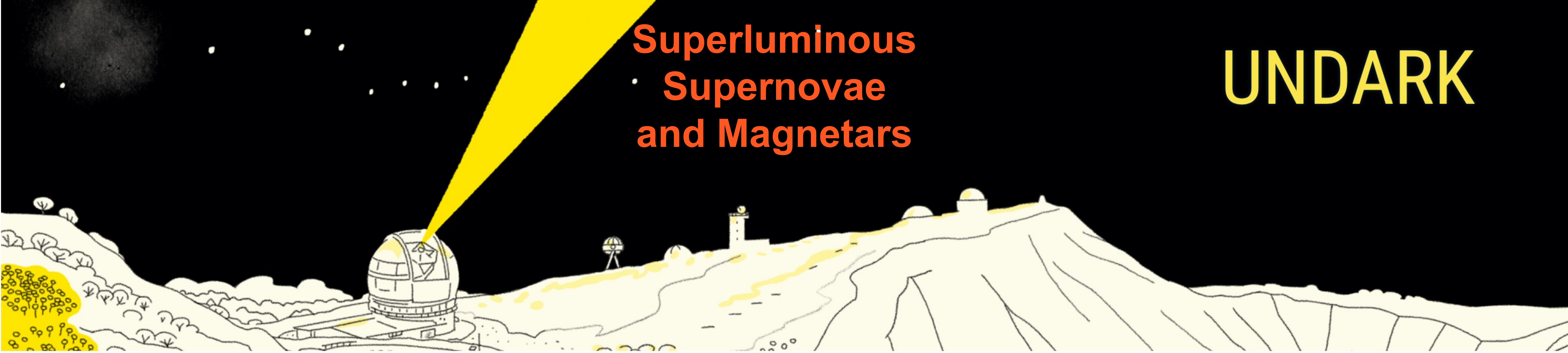
Superluminous Supernovae and Magnetars



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Superluminous Supernovae project part of the SGLF collaboration:
Supernovae and Gravitational Lenses Follow up

Why Superluminous Supernovae and Magnetars ?

Basic facts and reasons of this talk :

- **Superluminous Supernovae (SLSNe)**:

  → one of the favorite model to explain the very bright electromagnetic counterpart (EM) of SLSNe (and also of broad-line supernovae Ic-BL SNe) is the magnetar driven model

  → such events could be powered by the spin-down of rapidly rotating magnetars (e.g. **Omand+2024**, **Sarin+2024**).

- **Magnetar :**

  → Very highly magnetized neutron stars (~10^{9} to 10^{11} T or ~10^{13} to 10^{15} G) (e.g. **Olausen & Kaspi 2014**).

  → Existence proposed by **Duncan & Thompson (1992)**

  → Observational proof by **Kouveliotou+ (1998)**.

- **Dark matter :**

  → radio detection attempts using magnetar PSR J1745-2900 in Galactic Center (**Darling2020, Foster+2022, Battye+2022**)

  → One appealing property of the axion (a) is that it converts into photons (γ) within a strong magnetic field (B) as a+ B →γ

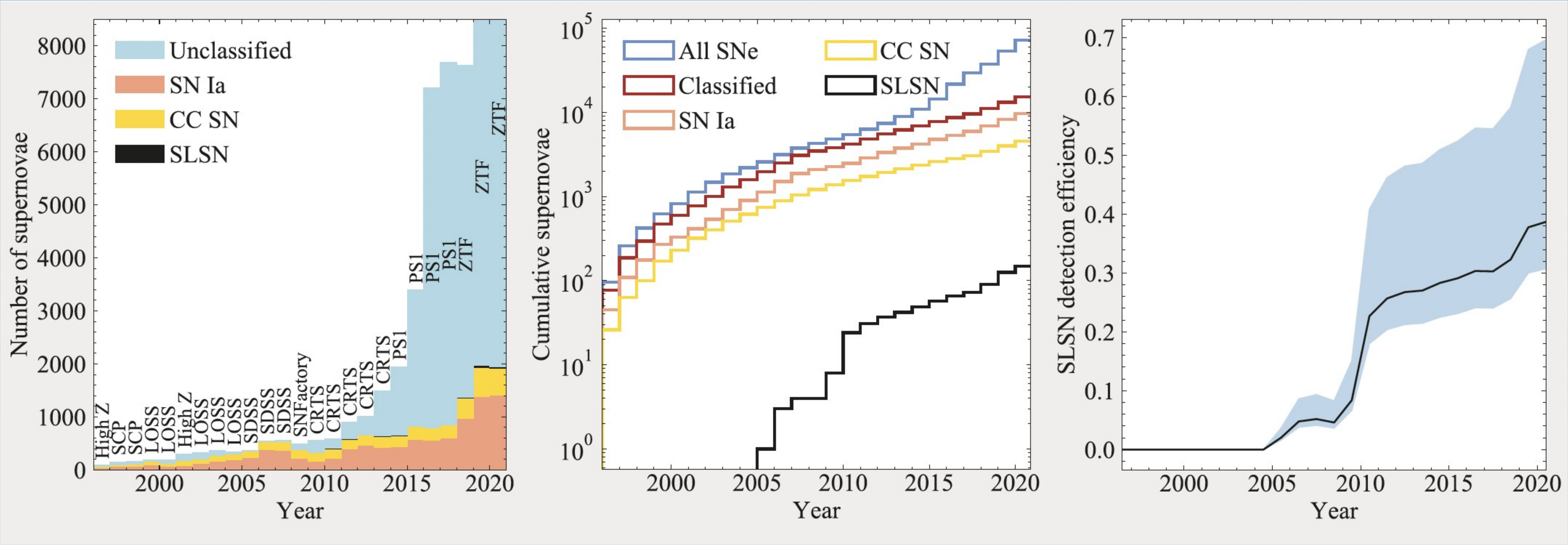
SGLF: Supernova and Gravitational Lenses Follow up

Participation to several projects on Supernovae in the IAC:

- Supernovae in the Infrared avec Hubble (SIRAH). **SIRAH P.I. Saurabh Jha**. Classification of SN Ia candidates ($0.02 < z < 0.07$) about 2 weeks before maximum light for HST follow up. **IAC P.I. is Ismael Pérez-Fournon**.
- LensWatch : LensWatch P.I. is Justin Pierel. LensWatch is a loose collaboration of groups searching for lensed SNe with targeted surveys of known strong-lensing systems (galaxies and clusters). Centered around HST and JWST and additional facilities proposals. **IAC P.I. is Ismael Pérez-Fournon**.
- Surveys of Superluminous Supernovae (SLSNe): **IAC P.I. is F. Poidevin.**
- EUCLID Key Project on Pair Instability and SLSNe: **Coordinated by T. Moriya and F. Poidevin** (includes **C.M. Gutiérrez** from IAC).
- See also **M. T. Botticella**'s talk on EUCLID in Rubin Synergies session from yesterday.
- Understanding the progenitors of core-collapse supernovae. **IAC project: P.I. is D. Aguado.** Collaboration with the Einstein Probe team (**Ning-Chen Sun**'s group).

Superluminous supernovae: observational facts

Two types of SLSNe : H-poor = type I, H-rich = type II → **This talk focused on type I.**

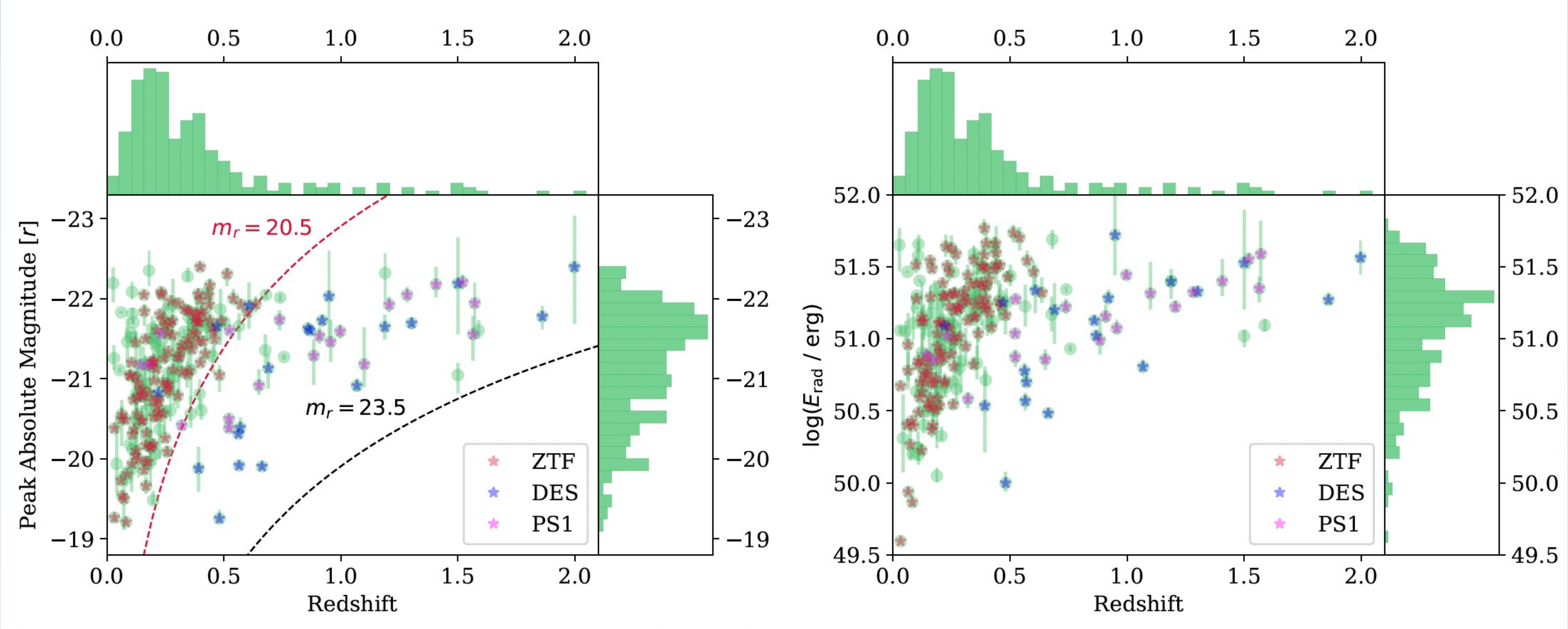


Left: Supernovae candidates and classification over about the last 20 years.Middle: Cumulative supernova counts. Right: SLSN detection efficiency, defined as the fraction of SLSNe out of all classified supernovae each year, compared to the fraction expected given their estimated occurrence rate.

Nicholl 2021

Superluminous supernovae: absolute magnitudes and total radiated energy

H-poor SLSNe peak between -23 < M_{opt} < -19 mag (AB). Classifications up to redshift = 2

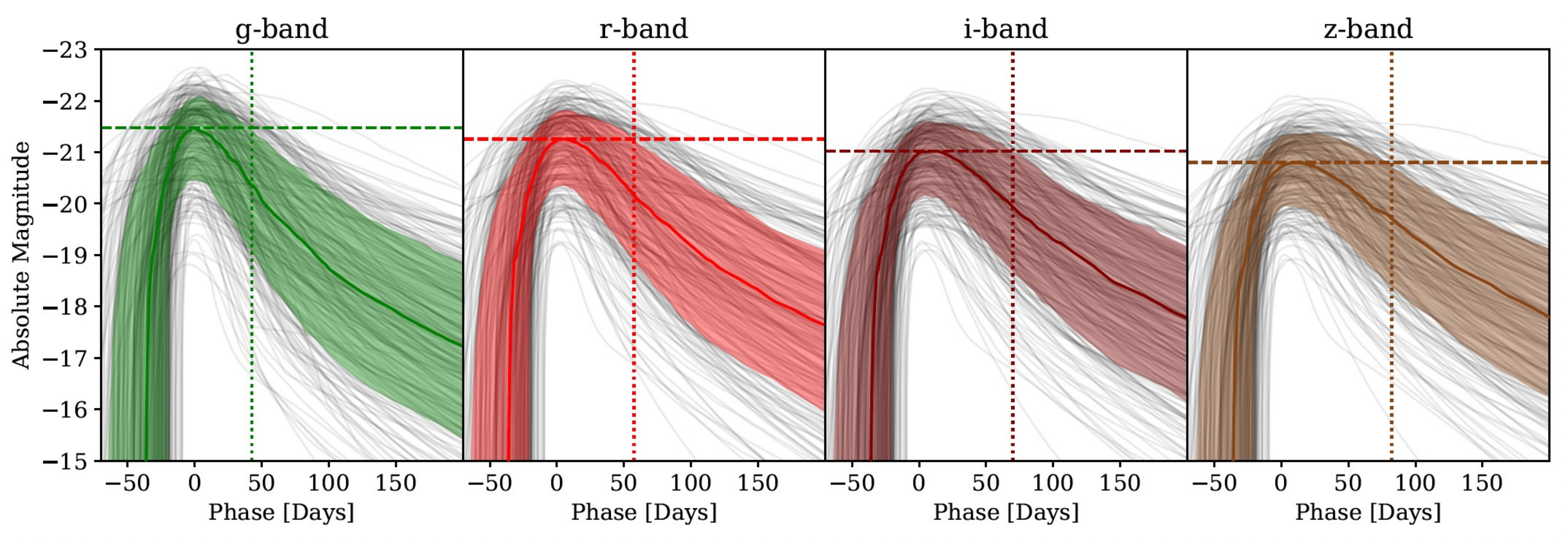


Left: Peak absolute magnitude in rest-frame r-band as a function of redshift for the full SLSN sample. The red dashed line indicates the nominal magnitude limit of ZTF, and the black line the limit for PS1 and DES. Right: Total radiated energy Erad during the first 200 days of the light curve for the full SLSN sample.

Gomez+2024

Superluminous supernovae: optical photometry properties

H-poor SLSNe rest-frame absolute magnitude light curves: fast and slow evolvers

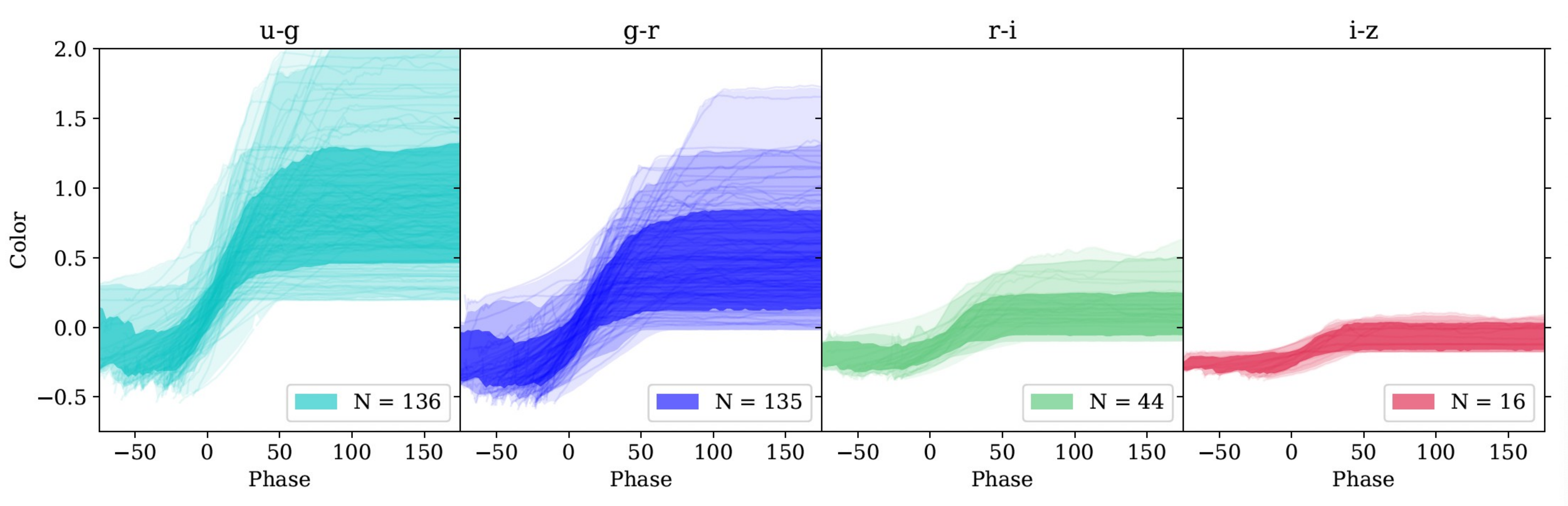


Rest-frame absolute magnitude light curves in the griz bands for the full sample of SLSNe as a function of phase from their respective peaks. The gray lines show the light curves of each individual SLSN, while the solid color curves and shaded regions represent the mean evolution of the full sample and their 1σ ranges, respectively. The horizontal dashed and vertical dotted lines demarcate the mean peak magnitude in each band and the mean τ_e decline timescale in each band.

Gomez+2024

Superluminous supernovae: color

H-poor SLSNe rest-frame colors as a function of phase

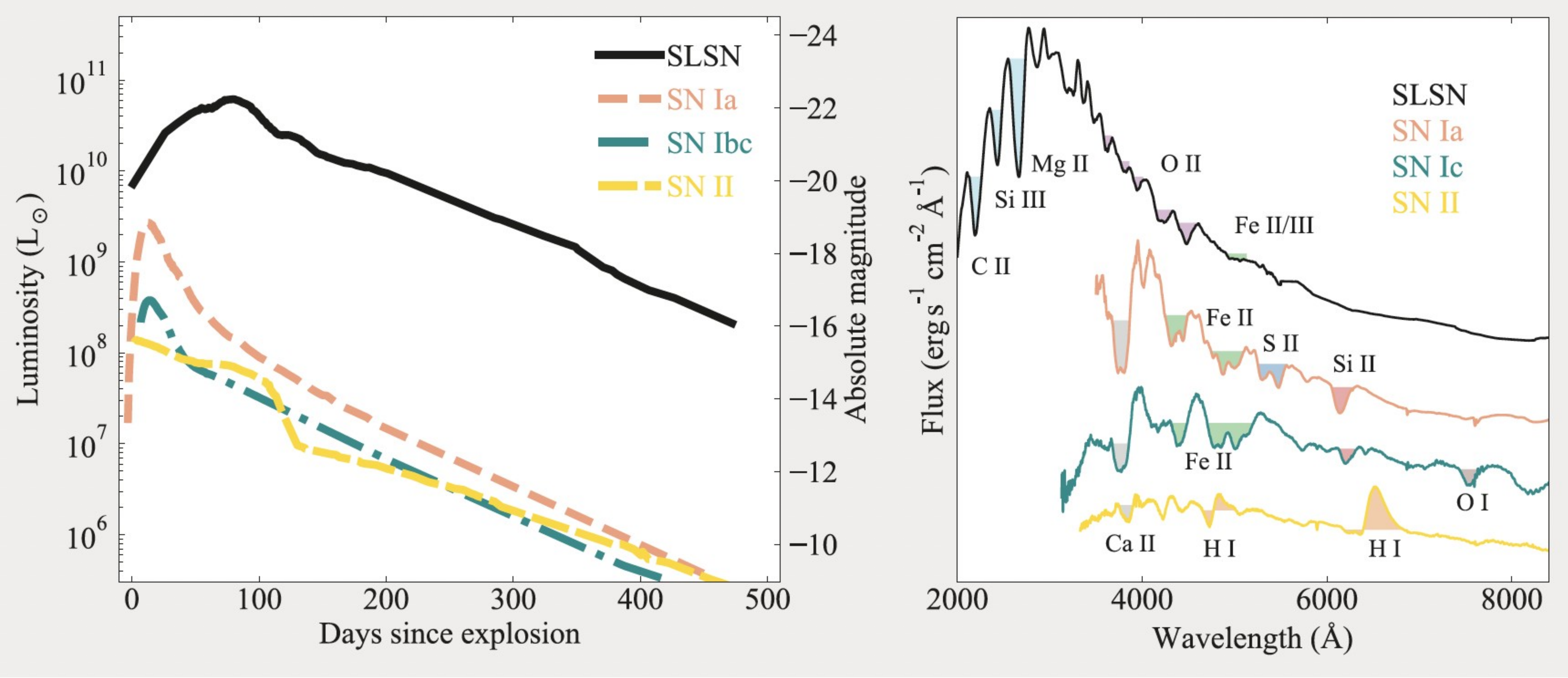


Rest-frame colors as a function of phase, derived from an interpolation of the SLSNe light curves using MOSFiT. We only include N objects for which there are observations available in the interpolated filters. The shaded regions represent the +/- 1, 2, and 3σ ranges. The redder filter pairs have a smaller span in colors in part because the shape of the SED flattens out at redder wavelengths, but these are also less well measured given that there are fewer observations available in these filters.

Gomez+2024

Superluminous supernovae: Basic properties

H-poor SLSNe basic properties compared to SN Ia, SN II (H-rich) and SN Ib/c (H-poor)



Left: The broad, luminous light curves of SLSNe release ~1000 times more energy than conventional CCSNe. Right: SLSNe are defined by a blue spectrum at the time of peak luminosity, with absorption lines of singly ionized oxygen. SLSNe show stronger lines in the UV, but still radiate significantly more UV flux than other supernova types.

Nicholl+2021

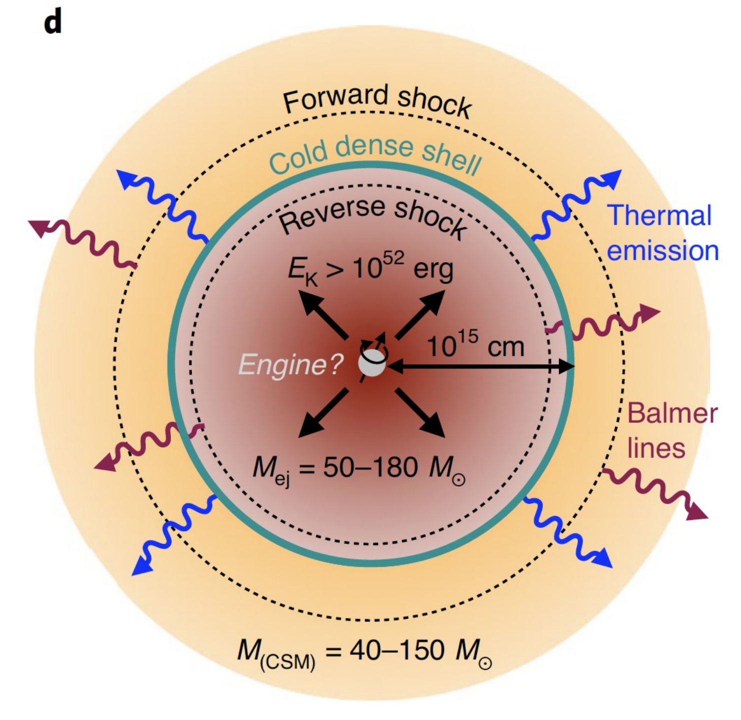
Superluminous Supernovae: progenitors and explosions

Progenitor:
→ Very massive stars (single or binary systems ?)

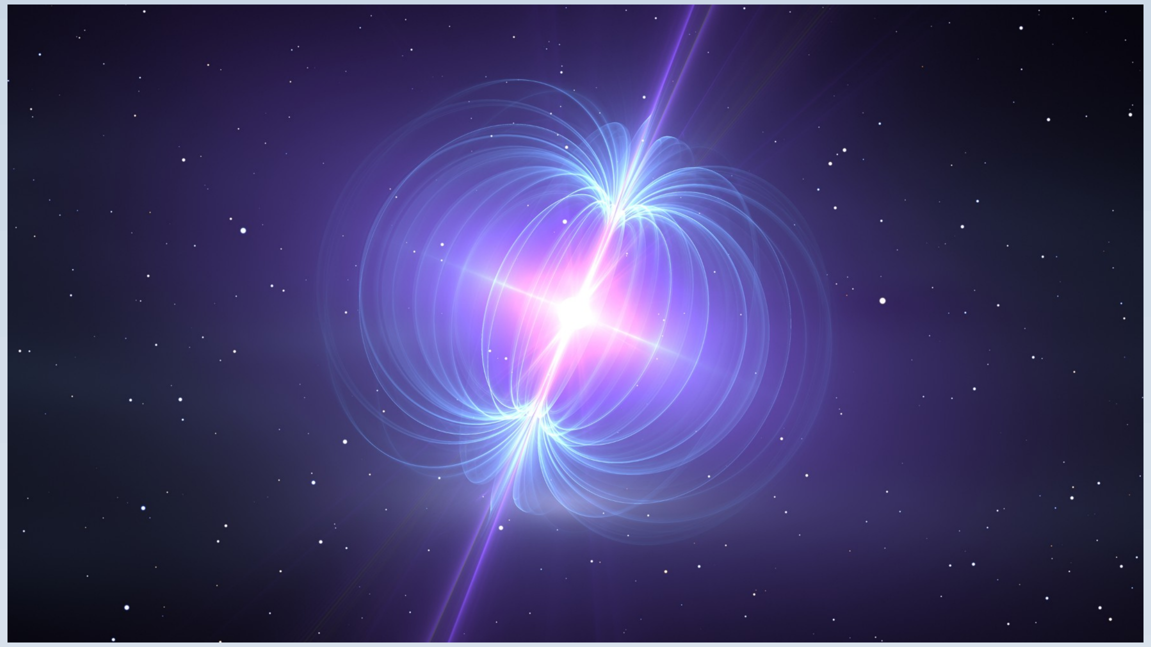
Type of explosion:
→ Core-collapse

Product of explosion and processes sustaining the explosion ?
→ Magnetar dipole spin-down ?
→ Black-hole ?
→ and / or interaction with circumstellar matter ?
Previously ejected matter from progenitor.

Galactic Magnetars→ see second part of the talk



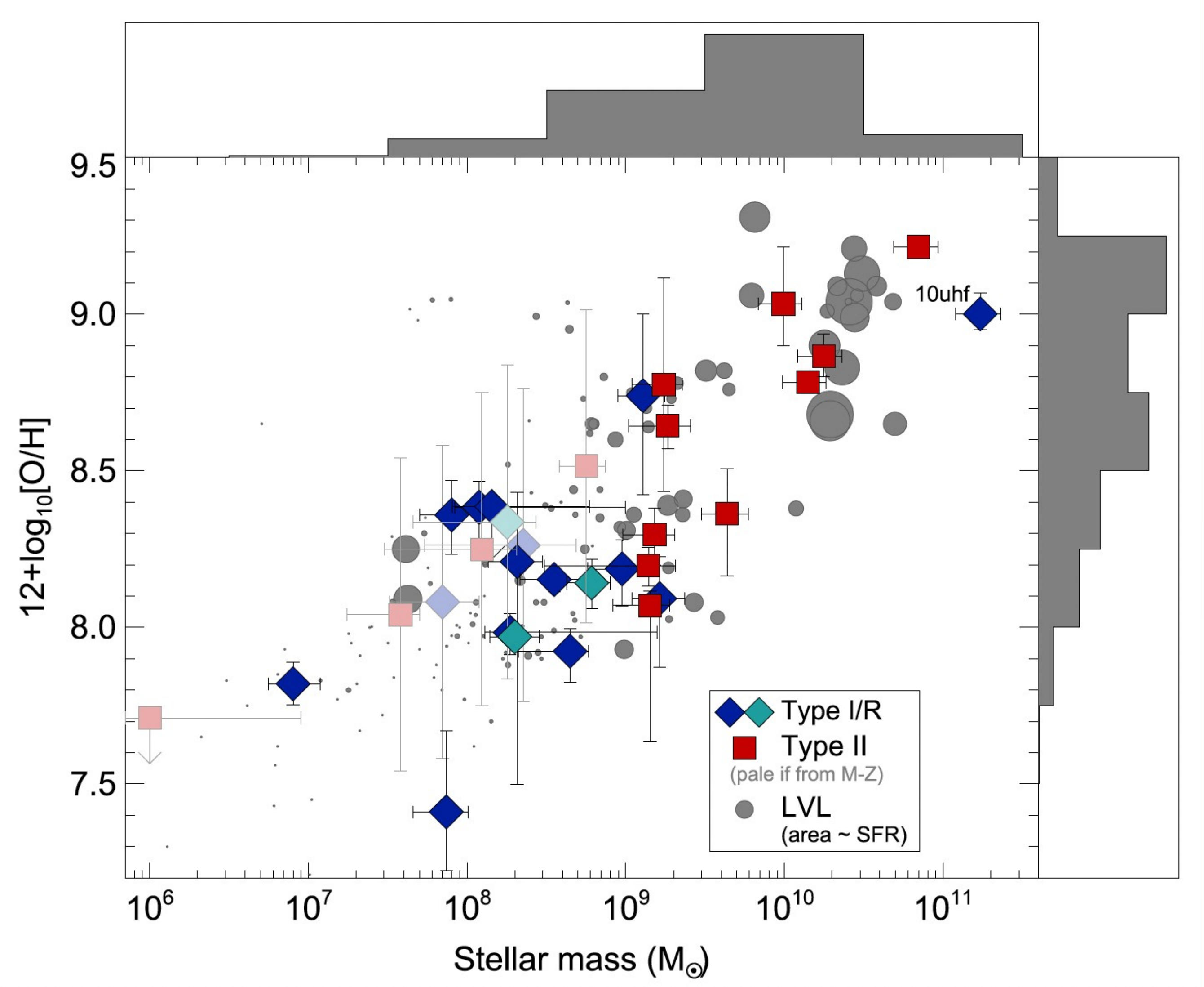
Schematic model for SN 2016aps by Nicholl (2020).



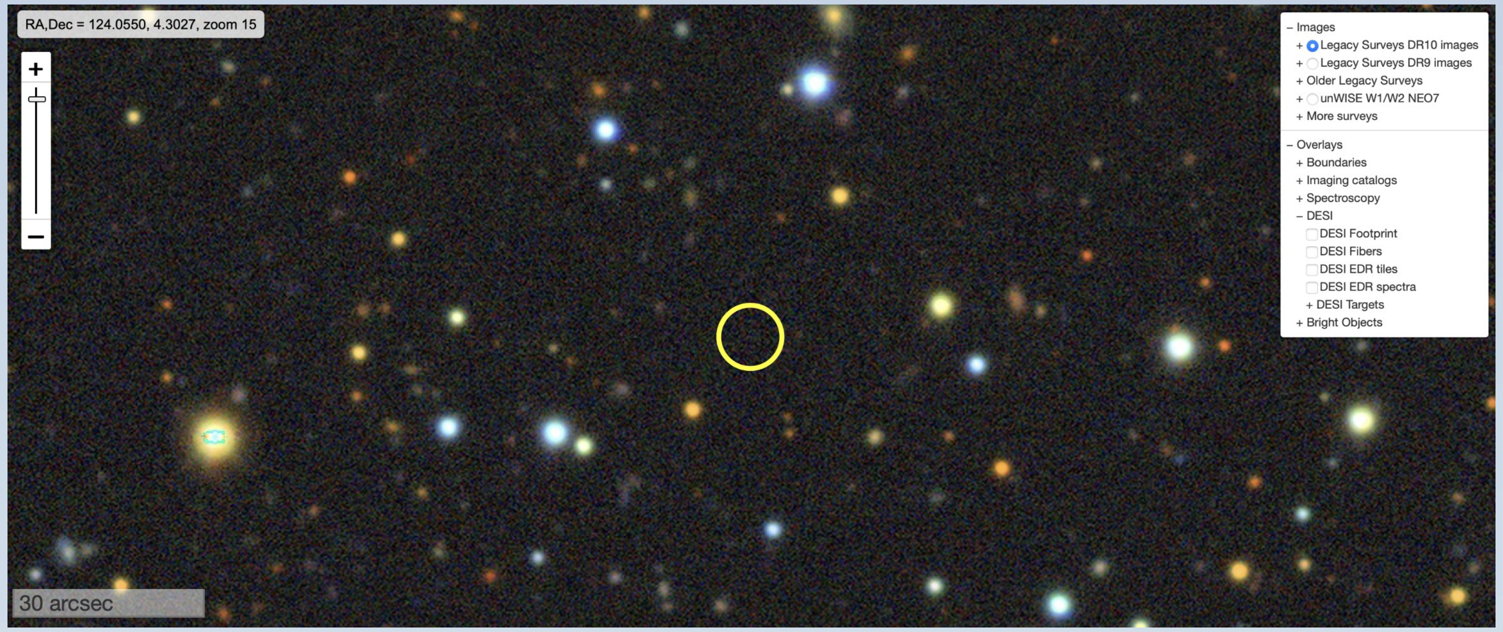
An artist's impression of a magnetar ©quantamagazine

Superluminous Supernovae: host galaxies

Host galaxies:
→ H-poor SLSNe detected in low metallicity galaxies (mainly faint dwarfs, compact dwarfs, …$M \leq 10^9\ M_{\odot}$)
→ Low-metallicity galaxies generally with $Z_{\odot} < 0.5$ (Perley+2016, Chen+2017)
→ Sometimes SLSNe look like orphans in Legacy Surveys



Perley+2016



The host galaxy of SN 2020ank (z=0.2485) is faint (g-band upper limit ~24 mag) as it was not observed up to the detection limits of Sloan Digital Sky Survey (SDSS), PS1, and Dark Energy Spectroscopic Instrument Legacy Survey.

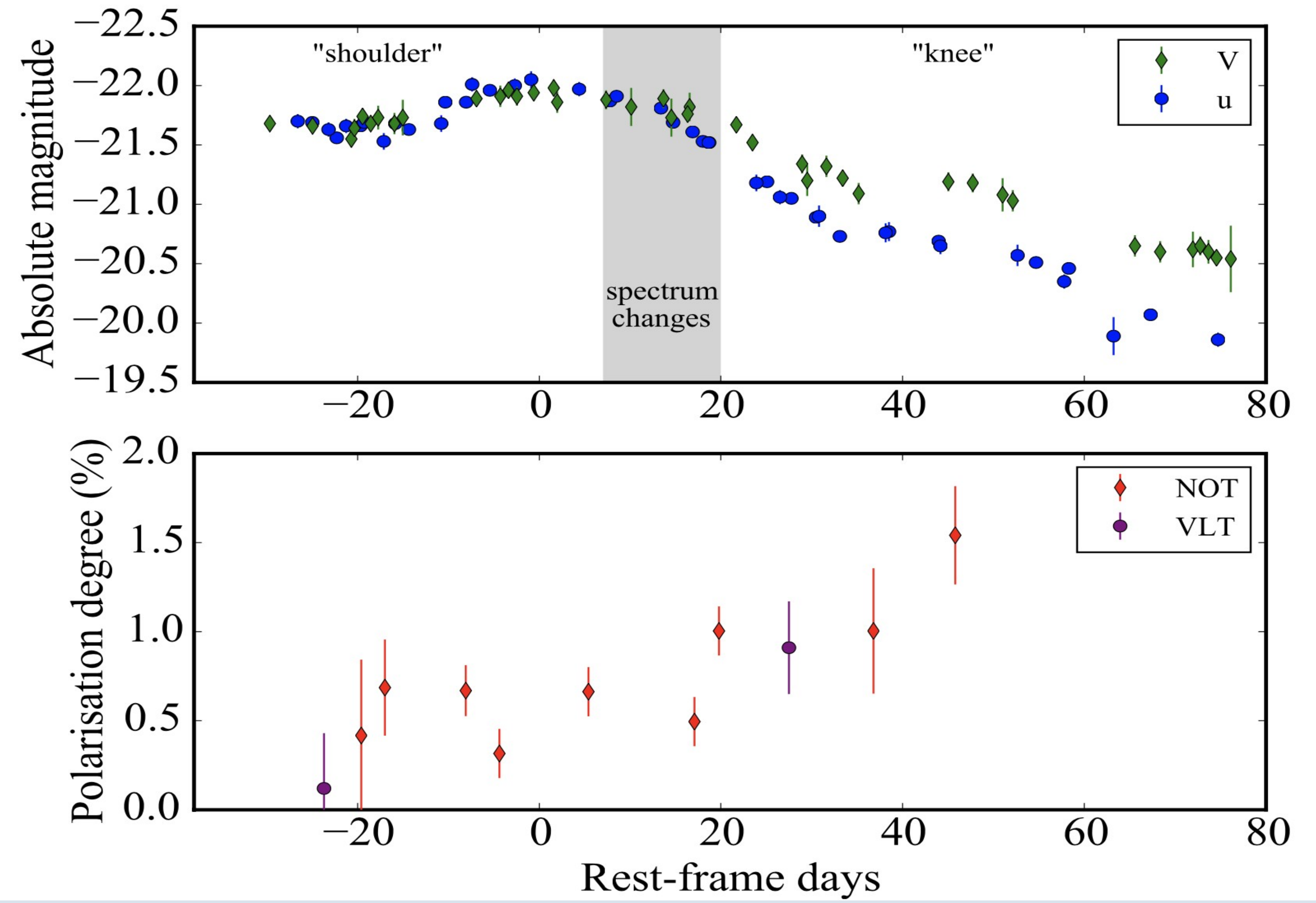
Poidevin+2020 – TNS classification report

SNe and SLSNe classification and follow-up by our IAC group (see wednesday's talk by I. Pérez-Fournon)

- We have developed methods that combine the tools available at the ZTF/LSST brokers mainly using ALeRCE, Lasair, Lasair Sherlock, and ATLAS forced photometry, to search for new supernovae, report them to TNS and spectroscopically classify some of them (using the Liverpool, NOT and GTC telescopes)
- Discovery and classification of ZTF supernovae using the LSST/ZTF brokers reported in the transient name server (TNS) by our group (see talk by Ismael Pérez Fournon from Wednesday in TVS session):
- > 2100 TNS discovery reports (TNS group SGLF)
- > 150 TNS classification reports (TNS groups SGLF and SIRAH)
- **11 SLSNe discovered by SGLF**
- **20 SLSNe classified by SGLF (Started with SN 2020ank)**

Superluminous Supernoae : Polarimetry

→ Relatively scarce measurements (~16 SLSN-I observed up to now) but interesting case studies
→ Possible mechanisms producing variations of polarization:
1)photosphere evolution – electron scattering (Leloudas+2017)
2)Interaction with CSM (Pursiainen+2023)
3)Jets ? (Soker+2024)

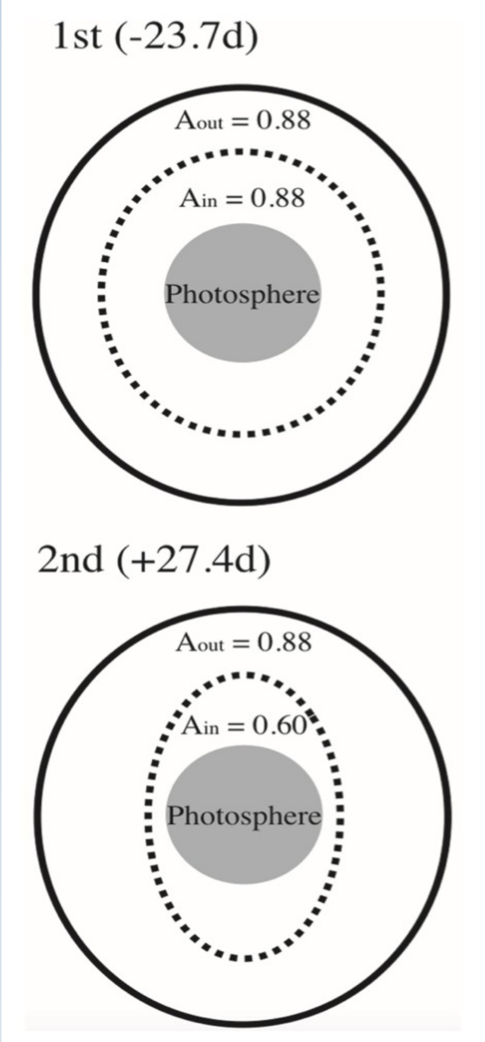


Leloudas+2017 (linpol)
Inserra+2016 (specpol)

How frequent are such variations ?

Variations consistent with a change of shape of the inner photosphere **(Inserra+2016)**

Two-zone aspherical ejecta models. Electron scattering and resonant line scattering



Our polarimetry and spectroscopy optical surveys of SLSNe
P.I. Frédérick Poidevin

- 3 surveys :
  - → 2021A: 10 hrs (ToO mode) on NOT + 9 hrs on LT (spec+phot)
  - → 2022B: 6 grey nights on NOT (spec+pol) + 9 hrs on LT (spec+phot)
  - → 2023B: 6 dark nights on NOT (spec+pol) + 9 hrs on LT (spec+phot) + 10 hrs on GTC (spec)

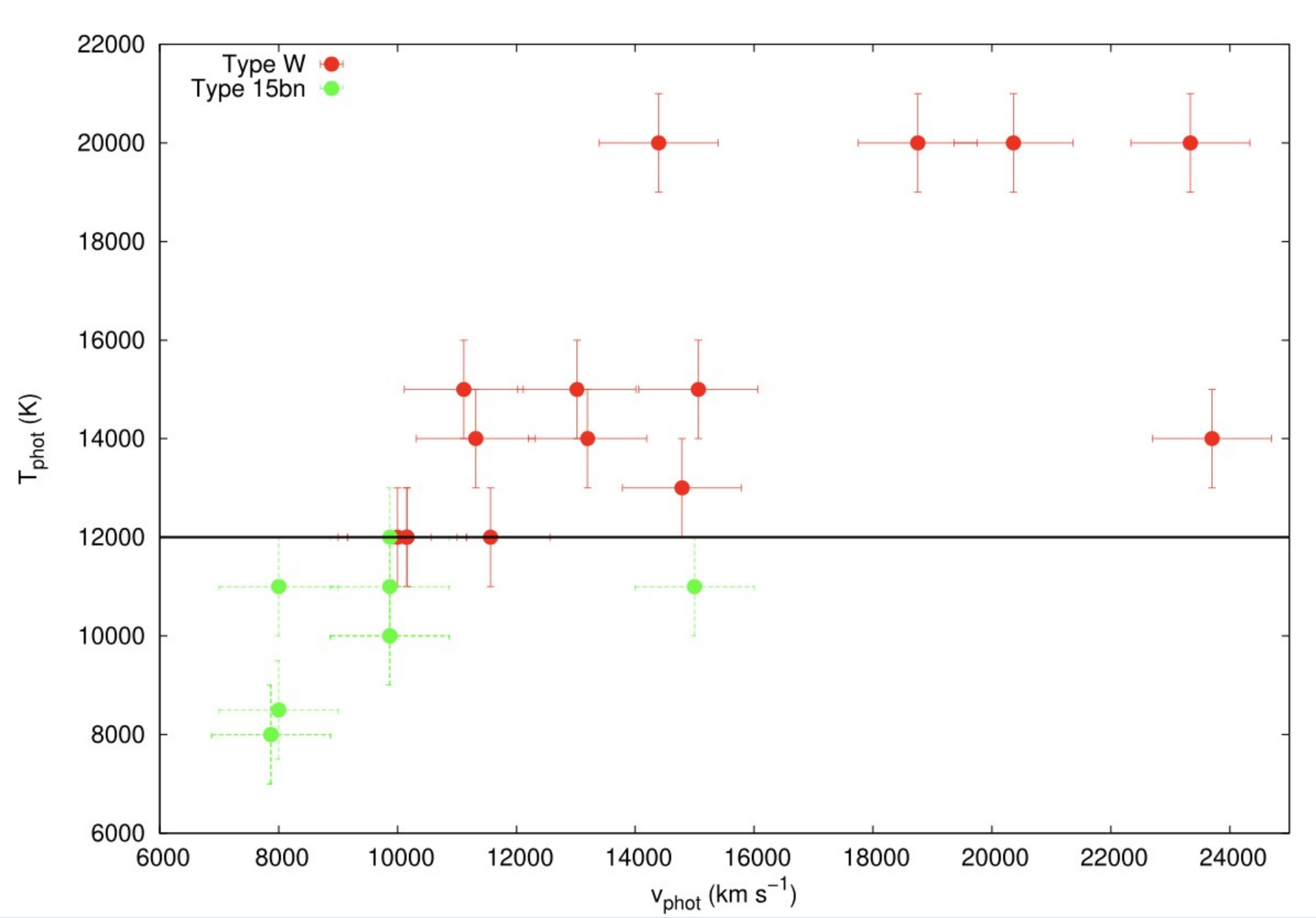
- **Survey 1:**
  - **→ 5 type I SLSNe + 1 over luminous SN follow-up**
  - **→ First publications : Poidevin+2022** and **Poidevin+2023**
- **Survey 2:**

  → 7 SLSNe-I (pol+spec) and 3 SLSNe-II (pol+spec) + classification of several candidates
- **Survey 3:**

  → 4 SLSN-I (pol+spec) + various SLSNe candidates (spec)

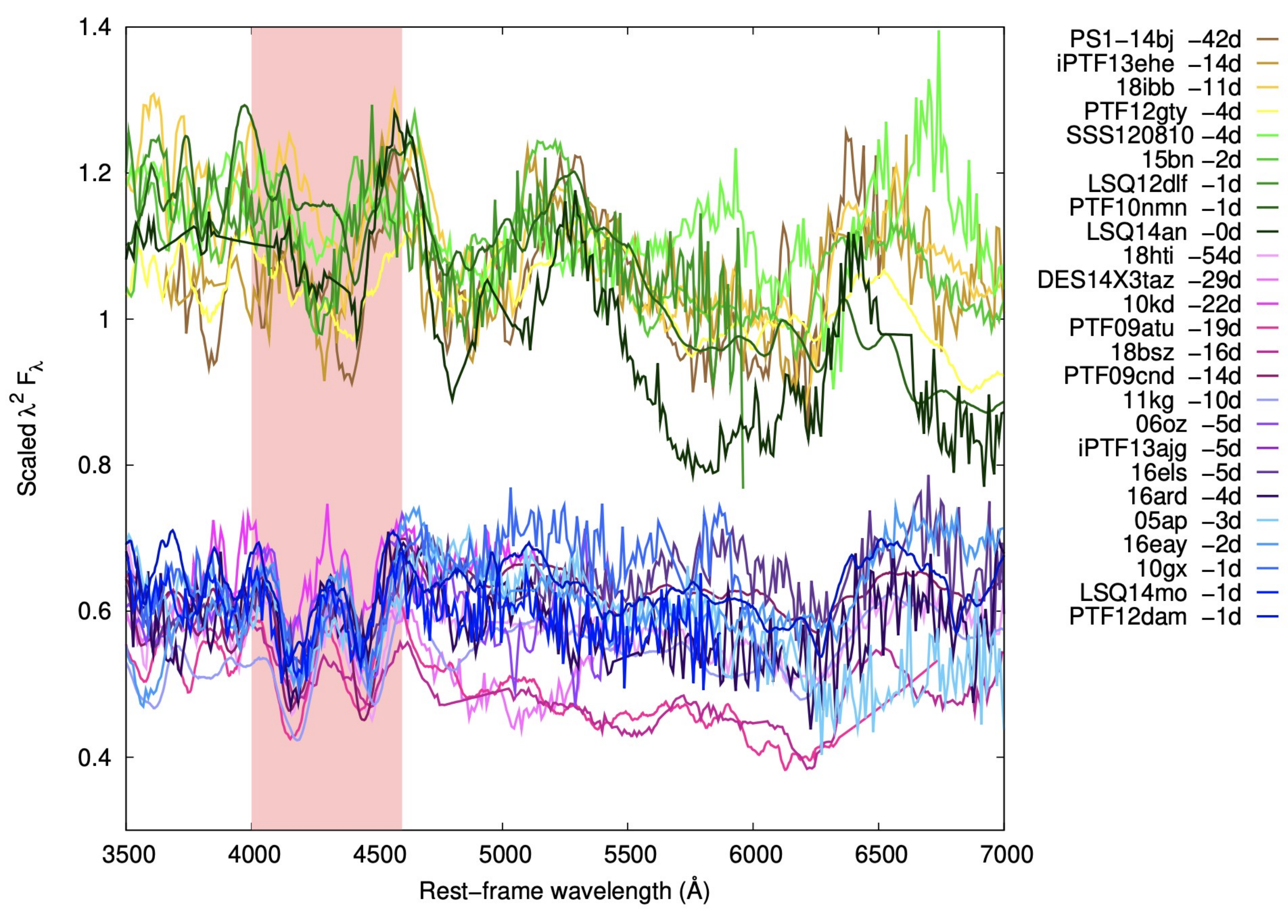
  → Observations of a few ambiguous transients (TDE or AGN ? SLSNe looking light curves before peak?)

2 subtypes of SLSN-I: Type W and Type 15bn (see Könyves-Tóth+21: SYN++ Thomas+2011) → Different polarization properties ?



Pre-maximum photospheric velocities as a function of photospheric temperatures of the 27 studied SLSNe-I obtained from SYN++ modeling. Type W SLSNe-I are shown with red dots, while Type 15bn objects are shown with green dots.

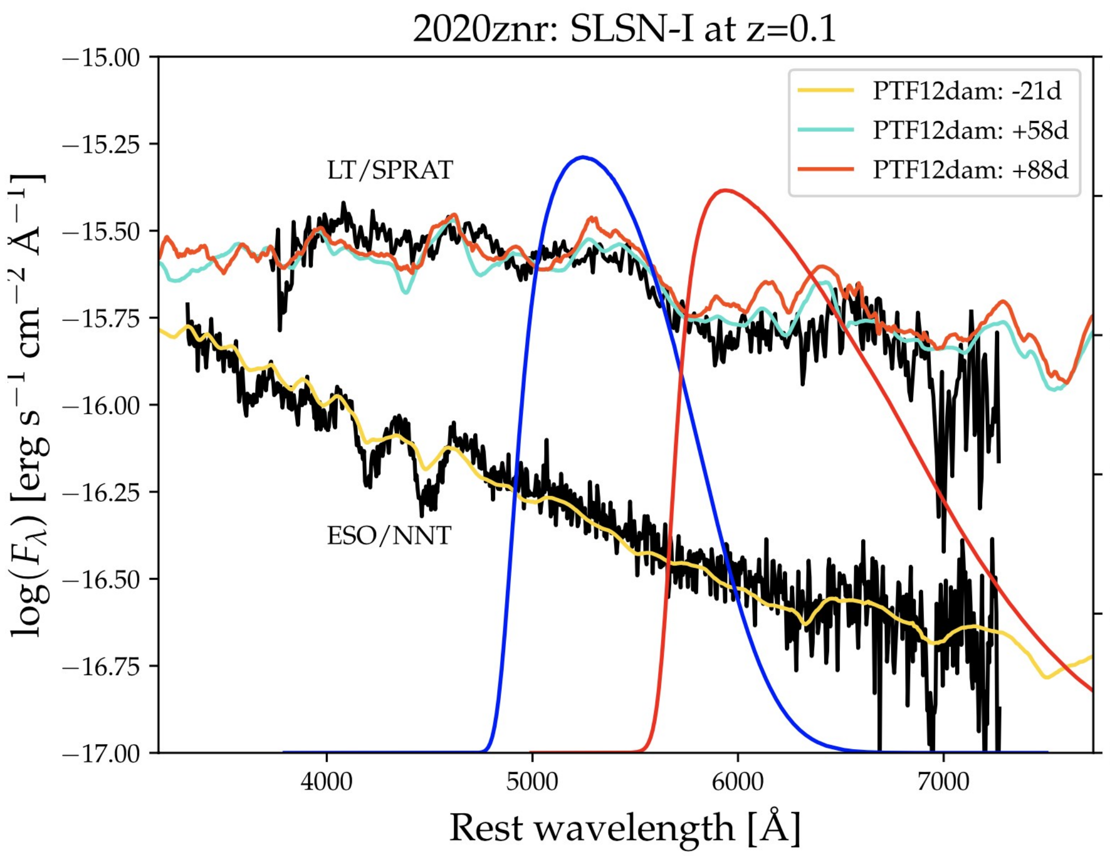
Könyves-Tóth+22

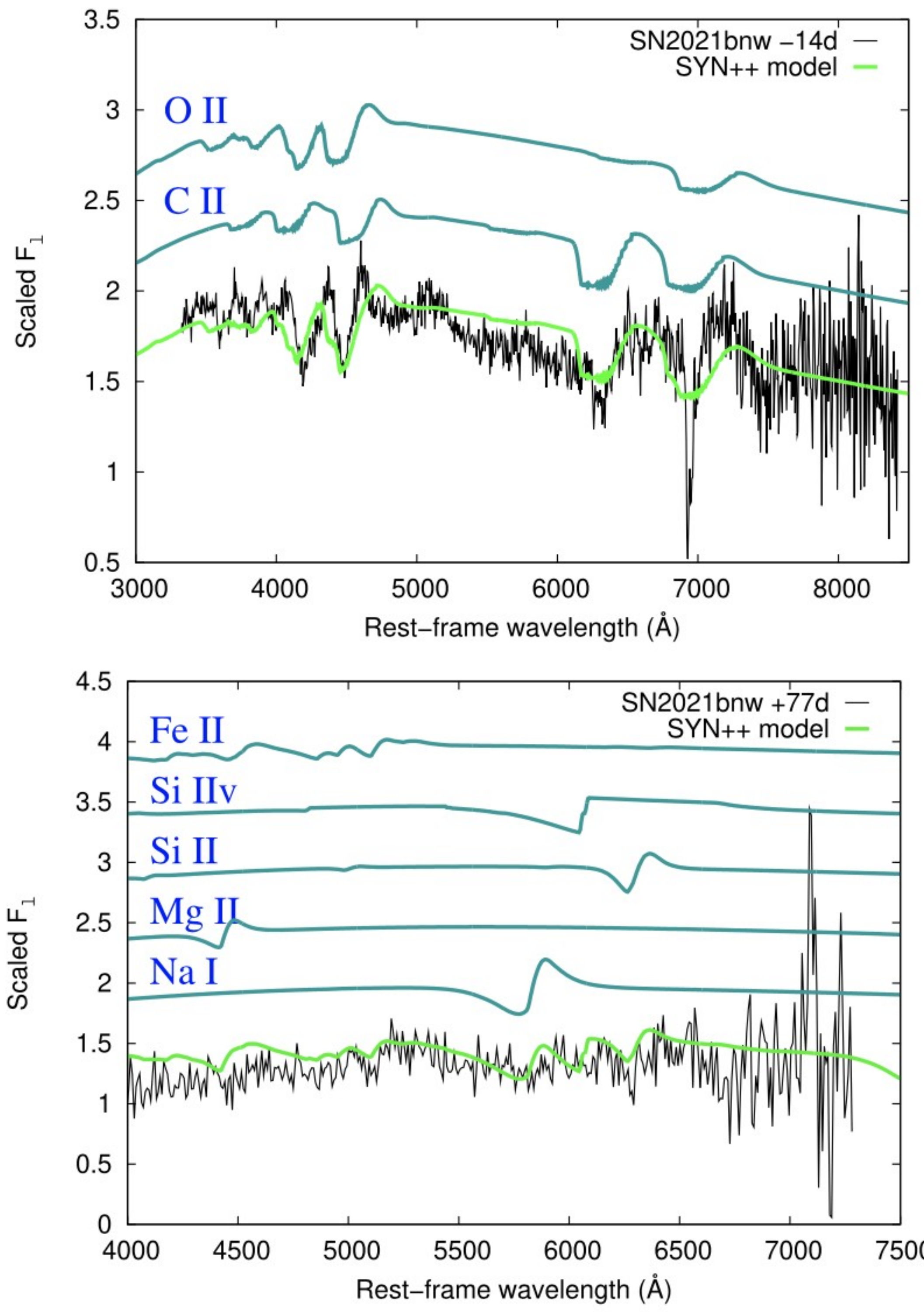


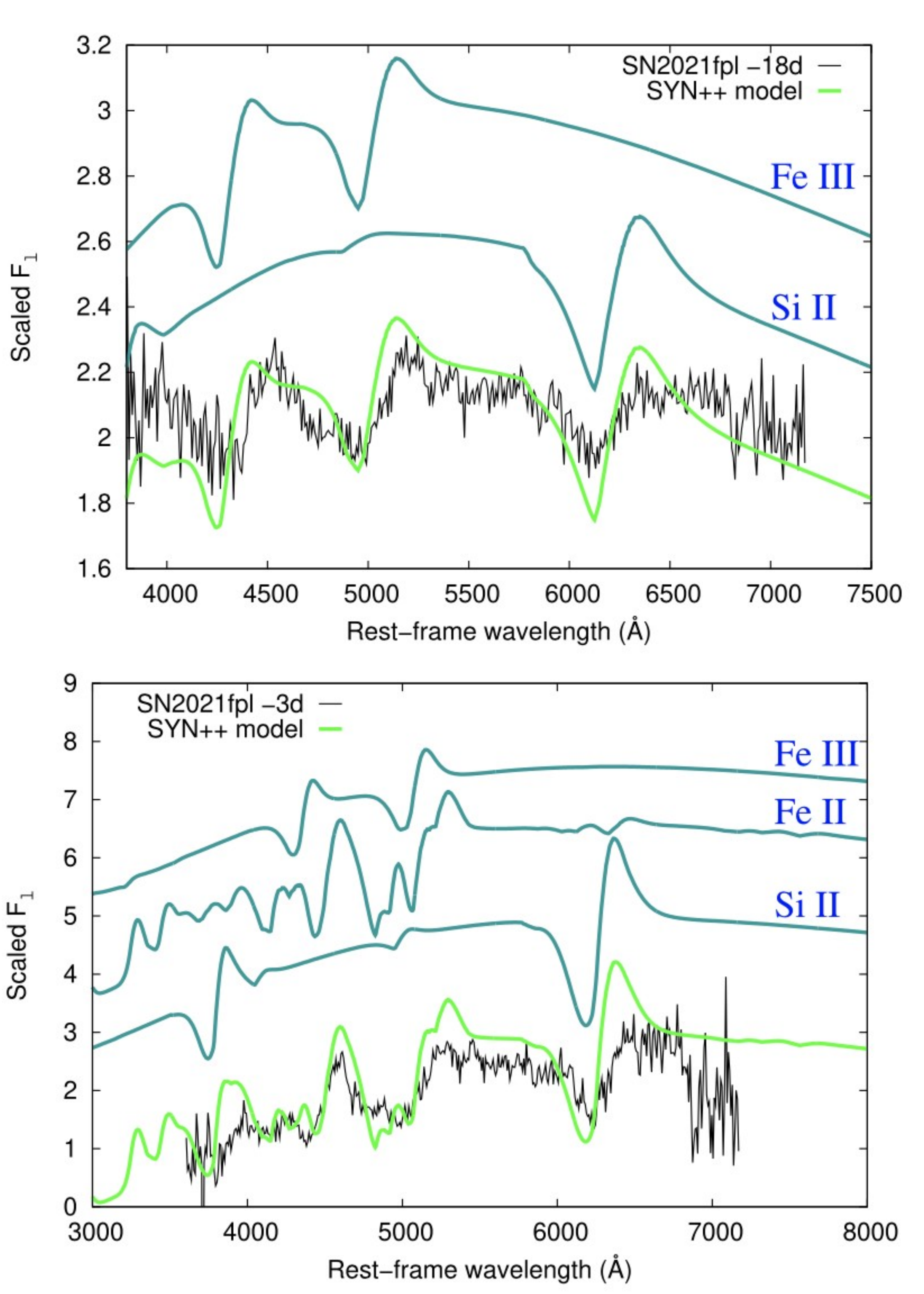
Continuum normalized pre-maximum spectra of the studied Type W (on the bottom with purple-bluish colors) and Type 15bn SLSNe-I (on the top with orange-greenish colors) + distinction between slow and fast evolvers.

Könyves-Tóth+23

First results from our surveys: SN 2020znr, SN 2021bnw & SN 2021fpl





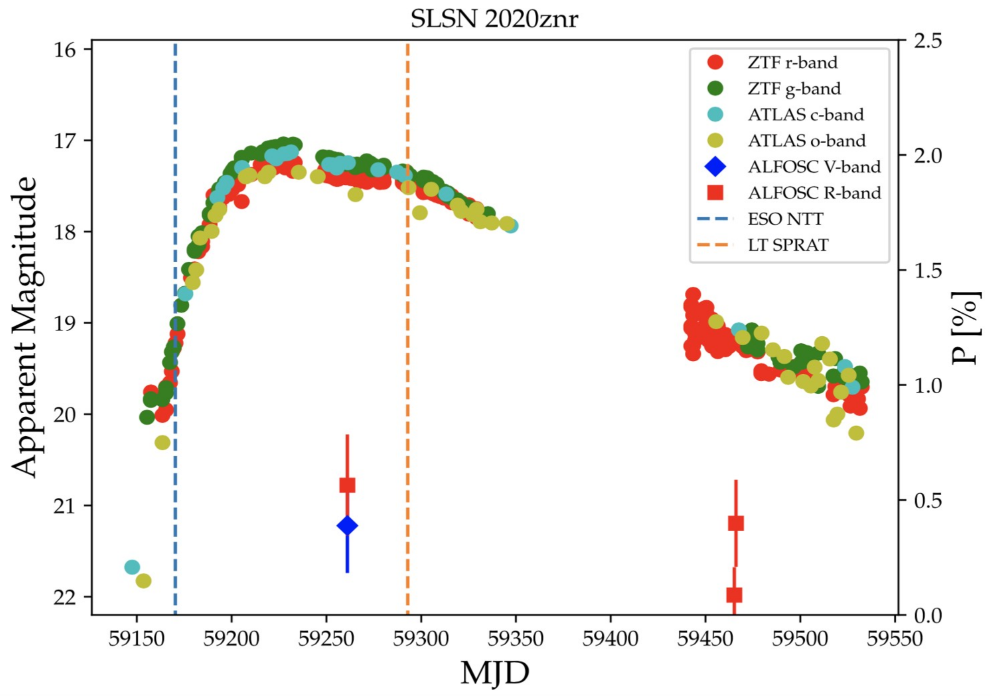


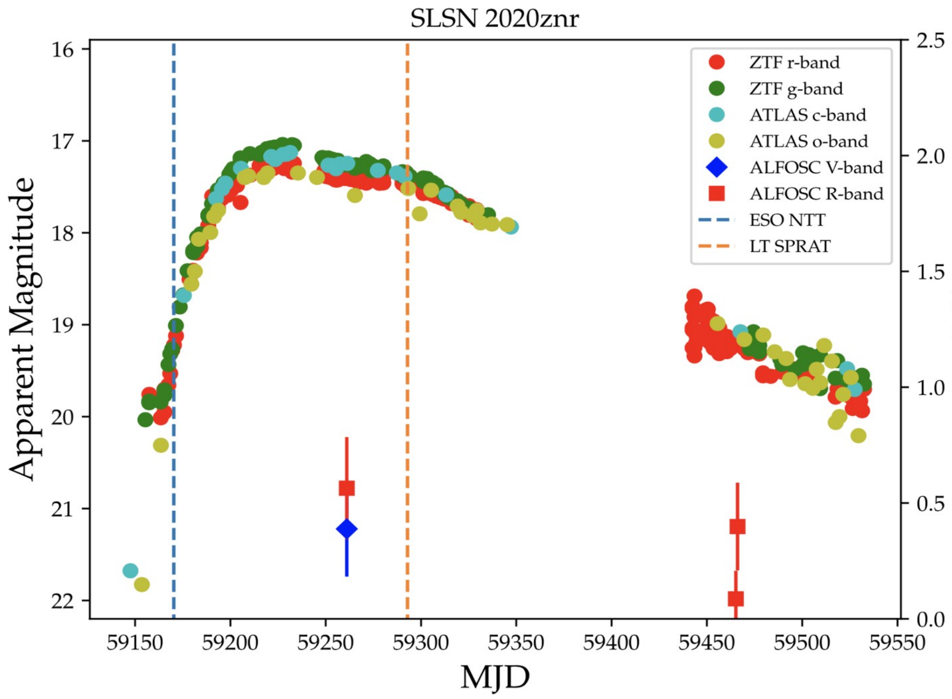
- SN 2020znr: W Type
- SN 2021bnw: W Type
- SN 2021fpl: 15bn Type

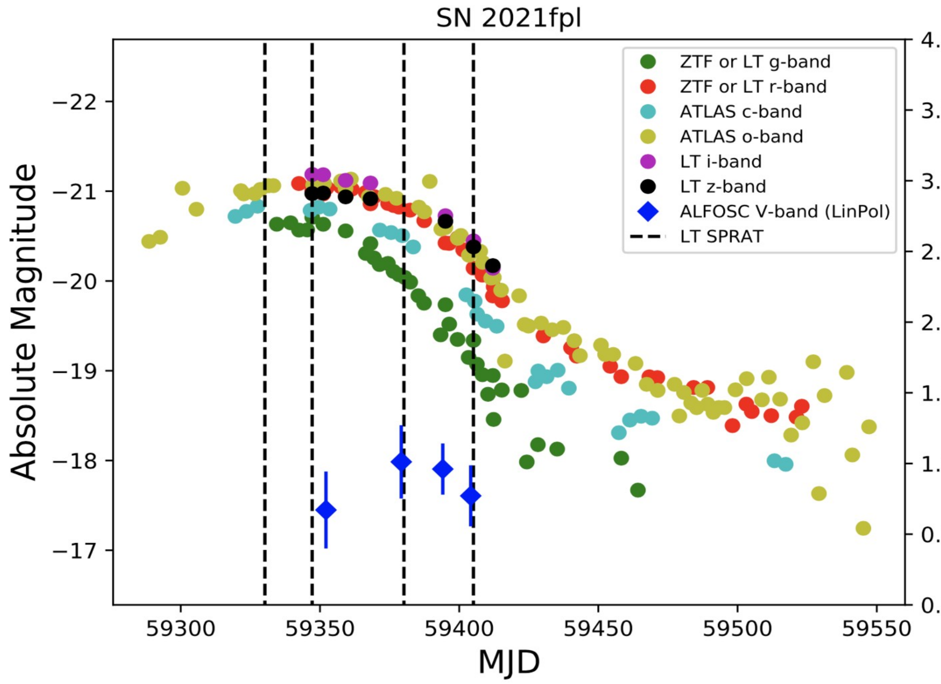
Poidevin+2022

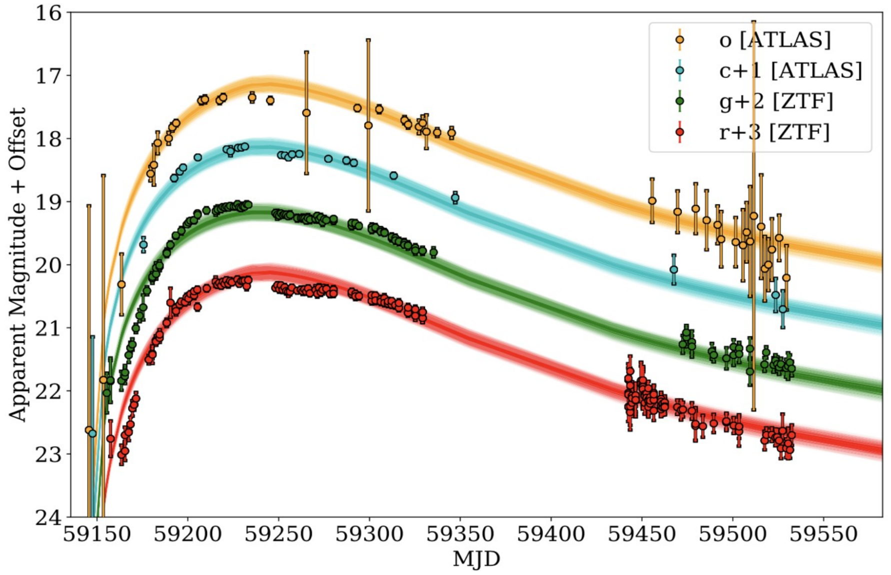
Poidevin+2023

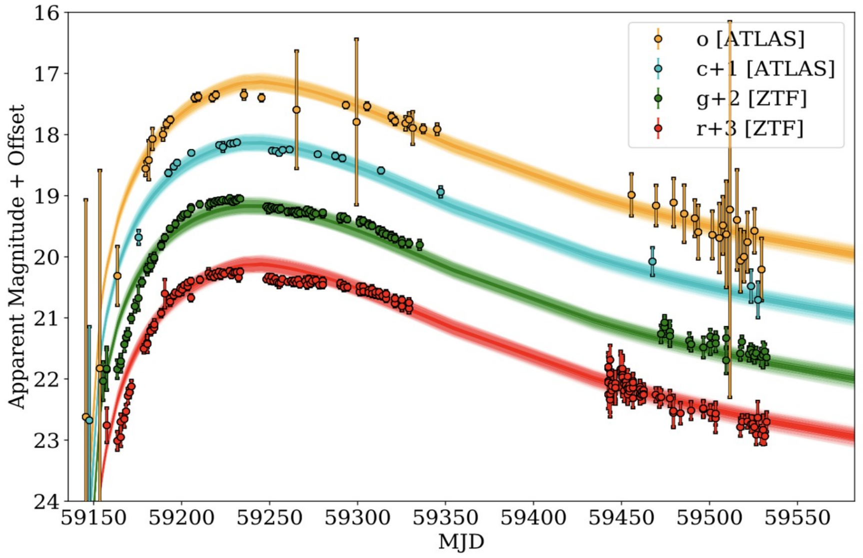
First results from our surveys: SN 2020znr, SN 2021bnw & SN 2021fpl

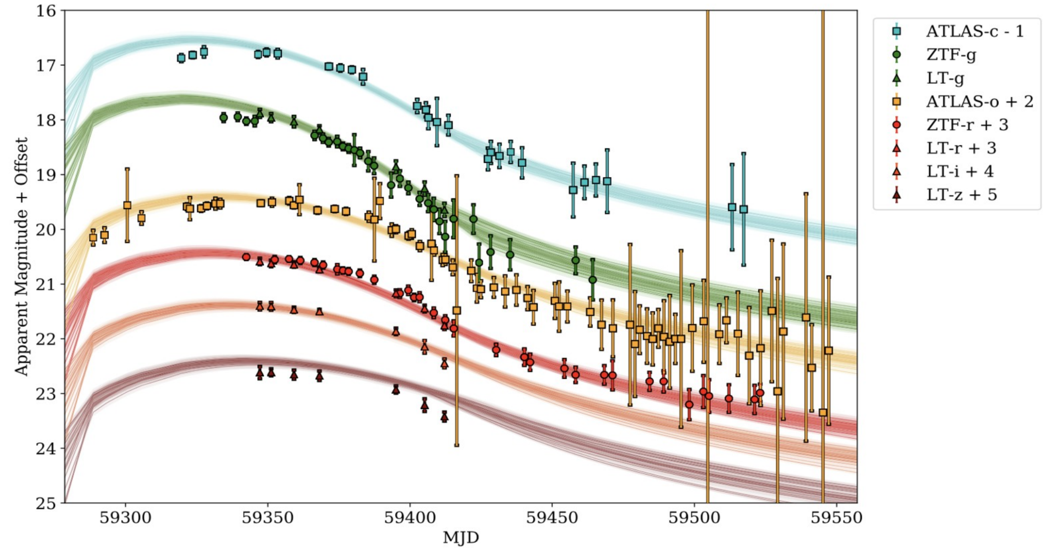












W Type –Slow Evolver | **W Type –Slow Evolver** | **15bn Type –Fast Evolver**

→ Magnetar driven light curve (LC) modeling by Conor Omand

→ We conclude W-type and 15bn-type SLSNe-I may have different polarization properties

Poidevin+2022 **Poidevin+2023**

Current collaborations with the ZTF group:

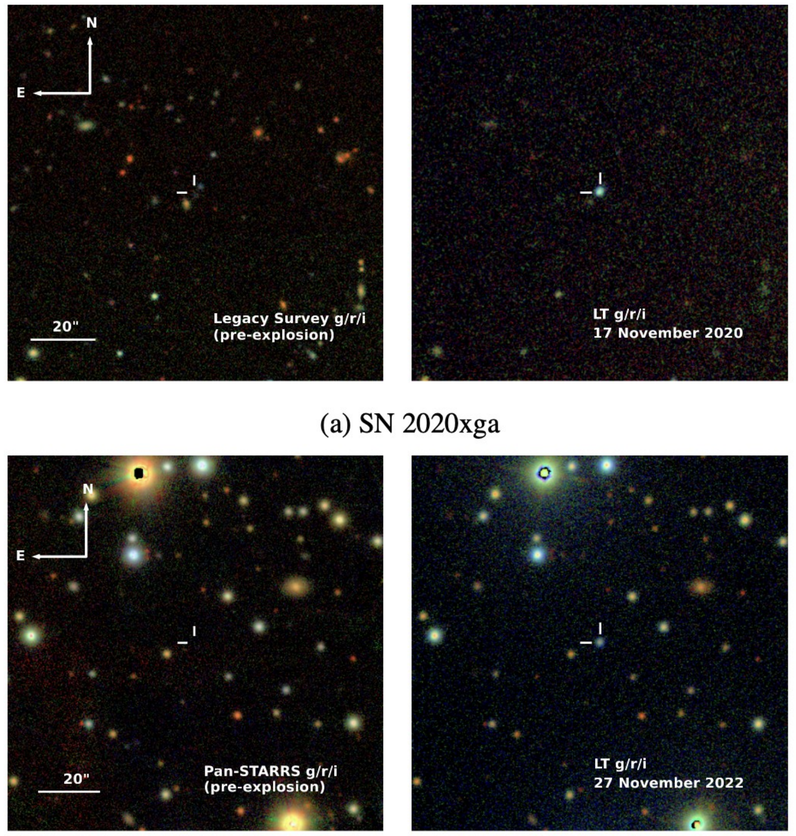
1) Gniki et al. paper in prep.: Work on superluminous supernovae SN 2020xga and SN 2022xgc.

→ We provided 2 spectra and data from 2 polarimetry epochs obtained with the Nordic Optical Telescope on SN 2022xgc (survey 2).

2) Poidevin et al. in prep.: Work on the peculiar luminous supernovae SN 2021lwz.

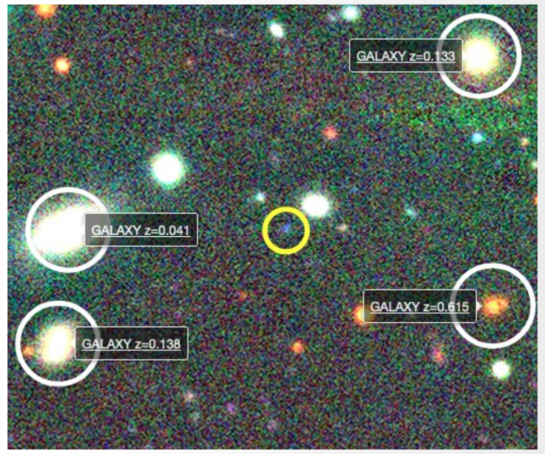
→ ZTF collaborators = S. West, S. Schulze, K.-R. Hynds, T. Kangas, R. Lunnan, D.A. Perley, N. Sarin, J. T-W. Chen, L. Yan.

→ ZTF group provided a large amount of photometry and spectroscopy data.



(a) SN 2020xga

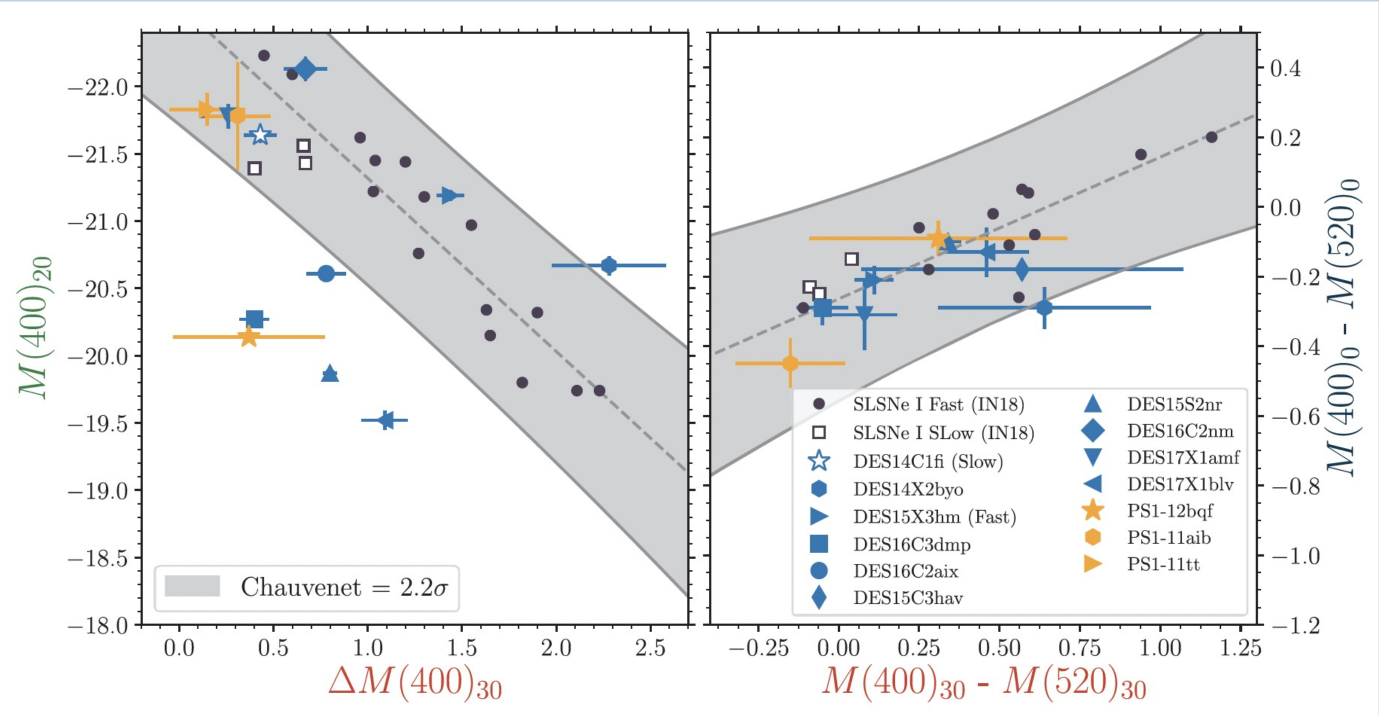
(b) SN 2022xgc

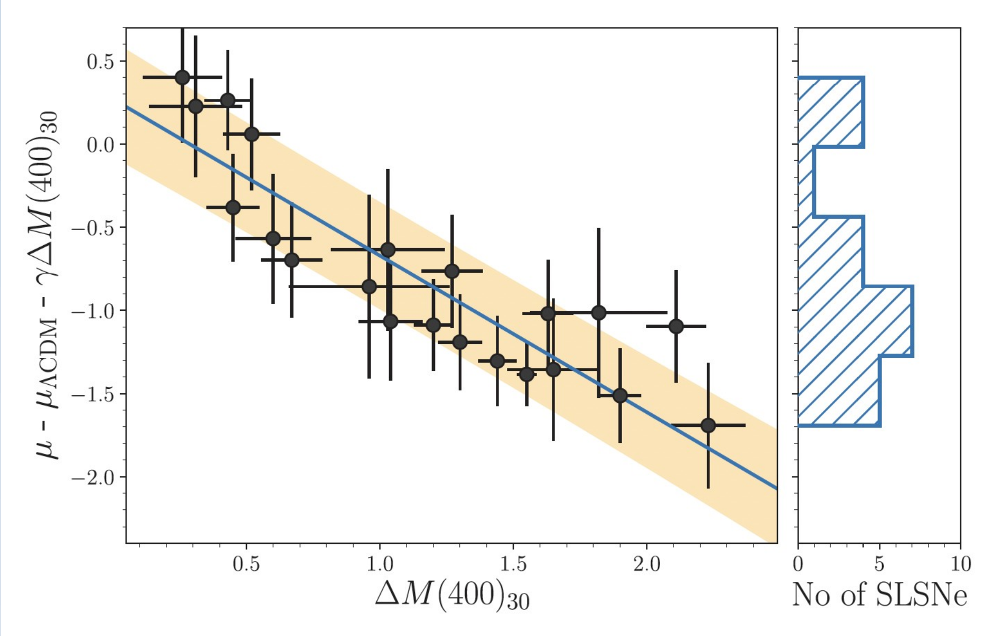


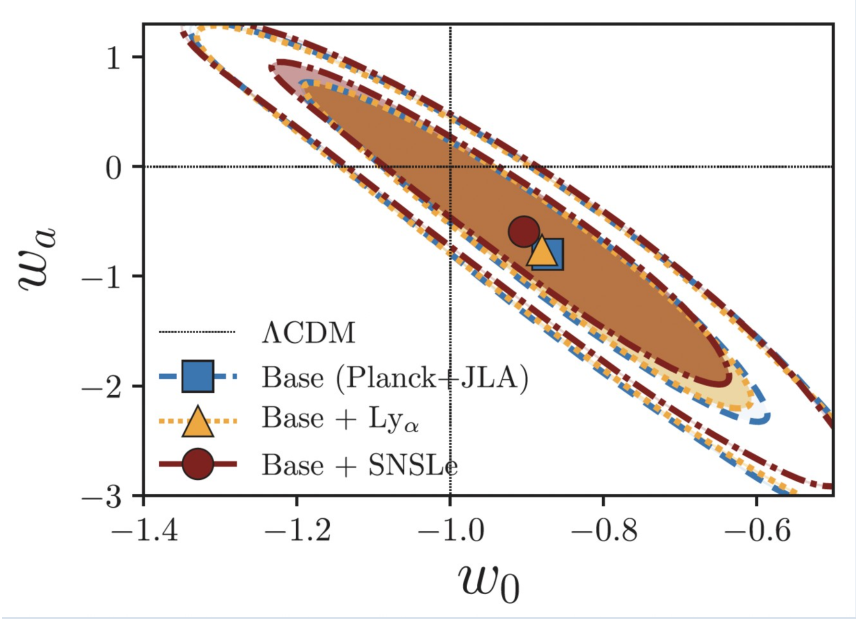
Legacy Survey public data host galaxy of SN 2021lwz

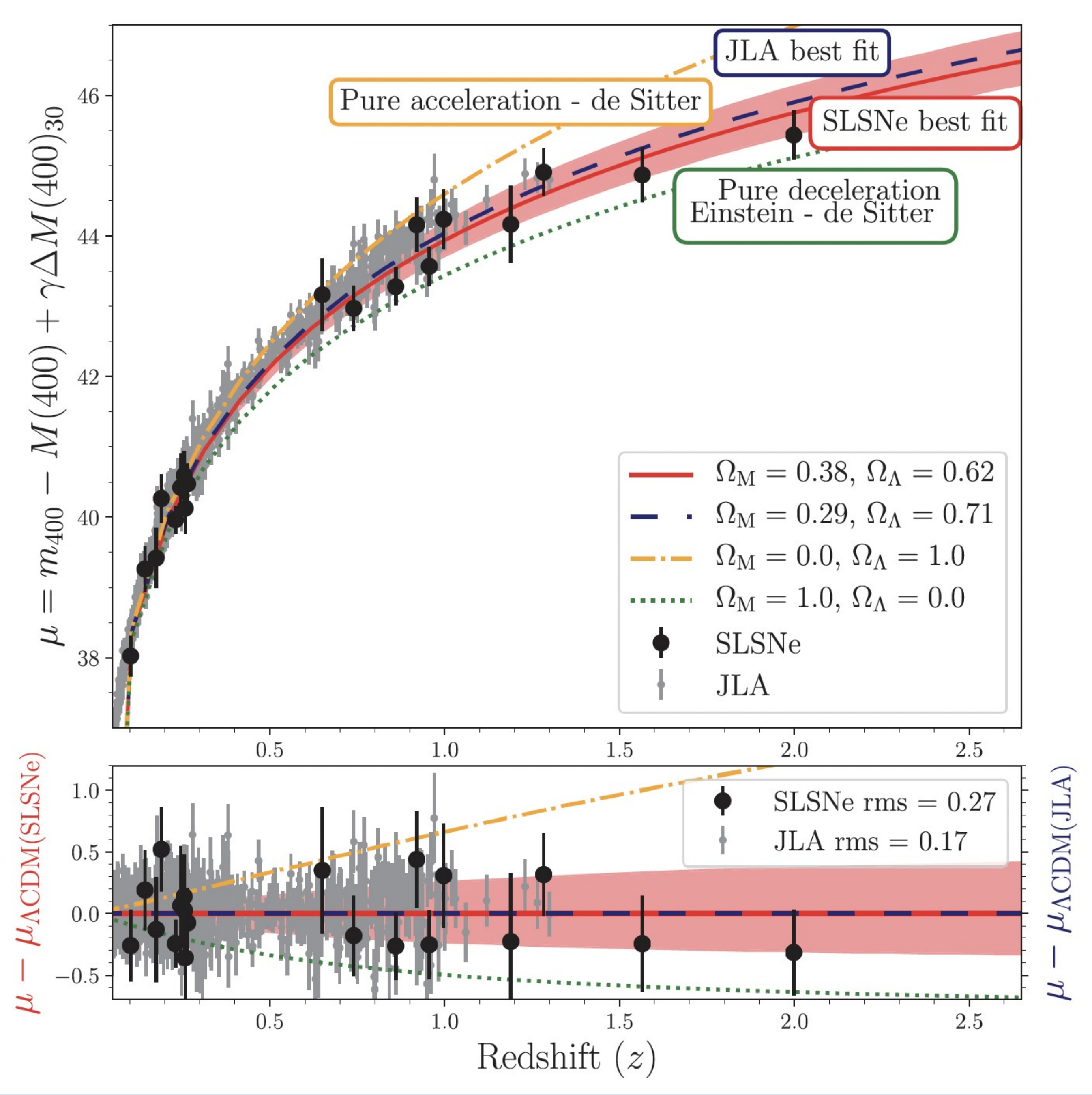
Cosmology with Superluminous Supernovae ?

“We use the peak–decline standardization method in our analysis, i.e. our distance estimator assumes that SLSNe I with an identical light-curve decline rate have the same average intrinsic luminosity at all redshifts. *The standardized distance modulus, μ_{obs}, is then given by :*
$\mu_{obs} = m(400) - M(400) + \gamma\ M(400)_{30}$”





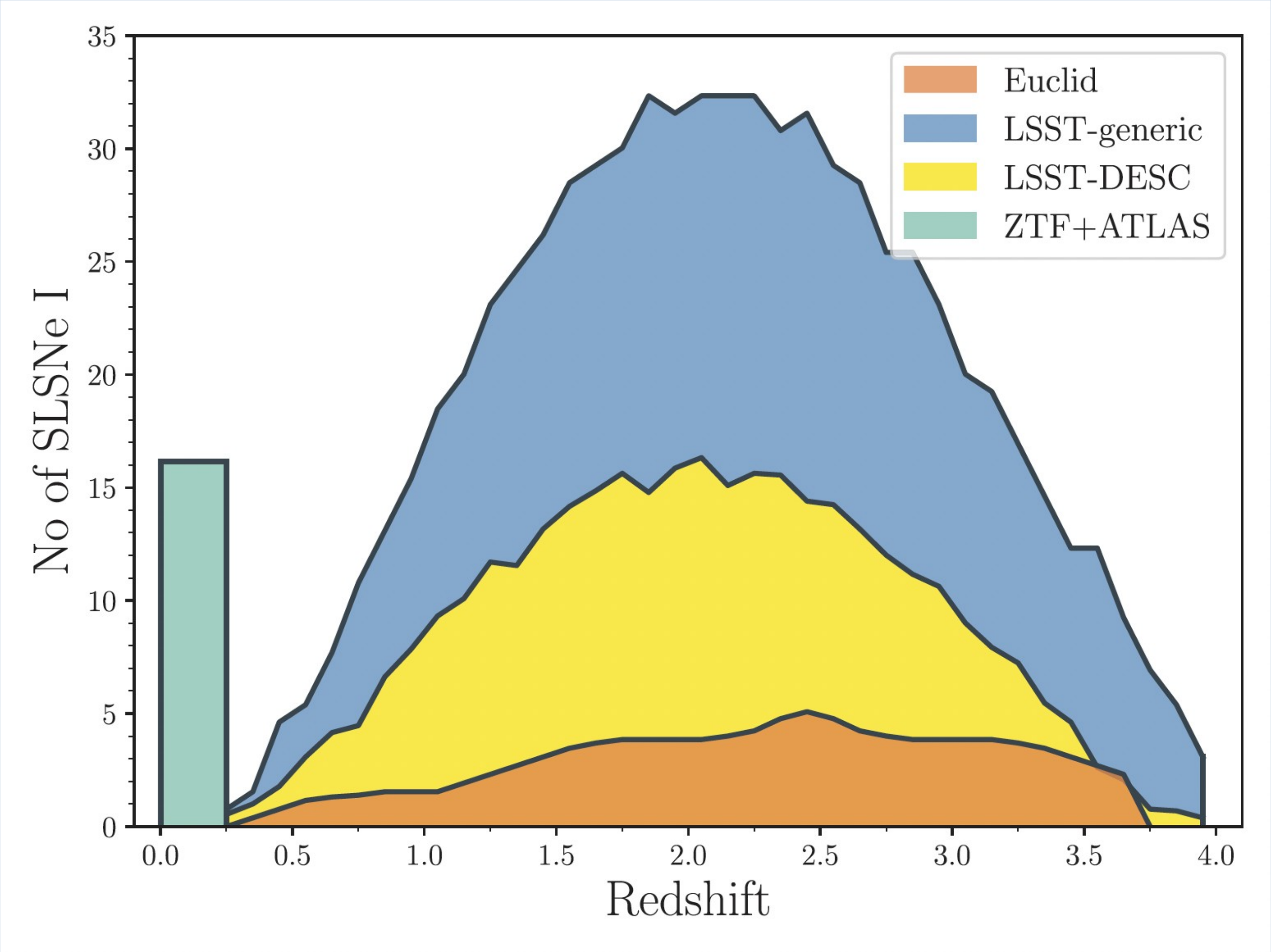


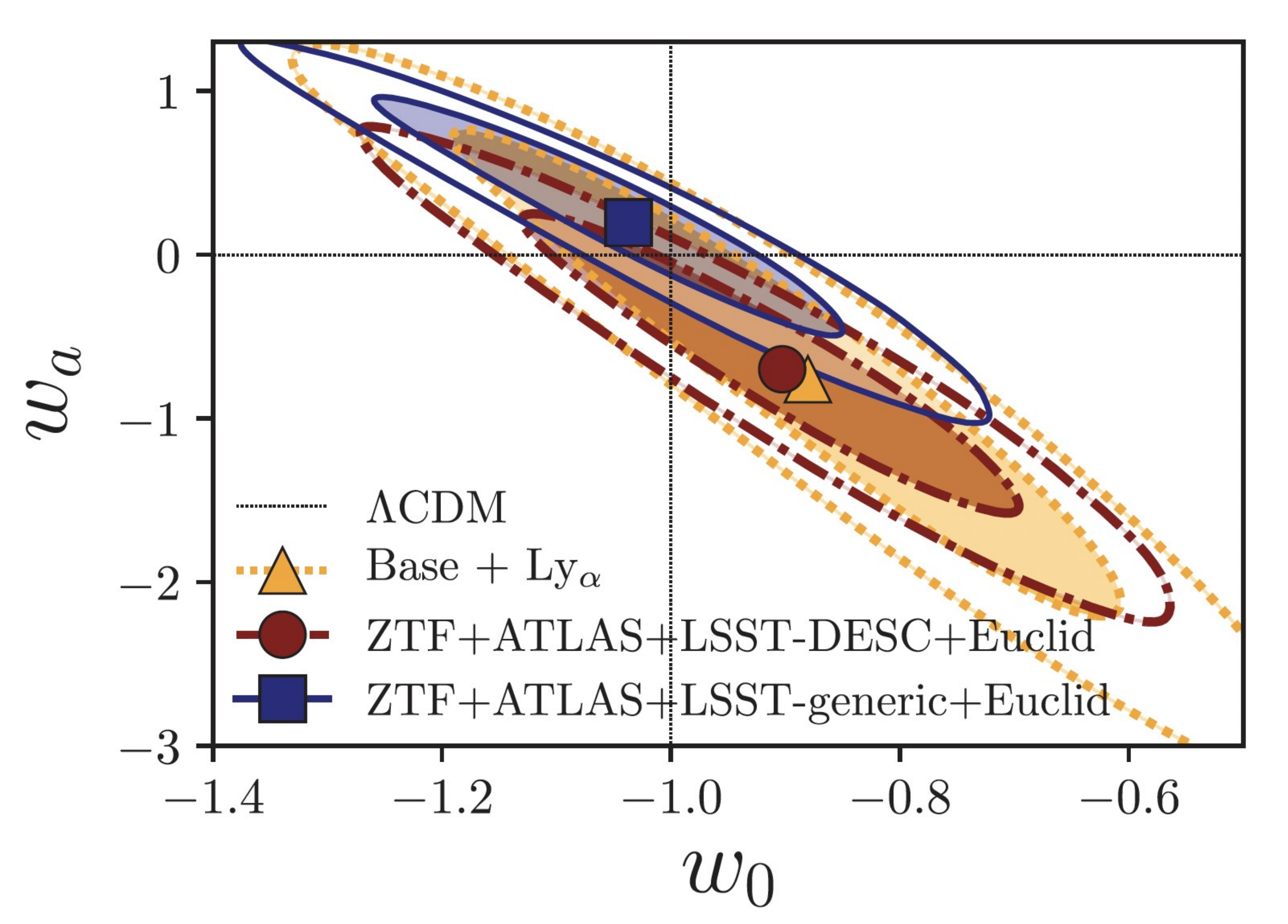


Inserra+2021

Superluminous Supernovae : Future survey projections
LSST , EUCLID, ...

→ Cosmology using SLSNe from LSST+EUCLID+ZTF+ATLAS...





Left: Predicted distribution of SLSNe I as a function of redshift. Bins are Δz = 0.1 for the LSST deep drilling fields SLSNe, while the Euclid rates, binned with a Δz = 0.5 (**Inserra+2018**), have been here resampled with a Δz = 0.1. A flat SLSN I distribution up to z ~ 0.3 from ZTF+ATLAS with a Δz = 0.1 bin size is also shown. Right: Constraints on the dark energy equation-of-state parameters *w0 and wa.*

Inserra+2021

Superluminous Supernovae : Classification of high redshift candidates with GTC

PROSPECTIVE with GTC in LSST and in EUCLID surveys:

→ To build a high redshifts (z>1) larger SLSNe sample will be challenging obviously !

- At redshifts z ~ 1, assuming an absolute magnitude of about -22 mag AB, a typical SLSN will have an apparent magnitude close to m=21.5 mag AB.
- **Tests to push up the limits to classify SLSNe up to redshift ~ 2.5** with low resolution spectroscopy from ground facilities.
- Using GTC, we plan to develop programs to discover and follow-up LSST-selected SLSNe in this higher redshift range.
- Euclid photo-z + galaxy SED (if available) will help select candidates

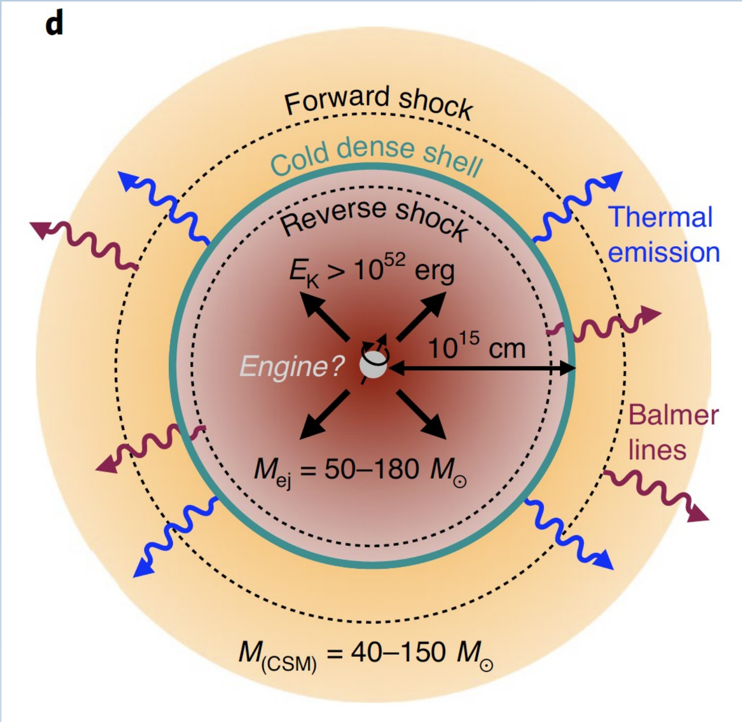
Superluminous Supernovae and magnetars

Progenitor:
→ Very massive stars (single or binary systems ?)

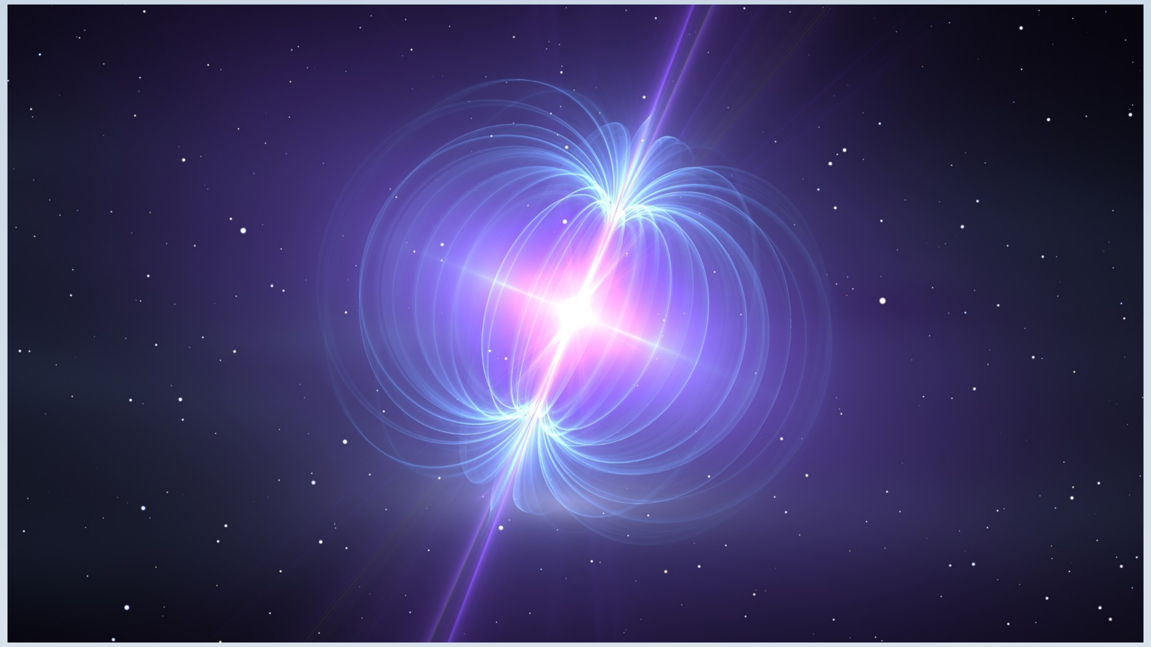
Type of explosion:
→ Core-collapse

Product of explosion and processes sustaining the explosion ?
→ Magnetar dipole spin-down ?
→ Black-hole ?
→ and / or interaction with circumstellar matter ?
Previously ejected matter from progenitor.

Magnetars→ second part of the talk

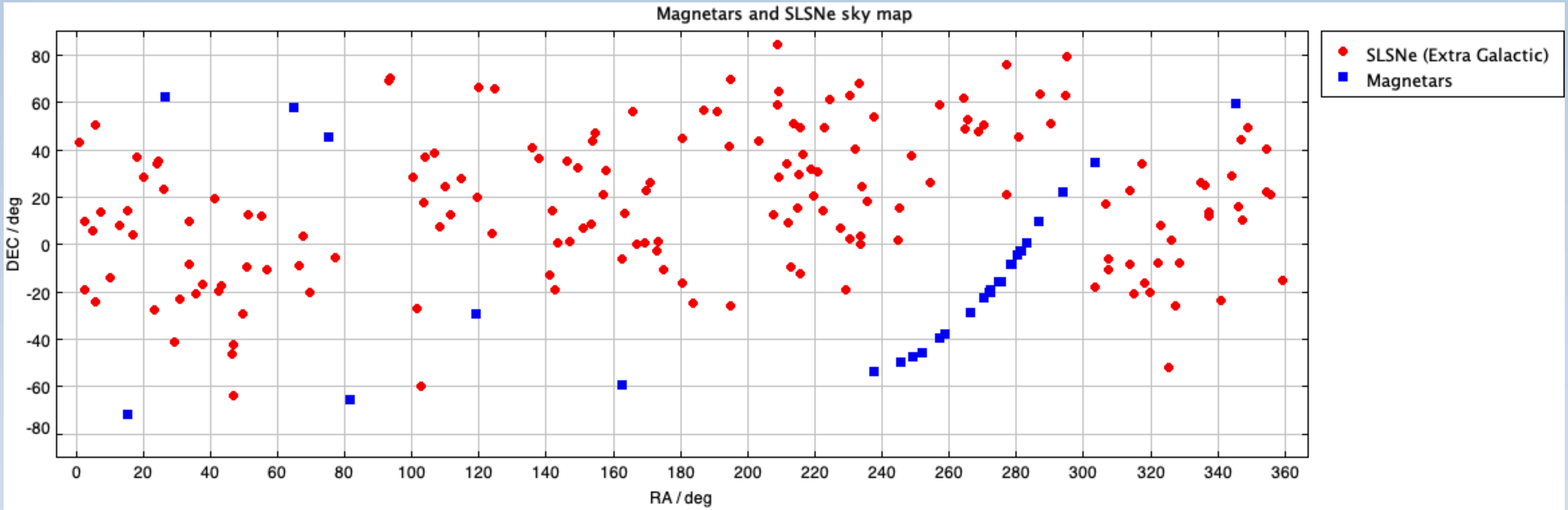


Schematic model for SN 2016aps by Nicholl (2020).



An artist's impression of a magnetar ©quantamagazine

Magnetars: location of SLSNe and Magnetars on the sky

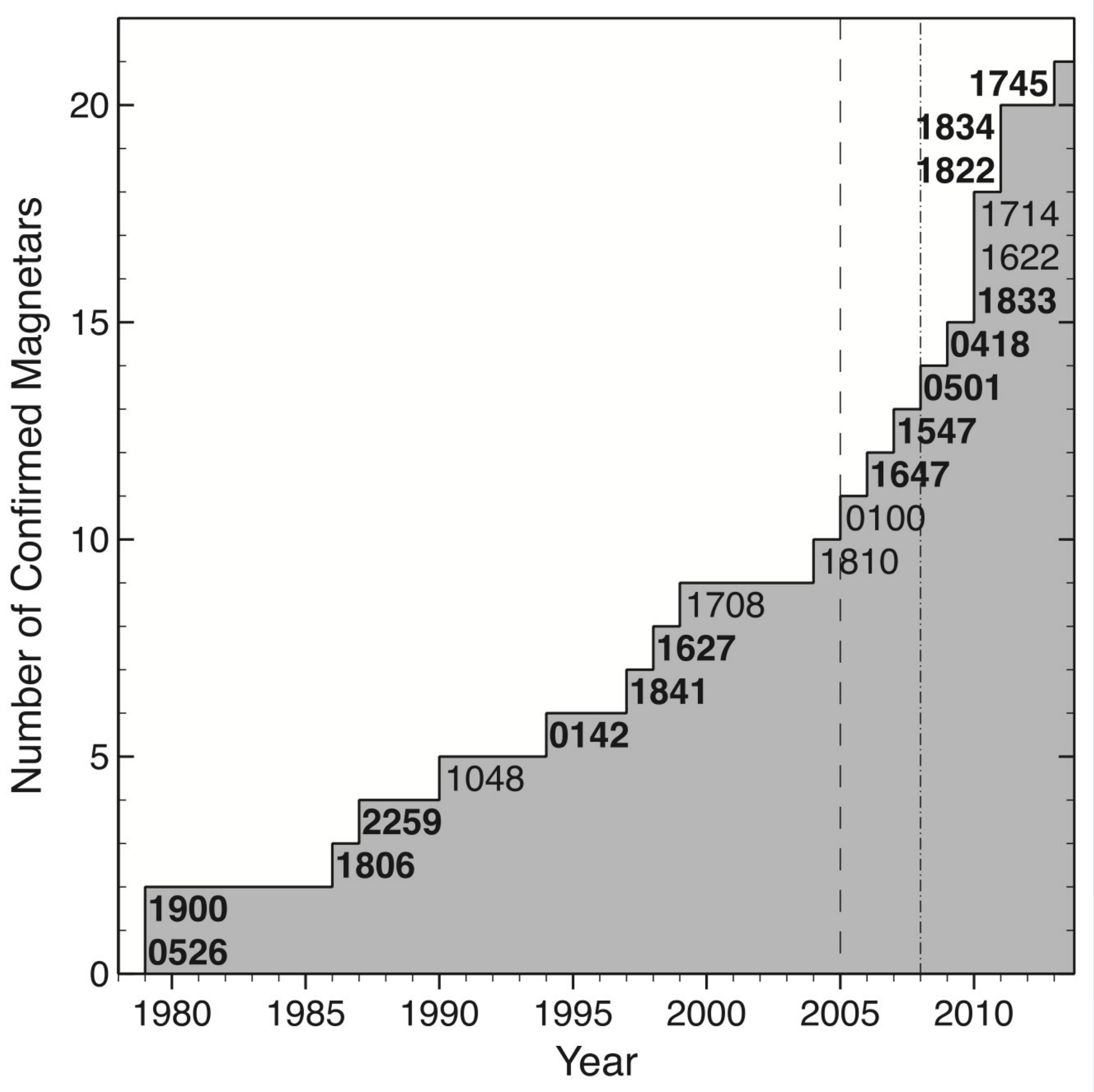


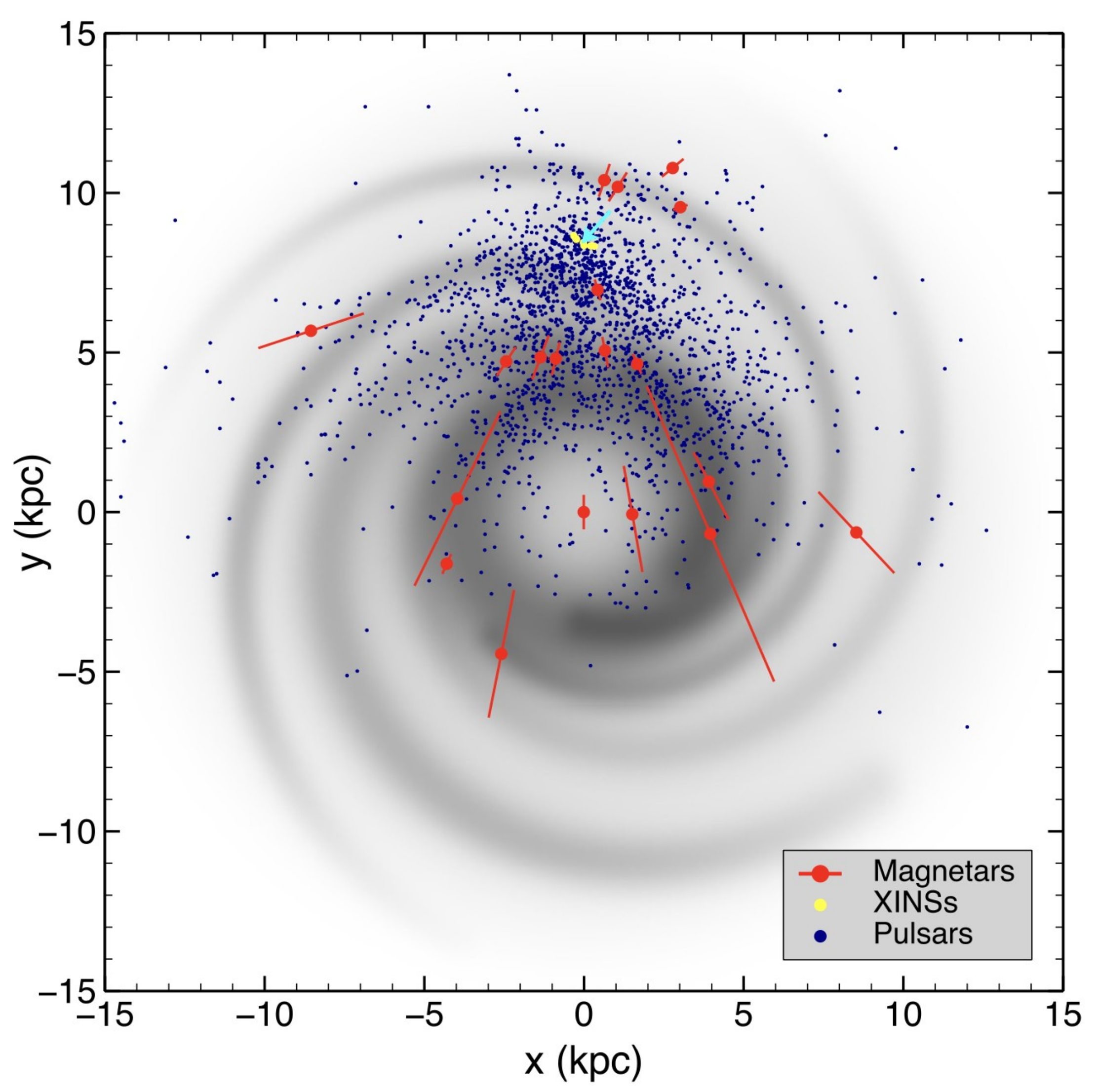
→ Magnetars (Mainly Galactic) mainly detected in the Plane-Of-Sky (McGill catalog)
→ SLSNe (Extra Galactic) more easily detected out of the Plane-Of-Sky

SLSNe coordinates retrieved from TNS for 166 H-poor SLSNe
0.03 < redshift < 0.67

Magnetar coordinates from Olausen & Kaspi (2014)
1.6 < distance < 62.4 pc + in LMC

Magnetars: McGill catalog from McGill pulsars group

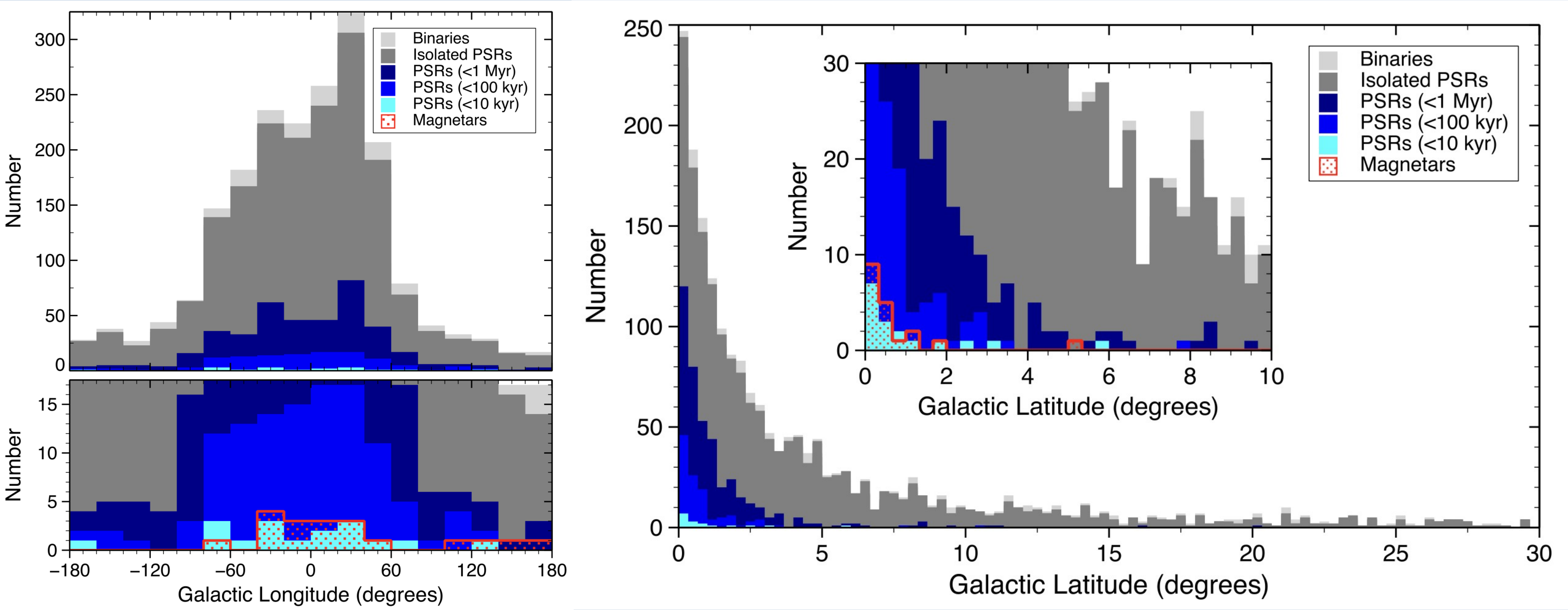




Left: detections from 1979. Middle: Galactic distribution. Right: Histogram as a function of Gal. Longitude
This catalog contains the current information available on 30 magnetars:
→ 16 soft gamma repeaters or SGRs (12 confirmed, 4 candidates)
→ 14 Anomalous X-ray pulsars or AXPs (12 confirmed, 2 candidate)
PSRs = Pulsars; XINSs = X-ray isolated neutron stars.

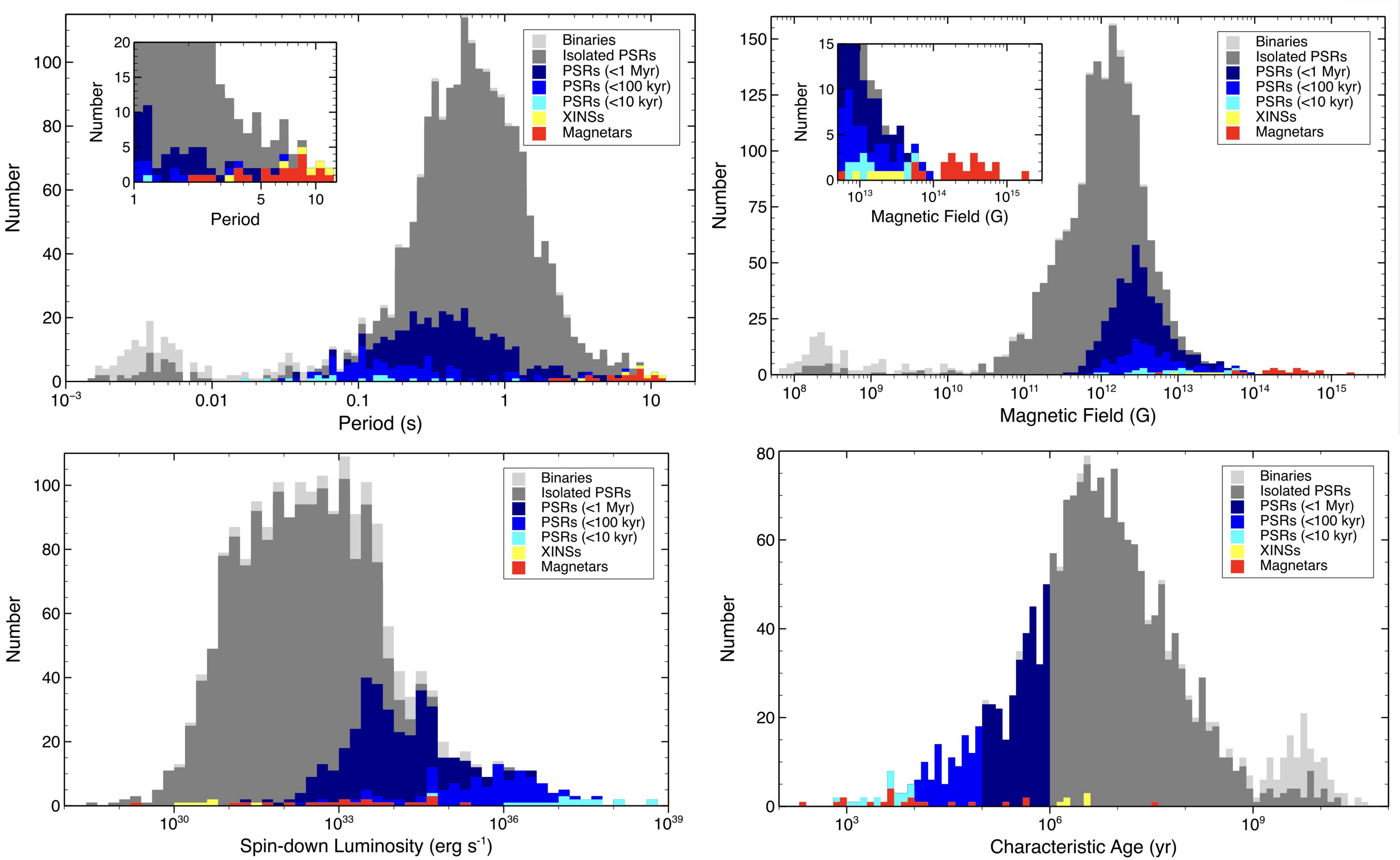
Olausen & Kaspi (2014)

Magnetars: McGill catalog from McGill pulsars group



Galactic Distribution: Galactic magnetars are mainly located in the Galactic plane **Olausen & Kaspi (2014)**

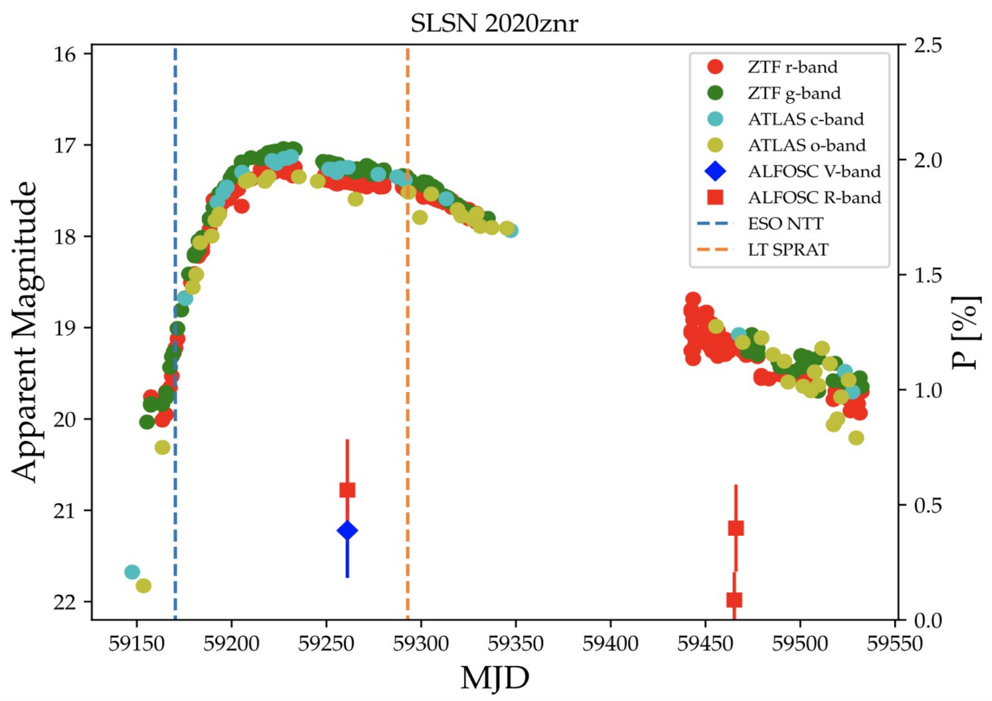
Magnetars: McGill catalog from McGill pulsars group

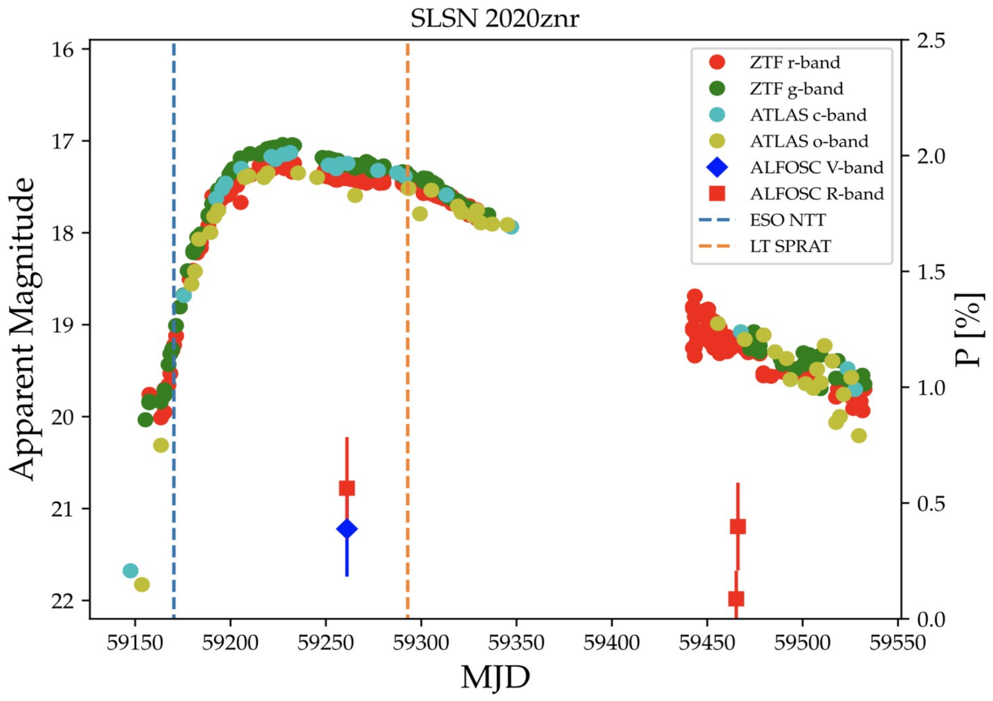


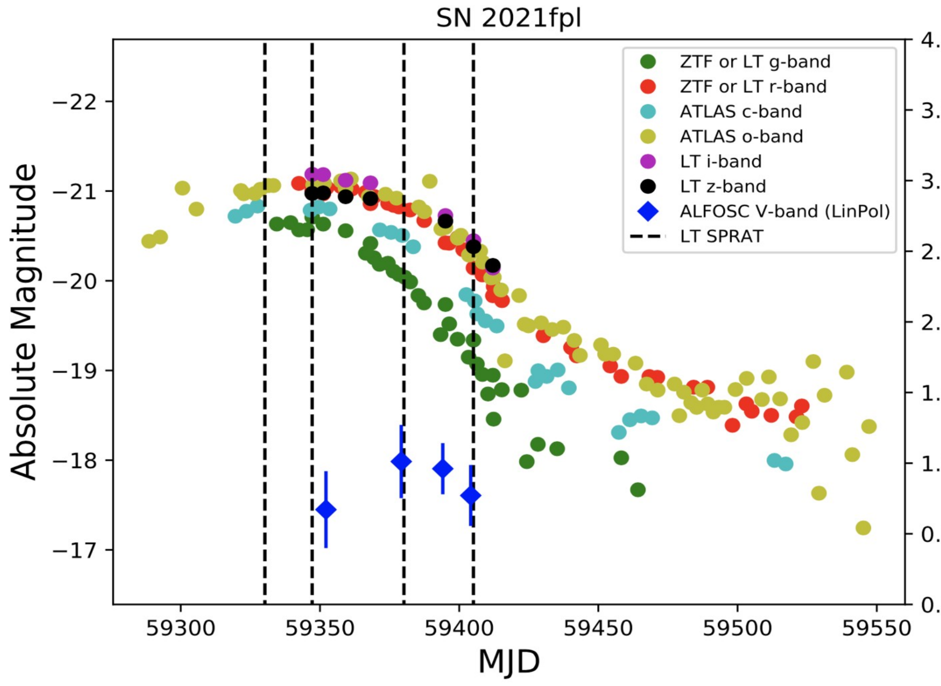
Physical Characteristics

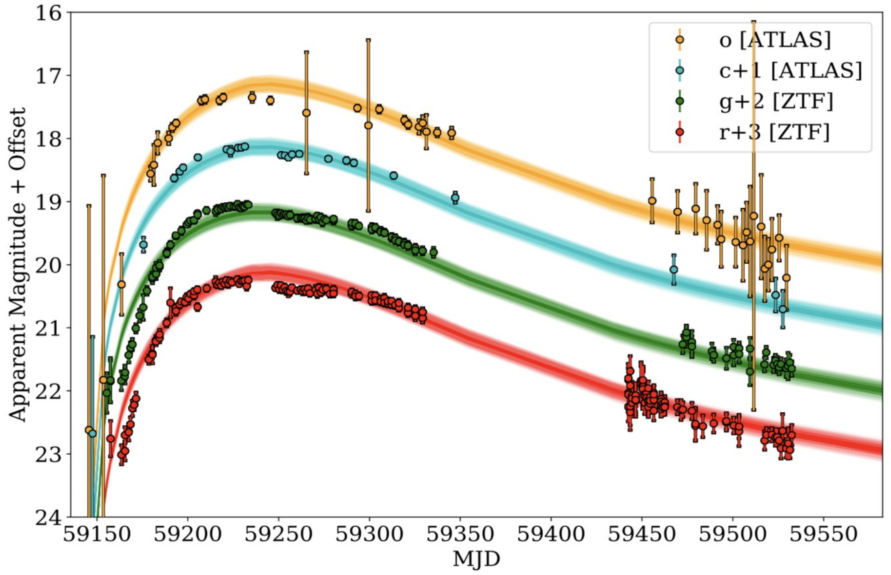
Olausen & Kaspi (2014)

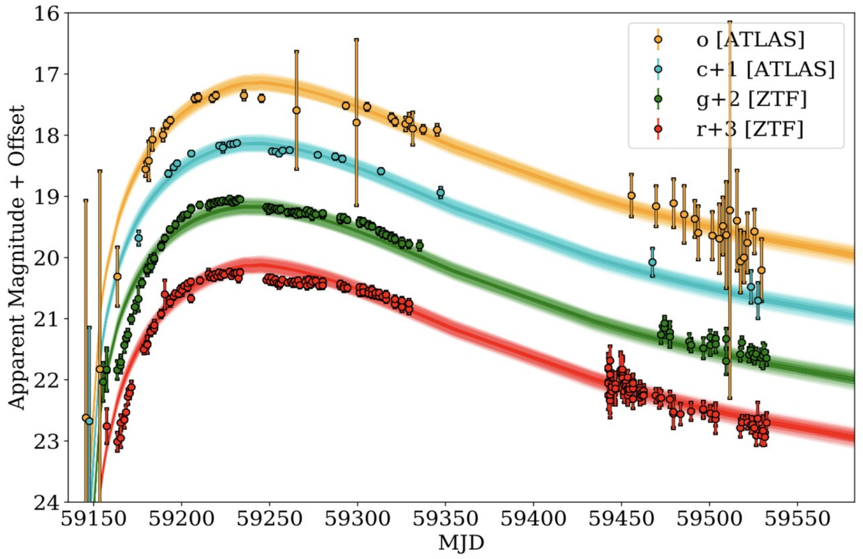
First results from our surveys: magnetar driven light curve modeling

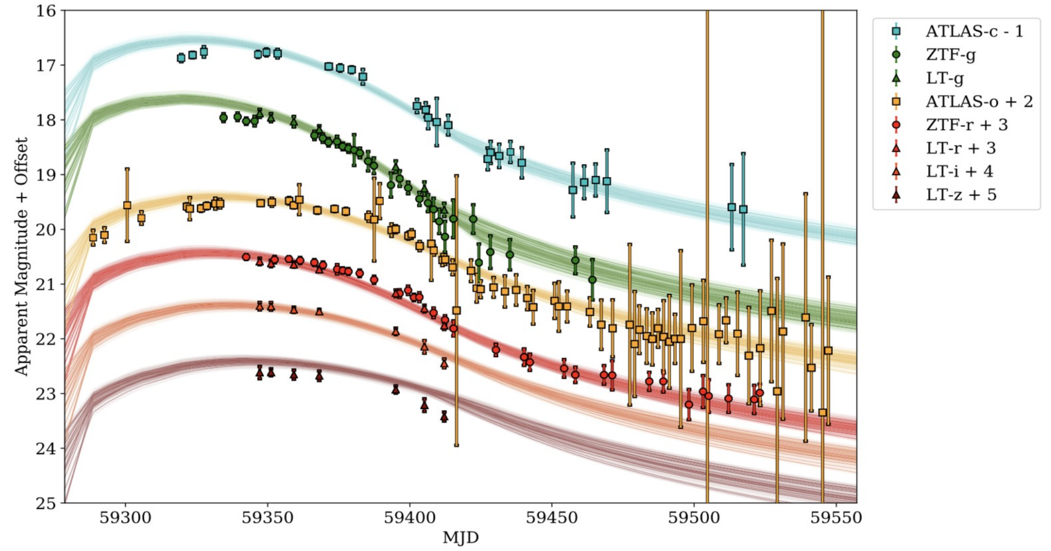












W Type –Slow Evolver **W Type –Slow Evolver** **15bn Type –Fast Evolver**

→ Magnetar driven light curve (LC) modeling by Conor Omand

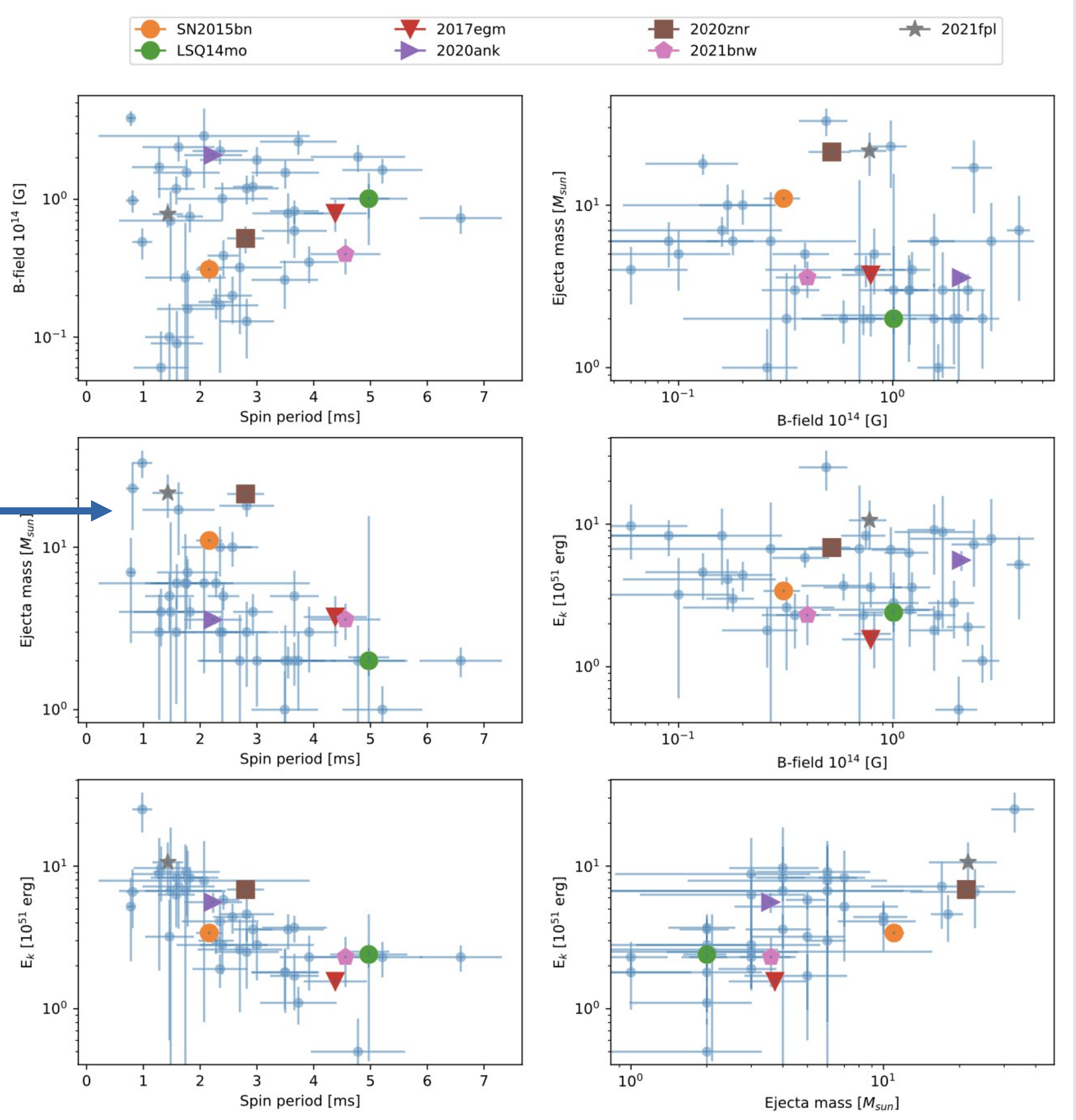
→ We conclude W-type and 15bn-type SLSNe-I may have different polarization properties

Poidevin+2022 **Poidevin+2023**

Results from SLSNe LCs modeling with MOSFiT assuming a magnetar model

Strong engines:

SN 2021fpl (15bn type)
SN 2015bn (15bntype)
SN 2020znr (W type)



Magnetar model parameters:

~1 < spin-period < 8 [milliseconds]
0.06 < B < 3 [10^{14} Gauss]
0.6 < M_{ejecta} < 30 [$M_{\odot}$]
0.5 < E_k < 3 [10^{51} erg]

Nichol+2017, Poidevin+2023

Magnetars: more facts, questions and concluding remark

- **Magnetars** strong magnetic fields decay after about 10,000 years, after which activity and strong X-ray emission cease (Kaspi 2010) / **new SLSNe** could be new fresh formed magnetars.
- Given the number of **magnetars** observable today, one estimate puts the number of inactive magnetars in the Milky-Way at 30 million or more (Kaspi 2010)
- Multi messenger connection between Gamma-ray Busrts (**GRBs**) and **SLSNe** (Prasanna+2023)
- Multi messenger connection between Fast Radio Bursts (**FRBs**) and **magnetars** ? JIVE detection of a magnetar in a globular cluster in M81: FRB 20200120E originates from a highly magnetized neutron star formed either through the accretion-induced collapse of a white dwarf, or the merger of compact stars in a binary system (Kirsten+2022).
- **Magnetars** channel(s) formation ?
- Will future experiments allow to test dark matter detection with **SLSNe** remnants if **magnetars** ?
- On the other way around: if **dark matter** (photon-axion conversion lines) can be detected in close-by **magnetars** will it be possible to test the nature of **SLSNe** central engines ?
- SKA, Rubin Observatory, LSST, ….

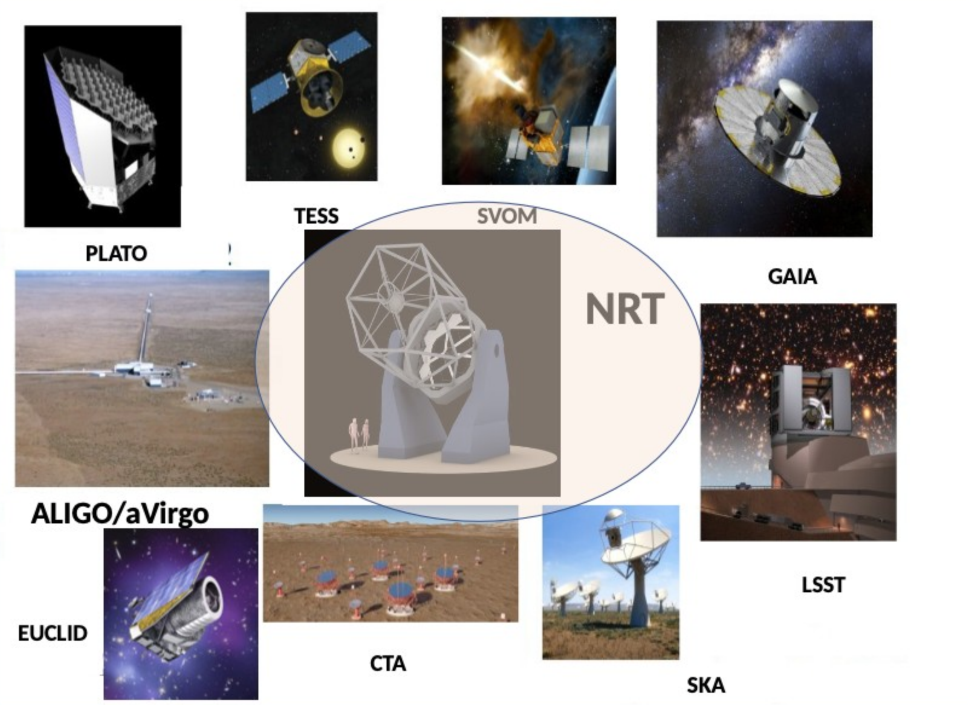
→ more bibliography, more discussions, more thinking, more ideas, more experimentations, ...

Thank You !

ORM future facility useful for LSST alerts follow-up: New Robotic Telescope

New Robotic Telescope (NRT) in a nutshell

- International collaboration to build the largest (∅ 4 m) entirely robotic telescope in the world.
- Based on the success of the LT and GTC.
- Standard for future telescopes.
- Quick response (on target in 30 s).
- FoV ~ 5´- 30´ diameter.
- Sited at ORM in La Palma (Spain).
- Full optical and near IR ranges. Focal stations at direct and folded Cassegrain.
- Optimal image quality dominated by seeing (ORM median ~ 0.7´´).



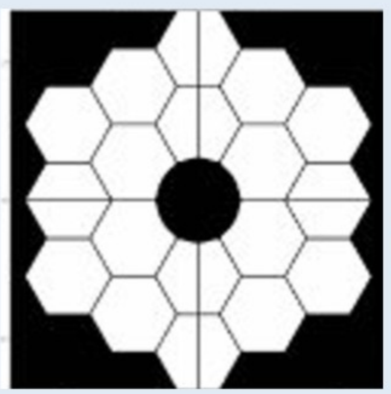
SCIENCE CASES

Detection, classification and characterization of

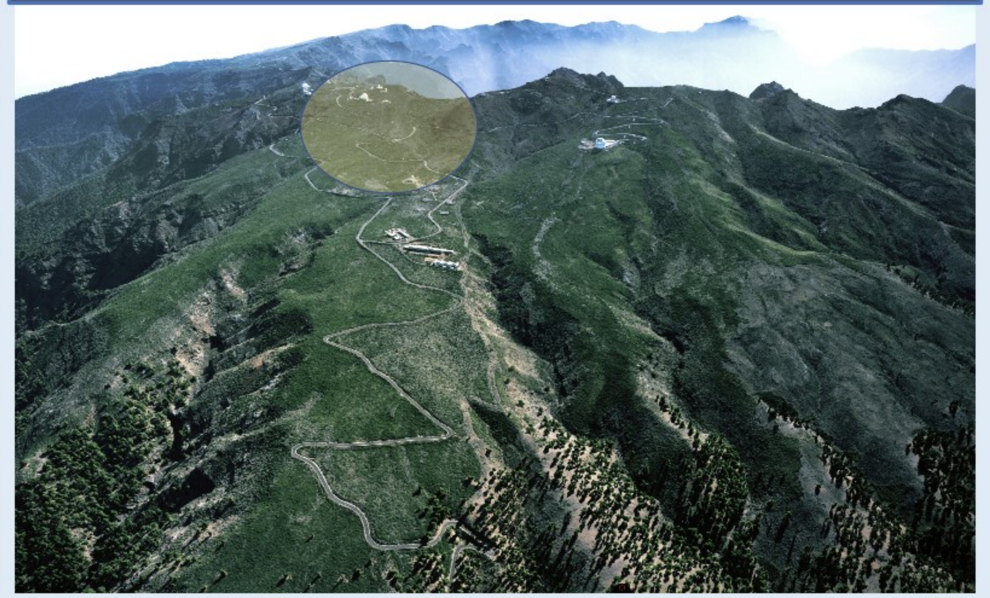
- Gravitational waves
- Gamma Ray Bursts
- Supernovae
- Exoplanets
- Tidal Disruptions Events
- . . .

SCHEDULING

- 2022 -2024 detailed design
- 2025-2026 Construction
- 2027 first light
- 2029 full operation



Roque de los Muchachos Observatory La Palma (Spain)



OPTICS

- Ritchey–Chretien (f/2 prime focus, f/10 total)
- Primary mirror formed by 18 hexagonal segments (1 m each)

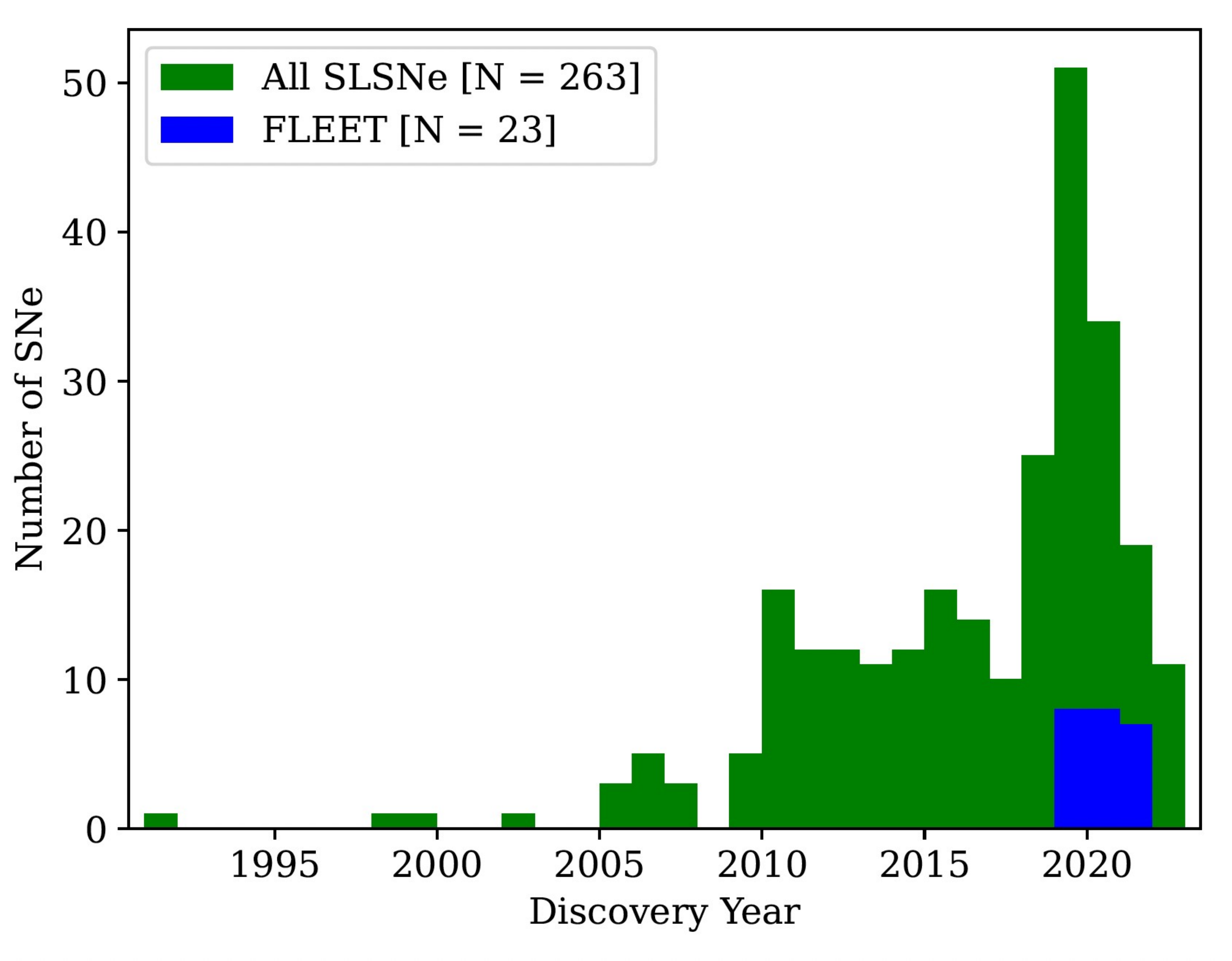
References

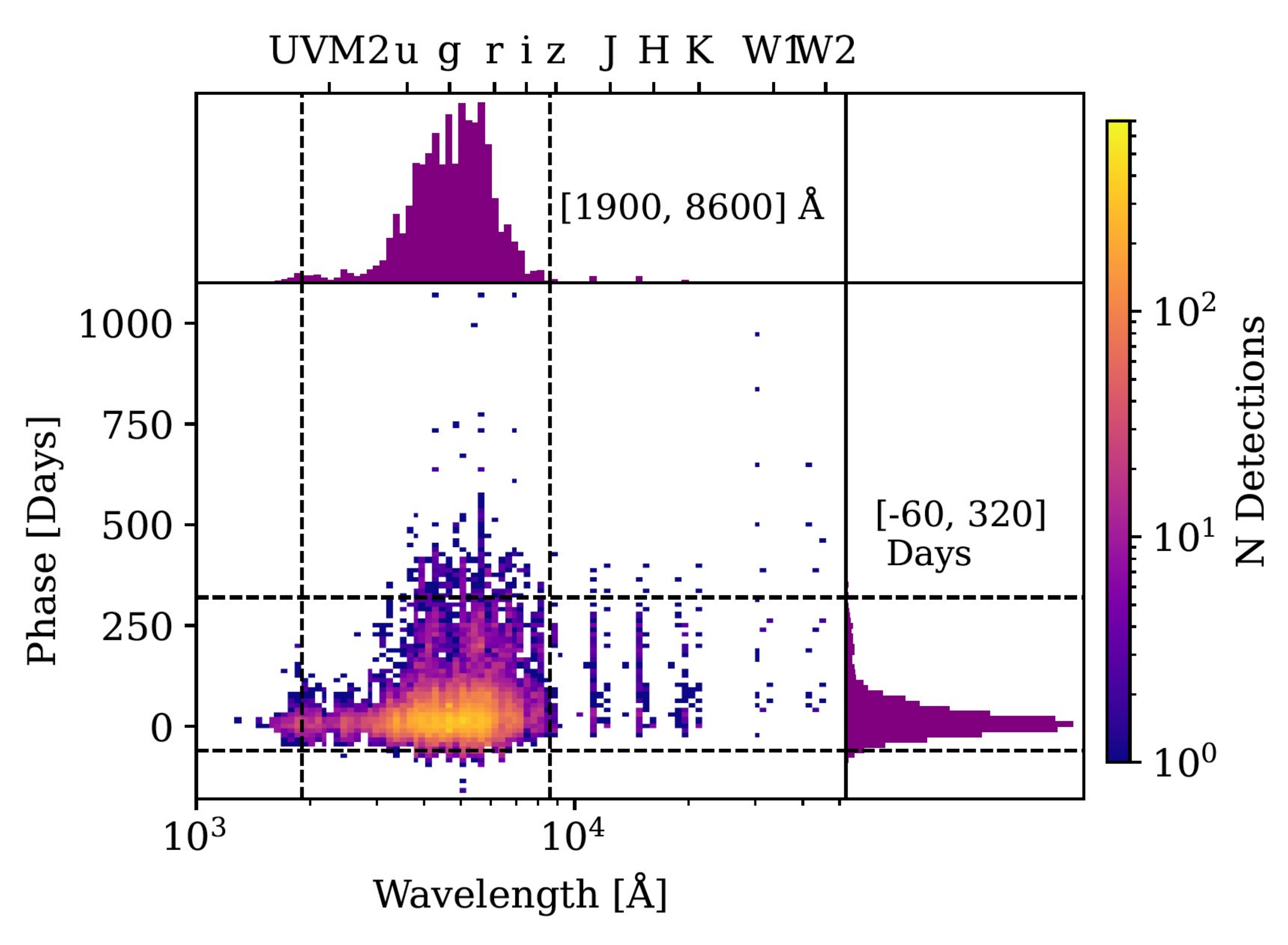
1. **Bento, J. et al.** Software architecture and development plan for a 4m fully autonomous observatory (New Robotic Telescope. Proc. SPIE 12189, Software and Cyberinfrastructure for Astronomy VII, 121890C
2. **Gutiérrez, C. M. et al.** The 4 m New Robotic Telescope project: an updated report. 2021 RMx. A.C. 53, 8 (2021)
3. **Harvey, E. J.** New Robotic Telescope optical design", Proc. SPIE 12182, Ground-based and Airborne Telescopes IX, 121821Z
4. **Rodríguez-Pereira, C. et al.** Update and preliminary performance analysis of the New Robotic Telescope structure", Proc. SPIE 12182, Ground-based and Airborne Telescopes IX, 121823R

Material provided by C. M. Gutiérrez

Superluminous supernovae: observed sample

H-poor = type I SLSNe sample

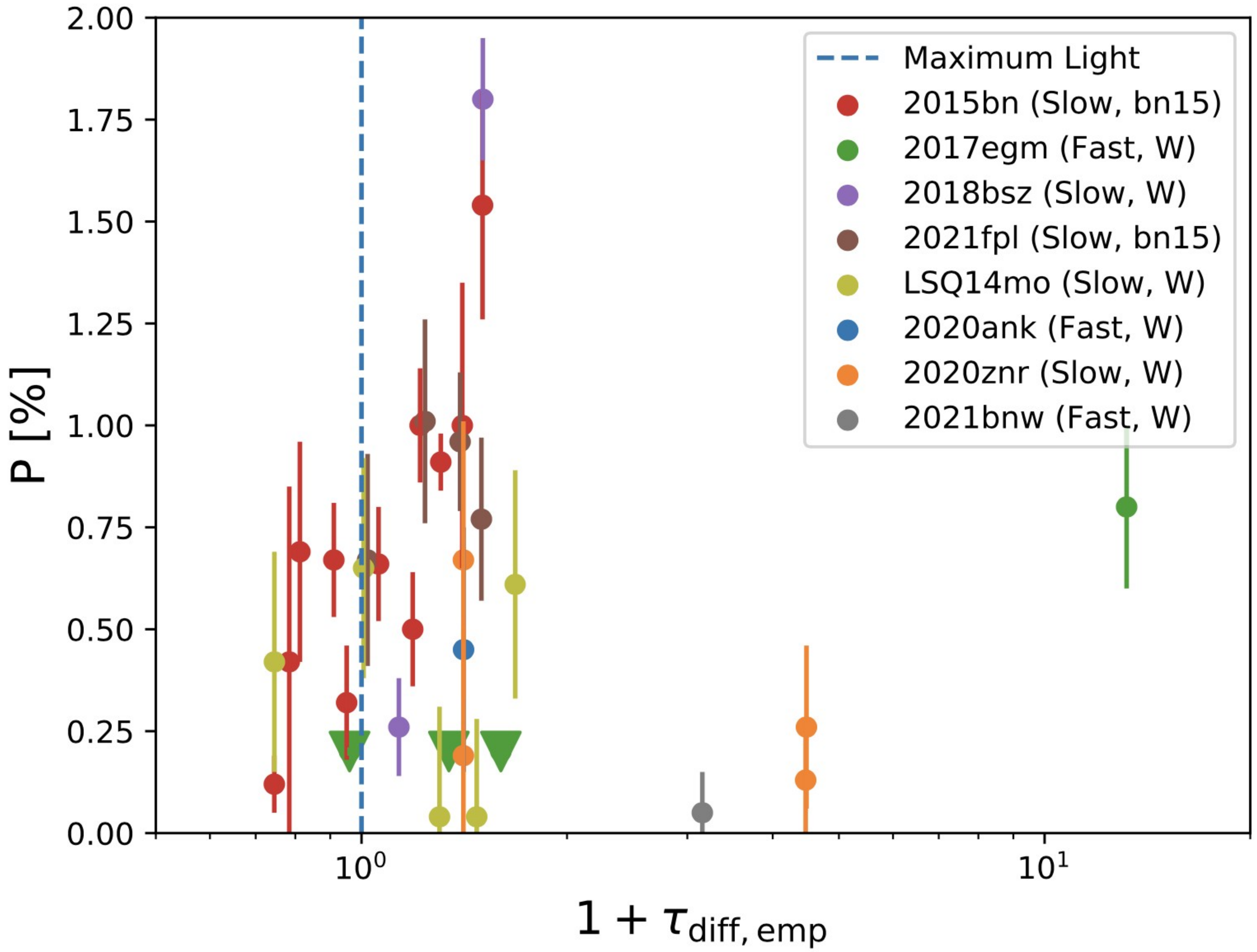




Left: Histogram of the discovery year of all SLSNe. Right: 2D histogram of rest-frame phase in days versus rest-frame wavelength for all photometric measurements of the full sample of SLSNe.

Gomez+2024

Results in context



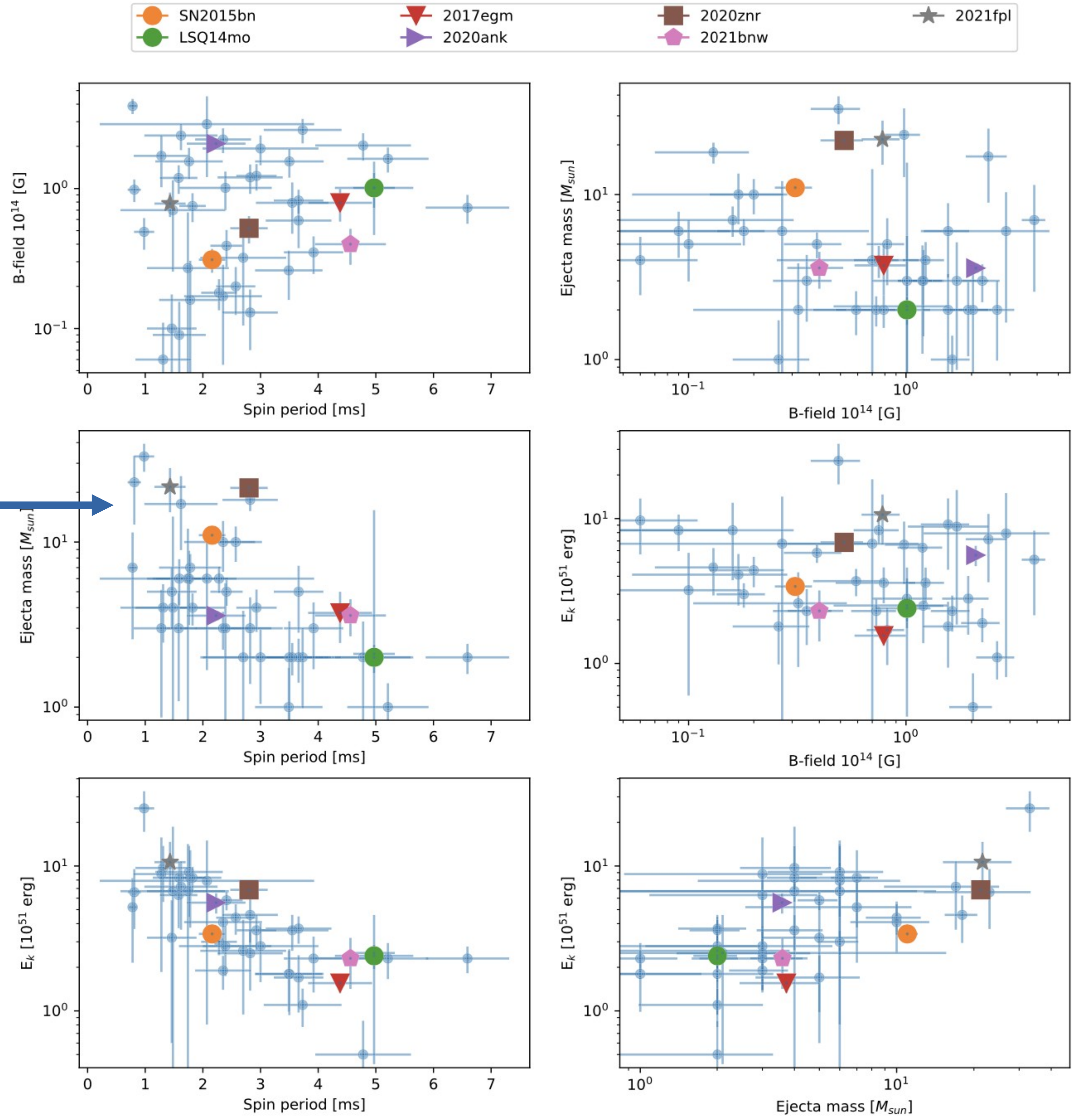
$T_{diff,emp}$ =
Empirical diffusion time scale = phase with respect to maximum light / rising time-scale

Lack of data at $T_{diff,emp} > 1$ and before nebular phase

Results from modelling With MOSFiT using a magnetar model

Strong engines:
SN 2021fpl (15bn type)
SN 2015bn
SN 2020znr (W type)

SLSNe produced by stronger engines could imply more mixing and clumping in the ejecta, and possibly additional sources of asymmetry in the system, than for SLSNe produced by weaker engines (Suzuki & Maeda 2021).

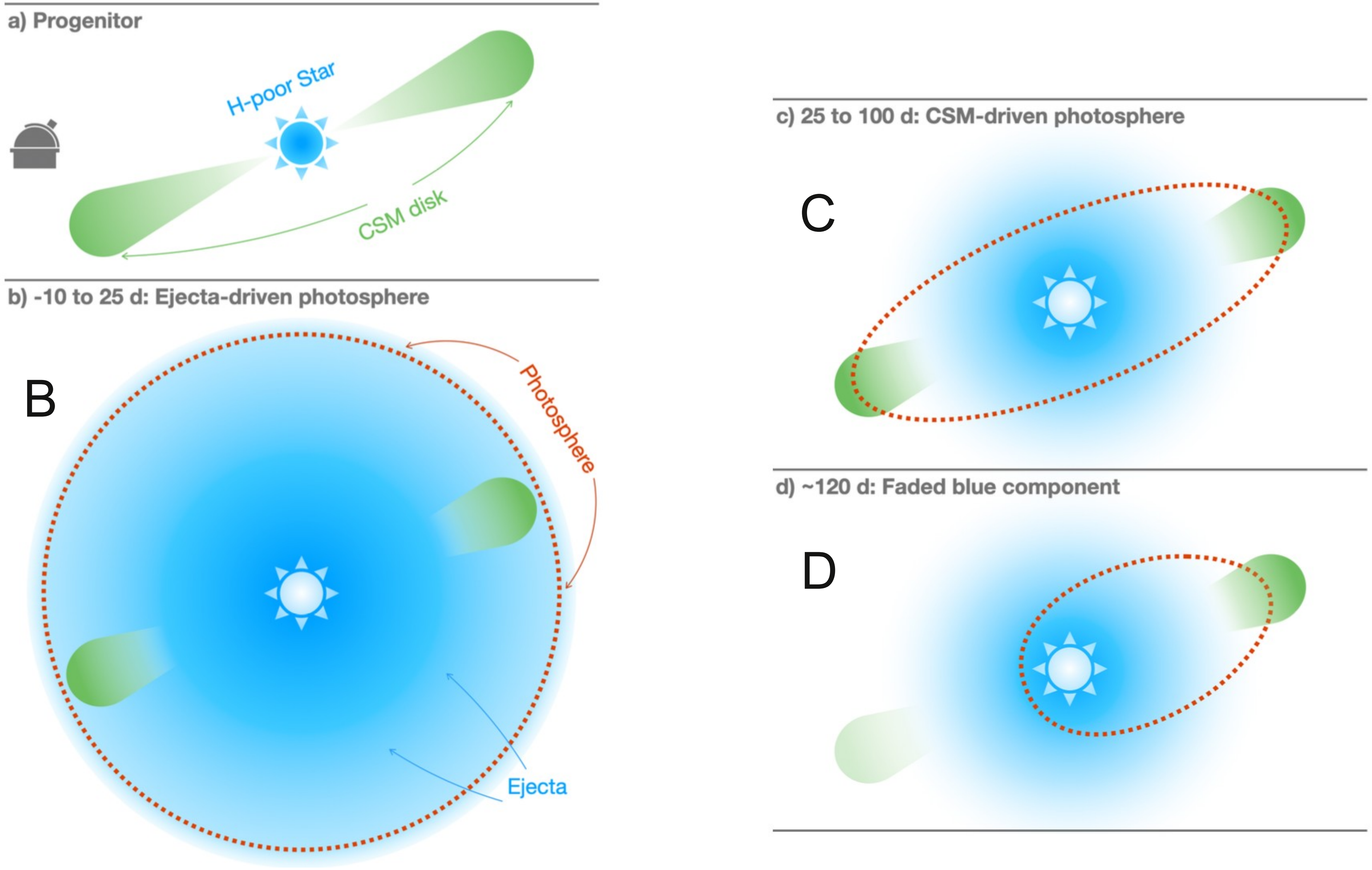


Other case studies: SN 2017cgi and SN 2018bsz

SN 2017cgi (complex polarization evolution)
SN 2018bsz (Hα emission emerging at ~ 30 days)

Hints of interactions with the CSM using polarimetry

Pursiainen+2022
Pursiainen+2023



B) Upon the explosion the ejecta quickly overtakes a significant part of the disk hiding the CSM emission lines. Only the faint blue component is possibly present. C) As the ejecta photosphere recedes, the CSM starts to re-emerge and multi-component emission becomes visible. At this stage the photosphere is CSM-driven. D) CSM on the near-side has completely re-emerged causing the photosphere to recede and the blue component to fade.