The Search for Failed Supernovae with *JWST*'s Mid-Infrared Instrument

Abstract

Typical core-collapse supernovae (SNe IIP) are the result of gravitational core collapse in red supergiants, the final evolutionary stage of stars with masses greater than 8 $M_{\odot}$. No SN IIP with a progenitor mass greater than $\sim$18 $M_{\odot}$ has been observed, despite observations that suggest red supergiants may have initial masses >30 $M_{\odot}$. If true, the absence of high mass progenitors may indicate that massive red supergiants end their lives as failed supernovae, collapsing directly into black holes. Ongoing searches for failed supernovae have uncovered a few potential candidates. However, there remains no confirmed failed supernova. Current failed supernovae candidates may only appear to vanish, shrouded by gas too cold to probe without *JWST*. We propose to conduct 15 micron wide-band observations of three failed supernovae candidates with *JWST*'s Mid Infrared Instrument (MIRI). Because MIRI is unique in its ability to directly image the 10-20 μm region at high resolution, these observations will detect failed supernovae imposters, i.e. stars hidden in cold dust clouds. These critical observations will either verify the existence of failed supernovae or constrain the properties of the stars that impersonate them. Either scenario will enable strong observational constraints on the frequency of failed supernovae and shed light on the origins of black holes.

■ Scientific Justification

Failed Supernovae: A Solution to the Gap in High Mass Supernovae Progenitors

Stars with initial masses 8-30 $M_\odot$ expand and cool after beginning helium core burning, resulting in red supergiants. When red supergiants experience core-collapse, they explode as Type IIP supernovae (SNe IIP; Smartt 2009). The minimum mass of a star needed to create a SN IIP is $\sim$8 $M_\odot$ (Smartt et al. 2009). However, despite observations of massive red supergiants ($M > 18$ $M_\odot$; Levesque et al. 2005), no SN IIP with a progenitor mass greater than $\sim$18 $M_\odot$ has been observed. The lack of high-mass red supergiant supernovae progenitors is known as the "red supergiant problem".

The most popular solution to the red supergiant problem is that high-mass red supergiants produce failed supernovae, collapsing directly into black holes rather than exploding as supernovae. Simulations of core collapse in massive stars often result in failed supernovae (Zhang et al. 2008). This is especially true in the 18-30 $M_\odot$ range where the majority of the stellar models implode directly into black holes (see Figure 1; Ertl et al. 2016). Further, stellar mass black holes ($\sim$5-15 $M_\odot$) have been observed in low-mass X-ray binaries in the Milky Way (Özel et al. 2010). The existence of these objects is best explained by black hole formation following core-collapse in massive stars. The theoretical and indirect evidence for the existence of failed supernovae makes them the most compelling solution to the red supergiant problem, which has inspired multiple observational searches for failed supernovae.

Ongoing surveys search for failed supernovae by looking for stars that disappear from the sky, indicating a possible collapse to a black hole (Kochanek et al. 2008). However, the majority of the disappearing stars uncovered by these surveys are extreme variable stars that dim significantly and rebrighten years later. So far, these surveys have uncovered three viable failed supernovae candidates which have not rebrightened over long timescales (> 5 years): N6946-BH1 (Adams et al. 2017b), NGC3021-CANDIDATE-1 (Reynolds et al. 2015), and M101-OC1 (Neustadt et al. 2021). Without high-resolution mid-IR observations of these candidates, it is impossible to tell if these candidates are actually black holes or just long-lived dimming events where the star is shrouded by cold gas. As such, no failed supernova is confirmed to exist.

We propose to conduct 15 micron wide-band observations of the three best failed supernovae candidates, N6946-BH1, NGC3021-CANDIDATE-1, and M101-OC1, with *JWST*'s Mid-Infrared Instrument (MIRI). These high-resolution observations, only possible with MIRI, will probe the crucial 10-20 μm region necessary to detect the stars hidden in cold gas clouds which masquerade as failed supernovae. **Just confirming one failed supernova will be a groundbreaking discovery.** Such a result will provide an answer to the origin of stellar mass black holes, confirming theoretical models, and provide a feasible formation pathway for the first black holes through the implosions of Pop III stars. If all three candidates are revealed to be extreme variable stars, these observations will provide valuable insight into the mechanisms which drive variability in massive, evolved stars, an understudied area of stellar evolution.

Ongoing Searches have Uncovered Credible Failed Supernovae Candidates

Due to the numerous failed supernovae surveys with the *Hubble Space Telescope* (*HST*; Sand 2018; Reynolds et al. 2015), the *Large Binocular Telescope* (*LBT*; Neustadt et al. 2021; Adams et al. 2017b), and others (Byrne & Fraser 2022), many failed supernovae candidates have been observed. Some of these candidates, like N4736-OC1 (Neustadt et al. 2021) and M51-DS1 (Jencson et al. 2021), have been observed to rebrighten, indicating that they are failed supernovae imposters. Extreme variable stars can masquerade as failed supernovae due to mass loss events which result in thick cold gas clouds hiding the star in the optical bands, see Figure 2. Because of this possibility, *JWST* mid-IR observations have long been recommended by the community (Neustadt et al. 2021; Adams et al. 2017a; Jencson et al. 2021) as the only way to confirm the complete destruction of the star. Without high resolution mid-IR observations, it is impossible to determine if a failed supernovae candidate is actually a black hole or just an extreme variable star shrouded in a thick layer of cold gas.

Regardless of if a failed supernovae is confirmed during this work, the proposed observations will enable more constraining limits on the failed supernovae frequency. It is expected that as many as 20-30% of massive stars will end their lives without visible supernovae (Smartt 2015). If no failed supernovae candidate proves to be real, this puts the upper limit of the failed supernovae rate at 22% (Neustadt et al. 2021), which would indicate that failed supernovae cannot be the only solution to the red supergiant problem. A lack of a confirmed failed supernova would demonstrate that models are over predicting failed explosions and that stellar mass black holes are likely the result of stars with initial masses >30 $M_{\odot}$. Without limits on the failed supernovae rate as determined by mid-IR observations, it will be exceedingly difficult to determine the fate of massive red supergiants.

Mid-IR observations of failed supernovae candidates are urgently needed in order to set constraints on the rate of failed supernovae and the number of optical failed supernovae imposters. Setting observing procedures for failed supernovae and limits on their expected frequency now is crucial; large scales surveys, like those planned with *JWST* and the *Vera C. Rubin Observatory*, will uncover large samples of these objects in the next couple years.

MIRI can Separate Real Failed Supernovae from Imposters

The best failed supernovae candidates, N6946-BH1 (see Figure 3), NGC3021-CANDIDATE-1, and M101-OC1, have remained at their post-dimming brightness indicating either a failed supernova or a very long-lived variability event. All of these candidates have years' worth of optical and near-IR observations that are consistent with the expected signatures of black hole formation from stellar implosion. However, these observations are incapable of probing colder gas clouds which may shroud stars and result in them appearing like failed supernovae. **In order to conclusively rule out the presence of a star, we propose to observe N6946-BH1, NGC3021-CANDIDATE-1, and M101-OC1 with MIRI's f1500w (15 μm) filter.** MIRI is the only instrument capable of resolving single stars hidden in cold gas clouds given the distance to these candidates (≥ 5 Mpc).

JWST and _HST_ Team up to Take Down Imposter Failed Supernovae

To determine if the three failed supernovae candidates are black holes, we request 15 micron wide-band imaging of these objects. Photometry will be done on the resulting .fits files to ascertain any point sources visible in the mid-IR. There are pre-disappearance *HST* images for all three candidates. The archival *HST* data will be compared to the new MIRI observations in order to determine if a point source is coincident with the pre-disappearance star. The observation of a coincident point source will indicate the presence of a dust obscured star. If no point source coincides with the location of a pre-disappearance candidate, these observations will prove that the candidate is a true failed supernova. The photometry completed as a result of this work will be published alongside the obtained *JWST* images.

Confirming Failed Supernovae is Low Risk, High Reward Science

The proposed observations will allow for the confirmation of the first ever failed supernovae. Moreover, this work requires very little telescope time, allowing for significant science with very little risk and telescope cost. If none of the candidates are real failed supernovae, these observations will be outstanding high resolution mid-IR images of extreme variable stars and will be invaluable for understanding the distribution of cold gas around these objects. Current models of extreme variable stars are not good matches for the behavior exhibited in the best failed supernovae candidates (Adams et al. 2017a; Neustadt et al. 2021). If these objects are variable stars, then they would represent unique cases that require extensive further study. Therefore, the proposed mid-IR observations of failed supernovae candidates will result in landmark publications and be a significant step in the progression of the field regardless of the outcome.

All of the failed supernovae candidates in the proposed work have multi-wavelength observations over long timescales. If any one of them is confirmed to be a real failed supernova then we have direct observational evidence of the formation of a black hole. The confirmation of a massive star directly collapsing into a black hole will have far reaching scientific consequences. A confirmed failed supernovae in the nearby universe will serve as an analogue to the black hole remnants of Pop III stars which merged to form todays supermassive black holes (Alvarez et al. 2009). Therefore, this work is directly related to *JWST*'s main scientific goal of shedding light on our cosmic origins. Confirming the existence of a failed supernovae will set the stage for *JWST*'s legacy while the telescope is still in its infancy, proving that *JWST* is a more than worthy successor to the *Hubble Space Telescope*.

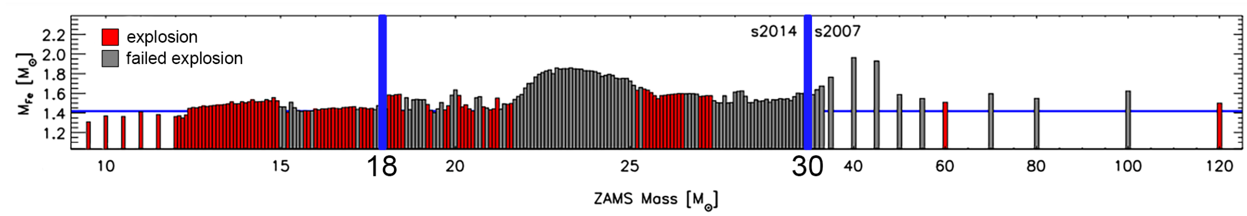

Figure 1: Simulated models of the explodability of stars with a given zero-age main sequence (ZAMS) mass and iron core mass (y-axis). The black bars indicate areas where the model fails to explode, forming a black hole instead (failed supernovae), and red bars are the exploding cases (supernovae). Note that the majority of the stars with initial masses 18-30 $M_\odot$ fail to explode, yet no failed supernovae have yet been observed. Confirmation of a failed supernova is the primary objective of this proposal. Originally from Ertl et al. (2016).

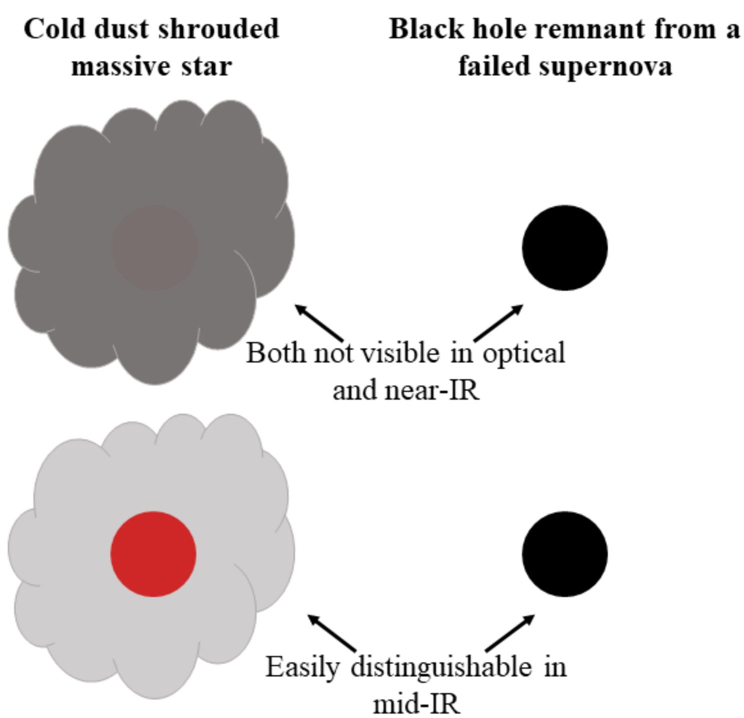

Figure 2: Like failed supernovae, cold dust shrouded massive stars seem to disappear from the sky in the optical and near-IR wavelengths. These variable stars are best distinguished from real failed supernovae when observed in the mid-IR (10-20 μm). Real failed supernovae, i.e. black holes, will not be detectable. In contrast, the cold dust which shrouds failed supernovae imposters is not opaque in the mid-IR allowing the star to be detected.

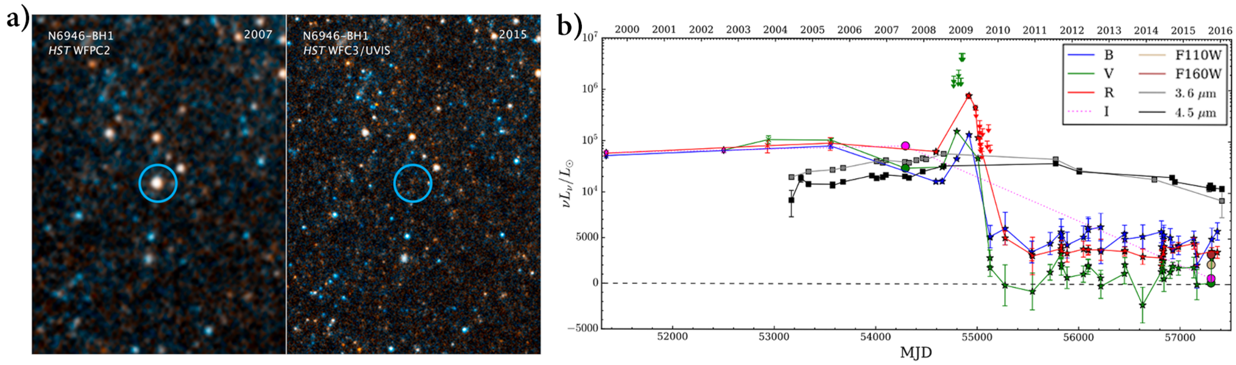

Figure 3: Images and light curves of N6946-BH1 pre- and post-disappearance. *HST* images of N6946-BH1 illustrate that the progenitor object has disappeared (see panel a; from HST 2017, hubblesite.org/contents/news-releases/2017/news-2017-19). Like the other two proposed failed supernovae candidates, continued monitoring of N6946-BH1 indicates no rebrightening following an initial outburst (panel b; from Adams et al. 2017b). All proposed failed supernovae candidates have been observed over long timescales by *HST*, and *LBT* for N6946-BH1 and M101-OC1, in multiple wavelengths without rebrightening, indicating that all three may be failed supernovae.

References • 2017, The Hubble Space Telescope • Adams, S. M., et al., 2017a, MNRAS, 468, 4968 • Adams, S. M., et al., 2017b, MNRAS, 469, 1445 • Alvarez, M. A., et al., 2009, ApJ, 701, L133 • Byrne, R. & Fraser, M., 2022, arXiv e-prints, arXiv:2201.12187 • Ertl, T., et al., 2016, ApJ, 818, 124 • Jencson, J. E., et al., 2021, arXiv e-prints, arXiv:2110.11376 • Kochanek, C. S., et al., 2008, ApJ, 684, 1336 • Levesque, E. M., et al., 2005, ApJ, 628, 973 • Neustadt, J. M. M., et al., 2021, MNRAS, 508, 516 • Özel, F., et al., 2010, ApJ, 725, 1918 • Reynolds, T. M., et al., 2015, MNRAS, 453, 2885 • Sand, D. J., 2018, The Identification of Failed Supernovae, HST Proposal. Cycle 26, ID. #15645 • Smartt, S. J., 2009, ARA&A, 47, 63 • Smartt, S. J., 2015, PASA, 32, e016 • Smartt, S. J., et al., 2009, MNRAS, 395, 1409 • Zhang, W., et al., 2008, ApJ, 679, 639