

## SN 2020jgb

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### ABSTRACT

The detonation of a thin ( $\lesssim 0.03 M_{\odot}$ ) helium shell (He-shell) atop a white dwarf (WD) is a promising mechanism to explain normal Type Ia supernovae (SNe Ia), while thicker He-shells ( $> 0.03 M_{\odot}$ ) may explain some recently observed peculiar SNe Ia. We present observations of SN 2020jgb, a peculiar SNIa discovered by the Zwicky Transient Facility (ZTF). Near maximum light, SN 2020jgb is sub-luminous (ZTF  $g$ -band absolute magnitude  $M_g \approx -18.2$  mag) and shows an unusually red color ( $g_{\text{ZTF}} - r_{\text{ZTF}} \approx 0.5$  mag) due to the strong line-blanketing bluewards of  $\approx 5000$  Å. These properties resemble SN 2018byg, a peculiar SNIa resulting from a “thick-shell” double detonation [Chang: the phrase double detonation should be in here somewhere, but my edited sentence is somewhat awkward]. Using detailed radiation transport models, we show that the optical spectroscopic and photometric evolution of SN 2020jgb are broadly consistent with a He-shell of  $\approx 0.08 M_{\odot}$  detonating above a carbon-oxygen WD of  $\approx 0.87 M_{\odot}$ . We detect a prominent absorption feature at  $\sim 1 \mu\text{m}$  in the near infrared (NIR) spectrum of SN 2020jgb, which could originate from the unburnt helium in the outermost ejecta. While the sample size is limited, similar  $1 \mu\text{m}$  features have been detected in all the thick He-shell DDet [Chang: DDet is not defined at this point] candidates with NIR spectra obtained to date. SN 2020jgb is also the first He-shell DDet SN discovered in a star-forming dwarf galaxy, indisputably showing that He-shell DDet occur in both star-forming and passive environments, consistent with the normal SNe Ia population. This favors the scenario that a substantial fraction of normal SNe Ia are triggered by He-shell DDet. [Chang: let’s discuss this point, because this particular SN is clearly not normal]

**Keywords:** Supernovae(1668), Type Ia supernovae(1728), White dwarf stars(1799), Observational astronomy(1145), Surveys(1671)

### 1. INTRODUCTION

It has been clear for decades that Type Ia supernovae (SNe Ia) are caused by the thermonuclear explosions in carbon-oxygen (C/O) white dwarfs (WDs) in binary systems (see Maoz et al. 2014, for a review). Nevertheless, the nature of the binary companion, as well as how it ignites the WD, remains highly uncertain.

The helium-shell (He-shell) double detonation (DDet) scenario is one of the most promising channels to produce SNe Ia. In this scenario, the WD accretes from a companion to develop a helium-rich shell, which, once becomes massive enough, could detonate. Such a detonation sends a shock wave into the C/O core to trigger a runaway thermonuclear explosion and inevitably disrupt and destroy the entire WD (Nomoto 1982a,b; Woosley et al. 1986; Livne 1990; Woosley & Weaver 1994; Livne & Arnett 1995). The DDet mechanism can produce explosions in WDs below the Chandrasekhar mass ( $M_{\text{Ch}}$ ).

There are several observational benchmarks for He-shell DDet triggered SNe. Shortly after the ignition of the shell, the decay of radioactive material in the helium ashes may power a detectable flash (Woosley & Weaver 1994; Fink et al. 2010; Kromer et al. 2010). The Fe-group elements in the ashes will blanket blue photons with wavelengths  $\lesssim 5000$  Å (Kromer et al. 2010), the duration of which depends on the mass of the He-shell. For thick enough shells, Boyle et al. (2017) suggest that the unburnt helium could provide an observational signal in near infrared (NIR) spectra, and Polin et al. (2021) predict significant [Ca II] emission in the nebular phase of the SNe.

Using different combos of He-shell mass and C/O core mass, one can reproduce a variety of observables in ‘normal’ SNe Ia with typical luminosities and spectral features near peak light (e.g., Polin et al. 2019; ?), or peculiar sub-luminous ones (e.g., Polin et al. 2019).

For the DDet SNe that show ‘normal’ characteristics near their peaks, the mass of the He-shell is expected to be low ( $\lesssim 0.03 M_{\odot}$ ; Kromer et al. 2010; Sim et al. 2010; Shen et al. 2018; Polin et al. 2019). The first DDet candidate with a thin He-shell is SN 2016jhr (Jiang et al. 2017), which exhibits an early red flash and keeps a red  $g - r$  color throughout its evolution, though it show a typical absolute magnitude at peak ( $M_g \approx -19$ ) for normal SNe Ia. The multi-band light curves involving the early flash and the major peak, as well as the optical spectrum close to the peak light, could be simultaneously fit by a near- $M_{\text{Ch}}$  DDet model (a  $1.38 M_{\odot}$  C/O core and a  $0.03 M_{\odot}$  He-shell). Recently, a thinner He-shell is discovered in SN 2018aoz (Ni et al. 2022a), a SN Ia showing a rapid redward color evolution within  $\approx 12$  hr after the first light, which could be explained by a sub- $M_{\text{Ch}}$  DDet model (a  $1.05 M_{\odot}$  C/O core and a  $0.03 M_{\odot}$  He-shell). After this red excess the photometry evolution is consistent with normal SNe Ia, when the ashes of the thin He-shell becomes optically thin. However, some of its peak-time and nebular phase spectral properties are not consistent with a He-shell DDet scenario (Ni et al. 2022b), making its nature debatable. To date, only a small fraction of SNe Ia have been discovered early enough for possible detection of early flashes (e.g., Deckers et al. 2022). While there could be a large underlying population of normal SNe Ia triggered by He-shell DDet, it is hard to prove so.

In contrast, if the He-shell mass is much greater than  $0.03 M_{\odot}$ , the ashes of the He-shell detonation could remain optically thick in a much more extended phase, resulting in the red color and low luminosity near peak light. SN 2018byg (De et al. 2019) is a prototype of thick He-shell DDet SNe. During the late stages of preparing for this paper, Dong et al. (2022a) presented another thick shell He-shell DDet candidates, SN 2016dsg, accompanied with an archival transient OGLE-2013-SN-079 (Inserra et al. 2015). All three candidates are faint, red, and show strong line-blanketing in maximum-light spectra. Dong et al. (2022a) also report a tentative detection of unburnt helium in SN 2016dsg. The small sample size to date suggests thick shell events might be intrinsically rare.

It has been suggested that some, if not all, of the calcium-rich (Ca-rich) gap transients, a population of faint SNe with conspicuous [Ca II] emission in the nebular phase, also arise from He DDet [Chang: need to decide and consistently call these He-shell DDet, He DDet, or just DDet] (Dessart & Hillier 2015; De et al. 2020; Polin et al. 2021). A subclass of Ca-rich transients resemble SNe Ia near peak lights (termed Ca-Ia objects), marked by the strong Si II absorption and the

absence of optical He I lines. There are only two Ca-Ia objects (SN 2016hmk and SN 2019ofm; De et al. 2020), both showing significant line-blanketing in spectra, and hence could be He-shell DDet objects. [Chang: Should cite Wynn’s paper somewhere in here] Nonetheless, they also exhibit properties of other types of sub-luminous SNe Ia, such as the strong O I absorption widely seen in 91bg-like objects (Filippenko et al. 1992) but not in other He-shell DDet candidates. Galbany et al. (2019) argue that SN 2016hmk is also consistent with a 91bg-like object arising from the deflagration of a near- $M_{\text{Ch}}$  WD. In a word, the nature of Ca-Ia objects remain ambiguous. **Mention red Ca-Ib/c?**

In this paper, we present the observations of SN 2020jgb, another promising thick He-shell DDet candidate. This peculiar SN Ia highly resembles SN 2018byg in photometric and spectroscopic properties, and exhibits a remarkable feature in the NIR spectrum that could be attributed to the unburnt helium. In Section 2 we report the observations of SN 2020jgb, which are analyzed in Section 3, where we show its similarities with other He-shell DDet SNe and discuss the tentative He I absorption features. We use a grid of DDet models to fit the data of SN 2020jgb, and present the results in Section 4.1. In Section 4.3 we discuss the diversity in the host environments of DDet events. We draw our conclusions in Section 4. [Chang: the references are a little off here, but you can maybe get rid of those references anyway]

## 2. OBSERVATIONS

### 2.1. Discovery

SN 2020jgb was first discovered by the Zwicky Transient Facility (ZTF; Bellm et al. 2019; Graham et al. 2019) on 2020 May 03.463 UT (MJD 58972.463) with the 48-inch Samuel Oschin Telescope (P48) at Palomar Observatory. The automated ZTF discovery pipeline (Masci et al. 2019) detected SN 2020jgb using the image-differencing technique of Zackay et al. (2016). The candidate passed internal thresholds (e.g., Mahabal et al. 2019; Duev et al. 2019), leading to the production and dissemination of a real-time alert (Patterson et al. 2019) and the internal designation ZTF20aayhacx. It was detected with  $g_{\text{ZTF}} = 19.86 \pm 0.15$  mag at  $\alpha_{\text{J2000}} = 17^{\text{h}}53^{\text{m}}12^{\text{s}}.651$ ,  $\delta_{\text{J2000}} = -00^{\circ}51'21''.81$  and announced to the public in Fremling (2020). The host galaxy, PSO J175312.663+005122.078, is a dwarf galaxy, to which SN 2020jgb has a projected offset of only  $0.3''$ . The last non-detection limits the brightness to  $r_{\text{ZTF}} > 20.7$  mag on 2020 April 27.477 (MJD 58966.477; 5.99 days before the first detection). This transient was classified as a SN Ia in Dahiwalé & Fremling (2020).

### 2.2. Host Galaxy Observations

On 2022 March 31, two years after the transient faded, we took a spectrum for its host galaxy using the DEep Imaging Multi-Object Spectrograph (DEIMOS) on the Keck II telescope (Faber et al. 2003), for a total integration time of 3200 s. The spectra were reduced with the PyPeIt Python package (Prochaska et al. 2020). The reduced spectrum is displayed in Figure 1. The host exhibits strong, narrow emission lines including H $\alpha$ , H $\beta$ , [N II]  $\lambda\lambda$ 6548, 6583, [O III]  $\lambda\lambda$ 4959, 5007, and [S II]  $\lambda\lambda$ 6716, 6731. By fitting all these emission features with Gaussian profiles we obtain an average redshift of  $z = 0.0309 \pm 0.0003$ . With the diagnostic emission line equivalent width (EW) ratios ( $\log [\text{N II}]/\text{H}\alpha = -1.19 \pm 0.07$  and  $\log [\text{O III}]/\text{H}\beta = 0.53 \pm 0.06$ )<sup>1</sup>, the host is consistent with star-forming galaxies in the BPT diagram (Baldwin et al. 1981; Veilleux & Osterbrock 1987).

To estimate the distance modulus to SN 2020jgb, we use the 2M++ model (Carrick et al. 2015) to obtain a peculiar velocity towards its host galaxy, PSO J175312.663+005122.078, to be  $179 \text{ km s}^{-1}$ . This, combined with the recession velocity in the frame of the cosmic microwave background<sup>2</sup> (CMB)  $v_{\text{CMB}} = 9136 \text{ km s}^{-1}$ , yields a net Hubble recession velocity of  $9307 \text{ km s}^{-1}$ , with a systematic uncertainty of  $250 \text{ km s}^{-1}$  [AAM: Dominated by the 2M++ cosmic flow?] [Chang: correct - you could even report pv as  $179 \pm 250$ ]. Adopting  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$ , and  $\Omega_\Lambda = 0.7$ , we estimate the luminosity distance to SN 2020jgb to be  $136.1 \text{ Mpc}$ , which yields a distance modulus of  $\mu = 35.66 \pm 0.06$ .

### 2.3. Optical Photometry

SN 2020jgb was monitored in the  $g_{\text{ZTF}}$  and  $r_{\text{ZTF}}$  bands by ZTF as part of its ongoing Northern Sky Survey (Bellm et al. 2019). We adopt a Galactic extinction of  $E(B - V) = 0.404 \text{ mag}$  (Schlafly & Finkbeiner 2011), and correct all photometry using the Fitzpatrick (1999) extinction model. We assume there is no additional extinction in the host galaxy. This assumption is supported by the lack of Na I D absorption at the redshift of the host galaxy, though see Poznanski et al. (2011) for caveats on the use of Na I D absorption as a proxy for extinction.

The forced photometry light curves<sup>3</sup> in absolute magnitudes in  $g_{\text{ZTF}}$ - and  $r_{\text{ZTF}}$ -bands are shown in Figure 2,

**Table 1.** Spectroscopic Observations of SN 2020jgb and the host galaxy.

$t_{\text{obs}}$	Phase	Telescope/	$R$	Range	Air
(MJD)	(d)	Instrument	( $\lambda/\Delta\lambda$ )	( $\text{\AA}$ )	Mass
58,976.42	−9.7	P60/SEDM	100	3770–9220	1.23
58,982.12	−4.2	NOT/ALFOSC	360	4000–9620	1.17
58,990.43	+3.9	P60/SEDM	100	3770–9220	1.23
58,997.44	+10.7	P60/SEDM	100	3770–9220	1.29
58,998.41	+11.6	Shane/Kast	750	3620–10720	1.28
59,008.41	+21.3	P60/SEDM	100	3770–9220	1.28
59,009.45	+22.4	Gemini-N/GNIRS	1800	8230–25150	1.07
59,010.40	+23.3	P200/DBSP	700	3200–9500	1.27
59,023.58	+36.1	Keck I/LRIS	1100	3200–10250	2.04
59,107.29	+117.3	Keck I/LRIS	1100	3200–10250	1.31
59,143.26	+152.2	Keck I/LRIS	1100	3200–10250	2.16
59,669.60	host	Keck II/DEIMOS	2100	4500–8700	1.14

NOTE—Phase is measured relative to the  $r_{\text{ZTF}}$ -band peak in the host galaxy rest frame. The resolution  $R$  is reported for the central region of the spectrum.

in which we show all the measurements with  $\text{SNR} > 2$ . The light curves are reduced using the pipeline from Miller et al. (2022, in preparation). [Chang: Should also add a citation to Yuhan’s paper as a see also]

### 2.4. Optical Spectroscopy

We obtained optical spectroscopic follow-up of the object from  $\sim -10$  days to  $\sim +150$  days relative to the  $r_{\text{ZTF}}$ -band peak, using the Spectral Energy Distribution Machine (SEDM; Blagorodnova et al. 2018) on the automated 60 inch telescope (P60; Cenko et al. 2006) at Palomar Observatory, the Kast Double Spectrograph (Miller & Stone 1994) at the Shane 3 m Telescope, the Andaluia Faint Object Spectrograph and Camera (ALFOSC)<sup>4</sup> installed at the Nordic Optical Telescope (NOT), the Double Beam Spectrograph (DBSP) on the 200 inch Hale telescope (P200; Oke & Gunn 1982), the Low Resolution Imaging Spectrograph (LRIS) on the Keck I telescope (Oke et al. 1995). Spectra were reduced using standard procedures (e.g., Matheson et al. 2000). Details of the spectroscopic observations are listed in Table 1, and the spectral sequence is shown in Figure 3.

### 2.5. Near-infrared (NIR) Spectroscopy

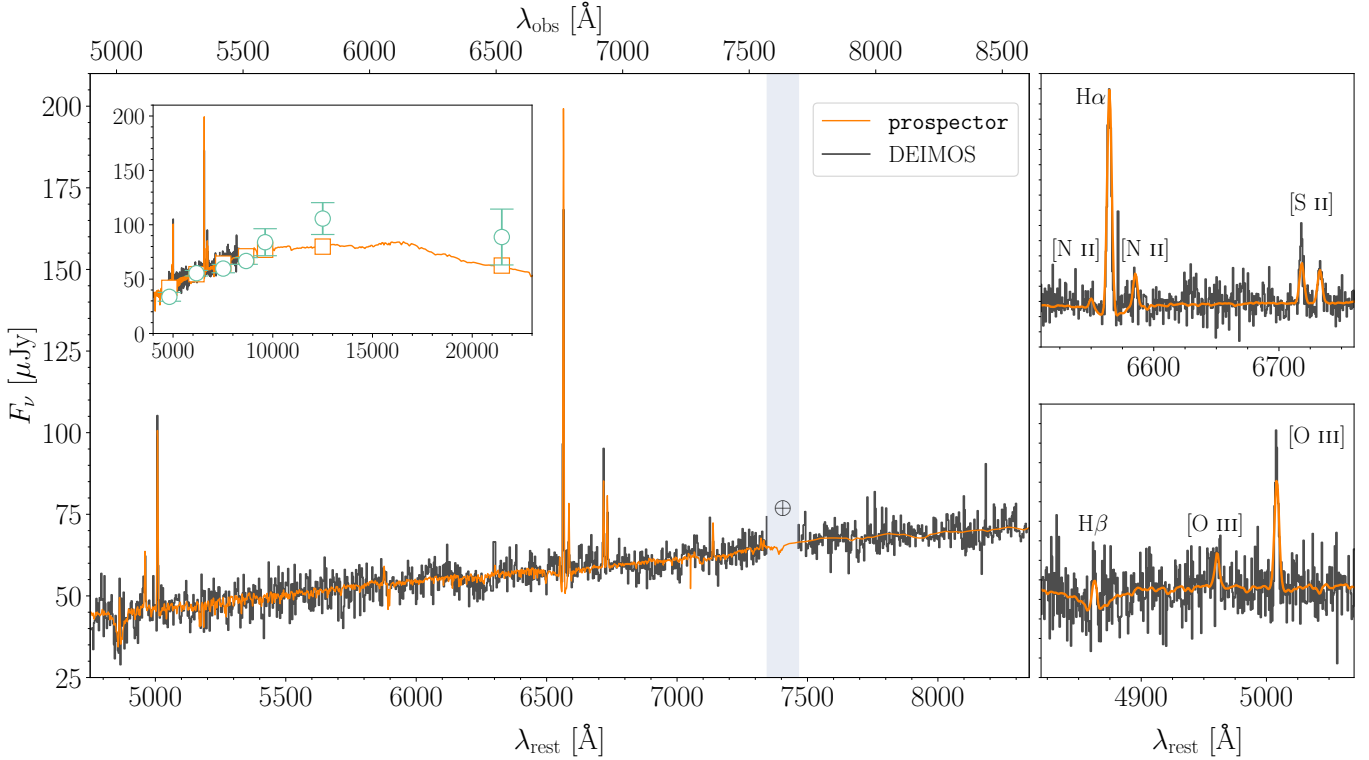
We obtained one NIR ( $0.8\text{--}2.5 \mu\text{m}$ ) spectrum of SN 2020jgb using the Gemini near-infrared spectrometer (GNIRS; Elias et al. 1998) on the Gemini North telescope on 2020 June 9 ( $\sim 22$  days after  $r_{\text{ZTF}}$ -band peak),

<sup>1</sup> Here [N II] denotes the EW of the [N II]  $\lambda$ 6583 line, and [O III] denotes the EW of the [O III]  $\lambda$ 5007 line

<sup>2</sup> See [https://ned.ipac.caltech.edu/velocity\\_calculator](https://ned.ipac.caltech.edu/velocity_calculator).

<sup>3</sup> <https://web.ipac.caltech.edu/staff/fmasci/ztf/forcedphot.pdf>

<sup>4</sup> <https://www.not.iac.es/instruments/alfosc/>



**Figure 1.** The spectral energy distribution (SED) of PSO J175312.663+005122.078, the host galaxy of SN 2020jgb, and the best fit model from **prospector**. When fitting the SED with **prospector**, the DEIMOS spectrum is automatically [AAM: maybe ask Anya for a more accurate description] rescaled to fit the archival photometry from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Chambers et al. 2016,  $g$ ,  $r$ ,  $i$ ,  $z$ ,  $y$  Kron magnitudes) and the VISTA Hemisphere Survey (VHS; McMahon et al. 2013,  $J$  and  $K_s$  Petrosian magnitudes). *Left:* the SED in the optical band (4750-8350 Å in the rest frame of the host galaxy). The black line corresponds to the observed spectrum, binned with a size of 2 Å. The orange line is the best fit model from **prospector**. The blue shaded region is masked in the fitting due to the strong telluric lines. *Inner panel:* the same comparison, but covers  $g$ -band through  $K_s$ -band (4000-24000 Å). Apart from the spectra, we also show the multi-band photometry (green circles) and the best-fit magnitudes (black squares). *Right:* spectra around the most prominent emission lines. *Top right:*  $H\alpha$ ,  $[N II] \lambda\lambda 6548, 6583$ ,  $H\alpha$ ,  $[S II] \lambda\lambda 6716, 6731$ . *Bottom right:*  $H\beta$ ,  $[O III] \lambda\lambda 4959, 5007$ .

for an integration time of 2400 s. The GNIRS spectrum was reduced with **PypeIt**.

### 3. ANALYSIS

#### 3.1. Photometric Properties

SN 2020jgb exhibited a fainter light curve than normal SNe Ia. In Figure 2, we compare the photometric properties of SN 2020jgb with the nearby, well-observed SN 2011fe (Nugent et al. 2011) and two He-shell DDet candidates, including the normal-luminosity thin shell candidate SN 2016jhr (Jiang et al. 2017) and the sub-luminous thick shell candidate SN 2018byg (De et al. 2019), with available photometric data on the Open Supernova Catalog<sup>5</sup> (Guillochon et al. 2017). All these light curves have been corrected for Galactic reddening,

while  $K$ -corrections have not been performed<sup>6</sup>. [Chang: I thought 11fe peaked brighter than −19.] [AAM: Double checked - essentially no Galactic extinction towards M101, so  $M_g \approx 18.98$  mag. However, in the datafile from the open supernovae catalog,  $g$ -band light curves are referred to 2017MNRAS.472.3437G, where I couldn't find the data.]

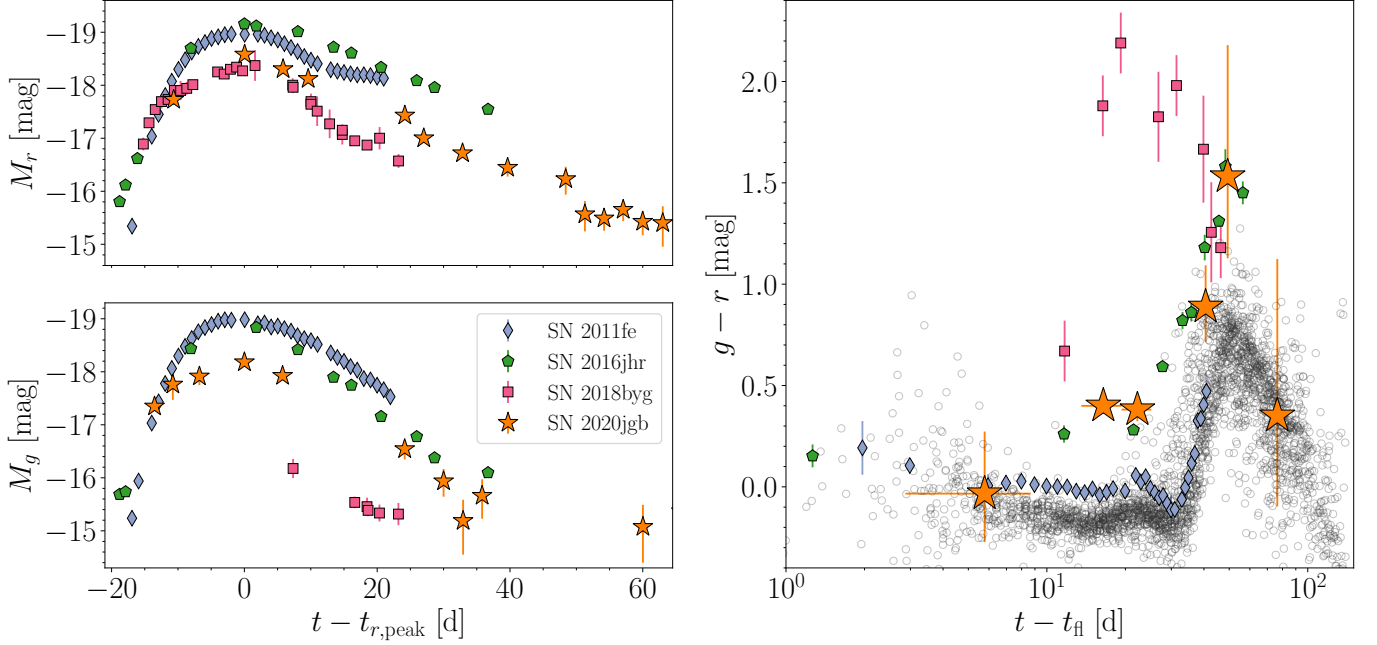
While the observational coverage is sparse in the rise to maximum light, from Figure 2 it is clear that SN 2020jgb is less luminous than normal SNe Ia (e.g., SN 2011fe). Furthermore, there is a flatter evolution in the  $r_{ZTF}$  evolution between −14 d and maximum light for both SN 2020jgb and SN 2020jgb than there is for SN 2011fe.

In the right panel of Figure 2, we compare the color evolution ( $g-r$ ) of these objects relative to the measured

<sup>5</sup> See <https://github.com/astrocatalogs/supernovae>.

<sup>6</sup> These SNe were all observed in slightly different  $g$ - and  $r$ -bands.





**Figure 2.** *Left:* Comparison of the multi-color light curves of SN 2020jgb with the normal SN Ia SN 2011fe, the thin shell DDet candidate SN 2016jhr, and the thick shell DDet candidate SN 2018byg. The upper (lower) panel shows the evolution in  $g$ -band ( $r$ -band) absolute magnitudes. *Right:* comparison of  $g - r$  color evolution to SN 2011fe and SN 2018byg, as well as 62 normal SNe Ia (open circles) with prompt observations within 5 days of first light by ZTF (Bulla et al. 2020).

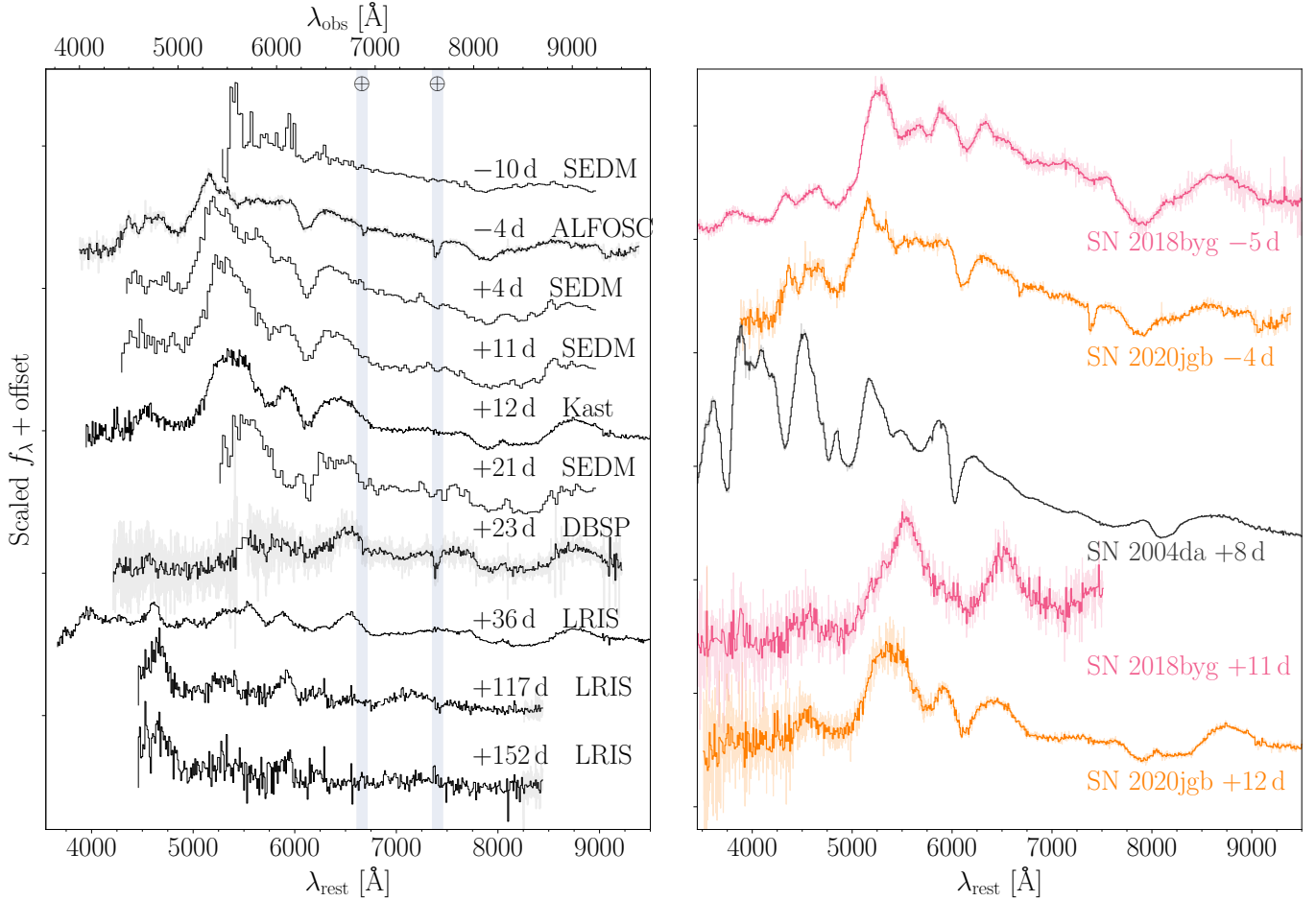
time of first light  $t_{fl}$ , accompanied by 62 normal SNe Ia (open circles) observed within 5 days of  $t_{fl}$  by ZTF (from Bulla et al. 2020). For SN 2020jgb the early rise of the light curve was not well sampled, so we estimate  $t_{fl}$  as the midpoint of the first detection and the last non-detection. We adopt an uncertainty on this estimate of 3 days. All three DDet candidates are undoubtedly redder than normal SNe Ia. At peak light, SN 2020jgb was not as red as the extreme case, SN 2018byg ( $g - r \approx 2.2$  mag), but exhibited a similar color as SN 2016jhr ( $g - r \approx 0.5$  mag).

### 3.2. Optical Spectral properties

In Figure 3, we show the optical spectral sequence of SN 2020jgb, and compare its spectra with some other SNe Ia near peak luminosity. For the spectra obtained after +100 d there is clear contamination from the host-galaxy, including the presence of narrow emission lines. For these spectra we subtract the galaxy light as measured in the DEIMOS spectrum from 2022 (see Section 2.4). The earliest spectrum was obtained by SEDM  $\approx 10$  days before the  $r_{ZTF}$ -band peak. We only show portions of the spectrum where the SNR  $> 2.5$ , where the continuum is almost featureless with some marginal detection of the Si II  $\lambda 6355$  at  $\approx 6100$  Å, the trademark of SNe Ia. In subsequent spectra the Si II features become more prominent and are clearly detected through +12 d. We measure Si II expansion velocities following a

similar procedure as in Childress et al. (2013, 2014) and Maguire et al. (2014). The fitting region is selected by visual inspection. The continuum is assumed to be linear, and the absorption profile after the continuum normalization is assumed to be composed of double Gaussian profiles peaked at 6347 Å and 6371 Å. Within the model, the continuum flux density at the blue and red edges are free parameters for which we adopt a normal distribution as a prior. The mean and standard deviation for the normal are the observed flux density and its uncertainty, respectively, at each edge of the fitting region. Three more parameters (amplitude, mean velocity, logarithmic velocity dispersion) are used to characterize the double Gaussian profile, whose priors are set to be flat. This means the depths and widths of both peaks are forced to be the same, as Maguire et al. (2014) has adopted in the optically thick regime. The priors of the three parameters are set to be flat. The Posteriors of the five parameters are sampled simultaneously with `emcee` (Foreman-Mackey et al. 2013) using the Markov chain Monte Carlo (MCMC) method. We find the mean expansion velocity is  $\approx 11,500$  km s $^{-1}$  near maximum light.

In many SNe Ia the Ca II infrared triplet (IRT) absorption has two distinct components (Mazzali et al. 2005), which are conventionally referred to as photospheric-velocity features (PVFs) and high-velocity features (HVF). The PVFs originate from the main line-forming region with typical photospheric (i.e., bulk



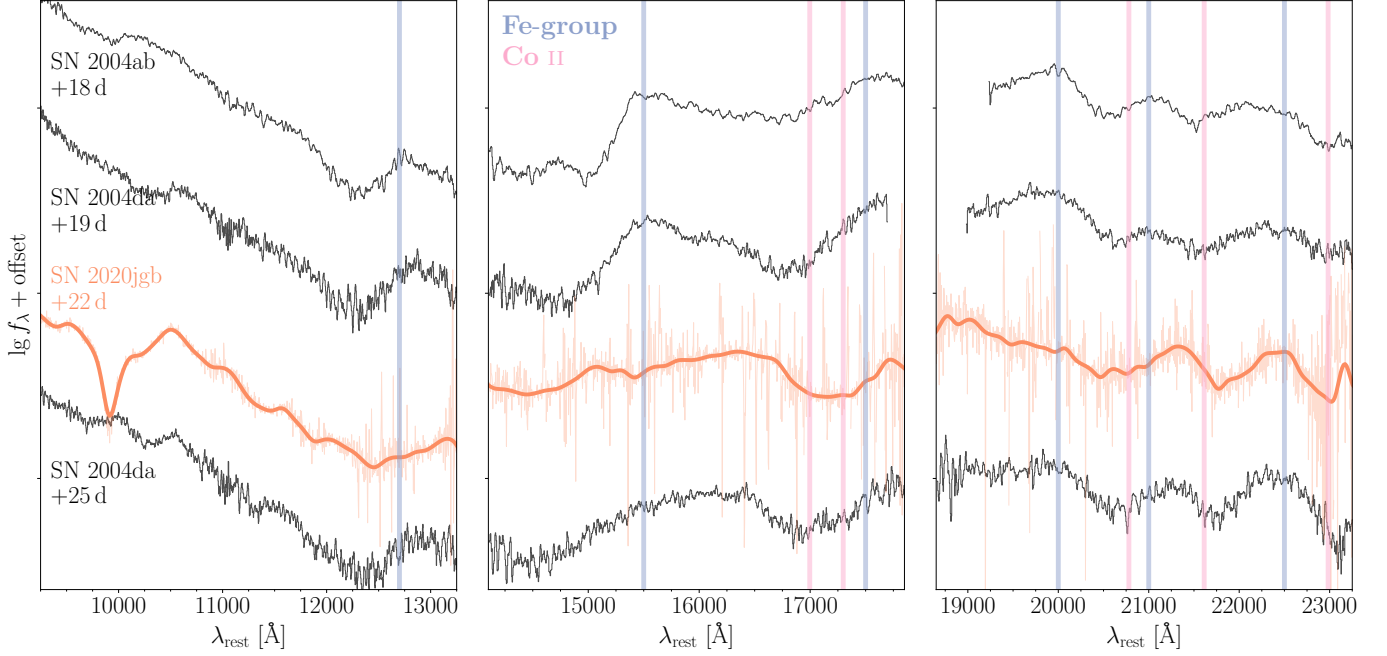
**Figure 3.** *Left:* optical spectral sequence of SN 2020jgb. Rest frame phases (days) relative to the  $r_{\text{ZTF}}$ -band peak and instruments used are posted next to each spectrum. The spectra are after Galactic extinction correction are shown in grey. The black lines are binned spectra with a bin size of  $10 \text{ \AA}$ , except for the SEDM spectra, whose resolution is lower than the bin size. In the last two spectra, we have subtracted the light from the host galaxy. Only regions with  $\text{SNR} > 2.5$  after binning are plotted. *Right:* spectral comparison with SN 2018byg (sub-luminous He-shell DDet; De et al. 2019) and SN 2004da (normal luminosity; Silverman et al. 2012).

ejecta) velocities, while the HVFs are blueshifted to much shorter wavelengths, indicating significantly higher (by greater than  $\sim 6000 \text{ km s}^{-1}$ ) velocities than typical PVFs (Silverman et al. 2015). Figure 3 shows that SN 2020jgb has prominent HVFs of Ca II IRT. The HVFs are visible in our first spectrum of SN 2020jgb, and remain prominent through +36 days. Using a similar technique in modeling the Si II features, we fit the HVFs and PVFs simultaneously. Both are fit by multiple Gaussian profiles assuming each line in the triplet can be approximated by the same profile (i.e., same amplitude and velocity dispersion). A best-fit expansion velocity of HVFs is  $\gtrsim 26,000 \text{ km s}^{-1}$ . A clear delineation between the HVFs and PVFs is visible  $\approx 4$  days before peak light. Since then we fit the broad absorption features with two different velocity components simultaneously. The velocity of HVFs slightly declines but

stays above  $\approx 24,000 \text{ km s}^{-1}$ , and the velocity of PVFs declines from  $\approx 11,000 \text{ km s}^{-1}$  to  $\approx 9,000 \text{ km s}^{-1}$ . As in normal SNe Ia, the relative strength between the HVFs and PVFs decreases with time. [Chang: might be worth a figure - especially if we have this measured for several other DDet now]

The nebular phase spectra of SN 2020jgb are dominated by the Fe-group elements, showing some enhancement in flux between  $\approx 4500$  and  $\approx 6000 \text{ \AA}$ . We did not detect any emission feature related to [Ca II]  $\lambda\lambda 7291, 7324$ , which is a hallmark for Calcium-rich gap transients and is also prominent in a few DDet candidates (e.g., SN 2016hmk and SN 2019ofm; De et al. 2020).

The optical spectral evolution of SN 2020jgb resembles that of SN 2018byg, a sub-luminous DDet with a thick He-shell. At early times, both SNe were relatively blue and featureless with broad and shallow Ca II IRT



**Figure 4.** The NIR spectra of SN 2020jgb and two SNe Ia with normal maximum luminosity (SN 2004ab and SN 2004da, [Marion et al. 2009](#)), taken about three weeks after the peak. For each spectrum, the continuum at  $\gtrsim 1.2 \mu\text{m}$  is significantly reshaped by the line-blanketing from Fe-group elements (blue vertical lines), which are continuous emission features composed of unresolved Fe-group lines peaking at  $\approx 1.27, 1.55, 1.75, 2.00, 2.10, 2.25 \mu\text{m}$  ([Marion et al. 2009](#)). Between these peaks lie multiple strong Co II absorption lines (pink vertical lines, assuming a typical post-maximum expansion velocity of  $8,000 \text{ km s}^{-1}$ ). Spectra for SN 2004ab and SN 2004da are obtained from [Marion et al. \(2009\)](#).

absorption. As they evolved closer to maximum light, they developed strong continuous absorption bluewards of  $\approx 5000 \text{ Å}$ , while the Si II  $\lambda 6355$  and the Ca II IRT became more prominent. S II was not detected in either object. In the DDet scenario, a large amount of Fe-group elements will be synthesized in the outer regions of the ejecta, which will cause significant line-blanketing near maximum light ([Kromer et al. 2010](#); [Polin et al. 2019](#)), and also high velocity intermediate-mass elements like Ca II ([Fink et al. 2010](#); [Kromer et al. 2010](#); [Shen & Moore 2014](#)). The similarity between SN 2020jgb and SN 2018byg, makes SN 2020jgb another promising DDet SN candidate.

SN 2004da is a normal SN Ia that shows similarities to SN 2020jgb in the NIR (Section 3.3), however, the two SNe are extremely different in the optical (Figure 3). From this comparison it is clear that SN 2020jgb is not a normal SN Ia.

### 3.3. NIR Spectral properties

The NIR spectrum of SN 2020jgb is compared with two normal SNe Ia at a similar phase in Figure 4 (data for SNe 2004ab and 2004da from [Marion et al. 2009](#)). SN 2020jgb shows a strong absorption feature at  $\sim 0.99 \mu\text{m}$ , which is not seen in normal SNe Ia. This feature was still significant two weeks later, as detected

by LRIS on Keck (see Figure 7), though it was only partially covered. Aside from this prominent feature, SN 2020jgb resembles normal SNe Ia in the NIR. The shape of the continuum redwards to  $\approx 1.2 \mu\text{m}$  is significantly altered by line-blanketing from Fe-group elements. Just like normal SNe Ia, SN 2020jgb shows an enhancement of flux at about  $1.3, 1.55, 2.0, 2.1$ , and  $2.25 \mu\text{m}$ , accompanied by several Co II absorption lines. It is especially similar to SN 2004da at +25 days after maximum light as the steep increase in flux at  $\approx 1.55 \mu\text{m}$ , known as the *H*-band break ([Hsiao et al. 2019](#)), has become less prominent.

[Marion et al. \(2009\)](#) present a sample of 15 NIR spectra of normal SNe Ia between +14 and +75 days after maximum light, and none of those spectra show prominent absorption features around  $1 \mu\text{m}$ . We have investigated several potential identifications for this feature (see below), none of which provides a completely satisfying explanation.

The most tantalizing possibility is that the absorption is due to He I  $\lambda 10830$ . If SN 2020jgb is a DDet SN, then unburned He could lead to observed absorption in the spectrum, as shown in the sub-Chandrasekhar-mass He-shell DDet models of [Boyle et al. \(2017\)](#). Figure 7 shows that the  $1 \mu\text{m}$  feature, if associated with He I  $\lambda 10830$ , has a high velocity ( $\sim 26,000 \text{ km s}^{-1}$ ), es-

pecially considering the phase of the SN. The Ca II IRT also exhibits similarly high velocities at the same phase ( $\sim 24,000 \text{ km s}^{-1}$ ), meaning high-velocity absorption is not impossible at this phase. The expansion velocity in the ejecta is roughly linearly proportional to the radius, so such a high velocity indicates that both the Ca II IRT and the tentative He I absorption line form far outside the normal photosphere, which has a velocity of only  $\sim 10,000 \text{ km s}^{-1}$ . In this sense, the He-shell DDet scenario is supported in that any unburnt helium would be located in the outermost ejecta.

We cannot claim an unambiguous detection of He I, however, as our spectra lack definitive absorption from other He I features that we would expect to be prominent, such as He I  $\lambda 20581$ . Considering a line velocity of  $\sim 26,000 \text{ km s}^{-1}$  and a host galaxy redshift of 0.0309, this line will be blueshifted to  $\sim 1.95 \mu\text{m}$  in the observer frame, which overlaps some strong telluric lines within  $1.8\text{--}2.0 \mu\text{m}$ . After telluric correction, the signal to noise ratio reaches  $\sim 5$ , with which we still cannot see any significant absorption feature. An upper limit of the equivalent width is determined to be  $< 2\%$  that of the He I  $\lambda 10830$  line, while theoretically, the  $\lambda 20581$  line is supposed to be only a factor of 6–12 weaker, depending on temperature (Marion et al. 2009). The observed  $1 \mu\text{m}$  feature in SN 2020jgb is as strong as the He I  $\lambda 10830$  line in many helium-rich Type Ib supernovae (SNe Ib). In SNe Ib the He I  $\lambda 20581$  line is weaker than the He I  $\lambda 10830$  line yet still prominent (Shahbandeh et al. 2022). In one of the models in Boyle et al. (2017), there is no obvious He I  $\lambda 20581$  absorption in the synthetic spectra (see their Figure 7), but the model is intended to be representative of normal-luminosity SNe Ia. If the  $1 \mu\text{m}$  feature is associated with He I, it is unusual that we do not detect a corresponding feature around  $2 \mu\text{m}$ .

Other possible identifications for the  $1 \mu\text{m}$  feature include Mg II  $\lambda 10927$ , C I  $\lambda 10693$ , Fe II  $\lambda 10500$  and  $\lambda 10863$ . The Mg II  $\lambda 10927$  line is prevalent in the NIR spectra of SNe Ia, but usually disappears within a week after peak (Marion et al. 2009). In SN 2020jgb the  $1 \mu\text{m}$  feature was still visible more than a month after peak in the Keck/LRIS spectrum. A Mg II  $\lambda 10927$  identification would require an absorption velocity of  $\sim 30,000 \text{ km s}^{-1}$ ,  $\sim 20\%$  faster than the HVFs of Ca II IRT at the same phase. While such a high velocity for Mg II has never been seen in other SNe Ia, since high-velocity intermediate-mass elements like magnesium and calcium can be synthesized by the detonation of the He-shell (Shen & Moore 2014), the Mg II origin of the  $1 \mu\text{m}$  feature cannot be strictly ruled out. But if we attribute this  $1 \mu\text{m}$  feature to high-velocity Mg II, we would expect an even stronger Mg II  $\lambda 9227$  line to be blueshifted

to the red edge of the Ca II IRT, which is not detected. Given the strength of the  $1 \mu\text{m}$  feature, the Mg II  $\lambda 9227$  line should not be completely obscured by the Ca II IRT features. [Chang: a new idea about this - if the 9227 line is there, then it would be possible to add this to the fit of the Ca IRT. It's probably too much, but I'm guessing that the fit does not substantially improve if this is done]

C I  $\lambda 10693$  is not observed as frequently as Mg II  $\lambda 10927$  in SNe Ia. Hsiao et al. (2019) presented a sample of five SNe Ia with C I detections, showing the C I feature is strongest for fainter, fast-declining objects. However, in their sample, the C I feature is a pre-maximum feature which fades away as the luminosity peaks, so the discrepancy in phase is large. The required expansion velocity  $\sim 22,000 \text{ km s}^{-1}$ , which is substantially faster than the estimated carbon velocity for the sample in Hsiao et al. (2019) ( $\sim 10,000\text{--}12,000 \text{ km s}^{-1}$ ), but still consistent with the HVFs of Ca II IRT [Chang: HVF or PVF?]. Nonetheless, no significant carbon absorption is detected in the optical. It is also noteworthy that the amount unburnt carbon is expected to be minimal in sub- $M_{\text{Ch}}$  WDs ignited by detonation (Polin et al. 2019), in contrast to near- $M_{\text{Ch}}$  WDs ignited by pure deflagration where the carbon burning can be incomplete. We therefore would not expect to detect any carbon features in a He-shell DDet SN.

The Fe II features in SNe Ia usually start to develop approximately three weeks after peak, which is about the same phase as we obtained our GNIRS spectrum. Two Fe II lines,  $\lambda 9998$  and  $\lambda 10500$ , are actually visible on the blue/red wings of the  $1 \mu\text{m}$  feature. The Fe II  $\lambda 10863$  line is not detected in the GNIRS spectrum. [Chang: of these 3 which is strongest?] They correspond to an expansion velocity of  $\sim 8,000 \text{ km s}^{-1}$ , which is consistent with the PVFs of the Ca II IRT at the same epoch. They also match the same two lines for normal SNe Ia (Marion et al. 2009), making the identification more reliable. Obviously, these two Fe II features are wider and shallower than the strong feature between them. We fit the  $1 \mu\text{m}$  feature with three Gaussian profiles. Two of them are set to be the blueshifted Fe II  $\lambda 9998$  and  $\lambda 10500$ , and the other is an uncorrelated Gaussian profile which mainly describes the deep absorption feature in the center of the line complex. We find that the shallower and wider Fe II lines only make up  $\sim 40\%$  of the total equivalent width, and the remaining  $\sim 60\%$  comes from the central feature, which cannot be accounted for by any Fe II feature at the same velocity. Given the similarity of the Fe-group line-blanketing between the GNIRS spectrum with the spectrum of SN 2004da at +25 days, the distribution of



Fe-group elements inside each supernova ejecta should be somewhat similar, so the central region of the  $1\mu\text{m}$  feature is not likely to be associated with Fe II either. [Chang: does a reference to Fig 7 make sense here? or is it not worth highlighting Fe in that figure]

## 4. DISCUSSION

### 4.1. Models

*A few sentences from Abi describing the models.*

In Figure 5, we show the comparison of the photometric and spectroscopic features of SN 2020jgb with DDet models from Polin et al. (2019). The peak luminosity reflects the total progenitor mass (C/O core + He shell), and we find models with a total mass of  $0.95 M_{\odot}$  generally reproduce the  $r$ -band peak brightness well. All the models shown in Figure 5 reflect a total mass of  $0.95 M_{\odot}$ . The overall  $r$ -band photometric evolution is best fit by the model with a  $0.87 M_{\odot}$  C/O core and a  $0.08 M_{\odot}$  He shell, while all three models underestimate the  $g$ -band brightness after the peak. This deviation may be attributed to a variety of factors on handling the explosion and radiative transfer. First, throughout the simulations we assume local thermodynamic equilibrium (LTE), which is not valid once the ejecta becomes optically thin. Typically the bulk ejecta of a sub- $M_{\text{Ch}}$  SNe Ia remains optically thick for  $\sim 30$  days since the explosion. But in modeling the brightness in  $g$ -band, the LTE assumption is even more tricky, because the major opacity in  $g$ -band comes from the Fe-group line-blanketing in the outermost ejecta, where the optical depth may evolve differently from that at the photosphere. Hence the LTE condition may quickly become inapplicable. Furthermore, our 1-D He shell model is not capable to capture the multi-dimensional effects in the explosion such as asymmetries. The viewing angle is known to have a significant influence on the observed light curves (Kromer et al. 2010; Sim et al. 2012; Gronow et al. 2020; ?), especially in bluer bands where the line-blanketing depends sensitively on the distribution of He-shell ashes (?). In previous studies on other DDet objects, the  $g$ -band brightness is systematically under-predicted shortly after the peak, despite the fact that redder bands can be fit decently (e.g., Jiang et al. 2017; Jacobson-Galun et al. 2020).

The model which best fits the photometry ( $0.87 M_{\odot} + 0.08 M_{\odot}$ ) also reproduces the major absorption features (e.g., Fe-group line-blanketing, Si II  $\lambda 6355$ , PVFs of Ca II IRT) and the corresponding expansion velocities near the peak light (see the right panel of Figure 5). However, we are not able to fit the continua in  $g$ -,  $r$ -, and  $z$ -bands simultaneously, and the strong Ca II HVFs are not seen in the synthetic spectrum. [Chang: confus-

ing to mention z-band here since we do not have z-band obs] These discrepancies could also be due to the asymmetry in the DDet, that SN 2020jgb was observed fairly close to the ignition point, where the abundances of Fe-group elements and high velocity calcium synthesized in the shell could be much higher than an angle-averaged 1-D model would predict. In addition, the predicted Si II  $\lambda 5972$  does not show up in the observed spectrum.

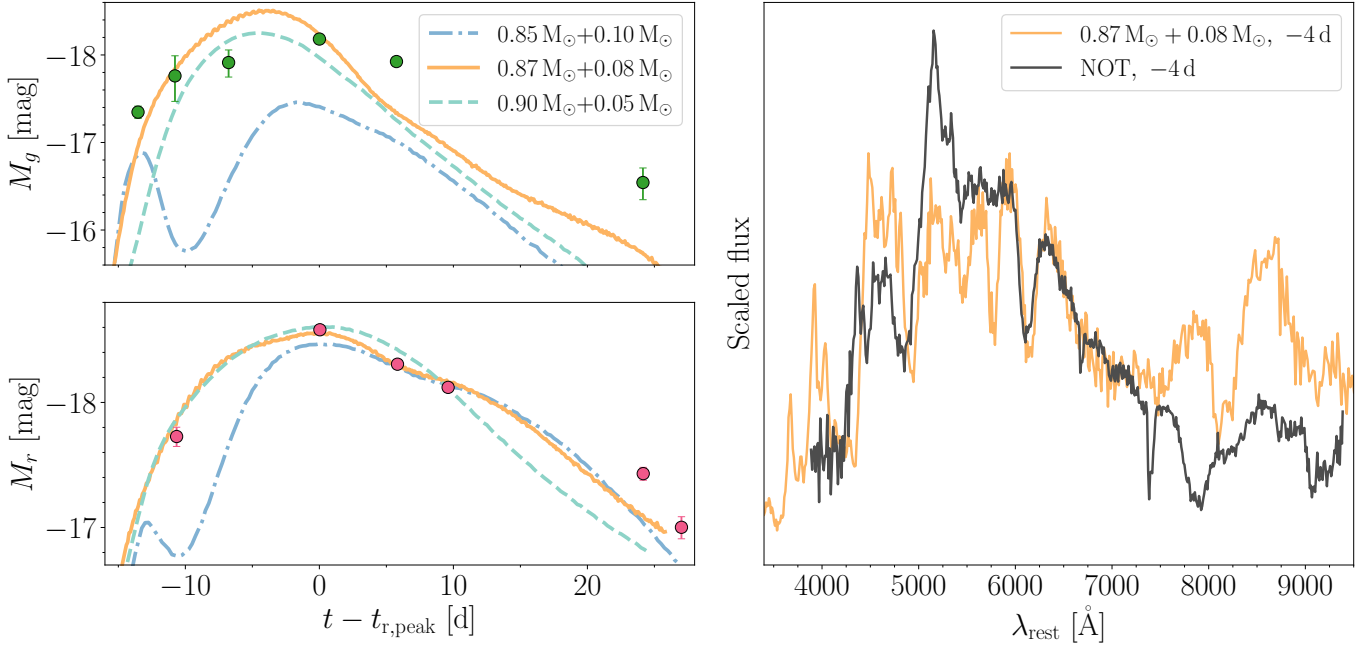
Given the strong qualitative match between the observations of SN 2020jgb and the DDet models of Polin et al. (2019), and the similarity between SN 2020jgb and SN 2018byg, we conclude that SN 2020jgb is indeed a He-shell DDet event.

### 4.2. The $1\mu\text{m}$ Feature

While the nature of the  $1\mu\text{m}$  feature remains uncertain, other He-shell DDet candidates show similar complexity in this region. In the currently small sample of six candidates, three objects (SN 2016jhr, SN 2018aoz, and SN 2019ofm) do not have any available NIR spectra, while the other three (all at different phases) each exhibit strong absorption features near  $1\mu\text{m}$ , as shown in Figure 6. SN 2016hmk has two deep absorption features around  $1.02\mu\text{m}$  and  $1.17\mu\text{m}$ , both are at a longer wavelength than the  $1\mu\text{m}$  feature in SN 2020jgb. Galbany et al. (2019) suggest both of them could be caused by Fe II, though they are deeper than in other SNe Ia. The velocity of the  $1.02\mu\text{m}$  feature is  $\sim 21,000 \text{ km s}^{-1}$  assuming a He I  $\lambda 10830$  origin, which, just like SN 2020jgb, is about the same as the HVFs of the Ca II IRT (see Figure 7). The PVFs of the Ca II IRT of both SNe have a similar expansion velocity of  $\sim 10,000 \text{ km s}^{-1}$ . Such a consistency in velocities is also seen in SN 2018byg (see Figure 7). The large width and lower signal-to-noise ratio for the  $1\mu\text{m}$  feature in SN 2018byg makes it difficult to determine an exact line velocity. The feature may be a mixture of several different lines in SN 2018byg.

Dong et al. (2022a) recently presented another thick He-shell DDet candidate, SN 2016dsg, with an absorption line around  $\sim 0.97\text{--}1.05\mu\text{m}$  in a low-SNR NIR spectrum at +16.6 days.<sup>7</sup> Assuming a He I  $\lambda 10830$  origin, the minimum of the absorption profile (at  $\sim 1.03\mu\text{m}$ , see Figure 4 in Dong et al. 2022a) corresponds to an expansion velocity of  $\sim 15,000 \text{ km s}^{-1}$ . Interestingly, SN 2016dsg shows the least prominent HVFs of Ca II IRT ( $v_{\text{SN 2016dsg}} \approx 15,000 \text{ km s}^{-1}$ ) among the four DDet candidates with NIR spectra. Once again, the scenario

<sup>7</sup> SN 2016dsg was discovered on the decline. The phase is relative to the discovery time.



**Figure 5.** *Left:* Comparison of the photometric evolution of SN 2020jgb with the He-shell DDet models from Polin et al. (2019). The model parameters are indicated in the legend as (C/O core mass + He shell mass). The upper (lower) panel shows the evolution in  $g$ -band ( $r$ -band) absolute magnitudes. *Right:* Comparison of the spectrum of SN 2020jgb with the  $0.87 M_{\odot}$  C/O core +  $0.08 M_{\odot}$  He-shell DDet model before peak luminosity. Each spectrum is normalized by the median flux between 6500 and 7500 Å, and binned with a size of 10 Å. The synthetic spectrum 4 days before the the  $r$ -band peak best matches the NOT spectrum (Galactic extinction corrected), which was obtained  $\sim 4$  days before the  $r_{\text{ZTF}}$ -band peak. All the phases have been rescaled to the host galaxy rest frame.

where both the unburnt helium and the high velocity calcium are located at the outermost shell is favored.

Unfortunately, none of the spectra for SN 2016dsg, SN 2016hmk, or SN 2018byg covers the  $2 \mu\text{m}$  region, thus it is not possible to identify the presence of helium decisively. But if the  $1 \mu\text{m}$  feature of these objects are of the same origin, they are more likely to be correlated with the high velocity ejecta lying in the outmost region in the supernovae, because at least for SN 2020jgb and SN 2016hmk, the difference in their photospheric velocities cannot explain the discrepancy in their line velocities of the  $1 \mu\text{m}$  feature. Then helium is still a promising candidate to cause strong absorption near  $1 \mu\text{m}$  for these sub-luminous He-shell DDet SNe Ia.

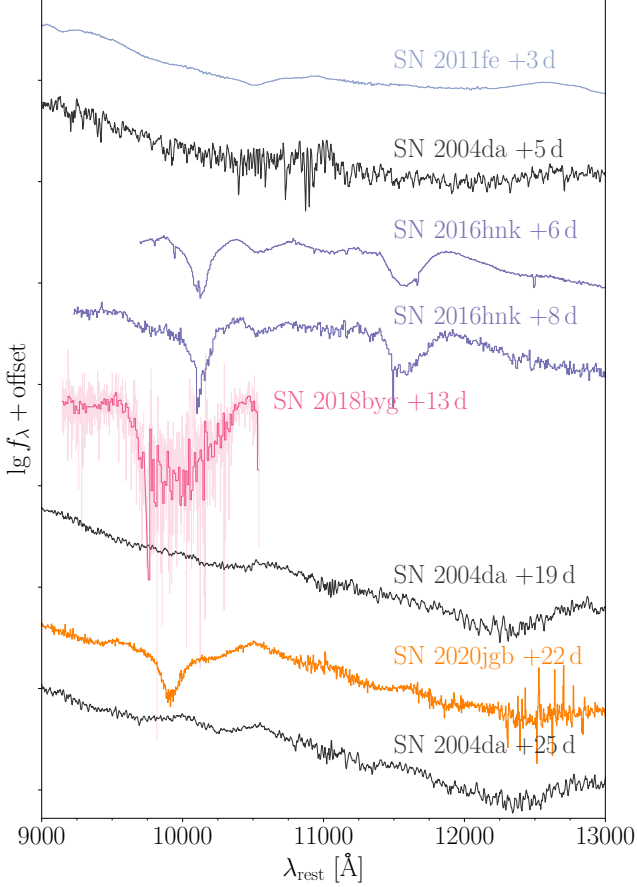
In conclusion, every thick He-shell DDet candidates with available NIR spectra displays a strong absorption feature near  $1 \mu\text{m}$ . This feature is not seen in normal SNe Ia. Interestingly, the available NIR spectra are all obtained at different epochs, suggesting this feature may be very long lived. If the feature is due to He I, then DDet explosions exhibit a wide diversity in the expansion velocity. While it remains to be confirmed in a larger sample, we speculate that anomalously strong absorption around  $1 \mu\text{m}$  is a distinctive attribute of DDet

SNe and that this feature can be used to identify and select events relative to normal SNe Ia.

#### 4.3. The Host Environment of He-shell DDet SNe

We model the host galaxy of SN 2020jgb using **prospector** (Johnson et al. 2021), a package for principled inference of stellar population properties using photometric and/or spectroscopic data. The input data included the Galactic extinction corrected DEIMOS spectrum, as well as the archival photometric data from the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; Chambers et al. 2016,  $r$ ,  $i$ ,  $z$  Kron magnitudes) and the VISTA Hemisphere Survey (VHS; McMahon et al. 2013, J and  $K_s$  Petrosian magnitudes). [Chang: If there are “knobs” that Anya tuned specifically for this fit, we should ask her to write about those. If the settings are the same as her papers then we should reference them.] In the best fit, the estimated stellar mass is  $\log(M_* [M_{\odot}]) = 7.79^{+0.07}_{-0.06}$ , and the specific star-formation rate (sSFR) is  $\log(\text{sSFR} [\text{yr}^{-1}]) = -10.25^{+0.09}_{-0.08}$ , with the uncertainties denoting the 68% credible regions.

In Figure 8, we show the sSFR and the stellar mass for the host galaxies of six He-shell DDet candidates. Again using **prospector**, we fit the stellar properties for all the other candidates with optical spectra from



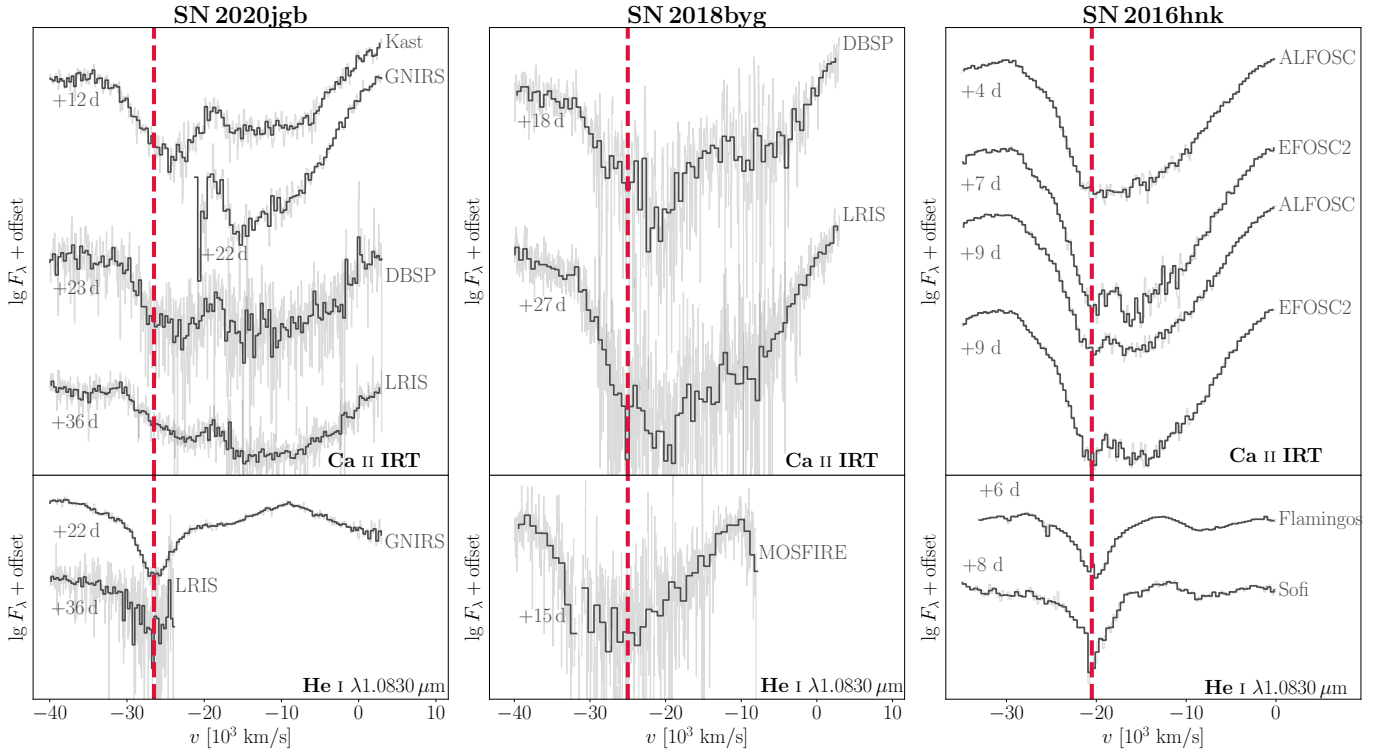
**Figure 6.** The NIR spectra (9000 to 13000 Å) of a few normal SNe Ia (SN 2011fe and SN 2004da) and three He-shell DDet candidates, which are all sub-luminous SNe Ia (SN 2016hmk, SN 2018byg, and this source, SN 2020jgb). Other than the spectrum of SN 2004da, all spectroscopic data are obtained from the WISEReP repository (Yaron & Gal-Yam 2012).

the Sloan Digital Sky Survey (SDSS; York et al. 2000) and photometry from the DESI Legacy Imaging Surveys (Dey et al. 2019,  $g$ ,  $r$ ,  $z$ ,  $W_1$ ,  $W_2$ ,  $W_3$ ,  $W_4$  magnitudes). With mid-infrared photometry available, *prospector* can better estimate the overall dust extinction in the host galaxy and the contribution of an active galactic nucleus (AGN) to the spectral energy distribution (SED). Unfortunately, two (SN 2016hmk and SN 2019ofm) out of six hosts are nearby ( $z \lesssim 0.03$ ) late-type galaxies with extended, spatially resolved spiral structures. Examination of the LS4 model shows that the galaxy aperture does not include the blue, diffuse star-forming regions of these galaxies. Fitting the SDSS spectra + LS4 photometry would inevitably underestimate their SFR. [Chang: is SFR defined?] For the host of SN 2016hmk, we instead adopt the results in Dong et al. (2022b), which uses broadband far ultraviolet (FUV) to far in-

frared (FIR) photometry from the  $z = 0$  Multiwavelength Galaxy Synthesis I (z0MGS; Leroy et al. 2019) to characterize the stellar population with *prospector*. For the host of SN 2019ofm, there are no IFS [Chang: is IFS defined?] data available, so we still show our best-fit stellar mass and sSFR in Figure 8, with the caveat that the sSFR should be regarded as a lower limit. The host of SN 2018aoz (NGC 3923) is a local ( $z = 0.00580$ ) early-type galaxy and is outside the SDSS footprint, so we adopt its stellar population properties from the Census of the Local Universe (CLU) catalog [AAM: References?]. [Chang: Kishalay’s big paper on Ca strong events]

Figure 8 reveals that DDet SNe emerge in both star-forming and passive galaxies, which is true for both thin He-shell objects of normal luminosity (SN 2016jhr in a star-forming host; SN 2018aoz in a passive host) and thick He-shell, sub-luminous objects (SN 2020jgb in a star-forming host; SN 2018byg in a passive host). There are also diversities in their locations in their hosts. SN 2020jgb has a small projected physical offset ( $\sim 0.2$  kpc) to the center of its host, a star-forming dwarf galaxy, so it is highly likely to originate from a young, star-forming environment. SN 2016hmk has a moderate projected host offset ( $\sim 4$  kpc) and a potential origin in an H II region with ongoing star-formation (Galbany et al. 2019). SN 2019ofm has a large projected offset ( $\sim 11$  kpc) but is still on the blue, diffuse spiral arm [AAM: How can I refer to the DECaLS image?] [Chang: This should be the LS paper that you mentioned before – you could also provide a link to the LS image server, but I’d be a little worried that link may change in the future]. Other objects, including the recently discovered SN 2016dsg [Chang: this is a 6 yr old SN so not recently discovered] and OGLE-2013-SN-079 (Dong et al. 2022a), show large projected host offsets ( $\gtrsim 10$  kpc) and lie in the galaxy outskirts, which usually indicates origin in old stellar population. [Chang: no reference to 18byg offset here?]

In this sense, the He-shell DDet sample resembles the normal SNe Ia population, which can occur in both star-forming and quenched galaxies (e.g., Sullivan et al. 2006; Smith et al. 2012), and is very different from some other types thermonuclear supernovae, such as Type-Iax supernovae (SNe Iax) which almost only appear in star-forming galaxies, or SN 1991bg-like and SN 2002es-like objects, which prefer old stellar environments (see the review in Jha et al. 2019). This favors the postulated sequence that He-shell DDet SNe may make up a substantial fraction of the normal SNe Ia, which is supported by studies on stellar metallicity observations (Sanders et al.



**Figure 7.** Spectra of SN 2020jgb, SN 2018byg, and SN 2016hbk in the velocity space, comparing the Ca II IRT absorption features (upper panels) and the  $1\ \mu\text{m}$  features assuming they are associated with He I  $\lambda 1.0830$  (lower panels). The red dashed lines mark the minimum of each  $1\ \mu\text{m}$  feature. Data for SN 2018byg and SN 2016hbk are obtained from the WISEReP repository (Yaron & Gal-Yam 2012). [Chang: add statement about “guide the eye”]

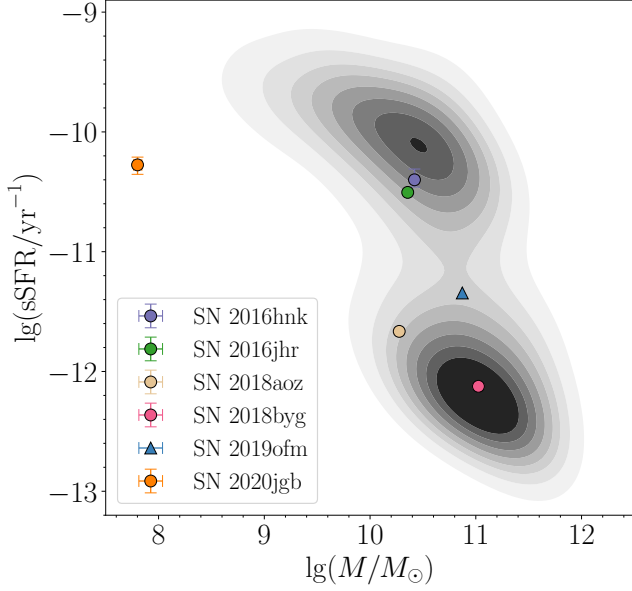
2021; Eitner et al. 2022) or stellar population synthesis (need references).

The diversities in host environments indicate multiple formation channels in the He-shell DDet SNe population. Those in the star-forming environments, SN 2020jgb being the most unambiguous example, could originate from some analogues of the two subdwarf B binaries with WD companions (Geier et al. 2013; Kupfer et al. 2022) discovered in young stellar populations. On the other hand, those with large host offsets could not be easily formed *in situ*. Similarly, many Ca-rich transients are also observed in remote locations (Lunnan et al. 2017), for which some dynamical formation channels have been proposed. To reach the outskirts of galaxies, WD binaries would need to be ejected and hardened by globular clusters (Shen et al. 2019) or supermassive black holes (Foley 2015) before explosions. Given that some Ca-rich transients show characteristic DDet properties (De et al. 2020), these channels may also be applicable to some of the He-shell DDet SNe.

The robust detection of SN 2020jgb in a star-forming region also agrees with independent studies on SNe Ia progenitors using stellar metallicity observations. After measuring the manganese abundance in [Chang: which dwarf], it is argued in de los Reyes et al. (2020) that

sub- $M_{\text{Ch}}$  SNe Ia dominates the chemical evolution of a galaxy [Chang: remind me to tell you about “it is argued in”], while near- $M_{\text{Ch}}$  SNe tend to take over at later times. This indicates that observationally, sub- $M_{\text{Ch}}$  SNe Ia might have a stronger preference towards younger stellar populations than near- $M_{\text{Ch}}$  SNe Ia. [Chang: Isn’t this also the conclusion of the Eitner paper?] Since He-shell DDet is one of the most favored channel to ignite a sub- $M_{\text{Ch}}$  WD, we would expect the majority of exploded SNe Ia in star-forming galaxies (at least the dwarfs) would undergo DDet. We note that while SN 2020jgb is the first confirmed He-shell DDet SN in a star-forming dwarf, which indicates that thick shell DDet SNe might be intrinsically rare, the same may not be true for thin shell DDet SNe since they would look just as *normal* a few days after explosion (Ni et al. 2022a). Unfortunately, few of them are observed in such an early phase to date (SN 2016jhr and SN 2018aoz being two of them), thus we might have missed a great number of He-shell DDet SNe. With more efficient time domain surveys kicking in [Chang: kicking in is a little too colloquial] in the near future and prompt follow-up observations being increasingly available, a systematic studies on the infant SNe Ia will help confirm this implication. [Chang: it can





**Figure 8.** The specific star-formation rate (sSFR) and the stellar mass for the host galaxies of He-shell DDet candidates. The properties for the hosts of SN 2016hmk and SN 2018aoz are taken from Dong et al. (2022b) and the CLU catalog [AAM: References?] [Chang: Kishalay’s big paper on Ca rich events is the only relevant reference], respectively. For the sSFR in the host of SN 2019ofm, only a lower limit is shown (the triangle). The background is a sample of galaxies from the SDSS MPA-JHU DR8 catalog (Kauffmann et al. 2003; Brinchmann et al. 2004). Galaxies with BPT classification as AGNs or LINERs are excluded, since certain spectral features (e.g., H $\alpha$  emission) due to nuclear activities might be misinterpreted as star formation.

maybe be argued that we will not improve on ZTF on this front in the near future]

## 5. CONCLUSIONS

We have presented observations of SN 2020jgb, a peculiar SN Ia. It has a low luminosity, red  $g_{\text{ZTF}} - r_{\text{ZTF}}$  colors, and strong line-blanketing in the optical spectra near maximum light, all of which are highly similar to SN 2018byg (De et al. 2019), whose observational properties could be explained by the detonation of a shell of helium on a sub- $M_{\text{Ch}}$  WD. Fitting the light curves of SN 2020jgb to a grid of models from Polin et al. (2019), we show a  $\approx 0.87 M_{\odot}$  WD beneath a  $\approx 0.08 M_{\odot}$  He-shell provides a reasonable match to the observed spectrophotometric evolution of SN 2020jgb.

A high-SNR NIR spectrum obtained three weeks after maximum light shows a prominent absorption feature near  $1 \mu\text{m}$ , which could be produced by the unburnt helium (He I  $\lambda 10830$ ) in the outermost ejecta expanding at a high velocity ( $\sim 26,000 \text{ km s}^{-1}$ ). At the same epoch, the Ca II IRT also exhibits similarly high

velocities ( $\sim 24,000 \text{ km s}^{-1}$ ). To date only four candidate He-shell DDet SNe have observed NIR spectra. Interestingly, all of them show deep absorption features near  $1 \mu\text{m}$ , which, if assumed to be He I  $\lambda 10830$ , would be expanding at a very similar velocity to the HVFs of Ca II IRT. For these candidates the Ca II HVFs and putative He I velocities show significant diversity ranging from  $\sim 15,000 \text{ km s}^{-1}$  in SN 2016dsg to  $\sim 24,000 \text{ km s}^{-1}$  in SN 2020jgb. If it is the unburnt helium and the newly synthesized calcium from the He-shell that produce these line features, such a consistency in the expansion rates of different absorption lines would be naturally explained. However, we could not find unambiguous evidence for other He I absorption features, such as He I  $\lambda 20581$ , so we cannot claim a definitive detection of helium in SN 2020jgb. Nonetheless, alternative possibilities (Mg II, C I, Fe II) that may cause the  $1 \mu\text{m}$  feature are even less likely. Helium is the most plausible explanation for the apparently ubiquitous  $1 \mu\text{m}$  features.

We propose that He-shell DDet SNe can be robustly detected with NIR spectra. Since the He I  $\lambda 20581$  is weaker or even invisible when the He-shell is thin (Boyle et al. 2017), and could be blended with strong telluric lines, one should not always expect to see significant absorption features near  $2 \mu\text{m}$ . For transients showing a clear  $1 \mu\text{m}$  feature, one can calculate the required velocity assuming an origin in He I  $\lambda 10830$  and check if it is comparable with the HVFs velocity in the Ca II IRT absorption at a similar phase. While the detonation recipe in a DDet model and the viewing angles would all affect the observed He I/Ca II velocity, we still expect the elements along the line-of-sight to expand at a similar velocity, if they all have a He-shell origin. Excluding the possibility of other strong lines is also necessary. If the NIR spectrum is obtained before the peak of the SN, strong Mg II and C I absorption (Hsiao et al. 2019) would be possible contaminants. Otherwise if the  $1 \mu\text{m}$  feature is seen in the transitional-phase spectrum when the inner region of the SNe become visible, we need to carefully rule out the possibility of Fe II origin (Marion et al. 2009). [Chang: I think this can be cleaned up a bit - think about this as bullet points, what is the most direct way to describe these steps?]

The He-shell DDet SNe in the tiny sample show diversities in various observational properties, including the peak luminosity, color evolution, chemical abundances and line velocities, which could be explained by a large variety of He-shell masses, WD masses, viewing angles, and the initial chemical compositions in the shell. In addition, they are discovered in both old and young stellar populations, SN 2020jgb being the first unambiguous

thick He-shell DDet candidate detected in a star-forming galaxy, similar to the normal SNe Ia population. This is in favor of the scenario that a significant fraction of normal SNe Ia are triggered by He-shell DDet. Multiple formation channels and progenitor systems may be required to explain the He-shell DDet population. [Chang: This paragraph is a little rushed, and would benefit from some citations to other work]

I am acknowledgements. [Chang: ZTF acknowledgement. Did you use Quest at all?]

*Facility:* PO:1.2m (ZTF), PO:1.5m (SEDM), Hale (DBSP), NOT (ALFOSC), Shane (Kast Double spectrograph), Keck:I (LRIS), Keck:II (DEIMOS), Gemini:Gillett (GNIRS).

*Software:* `astropy` (Astropy Collaboration et al. 2013, 2018), `emcee` (Foreman-Mackey et al. 2013), `matplotlib` (Hunter 2007), `prospector` (Johnson et al. 2021), `Pytype` (Prochaska et al. 2020), `scipy` (Virtanen et al. 2020), `seaborn` (Waskom 2021).

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