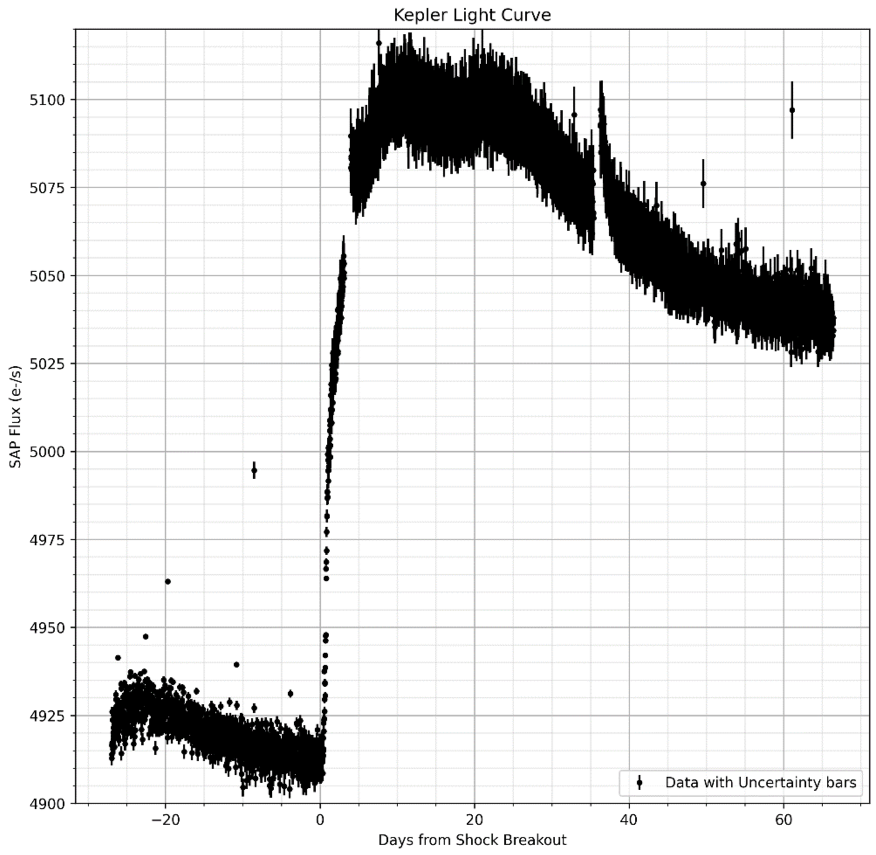
OSW Methodology in O3 and Next Steps for O4

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 for the 03 OSWs and our steps moving forward with O4

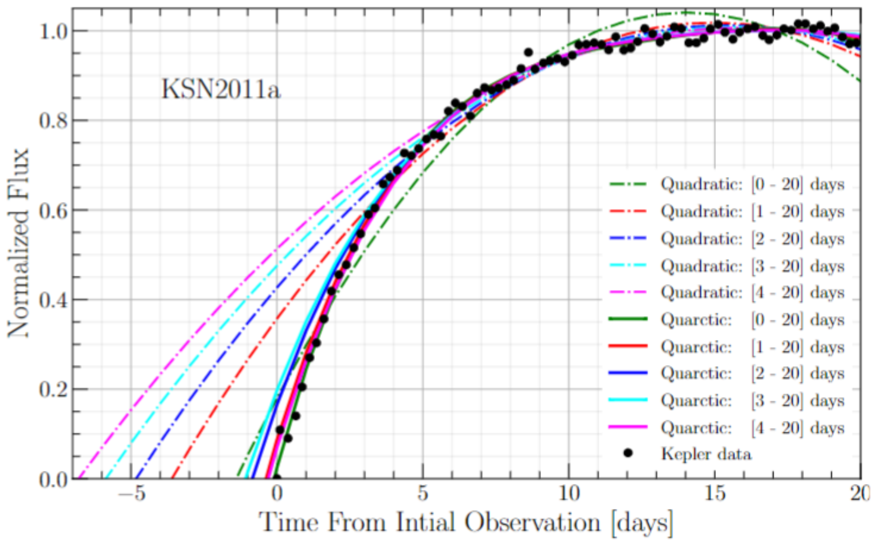
Methodology for O3

- Shapes are more homogenous in the first part of the light curve (homologous expansion for about a month) for CCSN, see for example P.J. Valley Ref. With this physical assumption we believed that we could use a light curve (that has data pre and post SBO) to develop a polynomial interpolation of the rise time during the homologous expansion
- We decided to utilize the Kepler Data (ksn2011a) to test the methodology since it was a complete light curve that would allow us to test the efficiency of modelling methods (in terms of comparing the outcome of the estimation of the SBO time with the actual one). In all methods of estimating the initial time of shock breakout, there are three kinds of uncertainty: amplitude of error in optical measurements, how late you start measuring the light curve, and the understanding of the pre SBO flux. In order to account for the optical error, we rescaled the Kepler optical observations
- In the Kepler data, we had to rescale both the data points and their uncertainty corresponding to the peak luminosity. This rescaling is covered more in depth in the next slides
- Note: the Kepler graph shows the units of SAP flux that are not normalized. SAP flux is the Simple Aperture Photometry flux which is a pixel summation time-series of all calibrated flux falling within the optimal aperture



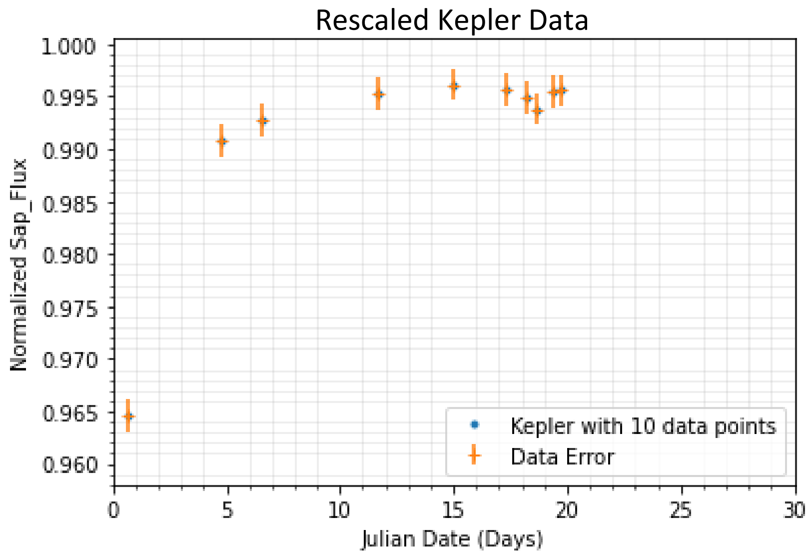
Methodology for O3 Cont.

- 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 collapse (depends on the mass of the progenitor). 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



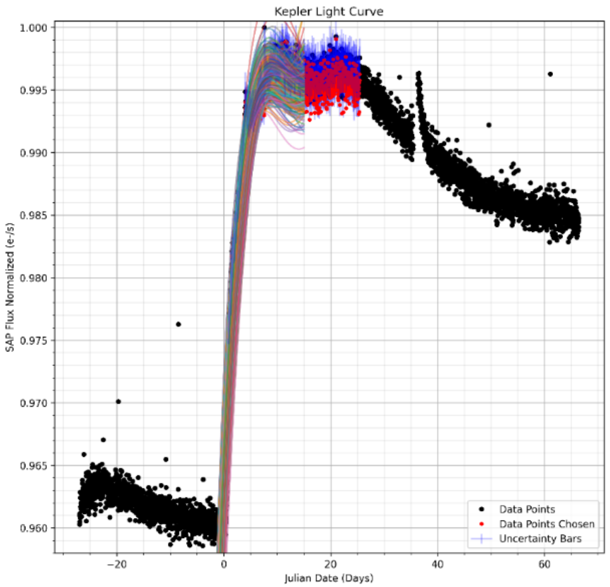
Methodology for O3 Cont.

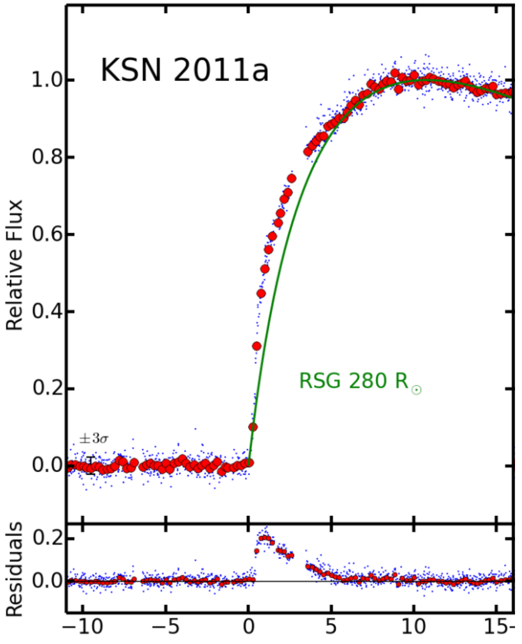
- The next type of polynomial we wanted to use was a quartic one. The reason we decided not to use a cubic function was because the cubic function produced an unphysical model of the light curve interpolation
- We selected only three candidates that had light curves with a few points (SN2019gaf, SN2019ehk, and SN2020oi) and had trends in the flux in the homologous phase
- In the candidates for 03, there were a few things that differed from them and the Kepler data. The light curves had different unit values (explicitly flux and SAP flux) for its luminosity, very few points in the data set that had greater uncertainty since they were measured from different telescopes, and did not have a known null luminosity at SBO at the time of the analysis. After opening the box, the null magnitude became available
- In order to account for the difference in units for the luminosity values, we normalized the Kepler data as well as the candidates' data. Normalizing the data meant that the peak luminosity was set as 1 and all points were then divided by this peak to get values that did not depend on units but on its relationship to the peak



Methodology for O3 Cont.

- To account for the difference in amount of data points for Kepler and the three candidates we decided to sample 10 random data points within the uncertainties in the Kepler Light curve (as seen in the top figure). The uncertainties bounds in the Kepler data came from averaging the error from a different telescope (SN2019gaf in our case) and adding it to the already normalized uncertainty values that came with the Kepler data. This allowed us to model the Kepler data as if it came from another telescope just like the three candidates of SN2019ehk, SN2019gaf, and SN2020oi
- In the normalized Kepler data, the luminosity at the time of shock breakout became zero for the average flux after removing the background at the time of SBO (bottom figure Ref: https://arxiv.org/pdf/1603.05657.pdf). We then used the normalized value of zero as our reference pre SBO flux when performing the quartic interpolation over the Kepler data
- We then set the interval for the 10 data points to be picked between 0.5-25 days to the model our three candidates, which had few points on the rise of the light curve. In the Kepler data we know the known time of SBO (value of zero once normalized), therefore by performing the quartic interpolation we were able to see how effective the method was (see review page where the figures to the right were taken)
- By performing the interpolation for 10,000 samples (since at 10,000 the standard deviation value in the histogram is consistent between runs) we obtained the histogram that showed the mean value for the estimated time and the standard deviation (sigma) of the SBO. We then decided to use an uncertainty of 2-sigma (0.50 days for the Kepler data) in order to have an upper limit of the error in estimating the SBO with the correct pre SBO flux





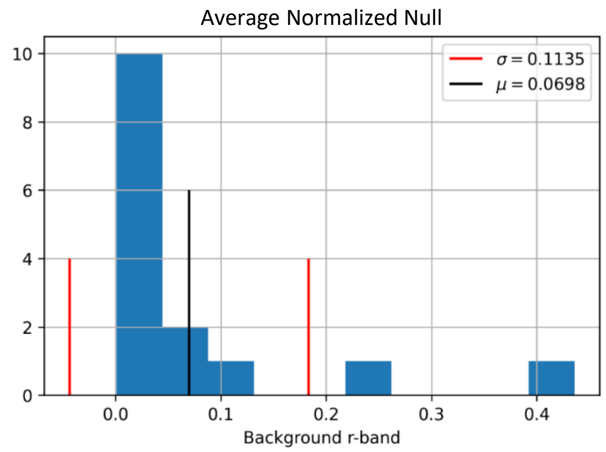
Methodology for O3 Cont.

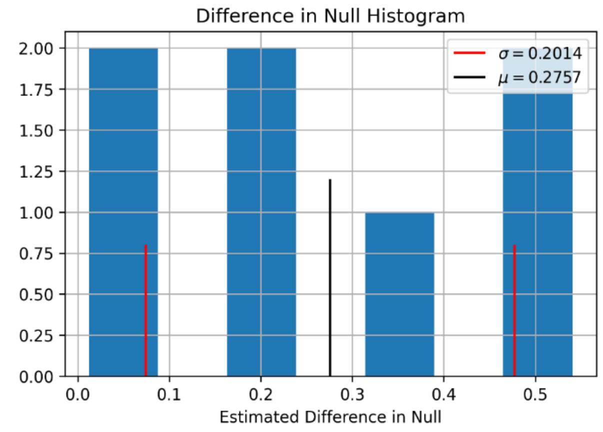
- The luminosity of the CCSN before the SBO is affected by the background light. If a CCSN is too close to a galactic center, it might not be visible at all. In the case of the Kepler data how much the peak is brighter than the pre SBO phase, greatly diminishes if the background light is not subtracted. It is subtracted in the light curves that we discuss in the review page
- In the supernovae archive data base (https://www.rochesterastronomy.org/snimages/archives.html), candidates from 2020-present contained pre and post SBO data for both the r-band and g-band spectrum for their magnitude. We selected using the r-band spectrum since it allows for a peak CCD and would not show as much distortion as other filters
- Since the flux of the r-band at last non-detection was not given before the box opening for SN2019gaf, SN2019ehk, and SN2020oi we decided to set the normalized flux at SBO equal to zero based on the Kepler tests. In the Kepler data, after subtracting the background it was exactly zero. This is what we assumed for our candidates since we didn’t know the SBO flux. Subsequently after the box was already open when we were able to acquire the pre SBO mag we assessed the impact of having made that assumption on our candidates
- In order to check the impact of this assumption, after exploring the SNe data base after the box opening, we decided to utilize the flux to magnitude equation below with several different candidates to study the average normalized null pre SBO flux between them

$$f_1 = \frac{f_2}{10^{(m_1 - m_2)/2.5}} \qquad \text{(*Eq.1)}$$

m_1 is the background null of the magnitude from a specific candidate’s data set, m_2 is the magnitude at the peak luminosity, f_2 is the peak luminosity of the normalized flux (set at 1), and f_1 is the calculated pre SBO flux of the normalized flux. The flux is the intensity such that the flux is equal to the luminosity divided by 4 pi times the distance away squared

Methodology for O3 Cont.

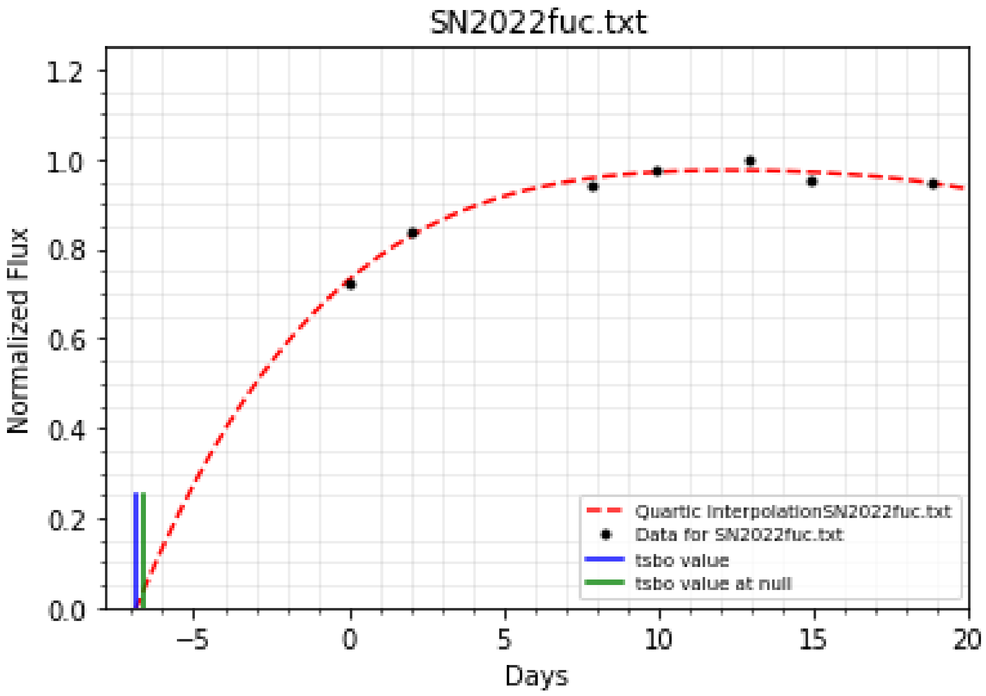




- Using the relationship between flux and mag on several candidates from the data base (candidates in table in extra slides), we obtained the following histogram (top left) for the r-band data where the x-axis is represented as the null values obtained. This histogram shows the average normalized null of all the candidates in the r-band spectrum when the peak luminosity is set at 1
- Going back to the assumption of setting the flux at SBO equal to zero, for the three O3 candidates, we then investigated the difference in the estimated time of SBO if we would have had the null magnitude and obtained the null flux from it
- Using the several candidates (who have a last non-detection) and observed the difference between setting the value of the null at SBO equal to zero or at the last non-detection. Doing so, we obtained the following histogram (located on the top right) that showed the average difference in all several candidates, that is:

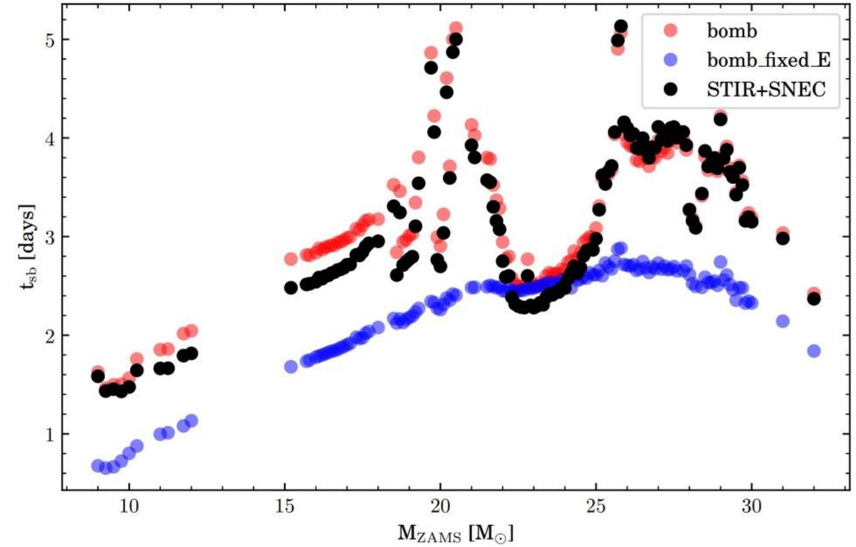
$$Difference_{null} = |t_{SBO,Flux\ 0} - t_{SBO,Flux\ null}|$$

where $t_{SBO,Flux\ 0}$ is the estimated time of SBO when the normalized null for the interpolation is set at zero and $t_{SBO,Flux\ null}$ is the estimated time of SBO when the normalized null for the interpolation is the last non-detection for the candidate observed (The figure on the bottom is an example of setting the null of SBO at zero and at the known null for a specific candidate)



Methodology for O3 Cont.

- We decided to use the comparison between the delay of the estimated shock breakout as a function of ZAMS mass from Couch et al. This allowed us to observe the relationship between the ZAMS mass and delay in SBO for a candidate with known mass. Out of the three O3 candidates, only SN2019ehk had a known progenitor which corresponded to a $\Delta t_{delay} = 1.5$ days. For SN2019gaf and SN2020oi, the mass was unknown leaving $\Delta t_{delay} = 0$ days
- In Smartt et al. (2009), it described "the Red Supergiant Problem" meant that there was a clear lack of high-mass($\gtrsim 17 M_\odot$) RSGs that have been detected as supernova progenitors. A possible explanation for this is "All massive stars above $17 M_\odot$ 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-$17 M_\odot$"
- Therefore, for cases that have a known progenitor mass we could use the figure from Couch et al (as shown) to estimate the delay. However, for cases where the mass is unknown, 3 days was subtracted as the conservative method approach since the graph shows that the highest delay for progenitors with mass $17 M_\odot$ is about 3 days



Methodology for O3 Cont.

- Using the methodology we described, we calculated the beginning and the end time of the OSW for each of the three candidates. The beginning of the OSWs, t_1, were determined in three steps: we estimate the SBO time (with respect to the $t_{discovery}$) t_{SBO}, with a quartic interpolation and then subtracted both Δt_{delay} and $\Delta t_{SBO,1}$ that is $t_1 = \Delta t_{SBO} - \Delta t_{delay} - \Delta t_{SBO,1}$ (where Δt_{delay} is the delay between the estimated shock breakout as a function of ZAMS mass and $\Delta t_{SBO,1}$ is the sum of the different type of uncertainties). SN2019ehk had a known progenitor mass of about 9.5 solar mass, which according to Barker:2021 et al corresponds to a 1.5 +/- 0.2 days delay between the collapse and the SBO, choosing $\Delta t_{delay} = 1.5$ days. $\Delta t_{SBO,1}$ is then calculated by adding the uncertainty with an additional two double standard deviation from the quartic interpolation, giving $\Delta t_{SBO,1} = 0.7$ days. For SN 2019gaf and SN 2020oi, since the mass of the progenitor was unknown, we accounted for this by using $t_1 = \Delta t_{SBO} - \Delta t_{SBO,1}$ which subtracts the upper limit from the conservative method of 3 days, choosing $\Delta t_{SBO,1} = 3$ days. After opening the box, we found out a bug in our code that subtracted an extra 1.5 days. This made the OSW 1.5 days longer than we planned to. It does not impact the validity of the results, but if we would have had a strong detection candidate in these CCSNe it would have made the statistical significance about 30% smaller
- The end of the OSWs, t_2, were determined using the same three steps as described above but add $\Delta t_{SBO,2}$ where $t_2 = \Delta t_{SBO} - \Delta t_{delay} + \Delta t_{SBO,2}$. For each of the three $\Delta t_{SBO,2}$ was then calculated as adding both the uncertainty of the delay with the double standard deviation from the quartic interpolation, choosing $\Delta t_{SBO,2} = 0.7$ days.
- Note: the uncertainty of the delay was taken from the figure from Couch et al. which is 0.2 days, and the double standard is the uncertainty of 0.50 days taken from the quartic interpolation uncertainty from the Kepler data

Methodology for O3 Cont.

The columns in the table are labeled Difference Between Time of SBO at Zero and at Average Null (σ_{null}), Uncertainty from Estimated Time of SBO (σ_{SBO}) from actual data, and Quadrature between the two. The difference between the time of SBO is obtained from the O3 candidates when the pre-SBO is at zero and at the average pre-SBO null calculated from using EQ1 on the other candidates (mean value in the histogram from previous slides). The uncertainty from estimated time of SBO is calculated from doing the Monte Carlo method on the quartic interpolation on the O3 candidates. The fourth column is from the relationship between the estimated SBO as a function of ZAMS mass. The fifth column is the sum of the uncertainties, however for SN2019ehk because the mass of the progenitor is known, it is the sum of the Kepler error (2sigma = 0.50) plus the estimated SBO fluxuations error (Δx=0.2 from Couch et al.). For candidates SN2019gaf and SN2020oi the fifth column is the conservative method approach where we subtracted three days since the mass of the progenitor was not known (although we noticed a bug in the code that subtracted an additional 1.5 resulting in 4.5 days)

	Difference in Days Between Time of SBO at Zero and at Average Background Null (σ_{diff})	Uncertainty from Estimated Time of SBO (σ_{SBO})	Quadrature $\sqrt{\sigma_{diff}{}^2 + \sigma_{SBO}{}^2}$	Δt_{delay} (days)	$\Delta t_{SBO,1}$ (days) with Kepler Uncertainty (σ)
SN2019ehk	0.3416	0.13	0.366	1.5	0.7
SN2019gaf	0.3297	0.51	0.607	0 (unknown mass)	4.5 (conservative method)
SN2020oi	0.0464	0.18	0.186	0 (unknown mass)	4.5 (conservative method)

What We Need for O4

- Magnitude and Flux data (preferably in r-band) with error
- Mass of the progenitors of the candidates known
- Last non-detection of the candidates (preferably in r-band) in magnitude and flux units
- More???

Extra Slides

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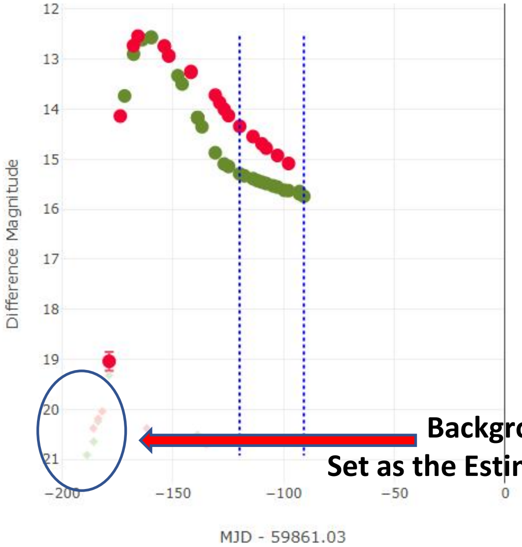
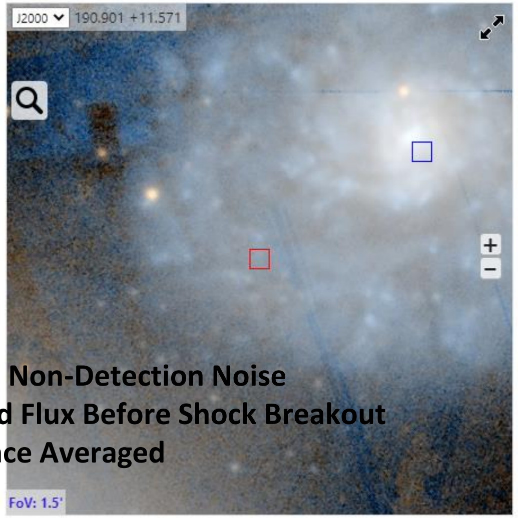
Object ZTF22aafoqrd



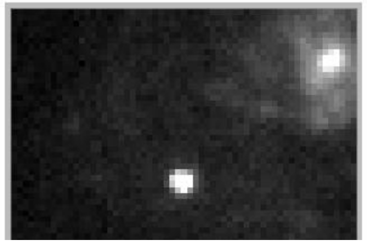
Background Non-Detection Noise
Set as the Estimated Flux Before Shock Breakout
Once Averaged

PanSTARRS



Transient position: red square.

Sherlock source: blue square.



- Object has 19 candidates between 120 and 91 days ago, at mean position:
  - (RA, Dec) = (190.893055, 11.576643)
  - (RA, Dec) = (12:43:34.333, 11:34:35.914)
  - (galactic_lon, galactic_lat) = (295.778384, 74.339041)
  - (ecliptic_lon, ecliptic_lat) = (185.346498, 14.937208)
- Galactic Extinction
- Conesearch Links (at 5 arcsec): | Simbad | NED | Transient Name Server | ZTF DR1

Sherlock

- Classified as SN, at 35.13 arcsec.
- Best crossmatch is galaxy
- The transient is possibly associated with *NGC4647*; a 11.94 mag galaxy found in the NED_D catalogue. Its located 18.79" S, 29.69" E (2.9 Kpc) from the galaxy centre. A host distance of 16.8 Mpc(z=0.005) implies a *m* - *M* = 31.13.

This image is the most recent. Click on these links to inspect the science, ref, and diff images in detail.

TNS

- TNS name is SN 2022hrs
- type SN Ia, z=0.0047, host is
- discovered by None
- discovery magnitude 15.0

Candidates (To sort, click the column headings)

MJD	UTC	Filter	magpsf	status	images
59672.316		g	20.908	non-detection	
59675.212		r	20.372	non-detection	
59675.333		g	20.643	non-detection	
59677.300		g	20.238	non-detection	
59677.363		r	20.184	non-detection	
59679.230		r	20.038	non-detection	
59682.214		g	19.318	non-detection	
59682.316	2022-04-13 07:35:34	r	19.037 ± 0.190	t	target ref diff
59687.369	2022-04-18 08:51:47	r	14.137 ± 0.029	t	target ref diff
59689.296	2022-04-20 07:05:35	g	13.735 ± 0.018	t	target ref diff

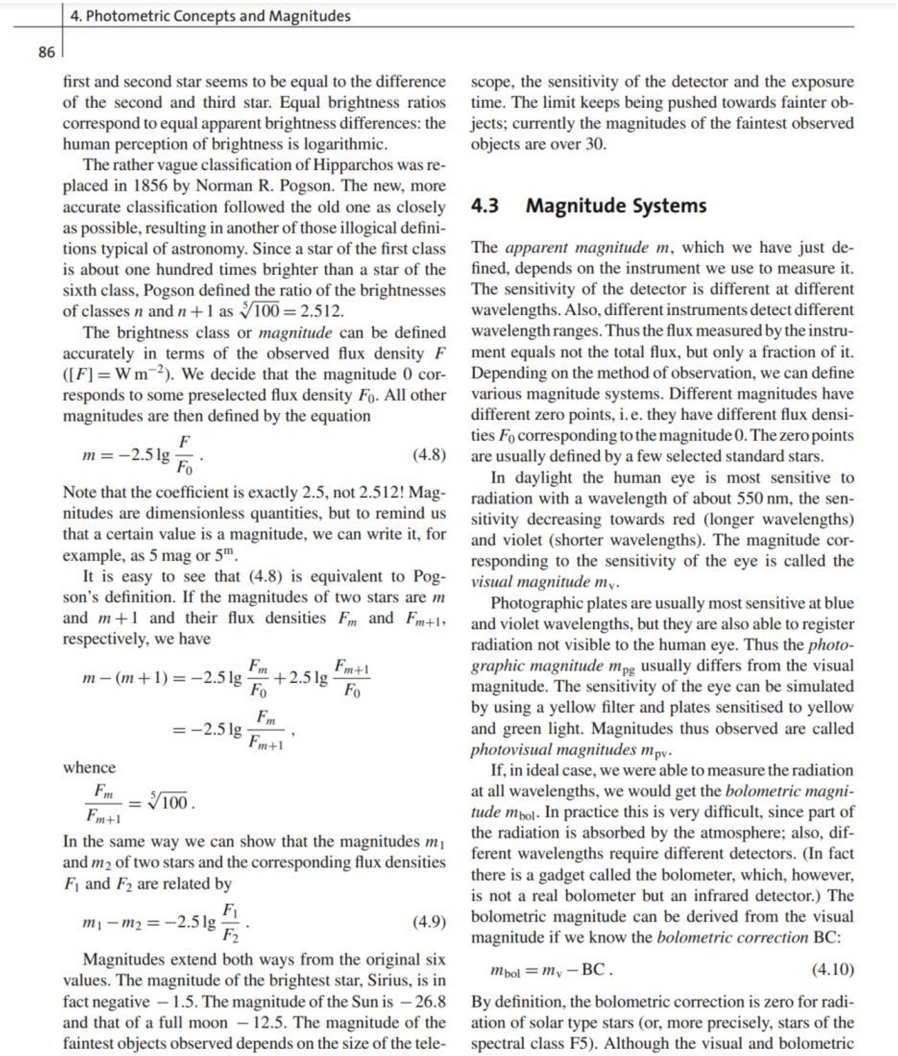
Null Band Ratio Between Flux and Mag

For each of the three candidates, the null band ratio between the flux and magnitude can be found numerical using the following equation:

$$f_1 = \frac{f_2}{10^{(m_1 - m_2)/2.5}} \qquad (\text{*Eq.1})$$

where m_1 is the background null of the magnitude for the data set, m_2 is the magnitude at the peak luminosity, f_2 is the peak luminosity of the normalized flux (set at 1), and f_1 is the calculated background null of the normalized flux

*Eq.1 from Fundamental Astronomy fifth edition by Hannu Karttunen et al



first and second star seems to be equal to the difference of the second and third star. Equal brightness ratios correspond to equal apparent brightness differences: the human perception of brightness is logarithmic.

The rather vague classification of Hipparchos was replaced in 1856 by Norman R. Pogson. The new, more accurate classification followed the old one as closely as possible, resulting in another of those illogical definitions typical of astronomy. Since a star of the first class is about one hundred times brighter than a star of the sixth class, Pogson defined the ratio of the brightnesses of classes n and $n+1$ as $\sqrt[5]{100} = 2.512$.

The brightness class or *magnitude* can be defined accurately in terms of the observed flux density F ($[F] = \mathrm{W\,m^{-2}}$). We decide that the magnitude 0 corresponds to some preselected flux density F_0. All other magnitudes are then defined by the equation

$$m = -2.5 \lg \frac{F}{F_0} . \qquad (4.8)$$

Note that the coefficient is exactly 2.5, not 2.512! Magnitudes are dimensionless quantities, but to remind us that a certain value is a magnitude, we can write it, for example, as 5 mag or 5^{m}.

It is easy to see that (4.8) is equivalent to Pogson's definition. If the magnitudes of two stars are m and $m+1$ and their flux densities F_m and F_{m+1}, respectively, we have

$$\begin{aligned} m - (m+1) &= -2.5 \lg \frac{F_m}{F_0} + 2.5 \lg \frac{F_{m+1}}{F_0} \\ &= -2.5 \lg \frac{F_m}{F_{m+1}} , \end{aligned}$$

whence

$$\frac{F_m}{F_{m+1}} = \sqrt[5]{100} .$$

In the same way we can show that the magnitudes m_1 and m_2 of two stars and the corresponding flux densities F_1 and F_2 are related by

$$m_1 - m_2 = -2.5 \lg \frac{F_1}{F_2} . \qquad (4.9)$$

Magnitudes extend both ways from the original six values. The magnitude of the brightest star, Sirius, is in fact negative -1.5. The magnitude of the Sun is -26.8 and that of a full moon -12.5. The magnitude of the faintest objects observed depends on the size of the telescope, the sensitivity of the detector and the exposure time. The limit keeps being pushed towards fainter objects; currently the magnitudes of the faintest observed objects are over 30.

4.3 Magnitude Systems

The *apparent magnitude* m, which we have just defined, depends on the instrument we use to measure it. The sensitivity of the detector is different at different wavelengths. Also, different instruments detect different wavelength ranges. Thus the flux measured by the instrument equals not the total flux, but only a fraction of it. Depending on the method of observation, we can define various magnitude systems. Different magnitudes have different zero points, i. e. they have different flux densities F_0 corresponding to the magnitude 0. The zero points are usually defined by a few selected standard stars.

In daylight the human eye is most sensitive to radiation with a wavelength of about 550 nm, the sensitivity decreasing towards red (longer wavelengths) and violet (shorter wavelengths). The magnitude corresponding to the sensitivity of the eye is called the *visual magnitude* m_{v}.

Photographic plates are usually most sensitive at blue and violet wavelengths, but they are also able to register radiation not visible to the human eye. Thus the *photographic magnitude* m_{pg} usually differs from the visual magnitude. The sensitivity of the eye can be simulated by using a yellow filter and plates sensitised to yellow and green light. Magnitudes thus observed are called *photovisual magnitudes* m_{pv}.

If, in ideal case, we were able to measure the radiation at all wavelengths, we would get the *bolometric magnitude* m_{bol}. In practice this is very difficult, since part of the radiation is absorbed by the atmosphere; also, different wavelengths require different detectors. (In fact there is a gadget called the bolometer, which, however, is not a real bolometer but an infrared detector.) The bolometric magnitude can be derived from the visual magnitude if we know the *bolometric correction* BC:

$$m_{\mathrm{bol}} = m_{\mathrm{v}} - \mathrm{BC} . \qquad (4.10)$$

By definition, the bolometric correction is zero for radiation of solar type stars (or, more precisely, stars of the spectral class F5). Although the visual and bolometric

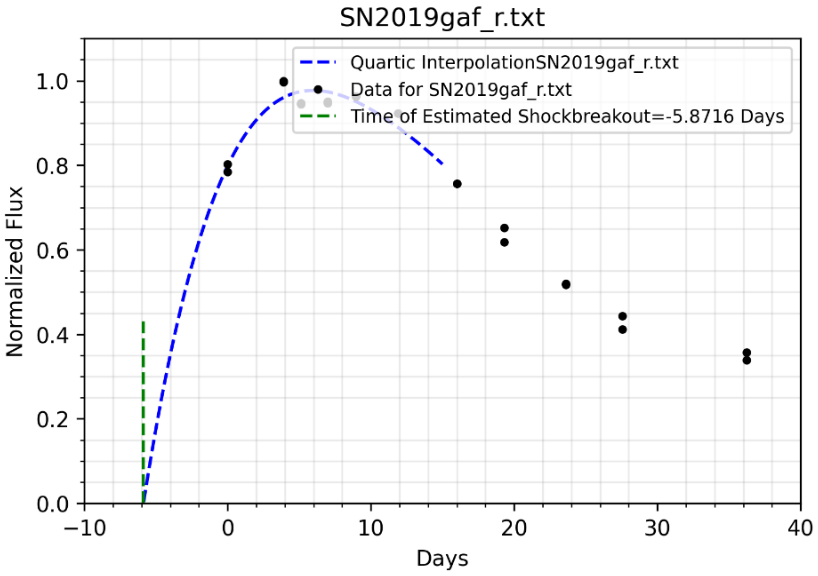
Average Null from Table of SN Candidates

Magnitude Light Curve Candidate	Host Distance (Mpc)	r-Band Average Null (Magnitude)	g-Band Average Null (Magnitude)	$\frac{f_2}{f_1}$, r-band	$\frac{f_2}{f_1}$, g-band	$f_{1,Null}$, r-band Normalized	$f_{1,Null}$, g-band Normalized
SN2022fuc	42.9	20.48	---	30.1995	---	0.033113	---
SN2022hrs	16.8	20.2	20.6	1159.85	1644.37	0.000862	0.000608
SN2022mxv	60	20.5	19.67	59.1562	26.1818	0.016904	0.038194
SN2022ngb	27.4	20.44	20.58	38.3001	21.1057	0.02611	0.047381
SN2022jzc	11.29-13.8	20.04	20.16	11.7166	9.99079	0.085349	0.100092
SN2022ihz	23.36-28.55	19.72	19.78	79.2136	59.2107	0.012624	0.016889
SN2022pgf	31.15-38.07	19.83	20.49	76.0677	124.051	0.013146	0.008061
SN2021rhu	12.2	19.89	19.25	880.643	536.537	0.001136	0.001864
SN2021adlw	19.47-23.79	19.38	---	9.62055	---	0.103944	---
SN2021acvl	35.04-42.83	19.63	19.09	4.37321	1.04713	0.228665	0.954993
SN2020hvf	25.8	19.7	17.80	563.378	123.367	0.001775	0.008106
SN2020hvp	19.47-23.79	18.33	19.65	19.3553	41.5719	0.051665	0.024055
SN2020jfo	19.47-23.79	20.34	20.54	227.405	275.677	0.004397	0.003627
SN2019yz	23.36-28.55	19.75	20.44	32.0922	31.6228	0.03116	0.031623
SN2019ehk	16.1	---	20.481				
SN2019gaf	25.3	---	20.6375				
SN2020oi	16.1	---	19.693				

Methodology for O3 Cont.

- In the example of 2019gaf, the difference between the null set at zero and the average was calculated to be a difference of 0.3297 days. This method was used for SN2019ehk (which resulted in a difference of 0.3416 days) where both candidates had a difference in flux at SBO of 0.0698 which came from the average null from the candidates in the database
- SN2020oi, used the same method however the r-band magnitude was found after the 03 run so the null magnitude was set as 0.00628 resulting in a difference of 0.0464 days

Null = 0



Null = 0.0698