Calculation of the On-Source Window of CCSNe through the Usage of the Expanding Photosphere Method and Light Curve Modeling

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We summarize the calculation of the on-source windows for optical triggers of the targeted searches for gravitational waves (GWs) from nearby core-collapse supernovae (CCSNe) through the usage of the Expanding Photosphere Method (EPM) and the benefits of using light curve modeling to aid these estimations. The earliest supernova EM emission is produced when the optical depth of the plasma lying ahead of the shock, which ejects the envelope, drops below c/v, where v is the shock velocity. This breakout may occur when the shock reaches the edge of the star, producing a bright X-ray/UV flash on time scales of seconds to a fraction of an hour, followed by UV/optical cooling emission from the expanding cooling envelope on a day time-scale. If the optical depth of the circumstellar material (CSM) ejected from the progenitor star prior to the explosion is larger than c/v, the breakout will take place at larger radii and extend the duration to days in time scale. The recent progress of wide-field transient surveys enable SN detections on a day time scale and are being used to set unique constraints on the progenitors of SNe of all types. For the targeted search for GWs from CCSNe using optical triggers, the data is only analyzed within a specific time interval, [t1, t2], where t_1 and t_2 are derived differently in the prompt observation and late observation scenarios. In the prompt observation scenario, t_1 and t_2 denote a GPS time that is earlier than the arrival of the GW at the respective detectors and the time of discovery. In the late observation scenario, t_1 and t_2 are derived through calculations if the first method fails to provide a short time interval, in the order of a few hours to 1-2 days, then the expanding photosphere method must be introduced using the actual size of the SN and a theoretical estimate for the angular size.

Time of First and Last Observation of SN GW Candidate

Understanding stages of CCSNe emission,

(1) GW emission to shock breakout

(2) Shock breakout to peak luminosity

(3) Peak luminosity to time of first SN observation

Databases to extract information on the time of first and last observation, distance, and progenitor information:

(1) IAU Central Bureau for Astronomical Telegrams

(2) Rochester Astronomy

(3) ASAS-SN

(4) The Astronomer's Telegram

(5) Transient Name Server (TNS)

Simplest approach to successfully include **phase 2 & 3** of SN emission (*only if the constraint leads to an on-source window on the order of a few hours to 1-2 days*):

assign a GPS time that is earlier than the arrival of the GW at the respective detectors = time of discovery (t_1) (with the addition of the estimated duration of phase 1 that is progenitor dependent) & t_2 as the time of first physical observation

Time of GW Emission and Explosion Caveats

Time of GW emission depends on the estimates of:

a) the radius of the progenitor in order to identify the shock breakout time. If the radius is known, then the speed of sound may be used to find out how long it has taken from core-collapse to breakout

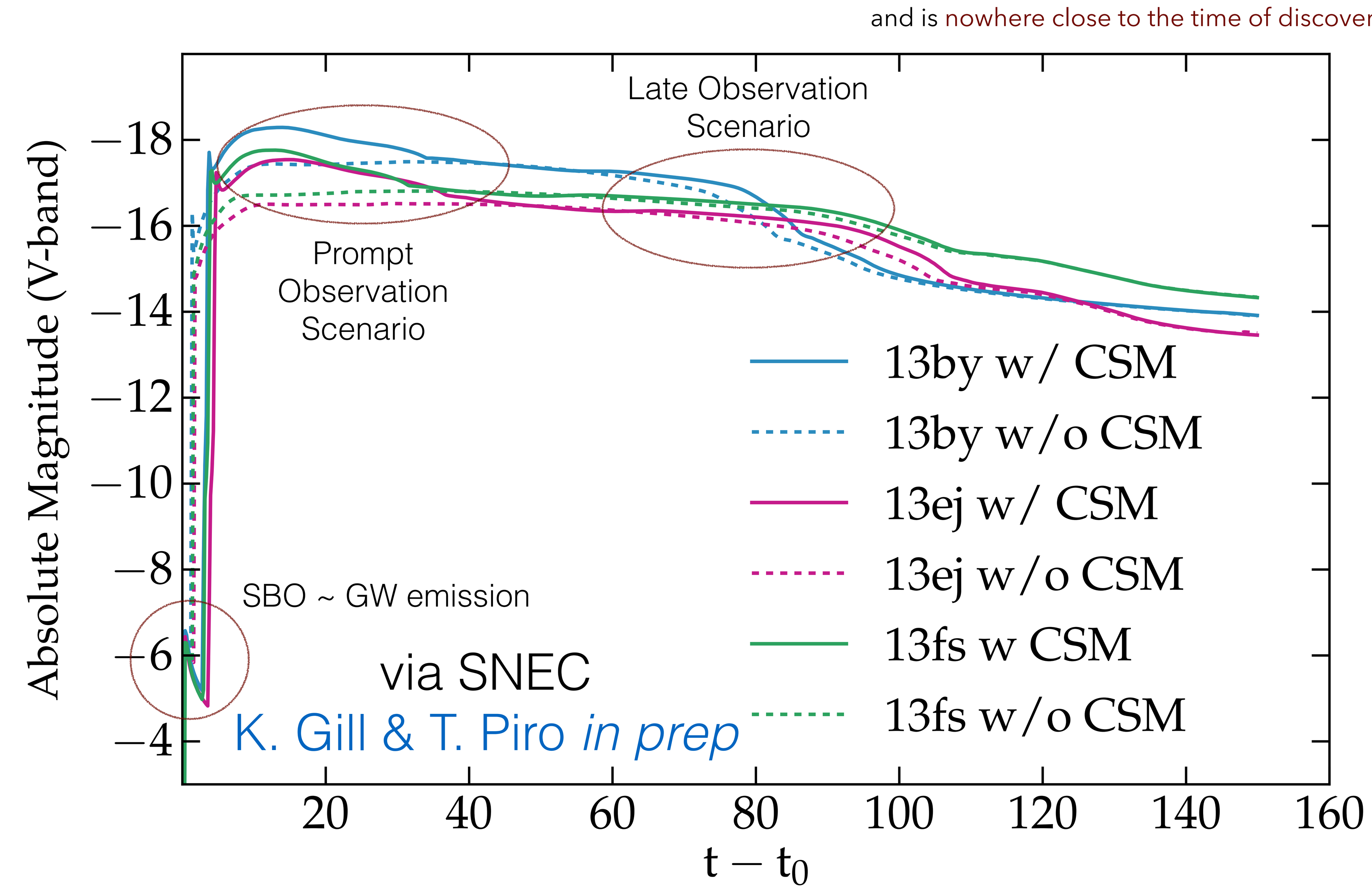
b) explosion time, which is characterized as the point of shock breakout, is needed to extrapolate backwards to account for the short time period when GW emission occurred.

How to correctly constrain the explosion time, characterized as the point of shock breakout, if?

a) time between discovery and follow-up observations have a delay of anywhere from 1-3 months

b) Distance is unknown, which means that only the information for the host galaxy is given (redshift data conversion into Mpc) (no follow-up observation).

c) shock propagation time is unknown, which means that SN itself was most likely discovered in its late phases (implies that the explosion happened long time back and is nowhere close to the time of discovery).



	Radius	Optical Emission Timescale	Length of peak luminosity
Wolf-Rayet	~10^{11} cm (5-10 $R_\odot$)	3 seconds	10 - 20 seconds
Blue Supergiant	~ 3 x 10^{12} cm (25-50 $R_\odot$)	100 seconds	15 minutes
Red Supergiant	~ 3 x 10^{13} cm (500-1000 $R_\odot$)	15 minutes	2 - 3 hours

Prompt Observation Scenario

The time of discovery, t_2, is already obtained through astronomers (ASAS-SN MOU contribution). In order to calculate t_1, the GPS time that is earlier than the arrival of the GW at the respective detectors, the time of the last observation needs to be taken into account and the time from the shock rebound to the time of shock breakout of the SNe is subtracted.

$$t_1 = t_{\text{last null observation}} - t_{\text{from shock rebound to shock breakout}}$$

is dependent on the identified progenitor provided and represents phase 1.

More Common: Late Observation Scenario

Expanding Photosphere Method

works best on early, detected, multiple epoch observations before hydrogen recombination - uses an estimate of the actual size of the SN from its expansion velocity and a theoretical estimate for the angular size based on the received flux density and the Planck function for the given color temperature.

- ★expansion of ejected material = spherically symmetric
- ★photosphere radiates as a dilute black-body at early times of SN evolution
- ★shape of the emergent multi-band photometry is Planck-like
- ★due to the fast expansion of the SNe, it's safe to assume a negligible initial radius, R_0

Calculating the Time of Shock Breakout

Deriving θ and v_{phot}, the following equation is used to find t_1.

$$t_1 = t_2 - D\frac{\theta}{v_{phot}}$$

where D is the distance, t_1 is the GPS time that is earlier than the arrival of the GW at the respective detectors, and t_2 is the time of discovery (the discovery date recorded).

When using EPM on CCSNe with only very late observation times, we cannot rely on the calculation of the velocity of the photosphere due to the late time observations nulling the assumption dealing with spherical symmetry associated with the shock breakout of the SN. The dust effects need to be accounted for, but it is difficult in terms of accuracy in quantifying these numbers due to the poor flux calibration present (therefore, we often need to extrapolate the spectral shape by fitting it to a standard hot or cool flux model) (ASAS-SN MOU contribution).

Introduce an extrapolation backwards from the first time of observation, t_2, (which subsequently was very late in terms of the actual SN explosion time) to the maximum luminosity peak of the SN, τ, (when optimally the SN should have been observed). This leads to a corrected time of first discovery, t_2 ➡ $t_2 = t_{observed} - τ$

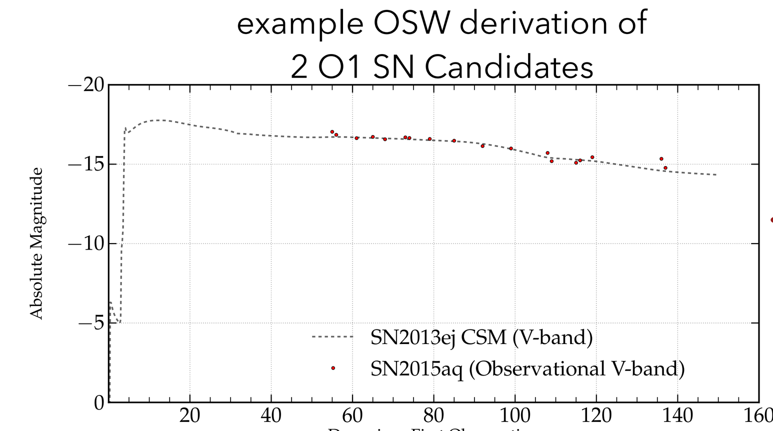
Why? The corrected multi-band light curves will be plotted with respect to the estimated time since shock breakout, which is derived from the least-square fitting method. This is crucial as the corrected multi- band light curves will illustrate the apparent magnitude of the SN candidate when it first experienced peak luminosity in its respective light curve.

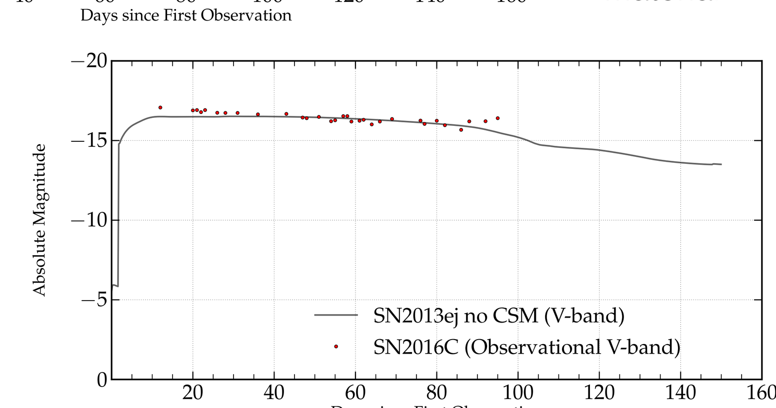
When U-band magnitude becomes smaller than the V-band magnitude = explosion will yield much less energy in the U-band than in the V-band = the apparent magnitude that would be recorded right after the SN candidate experiences peak luminosity and transitions into either the plateau phase in its light curve (if the SN candidate progenitor belongs to the Type II-P classification) or experiences a luminosity drop off. The intersection of the two lines belonging to U-band and V-band fluxes will be termed as the initial day since explosion, which is t_1.

→ subtracting those number of days since explosion from the time of first discovery, t_1, is derived. The following equation describes this process, where ($t_{intersection}$−t_2) is estimated multi-band light curves: $t_1 = t_2 - t_{progenitor}$

+ Light Curve Modeling (SNEC)

example OSW derivation of 2 O1 SN Candidates





CSM: Circumstellar Material

If the introduction of CSM-like behavior is regular in Type IIP SNe and survey observation times are fairly late for our SN candidates of interest,
then,

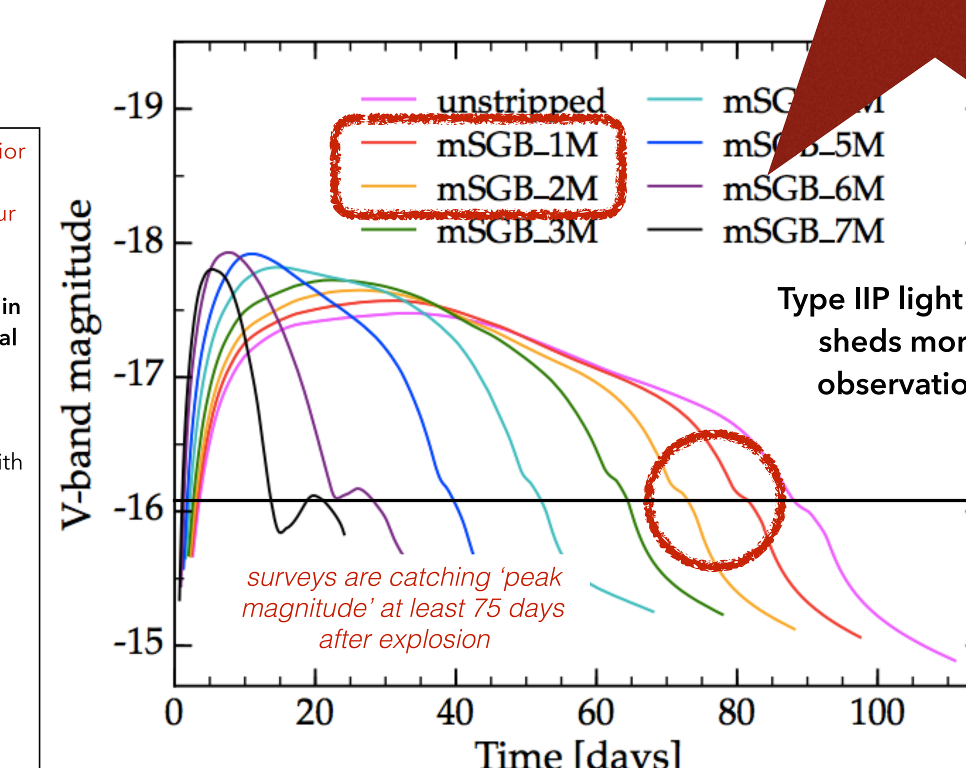
light curve modeling is necessary in order to understand on what actual timescale survey caught SNe explosion

brighter luminosities associated with Type IIP, especially at *SBO & respective peak luminosity*

redder Type IIP SNe leads to *contributing to the rate of faint CCSNe missed by optical surveys* (state-of-the-art surveys, such as ASAS-SN, still have a limiting magnitude threshold of 17)

Nearby (within 20 Mpc) *IR surveys are being introduced by Mansi et al.* - probe J-band & would be able to *catch these less luminous CCSNe* with more ease and provide

New Methdology!



Morozova et al. 2015

Type IIP light curve modeling sheds more light on the observation problem....