Small telescopes and short cadence monitoring surveys

The case of GalRSG project: monitoring galactic low-mass RSGs in search for late-stage outbursts possibly indicating imminent SN explosion

F. Bocchino, INAF-Osservatorio Astronomico di Palermo

CoI: S. Orlando, M. Miceli, O. Petruk (INAF-OAPa)

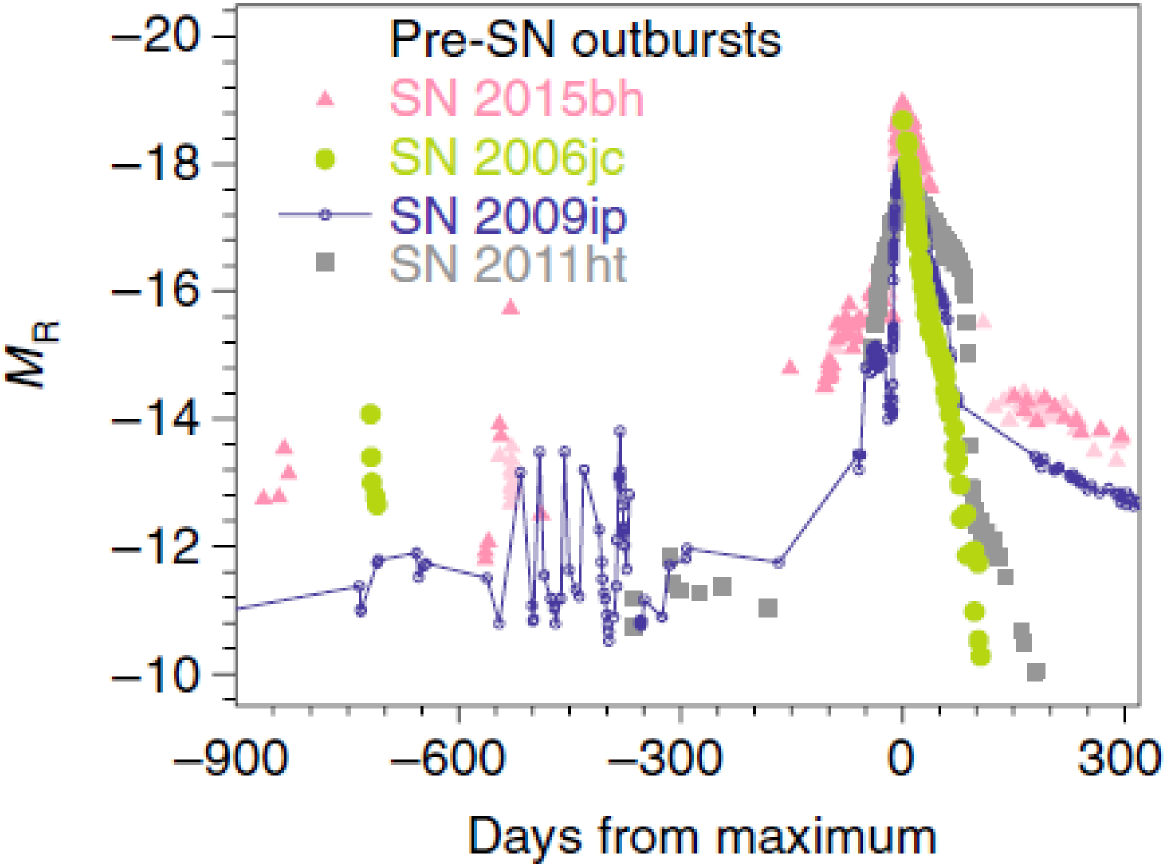
Pastorello (INAF-OAPd)

M. Limongi, A. Chieffi (INAF-OARm)

ChiantiTopics 2024– Firenze 26-29 February 2024

Pre-SN outburst

- SN2009ip: 40 Msun massive star undergoing several bursts and a final giant burst 3 weeks before explosion
- SN2006jc: burst 2 yr before explosion but no H (Type Ibn)
- SN2015bh: 35 Msun LBV (Boian & Gro 2018)

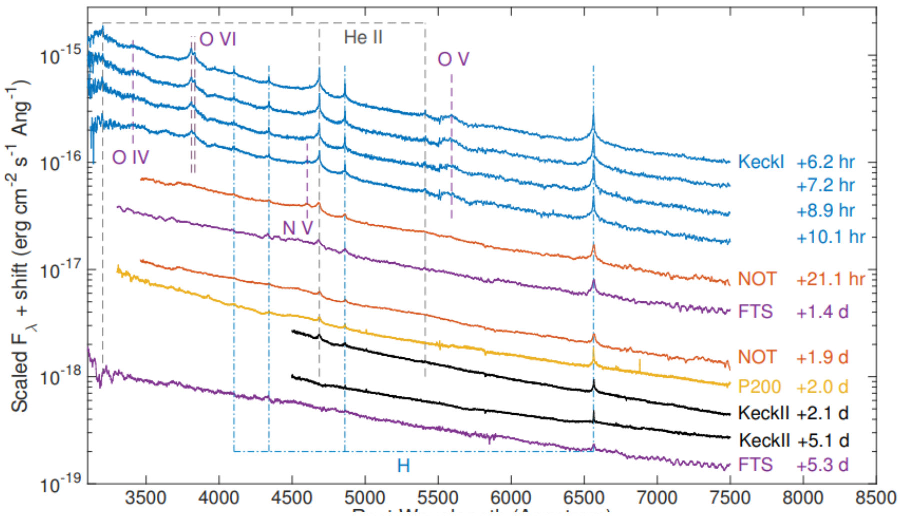


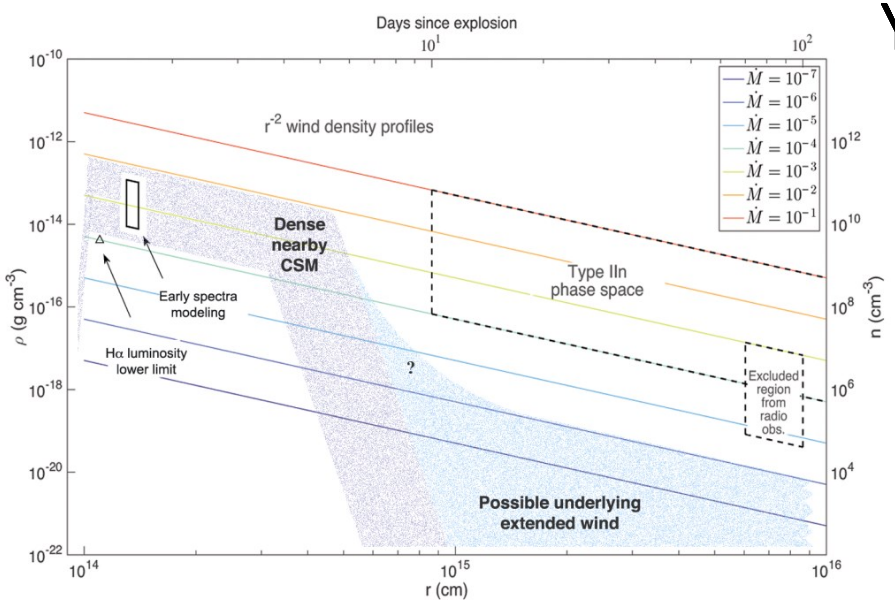
Pastorello & Fraser 2019

(see also Stratjohann+21)

Confined dense CSM in «regular» Type IIP/L SNe

- Early-time flash spectroscopy of **SN2013fs** reveals flash-ionisation signatures during the first 2 d after explosion
- **Consistent with massloss Mdot=10^{-3} $M_{\odot}$/yr for 1 yr, too much for standard RSG wind (< $10^{[-8,-5]}$)**
- Transition SN IIn -> IIP or IIL
- **Bruch+23 argues (60+/-20)% of SNII may be like that.**

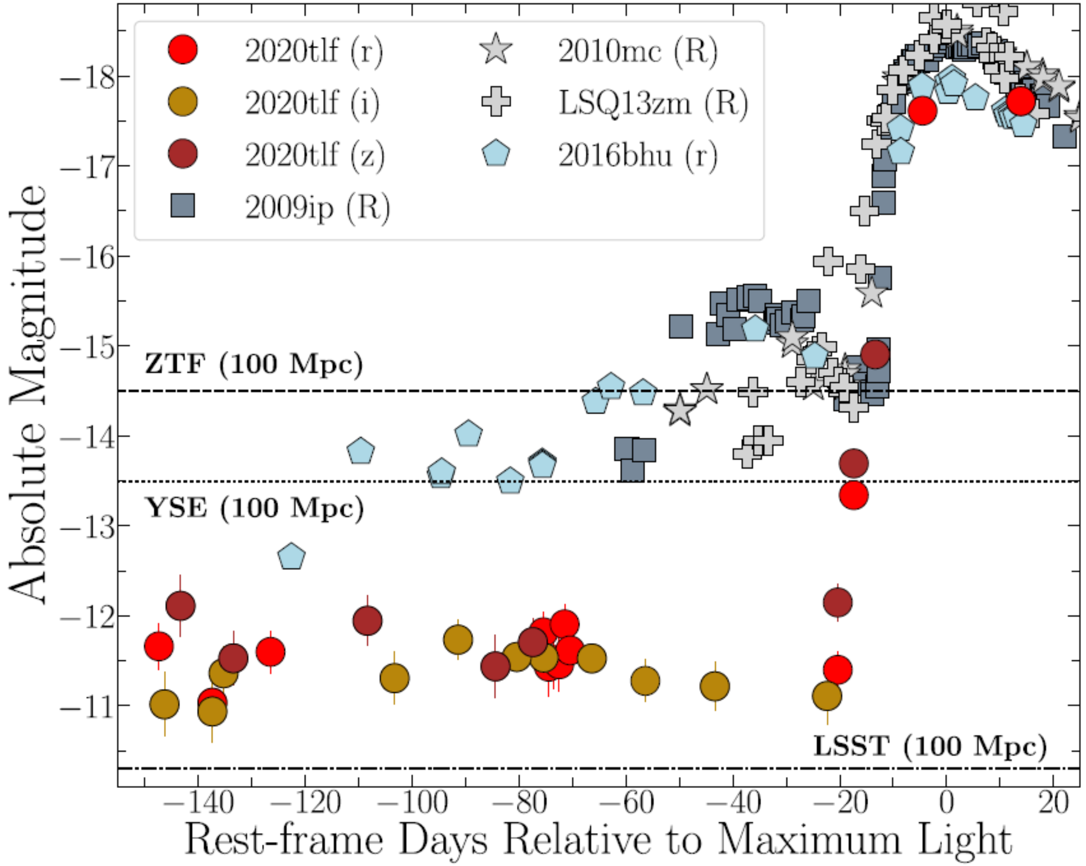




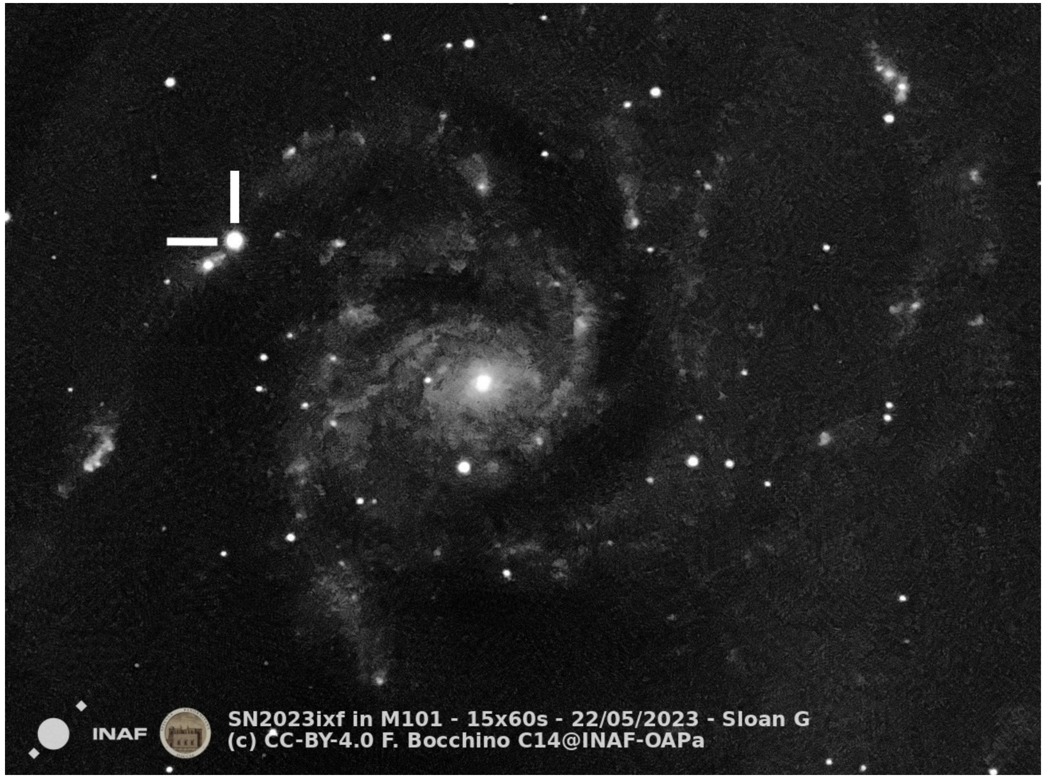
Yaron+17

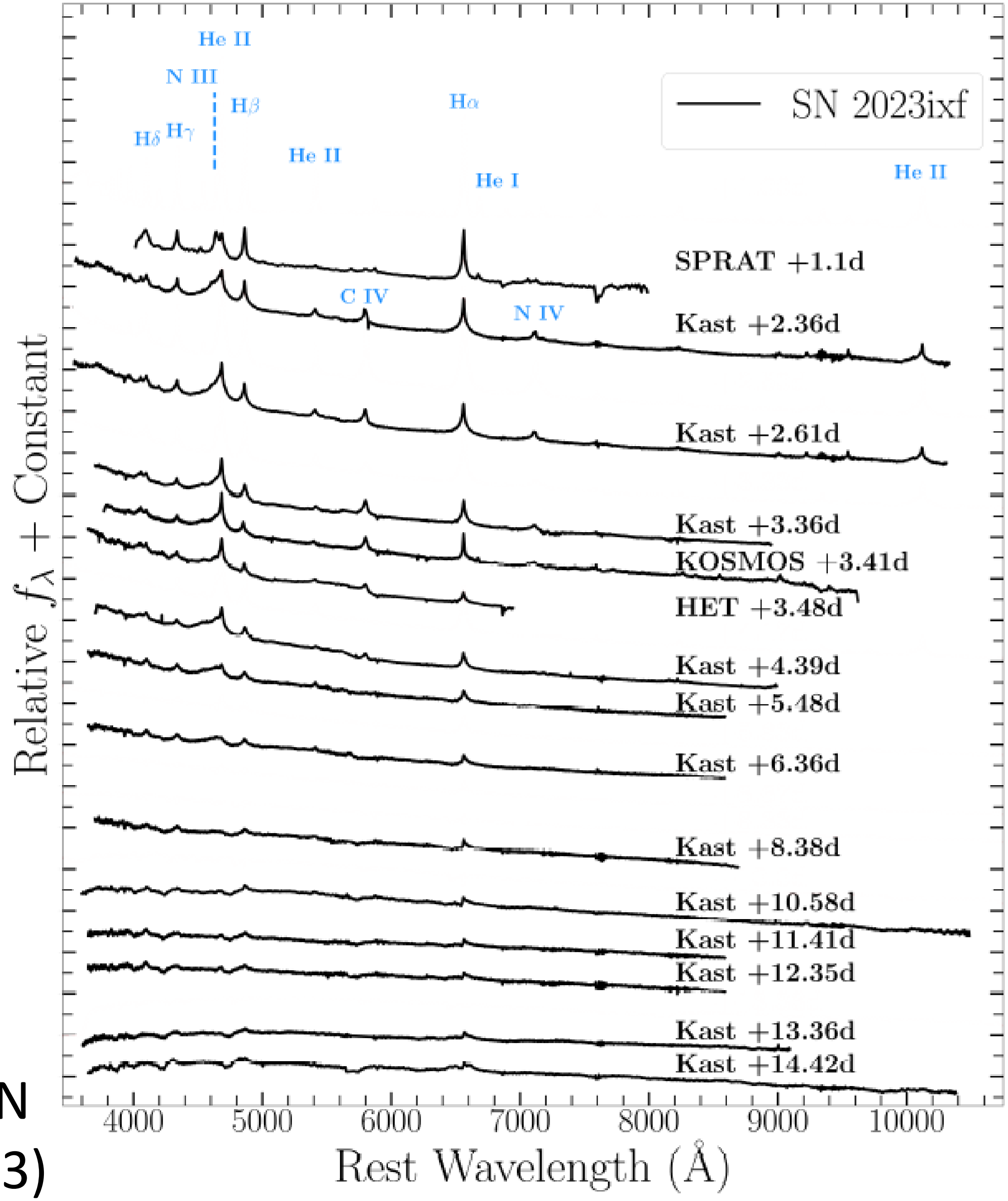
«low-mass» vs «high-mass» SNe precursors

- **SN 2020tlf** (37 Mpc, μ=37.6 mag) a Type II-P/L SN that has a confirmed detection of precursor flux. (Jacobson-Galan+ 2022)
- **Consistent with a massloss 0.01 $M_{\odot}$/yr , for 1 yr before explosion**
- **<u>Precursors of “low-mass” RSGs are much fainter</u>**



Here comes SN2023ixf



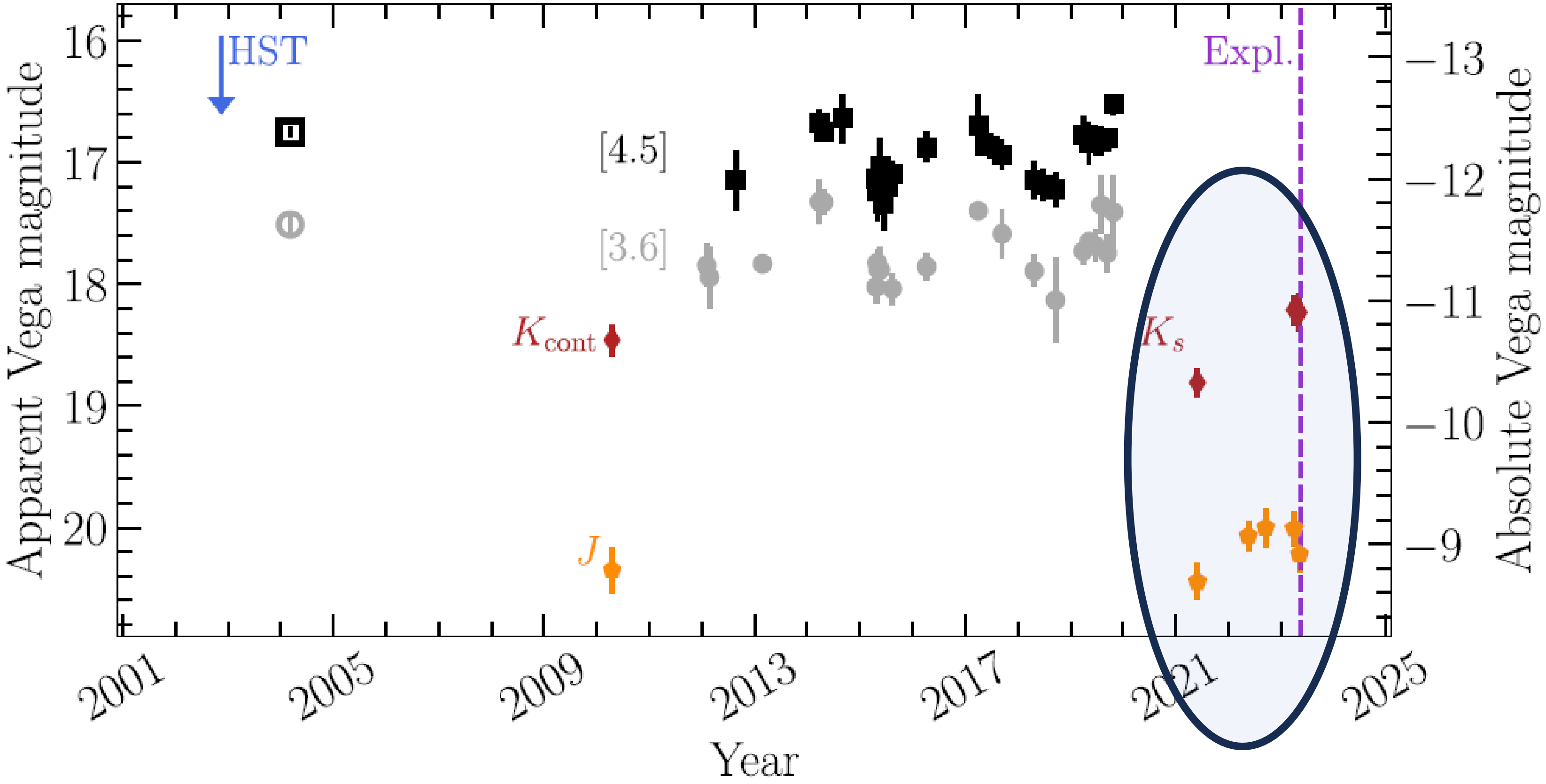


D=6.85 Mpc, μ = 29.2 mag

Evidences of compact CSM, then a «regular» SN
(Renzo 2023, modified from Jacobson-Galan+23)

NIR Outbursts in SN2023ixf?

- Jencson+23 reports on NIR Pre-SN lightcurves
- But Soraisam+23 argue they are fully explained by the 1000d periodicity found at 3.5 and 4.5 μm



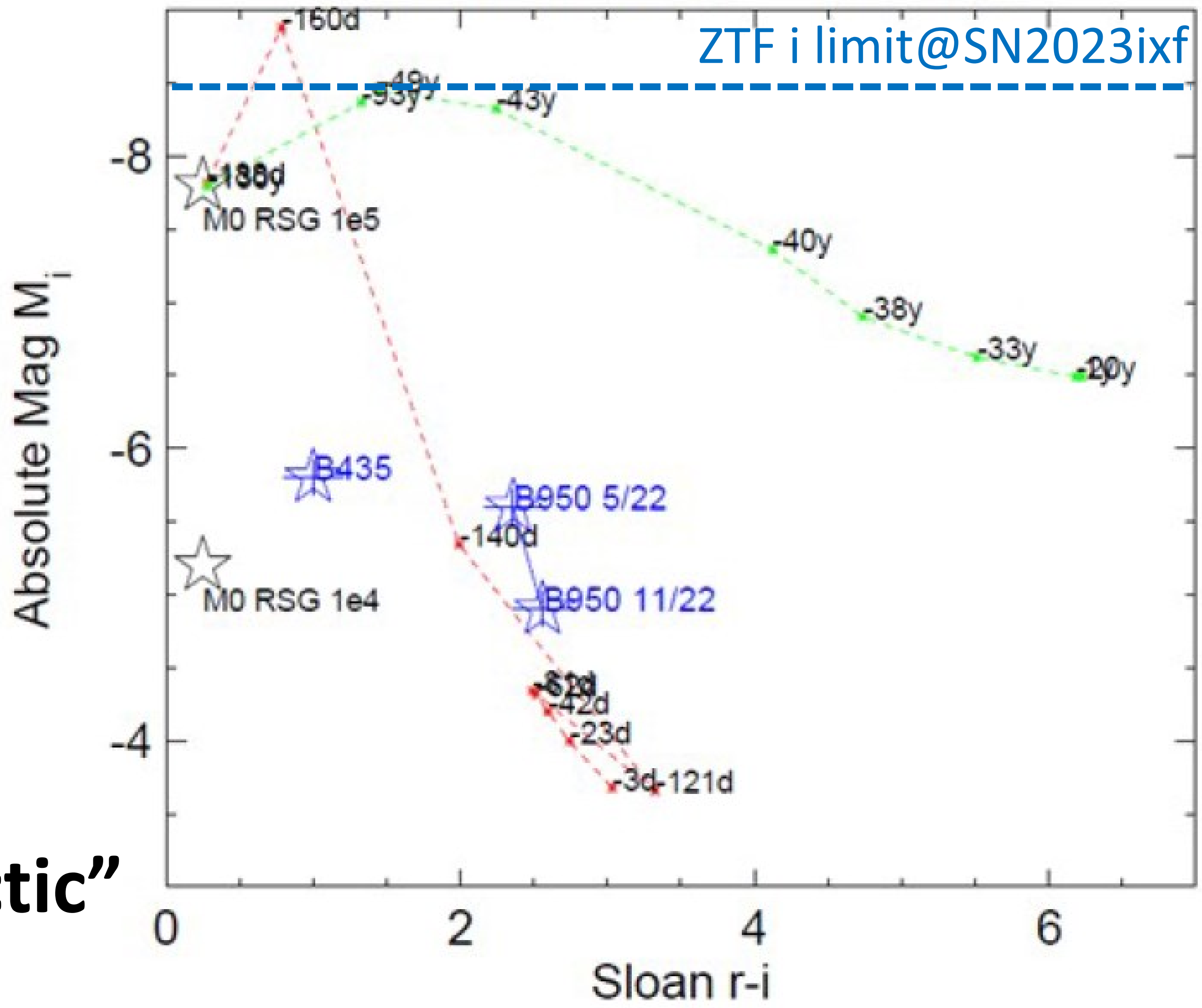
Models of precursors in “low-mass” RSGs ($\sim$7–15 $M_\odot$)

- **Nuclear flashes that ignite dynamical burning of oxygen (>$\sim$1000d pre-SN), neon ($\sim$200-100d), or silicon ($\sim$10-20d)** could lead to the ejection of the outer layers of the stellar envelope ***in the final years to months before explosion*** (Woosley et al. 1980; Meakin & Arnett 2007; Arnett et al. 2009; Dessart et al. 2010; Woosley & Heger 2015).
- Alternatively, **late-stage burning phases can induce gravity waves** that propagate outwards and inject energy into the stellar envelope, leading to eruptions of $\sim$1 $M_\odot$ worth of material ***in the final months before explosion*** (Quataert & Shiode 2012; Shiode & Quataert 2014; Fuller 2017; Wu & Fuller 2021).
- Additionally, **super-Eddington continuum-driven winds can be induced at the stellar surface during late-stage nuclear burning**, which can then cause enhanced mass loss and detectable pre-SN emission (Shaviv 2001a, 2001b; Ofek et al. 2016).
    - However, this mechanism is unlikely to be present in RSGs and is more suited to supermassive ($M_{ZAMS} \sim 30\ M_\odot$) luminous blue variable (LBV) stars.

(Jacobson-Galan+ 2022)

Sensitivity to detection of precursors in “regular” RSG

- Davies+22 start from an outburst of Morozova+18,20: wave-heating associated with late-stage nuclear burning of 15 $M_\odot$ RSG, E_{inj}=0.1 E_{bind}



We need to go “galactic”

Introducing GalRSG: A dedicated galactic monitoring campaign

- Higher sensitivity allows us to target mid/low-L RSGs (i.e. the majority) and their precursors. $10^5\ L_\odot$ -> $M_R \sim -7.5$
  - Absorption may not be a problem
- Multi-band optical/NIR homogeneous coverage
  - Current extragalactic precursors data come from very different instruments/setup
  - ZTF gri-filter survey (>2018) do not have i-filter data (no color) after 2020
- **Regular cadence**
  - **Need to be few days at most (optimal 1-2 days)**
  - **Current archive extragalactic data are often too sparse**

Scutum-Crux massive clusters.

They are all at ~ 6 kpc (μ ~ 14 mag) and coeval (~ 15 Myr)

Total 105 RSG

Nome	Coord J2000	# RSG	Dist. Kpc (mag)	Mass 10^4 $M_\odot$	Age Myr	Exctinction A(x) in mag							
						V	g	r	i	z	J	H	K
Chi Persei	022200 +570800	6	2.3 (11.8)	0.5-1	12.5	1.8		1.9	1.0	0.7			
NGC 7419	225420 +604854	5	3 (12.6)	0.5-1	14	5.4	5.7	4.0	3.0	2.2			
RSGC1	183757 -065248 (Sct)	13	5.8-6.6 (14.0)	2-4	7-12	23.2	24.7	17.3	12.8	9.6	5.4	3.4	2.3
Stephenson2 (RSGC2)	183920 -060141 (Sct)	26	5.8 (13.8)	2-4	16-20	12.9 11.9 13.4	14.2	10.0	7.4	5.6	3.1	2.0	1.3
RSGC3	184524 −032313 (Sct)	15	6.0 (13.9)	2-4	16-20	15.1	16.2	11.3	8.4	6.3	3.5	2.3	1.5
Alicante 8	183400 −071400	13+10	6.6 (14.1)	1-2	16-20		20.5	14.3	10.6	8.0	4.5	2.8	1.9
Alicante 7	184429 -033002	13+3	6.0 (13.9)	10	16-20	15.1	16.2	11.3	8.4	6.3	3.5	2.3	1.5
Alicante 10	184530 −034000	8+4	5 (13.5)	1-4	16-20	15.1	16.2	11.3	8.4	6.3	3.5	2.3	1.5

Additional field RSGs

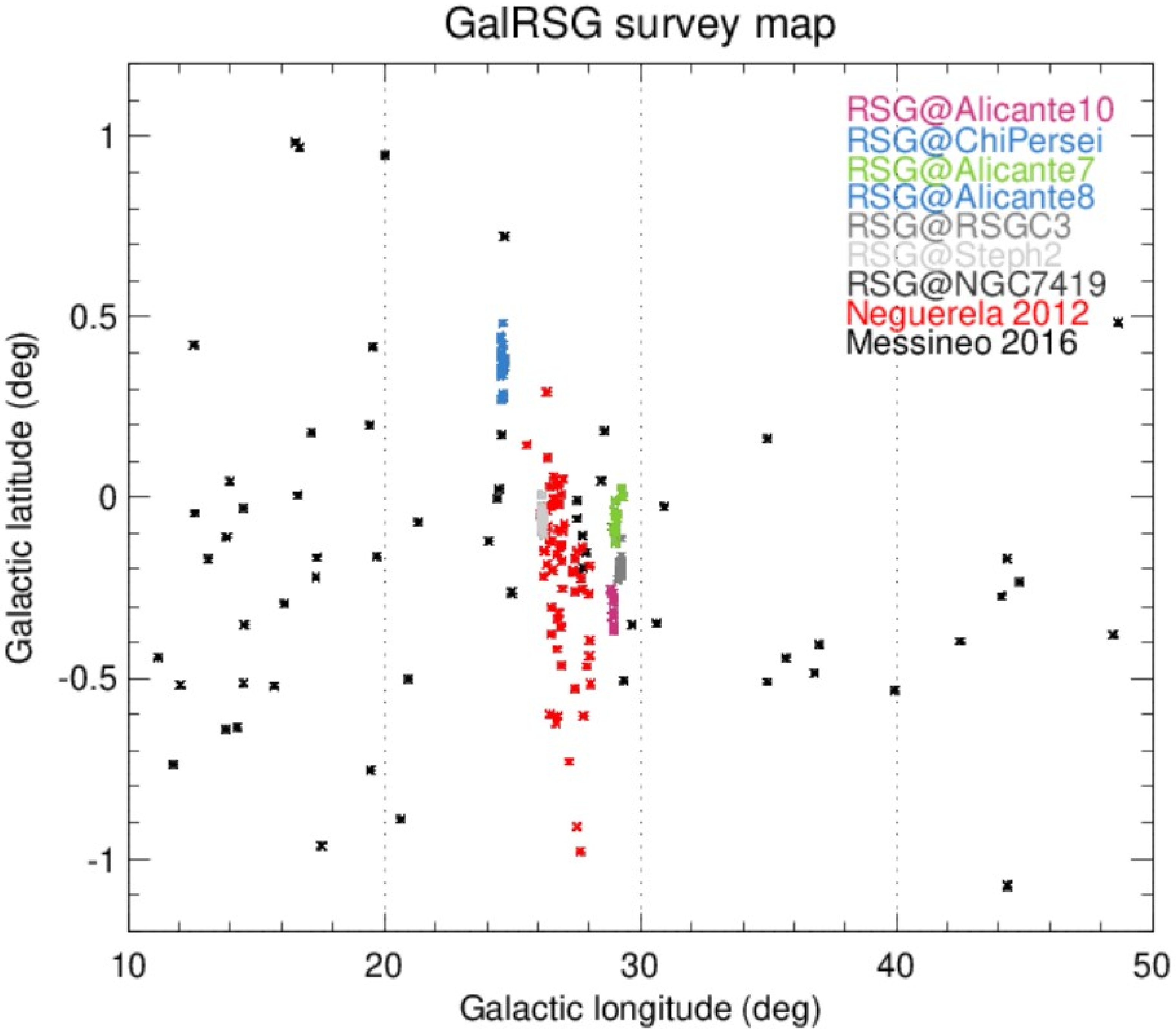
Neguerela+12, +72 RSGs

… Stephenson 2 is not an isolated cluster, but part of a huge structure likely containing hundreds of red supergiants, with radial velocities compatible with the terminal velocity at this Galactic longitude (and a distance ~6 kpc). In addition, we found evidence of several populations of massive stars at different distances along this line of sight.

Messineo+16, +62 RSGs

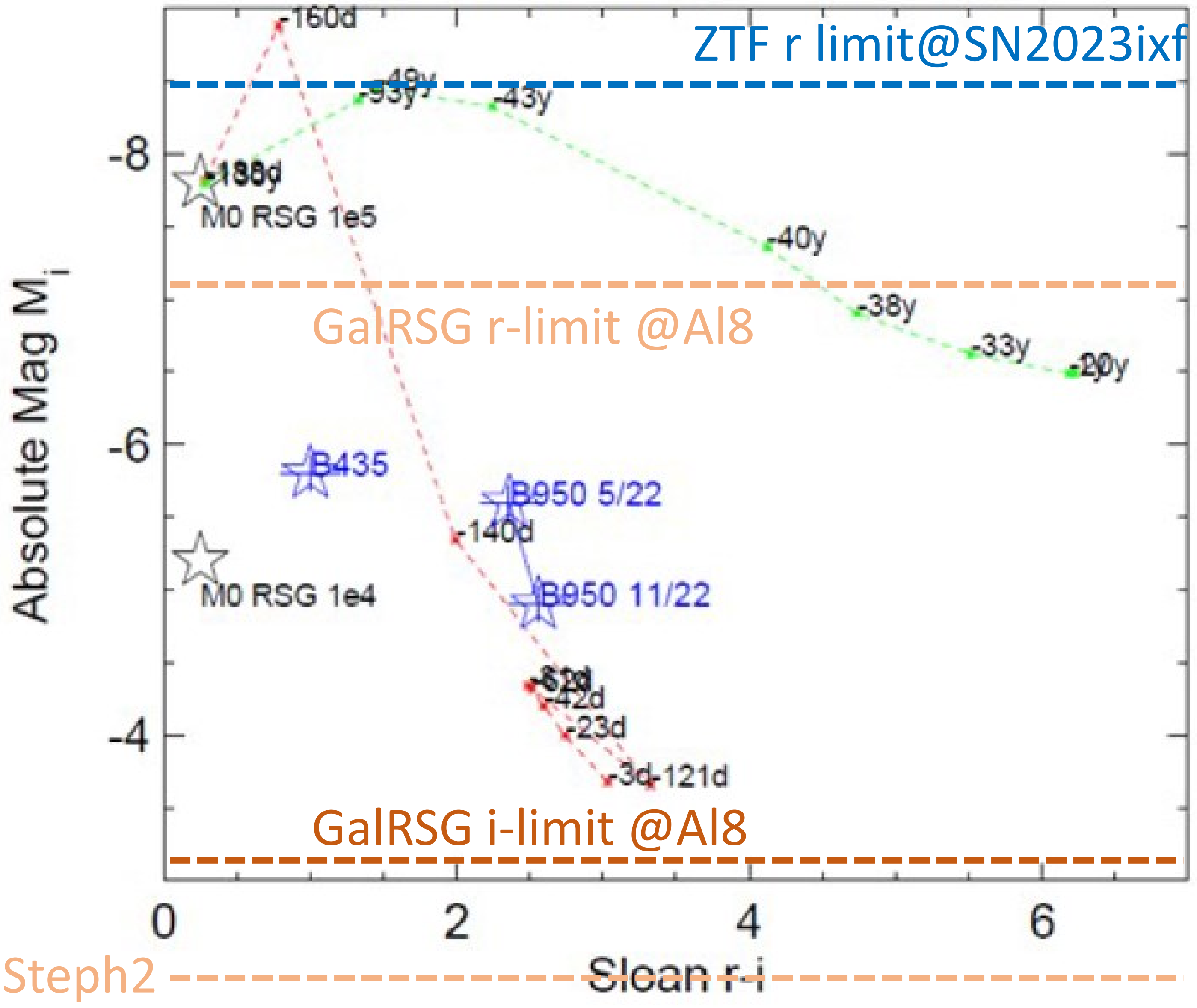
Discovery of an extraordinary number of red supergiants in the inner Galaxy (we selected the "High probability" list)

Grand Total: 239 RSGs



GalRSG Observational campaign

- **C14@INAF-OAPa:** pathfinder campaign, filler for the high-L objects when other are unavail
- **INAF-REM for RSGs in clusters:** 3-yr long term program
  - **2-day cadence, simultaneous griz-NIR images**
- **INAF VST for Field RSGs:** summer 2023 and 2024 program granted
  - Sloan iz filters, 5-10 days cadence in 2023, 5 days in 2024



The contribution of small telescopes to GalRSG: INAF REM

- REM (Rapid Eye Mount) is a 60 cm diameter fast reacting telescope located La Silla/ESO.
- The telescope hosts two instruments: REMIR, an infrared imaging camera, and ROS2, a visible imager with 4 simultaneous passbands. The two cameras can also observe simultaneously thanks to a dichroic placed before telescope focus the same field of view of 10×10 arcmin. Thus, 5 images are obtained at the same time: g,r,i,z, and IR.

The contribution of small telescopes to GalRSG: INAF REM

- Advantages:
  - Short cadences fully supported (down to 2 days)
  - Simultaneous multi-band optical/NIR, particularly useful for GalRSG sources in clusters
  - Availability of long-term projects in all AOs
- Disadvantages
  - Images bkg and artifacts sometimes present. Need postprocessing advanced cleaning to ensure accurate astrometry and photometry
- REM is maybe the best instrument for GalRSG-like science on compact clusters.

INAF VST for GalRSG

- The VST is a 2.6-m optical wide-field telescope installed at the ESO observatory of Cerro Paranal (Chile). From October 2022, VST is owned and managed by INAF.
- The available time offered at the VST via INAF-TAC is 90% of the overall time in the period.
- The only instrument at the VST is OmegaCAM. This is a wide-field camera, which covers 1 square degree on the sky, made of 32-CCDs, 16k x 16k detector mosaic, with 0.21 arcsec per pixel.
  - Sloan griz plus narrow band filters

The contribution of small telescopes to GalRSG: INAF VST

- Advantages:
  - Short cadences supported (5 days granted)
  - Large FOV ideal for field RSGs of Neguerela+12 and Messineo+16
  - High-sensitivity permits short exposures, then many fields can be imaged using only part of the night (GalRSG: only 2.4h for 8 deg^2 in 2 filters)
  - Availability of long-term projects in all AOs
- Disadvantages
  - Data processing not friendly (but Marilena and Enrica helped a lot !!!)
- *VST-OmegaCAM is optimal instrument to carry out a dedicated monitoring program of our field-RSG in the i and z bands in this large highly absorbed area of the galactic plane with a cadence of few days, and it will remain a very good choice also in the LSST era*

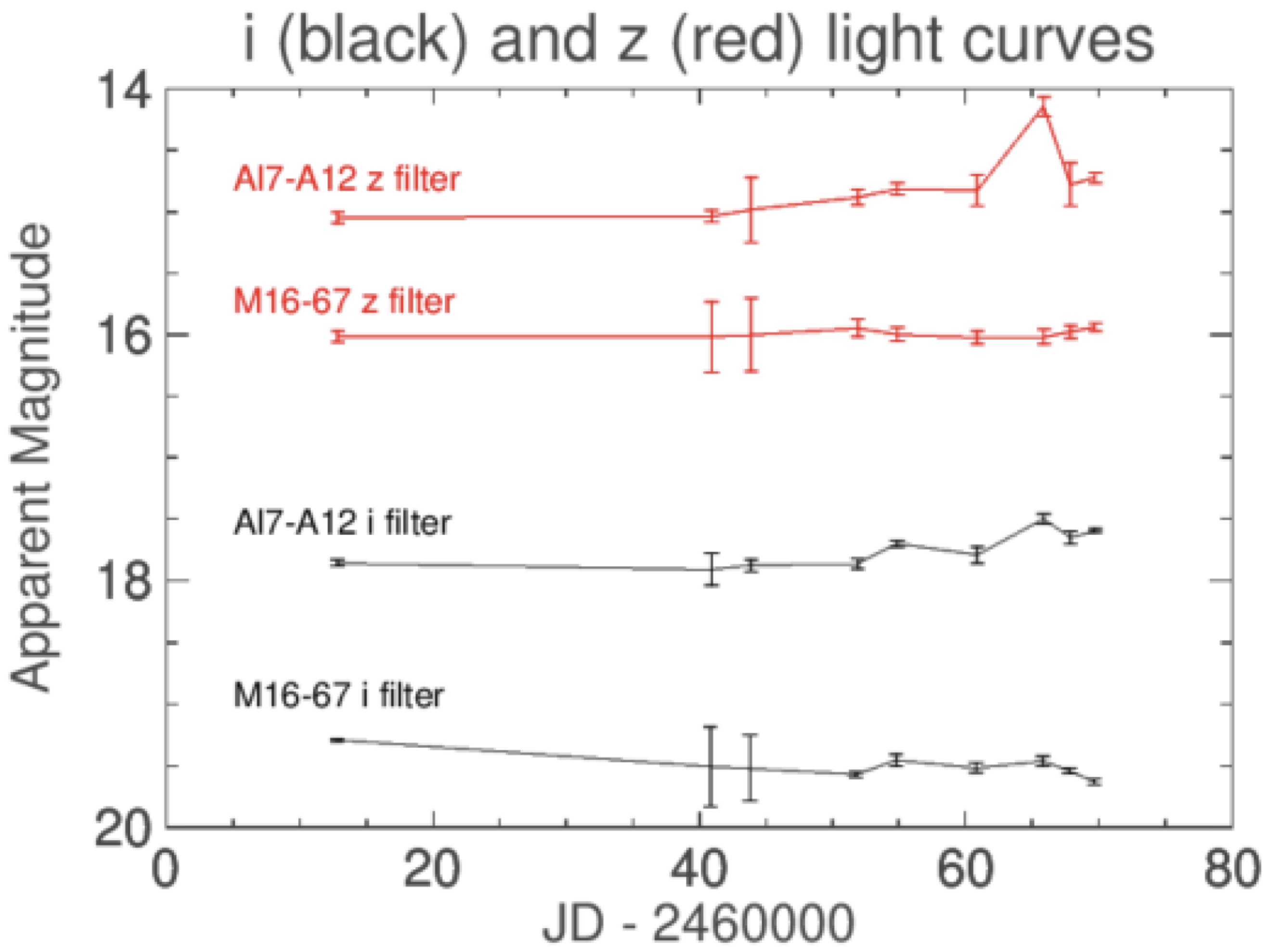
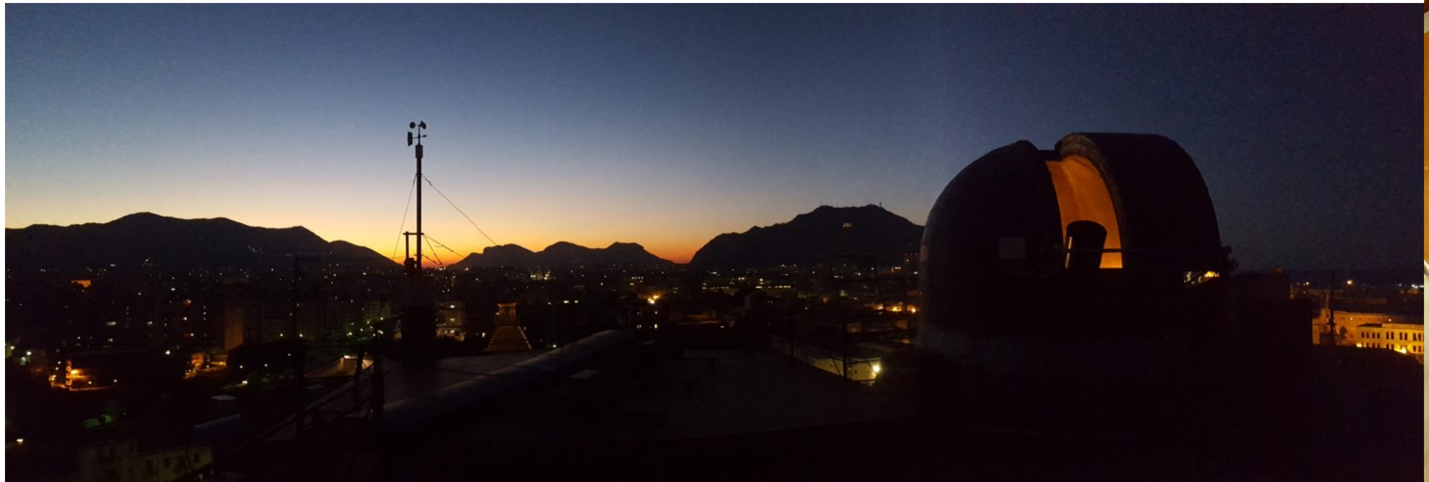


Figure 4: Preliminary photometric light-curve of 2 RSGs extracted from 9 out of 22 total frames in the VST OmegaCAM archive M16-B pointing (the analysis of the remaining archive frames is on the way). The sources have been selected in order to show a case with signs of variability according to the indicators chosen for subsequent light-curve analysis (Al7-A12) and a source which do not show those signs (M16-67). Moreover, the two sources cover the whole range of expected magnitude in our sample (see Fig. 3) and therefore they assess the goodness of our feasibility analysis. The campaign is perfectly able to detect variability amplitude with $\Delta m << 0.5$ mag, fully consistent with the scientific aims. The two larger error bars at abscissa ~ 40 are likely due to a tracking problem, which will be corrected offline. All the archive data have been taken with a 30 sec exposure in each filter and without any moon constraints.

The contribution of small telescopes to GalRSG: C14@INAF-OAPa

- The C14@INAF-OAPa is a Celestron 14’’ (37cm) f/10 (reduced to f/6.4) **fully robotic telescope**, permanently installed in one of the dome of INAF-OAPa, Palermo downtown, since 1990’s.
- Fully refurbished during COVID pandemic, now equipped with a low-cost CMOS BI high-QE cooled optical camera (QHY294, 11.6 MP)
- Sloan griz filters + 3 narrow bands Ha, O III and S II (8 nm FWHM)
- 29’ x 19’ arcmin FOV, 0.42’’/pix, 4.6 μm

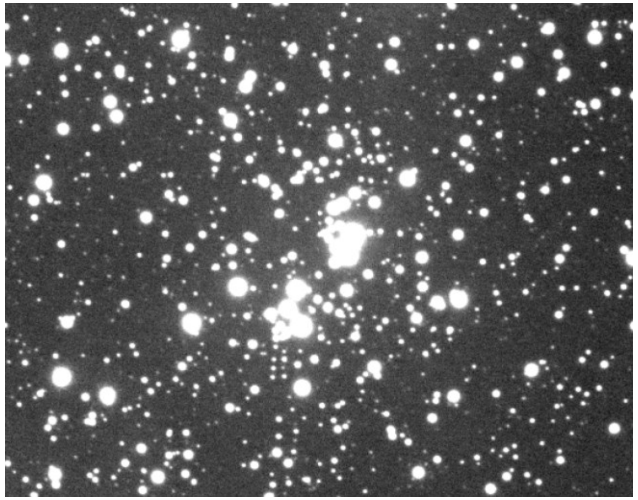


The C14@INAF-OAPa telescope

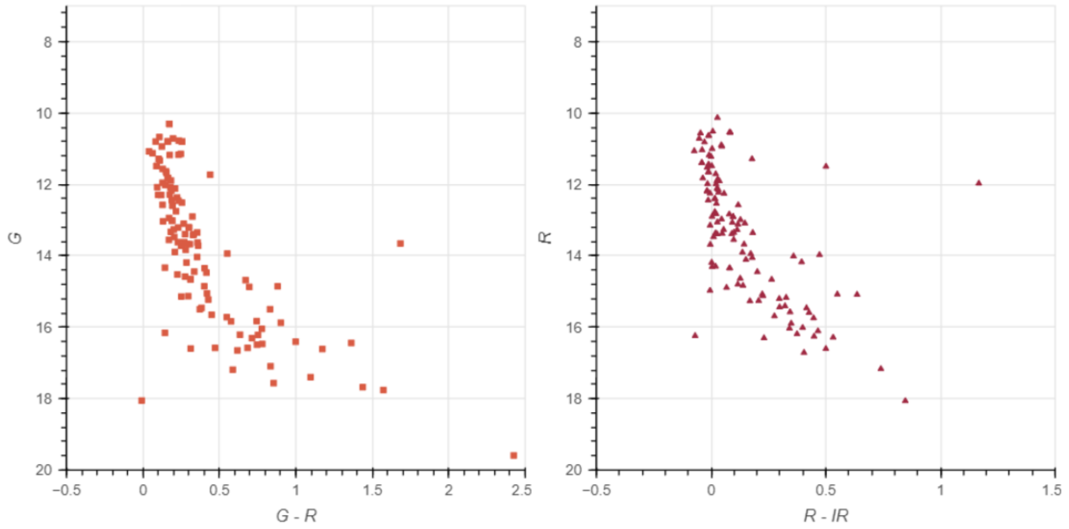
- Laboratory courses at UNIPA
  - Variable star studies
  - Realization of color-color/color-mag HR diagrams
  - Exoplanet transit detection
- Public outreach and other activities
  - E.g. Remote session from schools
  - E.g. Hilal observation by the agreement INAF-Italian Islamic communities
- Support to research activities
  - Monitoring stellar variability in exoplanetary systems (see. A. Biagini’s talk)
  - Pathfinder for larger optical projects

Example of undergraduate students’ works

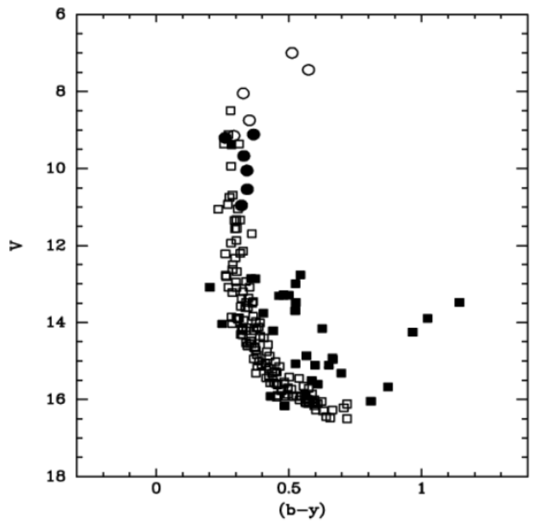
- HR color-mag diagrams of χ Per open cluster and comparison with literature works



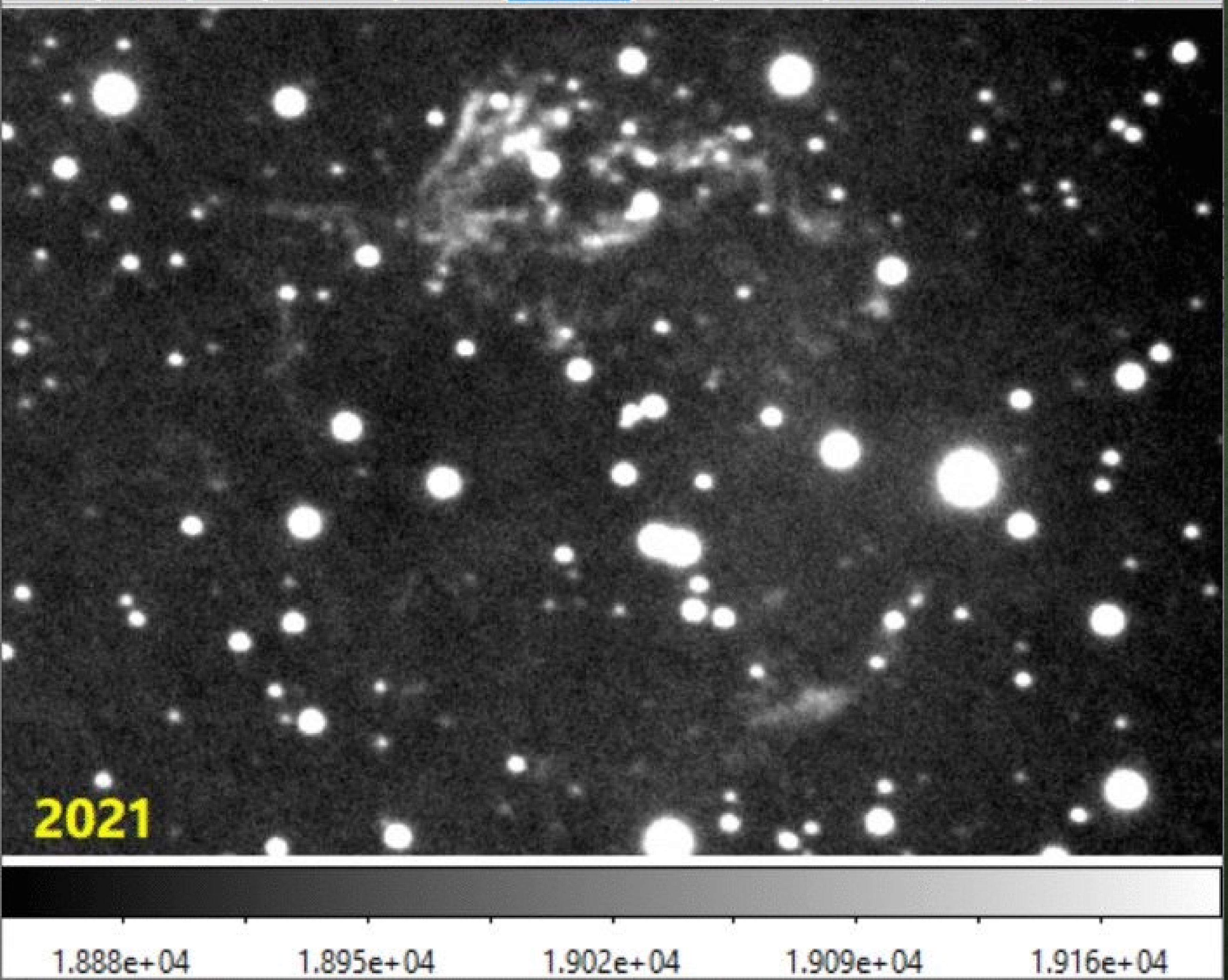
C14@INAF-OAPa image of χ Per open cluster



Derived HR diagrams of cluster members

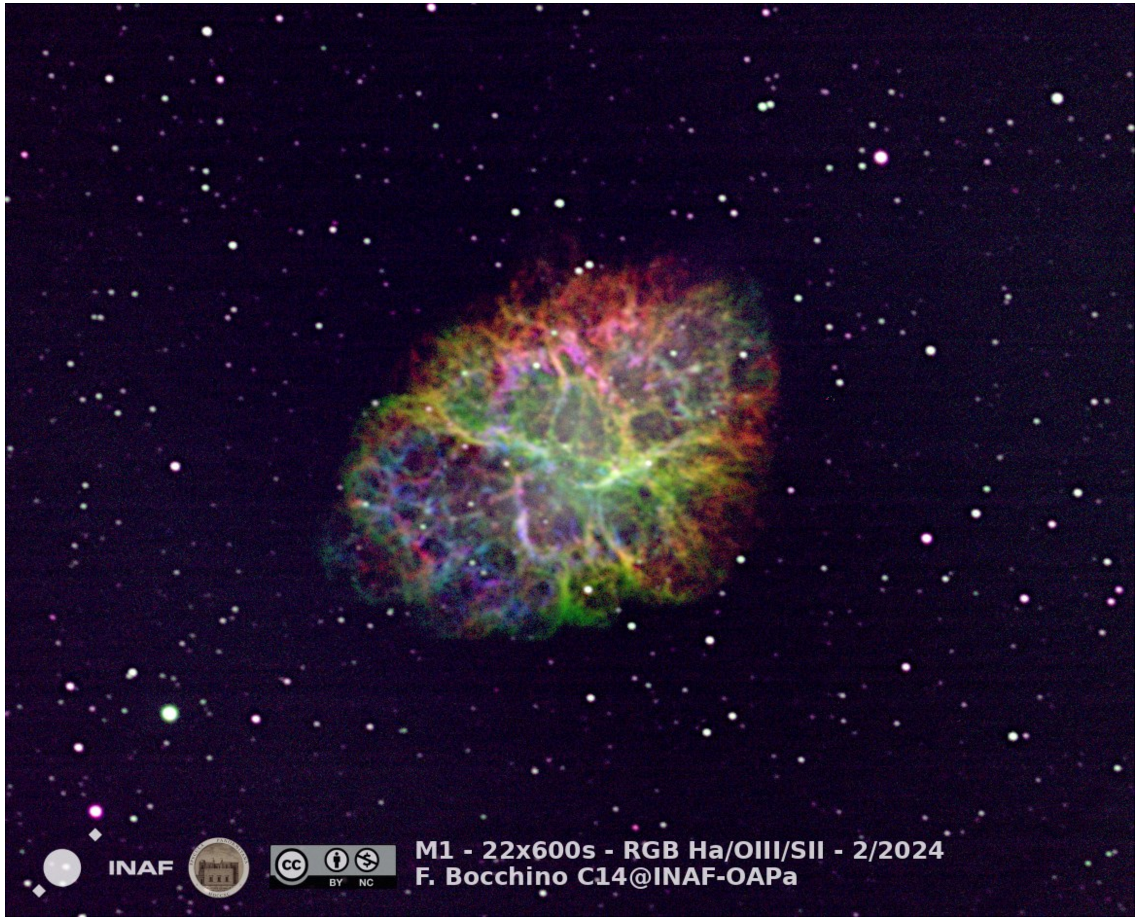


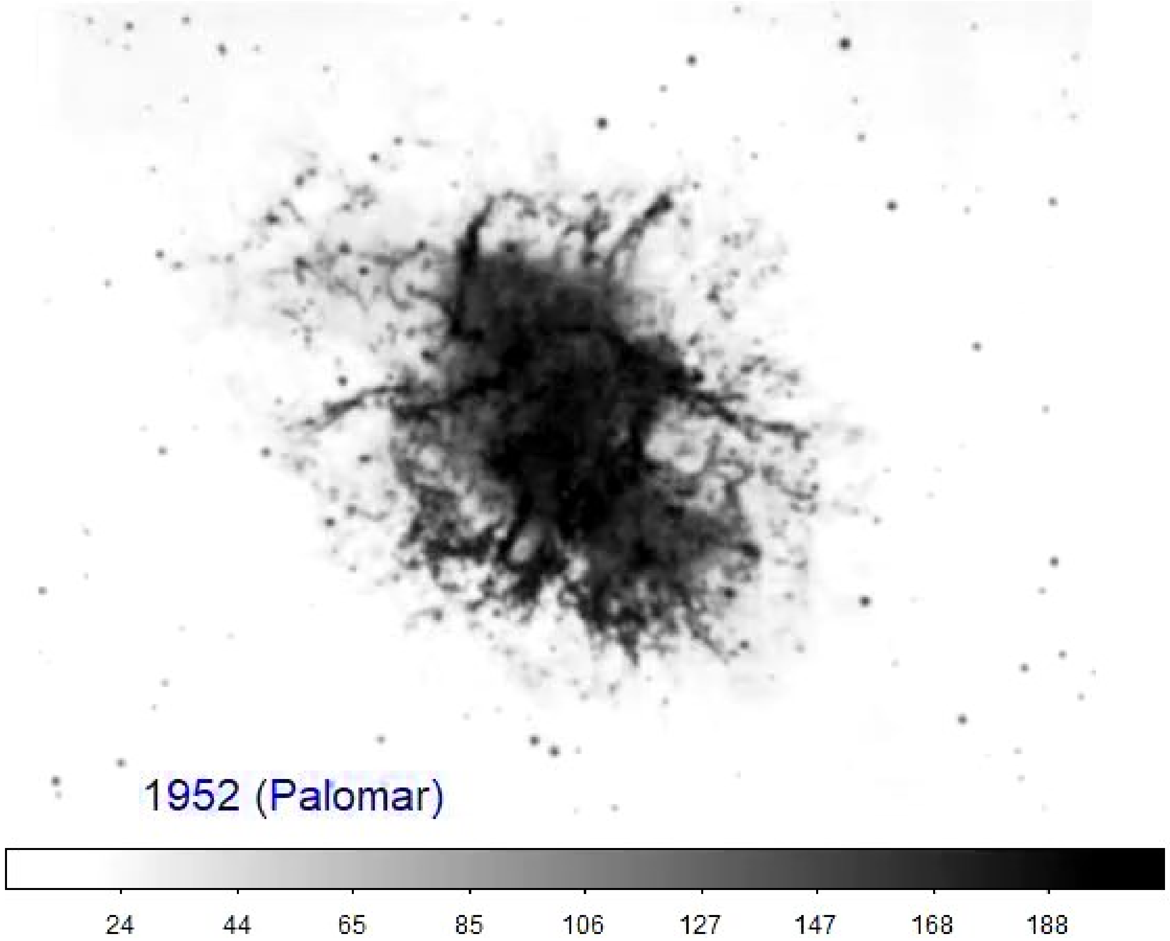
Literature HR diagram



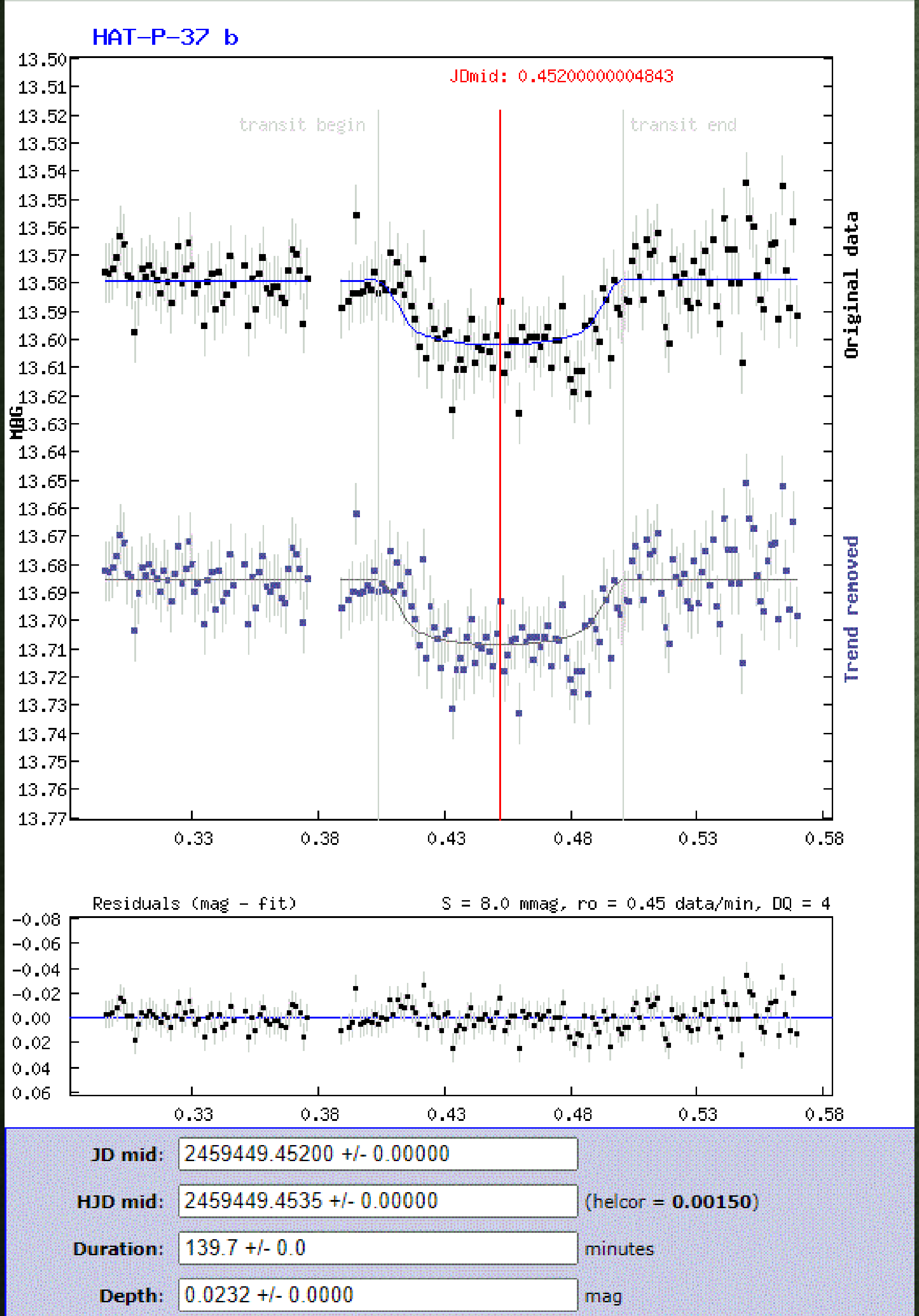
- Moto proprio atteso ca. 3 arcsec su baseline di 10 anni
- Osservazione del 2011 composita RGB da un lavoro di un gruppo greco.

The «educational» Crab





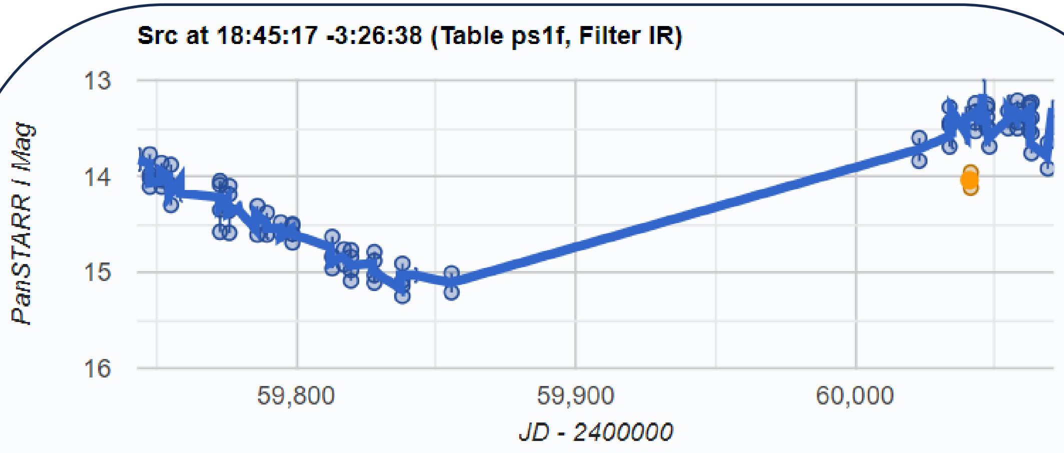
HAT-P37-B

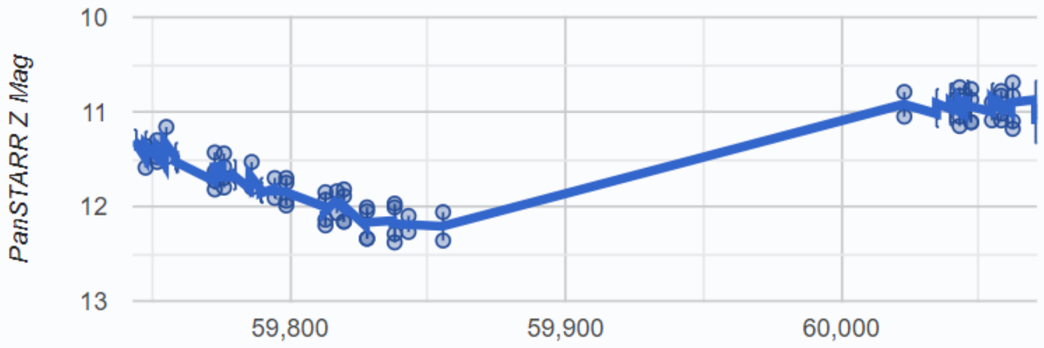


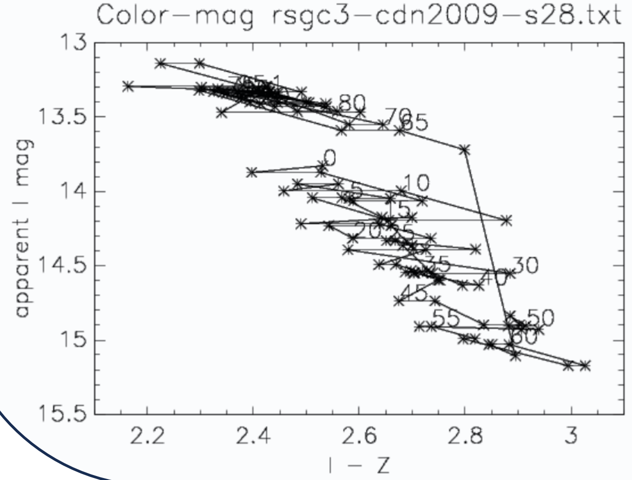
- V (mag) = 13.23
- Depth (mag) = 0.0204
- Duration (min) = 139.8

INAF

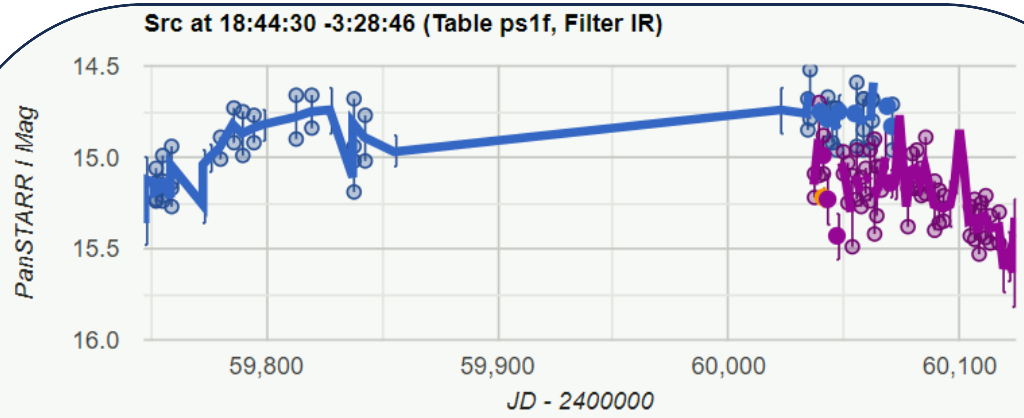
GalRSG C14 Light-curve examples (preliminary)

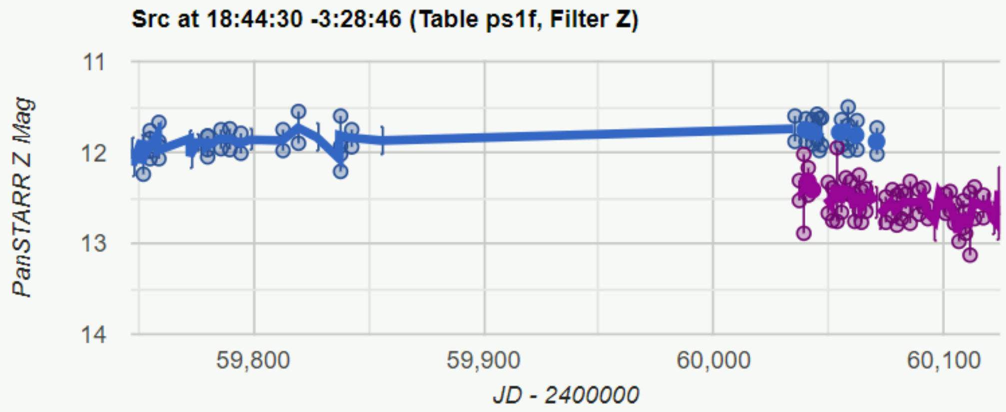






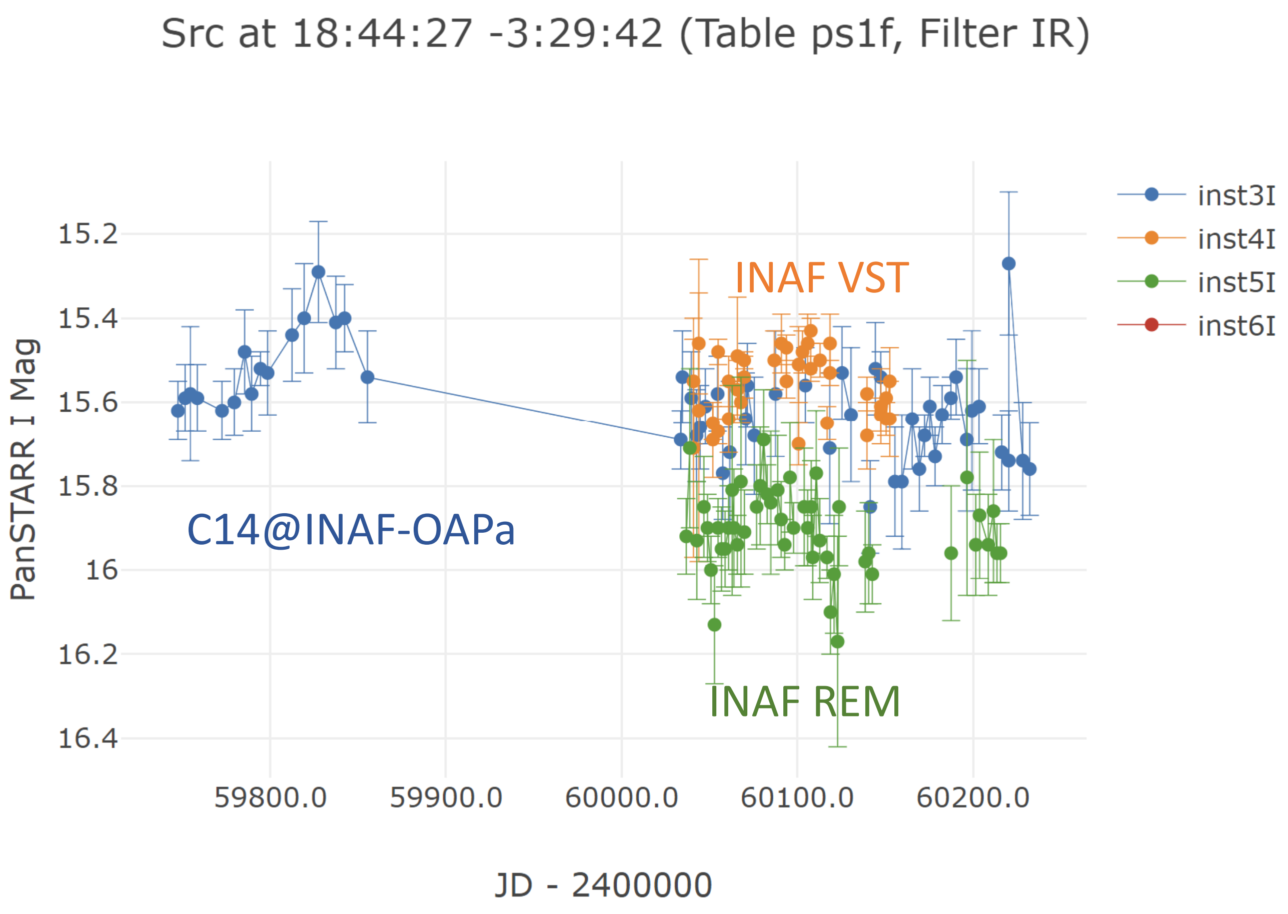
RSGC3 cluster
Source S28

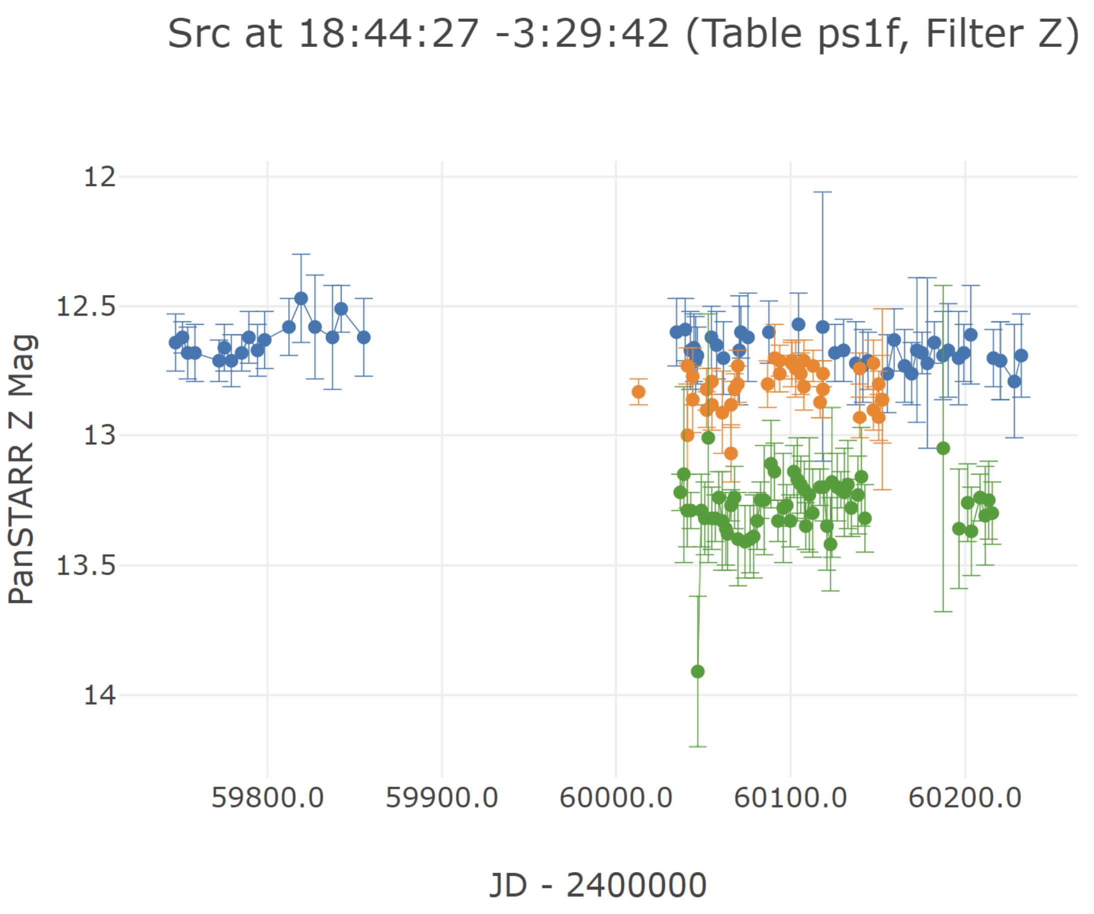




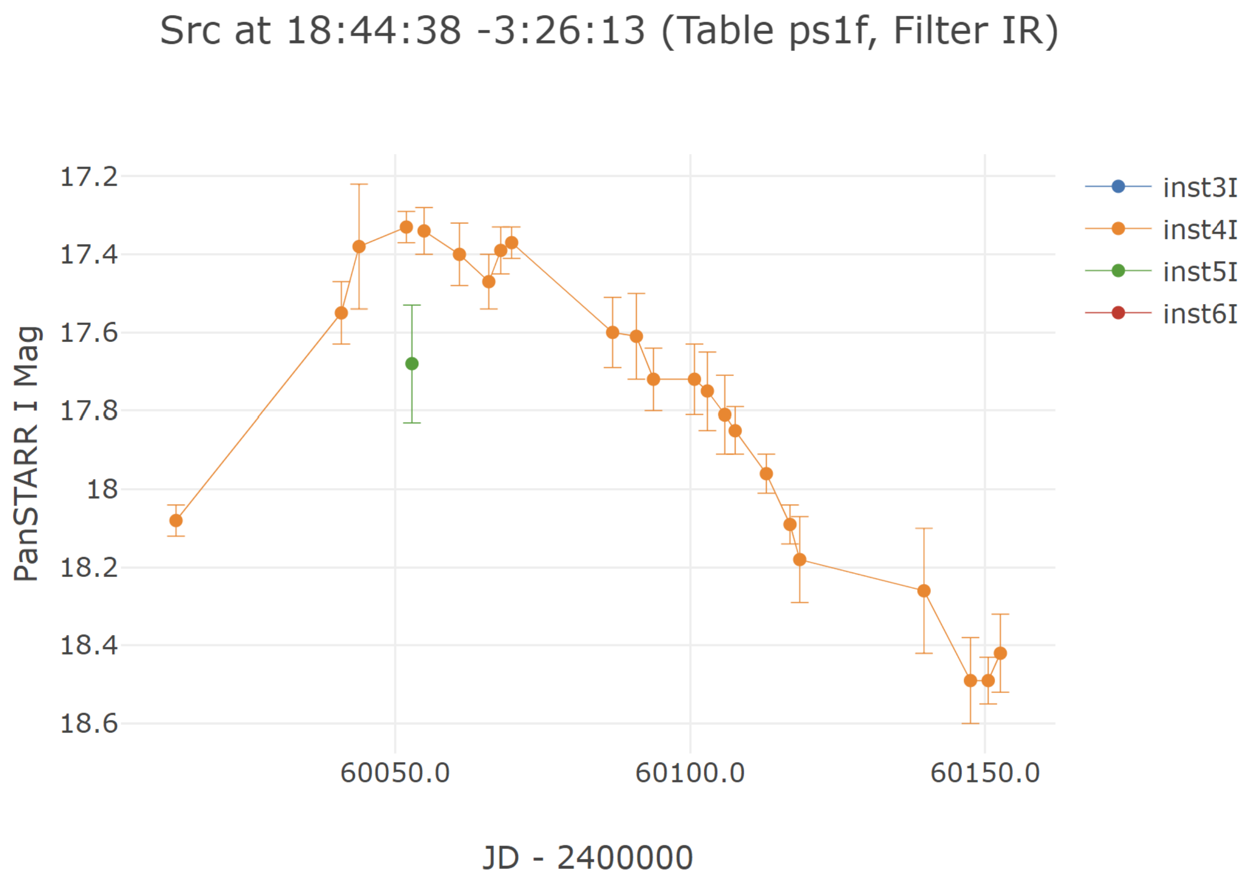
Alicante7 cluster
Source A6

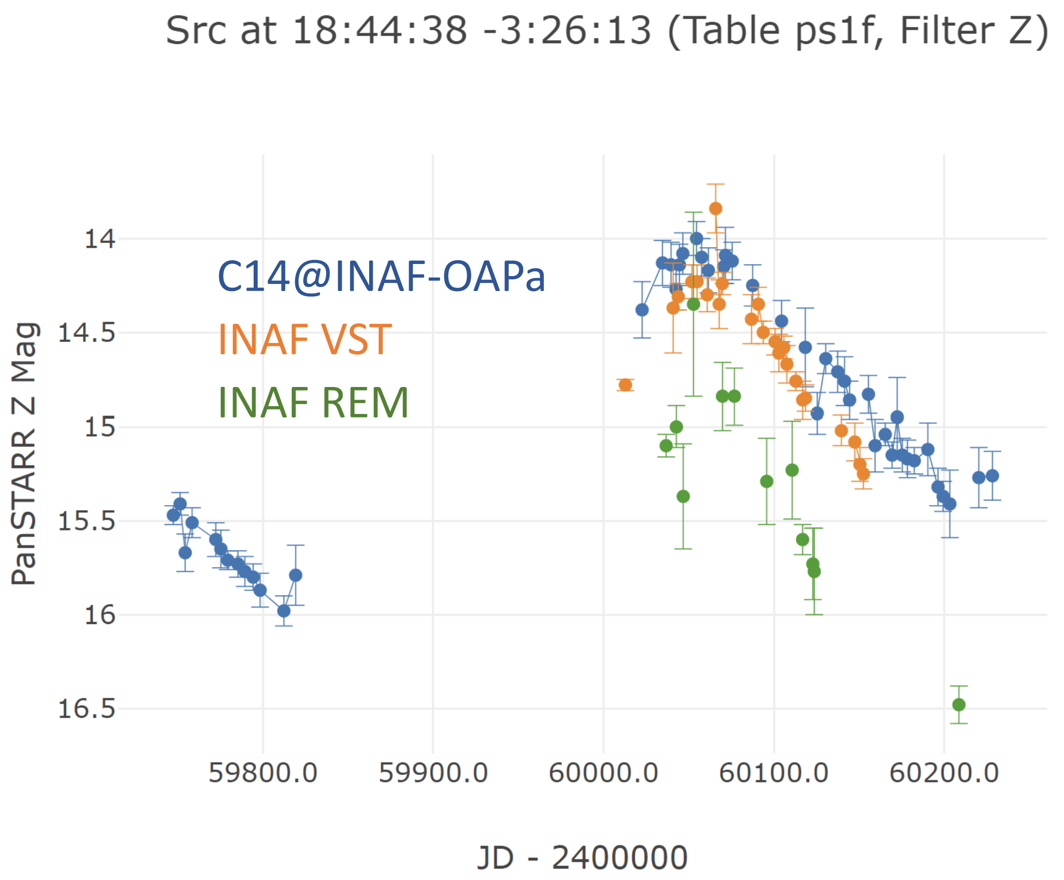
GalRSG: multi-(small)telescope lightcurve examples





GalRSG: multi-(small)telescope lightcurve examples





The contribution of small telescopes to GalRSG: C14@INAF-OAPa

- Advantages:
  - Very useful for pathfinder campaigns, but also as a monitoring aid
  - Long-term projects and short cadences fully supported, we use it whenever we want
  - Differential photometry with FOV catalog stars typically within 0.1-0.2 std mag uncertainty, which is ok for GalRSG
- Disadvantages
  - Limited sensitivity (also due to very bad local sky conditions)
  - Used only on a best-effort/voluntary basis, no dedicated personnel

Conclusions 1/2

- The approx. coeval and co-distant large sample of RSGs in the Scutum-Crux/central bar region provide a unique opportunity to study **faint pre-SN activity of “low-mass” RSGs**
- A dedicated monitoring optical/NIR campaign on these (and other?) RSGs, combined with state-of-the-art models, opens the possibility **to derive their evolutionary stages with high unprecedented precision**
- **Current surveys are not deep enough** for extragalactic “low-mass” RSGs **and/or lack iz and NIR colors**
- **Vera Rubin baseline survey cadence is too long**: 4-5 days (795 visits/10yr, split between ugrizy filters -> 30 days per filter), 14 days in high-dust galactic plane region

Conclusions 2/2

- **Small telescopes are unique facilities** for GalRSG-like kind of science, which requires short cadence, long-term, multi-band optical/NIR monitoring surveys
- A 1 or 2-day cadence small-telescope optical/NIR monitoring campaign of selected regions (GalRSG catalog, Local Group galaxies) will have **a tremendous impact on massive stars and CCSNe studies** and **may lead to prediction of an imminent SN explosion**
  - Next Galactic and L/SMC supernova progenitor is already in the 2MASS catalogue !!