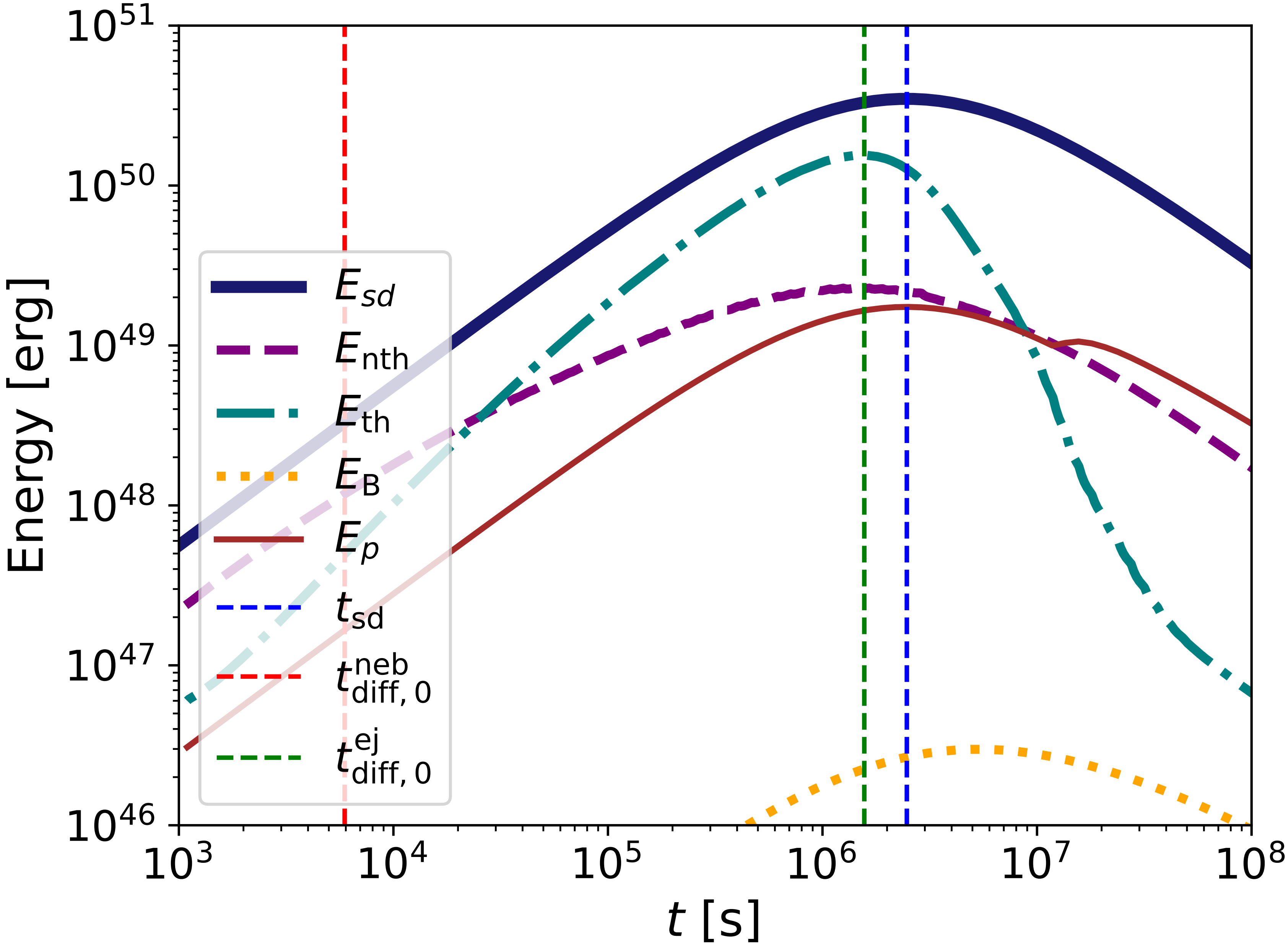
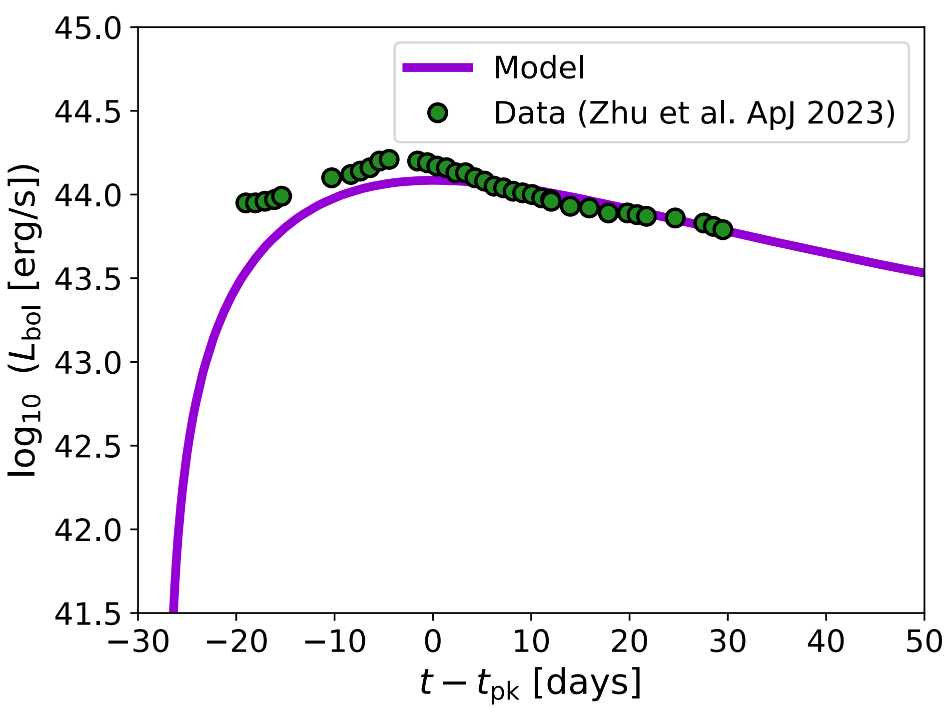
Energetics



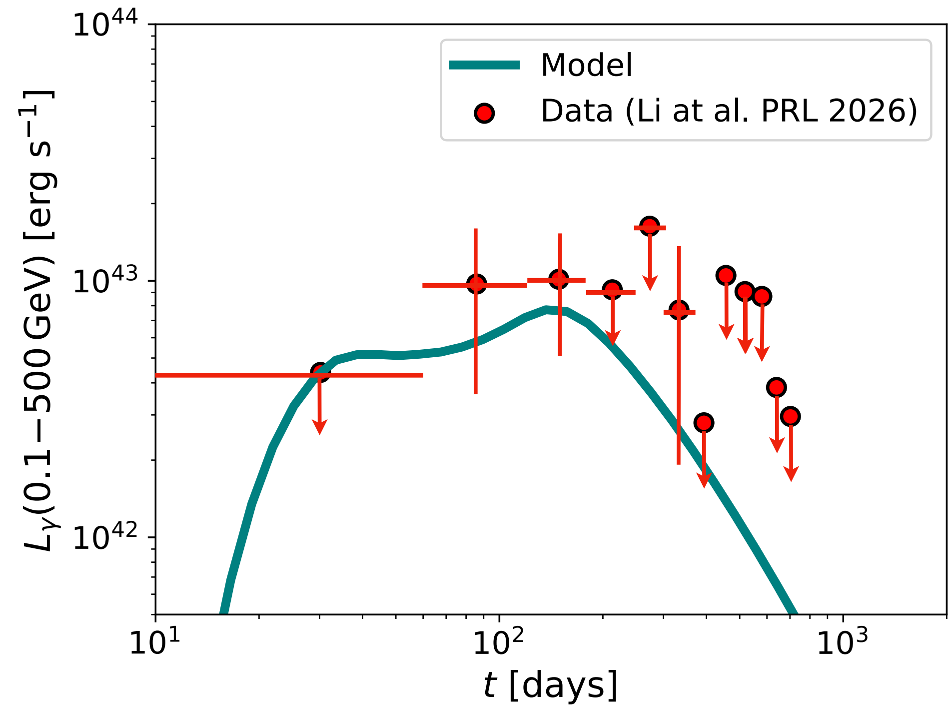
10^{51}
10^{50}
10^{49}
10^{48}
10^{47}
10^{46}
Energy [erg]
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
t [s]
E_{sd}
$E_{\rm nth}$
$E_{\rm th}$
$E_{\rm B}$
E_{p}
$t_{\rm sd}$
$t^{\rm neb}_{\rm diff,0}$
$t^{\rm ej}_{\rm diff,0}$

Observational Motivation: Nearest SLSN - SN 2017egm ($d_L \approx 135$ Mpc)

$P_i = 4$ ms $\quad B_d = 5 \times 10^{13}$ G $\quad M_{\rm ej} = 2.23\ M_\odot$



Resulting optical light-curve matches with the observed bolometric evolution

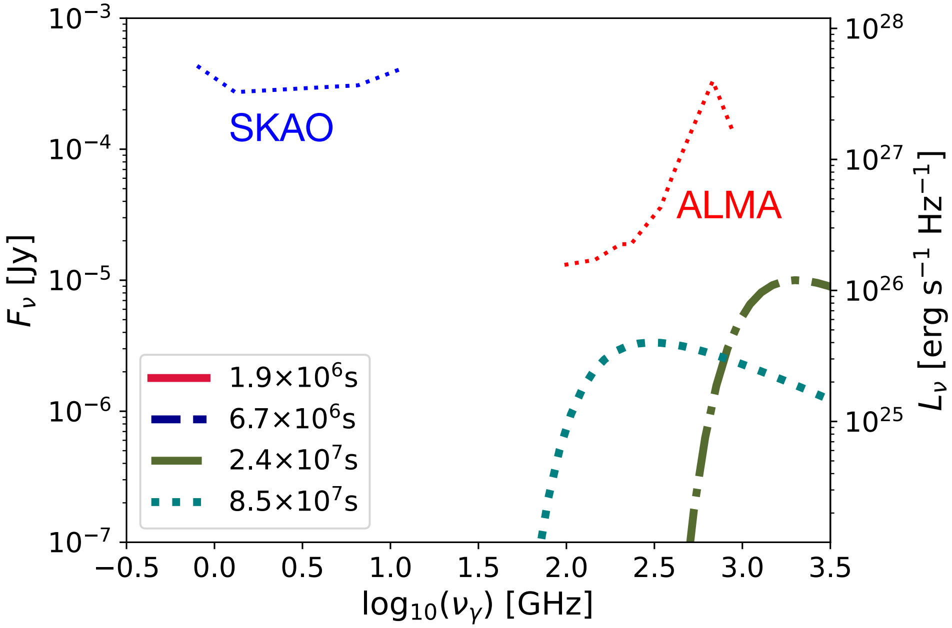


Detection of GeV gamma-ray emission

Evidence for a magnetar-powered SLSN

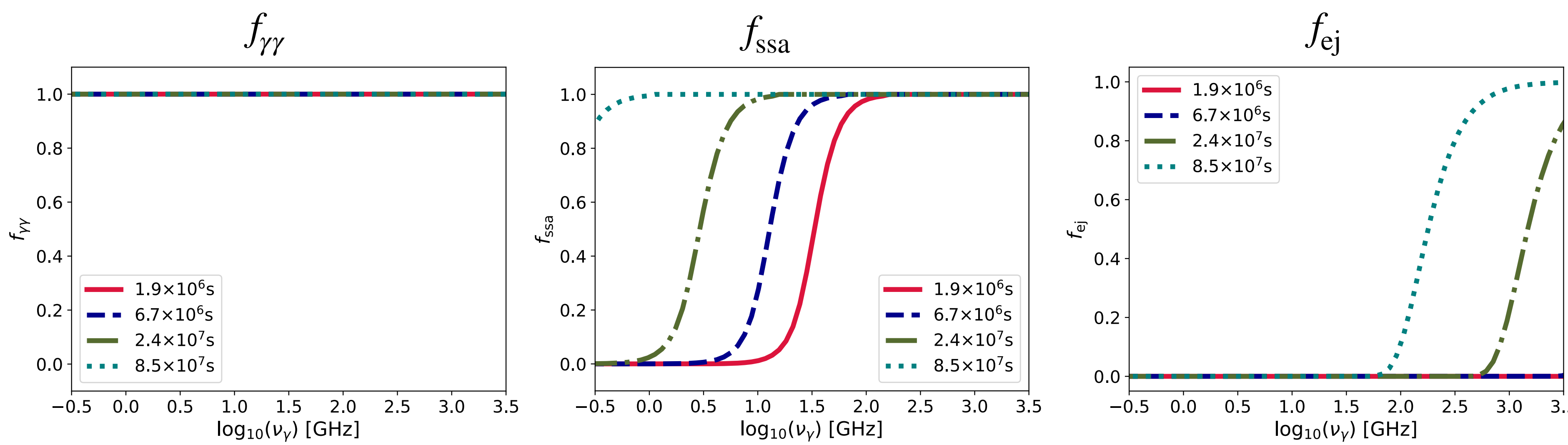
Multi-wavelength EM Spectra

Radio



Initially killed by SSA/ free-free

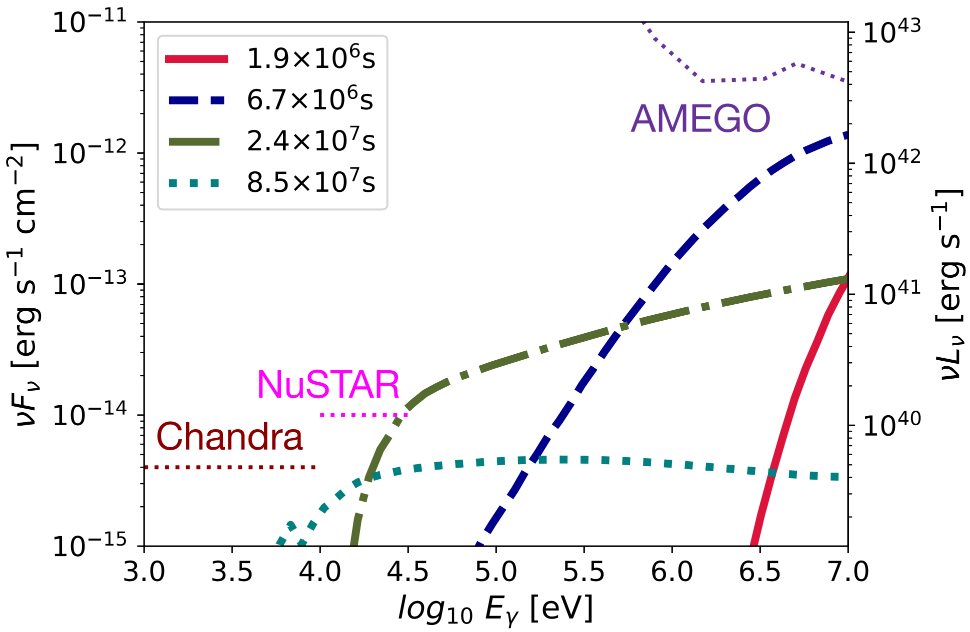
Radio



Multi-wavelength EM Spectra

Escape later as the ejecta opacity falls

X-ray/MeV



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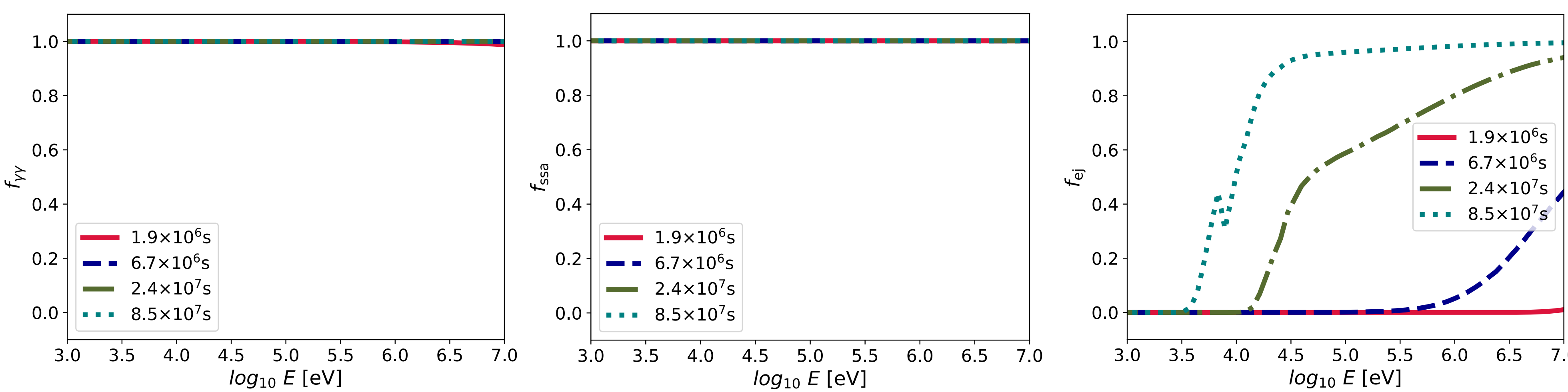
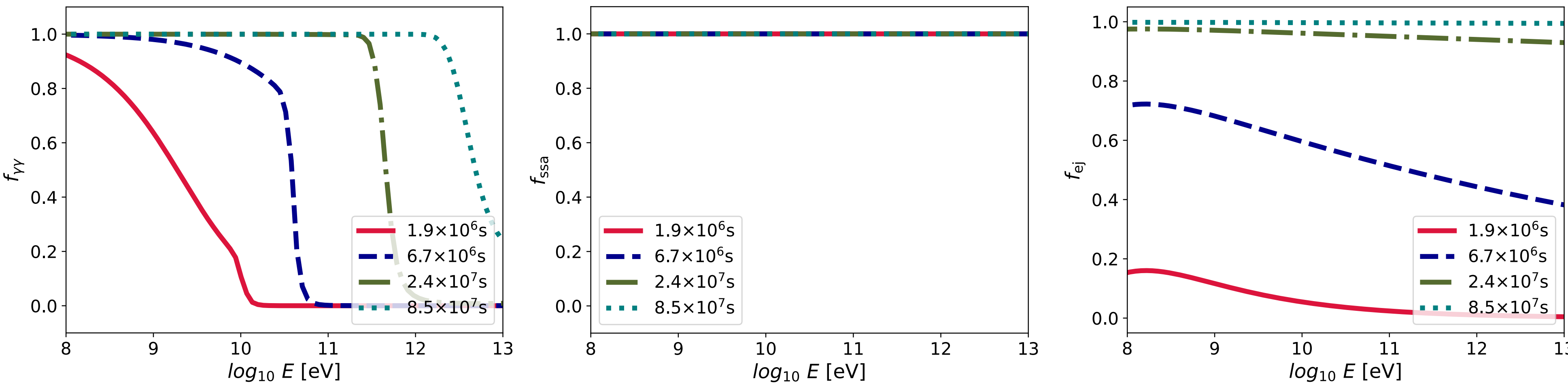


Multi-wavelength EM Spectra

HE and VHE γ-rays



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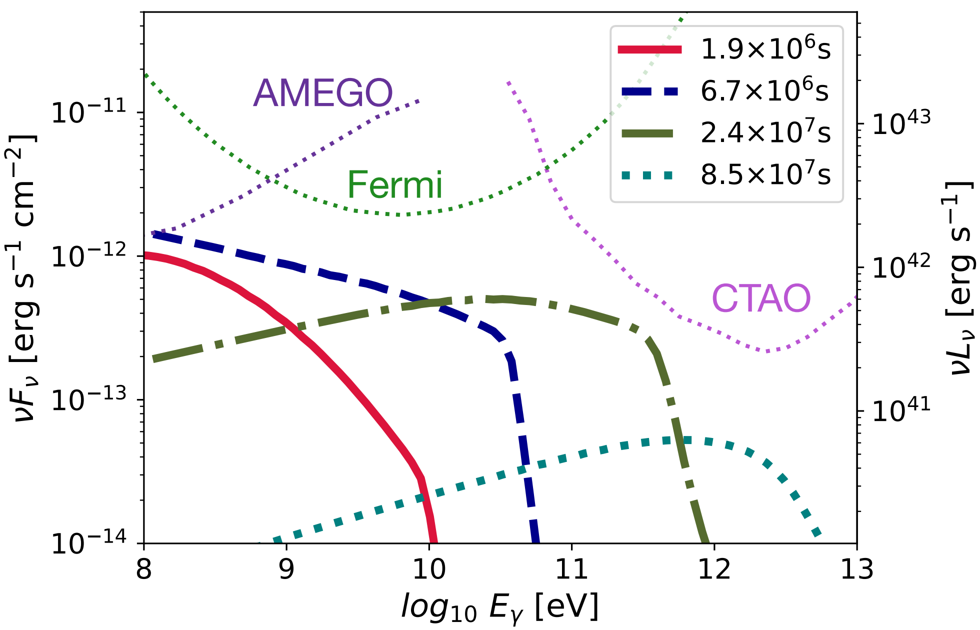
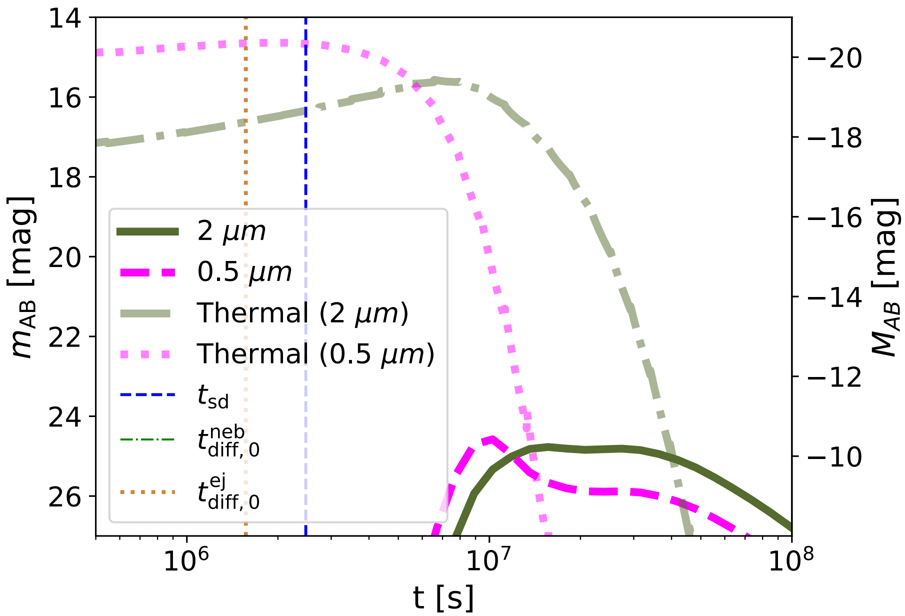


GeV photons: Escape relatively early

TeV photons: remain suppressed longer by $\gamma\gamma$ and ejecta attenuation

Light curves: when should we look?

Optical and Infrared



Optical: bright and easy to find

Light curves: when should we look?

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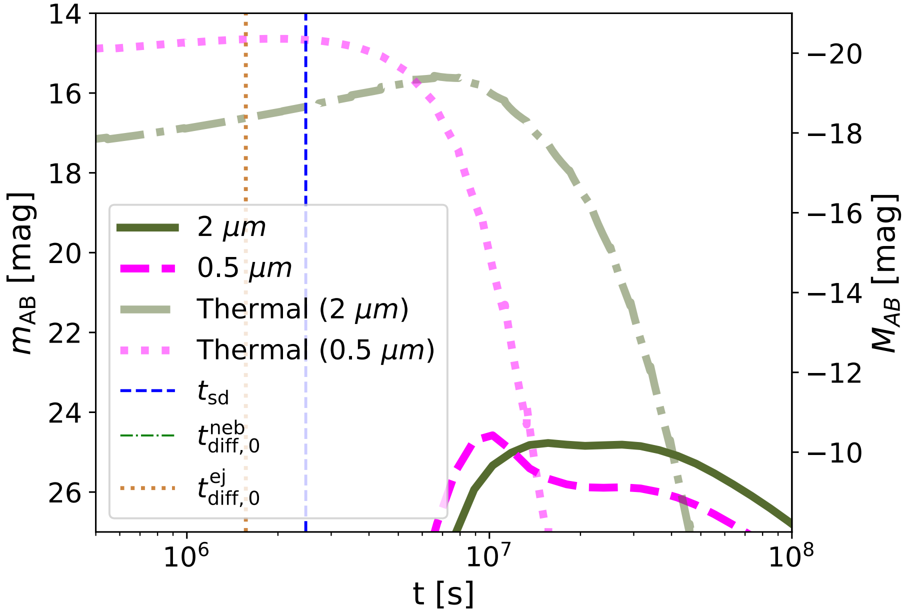

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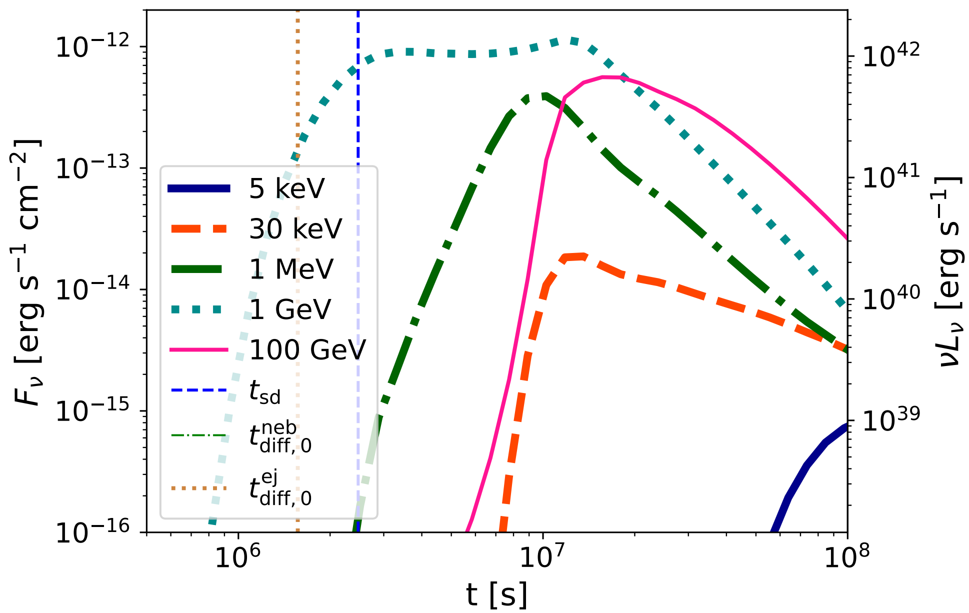
X-ray and γ-ray



GeV: around the spin
down timescale

Hard X-ray/MeV: later

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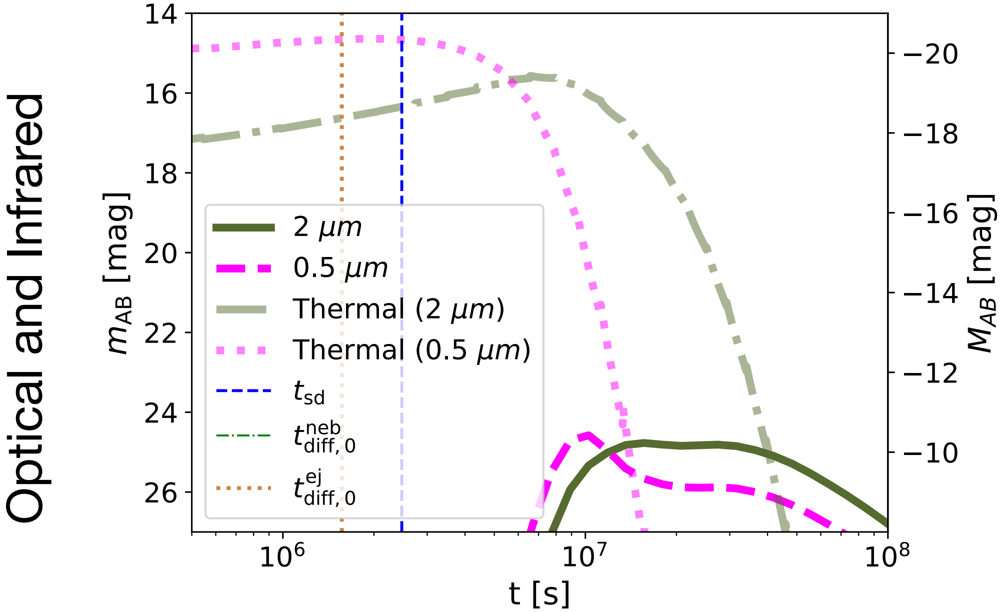

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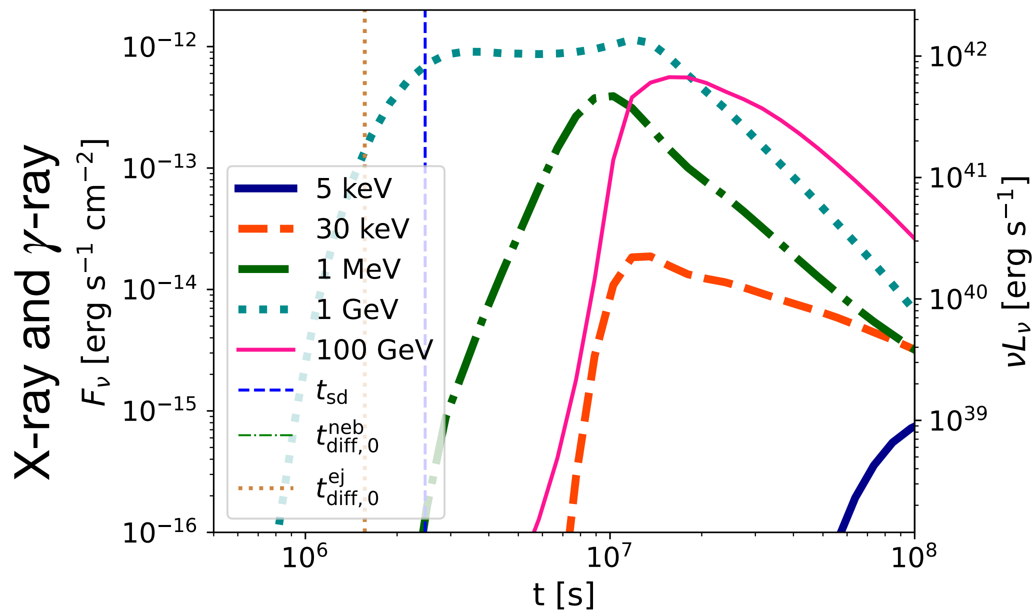

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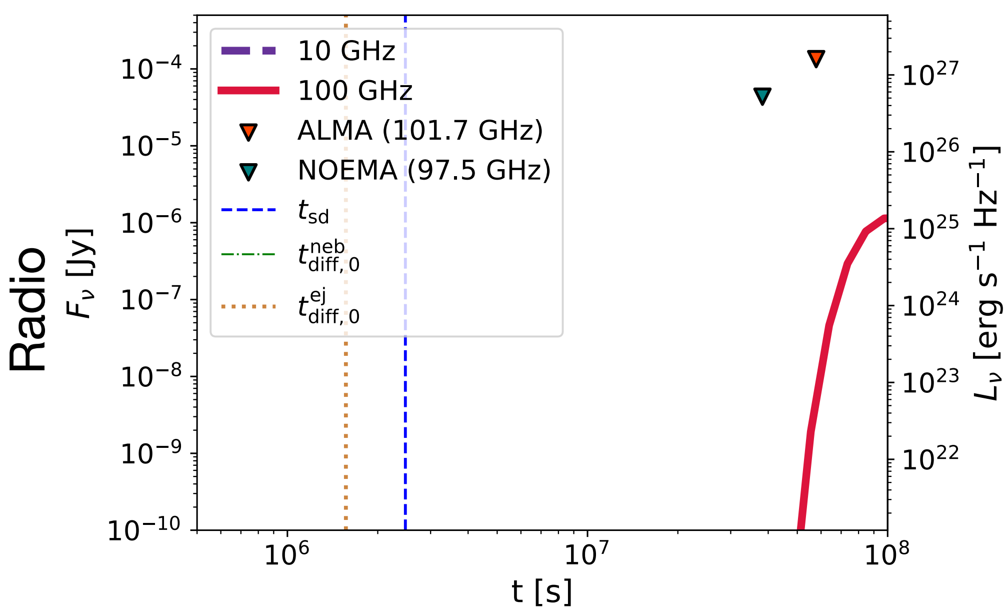
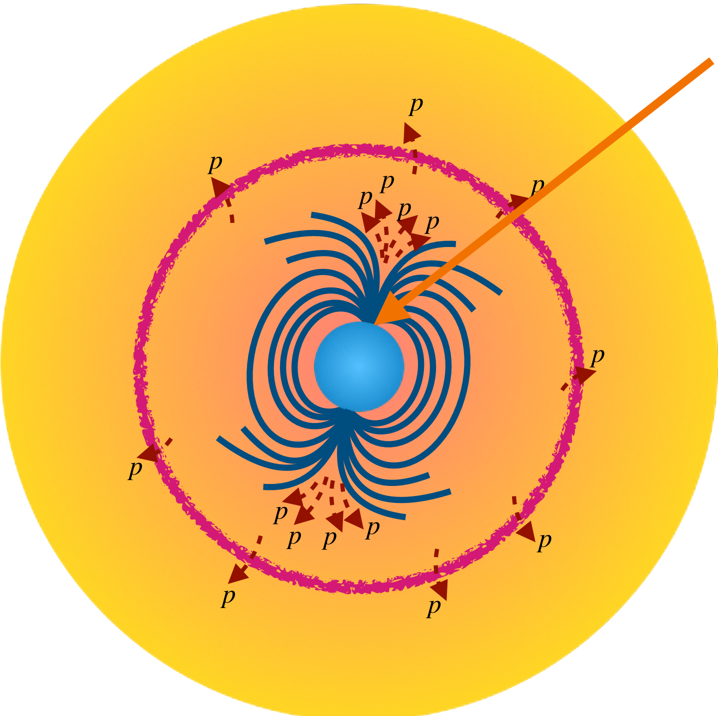


Radio: much later

Cosmic ray (CR) proton acceleration: injection spectra



CR protons extracted from the magnetar surface: Goldreich-Julian (GJ) number density of charges

$$n_{\rm GJ} = -\frac{\mathbf{\Omega} \cdot \mathbf{B}}{2\pi Zec}$$

$$\dot{N}_p = n_{\rm GJ} 2 A_{\rm pc} c = \frac{4\pi^2}{Ze} \frac{R_*^3}{c} \frac{B_0}{P^2}$$

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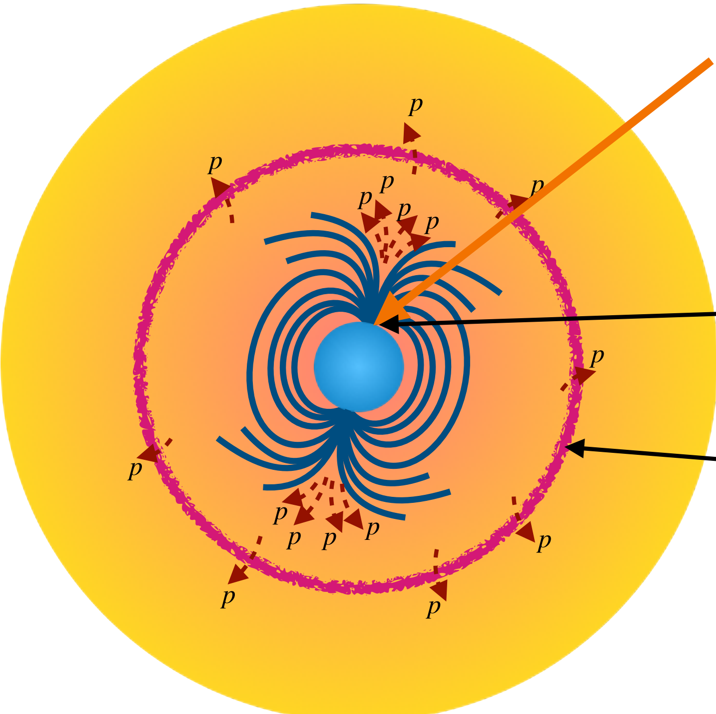

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Polar cap

+

Termination shock (TS)

Acceleration sites

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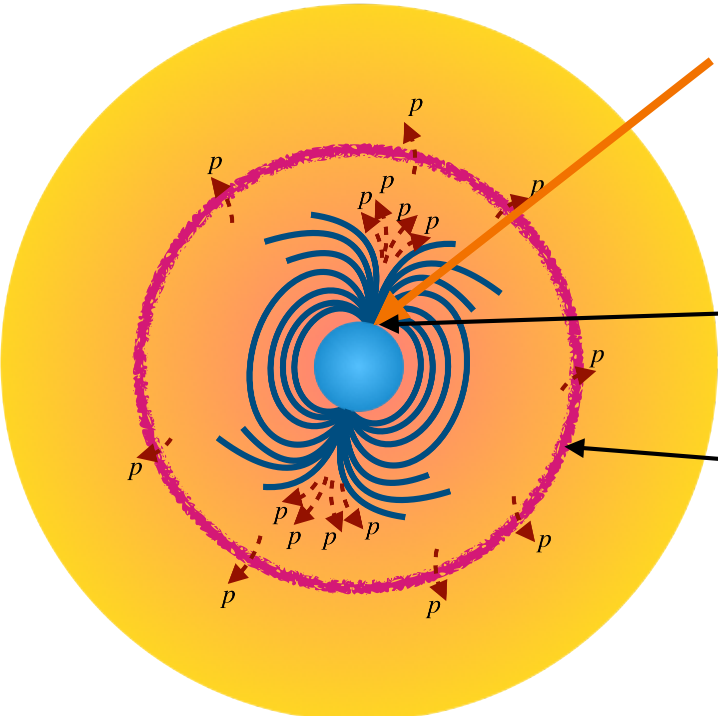

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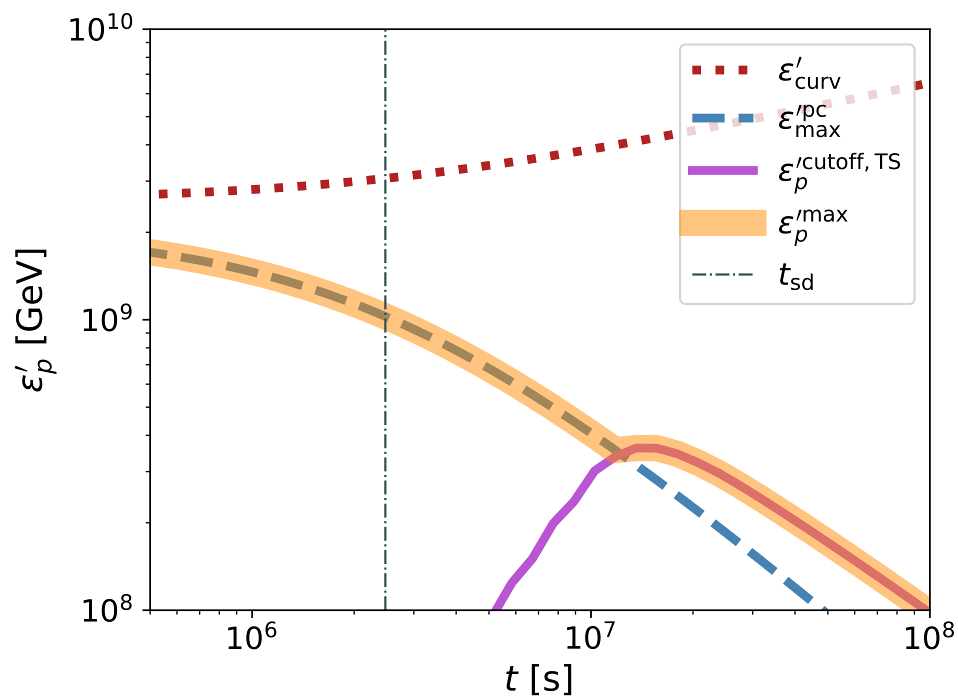
Acceleration sites

$$\frac{d\dot{N}_{p,\rm inj}}{d\varepsilon'_p} = \dot{N}_p^{\rm norm} Q_p^{\rm inj}(\varepsilon'_p) = \dot{N}_p^{\rm norm} \delta\left(\varepsilon'_p - \varepsilon_p^{\prime\rm cutoff,pc}\right)$$

$$\varepsilon_p^{\prime\rm cutoff} = \max\left[\varepsilon_p^{\prime\rm cutoff,pc}, \varepsilon_p^{\prime\rm cutoff,TS}\right]$$



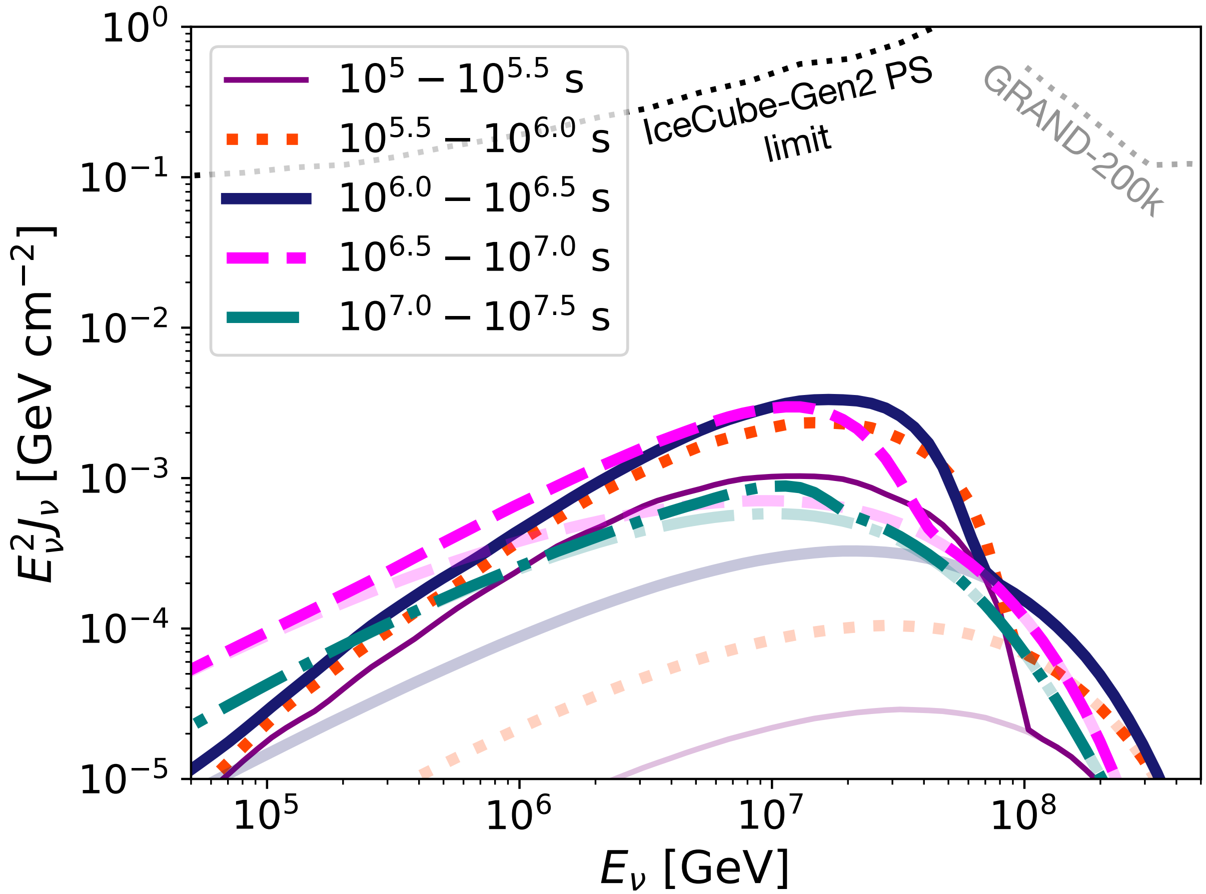
Neutrino signatures

In the nebula $p + \gamma \rightarrow \pi^{\pm} \rightarrow \nu$

Dominates near the peak

$p + p \rightarrow \pi^{\pm} \rightarrow \nu$ **In the ejecta**

Becomes important at late times



Neutrino energy: $\sim 10^7$ GeV $- 10^8$ GeV

Time of peak fluence $\sim 10^6$ s $- 10^{6.5}$ s post-collapse (a few weeks to a month)

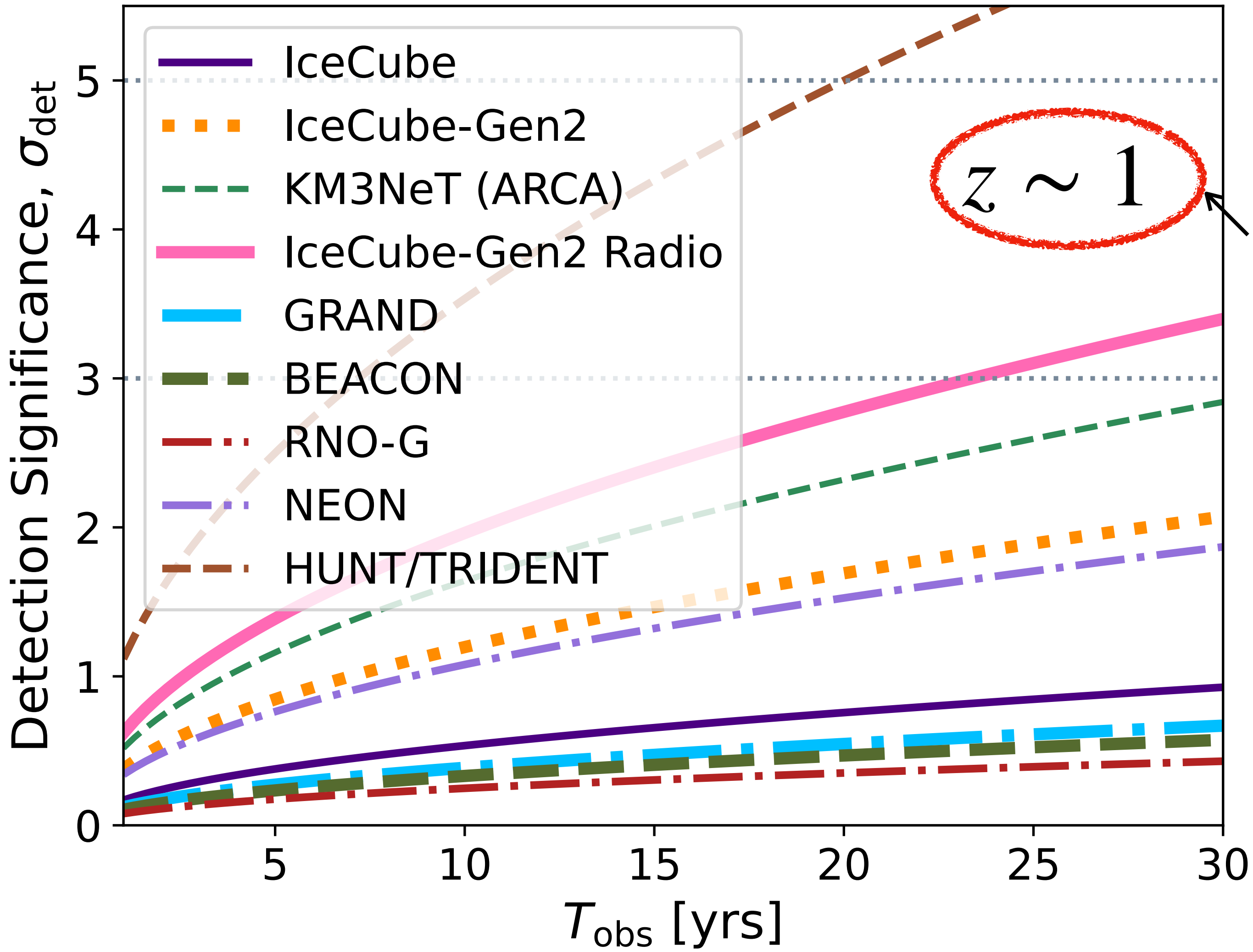
Peak fluence: $\sim$ few $\times 10^{-3}$ GeV cm^{-2} ($d_L \approx 100$ Mpc)

A single SLSN at ~ 100 Mpc, unlikely to be detected in neutrinos

Neutrino signatures: prospects from EM follow-ups

With Rubin LSST: position and time for candidate SLSNe

Instead of searching the entire sky at all times, we search around known SLSN positions and within the ~ 30-day window



Important since arbitrary choices add more background than signal

Summary and the road ahead

- **Growing population of SLSNe and more to come in the era of Rubin LSST**: what powers them is unclear

- **Magnetar-powered SLSNe: millisecond magnetar born from a SN can power SLSNe** - thermal optical emission and non-thermal EM/neutrino emission

- **Observational test:** For SN 2017egm (nearest SLSNe), the model calibrated to the optical emission also gives GeV emission consistent with Fermi.

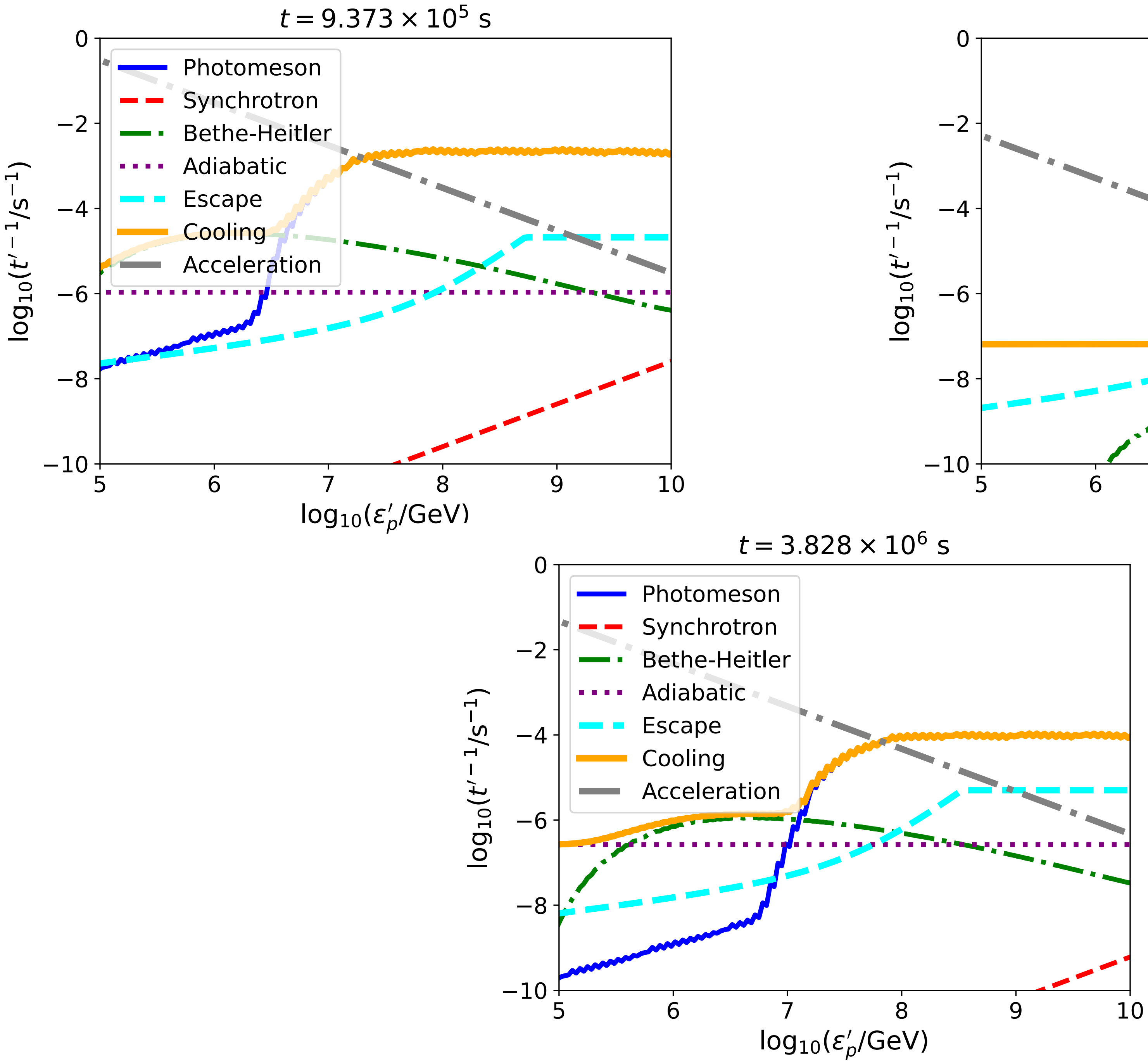
- **Rubin LSST's SLSN catalog + next-generation neutrino telescopes makes population-level neutrino searches realistic.**

Multimessenger observations can test what powers superluminous supernovae.

Thank You!

Backup

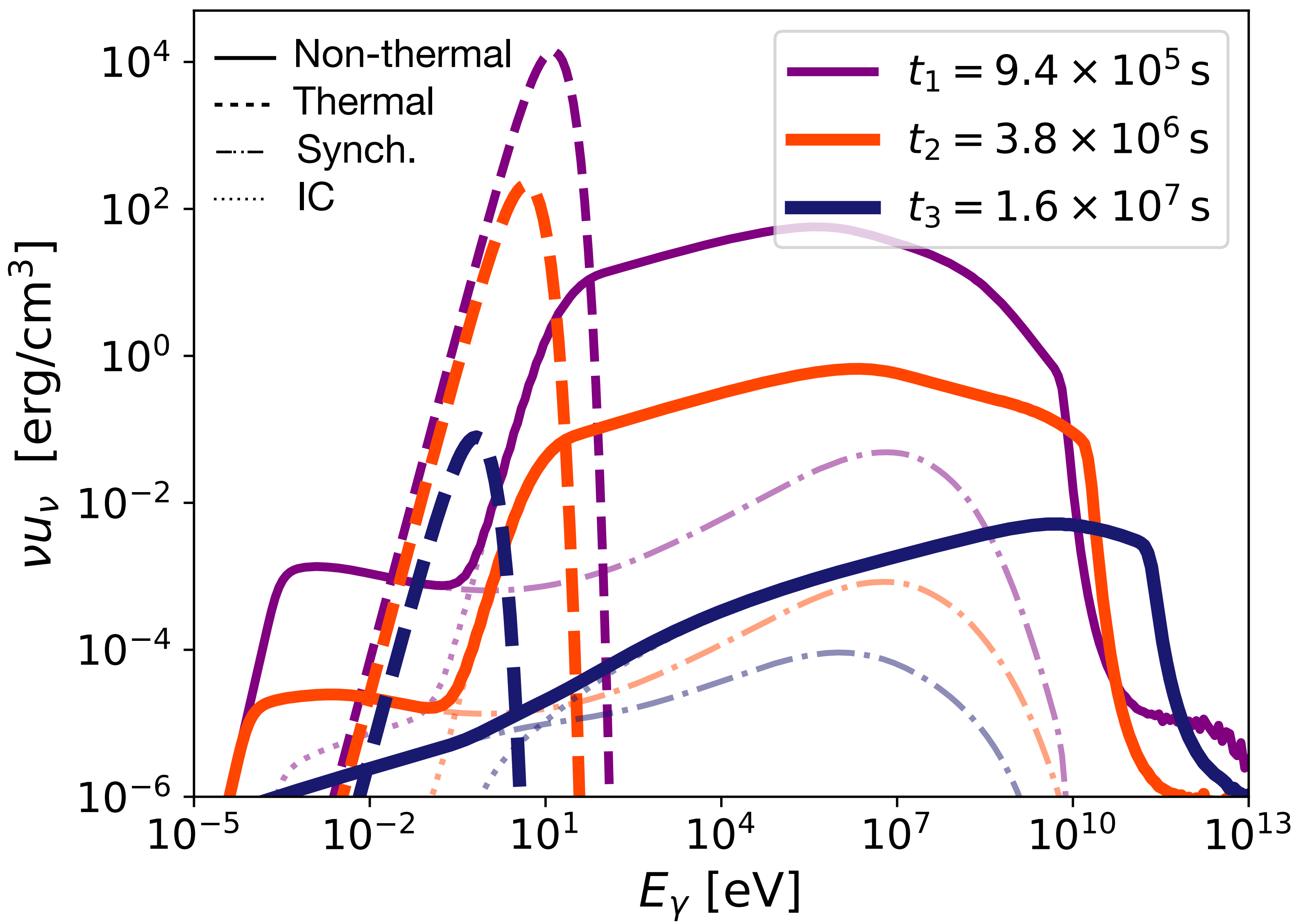
Timescales for neutrinos



Ejecta composition

Element	Comp. ($M_\odot \times 10^{-2}$)	Num. Frac. (N_0)
H	0.464	0.0109
He	155	0.9184
C	9.33	0.0184
N	1.07	0.0018
O	25.1	0.0372
Si	7.64	0.0064
S	2.86	0.0021
Ca	0.548	0.0003
Fe	0.360	0.0002
Co	0	0.0
^{56}Ni	10.5	0.0042

Nebular photon spectra



Evolution of nebular radius and optical depth