Shock-Breakout Flash Emission Spectroscopy of Young Supernovae:

A New Window into the Evolution and Death of Massive Stars

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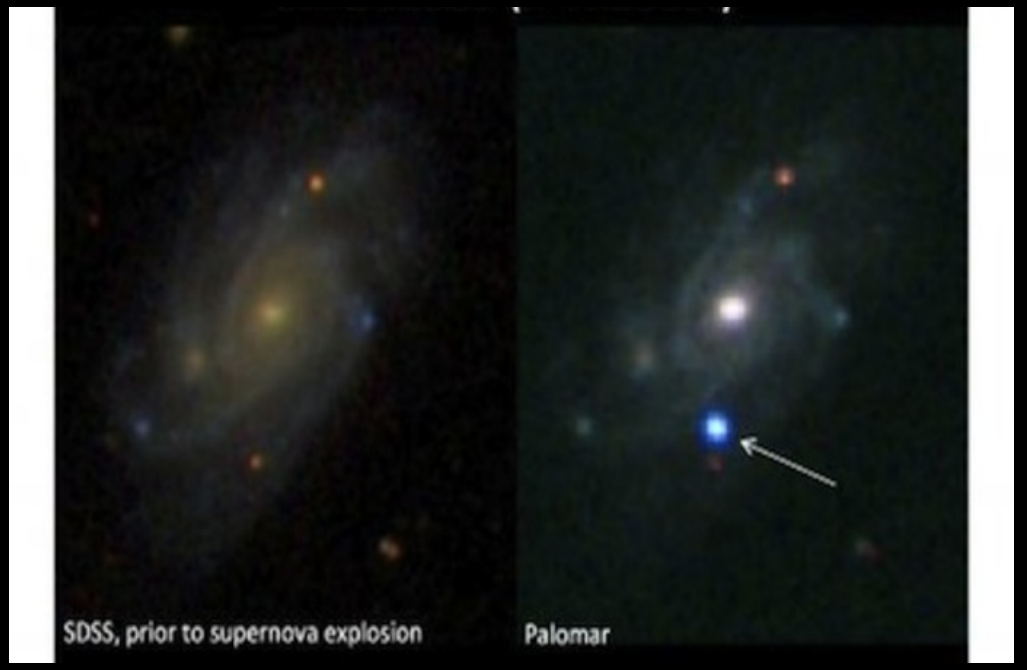
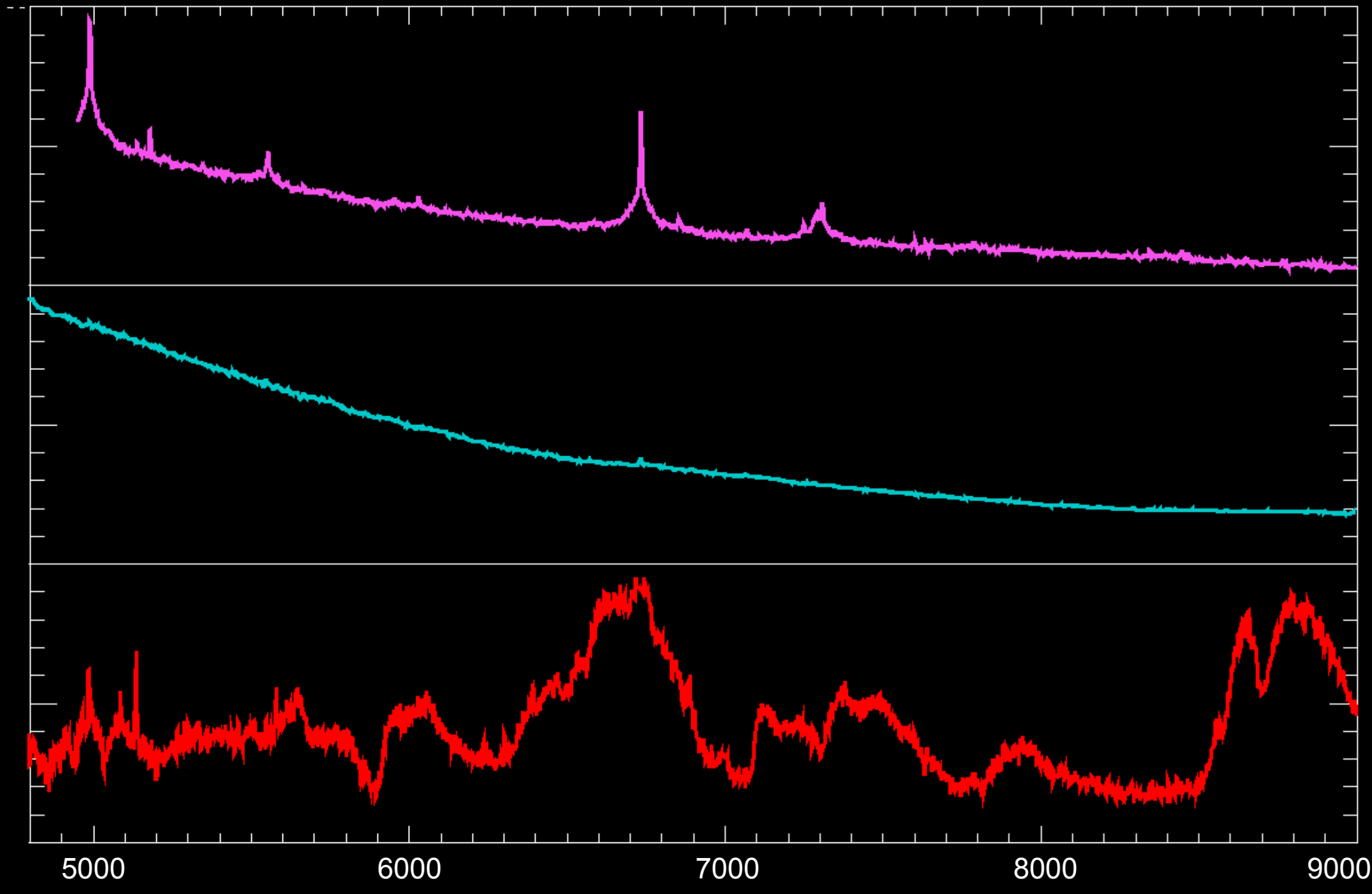


Three Supernova Spectra



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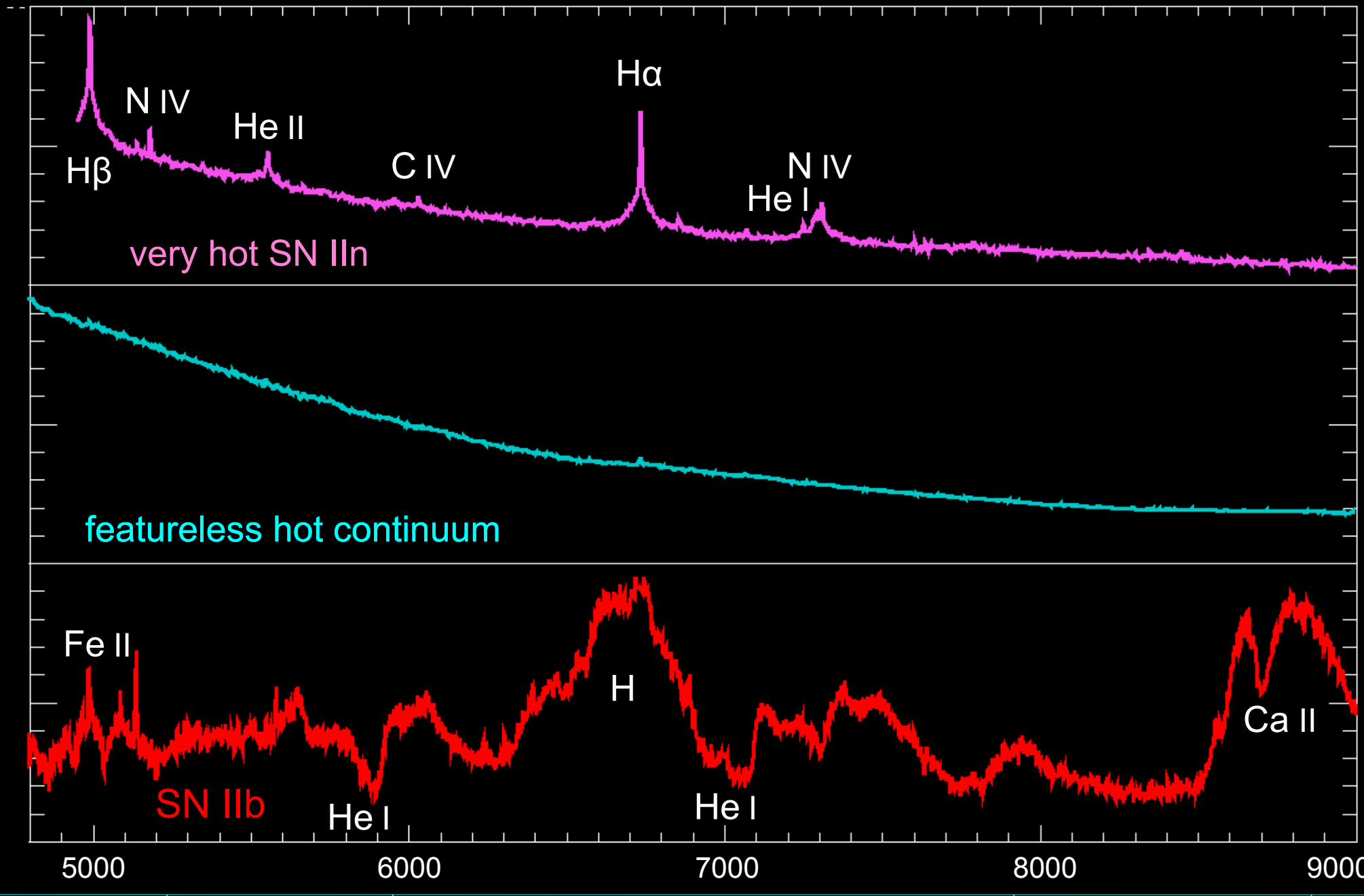

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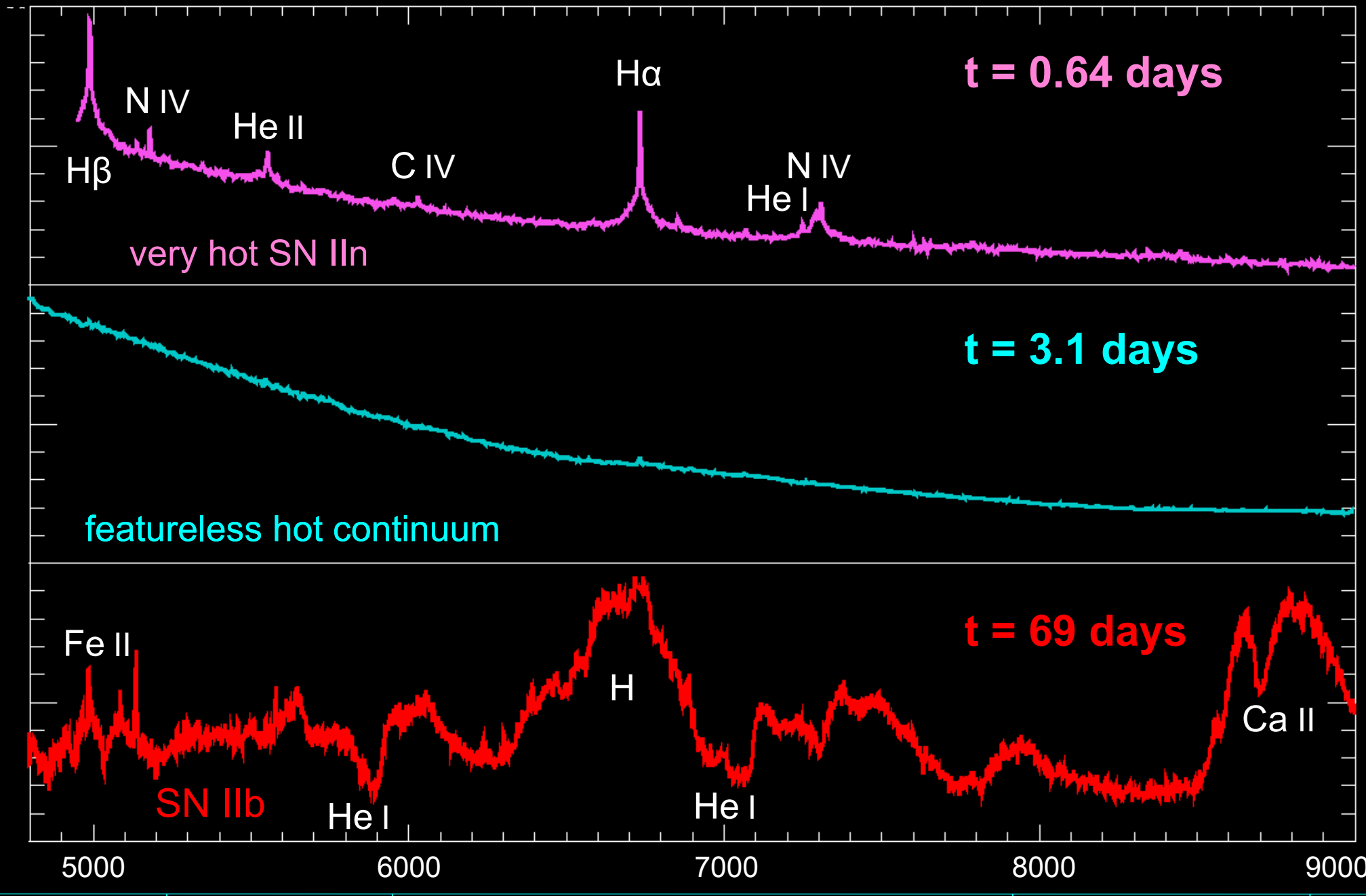
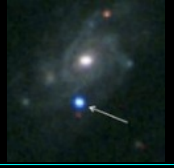
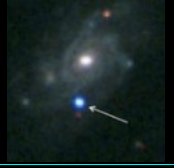




Palomar Transient Factory



Palomar Transient Factory

PTF → IPTF

PTF (2009-2012):

Various strategies, but typically **3-day cadence**.

Find large numbers of transients.

Intermediate PTF (2013-present):

Various strategies, but typically **1-hour cadence**.

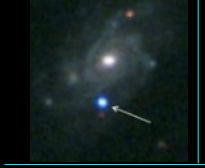
(3 visits per night, every night)

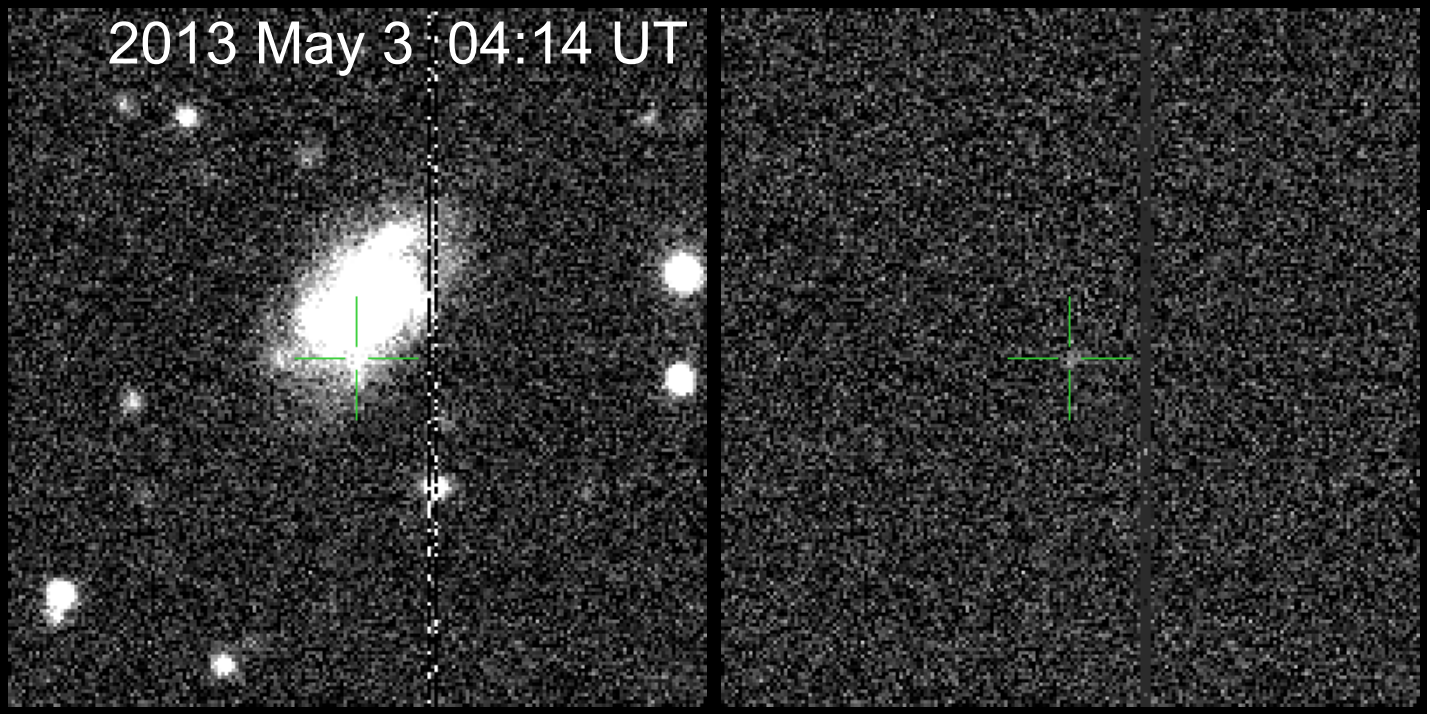
Find new types of fast-varying transients, and

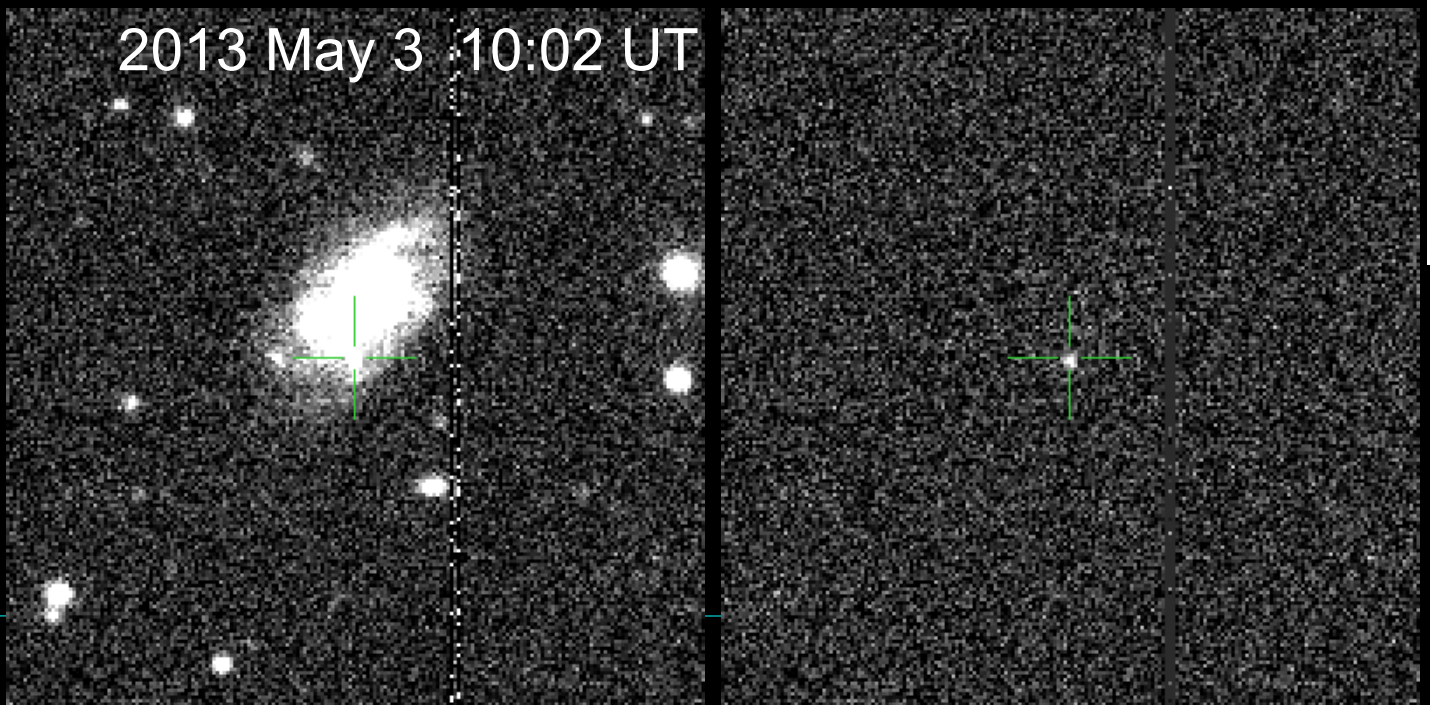
find "ordinary" supernovae very early.

IPTF “Night Shift”

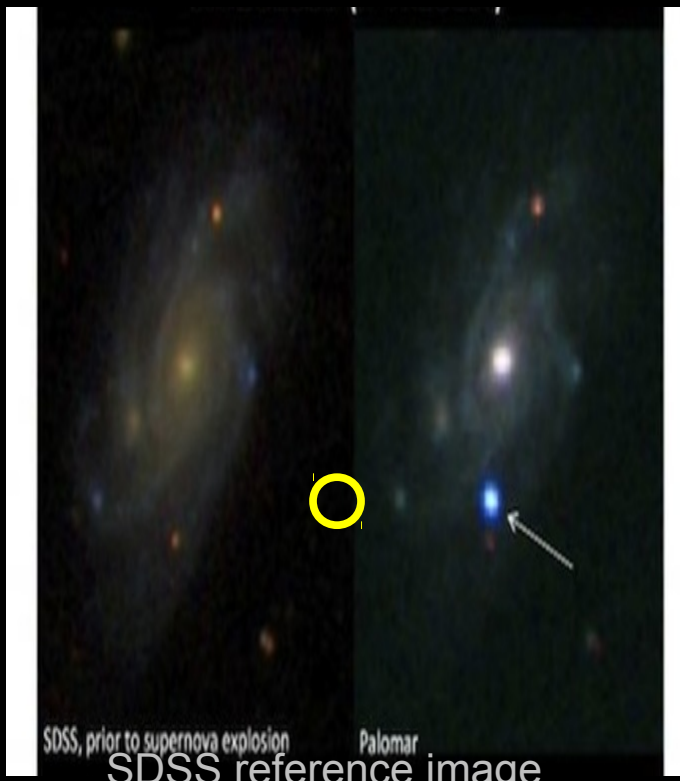
IPTF 13ast







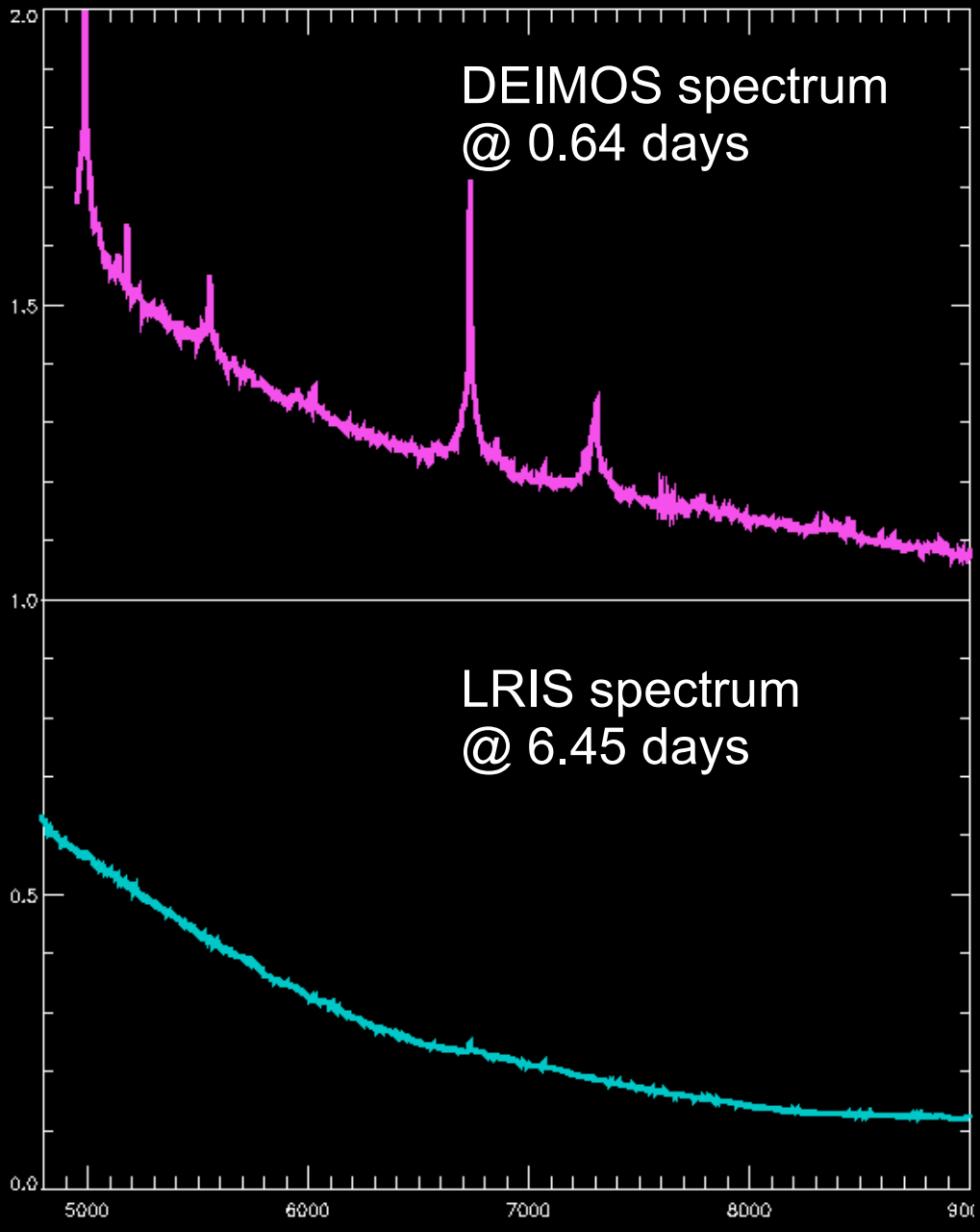
UGC 7610
(D = 108 Mpc)

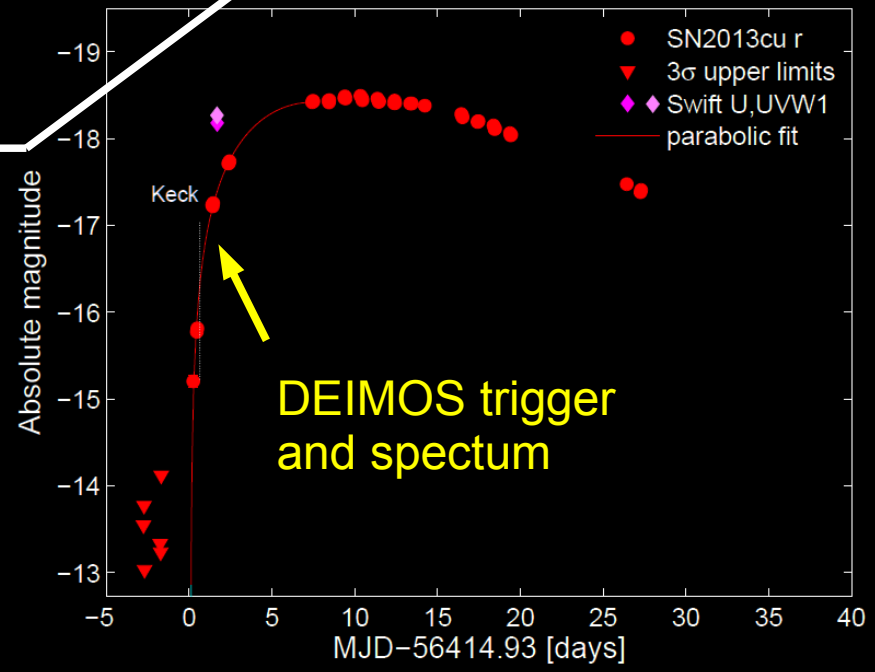


SDSS reference image

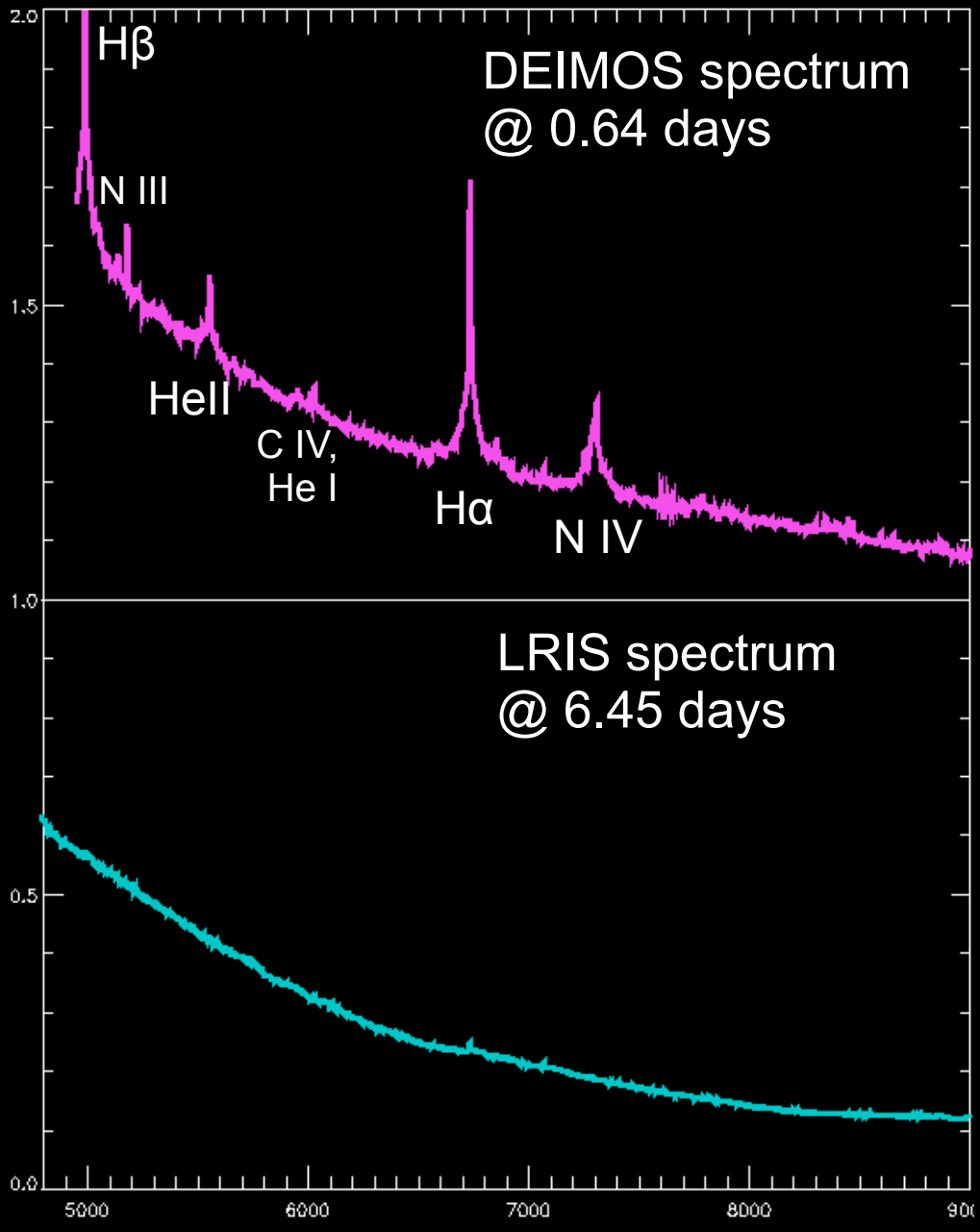
(Gal-Yam+2014,
Nature 509:471)

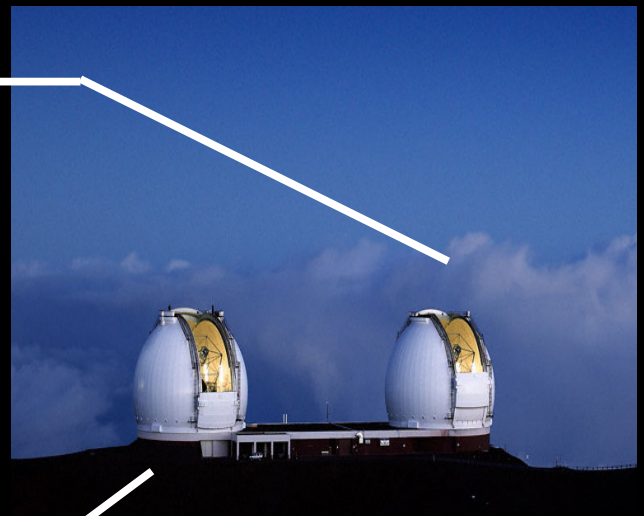
Keck Observations

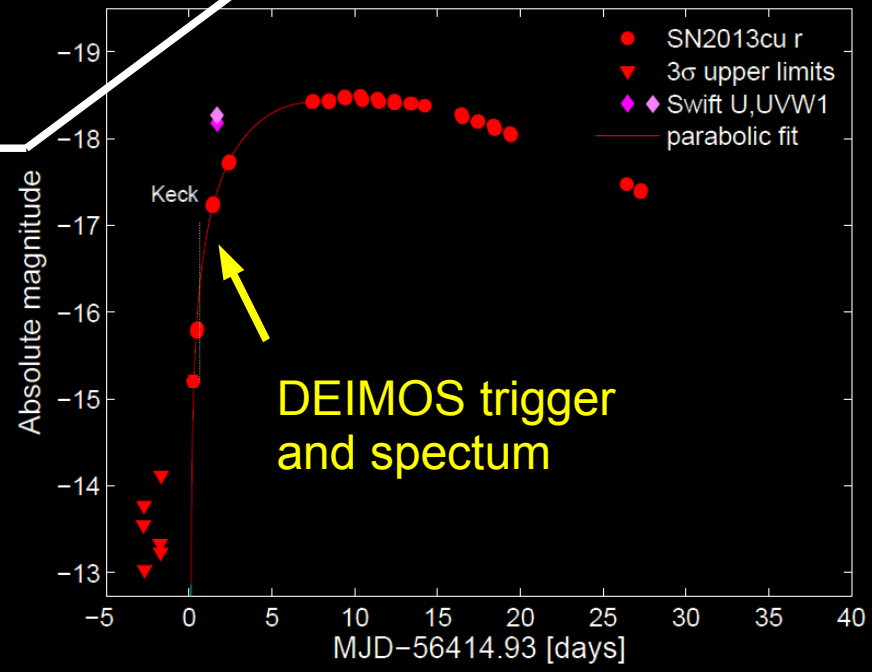




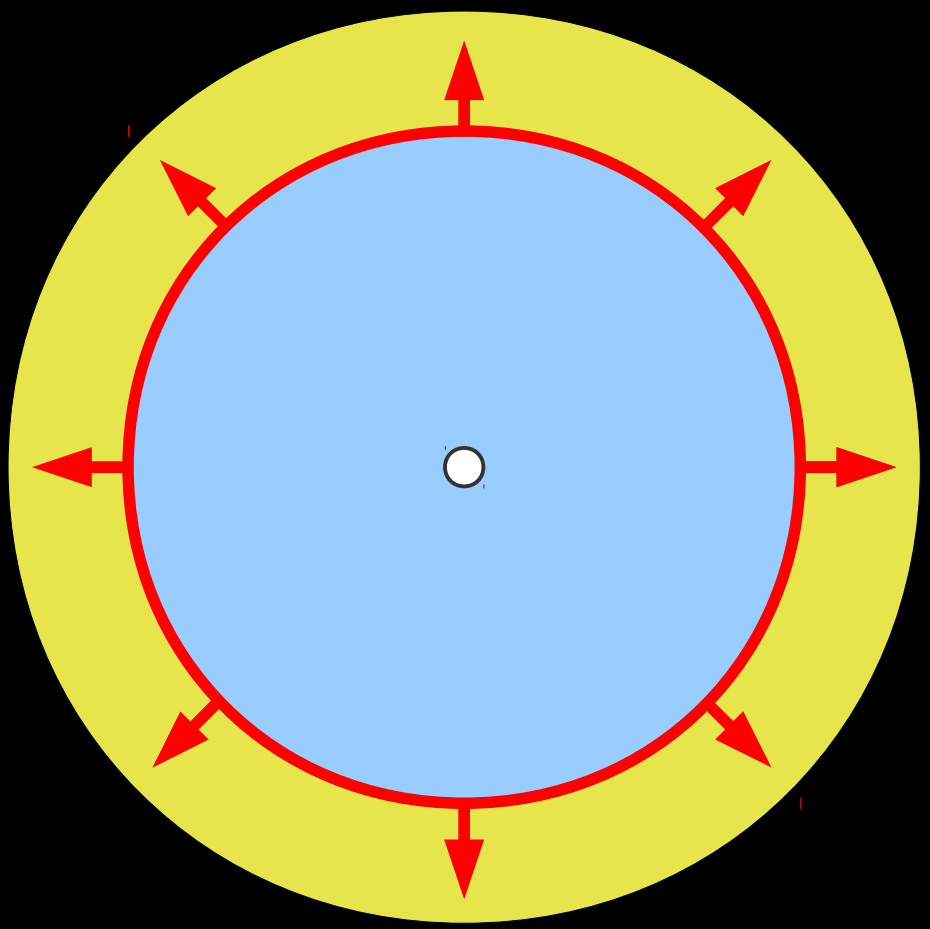
Keck Observations

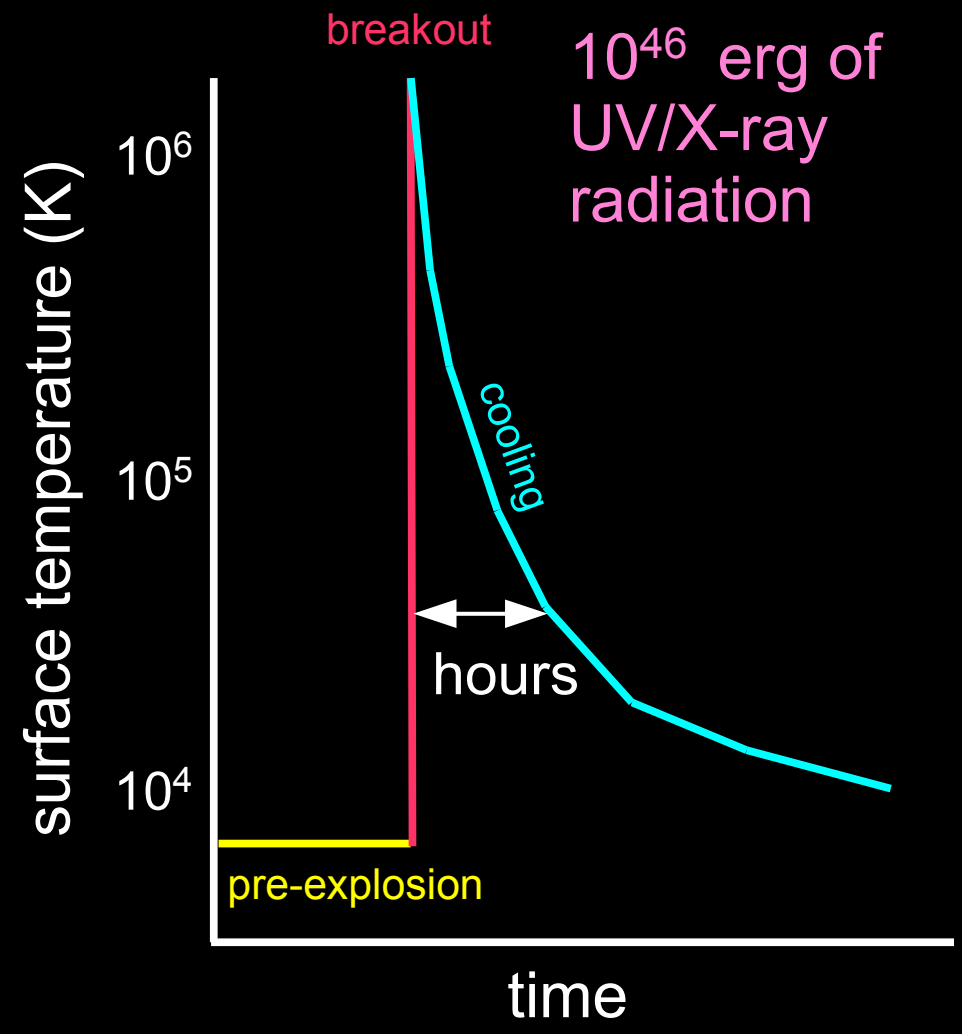




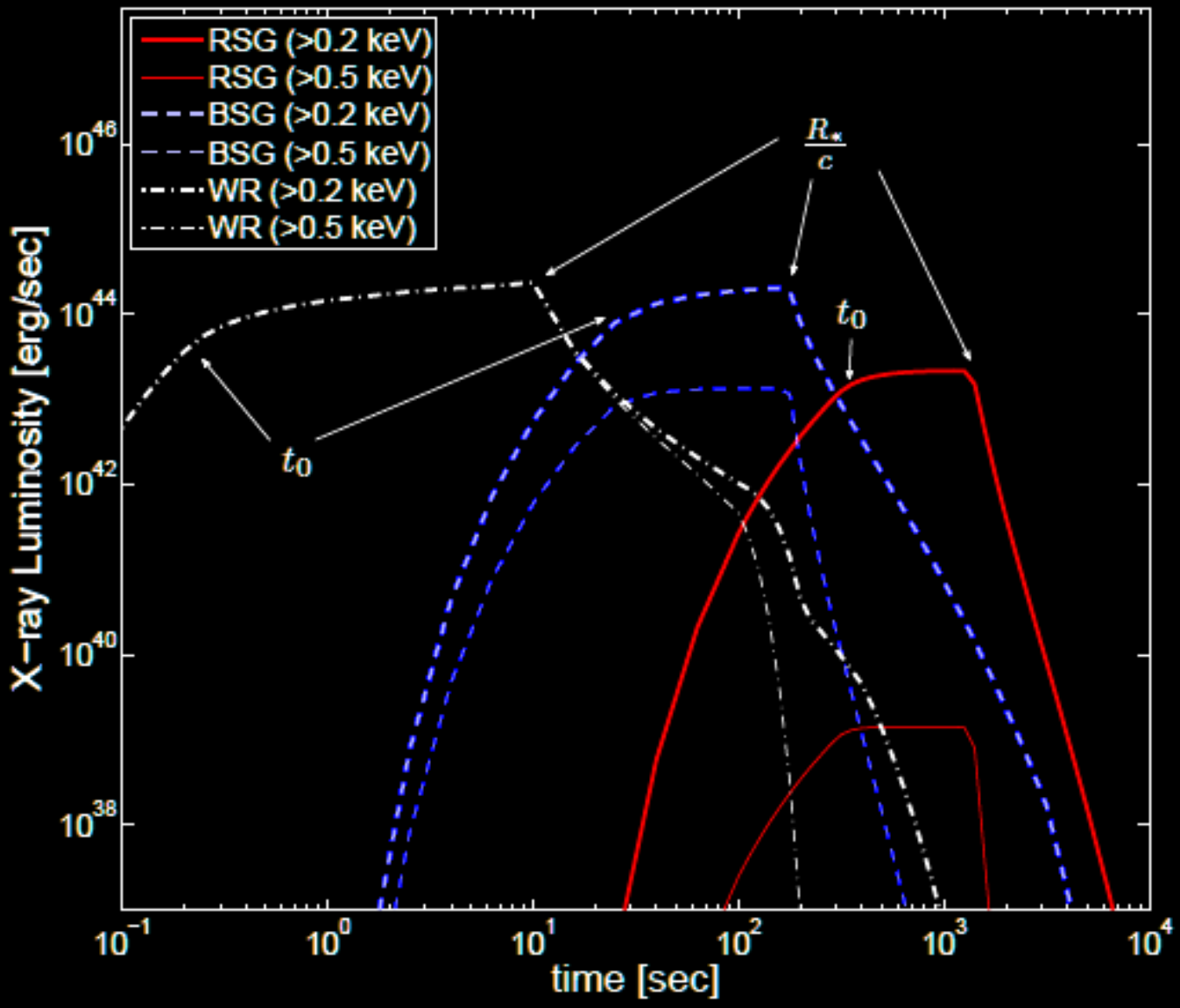


Supernova Shock Breakout

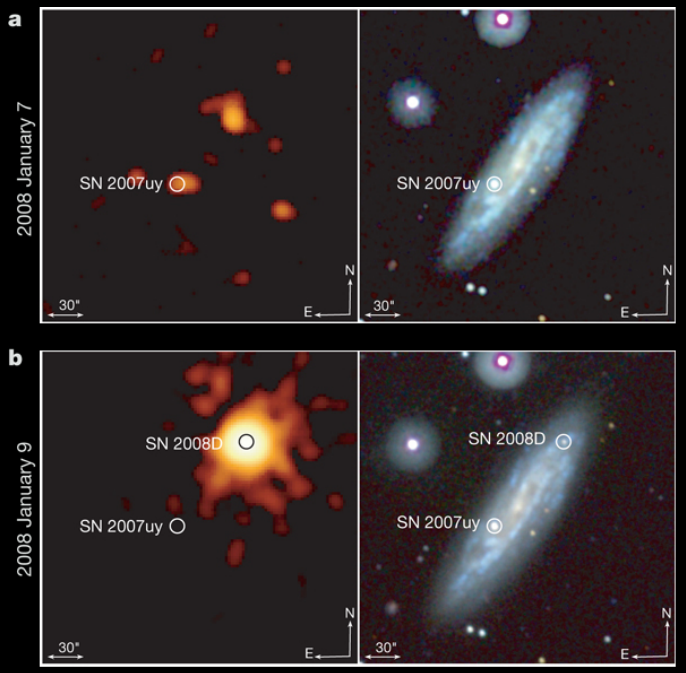


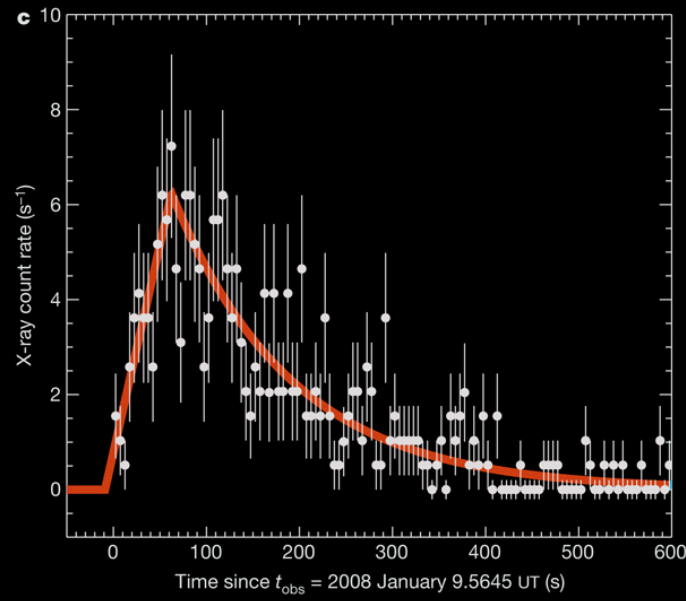


Shock Breakout Light Curves

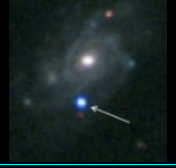


Nakar & Sari 2011

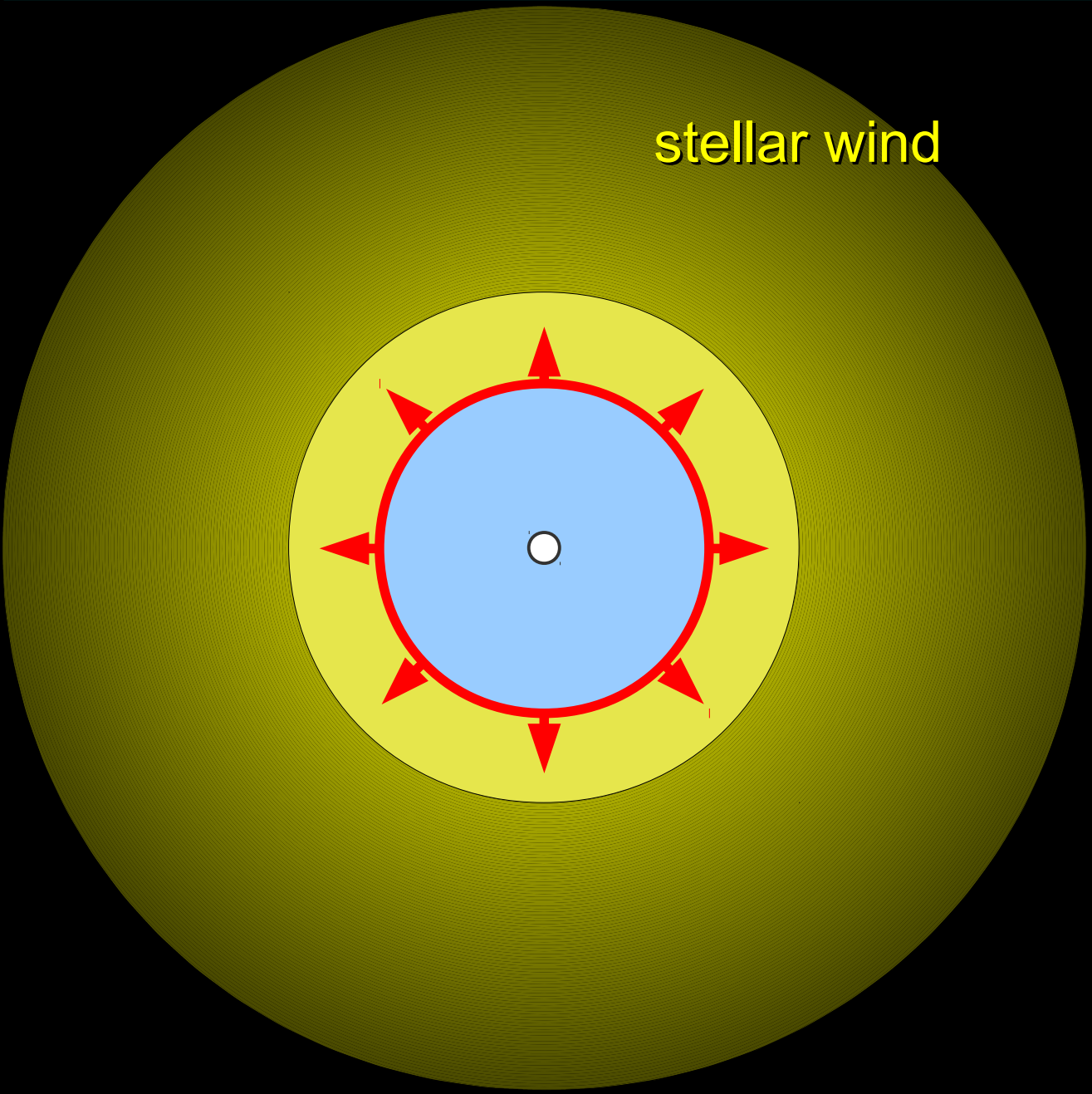


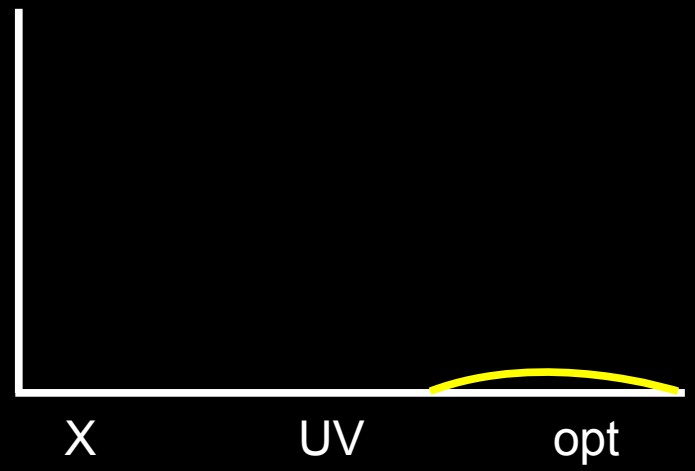


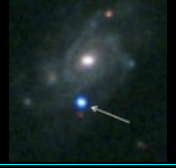
Soderberg et al. 2008



Shock Breakout Below a Stellar Wind







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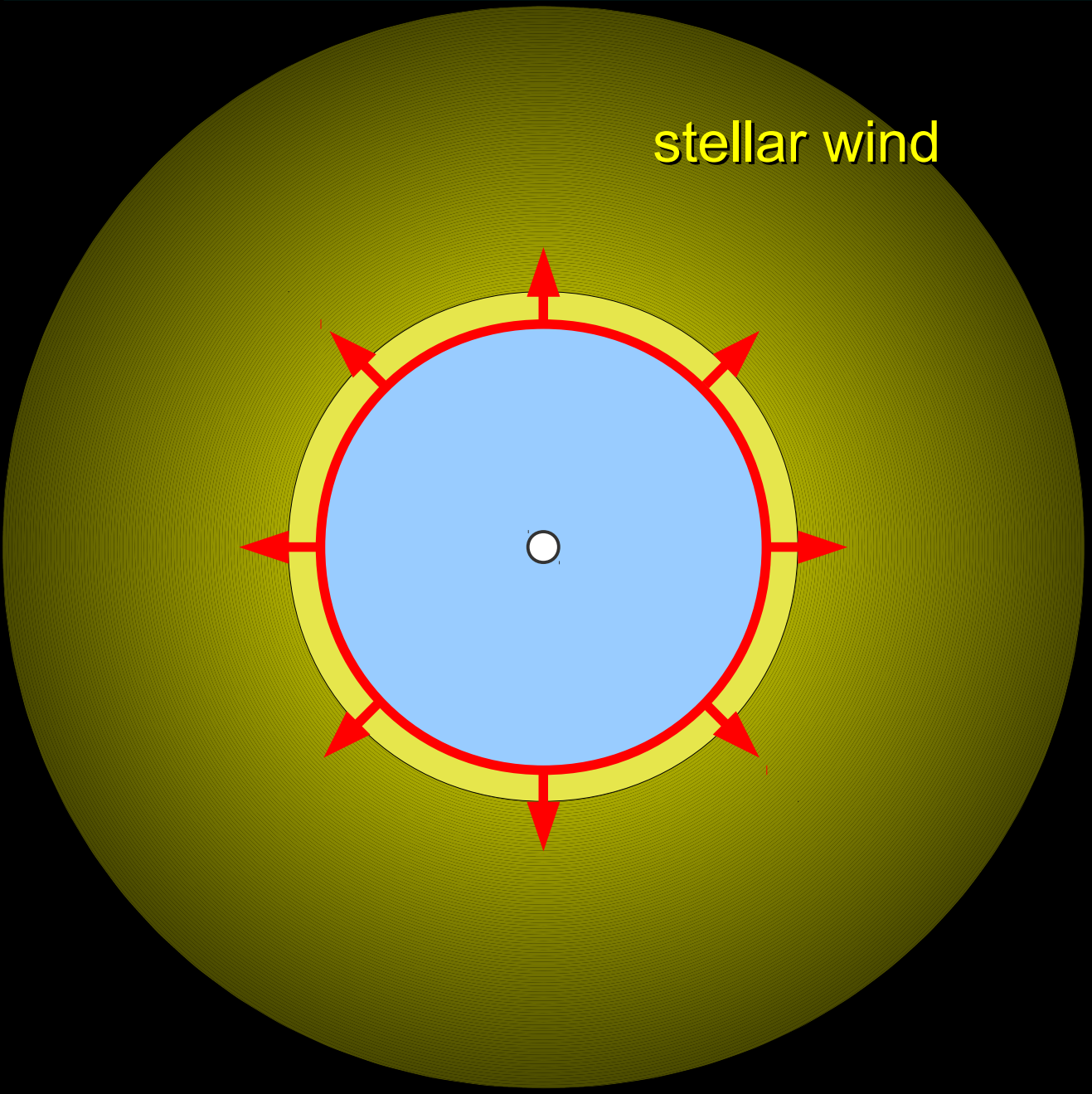
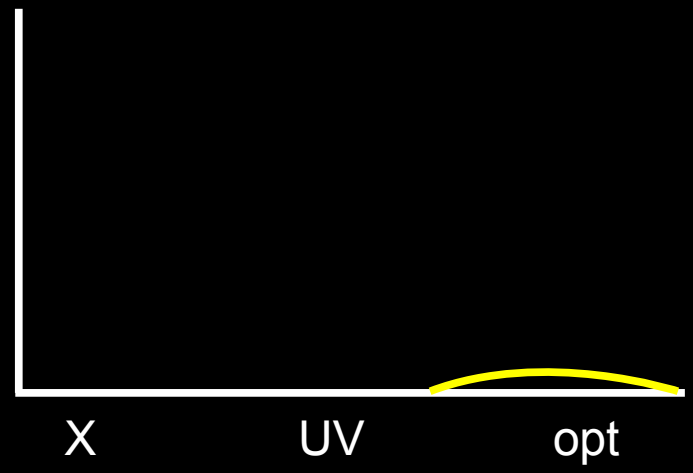
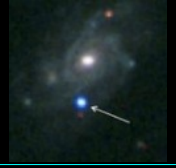




(spectrum just above stellar surface)



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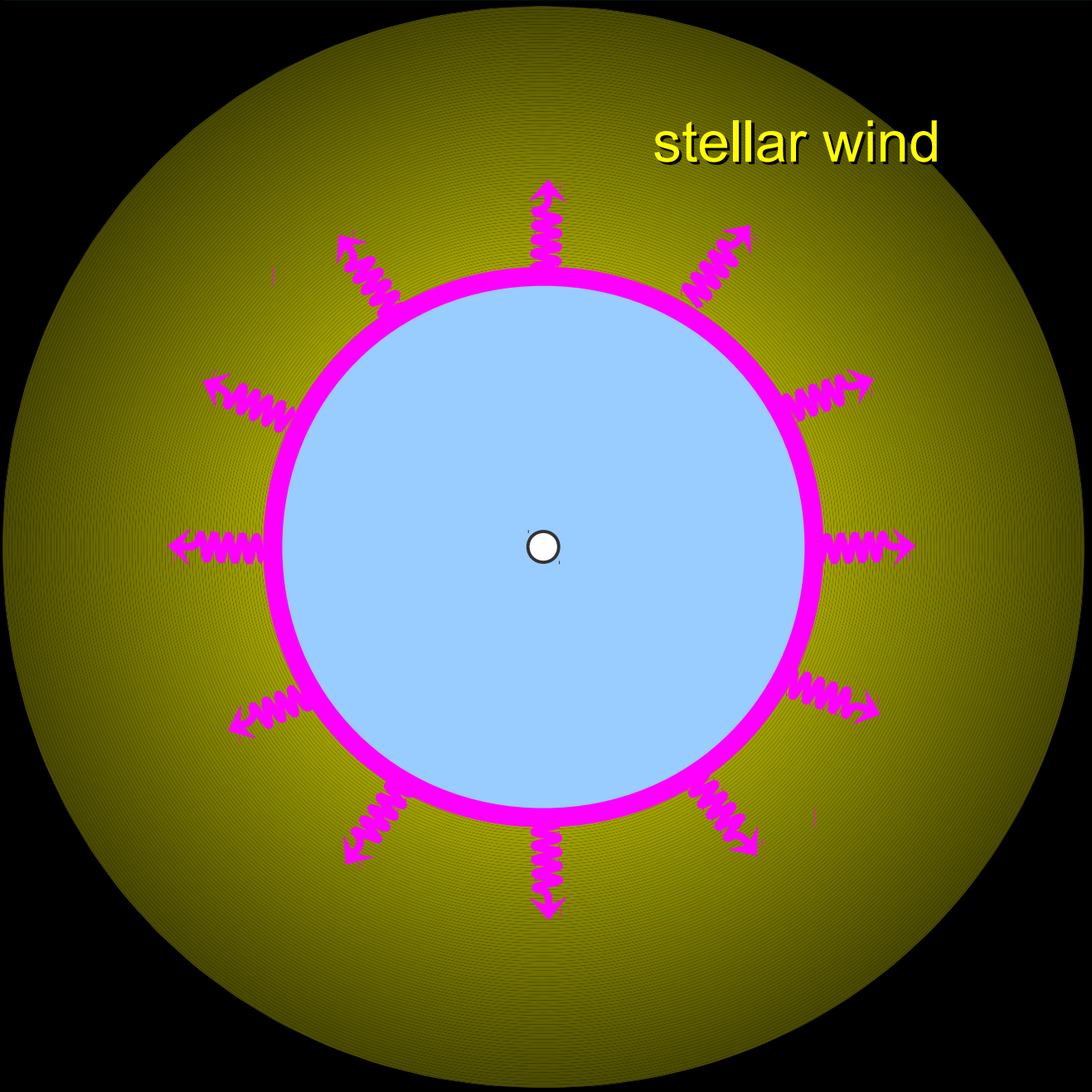

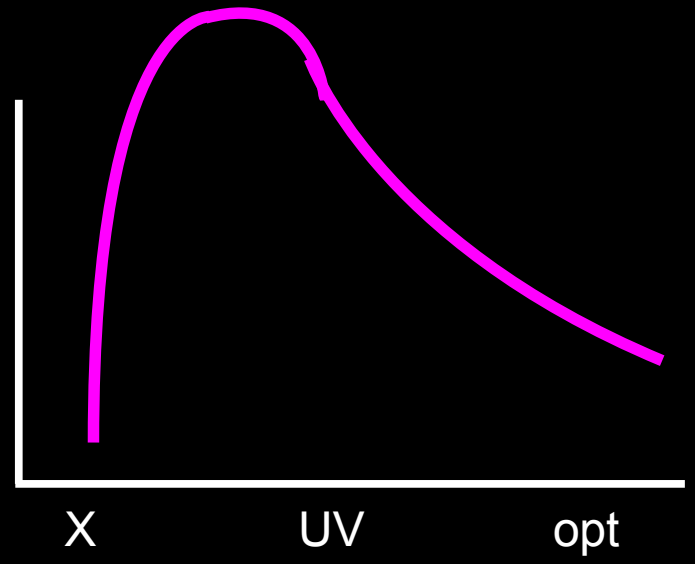

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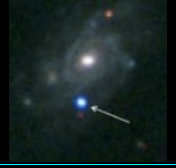

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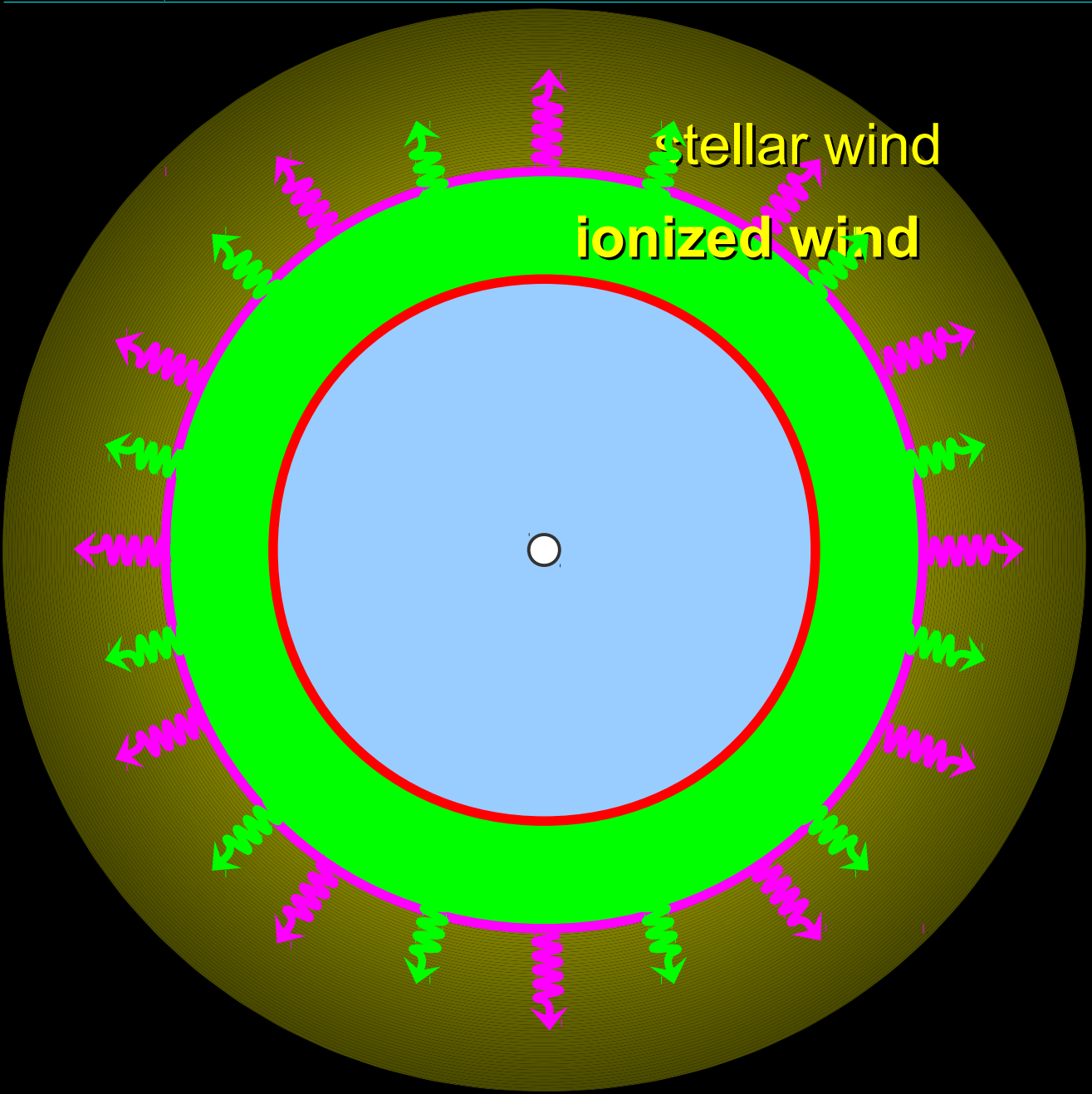

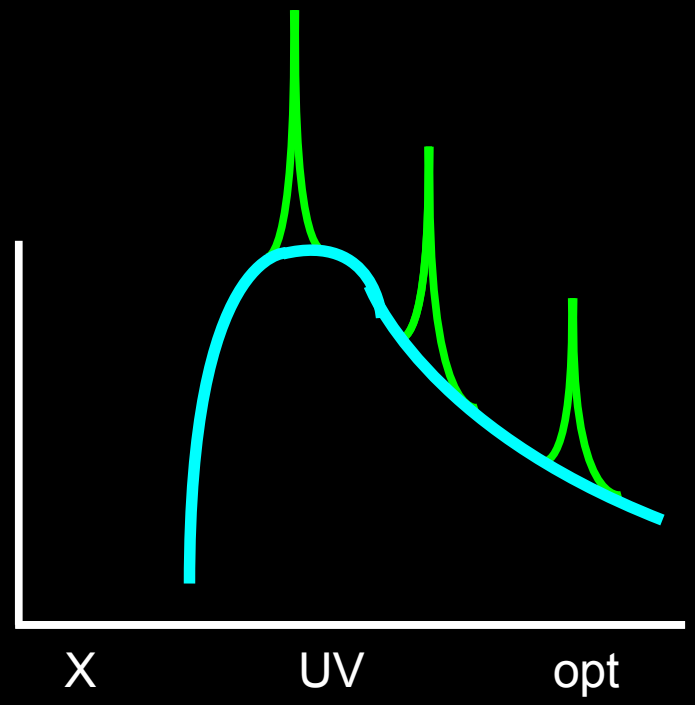

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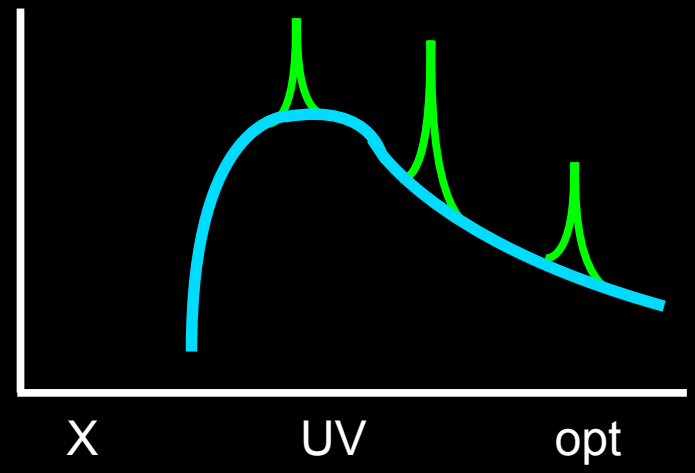

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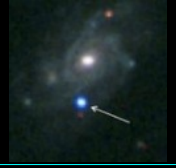

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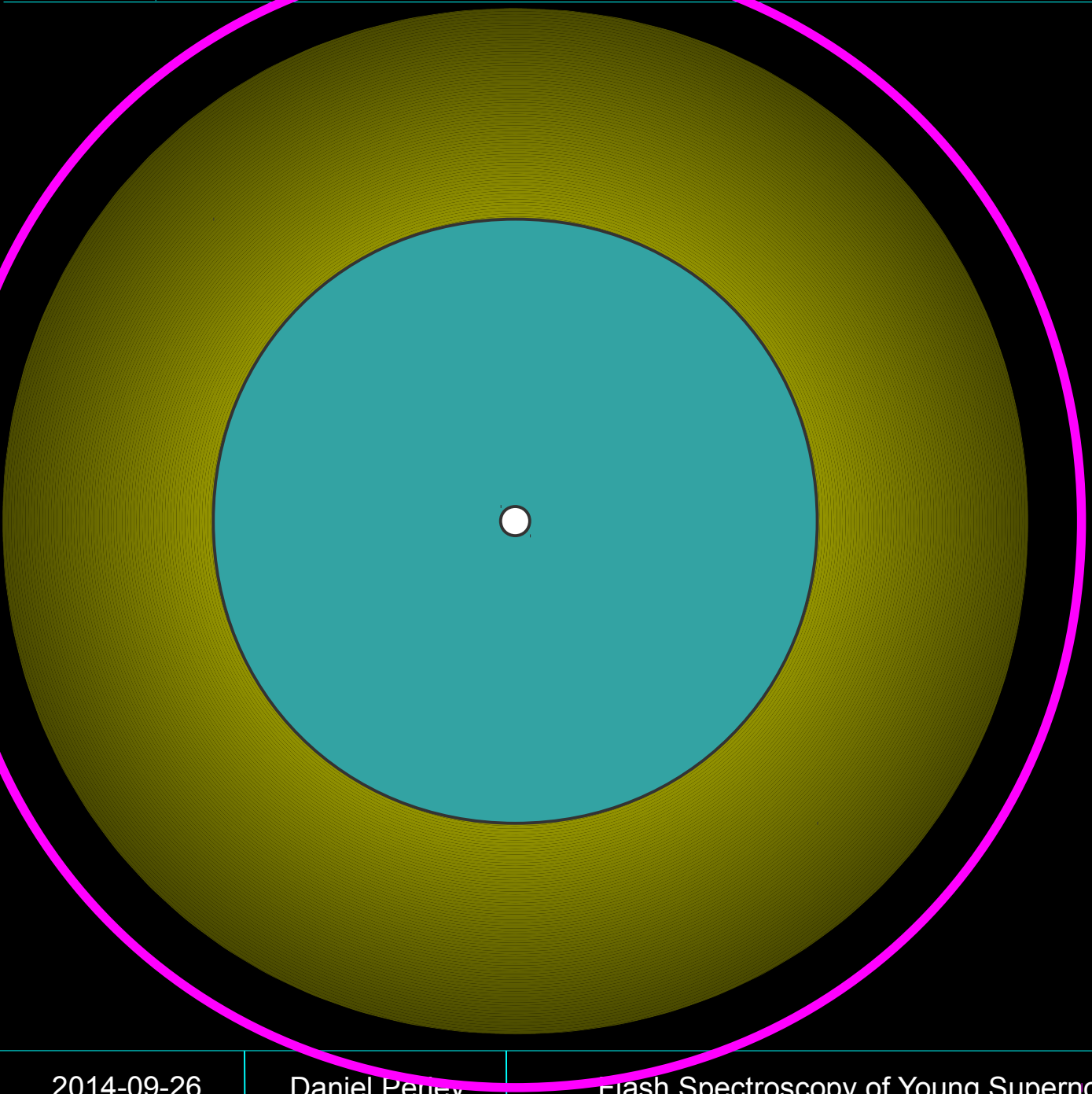
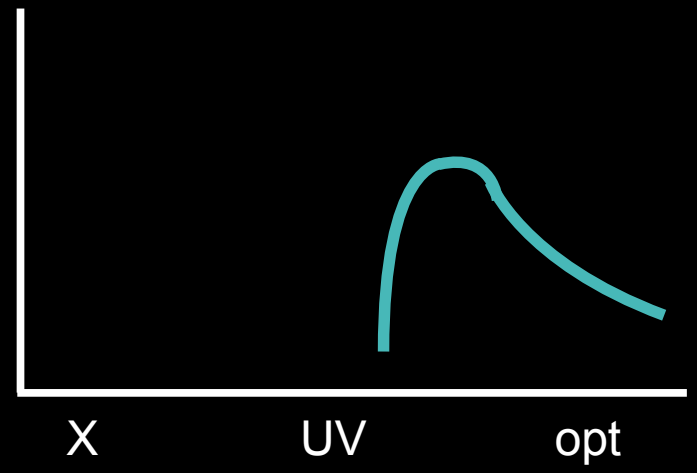
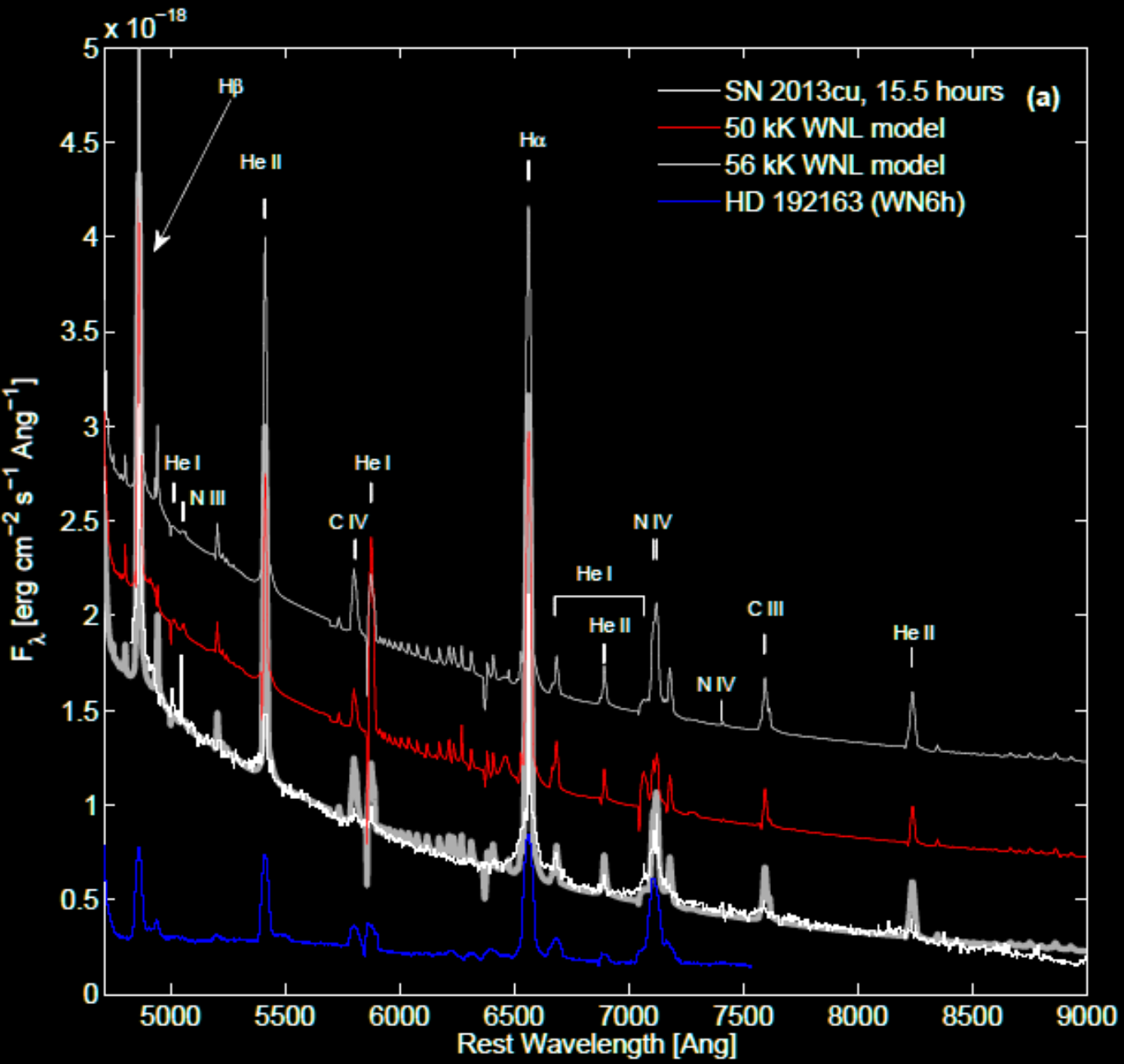




(spectrum just above stellar surface)

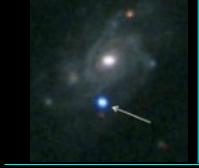
Flash Spectroscopy: Progenitor Diagnostic



Flash-excited spectrum resembles a Wolf-Rayet star of type WN(h)

(No oxygen: CNO-processed material is exposed in wind)

IIb progenitor *is* a WR?
Perhaps not (Groh 2014),
but evolutionary link probably exists



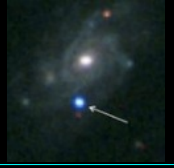
Pre-Explosion Behavior

Hα luminosity constrains **mass-loss rate** (for inner wind; probes material emitted in last ~10 years pre-explosion)

$$\sim 10^{-2}\ M_{\odot}/yr$$

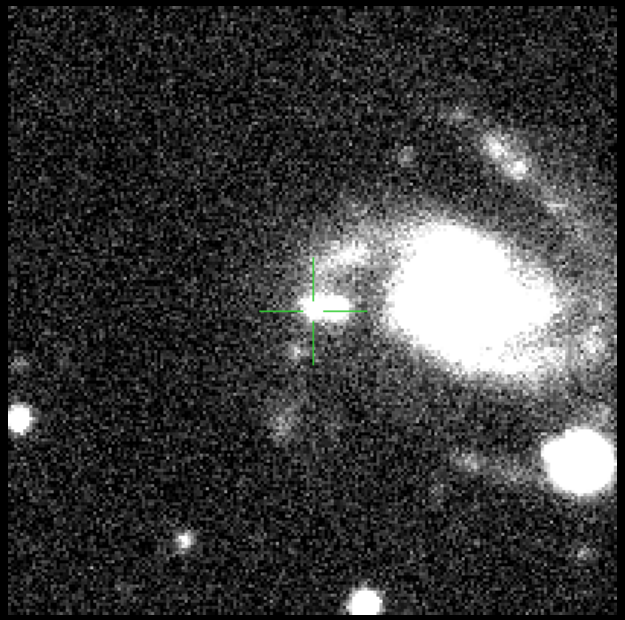
Extremely rapid mass loss!

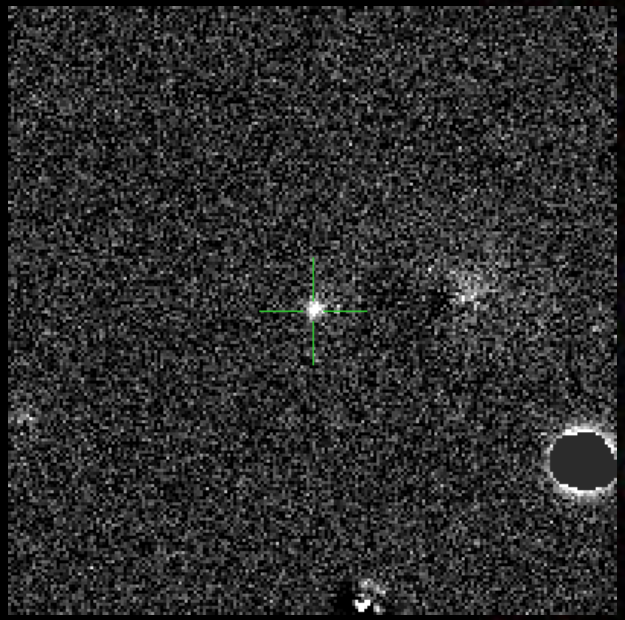
Cannot be steady-state and very unlikely to be coincidental: star was highly unstable just before explosion (onset of C burning...?)



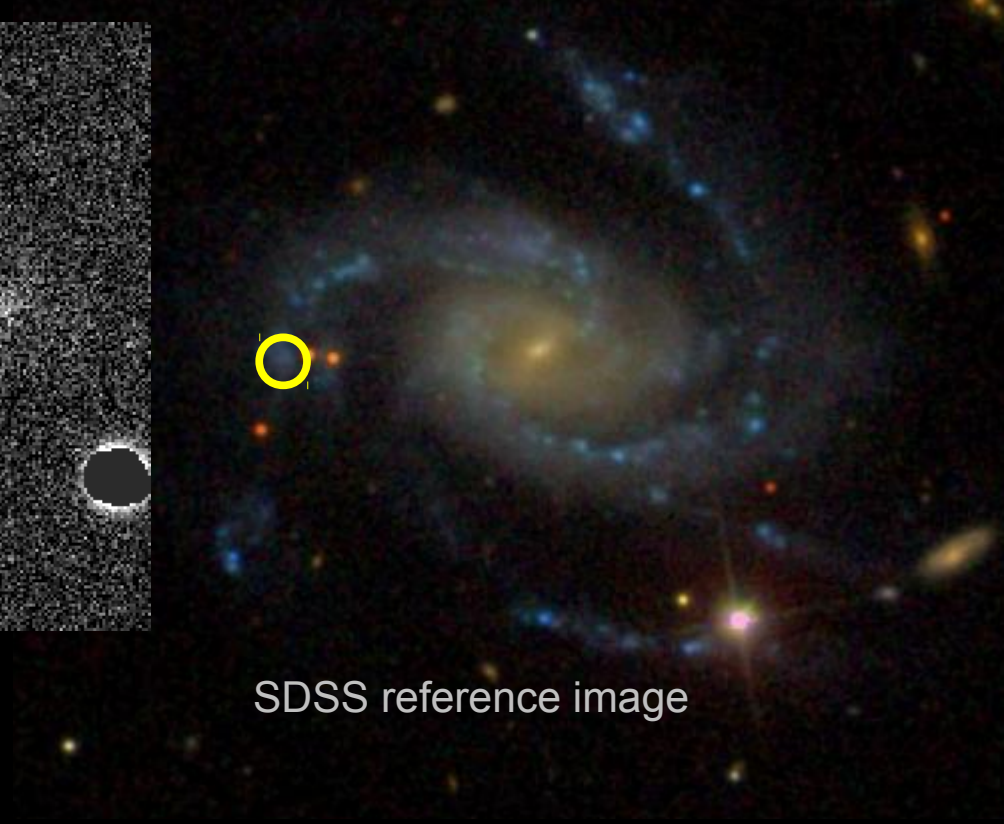
IPTF 13dqy

2013 October 8





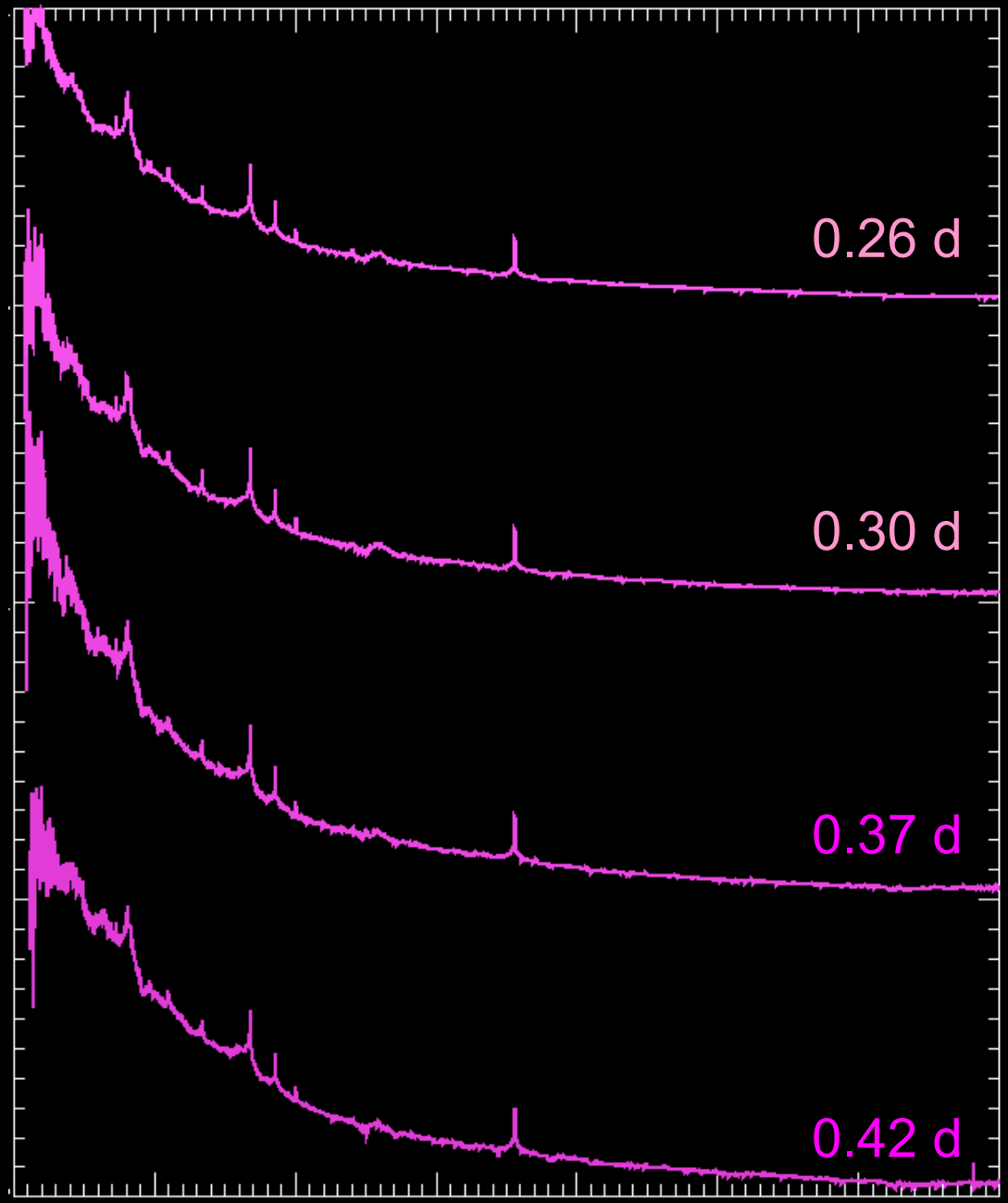
NGC 7610 (D = 51 Mpc)

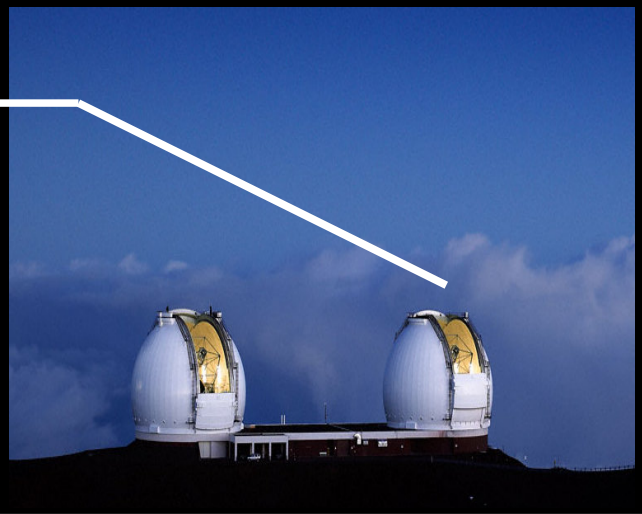


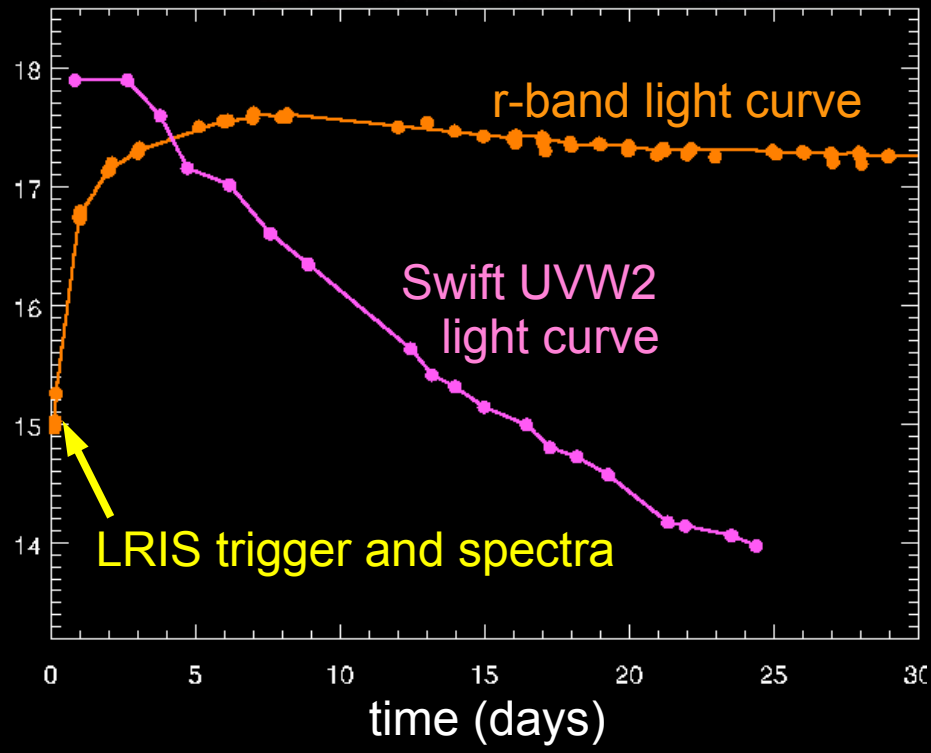
SDSS reference image

(Yaron+2014 in prep – still a work in progress)

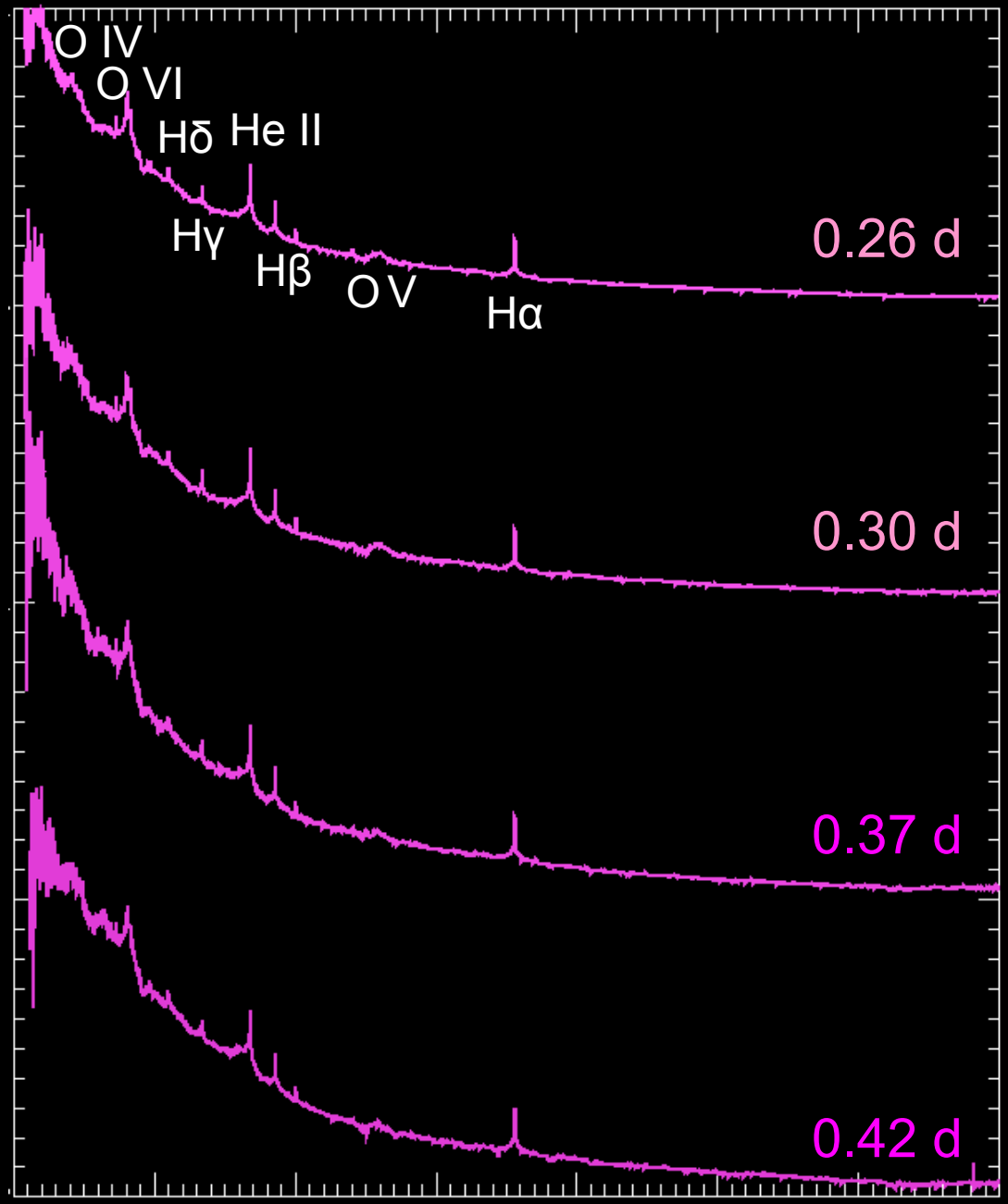
Early Keck Observations

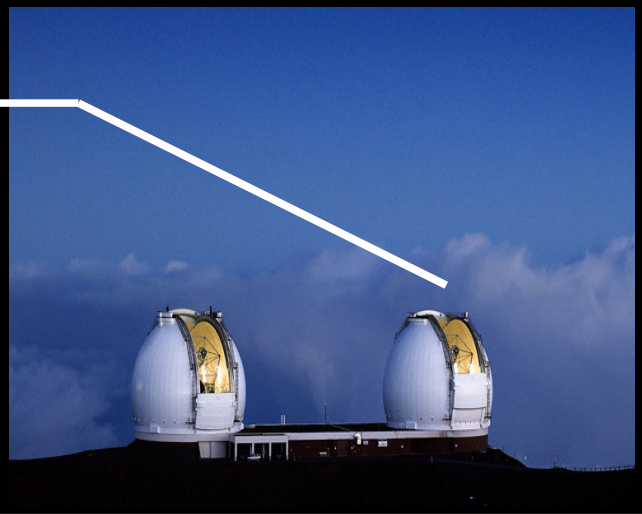


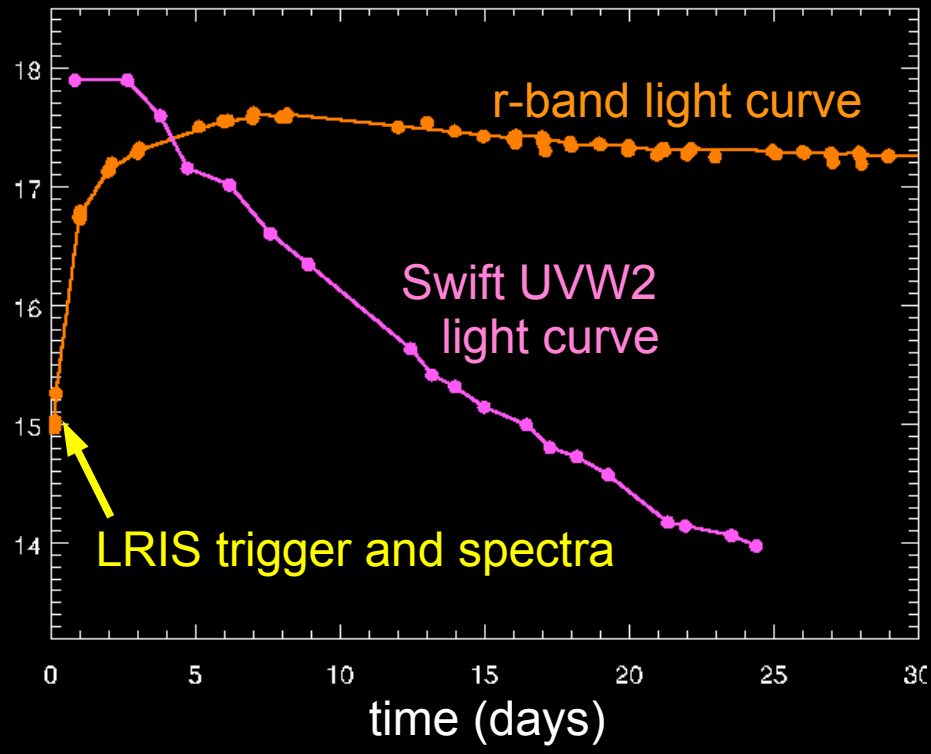




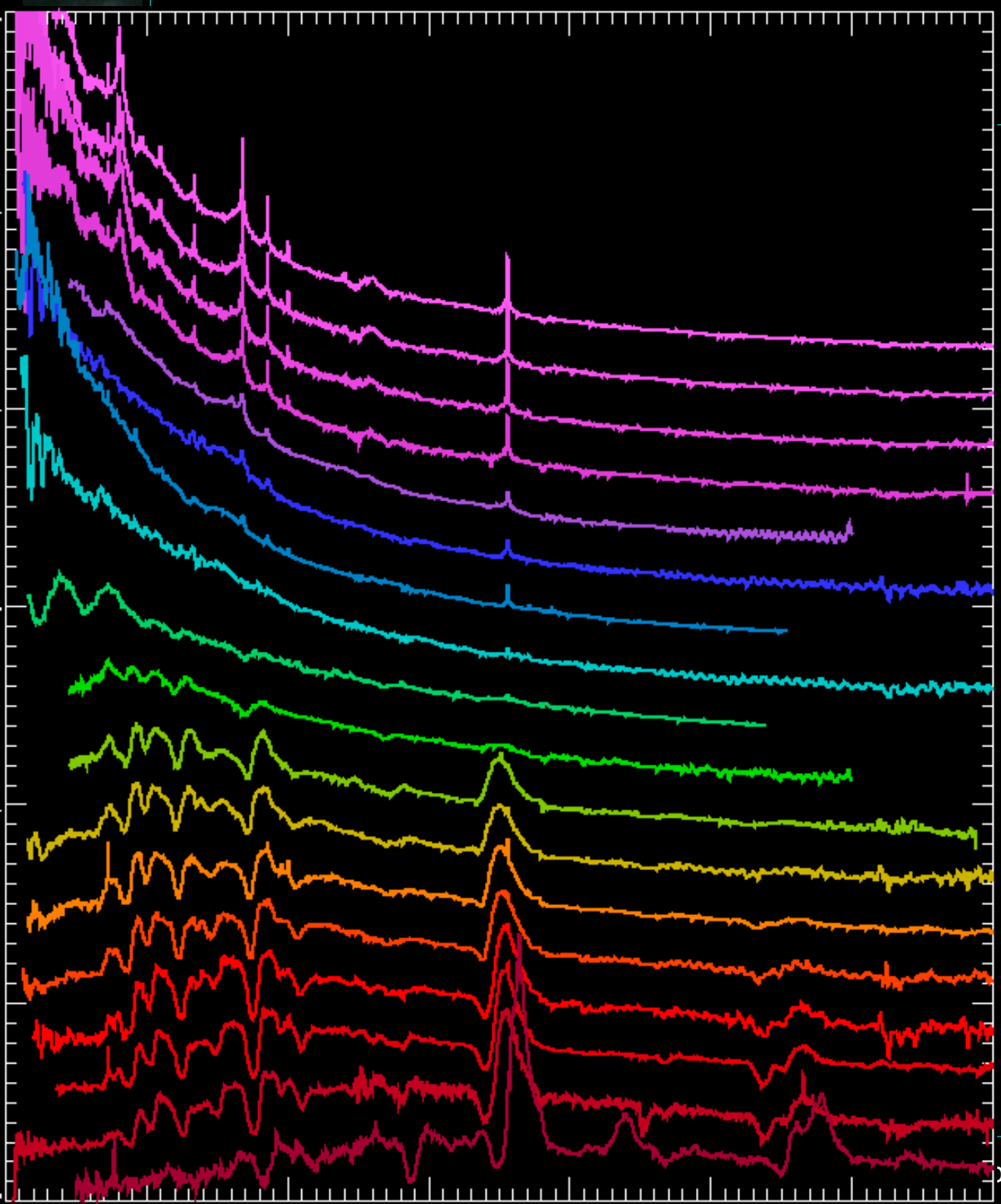
Early Keck Observations







13dqy Spectra

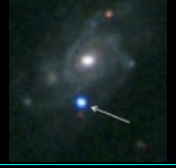


0.26 d
0.30 d
0.37 d
0.42 d
0.88 d
1.4d
2.0d
5.3d
8.8d
10.9d
20.2d
22.4d
27.1d
31.3d
43.3d

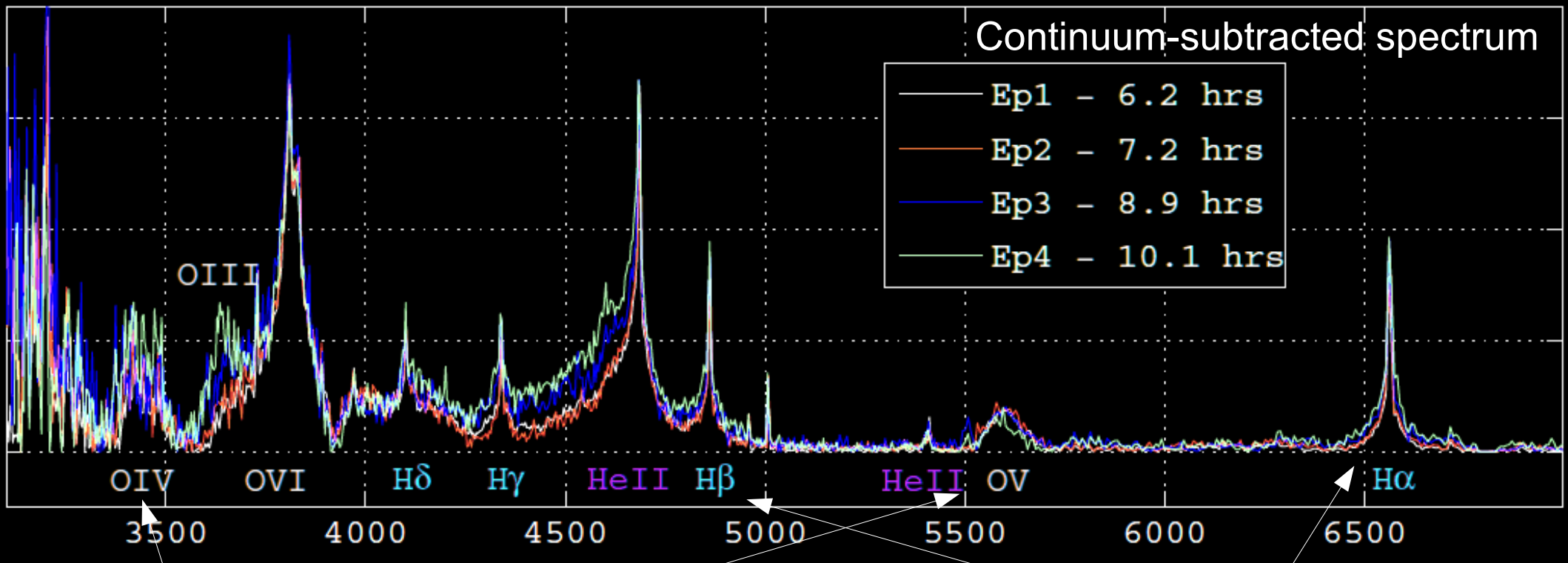
Flash-excited narrow lines

Hot continuum

II-P supernova



Line Profiles

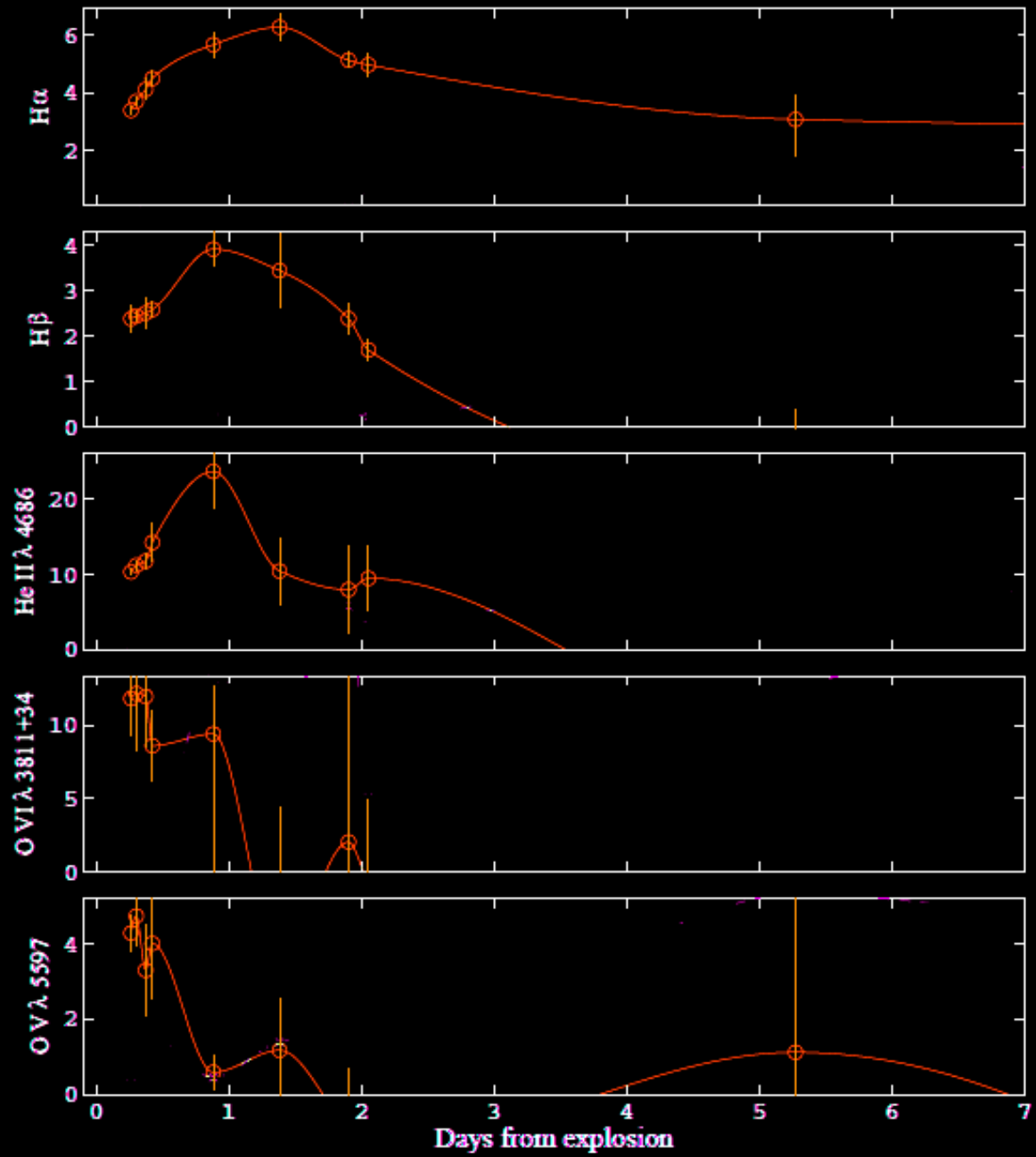


O IV, O V:
No narrow core,
Broad component *only*
(all material is inner; $\tau >> 1$)

but, O VI has a weak narrow component?

H I, He II:
Narrow core (recombination of outer material) +
Broad wings (Thomson scattering of inner material)

Line Flux Evolution

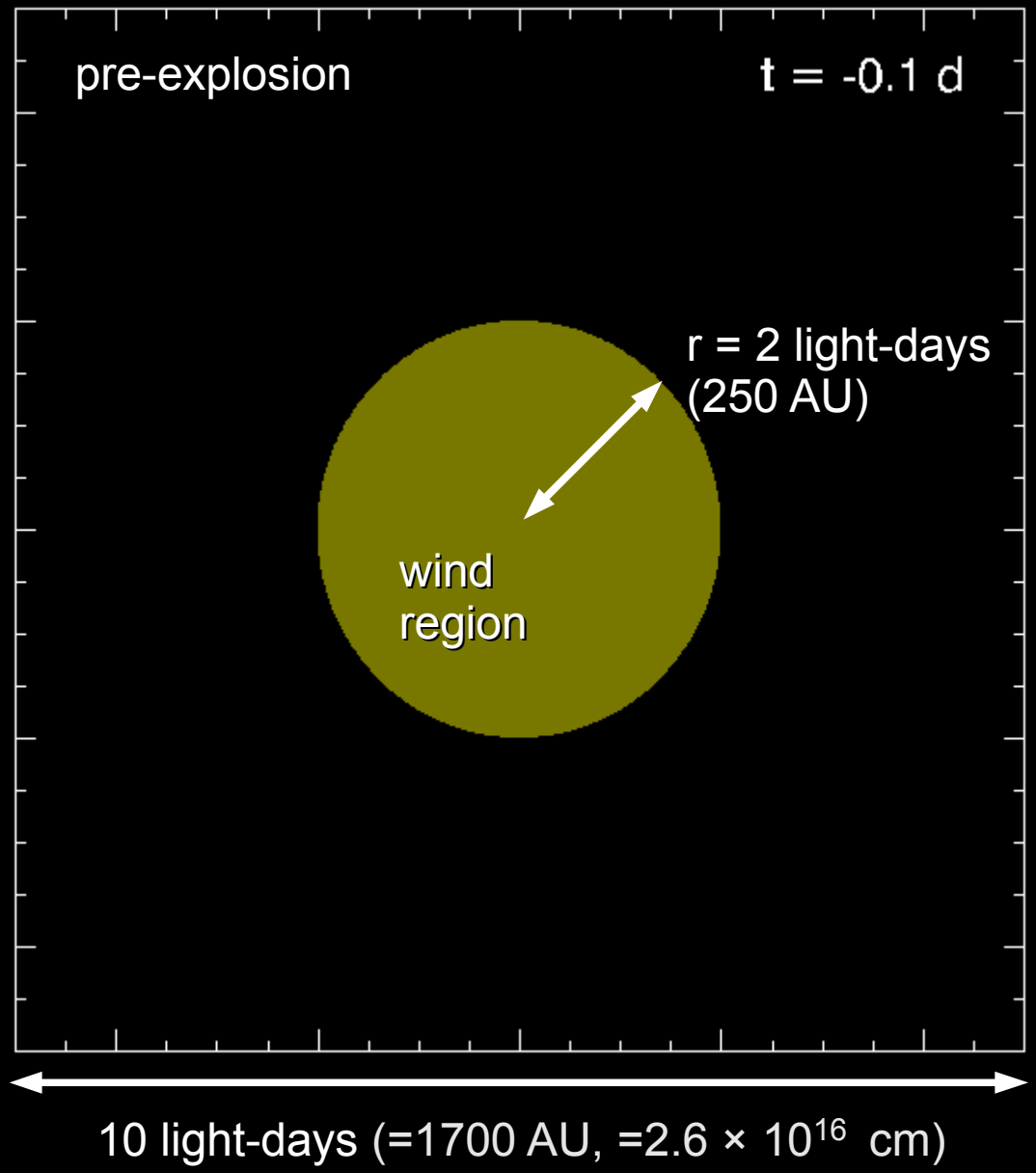


Hydrogen peaks at ~1.5 d; disappears between 6-8 d

He II peaks at ~1.0 d, disappears between 2-5 d

O V, O VI peak at <0.3 d and disappear by 2 d

Wind Light-Propagation Model



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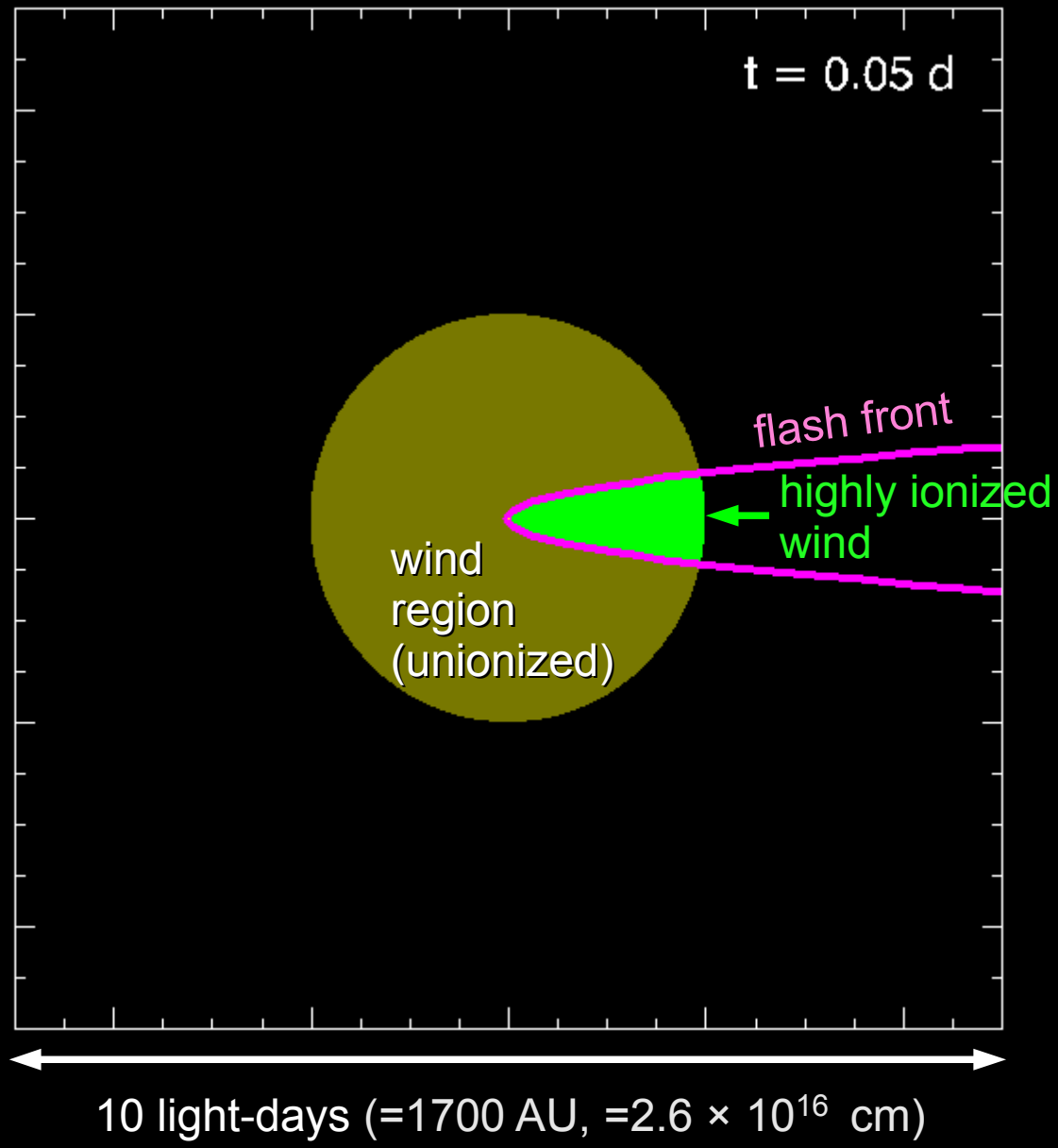
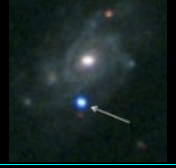
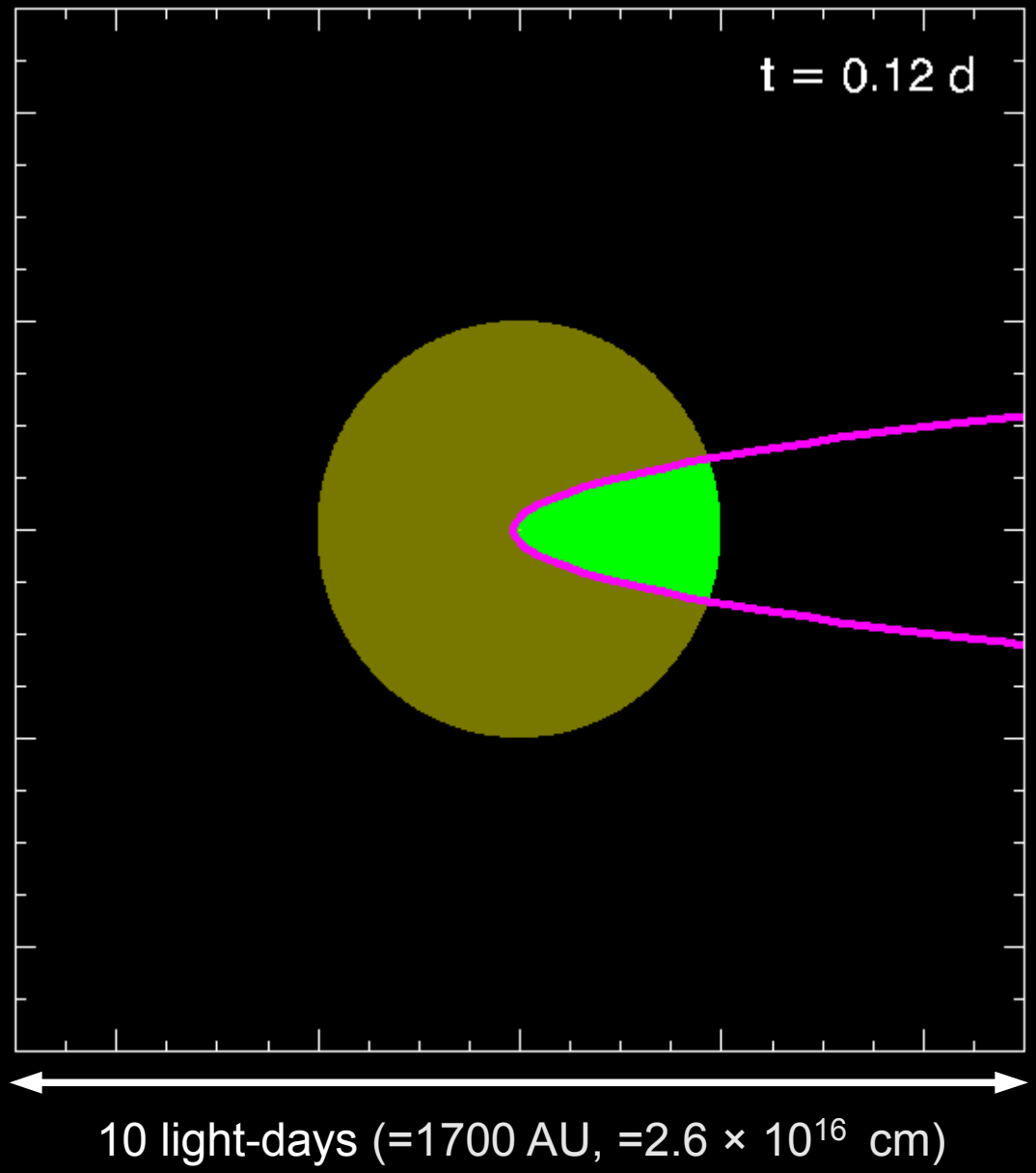
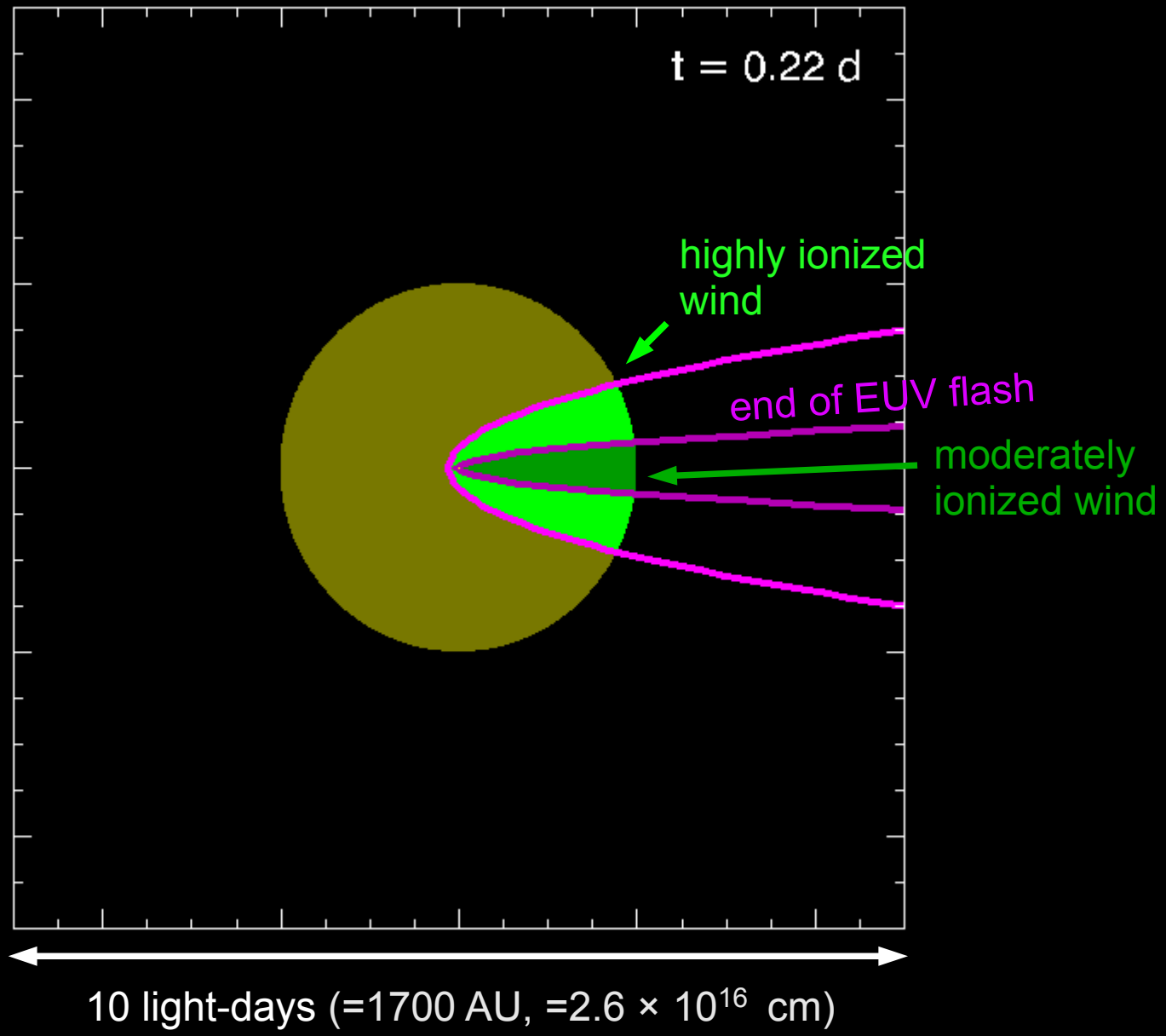


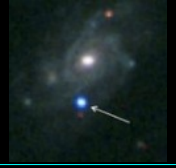


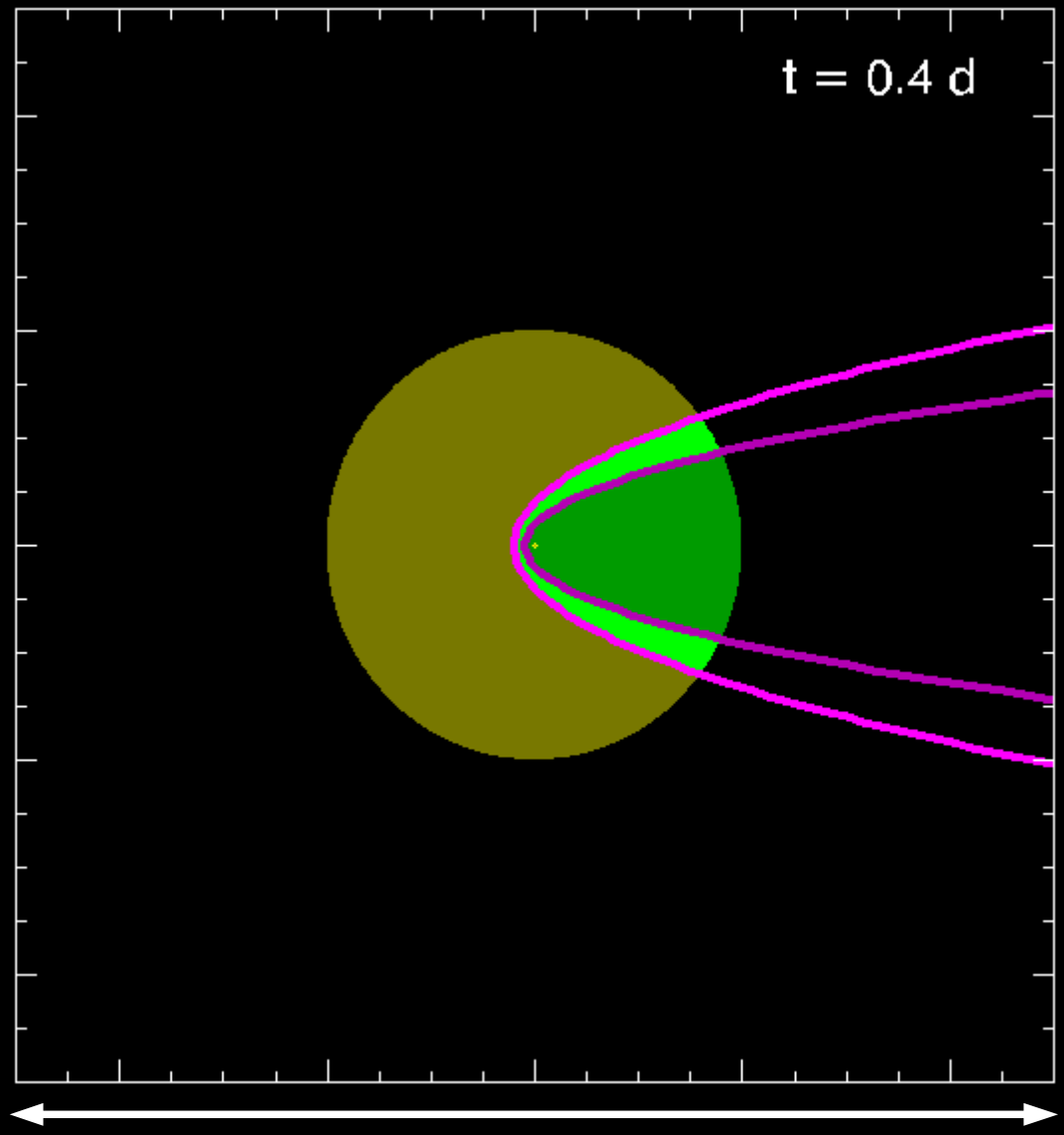
Wind Light-Propagation Model



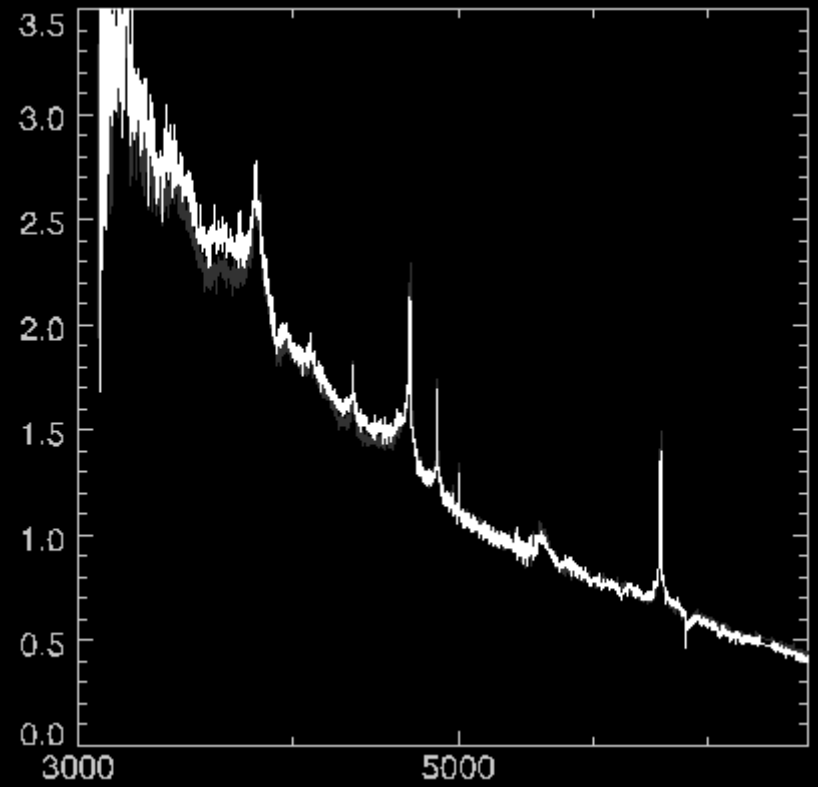
Wind Light-Propagation Model



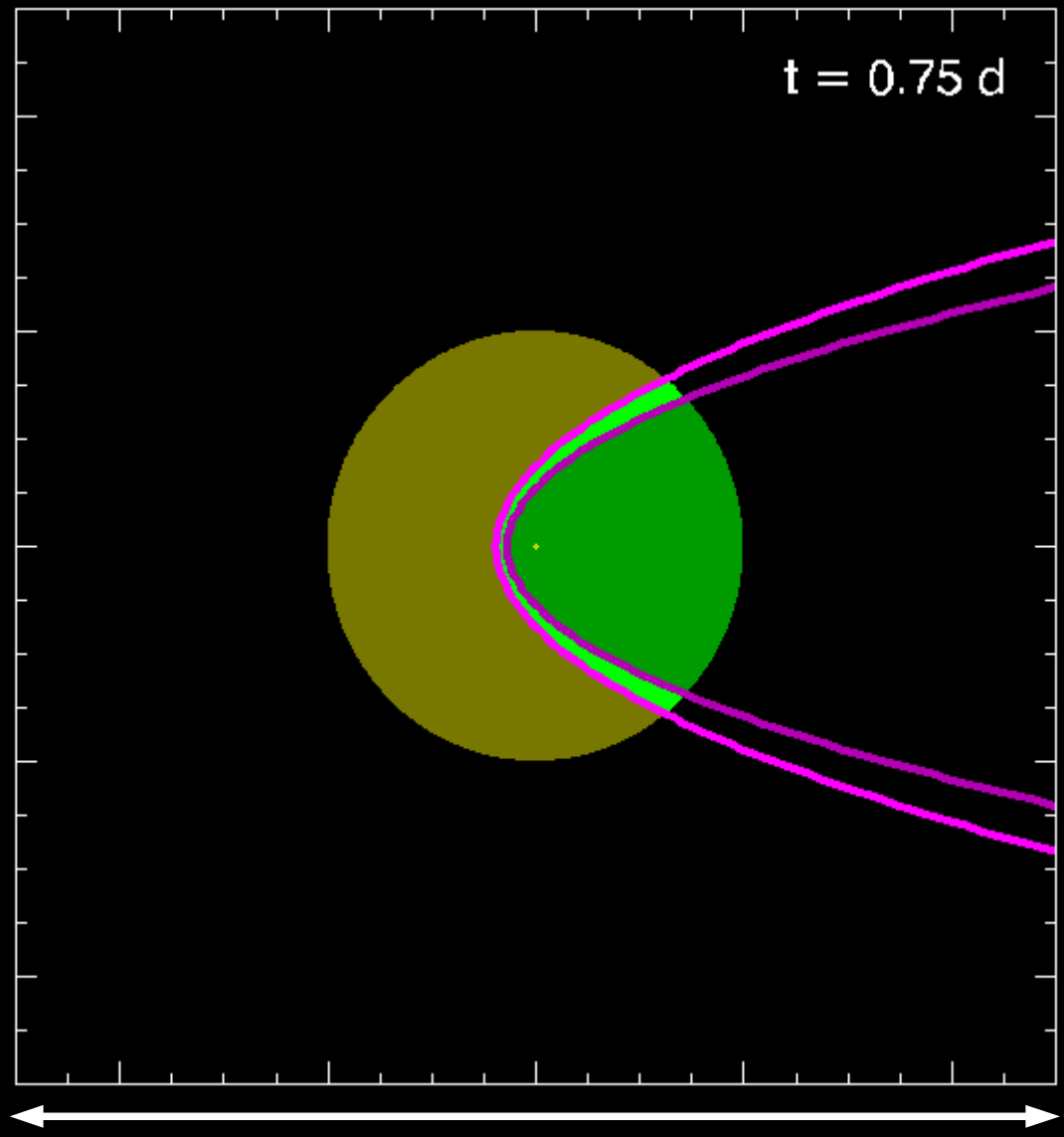




10 light-days (=1700 AU, =2.6 × 10^{16} cm)



Wind Light-Propagation Model



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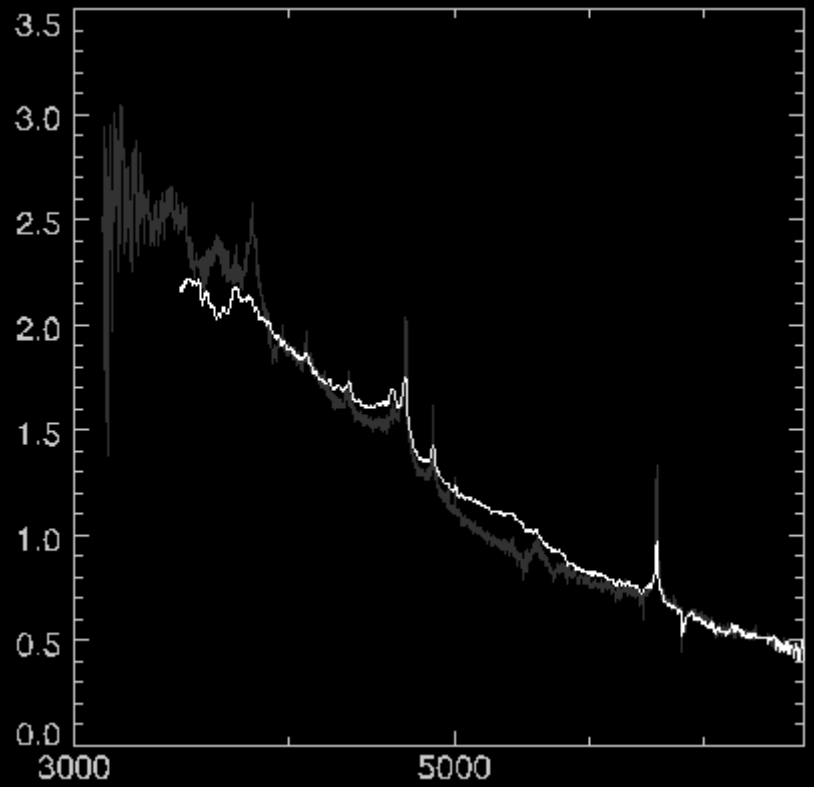
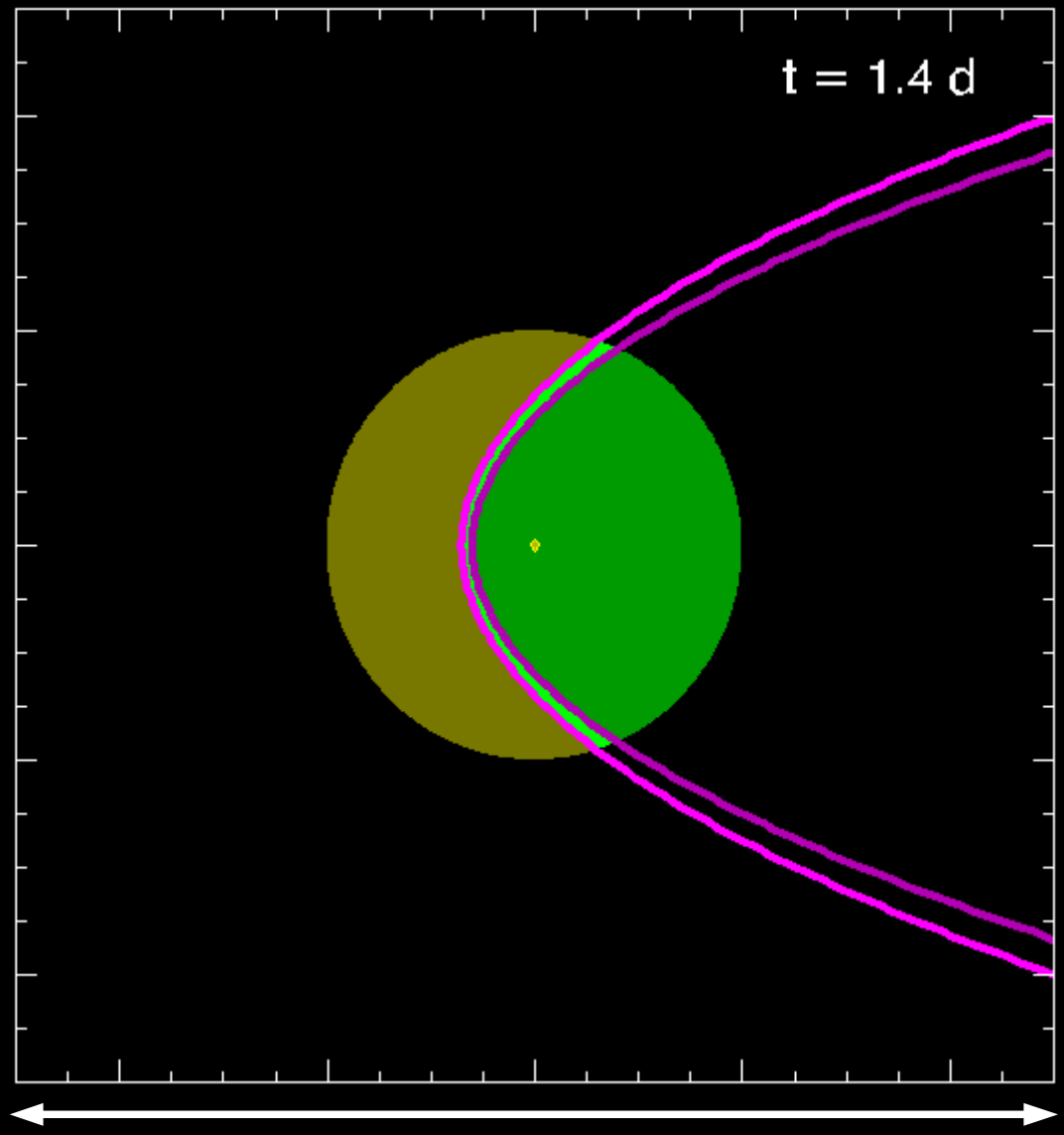
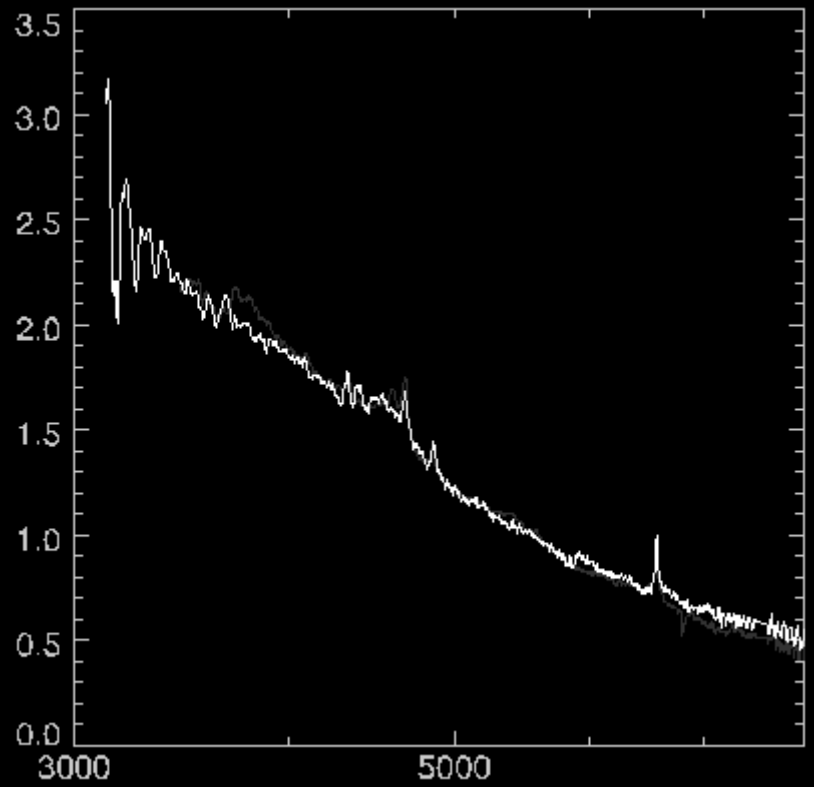
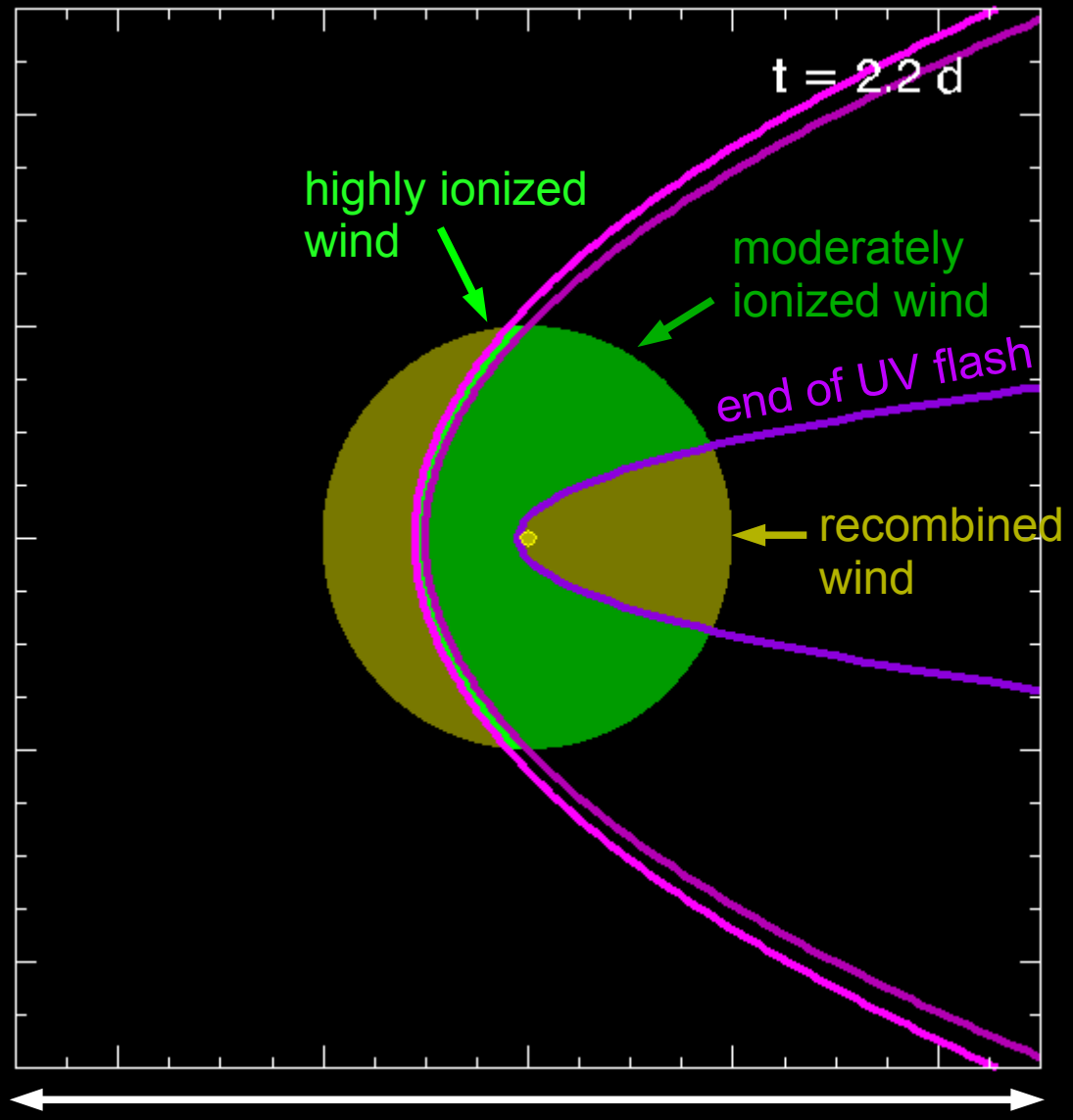


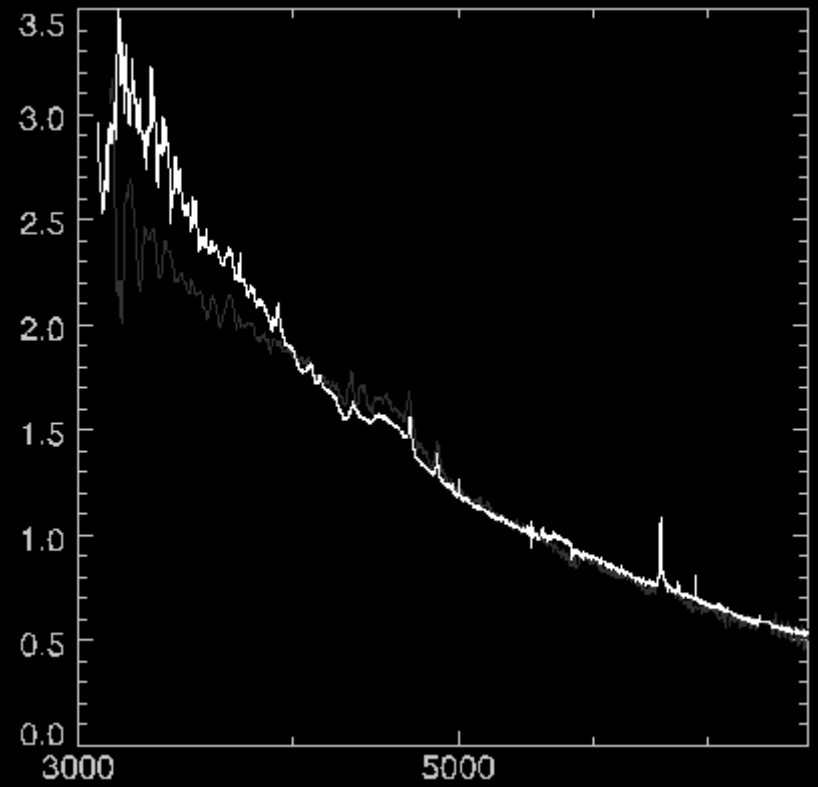
Wind Light-Propagation Model



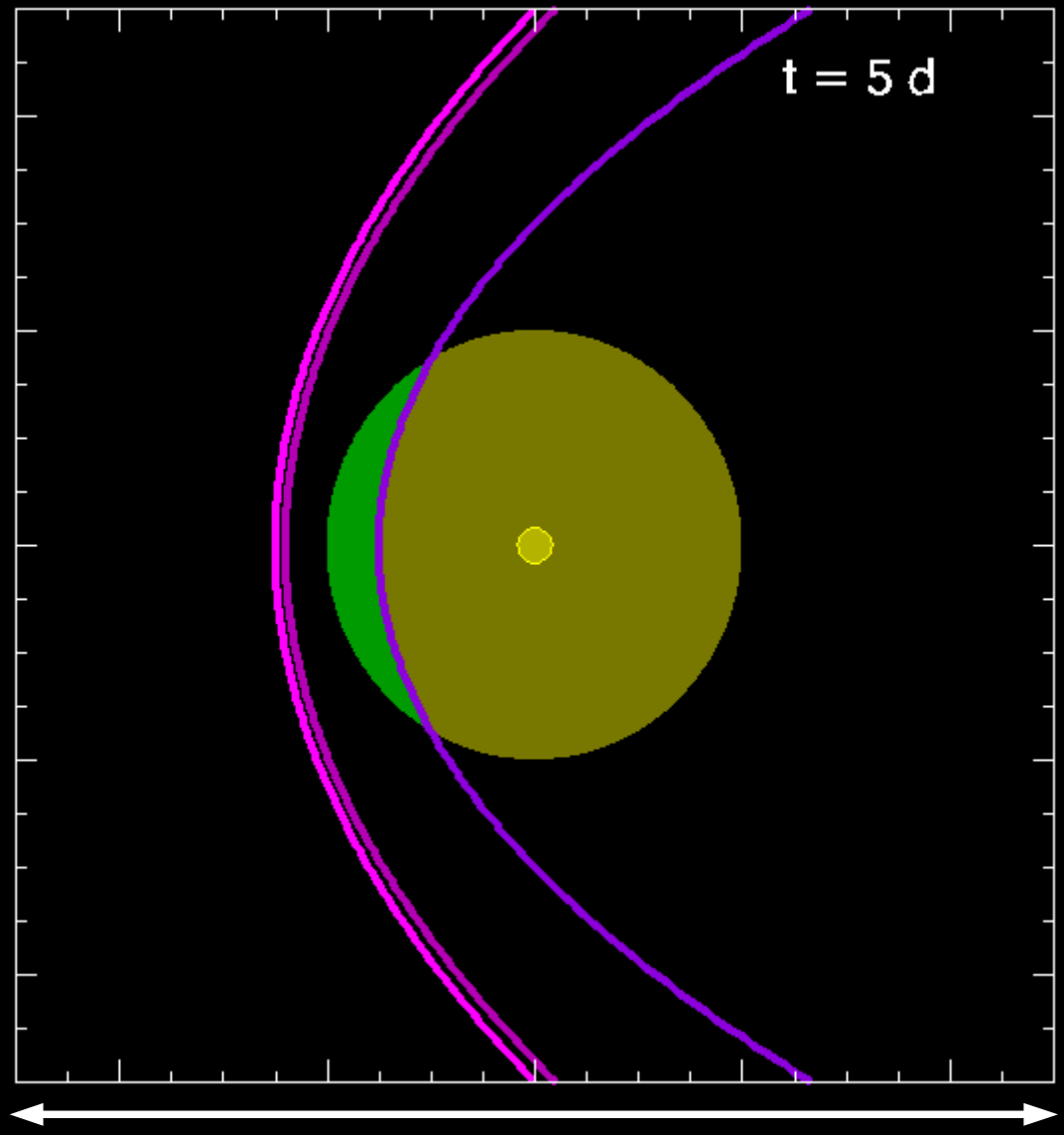


Wind Light-Propagation Model





Wind Light-Propagation Model



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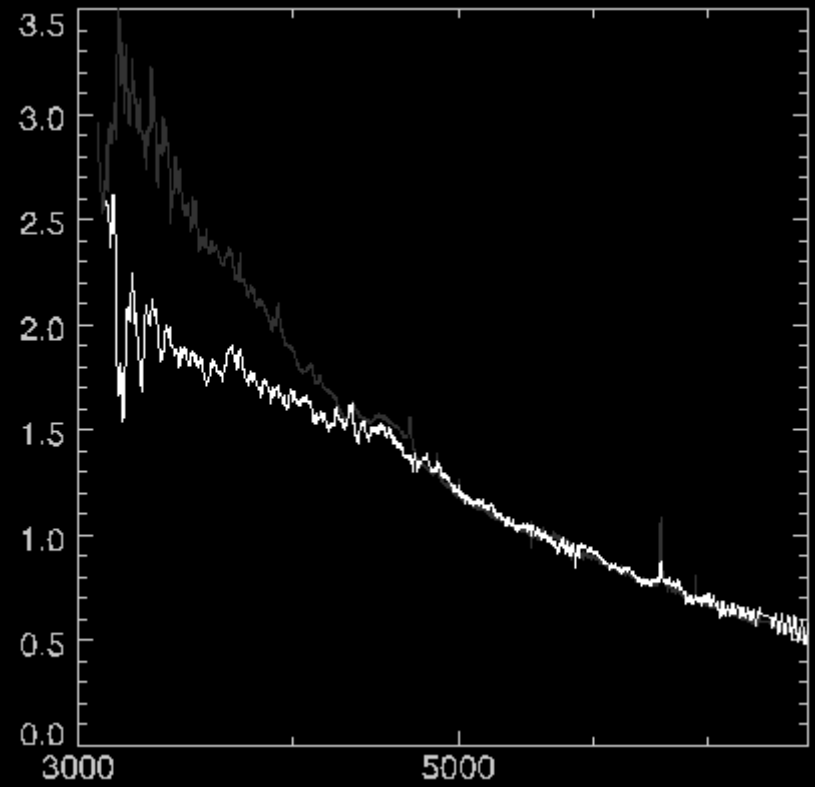
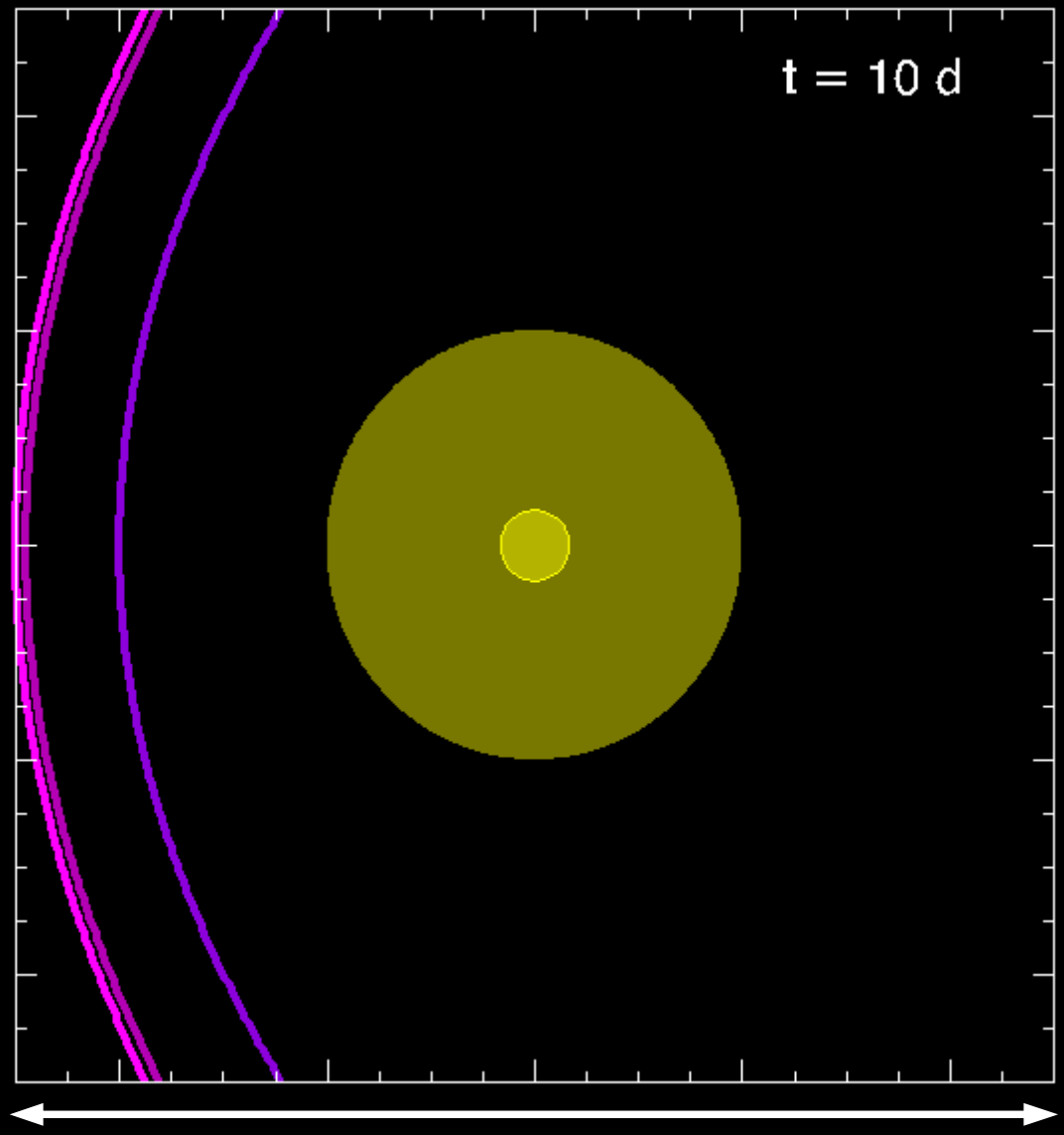
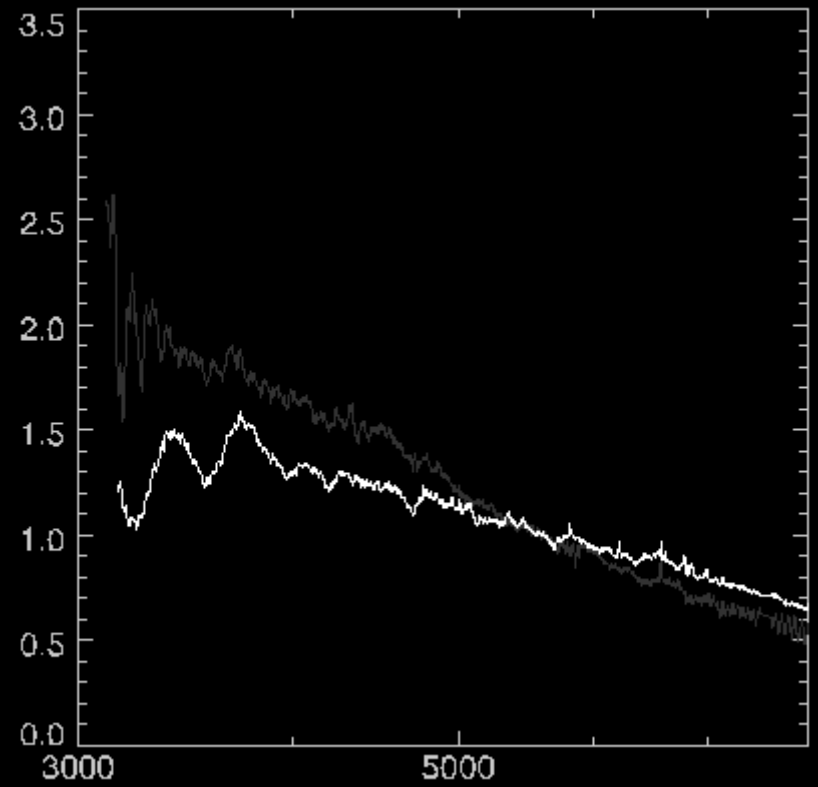
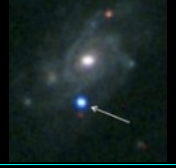


Wind Light-Propagation Model







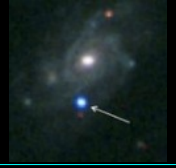
13dqy Preliminary Results

Shock-breakout flash:
Flash temperature ~10^5 K,
lasting ~1 hour
(RSG-like)

Mass-loss history:
Mass-loss rate equivalent ~10^{-4} $M_\odot$/yr
(Again not steady-state – late instability?)
Possible ~200 AU wind "bubble"?

Wind/surface composition:
H/O-rich. (Possibly N-poor?)

Just a toy model...
full theoretical modeling of
line width, flux evolution
should provide rich detail!



The Future

This is only the beginning!

Every core-collapse SN may very well behave this way.
- 2 out of 2 with <1 day observations
- Search of PTF archive finds several more transient H/He signatures in early (~few days) spectra.
- Early SN Ia spectra taken so far do *not* show these features.

1 SN/day at R < 100 Mpc.

Gemini RTOO proposal approved for 2014B and beyond
- Next PTF flash SN will have hourly/daily monitoring!

Most flash-excited lines are in UV
- Cycle 23 HST DDT proposal approved!

Much, much more to come!