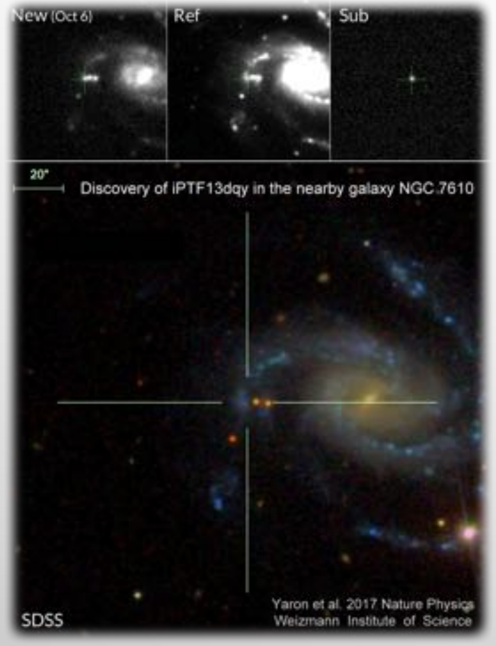
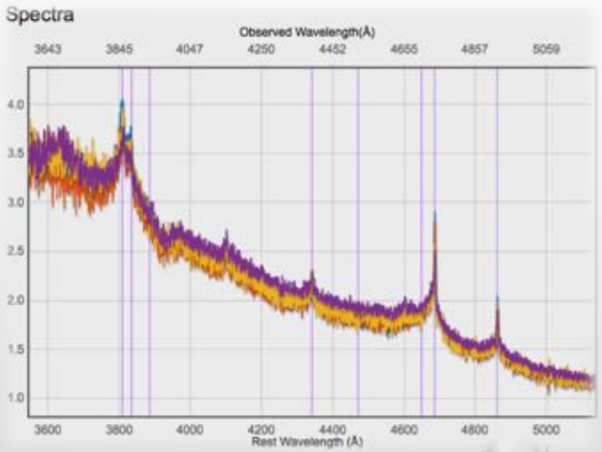
EARLY OBSERVATIONS OF TYPE II SUPERNOVAE &



Ofer Yaron
Weizmann Institute for Science

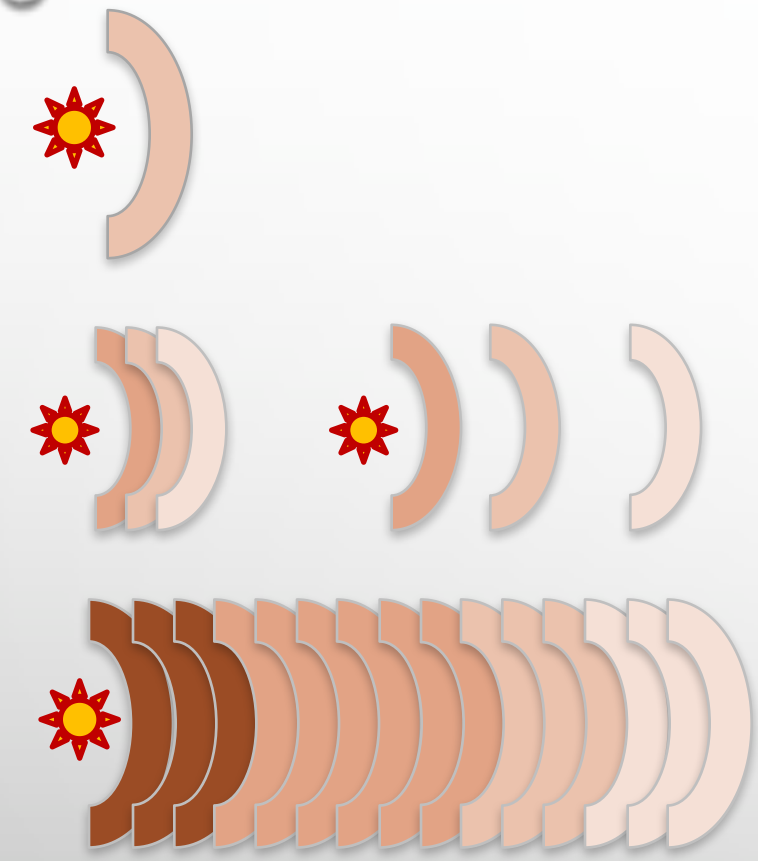


In collaboration with: A. Gal-Yam, D. Perley, J. Groh, A. Horesh, E. Ofek, J. Sollerman, C. Fransson, A. Rubin, and others…

Talk Outline

- *Brief* intro to observed CSM configurations
- What is *Flash-Spectroscopy*
- Unique events from the PTF/iPTF survey
- Additional events to construct "a sample" / statistics…
- Future expectations (just around the corner…)

Various signatures of CSM interaction in CC-SNe

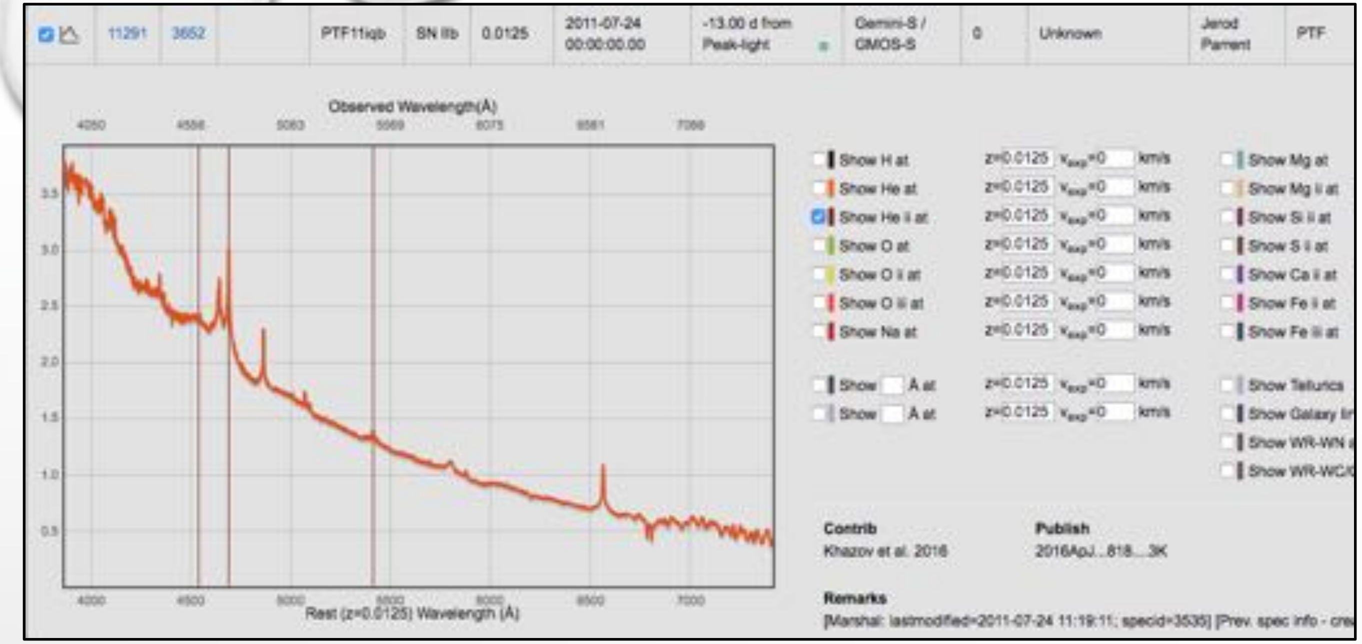


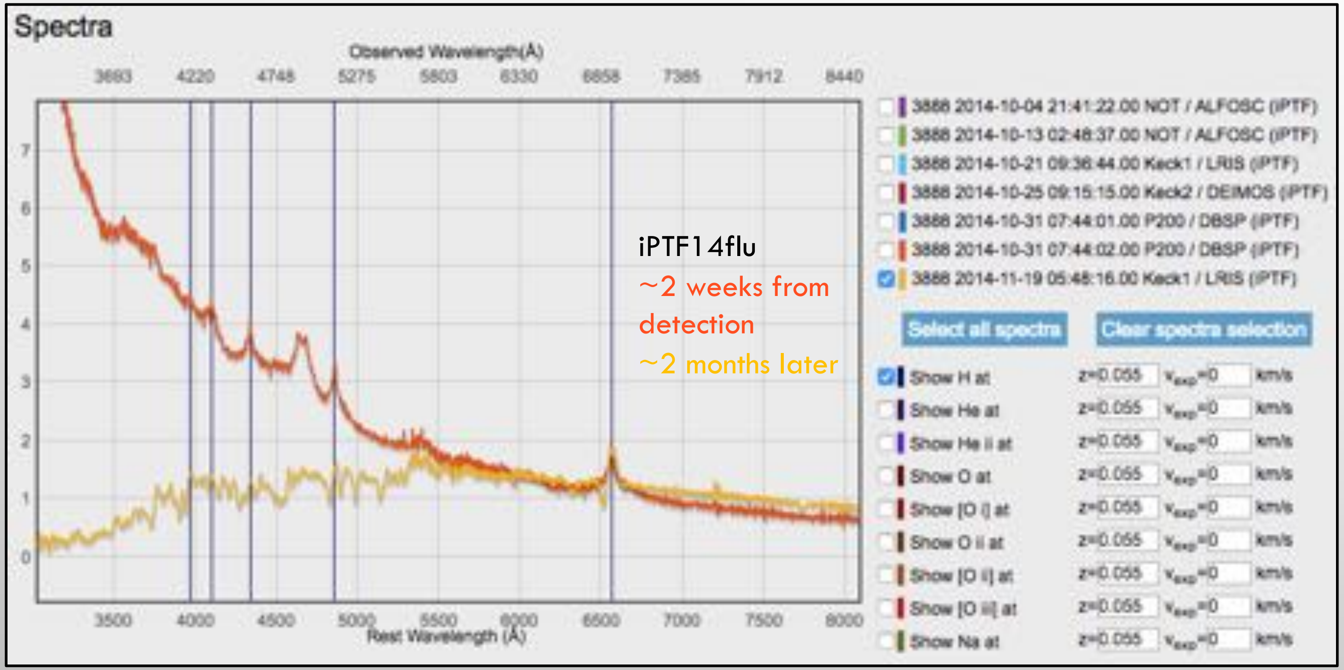
M_w , $\rho_w(r)$, ΔR / Δt

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 SNe
high M, ρ, ΔR
persistent emission lines over months/years





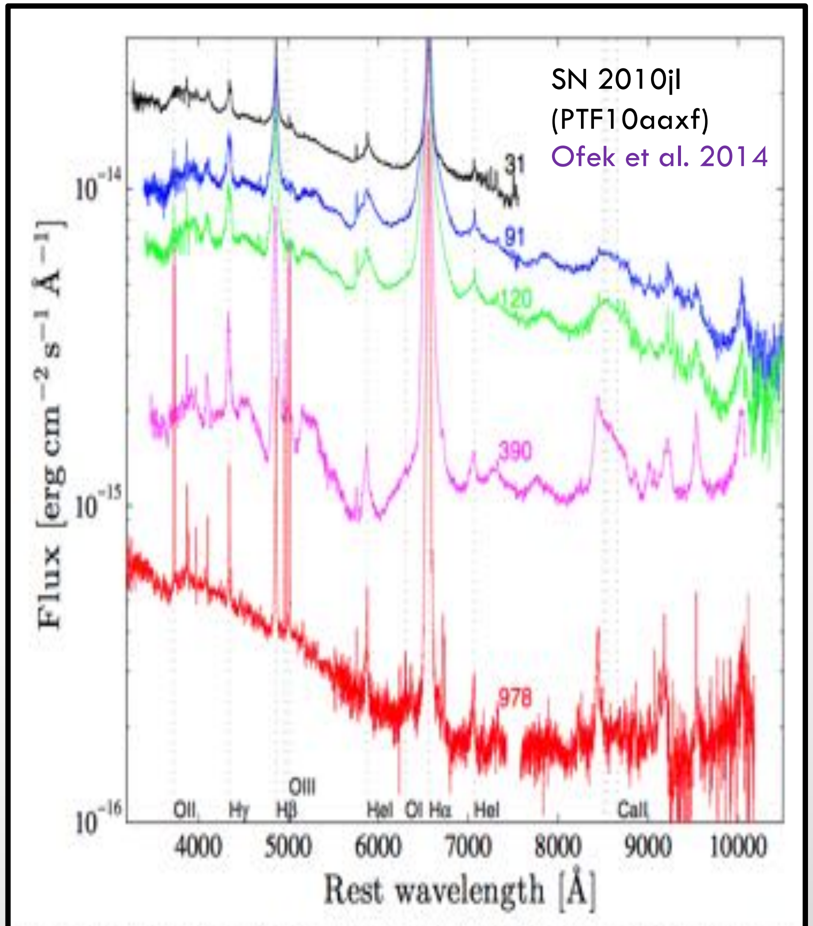
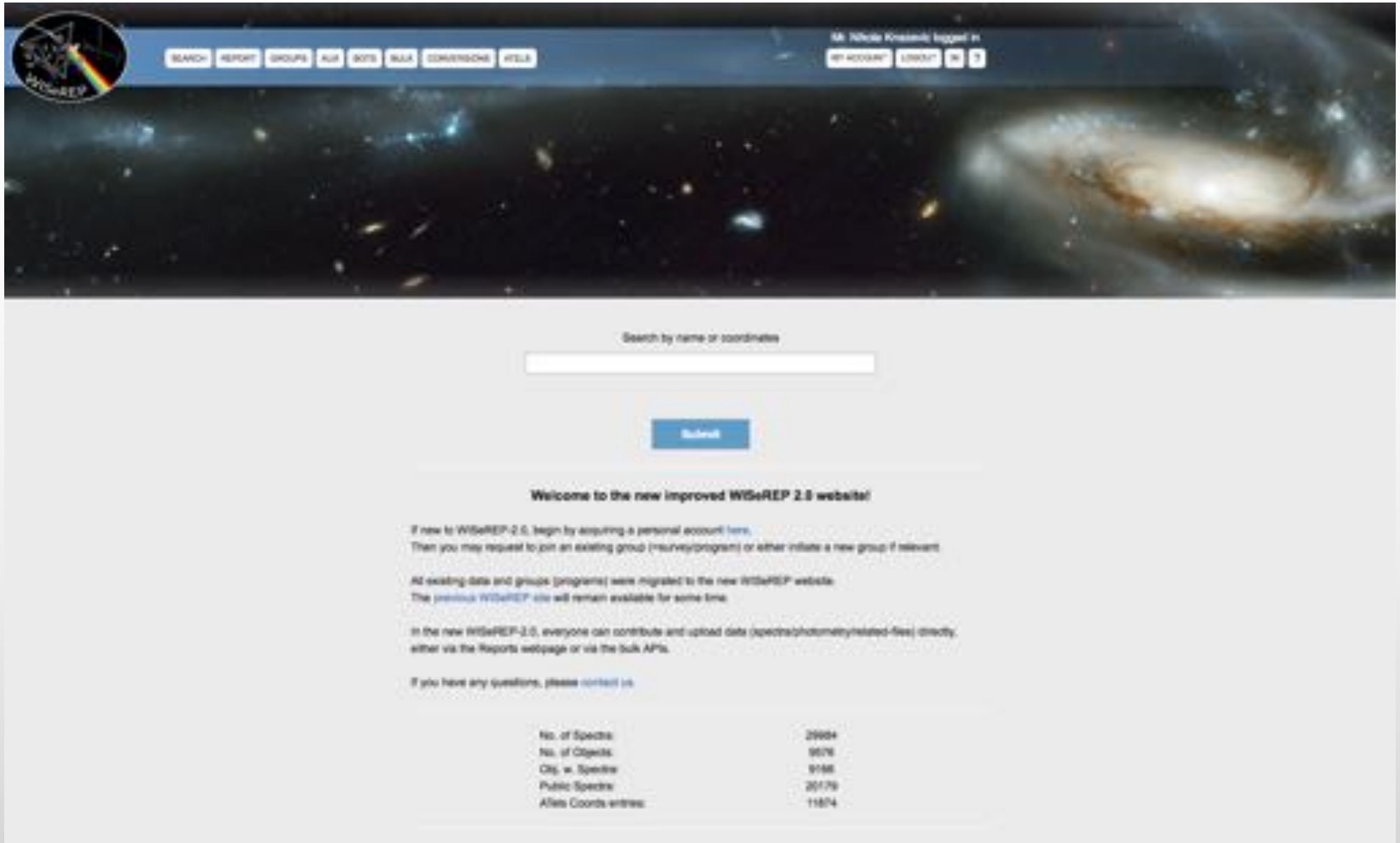


Figure 2. Selected visible-light spectra of SN 2010jl. The number near each spectrum marks its age in days (see Table 2). The last spectrum taken on day 978 may be contaminated by emission from the underlying star-forming region.

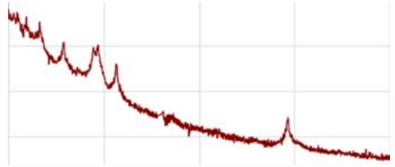
New WISeREP 2.0 coming online soon. STAY TUNED…



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)
- 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…?)

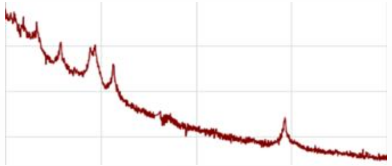
What is *FLASH-SPECTROSCOPY*



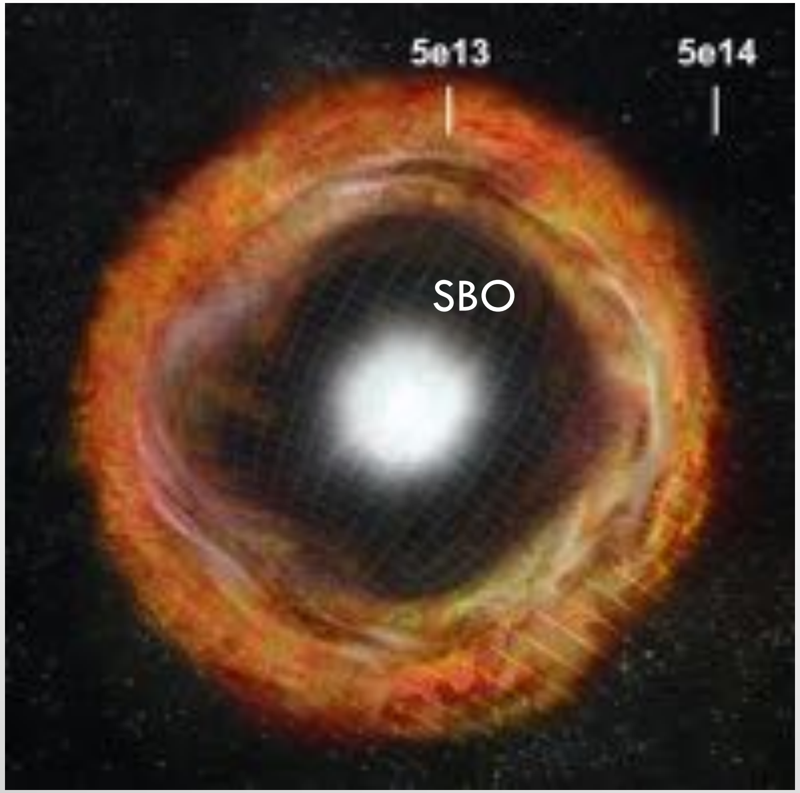
➔ **Prompt** (action+reaction), **Strong!**

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

What is ***FLASH-SPECTROSCOPY***

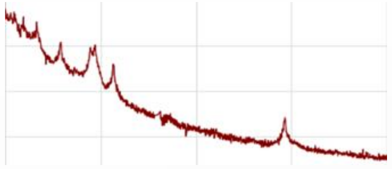


➔ **Prompt** (action+reaction), **Strong!**

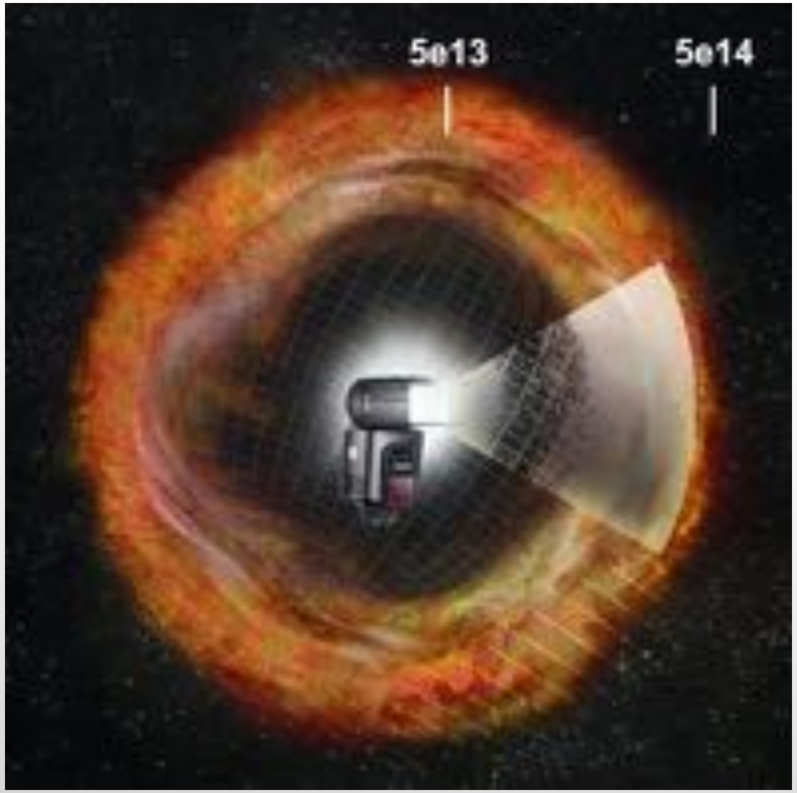


- Progenitor engulfed with a (relatively) optically thick wind / CSM (continuous or detached).
- Shock breaks out from the hydrostatic surface (or either in a surrounding optically thick wind).

What is *FLASH-SPECTROSCOPY*

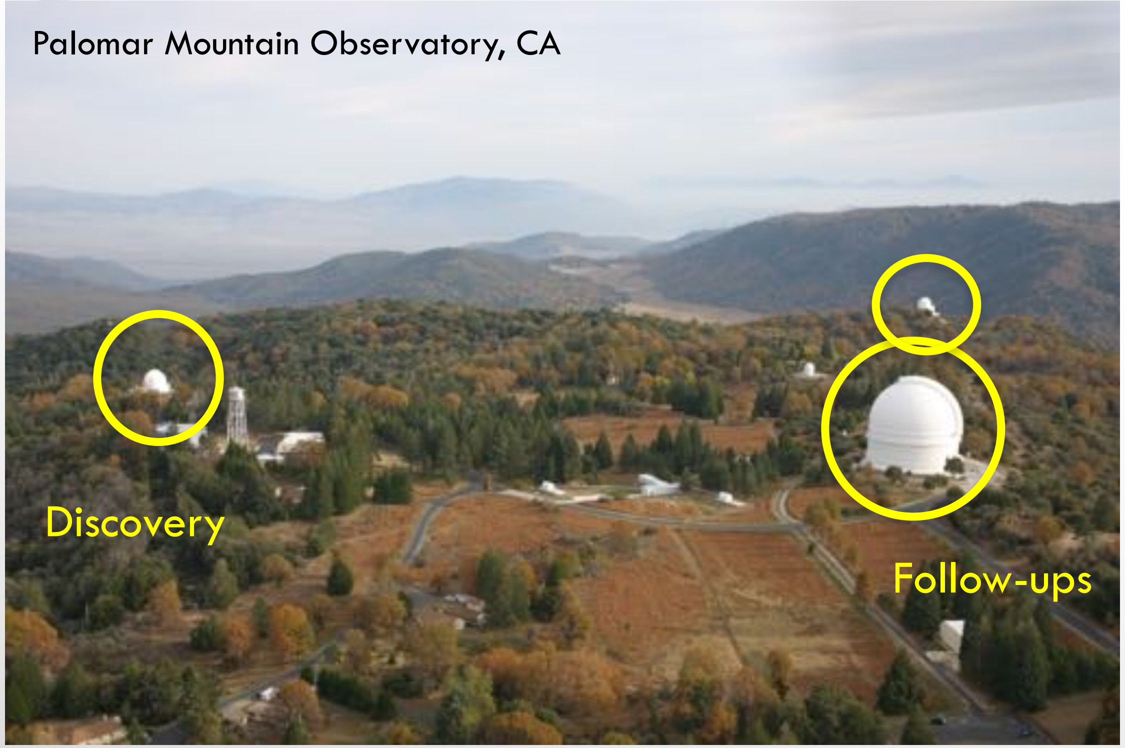


➔ **Prompt** (action+reaction), **Strong!**



- 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



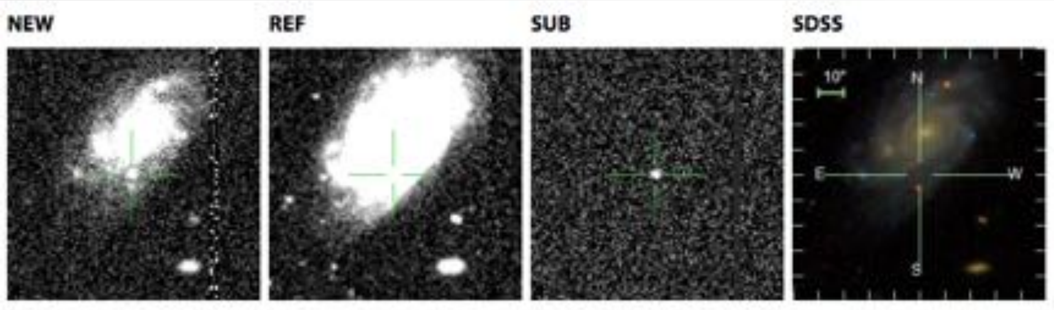
48” robotic telescope, wide-field ~7 deg^2 (~1500 deg^2 / night), 1-day cadence.

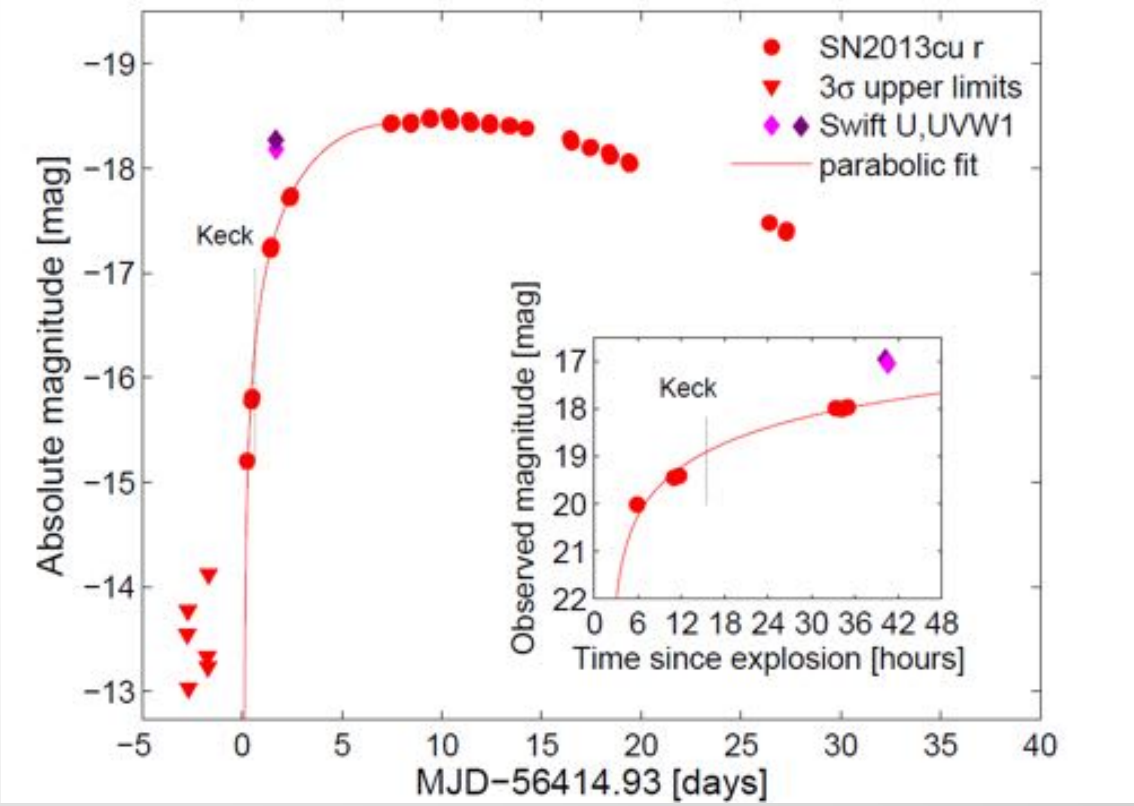
With human monitors at daylight in Europe during Palomar’s night time ➔ Quick response to young SN candidates (alerting & triggering of follow-ups).

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

Gal-Yam et al. 2014

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

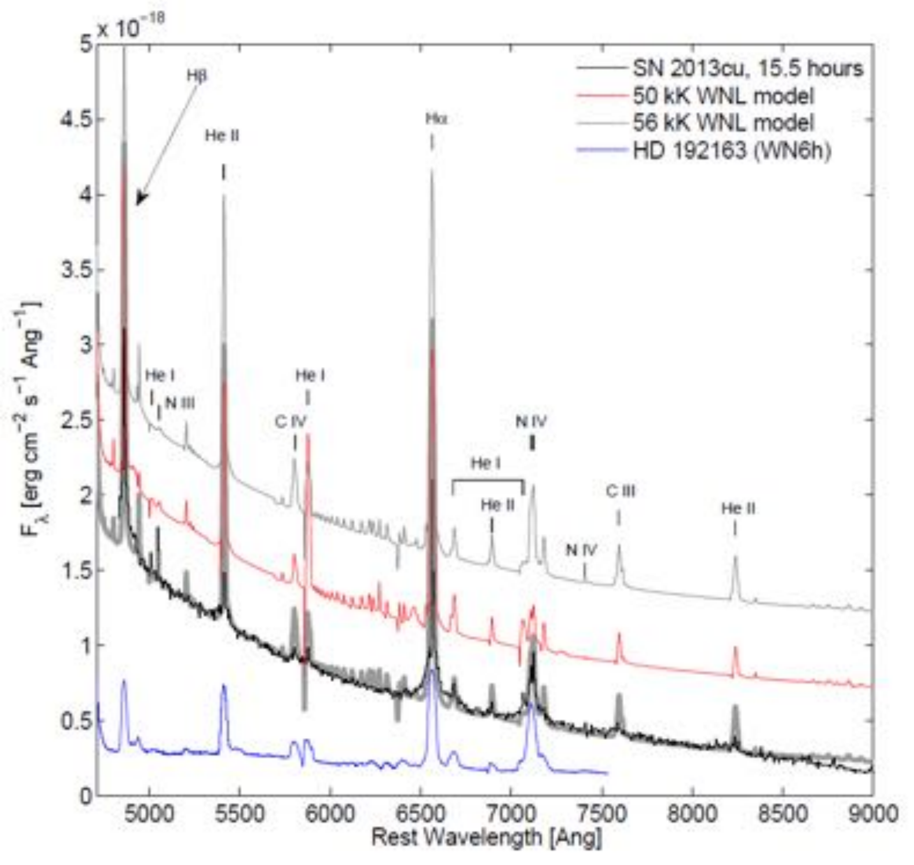




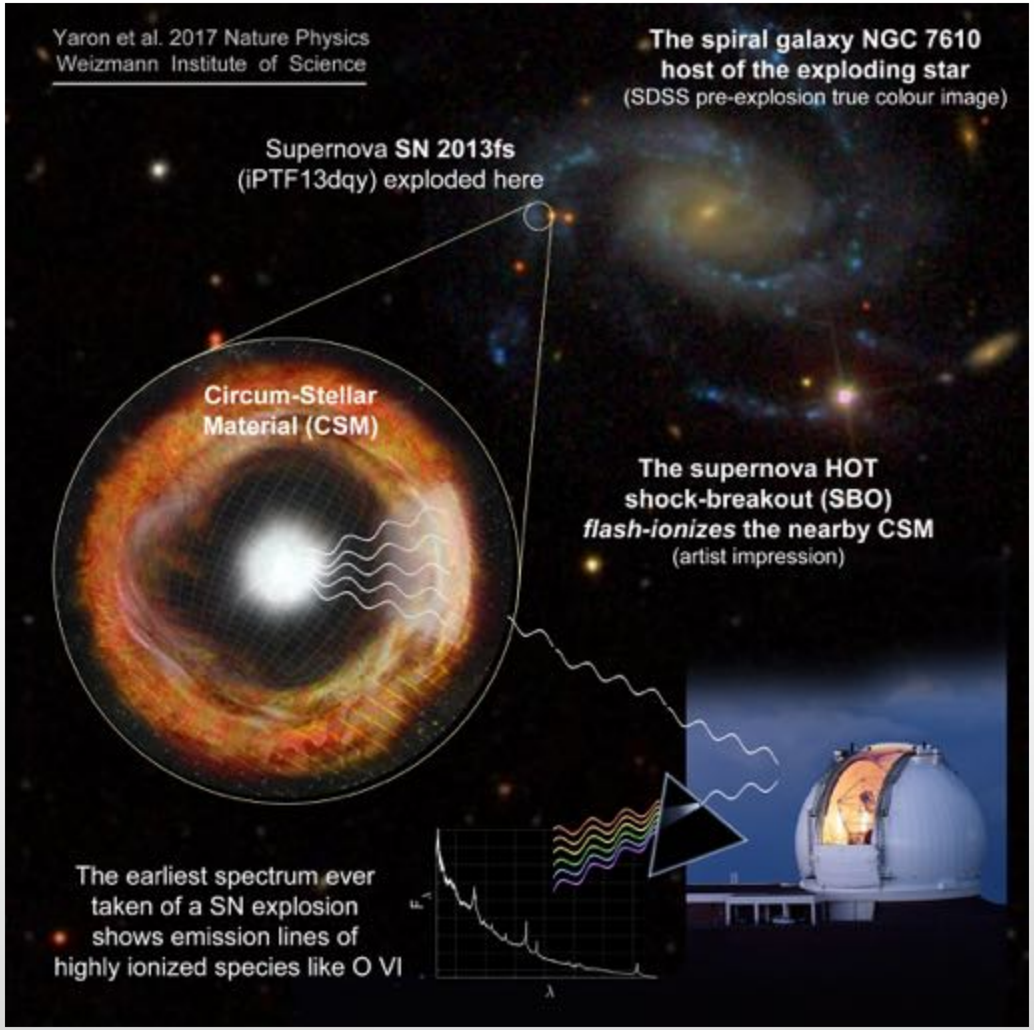
iPTF13ast (SN 2013cu)
A Flash-Spectroscopy event showing *WR-<u>like</u>* wind signatures

Gal-Yam et al. 2014

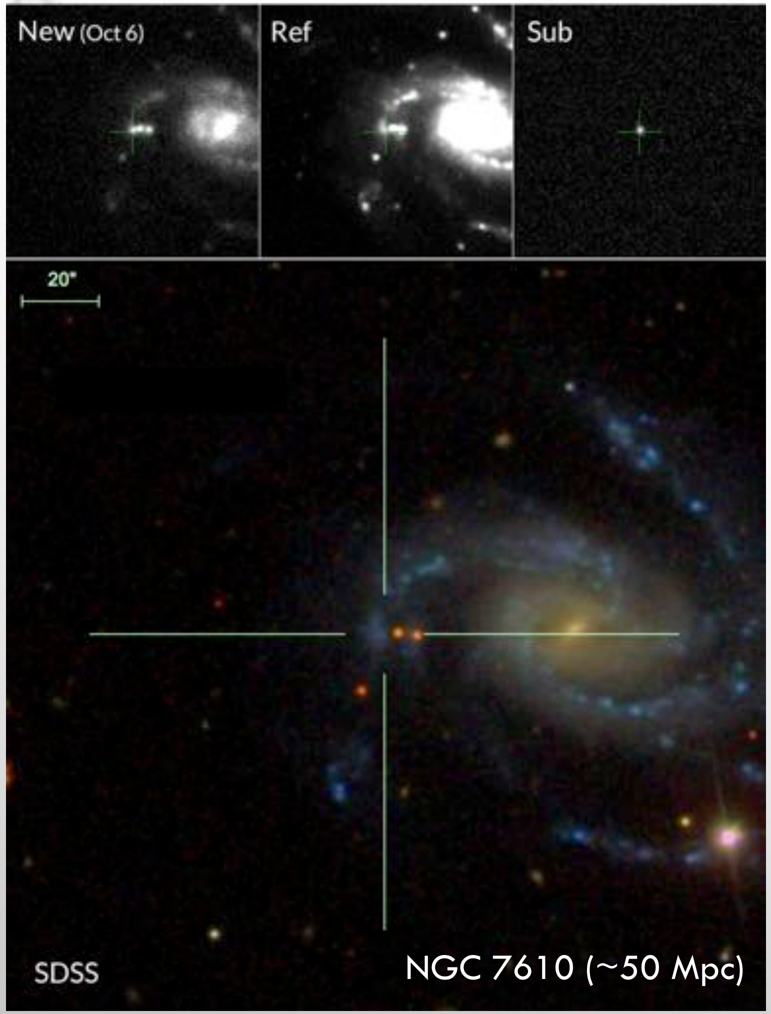
- Strong He, N (N IV 7115) and Balmer lines indicate a WN6(h) classification.
- By day 6 the spectrum is featureless.
- Later spectra match prototypical Type IIb SNe (semi-stripped progenitor; low H envelope mass)
- From high Mdot, rel. low v_{wind} and chemical abundance, progenitor likely a **LBV /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



The story of iPTF13dqy = SN2013fs

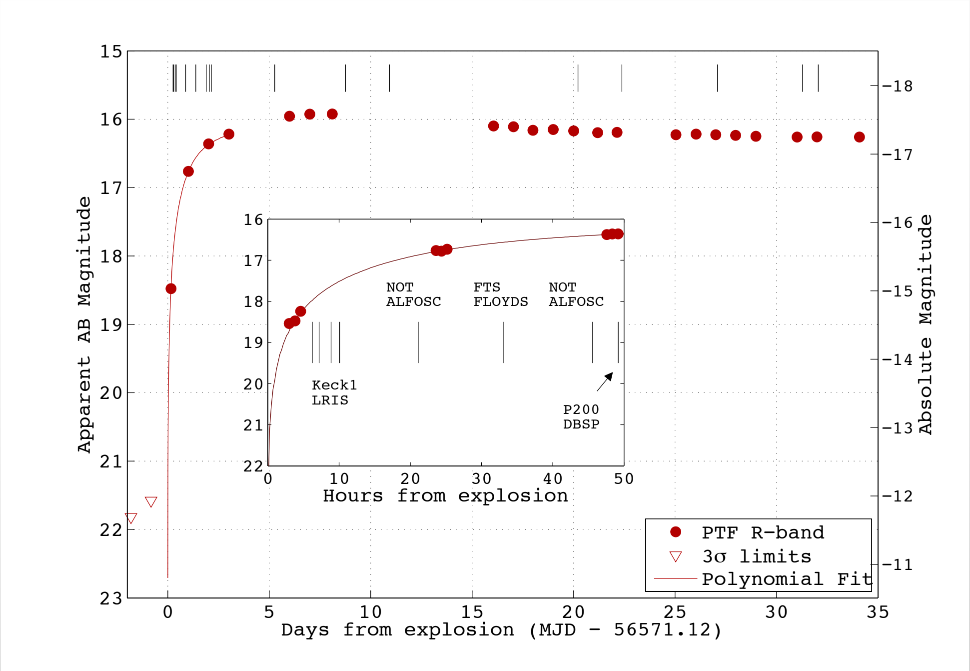


iPTF13dqy – *Flash-Spectroscopy* in its extreme



OY et al. 2017

- Discovery ~3 hrs from explosion.
- A set of 4 Keck spectra, 6-10 hrs.

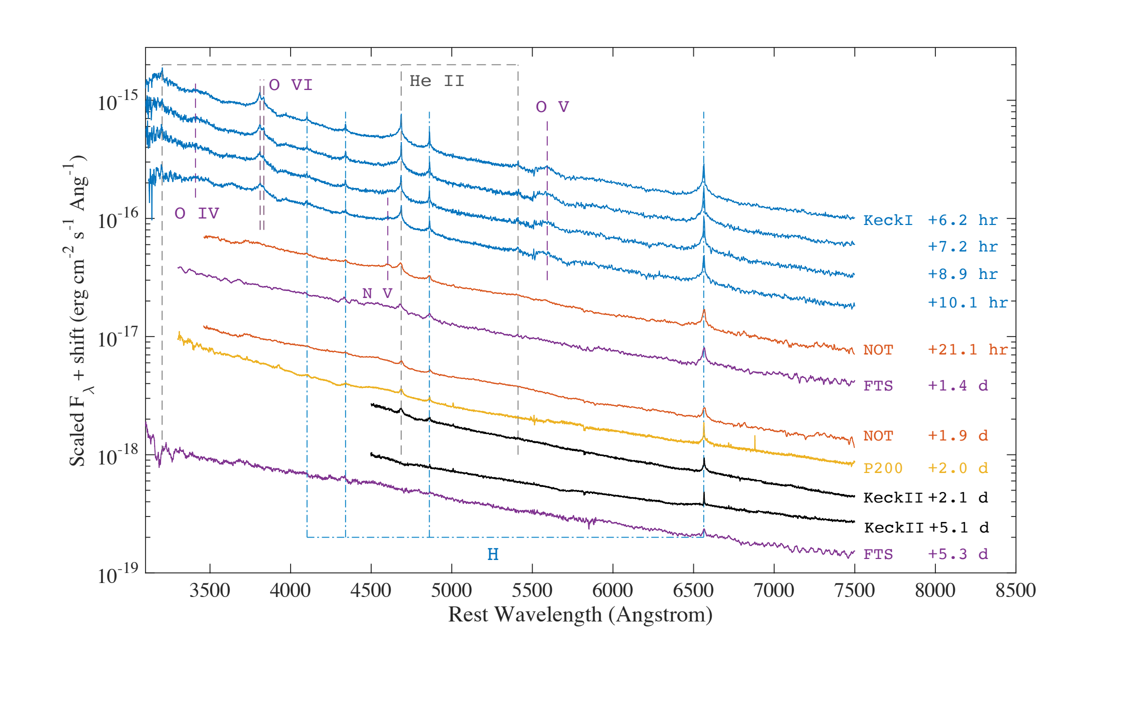


P48 R-band

iPTF13dqy – *Flash-Spectroscopy* in its extreme

OY et al. 2017

Early Spectral evolution (6 hrs to 5 d)

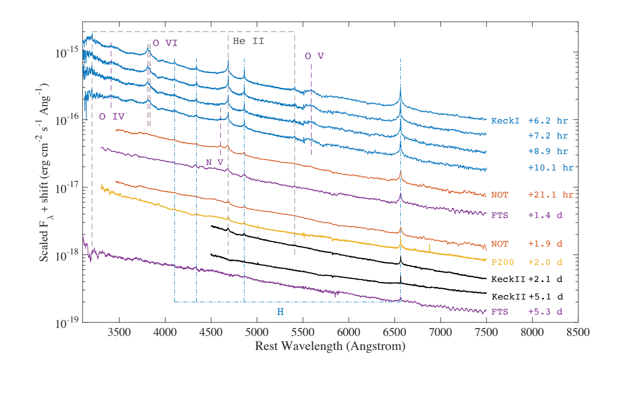


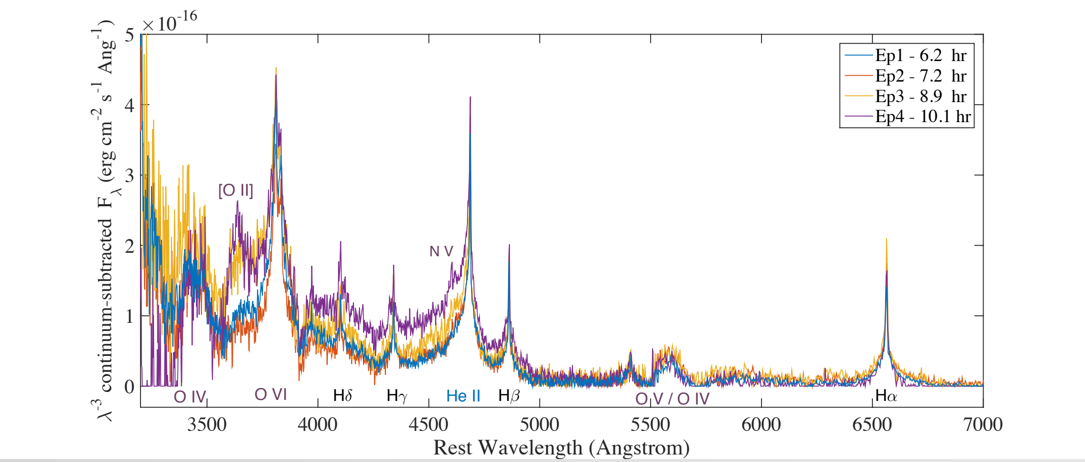
- High-ionization emission lines **(O VI)** dominate during the first 10 hrs.
- He II persists till ≥ 2 days.
- Lines gradually disappearing till a Blue/Featureless spectrum by day 5.

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-Spectroscopy* in its extreme

OY et al. 2017



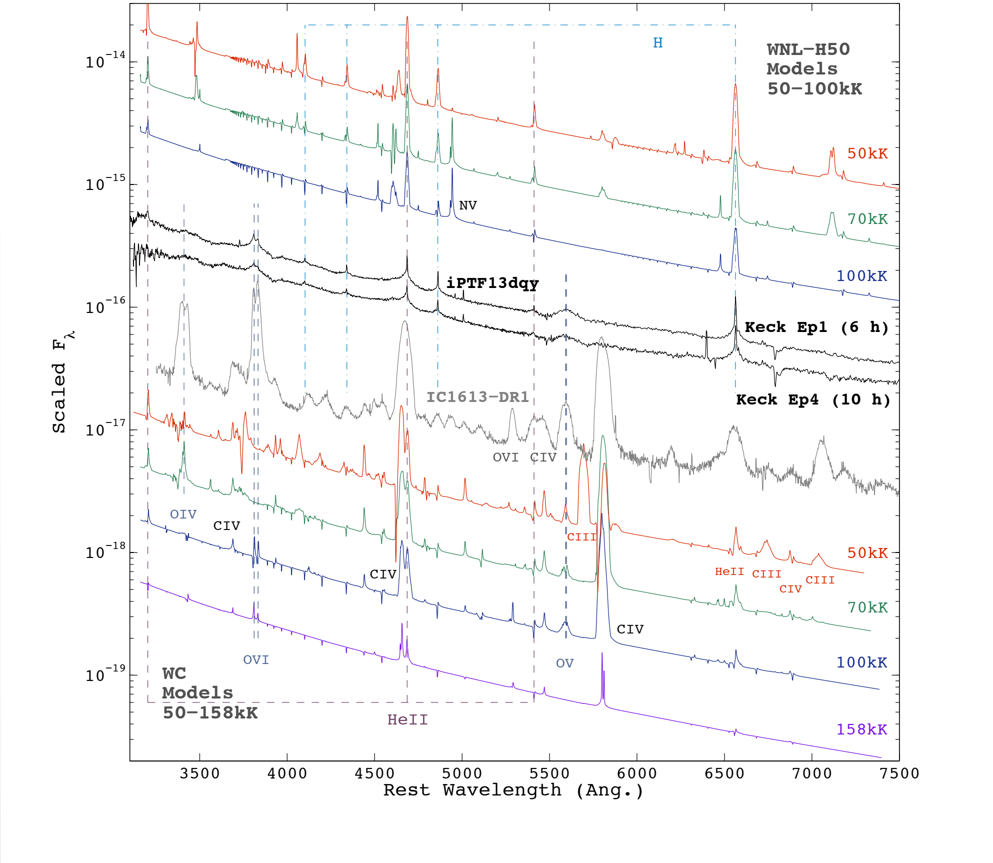


6-10 hrs Keck spectra, continuum subtracted

- 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.

$4\times10^{14} \leq r \leq 2\times10^{15}$

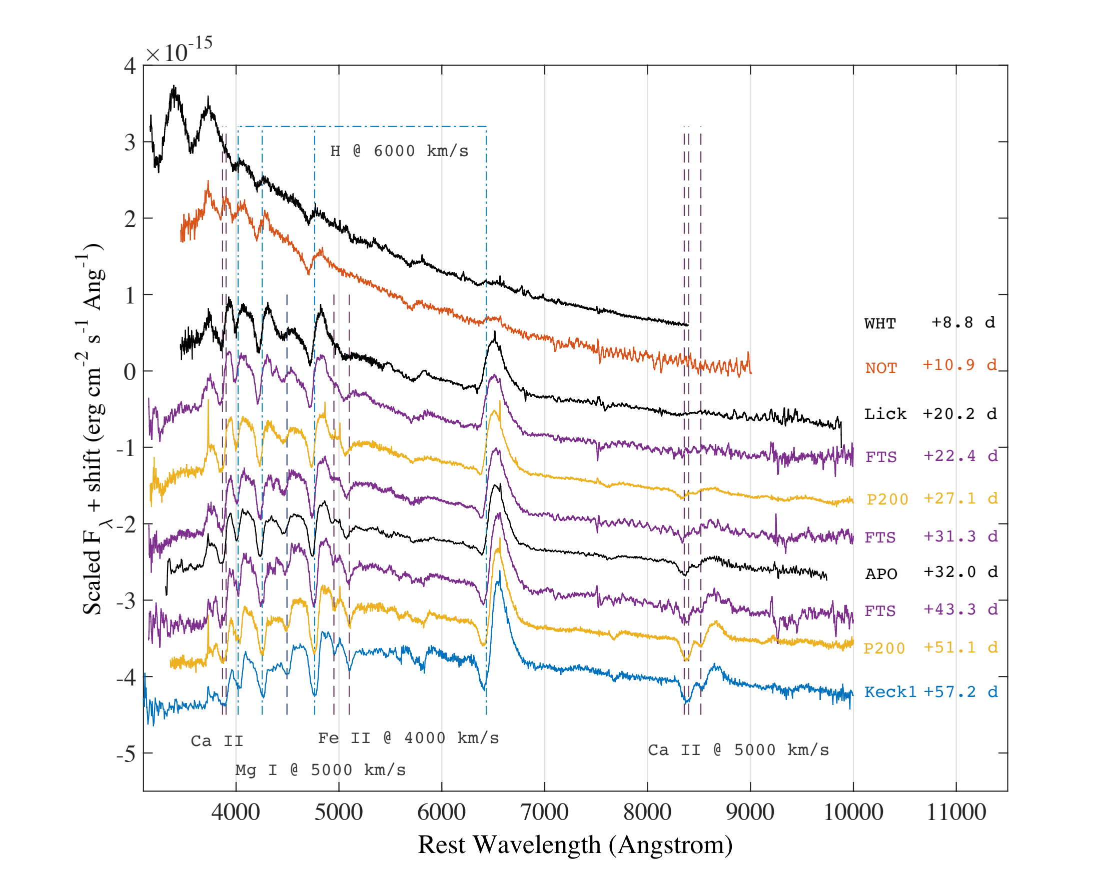
iPTF13dqy – Beginning ***HOT***



Comparison to Wolf-Rayet families models (POWR)

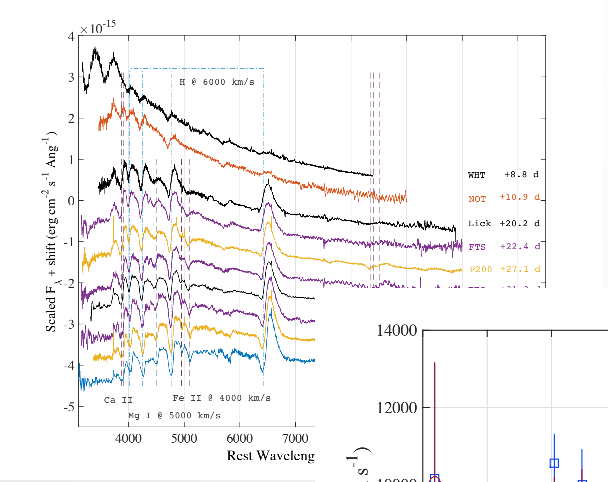
iPTF13dqy – Later data reveal a "standard" Type IIP

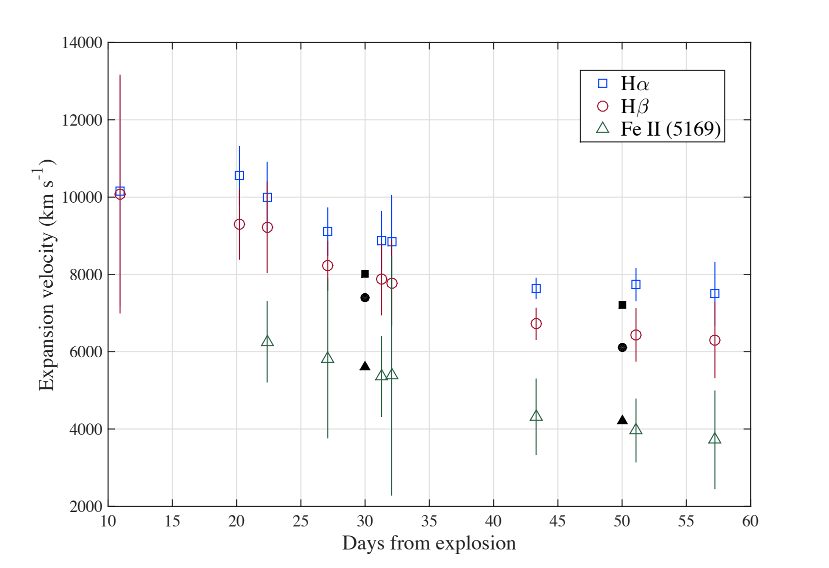
Later Spectra (days 8 - 57)



- Developed P-Cygni lines.
- Spectra are typical of normal Type II.

iPTF13dqy – Later data reveal a “standard” Type IIP

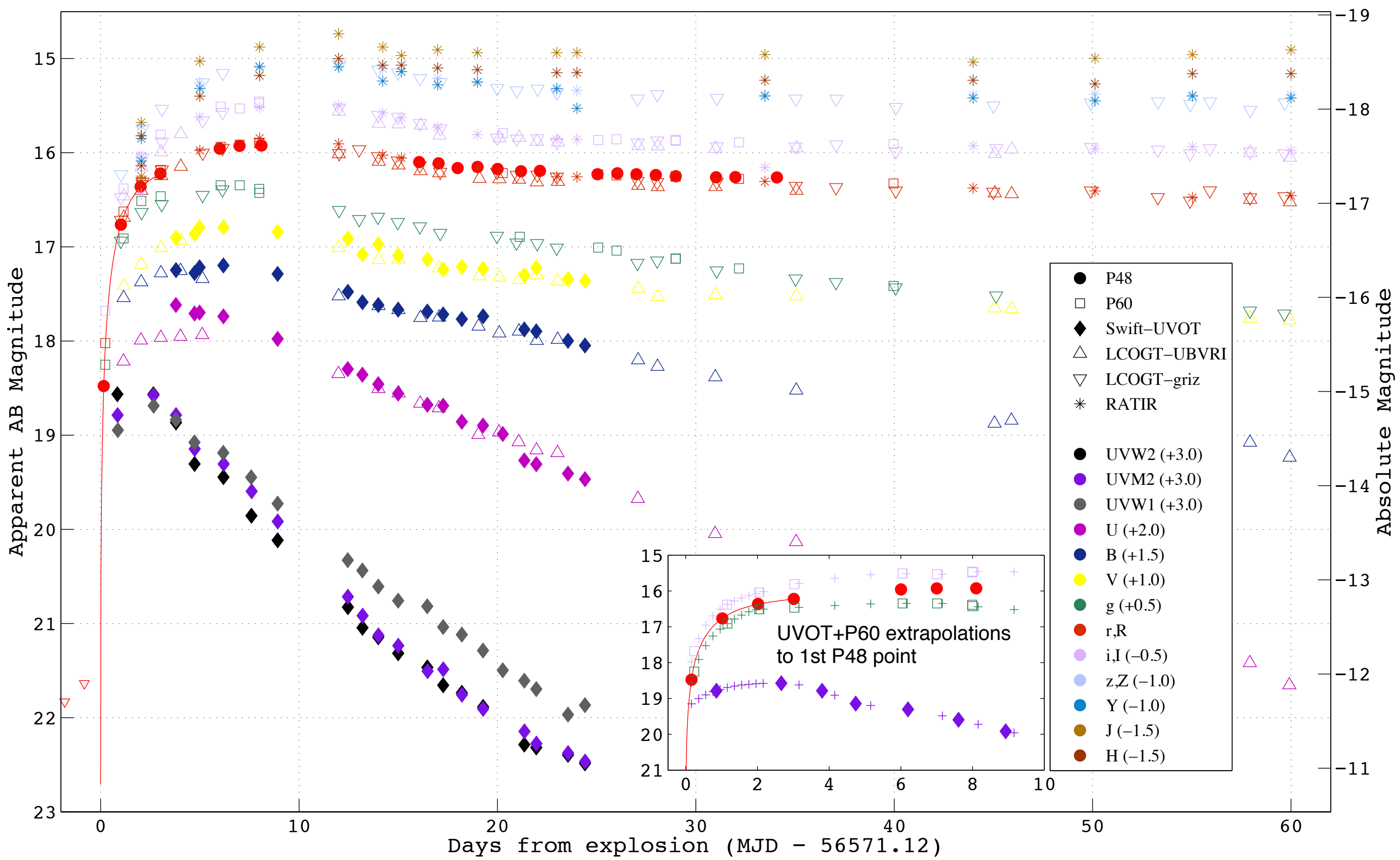




- Developed P-Cygni lines.
- Spectra are typical of normal Type II.
- As well as the expansion velocity evolution.

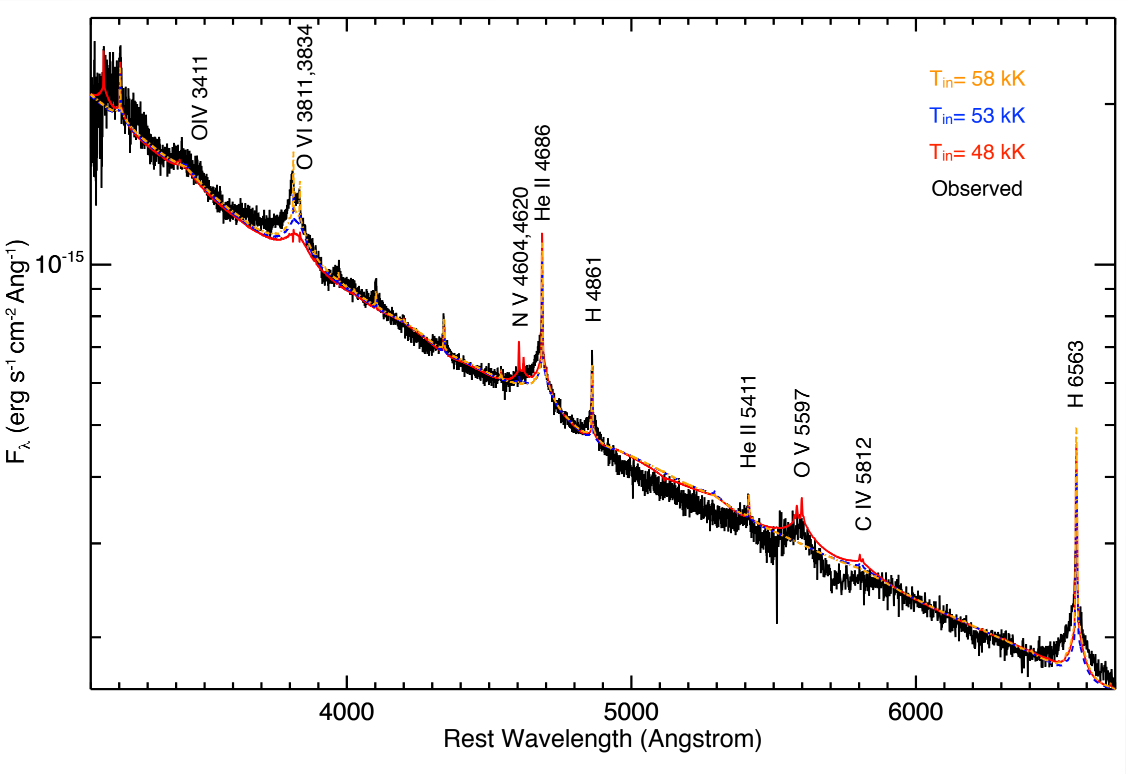
Black markers: the expansion velocities of the standard Type II-P SN 2004et at days 30 and 50 .

iPTF13dqy – Later data reveal a Type IIP

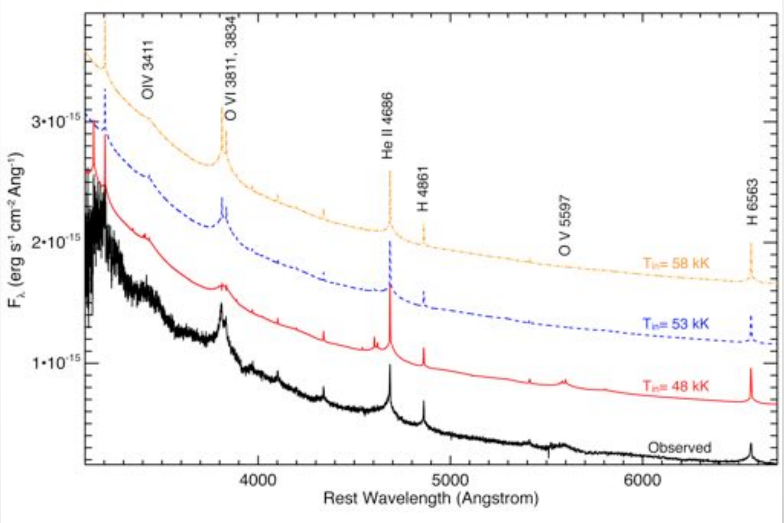


Multi-band LCs (first 2 months)

iPTF13dqy – CMFGEN modeling of the early spectra

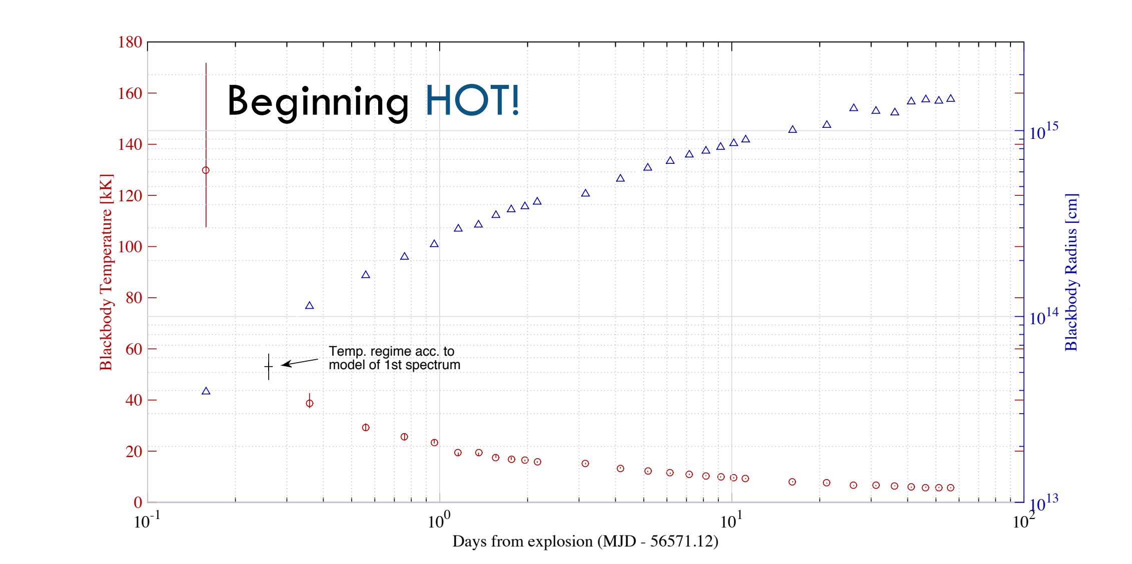


The three model spectra bracket the observed early spectrum;
the 53kK model (dashed blue) best recovers the oxygen ionization structure.



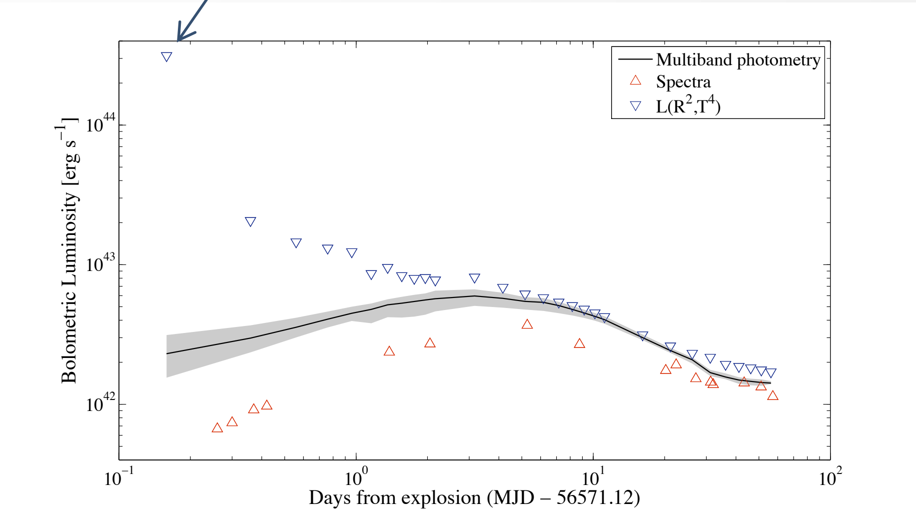
➔ Mdot = (2-4) x 10^{-3} (v_w=100 km/s) OR…
Mdot = (3-6) x 10^{-4} (v_w=15 km/s)
R_{in} ~(1-2) x 10^{14} cm

iPTF13dqy – Bolometrics



Bolometric luminosity estimates during the first 60 days, as obtained based on (1) photometry (SED fittings), (2) spectra and (3) BB temp. and radii.

L_{bol} (t~4 hrs) > 10^{44} ergs s^{-1}



Evolution of the BB temp. and radius based on the multiband photometry measurements.

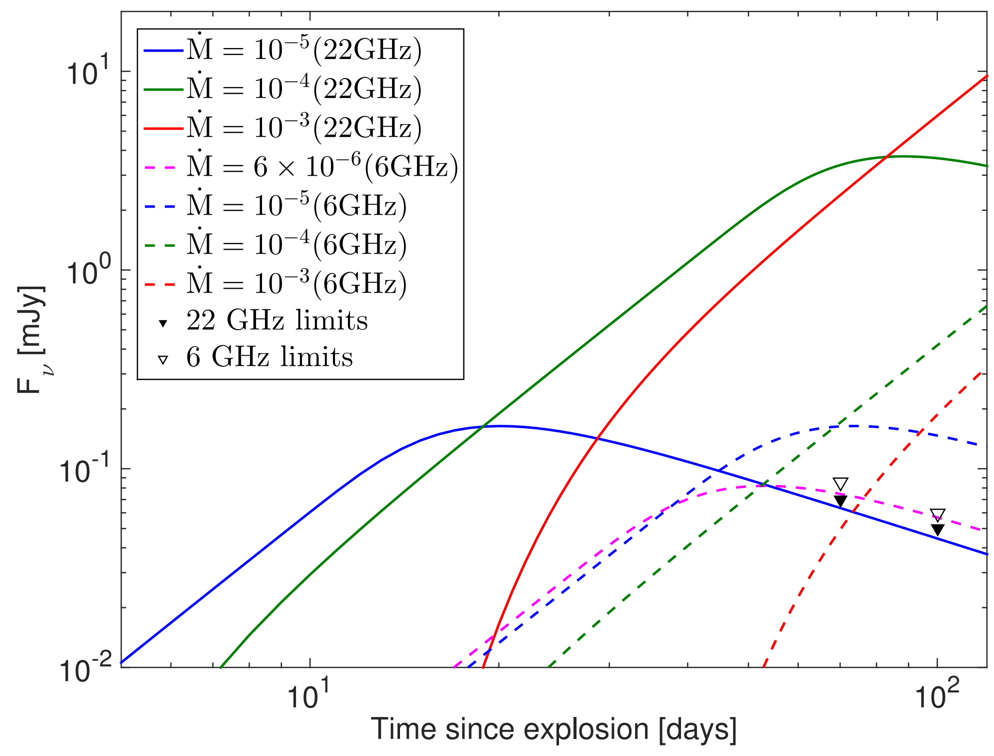
… in agreement with the temp. estimates from modeling of the early spectra, showing the emission lines from highly ionized species at temp. above 50 kK.

iPTF13dqy – Constraints from Radio

Jansky VLA radio observations (PI Assaf Horesh) on days 70,100 after explosion (centered on 6.1, 22 GHz) resulted in NULL detections.

The plotted colored curves display theoretical light curves of radio emission originating from the interaction of SN ejecta with an extended CSM.

The measured limits rule out a wide range of MLRs. In particular that the MLR estimate required to explain the early optical data could not have been sustained over long periods.



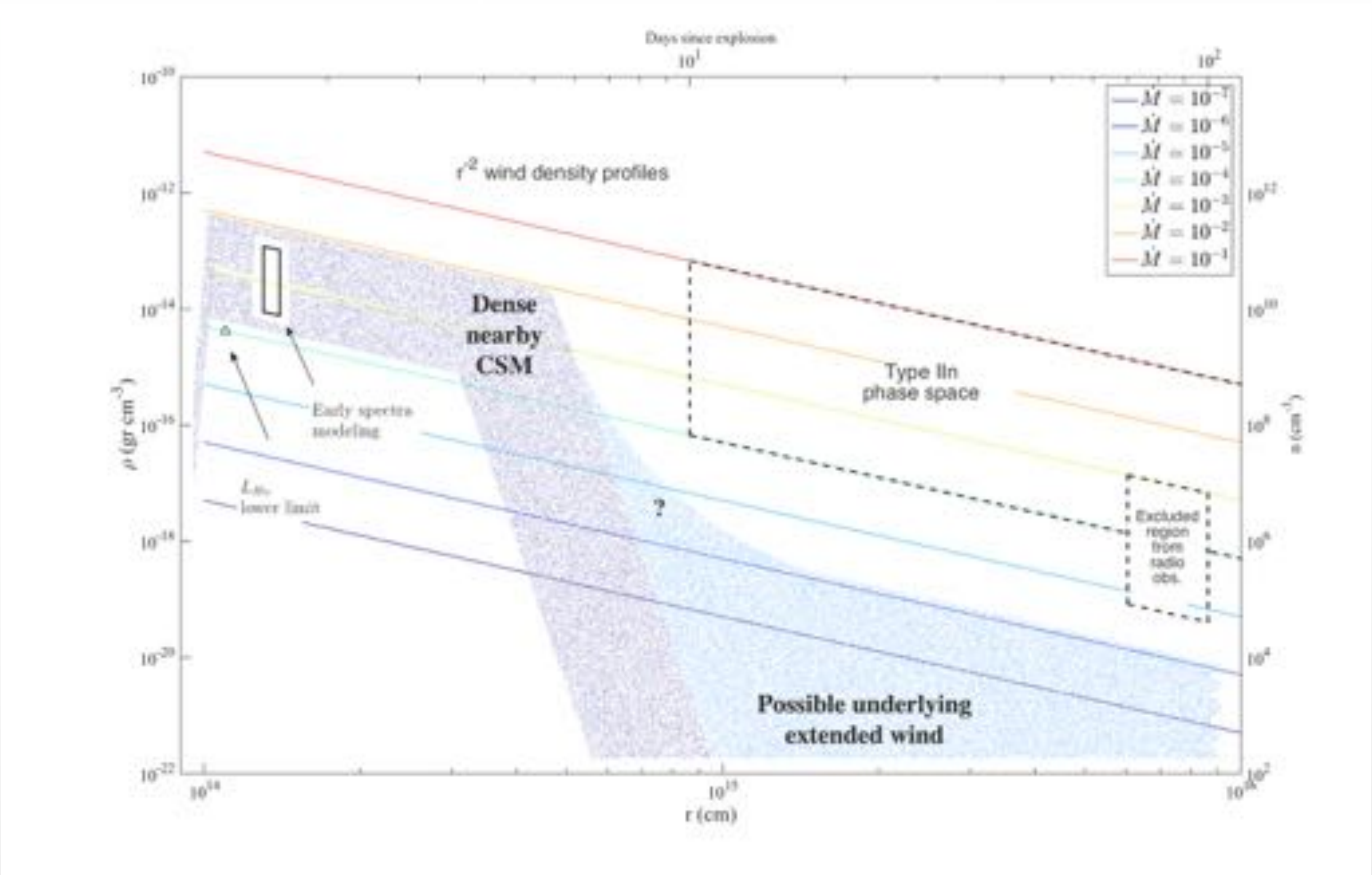
Concluding the characterization of the CSM & MLR

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

Colored diagonal lines:

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

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

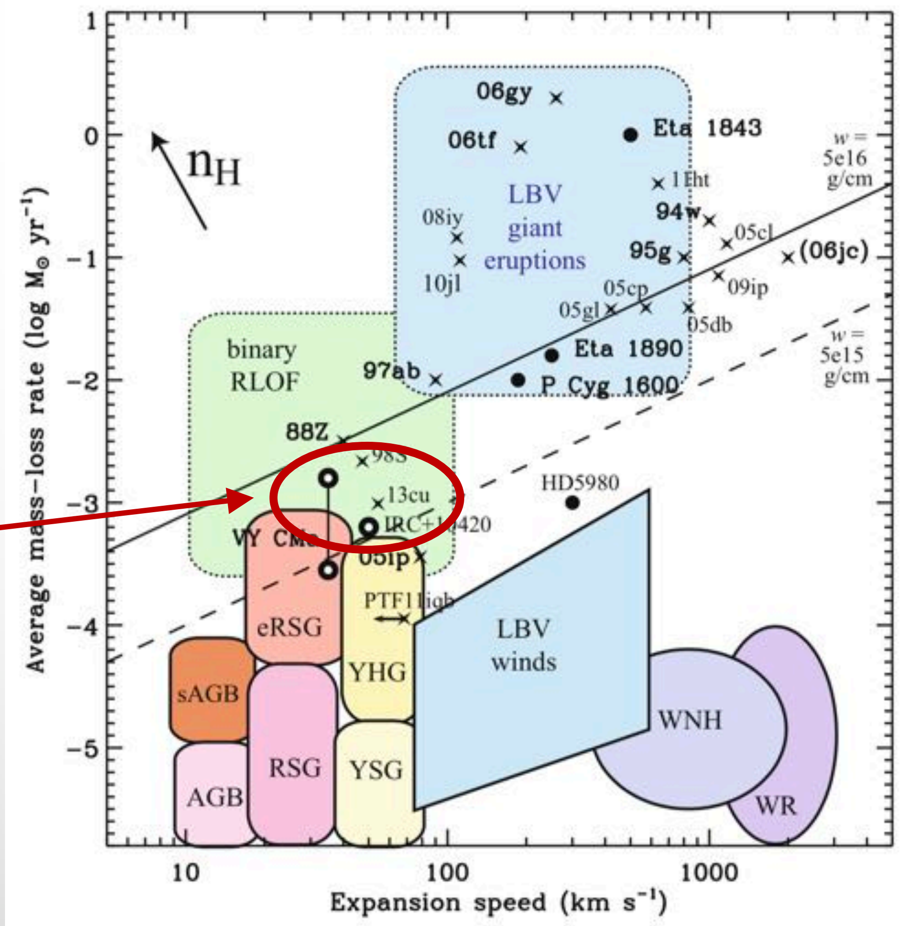


Concluding the characterization of the CSM & MLR

Mass-loss rate as a function of wind velocity, comparing values for interacting SNe to those of known types of stars (Smith, Handbook of SNe)

Location of the pre-SN mass-loss episode of iPTF13dqy

Mdot ~ 10^{-3} M_{sun}/yr, v_w <~ 100 km/s
(but over a short period!!!)



Wind density parameters – the lowest required to make a SN IIn

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).

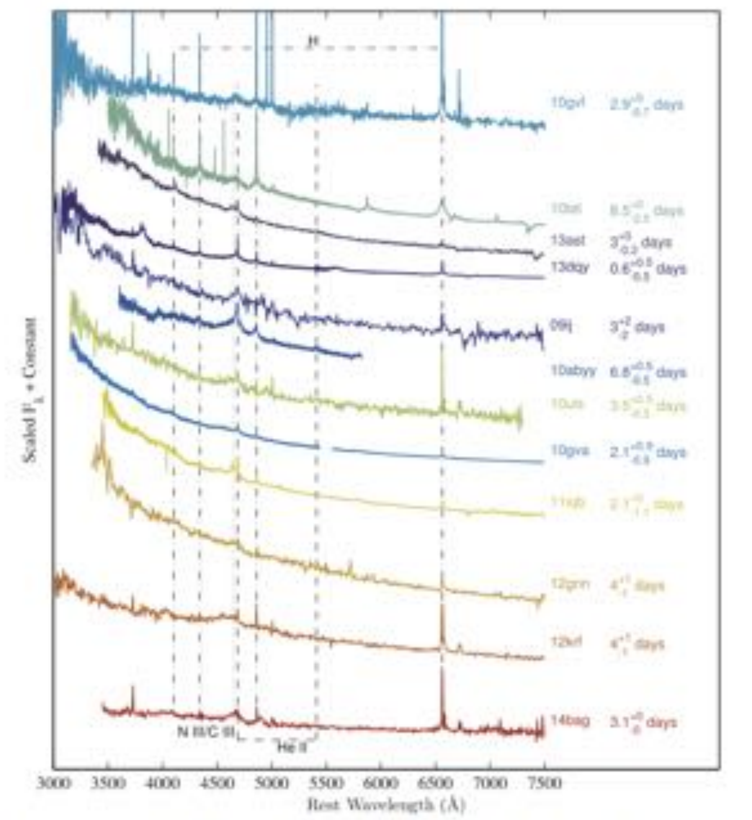


Figure 3. Spectra of our 12 FI events. On the right: an estimate of the age of the SN, with respect to the estimated explosion time (see the Appendix for details).

Khazov, OY, Gal-Yam et al. 2016

How common are flash ionized early spectra?

Results

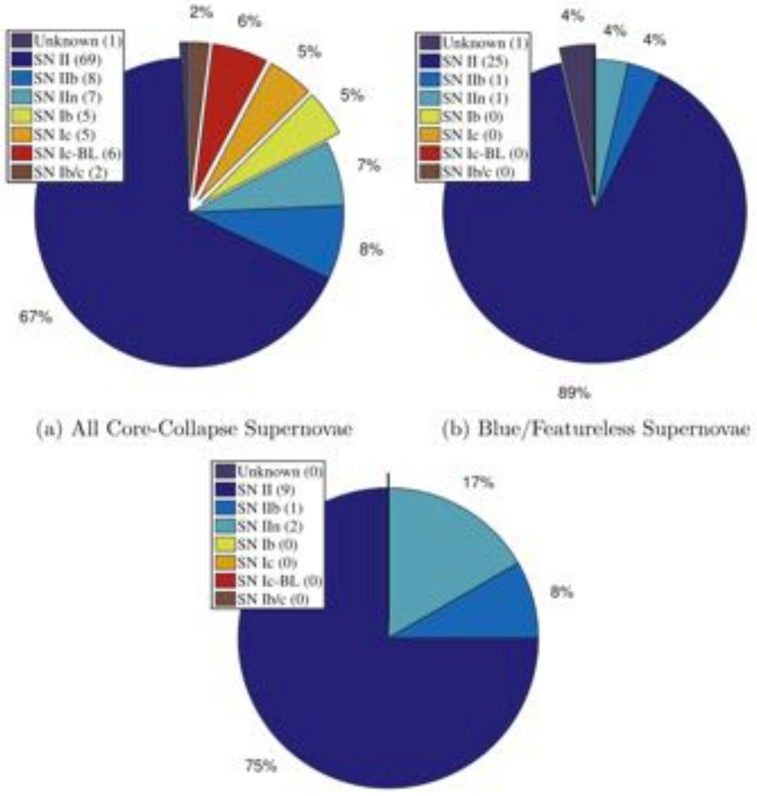
- All Flash-Ionized spectra found (12) are of Type II.

Event Fractions

Days from Explosion	Sample Size	FI	BF
9	84	14%	32%
5	55	18%	33%
2	11	18%	54%

- Within 2 days from explosion, 8/11 SNe are FI or BF.
- Within 5 days from explosion, 1/5 of the Type II show FI.
- These FI fractions are a lower limit!

- There is evidence that late-stage enhanced mass-loss may also be common among progenitors of Low-Luminosity type IIP SNe (SN2016bkv, Hosseinzadeh et al. 2018)



(a) All Core-Collapse Supernovae (b) Blue/Featureless Supernovae

(c) Flash-Ionized Supernovae

Figure 1. (a) Distribution by type of all 103 CC SNe whose first spectrum was taken <10 days after the time of the pre-explosion limit. Of these, 84 are SNe II. (b) Type distribution of events with BF first spectra (28 total). (c) Type distribution of FI SNe (12 total). There is only a single, featureless spectrum of the "unknown" SN, not enough for classification.

Khazov, OY, Gal-Yam et al. 2016

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-hydrostatitc pre-SN envelope configurations (density profiles) that are different from our prior expectations (therefore should affect fits to shock-cooling models etc…)

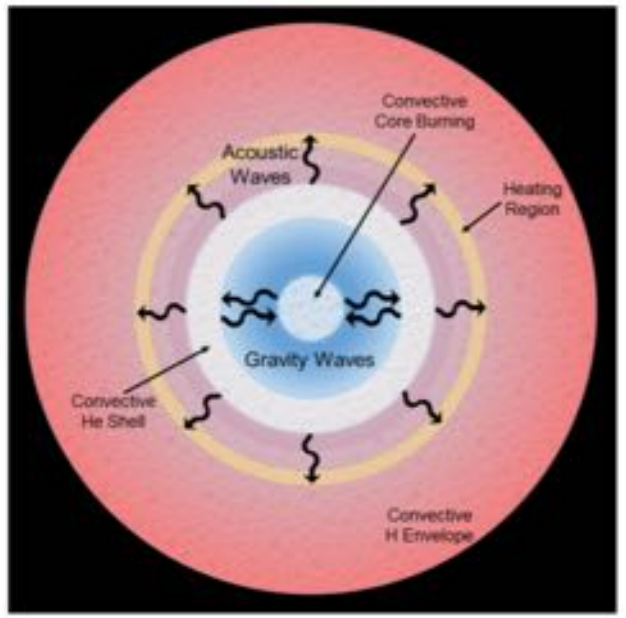


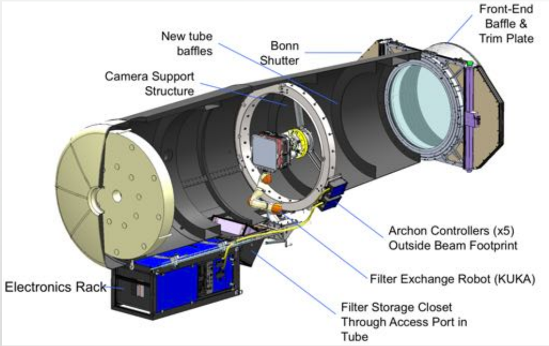
Figure 1. Cartoon (not to scale) of wave heating in a red supergiant. Gravity waves are excited by vigorous core convection and propagate through the outer core. After tunnelling through the evanescent region created by the convective He-burning shell, they propagate into the H envelope as acoustic waves.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

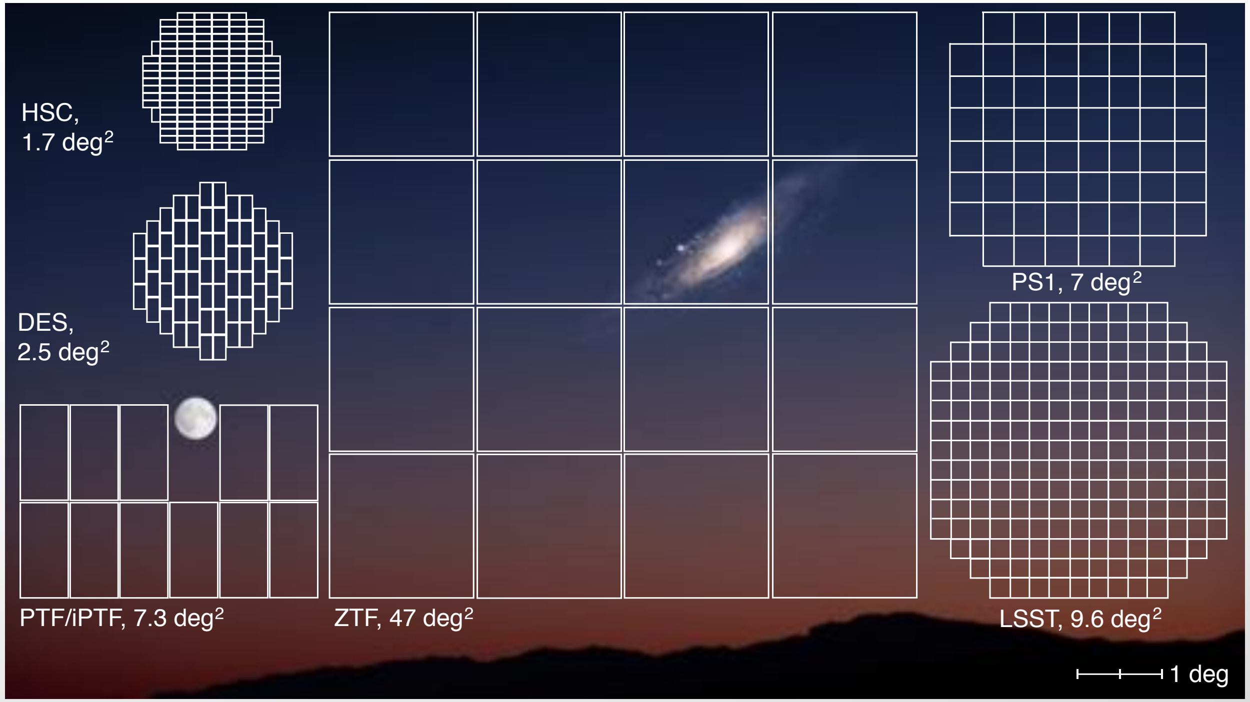
Jim Fuller 2017

What to expect in the nearby future

Zwicky Transient Facility

- Reworked optics, HUGE camera. FOV: 47 sq. deg. !!!
- Covering ~5000 sq. deg. /night (2-3 visits/night)
- 1-day partnership cadence

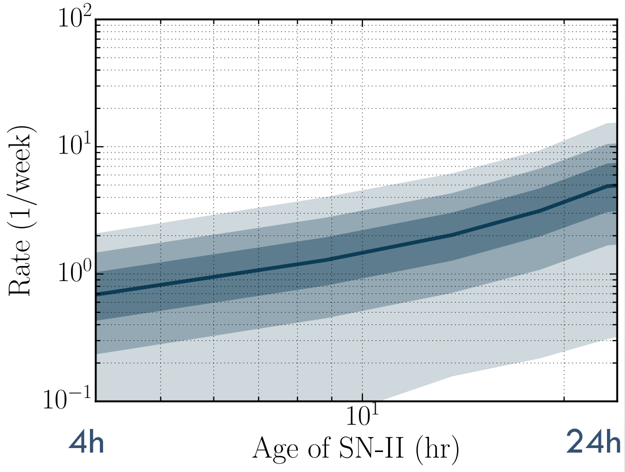


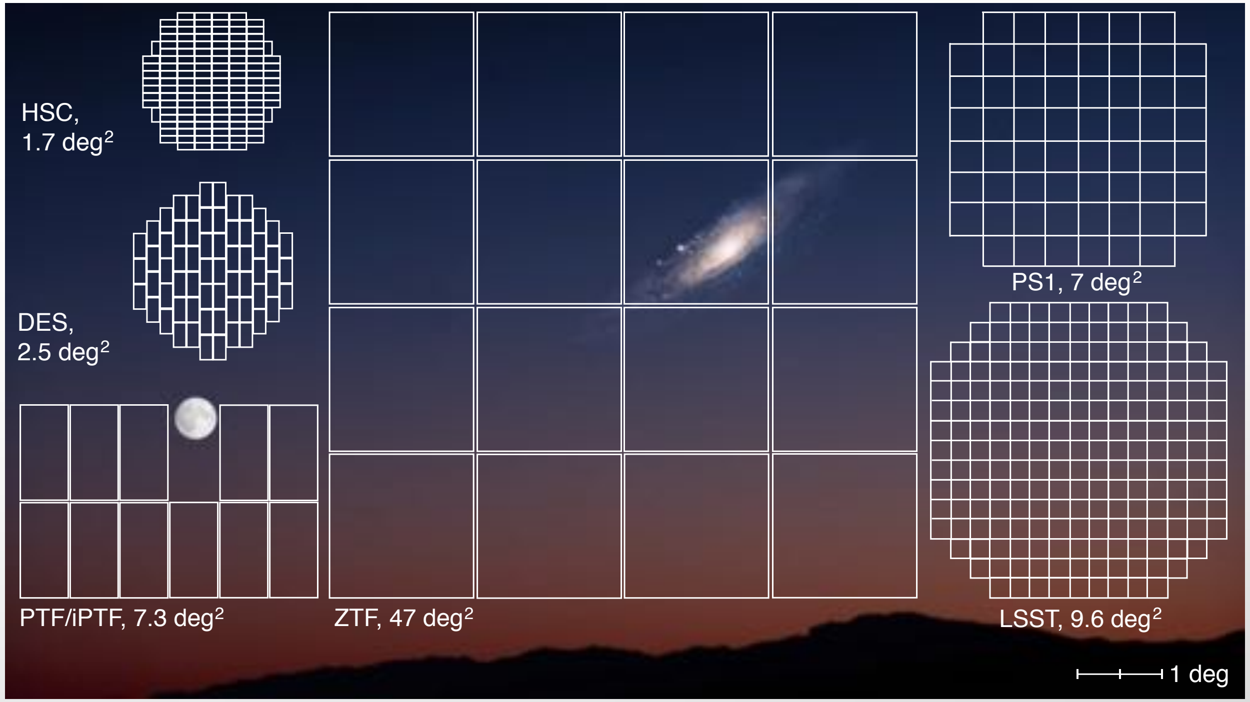


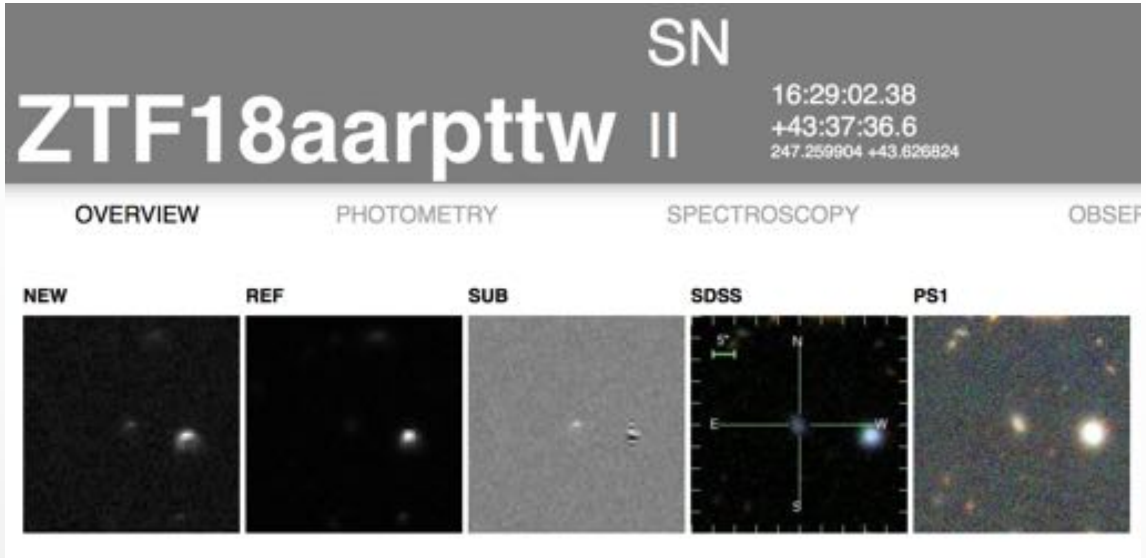
What to expect in the nearby future

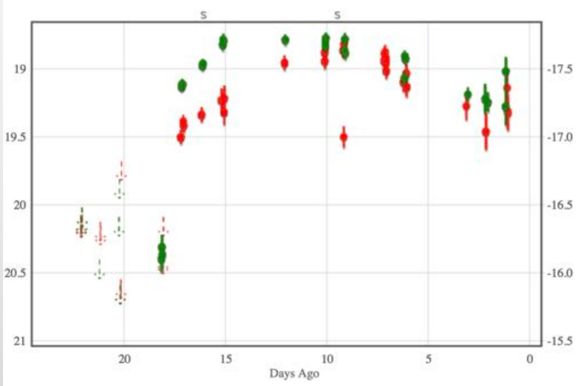
<u>Zwicky Transient Facility</u> ZTF

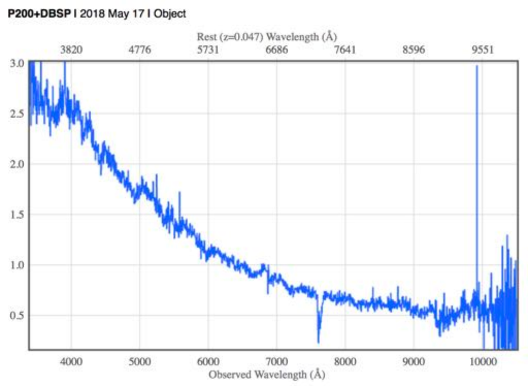
- Expected rate: 1..a few young (<1 day old) SN-II per week (to 20 mag)









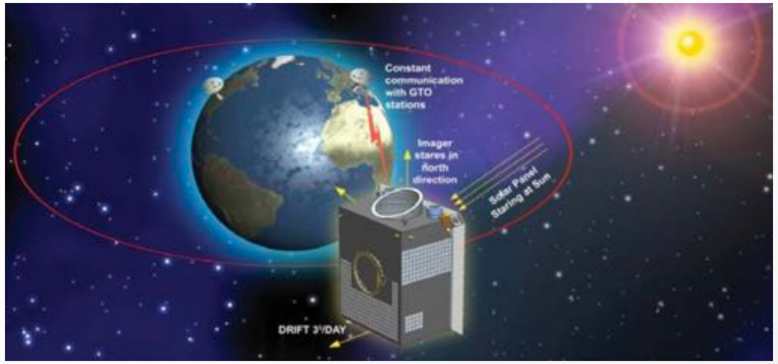


Example of a young type II from ZTF:

- Discovered May 8, with 2 days non-detection limit
- Spectrum at 8 days from discovery, just beginning to develop low-contrast P-Cyg lines.

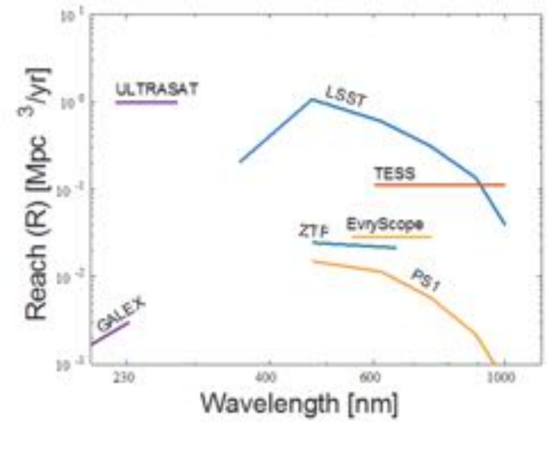
Discovered by ATLAS 2 d later, on May 10

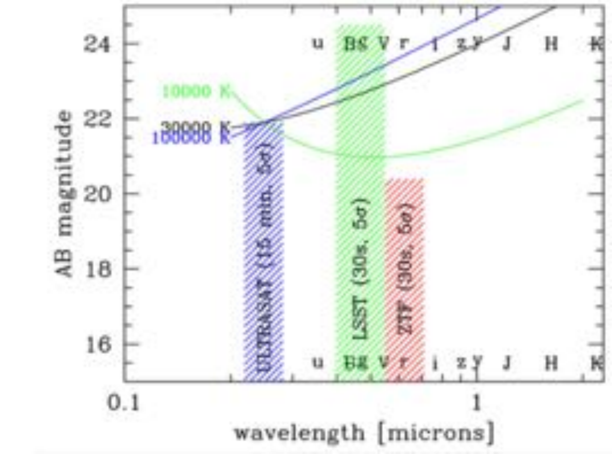
What to expect in the nearby future



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…

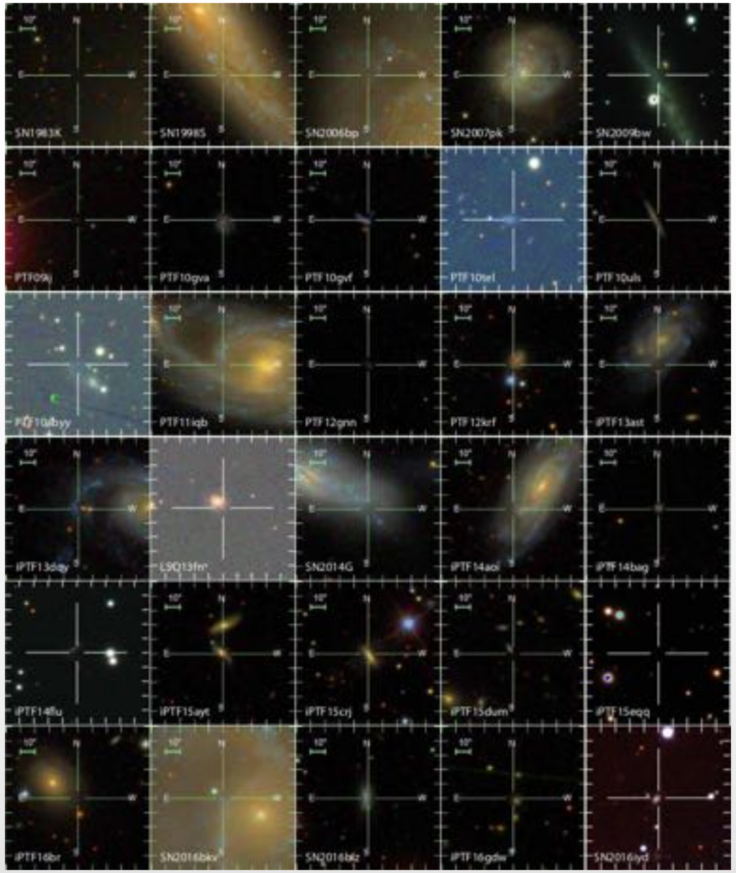
To conclude, take-home messages

- We have entered an era of < day 1 SN science - discovery and response.
- Early spectroscopy of CC-SNe directly probes the progenitor's ejecta, thus the progenitor's surface composition.
- It constrains the progenitor's mass-loss history, during the months-years prior to its demise; thus…
- Placing important constraints on the final stages of massive star evolution… as well as providing new sets of initial conditions for explosion models.
- We conclude that episodic enhanced (eruptive?) mass-loss by massive stars just prior to their terminal explosion, as proposed by several theoretical studies, also occurs among the progenitors of common types of CC-SNe.
- A continuum of CSM configurations exist, now verified by observations, extending from the short-lived *FS* events to the extended massive CSM of the "standard" (sustained interaction emission) Type IIn SNe.
- 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.

To conclude, take-home messages

Utilizing cutting-edge technology (wide-field surveys operations and facilities), it is OUR - the observers' - role to provide theorists and modelers of stellar evolution and stellar explosions with the required initial conditions and constraints, by gathering information from within the very first hours [and minutes] of SN explosions!

Thanks



Hosts of “flash-spectroscopy” events (Johansson, in prep.)