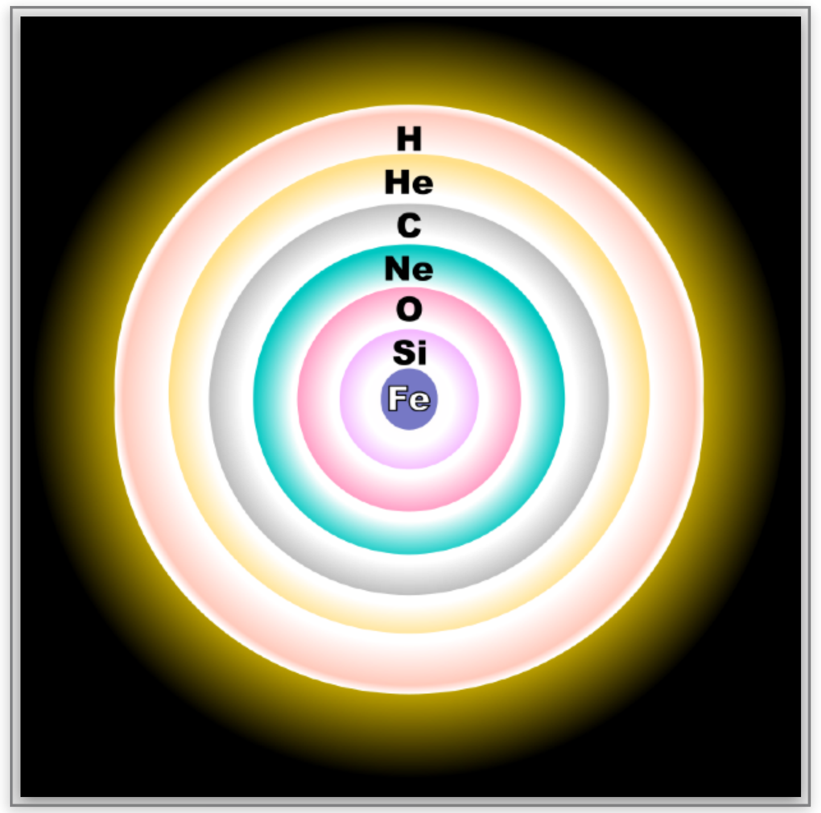
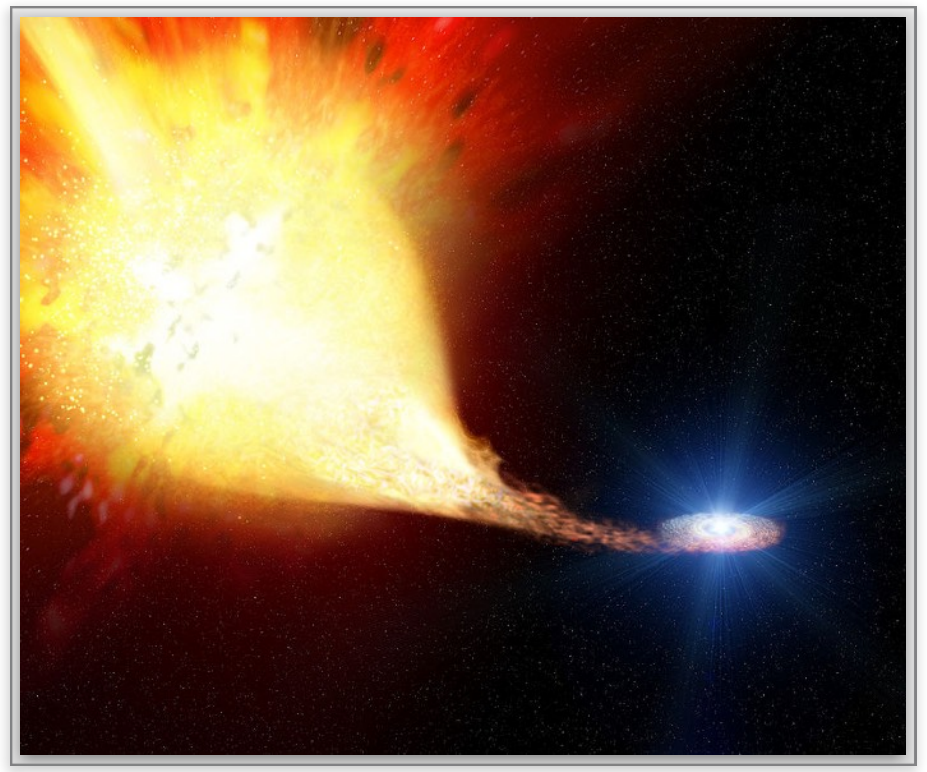
- Stefano Benetti (Primo ricercatore OAPd)
- Maria Teresa Botticella (Ricercatrice OACn)
- Enrico Cappellaro (Dirigente di ricerca OAPd)
- Nancy Elias-Rosa (Ricercatrice OAPd)
- Laura Greggio (Prima ricercatrice OAPd)
- Elena Mason (Ricercatrice OATs)
- Lina Tomasella (Ricercatrice OAPd)
- Paolo Ochner (C.T.E.R. UniPd; ass. OAPd)
- Leonardo Tartaglia (td OAPd - Aug 2022)
- Maria Letizia Pumo (rtdb UniCt; ass. OACt)
- Vincenzo Petrecca (PhD UniNa; ass. OACn)
- Andrea Reguitti (PhD student Univ. A. Bello; ass. OAPd)
- Irene Salmaso (PhD student UniPd; ass. OAPd)
- Giorgio Valerin (PhD student UniPd; ass. OAPd)
- [Yongzhi Cai (PhD UniPd; currently postdoc at Beijing Univ.)]
- [Achille Fiore (PhD UniPd; currently postdoc at ETC Trento]

# Stellar transients in the era of synoptic surveys

Scheda PDSNET (2.2-2.6 FTE/year staff)




# Motivations



In past years, the research on stellar transients was focused on classical core-collapse and thermonuclear supernovae, their progenitors, the explosion mechanisms, and their applications as standardizable candles.

The new generation of all-sky surveys shifted our interest to the characterization of new types of stellar transients, expanding the range of the transient luminosity function, because:

I. Models predict types of stellar explosions that are not fully consistent with the observational properties of traditional SN types: (pulsational) pair-instability, fall-back supernovae, electron-capture SNe, .Ia and other non-standard thermonuclear explosions.

II. Their possible link with important topics, such as the formation of compact objects, the sources of gravitational waves, neutrinos and high-energy particles.

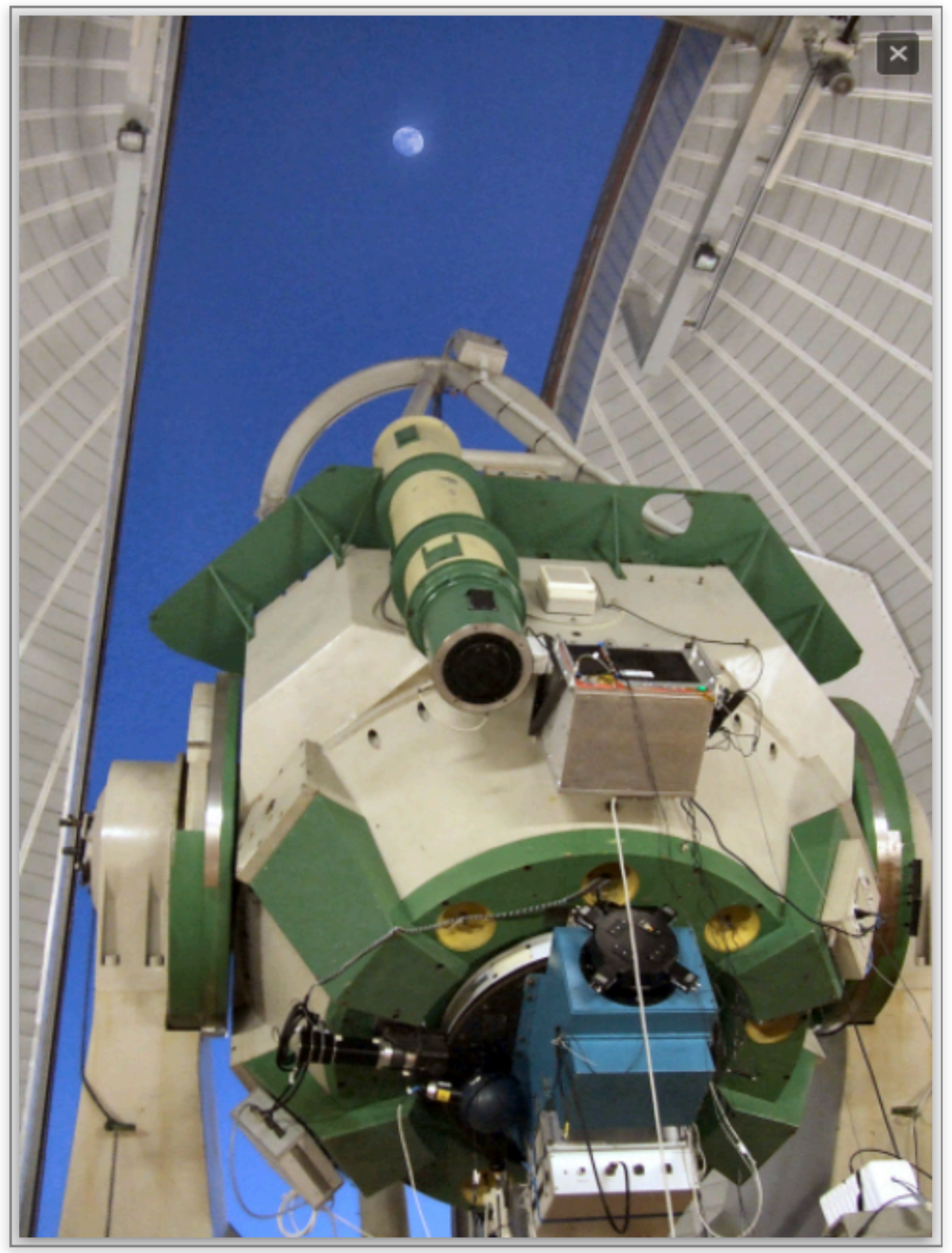
III. We want to study transients hosted in extreme environments (e.g. low metallicity, faint host, interacting galaxies) or unusual progenitors (very high-mass stars; interacting stellar systems)

# Main scientific collaborations

- ☑ NUTS/NUTS2 (Nordic optical telescope Unbiased Transient Survey): from 2016 - in progress; *https://nuts.sn.ie/*
  - over 40 researchers (INAF-OAPd, Dublin, Stockholm, Aarhus, Turku)
  - 75hrs/ semester in ToO with ALFOSC + 6 half-nights with NOTCam plus other supporting facilities (Liverpool Telescope, TNG, Asiago, GTC, WHT….)
- ☑ PESSTO/ePESSTO/ePESSTO+ (extended-Public ESO Spectroscopic Survey for Transient Objects): 2012 - 2023 *https://www.pessto.org/*
  - over 250 researchers
  - about 90-100 nights per year with NTT+EFOSC/SOFI (supporting facilities: VLT, Prompt, LCOGT….)
- ☑ Engrave (Electromagnetic counterparts of gravitational wave sources at the VLT; *http://www.engrave-eso.org/)*
  - Over 250 researchers with theoretical and observational expertise (many from INAF, mainly from the Grawita collaboration)
  - Hard-ToO triggers with multiple instruments mounted at VLT (plus ancillary facilities)
- ☑ Related programmes we are involved: Euclid, VRO/LSST, ThunderKAT, SOXS, NTE, ET…

# Methods

- Spectroscopic classification of new transients (Asiago Classification Program with the 1.82m Copernico Telescope; *Tomasella+ 2014, AN, 335, 841*)



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- Spectro-photometric follow-up of transients from the UV to the mid-IR (extended to X-ray and radio domains for ejecta-CSM interacting SNe)

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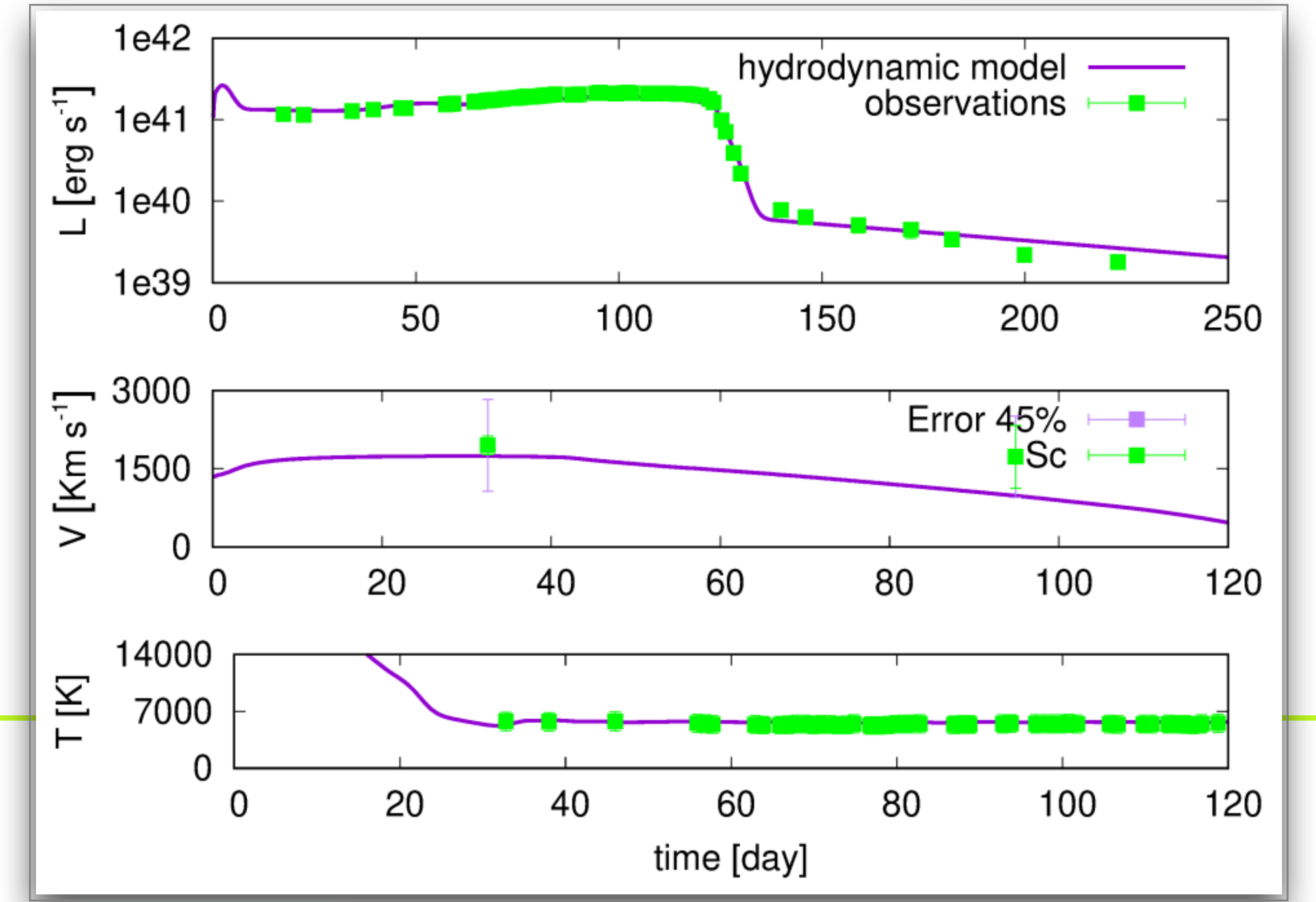
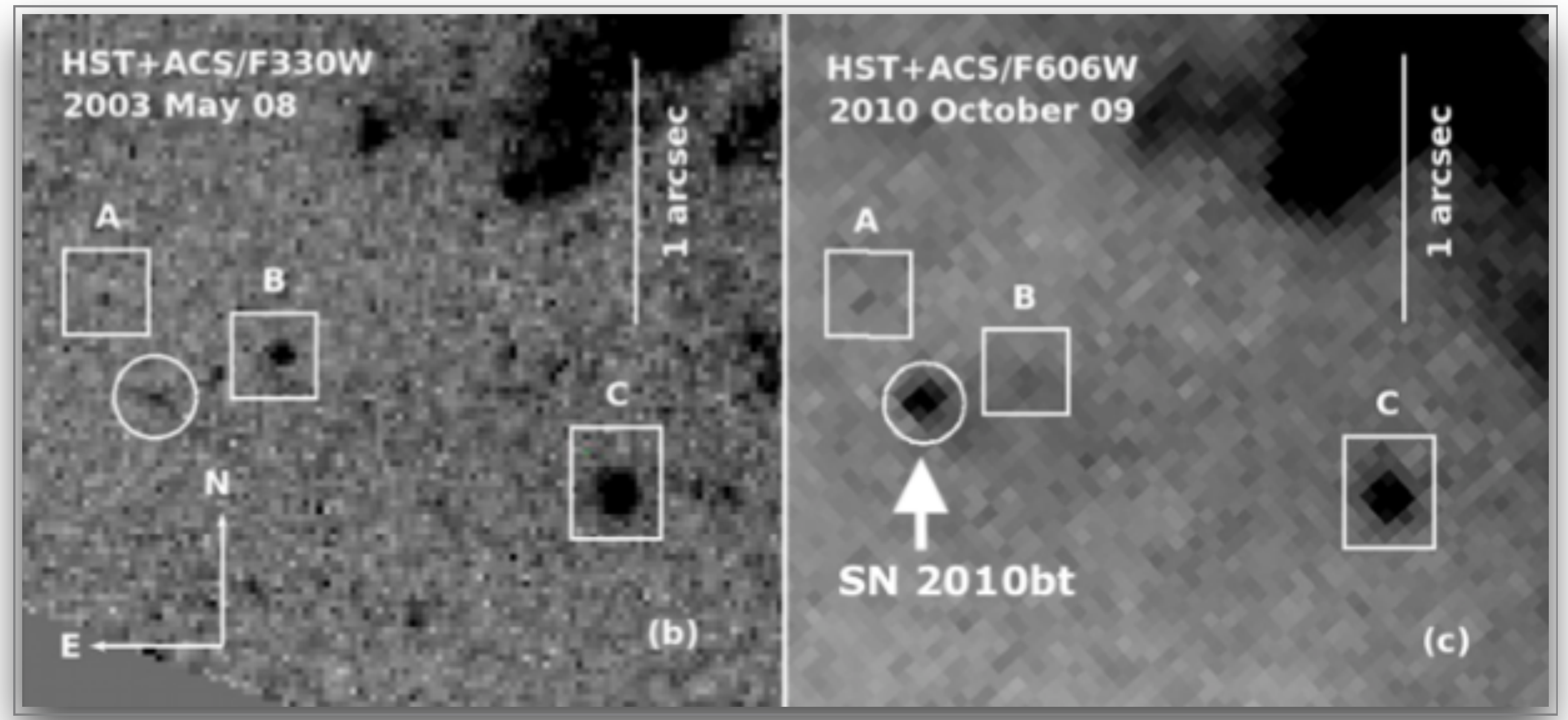
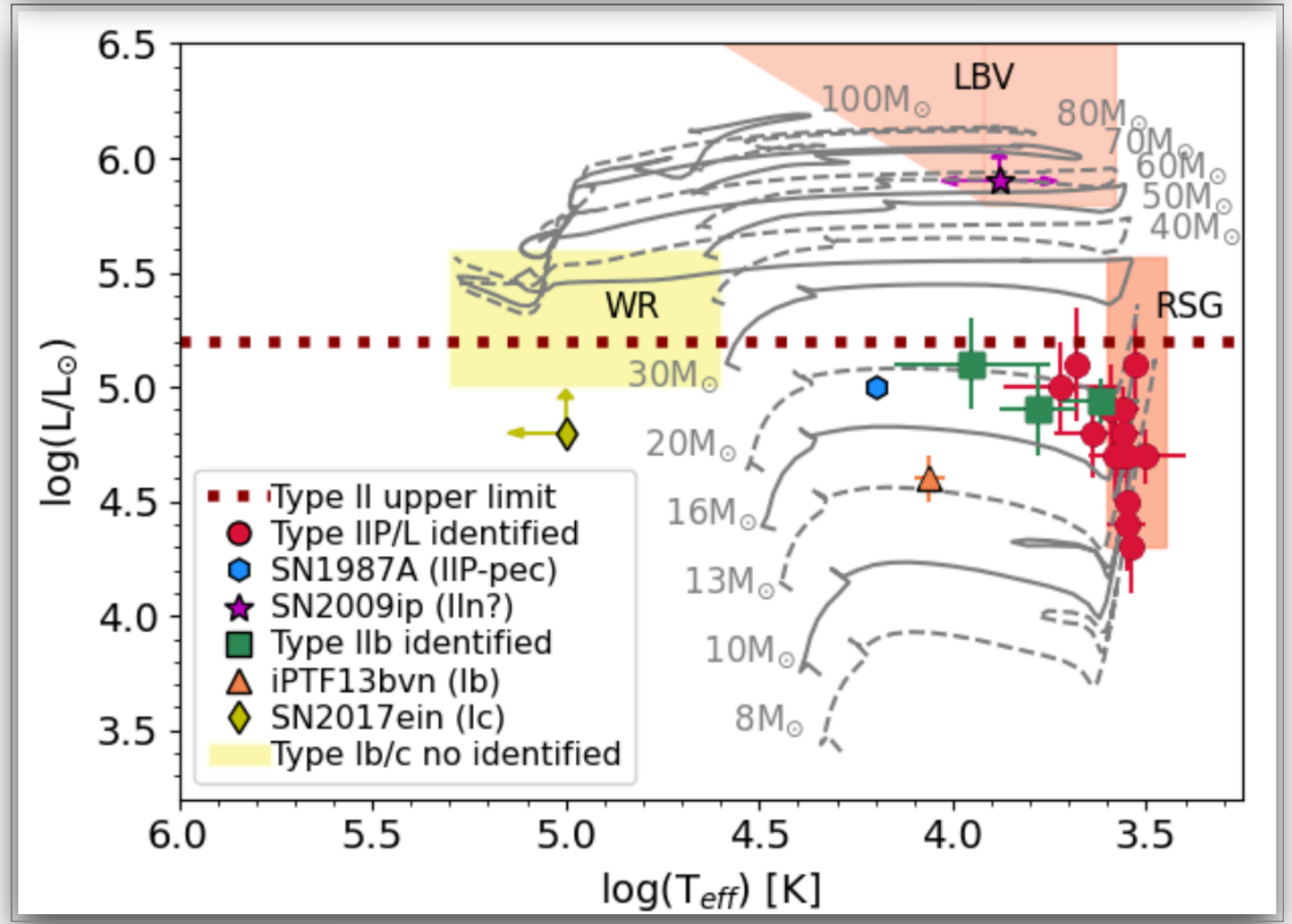



- Data modelling to infer the parameters of the progenitor and the explosion: energy, ejected mass, mass of radioactive material (e.g., *Pumo+ 2017, MNRAS, 464, 3013*), ejecta tomography, CSM geometry & composition

# Methods

- Finding quiescent progenitors from archive images of space (HST, Spitzer, WISE) and 8m-class telescopes with adaptive optics. From luminosity & colour/temperature, and the comparison with evolutionary tracks of single or binary massive stars => progenitor mass (see *https://sngroup.oapd.inaf.it/progenitors.html*)




*Elias-Rosa+ 2018, ApJ, 860, 68; Serenelli+ 2021, A&ARv, 29, 4*

# Methods

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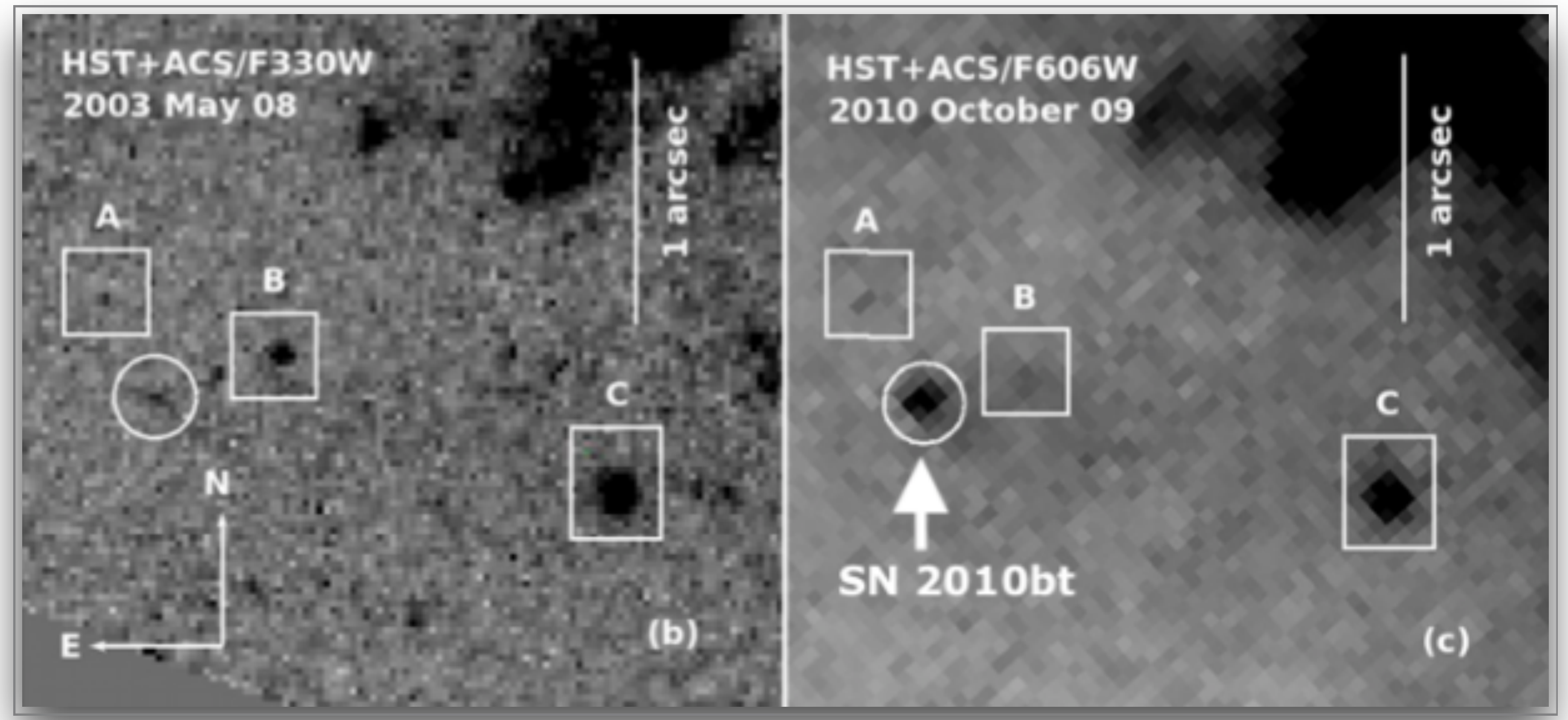
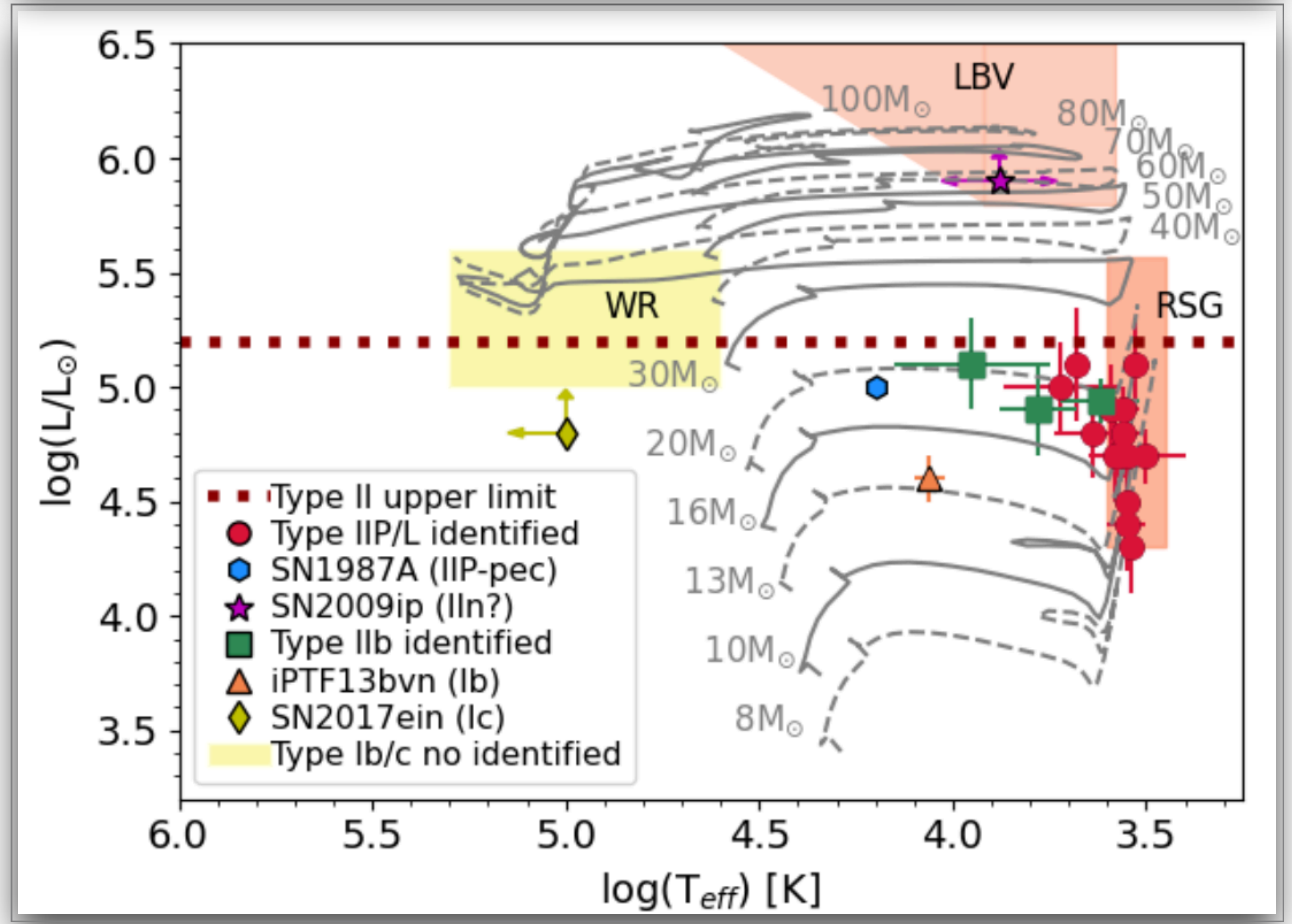
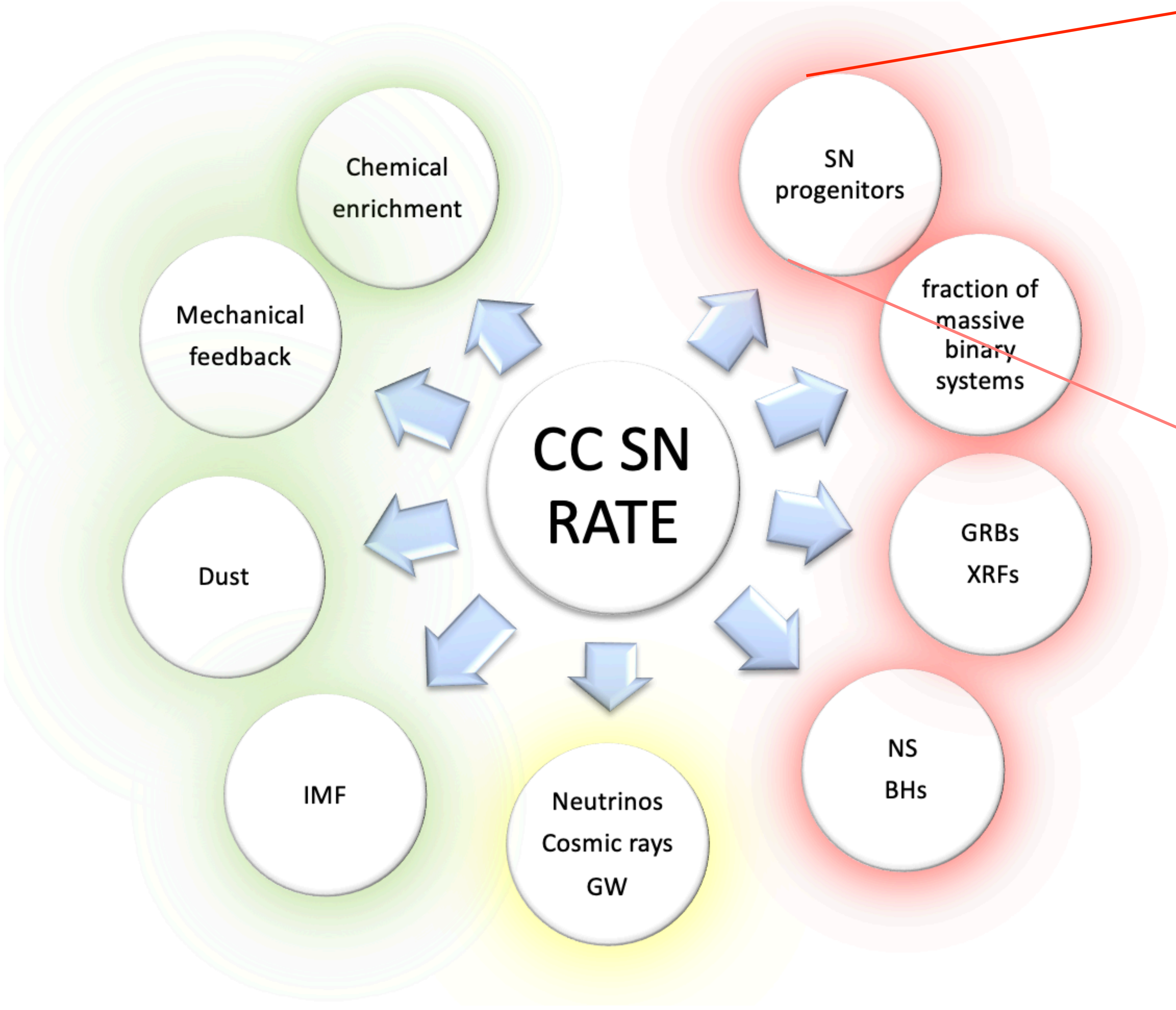
- Study of pre-SN variability for ejecta-CSM interacting SNe using survey data (ZTF, ATLAS, PanSTARRS, DLT40)
- Environment characterization (nearby stellar population, host galaxy metallicity)




*Elias-Rosa+ 2018, ApJ, 860, 68; Serenelli+ 2021, A&ARv, 29, 4*

# Methods




$$R_{CC}(t) = k_{CC} \times \psi(t)$$

$$k_{CC} = \frac{\int_{m_{CC,l}}^{m_{CC,u}} \phi(m)dm}{\int_{m_l}^{m_u} m\phi(m)dm}$$

$m_{CC,u} - m_{CC,l}$ mass range CC SN progenitors

- Local Universe
- Galaxy samples
- Cosmic volumes

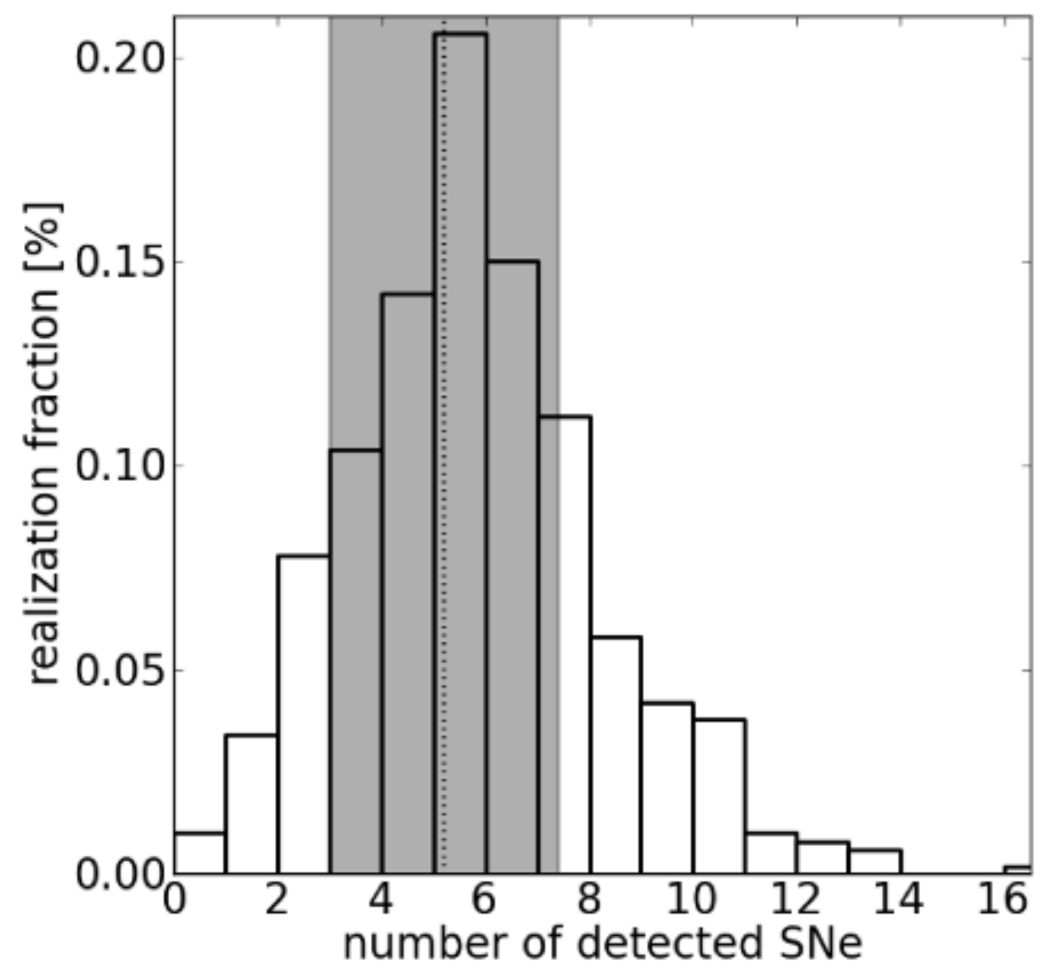
- Statistics - Rate of transients versus star formation rate

# Rates: state of the art and pending issues

- Core-collapse (CC) SN rates in the Local Universe (within 11 Mpc) - HAWK-I @ VLT (*Miluzio+ 2013, A&A, 554, 127*)

    ➡ Minimum progenitor mass for core-collapse SNe = 8 $M_\odot$

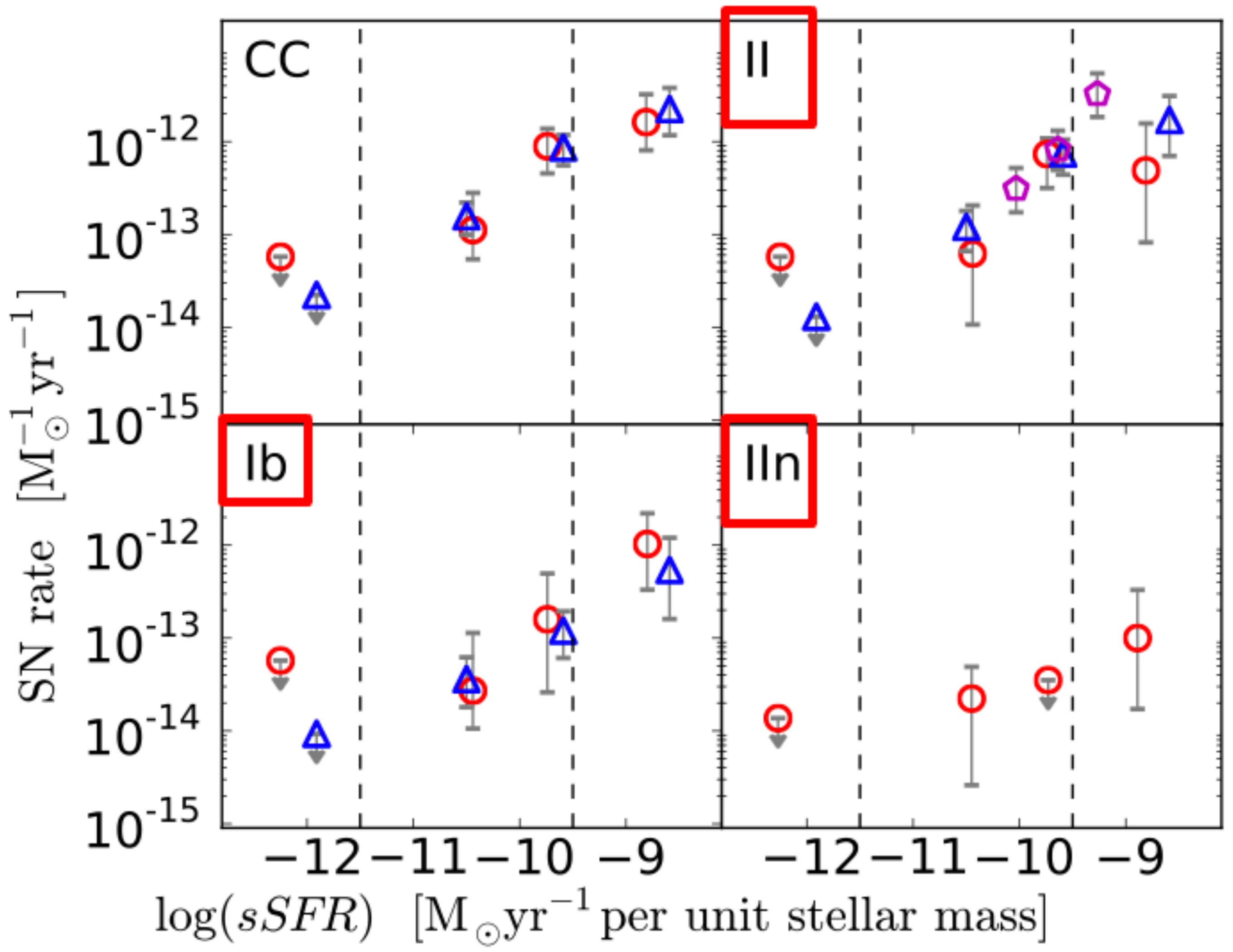
    ➡ 60% of CC SNe are missed due to dust extinction or their intrinsic faintness




- Rates of supernovae from massive stars in a sample of galaxies (*Botticella+ 2017, A&A, 598, 50*) and in cosmic volume (*Cappellaro+ 2015, A&A, 584, A62*) - SUpernova Diversity And Rate Evolution (SUDARE@VST-OmegaCAM)

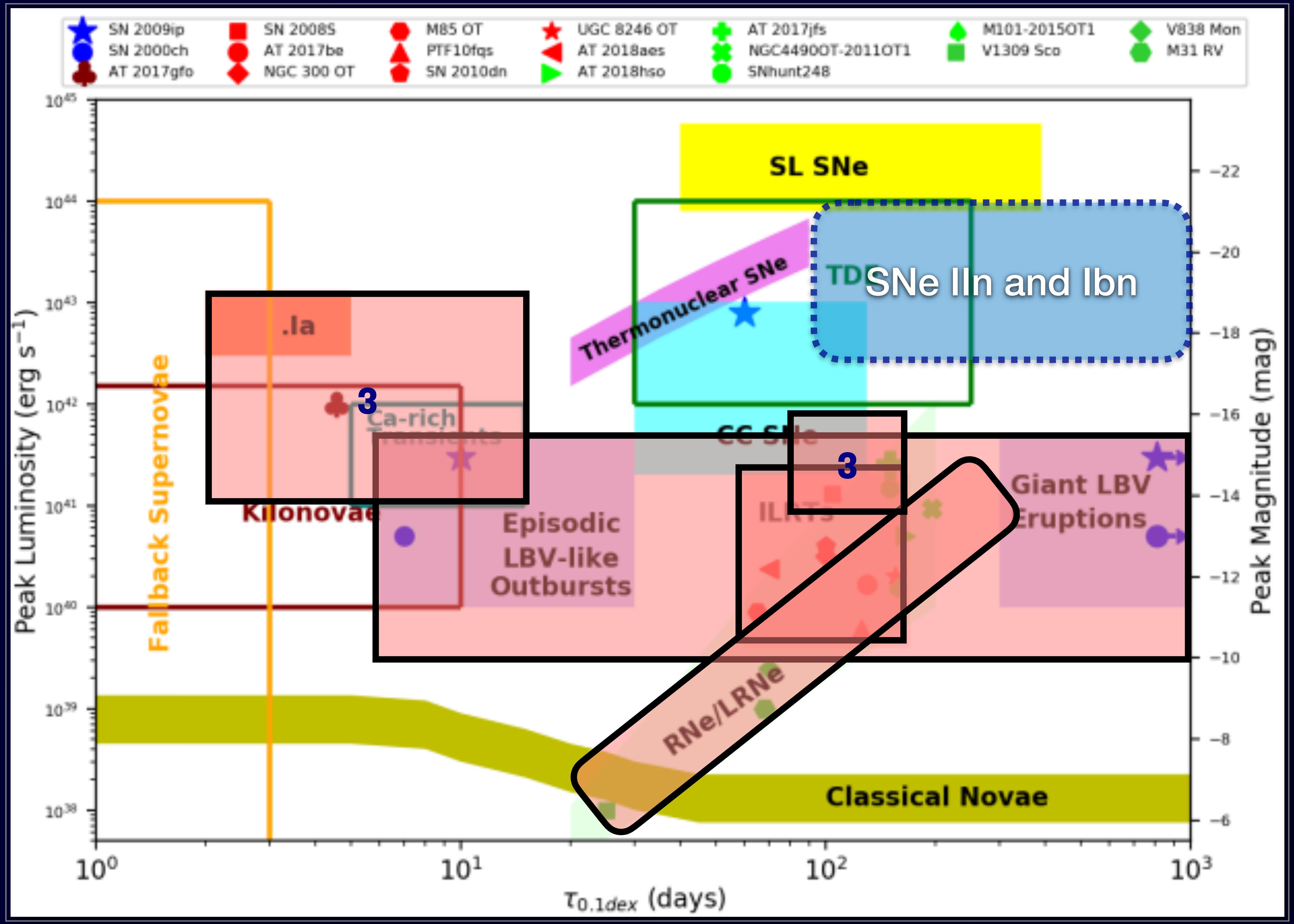
    ➡ Most stripped-envelope SNe arise from binary progenitor systems

    ➡ The uncertainties on the rates of SNe from massive stars and the SFRs are still too high to constrain the progenitors for each SN subtype



# Results: the stellar transient zoo

1. Gap Transients ([https://sngroup.oapd.inaf.it/gap.html](https://sngroup.oapd.inaf.it/gap.html))
   i. Major eruptions and isolated outbursts of massive stars
   ii. Luminous red novae (stellar mergers)
   iii. Intermediate-luminosity red transients (electron-capture SNe)
2. SNe interacting with circumstellar medium (SNe IIn, Ibn and Icn) and pre-SN outbursts
3. Faint core-collapse and thermonuclear SNe
4. Superluminous supernovae (SL SNe)
5. Classical core-collapse SNe - progenitors
6. [Electromagnetic counterparts of gravitational waves]



# Pre-SN outbursts and interacting supernovae

1. Pre-SN (eruptive) mass-loss - impostors
2. Luminous SNe in H-rich CSM (IIn) or He-rich CSM (Ibn)
3. Progenitors are H-rich massive stars (LBVs) or H-poor massive Wolf-Rayet or He stars in binary systems

*https://sngroup.oapd.inaf.it/interacting_SNe.html*

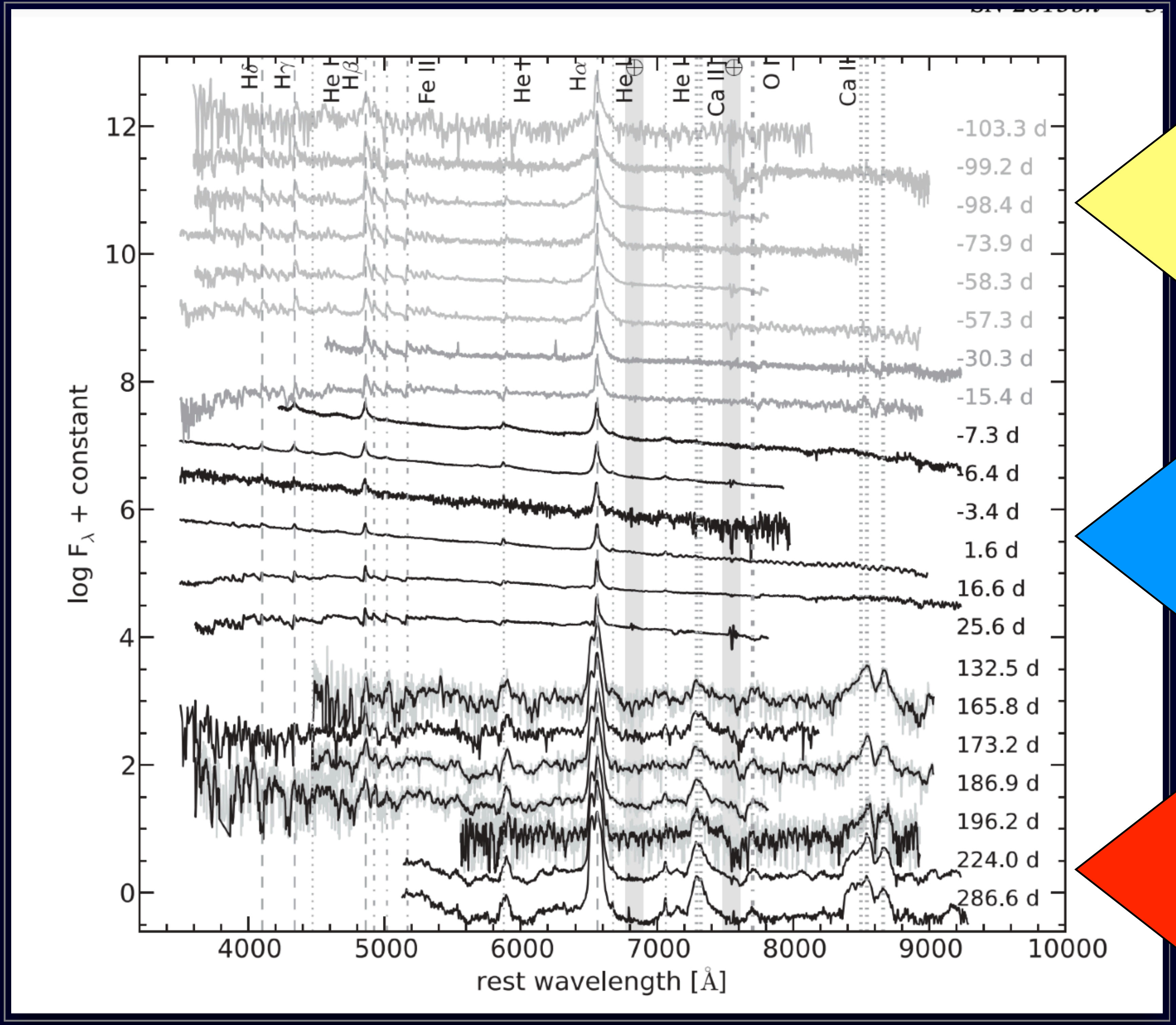
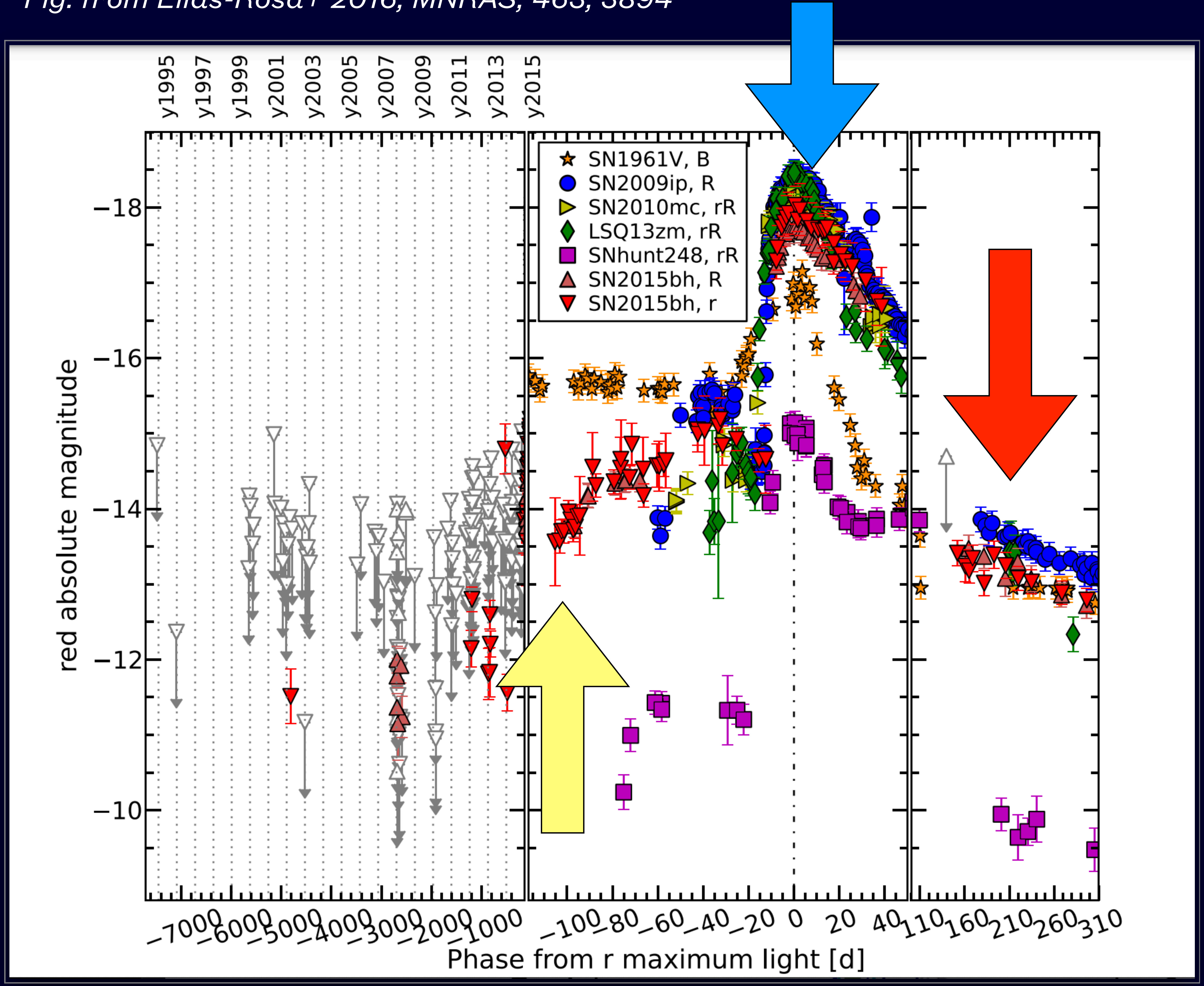
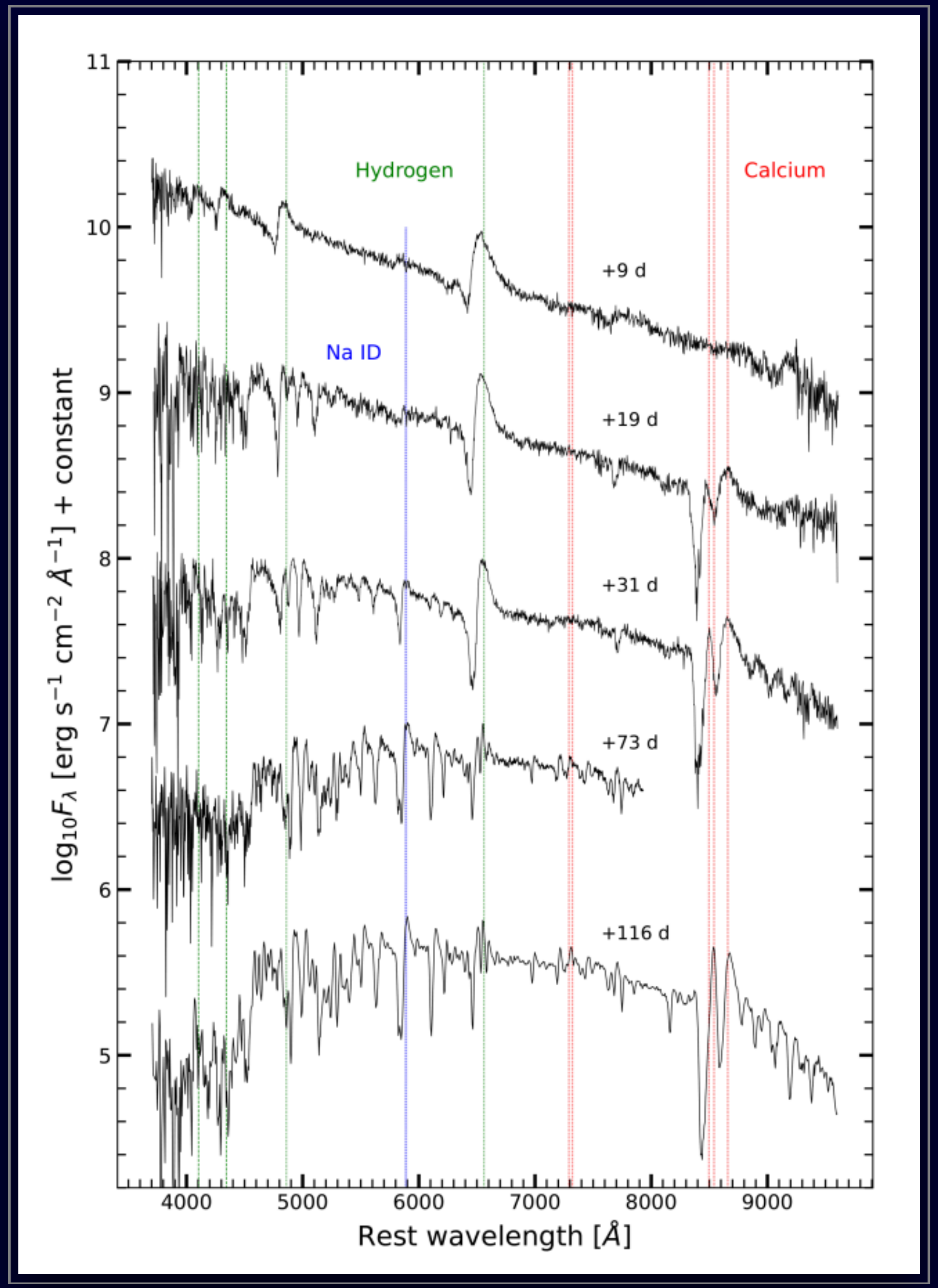


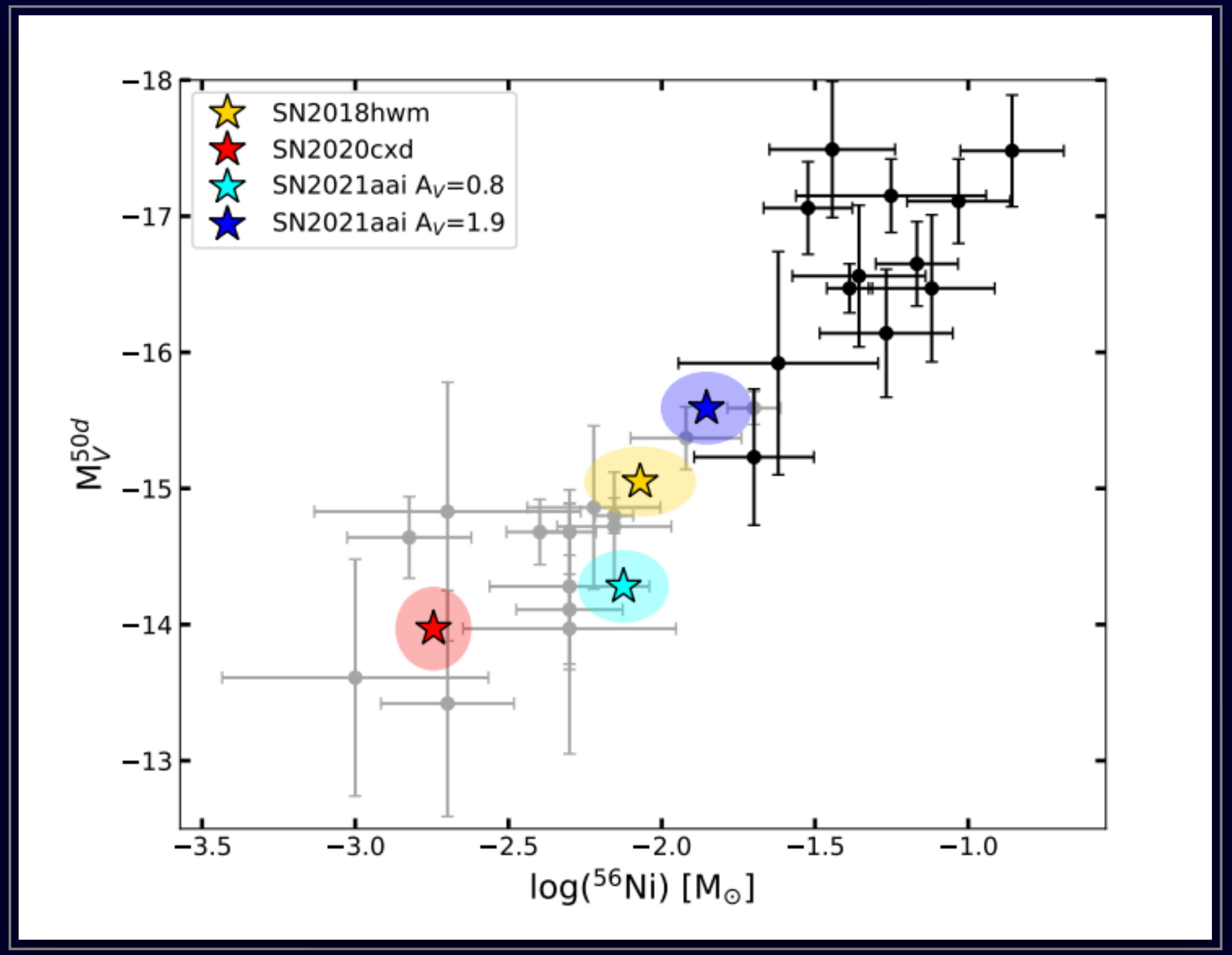

*Fig. from Elias-Rosa+ 2016, MNRAS, 463, 3894*



# Faint supernovae

*https://sngroup.oapd.inaf.it/faint.html*




*Valerin+ 2022, MNRAS, tmp, 1162*
*Reguitti+2021, MNRAS, 501, 1059*

<u>Faint core-collapse SNe (type II-P)</u>

1. One order of mag fainter than classical SNe IIP
2. $^{56}$Ni masses of a few $10^{-3}$ $M_\odot$
3. Low ejecta velocity (= low kinetic energy, ~$10^{50}$ erg)

CC of RSGs with final progenitor masses of 6-9 $M_\odot$

# Faint supernovae

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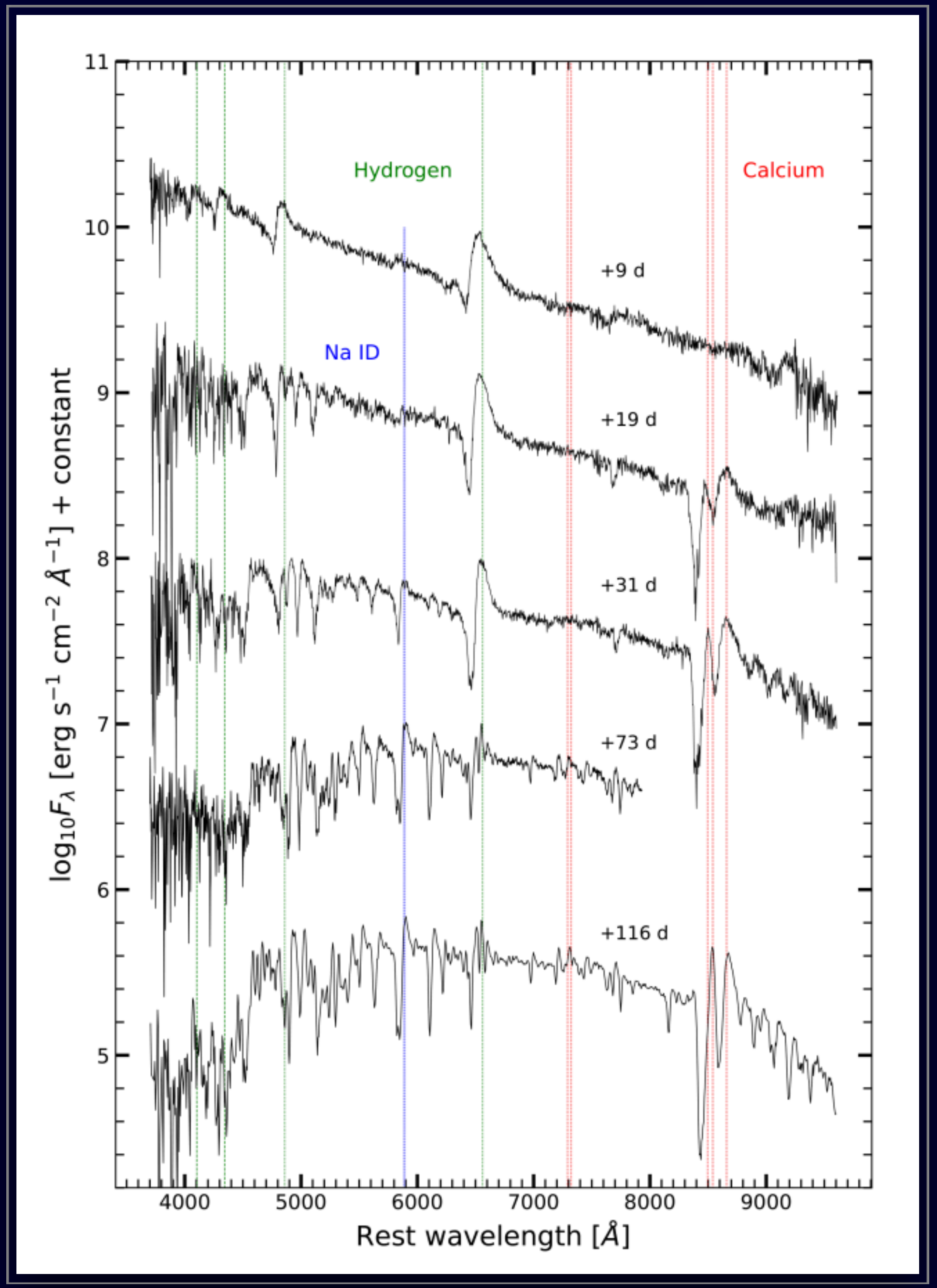


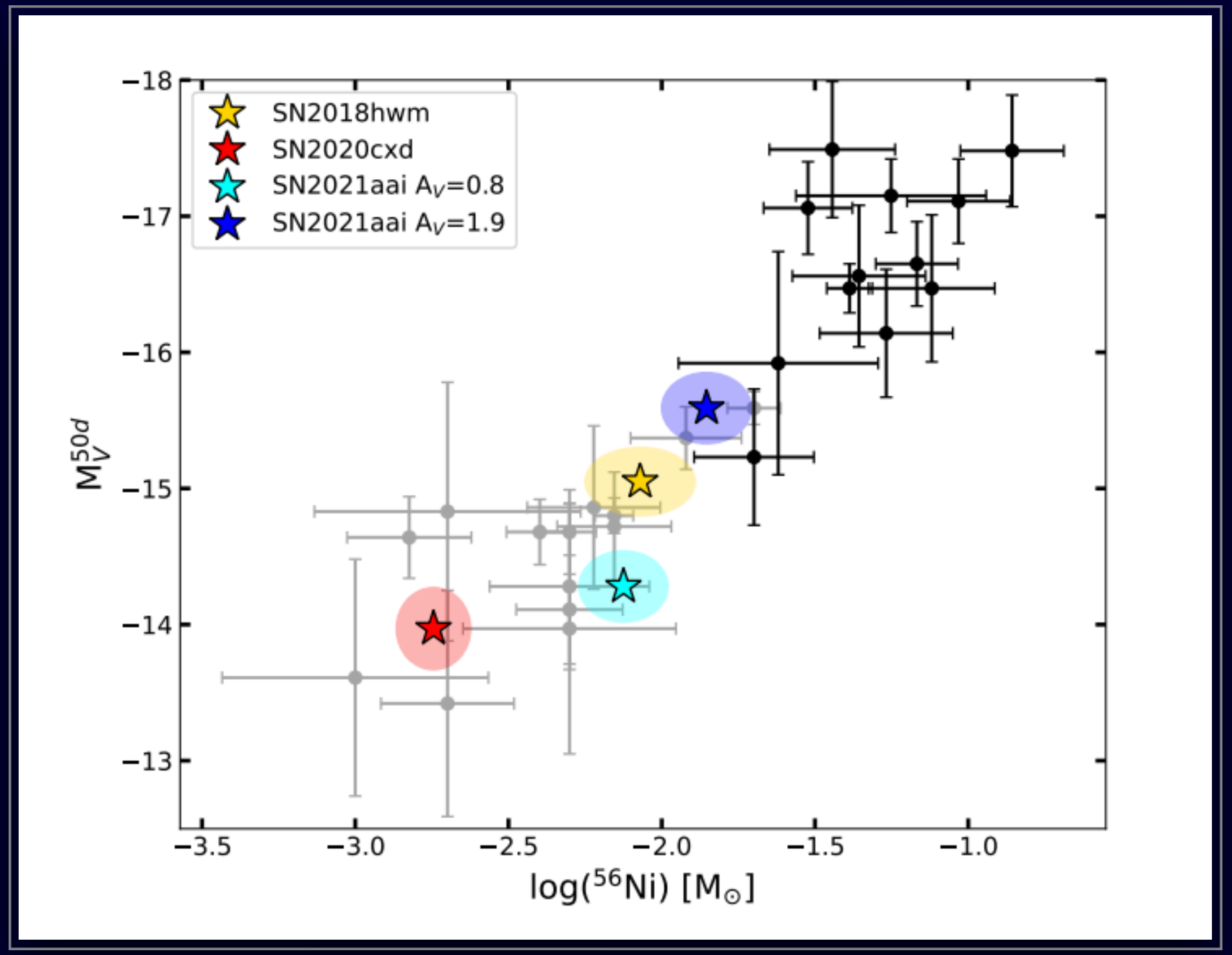


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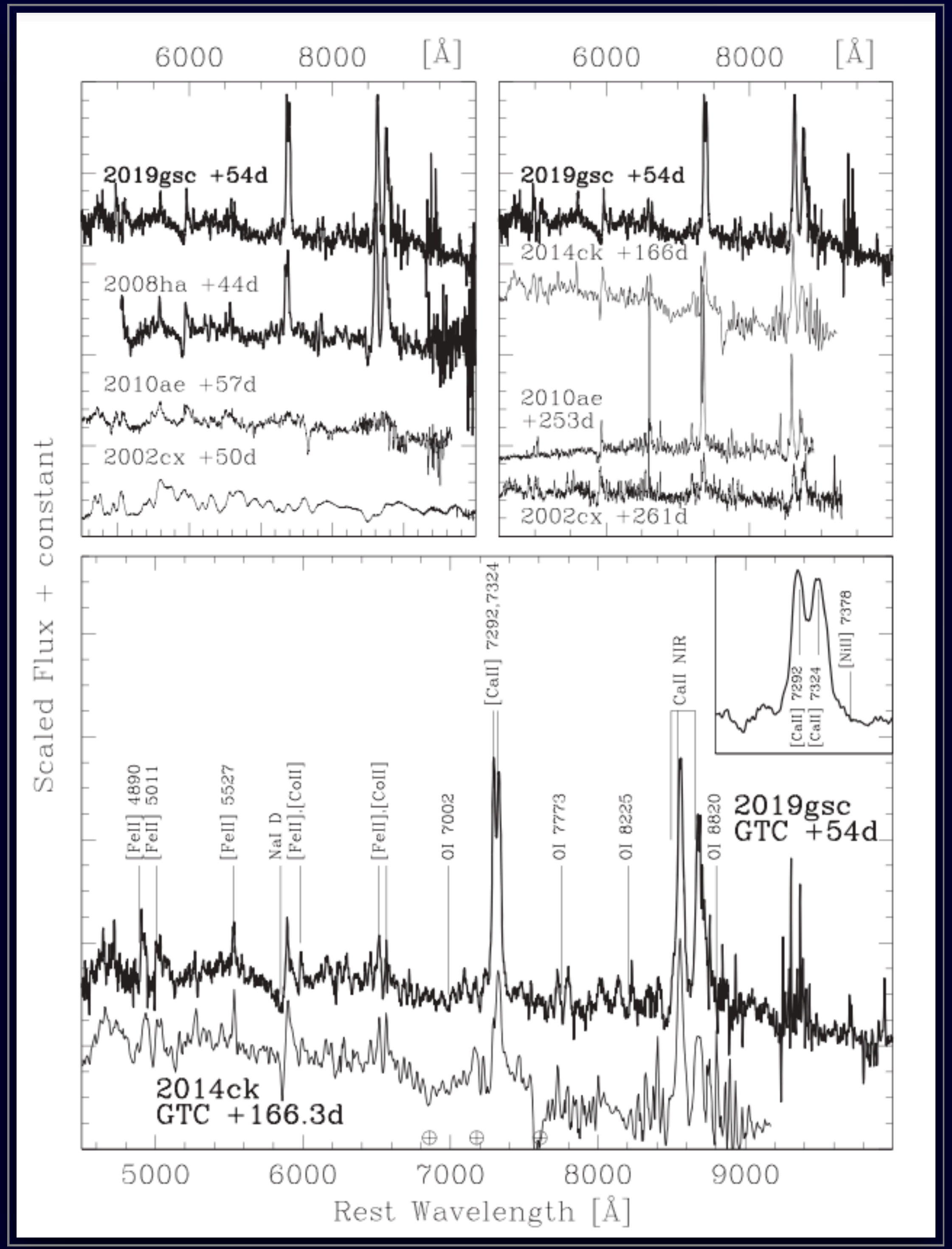
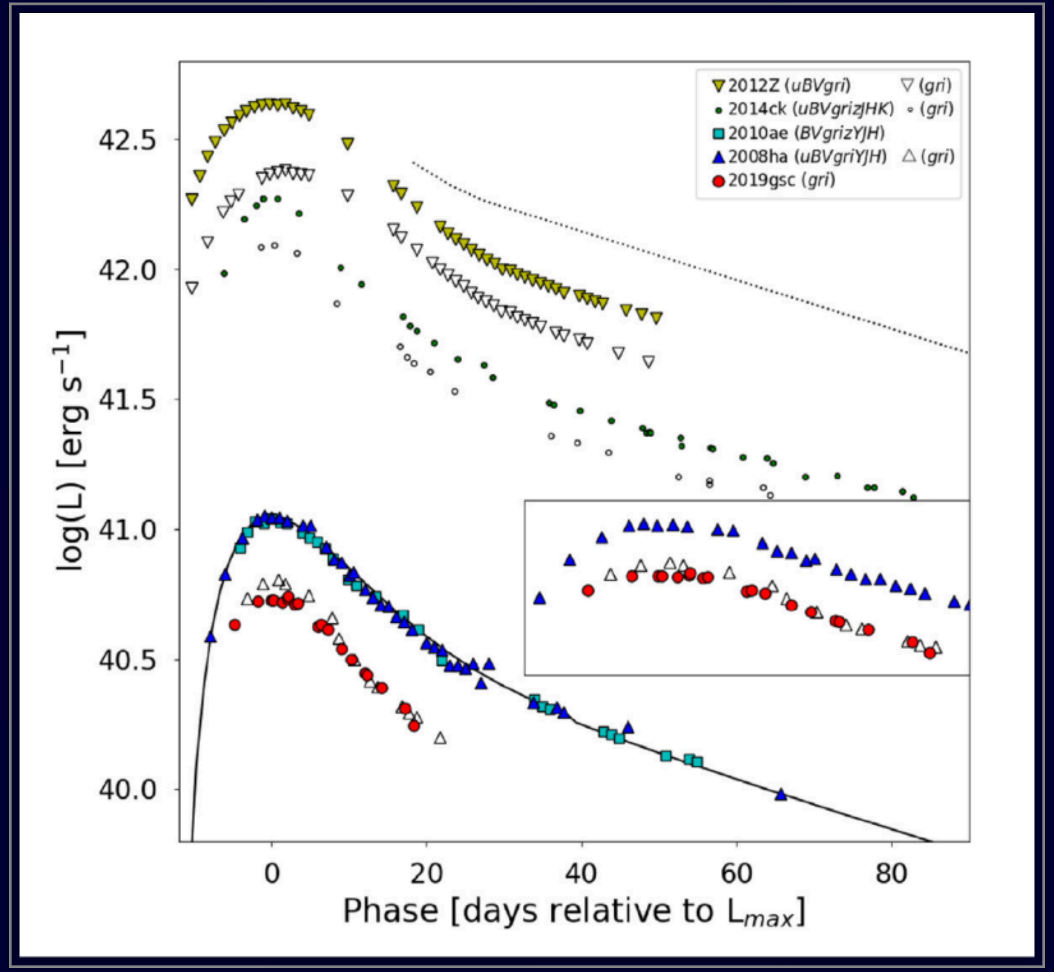
*Valerin+ 2022, MNRAS, tmp, 1162*
*Reguitti+2021, MNRAS, 501, 1059*

## Faint thermonuclear SNe

1. 1-2 orders of mag fainter than SNe Ia; fast-evolving
2. $^{56}$Ni masses of a few $10^{-3}$ M$_\odot$
3. Low ejecta velocity (= low kinetic energy, ~$10^{49}$ erg)
4. Ejected masses of $10^{-1}$ M$_\odot$ => inconsistent with a full-disruption WD scenario - failed deflagration?



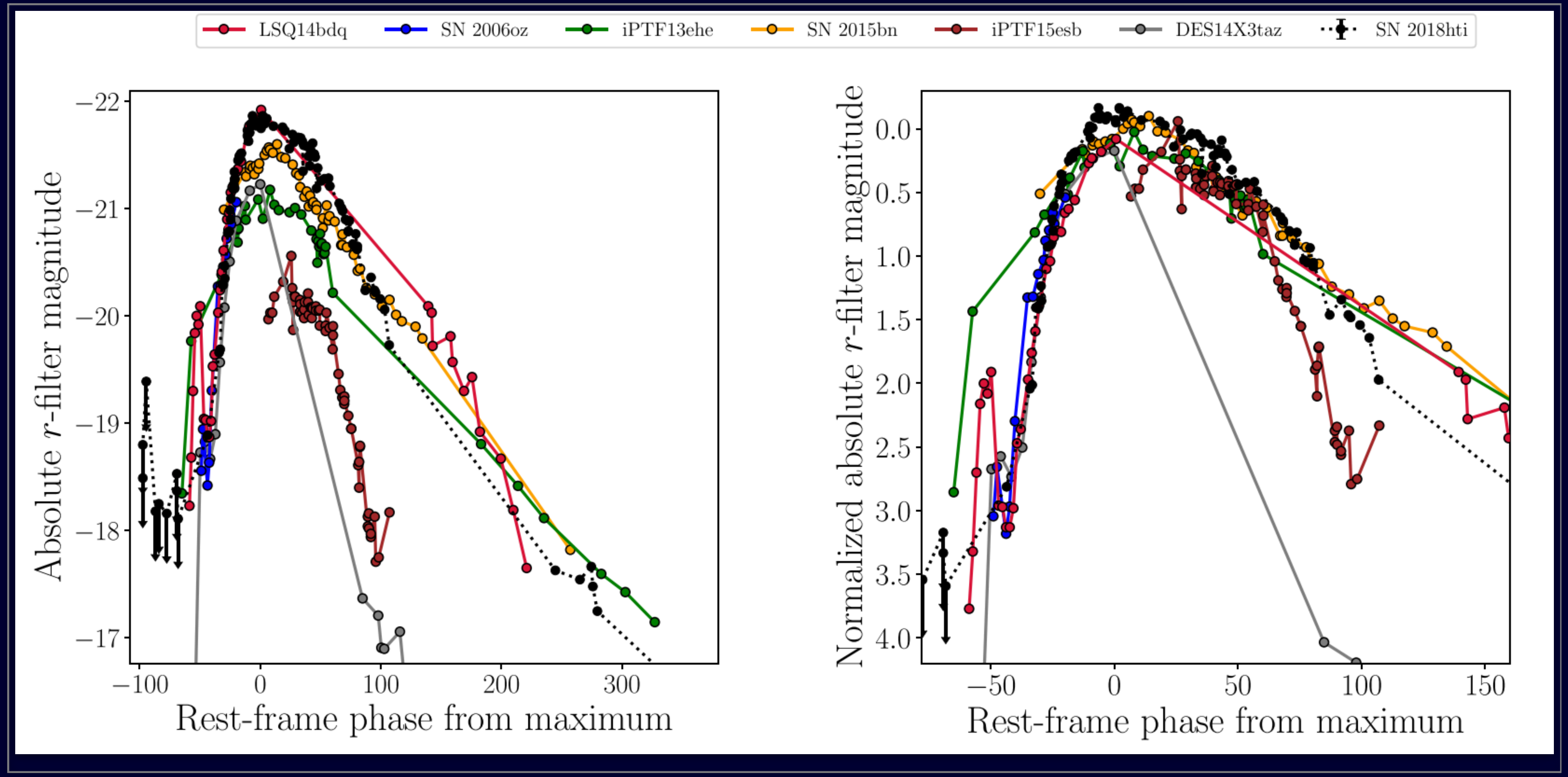

*Tomasella+ 2020, MNRAS, 496, 1132*
*Tomasella+ 2016, MNRAS, 459, 1018*

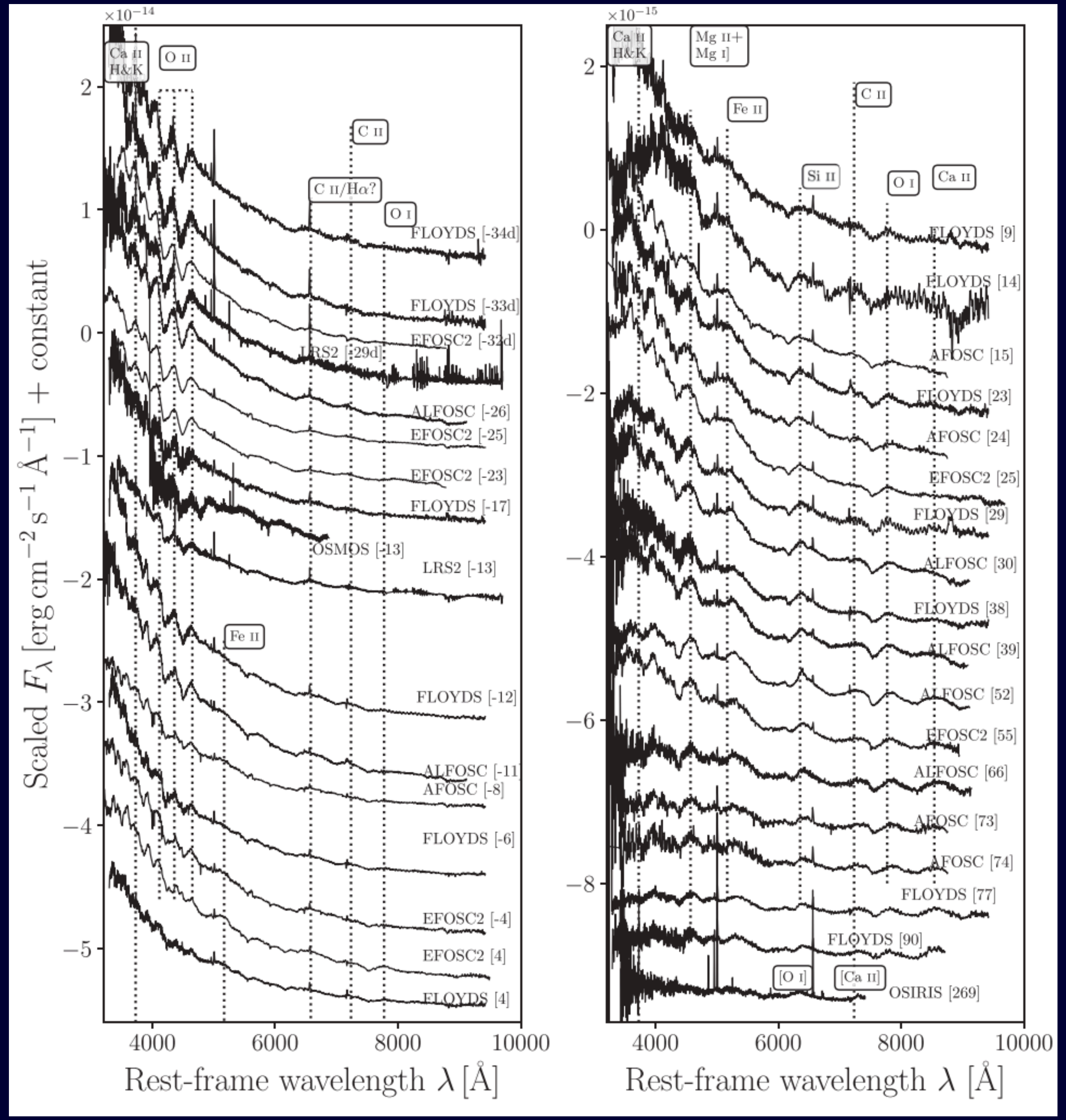
# Super-luminous supernovae

https://sngroup.oapd.inaf.it/slsn.html

## Observables

1. Extremely luminous (exceding $10^{44}$ erg $s^{-1}$) and hot
2. Long-duration visibility => massive ejecta
3. Usually hosted in dwarf metal-poor galaxies
4. Early spectra can be H-rich (SLSN-I) or H-poor (SLSN-II)
5. Late spectra sometimes show strong O features (this favour high ejected masses)




## Scenarios

- High $^{56}$Ni masses (a few solar masses) => PI SNe?
- Strong ejecta interaction with massive CS shells => PPI?
- Magnetar spin-down + $^{56}$Ni
- A combination of the above powering mechanisms

*Fiore+ 2022, MNRAS, 512, 4484; Fiore+ 2021, MNRAS, 502, 2120*
*Benetti+ 2014, MNRAS,441, 289; Nicholl+ 2013, Nature, 502, 346*

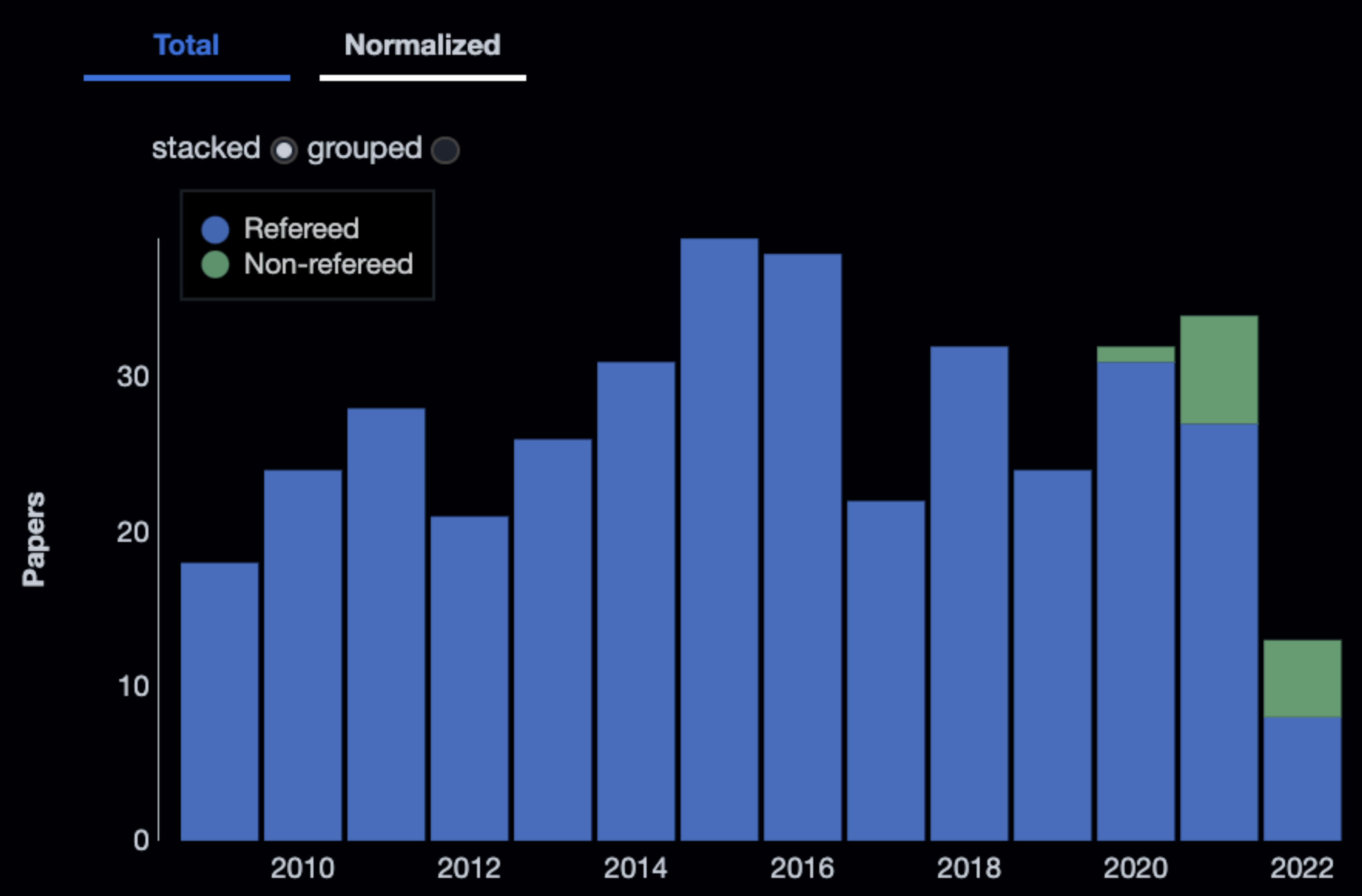
# High-impact scientific outcomes

- ✓ Our publications linked different species of massive stars with SN types
- ✓ We discovered the first stripped-envelope SN heralded by a pre-SN outburst; we introduced a new SN Type (Ibn), linking these explosions with Wolf-Rayet stars (or massive He stars in binary systems)
- ✓ For the first time we followed an erupting LBV that later exploded as a real SN (of Type IIn); we proved that these pre-SN outbursts are common, and found a surprising homogeneity in the SN observables.
- ✓ We first found a connection between SLSN explosions and normal core-collapse of stripped-envelope stars; we proposed that ejecta-CSM interaction play a major role in the observed properties of SLSNe
- ✓ We observed the first reliable pair-instability SN candidate (OGLE-2014-SN073; *Terreran+ 2017, Nat. Astr., 1, 713*)
- ✓ We first proposed that ILRTs are convincing electron-capture SN candidates
- ✓ We charaterized luminous red novae as stellar mergers, and found tight correlations among physical parameters, as well as provided tools to infer the progenitor masses
- ✓ We performed seminal systematic studies for a few subclasses of rare core-collapse SNe (e.g. faint II-P, 1987A-like)
- ✓ We  are providing rate estimates for many classes of stellar transients
- ✓ Late 2022: template light curves for VRO/LSST brokering will be released; in late-2023 we will release to the community the first complete and homogeneous database of gap transients

# Some numbers
(since 2009)

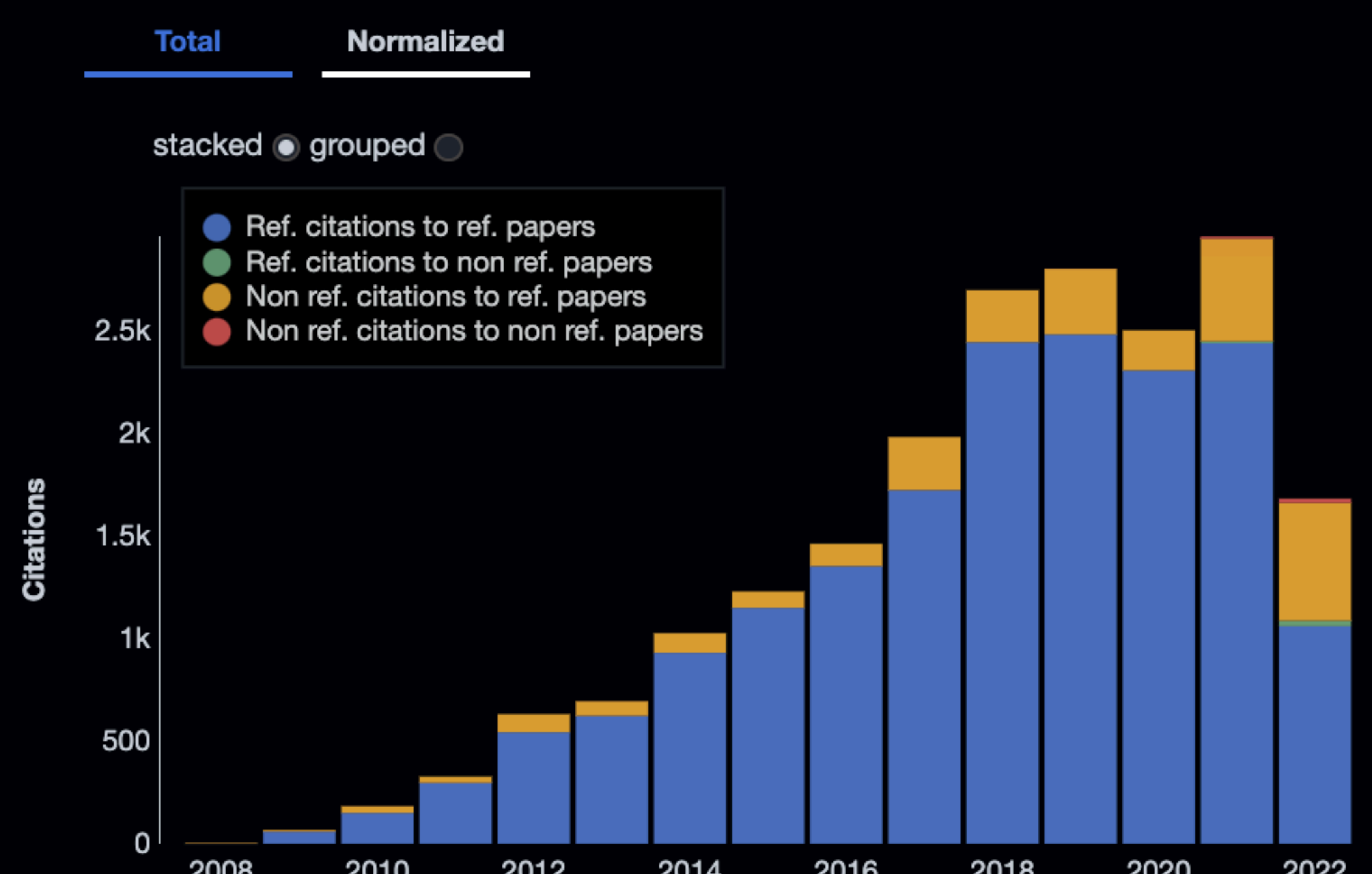
## Papers

| | Totals | Refereed |
|---|---|---|
| Number of papers | 382 | 369 |
| Normalized paper count | 33.9 | 33.6 |



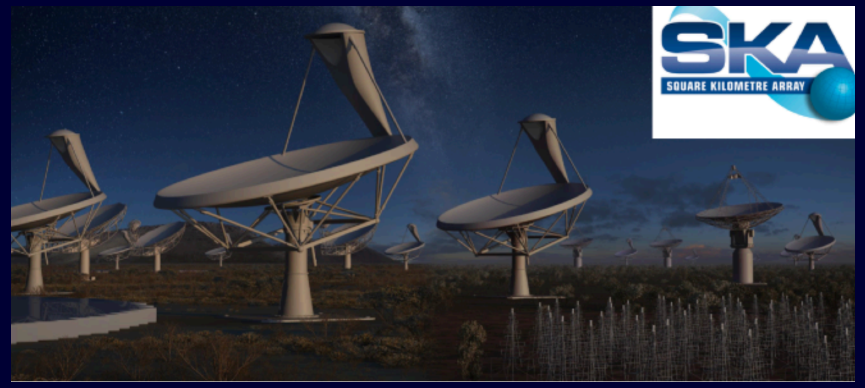

## Citations

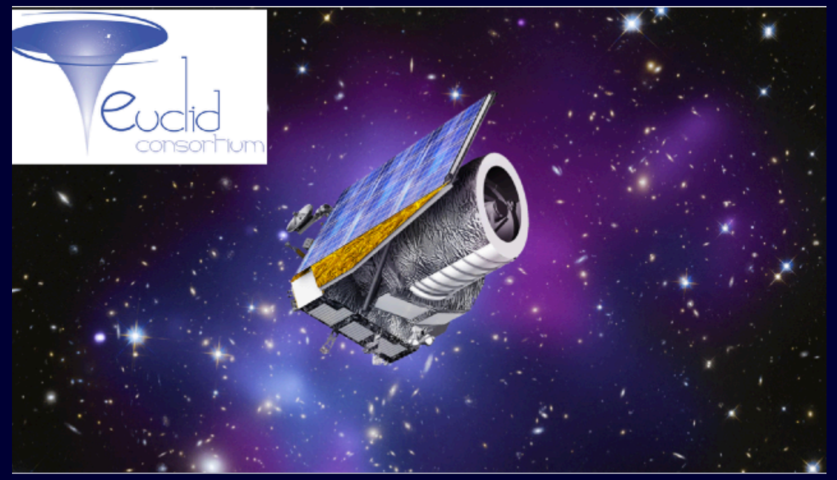
| | Totals | Refereed |
|---|---|---|
| Number of citing papers | 9148 | 9137 |
| Total citations | 20264 | 20196 |
| Number of self-citations | 2252 | 2244 |
| Average citations | 53.0 | 54.7 |
| Median citations | 25 | 27 |
| Normalized citations | 1020.2 | 1018.8 |
| Refereed citations | 17606 | 17570 |
| Average refereed citations | 46.1 | 47.6 |
| Median refereed citations | 21 | 22 |
| Normalized refereed citations | 896.1 | 895.4 |



# Leadership

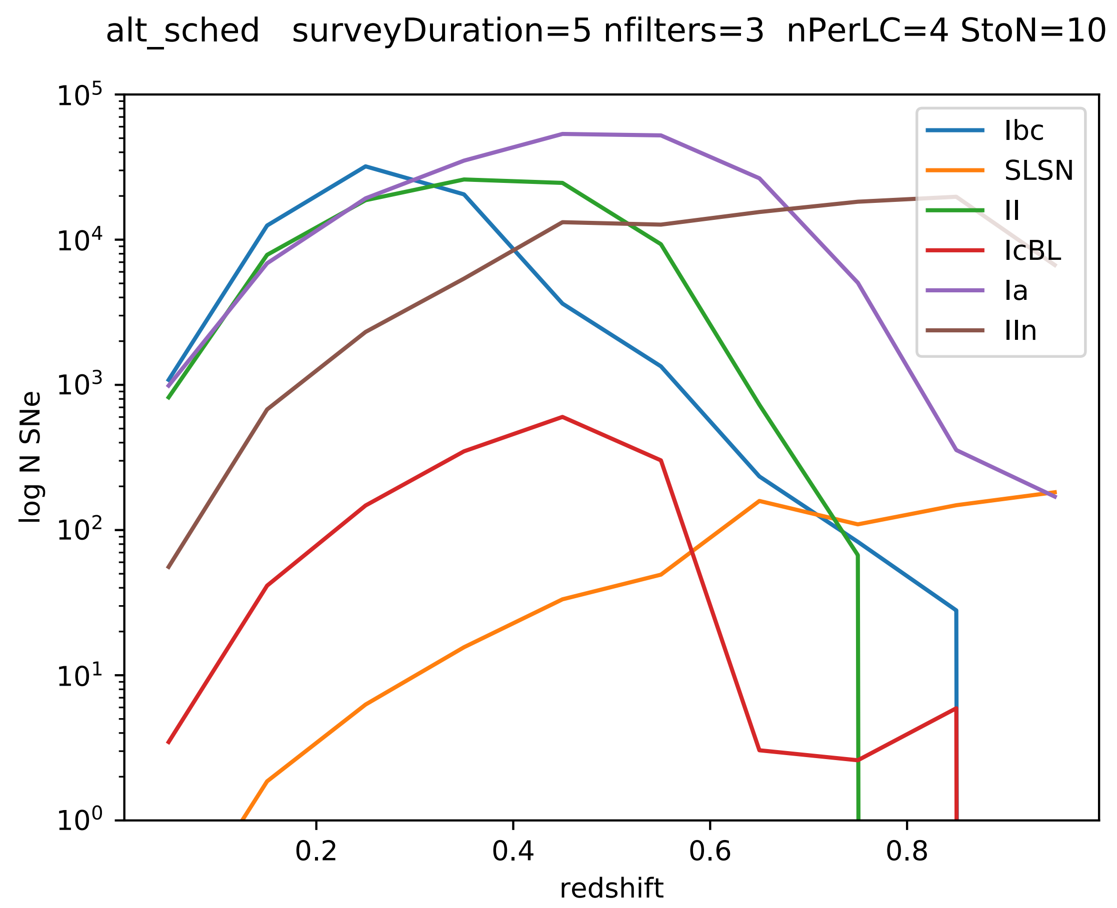
| | |
|---|---|
| ePESSTO+ | Botticella, Tartaglia, Mason |
| NUTS2 | Elias-Rosa |
| SOXS | Many of us |
| Engrave, Grawita | Cappellaro |
| PI of awarded HST time | Elias-Rosa |
| PIs of 8-10m class Telescope proposals | Tartaglia, Elias-Rosa, Mason |
| Asiago Telescope | Tomasella, Benetti |
| Large/Long Term proposals | Salmaso, Valerin, Reguitti |
| ThunderKAT | Elias-Rosa, Botticella |
| Euclid, ET | Cappellaro |
| VRO/LSST | Botticella |

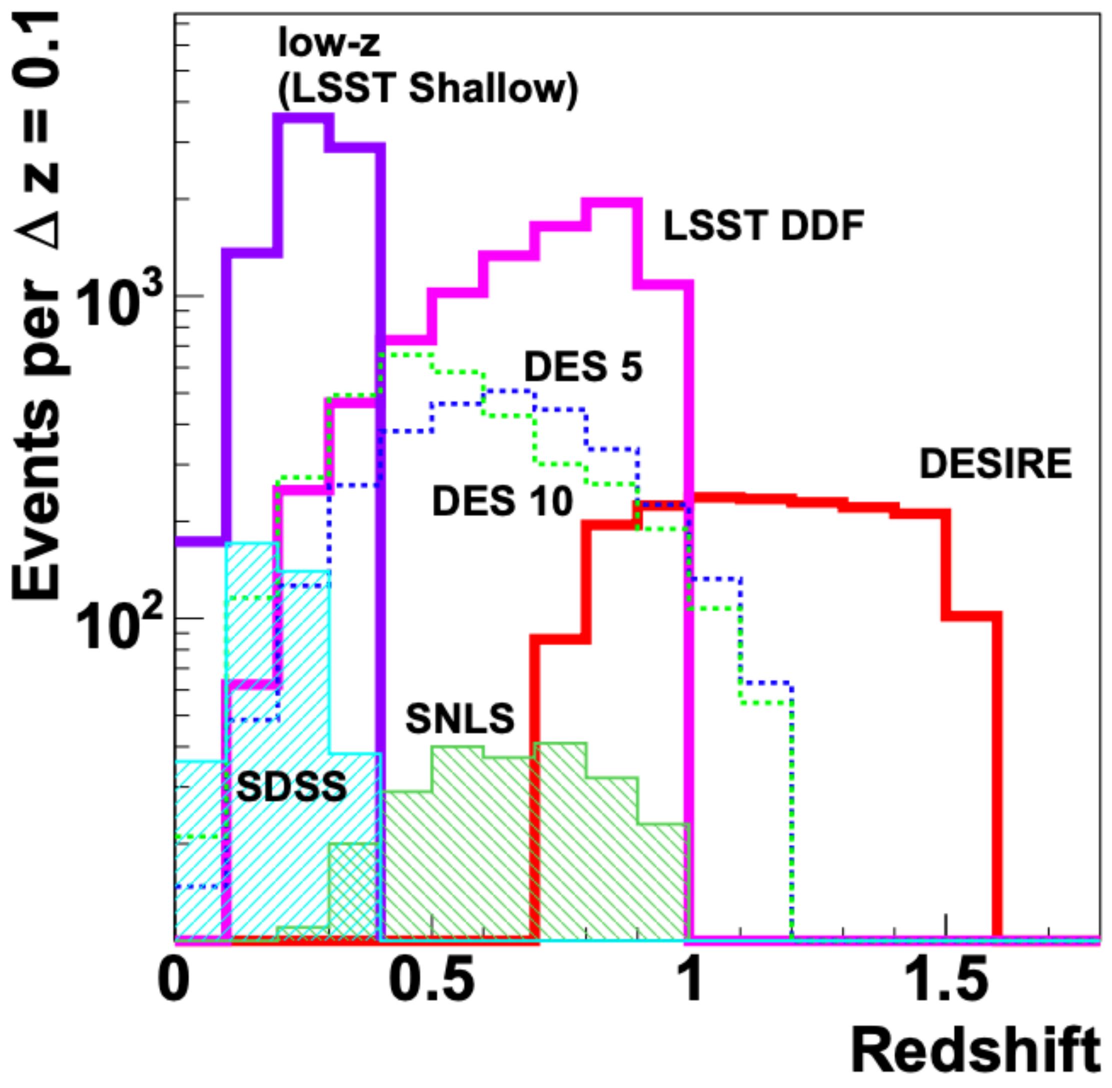



# Perspectives

- We want to study the death of the most massive stars, connecting the SN explosion (incl. dark SNe) with the stellar properties and evolution
- The connection SN explosion/massive star properties through the rates for all transient types as a function of z, mass, SFR, and metallicity
- We expect to find the missing fraction of transients in dusty environments (from infrared to radio domains)
- The combination VRO/LSST + SOXS will allow us to study in detail a harvest of exotic transients, providing the high-quality dataset requested to constrain the explosion mechanisms
- The growing available archives of space and ground-based high spatial resolution telescopes (as well as the new opportunities with JWST) will provide robust information on the transients' explosion sites, the progenitors and their former eruptive mass-loss history



# Critical issues

Despite the strong scientific impact of our research and our involvement in many forthcoming projects, we have to deal with:

- Currently we have no dedicated funds: the last one was awarded in 2014 (PRIN INAF; 135 kE); plus ~11 kE from PRIN-INAF 2017 (PI: Giroletti). In recent years, our program was also supported by 9 PhD students, four of which recruited (at OAPd) through agreements with international institutions (Beijing University, Queen's Univ. Belfast and Univ. Andres Bello Santiago).

  ➡ We applied for an PRIN-INAF Large Grant to study "Gap Transients" in the recent 2022 call, and Elias-Rosa applied to a PRIN-INAF GTO Grant on anaysis of HST data.

- Despite our involvement in many projects, in a very short time (~1-2 years), we will be severely understructured (by a factor of two) due to contract expirations and retirements.

  ➡ New recruitments (turn-over, and career progresses) are urgent to maintain our leading position in the research on transient events.