Magnetars as powering sources of GRB-associated SNe

17th Marcel Grossmann Meeting, session: GRB-SN connection
7-12 July 2024

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GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

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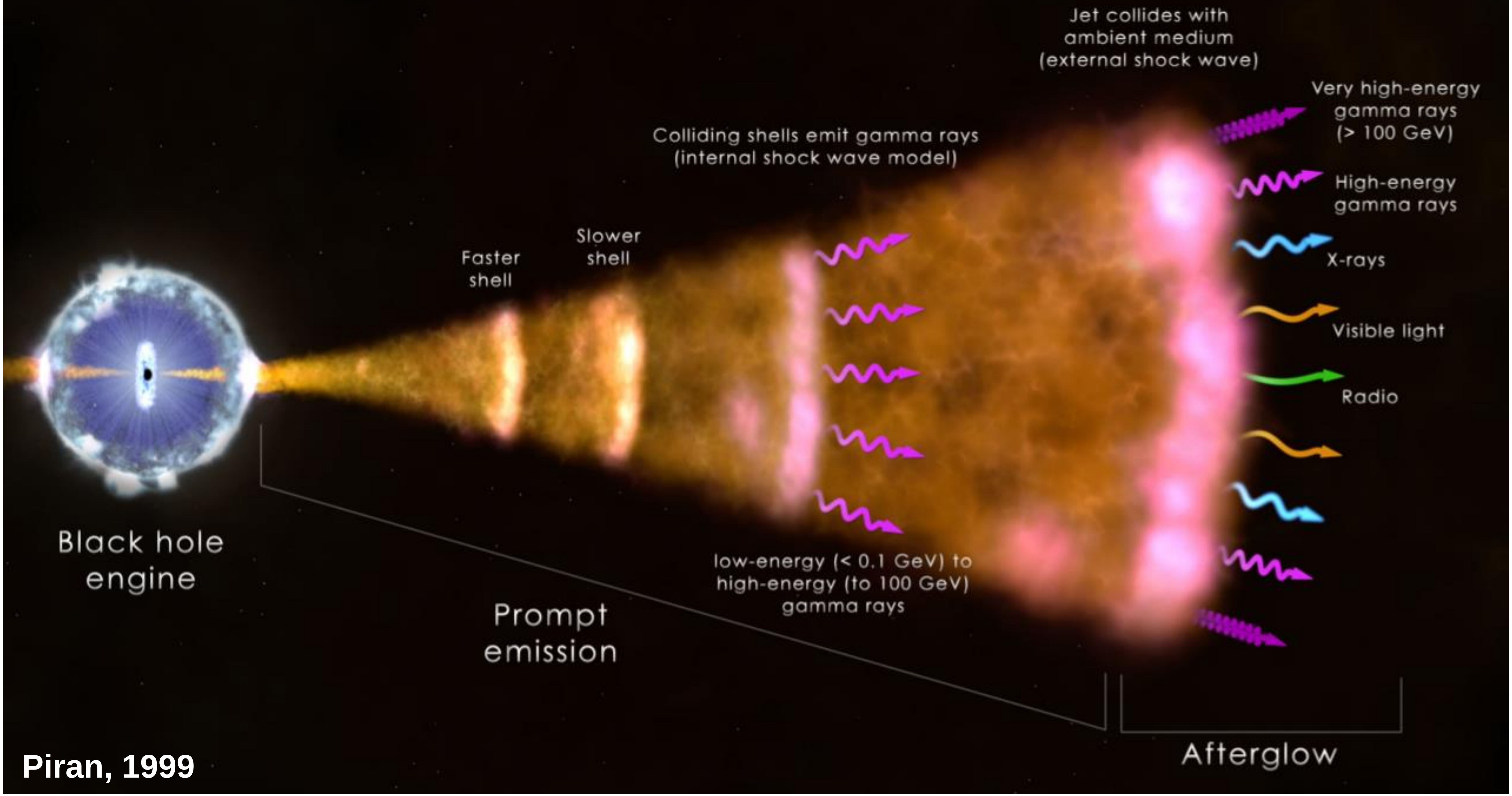
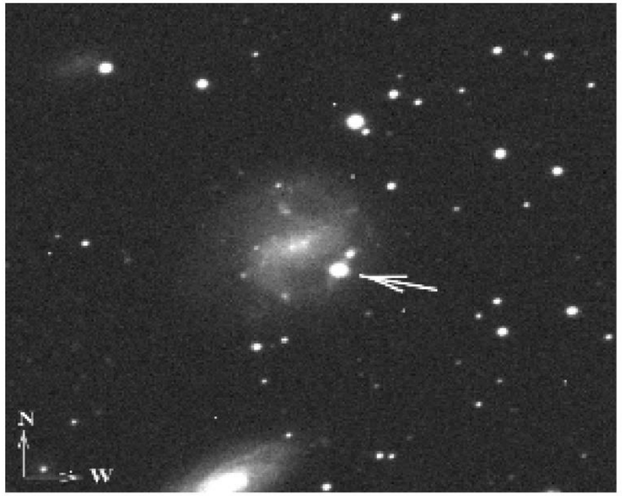
Fireball Model

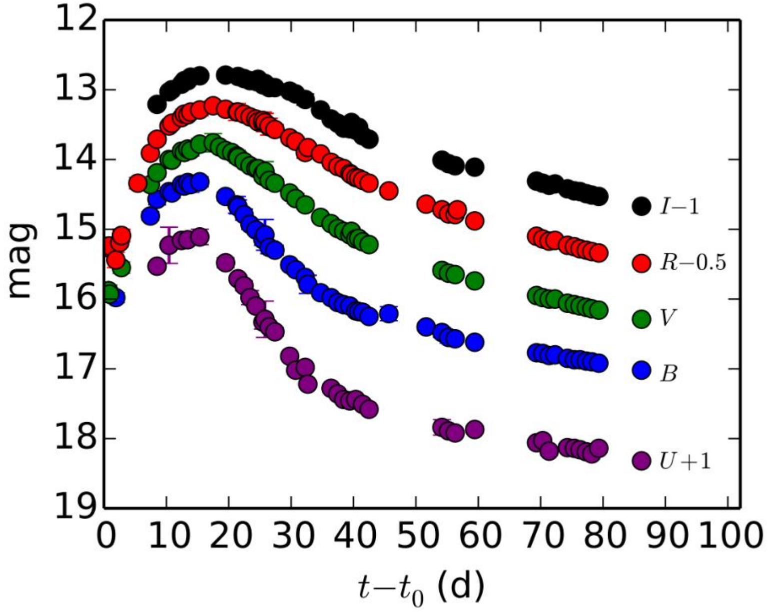


Piran, 1999

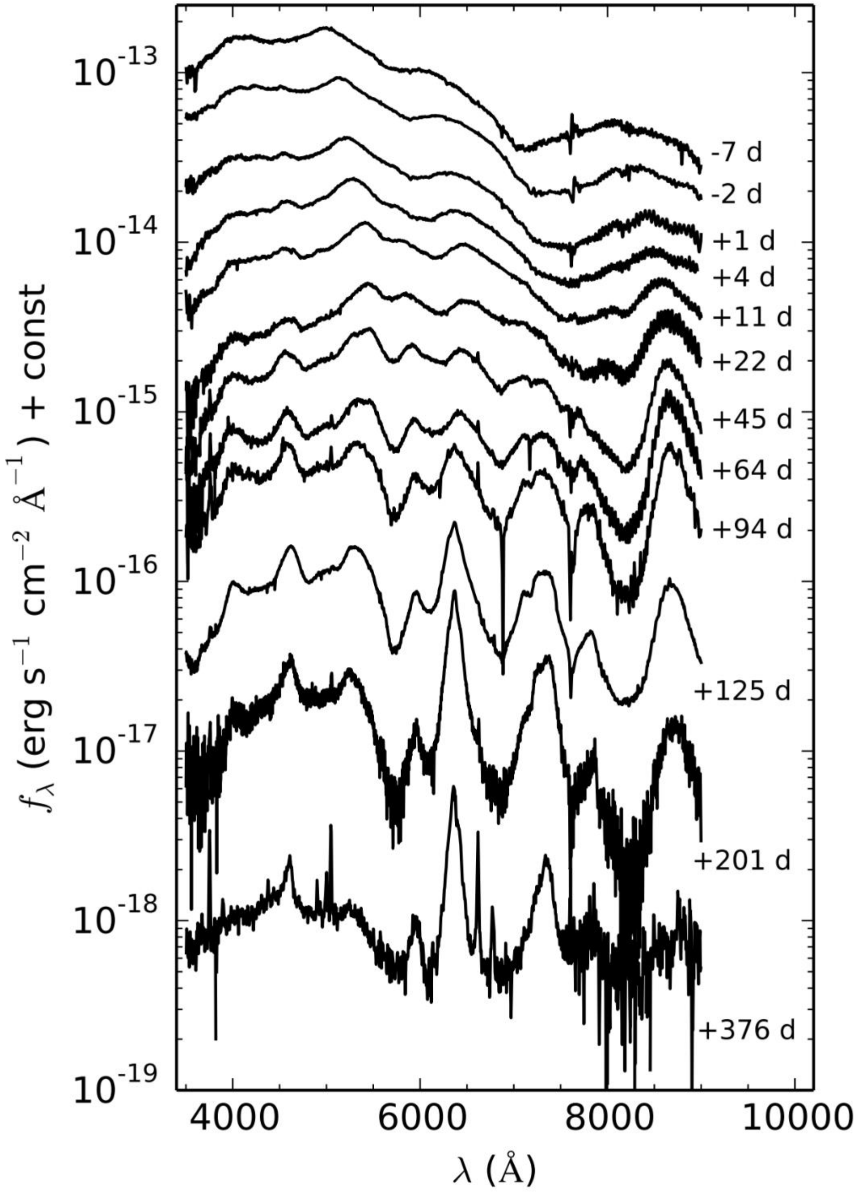
GRB-SNe connections - Discovery!



ESO 184-G82



Patat et al., 2001



Clocchiatti et al., 2011

1998

- Started with the closest LGRB 980425 and SN 1998bw.
- GRB 980425 exhibit lower luminosity than other cosmological LGRBs.

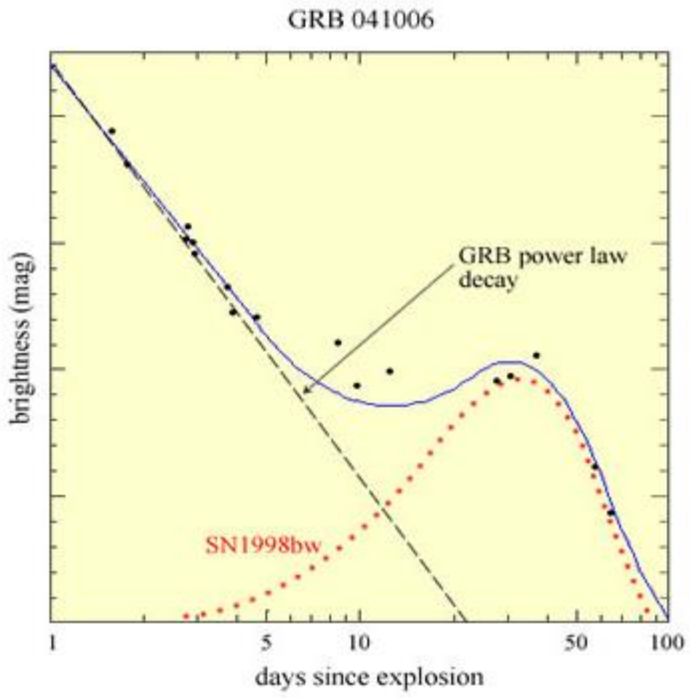
2003

- The discovery of GRB 030329 and associated SN 2003dh confirmed GRB-SNe association.

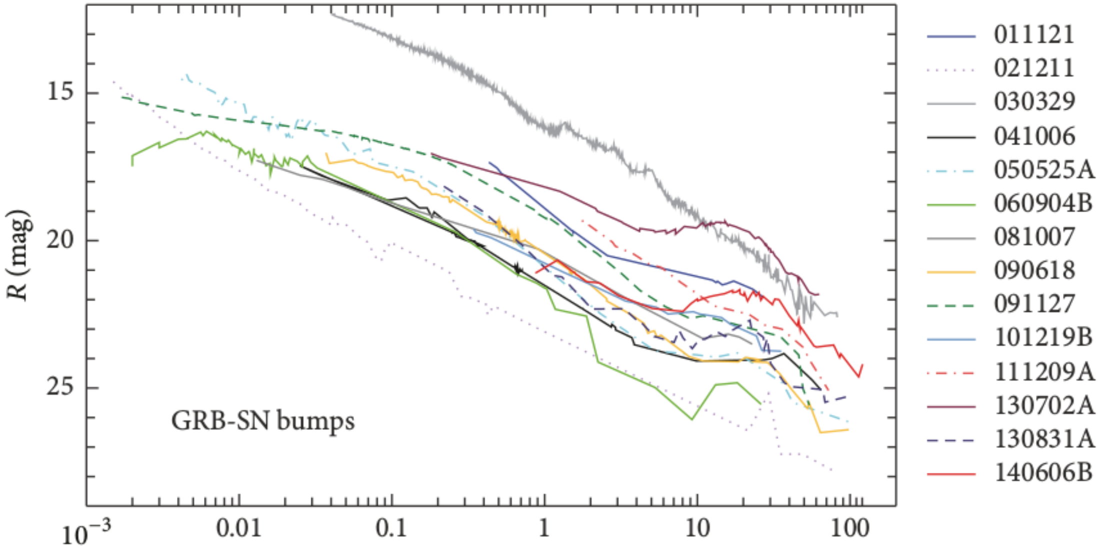
GRB-SNe connections - signatures

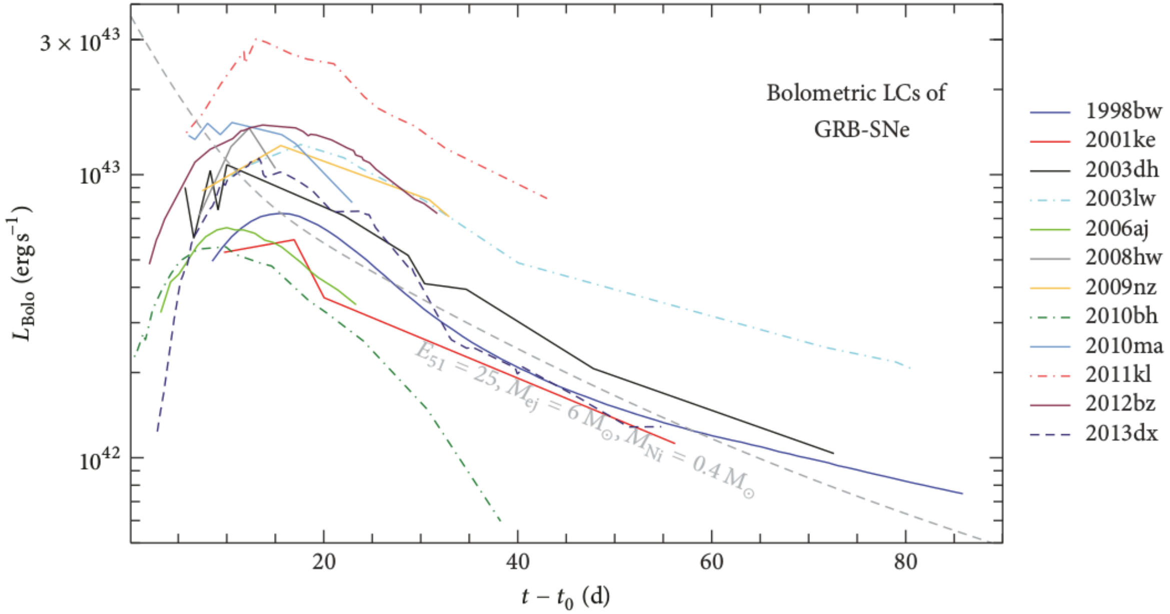
- To date, more than 50 LGRBs have been discovered with signatures of associated SNe and provide direct evidences of GRB-SNe connections.

- GRB-SNe light curves consist contributions from the Afterglow + SN + Host



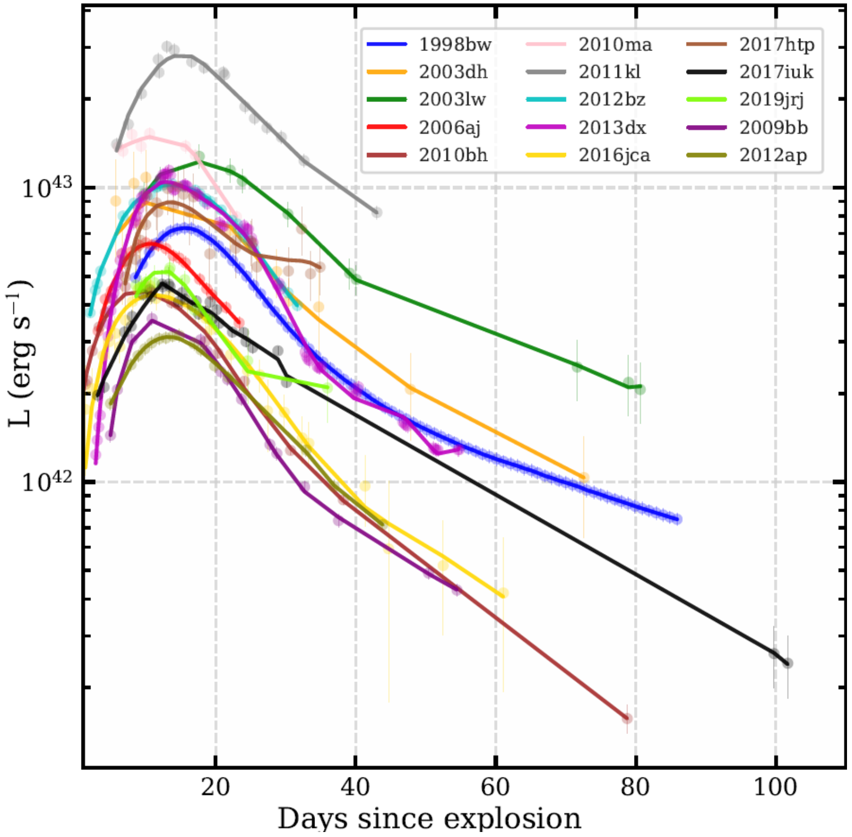
Stanek et al. 2005



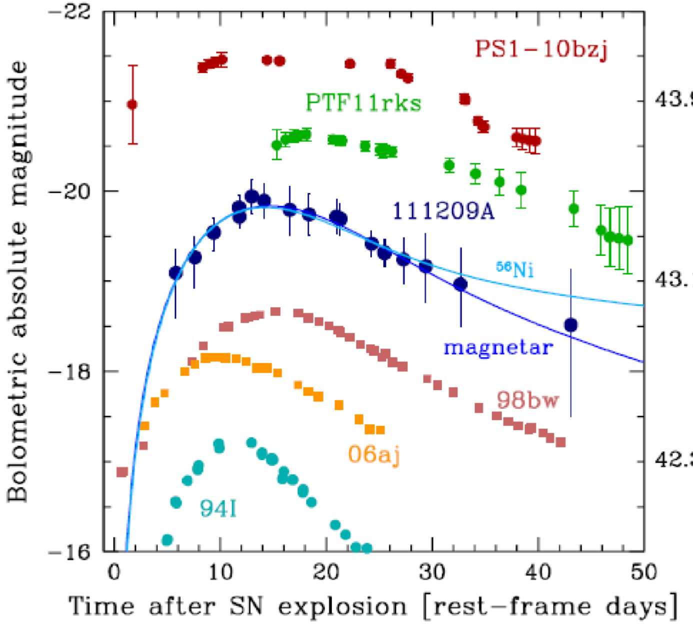


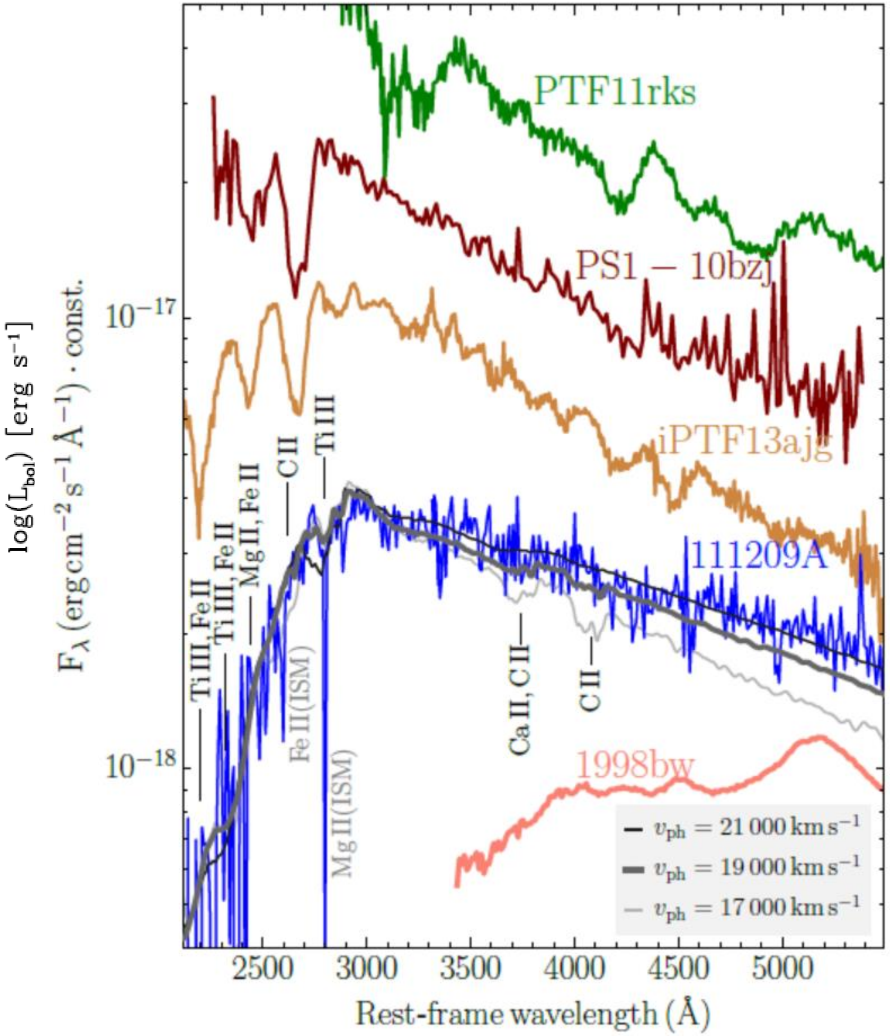
Cano et al. 2017

Unique and one and only ULGRB-SLSN case



Kumar et al. 2024b

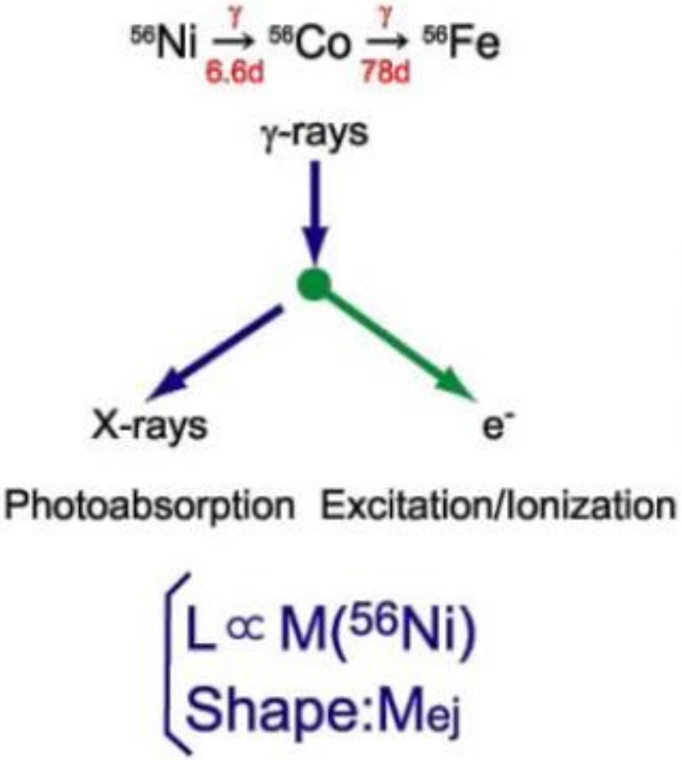


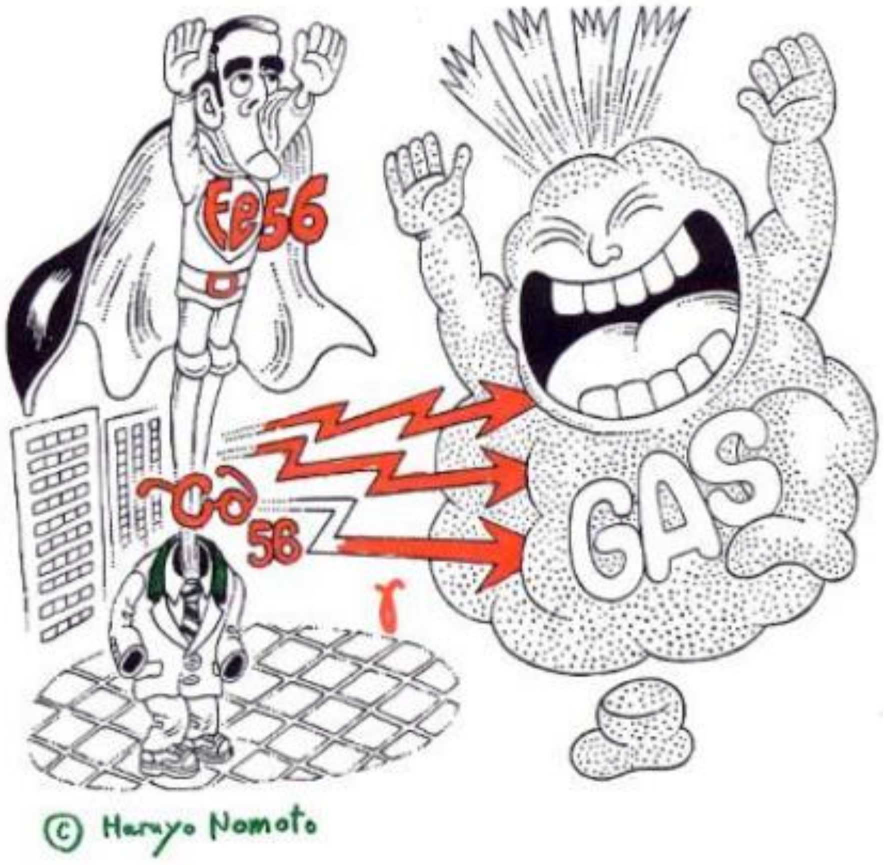


Greiner et al. 2015

Powering mechanisms of Supernovae

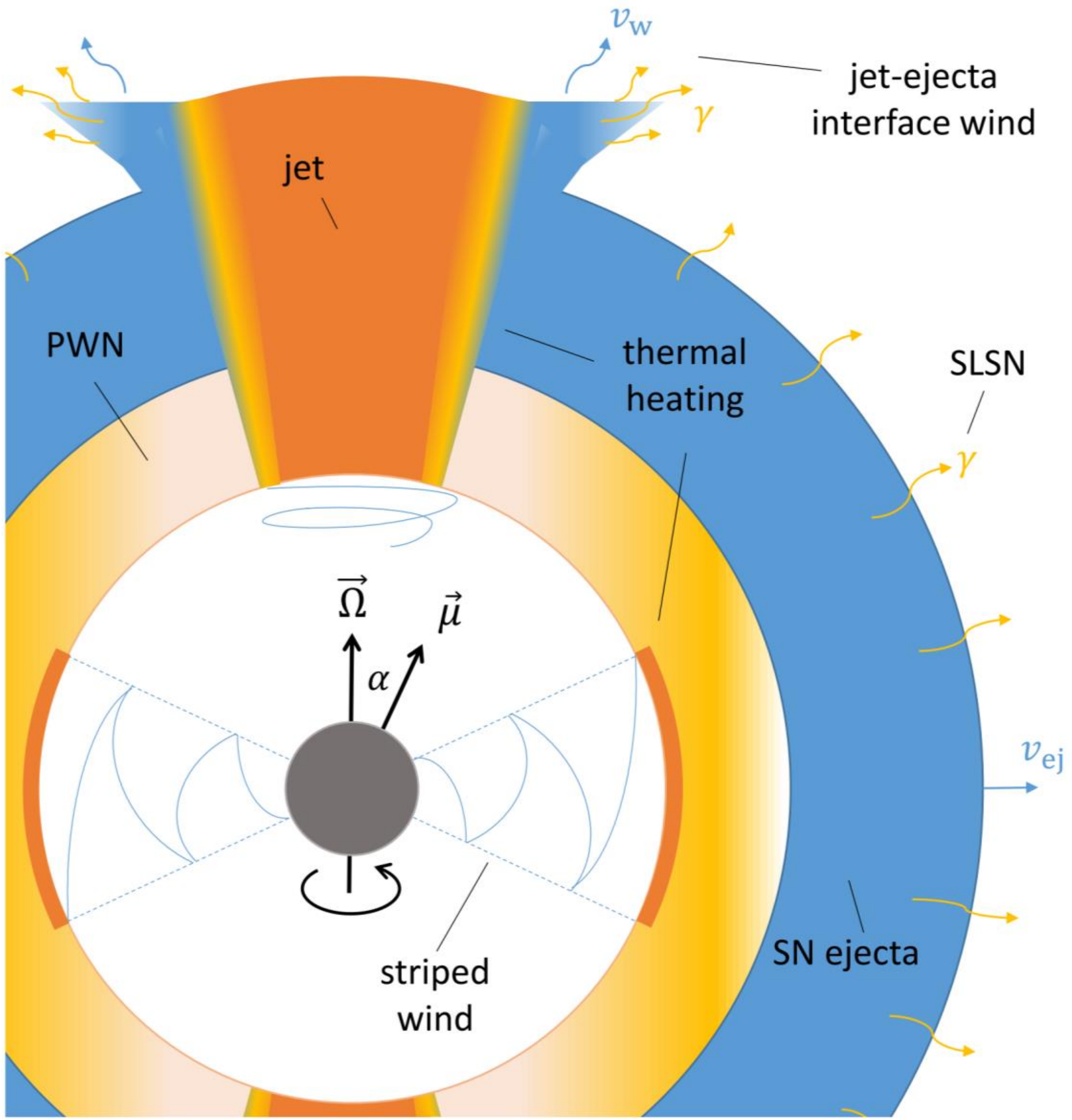
^{56}Co-decay





- **Radioactive Decay**
- **Pair-Instability SN**
- **Spin-down Magnetar**
- **CSM Interaction**
- **Hybrid**

Powering mechanisms of Supernovae



Margalit et al. 2018

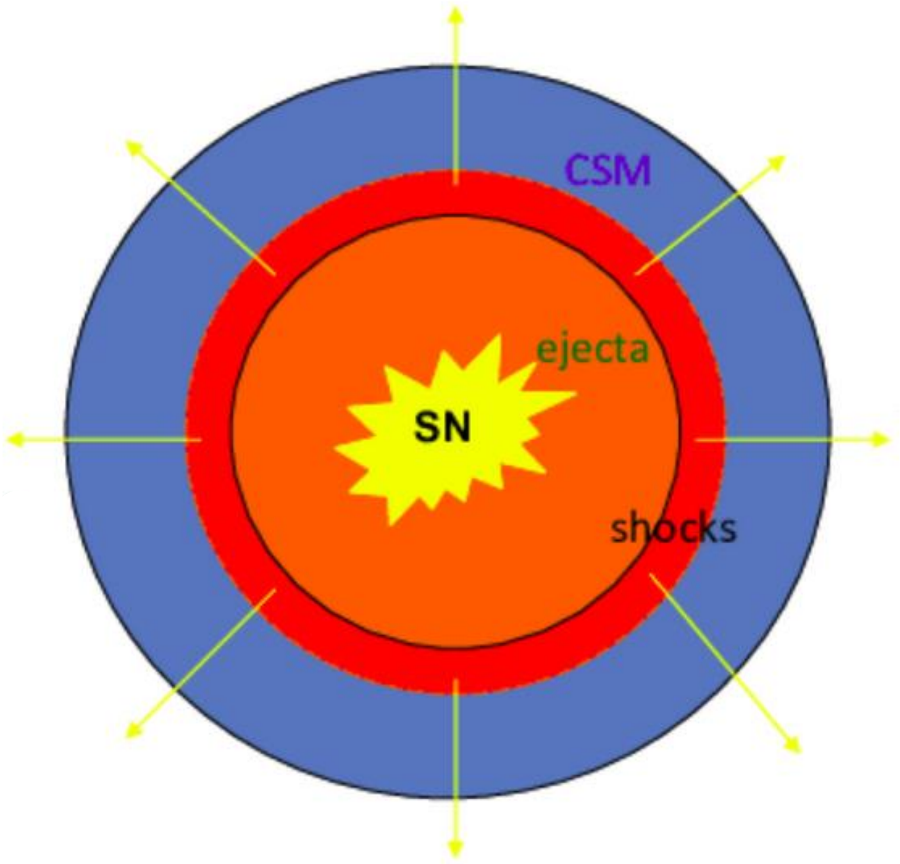
- Spin-down of a millisecond magnetar.
- Powered by rotation, energy extracted via magnetic field.

Power ~ B^2/P^4

Timescale ~ P^2/B^2

- Radioactive Decay
- Pair-Instability SN
- **Spin-down Magnetar**
- CSM Interaction
- Hybrid

Powering mechanisms of Supernovae



Chatzopoulous et al. 2016

- Mass loss and build-up of circumstellar matter around the massive stars are generic features of stellar evolution.
- SN ejecta collides & violently interacts with the CSM.
- Interaction with enshrouded CSM can boost the luminosity of SNe.
- Light curves of Type I SNe generally lack interaction signatures in their spectra.

Radioactive Decay

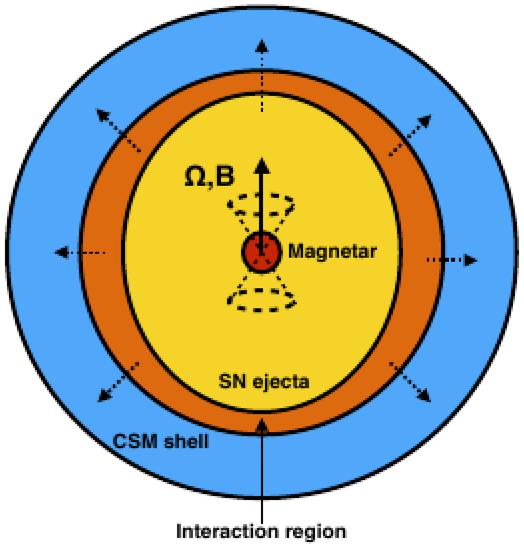
Pair-Instability SN

Spin-down Magnetar

CSM Interaction

Hybrid

Powering mechanisms of Supernovae



Massively, rapidly rotating CCSN interacting with the CSM

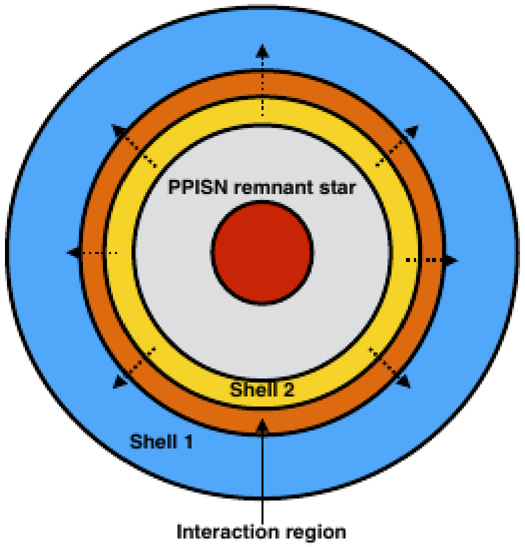
Radioactive Decay

Pair-Instability SN

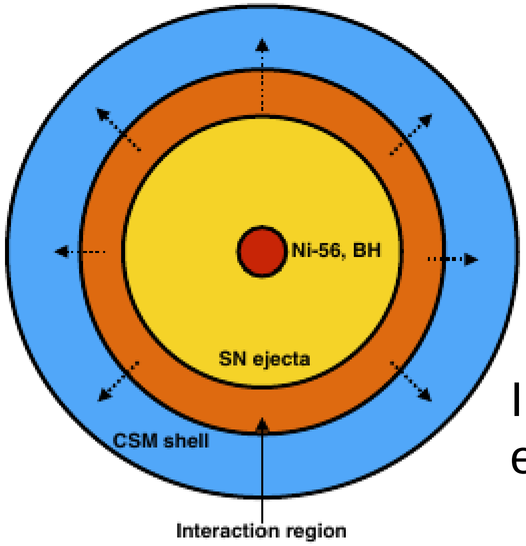
Spin-down Magnetar

Spin-down Magnetar

Hybrid



Multiple CSM interactions of a H-poor ejecta



Interaction of a radioactively powered H-poor ejecta with a CSM

Chatzopoulous et al. 2016

Powering Sources of SESNe - Magnetar origin?

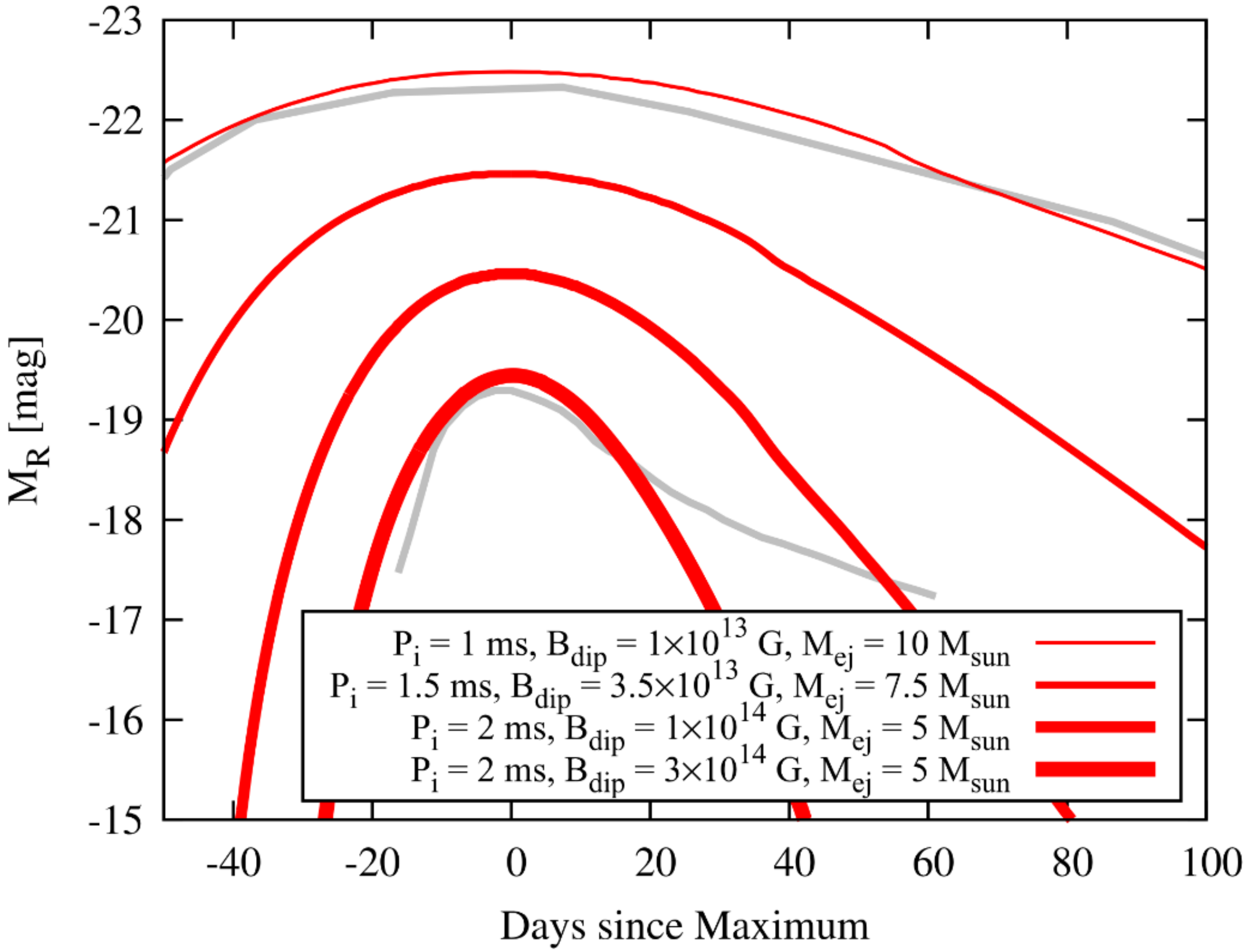
Millisecond magnetars driven SN light curves.
The upper gray line: SLSN PTF 09cnd.
The lower gray line: Ic-BL SN 1998bw.

Ordinary SNe Ibc
rotation ≳10 ms
magnetic field ≳5 x 10^{14} G

SNe Ic-BL
rotation ~ ms
magnetic field ≳5 x 10^{14} G

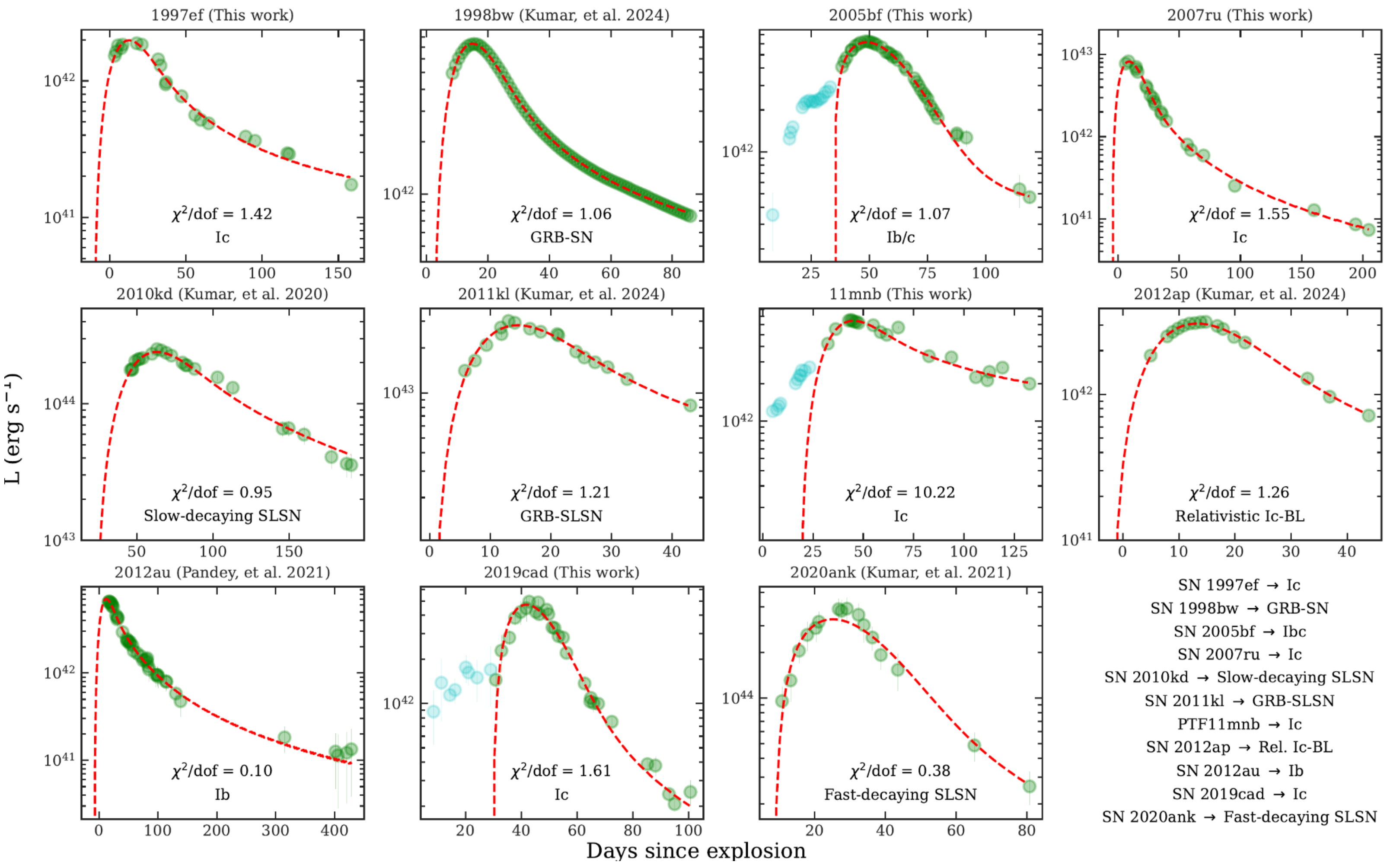
SLSNe
rotation ~ ms
magnetic field ≳10^{14} G

Claimed through modelling the energy injection from magnetized wind and ^{56}Ni decay

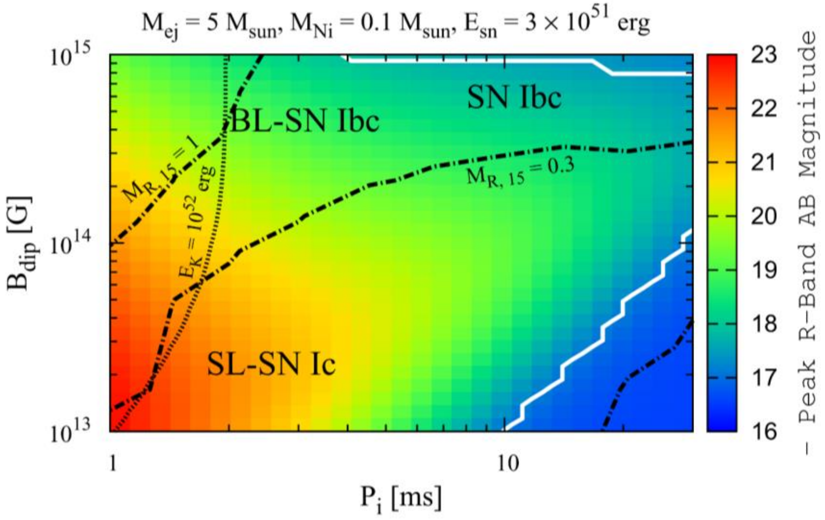


Kashiyama, K., et al. 2016

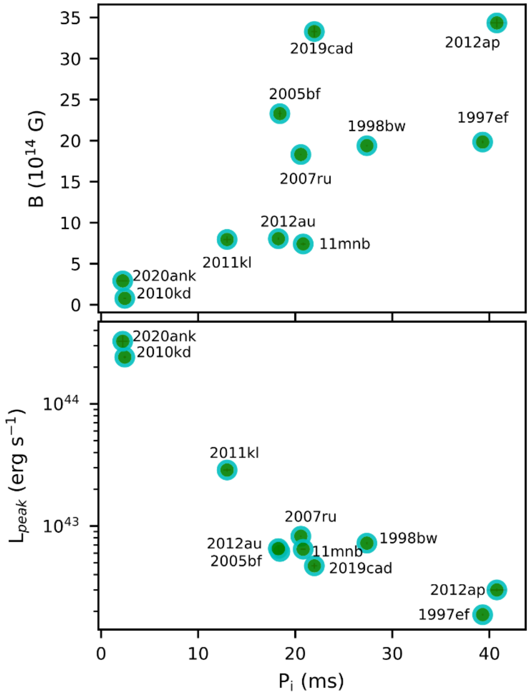
Powering Sources of SESNe - Magnetar origin?



Kumar & Steeghs, 2024a

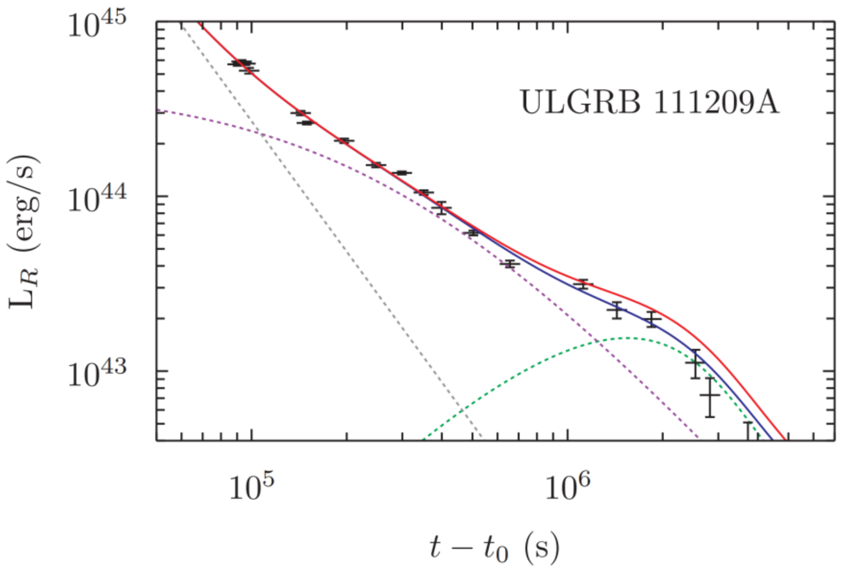


Kashiyama, et al. 2016

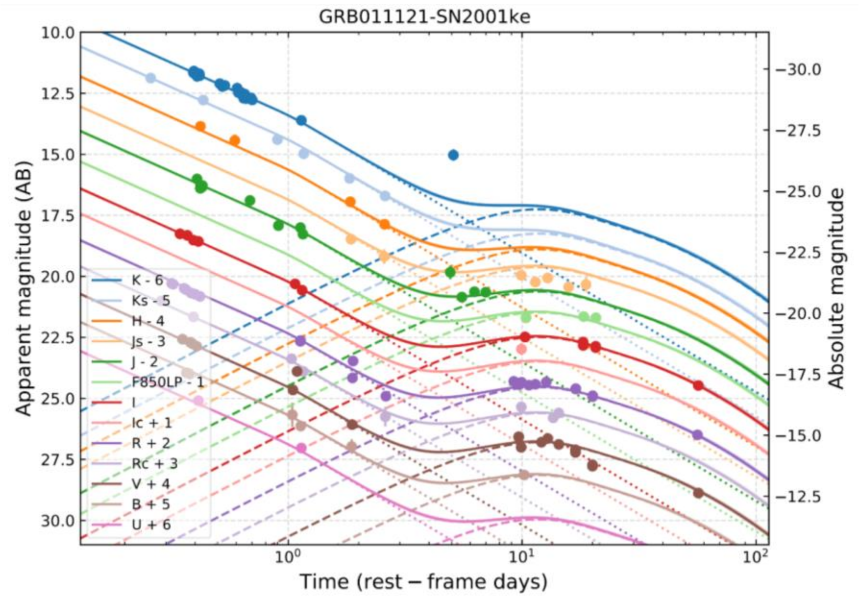


Kumar & Steeghs, 2024a

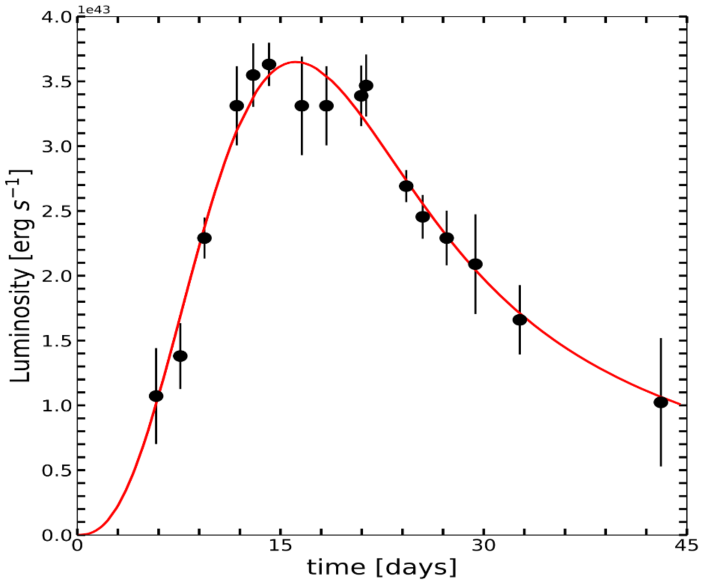
Powering Sources of SESNe - Magnetar origin?



Cano et al., 2016



Lian et al., 2022



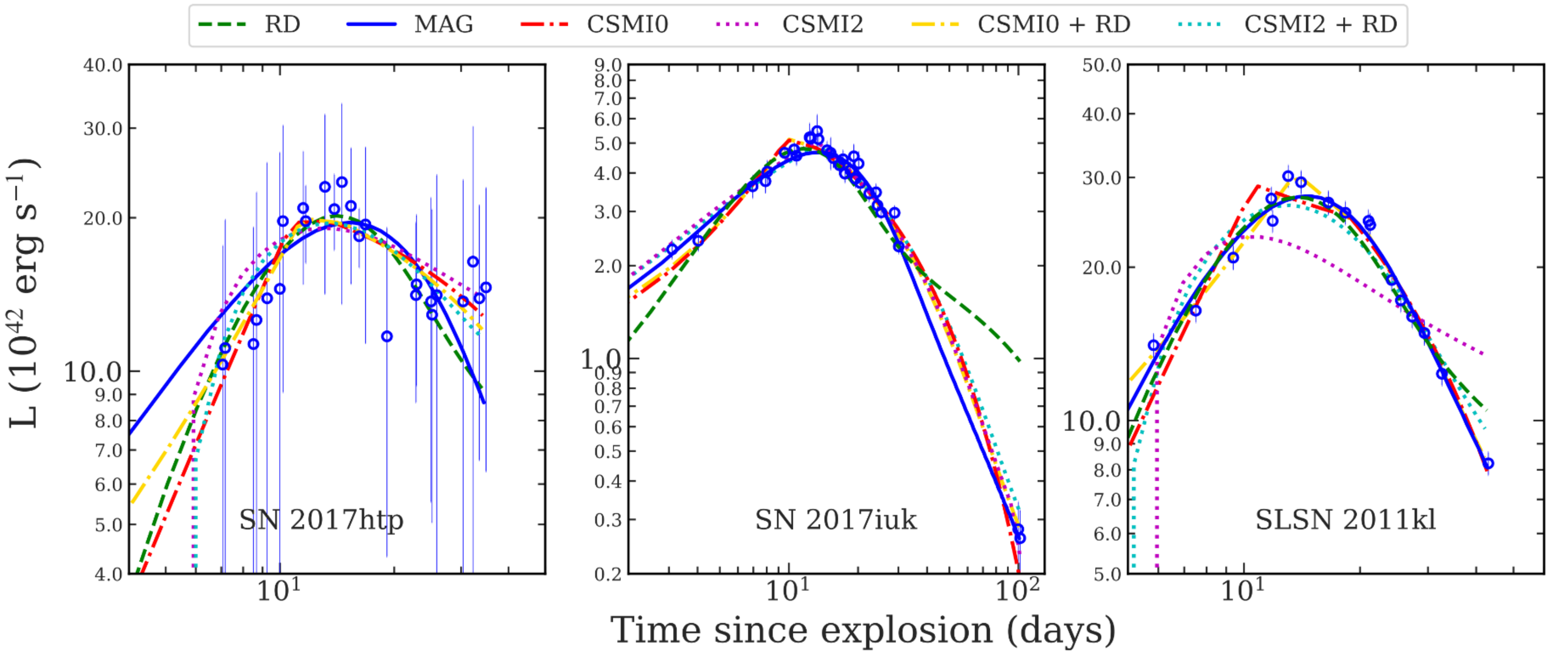
Lin et al., 2020

Successfully described all phases of ULGRB 111209A/SLSN 2011kl, from the early afterglow to the later SN considering a magnetar central engine.

Used the multi-band broken power-law plus Ni-56 model to fit the multi-band light curves of three afterglows and SNe.

Presented light-curve modelling of SLSN 2011kl using the Blandford & Payne (Blandford & Payne 1982) mechanism.

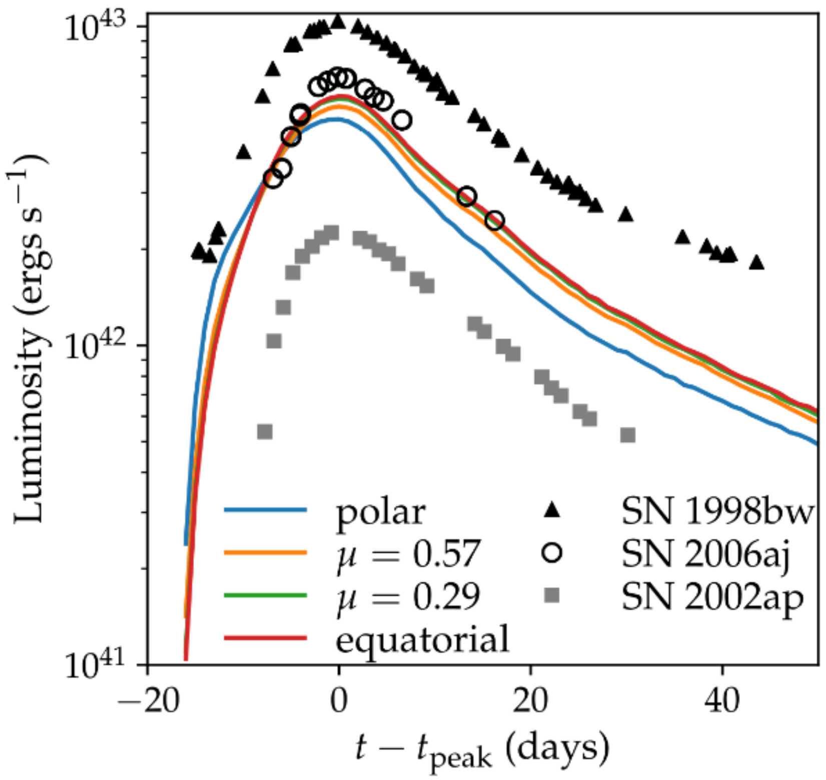
Powering Sources of GRB-SNe - Magnetar origin?



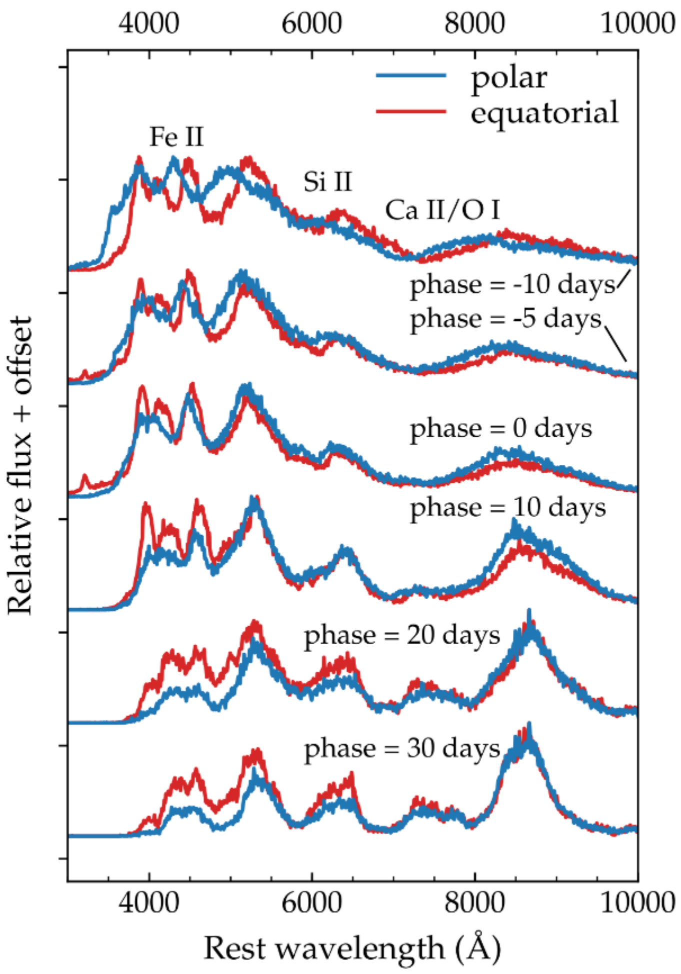
Kumar et al. 2022

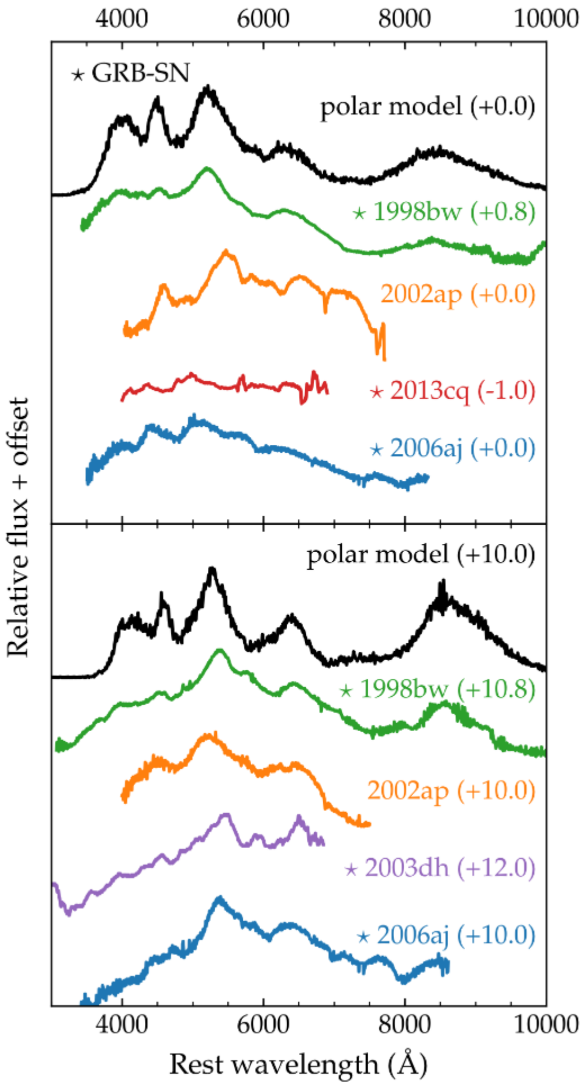
Utilising the MINIM code, bolometric light curves of SN 2017htp, SN 2017iuk and SLSN 2011kl are well-explained by spin-down millisecond magnetars as central engine powering sources.

Powering Sources of GRB-SNe - Magnetar origin?



Spectral Modelling

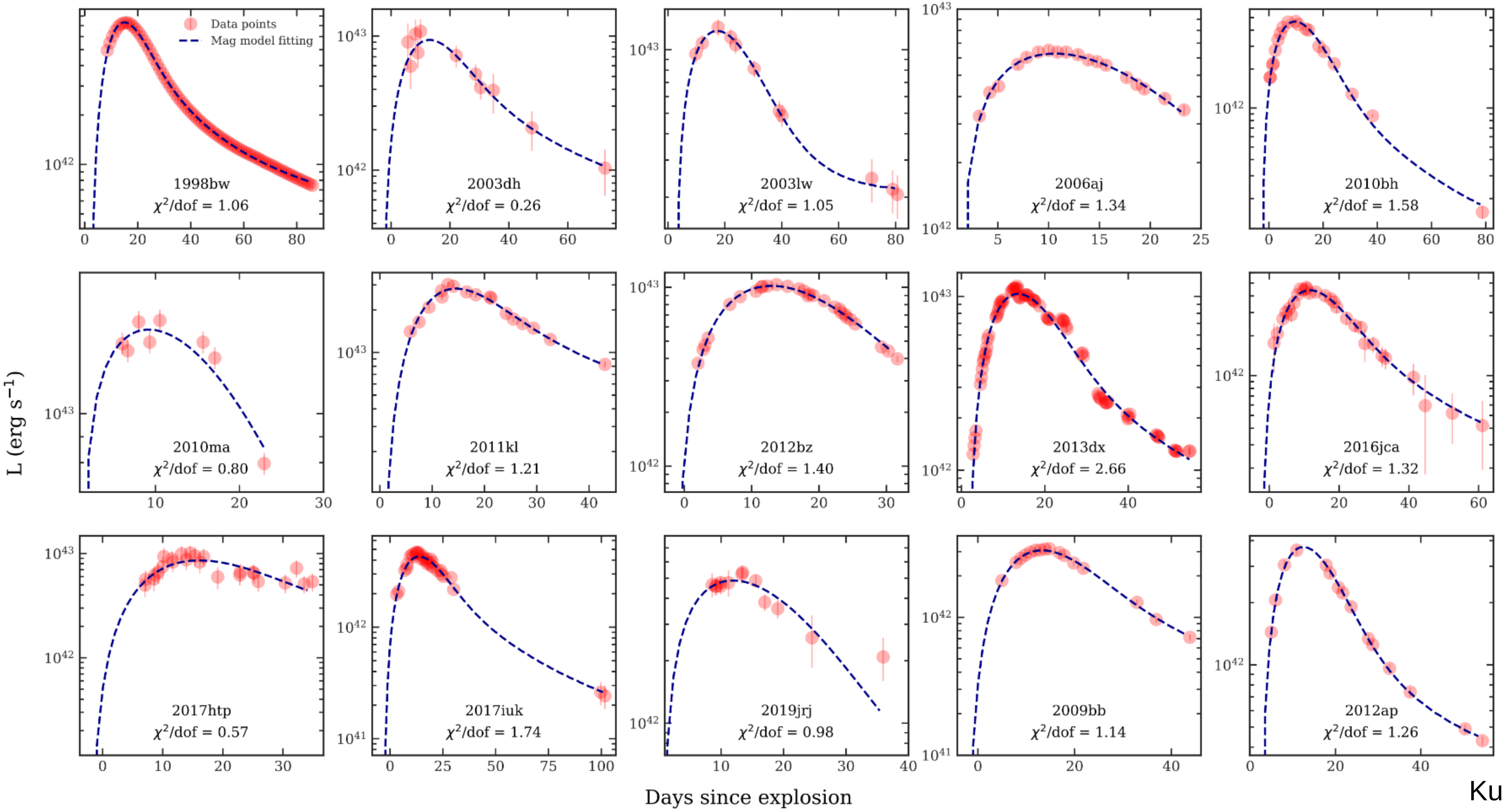




Spectral and light curve modelling of GRB-SNe through 2D relativistic hydrodynamics and radiation transport calculations. The yielded synthetic spectra and light curves align seamlessly with observed GRB-SNe.

Barnes et al. (2018)

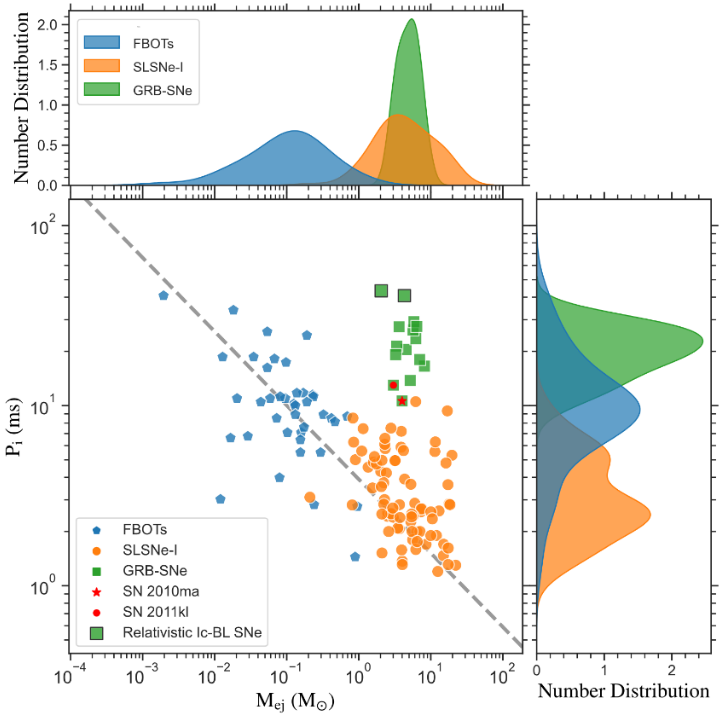
Powering Sources of GRB-SNe - Magnetar origin?

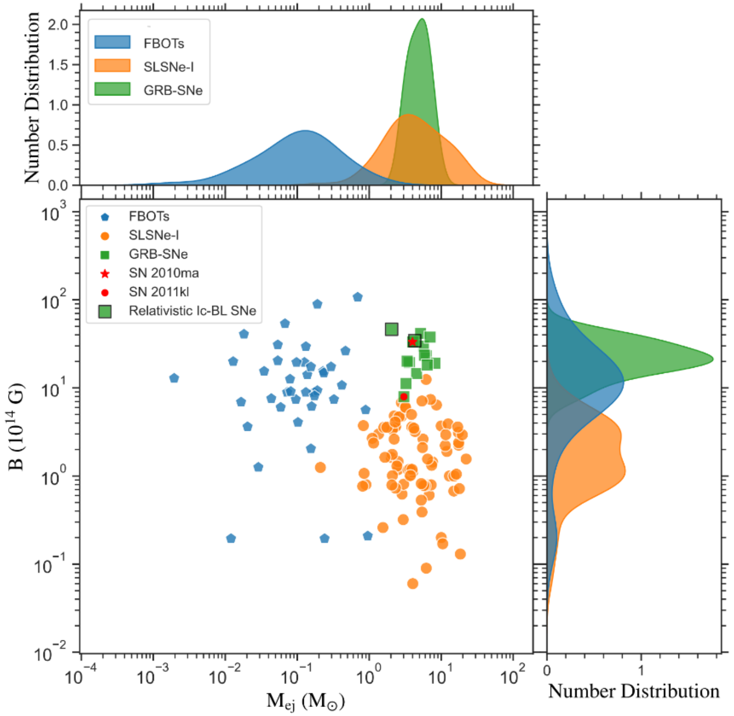


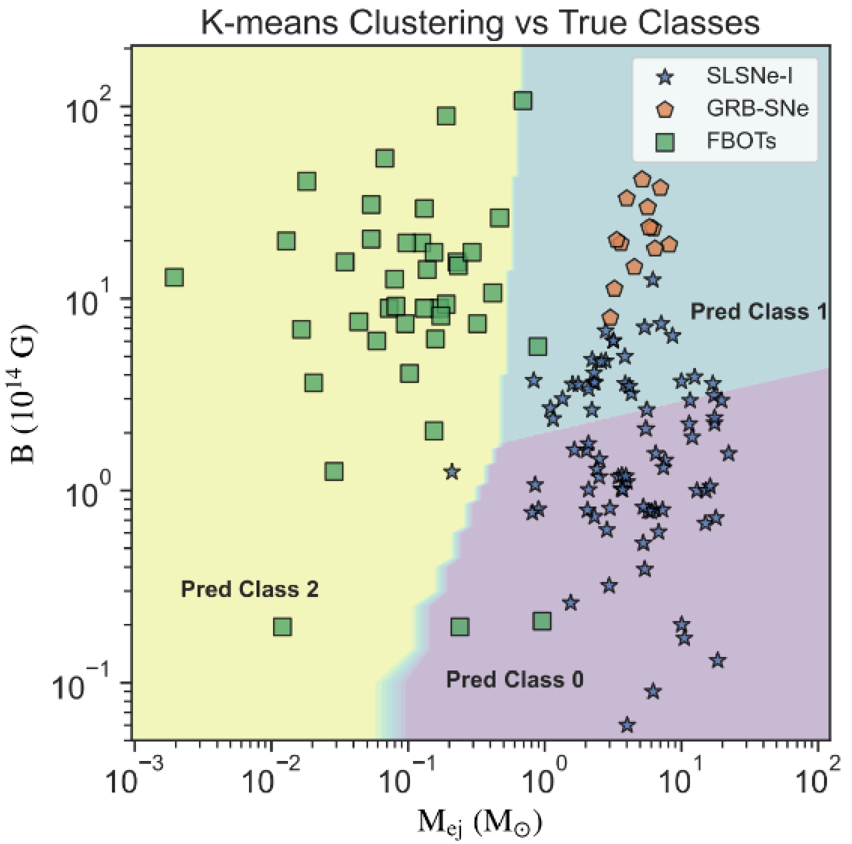
Kumar et al. 2024b

We present the semi-analytical light curve modelling of a sample of 13 GRB-SNe and 2 relativistic Ic-BL SNe 2009bb and 2012ap.

Powering Sources of GRB-SNe - Magnetar origin?





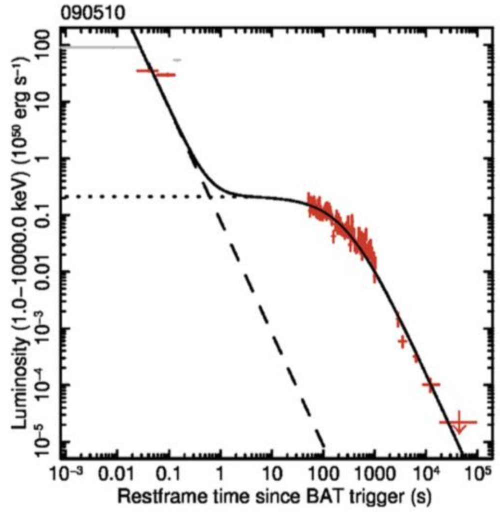


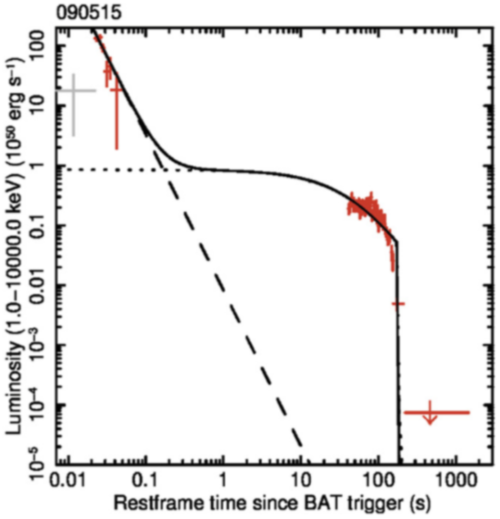
- GRB-SNe appear to occupy different parameter spaces for Mej, Pi, and B than those of FBOTs and SLSNe-I.
- The application of unsupervised ML clustering algorithms on Mej, Pi , and B for GRB-SNe, SLSNe-I, and FBOTs yields classification accuracy of ~95%.

Kumar et al. 2024b

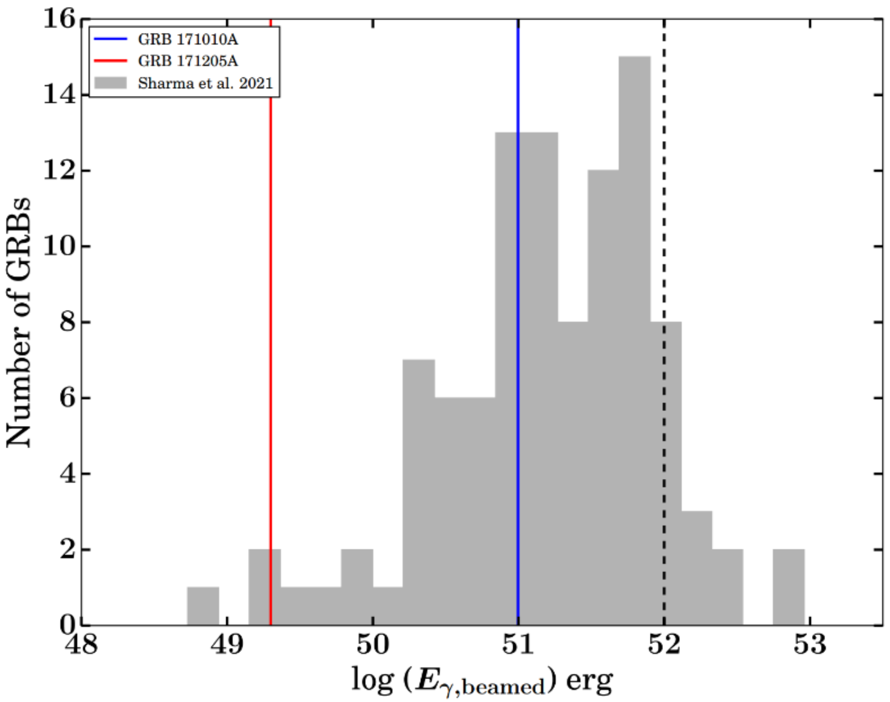
Powering Sources of GRBs - Magnetar origin?

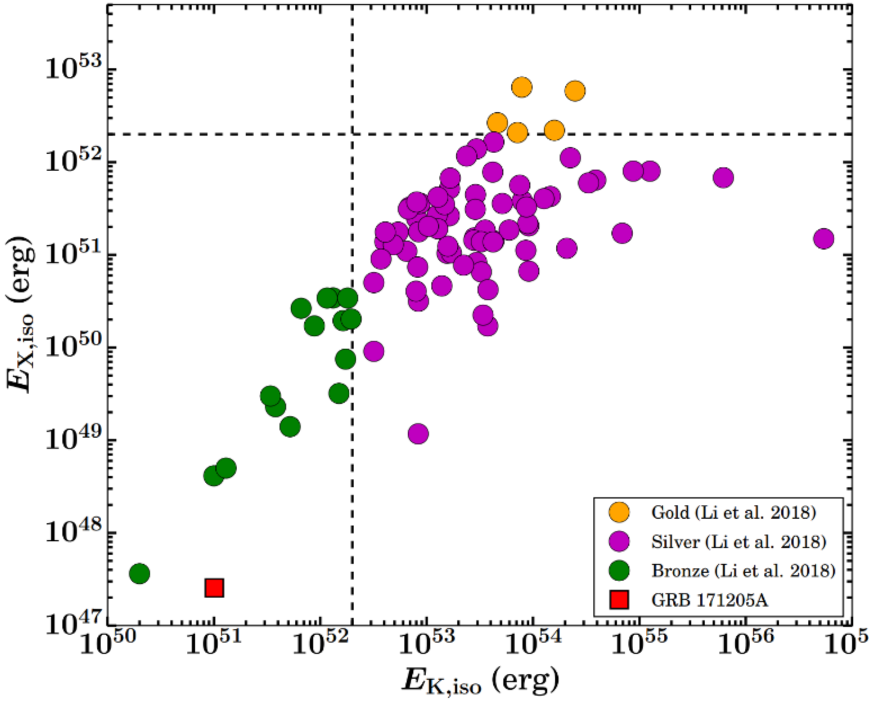
Magnetar signatures: plateau phase/shallow-decaying in the X−ray light curves: in around 80% of LGRBs and 50% of SGRBs





Rowlinson et al., 2013;
Bernardini, et al. 2015

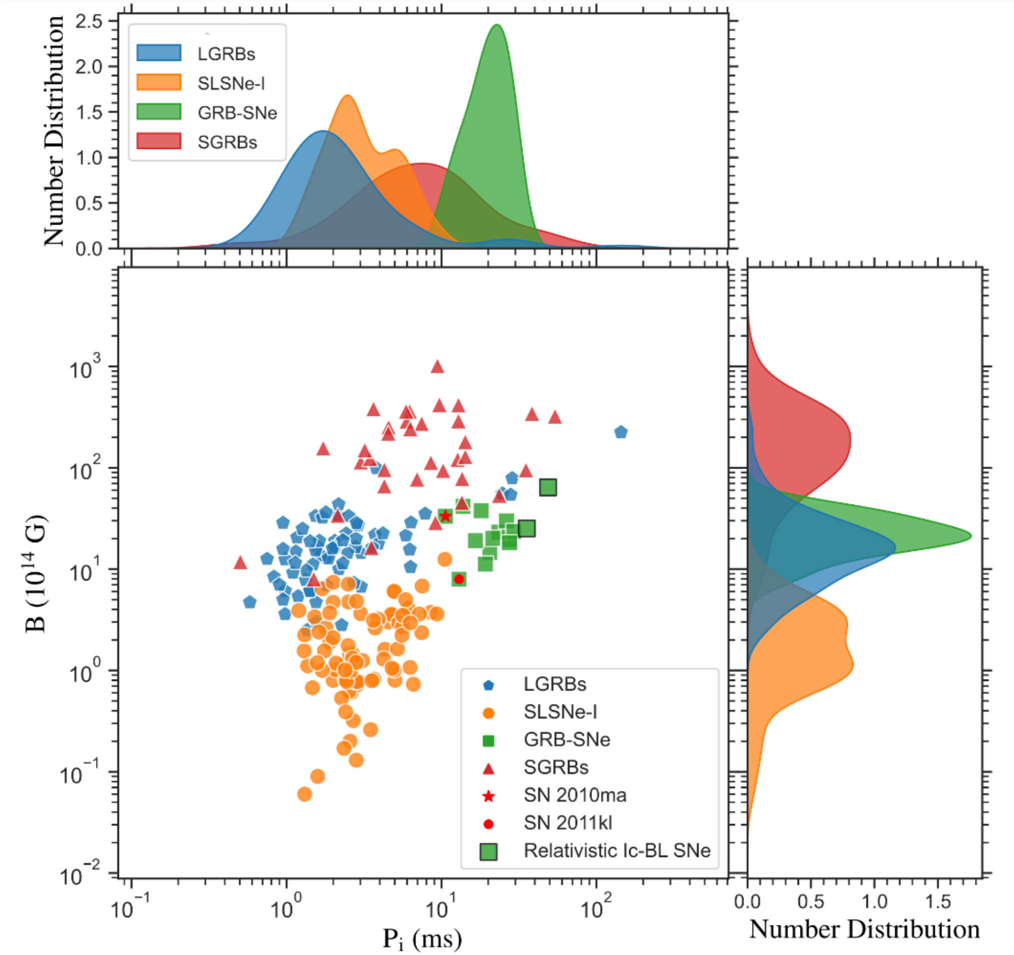


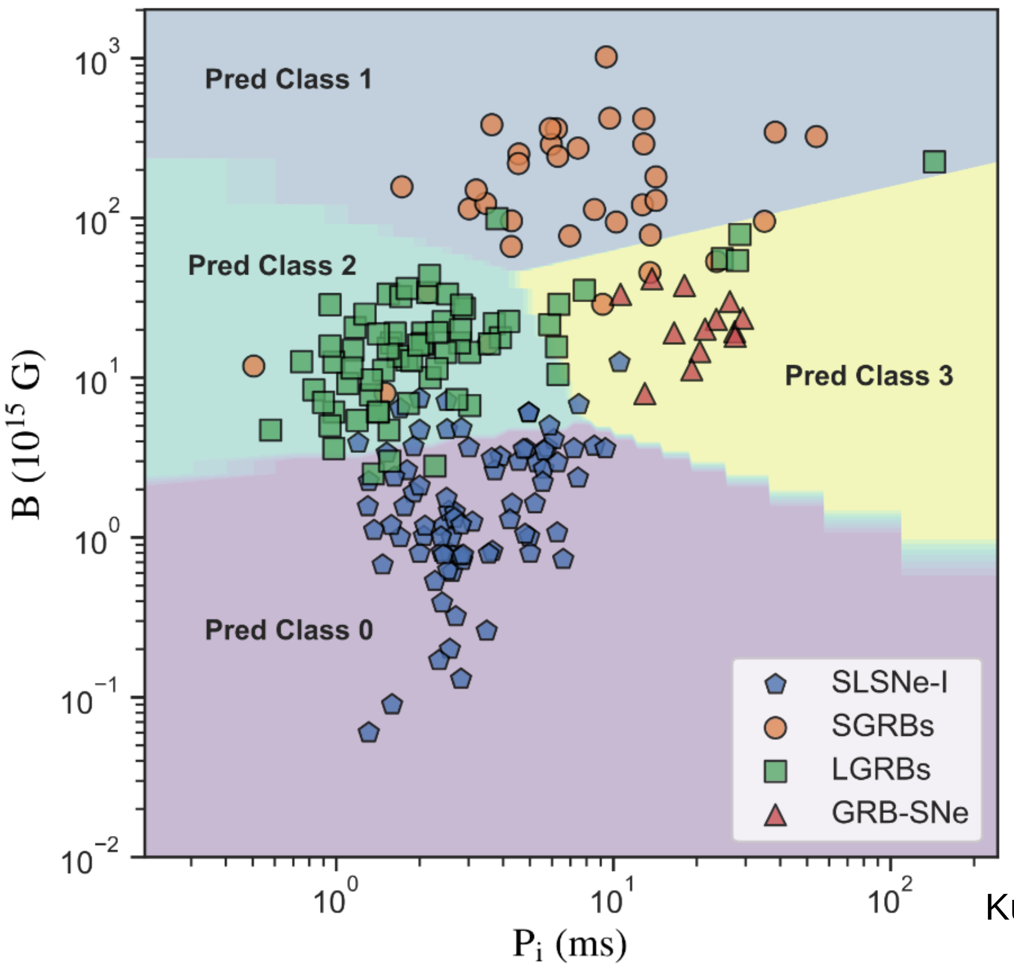


The comparison of isotropic X-ray and kinetic energies of the GRBs to the maximum energy budget of magnetars also indicates magnetar could be a powering source of many GRBs.

Kumar et al. 2022

Powering Sources of GRB and SNe - Magnetar origin?





Kumar et al. 2024b

- GRB-SNe appear to occupy different parameter spaces for Pi, and B than those of SLSNe-I, LGRBs and SGRBs.

- The application of unsupervised ML clustering algorithms on Pi and B yields classification accuracy of ~85%.

Summary

- Magnetars can govern various types of transients, from extreme SNe to GRBs, and other fast transients.
- Different magnetar properties, such as the initial spin period, magnetic field, and the central engine activity duration, can give rise to different types of transients.
- The Mej, Pi , and B parameters comparison among GRB-SNe, relativistic Ic-BL SNe, SLSNe-I and FBOTs do not show any noteworthy correlation among Pi and Mej or B and Mej.
- GRB-SNe and relativistic Ic-BL SNe presented here hold a different parameter space in Pi vs Mej and B vs Mej distributions.
- Pi vs B distribution of GRB-SNe also retain a different parameter space than those of SLSNe-I, LGRBs and SGRBs, with a small degree of overlapping.
- This analysis indicates a possible continuum in Pi vs B parameters space among SLSNe-I, SN 2011kl (faintest SLSN but brightest GRB-SN), GRB-SNe and two relativistic Ic-BL SNe, highlighting their crucial role in governing the luminosity of these events.

Thank You !!

Questions?

Questions to Investigate?

Bias Toward Rapidly Rotating Magnetars:

- Are we predominantly identifying only the most rapidly rotating magnetars, such as those associated with Superluminous Supernovae (SLSNe) and Gamma-Ray Bursts (GRBs)?

Magnetar Power Source:

- Can we definitively say that events like SLSNe and GRBs are powered by magnetars?

Detection in Lower Luminosity Supernovae:

- How can we detect the influence of magnetars in lower luminosity supernovae?
- What methods can we use to determine the true birth rate of magnetars?

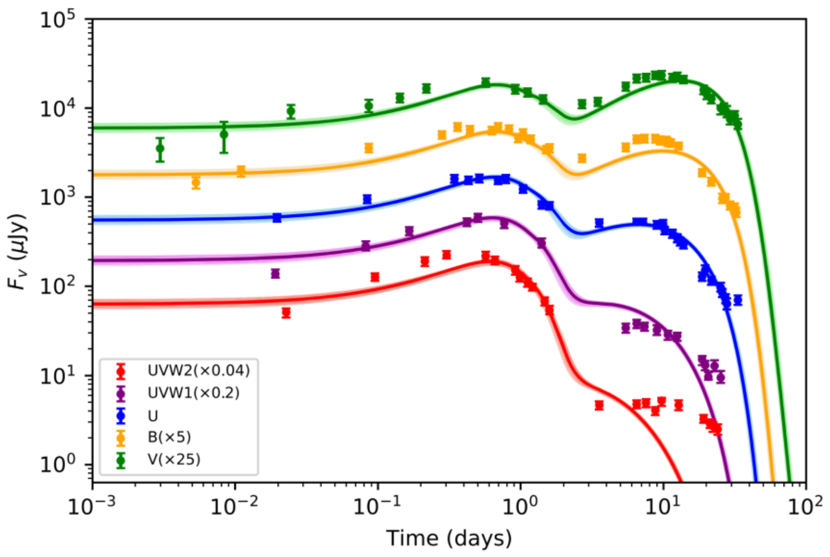
Relation to Other Wavelength Transients:

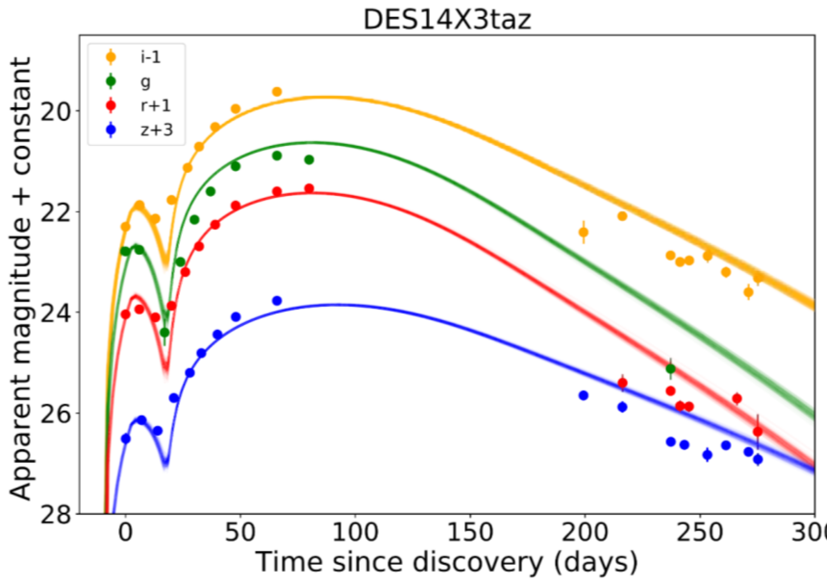
- How do magnetars relate to other transient events observed at different wavelengths, such as Fast Radio Bursts (FRBs)?

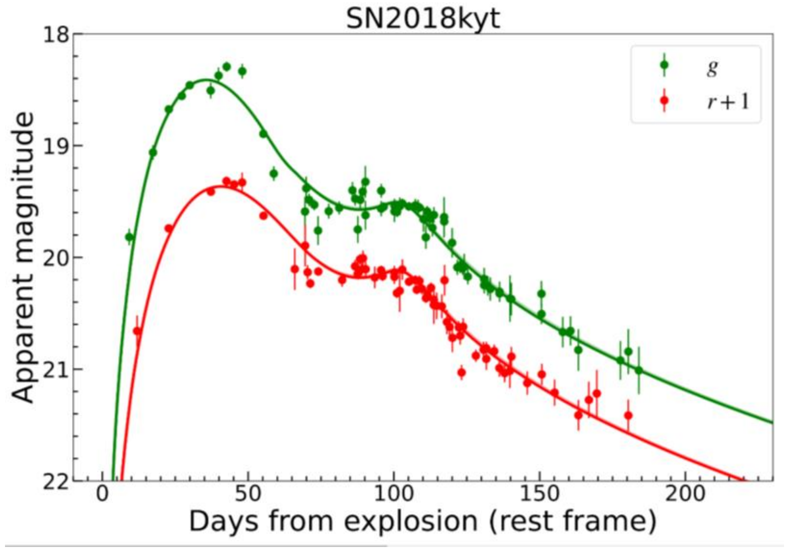
Neutron Star Mergers and Magnetars:

- Do neutron star mergers result in the formation of magnetars?

Powering Sources of weird SNe - Magnetar origin?







GRB+SN
Zhang et al., 2022

SLSN
Liu et al., 2021

SLSN
Dong et al., 2023

Double-peaked SN 2006a:
First peak: shock breakout emission driven by magnetar wind.

Main peak: a magnetar-aided supernova emission.

Double-peaked DES14Xtaz:
First peak: magnetar-driven shock-breakout thermal emission.

Main peak: powered by a radiative diffusion through the SN ejecta as in the standard magnetar-powered model.

SN 2018kyt with post peak bump:

Main peak: standard magnetar model.
Bumps: powered by magnetar Flare