# Deep HST/WFC3 Imaging of the Ca-rich Transient iPTF15eqv

Scientific Category: Stellar Physics
Scientific Keywords: Massive Stars, Supernovae, Transients
Instruments: WFC3
Proprietary Period: 6 months

Proposal Size: Small UV Initiative: Yes

| Orbit Request | Prime | Parallel |
|---|---|---|
| Cycle 25 | 6 | 0 |

## Abstract

The progenitor system of the class of "Ca-rich transients" is a key open issue in time domain astrophysics. These intriguing objects exhibit unusually strong calcium line emissions months after explosion, fall within an intermediate luminosity range between novae and supernovae (SNe), are often found at large projected distances from their host galaxies (up to 150 kpc), and may play a vital role in enriching galaxies and the intracluster medium.

A recent Ca-rich transient iPTF15eqv in the nearby galaxy NGC 3430 (D~30 Mpc) exhibited among the highest [Ca II]/[O I] emission line ratios ever observed in this class of objects, along with spectroscopic signatures consistent with the SN explosion of a ~10 solar mass star that was stripped of its H-rich envelope via interaction with a binary companion. This discovery challenges the notion that Ca-rich transients only originate from white dwarf progenitor systems.

Unlike many Ca-rich transients that are discovered in isolated locations, ground-based images show iPTF15eqv to be within close projected proximity of a fairly rich environment of hot gas and stars. We request a modest investment of six orbits of HST time to perform a high return investigation of iPTF15eqv using WFC3/UVIS to map its stellar environment, look for massive star companions, and place limits on their ages and mass using our BPASS stellar evolution models. These observations are only possible with the high resolution and UV capabilities of HST, and will help to definitively establish that at least some Ca-rich transients are associated with core collapse massive star explosions.

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Number of investigators: 10

## Target Summary:

| Target | RA | Dec | Magnitude |
|---|---|---|---|
| IPTF15EQV | 10 52 8.3300 | +32 56 39.40 | |

## Observing Summary:

| Target | Config Mode and Spectral Elements | Flags | Orbits |
|---|---|---|---|
| IPTF15EQV | WFC3/UVIS Imaging F275W | | 6 |
| | WFC3/UVIS Imaging F438W | | |
| | WFC3/UVIS Imaging F665N | | |
| | WFC3/UVIS Imaging F814W | | |
| | WFC3/UVIS Imaging F469N | | |

Total prime orbits: 6

## ■ Scientific Justification

### 1. Ca-rich transients

An emergent class of rapidly evolving explosions referred to as "Ca-rich transients" (a.k.a. SN 2005E-like and "Ca-rich gap") has garnered considerable attention in the last decade (Perets et al. 2010; Kasliwal et al. 2012). These intriguing events fall within an intermediate luminosity range between novae and supernovae (SNe) and are defined by unusually strong calcium line emissions that develop in optical spectra months after explosion (emission line ratio [Ca II]/[O I] $> 2$). Their unique properties suggest that the total calcium synthesized in each explosion is greater than that of normal Type I supernovae by factor of $5 - 10$ (Perets et al. 2010). **The potentially large calcium abundance of Ca-rich transients suggests that they may be vital drivers of chemical evolution in galaxies and the intergalactic medium** (Mulchaey et al. 2014; Mernier et al. 2016), and that they may help explain metal-poor stars with an extremely large over-abundance of Ca such as SDSS J234723.64+010833.4 discovered in the outer halo of our galaxy (Lai et al. 2009).

**The progenitor systems of "Ca-rich transients" is a key open issue in time domain astrophysics.** Many Ca-rich transients have been hosted by early-type galaxies lacking obvious massive star populations and are often found in isolated locations at large distances away from their host galaxies (as high as 150 kpc; (Perets et al. 2010; Kasliwal et al. 2012; Foley 2015; Figure 1). The relatively large delay-time distribution required to travel such large distances seem to favor an older white dwarf (WD) population, potentially in scenarios where WD binaries interact with a central supermassive black hole and become ejected from their host galaxy (Foley 2015). The observed light curves and spectra of Ca-rich transients have been modeled using WD stars undergoing helium detonations while accreting from a companion (Shen et al. 2010; Waldman et al. 2011; Dessart et al. 2015), or WD stars being tidally disrupted by neutron stars, stellar mass BHs (Metzger et al. 2012; Fernandez et al. 2013; Margalit et al. 2016), or intermediate mass BHs in dwarf galaxies or globular clusters (Rosswog et al. 2008; MacLeod et al. 2014; Sell et al. 2015).

**Although Ca-rich transients are generally treated uniformly and are most often associated with WD star systems, the observational classification may encompass more than one progenitor system** (Kawabata et al. 2010; Lyman et al. 2014; Valenti et al. 2014; Sell et al. 2015). Indeed, many properties of Ca-rich transients are consistent with progenitor stars having initial masses in the range of $8 - 12$ $M_\odot$ (Kawabata et al. 2010; Suh et al. 2011), perhaps most notable is that their early spectra best match those of core collapse Type Ib supernovae. Additional evidence can be found in new observations and analysis of the SN remnant RCW 86 (Gvaramadze et al. 2017). **However, seemingly contrary to the understanding that massive stars are natural progenitor systems of Type Ib Ca-rich transients is that close examinations of explosion sites using high resolution images with HST have thus far failed to uncover any sign of in situ star formation** (Perets et al. 2011; Lyman et al. 2013; Lyman et al. 2016, Lunnan et al. 2017). As we explain below, the nearby Ca-rich transient iPTF15eqv provides a rare opportunity to fully test these competing progenitor system hypotheses.

## 2. iPTF15eqv: A Ca-rich supernova from a massive star progenitor

In Milisavljevic et al. (2017) our team presented multi-wavelength observations of the Ca-rich transient iPTF15eqv in NGC 3430, which exhibited among the highest [Ca II]/[O I] emission line ratios ever observed ($> 10$) in this class and provided the strongest case yet that Ca-rich transients have multiple progenitor channels. Much of this breakthrough was made possible through the fortuitous close proximity of iPTF15eqv ($D \sim 30$ Mpc; among the closest ever discovered) that enabled optical and near-infrared photometric and spectroscopic observations of high signal-to-noise ratio at epochs $> 200$ days after explosion. This is among the latest epochs ever observed for a Ca-rich transient (Figure 3). Additional data included Chandra X-ray Observatory observations that ruled out most tidal disruption scenarios, and Jansky Very Large Array radio observations that imply a clean environment ($n \lesssim 0.1$ cm$^{-3}$) within a radius of $\sim 10^{17}$ cm of the explosion site. Together, the observations comprise a rich and deep data set (among the best ever gathered for a Ca-rich transient at late times) and revealed faint features that may potentially have been missed in lower signal-to-noise data from the majority of Ca-rich transients that have been discovered at higher redshifts.

Our optical and near-infrared photometry and spectroscopy of iPTF15eqv revealed signatures consistent with the supernova explosion of a $< 10\,M_\odot$ star that was partially stripped of its H-rich envelope via interaction with a binary companion (Figure 3). **These results challenge the notion that Ca-rich transients only originate from white dwarf progenitor systems, and provide robust evidence that an unknown percentage of Ca-rich transients are associated with massive star explosions.**

The relative line strengths observed in the optical+NIR data made it possible to estimate chemical abundances of iPTF15eqv. We derived O and Ca masses of $0.090^{+0.11}_{-0.08}$ and $0.006\pm0.002$ $M_\odot$, respectively. These estimates were in sharp contrast with those made for another well known Ca-rich transient SN 2005E by Perets et al. (2010) (0.037 and 0.135 $M_\odot$ for O and Ca, respectively). Some of the inconsistency may be attributable to different model assumptions, but it is very likely that additional discrepancies arise from the different natures of the explosions. Thus, the Ca abundance yield of Ca-rich transients may vary considerably across individual events, and **confident identification of the Ca-rich transient progenitor system(s) is crucial to understand the origin of the potentially large range of chemical abundance yields**.

The Ca/O abundance ratio is sensitive to the progenitor mass in core-collapse SNe. Models of supernova nucleosynthesis have routinely shown that larger masses of Ca are made for lower mass progenitors (Woosley & Heger 2007; Nomoto et al. 2013). For example, theoretical models predict that stars having main-sequence masses of 13 $M_\odot$ and 18 $M_\odot$ produce Ca/O ratios (by mass) of 0.025 and 0.005, respectively (Nomoto et al. 2013). Keeping with this trend, in order to produce a relatively large Ca/O ratio of $\approx 0.07$ observed in iPTF15eqv, the mass of its progenitor star would have been $< 13\,M_\odot$ and thus approach the threshold for core collapse ($8 \pm 1\,M_\odot$; Smartt 2009).

Stars in the mass range $8 - 12$ $M_\odot$ can exhibit structural peculiarities during their evolution that considerably affect the supernova explosion dynamics if they undergo core collapse. Electron captures on $^{24}$Mg and $^{20}$Ne in a degenerate O-Ne-Mg core of mass $\sim 1.37\,M_\odot$

can drive the core towards collapse in what is referred to as an "electron-capture supernova" (ECSN; Nomoto 1984). This progenitor scenario was invoked to explain the Ca-rich SN 2005cz (Kawabata et al. 2010). The winds of such stars are not strong enough to remove hydrogen envelopes, which led Kawabata et al. (2010) to suggest that binary interaction via Roche-lobe overflow or common envelope ejection could explain why no conspicuous hydrogen was present in their optical spectra of SN 2005cz.

A similar progenitor scenario could apply to iPTF15eqv. Perhaps the strongest signature of an ECSN is that it likely leaves behind a very special abundance pattern in its ejecta (see recent review by Mueller 2016), which may be abundant in isotopes of calcium (Wanajo et al. 2013). Notably, binary systems of stars in the mass range that develop to ECSNe can significantly extend the delay time distribution of core-collapse SNe (Zapartas et al. 2017; Figure 5). For single stars the maximum lifetime is approximately $\sim$ 50 Myr. However, binary progenitors can have lifetimes extending out to 200 Myr. **The extended lifetimes of binary systems in this mass range provides a pathway for progenitor systems to travel large distances (and hence to remote locations) before core collapse.**

## 3. Motivation for HST Observations

The leading candidate progenitor system of iPTF15eqv is an H-poor star of mass $\lesssim 10\,M_\odot$ that interacted with a nearby companion star, and the chemical abundances estimated from our late-time spectra suggest that the explosion may have been an ECSN. Consequently, iPTF15eqv forces a reconsideration of the "Ca-rich transient" observational classification, which may currently be applied to a heterogeneous progenitor population of white dwarf and massive stars.

**We request a modest investment of six orbits of HST/WFC3 time to map the stellar environment and identify massive star companions of iPTF15eqv.** Unlike many Ca-rich transients that are discovered in isolated locations (Figures 1 and 6), iPTF15eqv is within projected proximity of a fairly rich environment of hot gas and stars (Figure 2) with vigorous star formation. Ground-based images are unable to confidently resolve iPTF15eqv from nearby and potentially unrelated stars and material. The subarcsecond resolution of HST, however, can precisely place the location of the SN with respect to surrounding environment ($1'' \approx 150$pc) and measure the SED, He II, and H$\alpha$ emission. In turn, this would allow us to characterize any sources we may find using the BPASS models to determine properties of the progenitor star system's environment (e.g., mass, age, luminosity, star formation rate, metallicity) that we can use to constrain possible explosion scenarios (see, e.g., Milisavljevic et al. 2015; Eldridge & Maund 2016). We note that these observations may even detect the progenitor star's binary companion, depending on the amount of dust in the vicinity. Our team combines the theoretical and observational expertise needed to guarantee deliverable science from the requested HST observations. We emphasize that these observations – which can uniquely help to establish that at least some Ca-rich transients are associated with core collapse massive star explosions – are only possible with the high resolution and UV capabilities of HST.

## Description of the Observations

We require 6 orbits of HST time to obtain deep WFC3/UVIS exposures in the F275W, F438W, F469N, F665N, and F814W filters employing three-point sub-pixel dithering. The rapid fading of the SN light curve ensures that iPTF15eqv will be sufficiently faint and undetectable in all filters with the possible exception of F814W that is sensitive to [Ca II] 7291, 7324 emission lines. The UV filter F275W (centered near Mg II 2800) is an essential part of the proposed observations, as it will aid in revealing any hot, massive stars near the explosion site. The F469N filter, for which we allocate two orbits, will be sensitive to He II 4868 line emission that traces stripped stars such Wolf-Rayet (W-R). The F438W can be used to subtract continuum light from the F469N filter. **W-R stars are much brighter in filters sensitive to their strong, broad emission lines, particularly He II 4686, than their continua, by up to 3 mag** (Massey & Johnson 1998; see also Figure 7 of Shara et al. 2013) Furthermore, any nebula emission driven by the stripped stars should be hot and thus can ionize He II (Stanway et al. 2016; Gotberg et al. 2017). The F665N is sensitive to H$\alpha$ emission at the redshift of the host galaxy and will precisely place the SN within the nearby H II region emission observed in low resolution ground-based images (Figure 1). WFC3 images will be astrometrically aligned with ground-based MMT images (Figure 2). Using the WFC3/UVIS ETC we estimate that we can reach levels of $m_B > 28$ mag, or $M_B > -4.4$ mag in one orbit. The photometric limits will be slightly better than what Lyman et al. (2016) achieved for 2003dr and 2005E using HST observations in this filter. Notably, however, **unlike Lyman et al. (2016) and all other prior work that has compared photometric limits to single stars and integrated emission from globular clusters and dwarf galaxies, the BPASS models we will employ include binary star evolution and electron capture progenitors, which is essential in the Ca-rich core collapse explosion scenario applicable to iPTF15eqv. We also make use of the F275W and F469N filters, which have never been utilized before** and are particularly constraining in the models. Within various uncertainties, our program is designed to probe stellar masses down to $\sim 10$ M$_\odot$.

## Special Requirements

## Coordinated Observations

## Justify Duplications

No HST observations of the host galaxy NGC 3430 have been obtained before.

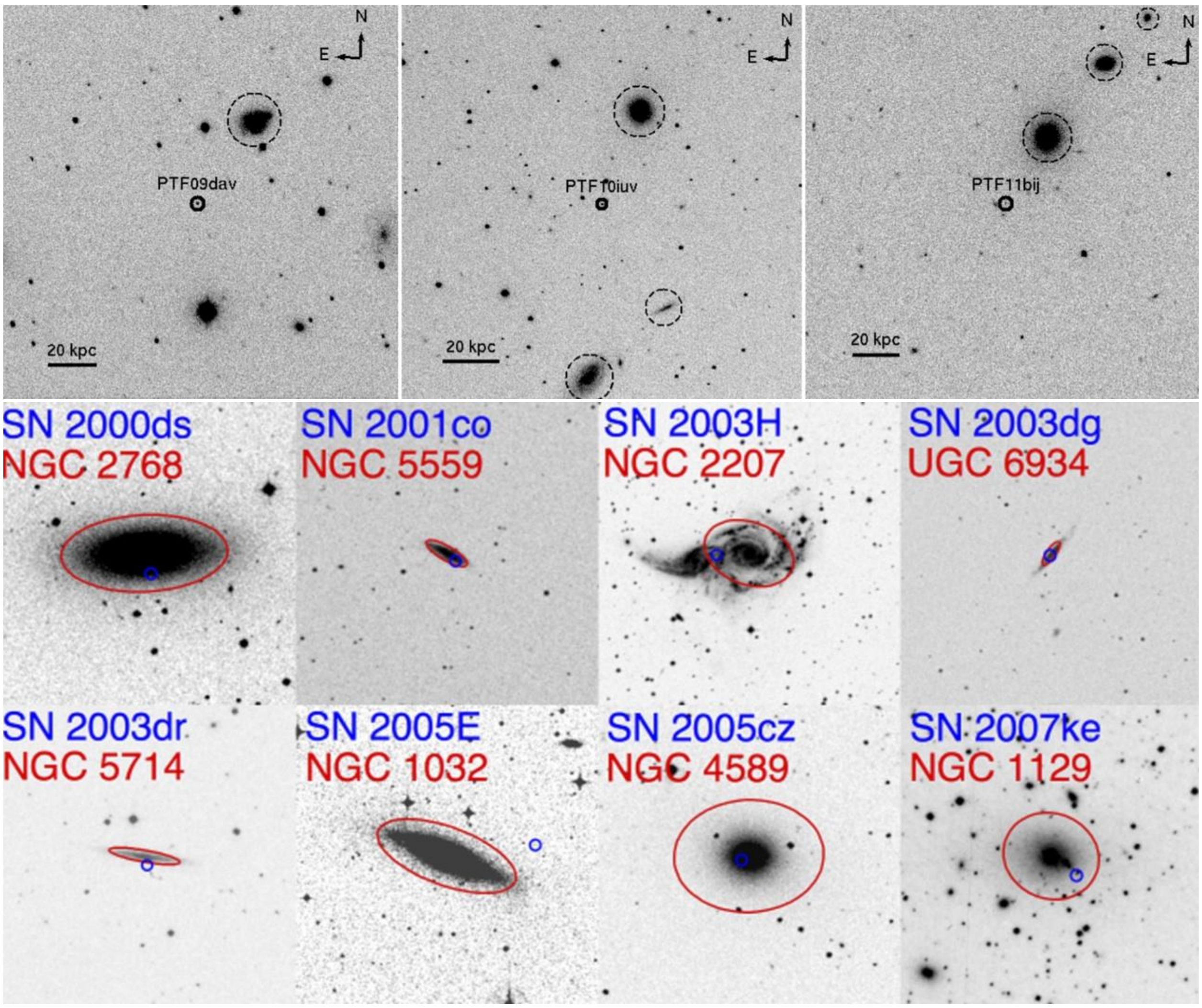


Figure 1: Example fields of Ca-rich transients from Kasliwal et al. (2012) (top row) and Foley (2015) (middle and bottom rows). Many, but not all, have large projected offsets from their host galaxies. The isolated locations and general lack of in situ star formation suggest that the progenitor systems have been "kicked" and have a relatively large delay-time distribution (Lyman et al. 2014).

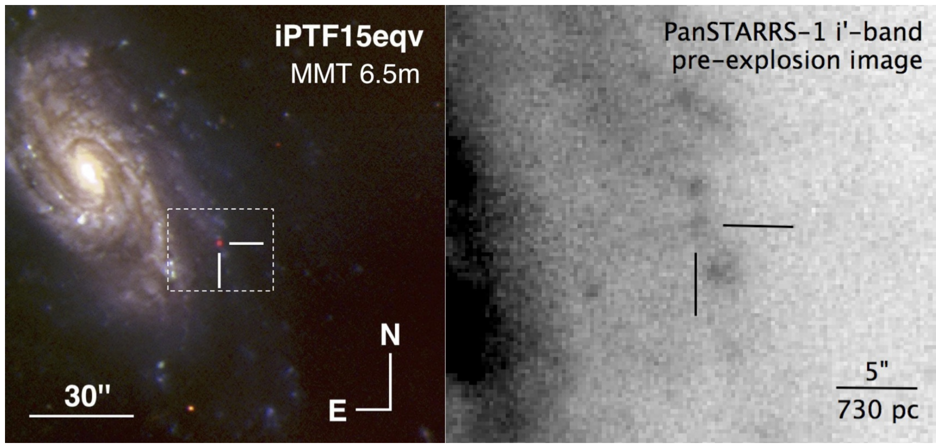


Figure 2: Left: Composite image of iPTF15eqv and host galaxy NGC 3430 ($D \sim 30.4$ Mpc) made from MMT 6.5m telescope + MMTCam observations obtained in $g'$ (blue), $r'$ (green), and $i'$ (red) bands. The red color of iPTF15eqv reflects the high equivalent width of the [Ca II] $\lambda\lambda$7291, 7324 emission lines (see also Fig. 3). Dashed white box demarcates region enlarged in adjacent panel. Right: Pre-explosion PanSTARRS-1 $i'$-band stacked image with location of iPTF15eqv marked. Unlike many other Ca-rich transients, the nearby environment of iPTF15eqv has indications of vigorous star formation. The requested HST observations will pinpoint the precise location of progenitor system at time of explosion with respect to these neighboring stars and gas, and depending on dust properties we may be able to detect the progenitor's companion star.

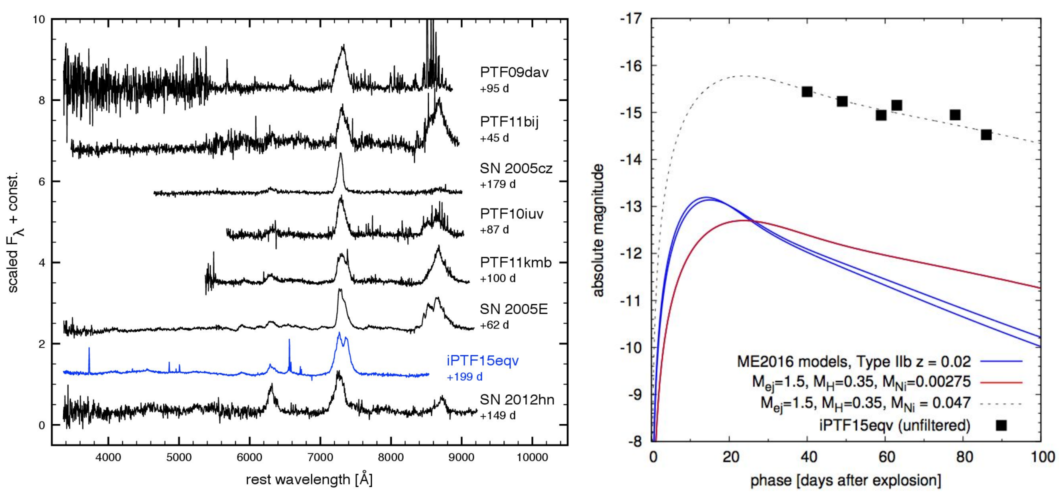


Figure 3: Left: Optical spectra of Ca-rich transients compared to that of iPTF15eqv. Right: The light curve of iPTF15eqv compared to bolometric light curves from models of ECSNe in close binary systems presented in Moriya & Eldridge (2016). These models are for stripped progenitor stars with 0.35 $M_\odot$ of hydrogen at the time of explosion. We find reasonable consistency between iPTF15eqv and a model having a total ejecta mass of 1.5 $M_\odot$ and 0.047 $M_\odot$ of nickel. Adapted from Milisavljevic et al. (2017).

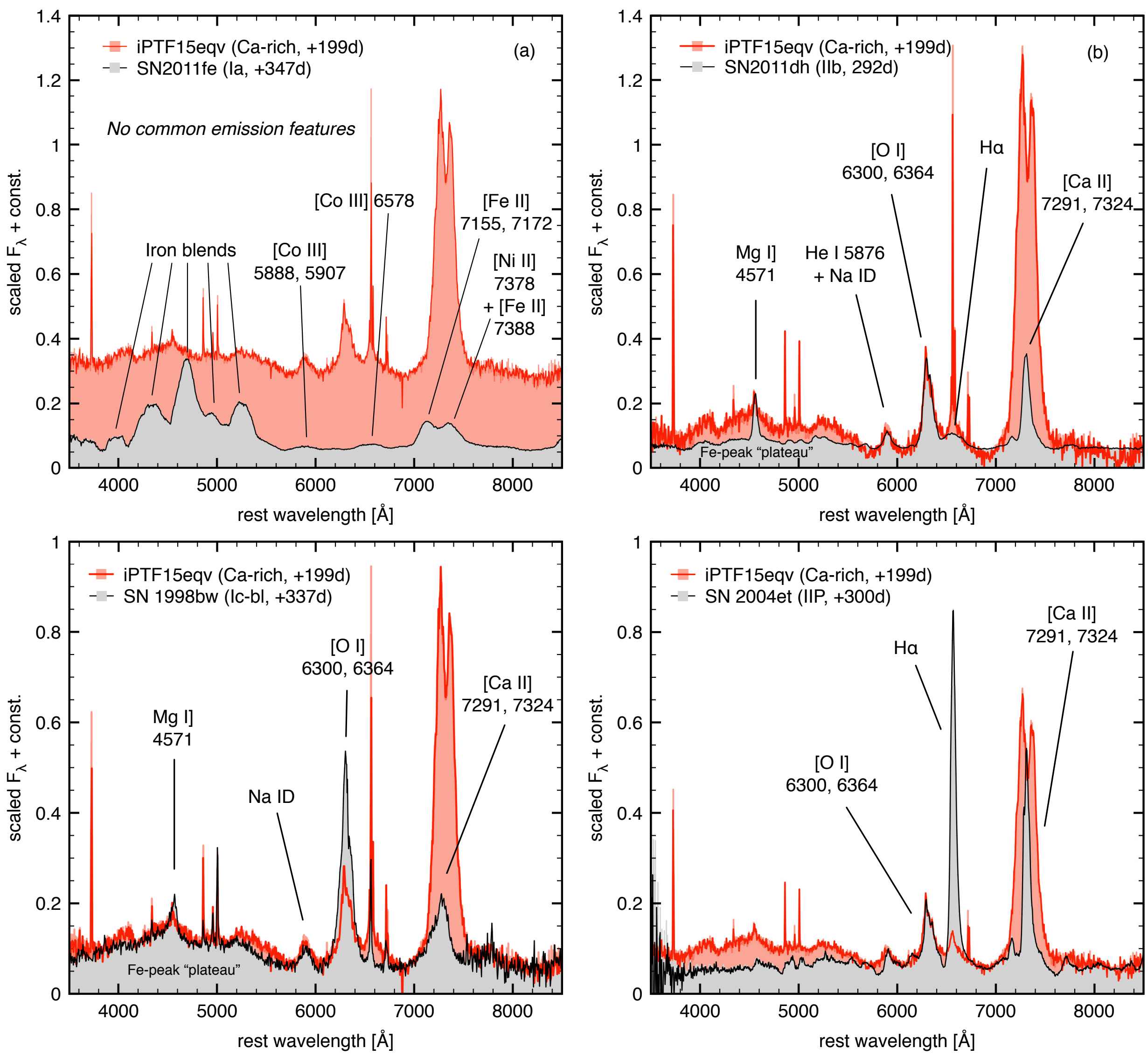


Figure 4: Spectral fingerprinting of iPTF15eqv. The spectral features of iPTF15eqv best match those of a core-collapse explosion with modest hydrogen ($< 0.35\ M_\odot$) and have little similarity to those observed in thermonuclear WD explosions. The high quality spectra are among the best ever obtained for a Ca-rich explosion at these late epochs where emission originates from ejecta closest to the explosion center. Adapted from Milisavljevic et al. (2017).

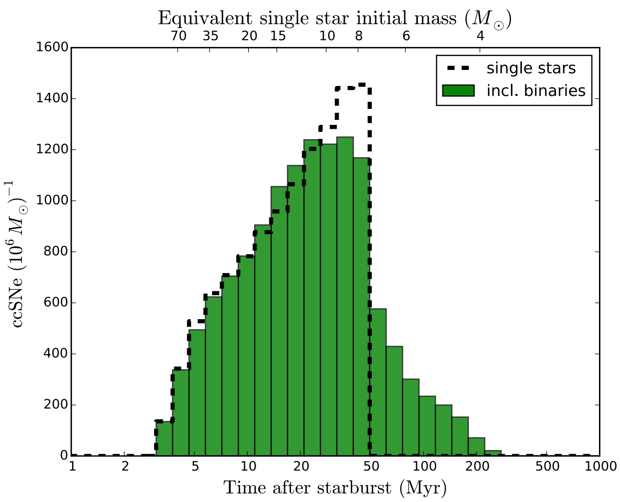


Figure 5: The delay-time distribution of core-collapse supernovae for a population consisting of 70% binary systems (green histogram) compared to the distribution for a population of only single stars (black dashed line). Top axis shows the initial mass of single stars with the corresponding lifetime given in the bottom axis. From Zapartas et al. (2017). The extended lifetimes of binary systems in this mass range provides a pathway for progenitor systems of Ca-rich transients to travel large distances (and hence to remote locations) before core collapse.

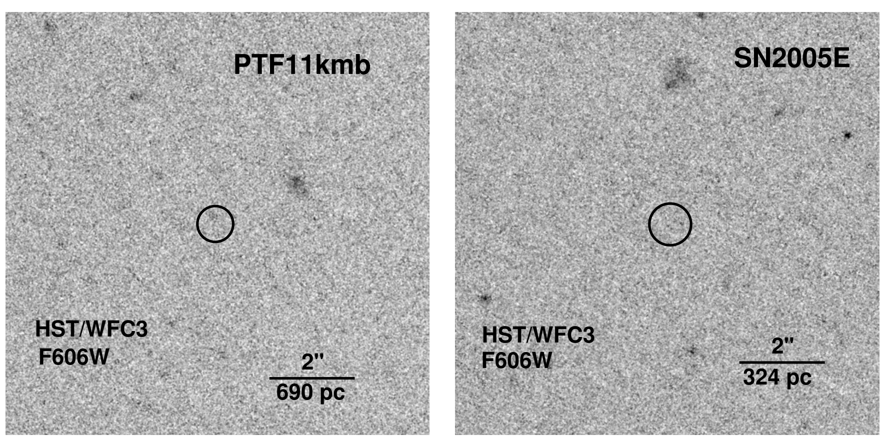


Figure 6: HST has imaged the explosion sites of a handful of Ca-rich supernovae in previous cycles (see, e.g., Perets et al. 2011, Lyman et al. 2016). Here we show two fields analyzed in Lunnan et al. (2017). Thus far no evidence of in situ star formation has been recovered. However, our target iPTF15eqv benefits from the fortuitously nearby distance of its host ($D \sim 30$Mpc; among the closest ever discovered), negligible extinction ($E(B-V) < 0.2$ mag), and close projected proximity to hot gas and stars (see Fig. 2). Furthermore, our program is designed to look for *stripped stars* by uniquely utilizing the UV filter F275W (broadband UV continuum) and narrowband F469N (sensitive to He II 4868 line emission that is strong in W-R stars).

**References:** Dessart, L., & Hiller, D. 2015, MNRAS, 447, 1370 • Eldridge, J. et al. 2008, MNRAS, 384, 1109 • Eldridge, E., Maund, J. 2016, MNRAS, 461, L117 • Foley, R. 2015, MNRAS, 452, 2463 • Gotbery, Y., et al. 2017, arXiv:1701.07439 • Gvaramadze, V. 2017, arXiv:1702.00936 • Kasliwal, M., et al. 2012, ApJ, 755, 161 • Kawabata, K., et al. 2010, Nature, 465, 326 • Lai, D., et al. 2009, ApJL, 697, L63 • Lunnan, R., et al. 2017, ApJ, 836, 60 • Lyman, J., et al. 2013, 434 527 • Lyman, J., et al. 2014, MNRAS, 444, 2157 • Lyman, J., et al. 2016, MNRAS, 458, 1768 • Massey, P., Johnson, O. 1998, ApJ, 505, 793 • Mernier, F., et al. 2016, A&A, 595, 126 • Metzger, B. 2012, MNRAS, 419, 827 • Milisavljevic, D., et al. 2015, ApJ, 815, 120 • Milisavljevic, D., et al. 2017, submitted to ApJ • Mueller, B. 2016, arXiv:1608.03274 • Nomoto, K. 1984, ApJ, 277, 791 • Nomoto, K. 2013, AR&A, 51, 457 • Perets, H., et al. 2010, Nature, 465, 322 • Perets, H., et al. 2011, ApJL, 728, 26 • Rosswog, S., et al. 2008, ApJ, 679, 1385 • Shara, M., et al. 2013, ApJ, 146, 162 • Shen, K., et al. 2010, MNRAS, ApJ, 699, 1365 • Sell, P., et al. 2015, MNRAS, 450, 4198 • Smartt, S. 2009, AR&A, 47, 63 • Stanway, E., et al. 2016, MNRAS, 456, 485 • Suh, Y., et al. 2011, ApJ, 730, 110 • Valenti, S., et al. 2014, MNRAS, 437, 1519 • Waldman, R., et al. 2011, ApJ, 738, 21 • Wanajo, S., et al. 2013, ApJL, 767, 26 • Woosley, S, Heger, A. 2007, PhR, 442, 269 • Zapartas, E., et al. 2017, arXiv:1701.07032