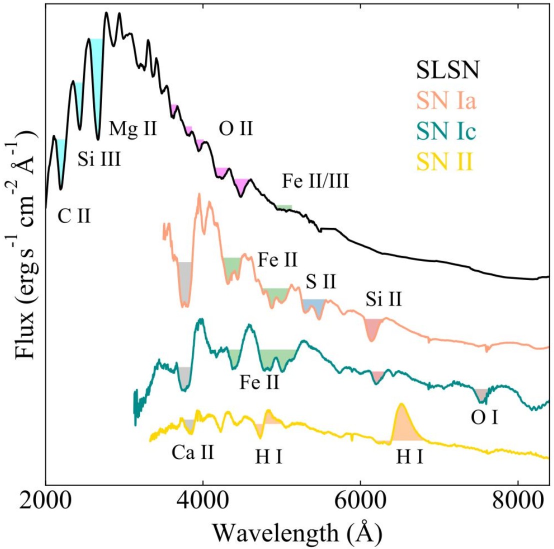
Late-Time Observations of Hydrogen-Poor Superluminous Supernovae

Peter Blanchard
CIERA Postdoctoral Fellow
Northwestern University
Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA)

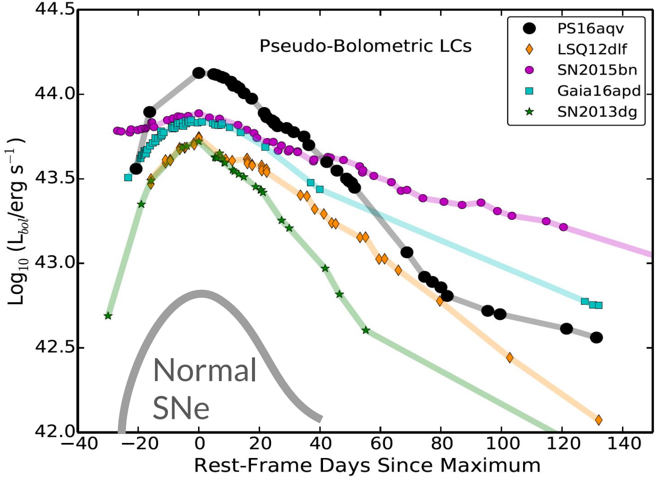
The Transient and Variable Universe - June 20, 2023

Hydrogen-Poor Superluminous Supernovae

Defies the standard radioactive decay model that explains the luminosities of normal supernovae



Nicholl 2021



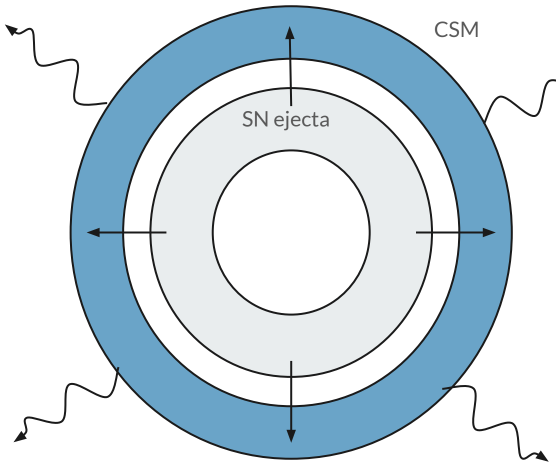
Blanchard et al. 2018

Key Questions:

- What powers their luminous light curves?
    - Are there multiple power sources?
- What types of stars explode as SLSNe?

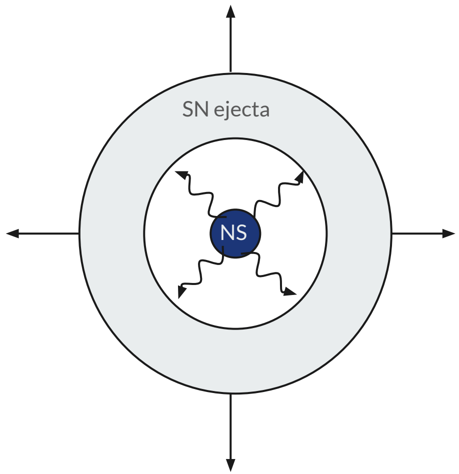
Proposed Models for SLSNe

Circumstellar Interaction



Shock interaction with previously ejected material (e.g. Chevalier & Irwin 2011)

Magnetar Central Engine

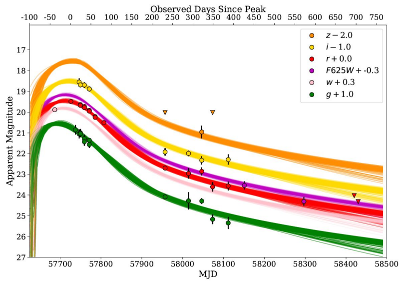


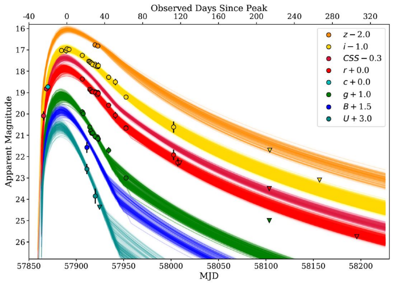
Rotational energy from a highly magnetized neutron star (e.g. Kasen & Bildsten 2010, Woosley 2010)

The Magnetar Model Explains SLSN Diversity

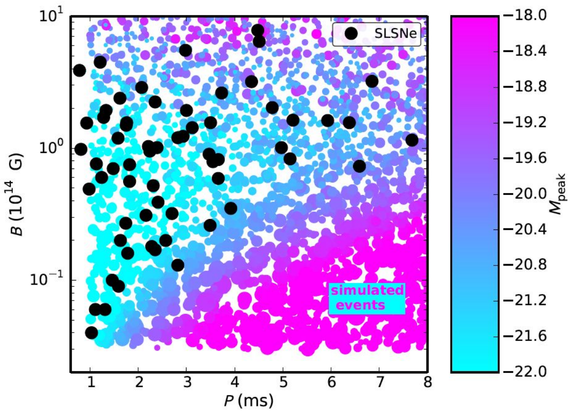
Magnetar models are able to explain the wide range of observed timescales and luminosities

Requires NS spin periods of ~1-8 ms and magnetic fields of ~10^{13}-10^{15} G

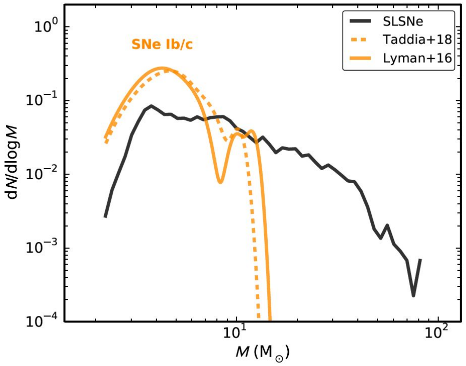




Blanchard et al. 2019
Blanchard et al. 2021



Blanchard et al. 2020



Progenitors are on average more massive than those producing normal SNe

(see also sample studies by Chen et al. 2023, Angus et al. 2019, De Cia et al. 2018, Lunnan et al. 2018, Nicholl et al. 2017)

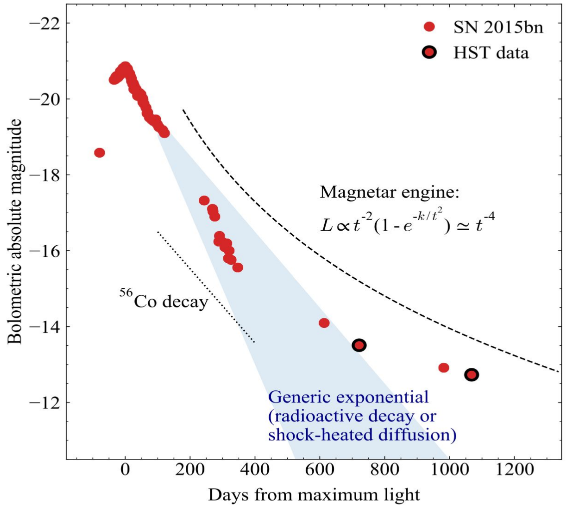
The Physics of Magnetar-Powered SNe

How does a magnetar transfer its energy to the surrounding SN ejecta?

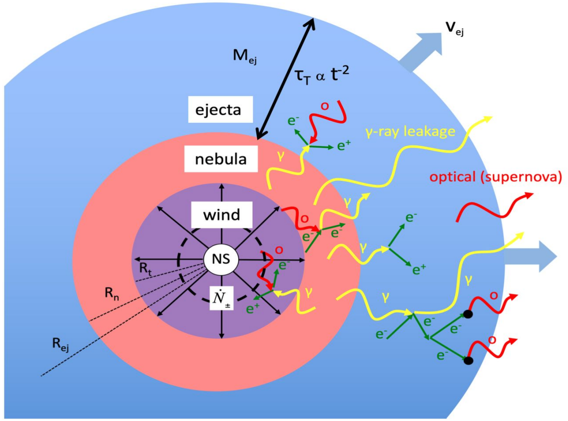
How does it impact the structure and ionization state of the inner ejecta?

Searching for Unique Signatures with Late-time Follow-up

Magnetar spin-down predicts continued heating to late times → Light curve will track the thermalized engine luminosity



Nicholl 2021

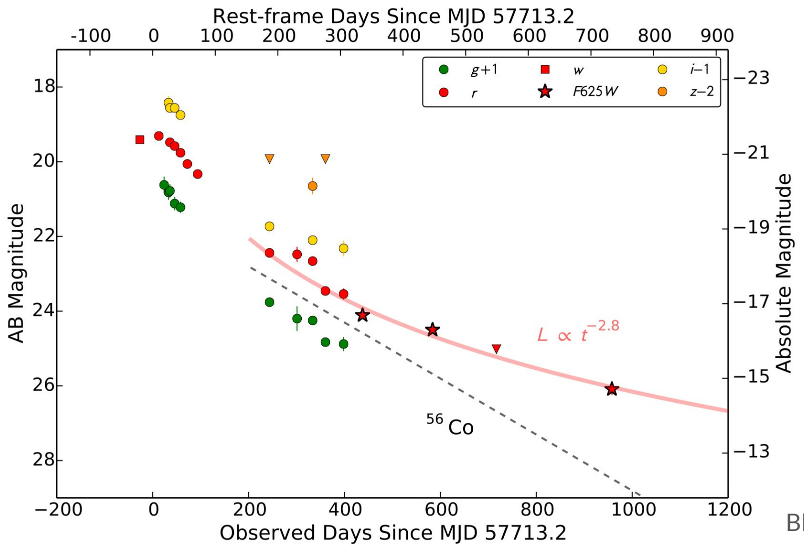


Vurm & Metzger 2021

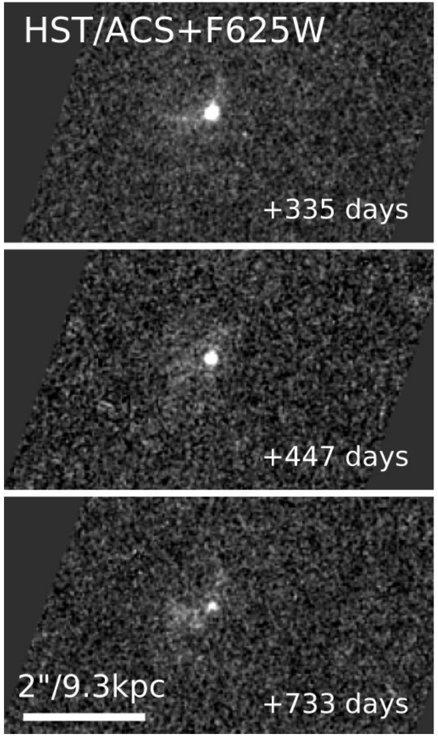
How is the magnetar's energy thermalized?
How much energy leaks out?

SN 2016inl

Late-time HST observations reveal light curve flattening consistent with the power-law spin-down of a magnetar

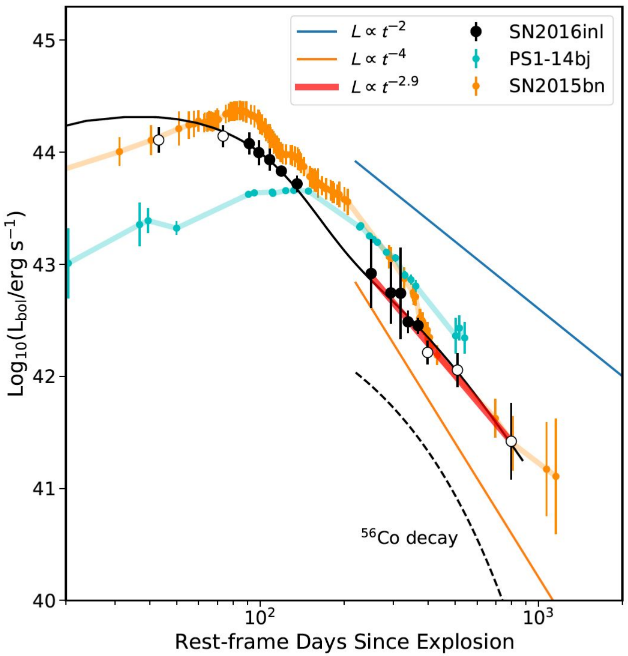


Blanchard et al. 2021



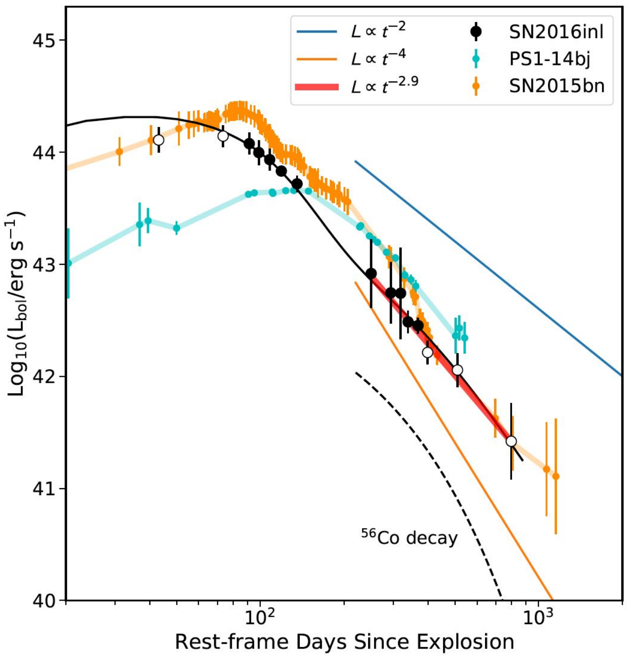
Rules out exotic theories such as pair-instability SNe

Evidence for Diverse Late-time Behavior



Blanchard et al. 2021

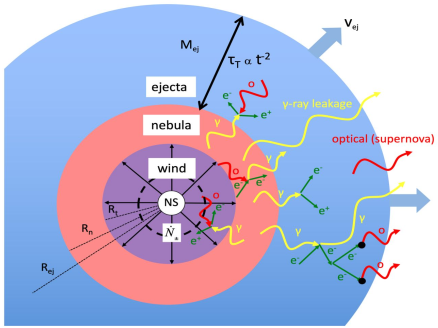
Evidence for Diverse Late-time Behavior



Blanchard et al. 2021

SLSNe follow power-law declines at late times with steeper slopes than expected for complete thermalization of the magnetar's energy

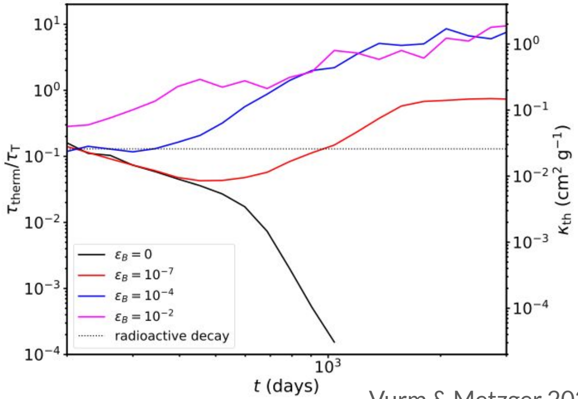
Implies that an increasing fraction of high energy radiation is leaking out



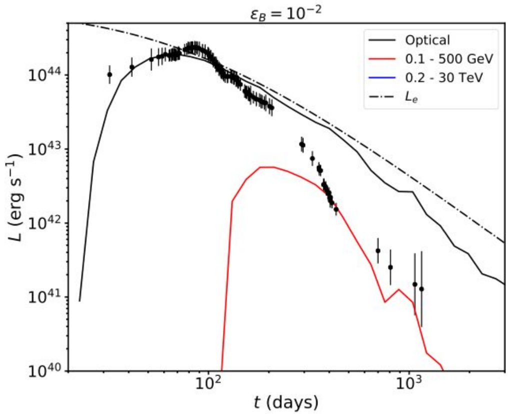
Vurm & Metzger 2021

Radiative Transfer Simulations Predict Complex Behavior

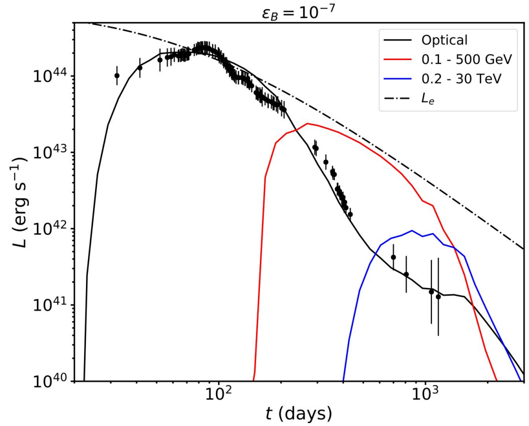
Gamma-ray thermalization opacity



High magnetization



Low magnetization

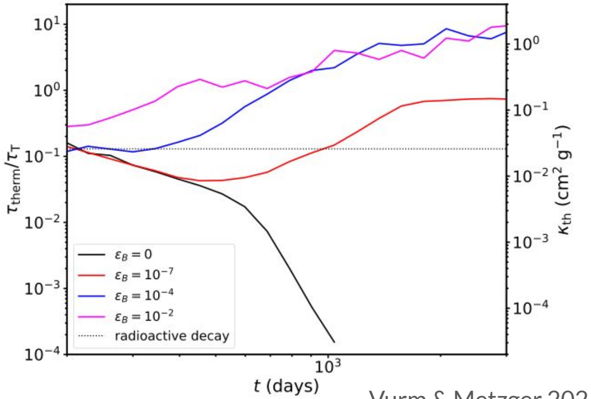


Vurm & Metzger 2021

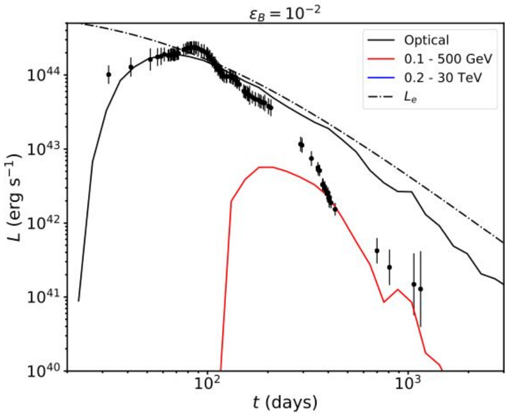
Late-time slope and evolution are sensitive to the gamma-ray opacity, which in turn is related to properties of the magnetar wind nebula (Vurm & Metzger 2021)

Radiative Transfer Simulations Predict Complex Behavior

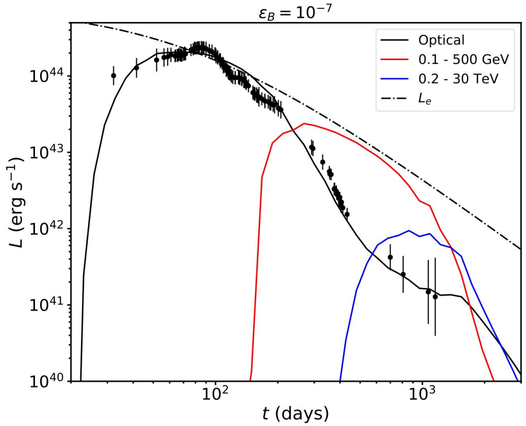
Gamma-ray thermalization opacity



High magnetization



Low magnetization



Vurm & Metzger 2021

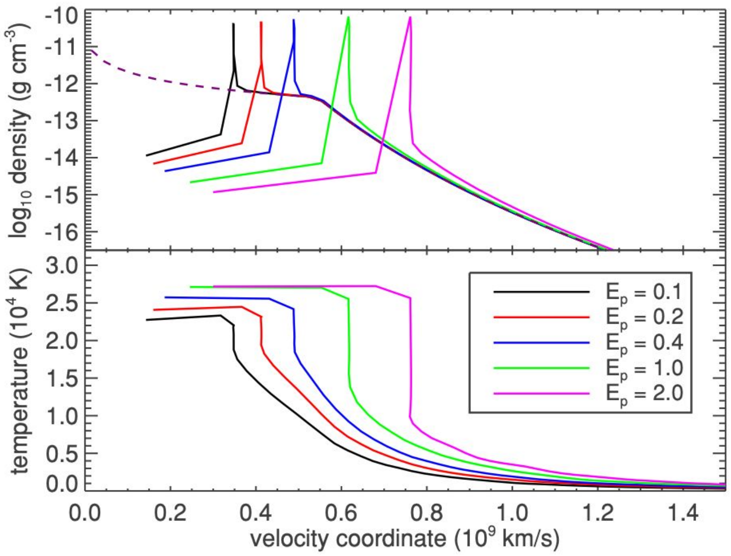
Late-time slope and evolution are sensitive to the gamma-ray opacity, which in turn is related to properties of the magnetar wind nebula (Vurm & Metzger 2021)

These predictions strongly motivate future observations with HST/JWST to probe the thermalized luminosity at even later times and with high-energy telescopes to directly search for the escaping energy

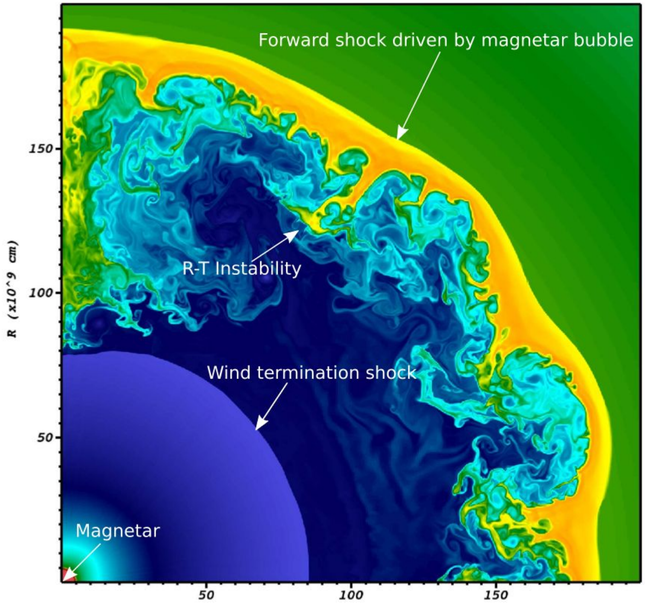
See existing high-energy limits by Bhirombhakdi et al. 2018, Margutti et al. 2018, Renault-Tinacci et al. 2018, Andreoni et al. 2022

Hydrodynamical Effects in Magnetar-Powered SNe

Energy injected by the magnetar blows a bubble in the inner ejecta that expands and sweeps the ejecta into a dense shell → fluid instabilities lead to mixing/clumping of ejecta

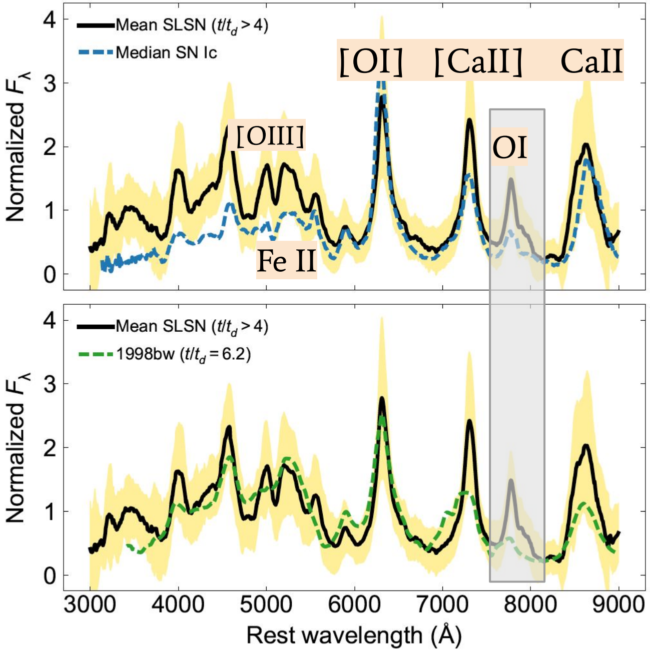


Kasen & Bildsten 2010

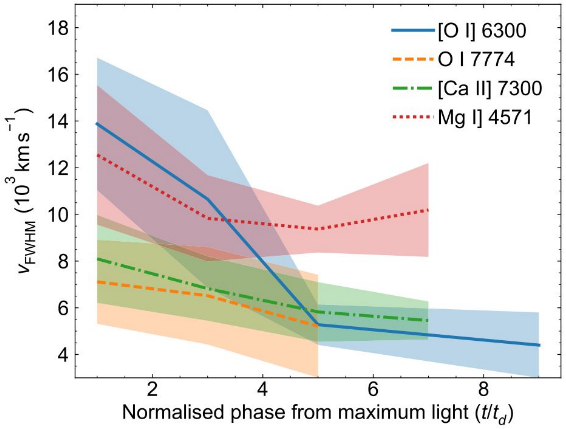


Chen et al. 2016

Nebular Phase Spectra of SLSNe

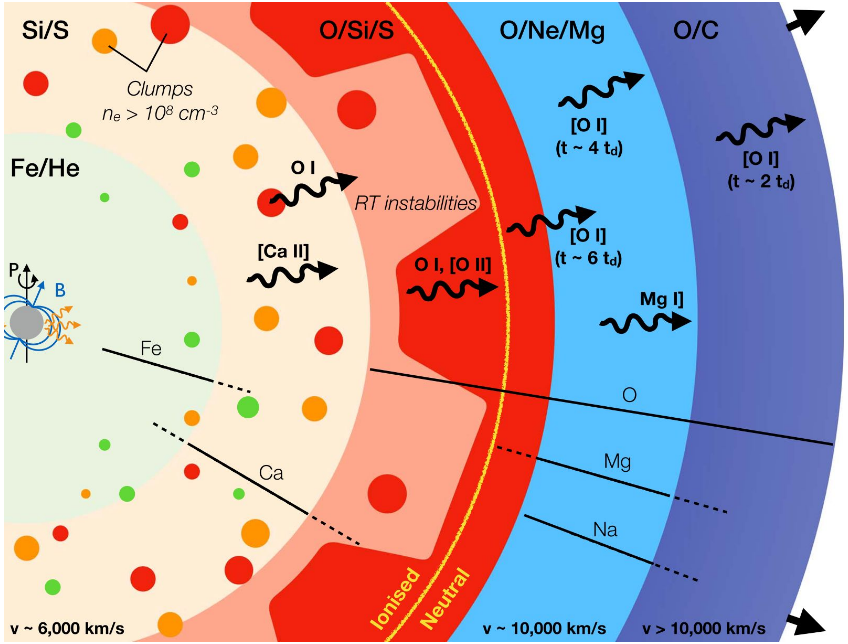


- Strong Fe II, [OI] 6300, [OIII] 5007, [Ca II] 7300, and OI 7774 lines
- Velocity structure indicates OI and [Ca II] are from the inner ejecta
- Distinct from normal SNe



Nicholl, Berger, Blanchard, et al. 2019

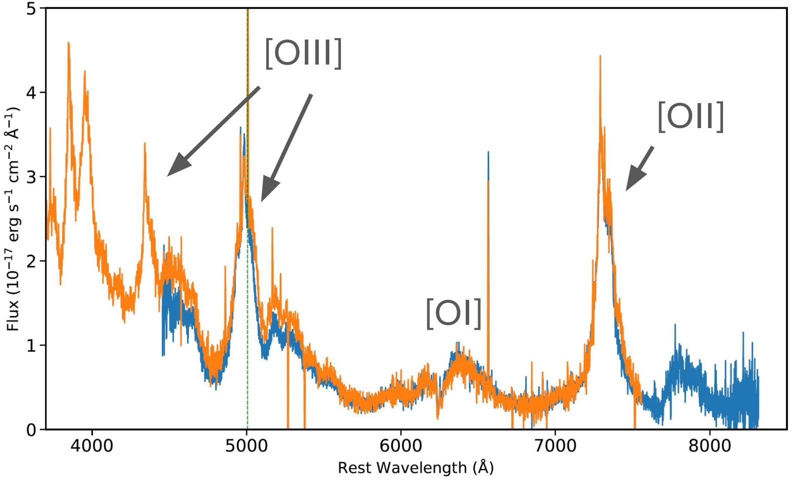
An Emerging Picture of the Ejecta Structure



Nicholl, Berger, Blanchard et al. 2019

Observed emission-line properties are consistent with a clumpy, ionized inner ejecta as predicted by simulations

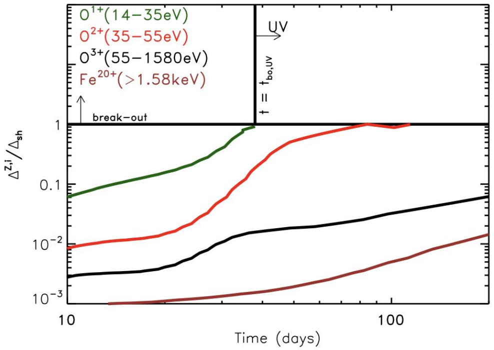
Insights From New Observations



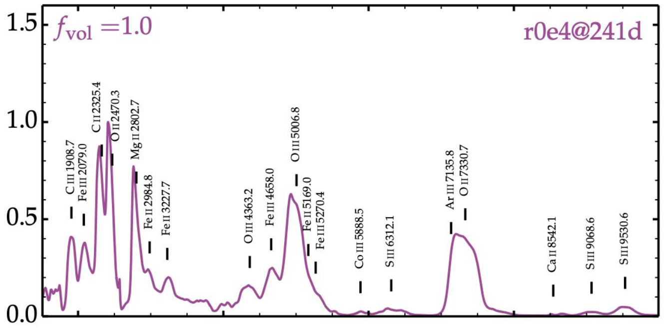
Weak [OI] and strong [OII] and [OIII] lines

→ High fraction of ejecta is ionized

Blanchard et al. in prep.



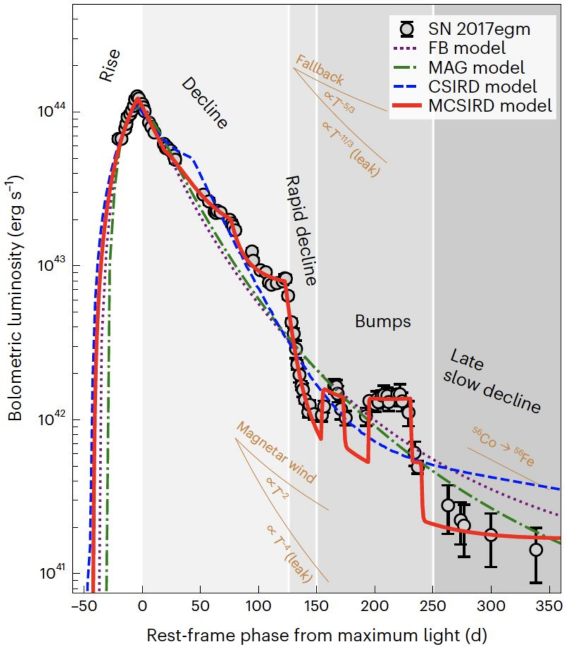
Metzger et al. 2014



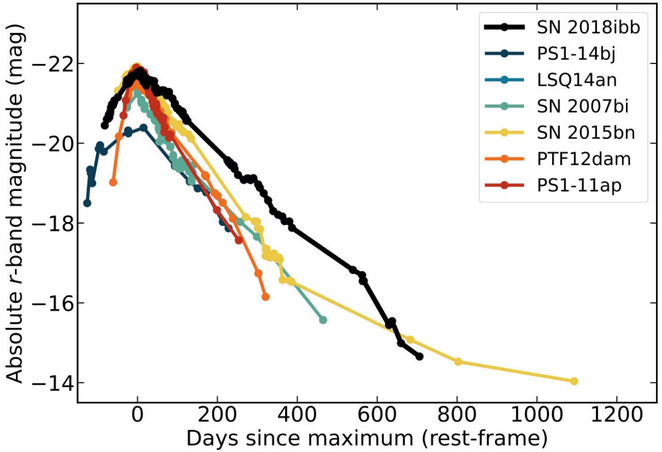
Dessart 2019

The Growing Number of (Pulsational) Pair-Instability Candidates

SN 2017egm (Lin et al. 2023)



SN 2018ibb (Shulze et al. 2023)



These events further highlight the need for late-time observations to probe the underlying power source

Summary

Late-time light curves of SLSNe

- Late-time HST observations of SN2015bn and SN2016inl revealed power-law declines consistent with magnetar energy input

- Future observations at both optical and high-energy wavelengths will constrain the properties of the magnetar wind nebulae, providing the definitive test of this model

Nebular Phase Spectra of SLSNe

- Observed emission-line properties are consistent with a clumpy, ionized inner ejecta as predicted by hydrodynamical simulations of magnetar-powered SNe

Some of the work presented here is based on observations from Keck and MMT obtained through time provided by Northwestern/CIERA