The transient sky in the era of multimessenger astronomy

G. Valerin & I. Salmaso on behalf of the Padova SN group

SN 2023ixf
Asiago Schmidt telescope
Courtesy of A. Reguitti

STAFF

Enrico Cappellaro

Laura Greggio

Stefano Benetti

Andrea Pastorello

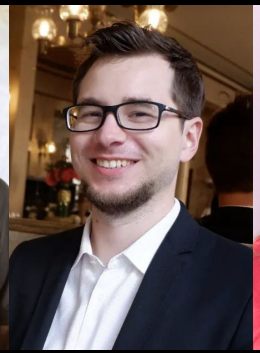
Lina Tomasella

Nancy Elias-Rosa

POST-DOC

Andrea Reguitti

Giorgio Valerin



Irene Salmaso

MASTER

Francesco Guidolin

Science Interests

- Classification program
- SNe Iax
- Faint Core-collapse SNe
- Progenitor study
- Rates
- Gap Transients
- Interacting SNe
- Radio Transients
- Multimessenger Astronomy

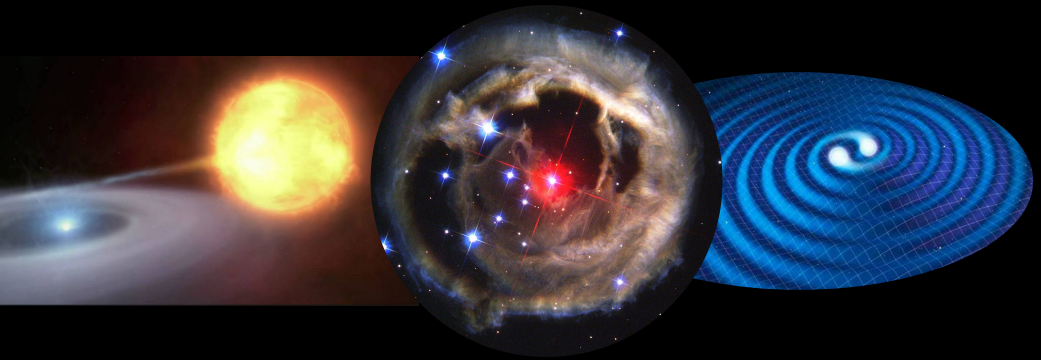
Padova-Asiago Supernova Group

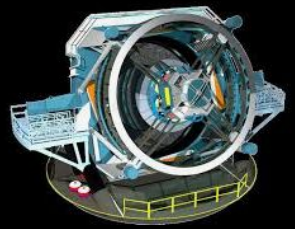
Science Interests

- 🔭 Asiago classification program
- ⚡ Peculiar thermonuclear SNe
- 💥 Faint Core-collapse SNe
- 🤳 Archival search and progenitor study
- 💫 Gap Transients (ILRTs, LRNe, LBVs)
- ☁️ Interacting SNe
- 📡 Radio Transients
- 💬 Multimessenger Astronomy (GW, neutrinos)

Collaborations and future projects

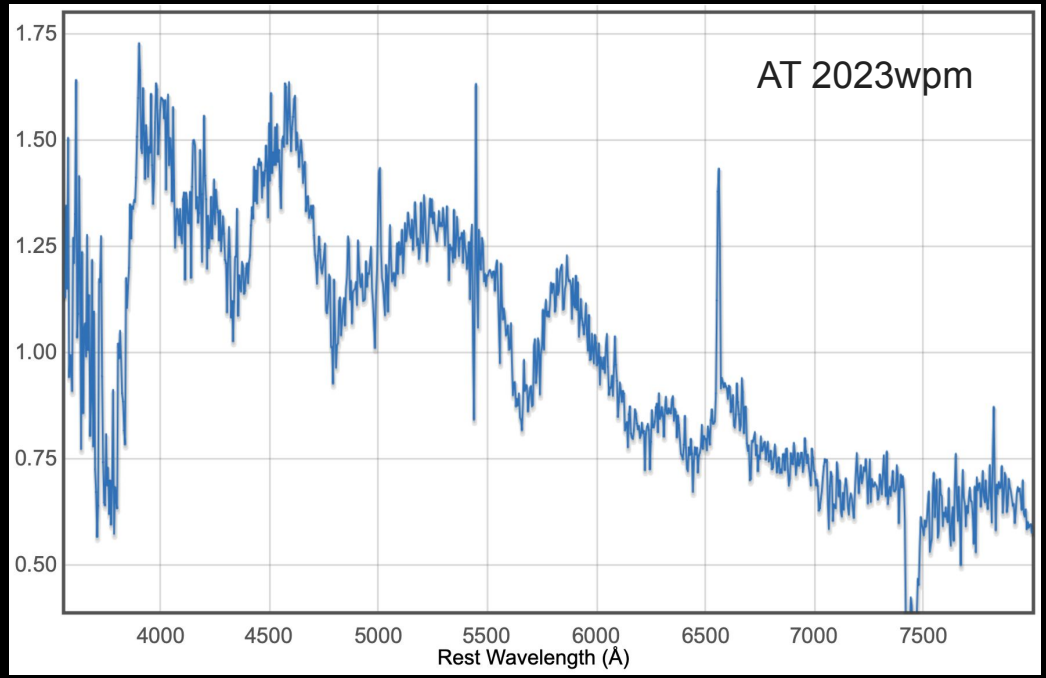
- NUTS2, ePESSTO+
- ThunderKAT
- ENGRAVE, GRAWITA
- Einstein Telescope
- LGWA
- EUCLID
- LSST
- SOXS





Transient classification program

Program started in 2013
(Tomasella et al. 2014)



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

Transient classification program

ATel & Astronotes

≡ AstroNote 2023-308

AstroNotes | Stats

2023-11-15 09:04:12 Type: Object/s-Discovery/Classification Bibcode: 2023TNSAN.308....1T

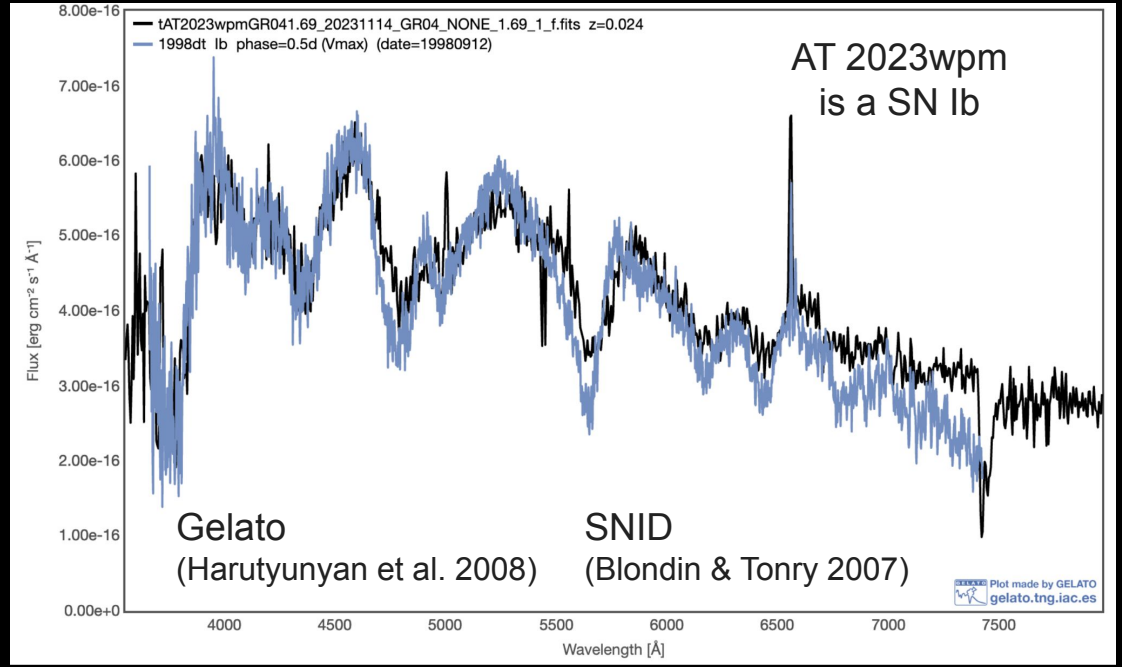
Asiago spectroscopic classification of optical transient

Authors: Stefan Taubenberger, Christian Vogl, Simon Huber, Stefan Schuldt, Jana Grupa, Allan Schweinfurth (MPA), Lina Tomasella, Stefano Benetti, Enrico Cappellaro, Andrea Pastorello, Irene Salmaso, Andrea Reguitti (INAF OAPd)

Source Group: Padova-Asiago

Keywords: Supernova, Spectroscopy, Optical

Abstract: The Asiago Transient Classification Program (Tomasella et al. 2014, AN, 335, 841) reports the spectroscopic observation of AT2023wpm (ZTF23abovaur) in LEDA 1656929



- ~650 classified transients in 10 yrs
- Up to ~38% of newly discovered SNe classified from Asiago in the first years
- Second wind with RoboCop?

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

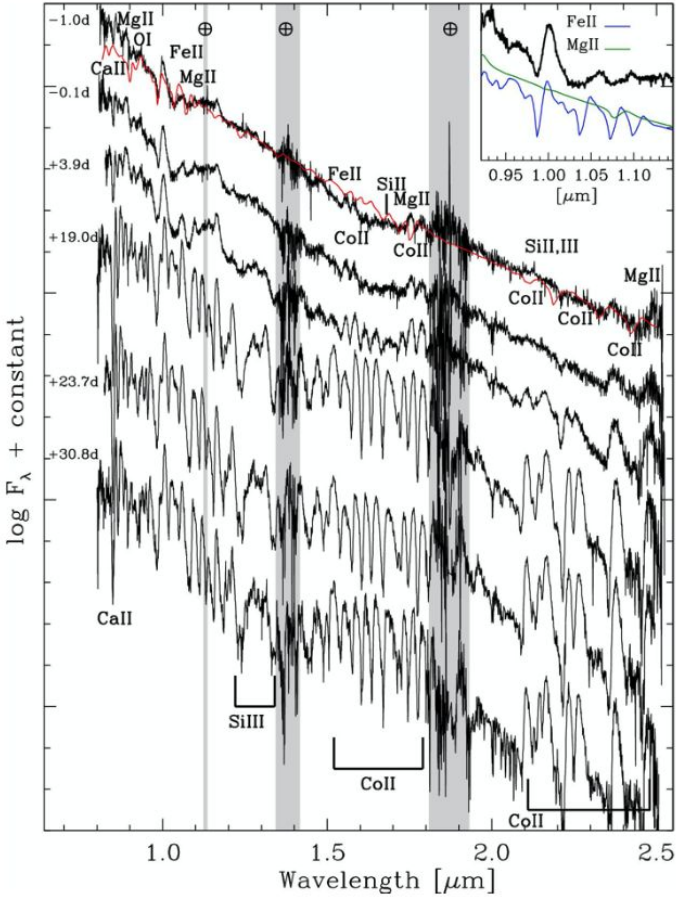
⚡ Thermonuclear SNe

Iax

- Low luminosity (-19 mag < M_V < -13 mag), fast rise to maximum light (~10 to 20 days)
- Low velocity ejecta (~2000-6000 km/s)
- C/O WD + He-star good progenitor candidates (but diversity within the class: multiple progenitors/explosion mechanism?)

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

Tomasella et al. 2016

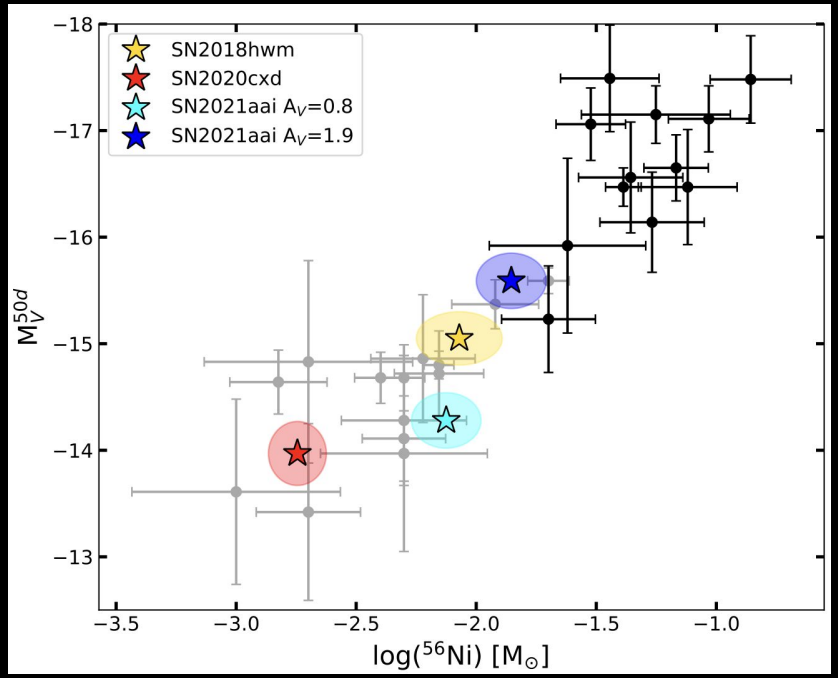


Faint core-collapse SNe

The most common core-collapse outcome is a SN IIP or IIL, but there is a variability within the class

- -18 mag < M_V < -13 mag
- 10^{-3} $M_\odot$ < M(^{56}Ni) < 10^{-1} $M_\odot$
- 10^{50} erg < E_{kin} < few 10^{51} erg

Correlations between parameters suggest that such variability is linked to the mass of the progenitor star



Valerin et al. 2022

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

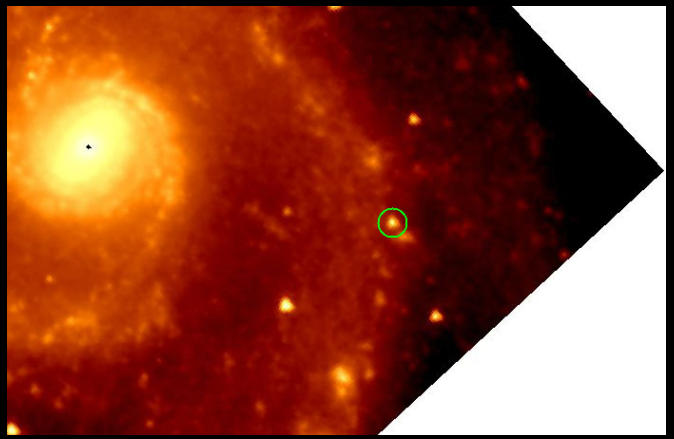
🤰 Archival searches: **Progenitors and their variability**

Search science archives for pre-explosion images

Both in the Optical (*HST, CFHT, DES, ESO, NOAO…*)

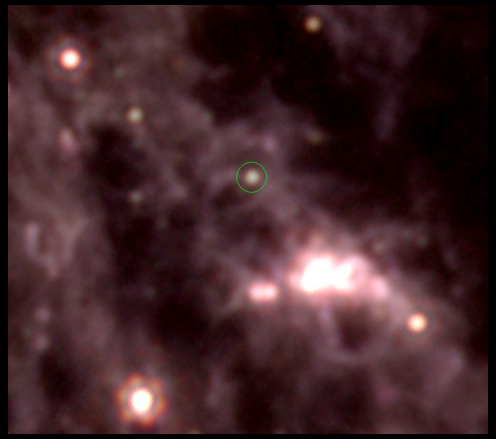
And in the MIR (*JWST, Spitzer, WISE*)

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

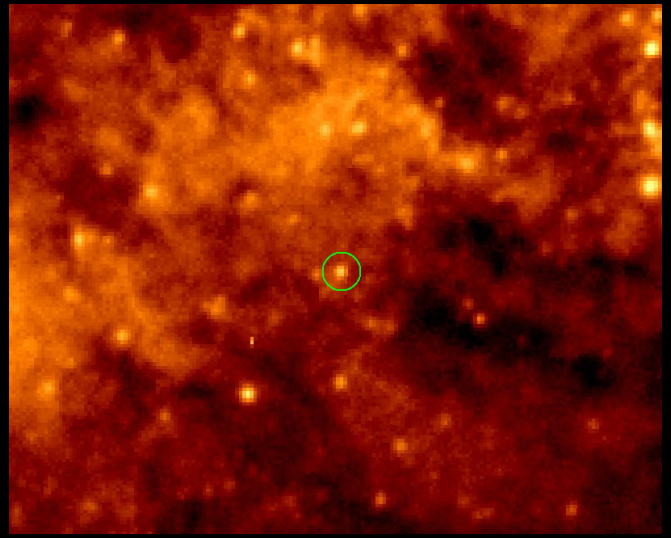


Spitzer image of AT 2019abn in M51

AT 2019abn detected by JWST/MIRI



Progenitor of AT 2021biy in CFHT data, Cai et al. 2022a

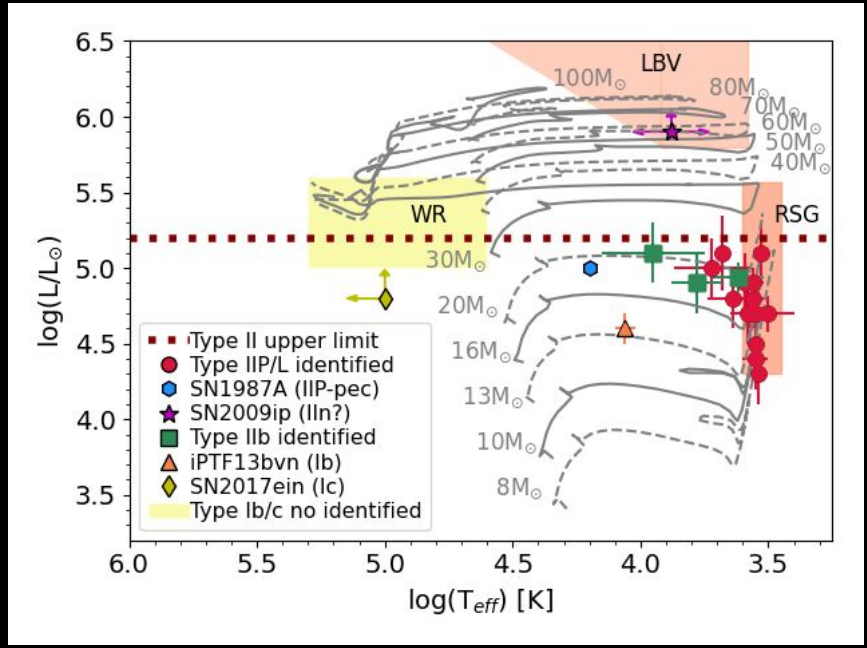


Fate of massive stars

Constraints on the progenitors of CC-SNe

Connect the SN explosion with the stellar evolution

- Why are we not detecting massive (>17 $M_{\odot}$) red-supergiants SN progenitors?
- Which is the fraction of stripped envelope SNe in binary systems?
- Which are the most massive stars that end their life as a SN?

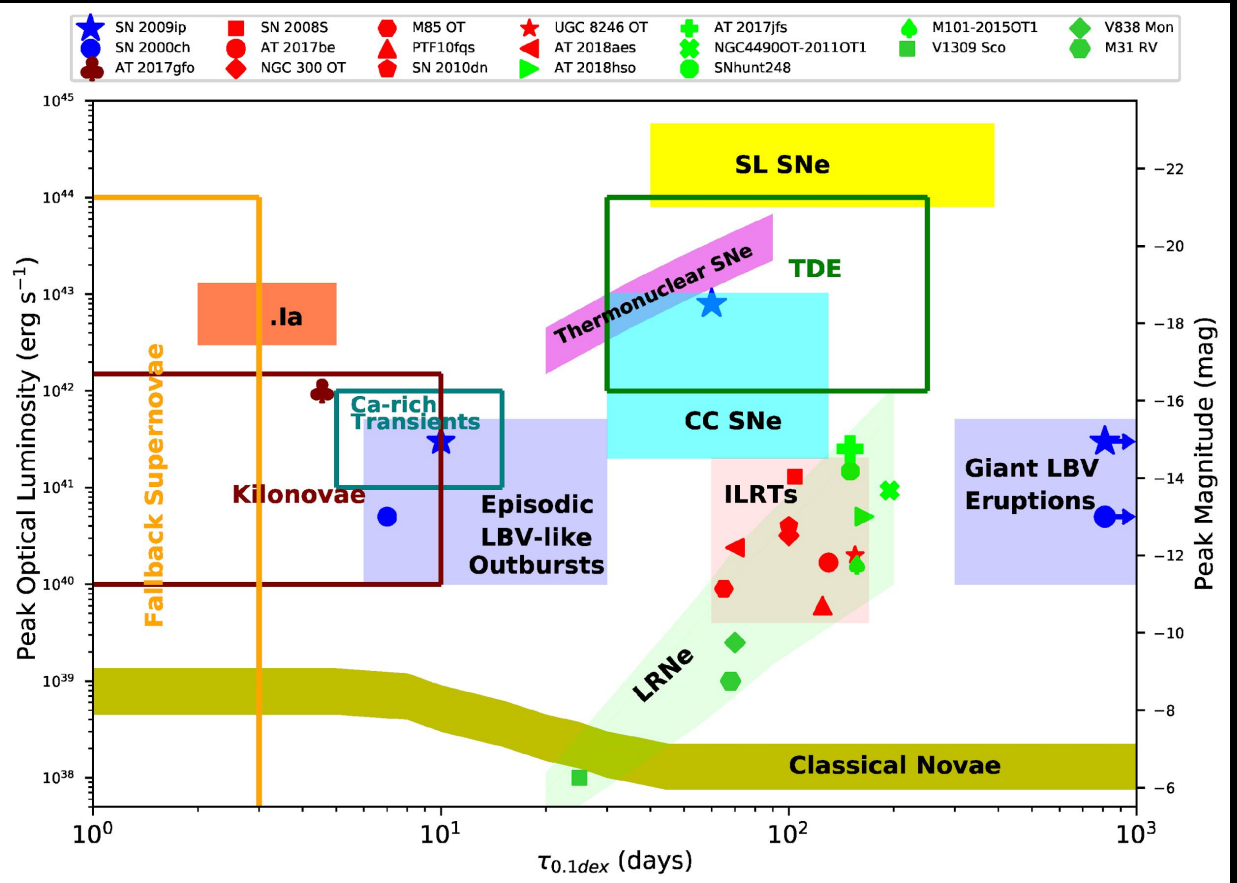


NER: PI of observational programmes for the hunt of SN progenitors

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

Gap Transients

Cai et al. 2022



Luminous Red Novae (LRNe)

Intermediate Luminosity Red Transients (ILRTs)

Outbursts of massive stars

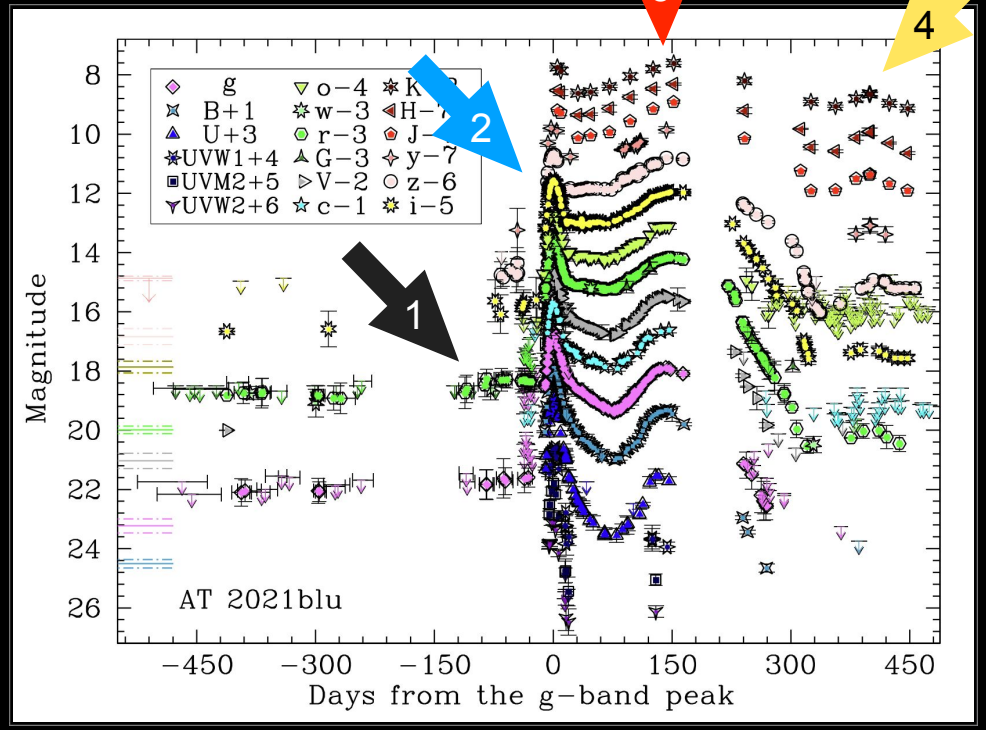
Giant LBV eruptions (Eta-Car like)

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

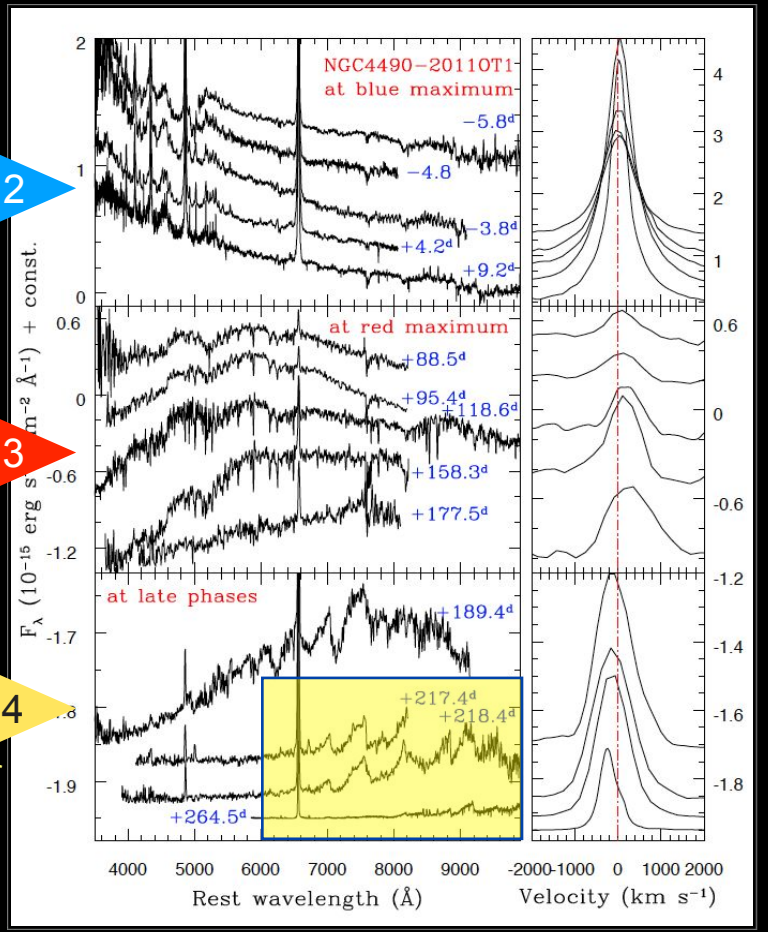
http://graspa.oapd.inaf.it/gap.html

Luminous Red Novae

Pastorello et al. 2023



Pastorello et al. 2019a

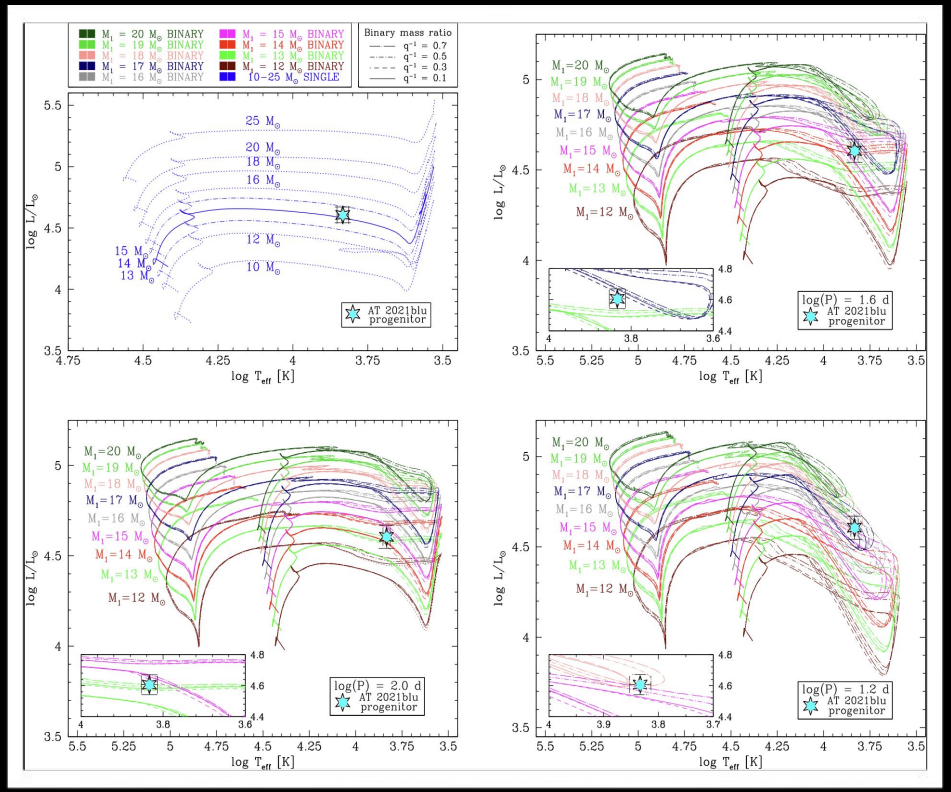


Molecular bands!

http://graspa.oapd.inaf.it/gap/lrn.html

Luminous Red Novae

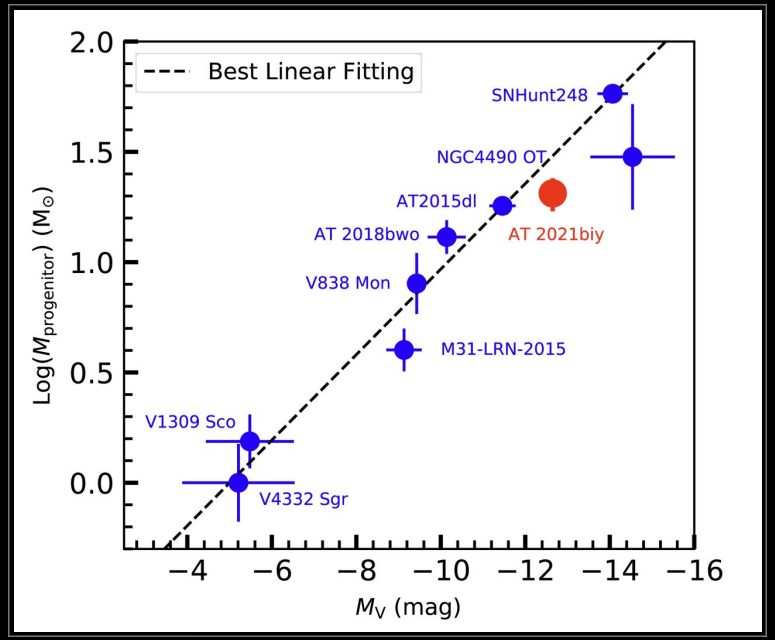
Quiescent progenitor detection



Pastorello et al. 2023

Indirect methods:

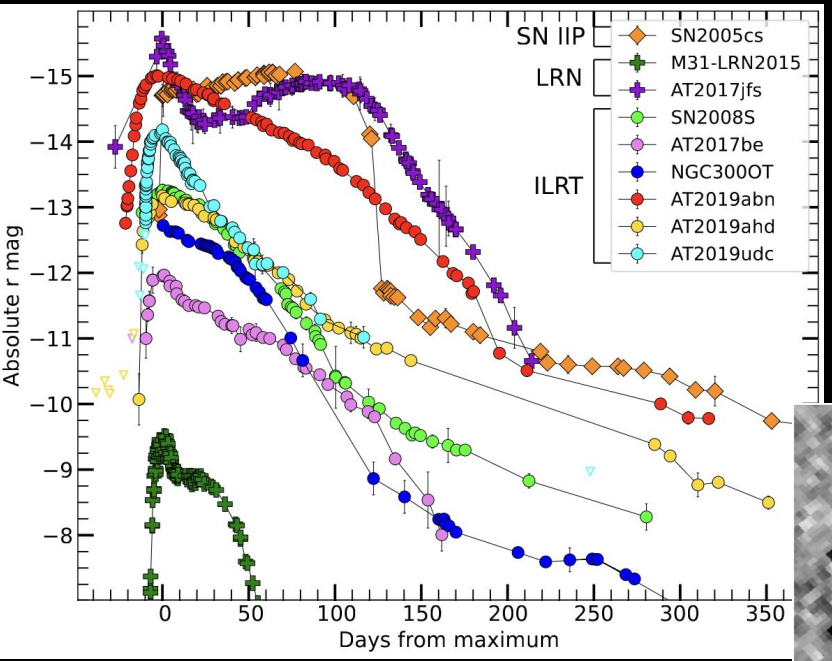
The luminosity and the duration of the outburst depends on the masses involved



Cai et al. 2022

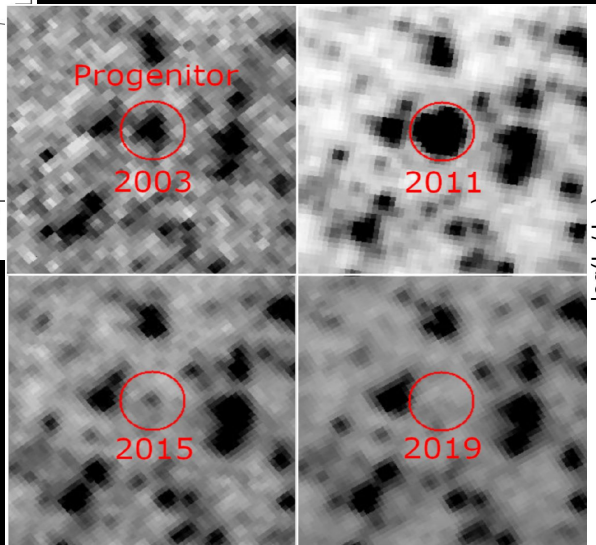
http://graspa.oapd.inaf.it/gap/lrn.html

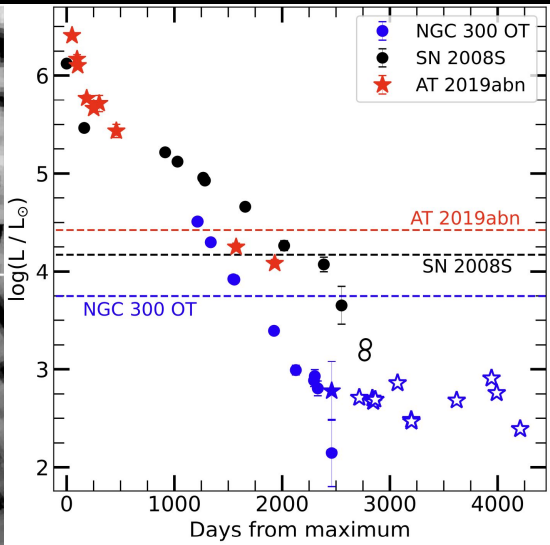
Transients



- Peak absolute magnitude:
  -15 mag < M_r < -12 mag
- Supernova-like light curves, possible contribution from ^{56}Co decay
- MIR dimming below progenitor level until disappearance

Valerin et al. 2024

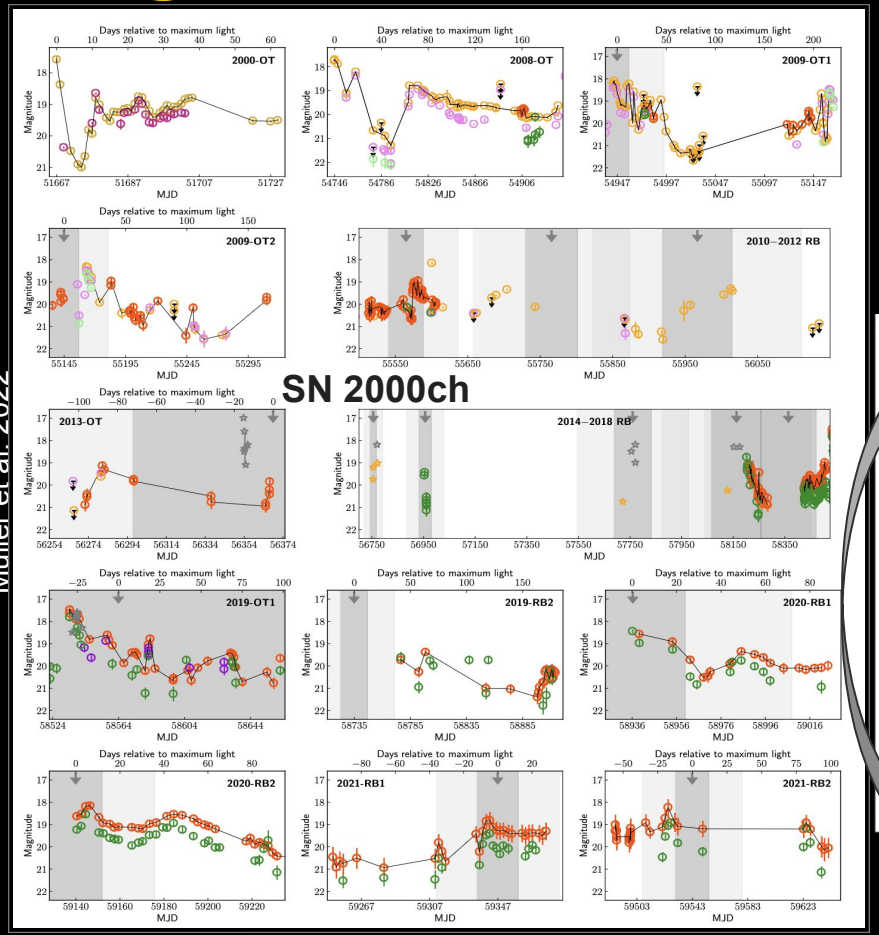




- Electron Capture Supernovae from SAGB progenitors?

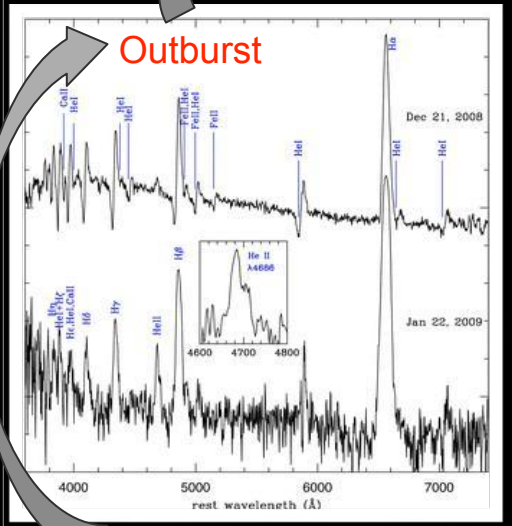
http://graspa.oapd.inaf.it/gap/ilotredtr.html

LBV outbursts and giant eruptions

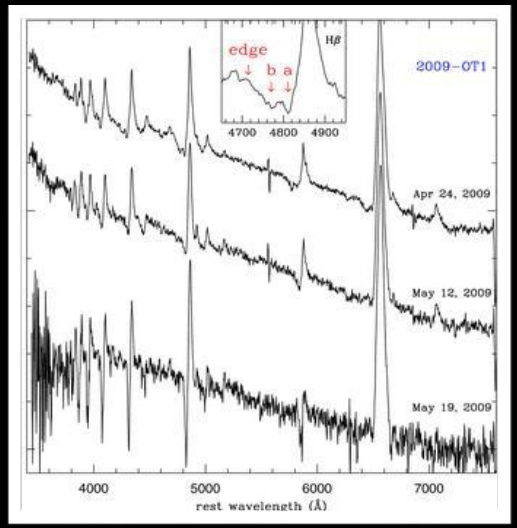


Müller et al. 2022

Erratic behaviour,
multiple outbursts



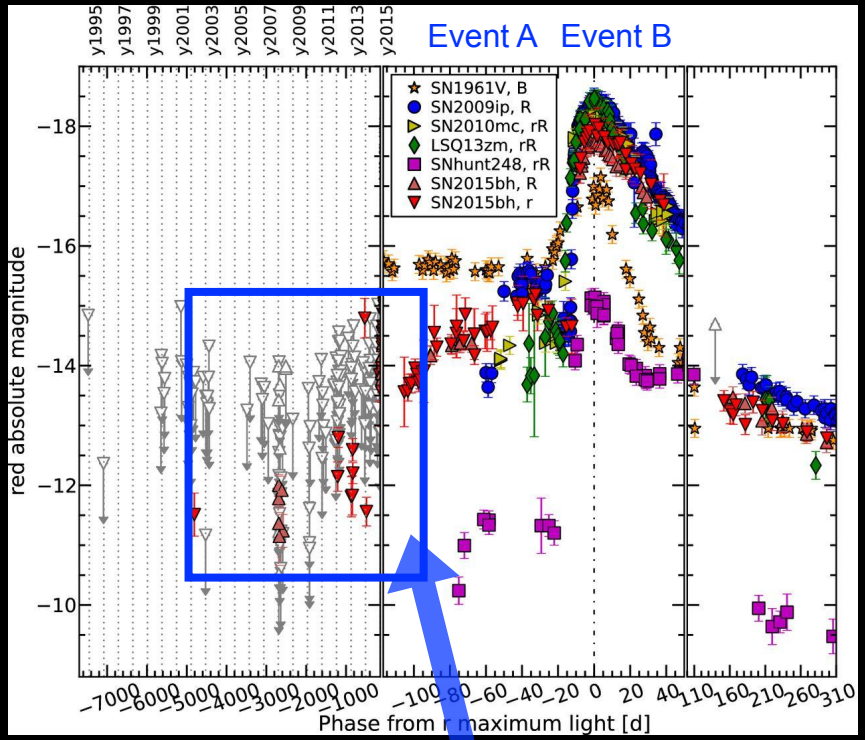
Evolution



Pastorello et al. 2010

http://graspa.oapd.inaf.it/gap/giantburst.html

Gap transients can become SNe



Elias-Rosa et al. 2016

We need to study the pre-SN eruptive phases!

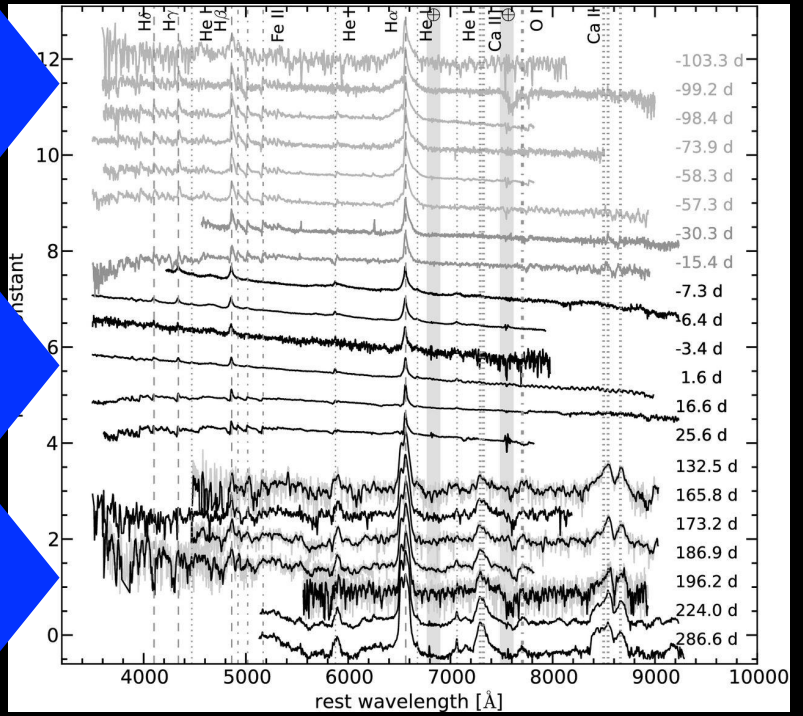
Pre-SN IIn outbursts: SN 2009ip-like transients

Erupting LBVs or lower mass stars in binaries?

Event A

Event B

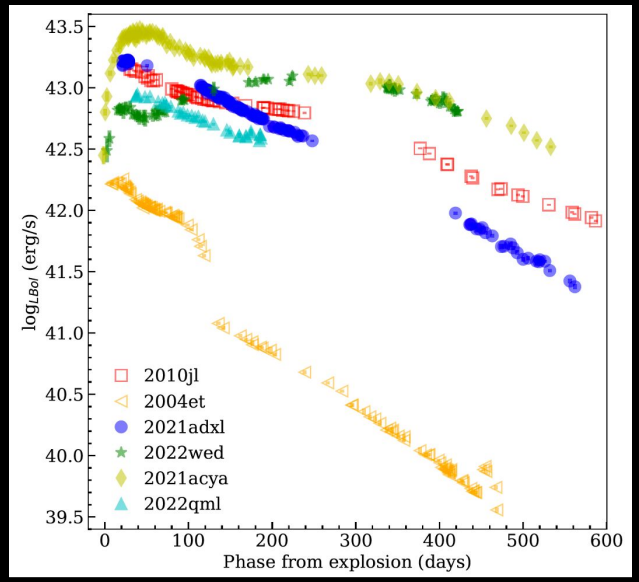
Late



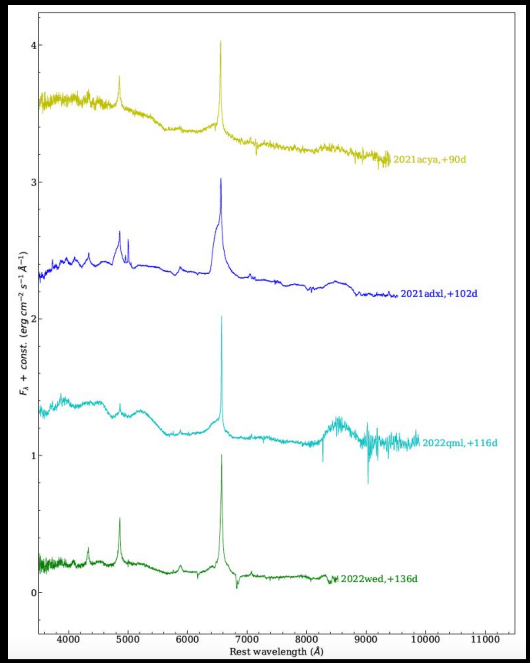
http://graspa.oapd.inaf.it/gap/giantburst.html

Interacting Supernovae

- SNe whose ejecta interact with CSM
- Spectra and light curve heavily depend on CSM properties
- Efficient conversion of E_k into radiation -> brighter and longer light curve, slower spectral evolution
- CSM gives insights on the last evolutionary stages of massive stars
- Shock can accelerate particles and produce high energy neutrinos



Salmaso et al. in prep.



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

Counterpart of radio transients

Today's objective:

Unveiling hidden SN population

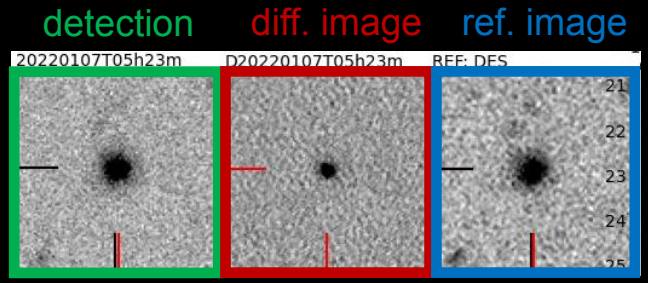
Apparent mismatch between the measured CC-SNe rate (mostly from optical observations)

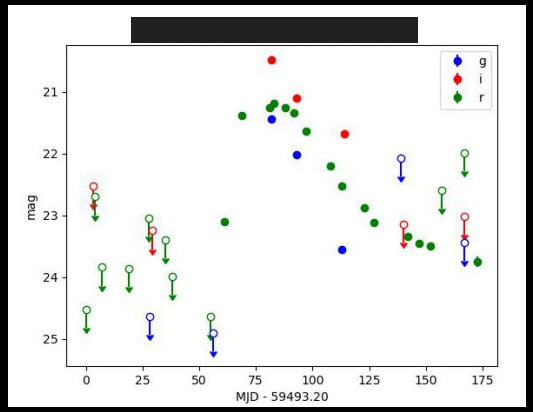
and

the cosmic massive star formation rate

Tomorrow's objective:

Correlate optical and radio transient properties

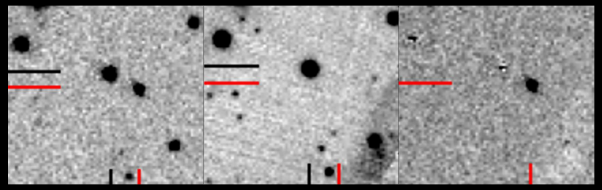




EC developed the transient search tool

NER, EC, IS, SB, LT participate in this research and are members of ThunderKAT (SARAO/MeerKAT)

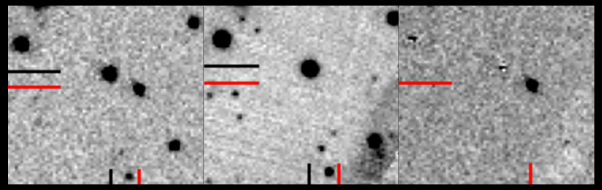
From multiwavelength to multimessenger



Observed Template Subtraction

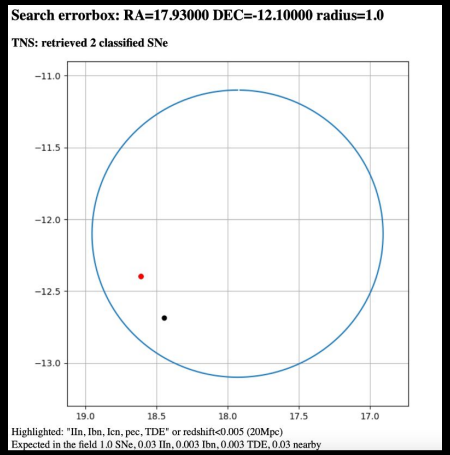
Same template subtraction strategy for neutrinos and GWs: look for unknown transients inside the errorbox

From multiwavelength to multimessenger



Observed Template Subtraction

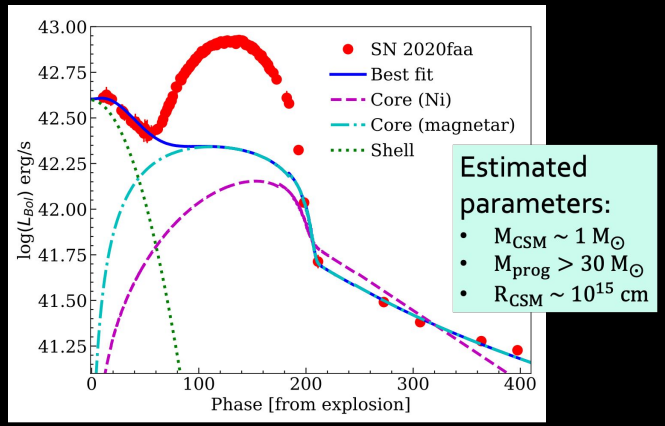
Same template subtraction strategy for neutrinos and GWs: look for unknown transients inside the errorbox



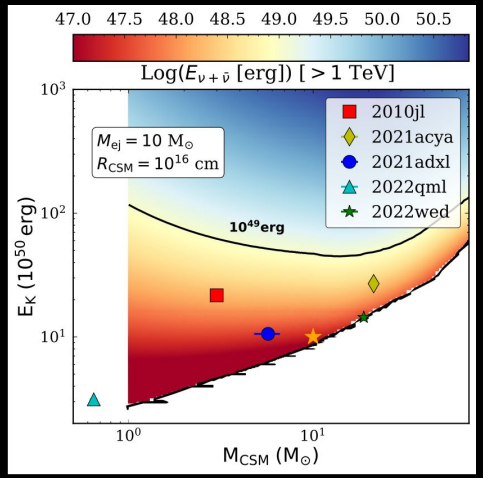
Search for classified transients

At the same time…

Salmaso et al. 2023



Salmaso et al. in prep.



Study of potential emitters

Collaborations

NUTS2

- 30+ members from Europe
- Padova node alone contains 30% of the members
- Access to NOT telescope through members from Scandinavia
- 65 hours/semester of soft ToO (ALFOSC) + 6 half-nights/semester (NOTCam)
- 30+ papers until 2021

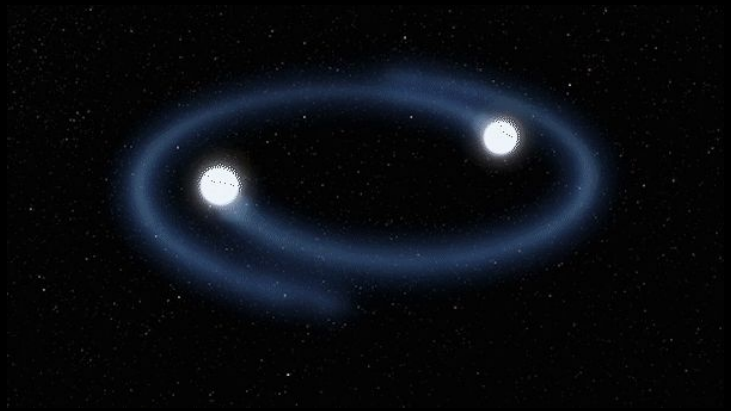
ePESSTO+

- 500+ members, mostly from European community (but also Asian and Chilean)
- Started 2012, still on-going (due to delays with SOXS)
- Granted 90 nights/semester at ESO 3.58m NTT telescope + EFOSC2 (and SOFI until last August)
- 100+ papers until 2020

Collaborations

ENGRAVE

- 250+ members from the European community (PI S.J. Smartt; Oxford University)
- Follow-up of EM sources from GWs, mostly with ESO facilities (VLT)



http://www.engrave-eso.org/

GRAWITA

- ~100 members from the Italian community (PI E. Brocato, INAF-OAAb)
- Search and follow-up of electromagnetic counterparts of GWs events and GRBs
- Recent paper on Nature on a Gamma-ray flash from M82, using data from INAF facilities (Asiago and Campo Imperatore Schmidts + TNG)

https://grawita.inaf.it/

Gravitational Wave Astronomy

TODAY

Ligo/Virgo/Kagra (LVK)

Search for counterpart in O4 run

Founder members of the Italian (GRAWITA) and European (ENGRAVE) collaborations

EC: in the board of GRAWITA

All: Alert team, contribution to the search (VST, Schmidts) and follow-up (VLT, LBT, TNG, Asiago …..) of WGs

https://www.ligo.org/ https://www.virgo-gw.eu/

TOMORROW

Einstein Telescope (ET)

Contribution to Blue Book

NER, EC: chapter *Stellar collapse and rotating neutron stars* (DIV7 of OSB)

EC: CoI of the PNRR ETIC

Laboratorio ADONI: Test di ottica adattiva per ET

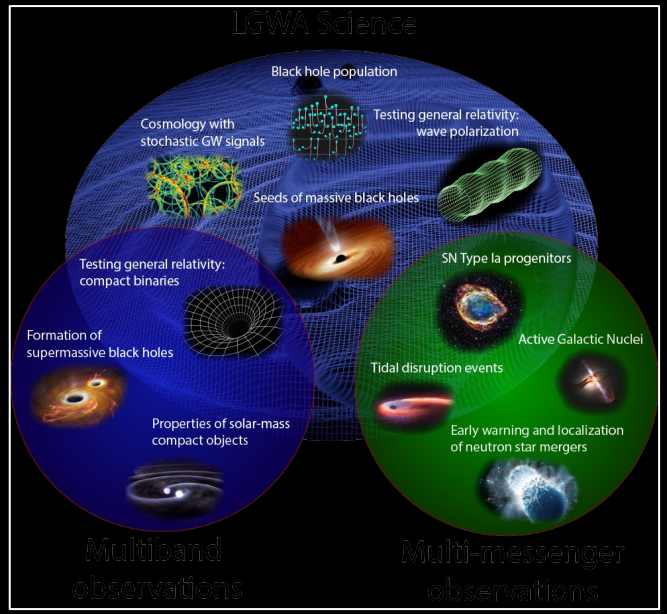
EC: PI of INAF as co-proponent

https://www.einstein-telescope.it/

Long term vision: LGWA

LGWA is a mission concept to measure the vibrations of the Moon caused by GWs. Observation band 1mHz to a Hz (peak sensitivity in the decihertz band). **Its pathfinder mission Soundcheck was selected in 2023 by ESA into the Reserve Pool of Science Activities for the Moon.**

LGWA Science

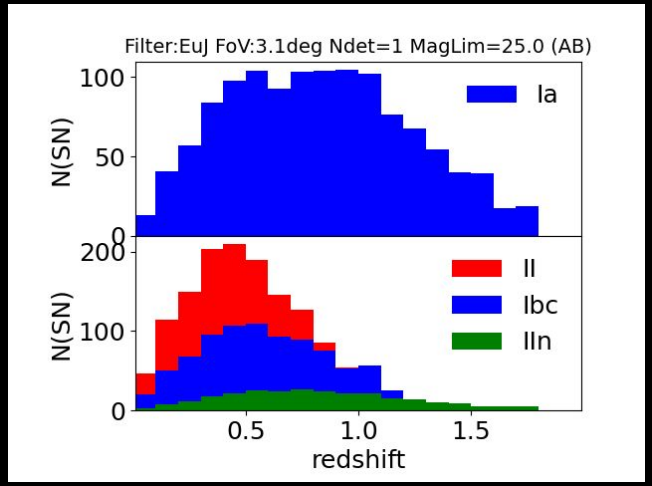


SB: member of LGWA Steering Group

SB, EC, LT: co-authors of LGWA White Paper (https://arxiv.org/abs/2404.09181) and member of LGWA WG1 (GW Science and Multi-Messenger Astronomy)

http://lgwa.unicam.it/

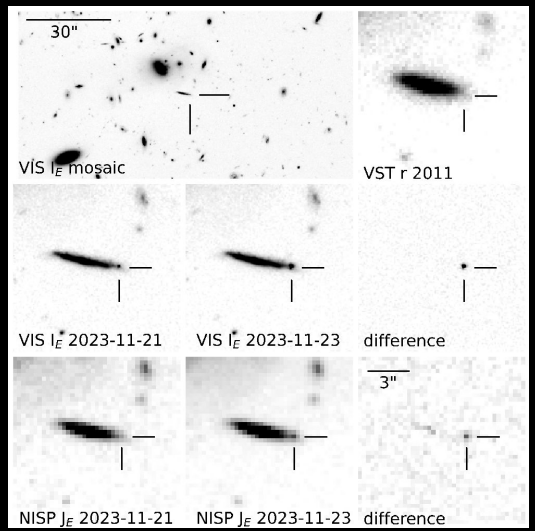
Search for Transients in EUCLID Deep and Self-Calibration fields



- Unique access to redshift range 1-2
- Unique very deep NIR
- Extraordinary VIS spatial sampling
- Opportunity of coordination with LSST
- As transient SWG we were granted immediate access to EUCLID images

EC developed:

- A simulation to estimate transient counts
- A pipeline for EUCLID raw data quick reduction
- The transient search pipeline



Euclid. I. Overview of the Euclid mission
Euclid collaboration 2024

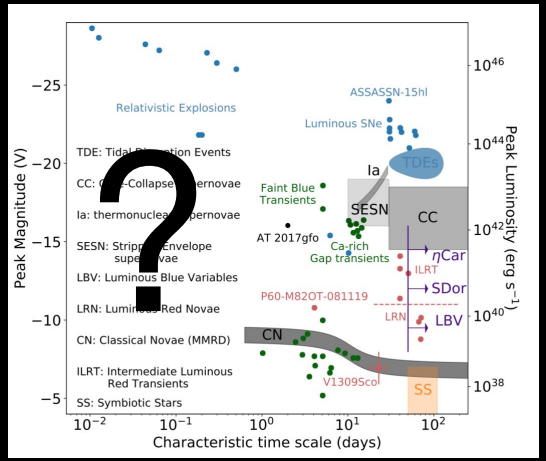
https://www.euclid-ec.org/

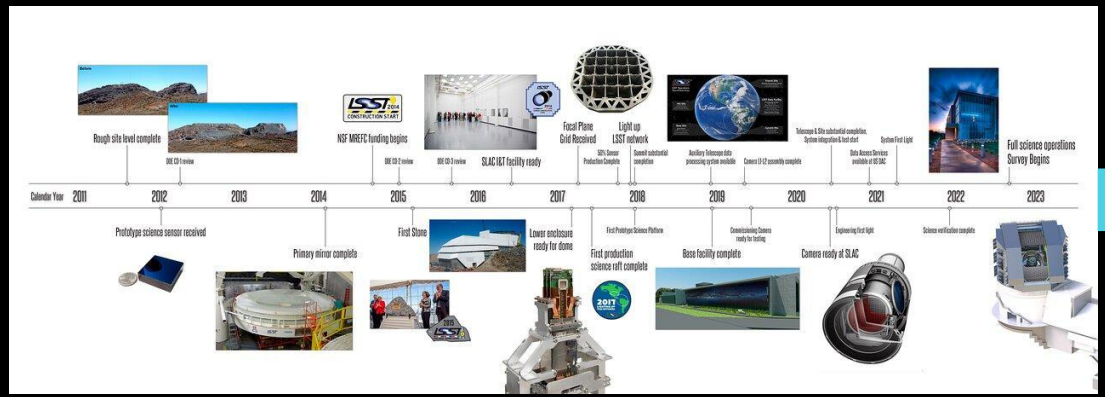
VRO/LSST

Transient and Variable Stars Collaboration

- 1 approved project with data right holders (AP, LT, AR, IS, GV) on the study of peculiar supernovae, Gap Transients, “dark” supernovae. Current involvement in LSST DP0.2.
- Other PIships to be negotiated via in-kind contributions (SOXS, VST) - SB, NER, LT (classifications and additional follow-up resources)

Science goal:
Mapping the unknown



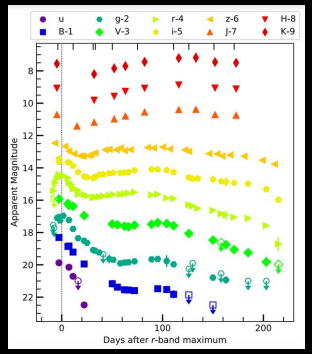


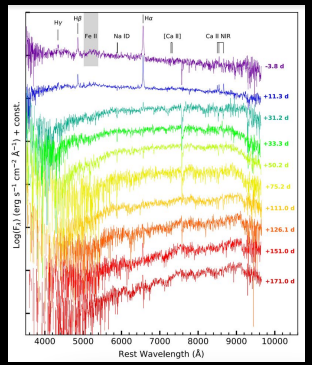
Covid Delay

Survey operations begin - spring 2025

https://www.lsst.org/

LSST preparatory phase





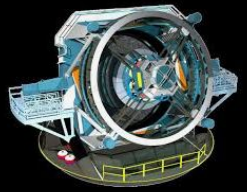
Pagina introduttiva: http://sngroup.oapd.inaf.it/ilot.html

Attualmente 50 oggetti inclusi di varie classi, dalla letteratura o non ancora pubblicati.
Altri 40 oggetti individuati, con curve di luce e spettri sotto analisi. Altri saranno aggiunti non appena scoperti.

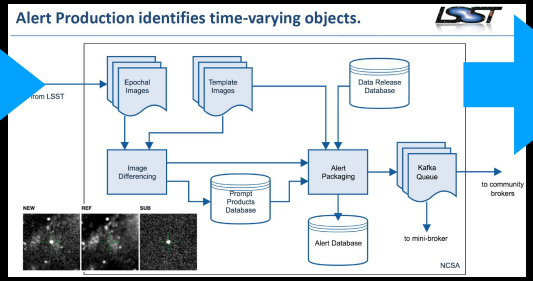
ASASSN-15qi	Milky Way	22:54:05.373	+58:15:02.02	13.64	2015/10/03	YSO	...	...
AT2017oe	NGC 2537	08:13:13.380	+45:59:29.54	18.5	2017/01/06	ILRT	...	...
AT2017dau	UGC 09113	14:14:17.08	+35:25:43.47	19.28	2017/04/482	Impostor?	...	...
AT2017qha	UGC 10213	16:07:23.710	+10:25:40.19	20.58	2017/04/20	Impostor	...	...
CK-Vul	Milky Way	19:47:38.0	+27:18:48.0	3 V	1670/06/20	LRN/Nova	...	...
HFF14Spo-NW	anonymous	04:16:09.256	-24:04:11.78	29.30	2014/01/07	Impostor/LRN	...	...
HFF14Spo-SE	anonymous	04:16:09.360	-24:04:12.87	27.98	2014/08/28	Impostor/LRN	...	...
LMC-R71	LMC	05:02:07.394	-71:20:13.12	7.1	2012/04/02	LBV	S Dor	...
LSQ13zm	SDSS J102854.56+196254.8	10:28:54.591	+19:52:54.91	17.2	2013/04/13	Impostor?+SN	M?+II-n?	...
M101-2015OT1	M 101	14:02:16.78	+54:26:20.5	16.5	2015/01/20	LRN	S2	...
M31-LRN2015	M 31	00:42:07.99	+40:55:01.1	19.0	2015/01/13	LRN	S2	...
M31-RV	M 31	00:43:02.433	+41:12:56.17	14.9 I	1968/09/03	LRN	S2	...
M66-2006OT1	NGC 4362	12:25:23.80	+18:10:56.0	14.0	2006/01/07	ILRT/BLRN	Sp	...
NGC2363A-V1	NGC 2366	07:28:43.37	+69:11:23.95	17.88	1996/01/08	Impostor	S	...
NGC2403-V37	NGC 2403	07:37:07.83	+65:34:29.3	19.0	1916/02/03	Impostor	S Dor / Mb	...
NGC2748-2015OT1	NGC 2748	09:13:27.50	+76:27:41.0	18.3	2015/02/10	Impostor	S1	...
NGC3437-2011OT1	NGC 3437	10:52:34.53	+22:56:05.2	18.4	2011/01/10	BLRN	S2	...
NGC4490-2011OT1	NGC 4490	12:30:41.84	+41:37:49.7	16.0	2011/08/16	BLRN	S2	...
NGC4656-2005OT1	NGC 4656	12:43:45.84	+32:06:15.0	16.5	2005/03/19	Impostor	S1d?	...
NGC55-2014OT1	NGC 55	00:15:08.75	-39:12:50.1	16.7	2014/10/06	Impostor/Nova	S1/Fe nova	...
NGC5806-2014OT1	NGC 5806	14:59:09.47	+01:54:26.6	20.3	2014/05/21	BLRN	S2/S3	...
NGC6509-2011OT1	NGC 6509	17:59:22.995	+06:17:26.56	18.5	2011/06/24	ILRT	S1d	...
OGLE-2002-BLG-360	Milky Way	17:57:39.97	-29:46:04.8	15.92 I	2002/01/09	LRN	S2/S3	...
PTF10qa	M 99	12:18:50.16	+14:26:39.2	20.1	2010/03/16	ILRT/BLRN	Sp	...
Shrunt275	NGC 2770	09:09:35.12	+33:07:21.3	19.9	2015/02/07	Shlin	Mb+II-2	...
UGC12307-2013OT1	UGC 12307	23:01:11.53	+12:43:21.8	18.3	2013/08/08	BLRN	S2	...
UGC2773-2009OT1	UGC 2773	03:32:07.24	+47:47:39.6	17.6	2009/08/18	Impostor	SI	...
V1309Sco	Milky Way	17:57:32.94	-30:43:10.0	9.5	2008/09/02	LRN	S2	...
V4332Sgr	Milky Way	18:50:36.74	-21:23:28.8	8.9	1994/02/24	LRN	S2:	...
tPTF13z	SDSS J160200.05+211442.3	16:02:00.12	+21:14:41.4	18	2013/02/01	Impostor+SN	S?+IIn/f	...

Templates of rare transients

LSST rare transient discoveries



VRO/LSST alerts



objectId	ramean	decmean	mjdmin	mjdmax	magrmin	latestrmag	sherlock_classification	score
ZTF18abdnchn	355.04821866666666	24.40804168333337	58346.349641200155	58437.21590203002206	None	None	NT	Not Near PS1 star
ZTF18abvqkfg	43.685017866666667	47.44279026111114	58367.425763899926	58462.270393500105	None	None	NT	Not Near PS1 star
ZTF17aaaqrqx	327.04349189123239	47.866767447401408	58250.456844900105	58457.160578699978	16.2591	18.4422	NT	Not Near PS1 star
ZTF18aaxsage	9.800914709999999	-5.2007028	58423.243535010021	58456.185011600144	16.6615	18.43	NT	Not Near PS1 star
ZTF18abmjaye	75.32495640707795	46.864209271754366	58342.491281660005	58464.280068939987	16.6665	18.8811	NT	Not Near PS1 star
ZTF18accmnyu	142.62426130666665	16.343655773333334	58425.498124999925	58461.52254630002	16.9433	17.7337	NT	Not Near PS1 star
ZTF18abuhyjr	39.065207178047619	-1.1996821180476192	58372.484644119993	58456.257269850005	17.2658	18.7595	NT	Not Near PS1 star
ZTF18abugmng	351.5054167772	38.146332668600001	58370.301423099984	58456.153634329999	17.3337	17.6203	NT	Not Near PS1 star
ZTF18abtrswjk	38.298014174074074	-1.3095661407407405	58369.476215300016	58462.274513899814	17.4162	17.5588	NT	Not Near PS1 star
ZTF18aakkjdo	177.45079423809524	25.650587876190478	58276.196576400006	58450.018275499981	17.4824	17.6624	NT	Not Near PS1 star
ZTF18aaeagau	124.86382430833332	22.636784966666666	58372.515599029985	58455.456747699995	17.5226	18.6124	NT	Not Near PS1 star
ZTF18acrukpd	84.854946255555556	-6.1500679666666667	58450.398379600014	58462.353034399999	17.5524	17.5524	NT	Not Near PS1 star
ZTF18abmenfr	346.8452078	43.603900947058824	58358.405636600022	584				
ZTF18abvtcpk	46.449476869181185	18.668137145454543	58374.436539399999	584				
ZTF18abtqtde	349.64964474	41.133305549	58428.178391200025	584				
ZTF18acauwik	350.81365819	35.621342229999996	58423.222812499985	584				
ZTF18acewvqf	142.38697635714285	67.8147391	58454.465104199946	584				

LSST community brokers

SOXS
(Son Of X-Shooter)

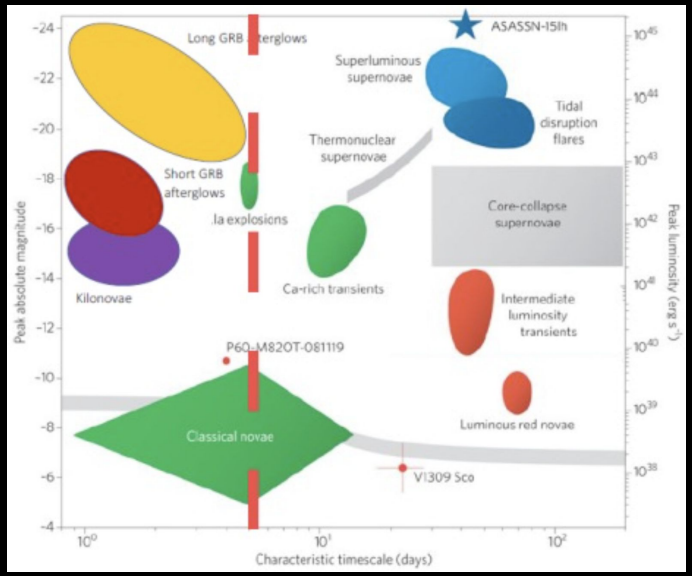
Unique spectroscopic/imaging facility
for the ESO-NTT 3.5-m telescope in La Silla

OAPd will be one of the three nodes (with INAF - OA-Brera/OACN) supporting the SOXS operation. The whole Consortium+ESO time will be entirely managed by the consortium!

Two *assegni di ricerca* are foreseen to help in this fundamental task

All Padova-Asiago SN group members are involved in the 13 SOXS WGs

EC: in the SOXS board
AP: WG7 (Intermediate luminosity transients) deputy
SB: WG13 (Classifications) leader



http://www.brera.inaf.it/~campana/SOXS/Son_of_X-Shooter.html

STAFF

Enrico Cappellaro

Laura Greggio

Stefano Benetti

Andrea Pastorello

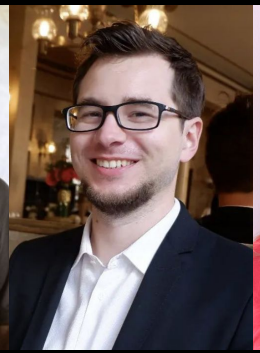
Lina Tomasella

Nancy Elias-Rosa

POST-DOC

Andrea Reguitti

Giorgio Valerin



Irene Salmaso

MASTER

Francesco Guidolin

Science Interests

- Classification program
- SNe Iax
- Faint Core-collapse SNe
- Progenitor study
- Rates
- Gap Transients
- Interacting SNe
- Radio Transients
- Multimessenger Astronomy