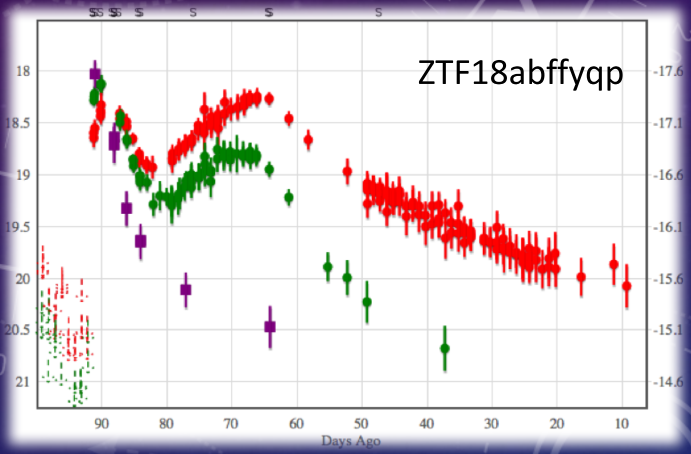
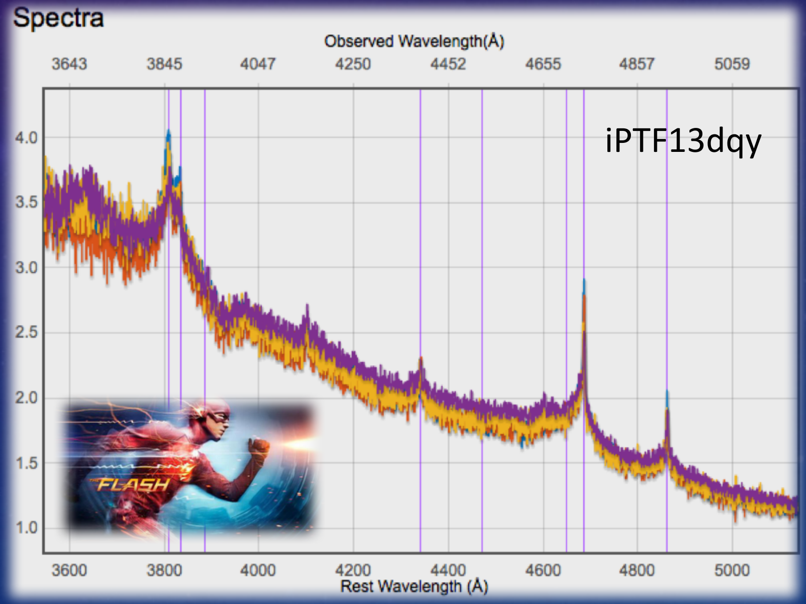
EARLY Observations of Type II SNe
&
Some Recent Findings From ZTF

Ofer Yaron
The Weizmann Institute for Science





iPTF13dqy study - In collaboration with: A. Gal-Yam, D. Perley, J. Groh, A. Horesh, E. Ofek, A. Rubin and others…

“Historical” note…

SN1983K – The earliest(?) “Flash-spectroscopy” event hinting at the existence of nearby CSM…

THE SUPERNOVA 1983k IN NGC 4699: CLUES TO THE NATURE OF TYPE II PROGENITORS

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Received 1984 April 18; accepted 1984 August 8

ABSTRACT

Optical spectrographic and photometric observations of the Type II supernova 1983k in NGC 4699 are presented. For the first time, high quality spectra have been obtained of a Type II supernova before it reached maximum light. The first of these, taken nearly 10 days before maximum, showed high-ionization N III and He II emission lines atop a strong blue continuum. Near maximum, the emission lines disappeared, leaving weak H I, He I, and Ca II absorption lines. By a month after maximum, the spectra were dominated by P Cygni–like emission lines of H I, again consistent with a Type II classification.

The light curve, which showed a very extended peak, and the absorption lines seen at maximum provide independent evidence that the progenitor of this supernova had an extensive, preexisting circumstellar shell. The strong nitrogen lines seen before maximum imply that the surface layers of the progenitor were significantly overabundant in this element. Both of these characteristics are consistent with the progenitor having been an exploding Wolf-Rayet star or a red supergiant.

Subject headings: galaxies: individual — stars: supernovae

“Historical” note…

SN1983K – The earliest(?) “Flash-spectroscopy” event hinting at the existence of nearby CSM…

The strong Wolf-Rayet–like spectra seen in the first premaximum observations represent a hitherto unobserved phase in the development of Type II supernovae. Although detailed knowledge of physical conditions is required to accurately determine abundances, the prominent nitrogen lines very likely imply that at least some of the gas in the progenitor star was significantly nitrogen enriched. This spectrum abruptly disappeared at the approach of maximum light, which is the point at which the shock wave most likely emerged at the photosphere (Falk and Arnett 1977). Thus, it seems probable that the nitrogen-rich material lay either at the surface or perhaps in the circumstellar shell of the progenitor. This is supported by the blueshift of the emission-line peaks at this stage, which is most readily explained if the emission-line region was at or near the outer surface of the expanding progenitor envelope. *We conclude that SN 1983k most likely resulted from a massive star with an extended envelope, which had undergone significant mass loss prior to exploding and whose surface layers contained nitrogen-enriched material.*

Of course, the Wolf-Rayet–like premaximum spectrum raises the obvious question of whether the progenitor could have been a Wolf-Rayet star. Maeder and Lequeux (1982) have concluded that the evolution of many such stars is likely to culminate in a supernovae explosion, and that one of every three to seven supernovae in our Galaxy had Wolf-Rayet progenitors. However, it is equally possible that the Wolf-Rayet–like spectrum resulted from the physical conditions produced by the supernova explosion, and was not a property of the progenitor. Many authors have considered the most likely progenitors of type II supernovae to be massive red supergiants. In fact, the values of the radial velocities measured from the premaximum and maximum absorption, and later from the postmaximum Hα emission line width agree surprisingly well with

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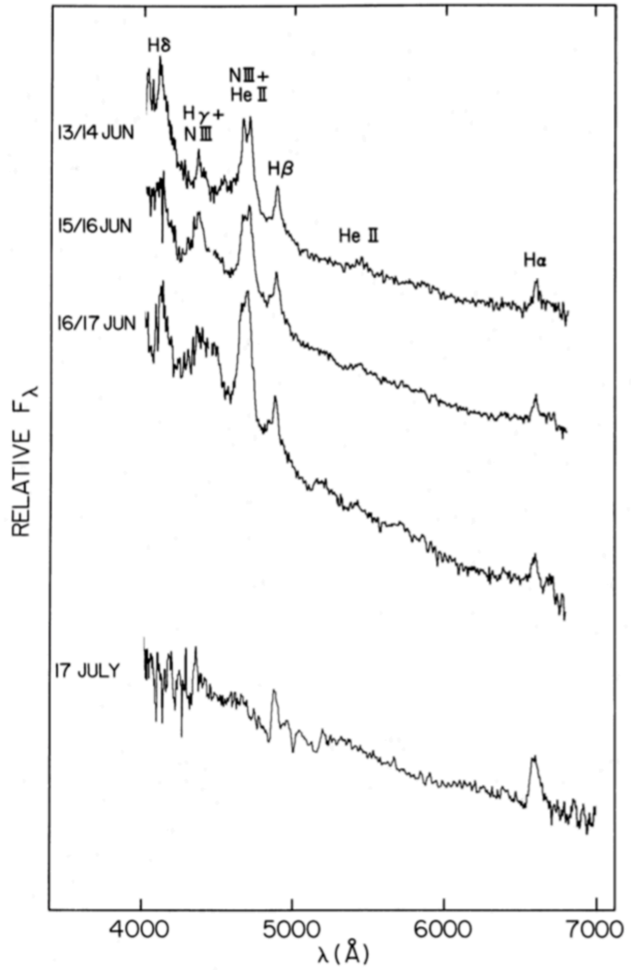
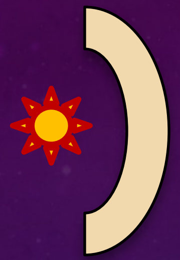
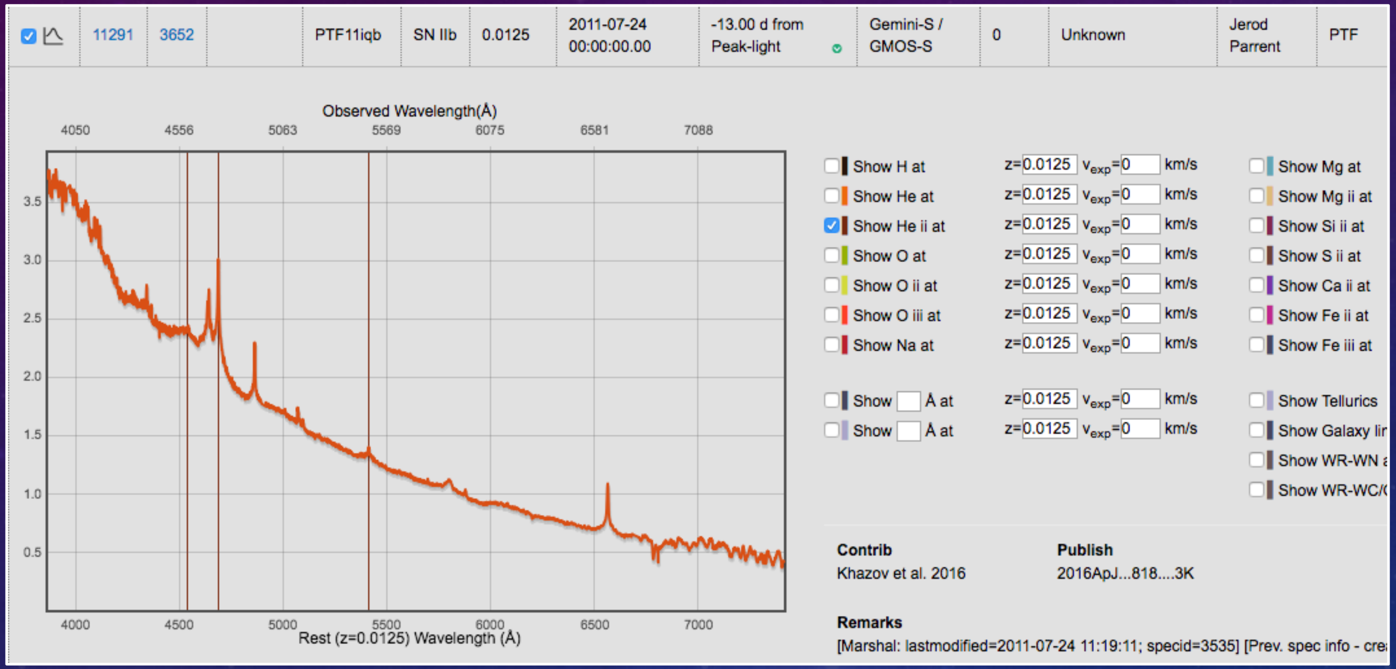


FIG. 2.—SIT Vidicon spectra of SN 1983k obtained with the CTIO 1.5 m telescope in 1983 June and July. The July spectrum is the average of observations made on 16 and 18 July (UT).

Various Signatures of CSM Interaction in CC-SNe



M_w , $\rho_w(r)$, $\Delta R(\Delta t)$

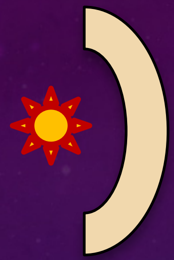


Flash-spec events

low M, high-ish ρ, small ΔR

➔ emission lines gone within several days

Various Signatures of CSM Interaction in CC-SNe



M_w , $\rho_w(r)$, $\Delta R(\Delta t)$

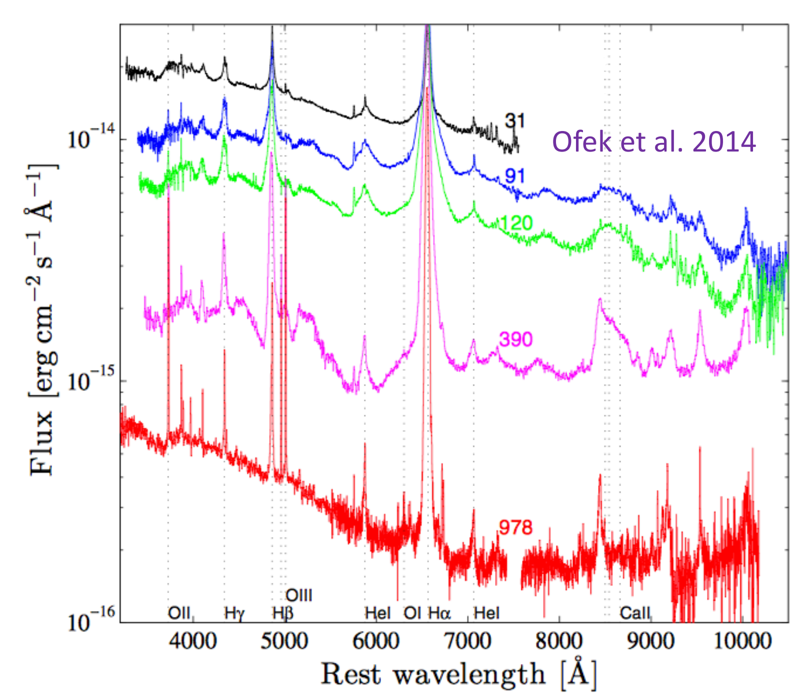
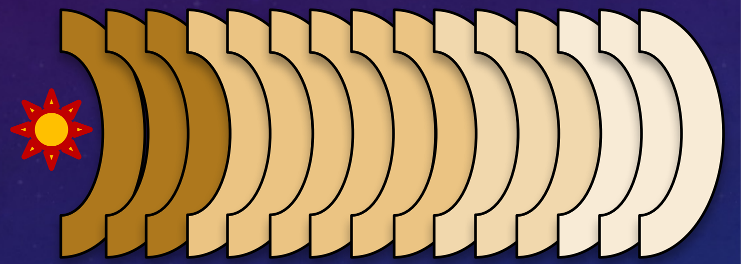


Figure 2. Selected visible-light spectra of SN 2010jl. The number near each spectrum marks its age in days (see Table 2). The last spectrum taken on day 978 may be contaminated by emission from the underlying star-forming region.

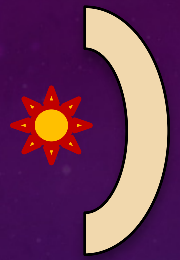


Flash-spec events
low M, high-ish ρ, small ΔR
➔ emission lines gone within several days

Type IIn (SLSNe II?)
high M, ρ, ΔR
persistent emission lines over months/years

Various Signatures of CSM Interaction in CC-SNe

M_w , $\rho_w(r)$, $\Delta R(\Delta t)$



Flash-spec events

low M, high-ish ρ, small ΔR

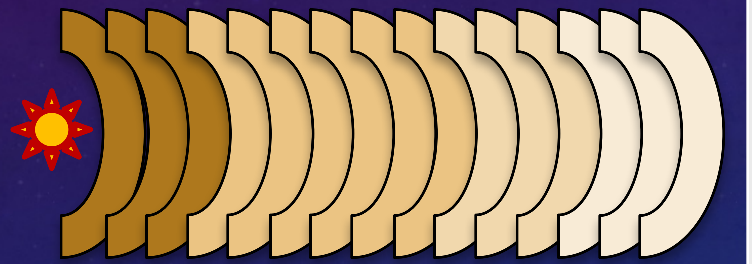
➔ emission lines gone within several days

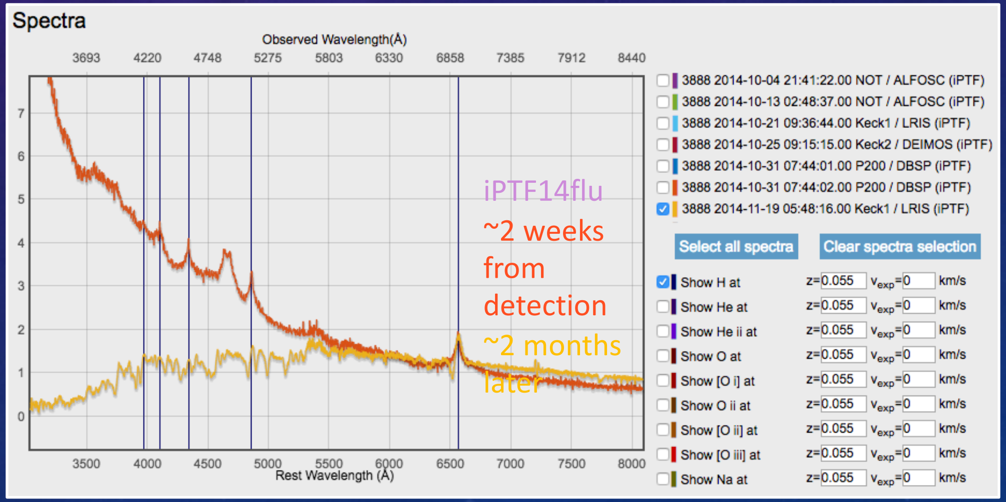
A continuum of "transitional" CSM extents…

➔ emission lines gone within several weeks

OR… multiple detached shells…?

➔ successive rebrightenings…





Type IIn (SLSNe II?)

high M, ρ, ΔR

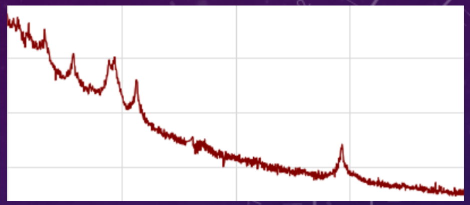
persistent emission lines over months/years

Evidence for Pre-SN (enhanced/eruptive) mass-loss events

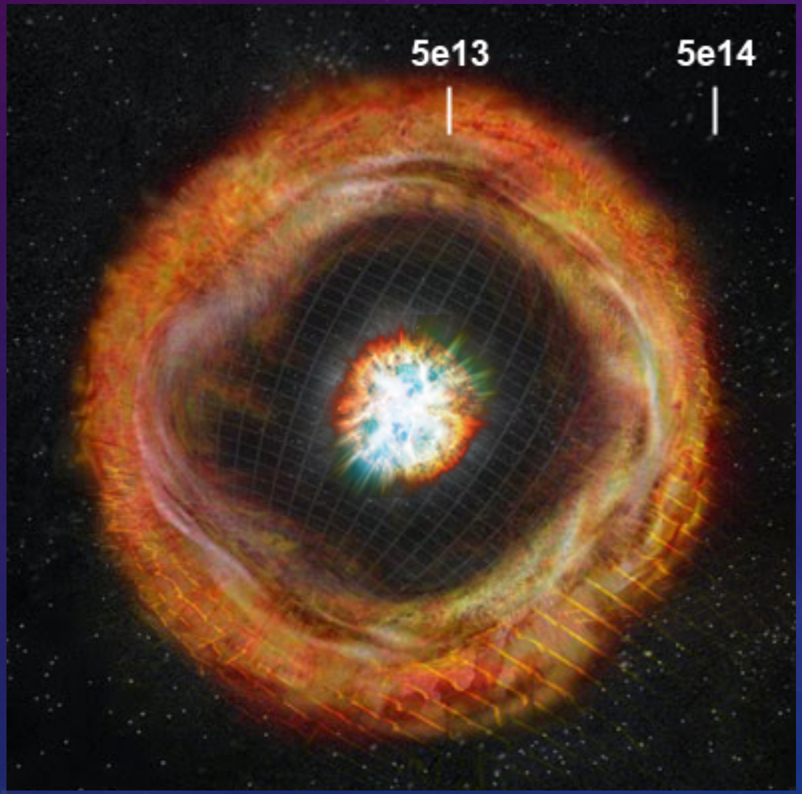
- SN precursor outbursts observed for Type IIn.
  e.g. **Precursor of SN 2010mc ejected 10^{-2} M_{Sun} at v~2000 km/s 1 month prior to SN** (Ofek et al. 2013)
- …and are likely common! >50% with at least 1 precursor brighter than M_{abs}~-14 and within ~100 days prior to SN. (Ofek et al. 2014)
- BUT… Pre-SN mass-loss is not limited to Type IIn. Early spectra (*Flash-Spectroscopy*) reveal CSM around various Type II SNe.

- Can all these serve as some evidence for a causal connection between mass-loss episodes and the final SN explosion…?
- How do the outer layers of a massive star "know" that it is about to explode? (or either "receive information" from the vigorous final burning stages taking place in the core…?)

What is *FLASH-SPECTROSCOPY*

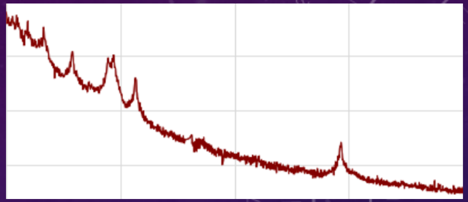


Flash ➤ Prompt & strong illumination

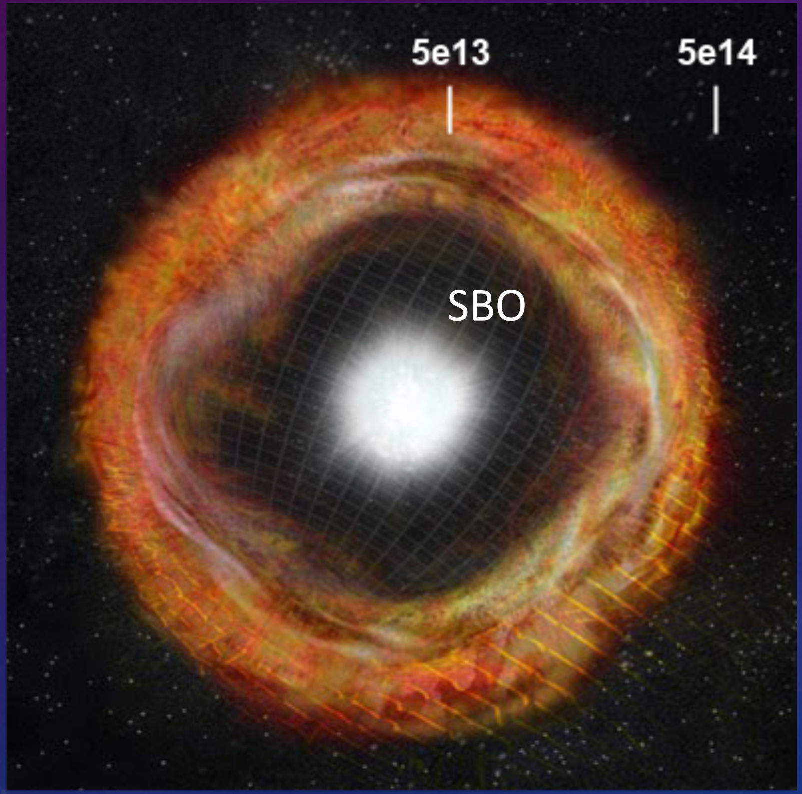


- Progenitor engulfed with a (relatively) optically thick wind / CSM (continuous or detached).

What is *FLASH-SPECTROSCOPY*

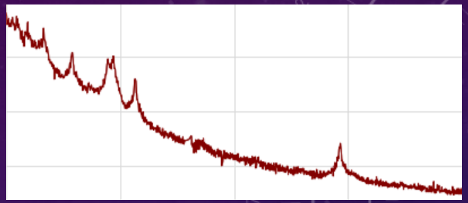


Flash ➤ Prompt & strong illumination

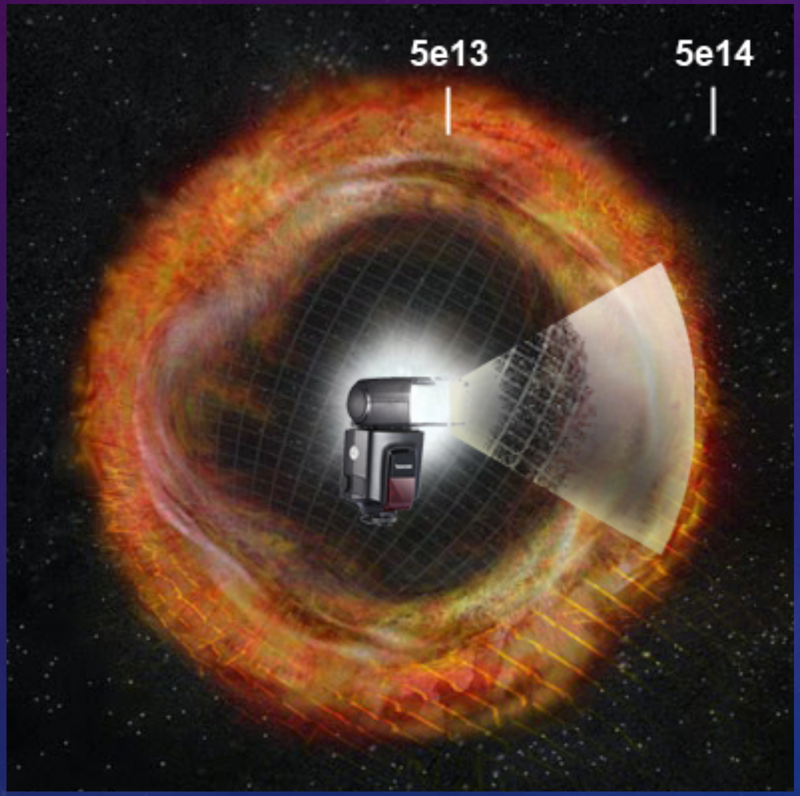


- Progenitor engulfed with a (relatively) optically thick wind / CSM (continuous or detached).
- Shock breaks out from the hydrostatic surface (or either in a surrounding optically thick wind).

What is *FLASH-SPECTROSCOPY*

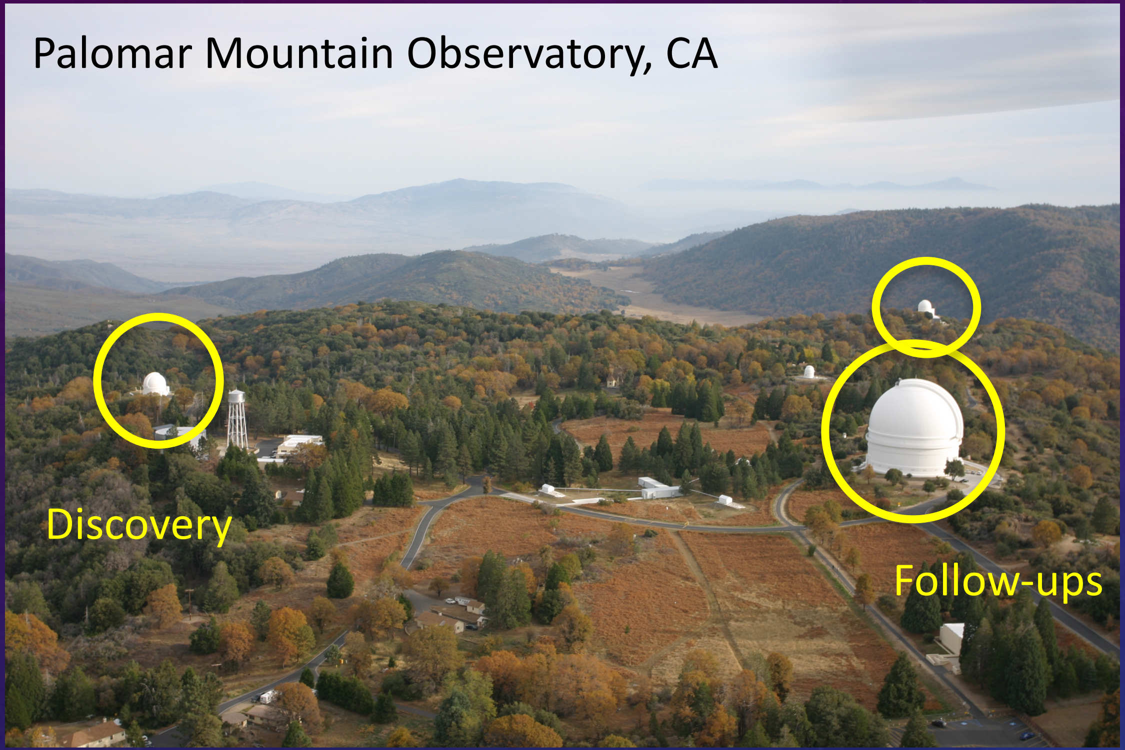


Flash ➤ Prompt & strong illumination

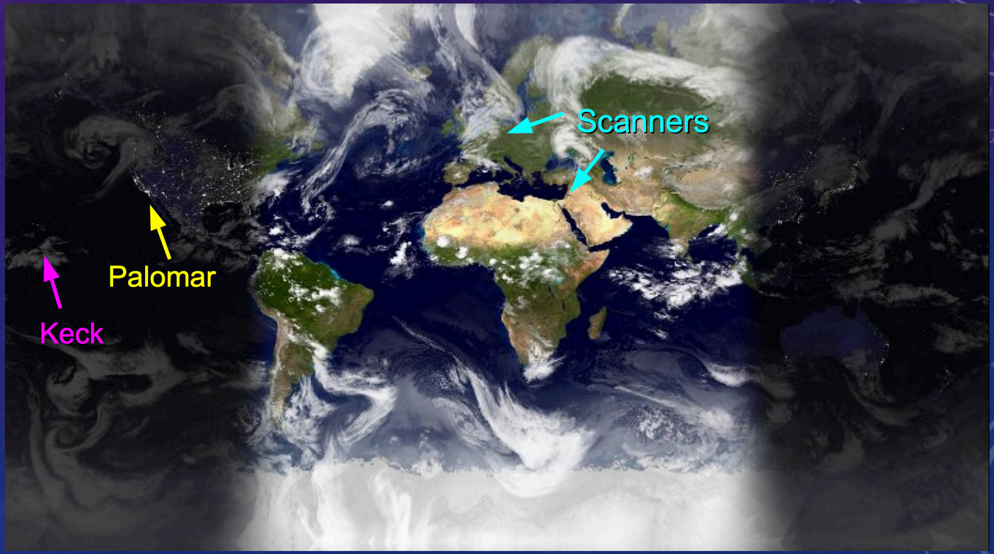


- Hot SBO flash ionizes the CSM.
- CSM reacts immediately to the strong radiation field.
- Recombination (min-hrs) ➔ narrow (CSM-velocity) emission lines. (Light crossing time may smear spectral evolution.)
- With typical v_{exp}~10,000 km/s, CSM swept by ejecta within a few days (~5 d till 5e14 cm).

PTF/iPTF was not only a powerful discovery machine



With human monitors at daylight in Europe during Palomar's night time ➔ Quick response to young SN candidates (alerting & triggering of follow-ups).

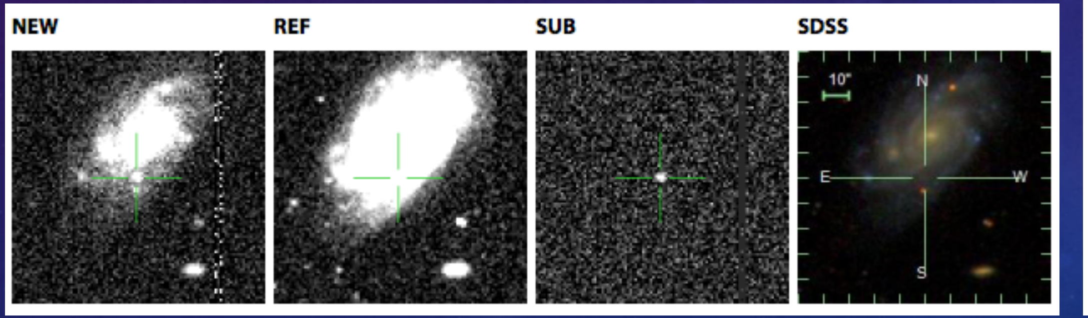


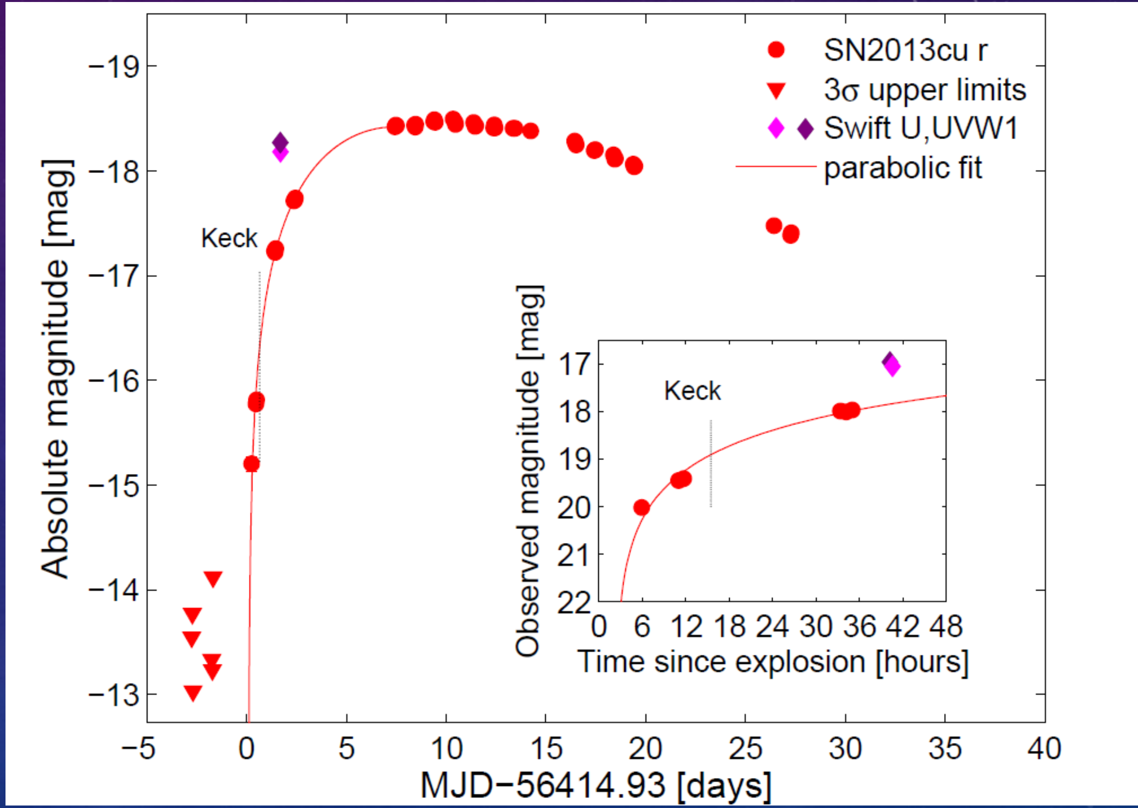
48" robotic telescope, wide-field ~7 deg^2 (~1500 deg^2 / night), 1-3 days cadence.

iPTF13ast (SN 2013cu)
A Flash-Spec event showing WR-like wind signatures

Gal-Yam et al. 2014

- Discovered May 2013 in UGC 9379, ~100 Mpc.
- Keck spectrum obtained 4 hr after photometric confirmation, ~15 hr after explosion.

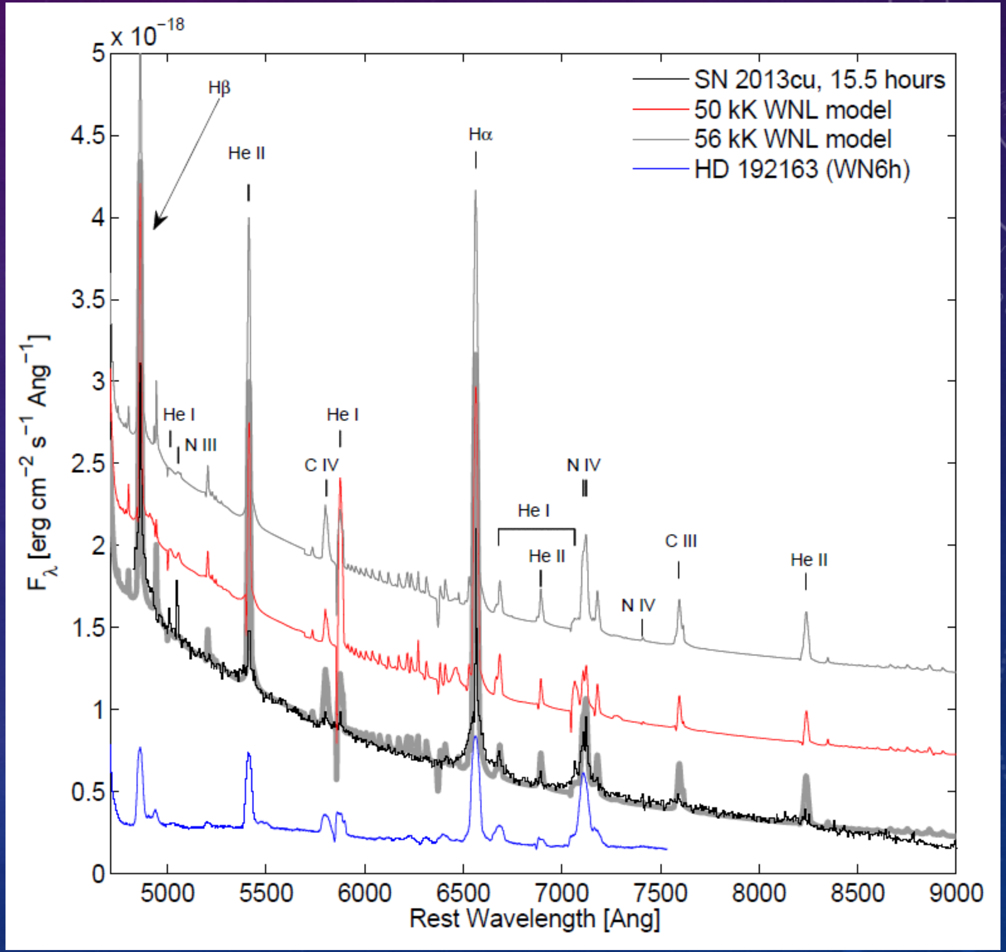




iPTF13ast (SN 2013cu)
A Flash-Spec event showing WR-like wind signatures

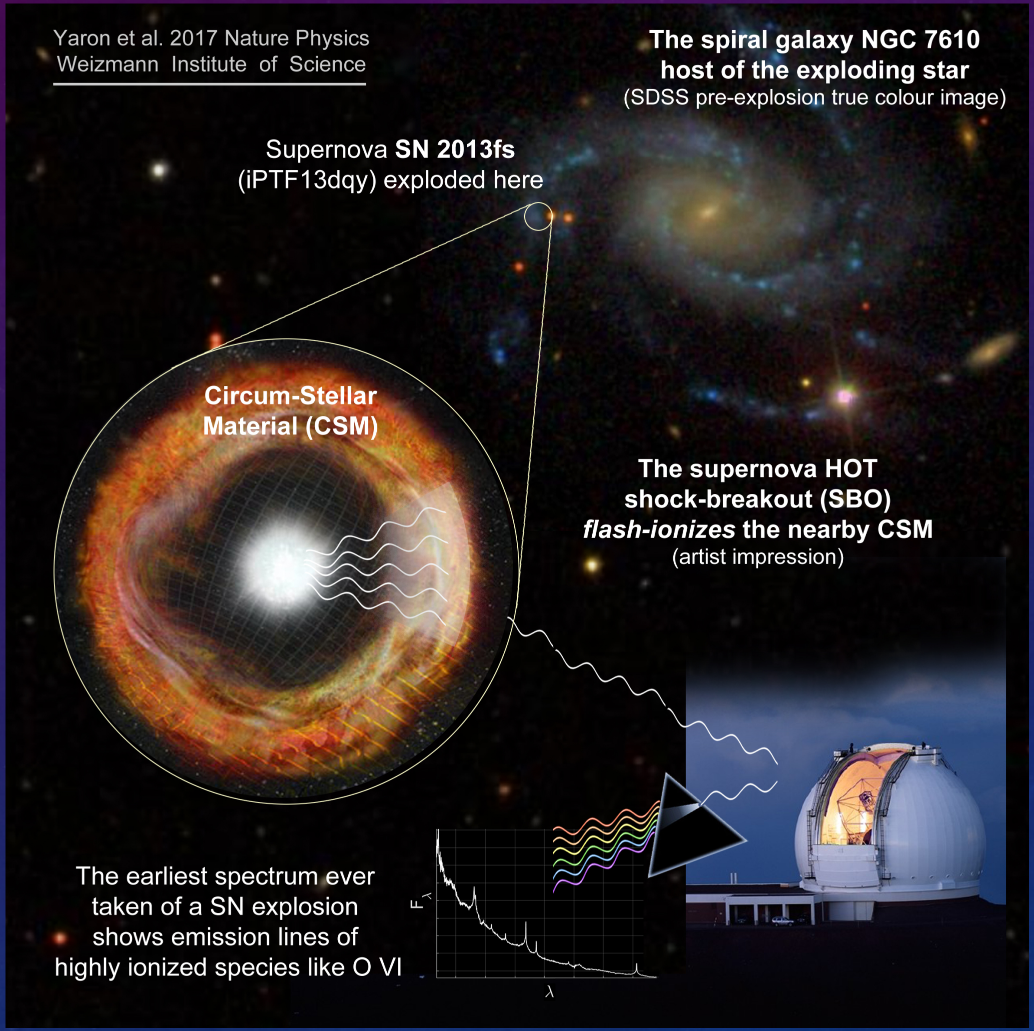
Gal-Yam et al. 2014

- Strong He II, N (N IV 7115) and Balmer lines indicate a WN6(h)-like classification.
- By day 6 the spectrum is featureless.
- Later spectra match prototypical Type IIb SNe (semi-stripped progenitor; low H envelope mass)
- From high Mdot, rel. low v_{wind} and chemical abundance, progenitor likely a LBV / YHG (Groh 2014)



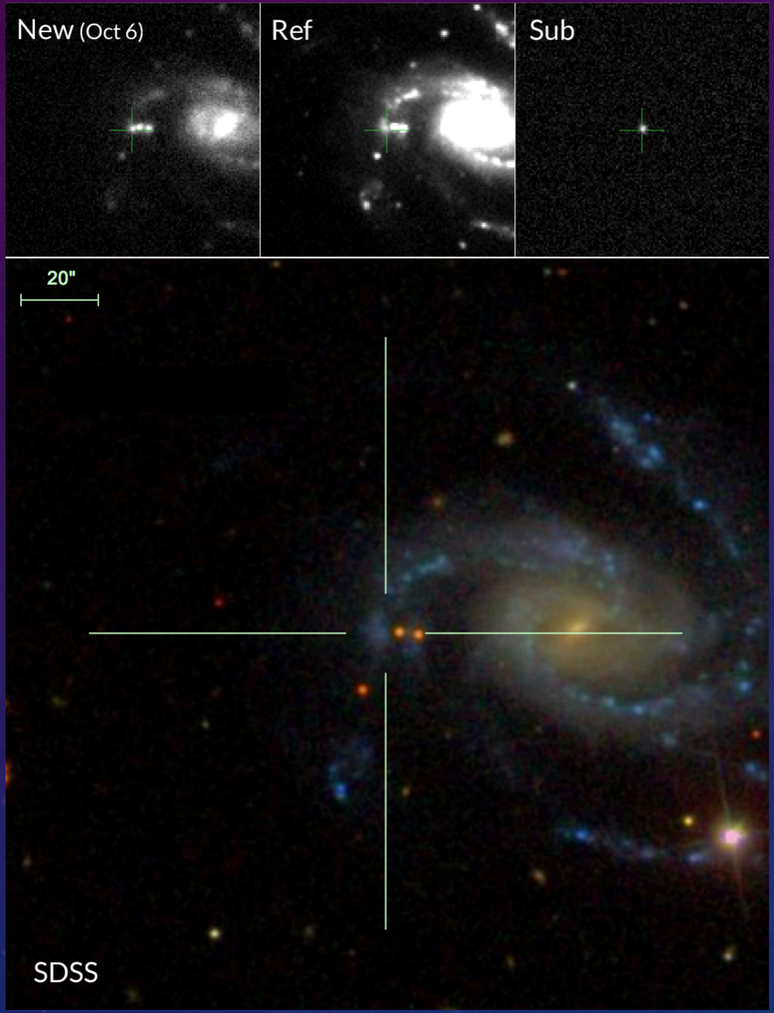
The story of iPTF13dqy = SN 2013fs

The earliest SN spectra ever taken…?

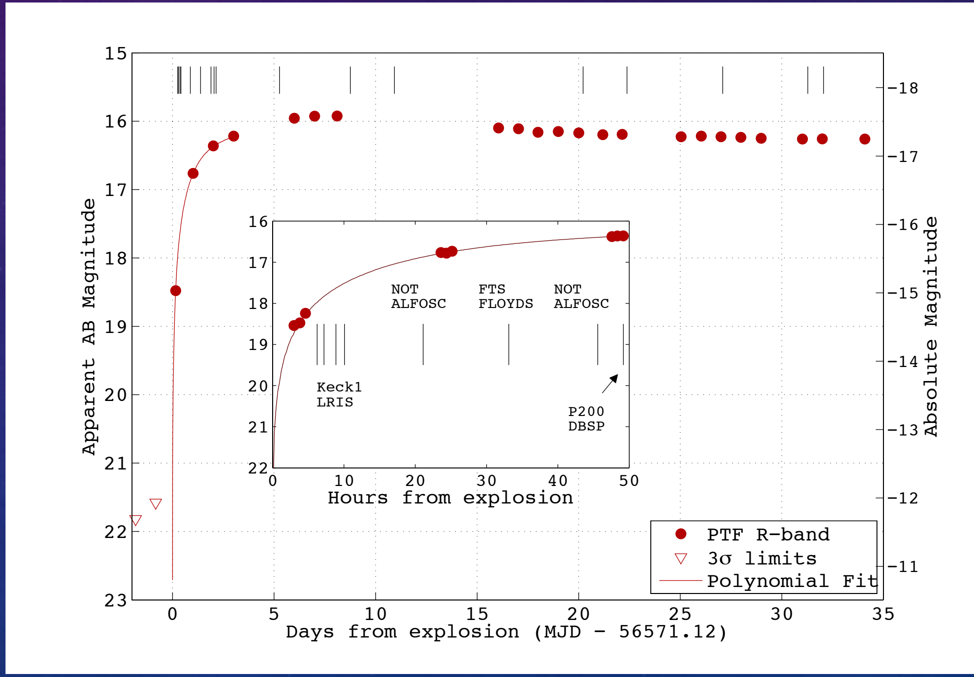


iPTF13dqy – Flash-Spec in its extreme

OY et al. 2017



- Discovery ~3 hr from explosion.
- A set of 4 Keck spectra between 6-10 hr.

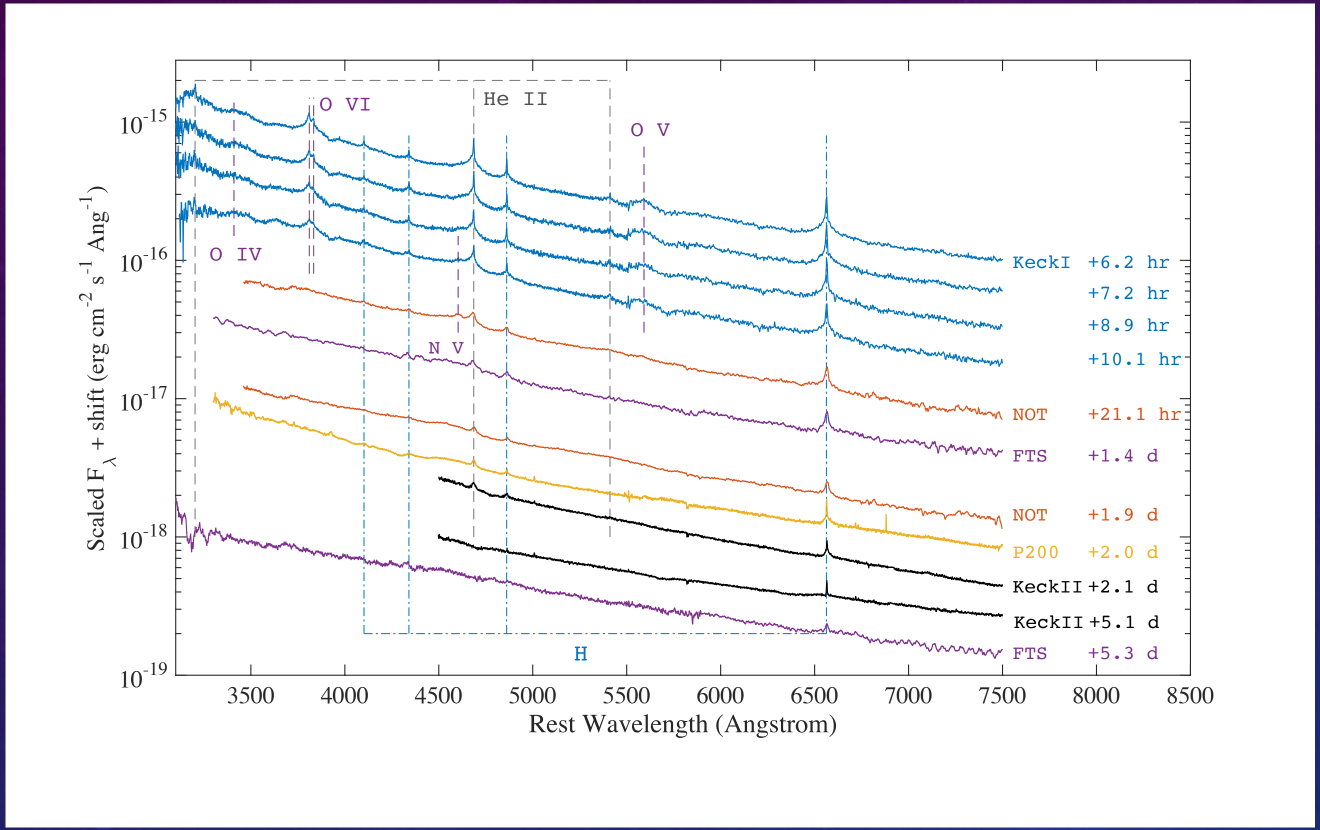


P48 R-band

iPTF13dqy – Flash-Spec in its extreme

OY et al. 2017

Early Spectral evolution (6 hrs to 5 d)



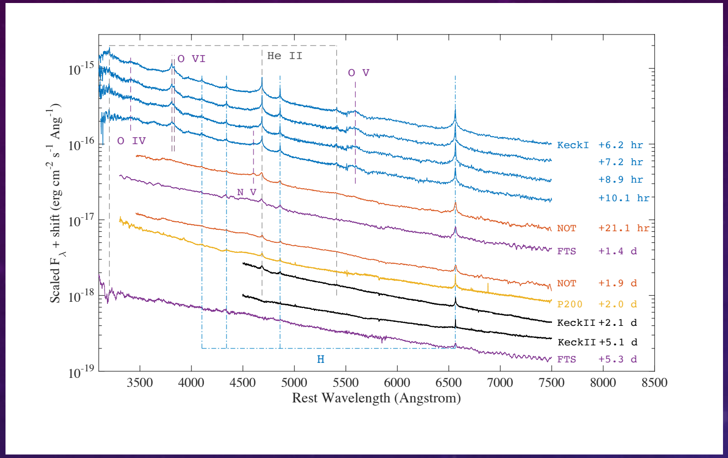
- High-ionization emission lines (O VI) dominate during the first 10 hrs.
- He II persists till ≥ 2 days.
- Lines gradually disappearing till a Blue/Featureless spectrum by day 5.

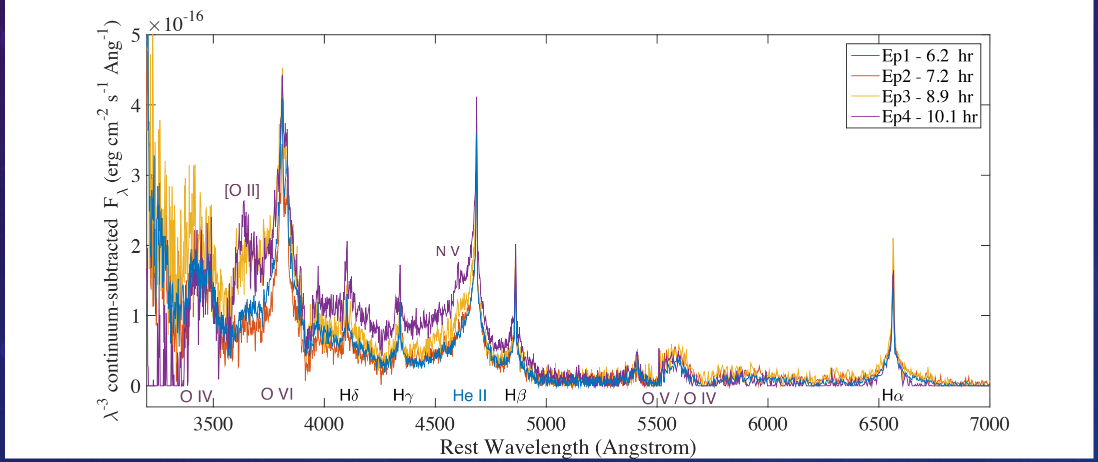
So… assuming $v_{CSM} \leq 100$ km/s, SN ejecta ~ 10^4 km/s, CSM swept within 5 d → CSM was emitted from progenitor within ~500 d before explosion (v_{CSM} dependent), and is confined within $\leq 5 \times 10^{14}$ cm.

iPTF13dqy – Flash-Spec in its extreme

OY et al. 2017

Early Spectral evolution (6 hrs to 5 d)



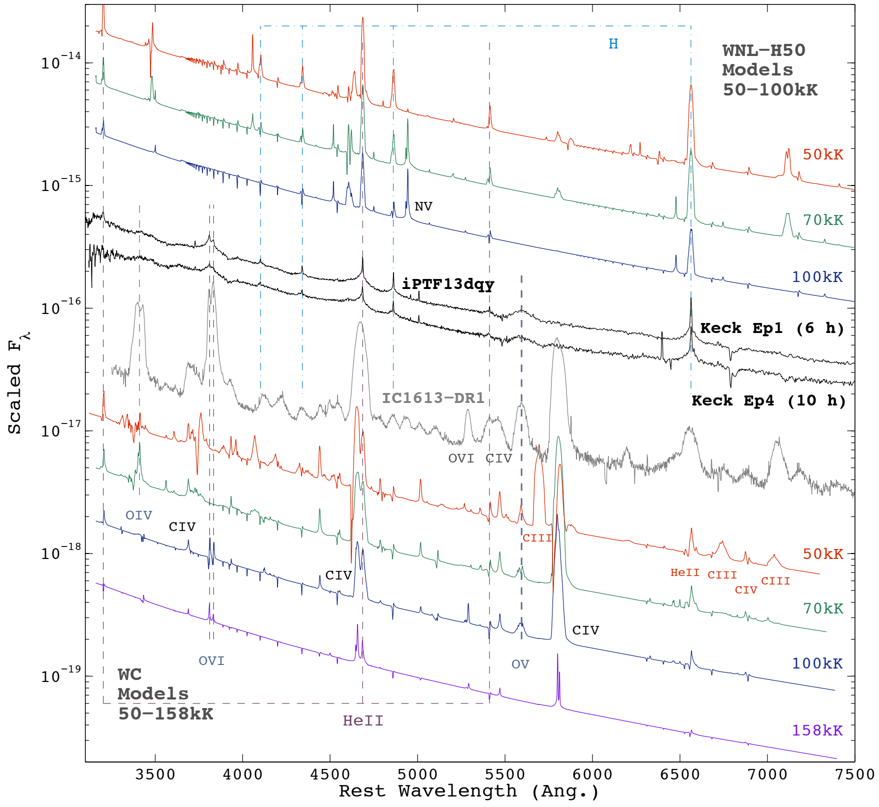


6-10 hr Keck spectra, continuum subtracted

- High-ionization emission lines (O VI) dominate during the first 10 hrs.
- He II persists till ≥ 2 days.
- Lines gradually disappearing till a Blue/Featureless spectrum by day 5.
- Light-crossing time effects, yet further constraining CSM extent.

$4 \times 10^{14} \leq r \leq 2 \times 10^{15}$

iPTF13dqy – Beginning HOT!

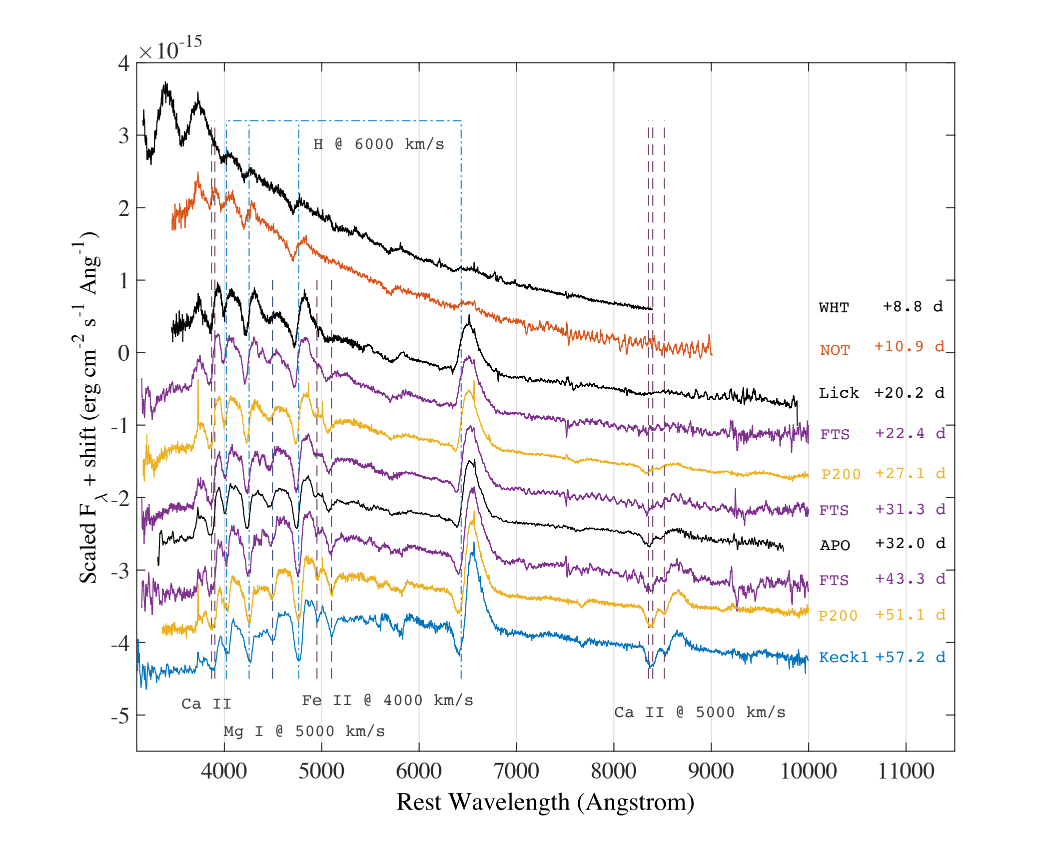


Comparison to models of Wolf-Rayet families (POWR)

iPTF13dqy – Later data reveal a "regular" Type II(P)

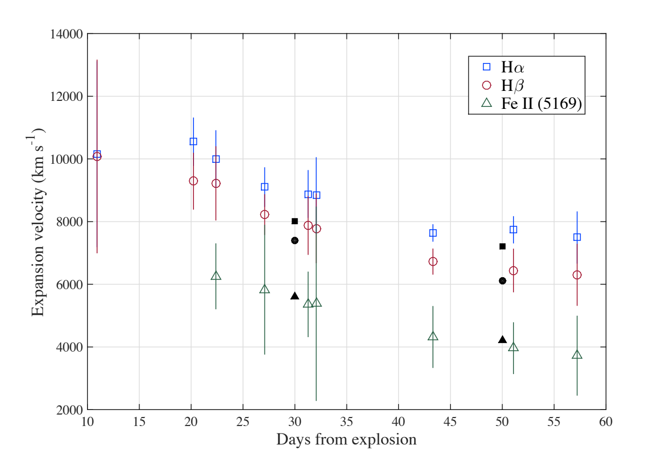
OY et al. 2017

Later Spectra (days 8 - 57)



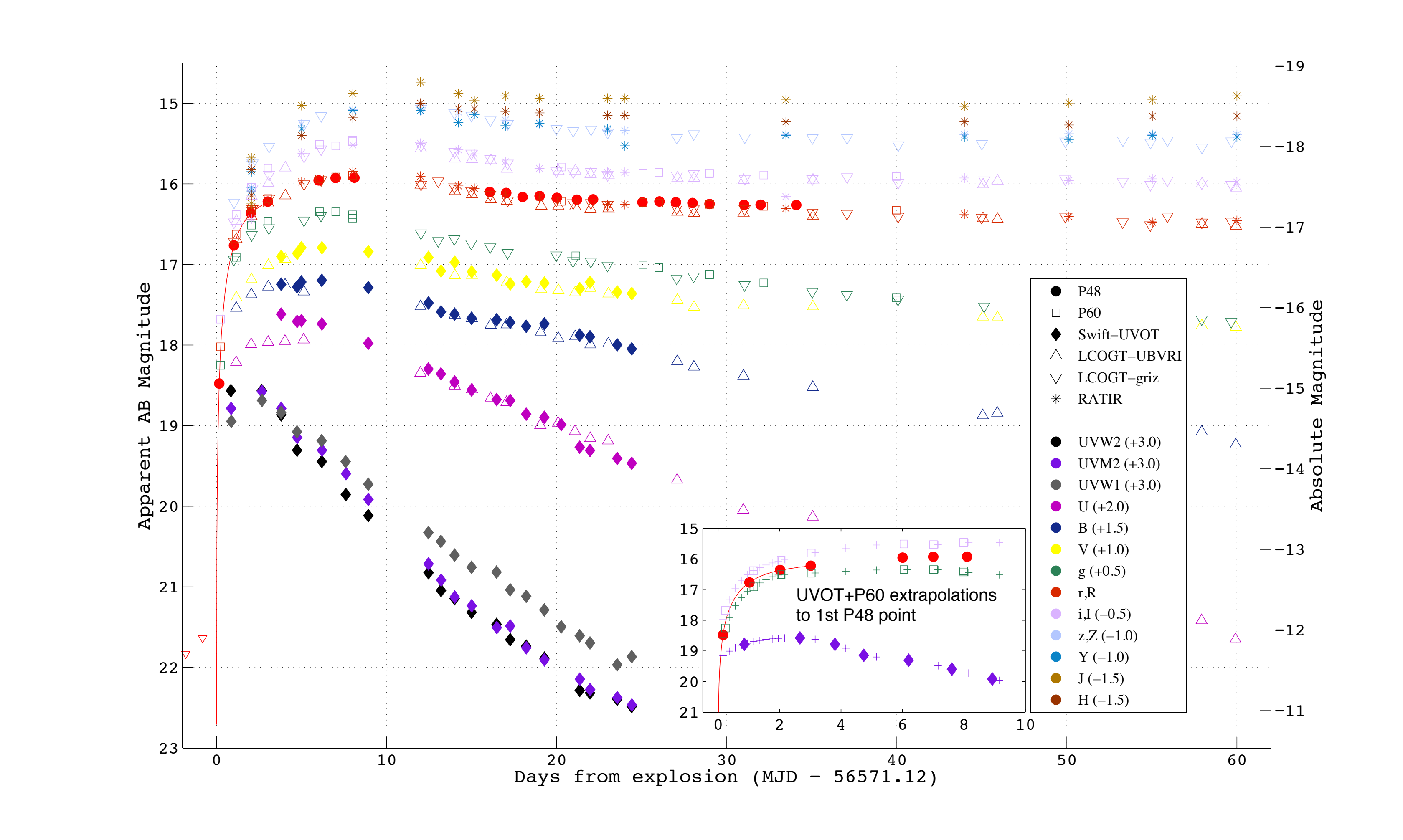
- Developed P-Cygni lines.
- Spectra consistent with typical Type II.
- As well as the expansion velocity evolution.

Black markers: the expansion velocities of the standard Type II-P SN 2004et at days 30 and 50 .

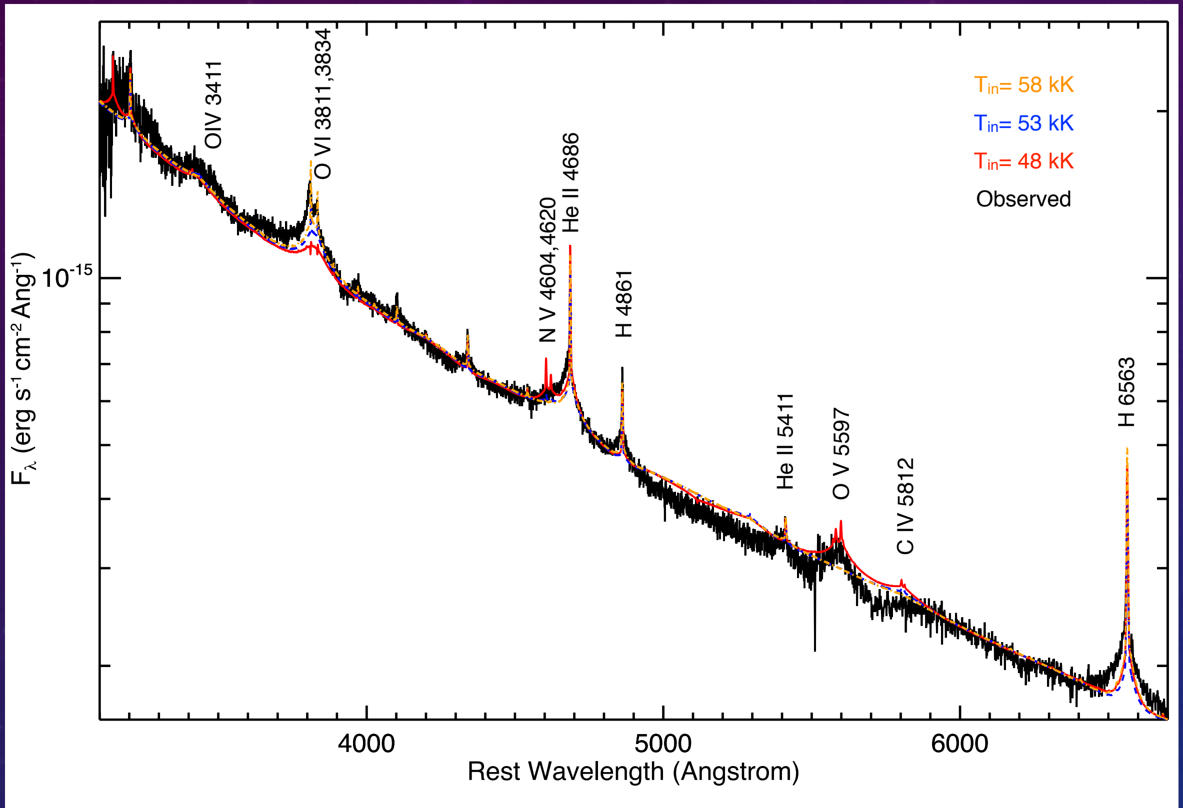


iPTF13dqy – Later data reveal a "regular" Type II(P)

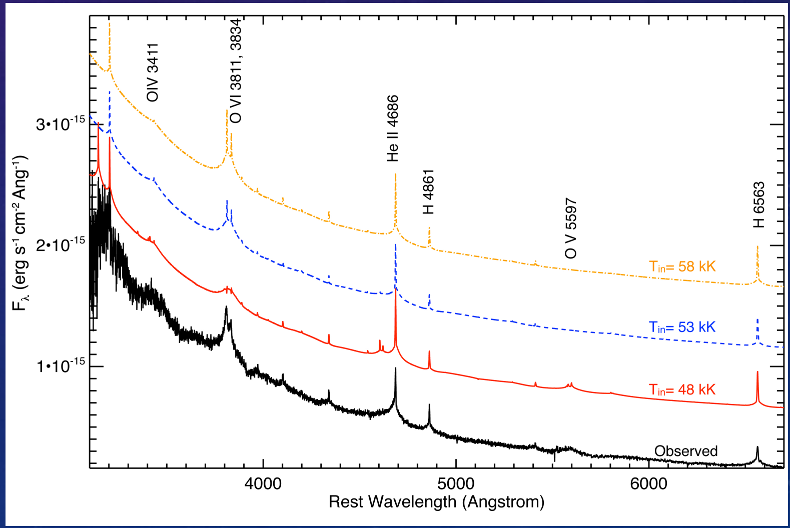
OY et al. 2017



iPTF13dqy – CMFGEN modeling of the early spectra



The three model spectra bracket the observed early spectrum; the 53kK model (dashed blue) best recovers the oxygen ionization structure.

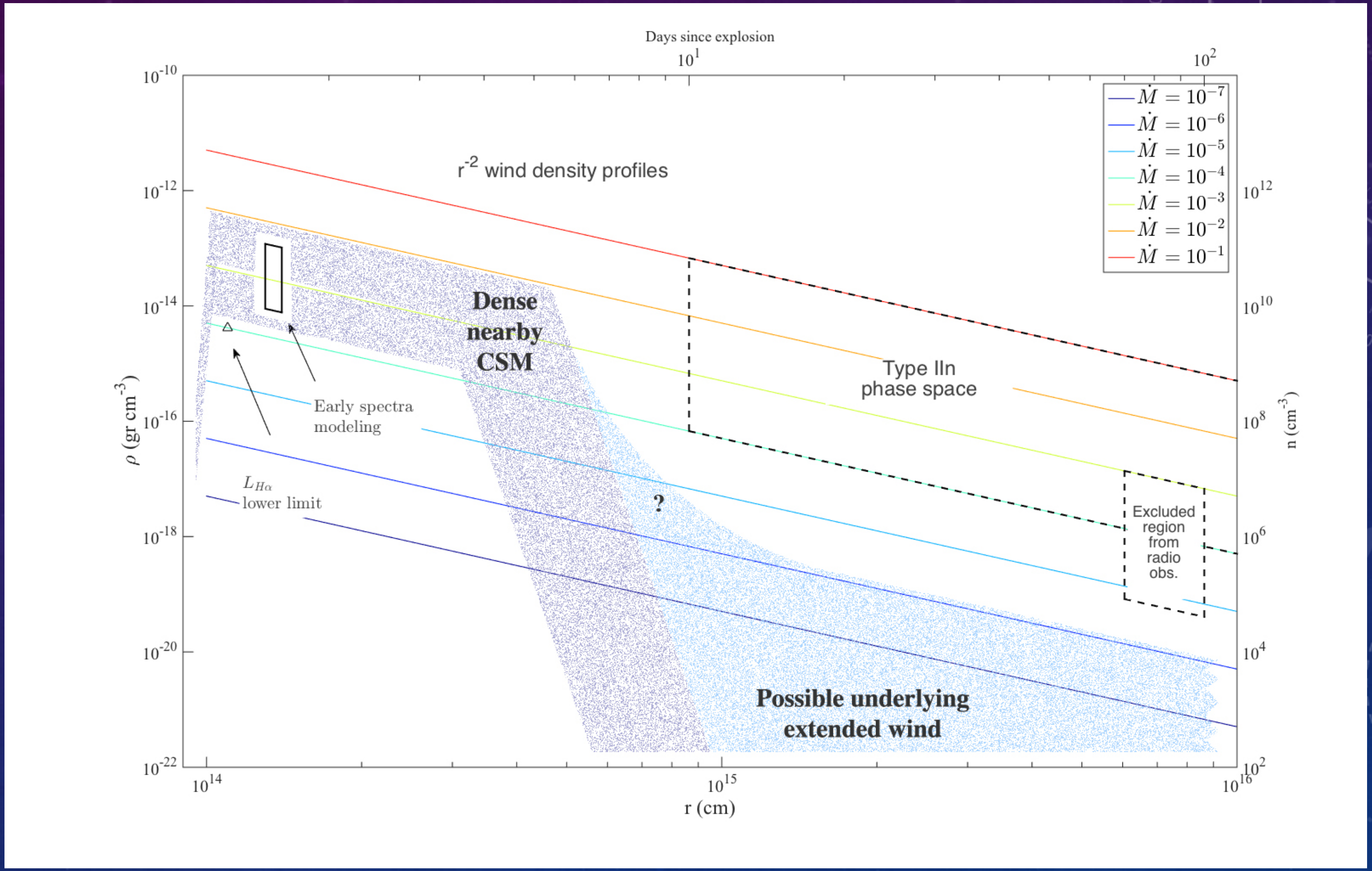


➔ Mdot = (2-4) x 10^{-3} (v_w=100 km/s) OR…
Mdot = (3-6) x 10^{-4} (v_w=15 km/s)

R_{in} ~(1-2) x 10^{14} cm

Concluding the characterization of the CSM & MLR

Our multi-wavelength observations require a nearby+confined CSM density profile!



Colored diagonal lines:

Constant Mdots - 10^{-7} to 10^{-1} following:

$$\rho_w = Kr^{-2} = \mathrm{Mdot}/4\pi v_w r^2$$

Motivated by the findings of iPTF13ast/13dqy…

How common are flash ionized early spectra?

- PTF/iPTF sample 2009-2014.
- 103 CC-SNe, 84 of Type II, having a first spectrum within 10 days from the time of the SN pre-explosion limit.
- FI (Flash-Ionized) spectra all show Hα, Hβ and prominent He II λ4686 (by systematic EW measurement criterion).

Results

- All Flash-Ionized spectra found (12) are of Type II.
- Within 2 days from explosion, 8/11 SNe are FI or BF.
- Within 5 days from explosion, 20% of the Type II show FI.
- These FI fractions are a lower limit!

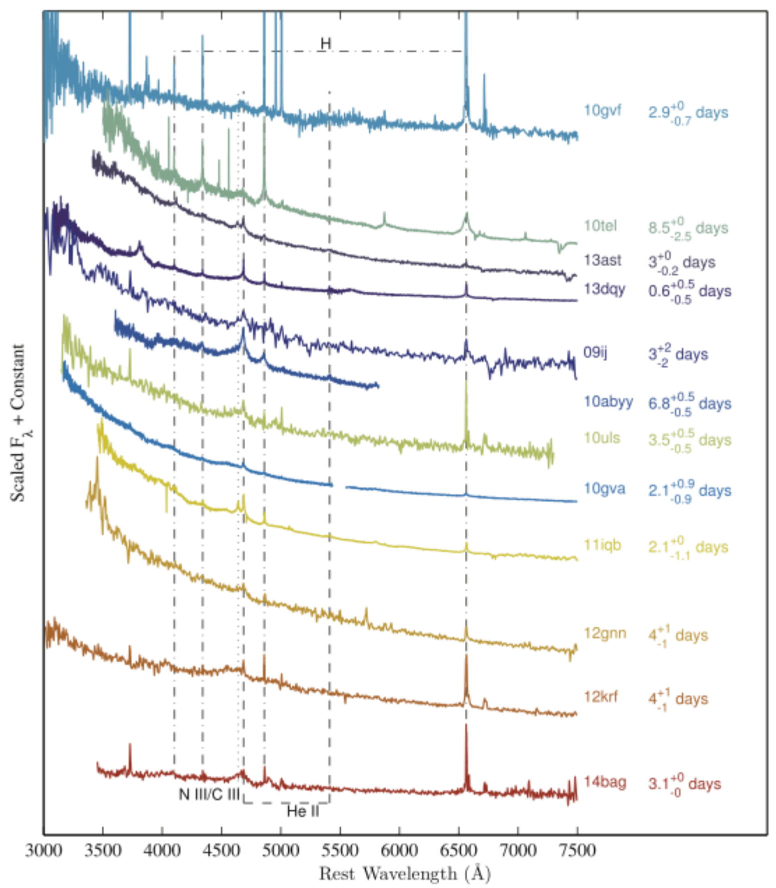


Figure 3. Spectra of our 12 FI events. On the right: an estimate of the age of the SN, with respect to the estimated explosion time (see the Appendix for details).

Khazov, OY, Gal-Yam et al. 2016

How common are flash ionized early spectra?

- SN 2014G – A canonical type II-L showing *FI* spectra for > 3 days. Terreran et al. 2016

Comparison of SN 2014G to WR-WN star and to SN2013cu, SN1998S

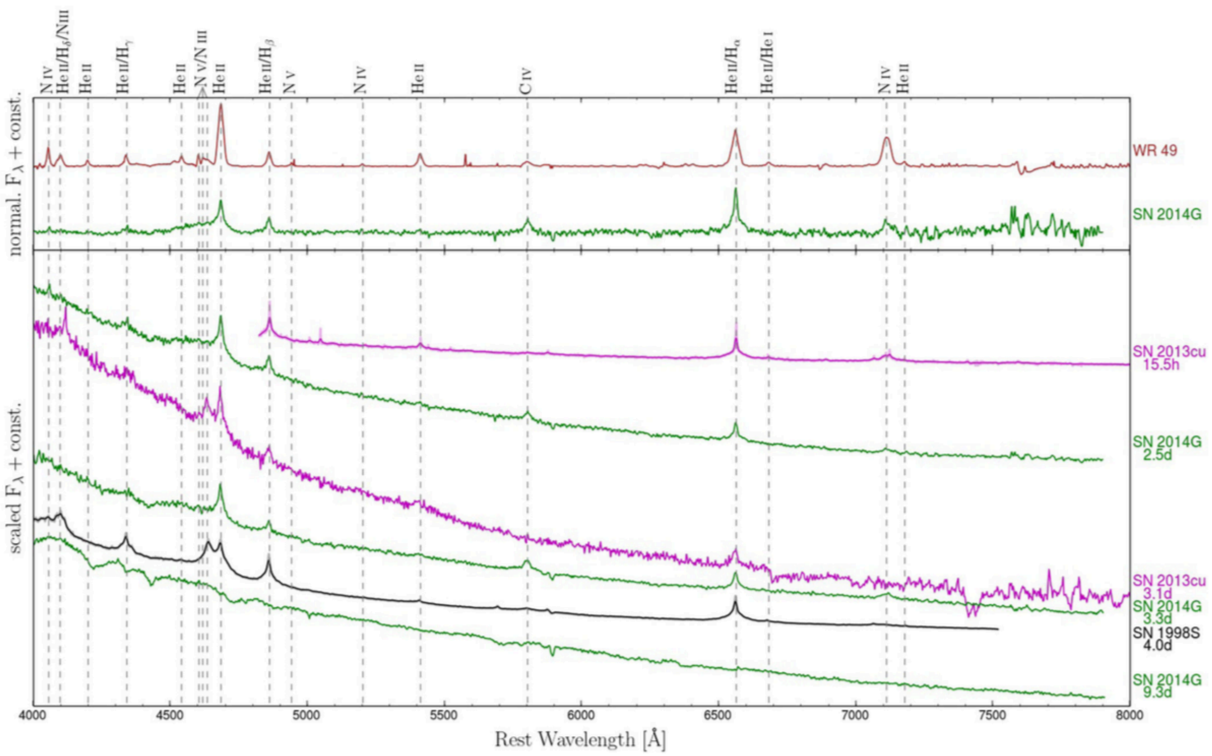


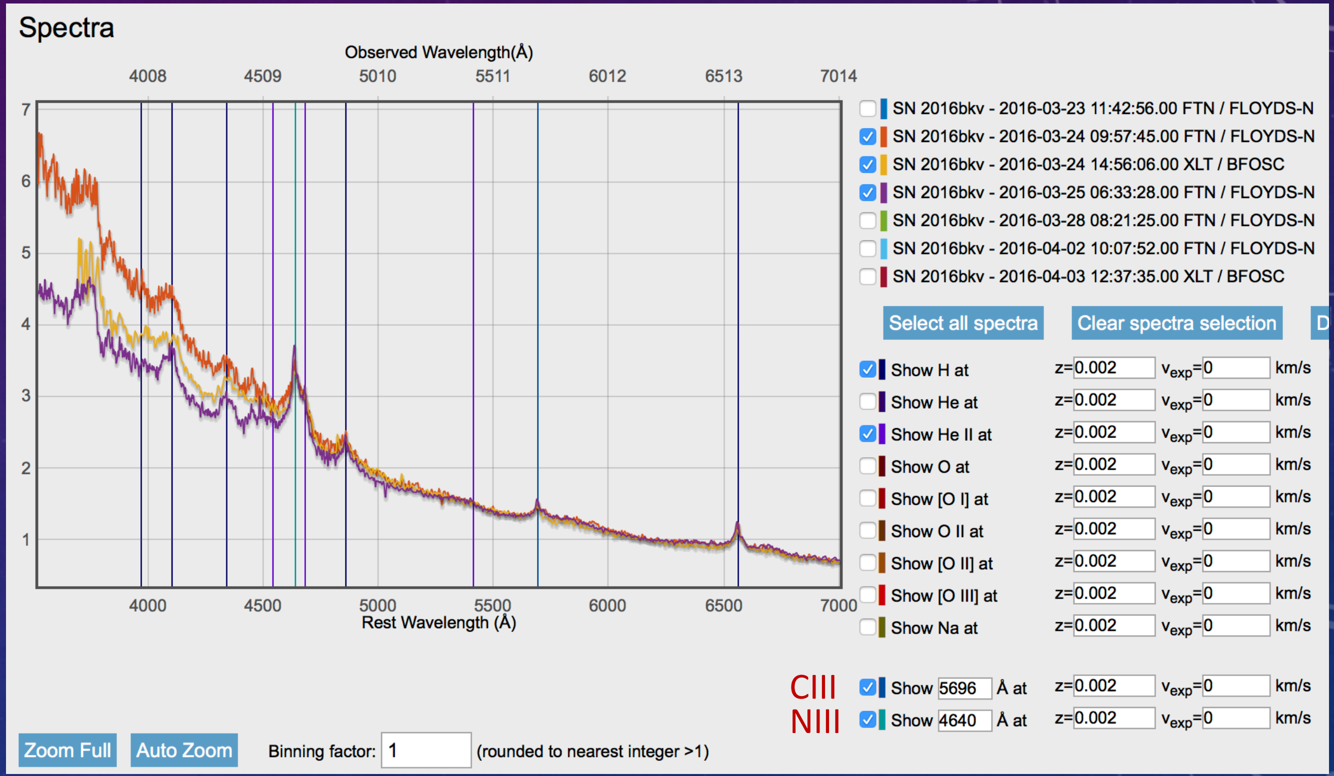
Figure 6. Top panel: comparison between the normalized classification spectrum of SN 2014G and the WR star WN 49 (Hamann-R., Koesterke & Wessolowski 1995). Bottom panel: comparison of early-phase spectra of SN 2014G with those of SNe 1998S (Leonard et al. 2000) and 2013cu (Gal-Yam et al. 2014). The spectra of the two latter SNe were taken with a high-resolution spectrograph, so a Gaussian smoothing has been applied in order to match the resolution of the spectra of SN 2014G. Moreover, the spectra have been scaled for better comparison.

How common are flash ionized early spectra?

- SN 2014G – A canonical type II-L showing *FI* spectra for > 3 days. Terreran et al. 2016

- Late-stage enhanced mass-loss may also be common among progenitors of Low-Luminosity type IIP SNe; SN 2016bkv - Hosseinzadeh et al. 2018

Early spectra (3-5d) of SN 2016bkv with lines of H, HeII, CIII, NIII over-plotted



Screenshot taken from the **NEW WISeREP v2.0**
https://wiserep.weizmann.ac.il

A plethora of theoretical studies to explain pre-SN outbursts/mass-loss

e.g.

- Wave heating - Convectively driven hydrodynamic waves during late nuclear burning phases (core Ne/O…) able to deposit considerable energy in the envelope layers (Quataert & Shiode 2012, S&Q 2014)
- Wave-induced mass ejection models by Fuller 2017 predict large - but not extreme - MLRs: $10^{-3} - 1$ Msun/yr, and velocities <~ 100 km/s, like estimated for SN2013fs.
- The various models produce non-hydrostatic pre-SN envelope configurations (density profiles) that are different from our prior expectations, therefore should affect fits to shock-cooling models etc…

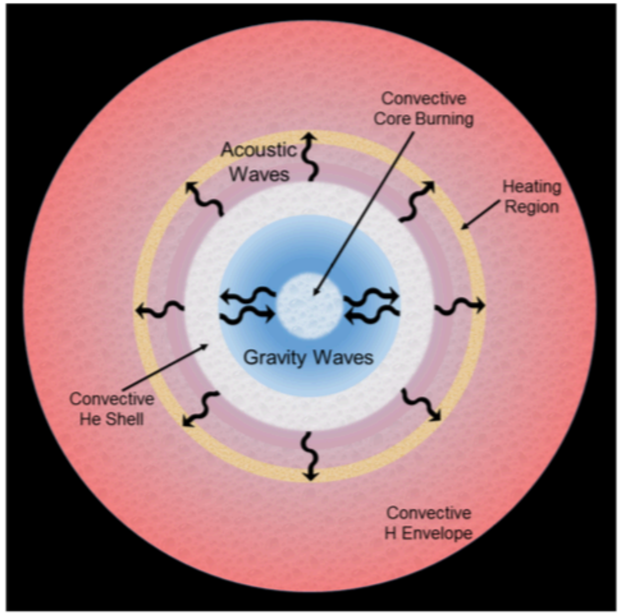
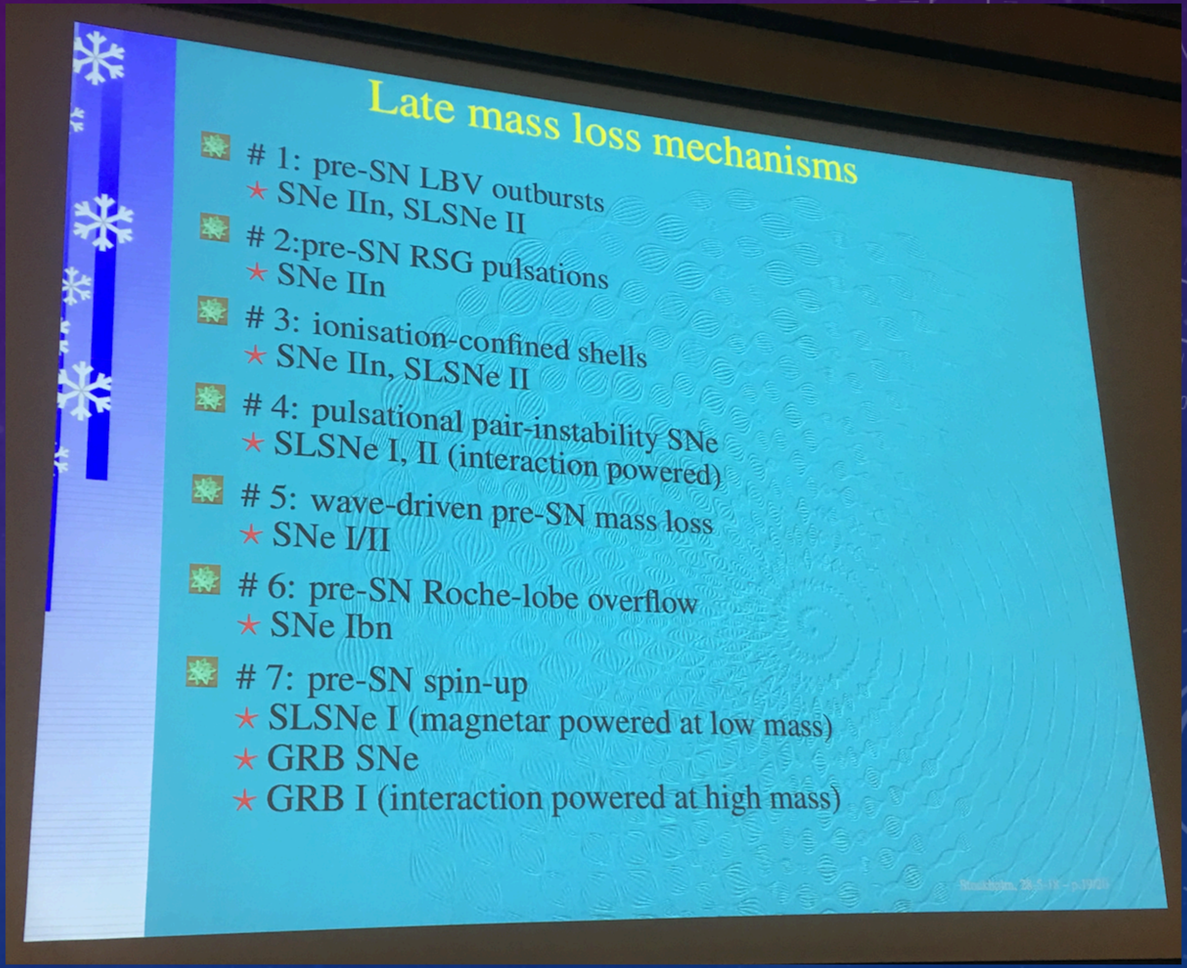


Figure 1. Cartoon (not to scale) of wave heating in a red supergiant. Gravity waves are excited by vigorous core convection and propagate through the outer core. After tunnelling through the evanescent region created by the convective He-burning shell, they propagate into the H envelope as acoustic waves. The acoustic waves damp near the base of the envelope and heat a thin shell.

Jim Fuller 2017

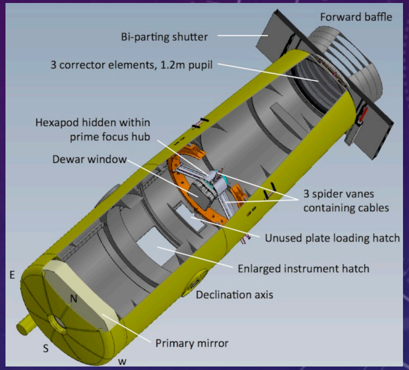
A plethora of theoretical studies to explain pre-SN outbursts/mass-loss

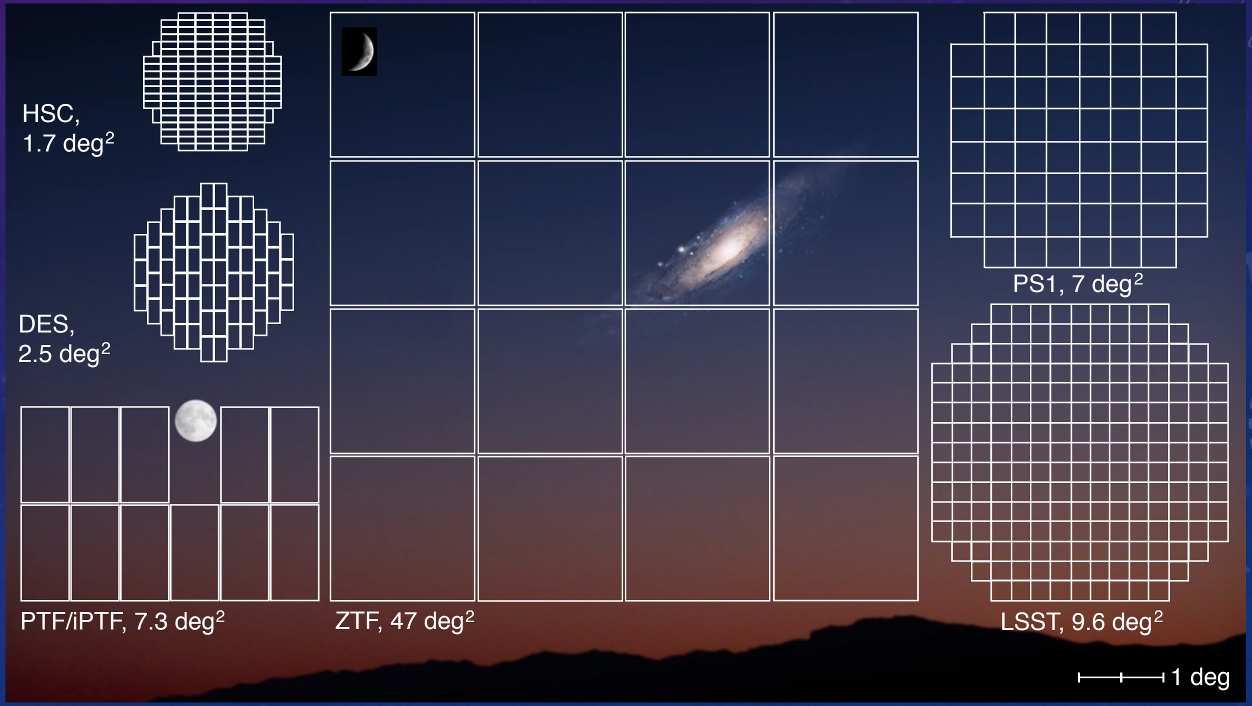
A list presented by Norbert Langer at the Stockholm meeting in May 2018



The ZTF - Zwicky Transient Facilty - Survey

- Palomar 48-inch with reworked optics, huge camera – 47 deg^2 FOV
- 40% public, 40% partnership, 20% Caltech
- x10 over iPTF in volumetric survey speed
- Covering entire northern sky every ~3 days
- 1-day partnership cadence (2-3 visits/night)
- Dedicated low-res spectrograph (SEDM) on the P60…

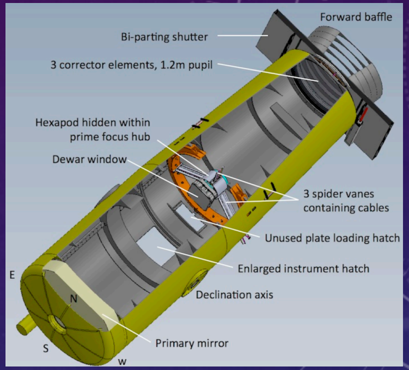


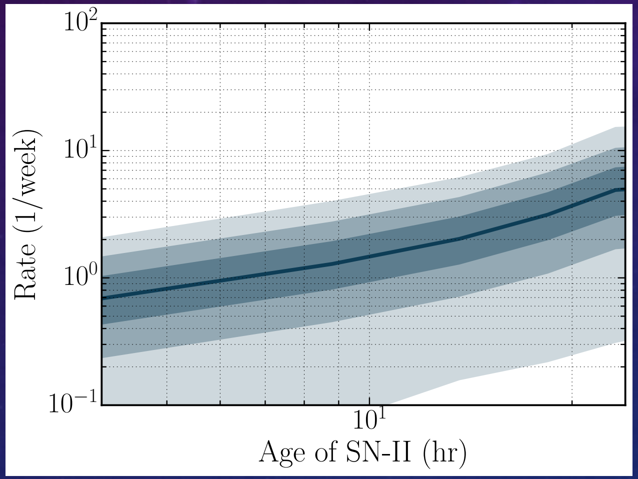


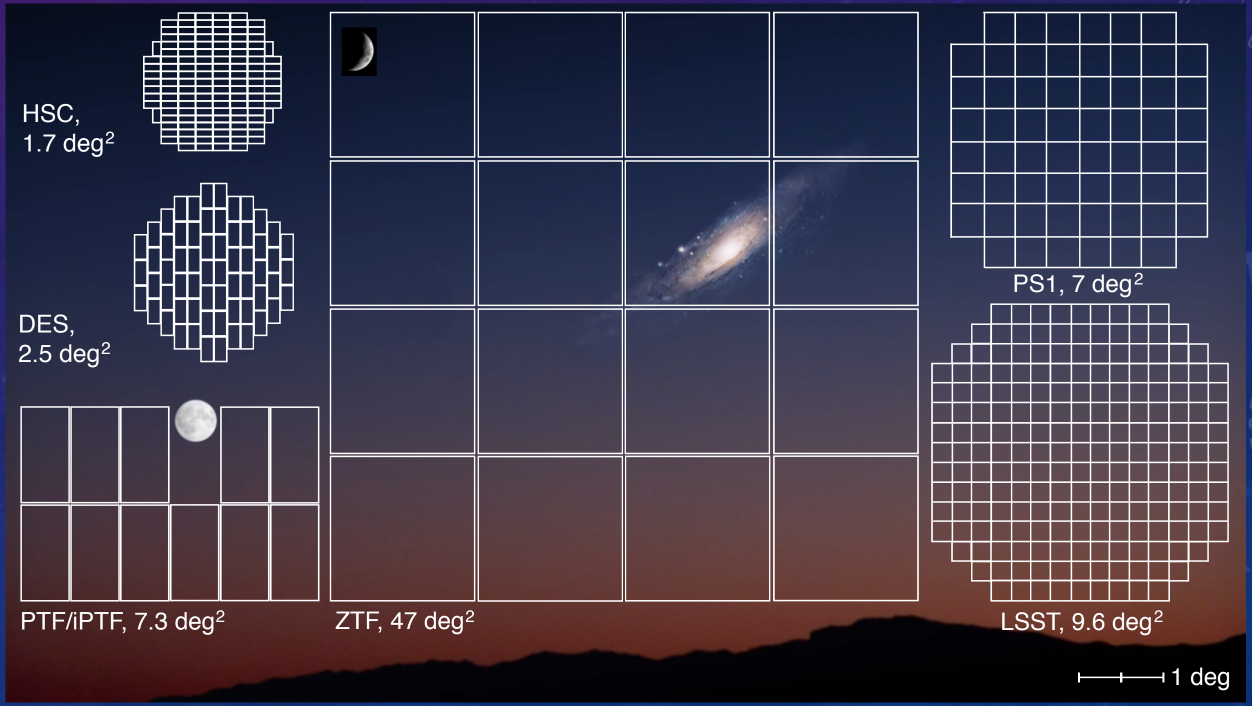
The ZTF - Zwicky Transient Facilty - Survey

- Infant SNe expected rate:

1-a few young (<1 day old) Type II SNe per week (to 20 mag)

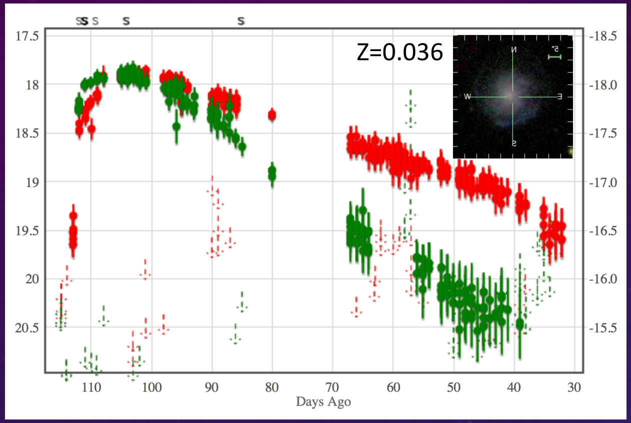




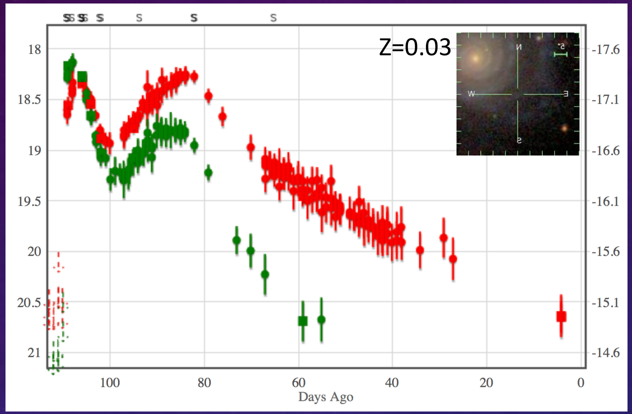


ZTF Type II SNe "Flash" events

ZTF18abeajml – SN2018dfc 1-d lim

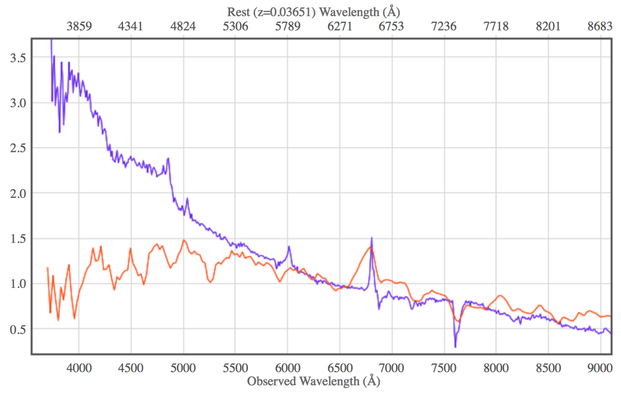


ZTF18abffyqp – SN2018dfi   1-d lim

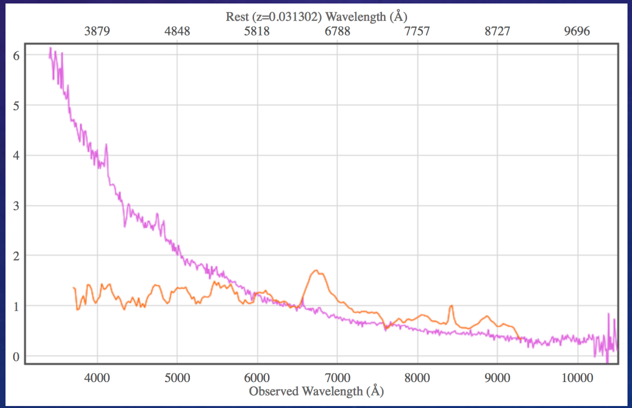


Examples of well-sampled LCs (P48 g,r) of classified Type II SNe with tight non-detection limits, showing "flash" early spectra (He II 4686, C IV 5801, N V 4604…).

WHT, P60-SEDM spectra – days 2,28

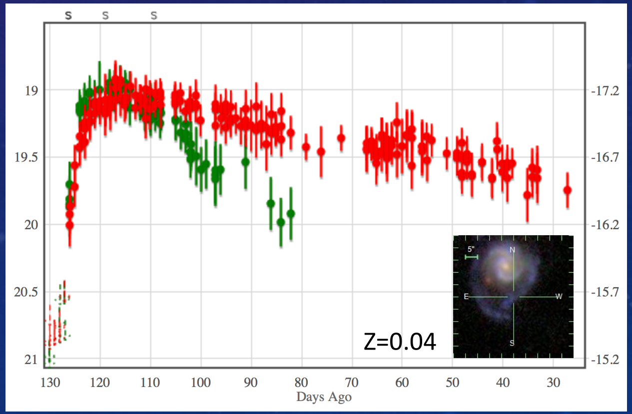


P200, P60-SEDM spectra – days 1,27



We also have examples of young Type IIs with early spectra **NOT** showing flash features.

ZTF18abckutn– SN2018cxn 1-d lim



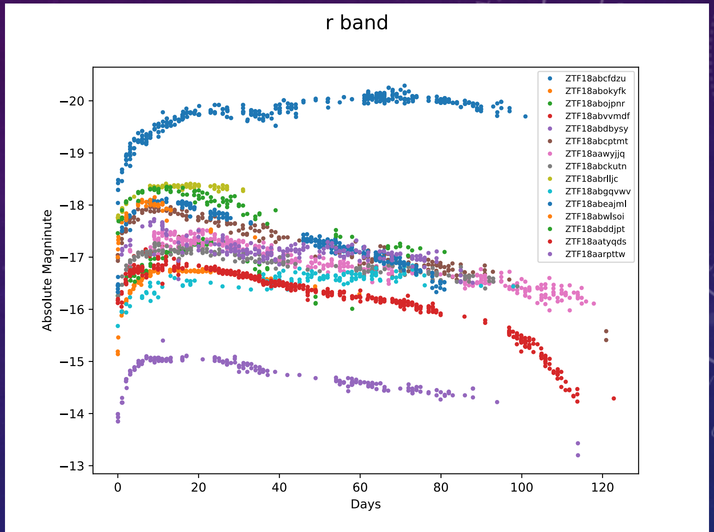
ZTF Type II SNe "Flash" preliminary numbers

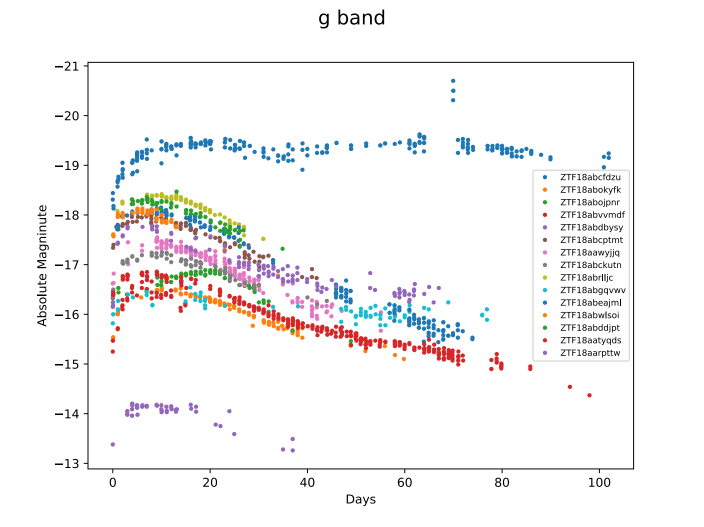
Within partnership survey (Mar-Oct 2018)

- Total no. of infant (<=2.5 days limits) Type II SNe : ~30

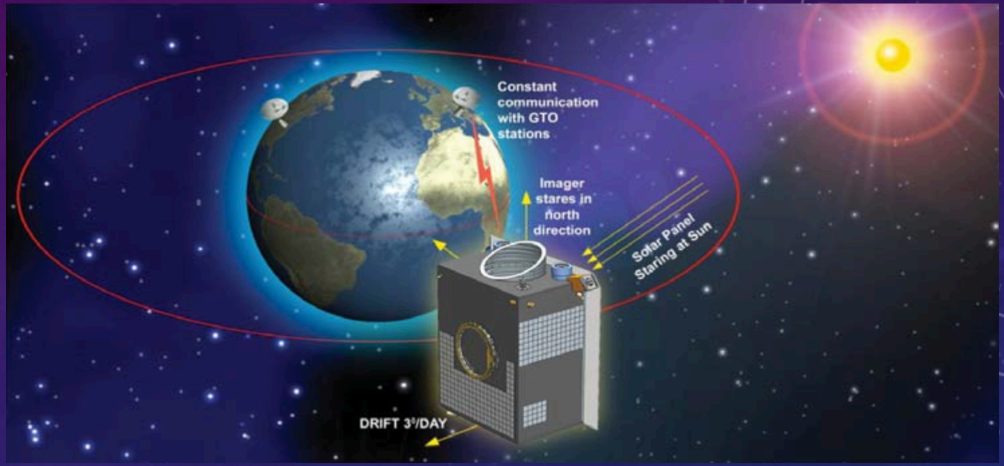
- Having an early spectrum (within 7 d from Non-Det): 14 (47%)
- Of those - early spectrum showing *Flash*: 7 (50%)
- Of those - early spectrum showing *B/F*: 2 (14%)
- Of those - early spectrum showing *Other*: 5 (36%)

- Having an early spectrum (within 2 d from Non-Det): 11 (37%)
- Of those - early spectrum showing *Flash*: 7 (63%)
- Of those - early spectrum showing *B/F*: 1 (10%)
- Of those - early spectrum showing *Other*: 3 (27%)



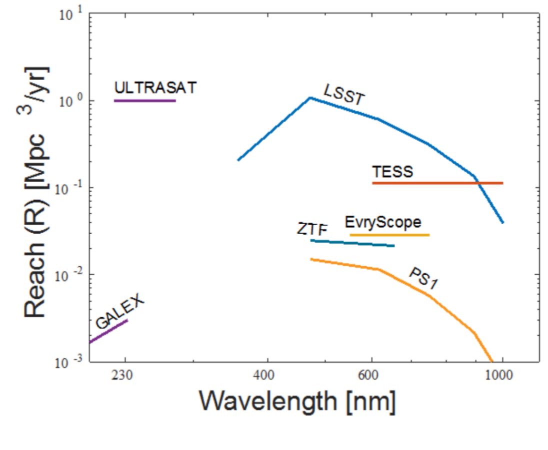


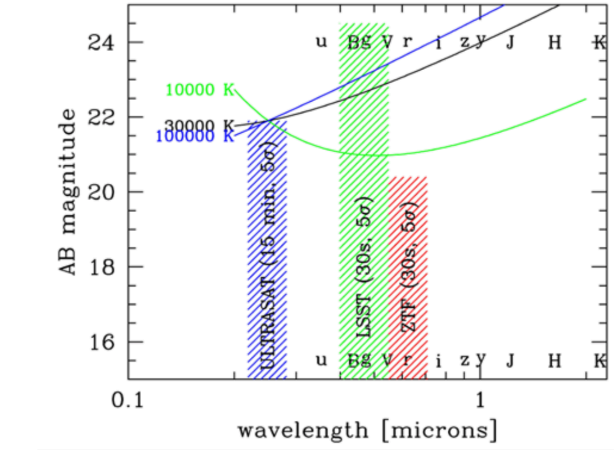
What to expect in the coming years



ULTRASAT – proposed wide-field UV satellite

- FOV > 200 sq. deg.
- Opening a new band (NUV, 220-280nm) and a new temporal cadence (1.5 min) not accessible to any other survey.
- Main science goals:
  - Shock breakout and early shock cooling of CC-SNe.
  - Emission from GW events – NS-NS, NS-BH.
- Also: BlackGem, LSST…





To conclude, take-home messages

- We have entered an era of < day 1 SN science - discovery and response.
- Early spectroscopy of CC-SNe:
  - Directly probes the progenitor's ejecta/envelope composition,
  - Constrains the progenitor's late mass-loss history,
  - Thus… placing important constraints on the final stages of massive star evolution… as well as providing new sets of initial conditions for explosion models.
- Episodic enhanced mass-loss by massive stars just prior to their terminal explosion, as proposed by several theoretical studies, occurs also among the progenitors of common types of CC-SNe.
- A high rate of early discoveries and prompt follow-ups of Type II SNe will help us answer what fraction of CC-SNe show flash features within the first few days? …shedding light on the possible interpretations of flash-spectroscopy and the possible origins of the CSM.
- The nearby future will be illuminating (hectic?)… *Flash-Spectroscopy* events are NOT RARE, thus application of this method to future observations and samples is a promising prospect.

Thanks