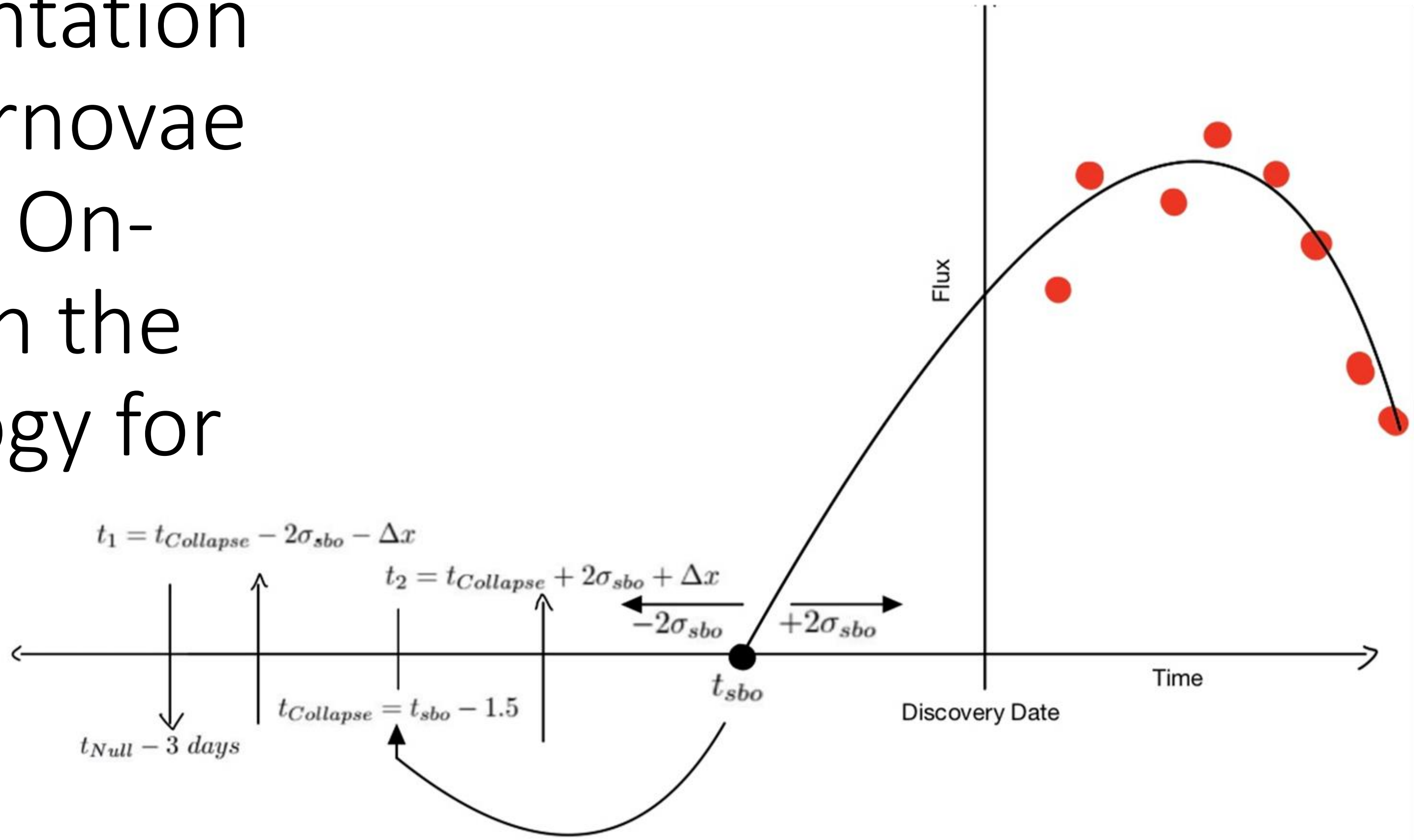
Review Readiness Presentation for Core Collapsed Supernovae (CCSNe)Targeted Search On-Source Window (OSW) in the 03 Data, and Methodology for 04 Data



D. Ramirez, M. Benjamin, C. Richardson, M. Zanolin, C. Moreno, M. Szczepanczyk

Literature Slide

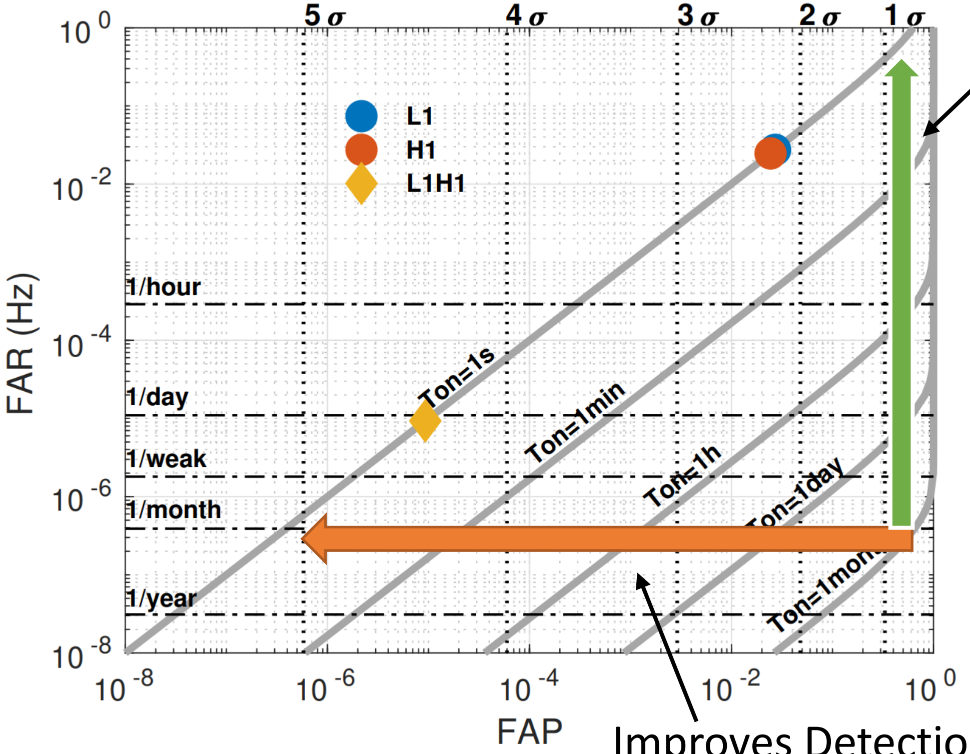
- Gill et al, Bayesian interpolation for some 03 candidates with physics-based modeling (with Harvard code): https://arxiv.org/pdf/2201.03609.pdf
- Last published CCSNe Search : https://arxiv.org/abs/1908.03584
- Waxman et al, physics-based light curve modeling with no radioactive decay included: https://arxiv.org/pdf/1607.03700v2.pdf
- Nagy et al, physics-based light curve modeling with radioactive decay included : https://arxiv.org/pdf/1409.6256v2.pdf
- Couch et al, estimation of delay between collapse and shock breakout: https://arxiv.org/pdf/2102.01118.pdf
- Antelis et al, comparison between the False Alarm rate and False Alarm Probability: https://dcc.ligo.org/DocDB/0177/P2100263/003/CCNSe_GW_cWB_and_ML.pdf
- Smartt et al Paper, the lack of red super giants in the local universe: https://arxiv.org/pdf/0908.0700.pdf
- W. V. Jacobson-Galán et al, homologous expansion for light curves within a month: https://iopscience.iop.org/article/10.3847/1538-4357/ac3f3a/pdf
- P. J. Vallely et al, early-time observations of core-collapse supernovae: https://arxiv.org/pdf/2010.06596.pdf
- Previous presentation links:
  - https://dcc.ligo.org/LIGO-G2101854
  - https://dcc.ligo.org/LIGO-G2100944
- Code for the Quartic Interpolation: https://git.ligo.org/dymetris.ramirez/on-source-window/-/tree/main/

The On-Source Window

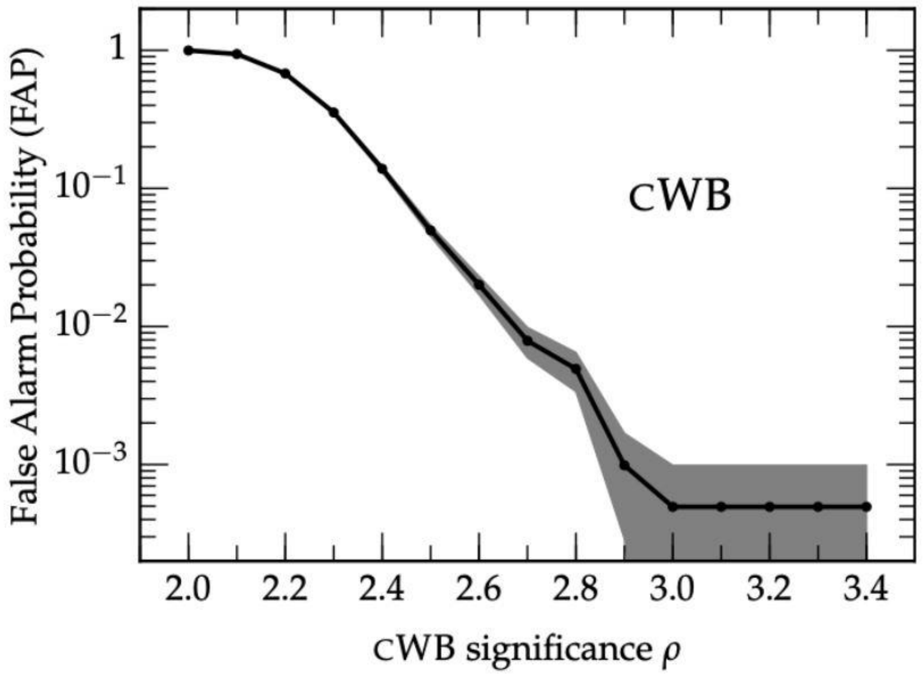
- The On-Source Window (OSW) is the interval of time that, with a desired confidence, contains the GW emission of an optical supernova (SN) target
- The estimation of the OSW is made or two ingredients, the estimation of the shock breakout and the delay between the collapse and shock breakout
- In this presentation, we will discuss the methodology of for the 03 OSWs
- Not covered here: benefits of knowing the direction of the CCSNe

Benefits of Using an OSW

- $FAP = 1 - e^{-T*FAR} \cong T * FAR$



Increases Reach



Improves Detection Confidence

Summary of Uncertainties

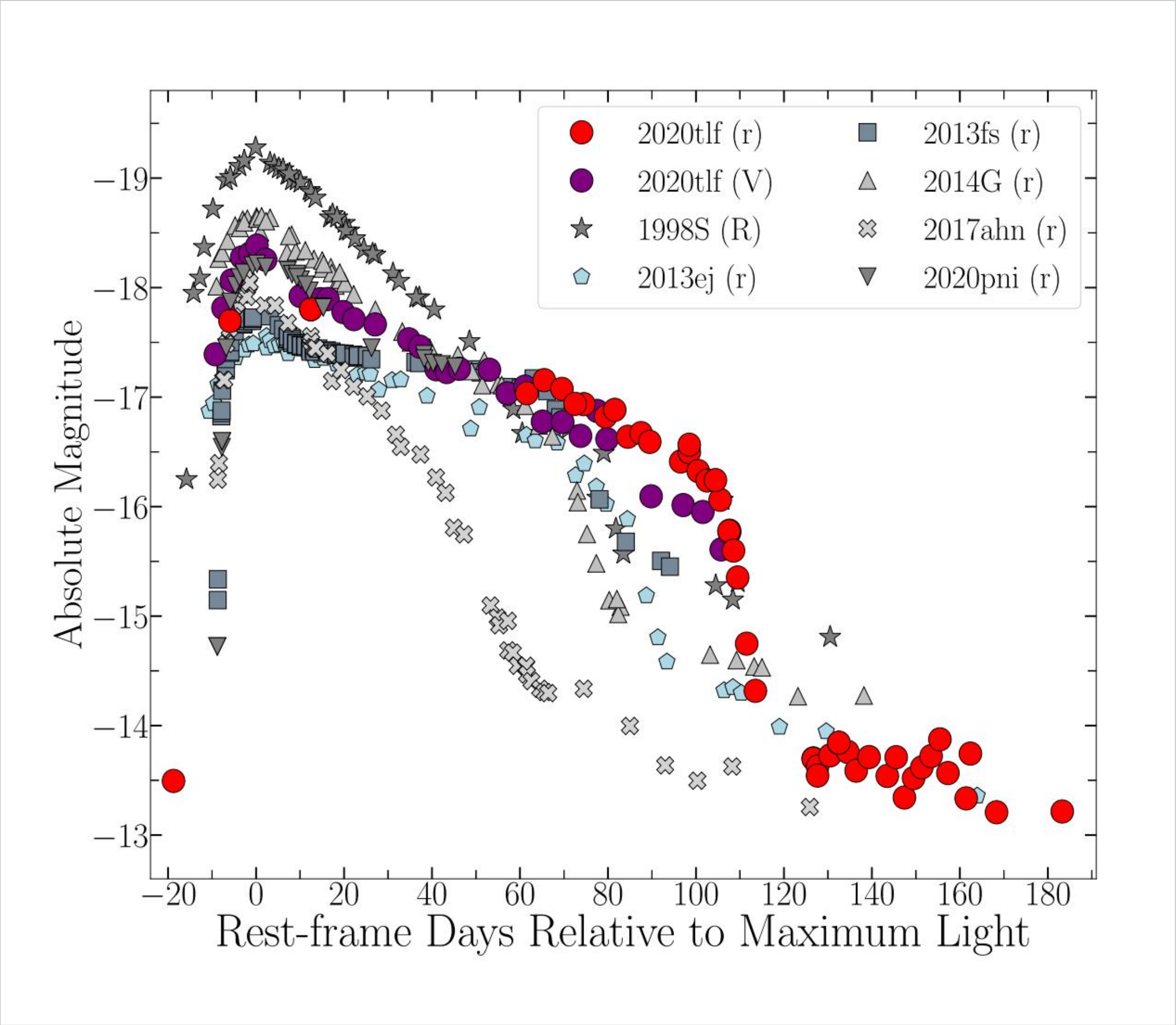
- Time of discovery
- Physics based or Polynomial based interpolation
    - Polynomial interpolation is based solely on the data
    - Physics has a light curve that might already have a steep ramp up
    - Type of electromagnetic telescope used (Ground-Based vs Space)
    - Role of the band used in the interpolations (Ex: r-band, g-band, etc.)
    - Morphological variability of light curves
- Delay between GW emission and Shock breakout
- Previous knowledge on the progenitor

Three Types of Probabilistic Statements in Optically Triggered CCSNe Searches

- Detection confidence probability
- Confidence it includes the Gravitational Wave (GW) probability (?)
- Detection efficiencies probability
- In case of poor data, we adopt a conservative methodology (t2 = discovery time and t1 = last null – conservative estimate of the delay between collapse and shock breakout)

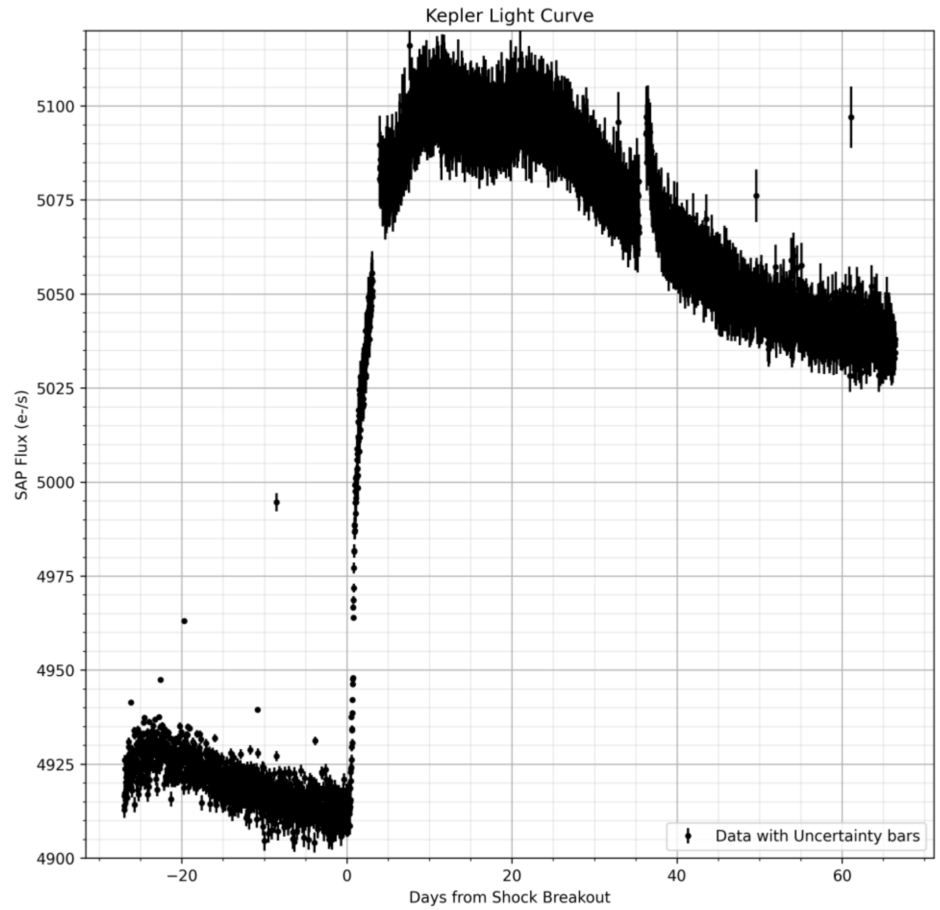
Homogeneity in the Early Part of the Light Curves

- Shapes are more homogenous in the first part of the light curve (homologous expansion for about a month)
- ***Final Moments. I. Precursor Emission, Envelope Inflation, and Enhanced Mass Loss Preceding the Luminous Type II Supernova 2020tlf*** *(2022)*



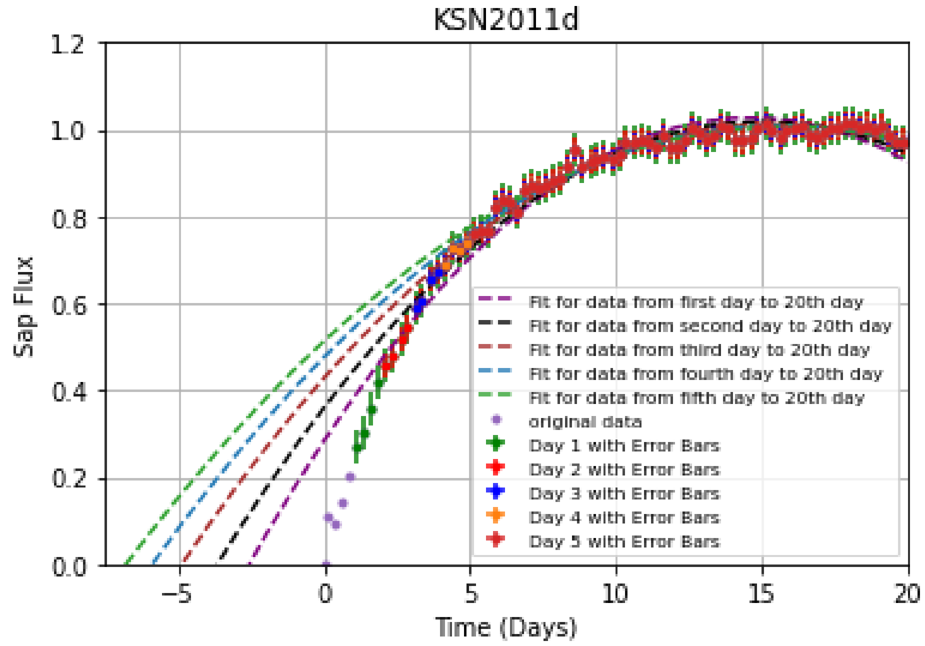
The Purpose of Utilizing Kepler Data

- Utilizing the Kepler Data (ksn2011d) is beneficial as it has recorded data before and at the time of shock breakout. Therefore, we are then able to use these completed light curves in testing the efficiency of our modeling methods
- In all methods of estimating the initial time of shock breakout, there are two kinds of uncertainty: amplitude of error in optical measurements and how late you start measuring the light curve
- In testing the quartic interpolation, we want to use these data sets to quantify its accuracy to derive the time of shock breakout if the complete data set was only collected a few days after the initial time of shock breakout

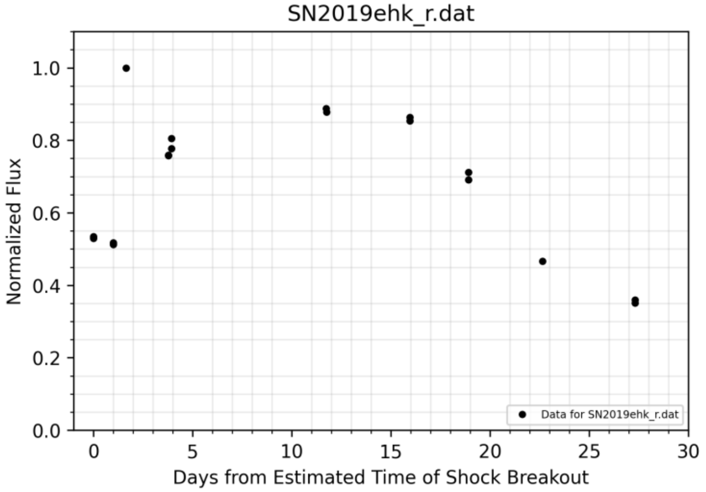


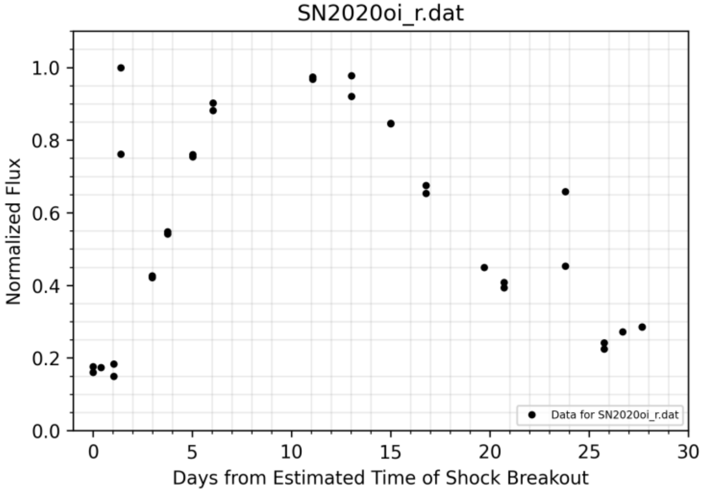
Problem with the Quadratic

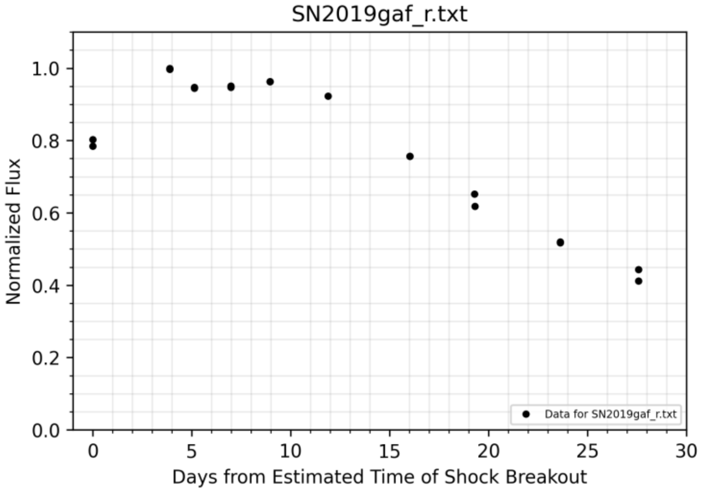
- From ground-based telescopes the early part of the light curve is always missed. The light curve could start either an hour, a day, or a couple of days after the time of initial shock breakout (but we don't know for sure). Capturing the light curve as early as possible is preferred for a more precise backward interpolation however, that is not always the case
- The simplest possible interpolation of the light curve to estimate the time of the shock breakout is the quadratic fit which is unfortunately typically bias because the curvature for the light intensity toward the peak is smaller than the bottom



Typical Number of Data Points



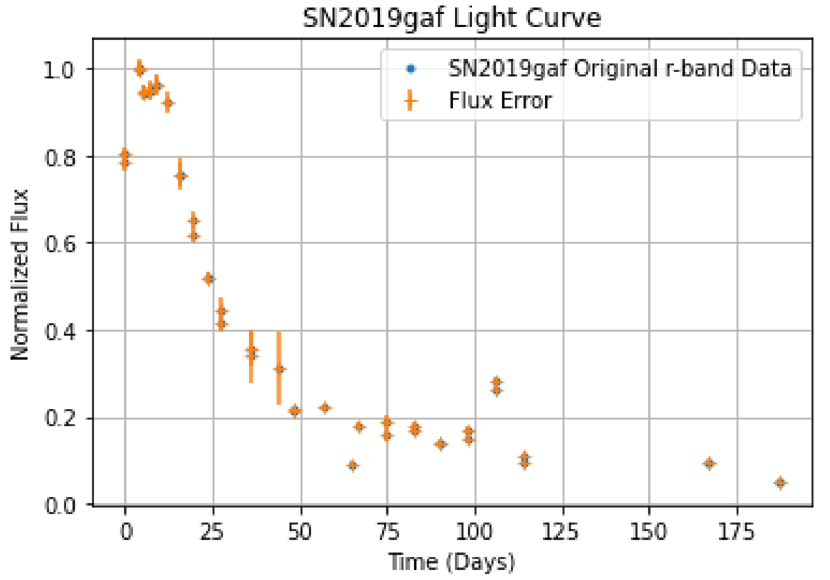




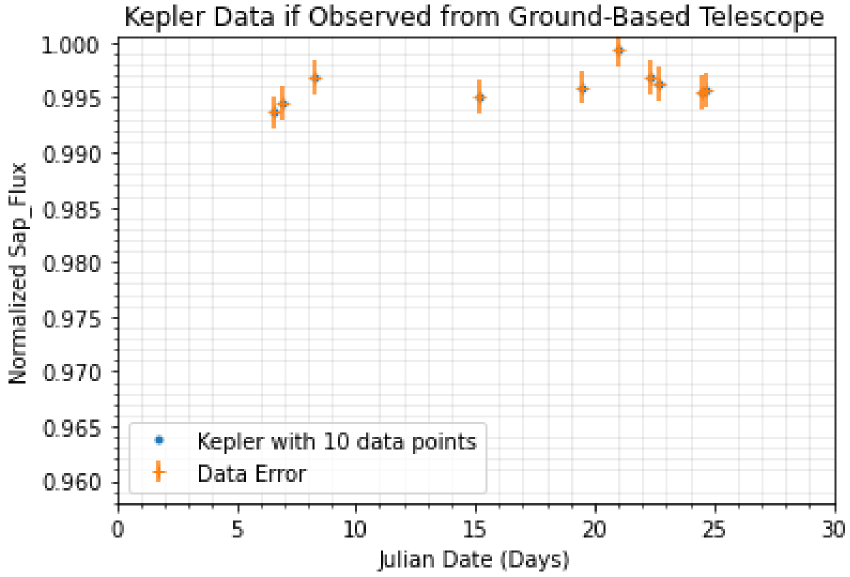
SNe Candidate Light Curves Recorded from Ground-Based Telescopes Between a Month Interval

Typical Optical Error

- In the Kepler data we rescale the optical observations to mirror that of ground-based telescopes
- $\sigma_{SN2019gaf} = \frac{\delta flux_{mean}}{flux_{mean}} = 0.035$
- $\sigma_e = \frac{\delta flux_i}{flux_i} \rightarrow \sigma_{Kepler} = \frac{\sigma_{e,avg}}{N} * 100 = 0.056$
    - Where (i) stands for each specific data point in SN2019gaf and (N) is the number of data points in SN2019gaf



σ = 0.035



σ = 0.056

Quartic Interpolation for Kepler

Use a χ^2 analysis to estimate the slope of the data based on an interval of 7-25 days.

↓

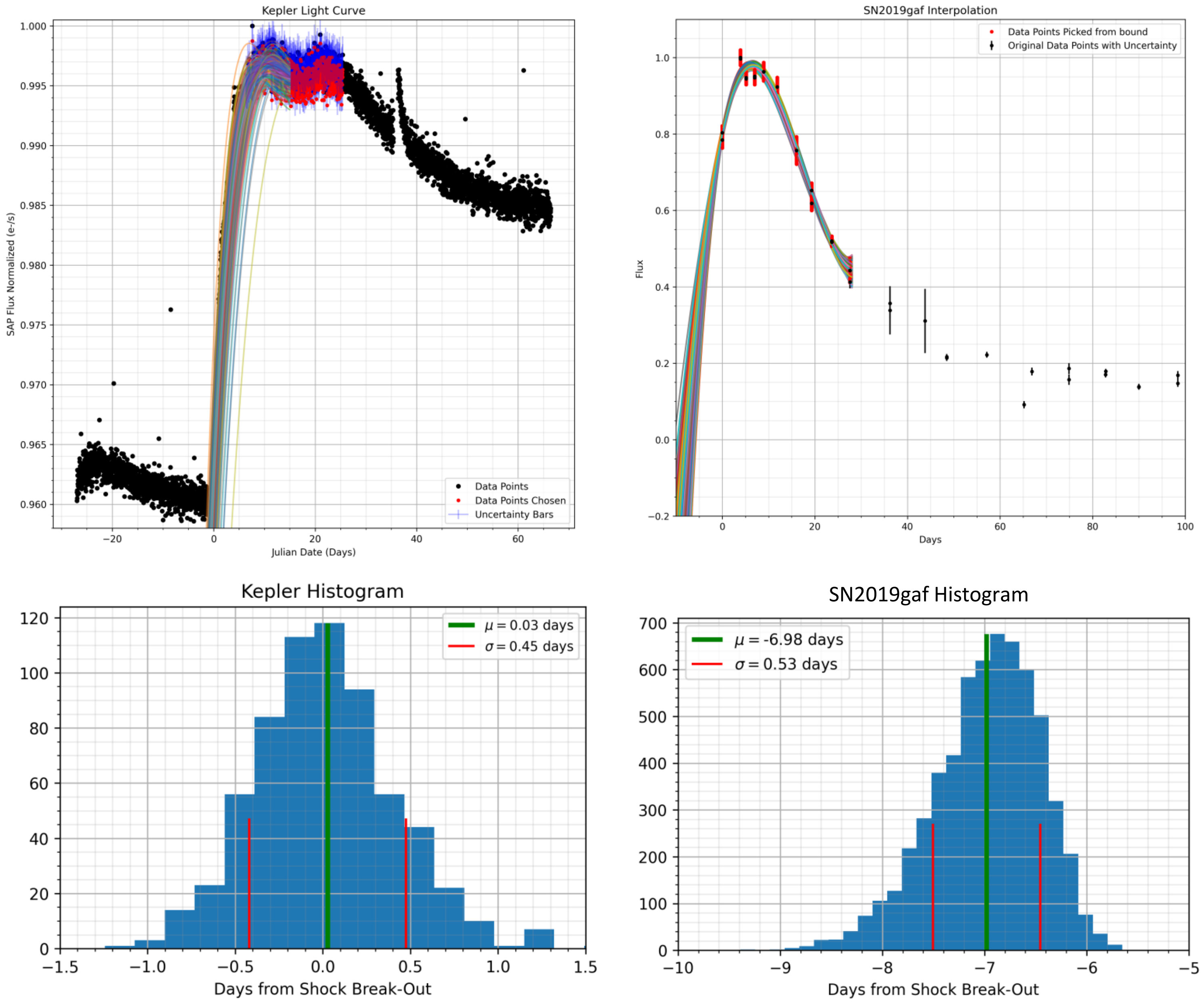
Produce a histogram that shows what the estimated shock breakout time is for all iterations ran

↓

The standard deviation value produced will then be used to account for the uncertainty of the quartic function

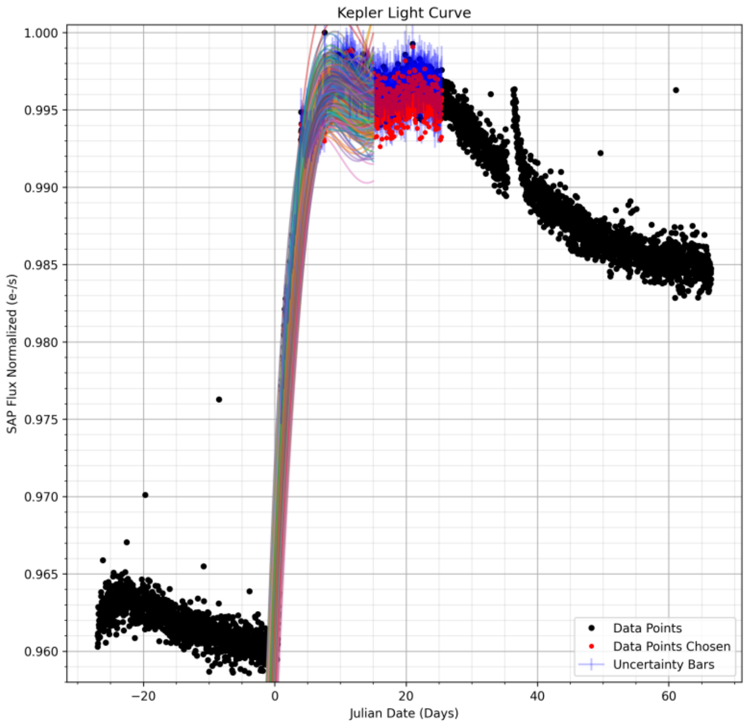
Rescaling the Intensity Error from the Kepler Data to Match that of a Ground-Based Telescope

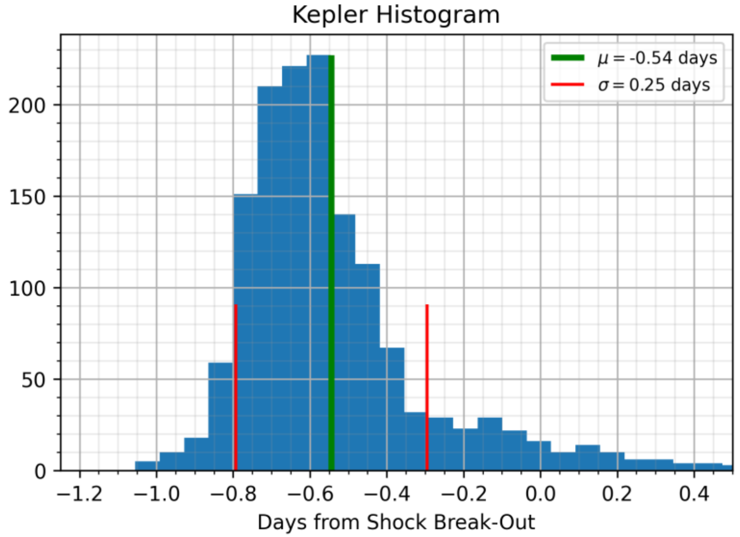
- 10 random points from the SN2019gaf Kepler data with rescaled errors
- We see that in the histogram for Kepler, this uncertainty of +/- 0.45 days contains the actual time of shock breakout (which is indicated at 0). We use an uncertainty of 2 times sigma when creating a range of uncertainty for estimating the shock breakout. That way we can say that the probability of it having the time of initial shock breakout is ≥ 95%

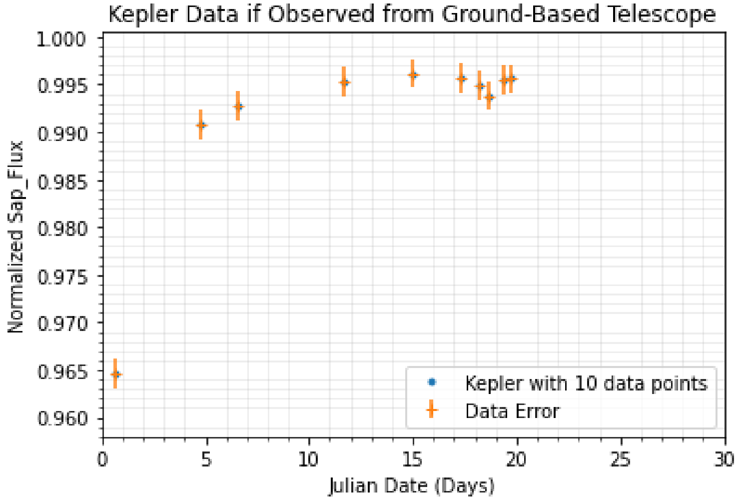


Rescaling the Intensity Error from the Kepler Data to Match that of a Ground-Based Telescope Cont.

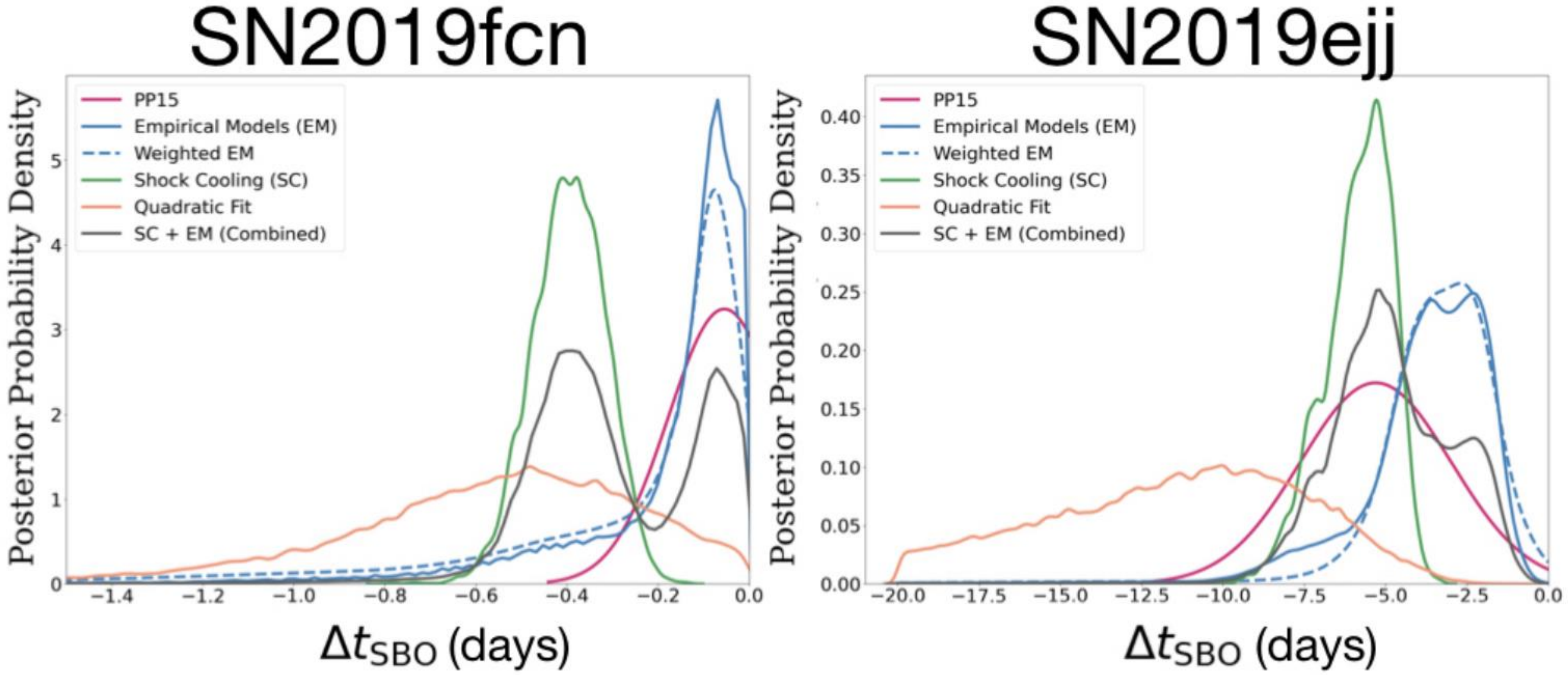
In the case where the light curve of Kepler was recorded half a day from time of initial shock breakout, we can see that the variance decreases from +/-0.45 to +/-0.25. This is because the light curve has data that is closer to the time of shock breakout which will improve the overall efficiency of the quartic interpolation





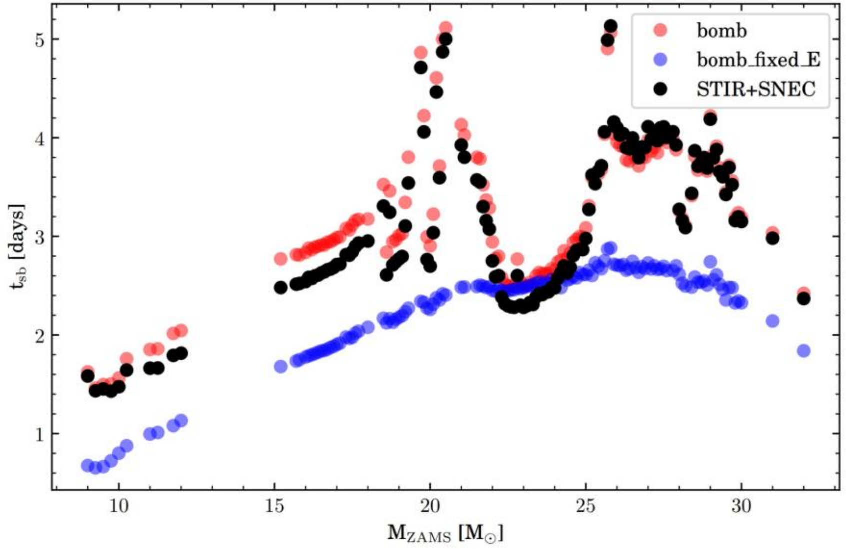


Physical Based Interpolations to the Light Curve



Estimating the Delay from Collapse to Shock Breakout

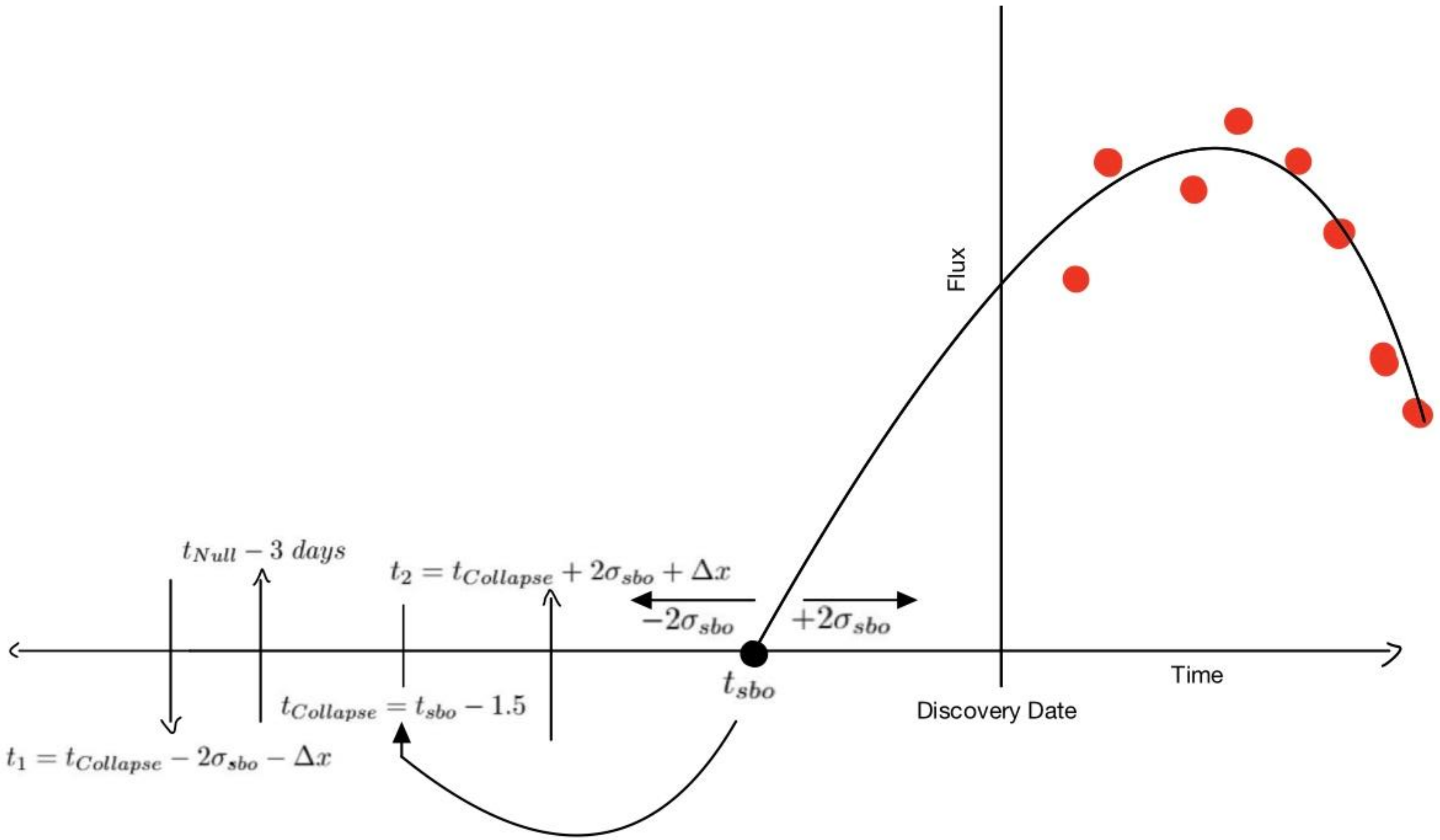
- Smartt et al. (2009), described “the Red Supergiant Problem” meant that there was a clear lack of high-mass($\gtrsim 17M_\odot$) RSGs that have been detected as supernova progenitors. A possible explanation for this is “All massive stars above $17M_\odot$ could produce IL-L, IIn and Ibc SNe”
- It is also stated that “The relative frequencies of the II-P SNe compared to all other core-collapse types match the stellar numbers from an IMF between 8.5-$17M_\odot$”
- From Couch et al. we can see the comparison between the day of the estimated shock breakout as a function of ZAMS mass
- For cases that have an unknown mass, to account for any this uncertainty we are just subtracting 3 days (minus the Kepler uncertainty as well)



Summary of the Methodology

- When calculating for the time of collapse, the initial point (for where the quartic fit passes the x-axis at y = 0) is subtracted by a value that is determined from figure 6 in Couch et al. (this is to account for the time of shock breakout in respect to mass). Depending on if that mass is known can change what value of shock breakout is subtracted from the initial point. For now, it is just assumed at 1.5 for progenitors with mass < 12 $M_\odot$
- If the mass is known for the progenitor, the values of t_1 and t_2 can be found. t_1 is the initial time of the on-source window and t_2 is the final time of the on-source window
- The determined initial value of the shock breakout time is subtracted by a sigma value (derived from the quartic fit done on the Kepler Data σ_{sbo}) multiplied by a value of two. It is also subtracted by a Δx which is the uncertainty in the delay between the collapse and shock breakout. This is done to account for uncertainty in the quartic fit. Which then gives you the value of t_1 for a known mass. Repeating this problem but with addition would get you the value of t_2.
- For cases where the mass of the progenitor is unknown, t_1 is calculated by subtracting the last null by the conservative estimate of the delay between collapse and shock breakout to allow for a range of uncertainty for the OSW. t_2 is then calculated as just the discovery time

Quartic Interpolation for Estimating the OSW



OSW Table

For SN2019ehk, SN2019gaf, and SN2020oi those OSW values (Δt) were obtained using the quartic interpolation. As for SN2019ejj and SN2019fcn, those values were obtained from https://arxiv.org/pdf/2201.03609.pdf.

Name	Discovery	Discovery Date	t1	t2	Δt (days)	Distance (Mpc)	Mass (Solar Mass)	Radius (Solar Radius)	OSW Level
SN2019ehk	Jaroslaw Grzegorzek	1240612088	1240021976	1240142936	1.40	22.45	~10	100-2300	1
SN2019ejj	ATLAS (ATLAS Bot1)	1240813141	1240037010	1240691922	7.58	15.7		[1.3 (+0.4 and −0.3)] × 10^3	1
SN2019fcn	Krzysztof Stanek-Paczynski	1241391762	1240878546	1241270802	4.54	15.7		(2.3 ± 0.3) × 10^3	2
SN2019gaf	ATLAS (ATLAS Bot1)	1242997592	1242053240	1242372920	3.70	26.95			1
SN2019hsw	Krzysztof Stanek-Asiago	1244862450	1243740114	1244431314	8	24.70			1
SN2020oi	ZTF (ALeRCE)	1262437272	1262000088	1262319738	3.70	23.35		5797	1
SN2020cxd	ZTF (ZTF AMPEL NEW)	1266151466	1265892266	1266410666	6	17.42			1
SN2020dpw	Miho Kawabata	1266746500	1266285700	1266631300	4	21.54			1
SN2020fqv	Oschin, Jujia	1269648018	1268870418	1269388818	6	32			1

Estimated Delay in the Discovery (Da
SN2019ehk: 5.1343 (+/- .50)
SN2019ejj: Gill et al: 4.81 (+2.21/-1.56) Quartic: 4.601 (+/- .50)
SN2019fcn: Gill et al: 0.33 (+0.32/-0.31) Quartic: 0.113 (+/- .50)
SN2019gaf: 6.9316 (+/- .50)
SN2019hsw:
SN2020oi: 1.0559 (+/- .50)
SN2020cxd:
SN2020dpw:
SN2020fqv:

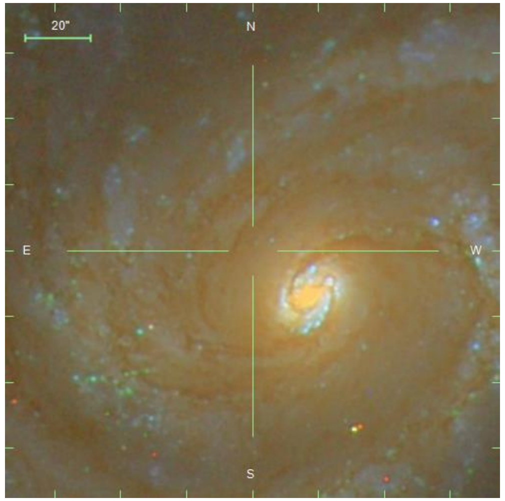
Extras

SUPERNOVA SEARCH 03
BEST CANDIDATES

https://wiki.ligo.org/Bursts/SNSearchO3OSW

SN2019ehk

NGC 4321
M100



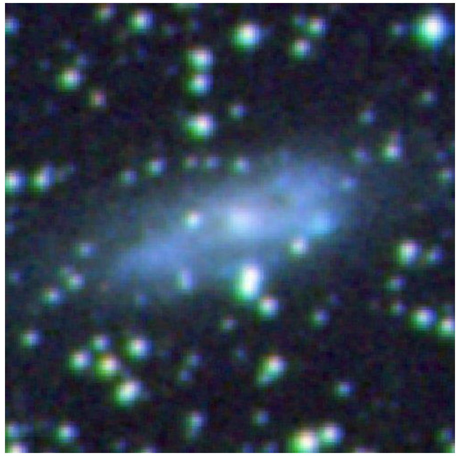
REFERENCES:
https://arxiv.org/pdf/2009.02347.pdf
https://arxiv.org/pdf/2005.01782.pdf

Check luminosity

RUN	O3a
TYPE	IIb
DISTANCE	22.45 Mpc TNS: 18.54 (z=0.0043)
DISCOVERY TIME	2019 April 29 T22:27:50
t1 (UTC)	1239973592 2019 April 22 T13:06:14
t2 (UTC)	1240070360 2019 April 23 T15:59:02
Δt (days)	1.52
Radius (solar radius)/R_csm	100-2300/4 x 10^{13}cm
Kinetic energy/Mass-loss	1.8 ± 0.10 x 10^{50}erg/$< 10^{-5} M_{\odot} yr^{-1}$
Mass ($M_{\odot}$)	$\approx 9 - 9.5$ low mass progenitor (ZAMS)
OSW Level	1
RA/DEC	12:22:56.150 / +15:49:34.03 (185.733958 / +15.826119)
LINK	TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

SN2019ejj

ESO 430-G20

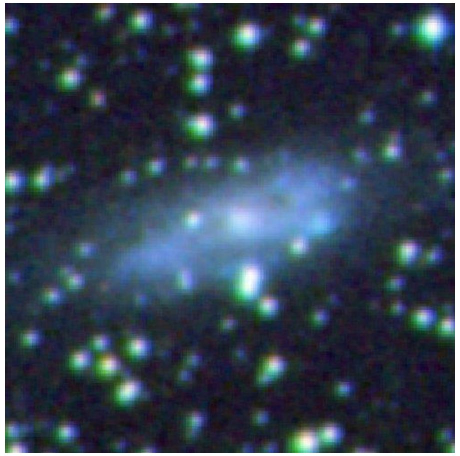


REFERENCES:
https://arxiv.org/pdf/2102.07353.pdf

RUN	O3a
TYPE	II
DISTANCE	13.45 Mpc TNS: 17 Mpc (z=0.003)
DISCOVERY TIME	2019 May 02 T06:18:43
t1 (UTC)	1240037010 2019 April 23 T06:43:12
t2 (UTC)	1240691922 2019 April 30 T20:38:24
Δt (days)	7.58
Radius (solar radius)	[1.3 (+0.4 and −0.3)] × 10^3
Explosion energies	
Mass ($M_\odot$)	
OSW Level	1
RA/DEC	08:07:08.760 / -28:03:11.66 (121.7865 / -28.053239)
LINK	TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

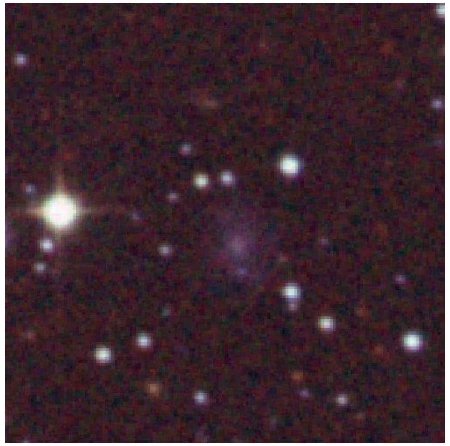
SN2019fcn

ESO 430-G20



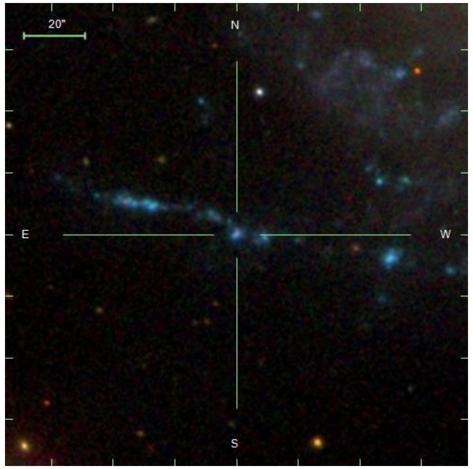
RUN	O3a
TYPE	II
DISTANCE	15.25 Mpc. TNS: 17.4Mpc (z=0.003402)
DISCOVERY TIME	2019 May 08 T23:02:24
t1 (UTC)	1240878546 2019 May 03 T00:28:48
t2 (UTC)	1241270802 2019 May 07 T13:26:24
Δt (days)	4.54
Radius (solar radius)	(2.3 ± 0.3) × 10^3
Explosion energies	
Mass ($M_{\odot}$)	
OSW Level	2
RA/DEC	08:07:08.054 / -28:03:22.90 (121.7835 / -28.05636)
LINK	TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

SN2019gaf



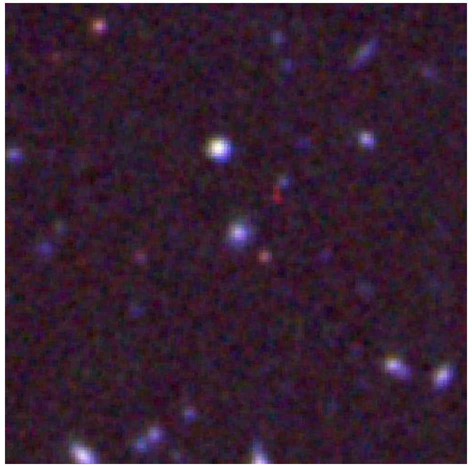
REFERENCES:

RUN	O3a
TYPE	IIb
DISTANCE	26.95 Mpc TNS: 18.54 (z=0.0043)
DISCOVERY TIME	2019 May 27 T13:06:14
t1 (UTC)	1241751532 2019 May 13 T02:58:34
t2 (UTC)	1242059116 2019 May 16 T16:24:58
Δt (days)	3.56
Radius (solar radius)	
Explosion energies	
Mass ($M_\odot$)	
OSW Level	1
RA/DEC	20:36:55.239 / +02:48:24.62 (309.2301634 / +2.8068387)
LINK	ATel1282, TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

SN2019hsw NGC 2805  REFERENCES: https://arxiv.org/pdf/1910.13319.pdf No physical information, just was discovered.	RUN	O3a
	TYPE	II
	DISTANCE	24.7 Mpc TNS: 18.54 (z=0.005779)
	DISCOVERY TIME	2019 June 18 T03:07:12
	t1 (UTC)	1243740114 2019 June 05 T03:21:36
	t2 (UTC)	1244431314 2019 June 13 T03:21:36
	Δt (days)	8
	Radius (solar radius)	
	Explosion energies	
	Mass ($M_\odot$)	
	OSW Level	1
	RA/DEC	09:20:33.757 / +64:04:22.96 (140.140655455 / +64.0730454545)
	LINK	TNS, OSC, ASRAS
	ACTIVE DETECTORS	L1-H1

SN2020oi

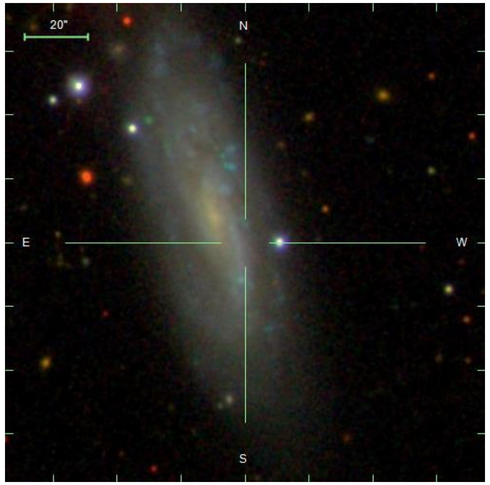
NGC 4321
M100



REFERENCES:
https://arxiv.org/pdf/2006.13952.pdf

RUN	O3b
TYPE	Ic
DISTANCE	23.35 Mpc
DISCOVERY TIME	2020 January 07 T13:00:54
t1 (UTC)	1261567764 2019 December 28 T11:29:06
t2 (UTC)	1261875348 2020 January 01 T00:55:30
Δt (days)	3.56
Radius ($R_\odot$)	5797
Explosion energies	0.3 – 10 keV
Mass-loss ($M_\odot\ yr^{-1}$)	1.4 x 10^{-4}
OSW Level	1
RA/DEC	12:22:54.930 / +15:49:24.96 (185.728875 / +15.8236)
LINK	TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

SN2020cxd

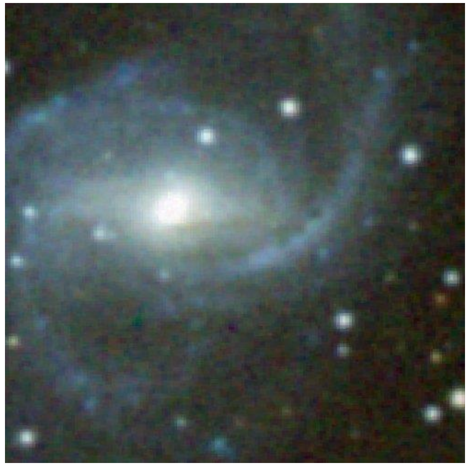


REFERENCES:
https://arxiv.org/abs/2107.13439.pdf
https://arxiv.org/pdf/2009.01242.pdf

RUN	O3b
TYPE	IIP
DISTANCE	17.42 Mpc
DISCOVERY TIME	2020 February 19 T12:44:08
t1 (UTC)	1265892266 2020 February 16 T12:44:08
t2 (UTC)	1266410666 2020 February 22 T12:44:08
Δt (days)	6
Radius (solar radius)	1.3 x 10^{13}cm
Energy_rad/Energy_kin	1.52 x 10^{48}/4.3 x 10^{50}erg
Mass ($M_{\odot}$)	$\lesssim$ 15 (ZAMS)
OSW Level	1
RA/DEC	17:26:29.260/ +71:05:38.58 (261.621917 / +71.09405)
LINK	TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

SN2020dpw

NGC 6952



REFERENCES:

RUN	O3b
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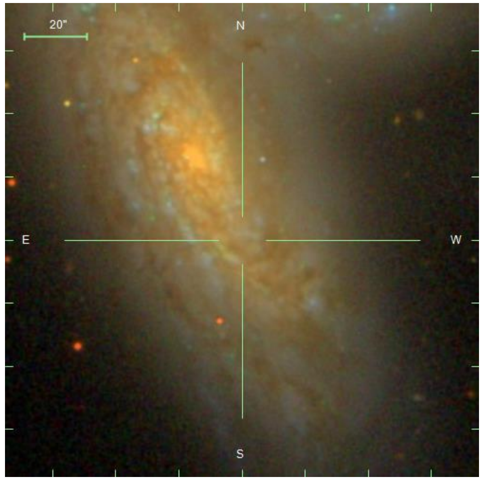
DISTANCE	21.54 Mpc
DISCOVERY TIME	2020 February 26 T10:01:22
t1 (UTC)	1266285700 2020 February 21 T02:01:22
t2 (UTC)	1266631300 2020 February 25 T02:01:22
Δt (days)	4
Radius (solar radius)	
Explosion energies	
Mass ($M_{\odot}$)	
OSW Level	1
RA/DEC	20:37:10.550 / +66:06:10.66 (309.293958 / +66.102961)
LINK	TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

SN2020fqv

NGC 4568



REFERENCES:
https://arxiv.org/pdf/2110.10742.pdf

RUN	O3b
TYPE	IIb
DISTANCE	32 Mpc
DISCOVERY TIME	2020 March 31 T08:06:02
t1 (UTC)	1268870418 2020 March 22 T00:00:00
t2 (UTC)	1269388818 2020 March 28 T00:00:00
Δt (days)	6
Radius (solar radius)	10^4cm
Explosion energies	$\sim 5\text{x}10^{46}$erg
Mass ($M_\odot$)	13.5 – 15 (ZAMS)
OSW Level	1
RA/DEC	12:36:33.260 / +11:13:53.87 (189.138583 / +11.231631)
LINK	TNS, OSC, ASRAS
ACTIVE DETECTORS	L1-H1

Using Different Band Filtering With the Quartic Interpolation

- We know that when the U-band filter flux becomes smaller than the V-band filter flux, then the explosion will yield much less energy in the B-band light curve data than in the V-band light curve data
- To observe this for SN2019ejj we must obtain the data for the V and U band filter