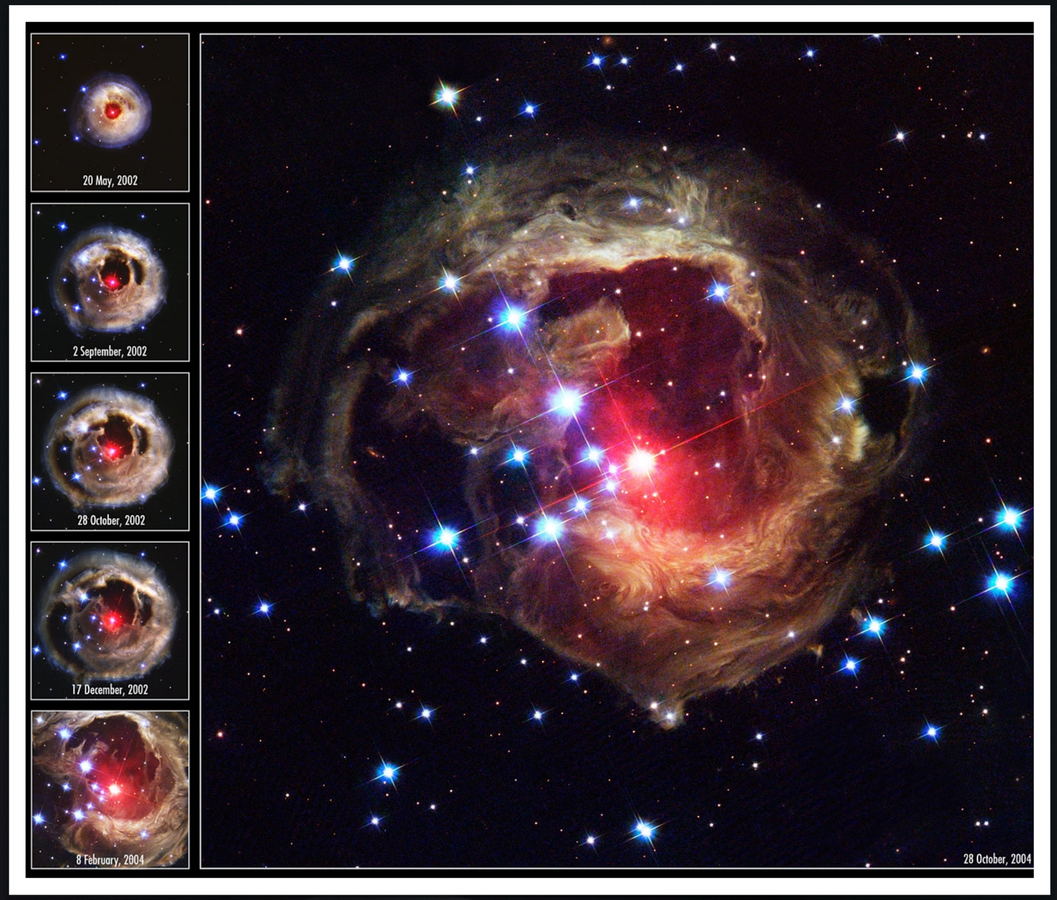
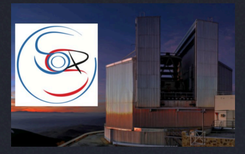
EJECTA-CSM INTERACTING GAP TRANSIENTS (ILOTs - WG 7)



R. Kotak (Turku Univ., WG7 leader), A. Pastorello, S. Benetti, E. Cappellaro, N. Elias-Rosa, I. Salmaso, G. Valerin (INAF-OAPd), A. Reguitti (INAF-OAB), E. Mason (INAF - OATs), M. T. Botticella, M. Della Valle (INAF - OACn), L. Tartaglia (INAF - OAA), G. Pignata, J. Anderson (MAS), S. J. Smartt (QUB/Oxford), M. Stritzinger (Aarhus Univ.), H. Kuncarayakti, E. Kankare, S. Mattila, T. Nagao, P. Charalampopoulos, T. Kangas (Turku Univ.)

Napoli, SOXS Consortium Science Meeting, 25-27 June 2024



Gap Transients

1. Luminous Red Novae (LRNe) - usually yellowish giant-to-hypergiant progenitors (in a wide mass range) in close binaries. Merger events?
2. Intermediate-Luminosity Red Transients (ILRTs) - Dust-embedded 8-15 $M_\odot$ progenitors. Electron-capture SNe?
3. SN impostors - massive (M_{ZAMS} > 40 $M_\odot$) progenitors (LBVs, WR...); non-terminal events
   - Major LBV eruptions (Eta-Car, SN 2000ch, SN 2009ip in 2009-2012)
     => erratic variability with multiple outbursts; M_V ~ -11.5 to -14.5
   - Isolated major stellar outbursts (SN 2007sv, the 2004 precursor of SN 2006jc)
     => single outburst event; M_V ~ -13 to -14 mag
   - Extreme S Dor variability (e.g. R71, M33 Var C, AE & AF And, UGC 2773-2009OT1)
     => quite heterogeneous DM < 3 mag, M_V > -11 mag
4. Faint thermonuclear SNe (.Ia, Ca-rich transients, faint Iax)
5. Faint type II SNe (1997D-like and 1999ga-like events) - ECSNe, Fe core-collapse of ~8 $M_\odot$ RSGs or fall-back SNe of M > 25 $M_\odot$ stars?

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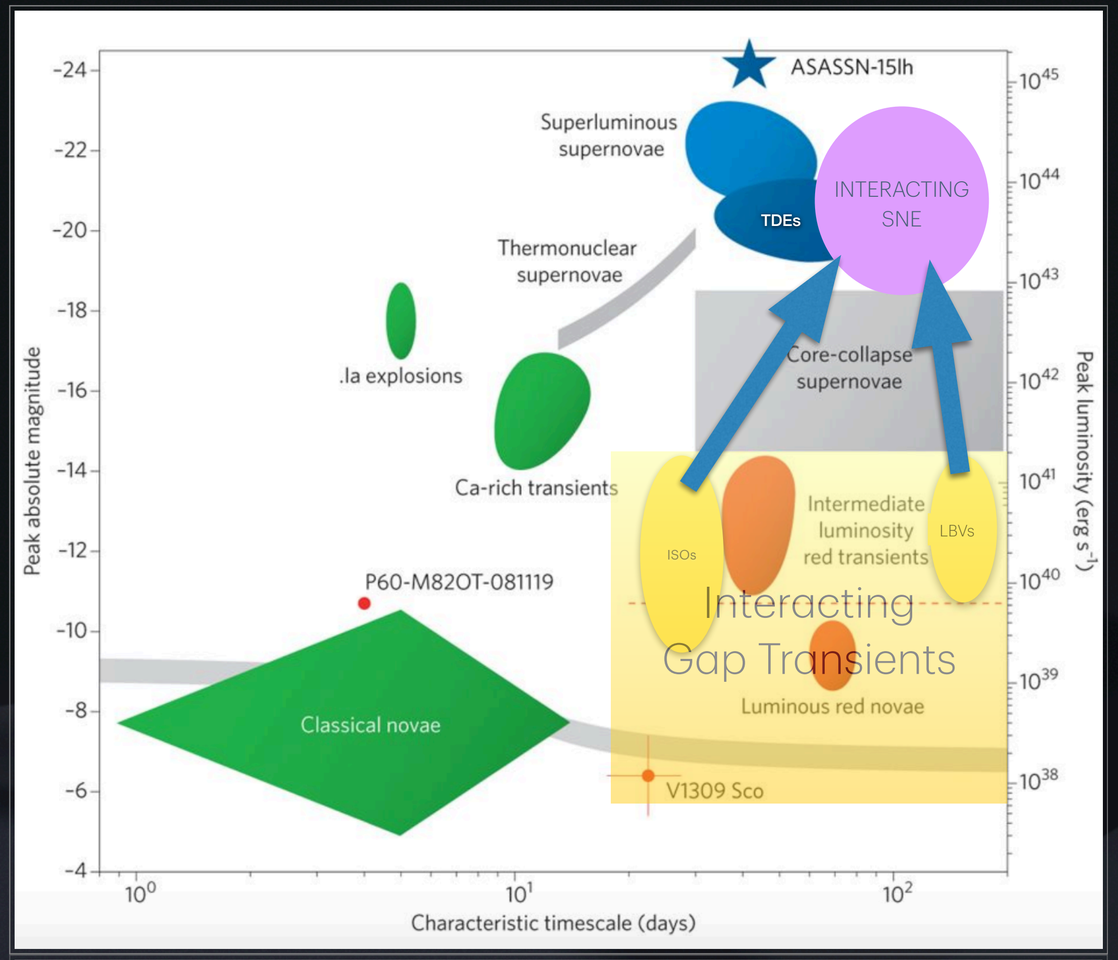
Interacting Gap Transients

Magnitude range from -5 (Galactic) to -15

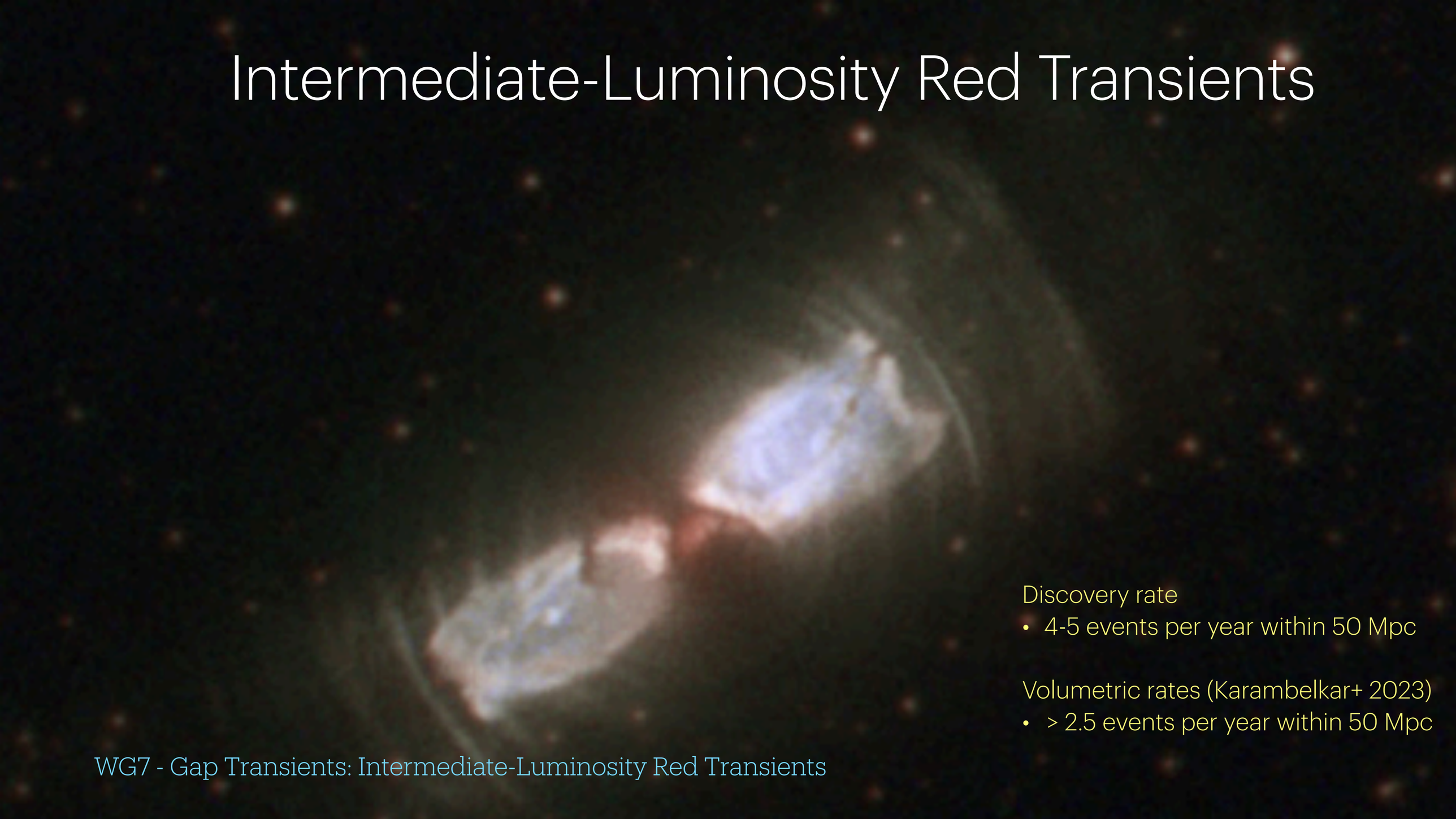


Targets x SOXS WG7

- Intermediate-luminosity Red Transients (ILRTs)
- Luminous Red Novae (LRNe)
- Isolated outbursts of massive stars
- Giant LBV eruptions (Eta-Car like)
- Pre-SN eruptions (including 2009ip-type Events A)

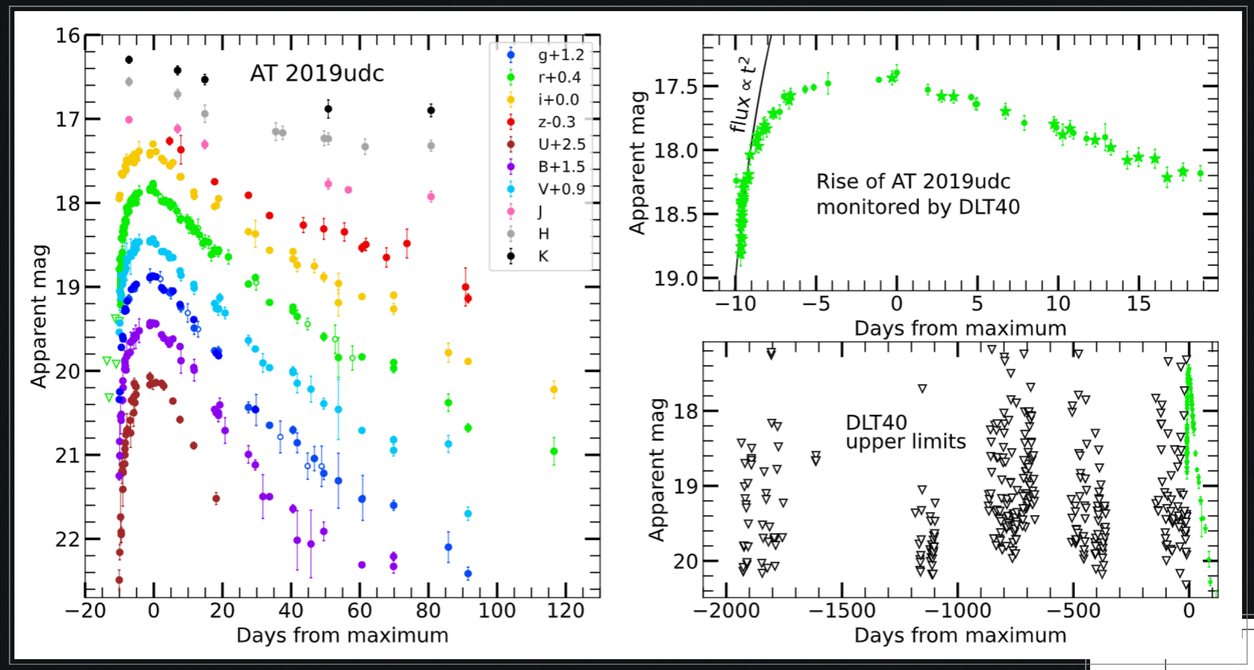
Tightly linked to ejecta-CSM interacting SNe (Type IIn, Ibn)

Intermediate-Luminosity Red Transients



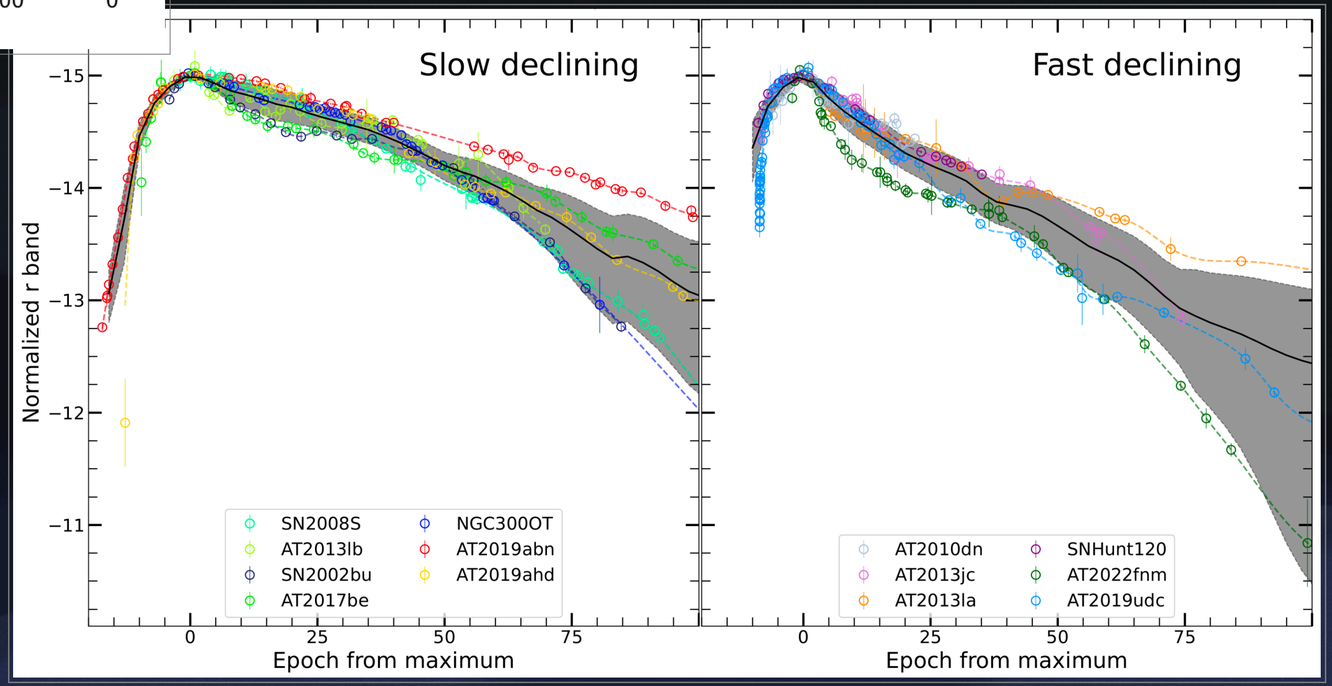
Discovery rate
- 4-5 events per year within 50 Mpc

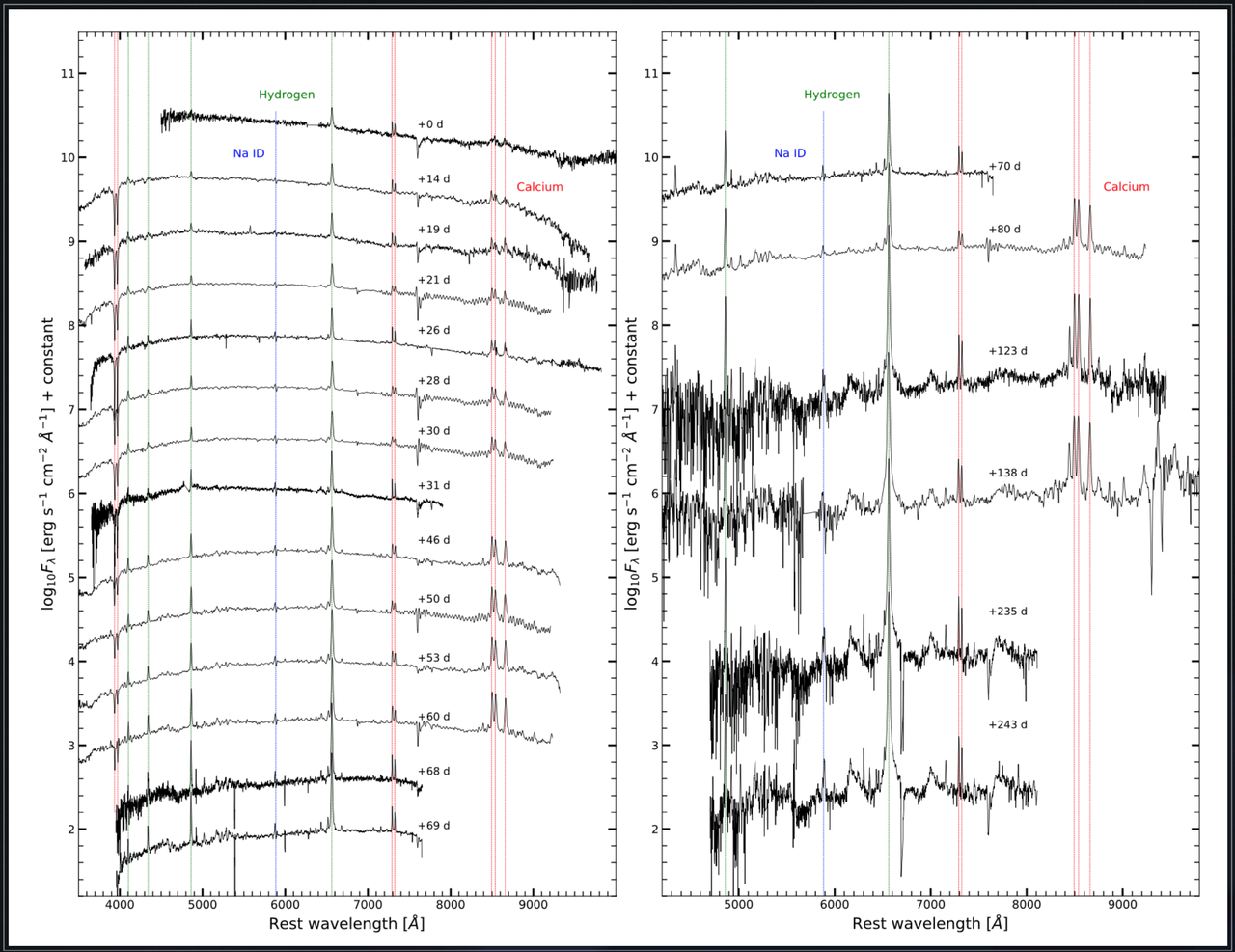
Volumetric rates (Karambelkar+ 2023)
- > 2.5 events per year within 50 Mpc



Valerin et al. 2024

- Peak absolute magnitude: -12 to -15 mag
- Type IIP or IIL SN-like light curves
- Late-time decline roughly consistent with the ^{56}Co decline

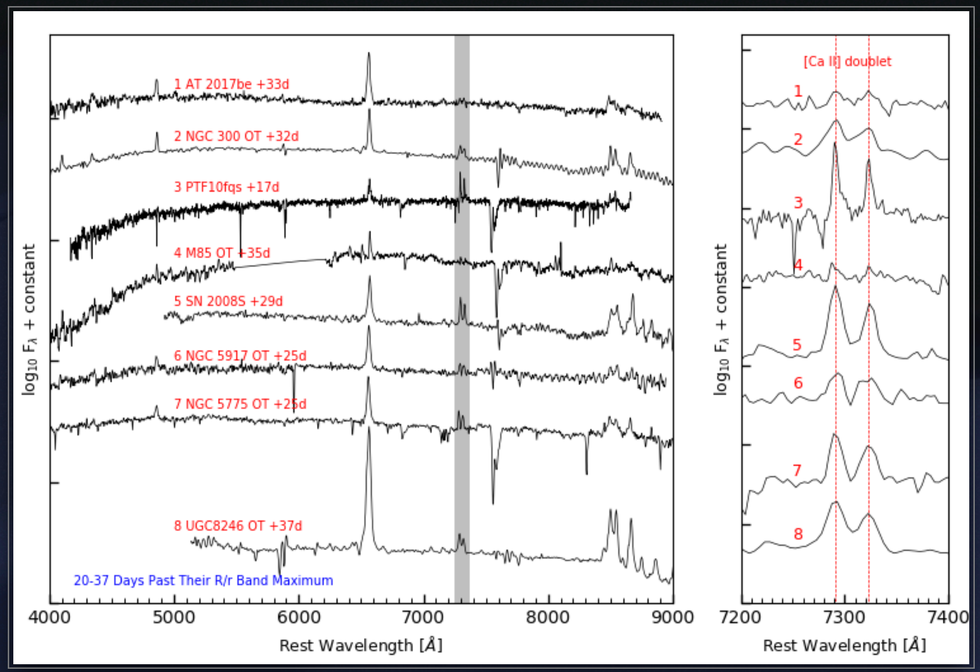




NGC300-2008OT, Valerin et al. 2024

- Type IIn-like spectra (dominated by Balmer emission lines)
- [Ca II] emission near 7300 A, with prominent Ca II H&K (in absorption) & Ca II NIR (in emission)
- Optical spectra never show molecular band signatures

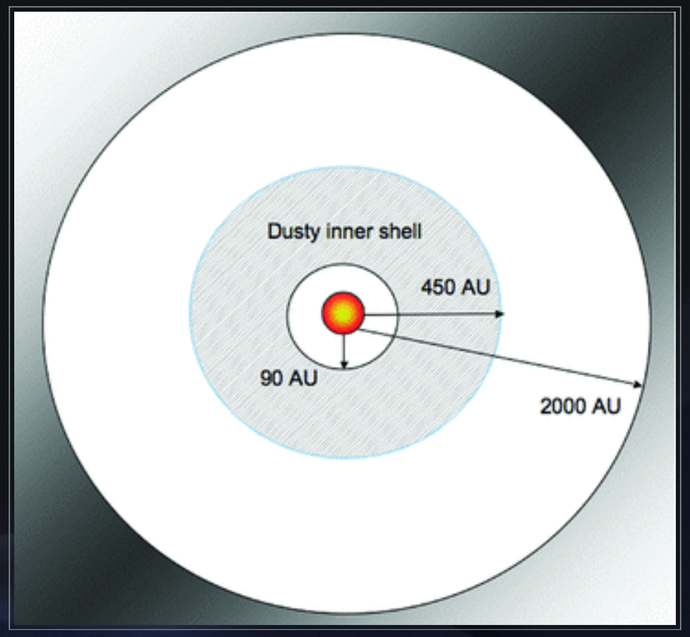
Cai et al. 2018



WG7 - Gap Transients: Intermediate-Luminosity Red Transients

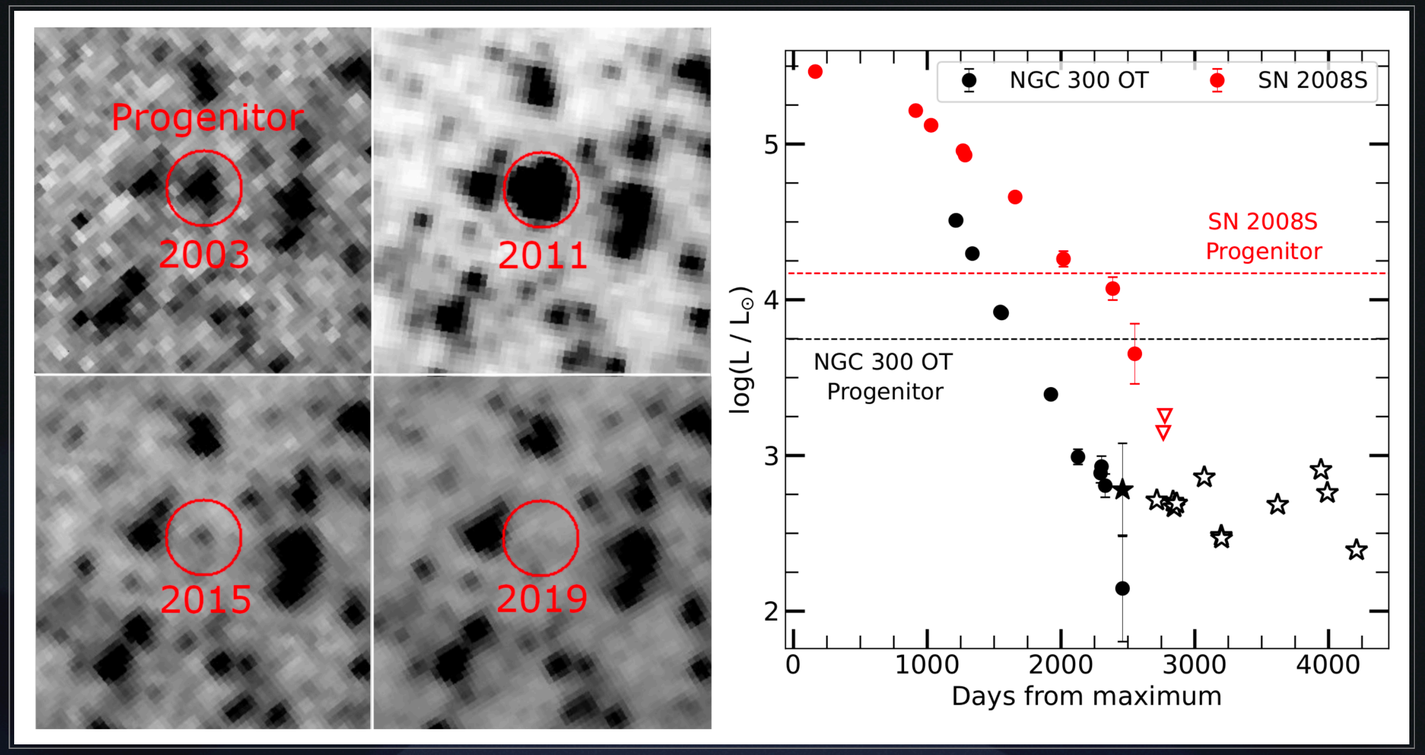
- Outbursts from low-mass LBVs or B[e] hypergiants in a dusty cocoon
- Outbursts due to binary interaction involving a S-AGB
- Electron-capture SNe from S-AGB stars

2008S, Botticella et al. 2009



Progenitors: 7-10 $M_{\odot}$ stars in dusty CSM

NGC300-2008OT, Valerin et al. 2024
(see also Adams et al. 2016)



Progenitors: Wise and Spitzer archives (+ JWST in the future)
Post-outburst disappearance of the progenitors in the MIR => JWST!

Luminous Red Novae

Current discovery rates
- 1-2 per decade in the LG (faint)
- 8-10 per year within 50 Mpc

Volumetric rates (Karambelkar+ 2023)
- 5-16 per year within 50 Mpc

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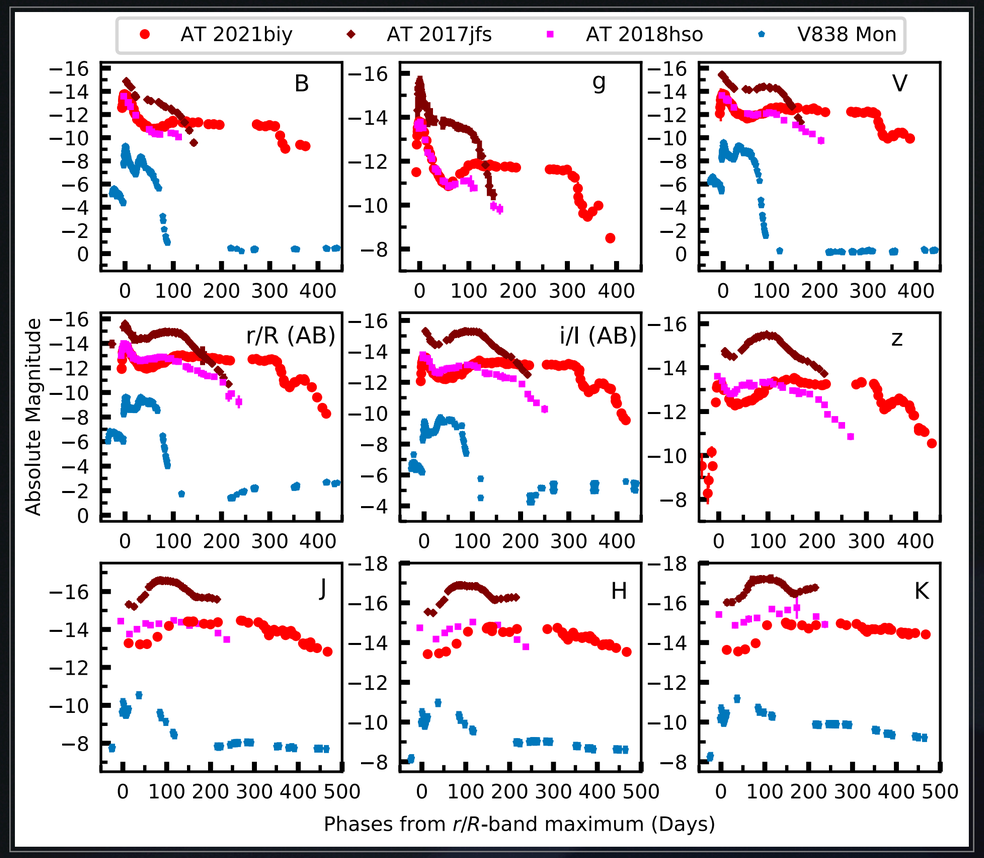
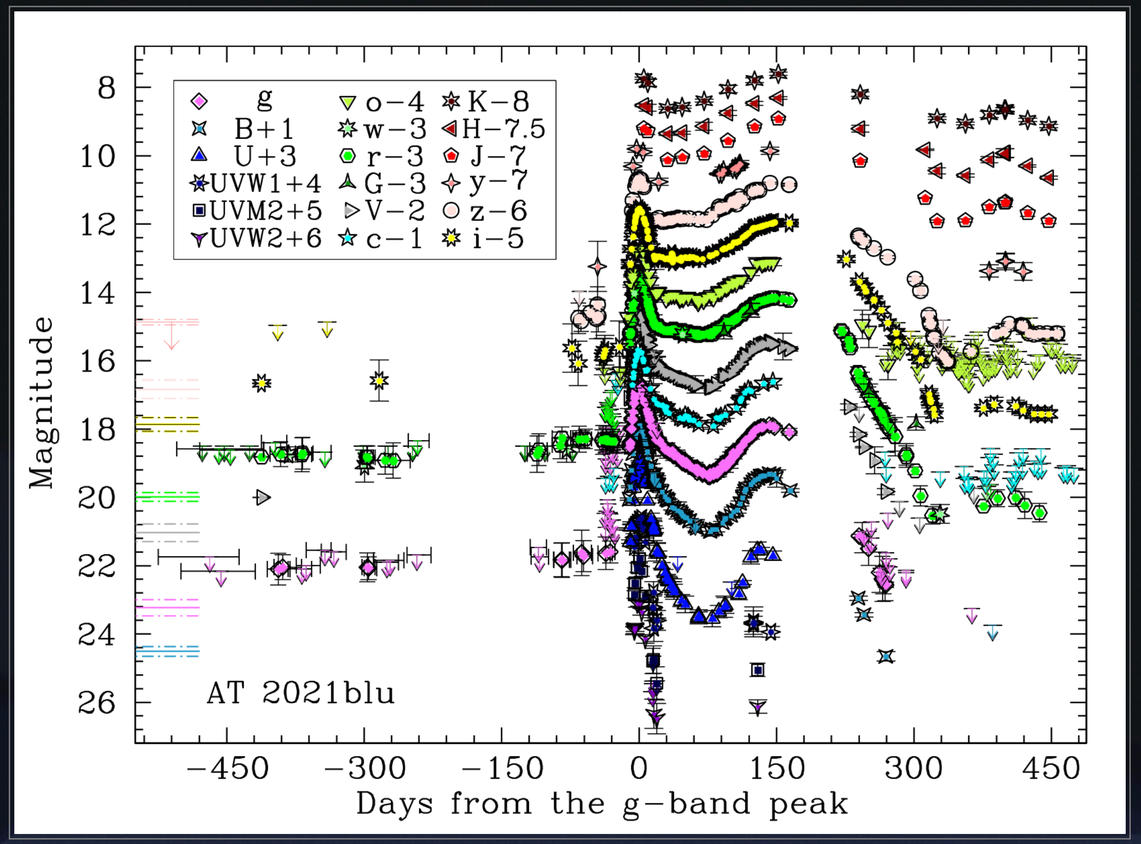
LRN lightcurves

Cai et al. 2022



Pastorello et al. 2023



Peak absolute magnitudes

- Galactic RNe: M_V > -10 (up to -5) mag
- LRNe: M_V ~ -10 to -15 mag

WG7 - Gap Transients: Luminous Red Novae

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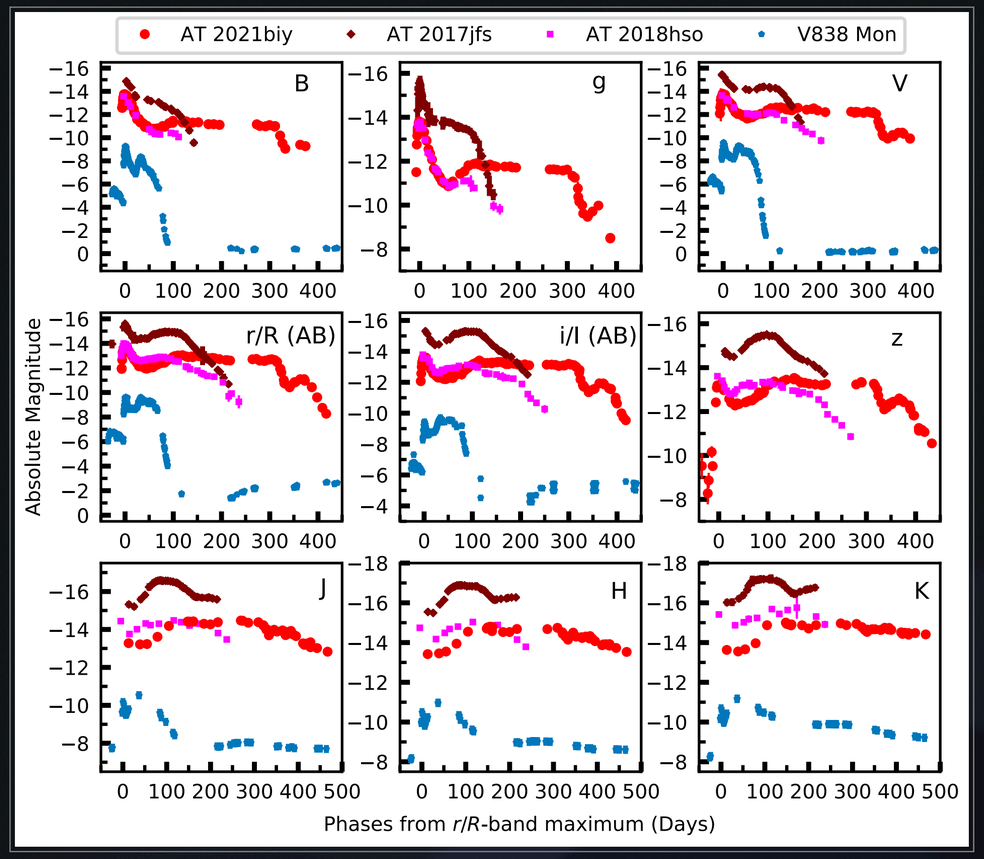
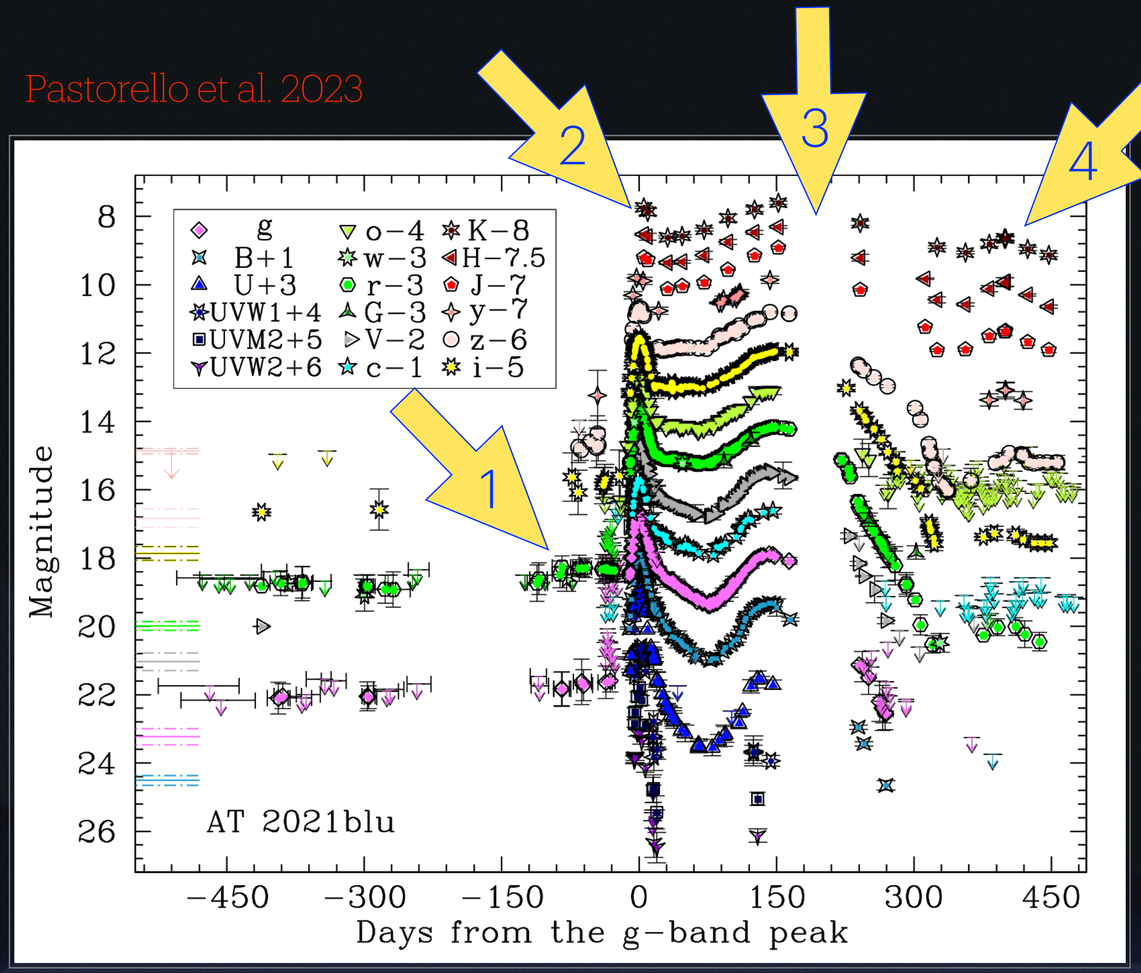


Pastorello et al. 2023

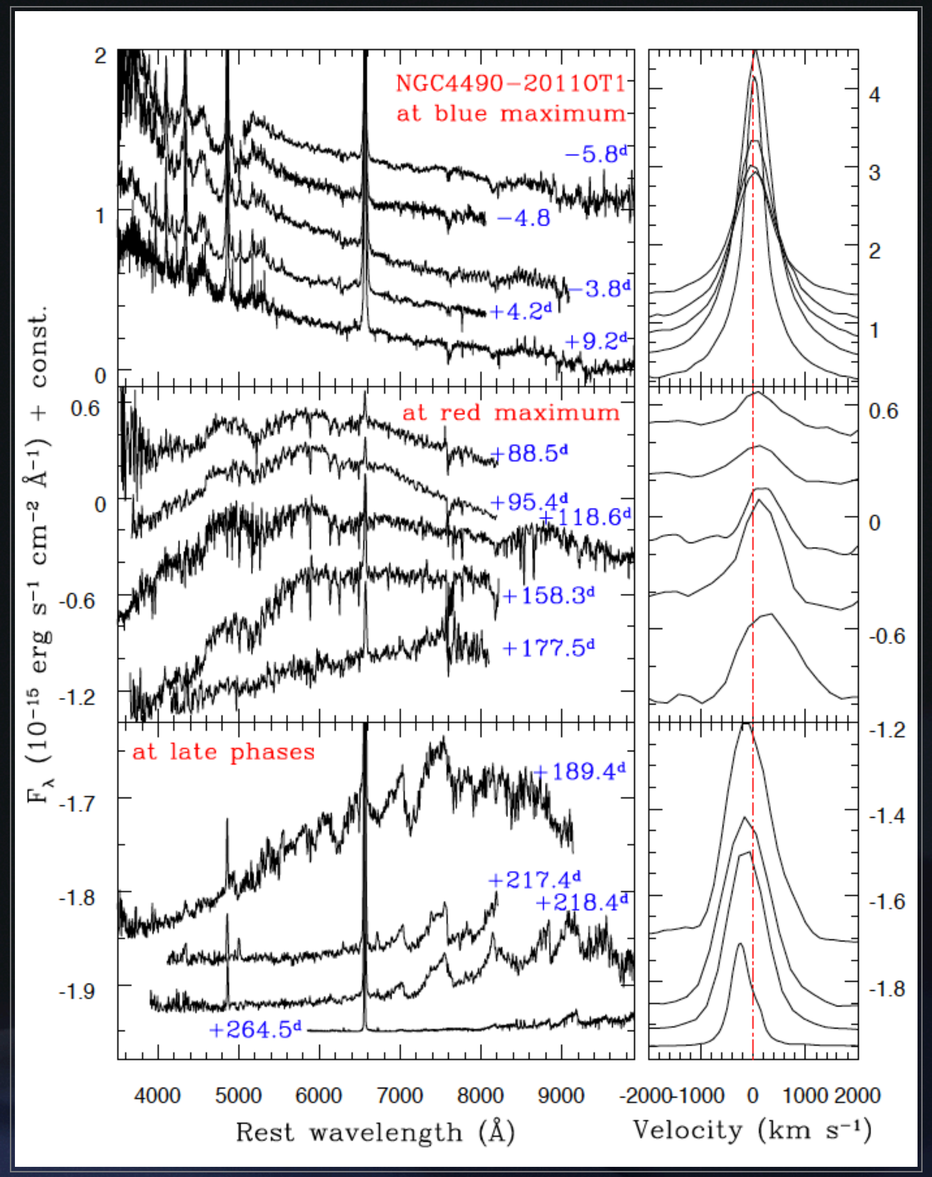


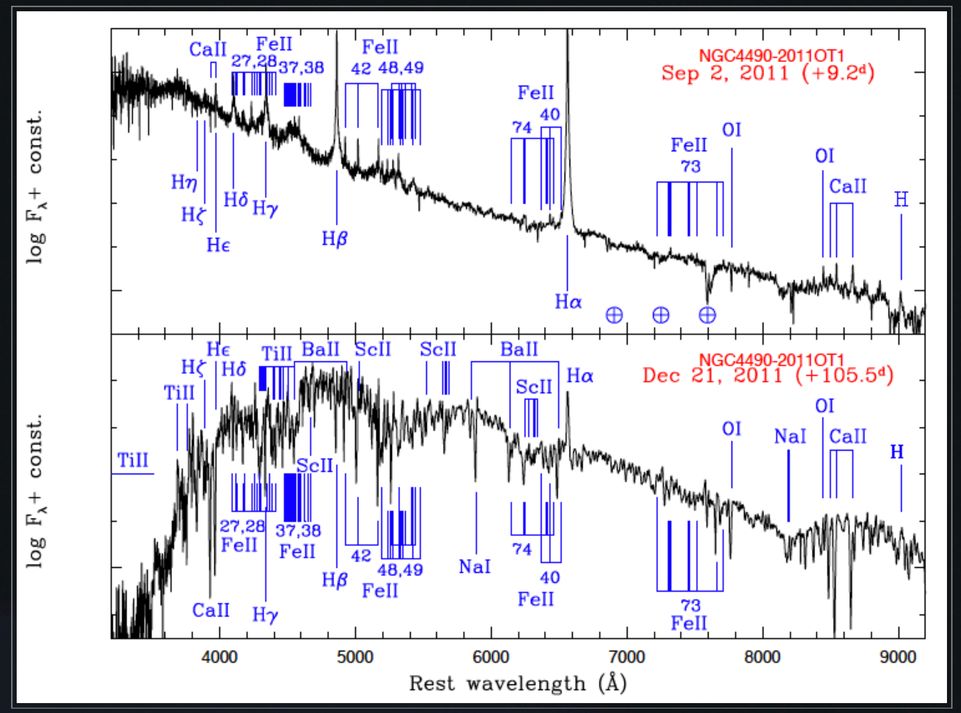
Peak absolute magnitudes

- Galactic RNe: M_V > -10 (up to -5) mag
- LRNe: M_V ~ -10 to -15 mag

1. Slow pre-outburst brightening
2. Early short-duration blue peak
3. Broad red peak or plateau
4. Late hump (mostly in the NIR)

NGC 4490-2011OT1

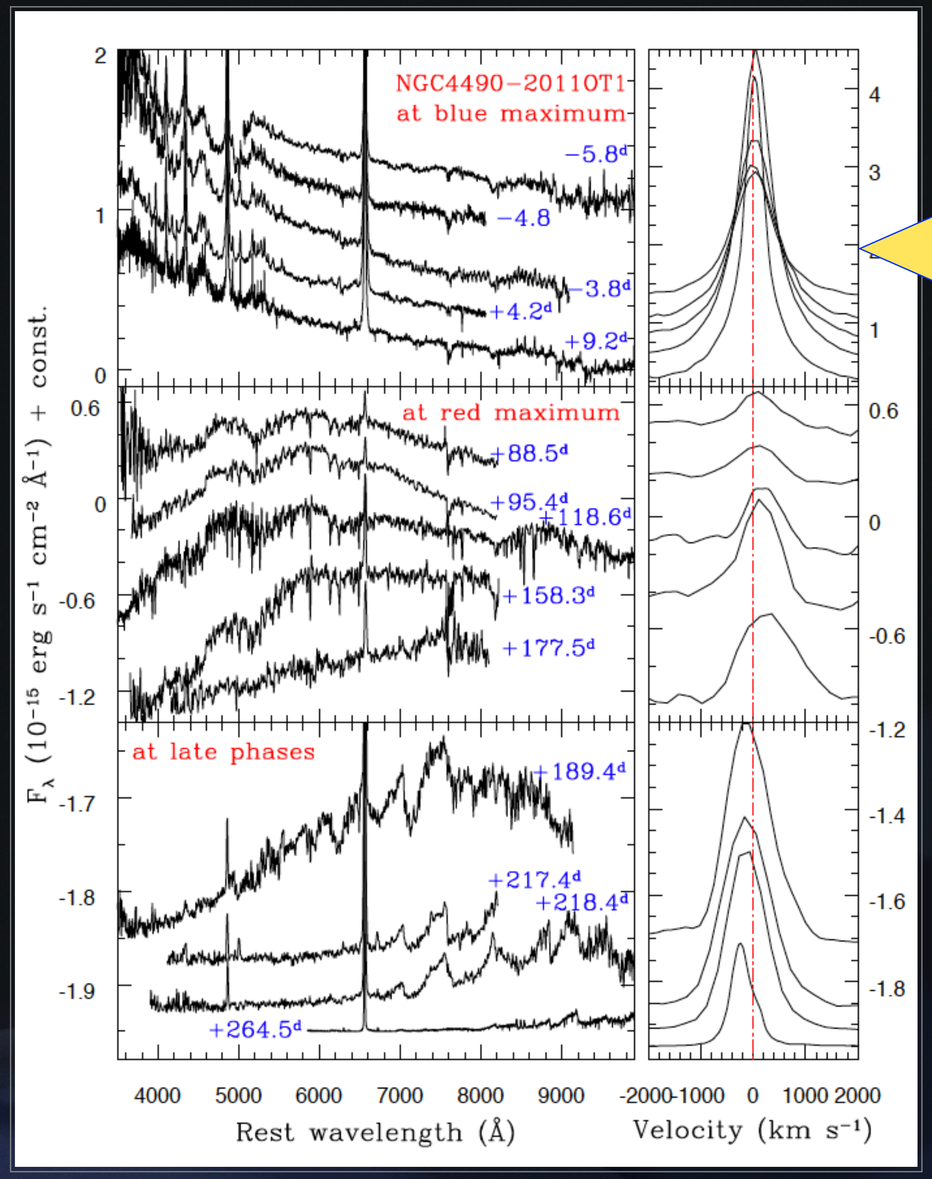




Pastorello et al. 2019a

Phase 1 still never observed in spectroscopy!

NGC 4490-2011OT1



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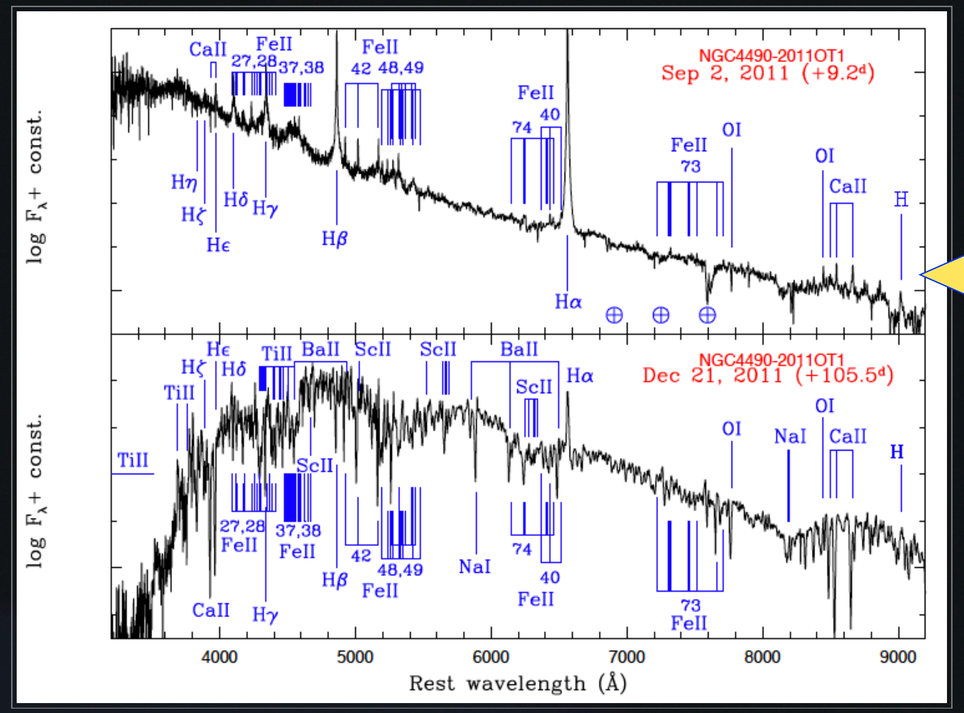

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Pastorello et al. 2019a

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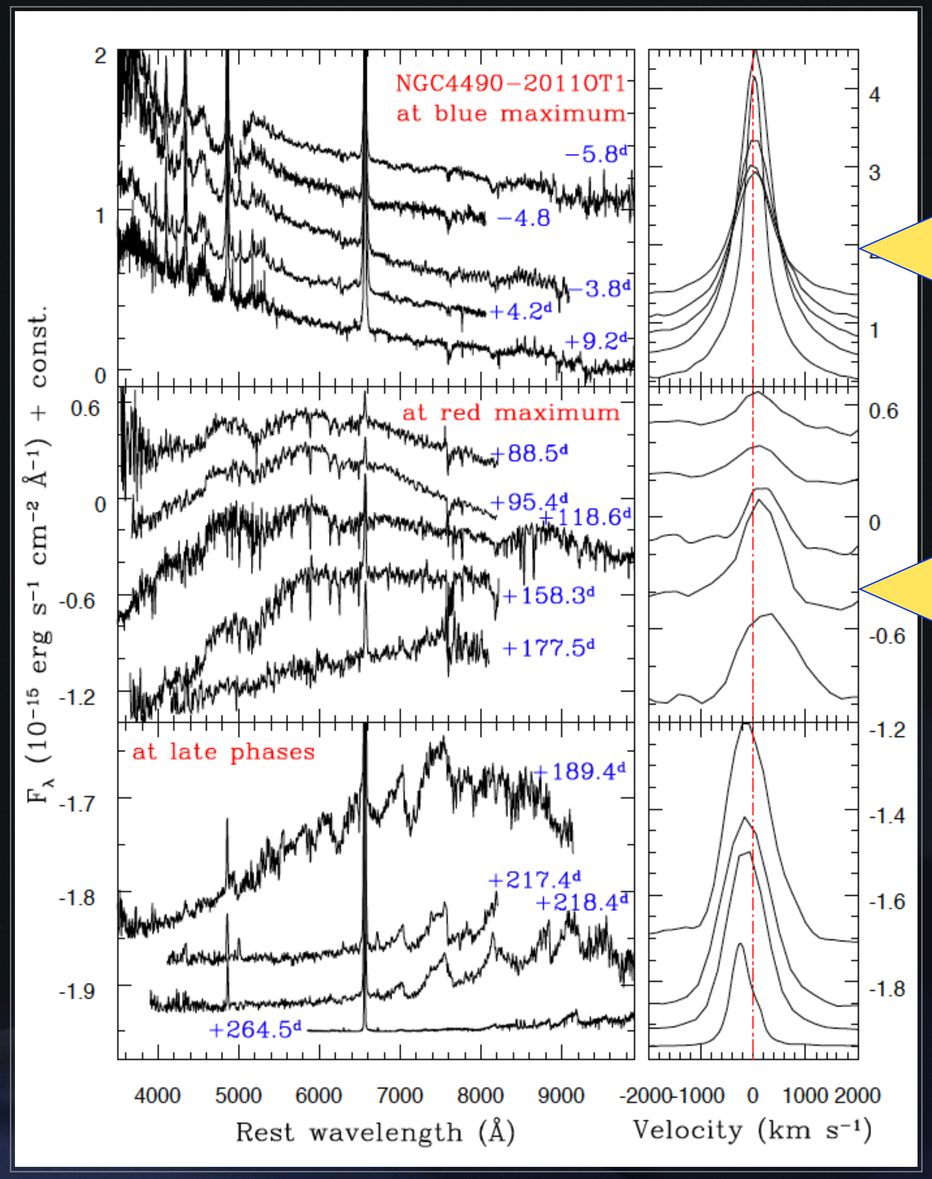

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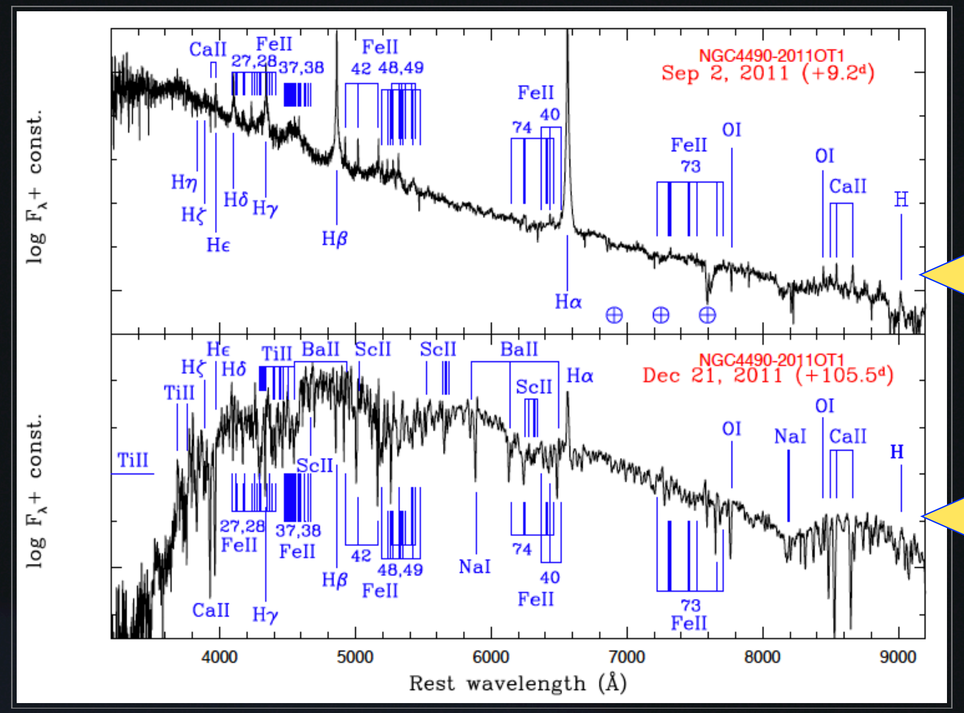

2

3

A forest of metal lines (FeII, ScII, TiII)

Pastorello et al. 2019a

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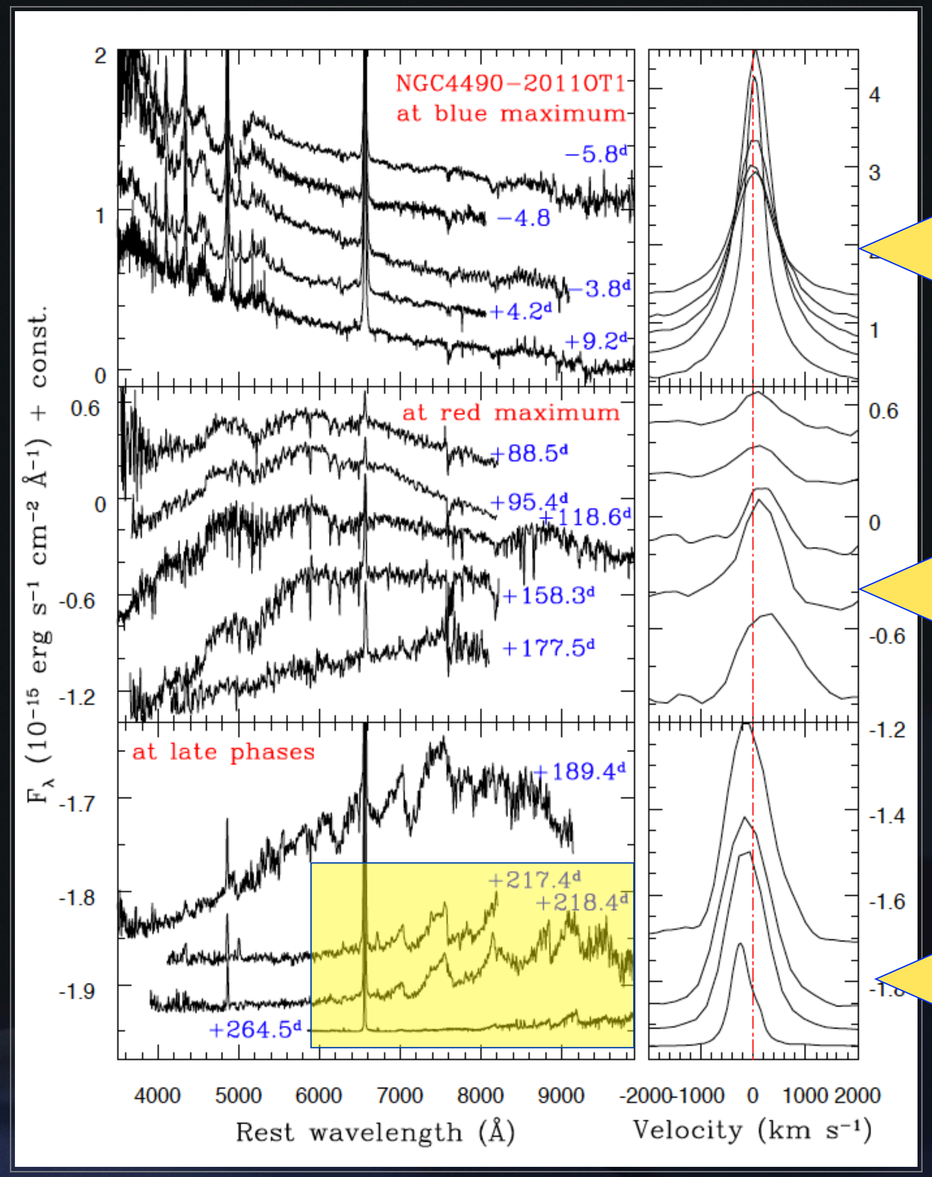

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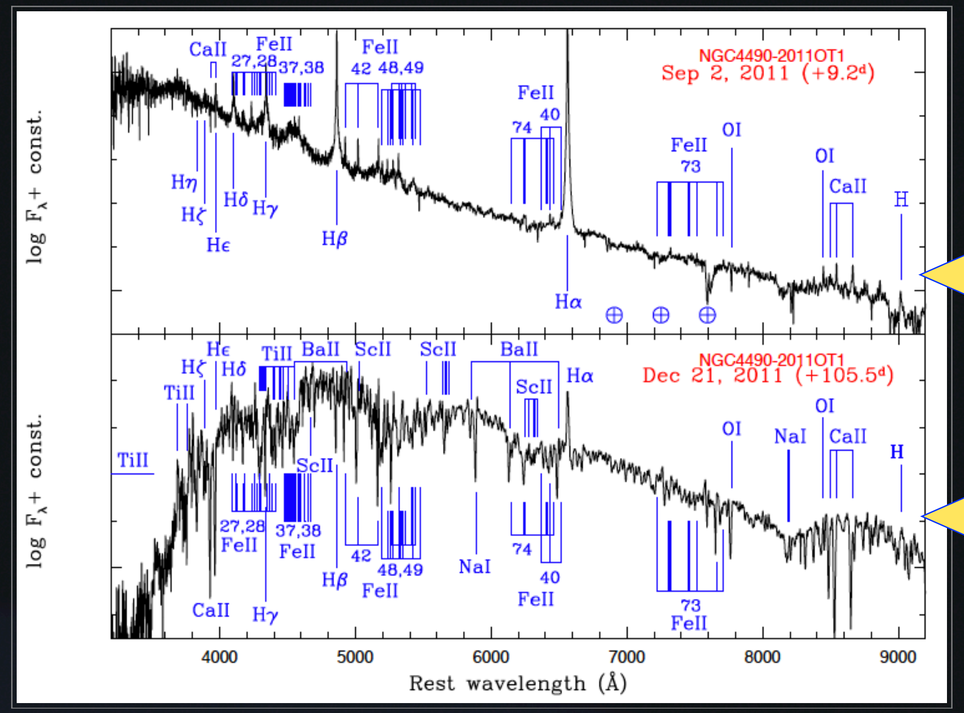

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Pastorello et al. 2019a

Molecular bands!

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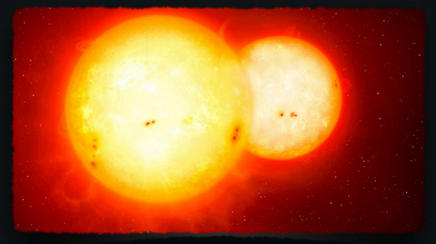
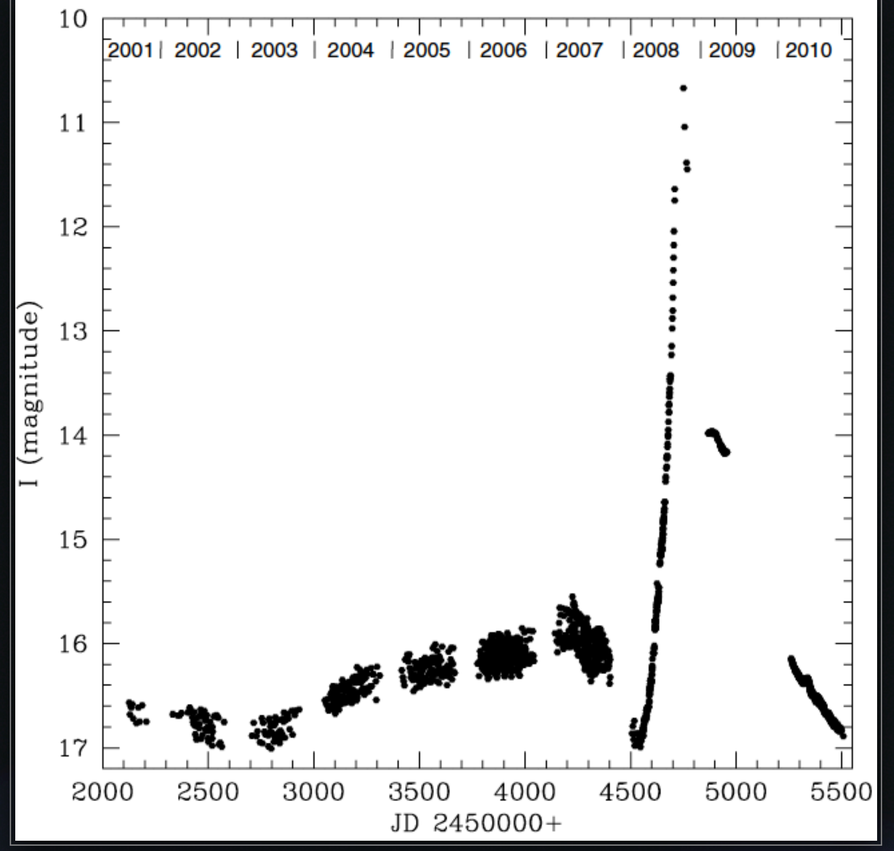
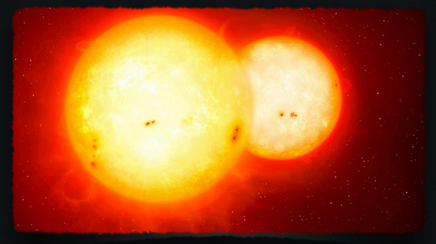


V1309 Sco

Tylenda et al. 2011

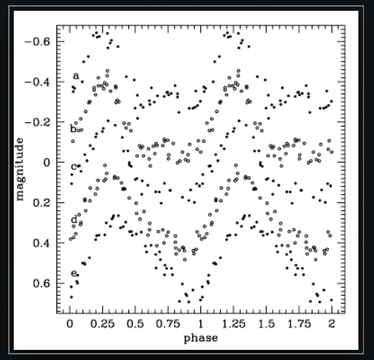


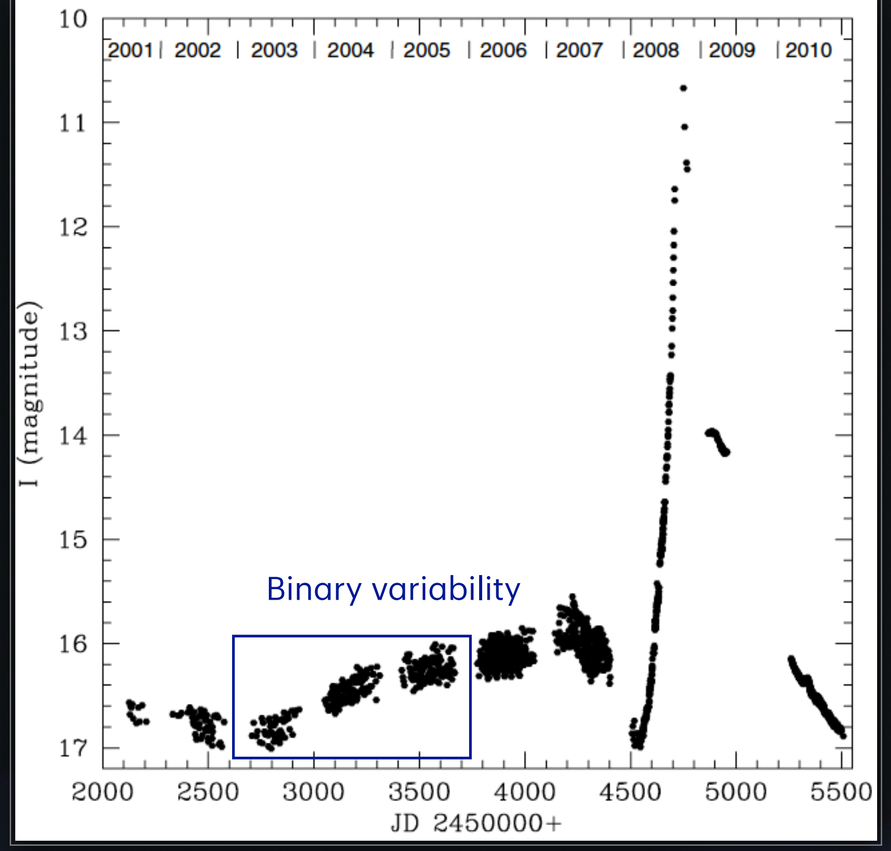


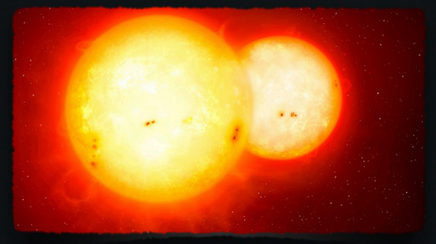
V1309 Sco

Tylenda et al. 2011

2002-2005







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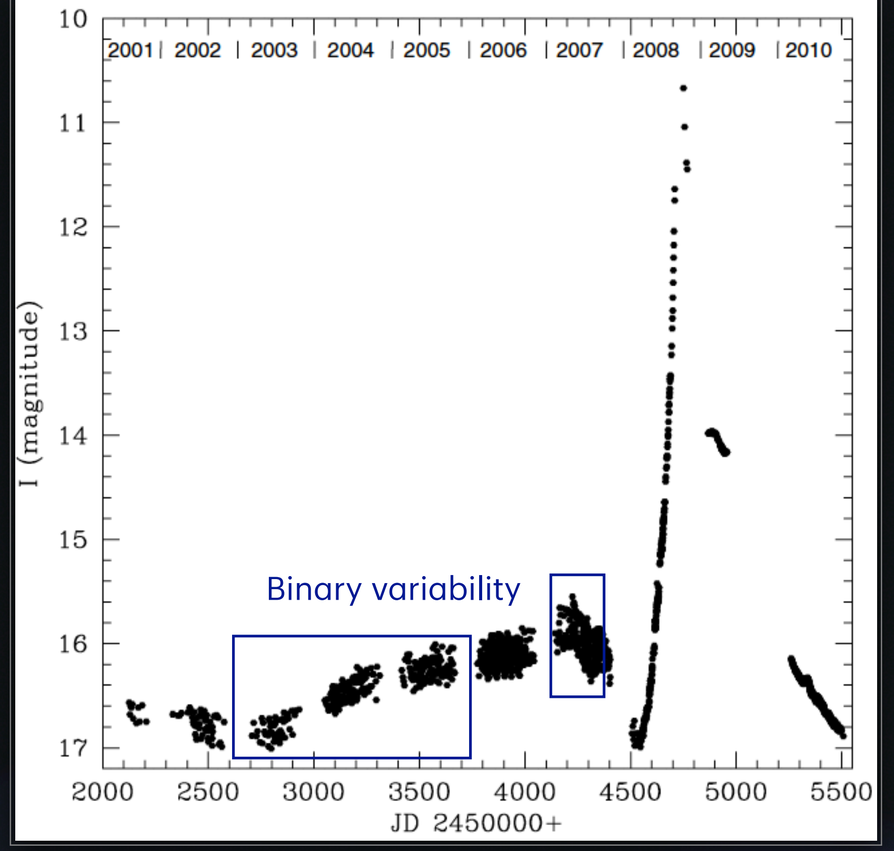

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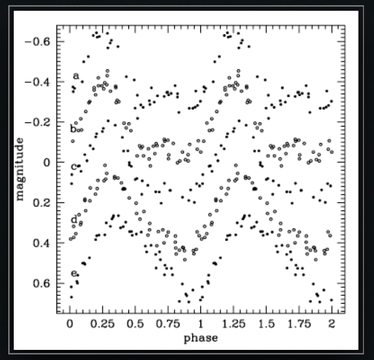
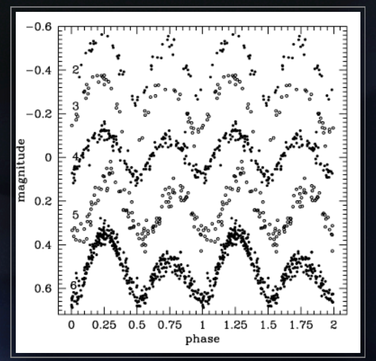
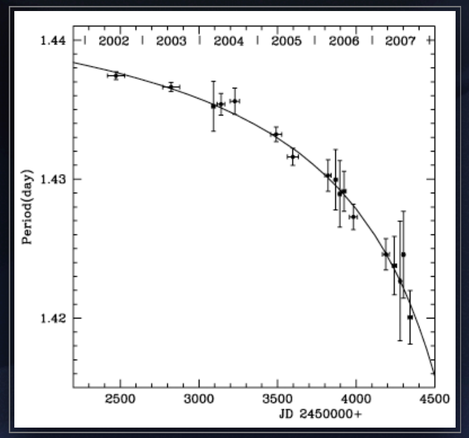
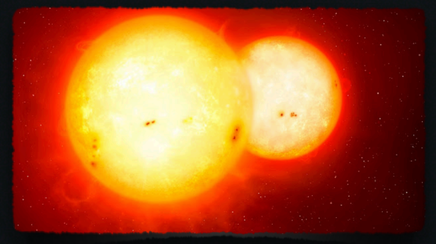


2007-2008







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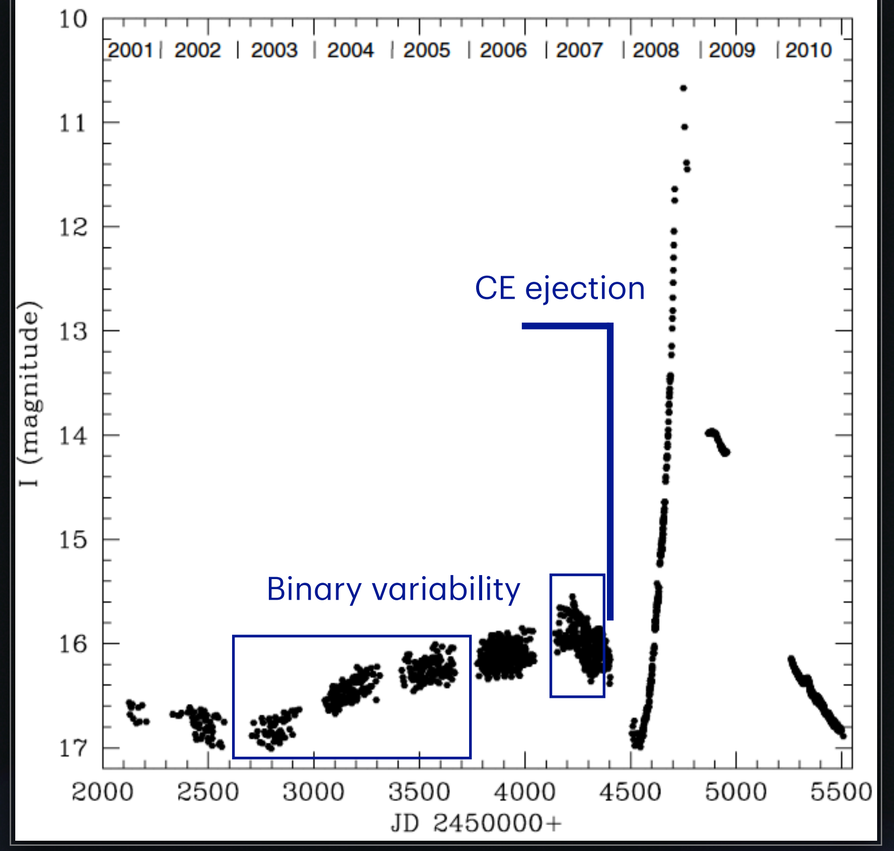
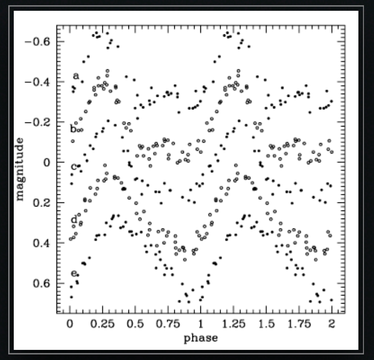


2002-2005



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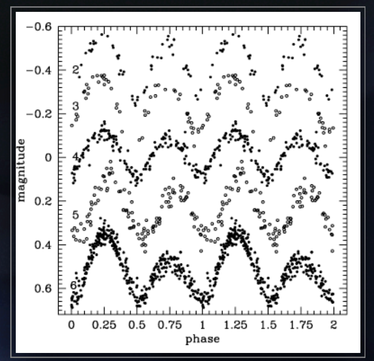
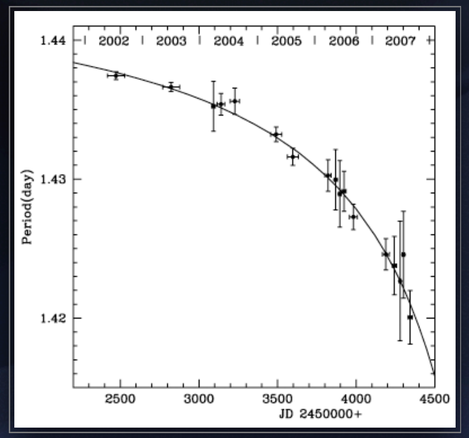
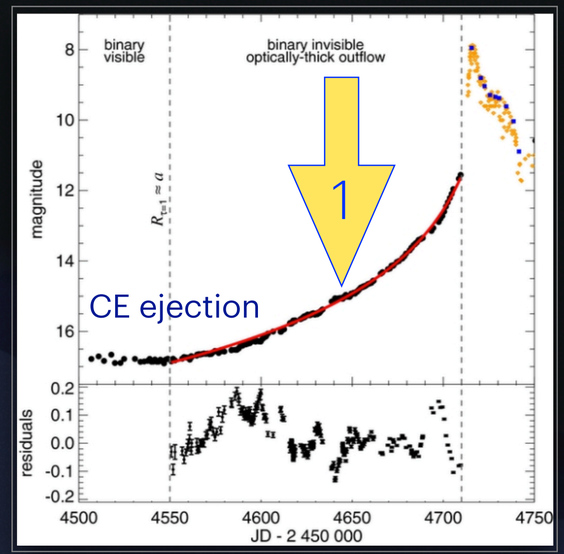
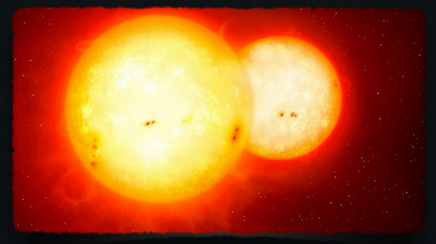




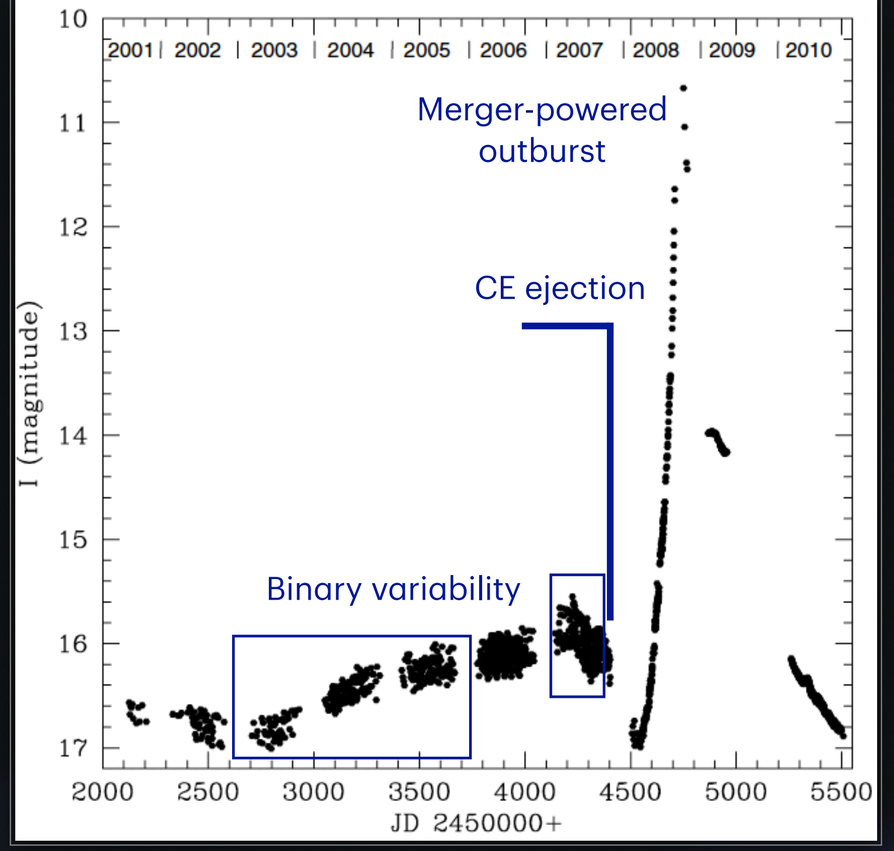


WG7 - Gap Transients: Luminous Red Novae



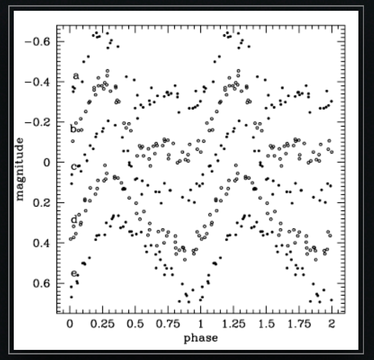
V1309 Sco

Tylenda et al. 2011



Merger-powered outburst

2002-2005



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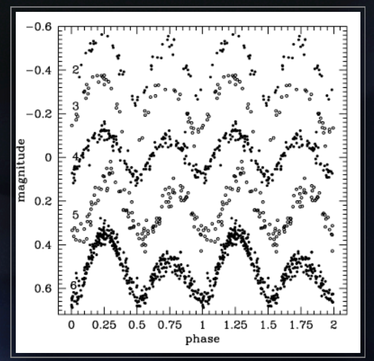

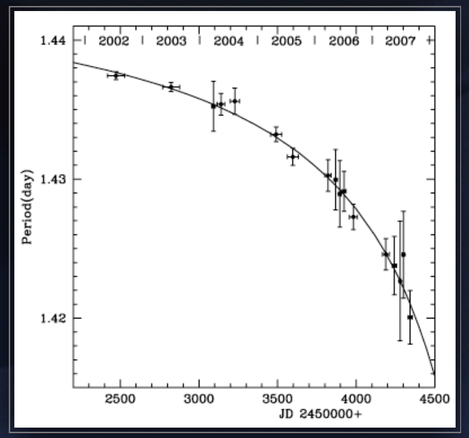

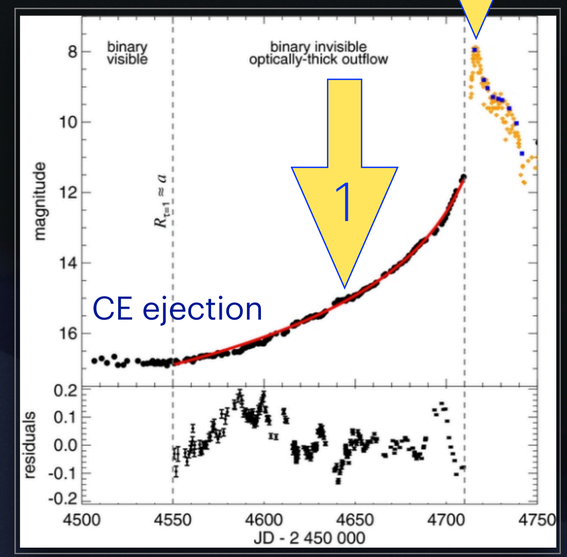

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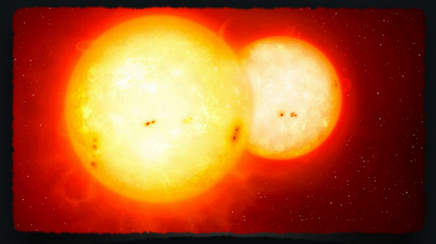

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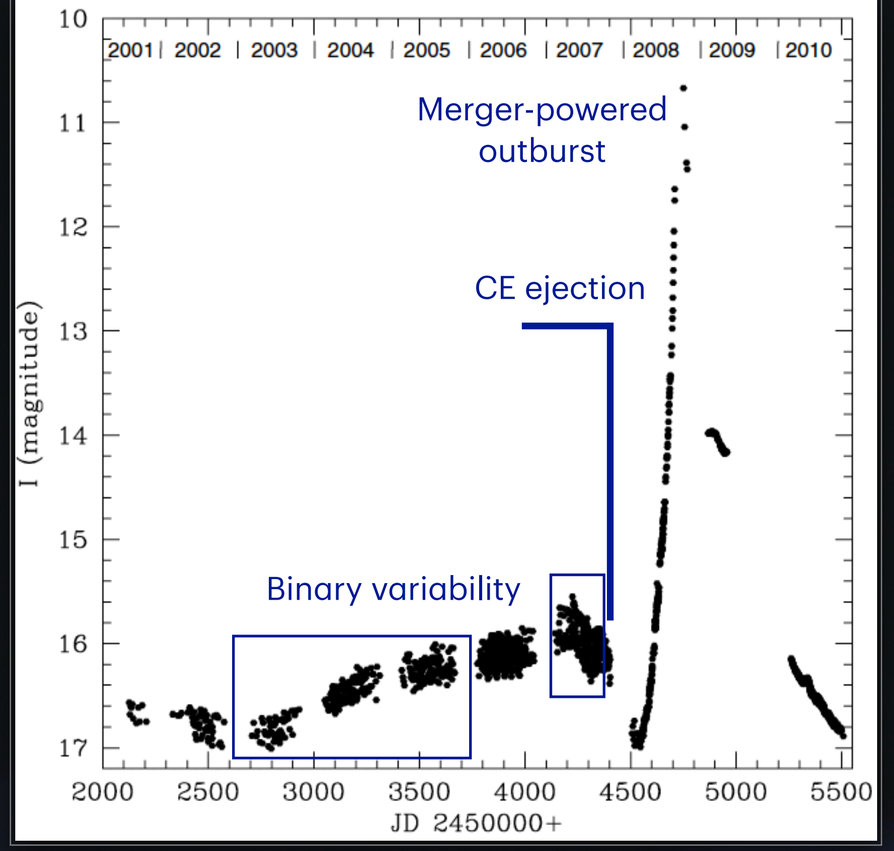
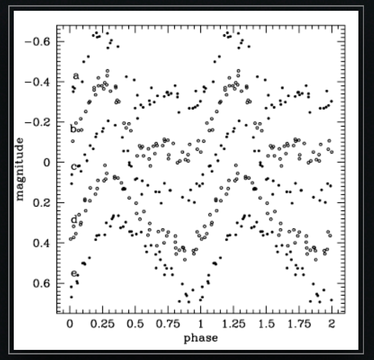
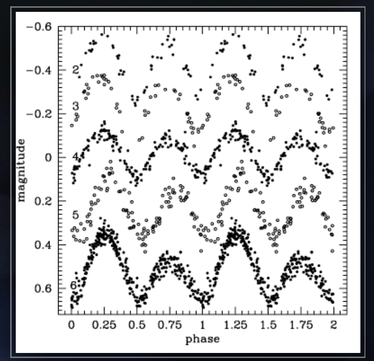


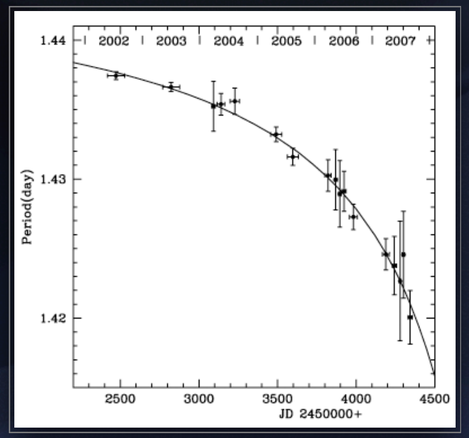
Merger-powered outburst

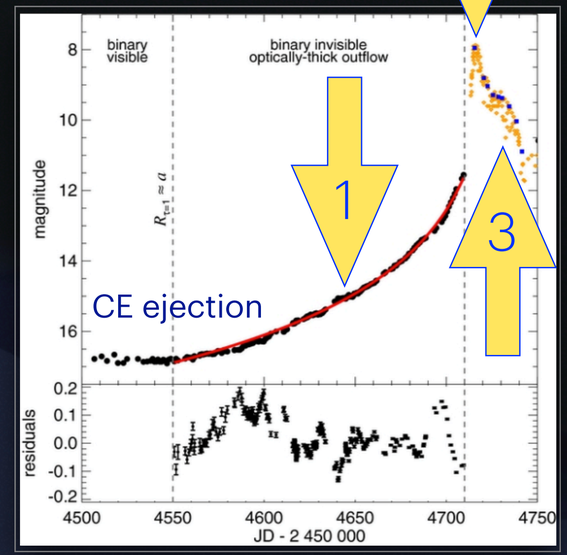
2002-2005



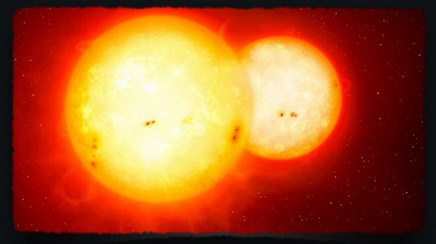
2007-2008





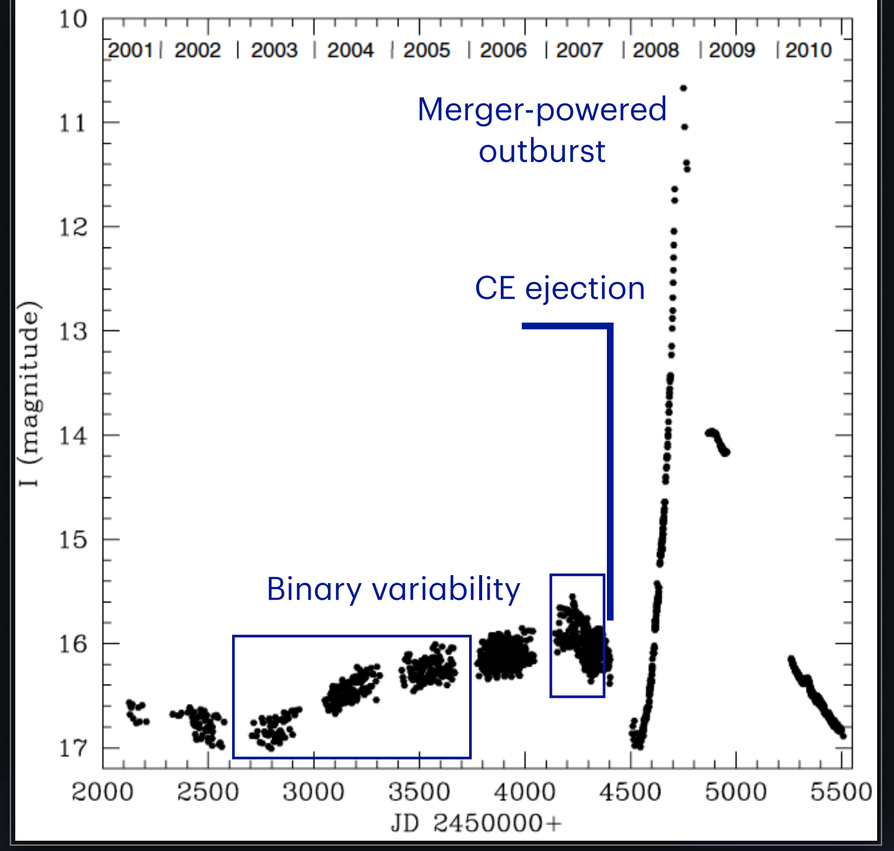


WG7 - Gap Transients: Luminous Red Novae



V1309 Sco

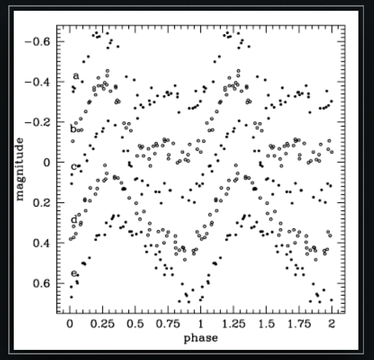
Tylenda et al. 2011



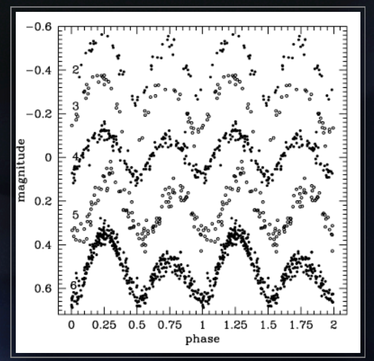
The global picture is quite convincing, but see Soker's papers on alternative jet-powered scenarios

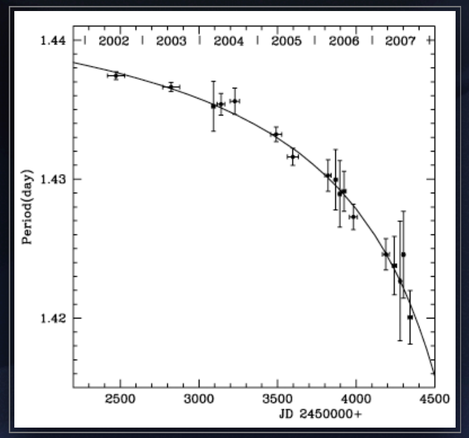
Merger-powered outburst

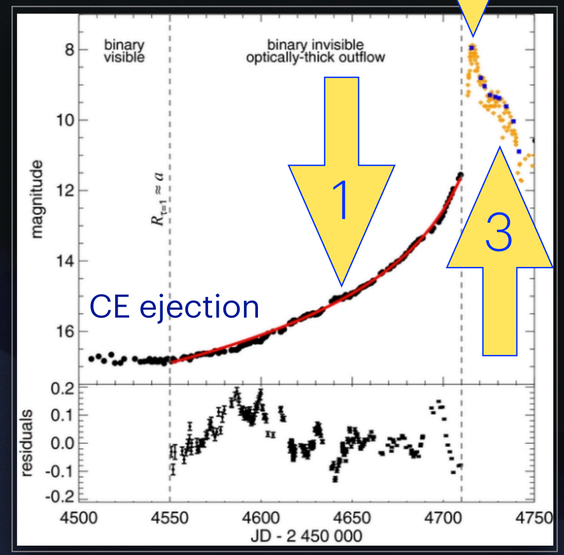
2002-2005



2007-2008

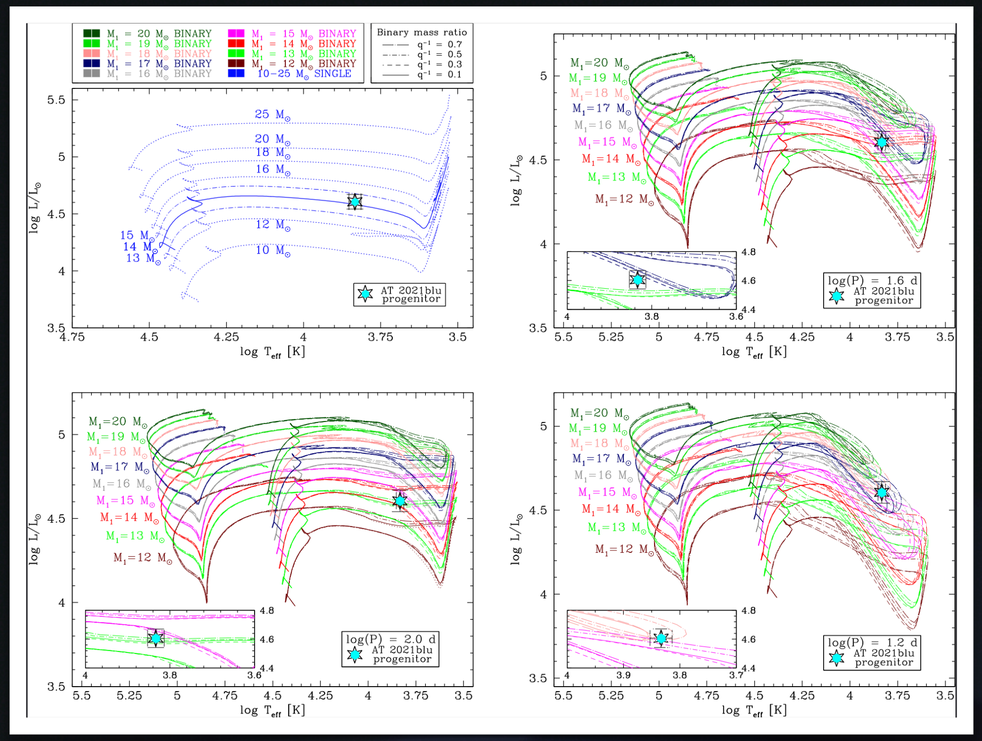


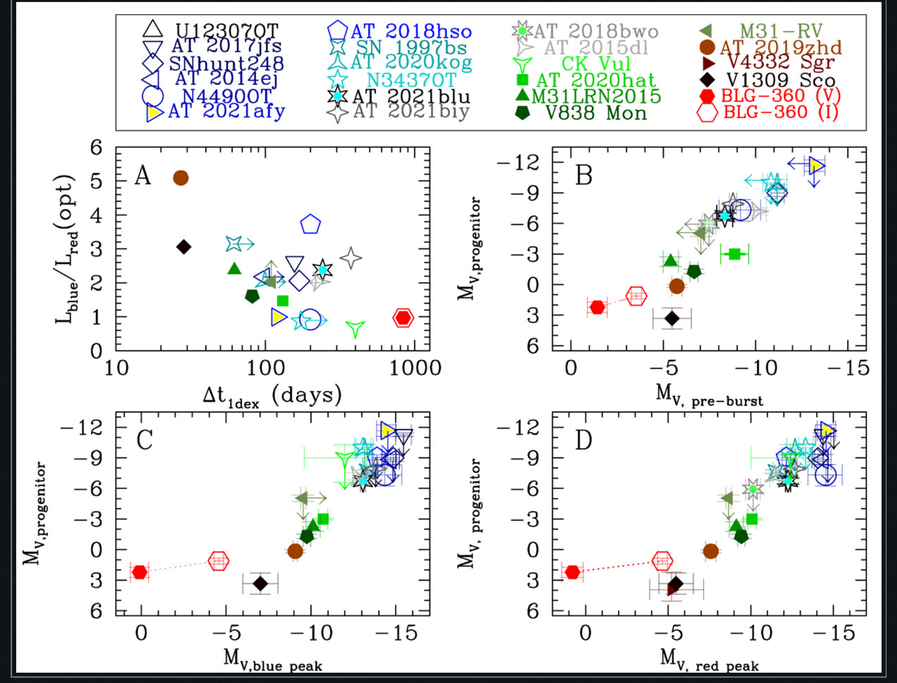




Mass of the primary

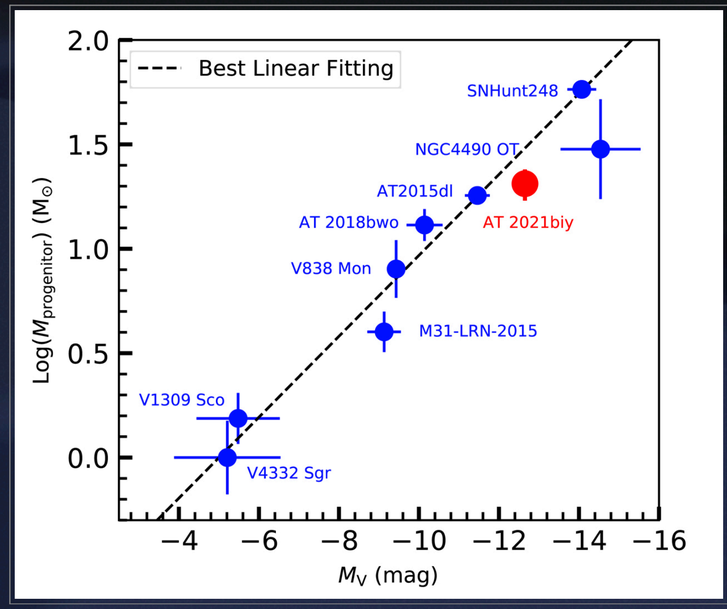
Direct method: quiescent progenitor detection





Pastorello et al. 2023

Cai et al. 2022

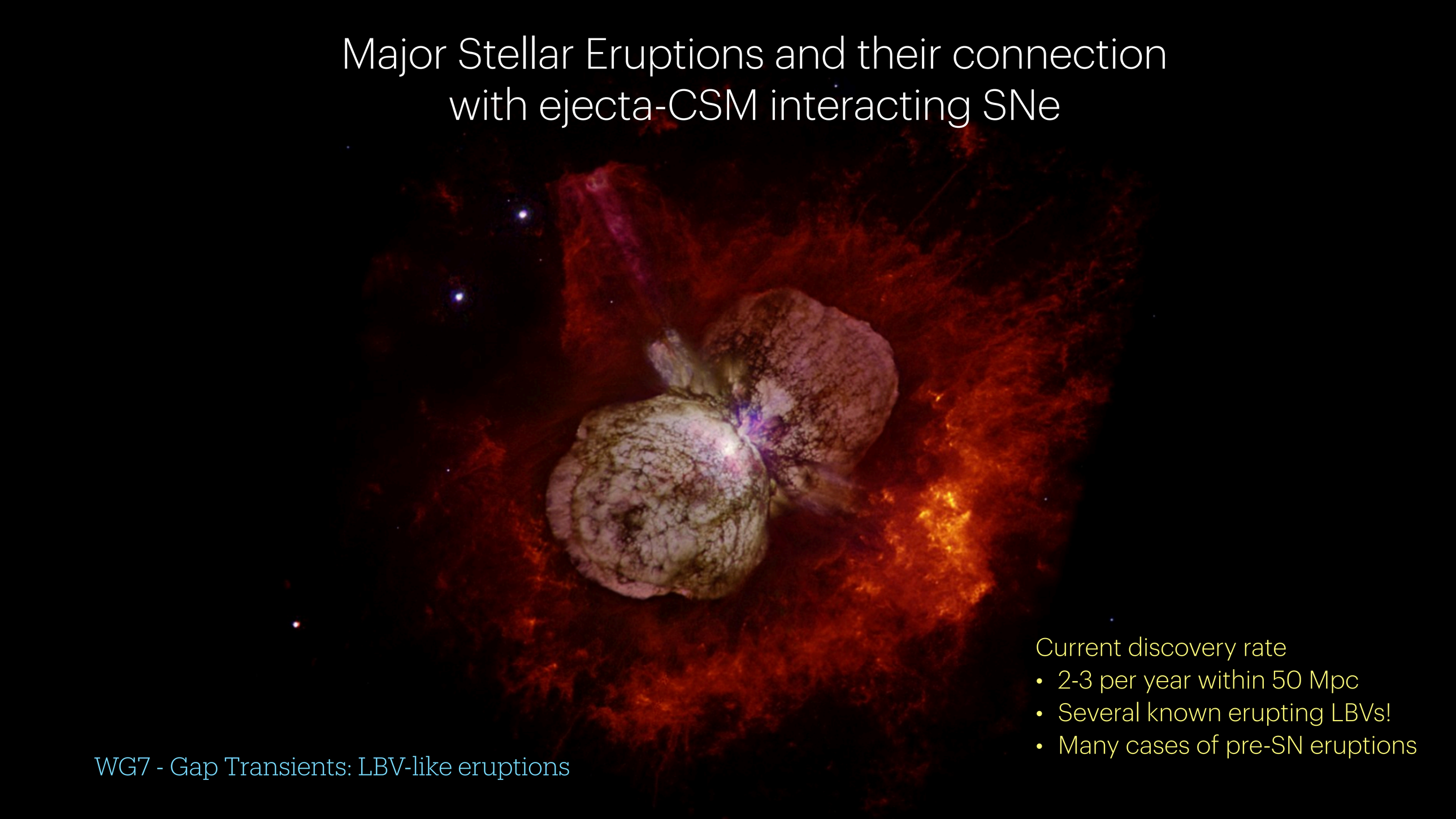


Indirect methods: correlations

- The LRN luminosity is correlated with the luminosity of the quiescent progenitor
- The luminosity of LRNe is correlated with the duration of the outburst
- The luminosity and the duration of the outburst depends on the masses involved

WG7 - Gap Transients: Luminous Red Novae

Major Stellar Eruptions and their connection with ejecta-CSM interacting SNe

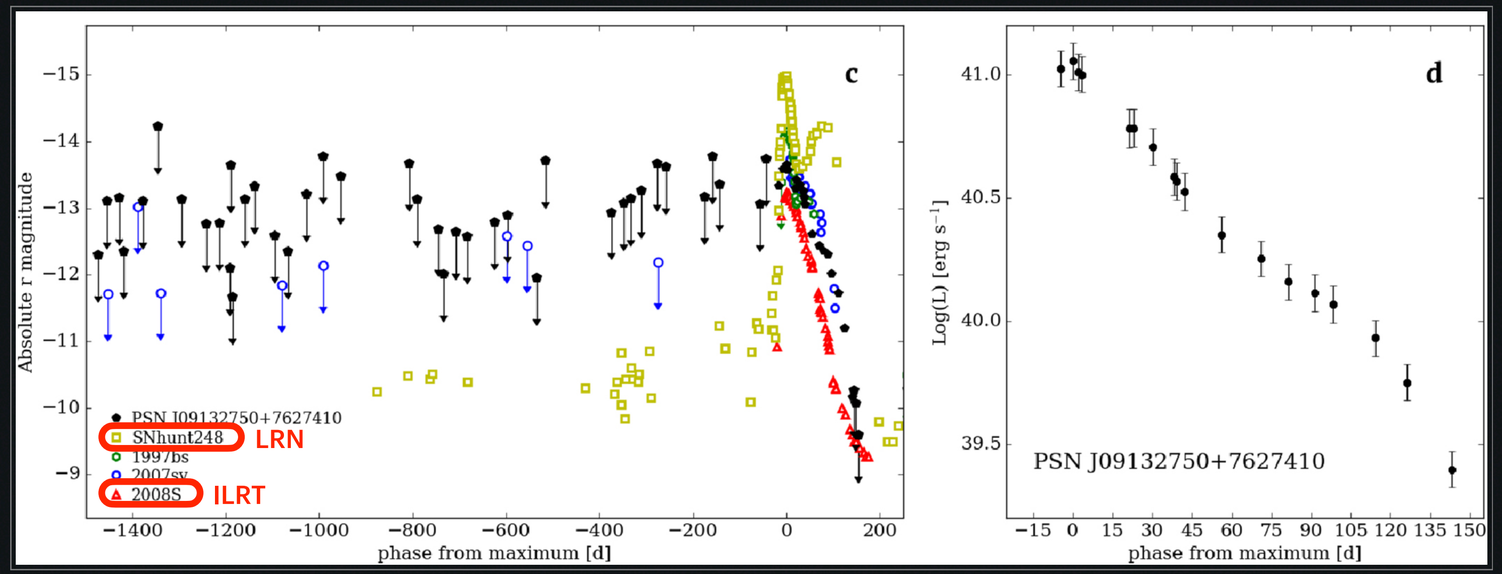


Current discovery rate

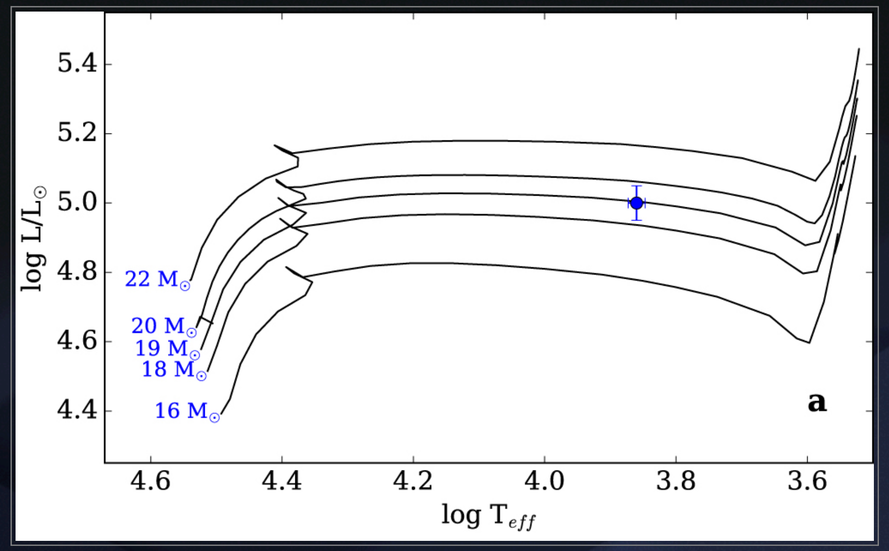
- 2-3 per year within 50 Mpc
- Several known erupting LBVs!
- Many cases of pre-SN eruptions

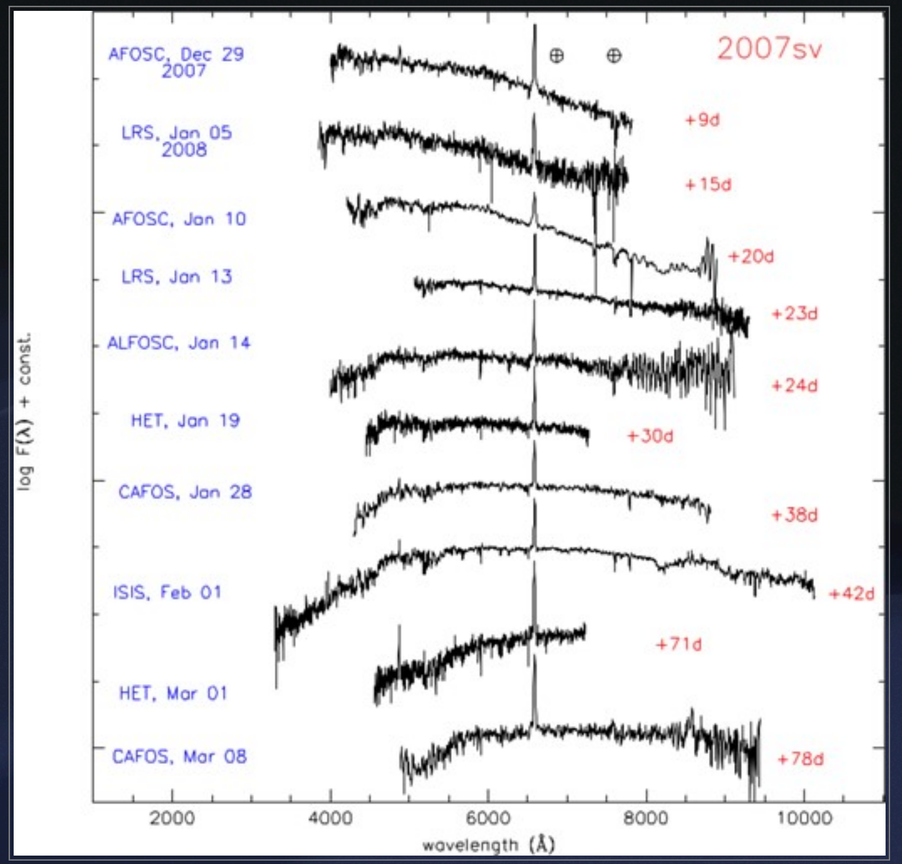
Luminous, isolated stellar outbursts

- About 3-4 month-lasting light curves
- Evident SED evolution; SNIIn-like spectra
- Moderate-mass supergiant progenitors?



Tartaglia et al. 2015, 2016

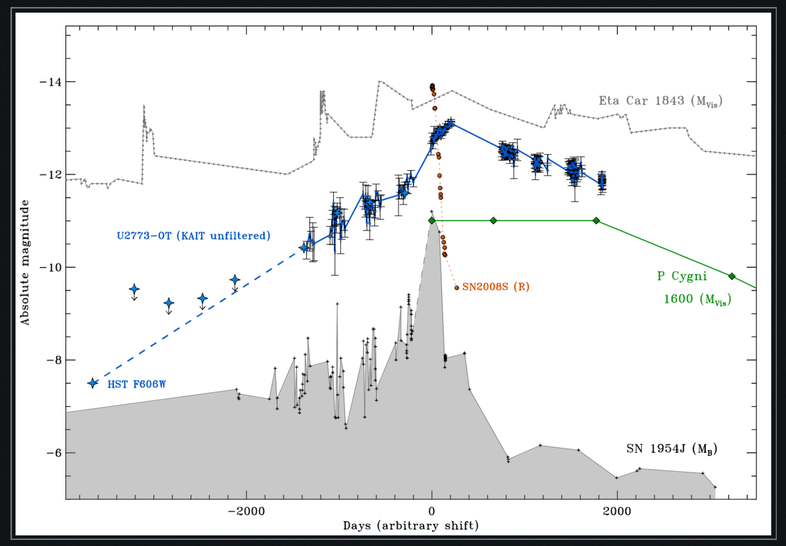


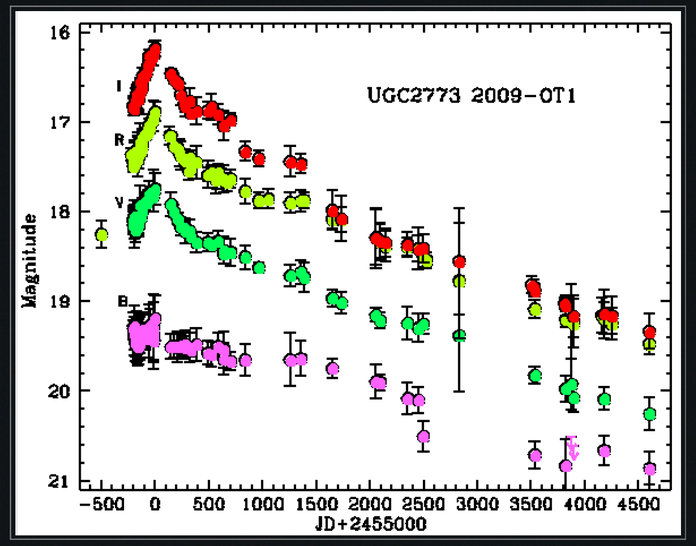


Long-lasting stellar eruptions

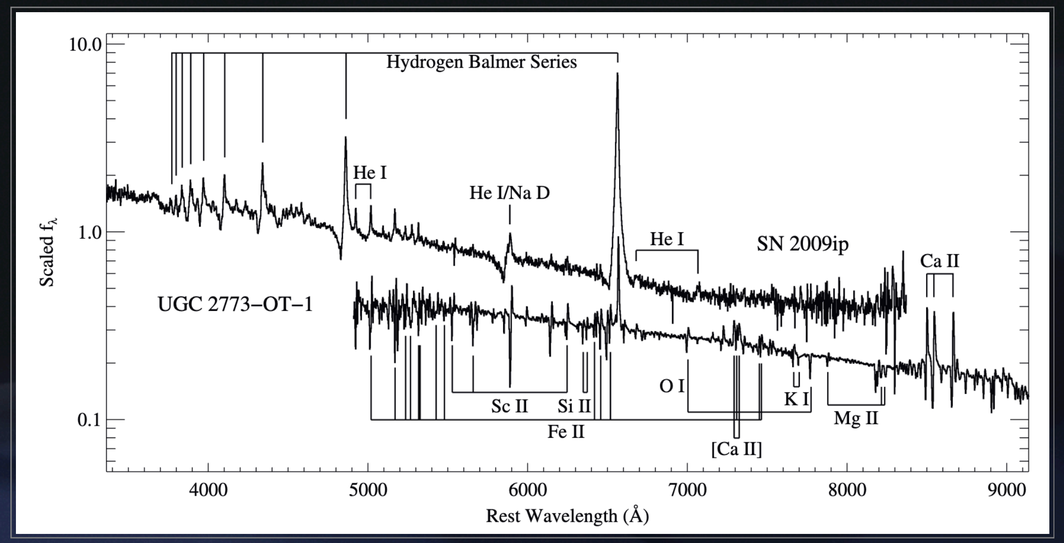
Slow-evolving light curves

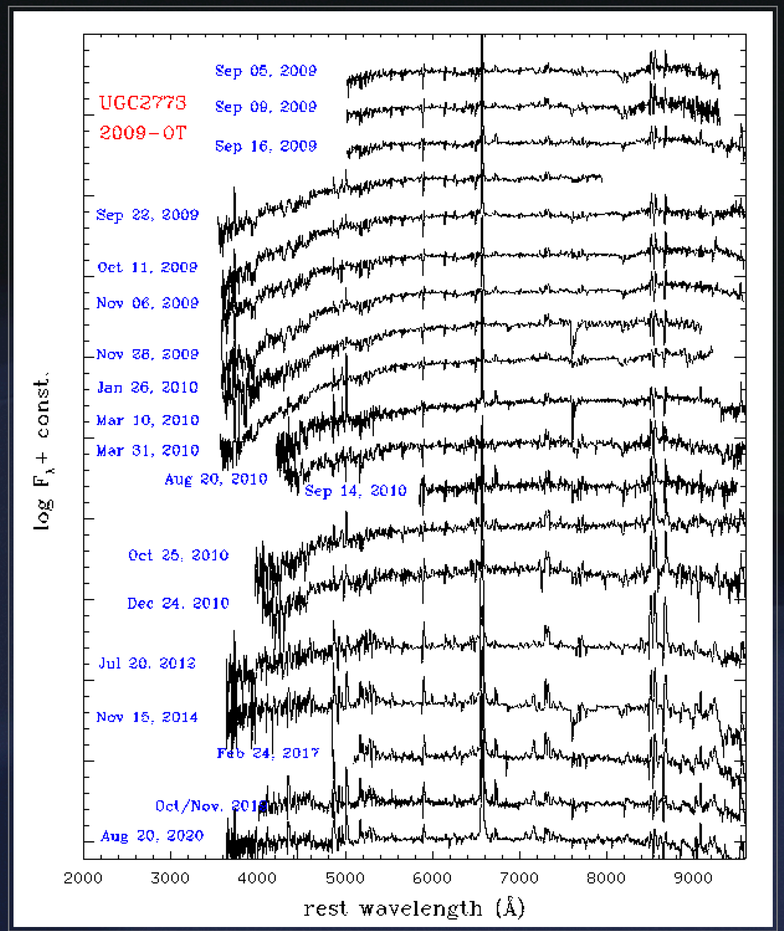
- Giant eruptions of moderate-mass LBVs
- S Dor-like events





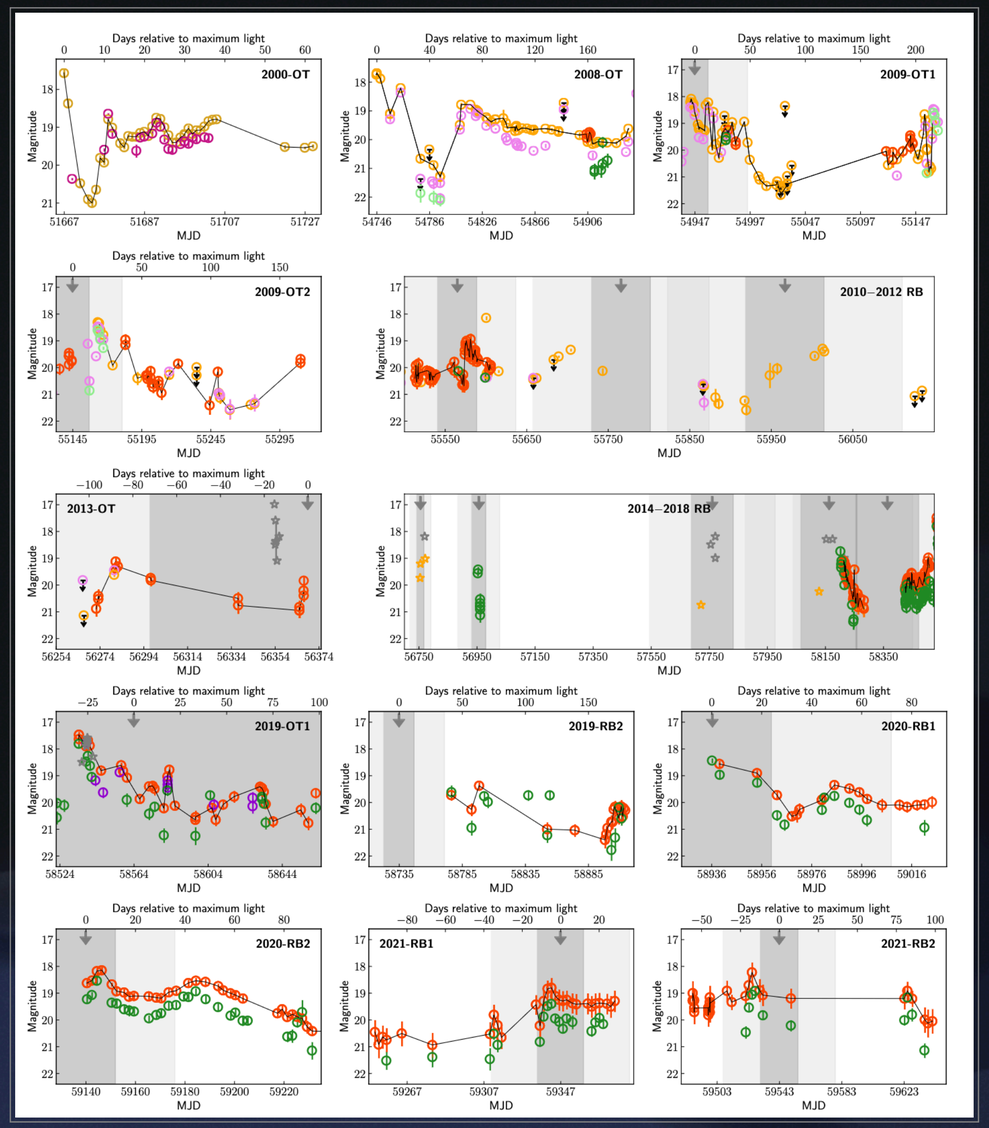
Smith et al. 2010, 2016
Foley et al. 2011
Pasto et al. 2666





WG7 - Gap Transients: giant stellar eruptions

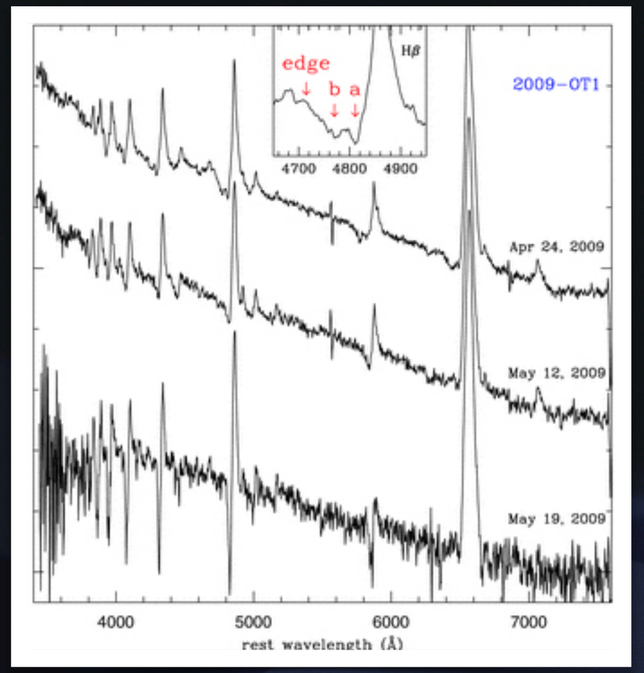
Monitoring new outbursts of LBV-like giant eruptions



WG7 - Gap Transients: LBV-like eruptions

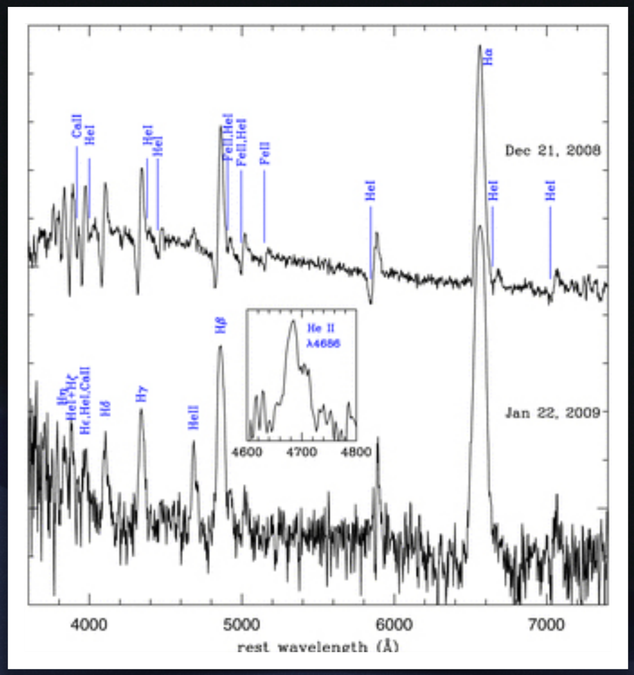
AT 2000ch - Müller et al. 2022

Multiple (quasi-periodic) outbursts, massive LBVs



Outburst spectral evolution

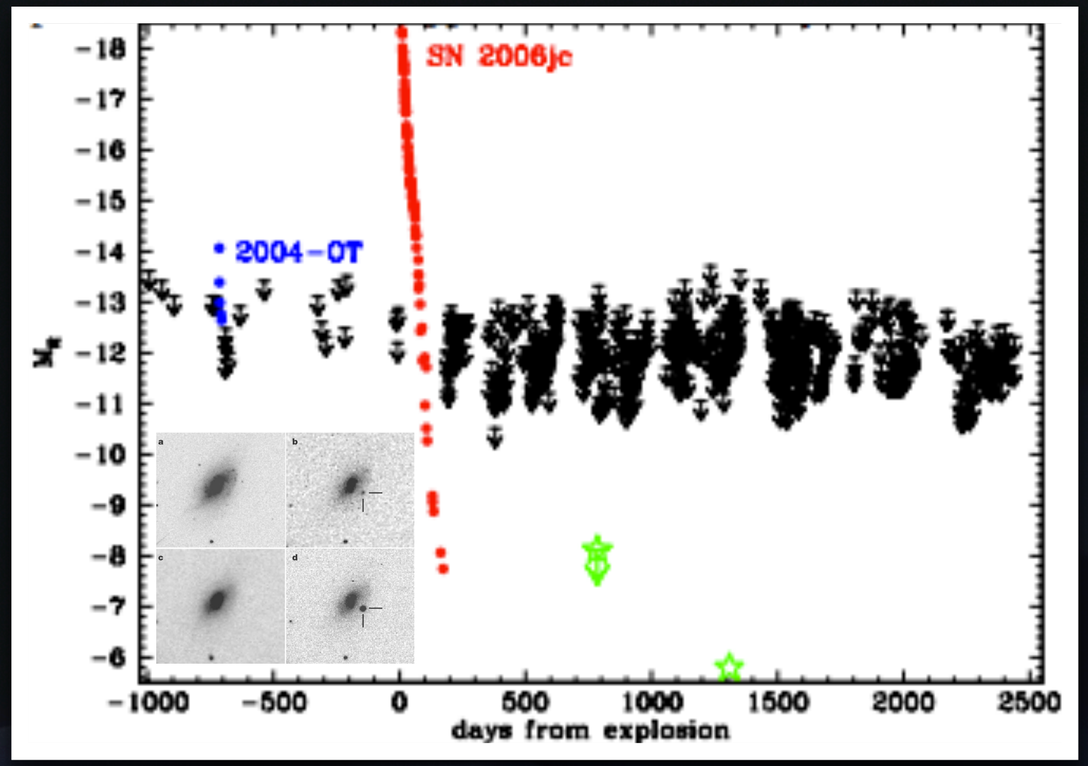
Pastorello et al. 2010



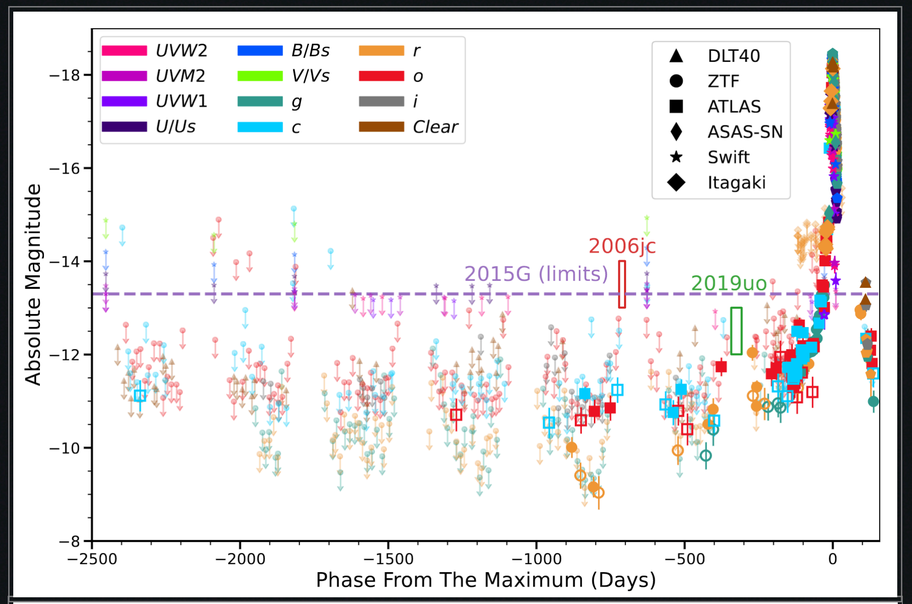
Outburst vs. quiescence

Gap transients become SNe

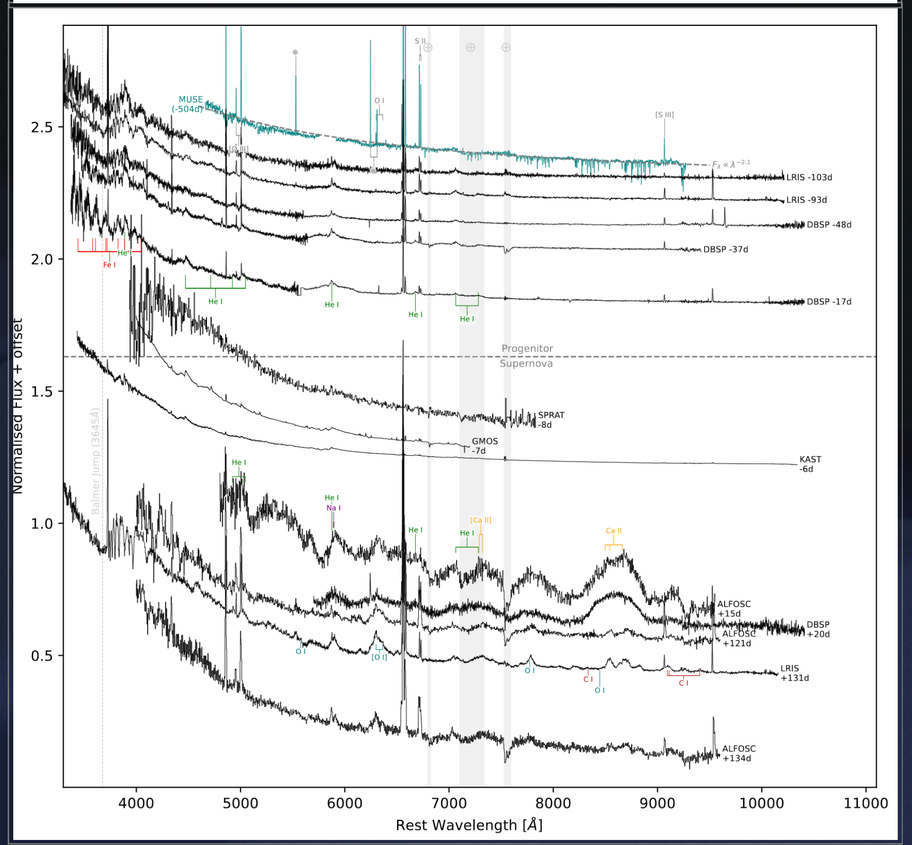
Pre-SN Ibn outbursts: SNe 2006jc & 2023fyq



Maund et al. 2016



Dong et al. 2024

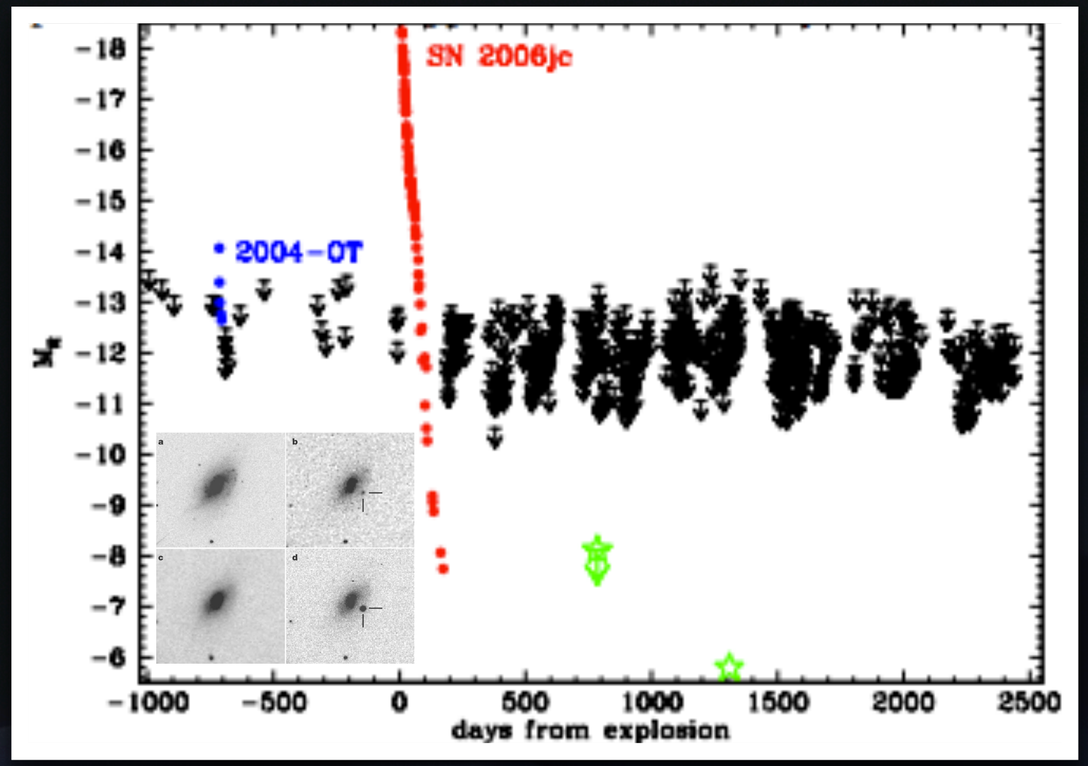


Brennan et al. 2024

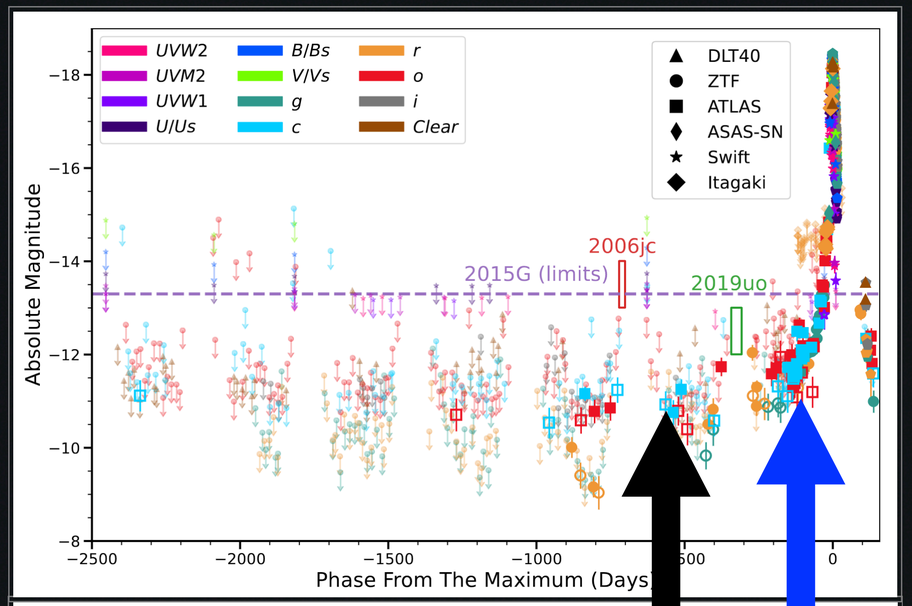
WG7 - Gap Transients: pre-SN outbursts

Gap transients become SNe

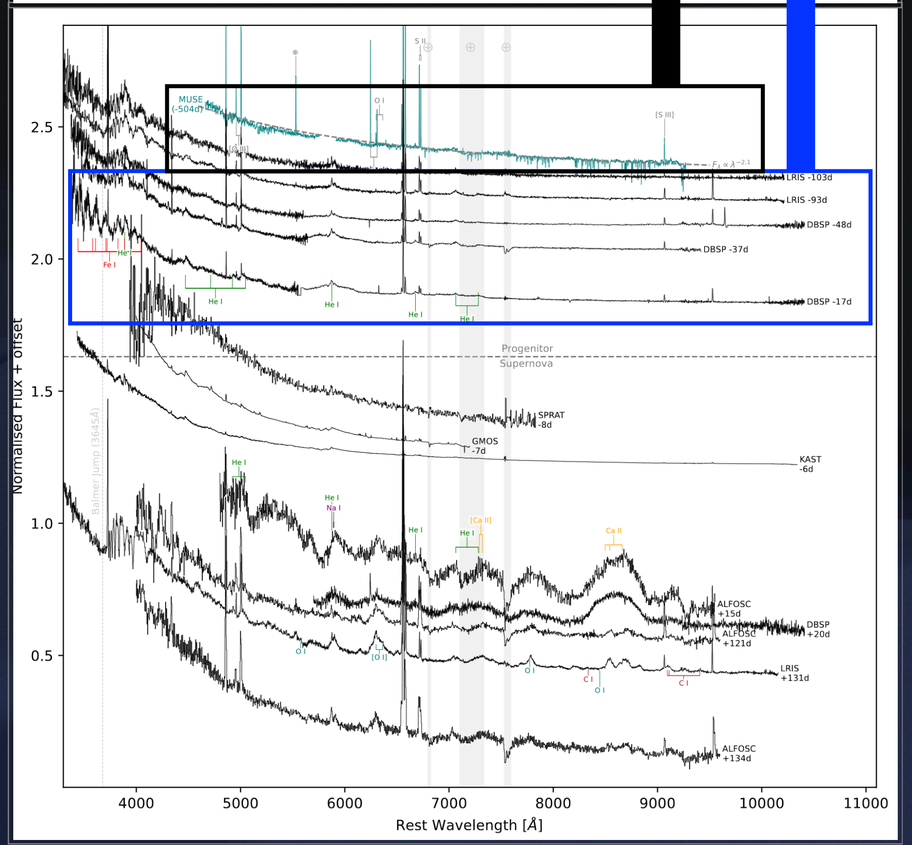
Pre-SN Ibn outbursts: SNe 2006jc & 2023fyq



Maund et al. 2016



Dong et al. 2024



Brennan et al. 2024

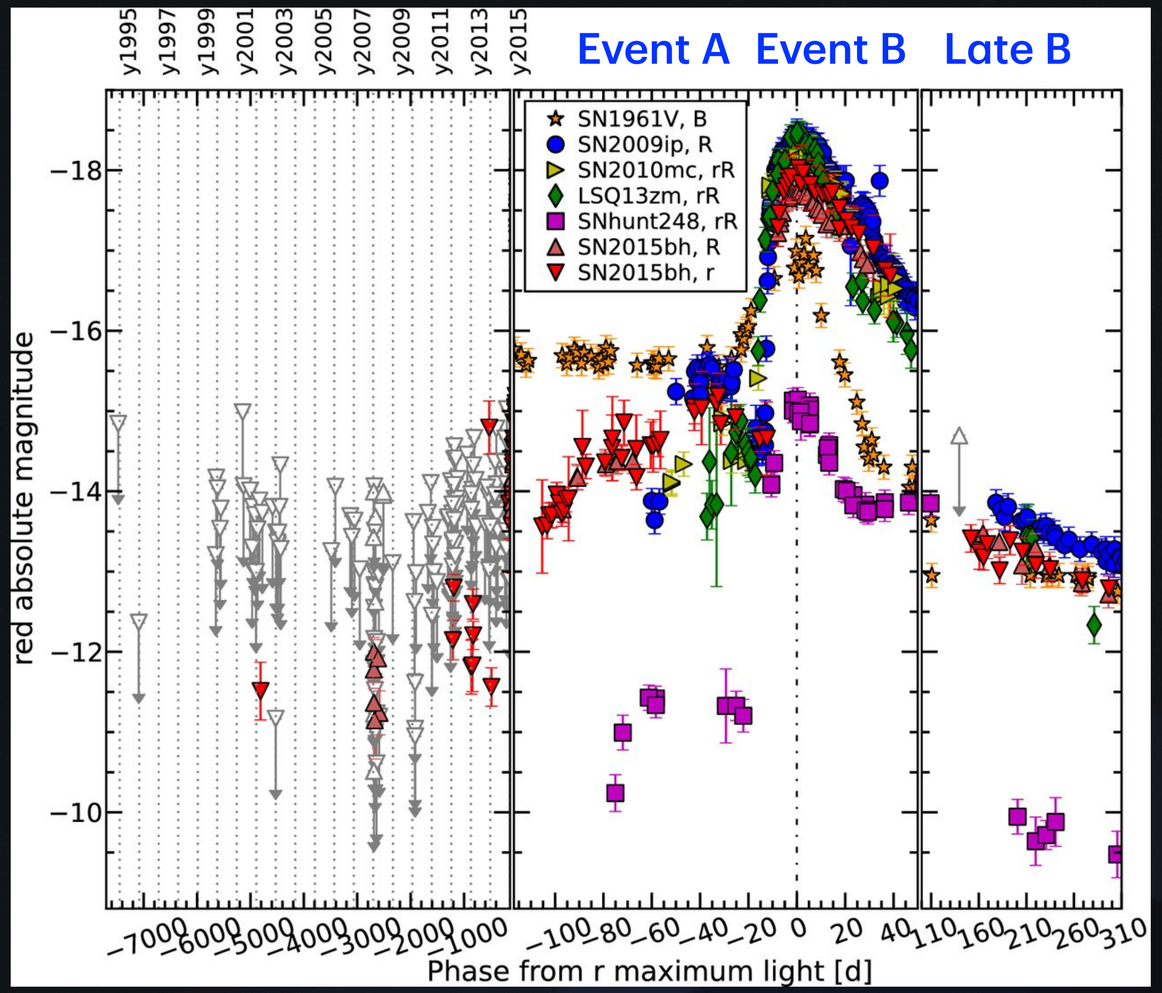
LBV-like eruptions of a massive WR or binary interaction?
High S/N, fair resolution SOXS spectra needed!

WG7 - Gap Transients: pre-SN outbursts

Gap transients become SNe

Pre-SN IIn outbursts: SN 2009ip-like transients

Erupting LBVs or lower mass stars in binaries?

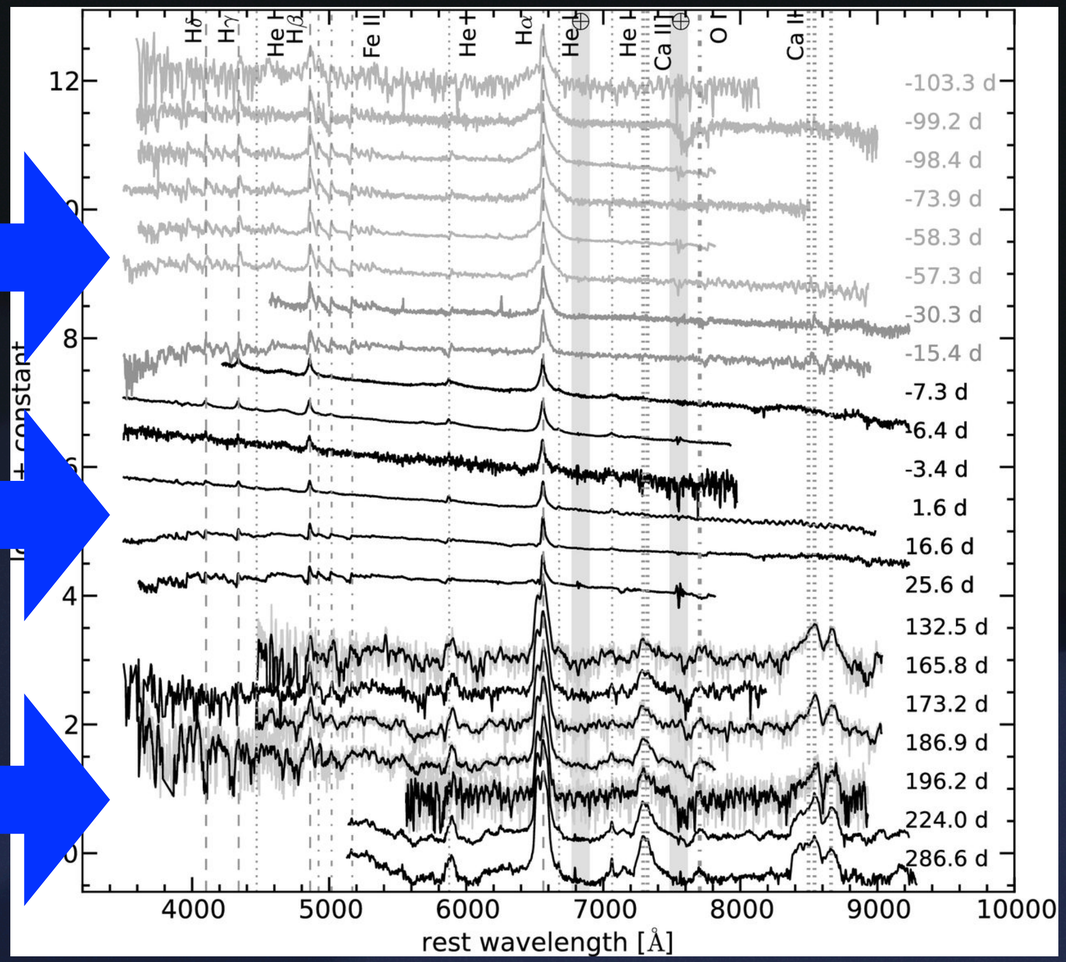


Elias-Rosa et al. 2016

Event A

Event B

Late B

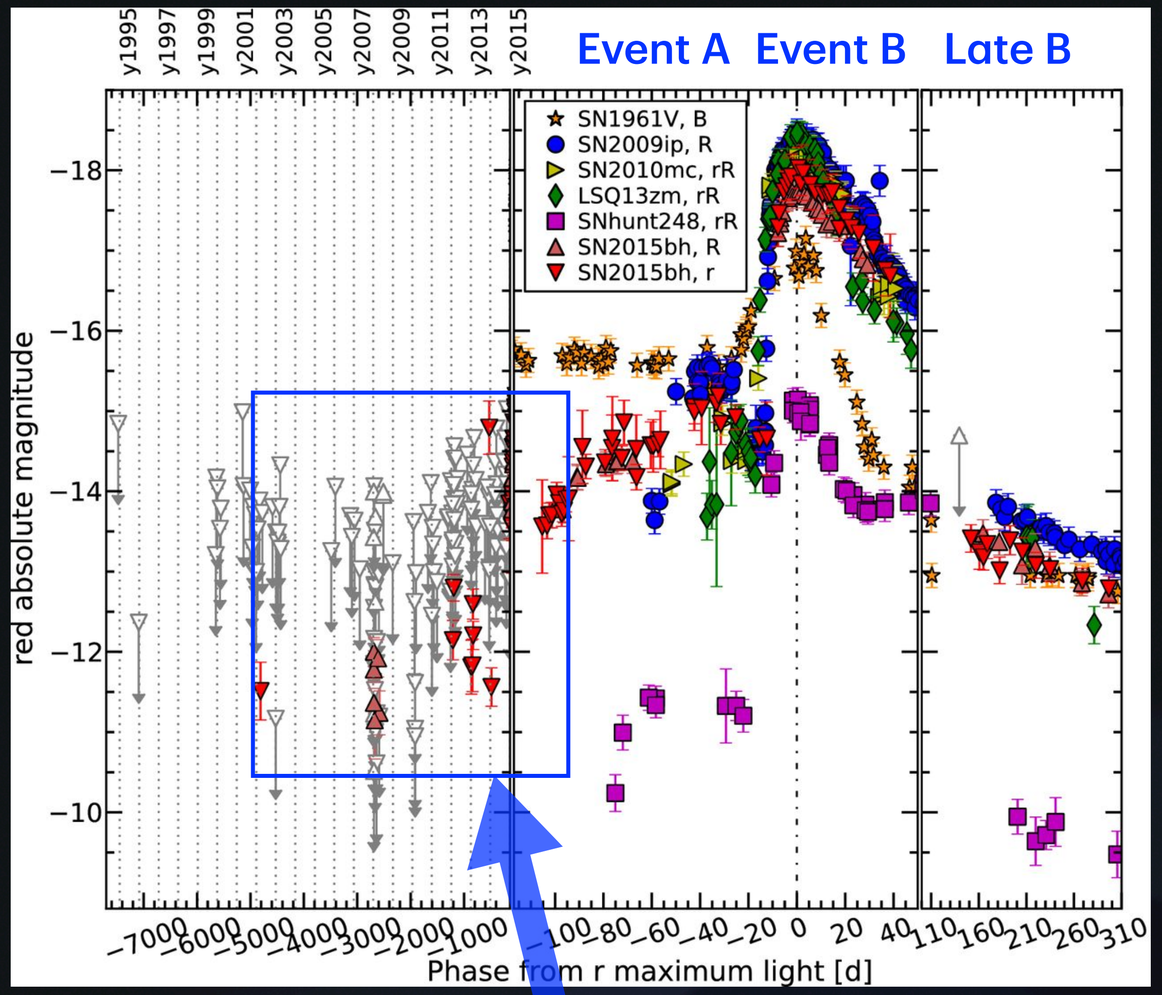


WG7 - Gap Transients: pre-SN outbursts

Gap transients become SNe

Pre-SN IIn outbursts: SN 2009ip-like transients

Erupting LBVs or lower mass stars in binaries?



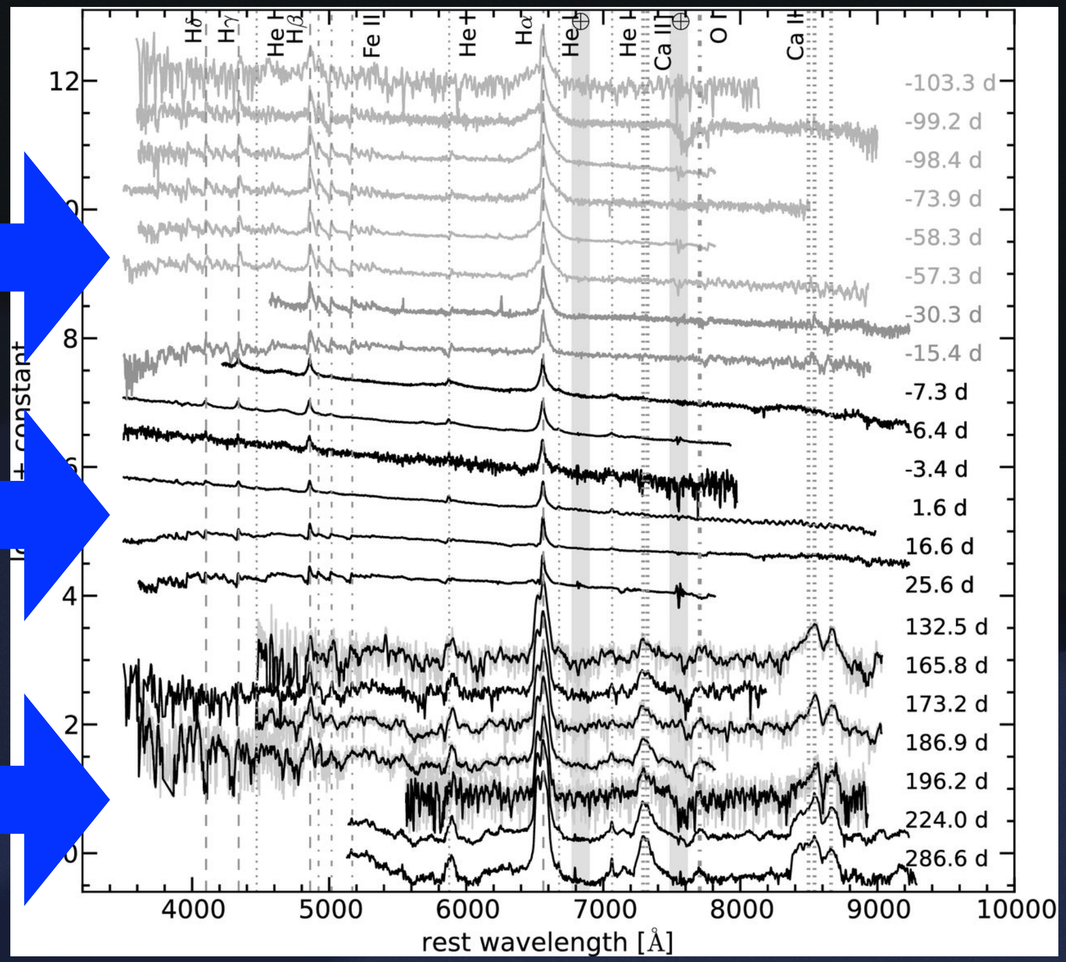
Elias-Rosa et al. 2016

We need to study the pre-SN eruptive phases!

Event A

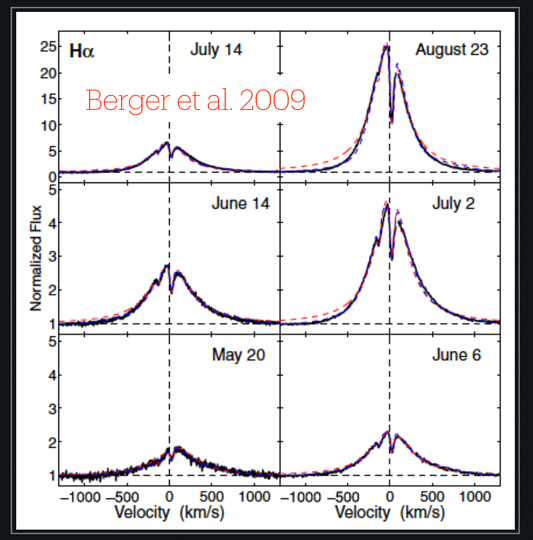
Event B

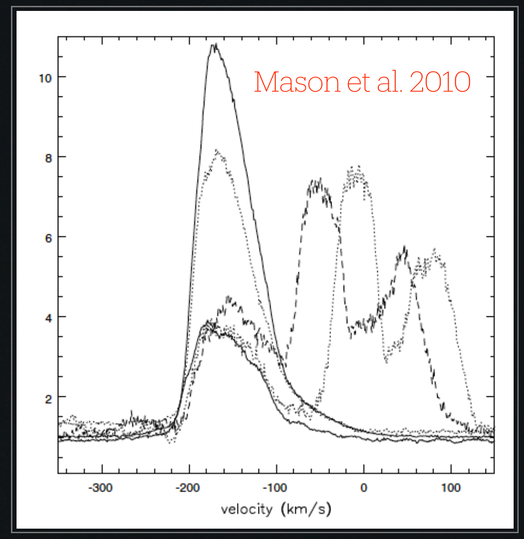
Late B

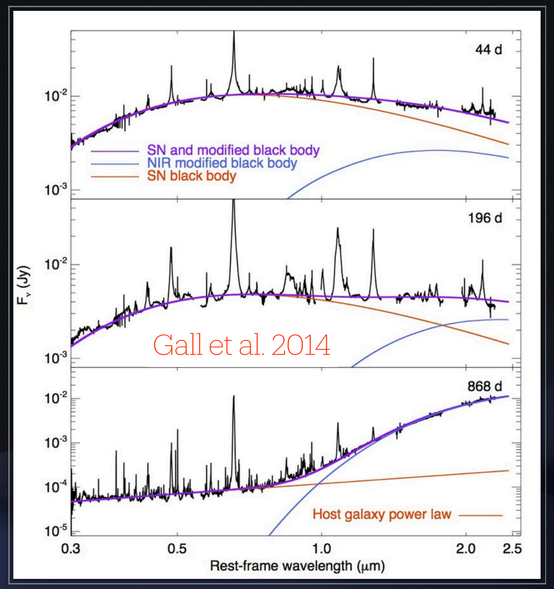


Why SoXS?

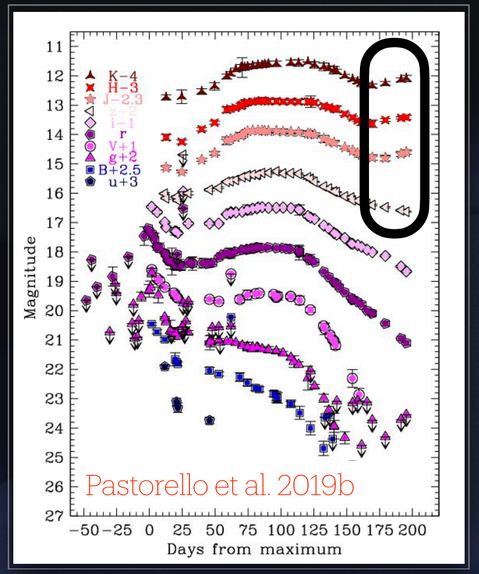
1. Fair resolution
   - to measure the wind velocity using the narrowest lines,
   - to unblend the spectral features and study their profiles => characterization of the different kinematic components;
   - to resolve the forest of metal lines at λ < 4000Å,
   - to resolve the Na ID from the ISM (for reddening estimate).



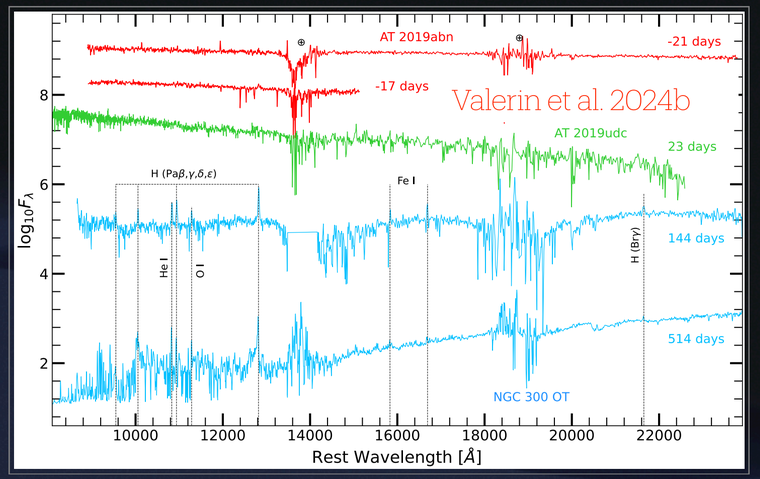




2. SED sampling
   - The wide wavelength range allows us to constrain the flux time evolution of the different emitting regions (the ejecta, the CSM, light echoes, dust emission)



3. NIR coverage
   - Investigating peculiar LC features, such as the post-plateau NIR hump in LRNe



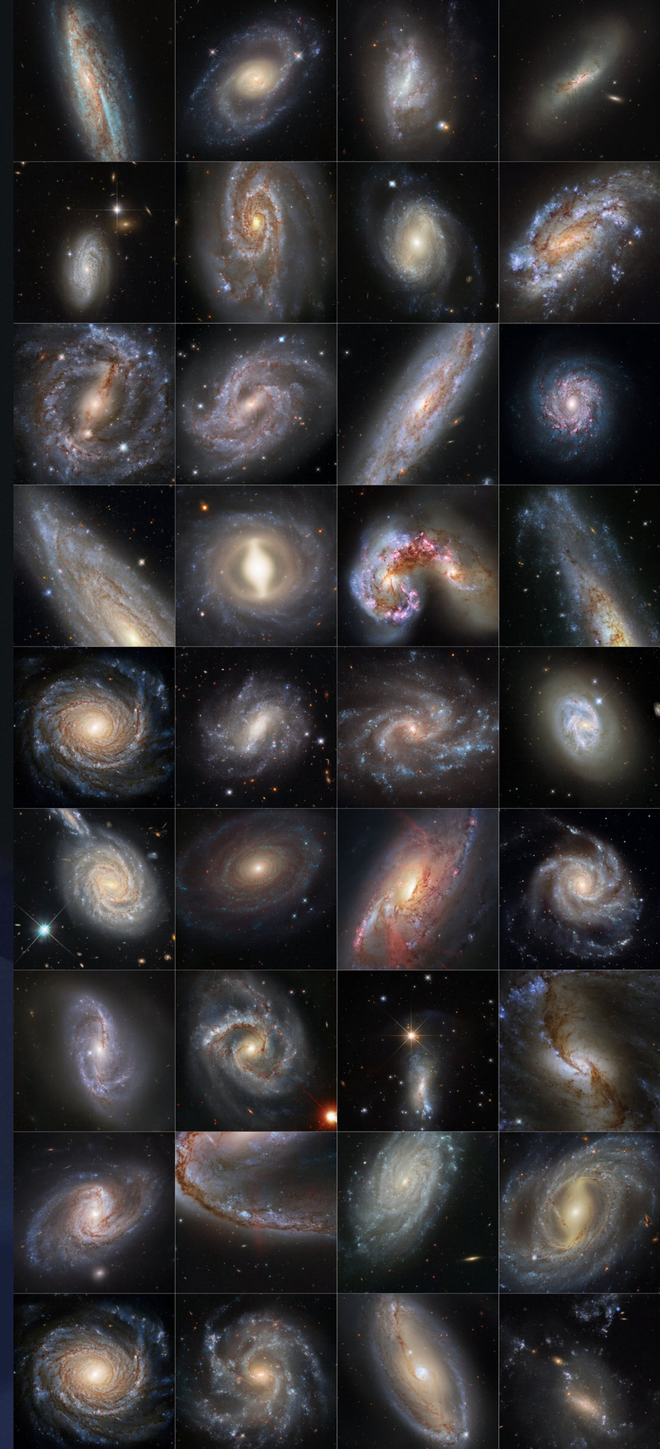
4. NIR spectra of interacting GTs are rare!
   - A handful of poor-quality NIR spectra available for IGTs! Line ID in the NIR (Fe-peak lines? CNO lines? Molecules?)

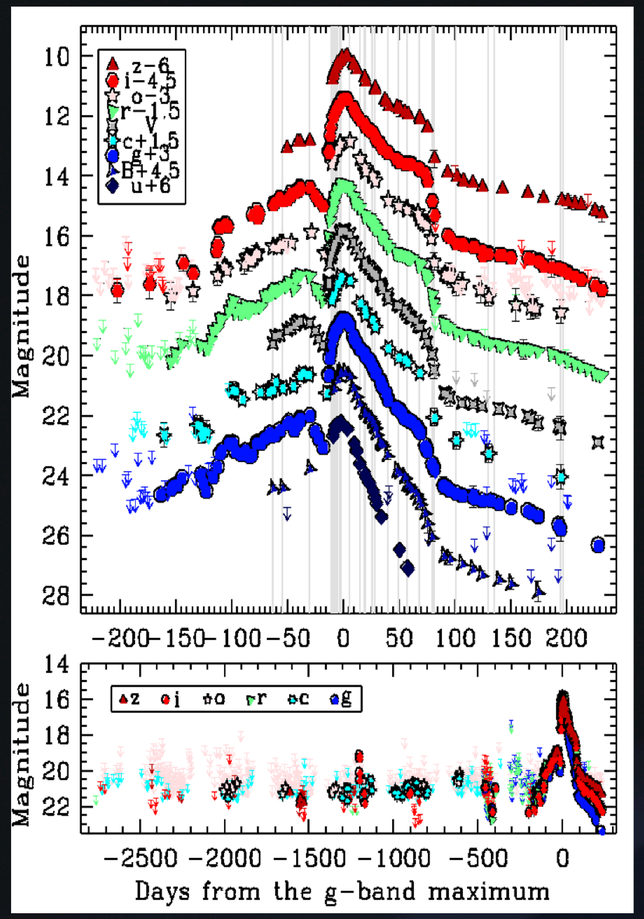
Rates

Rates are not well constrained at all
(see, e.g., Karambelkar et al. 2023; Cai et al. 2021)

Current discovery rates

- ILRTs: 4-5 per year within 50 Mpc
- LRNe: 8-10 per year within 50 Mpc
- Faint RNe (mergers of low mass systems) are relatively common ~ 1 / 5 yrs in Local Group galaxies.
- LBV-GE /ISO: we expect ~2-3 per year within 50 Mpc
- pre-SN impostors: < 10 per year within 100 Mpc





Example: Fig. shows a relatively rapid transition from "too faint for SoXS" to "start of SoXS campaign"

Trigger criteria

- Need to account for a range of timescales and cadences
- Need to account for possible rapid variations, and react accordingly

Main criteria: intrinsic luminosity and distance, archival progenitor data

Cut-off: apparent magnitude, visibility windows, imaging supporting follow-up facilities (and 8m telescopes for late spectroscopy)

Reasonable follow-up possible for < 19 mag objects

- Abs mag -5 to -10 in the MW and the Local Group
- Abs mag < -12 at 15 Mpc
- Abs mag < -13.5 at 30 Mpc
- Abs mag < -14.5 at 50 Mpc

Time request: 200hr per year

TRANSIENT	D. RATES (D<50MPC) (N° PER YEAR)	OBJECTS TO FOLLOW (PER YEAR)	N° SPECTRA PER OBJECT	TIME REQUESTED PER YEAR
ILRT	4-5	4-5	6-8	40h
LRN	8-10	4-5	8-10	80h
LRN IN THE LOCAL GROUP	0.2 (D<3 Mpc)	0.2	15	10h
LBV-GE / ISO	2-3	2-3	6-8	30hr
PRE-SN IMPOSTORS	<10 (D<100 Mpc)	4	8-10	40hr

* distinction among different classes only possible once the campaign is underway
* We propose to follow all LRNe in the LG, and all ILRTs and all GEs/ISOs within 50 Mpc
* Outliers: we can follow very luminous events (> -15.5 mag) also above 50 Mpc

Sample size:

Currently, very few gap transients have full optical-near-IR datasets
We need to increase the sample to explore the variety of GTs observables => new subtypes

At the end of 5-yrs of SoXS operations, we would aim to have:

- 20-25 ILRTs
- 20-25 LRNe (hopefully 1-2 in the Local Group)
- About 10-15 non-terminal stellar outbursts (incl. Giant Eruptions and major outbursts of massive stars)
- About 20 pre-SN outbursts + SN Evolution (to be somehow coordinated with WGs 6,8)

DISCUSSION POINTS

- Follow-up coordination

1. A (small) fraction may be split with other WGs e.g. CCSNe, classification, faint type I or II SNe potentially fall within this WG, so we should coordinate!
2. Sometimes discriminating ILOTs and bright novae can be tricky at early phases - need to coordinate with WG4 for classification and (eventually) starting the follow-up campaign. The target will then flow to the correct WG once the classification will be unequivocal.
3. Others, such as 2009ip may initially fall in WG7, but may be shared with other WGs (e.g. WG6, WG8)

- Observational time management

  - Our current total request for follow-up is 200 hrs for following objects up to 19 mag.
  - Propose pooling up to 25% of WG7 time with a similar amount from other WGs in case of targets of shared interest => Best managed on a case-by-case basis.

- Classification of potential Gap Transients

  Favour: classification of all gap transients brighter than ~ +20 within distance cut-off (currently 50 Mpc, but might be more) - Rates are poorly constrained, and could be high for some sub-groups